Experiments with Plasmas

P. I. John

Preface

The enforced seclusion caused by COVID-19 nudged me to start experimenting with blogging. I had kept notes on my work, personal life, and professional experiences on my laptop, which turned out to be handy raw materials for my blogs. Some blogs were on plasma physics experiments, plasma processing, thermonuclear fusion and other facets of plasma physics. I started writing on the Medium blogging site last year. These blogs attracted good response.

Medium has many metrics for evaluating your post, including the number of viewers, readers and the time spent on the post. Fans represent the users who clapped for any given story. You can get an idea of the reaction or overall sentiment of an article's performance from this data, which is an insight that you may not be able to get on other platforms. I have close to 1400 followers on Medium now.

Many of the readers of the stories related to my work in plasma physics are research students and young faculty members. Their comments and requests for advice prompted me to prepare some of the blogs in a book form. Many of the articles describe the struggles of an experimentalist, and in many places, I have discussed how I overcame difficulties. I thought that compiling them into an E-Book form may be of some lasting value for students who are planning a career in research.

Many colleagues and friends have responded to my blogs. I thank them all for the encouragement.

John Pucadyil

Acknowledgements

Thoughts about my life lead to a recurring realization that I have been very fortunate to be at the right place at the right time on many occasions. An accident of going to Aligarh made me choose Plasma Physics as a career discipline. It was also an accident that PRL was planning to start work in Experimental Plasma Physics when I was beginning to be disillusioned with continuing to work at Aligarh. After a decade in PRL, the Plasma Physics Programme and Aditya happened through the collective efforts of many people. An understanding Director and a supporting Council made Plasma Processing and FCIPT possible. The exposure to IAEA made me aware of the importance of ITER. The DAE dispensation supportive of Indian participation in ITER also happened at the right time. All these opportunities presented themselves, and one needed only a reasonable competence and an honest commitment to fulfil the demands these opportunities made.

It does not mean that all these things just happened. I can honestly say that I put in a lot of hard work. But I must also acknowledge that many students, colleagues, mentors and friends contributed significantly to help make these things happen. I would like to acknowledge here some of these names.

Prof Rais Ahmed, former Head of the Physics Department at the Aligarh Muslin University, made me realize that science transcended the task of creating new knowledge to drive economic advancement and social change. Prof M S Sodha, former Professor of Physics at IIT Delhi, had always supported my efforts in what he called “getting literate in

Plasma Physics". Professor P K Kaw at the Institute for Plasma Research is a mentor I have seen in many roles; as a great plasma physicist, as a powerful motivator, as an interpreter with great clarity of thought, as a person with profound philosophical and spiritual moorings, as a clever and nuanced strategist, and above all as a person with a grand vision of the role of India in fusion and plasma physics. Prof Abhijit Sen was always a patient listener to my problems when I undertook a risky effort to convert plasma physics knowledge into products of industrial value and offered me sage advice. Prof Devendra Lal, though somewhat ambivalent about Plasma Physics, would constantly send me a stream of reprints and news on Plasma Physics as if to spur me on to higher ambitions.

Dr P K Iyengar and Prof S Ramaseshan, former members of the Governing Council of the Institute for Plasma Research gave me great support, especially during the development of the Plasma Processing Programme and the setting up of the Facilitation Centre for Industrial Plasma Technologies (FCIPT). Dr Anil Kakodkar, former Atomic Energy Commission Chairman, encouraged the concept of the National Fusion Programme and the Board of Research of Fusion Science and Technologies (BRFST) for drawing University faculty into Fusion research. Prof P Ramarao, former Secretary, Department of Science and Technology (DST), helped the Plasma application programme by making it part of the Indo-German initiative in Surface Engineering. Prof V S Ramamurthy, former Secretary, DST, enabled the development of a vital plasma technology for medical waste destruction.

I owe great gratitude to my colleagues in the Plasma

Physics Group at PRL and IPR. Prof Yogesh Saxena was an early collaborator in the experimental work where his skills in computation-based design and data analysis made a huge impact. Prof Shiban Mattoo brought a critical mind to our efforts in setting up complex experiments. Dr Dhiraj Bora and Dr Venkat Ramani joined the group as students and took on extremely demanding responsibilities later.

Prof Igor Alexeff, University of Tennessee, and Prof Charles Wharton, Cornell University, made it possible to create the PRL-NSF programme on Intense Electron Beam Experiments

I am deeply obliged to my students Kamlesh Jain, Chenna Reddy, Vijay Shankar, Deepak Gupta, Purvi Zaveri, Sambaran Pahari, Subroto Mukherjee and Shantanu Karkari for being willing fellow practitioners in the art of building complex plasma devices and making them yield exciting data. I thank Dr Avinash Khare for contributing to our understanding of the nonlinear sheath evolution and the dynamics of non-neutral plasmas. Dr Hari Ramachandran's deep insight helped to make sense of the non-neutral plasma observations. With his characteristic enthusiasm, Ganesh Prasad enabled me to take on many ambitious projects in plasma application development. Sudhir Nema made me appreciate the power of Plasma Chemistry. Ashish Chainani made me realize that science can be gleaned from mundane work in application-driven research.

I thank Dr Shashank Chaturvedi for his continued support of the application programme at IPR and for his efforts to link it to the ATAL start-up programme. Dr Ravi Kumar provided great administrative support in the conception and realization of the National Fusion Programme

(NFP). Dr Ashish Ray and Dr Amit Roy of the BRFST Advisory Board made the difficult task of identifying promising investigators from Universities to fulfil the NFP objectives.

John Pucadyil

About the Author

Prof. P. I. John served as Senior Professor at the Institute for Plasma Research, Gandhinagar. Earlier, he had held the Meghnad Saha Chair in Plasma Science and Technology at the Institute. He took his Ph D degree from the Aligarh Muslim University in 1969 and served there as a faculty member until 1972. Then, he left the University to join the Physical Research Laboratory to establish a programme in Experimental Plasma Physics. He was a member of a group of scientists who established the Plasma Physics Programme in 1982, which evolved into the Institute for Plasma Research in 1986.

In 1997, Prof. John set up the Facilitation Centre for Industrial Plasma Technologies (FCIPT) to link IPR with industries, which successfully demonstrated that it was possible to translate knowledge in Physics into industrially relevant technologies commercially viable manner.

Prof. John has mentored many plasma physicists working in India and abroad. In addition, he led many initiatives of the Department of Science and Technology including the Satellite Research Programme and the Cross-Disciplinary Plasma Sciences Programmes to promote Plasma Physics research in universities.

Prof. John participated in negotiations for India's membership in the ITER Project and helped establish ITER-India to manage the Indian commitment to ITER. He was a member of ITER's Science and Technology Advisory Committee and represented India on the ITER Council. In addition, he served as the Co-Chairman of the Committee for Collaboration in Fusion Research between India and Euratom

Partners.

Prof. John developed the National Fusion Programme for broadening the base of Indian research in fusion science and technology by funding universities and educational institutions in research in this area and continues to serve as Chairman, Plasma and Fusion Research Committee of the BRNS.

Prof. John has 91 publications in international journals and holds 12 patents for plasma devices and plasma processes. His book 'Plasma Sciences and the Creation of Wealth', published by Tata McGraw-Hill in 2005, addresses a broad audience on the value addition through plasma-based technologies. The book has been translated into the Chinese language. His second book "Plasma Processes for Energy and Environment" was published by Lambert Publishers in November 2017.

Prof. John is a Fellow of the Indian Academy of Sciences and Gujarat Science Academy. He was a consultant to the International Atomic Energy Agency, Vienna, on industrial plasma applications and to the International Centre for Theoretical Physics, Trieste, on capacity building in plasma physics. He served as Head Physics Section of the IAEA from 2002–03.

In recognition of the contributions made by Prof John to Science and Technology, the Government of India honoured him with Padma Shri in 2010.

Prof. John's interests transcend science and technology; he paints in oils, writes poetry and is a regular blogger. He has published a book of poetry, "Feng Shui and Other Poems". He is married and has two children.

Contents

1. First Steps

There are two ways of learning new things. In one, you read up everything (prior art in the patent patois) on the field before doing anything. Then, in a second approach, you plunge into the new thing and learn as you struggle. This is the empirical, seat-of-the-pants approach to learning. Being somewhat impulsive, I have been a practitioner of the second school of learning.

Prelude

Chance made me an experimental plasma physicist. Going from University to University in search of an opportunity to work for a Ph, D, I ended up at the Aligarh Muslim University. I had not realized at that time that the Physics department had lost its earlier glory as a seat of physics research. The work in Cosmic Rays led by Prof. P. S. Gill, Nuclear Physics by H S Hans and Spectroscopy by Prof. Putcha Venkateswaralu had ended. Prof. Rais Ahmed, the head of the department who had worked on speech

recognition in England, was trying to rebuild the research base of the department. He was aware of the work at Harwell on thermonuclear fusion and at Oxford on ionized gases and induced me to take a risk in starting experimental work in plasma physics. The department had no prior art or faculty members established in this area. Prof. D. C. Sarkar, who was suggested as my guide, had worked in the Varian Laboratories in the US in plasma physics. Without thinking of the consequences of my choice, I rashly agreed to his suggestion to set up an experiment. Looking back, I believe that while I had stepped into an extremely risky situation, I had the ideal conditions to become an independent experimentalist since there was no one to tell me what to do.

Preparations

The topic of the thesis was an experiment to simulate the Luxembourg effect in which the powerful Radio Luxembourg modulated the ionospheric plasma such that weak European stations became gratuitous carriers of Radio Luxembourg. The Luxembourg Effect was first documented by Prof Bernard Tellegen. The story is that Tellegen was in the Netherlands, listening to a station transmitting from Beromunster, Switzerland, on 652 kHz. In the background of the Swiss signal, he could hear the audio of Radio Luxembourg, which usually broadcast on 252 kHz. He was far away from each station that neither station's signal would have been strong enough to overload his receiver. The two signals seemed to be mixing somehow through a phenomenon of cross modulation between two radio waves, one of which is strong, passing through the same part of the ionosphere, a plasma region in the upper atmosphere.

In my M.Sc course, I had not heard of Plasma Physics.

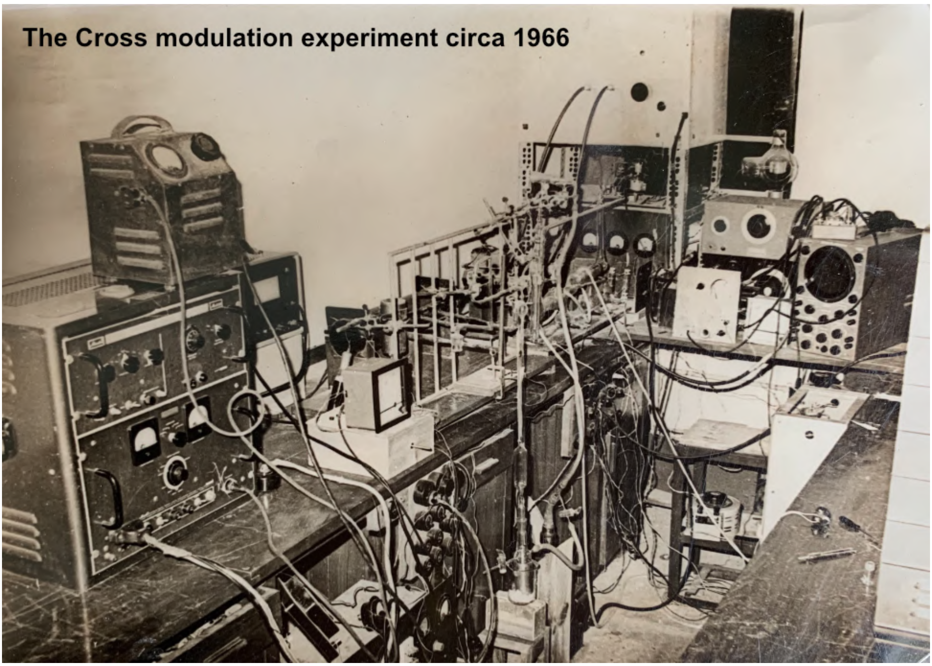
So, having no prior knowledge, I set up a plan to read the essential books and papers in plasma physics. The department had journals like Physical Review Letters, Physica and Nuovo Cimento. The last two journals had articles from European Plasma Physics Laboratories. Though Nuovo Cimento was essentially dedicated to particle physics, the journal reported occasional experimental work in plasma physics. The textbooks were W. B. Thompson's "An Introduction to Plasma Physics" and Von Engle's "Ionized Gases", both excellent for a basic understanding. I learned from the research journals that nonlinear interaction between electromagnetic waves was a topical and important subject.

Learning experimental techniques was the hard part. Review of Scientific Instruments became quite handy. So did the American Journal of Physics, primarily meant to support physics education. I had to learn vacuum techniques, how to build high-power RF circuits, how to modulate a carrier wave, how to use Langmuir double probes to measure the plasma density, how Klystrons operate, how microwaves propagate through waveguides, how to make waveguide components like horns and couplers. The department had a 14.5 MeV neutron generator driven by a DC accelerator which used an RF plasma source as the proton source. The source was my first introduction to laboratory plasma. My friend Rajeshwari Prasad Mathur, working on the accelerator, would tell me about his problems with the plasma source.

The Experiment

My Radio Luxembourg was a high-power Radio-frequency source that would be used to form the plasma and, because of the amplitude modulation, would produce a periodical variation of the plasma parameters like density and electron temperature. Dr K. A. George from the Tata Institute for Fundamental Research advised me on how to build the RF equipment necessary for the work. An old Amateur radio handbook in the Department library was my guide. I designed and built a simple push-pull circuit using World War II vacuum tubes foraged from the Electrical Engineering department. The tubes had no data sheets, and I generated the current-voltage characteristics experimentally. Dr George also supplied me with a glass discharge tube with a Langmuir double probe in his TIFR workshop.

The modulated RF discharge plasma with time-varying parameters was the medium through which an X-band microwave signal travelled, and its amplitude picked up the modulation. The microwave source, transmission lines and power supply were scraped together from Prof. Putcha Venkateswaralu's laboratory, who had left by this time to join


The Cross modulation experiment circa 1966

the new IIT at Kanpur. My research scholar friends, Subhas Chandra, Yogendra Kumar and Rajeshwari Prasad Mathur, were very helpful in helping me chart the unfamiliar environment in the Physics Department.

I measured the modulation transferred to the microwaves while they went through the RF plasma. Prof Sodha, who used to visit the department from the IIT, Delhi, helped me to work out a simple theory to calculate the modulation transfer using the measured plasma parameters like thee density etc. The comparison yielded a reasonable agreement, except for a bump in the measured modulation at the low-frequency end. The results were published in Radio Science (1).

I justified the excess modulation due to acoustic resonances in the low-pressure gas. Although this created some controversy in the thesis defense, I could defend it successfully. I had Uno Ingard's paper (2) on the generation of sound waves because of neutral gas heating in an RF discharge as my supporting work. Later, I proved the validity of this interpretation by observing neutral acoustic waves in modulated RF discharges and publishing a paper on this in the Journal of the Phys. Soc. Japan (3). This was a lesson in the importance of the supremacy of observation in experimental work and standing by one's convictions. My thesis work taught me everything from glassblowing to machining, and I got Ph D degree in 1969.

Looking Back

Looking back with the sophistication gained through five decades of making and manipulating plasmas, I find my first experiment crude and unsophisticated. I did not extract as much information from the experiment as I could have. For example, had I measured the phase modulation of the microwaves, I could have extracted the density of the plasma and its modulation and cross-checked the density data from the Langmuir probe. The generation of acoustic waves and its resonance at low frequency should have been studied more extensively. On the other hand, now I realize the huge risk I had undertaken in volunteering to build the experiment with such limited resources. The sum of it all was that by setting up such an experiment, I learned Plasma Physics and gained a great boost of self-confidence. I was mentally ready to do greater things. My dream those days was to build a Q-machine without really appreciating the complexity of such a device. This remained a dream until I collaborated in starting a project in the Institute for Plasma Research to create a thermally ionized plasma confined with surface magnetic fields much later. Within a few years, I left Aligarh to join the Physical Research Laboratory in Ahmedabad and set up an experiment with Yogesh Saxena to simulate the plasma conditions of the Equatorial Electrojet region.

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2: Simulation of Electrojet Instabilities

Plasma Physics in India began in Allahabad in 1920 with Saha's fundamental theoretical investigations of ionization rates in thermal equilibrium plasmas. In 1938, Saha moved to the University of Calcutta to establish the Institute for Nuclear Physics. With the setting up of the first cyclotron, experiments with the duoplasmatron ion source started. A toroidal pinch experiment had operated at the Tata Institute of fundamental research in the early 1960s. However, with the failure of the ZETA experiment in Harwell in, England, this work was stopped.

The Revival

Vikram Sarabhai picked up the threads again when he assembled a group in the Physical Research Laboratory (PRL) in Ahmedabad in the early 1970s. In Abhijit Sen's words (1),

“The year was 1970, and a faculty meeting was in progress in the committee room of the PRL. In the middle of that meeting, Sarabhai suddenly rose and went to the blackboard to announce his plans to start an experimental plasma physics pro gramme in PRL that would act as a seed programme for a future fusion research programme in the country. He then briefly explained why it was important to do so for the present needs of PRL and the country’s future energy needs. The announcement surprised everybody as PRL was primarily engaged in space research, e.g. study of cosmic rays, ionospheric phenomena and some areas of basic theoretical physics. However, as he sketched the outline of his plans on the blackboard, for which he also allocated a modest budget, it became clear that he had a clear strategy in mind for moving forward.”

By 1970. a theory effort took shape with the infusion of personnel from TIFR, IIT Delhi, PPPL and US universities. The plan was to establish an experimental programme in basic plasma physics with a strong orientation towards the simulation of space plasma phenomena. However, there was a clear purpose of eventually acquiring the skills necessary for fusion research. Leaving my faculty position at the Aligarh Muslim University, I joined PRL in 1972 and was assigned to set up the programme. Yogesh Saxena, who had worked on Cosmic Ray Physics, was an early collaborator.

The Equatorial Electrojet

Prof. Satyaprakash’s rocket experiments from PRL had observed instabilities in the Equatorial electrojet region, which carried a current due to electrons drifting across the magnetic field in the Earth’s ionosphere. The Equatorial electrojet region of the ionosphere at about 100 km height can be characterized as a low density, weakly ionized plasma region where the electrons are magnetized, and collisions with neutral molecules dominate the ions. It has an east-west electron current, vertical density gradient and a vertical polarization electric field and is immersed in the geomagnetic field. The currents and the density gradients in this collisional plasma act as free energy sources and can drive instabilities in the plasma. Radar backscatter and the PRL rocket experiments revealed primarily two types of instabilities in the electrojet region. One is a long wavelength instability excited in the regions where electric fields and density gradients are in the same direction and are now accepted as the high-frequency analogue of the Simon-Hoh or cross-field instability. The other is a short wavelength instability caused by the relative streaming of electrons past the essentially stationary ions with speed exceeding the local ion acoustic velocity and is called the Farley-Buneman or two-stream instability. The experimental observations in the ionosphere have revealed many discrepancies with the existing theoretical analysis. This, as well as the fact that a laboratory experiment is amenable to close control over the relevant parameters, has been the primary motivation for the present study.

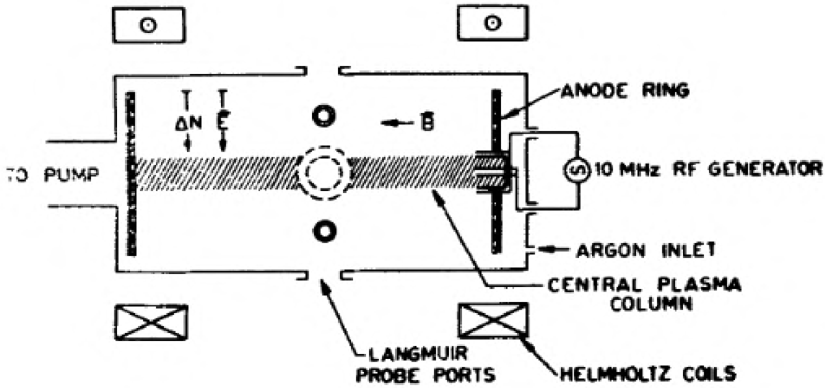
The Experimental Simulation

In setting up the experiment, we put priority on spectral and nonlinear dispersion characteristics, of interest in theoretical work related to the instabilities. Modern digitally implemented statistical signal analysis techniques have rendered these measurements feasible, and our diagnostics were based greatly on these techniques. The first experiment was designed to simulate ionospheric conditions in which these instabilities occur.

A critical requirement of this experiment was to have a plasma region with a variable density gradient. The original plan was to create a plasma by photoionization of Caesium vapour by Ultraviolet light from Mercury discharge lamps. Such a source would have uniform plasma production within the volume because of the transparency of the plasma to the ultraviolet light. However, I realized that this source would have a diffusion-controlled density gradient which would not be externally variable.

In the summer of 1974, I got an opportunity to visit the Plasma Physics laboratory of the University of California Los Angeles campus, which was a significant centre of plasma physics, working in frontier areas like parametric instabilities and building large volume uniform plasma sources using the McKenzie technique of surface magnetic condiment. The giant devices referred to as machines were a revelation to me familiar with small experiments in the corner of a room. This was a great learning experience as it liberated me from being constrained to think small because of resource limitations to being comfortable with the idea of big devices. My colleague Prof Kaw also happened to be visiting UCLA at this time, and I had many opportunities to discuss the physics of the ongoing experiments with him. In addition, we discussed ideas of what we could do back in India to try to be at the forefront of experimental work.

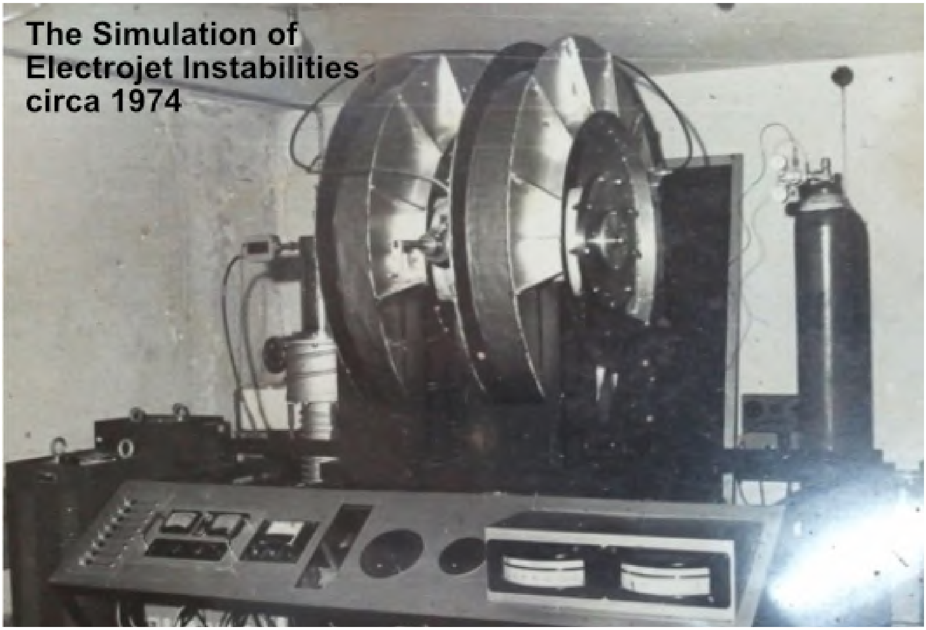
On my return from the UCLA visit, we discarded the photoionized Caesium plasma approach in favour of a more elegant method of using an axial plasma column at the centre produced by capacitively coupled RF power. The magnetic field along the axis ensures that the density along the axis is



The cross field instability experiment. Radial diffusion from a magnetized central column produces radial density gradient

uniform. As a result, plasma diffuses out radially to fill the chamber. The radially density gradient is controlled by the density of the central column, which was variable with the RF power. The critical requirement of the radial electric field was realized by having the plasma terminate on concentric metal rings on which a variable potential gradient was imposed. The parallel conductivity of the plasma ensured that this end wall potential distribution would be replicated within the plasma.

Raising the potential gradient or the magnetic field, which steepened the density gradient, triggered the instability. The azimuthal ExB drift of electrons in a collisional plasma driven by the radial electric field and the axial magnetic field would cause both low-frequency and high-frequency plasma instabilities, which can be detected using Langmuir probes which can pick up both density and potential fluctuations. Farley-Buneman instability is triggered when electrons stream with a velocity exceeding the ion sound speed. The cross-field instability is a flute-like instability which arises due to a density gradient parallel to the electric field. The plasma in equatorial electrojet is weakly ionized collisional plasma with



the abovementioned characteristics. The cross-field and two-stream instabilities are believed responsible for the density irregularities observed in the equatorial electrojet region using radar backscatter and rocket-borne probes. Seeing the distorted density perturbations picked up by Langmuir probes on the oscilloscope screen gave us an incredible thrill.

The Physics

The experimentally obtained dispersion relation obtained by my colleague Yogesh Saxena using cross-correlation techniques on data stored on an analogue recorder differed significantly from the linear theory predictions indicating the contributions from nonlinear effects. Dispersion characteristics of the instabilities obtained experimentally for different values of the applied electric field indicate a good agreement with linear theory for small values of the electric field. Still, they diverge significantly from the theoretical predictions for large values of electric fields. A nonlinear frequency shift from linear theory predictions is indicated.

The data storage technique was strongly influenced by the collaborators from the rocket experiments group, for whom the duration of a single transient rocket flight was all the time they had to collect the data. The situation in a laboratory experiment is quite different, where we can get instability data every time we turn on the plasma. Therefore, the data could have been more conveniently analyzed using spectrum analyzers.

We had great fun discussing the experimental data with the theoreticians. The oscilloscope photographs of observed waves were non-sinusoidal. This triggered an explosion of questions on the experimental process. A delightful part of these discussions was that they generated a lot of ideas on how to interpret the results, how they differed from the predictions of the linear theory etc. The first publication was on the nature of the spectrum of high-frequency instability. More publications (2–4) followed on the nonlinear aspects of the cross-field instabilities

Looking Back

Thus began the revival of experimental plasma physics in India. The Electrojet Instability experiment and later experiments broadened our understanding of the behaviour of different types of plasmas. Plasma theory came alive when we could experimentally visualize the predictions made in theory. In comparing our experimental results with theoretical predictions, we learned what was needed to improve the theory. This was the best way to learn plasma physics.

The lack of critical laboratory parts required to do these experiments because of import restrictions made us improvise and invent out-of-the-box solutions. For example, we devised vacuum RF couplers with Amphenol connectors embedded in an epoxy cast. High voltage feedthroughs were made using outsized O-rings to make electrically floating vacuum flanges. Sinusoidal voltage bias on a Langmuir probe ramped it to create current-voltage characteristics. We learned to trigger vacuum spark gaps with Bostick plasma guns from two wires embedded in a plastic stub. We learned that a piece of paper with pencil scratches would act as an overvolted surface discharge source to trigger a coaxial plasma gun. Finally, we even learned to create high voltage pulse trains with nanosecond rise-time by using a double-Blumlein pulse-forming a line with discarded Coaxial cables and rotating spark gaps (5).

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3 Solitons and Single Particle Confinement

By 1975, the work on the Electrojet instabilities was completed. While evaluating the next steps we should take, a fortuitous visit by Prof Igor Alexeff from the University of Tennessee took place. He had done interesting plasma experiments at the Oak Ridge National Laboratory earlier. He suggested that we should try to set up experiments on ion-acoustic solitons.

Large Volume Plasma Device

My UCLA visit had shown me that a field and gradient-free quiescent Plasma with dimensions far larger than wavelengths or particle mean-accessible paths is desirable for many plasma physics experiments. We built a machine satisfying these conditions in which large amplitude waves and intense ion beams could be launched. Plasma is produced in low-pressure Argon by impact ionization by

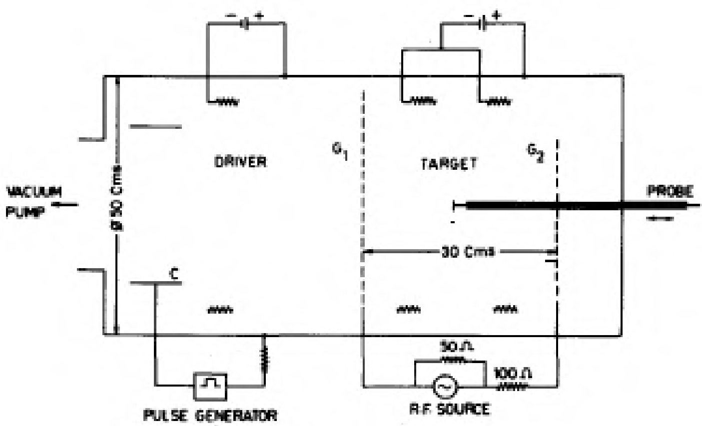


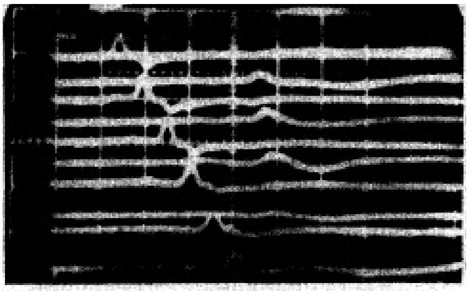
Fig. 1. Schematic drawing of the double plasma machine.

electrons from many spatially distributed hot tungsten filaments. The usable volume is cylindrical, 30 cm in diameter and 100 cm in length. The typical plasma density is 10(8)/cm3, and the electron temperature is 2–7 eV. The apparatus can be operated in the dual-plasma mode by a negatively biased grid at the centre plasma, which inhibits electron flow between the two sections. Raising the potential of one Plasma with respect to the other, large amplitude waves and dense ion beams (Nb/Np ~ 1) can be launched into the experimental plasma region. Langmuir probes, located at various points, are the diagnostics.

Many experiments have been performed on positive ion acoustic pulses, but few on the negative, rarefaction waves. To contrast their behaviour, we experimented on ion rarefaction waves. The positive pulses applied to a grid form the well-known solitons: a compressional pulse evolves into an ion acoustic soliton, propagating with a velocity greater than the ion acoustic velocity and width inversely proportional to the square root of the amplitude. The negative pulses start with the same width and height as the positive pulses. They then broaden and suddenly develop a double peak. We hit the bonanza right in the beginning when we observed fissioning a large amplitude rarefaction wave. Away from the launcher, the leading edge sharpened and later split into two pulses. The characteristic bifurcation appears only at high amplitudes. The nonlinear splitting is explained theoretically in terms of coupling a gaussian pulse to its second harmonic. The experimentally observed amplitude of the second harmonic component agrees reasonably well with the values obtained using the mode coupling calculation.

Soliton Experiments

After Alexeff's departure, we continued with the ion acoustic wave experiments. Soliton behaviour in homogeneous plasmas has been exhaustively studied. However, as the soliton properties result from a balance between nonlinearity and dispersion, we thought it would be interesting to examine its behaviour in inhomogeneous plasmas.



In plasmas with electron temperature exceeding the ion temperature, a compressional pulse evolves into an ion-acoustic soliton, travelling with a speed greater than the ion-acoustic velocity and width inversely proportional to the square root of the amplitude. As the soliton properties result from a balance between nonlinearity and dispersion, we examined its behaviour in inhomogeneous plasmas. A region with density decreasing with distance from the grid is created by keeping a large hollow cylinder into which plasma diffuses from outside. The density gradient produced in this manner is diffusion-controlled and hence gaussian. When solitons are launched into a negative density gradient, they propagate with decreasing amplitude and increasing velocity as predicted by theoretical studies. Conversely, when solitons are launched into a negative density gradient, the amplitude decreases, and the velocity increases as the pulse propagates.

Density gradients are produced by the proper spatial distribution of electron-emitting filaments or by having plasma diffuse into a cylindrical cavity. The experiments reveal that solitons are damped when they travel into decreasing density and amplify when they travel along a positive gradient [1]. The velocity of the soliton behaves conversely. Results agree with the theoretically predicted behaviour.

Reflected ions are seen preceding the solitary wave. The time delay between reflected ions and the solitary wave peak increases as the wave travels down the density gradient. The rarefaction wave following the solitary pulse is also seen to damp.

The ion-acoustic solitons result from a balance of dispersion and nonlinear properties. Since the presence of strong radio-frequency fields alters the dispersion characteristics of the Plasma, we wanted to examine the propagation of ion-acoustic solitons in the presence of such fields. RF electric field of frequency lower than the electron plasma frequency is created in the target region. As the RF electric field increases, effective electron temperature decreases, resulting in a reduced dispersion and slower solitary waves [2]. When the electric fields are further increased, the soliton amplitude decreases continuously. The wave shape becomes highly asymmetric. At larger fields, there is a breakdown near the grids, as indicated by an increase in the dc probe current.

Experimental and theoretical studies on the propagation of ion-acoustic solitary waves in weakly inhomogeneous plasmas with weak density gradients (with scale sizes many times the width of the soliton) have shown that the waves can retain their stationary structure by readjusting their amplitude and speed to match the slowly changing dispersion, the change in dispersion being a consequence of the density gradient existing in the Plasma. We studied ion-acoustic solitons' behaviour in plasmas with sharp density gradients with scale sizes of the order of or smaller than the width of the soliton. We observed partial reflection of ion-acoustic solitons from an ion-rich sheath of a negatively biased grid. The wave packet from a partial reflection of the soliton from a plane within the sheath region where the density-gradient scale size is smaller than the soliton width [3]. As the grid bias is made more and more negative, the density-gradient scale sizes are altered, and the distance of the reflecting plane from the grid increases for a given width of the incident soliton. However, the density-gradient scale size at the reflecting plane remains unaltered. Theories on the propagation of ion-acoustic solitary waves in sharp density gradients (with scale size smaller than or of the order of soliton width) do not exist. The observations that the reflected wave spreads, its amplitude reduces as it moves away from the reflection region, and the wave packet moves with subsonic speed indicate that the reflected wave may be highly dispersive.

Single Particle Confinement

With the success of these experiments, a more sophisticated experiment on the confinement of single particles in a non-adiabatic magnetic mirror was attempted along with Dhiraj Bora and Saxena. The motivation was the theoretical work by Prof Ram Varma, which attributed the non-adiabatic loss of particles from a mirror trap to tunnelling from the adiabatic potential well by particles of energy lower than the maximum height of the potential barrier. It predicted the decay of the number of particles from the trap with multiple lifetimes. An ultra-high vacuum chamber with multiple water-cooled solenoids forming asymmetric mirrors was set up. Electrons were injected into this from a thermionic injector. An electrode beyond a mirror throat collected electrons leaving the trap. The low electron density ruled out collective behaviour. The experimental results conformed to theoretical predictions in some essential respects [4]:

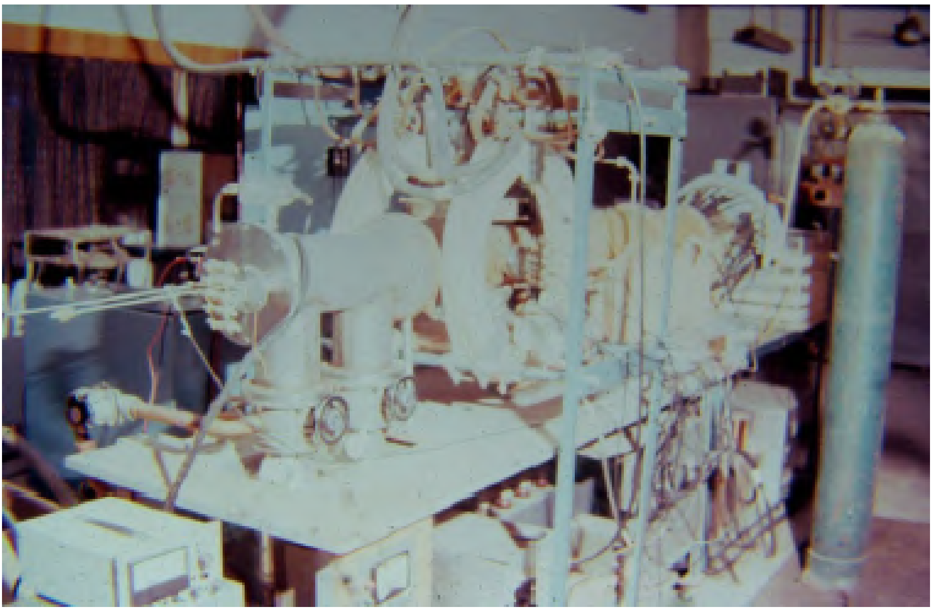
• The existence of more than one decay time

• Their dependence on the magnetic field gradient and particle energy

The slope of lifetime values versus magnetic field at different pitch angles, radical positions, and particle densities agreed with theoretical predictions [5].

More Experiments

Hannes Alfven proposed that when Plasma and neutral gas interact in relative motion across a magnetic field, rapid ionization of the neutral gas will happen when the velocity exceeds a critical value. He used this as a basis to explain the



solar system's formation. However, a theory developed at PRL by Prof Ram Varma proposed the existence of a threshold velocity determined by the kinetic energy of the ion species for the interaction to happen. The experimental device produced fast-moving plasma streams from a coaxial plasma gun impinged on a neutral gas cloud formed by releasing gas into a vacuum through a fast-opening gas valve. The experiment by S. K. Mattoo and Venkata Ramani confirmed the critical velocity phenomenon while showing the absence of the threshold velocity [6-8].

Thus, the plan to establish an experimental programme in Plasma Physics, oriented toward the simulation of space plasma phenomena, got off to a good start. However, in choosing each experiment, there was an unstated purpose of acquiring the skills necessary for fusion research. My next venture in experiments with intense electron beams was to meet that objective.

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4 Intense Electron Beams

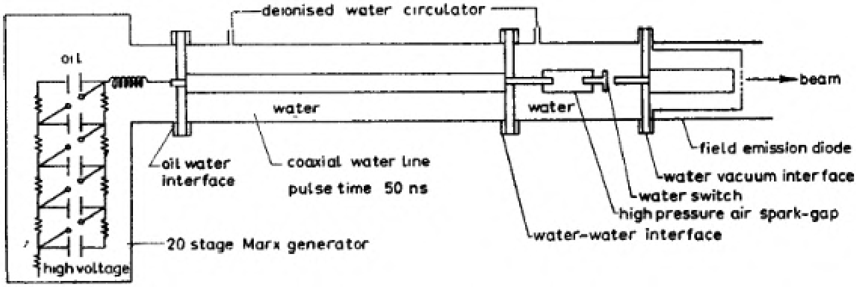
A talk by Prof Igor Alexeff of the University of Tennessee on the work in the Soviet Union by Leonid Rudakov and others on inertial fusion using intense electron beams triggered my interest in intense electron beams. Electron beams have interesting physical properties, even at moderate beam energies and currents, say a few hundred keV and tens of thousands of amperes. The associated space charge is intense, producing self-electric fields of the order of MV/cm. The self-magnetic fields are strong enough to turn the beam trajectories into complex shapes or even reflex the beam electrons. When injected into a plasma, the electric field gets cancelled by the expulsion of plasma electrons. The rising front of the self-magnetic field drives return currents. When such beams pass through plasmas, fascinating effects involving the interaction of beam fields with plasmas will happen.

Pulse Power Technology

The essential elements of sub-microsecond pulse power technology are high energy density capacitors, high-pressure spark gaps, Marx generators and transmission lines for pulse formation, etc. This field was born in the early 1960s at Aldermaston, UK, and we had to catch up with more than a decade's accumulated knowledge. We experimented with every aspect, including making energy storage capacitors by rolling polyester sheets sandwiched with aluminium foils. A Marx generator erected on a wooden frame with exposed spark gaps was the learning tool.

Alexeff suggested writing a proposal for investigating the interaction between intense electron beams and plasmas for funding by US National Science Foundation. I submitted this with Alexeff and Charles Wharton of Cornell University as collaborators. NSF sent an expert to look at our capabilities and, based on his report, reviewed the proposal. They said that while the proposal's objectives were sound, they doubted whether Indians would be able to master the Intense Pulsed Electron Beam technology. I thought that the best way to respond to this rebuff was to demonstrate our capability independently. I managed to get funding to start this work from PRL. Denial regimes are the best triggers for indigenous capacity building.

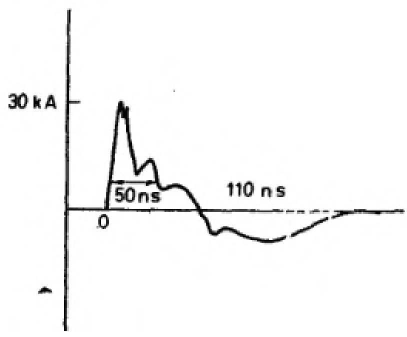
By this time, Kamalesh Jain had joined as a research student. My other collaborators were Dr Punitha Velu and Dr Prabhakar Rao. Rao had a PhD from Oxford and had experience in high voltage techniques. We did not have the low inductance energy storage capacitors required for these applications and so decided to make our own capacitors by using aluminum foils and plastic sheets rolled into tight cylinders. The capacitors were mounted on a wooden stand and spark gaps were used to trigger the Marx erection.



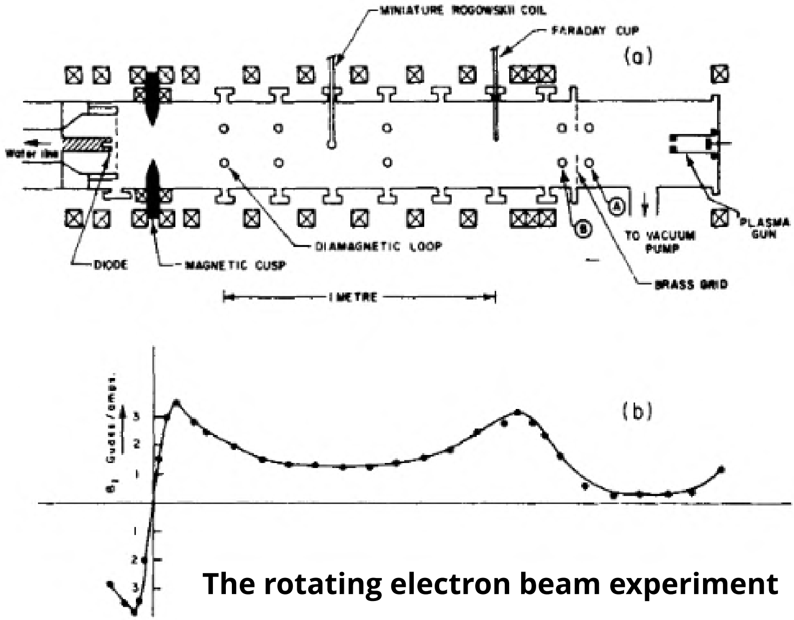
The schematic diagram of the intense electron beam experiments. The Marx generator is on the left.

After gaining confidence from our makeshift bank, we procured plastic case capacitors from Maxwell. We finally put together a 20 stage Marx bank using these capacitors housed in an oil-filled tank. The spark gaps were housed in a long Perspex column and dielectric surface flash triggered the spark gap switches. The Marx output charged a 100-nS water pulse forming line, which switches through an over-volted water switch into a graphite cathode generating a 300 kV 30 kA 100 nanosecond annular beams. This is nominally a beam carrying Gigawatt power. We described this work in a paper in Sadhana [1].

Pulse power technology was a classified field, and hence even friends in US could not advise us if we had problems. For example, the Perspex flange in the water switch often used to crack, and we realized it was due to the shock generated during the switch firing. When I asked US expert Magne Christianson how to solve this problem, he admitted that he had the



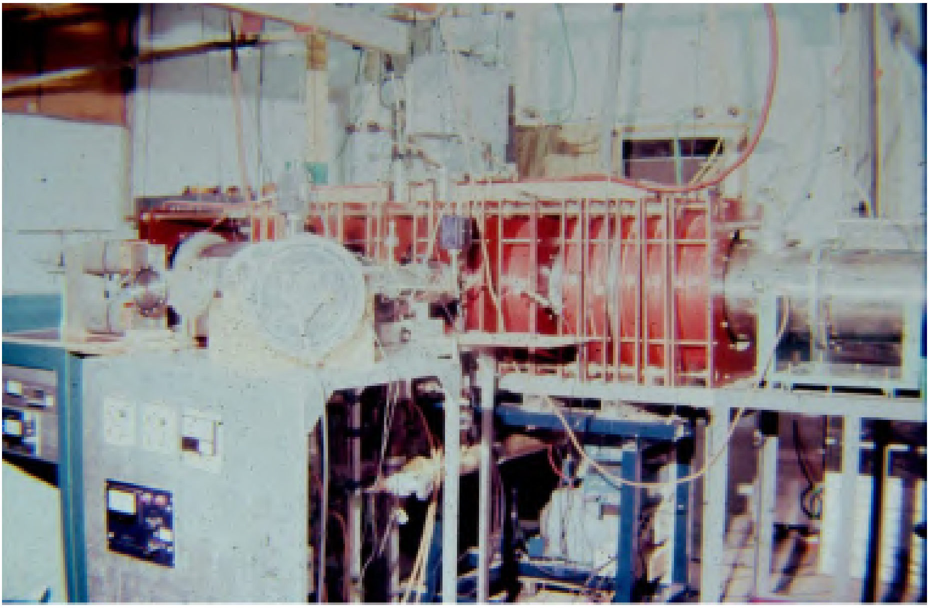
The 100 nanosec current pulse



The rotating electron beam experiment

answer but could not help us since it was classified. So, we had to solve such problems from the first principles.

A very important lesson that we learned from these early forays was that although these are conceptually very simple systems, the complexity lies in the practice and prescriptions. For example, the water vacuum interface was a Perspex flange on which the cathode is attached. This is a classic triple junction where dielectric, metal and vacuum meet and is prone to electrical breakdown dumping energy in a radial flashover. We had to understand how to embed the radial electrical field in the dielectric thereby stopping the avalanche build up along the dielectric surface. Solving such problems involves building prototypes, testing them and thereby building up a knowledge base.

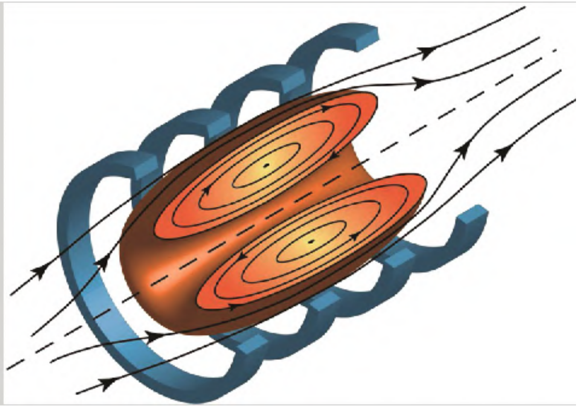


The Rotating Electron Beam Experimental Machine

Rotating Beams

By the time we were ready with the beam, laminar beam plasma interaction studies had been exhausted, and we decided to get into the novel territory of rotating electron beams. When a paraxial beam is sent through a non-adiabatic cusp magnetic field, it gets converted into a beam rotating around the axis. The experiments we performed on the effects observed when rotating electron beams for propagate through plasma, formed Jain's thesis. He observed effects like excitation of a cross-field return current layer after the beam exits the plasma, generation of magnetosonic waves by the return current layer, and heating by magnetosonic waves [2-4].

The device also led to another thesis by Vijay Shankar on the self-field effects and the effects of charge neutralization on the dynamics of intense beam propagation through non-adiabatic cusp fields. He studied the dynamics



leading to the conversion of the laminar beam into a rotating beam by the action in the cusp region and the effects of charge neutralization and beam self-field on the conversion [5].

Compact Torus

Kamlesh Jain who had joined as a post-doctoral student, upgraded the electron beam generator to produce higher energy and longer duration beams by directly firing the Marx generator into the diode. The beam was now strong enough to excite return currents, which were so high as to reverse the original mirror magnetic field. This results in the formation of a field-reversed configuration commonly known as a compact torus [6].

The CT formation works as follows: A high current electron beam, spiraling around the axis is injected into a metal chamber kept in an external, axial magnetic field. The chamber contains neutral gas (hydrogen) at the required pressure. The spiraling beam is like a current carrying coil and generates a. magnetic field of its own, in a direction opposite to the external field. Two things simultaneously happen when the spiraling beam passes through gas. First, the magnetic field at the axis is reversed due to the self-field of the beam, and the neutral gas is converted into a plasma by the absorption of the beam energy. Secondly, when the pulsed beam leaves the electrically conducting. plasma after embedding the reversed field, an almost equal current is induced in the plasma, with the result that the reversed field configuration is sustained now by the plasma currents. To increase lifetime of reversed field configuration, Marx generator was directly connected to the field emission diode and thus, a long duration electron beam was injected into the neutral gas. Due to increase in the duration of the electron beam, we observed formation of a long-lived reversed field configuration. Detailed temporal evolution of magnetic field topology in our experiment was obtained by a two-dimensional mapping of the magnetic flux surface with the help of an array of magnetic probes. Reconnection of the beam-produced field and the external magnetic field has been observed which results in the formation of a prolate spheroid.

I gave an invited paper on our rotating electron beam experiments at the International Conference in Plasma Physics held in 1982 in Goteborg, Sweden. The chairman of the session was Prof. Ravi Sudan from Cornell University who suggested that PRL should set up a collaborative programme with Prof Charles Wharton of the Cornell University.

PRL-NSF Collaboration

Prof Wharton visited us and sent a report to NSF highlighting what we had done independently in pulse power development. NSF funded our proposal for an experiment on understanding what happens when a high current beam is injected into a toroidal system, a hollow cylinder bent into a ring. This time NSF got convinced that we had the requisite expertise to deal with pulsed power systems and suggested putting in a new proposal. For this purpose, an REB generator based on Tesla Transformer charging a pulse forming line driving a graphite cathode was built. Thus, the first toroidal device in IPR in which Chenna Reddy started experiments on injection and stacking of high current electron beams was built.

The basic idea was to see if one can load a ring current so that one may be able to form. tokamak-like configuration with relativistic electron - beams replacing thermal current carriers. Plasma was injected into the torus with the help of a gas injected, washer stack plasma gun. Using plasma as anode, the electron: beam was injected into the torus. The beam injection was studied in two different plasma densities. When beam was injected inta low-density plasma, the beam was lost by hitting the injector from the back after one toroidal transit. No net toroidal current was observed. In the case of injection into a high-density plasma, the beam drifted inward, cleared the injector, and was trapped. A net toroidal current of about 5 kA was generated in this case, Temporally and spatially resolved measurements with miniature Faraday cups and small Rogowski coils showed that beam trapping was due to a fast return current decay.

The return current decay time calculated from ion-acoustic turbulence was found to be consistent with the observed net current rise time. Localized measurements of the poloidal field indicated a net current channel. moving radially inward with no observable vertical motion. This is attributed to the drift injection-energy: loss mechanism proposed for beam trapping. From these measurements it was also found that about 50% of the beam energy appears as plasma perpendicular energy and the heating was mainly due to return current dissipation. The current profiles obtained from the magnetic field measurements indicated that the system goes into a low q state as time progresses.

The beam energies calculated from the observed net currents and shift of the current channel were found to be consistent with the beam energy transfer observed from diamagnetic measurements [7].

We also had enough money to build a new plasma physics laboratory in PRL. The toroidal plasma device evolved into BETA, an acronym for Basic Experiments in Toroidal Assembly.

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5. Non-neutral Plasmas

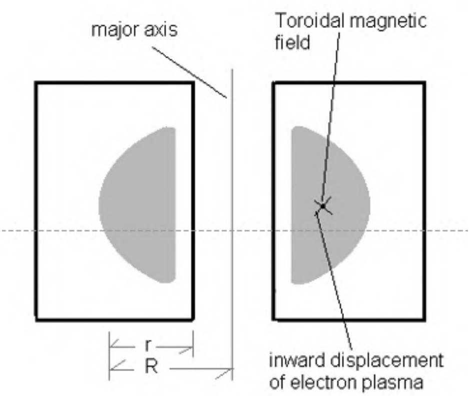
In the late eighties, I got interested in the physics of dense clouds of electrons confined in electromagnetic traps. They are plasma-like, exhibiting collective effects like waves, instabilities and self-organization. John Malmberg and his co-workers at the University of California in San Diego pioneered studies on the fundamental properties of linear columns of electron plasmas like equilibrium, instabilities, transport, vortex dynamics, relaxation to thermal equilibrium, cryogenic transition to Coulomb crystals etc.

Toroidal Electron Clouds

Non-neutral toroidal clouds of electrons or ions are interesting from several points of view. In the early days of controlled thermonuclear fusion research, it was shown by Budker [1] that pure ion clouds could be trapped in a toroidal field with the self-consistent space charge field producing a rotation in the poloidal direction and thereby preventing the charge separation effects. However, these devices were not considered suitable for fusion systems because it had been shown that the density limit due to space charge does not permit significant plasma pressures to be trapped in realistic magnetic fields. However, recent theoretical work has shown that by appropriately shaping the equipotential contours, one may improve on the density limits and thus go into attractive parameter regimes.

Over the years, one has also learnt from experiments with electron clouds that confinement of singly charged species in cylinders is excellent because like-particle collisions do not lead to any net transport of the electron fluid across field lines. Thus it appears helpful to re-investigate the potential of toroidal traps as interesting pure ion fusion systems. Similarly, there is interest in toroidal electron clouds from the point of view of betatron accelerators and the trapping of ions in potential wells created by electrons [2]. Finally, as a fundamental system pure electron or ion systems are interesting because of the severe constraints, they impose on overall particle motions and transport etc.

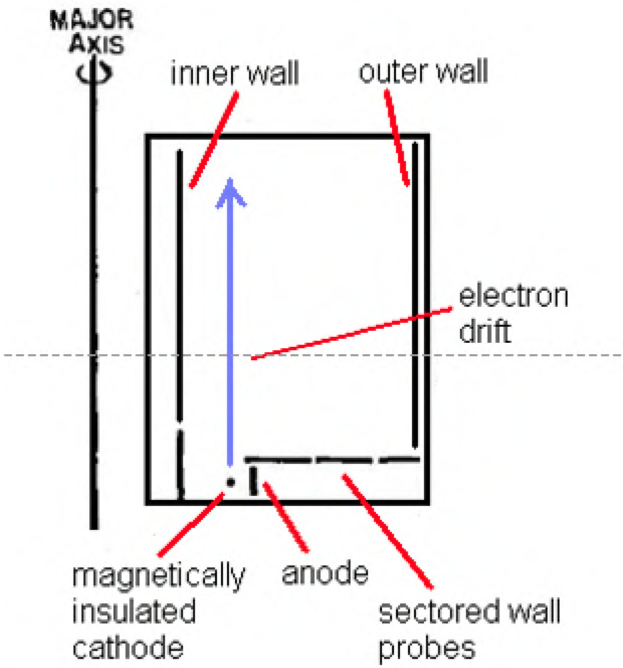
We found no reported work on the physics of ring-shaped non-neutral plasma trapped in toroidal devices. A torus is a cylinder bent into the shape of a ring. We speculated that strong toroidal effects should occur if the radius of the cylinder and the ring become comparable. Being a virgin territory, we exploited this opportunity to do novel experiments. We built a device with a central conductor inserted into a cylinder along its axis. The current carried by the central conductor created a ring-like magnetic field. Electrons were injected into this device from the periphery by rapidly increasing the toroidal magnetic field, which produced an ExB flow towards the minor axis. The cloud trapped in the device exhibited collective properties. Puravi Zaveri presented the first results on the formation and existence of equilibrium of a very low aspect ratio non-neutral plasma ring at the International Conference in Plasma Physics held in Delhi in 1989.



Concept of the toroidal Nonneutral Plasma experiment

Toroidal non-neutral plasmas are fundamentally different from cylindrical ones. Being endless, electrostatic confinement along the B field is not needed. Under the self-electric field, the electrons move in the E x B direction, overcoming toroidal drifts to give confinement without a rotational transform. The balance between the electrostatic hoop force, diamagnetism, or centrifugal forces in the outward direction and the inward image forces generate equilibria that shift towards the inner walls near the central axis. Toroidal effects such as radial shifts and deviations from rigid rotation increase as the aspect ratio approach unity.

Non-neutral and neutral plasmas respond to forces along the major radius. A current-carrying plasma in a conducting shell attains equilibrium due to image currents, which repel the ring, producing an outward shifted equilibrium. The equilibrium of the charge ring is due to image charges, which attract the ring resulting in an inward-shifted equilibrium.

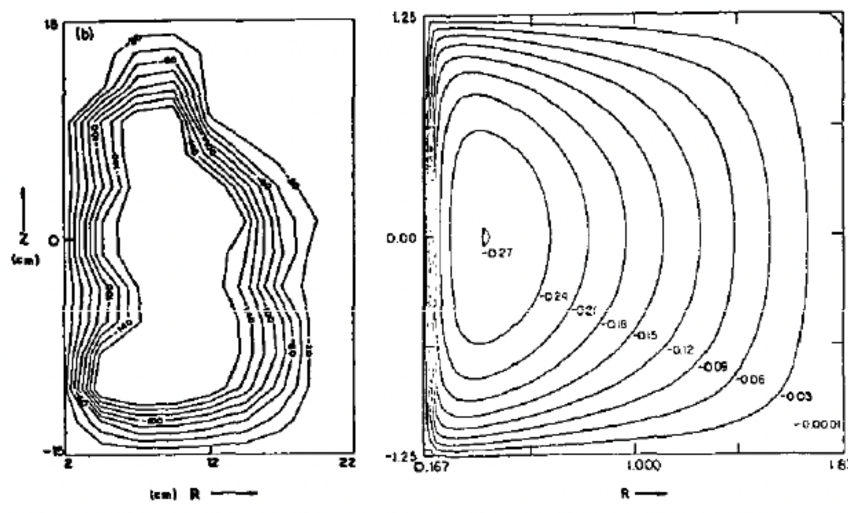


Schematic diagram of the Nonneutral Plasma experiment

Neutral plasma needs an externally imposed rotational transform to overcome the effects of first order drifts. This is self consistently provided in the non-neutral plasma by the zeroth order, azimuthally closed Ex B drift. Consequently, while the shape of the magnetic surfaces is controlled by diamagnetism in neutral plasmas, it is independent of diamagnetism in non-neutral plasmas. The physical reason for this is that diamagnetism, hoop force and restoring force are all proportional to the square of density in the non-neutral plasma.

For the case of neutral plasma, stable static equilibria governed by J x B forces balancing the pressure gradient are possible. However, because of Earnshaw's theorem, stable static equilibria for non-neutral plasmas are ruled out. Therefore, the equilibrium of non-neutral plasma can only be dynamic, involving flows.

A rotational transform must be externally imposed to overcome the effect of first-order drifts in neutral plasmas. In contrast, in the non-neutral plasma, the rotational transform



Equipotential contours obtained by a potential probe showing the inward shifted equilibrium

is self-consistently provided by the zeroth order ExB drift. A consequence of this is that whereas in neutral plasmas, the shape of magnetic surfaces is controlled by the plasma current, in a non-neutral plasma, the shape is independent of the diamagnetism. A simple way to see this is as follows: In a neutral plasma, the diamagnetism is controlled by plasma pressure. At the same time, the rotational transform (and hence the restoring force) is externally imposed and therefore is independent of plasma pressure. As a result, when plasma pressure is increased, the force along R due to diamagnetism increases, while the restoring force due to compression of poloidal flux remains the same. This causes the plasma to be pressed against the outer wall, the outward shift of the magnetic axis increases and the shape of magnetic surfaces changes significantly when the ratio of pressure to the poloidal field energy increases. On the other hand, in a non-neutral plasma, the diamagnetism is controlled by the density. Thus, when diamagnetism is increased by increasing the density, all the forces increase proportionately, leaving the equilibrium unchanged.

The first paper on the equilibrium features came out in the prestigious Physical Review Letters in 1992, the first paper in experimental plasma physics from India to appear in that journal [3]. Interesting complementarity between charged non-neutral plasmas and current-carrying neutral plasmas, like the capacitive effects replacing inductive effects etc., are discussed in the paper.

I remember two incidents connected with talks I gave on non-neutral plasmas. The first one happened in Indore when I gave a talk at the Annual Conference of the Plasma Science Society of India in the Centre for Advanced

Technology in Indore in 1991. The Hindi newspapers from Indore promptly reported that “Scientists had discovered unnatural plasma”. The other incident relates to an invited talk I presented at the 1992 International Conference in Plasma Physics in Innsbruck [4]. Among the audience was Prof. John Malmberg, the pioneer of non-neutral plasma research, who complimented me on the novelty of our approach.

Steady State Electron Clouds

In Sameer Khirwadkar’s work [5], we invented a method of plasma formation based on the modification of the vertical drifts into closed diocotron drift trajectories by combining the self-consistent space-charge electric field with an externally applied radial electric field. Unlike earlier experiments that used time-varying magnetic fields to transport particles and form toroidal clouds, we could access the inward-shifted toroidal equilibria in a steady state. Furthermore, finite resistivity of the wall may also play a role in the formation of the cloud through this mechanism which is essentially the capacitive analogue of the trapping of current-carrying electron beams in toroidal cavities due to magnetic energy loss. We have confirmed that the toroidal electron cloud is not tethered to the injector but is in a true, self-consistent equilibrium generated by its interaction with the conducting wall by stopping injection and monitoring the macroscopic behaviour of the cloud using both potential and wail probes. As an indicator of the equilibrium position, the potential axis does not undergo any drastic displacement after the injector turn-off. Oscillations on the wall probe indicate the presence of the cloud for hundreds of diocotron periods: the potential and the oscillations decay with the same period. Presence of oscillations and the dependence of the lifetime on the background gas pressure imply that both charge-neutralization and anomalous transport may determine the lifetime of the cloud. The equilibria obtained by image forces on conducting walls can be modified by applying a radial electric field produced by a positive bias on the inner wall. Peak cloud potential increases with external bias, and the potential axis shifts outwards. The electron plasmas formed with the positive bias are detached from the inner wall by a vacuum region and a separatrix. The outward shift of the potential axis increases linearly with the bias.

The observed outward shift of the toroidal cloud under the influence of a radial E-field can be understood by modifying the force balance condition due to charges in the boundary [6-7]. Since the outward electric field imposes an inward force on the cloud, the contribution from the image charges can be reduced, resulting in an outward shift of the cloud. This shift away from the positively biased inner wall results in the cloud gaining potential energy. The saturation of the effects of the bias at large values may be due to the nonlinear nature of the internal capacitance of the cloud.

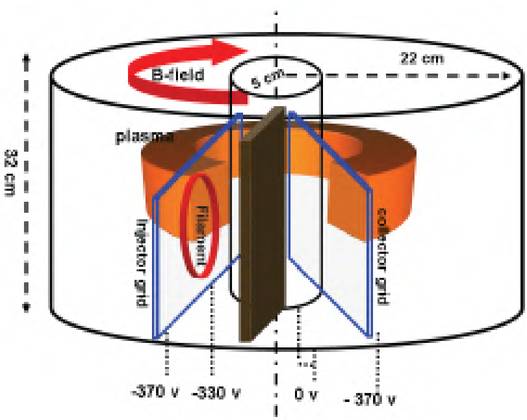
We have also studied the dynamic response of the cloud to changes in boundary conditions. When the cloud is initially formed with a bias which is suddenly removed, the cloud responds by moving inwards in a secular manner. The characteristic time for relaxation is larger than the diocotron period. The precessional motion around the equilibrium, seen in experiments with linear electron plasma columns, is not observed in the signals from the probes within the plasma. However, the wall probes record oscillations, which may indicate the non-rigid rotor nature of the cloud.

When the equilibrium is supported by a positive bias on the inner wall, we see a separatrix parallel to the inner wall. Beyond the separatrix, the potential is zero, indicating the absence of electrons, without which the electrostatic probe cannot measure the potentials. The width of the zero potential region is independent of the magnetic field and nonlinearly dependent on the bias.

The wall probes pick up electrostatic oscillations in the cloud primarily in the two frequency ranges. While the injector is operating, the oscillations start as soon as the transient phase of injection is completed. The frequency is in the range of 1M Hz. These signals are seen on the potential probes immersed within the plasma.

SMARTEX C

The turbulent birth of toroidal non-neutral plasmas by cross-field transport was a fundamental difference from the near-equilibrium placement in the Malmberg trap. This method also limited the number of electrons injected into the trap. Therefore, we speculated that the plasma formed by injection parallel to the magnetic field would be more quiescent.

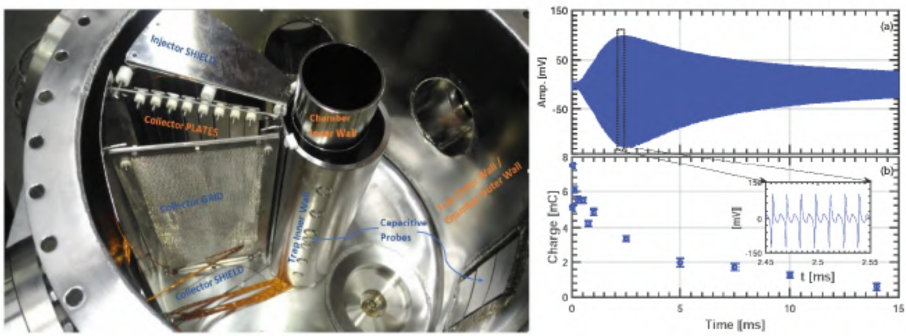


However, to do this in a torus, the filaments would have to be placed inside the drift space; the torus would no longer be closed. As a result, some theoreticians believed that there would be no equilibrium. The experimentalists, thought otherwise.

Sambaran Pahari built this device [8]. When heated, a circular tungsten filament loop placed on a poloidal cross-section emits thermionic electrons. A negatively biased grid placed in front of the filament is pulsed positive to extract electrons parallel to the minor axis. Another grid collector behind the filament in the poloidal cross-section is biased negative. As the toroidal magnetic field, established by pulsing a current through a multi-turn coil, reaches its flat top, the injector grid is pulsed positive with respect to filament to extract electrons along the field lines. After that, the grid reverts to negative bias, stopping further fueling. The injected electrons are trapped toroidally between the negatively biased injector grid and collector grid.

Experiments in SMARTEX-C (Small Aspect Ratio Toroidal Experiment-C shaped) have led to observing several novel features of toroidal electron plasmas. These plasmas have intrinsic confinement properties and unique mode structures in a small aspect ratio limit. The experiments and their interpretation by Sambaran and Hari Ramachandran demonstrate that rotational transform due to self-electric fields and a purely toroidal magnetic field can lead to significant confinement in toroidal geometries. To the best of our knowledge, the confinement time is the longest reported so far in the absence of an external electric field. In the limit of the small aspect ratio, due to strong toroidicity, the self-consistent electric field induced on the inner wall is sufficiently strong to make any external force field redundant.

SMARTEX-C has brought to the forefront several novel properties and the urgent need to further address these issues with new experiments and theory. The compressibility of fluid in the presence of strong inhomogeneous magnetic field brings an entirely new perspective. All of this may bring a paradigm shift in the investigations of toroidal electron plasmas. In particular, the amplitude saturation and frequency evolution warrant a further understanding of the evolution of the vortex. Efforts to confine toroidal electron plasmas have stood the test of time and made significant strides in the last decade. With the recent results on confinement, traditional transport theories have been put to the test.



The SMARTEX C machine and the high frequency associated with the diocotron oscillations

Interestingly, the confinement time is independent of magnetic field strength, suggesting that transport occurring could be due to magnetic pumping. But the confinement time scales far exceed that indicated by the transport theory for a typically 1–10 eV plasma even after accounting for the low aspect ratio of the trap. These confinement times are the longest reported and have breached the previous record by orders of magnitude. The device is presently being upgraded with a 500-sec steady-state magnetic field, and additional getter pumps to consolidate the results. Additional diagnostics for temperature measurement are being developed.

A series of contemporary large aspect ratio toroidal traps have also emerged in the last decade. A similar trap that strives to confine the plasmas on open field lines have succeeded up to 1 second, close to theoretical limit set by the transport theory [9]. A stellarator has succeeded in holding the plasma for 100 ms on nested flux surfaces, while one that employs dipole fields has achieved more than 100 sec. Much of the recent motivation and interest in toroidal traps seem to follow from the possibility of creating electron-positron pair plasmas due to the expected lack of instabilities in such plasmas and because of their relevance to astrophysical objects. Amidst all this, SMARTEX-C has a unique role as the fluid's assumed incompressible nature is expected to break down in the presence of strong toroidicity. With recent advancements and promising results, it remains to be seen if thermal equilibrium can also be achieved in toroidal traps as in cylindrical geometries.

Concept of A Novel Electron Plasma Trap

We explored the trapping of electrons in a novel trap in which a poloidal magnetic field is produced by an internal conductor inside a toroidal vacuum chamber. This kind of trap has additional invariants because of the conservation of toroidal canonical angular momentum. It will be interesting to see how these additional symmetries and constraints modify the confining properties of this trap. Equilibrium considerations have shown that fluid drift surfaces with finite pressure and finite mass are displaced inwards with respect to equipotential surfaces. With toroidal current, it is found that in a large aspect ratio conducting torus, the equilibrium is governed by a competition between forces produced by image charges and image currents. From stability investigations, it has been found that for toroidal systems, the quantity n/B, which is the density of electrons per flux tube, plays the same role as n in cylindrical systems.

Summary

Non-neutral plasma experiments were conceptually simple but required high technological skills and support to make them work. The persistent and skilful commitment shown by the students, Purvi Zaveri, Sameer Khirwadkar and Sambaran Pahari, contributed much to the success of the experiments. In addition, the perceptive understanding of the electron cloud dynamics developed by Predhiman Kaw and Avinash Khare based on their deep knowledge of plasma physics played a crucial role in creating a coherent account of the non-neutral electron clouds trapped in toroidal traps. Studies of toroidal non-neutral plasmas continue at IPR.

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6. A Variety of Plasmas

The fourth state of matter has many manifestations: a tiny electrical spark to the blazing sun. These diverse manifestations of the plasma phenomena have evoked my curiosity from the beginning of my scientific career. Later on, when I started having students who worked for a Ph D with me, they were willing collaborators in these learning adventures of exploring different kinds of plasmas.

The Corona

Electrical coronas form when electric fields intensify at a sharp point causes the ionization of air. On nights, one can observe coronas on high-voltage electrical lines. The crown-like appearance gave it the name.

The presence of dust particles is ubiquitous in many electrical corona situations. With my student Deepak Gupta, we studied the modification of the negative corona current pulse shape in the presence of fine dust particles. Some of the observed current pulses showed multiple avalanches in a single corona current pulse when dust particles are present very near a high-voltage active electrode.

We used photographic methods to simultaneously measure the location and charge of the dust particles when multiple avalanches occur. Dust charges are estimated from the deflected dust trajectory under the influence of electrical, gravitational and gas drag force. The axial electric field due to space charge was estimated by considering the discharge to be of finite radius and with uniformly distributed charge density along the radial direction.

Deepak complemented the experimental work with a numerical simulation of a needle to plane negative corona discharge, which solves one-dimensional time-dependent continuity equations for electrons, positive ions and negative ions simultaneously along with a three-dimensional Poisson equation in a nonuniform numerical grid. He modelled dust charging using Orbit Motion Limited theory including the effects of electrons, positive ions and negative ions. The time-dependent dust charge equation is solved simultaneously with other discharge equations. This study explained the formation of step on the leading edge of corona current pulses in the presence of dust particles (for which no consistent theory exists) for the first time. Results explain experimentally observed modified current pulses in the presence of dust particles. The charge on the dust for modified pulses is close to that obtained experimentally. Simulation with SF6 gas is also carried out to understand the contribution of space charge in defining the modified current pulse shapes.

The Ion Sheath

Plasma in contact with a physical boundary forms a sheath, a region of space charge qualitatively different from the bulk plasma. The upsurge of interest in the study of transient and equilibrium ion sheaths is motivated by the necessity to understand their role in technological applications like plasma source ion implantation (PSII), which is a technique for ion implantation for surface modification of materials. Sheath physics plays a crucial role in this technique. When a large negative potential is applied to the target immersed in plasma on a timescale short compared to the inverse of ion plasma frequency, the electrons are repelled away from the electrode, exposing stationary ions, thus forming an ion matrix sheath. On longer timescales, the ions are accelerated towards the target while the sheath expands away from the target.

The transient sheath evolution resulting from an instantaneous pulse of the negative voltage applied to the electrode was a topical problem. The basic assumption in all these models is that the conduction current alone is significant. However, in an expanding sheath, the displacement current is substantial due to changing electric field. The general conclusion seems that the contribution from the displacement current in the rising part of the pulse is significant.

Subroto Mukherjee, took up an experimental study to ascertain the role of displacement current in the sheath expansion. In the experiment, a large negative bias is applied to a disc electrode immersed in a uniform plasma. The focus is on the flat-top phase of the pulse where the applied voltage is constant. The total current collected by the electrode is recorded as a function of time. The results are explained in a model where the expanding sheath is regarded as a variable capacitor.

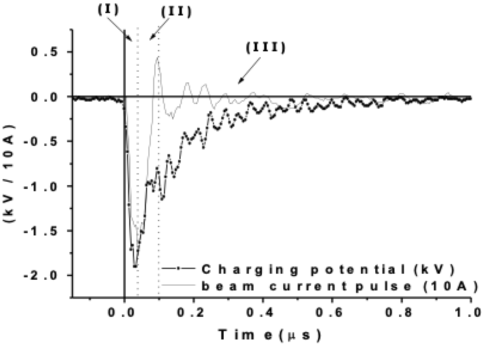
In an expanding sheath, the electric field changes with time even when the applied voltage is constant because the sheath plasma interface penetrates the plasma starting from the ion matrix sheath thickness and the effect of the resultant displacement current must be taken into account. This can be elegantly done by considering the sheath as a variable capacitor with varying thickness. We have experimentally measured the electrode current as a time function during the voltage pulse's flat top. It is also shown that even during this phase the contributions from the displacement current in the sheath are significant.

There are differences between experimental and theoretical results. One of the reasons is the secondary electron emission from the disc, giving an additional current to be added to the current predicted by the model. The current generated by the secondary electrons can be substantial, and adding this current to the current generated by the sheath motion is necessary. Thus, the net current to the electrode increases over that predicted by the model depending on the bias voltage. As a result, the total current, including the secondary emission current, is in better agreement with the experimental current.

Plasma Charging of Objects

Electrical charging of objects is a ubiquitous phenomenon observed during exposure of macroscopic bodies with a plasma, such as satellites orbiting in earth's exosphere, the vacuum vessel containing the plasma in laboratory setups and the substrates introduced in plasma for processing etc. The charging takes place because of the energetic electrons impinging on the object. When the object is immersed in plasma, the ions present around the object will tend to neutralize the electrostatic potential developed at the surface. As a result, the peak potential will be governed by the response time of the opposing charge species inside the plasma.

Shantanu Karkari studied the charging mechanism of an isolated electrode immersed in a collision-less, non-equilibrium plasma; by irradiating its surface with a 100 ns pulsed electron beam. The pulse duration of the electron beam must be shorter than the ion response time, which is typically 200 times slower than background electrons. The electron beam generator has been optimized to operate in the pressure range, which is two orders in magnitude lower than the conventional operational pressure range, by providing a differential gas flow through the entire discharge tube. This has been achieved by an electromagnetically operated gas dosing valve which can deliver a pre-requisite amount of gas into the discharge. In contrast, the background gas pressure inside the chamber was not affected during the experiment.



Shantanu developed a 1-dimensional particle in cell simulation to study the propagation properties of the electron beam through the background plasma. This oscillatory decay in the sheath edge boundary can be related to the oscillatory potential fall observed in the experiment; this is because the capacitance of the space charge is sinusoidal, hence the induced voltage over the decaying potential is also observed to be sinusoidal.

Overall, the physical dynamics can be summarized as follows:

- Pulsed electron beam charge the surface to a negative potential, immersed within a space of electrons.
- The positive ions shield the electrode potential along with the cloud of negative space charge to a distance So
- Electrode potential decays due to positive ions neutralizing and removal of electrons from the initial cloud of electrons.
- The quasineutral boundary decays due to reduction in the space charge, but it oscillates during the potential fall.
- The oscillation of the sheath boundary can induce oscillation in the observed potential.

Looking Back

These activities where students could pursue small experiments and get trained in experimental work performed an essential function in both Physical Research Laboratory and the Institute for Plasma Research. Many second-generation Plasma Physicists in India were trained through basic research programmes. Many returned to the Institute after a stint of work in other laboratories to take up major responsibilities. They thus formed the human resource base necessary for carrying out the present and future fusion research programmes.

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7. Engineering ADITYA

Fusion reactions make the sunshine and give the hydrogen bomb terrible destructive power. Fusion research started in the 1950s when scientists realized that controlled thermonuclear fusion reactions in the laboratory would open a path to unlimited and safe nuclear energy. As a result, many countries began building fusion devices, magnetic bottles to keep the hot plasma confined. A type of magnetic bottle, called the Tokamak, invented by the Russians, successfully obtained the extreme temperature and other conditions necessary for fusion.

The Background

In India, early efforts in high-temperature plasma research at the Tata Institute for Fundamental Research were abandoned in the 60s. However, Vikram Sarabhai picked up the threads again when he assembled a group in PRL in the early 1970s. The group also acquired engineering expertise. The plan was to establish an experimental programme in plasma physics oriented toward the simulation of space plasma phenomena. However, there was an unstated purpose of eventually acquiring the skills necessary for fusion research. In 1982, the Department of Science & Technology, realizing the importance of starting an indigenous fusion research programme, established a Plasma Physics Programme in PRL under its "Intensification of Research in High Priority Programmes".

The ADITYA Concept

The Aditya concept developed under two conflicting demands. Being the first Tokamak to be built indigenously with no direct help from experts, it had to be reasonably straightforward in engineering terms. On the other hand, a contrary view was that being a late entrant to the field of tokamaks, Aditya had to be complex enough to be capable of doing exciting experiments. This dichotomy led to various conflicts on the scale and complexity of the machine.

The project team for building the machine had the following constitution: Y C Saxena and Dhiraj Bora (magnets and structure), N Venkata Ramani (Vacuum System), S K Mattoo (Diagnostics) and me in charge of Power Systems. Predhiman Kaw, an internationally known plasma physicist and the Director of IPR, led us through many tutorials to initiate us into the physics of tokamaks. I had seen Versator tokamak at MIT at close hand thanks to an invitation of my colleague Prof. Abhijit Sen to visit him in Boston. Versator, with its picture frame coils and a capacitor bank, looked quite doable.

To acquire a first-hand assessment of the engineering support we could get in India, we visited BARC Central Workshop, BHEL at Hyderabad and Bhopal, L&T, IBP Vacuum Division, Kamani Copper in Baroda, and many other places. Discussions with L&T convinced us that a torus formed out of four welded quadrants was a feasible engineering concept. The Vacuum Group in BARC also thought that this concept made sense.

There was no history of large aperture high current wound magnets in India. So, we thought magnets formed out of brazed copper plates would be a sound concept in magnet design.

Pulsed Power for ADITYA

Predhiman used to say that the Princeton Plasma Physics Laboratory, where he had worked, could do great plasma experiments because they had the best power supply in the world. So, as project leader for Aditya Pulsed Power System (APPS), I ensured to meet Aditya's peak power demands of 500 MVA with an average demand of 50–60 MVA.

We could draw Pulsed power from capacitor banks, and we had some competence in this. However, the Capacitor Bank for Aditya's total capacity turned out too large to be viable. Procuring Energy Storage Capacitors also was problematic.

Princeton and most other Fusion Labs had Flywheel Generators where mechanical energy is stored in massive flywheels and extracted in high-power, short-duration pulses. We started to think in that direction. Unfortunately, importing

such machines was impossible due to the 1974 US sanctions. Prehuman and I visited BHEL Bhopal to explore the feasibility of the indigenous development of such devices. We were discouraged by the projected timescales.

What was left was the power grid. The idea of directly tapping the electricity grid to draw a large quantity of power transiently to energize the tokamak magnets and drive the plasma current was radical in 1982. The UK's Joint European Torus (JET) was the only Tokamak currently using Grid Pulsing. Our power supplier was the Ahmedabad Electricity Company. Their total power capacity was inadequate to meet our demand.

We knew that the Gujarat Electricity Grid was powerful even in those days. So, we started talking to them. Pulsing the GEB grid to extract 50 MVA (enough to power a small town) for a few seconds was an idea that made GEB very uncomfortable. Tata Consulting Engineers did extensive grid impact simulations to convince GEB of our sanity. What finally convinced them was the promise of massive tariffs from the 50MVA peak power demand! GEB agreed to lay a 132 kV line from Ranasan to the IPR site at Bhat, for which we had to pay.

The heart of the APPS was the Ohmic Transformer, an Inductive Energy Storage system that stores magnetic energy. The disruption of the inductor current provides the high voltage pulse necessary to create the toroidal voltage loop to produce the plasma and drive a high plasma current. We chose AEG, a German Company, to supply the APPS. Their design stood out for the overall simplicity. Charles L Neumeyer from Princeton helped us in the final decision-making.

We had a design review of Aditya at the Texas University in Austin, organized by Swadesh Mahajan. Experts listened to our design presentations. The general comment was that the design was sound but that we were being very ambitious in our first machine.

The ADITYA subsystems were engineered by 1987, and we did the machine assembly the following year. The Assembly and Commissioning team used to work from early morning to midnight with an erection team for almost a year before the machine got assembled.

The First Plasma in ADITYA

ADITYA was a system with electrically active components like magnetic field coils distributed over large volumes. We decided to do an impulse test on the coil systems to assess their vulnerability to electrical failure. The first attempt produced a shower of sparks all over the machine. The faults took almost a month to identify and seal electrically until the machine became breakdown-proof.

At last, by early 1989, the machine was ready for commissioning. Unfortunately, that was when the primary 50 MVA transformer failed due to an accidental short circuit of the secondary distribution system. The transformer had to be sent back to Bangalore for repair. The repair was to take almost a year. We were heartbroken.

The delay was too long and unacceptable. So we found a plan B. Sathyanarayana, Yogesh Saxena, Harshad Pujara, K. K. Jain and I decided to build a multistage capacitor bank to energize the ohmic transformer.

Tokamaks require toroidal loop voltage for the breakdown of the neutral gas, current rise, and the flat top phase. The temporal profile of the loop voltage established by the change of flux linked by the ohmic transformer has to be a noncosine waveform. A combination of capacitors charged to different voltages is switched at appropriate times to realize an experimental demand for an initial high loop voltage followed by a lower sustaining loop voltage.

A capacitor bank thus generated the first plasma in Aditya, a concept we had abandoned, favouring a more versatile Grid driven power system. In the Internal Conference in Plasma Physics, held in Delhi in 1989, we could declare that ADITYA was operational after a seven-year effort.

Capacitor Bank discharges were a quick way to learn plasma control. We became experts at producing high-quality, repeatable discharges quickly. APPs came into full-fledged operation in a year, and we went on to regular Grid driven power shots without much problem. Later, we strengthened the 50MVA Transformer by adding an external inductance to make it sturdier by increasing the impedance.

Fluctuation-induced particle transport

While many studies on the tokamak plasma physics have been undertaken, a significant breakthrough was the discovery of intermittency in fluctuation-induced edge transport.

The spectral characteristics of fluctuation-induced particle transport in the scrape-off layer (SOL) region of ADITYA tokamak, determined from the ensemble-averaged cross-power spectrum, and the phase difference between the density and the potential fluctuations show that the net frequency-integrated flux, due to all the changes together, is found to be outward.

In addition to the spectral analysis, further analysis of the amplitudes of the fluctuations revealed a surprising phenomenon. The probability distribution functions (PDFs) of the amplitudes displayed marked non-Gaussian features indicating the presence of intermittency in turbulent fluctuations. These non-Gaussian characteristics are seen to be similar in the scrape-off layer as well as in the plasma edge, a few centimetres inside the limiter. The measurements also demonstrated that the intermittency evolves during the discharge, perhaps, due to the evolution of critical parameters even in the flat-top current phase.

Intermittency implies the creation and destruction of spatially coherent structures over short periods. The short-lived coherent structures can arise through nonlinear processes and then collapse due to secondary instability, leading to a new intermittent energy dissipation mechanism that supplements unstable modes' direct coupling to the damped modes. Another possible consequence of the intermittency is its influence on the dissipation mechanism of fluctuations and anomalous transport, which could acquire a 'bursty' behaviour.

Looking Back

I believe designing, building, and operating ADITYA was a great challenge and an excellent opportunity for learning and developing teamwork. Among its many unique achievements, it has India's most advanced ultra-high vacuum system with a large deployment of turbo mechanic pumps. ADITYA has India's most extensive pulsed power system and the first inductive energy storage system. It is the only power consumer tapping two different power grids, and the only power consumer that measures its power consumption.

Under which the Tokamak ADITYA was engineered, PPP grew into the Institute for Plasma Research (IPR) in 1986. Within three decades, India acquired an international presence in Plasma Physics and its diverse applications. For example, it is a partner in the International Thermonuclear Experimental Reactor (ITER) project, a device to prove fusion's viability as an energy source.

ADITYA was the first Tokamak to discover intermittency in a tokamak edge plasma which has far-reaching consequences regarding our understanding of plasma turbulence and the nature of transport in tokamak plasmas. This discovery has triggered further experiments on several other tokamaks in the world.

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8. Plasma as an Industrial Tool

In early 1990, I was escorting Prof Ramaseshan, former Director of the Indian Institute of Science, around the ADITYA tokamak, which we had commissioned at the Institute for Plasma Research (IPR) in late 1989. A tokamak is a complex machine in which plasmas confined in a toroidal magnetic field are heated to millions of degrees by driving large currents through the plasma. State-of-the-art machines produce plasmas at 100 Million degrees where thermonuclear reactions take place. After appreciating everything about the device and what we had done, he asked me how many people would be affected by what we did with ADITYA.

I had never asked this question myself. So I enlarged the ambit of the question and asked how many people would be affected by what we had done over the years, developing the rich experimental knowledge base created over two decades of producing and manipulating plasmas to support fundamental research at PRL and IPR.

Mulling over this, I had an epiphany and the idea of finding short-term commercial applications of the plasma physics knowledge we had acquired over many years crystallized. Plasma phenomena like the response to external electromagnetic energy fields, collective phenomena like waves and oscillations, energy transport through instabilities, high chemical reactivity, microscopic electric fields, sheaths, radiation and particle flux mediate plasma processing. The role of plasma processing in Silicon chip manufacturing made the world realize that plasma physics offers unique and novel opportunities in high-energy density and high-value-added material processing.

In the early 90s, I realized that the knowledge base in plasma physics and plasma-surface interactions has immense potential for near-term industrial applications. This reflected the contemporary appreciation that plasma science offers unique and novel opportunities in high energy density material processing. In 1997, IPR took the initiative to establish links with industry for developing and commercializing plasma-based industrial technologies by setting up the Facilitation Centre for Industrial Plasma Technologies. FCIPT consolidates all technology development, demonstration, incubation and commercialization activities.

The Plasma State

The unique properties of the Plasma State make it a powerful industrial tool. These are based on the following effects, characterizing the plasma environment:

1. Presence of electrons, which can extract energy from electric fields.

1. Conversion of electron kinetic energy into space charge electric fields and thermal energy.

1. The tendency of the plasma to shield and localize externally applied electric potentials creating intense electric field regions called sheaths or double layers through which plasma particles can be accelerated.

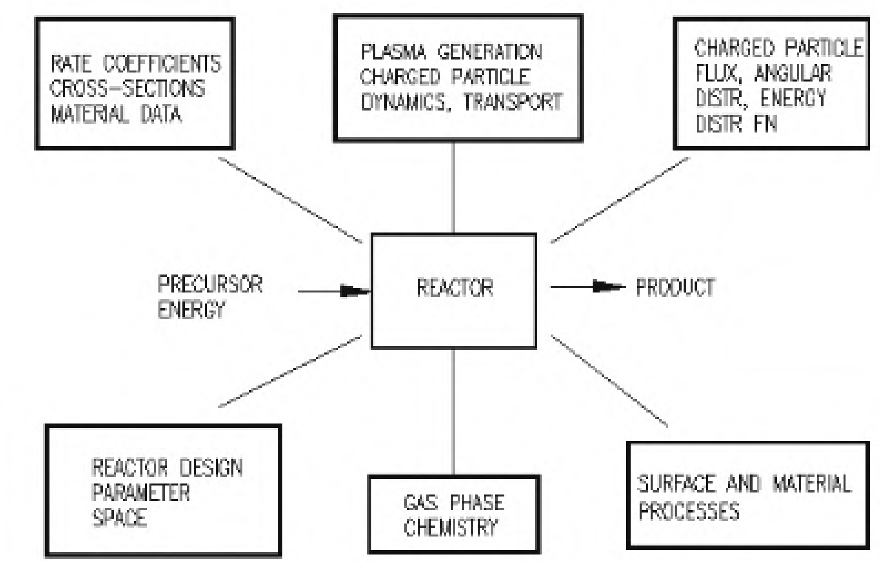
1. Creation of chemically active species from neutrals by collision with energetic electrons and ions.

1. The interaction of energetic plasma particles with surfaces releases particles by sputtering and evaporation.

1. The background of energetic radiation in plasma is produced either by atomic processes or by interaction with

electromagnetic fields.

Quite often, many of these effects manifest simultaneously in a plasma reactor. While this results in a wealth of phenomena, it also obscures the cause-effect relationship. This has hindered the development of plasma processing into a precise science. Plasma processing is one of the disciplines where the application has led science. But this situation is changing because of the realization that understanding the science behind a process is crucial to its improvement. Specific plasma properties can be optimized and enhanced, leading to a focus on a particular application. Thus we have fusion plasmas where particle temperatures are enhanced, impurity content minimized, and confinement enhanced or MHD plasmas where flow velocity and conductivity are improved. Similarly, we can define processing plasmas where the parameters relevant to plasma processes are improved or optimized.



The Process Plasma

The process of plasma differs from other plasmas in several ways. First of all, no confinement is required, and in fact, one prefers de-confinement since the throughput of processing depends upon fluxes of ions and electrons depositing their energy on the process substrate. Hence, there is often a lack of equilibration between species. This means that plasma formation and loss characteristics will imprint specific properties on the plasma. Secondly, we will see that the species which are used to form the plasma determine some of the properties due to the specific atomic physics and chemistry. In the context of plasma processing, Oxygen and Nitrogen plasmas are as different as plasma and neutral gas. An ideal plasma-processing reactor has plasma generation, gas-phase chemistry and surface and material interaction processes that primarily determine the reactor's functioning. Each of these requires inputs from plasma and material sciences, which determine the spatial and temporal variation of relevant quantities. The operating and design parameters are composed of a combination of initial and boundary conditions and input data such as gas composition, pressure, flow rates, power etc. Another input data set involves species interactions with each other and boundaries such as cross sections, rate and transport coefficients, emission, reflection and sticking coefficients, etc. The processes vary in space and time, for plasmas are notorious for involving disparate time and space lengths.

Plasma generation encompasses ionization reactions, charged species transport, kinetics, and electromagnetic theory. The plasma generation and gas phase phenomena are coupled through collisions between electrons, ions and neutral species. The reacting species are created by the collisional processes experienced by the constituent particles of the plasma. Plasma-material interaction and its evolution during processing are perhaps the most important because a modified surface or a surface synthesized by plasma is the product of plasma processing.

Each plasma process operates in restricted multi-dimensional parameter space, and the volume of this space determines the overall economics, quality, performance and other parameters, which will make the process competitive and industrially relevant. There are a number of constraints imposed on this operating window. For example, there can be process limits imposed by the plasma and reaction rates, efficiency limits imposed by how electrical energy is converted into plasma density, emission limits imposed by what fraction of the process raw materials are consumed in the process etc.

In fundamental research, the purpose is to find new knowledge without concern for its practical utility. However, Industrial applications of plasma are a vast field, and we had to set up some rules to ensure that we would only deal with actual needs posed by industries. So, we started a campaign to inform initiatives of what we could do and invite them to interact with us. A newsletter, Plasma Processing Update, was one of the media through which we communicated, in addition to industry-focused workshops and campaigns.

9. The FCIPT Initiative

In the early 1990s, during the period of a lull following the commissioning of the Indian Tokamak “ADITYA”, the idea of converting our rich experimental knowledge base created over two decades of producing and manipulating plasmas to support research at the Institute for Plasma Research to industrial applications appeared attractive. This also reflected the prevailing perspective that plasma science offers unique and novel opportunities in high-energy density and high-value-added material processing.

Putting Plasmas to Work

Plasma-assisted manufacturing exploits plasma as an industrial tool. Plasma can respond to external electromagnetic energy fields and transport energy. The fluid properties are enhanced by the particles setting up internal self-consistent electric and magnetic fields, resulting in collective effects like flows, waves, instabilities and self-organization. Each specie may have independent energy distribution, not necessarily in equilibrium with other species. The internal energy comprises thermal, electric, magnetic and radiation fields, whose relative magnitudes allow the plasma state to exist in extended, multi-dimensional parameter space.

Plasma processing was surging internationally with the realization that the fourth state of matter offers unique opportunities in material processing. Properties like high chemical reactivity, microscopic electric fields, sheaths, radiation and particle flux mediate plasma processing. Plasma-based manufacturing integrates the plasma-material interaction phenomena with the manufacturing process. The technology adds value to conventional materials and makes new types of materials and processing techniques possible. Moreover, the characteristics of both the equilibrium and non-equilibrium plasmas can be exploited for commercial uses.

There were no pre-existing models of similar activity in basic research organizations in India. The Plasma Processing Programme had some unique features not encountered in basic research. Some examples are the necessity for it to be relevant to the industry, the fact that it can make or lose money in its commercial exploitation, the contractor-client relationship with industries, etc. It was the first time in India that a basic research institute ventured into a commercial application programme. So, the business plan evolved and matured along with our learning curve. The programme had to be industry-driven to make it agile and responsive to rapid changes and focused on a few thrust areas where the immediate impact would be possible. Financial self-reliance was a goal from the beginning.

Setting up FCIPT

In 1997 IPR permitted us to set up the Facilitation Centre for Industrial Plasma Technologies (FCIPT) in a rented building in the industrial area of Gandhinagar to act as a bridge with industry. We consolidated all technology development, demonstration, incubation, and commercialization activities here. FCIPT had a multi-disciplinary group of physicists, material scientists, chemists and engineers and infrastructure for process and instrumentation development for plasma technologies. The manufacture and supply of complete reactors to industries and research institutions is an integral part of the technology transfer process.

FCIPT is a path breaker in India in converting physics-based research into commercially and societally valuable devices and processes. Instead, we have learned how to use the plasma environment to do various useful things.

We can nitride industrial components ranging from precision moulds to hydro turbine parts and reach defined hardness and case depth values.

Optical quality reflective and anti-reflective coatings can be synthesized over large areas with as high as 95% reflectivity using Plasma Enhanced Chemical Vapour Deposition with safe monomers.

Super-hydrophobic fluorocarbon films can be deposited

on surfaces with pulsed DC, RF and expanding plasma jets, which make them slide without friction.

High enthalpy flows can be created to test material properties at high temperatures and ignite a scramjet by producing hydrogen-rich fuel from kerosene.

We can densify, spherodize or segregate ceramics in in-flight high-temperature plasma jet reactors and produce aerosols and Nanoparticles.

Angora wool can be textured in atmospheric pressure cold plasma to enhance the spinnability of the wool.

We can destroy medical waste with a 95% volume reduction and undetectable levels of dioxins.

Many technologies were transferred to industries through the supply of complete process plants manufactured by FCIPT. The ability of cold plasmas to etch surfaces was exploited for the micro roughening of the extremely smooth surface of Angora wool fibres, enabling the wool to be spun easily. We developed an atmospheric pressure dielectric barrier discharge system to produce large-area Helium-free cold plasma into which continuous steams of wool fibre can be introduced and retrieved after treatment. A technology demonstration unit for using Angora wool farmers has been functioning at Kulu in collaboration with the Wool Research Board and the Government of Himachal Pradesh.

The Surface Engineering Initiative

Plasma processing got a big boost when it became part of the Surface Engineering initiative of the Department of Science and Technology when Prof. P. Rama Rao was the Secretary DST. This programme opened up collaboration with

German Institutions. I was a member of a delegation which visited the Fraunhofer Institutes to set up programmes of institutional collaboration. We partnered with the Technical University of Clausthall and the Nuclear Institute in Dresden on plasma ion implantation, which involved visits and exchange of research personnel. In addition to providing

commercial scale implantation service to industries, we were able to sell a pulsed, high voltage system for plasma ion implantation to the Technical University.

Plasma processing has transcended conventional material processing applications into waste destruction, environmental remediation, water purification, flue gas treatment etc. It is emerging as an enabling tool with a wide spectrum of applications relevant to modern industrial society.

Developing advanced technologies has many dimensions. It has more to do with men and society than with machines. Organizing men and systems and solving interface problems are critical to high technology development programmes. I had great help in this from many friends from within IPR and outside. I would like to record my sincere thanks to all of them.

In its twenty-fifth year, FCIPT is continuing the mission it started in 1997 to bridge the knowledge base of the Institute for Plasma Research with the needs of the industry. FCIPT can deposit Super-hydrophobic fluorocarbon films with expanding plasma jets to create surfaces which do not wet water and make them slide without friction. It can develop nanoparticles with controlled size at large throughputs. It can treat soft materials to improve texture, surface energy and other properties using cold plasmas. Inline textile processing improves wettability, colour adhesion and other properties.

It can create cold plasma jets and apply to the human body to treat diseases ranging from skin blemishes to cancer. And activate water and use it for medical and agricultural applications. In addition, it can create nano-scale patterns on surfaces by ion bombardment and use such surfaces to enhance Raman emission and thus identify materials at very low concentrations.

International Exposure

I go many opportunities to talk about our unique Institute-Industry collaboration initiative in international fora. For example, in September 2000, I participated in the third conference on “Physics and Industrial Development: Bridging the Gap” at Durban, South Africa. This was the third of a series of biennial conferences initiated by the Commission on Physics and Development (C13) of the International Union of Pure and Applied Physics (IUPAP) to empower physicists in developing countries to foster physics-technology bonds in developing countries. I described the IPR initiative establishing links with the Indian industry for developing and commercializing advanced plasma-based industrial technologies. There were many participants from developing countries who found this initiative very inspiring.

Another talk was given at the United Nations University in Tokyo, where some scientists met to discuss the possibilities of international cooperation in applications of plasma sciences. The meeting (Sept 16–18, 1996) was sponsored by the Institute of Advanced Studies of UNU and organized by Prof. Takaya Kawabe of the University of Tsukuba, a distinguished plasma physicist of long-standing and known for his commitment to promoting international cooperation.

On 30th October 2021, FCIPT became one of the 'Atal Incubation Centres' as a part of the 'Startup-India' mission. As an AIC, it would support the nucleation and growth of startups based on Plasma Based Technologies in India and utilize the multi-disciplinary team of scientists, academics, students and industry representatives. Its location in the GIDC industrial zone is an added advantage.

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10. Designer Plasmas

Plasma Processing is transforming from an empirical practice to a science-based discipline. This is driven by techno-economic considerations like improved ionization efficiency and higher densities, the need for uniformity over large-scale sizes and enhanced process reliability and throughput. The most significant changes are happening in how the processing plasmas are actively controlled to realize control of internal plasma parameters. These developments are, in turn, paving way for new types of processing. Future growth of plasma processing is linked to the concurrent development of plasma sources, diagnostics and control.

What can be controlled?

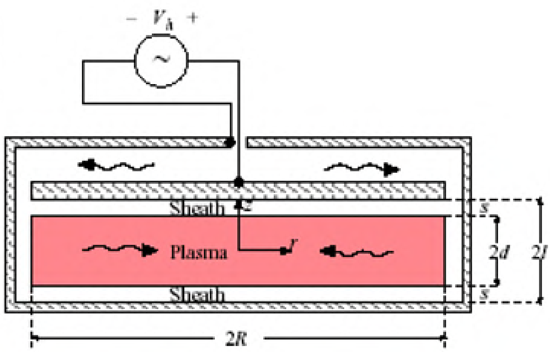
Internal plasma parameters like electron energy distribution function, electron and ion density, ion flux and energy, radical density and flux drive the processes. Direct control of these parameters is essential, though non-trivial, task.

There is a parallel to this in fusion research. Early and present-day fusion research is distinguishable by the extent of additional knobs available to the experimentalist to control the plasma parameters [1]. An early tokamak was a very primitive device. The current driven by the capacitor bank in the magnet winding generates a toroidal emf, which produces a discharge and drives a current. The plasma impedance and the stored energy determine the peak current and its duration. The plasma is in equilibrium by leaning against the outer wall.

The first element of control came in improving the equilibrium using the vertical magnetic field to supplement the equilibrium generated by the conducting wall. Next, the pulsed inductive discharge was transformed into a steady state device by a non-inductive current drive using RF fields or tangentially injected neutral beams. Wall cleaning, gas puffs and injecting fuel pellets into plasmas control the density. Current profiles are managed by radial control of conductivity and current drive. Additional coils modified the poloidal edge field to divert the edge plasma and remove impurities.

RF Capacitive Reactor

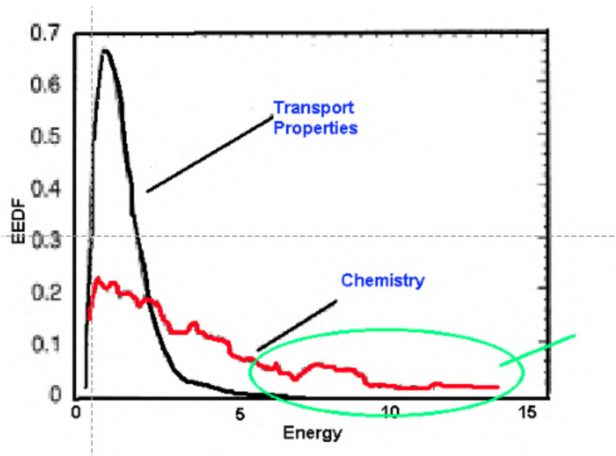
We can consider the parallel plate capacitive reactor [2] to illustrate how to build more knobs in a plasma-processing context. The mobile electrons respond to the radio frequency field and oscillate between the plates [3], with ions essentially immobile. Because of the electron loss, a time-averaged positive space charge and positive plasma potential trap the electrons. Hence there is a steady electric field from the plasma towards both plates, through the sheaths, which drive a steady ion flow to both electrodes.



The electrons are lost to the electrodes only when the oscillating cloud approaches the electrodes. During this time, the instantaneous sheath potential collapses, allowing sufficient electrons to reach the electrode to discharge the ion charge. The sheath impedance is generally higher than the bulk plasma impedance and controls the current. The sheath can be resistive if the ion transit time through the sheath is smaller than the RF period and capacitive if the reverse is true.

The role of electron temperature

The electron energy distribution (EED) is determined by the balance between the energy absorbed by the electrons from the electric field and the energy lost or gained by collisions with other particles and boundaries. In ideal plasmas, these processes completely balance each other, and we get a Maxwellian distribution. However, the real-life processing plasmas deviate significantly from this perfect state. The bulk part of the EED determines the transport properties like diffusion, whereas the tail part of the distribution determines the chemical reactions like breeding of active species etc.



For each chemical process, there is a threshold point on the EED. For example, for silicon film deposition from Silane, the threshold energy is 8.5 eV, which is the dissociation energy of SiH4. There must be an optimum number of electrons in the plasma at this energy for the breeding to be high. On the other hand, too many energetic electrons will create unwanted species, which can interfere with the necessary process. The reason why plasma processing generally does not have selectivity is because of the spread of electron energy.

What controls the electron temperature?

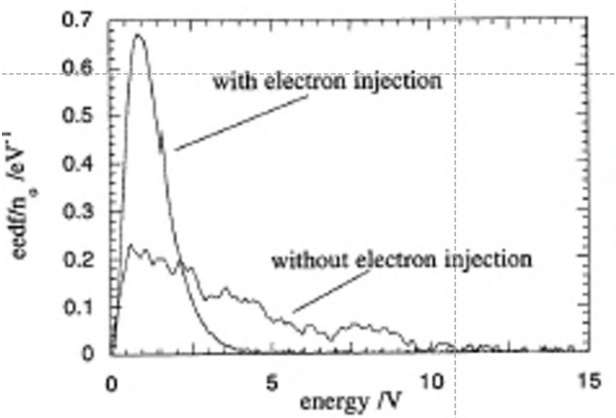
Generally, the particle balance determines the electron temperature in the system. However, the plasma in a parallel plate capacitor is very inhomogeneous. There are sheaths, pre-sheaths and core plasma regions. Each region has a dominant heating mechanism.

RF voltages [~1000 V] drive the radio frequency discharges at 13.56 MHz. Since the applied voltage is much larger than the electron temperature, the sheaths are many times the Debye length. An electron bouncing back and forth between the sheaths repeatedly interacts with the high field region but only weakly with the bulk field during its drift through the bulk plasma.

This sheath is time-dependent. As the negative sheath is built up, the electrons are pushed into the bulk. The successive build-up and collapse of the sheath are like a moving electrostatic wall, bouncing the electrons back and forth. This process is called stochastic sheath heating [Gozadinos 2001]. In addition to the electron heating by the moving sheath boundary, heating is also associated with the compression and rarefaction of the electrons in the pre-sheath. This is often referred to as pressure heating [4].

Advantages of low electron temperature

A high electron temperature is often not suitable for many types of plasma processing. In silicon thin film deposition, The SiH3 radicals are believed to be the ideal precursors to fabricate the favourable networks in a-Si: H and mc-Si films. Since the threshold electron energy for SiH3 production is lower than for SiH and SiH2, Te reduction selectively enhances the breeding of SiH3 over SiH and SiH2 radicals [5].



In DLC deposition, methyl radicals like CH3 are important precursors for film deposition. At high electron temperatures, methane is dissociated to produce CH2 radicals. CH2 radicals react with the surface producing more graphite than diamond. At low electron temperatures, the dissociation of CH4 into CH3 and H dominates. The density of CH3 is relatively low in normal discharges and can be increased as we lower the electron temperature [6].

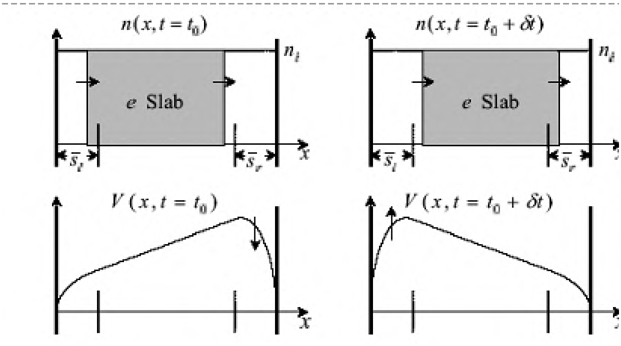
A grid separating the plasma production region from the processing region interrupts the flow of electrons between the regions. Electrons with energy lower than the grid bias will be reflected, and only higher energy electrons will be allowed to flow into the process region. These beam-like electrons can suffer inelastic collisions and cool, lowering the electron temperature. This method can vary electron temperature over a wide range, from 0.5 eV to 2.5 eV.

In gamma discharges, when the discharge is sustained by energetic secondary electrons emitted by the electrode, there is enhanced electron density and reduced electron temperature. The same effect can be achieved by injecting energetic electrons from an independent source into the RF capacitive plasma. This improves the inelastic collision rates resulting in an increase in ion production, which increases electron-ion energy exchange cooling the electrons [7].

Helium plasmas have high-energy tails because of super-elastic collisions with metastables. Mixing with a molecular gas effectively changes both Te and electron density in a low-pressure plasma discharge. However, the higher the electron density, the weaker the Te tuning effect due to electron-electron collisions.

What determines the electron density?

The electron density [8] scales as power and hence as the square of the frequency. Higher density in conjunction with higher bulk electron temperature increases the reaction rates.



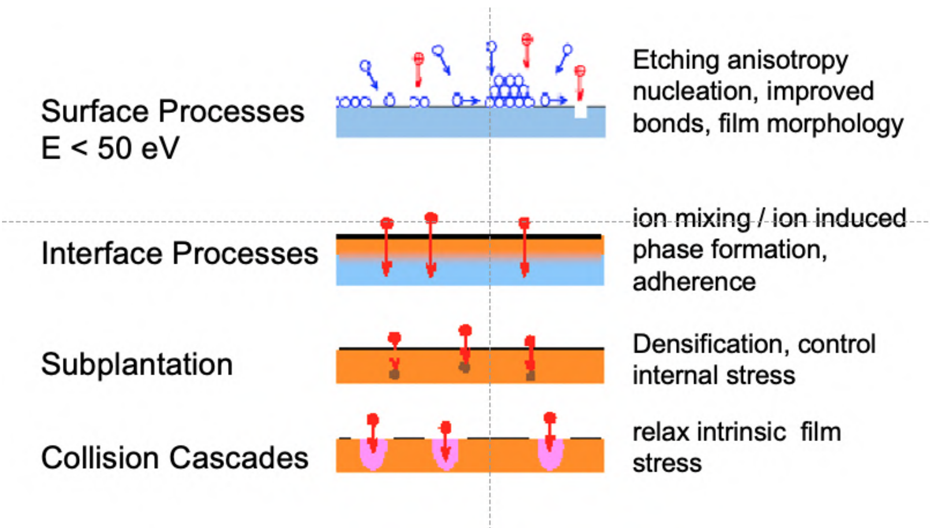
At very high frequencies, inductance is important and resonates with the sheath capacitance. For a density of 10(10) /cm3, the plasma frequency is in GHz and the series resonant frequency is in the range of 100 MHz. As the electron slab sloshes, a strong dipole field develops across the plasma bulk. The cycle-averaged potential and the RF potential bunch and launch electrons alternately from the sheaths into the bulk. This process accelerates electrons to energies well above the thermal energy in the bulk plasma.

The RF voltage drop across the bulk plasma cancels the RF sheath drop. At resonance, the internal electric field increases substantially [9]. The plasma impedance approaches a pure resistance, and very low voltages can cause breakdown and plasma formation. The phase of the RF field in the plasma bulk is opposite to that in the sheath. The sheath thickness scales as $1/\omega$, and we find that the density scales as the third power of frequency.

The role of ion bombardment

Ions play various roles in plasma processing.

- Etching anisotropy is determined by ion energy
- Ion bombardment of the surface at energy in the range of 50 eV can lead to increased atomic mobility and surface activation, which homogenizes film nucleation, improving bond formation, controlling film morphology and



changing surface topography.

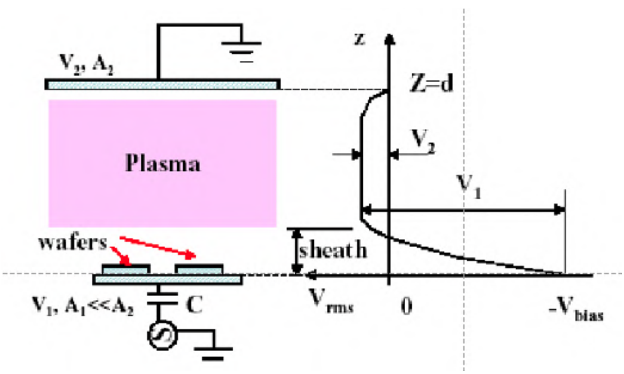
● Multiple ion species lead to ion mixing and ion-induced phase formation, which can change the adhesion of the film to the substrate.

● High-energy ions aid the process of sub-plantation, clamping the film to the substrate, which causes a change in film density and internal stress.

● Collision cascades can dissipate energy and aid in relaxing the intrinsic film stress.

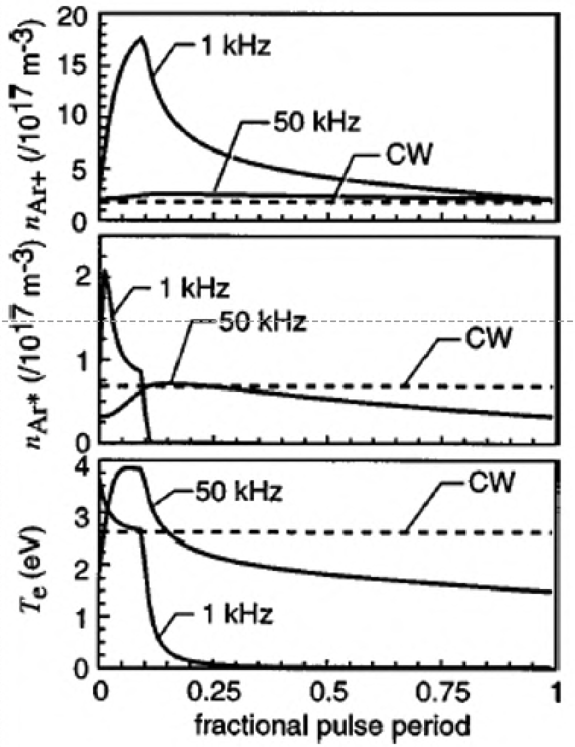
In addition to the average plasma potential, during the positive phase of the driving voltage, the plasma potential follows the driving voltage. During the negative phase, the electrons are decoupled from the electrode by the ion matrix sheath, the potential is held close to the ground potential. The net effect is that the time-averaged plasma potential is non-zero. Ions fall through this potential, a sum of the electrode bias and the plasma potential, reaching the powered electrode with high energy.

We must separate the plasma density control from ion extraction to control the ion energy and flux. High frequencies effectively control the density, while low frequencies impose voltages on the electrodes to which ions can respond. This is the concept of dual frequency reactors [10].



Ion energy control is an intriguing problem. Karkari, experimented with electron beams irradiating the substrate to charge them and create a controlled bias. One can speculate whether energy control is possible by adapting the 'RF compensation technique' used in Langmuir probe application in RF plasmas, where the probe is made to ride with the oscillating plasma potential by the feed back with the appropriate phase.

Active Control by Pulsing



Power modulation is an effective method of controlling plasma parameters [11]. The ion density increases rapidly during the on period to reach maximum values almost ten times the corresponding steady value. During the off period, the viscosity drops slowly on a time scale of about 100 ms.

The ion loss from the plasma is determined by the ion Bohm speed, which decreases significantly during the off period due to a drop in the electron temperature. Thus the ions remain trapped in the bulk plasma for long periods.

Inelastic collisions with molecules drain the electron energy very efficiently. So if we switch off the electric field after the plasma is formed, the transfer of energy from electrons to neutrals can be switched off. A repetitive train of pulses will create fresh bursts of short-lived plasma with energetic electrons and cold neutrals. This is the scheme for producing atmospheric pressure cold plasmas.

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11. Novel Plasma Sources

Plasma sources come in a bewildering range of parameter space and types, although they are all based on generic categories like glow discharge, arc etc. Despite decades of progress in the field of plasma sources, novelty is still possible and is a dream of every plasma physicist. In pursuing plasma-based applications, I have been fortunate to have invented some exciting and novel plasma sources. In this chapter, we shall take a look at these.

Constricted Anode Plasma Source

In one of the applications related to the deposition of SiOx films on metallic substrates, we needed to operate a glow discharge at very low pressures. The problem was to sustain the discharge at low pressure without supplying ionizing electrons through secondary sources. We thought that if we restrict the area of the anode electrode to very small sizes, we could trap the primary electrons emitted from the cathode through many collisions between its transport to the anode. Unlike in regular glow discharge configurations where the cathode is usually smaller in area than the anode, in the present investigation, the anode area is extremely small compared to the area of the cathode (anode area: cathode area ~1/150) [1].

The anode is a fine point kept in the middle of the discharge chamber. The anode is given a large positive voltage of a few hundred

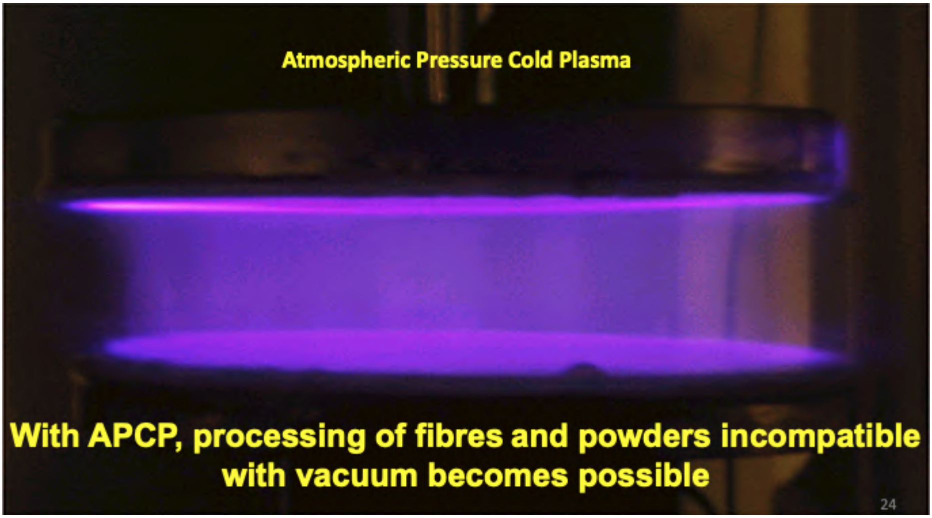
volts. The entire wall of the chamber acts as the cathode. The electrons emitted from the cathode are reflected from the cathode many times before being captured by the anode. The plasma thus formed also acquires the positive potential of the anode (~ few hundred volts), which acts as a trap for the electrons.

The initial production of the plasma is aided either by operating the chamber initially at relatively high pressure and then reducing the pressure to low values or by putting a thermionic electron source to start the discharge.

Ambient Pressure Cold Plasma Jets

When plasma is produced by ionizing a gas by an electrical discharge, like in a welding arc, the electrons absorb energy from the electric field and, being highly mobile, collide among themselves frequently and randomize their energy. As a result, their temperature can reach many thousands of degrees Kelvin. When they collide with ions and neutral molecules, they transfer a small fraction (proportional to the electron-ion mass ratio) of their energy. Collisions frequent at atmospheric pressure, and the electrons and heavy particles reach a state of thermodynamic equilibrium, despite the low energy transfer fraction. As a result, all the species in the plasma remain at almost the same temperature. Such plasmas produced in arcs or lightning can reach temperatures over 10,000 degrees and are called the equilibrium of hot plasmas.

When the pressure is low, as, in the Neon tube or fluorescent lamps, the collisions between electrons and heavier particles occur less frequently, the electrons remain hot while the heavier particles remain cold; there is no thermodynamic equilibrium. The electrons have a very high temperature (up to a few eV, 1 eV ≈ 11,600 K), whereas the temperature of heavy particles is relatively low. For this



reason, they are called non-equilibrium or cold plasma. The presence of highly energetic electrons facilitates electron impact excitation, ionization and dissociation of molecules at low gas temperatures. The company of all these species makes cold plasmas chemically very active.

Can we make cold plasma in ambient atmospheric pressure? When the electron energy is above 3 eV, the transfer of power through in-elastic collisions is very efficient. Inelastic collisions with molecules drain the electron energy very efficiently. The physics of these devices is based on the suppression of electron-neutral energy transfer by discharge pulsing. At atmospheric pressure, the energy transfer time is of the order of nanoseconds. If the electric field is switched off at comparable times, the electrons are de-energized in nanoseconds and the plasma remains cold. A repetitive train of pulses will create fresh bursts of short-lived plasma with energetic electrons and cold neutrals. This is called pulsed plasma. A repetitive train of pulses will create new bursts of short-lived plasma with energetic electrons and cold neutrals.

This is one of the schemes invented by Plasma physicists for producing atmospheric pressure cold plasmas.

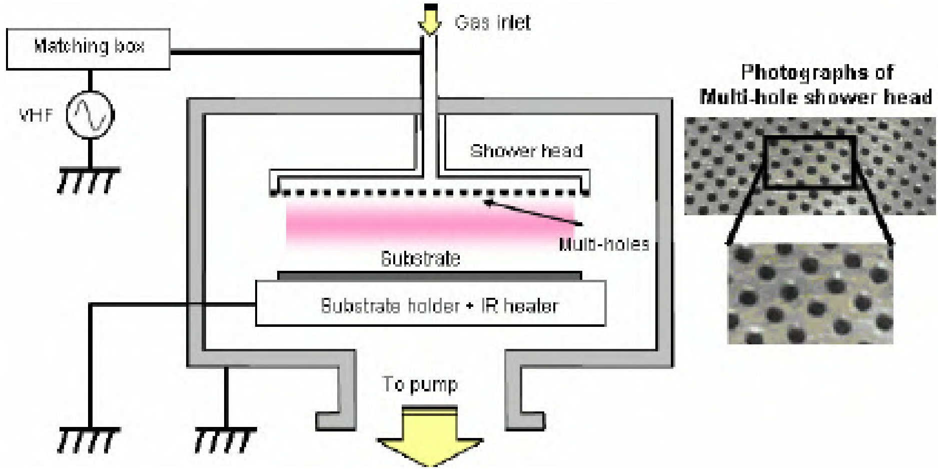
Multihole Cathode VHF Plasma

High-frequency plasma discharges are the workhorses of the thin film electronic device industry [2]. Radiofrequency (13.56 MHz) and very-high-frequency (VHF) (25–150 MHz) plasmas can be suitably controlled for high-precision thin film process requirements of deposition, reactive and deep-reactive ion-etching, etc. Recent results point toward increasing importance of VHF plasmas in the industry due to the higher deposition rates that can be achieved with it compared to rf plasmas. We built such a device and found that the plasma parameters indicate a higher ion density and lower electron temperature for the VHF (55 MHz) plasma compared to the rf (13.56 MHz) plasma.

A capacitively coupled diode-type PECVD system with an excitation frequency of 55 or 13.56 MHz and an MHC 22 cm diameter was used for this study [3]. The MHC consists of a square array of 2.5 mm diameter holes, which are centred 5 mm from each other. The separation between electrodes was fixed at 3 cm. The plasma parameters were reproducibly measured by a self-compensating disk LP designed to work in 55 and 13.56MHz plasmas.

The decrease in T, from rf to VHF, causes a reduction in the plasma potential and reduces ion

bombardment. The lower T, is also known to give better quality Si: H films due to an increase in SiH radicals in aSiHy: H plasma. As the frequency f is increased from 13.56 to 55 MHz, a significant increase in the ion saturation current, which is proportional to N, was observed. Hence, the



higher N; for VHF gives a higher deposition rate than plasma at equal power density. We also have measured;, and T, as a function of the power density P.

Graphite Plasma Torch

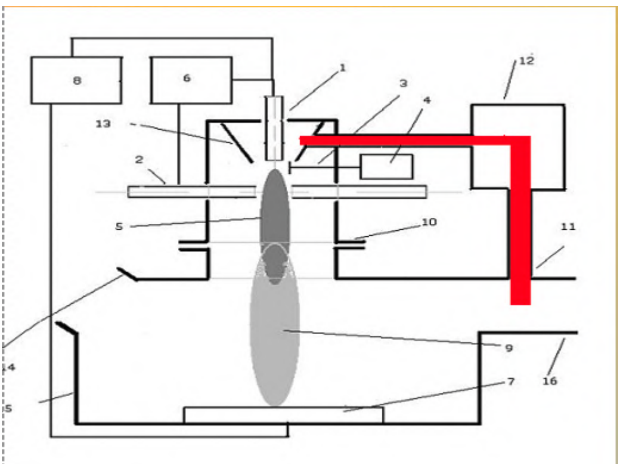
The plasma torch is the heart of the pyrolysis system. for reliability and energy efficiency, we decided to use a torch with graphite electrodes as both cathode and anode for Pyrolysis.

Graphite plasma torch comprises a tubular anode and two rod-shaped cathode. The electrodes are mounted on a holding arrangement with the anode electrodes at an angle of 90 deg. An arrangement is made to rotate the cathode in linear and angular motion. The electrodes are powered by a 250A and 100 V power supply. The significant advantage of the graphite plasma torch is that it does not require electrode cooling, thus enhancing efficiency by eliminating heat losses. In addition, one can strike the plasma without gas flow. In the absence of plasma gas (N2 or air), the pyrolysis gas composition is dominated by combustible hydrocarbon gases which makes the secondary burning easier. Plasma torch operation is controlled automatically through instrumentation. The entire torch operation is auto-controlled to sustain continuous pyrolysis reactions.

The graphite plasma torch generates a non-transfer arc. Spectroscopic measurements show that the temperature ranges from 20,000 K in the plasma core to 3,000 deg K in the plume. With the use of a graphite plasma torch, it has become possible to enhance the temperature of the reaction zone. At higher temperature (>10000 deg K), super thermal Pyrolysis takes place, which provides high solid to gas conversion efficiency.

Endogenous Gas Feed Plasma Torch

Conventional plasma torches require large gas throughput to stabilize the arc, resulting in product gas dilution and reduction in energy efficiency. We have Innovated the graphite torch exploiting the gas generation in the Pyrolysis of organic matter. An inline suction pump sucks the product gas and sends it through a filter to remove soot particles. It is then fed to the plasma torch. We had a 35% gain in energy efficiency with this torch. It also increases electrode life by reducing the electrode erosion rate. We received a Patent for the Endogenous Gas Feed concept in



Endogenous Gas Feed Plasma Torch

2007.

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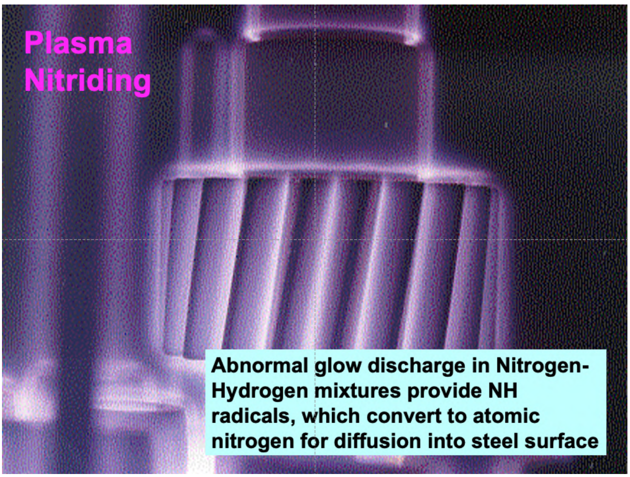
12. Surface Engineering with Plasmas

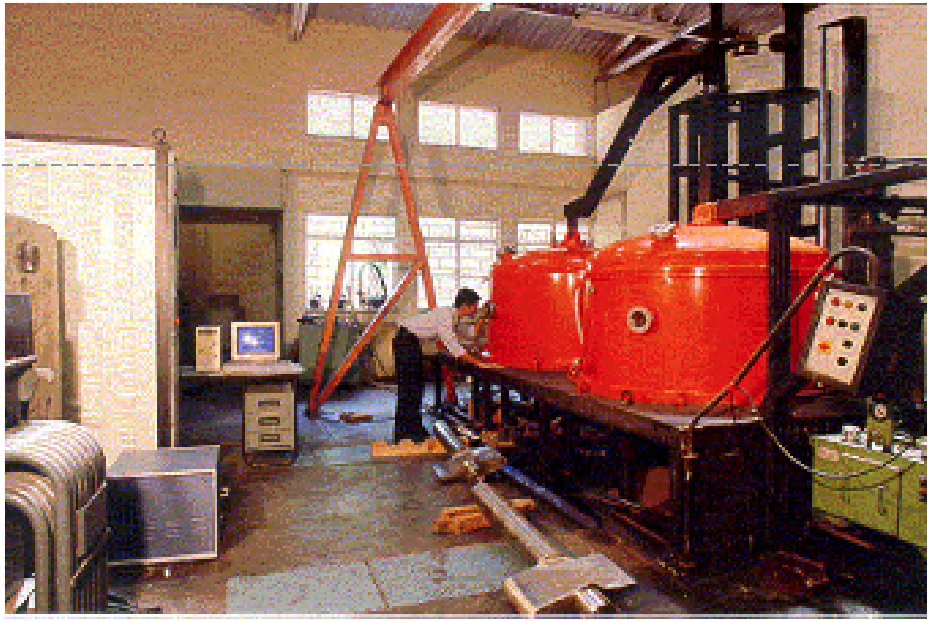
The Institute for Plasma Research decided to pursue a programme in development of industrially relevant plasma applications in 1990. The first foray was into plasma nitriding because of the interest shown by several industries manufacturing dies in Ahmedabad. Plasma Nitriding is a surface hardening technique, wherein a controlled incorporation of atomic nitrogen in metals by thermo-chemical diffusion produces a hard, wear resistant case. It’s an environment friendly process, and offers good control on the overall parameters of the process in general, and the white layer formation in particular.

Plasma Nitriding

Plasma nitriding is a medium temperature (400–600 deg C), low distortion process capable of producing tailored microstructure and hardness profile. When a high negative voltage is applied to the workpiece placed in a low-pressure vessel, a glow discharge occurs around the electrode. Energetic ions formed are accelerated towards the cathode and heat the parts by their kinetic energy. This effect of ion bombardment and the presence of active radicals allow the nitrogen atoms to diffuse into the surface thereby significantly strengthening it by forming nitrides with the alloying elements present in the steel.

To scale the reactor up in size to meet the industrial needs, we built a series of successively complex reactors starting with the first prototype: a cold wall furnace with only plasma heating. We added heat shields to minimise heat loss and increase thermal efficiency and uniformity. We built auxiliary heated hot-wall reactor by actively heating the vacuum vessel with a heating element. Heating of the work piece is obtained by the combination of plasma heating and radiation and convection heating by the wall. We also added automation and computer control to build state-of-the-art systems during this time. Instrumentation developments include IGBT pulsers up to 100 A capacity, arc interruption capability, computer based process control etc. State-of-art systems with IGBT pulsers, auxiliary heating, and





The Nitriding Job Shop

computer based process control were developed. The system is automated using SCADA software.

To spread the use of plasma nitriding, we set up in-house facilities of large industrial nitriding systems for technology demonstration and job work. The job shop services high-value components like plastic dies etc. on a commercial basis to serve high value customers like Cincinnati-Milacron and other die manufacturers. We also signed an agreement with the Indo-German Tool Room in Ahmedabad to nitride the products they manufacture. FCIPT has developed an extensive database on Nitriding of tool and alloy steels, and titanium. Large Nitriding systems have been built for technology demonstration and job work.

Plasma Nitriding of Hydropower Components

An appropriate field of application of nitriding technology in India is the hydropower sector where the generating units face problems of forced outages due to erosion caused by silt to turbine components such as runner, guide vanes, surface liners of turbine top cover and bottom ring and labyrinth sealing ring. The Himalayan rivers carry huge quantity of silt load during the monsoons. The silt comprises of 90–95% quartz particles, which, causes abrasive loss of material from the affected components.

Along with National Hydro Power Corporation, we led a campaign of nitriding of hydropower components like turbine runner, guide vanes, draft tube cones, check plates and labyrinth made of AISI 13CrNi4 steel to mitigate wear due to silt. 13CrNi4 are usually annealed at 790–815 deg C. The typical ultimate tensile strength obtained is approximately 550 MPa. They are then austenized at 955–980 deg C and tempered at 595–620 deg C. The typical hardness is 350–400 HV. Since silt has a hardness of 800 HV, it was believed that if the surface hardness of these components were more than 800 HV, life of these components could be increased. We were successful in developing nitriding process for AISI 13CrNi4 martensitic stainless steel to produce a surface hardness of 1200HV and a case depth of 250 microns. Field trials and assessment of nitriding technique to mitigate wear demonstrated component life increase by a factor of two.

Plasma Nitriding of Injection Moulding Components

Injection moulding machines consists of tip, seat and

Hydropower components

valve as integral assembled parts in the injection unit fitted in the front side of feed screw. These components are made of H13 steel and usually undergo very high sliding wear during operation. Hence there is a requirement of enhancing wear resistance of these components by suitable heat treatment method with minimum distortions. Cincinnati Milacron utilizes plasma nitriding services offered by FCIPT for nitriding of their injection moulding components. Their requirements demand surface hardness of 67 to 70 HRC with minimum distortion and faster delivery schedule. FCIPT is able to meet all their requirements and their components are being successfully nitrided on a regular scale.

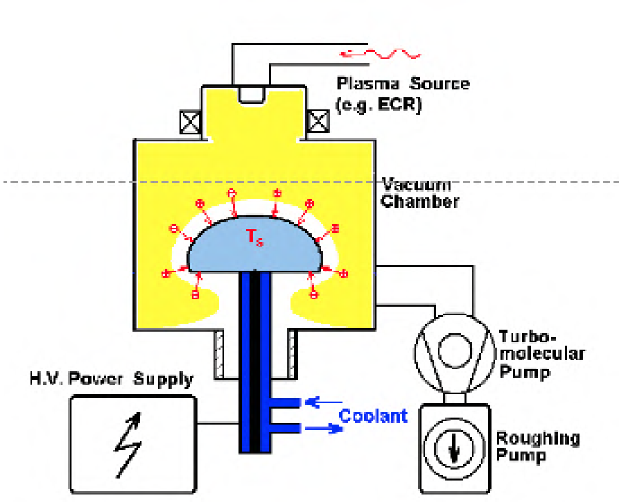
Surface Engineering for Nuclear Reactor Components

The steam generator modules of Prototype Fast Breeder Reactor (PFBR) employ Cr-Mo steel tubes, which are subjected to vibrations at high temperatures. In order to damp the vibrations, these tubes are held with clamps made of Inconel 718, which can yield high strength at elevated temperatures. However, though the bulk properties are excellent, the IN718 clamps are subjected to fretting wear at such high temperatures (~600 deg C). A wear resistant surface such as nickel aluminide would be able to improve the fretting wear resistance. In order to generate such a nickel aluminide layer with appropriate phase control, plasma aluminizing using magnetron sputter deposition in conjunction with diffusion processing is being explored as an alternate to conventional spray processing.

Plasma Immersion Ion Implantation (PIII)

In PIII, the target to be implanted is immersed in a plasma and a pulsed negative bias is applied on the target. Ions are electrostatically attracted to and injected normal to the target surface. This process thereby eliminates the line of sight restrictions of beam line implantation. Irrespective of the target shape, the plasma envelops it uniformly, ensuring that the implanted dose of ions is uniform all throughout the target.

The implantation of high energy ions into the surface regions of the target results in chemical and micro-structural changes at the surface leading to substantial improvement of the performance of the material against corrosion, wear, fatigue, etc. Secondly, the simultaneous PIII treatment of multiple targets is also achievable. This has a tremendous effect in batch implantation and hence reducing the cost. Elimination of line of sight restrictions of beam line implantation process is making ion implantation a cost effective approach for the surface modification of materials. PIII provides the opportunity to implant gaseous ions on metal (nitrogen on steel, aluminium), metal ions on metal



Plasma Immersion Ion Implantation

(tantulum on copper), and selective doping of semiconductor materials (boron doping of silicon).

Shallow Implantation Diffusion Hardening (SIDH)

The paradigm that plasma physics can provide critical inputs in the advancement of old technologies is borne out in the development of shallow implantation diffusion hardening (SIDH) process. Plasma density enhancement using magnetic traps and the collisionless sheath operation at low pressures allow high ion energy flux to be delivered to targets. Simultaneous heating of the sample with bipolar current flow increases the diffusion of the implanted species into the bulk. Thus this process substantially improves the efficiency of nitrogen deposition into the bulk resulting in tailored hardness profiles, reduced cycle time and simplified gas chemistry.

We developed Shallow Implantation and Diffusion Hardening (SIDH) under the Indo-German Collaborative Project on Plasma Source Ion Implantation (PSII) work. The shallow implantation diffusion hardening process takes the advantage of dose uniformity and assured penetration from plasma based ion implantation and subsequent thermally enhanced diffusion of implanted ions inside the metal. Hence, this process leads to larger effective implantation depths and shorter processing times. This process is particularly suited to stainless steels, which are otherwise difficult to nitride. Also this process can work in a much lower temperature range than plasma nitriding and hence the chromium of the steel remains unaffected during SIDH. As a result of this the workpiece retains its corrosion resistance property. Also this lower temperature causes lower distortion of the workpiece which has been demonstrated on high precision cutting tools.

The sample, kept in a dense plasma, is sequentially biased negative and positive with respect to the floating potential, resulting in ion and electron flux alternately. The ions penetrate the surface to some extent because of their kinetic energy, and then undergo diffusion because of the heating of the sample. The results indicate significant changes in surface hardness (5 times at 25 gm load) after 3 - 6 hours of treatment, with effective penetration depths of 100 micron.

Results of a specific study on X 60 NiMoTi17.12.2 undertaken to examine the comparative performance of plasma nitriding, PSI and SIDH processes on nitrogen incorporation is given in the figure. Previous comparisons of high energy implantation and nitriding, were done under different conditions, at best keeping the temperature fixed, with widely varying dosages In the present study the incident flux is nearly same, hence the difference in the results is only in the retained dose.

PSII of Aluminum and Titanium

A unique combination of material properties- dielectric, thermal, mechanical, optical, wear and corrosion resistance -

make aluminium nitride (AlN) a material of choice for many applications as heat sinks, thin film resistors, hard coatings and in the field of semiconductors. Due to the large chemical affinity of aluminium to oxygen, the major difficulty in depositing AlN resides in the oxygen contamination control.

XPS results indicate that nitrogen is chemically bound to Al for all the implanted samples. Observed binding energy values are in well agreement with the existing literature. Figures 1 and 2 show the binding energy values of N1s peak at 397.5 eV (corresponding to AlN) and 399 eV (corresponding to adsorbed nitrogen) for 3 keV energy with 1 × 1018 dose and 10 keV energy with 1 × 1018 dose respectively. These binding energy values suggest that AlN formation has occurred.

XRD results indicate crystalline AlN formation in the implanted samples corresponding to 3kev energy and 2 × 10 18 dose and also 10 keV energy and 1× 10 18 dose. A little amount of magnesium impurity was there in our starting Al samples.

Titanium suffers from its low hardness and poor wear resistance. Plasma nitriding of titanium and formation of TiN on its surface makes significant increase in its surface hardness and wear resistance without compromising its excellent corrosion resistance. These mechanical properties are strongly dependent on the formation of nitrided phase (TiN), its microstructure and also crystallographic orientation of grains in polycrystalline TiN. There exist several reports on the formation of nitrided phases (TiN, Ti2N etc.), their microstructures and preferred orientations in plasma nitrided titanium. Only a very few reports of (200) and (220) preferred orientations of TiN and (002) preferred orientation of Ti2N are there. Probably the most well known model suggested by

Kolbel, has been considered as a very promising approach to explain the layer formation mechanism for plasma nitriding of ferrous materials. The model has subsequently been suggested to apply also to the nitriding of titanium. It assumes that metal mononitrides, FeN or TiN are created within the glow discharge and then deposited on the substrate surface where they gradually decompose by losing nitrogen owing to diffusion. Homogeneous nucleation of mononitride like TiN in plasma may also result from the deposition of both sputtered titanium and nitrogen on titanium substrate.

XRD results confirm TiN formation even at 300C. XRD analysis reveals that Ti2N starts forming at 425C. Scanning electron micrographs show formation and growth of TiN crystallites, preferably at the grain boundary regions of titanium which is clear in the temperature range of 600C to 900C. This is probably an indication of grain boundary diffusion of nitrogen in titanium at high temperatures. The preferred orientation of TiN and Ti2N are (111) and (002) respectively from the x-ray diffraction profiles.

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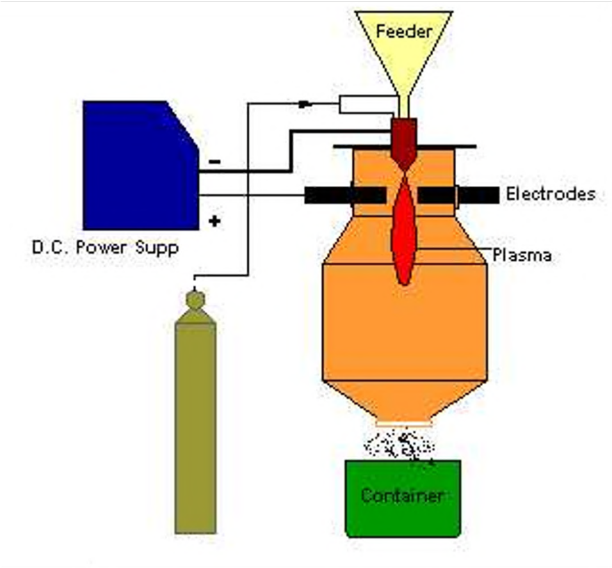
13. In-flight Mineral Processing

The Plasma Processing group at the IPR was invited by the Department of Scientific and Industrial Research (DSIR) to work with C. S. Zircon Products Private Limited, Sirmaur, Himachal Pradesh, who wanted to exploit an expired patent held by IonArc, the USA to use an inflight plasma process to refine Zircon into Zirconia. Our charter was to integrate the inflight reactor with a power supply built at IPR, commission the reactor at the IPR site and develop the dissociation process to a level where the industry could take over. This was our first foray into thermal plasma produced by plasma torches. We had to develop special sand feeders because the commercial feeders would wear out handling the tough zircon sand. We also learned that even patents of successful commercial processes often hid many problems which would pop up in an actual operation.

The inflight reactor was used later for many applications, such as spherodizing irregular alumina particles



made by the calcination process to improve its flow properties in applications like plasma spray coating. The particle, riding through the plasma, melts and condenses into a spherical shape when it comes out of the plasma plume. It was found that almost 98 % of the powder got spherodized.

Zircon Dissociation in a Plasma Furnace

Zirconia or zirconium oxide is an oxide ceramic with a high melting point, good chemical resistance, high strength and, when doped with certain oxides, show high ionic conductivity. Alumina-zirconia ceramics are widely known for increased stability, corrosion resistance, thermal shock resistance and wear resistance. The material is used in sintering, plasma spraying and pottery. The typical sintered products are scissors and shears, wire drawing dies, hot extrusion dies, seals in chemical valves, automobile engine parts, bio-medical components, piezo-electric crystals and

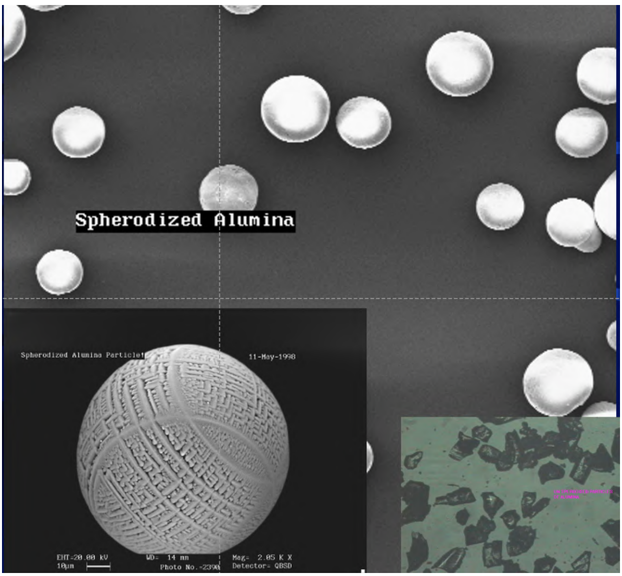
high-temperature refractories. In plasma spraying, it is used for thermal barrier coatings in turbine blades and anti-corrosion coating in harsh environments. Stabilized zirconia and zircon have been extensively used in the glass industry as refractory lining in the melting vats, polishing of glass and as an opacifier in enamels.

The primary raw material for extracting zirconia is the mineral zircon -zirconium silicate- present in the Kerala and Orissa sands along with rutile and ilmenite and available under licence from the Department of Atomic Energy. The major suppliers are Indian Rare Earths, and Kerala Minerals and Metals Ltd. Zircon is a very stable compound and to extract zirconia requires chemical or thermal dissociation. In the chemical route, zircon is fused with sodium hydroxide above 600 degrees C to produce sodium silicate and sodium zirconate, from which sodium silicate is removed by leaching. Sodium zirconate is hydrolyzed to produce hydrated zirconia, which after calcination, produces an impure oxide which is further purified by acid leaching. Chlorination of zircon produces zircon tetrachloride, which after hydrolysis and calcination also yields zirconia powders. The chemical route is being followed by Ms C S Zircon, Himachal Pradesh, and Indian Rare Earths, Kerala, which together produce about 400 tonnes of zirconia. The Institute for Plasma Research (IPR), under a multi-lateral agreement signed with the Department of Scientific and Industrial Research, Government of India (DSIR), National Research Development Corporation (NRDC) and C S Zircon Ltd have taken up the task of indigenous development of a process for the direct dissociation of zircon in a plasma furnace. The plasma route will reduce the number of steps involved in the dissociation process, making the process economically more attractive. In addition, it also promises the production of higher purity zirconia than that produced by the chemical route, enabling the manufacturer to meet the higher-end market served by imported zirconia.

Spherodization of Alumina

Spherodized alumina finds applications in sintered products, alloying, bio-medical applications, paint dispersion, and ceramic coatings. Spherodization of irregular alumina particles using high enthalpy inflight thermal plasma reactor is investigated. The feed arrangement is housed at the top of the reactor and conveys alumina particles (125 size) into the cathode-anode gap of the plasma torch. The torch was connected to a 50 kW power supply. After obtaining the stable arc, the alumina powder was fed into the reactor. The treated powder was collected at the bottom of the reactor. Commercial grade nitrogen was used as plasma and carrier gas. The flow of plasma and carrier gas was controlled using a rotometer.

One of the main advantages of a plasma inflight reactor is that the plasma tail flame extends up to about 3 feet. Therefore, when the material in the powder form was fed through a feeder arrangement around the nozzle, the powder enters the core of the flame and travels inside the love for a sufficient length of time. This allows us to carry out surface modification like spherodization very effectively.



Two types of

powder feeding arrangements were used. In the first type, the alumina was allowed to pass through the feed-through holes by gravitational force, i.e., without carrier gas. The feed rate was varied by changing the hole size of the feeder. Four experiments were carried out for various power inputs to the plasma gun, powder feed rate etc.... In the second type, the alumina powder was fed using the carrier gas, nitrogen gas. Here, the feed rate was varied by changing the hole size and the carrier gas flow rate. Seven experiments were carried out by changing power input to the plasma gun, plasma gas flow rate, carrier gas flow rate, powder feed rate etc.

The feedstock and the spherodized powder were characterized using an optical microscope and X-ray diffraction. Optical microscopy yielded information on the morphology of the particles. X-ray diffraction patterns were used for the identification of phase changes and contamination.

The advantage of using the carrier gas for feeding the powder is that each powder particle gets separated far apart from the other before entering the plasma. Also, the particles are pushed well inside the plasma.

When the powder enters the plasma, the surface of the powder particles is exposed to a temperature which is much higher than the evaporation temperature. So, in all the trials, a small amount of the powder evaporates from the surface during the travel through the flame. When thrown to colder regions, the evaporated particles get condensed and deposited on the inner surface of the reactor. The powder particles are injected well inside the plasma when the carrier gas is used to feed the powder. Hence, more evaporation occurs, which results in less recovery. Apart from the deposition of fine alumina particles on the surface of the reactor, a small amount of fine particles are also carried by the outgoing nitrogen gas through the exhaust. Still, it is less compared to the amount deposited on the walls.

The optical micrograph of as received alumina powder shows that the size of most of the particles varied from 50 to 80 microns. Only a small amount of particles have sizes below 50 and above 80 microns. Some of the particles were found to be completely transparent. The shape of most of the particles was found to be irregular. The optical micrograph of the plasma treated and purified powder is shown in Figure 3. It was found that almost all the powder got spherodized (~98 %). Some of the particles are transparent. The size of the particles varies from 35 to 90 microns . Very few particles have sizes less than 35 and more than 90 . The powder collected from the reactor walls was found to be sticky due to its small particle size.

The X-ray diffraction (XRD) patterns of as received and as treated powders were taken. From the peaks of the XRD patterns, it was found that both materials have a corundum (trigonal) structure. No peak corresponding to carbon was found even in as treated powder. This clearly shows that the percentage of carbon in treated alumina powder must be less than 3 to 4 %.

Silica Fusing

The motivation for developing this new technology came primarily from material scientists. The plasma part was usually treated as a black box,; hence, thee sources were not adequately understood and were not specifically tailored for the application in mind. Physico-chemical properties, the temperature profile of plasma, modification of electrical characteristics of the plasma by the introduction of the powder, thermal history of particles, introduction of particles into the flame etc., plays crucial role, and careful understanding of them is necessary for optimization.

A series of experimental campaigns were conducted to develop a plasma torch suiting the present application. In addition, experiments were carried out for fusing silica in different plasma sources, including the one mentioned above. Although the magnetic field gives expanded plasma flame, it complicates the design of the plasma furnace. In addition, it will add to the capital and running expenses of the furnace.

The FCIPT torch operates in high impedance mode (>1 ohm) without applying a magnetic field and produces an enlarged plasma column. The geometry also allows one to introduce powder into the flame through the electrodes and periphery. In addition, the coating of the electrodes with molten silica is minimized.

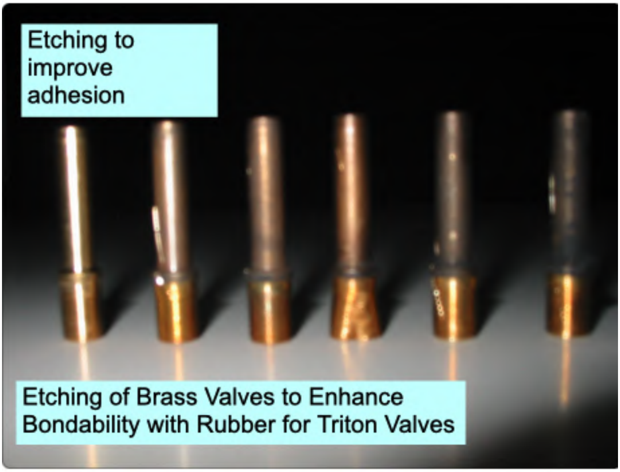
14. Plasma Etching and Texturing

Plasma etching is a two-step process in which chemically reactive species generated inside the plasma interacts with solid material to form volatile compounds which diffuse from the surface and are evacuated. An example is the dissociation of CF_4 releasing fluorine, which reacts with silicon to form SiF_4 gas. The result is microscopic milling of the surface. Plasma etching is a generic term which includes process varieties like reactive ion etching, reactive sputter etching and plasma ashing.

The type of surface modification will depend on the substrate and process parameters. The depth of treatment depends on the substrate temperature, process time and diffusion characteristics of the material. Plasma action is limited to surface etching for depth up to a few microns. As a result, the surface property changes, but the bulk properties are preserved. The technique makes the surfaces cleaner, harder, rougher, wettable and adherent. Inert ion sputtering is more of a physical process than chemically reactive plasma sputtering. In chemical sputtering reactions occur, volatile products are formed. The gases used are Ar, He, O_2, H_2, H_2O, CO_2, Cl_2, F_2 and organic vapours.

Etching of Automobile Valve Stems

Metal reinforced rubber products require both an adhesive to bond the metal to the rubber and a curing process to improve the mechanical properties of rubber. The overall chemical process produces polluting liquid effluents. In a process developed for a valve manufacturer, brass valves were treated in the air plasma generated by a 10 kHz pulsed dc plasma source. Plasma-treated brass valves moulded with



rubber showed improved adhesion.

Plasma interaction with polymer surface leads to removal of organic materials, cross-linking via activated species of inert gases, ablation and surface chemical restructuring by adding polar functional groups. These processes increase surface energy and improve adhesion between surfaces. As a result, plasma treatment can produce hydrophobic or hydrophilic surfaces on metals, plastics, glasses and polymers.

The mechanism of the FCIPT process is the following. Brass reacts with sulfur-containing intermediates resulting in the formation of interfacial non-stoichiometric sulfides. During vulcanization, brass is corroded by sulfur-containing species, forming duplex sulfide films. The sulfide film consists of non-stoichiometric CuxS at the sulfide-rubber interface and ZnS at the sulfide-metal interface. These sulfides, especially the CuxS, grow into the rubber matrix when it is in the flowing condition during vulcanization. Copper has the special characteristic of forming non-stoichiometric sulfides, which grow as dendrites. This is one of the reasons that brass and some other copper alloys are good at reacting and bonding with rubber.

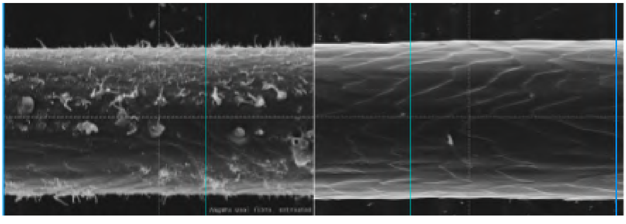
This rubber-brass bond is very durable and has high resistance to dynamic and thermal ageing, typical in its use in automobile and truck tyres. In addition, this process is environmentally friendly compared to conventional treatment, which uses chemicals and acids.

With India's leading manufacturer of these valves, FCIPT has set up an industry-scale system for large-scale commercial exploitation treating 5000 valves per batch.

Plasma Texturing of Angora Wool

Angora Rabbit fibre measuring between 10 to 12 microns in diameter and 40 to 70 mm in length is considered one of the finest luxury fibres. The angora fibre possesses cavities in which air is occluded. These air occlusions give Angora its high thermal insulation and its extreme lightness in weight. Angora fibre has a low density of about 1.15 gm/cm3 compared to 1.33 gm/cm3 for wool. However, the natural Angora fibre has the limitation that it needs a considerable twist to hold the fibres firmly in the yarn while spinning. In addition, angora fibres are generally woven using Merino for the warp and Angora for the weft. These limitations of Angora fibre lead to reduced productivity, increased fibre loss and limited product range.

The plasma etching of the Angora fibre surface increases the friction and cohesion between the fibres. It promotes the non-polluting mechanical processing of textile material without difficulties such as static, shedding, and fibrosity. After plasma treatment of Angora fibres, it facilitated mill



Angora Strand Before and After Etching

spinning and hand spinning of yarn without shedding and later hand weaving of fabric without fibrosity. 100% Angora Products such as Stole, Shawl, Scarf, Cap, Sweater, and Ponchos developed from plasma-treated fibres can be manufactured. The dyeing of these products is done using Natural Dyes. The plasma treatment to Angora fibres also improved wettability and dye uptake, which is an added advantage.

The etching technology has been developed in collaboration with the National Institute of Design. Atmospheric Pressure Plasma to Process Angora Wool (APPAW) has been commissioned and synchronized with Roller Worsted Card for continuous plasma treatment of Angora wool in the web form at approximately two kg/H production rate with the help of the Weaving and Designing Training Centre of Central Wool Development Board (CWDB) and Shiva Weavers Co-operative Society at Kullu.

Plasma Etching of Polymers

A significant problem that prevents adequate adhesion is the presence of organic contamination on the surface.

Contamination may exist in the form of residues, mould release agents, anti-oxidants, carbon residues or other organic compounds. Oxygen plasma is excellent for removing organics and is commonly used for this purpose. Oxygen plasma causes a chemical reaction with surface contamination resulting in their volatilization and removal from the plasma chamber. Care must be taken in selecting process parameters to ensure that organics are entirely removed. Critical parameters may include sufficient power density to remove but not polymerize the organics. In RF plasma, oxygen (O_2) is fragmented into monatomic oxygen (O), O^+ and O^-. O at the pressure around 0.1 torr. The reactive plasma species readily combine with any organic hydrocarbon and produce water vapour, CO and CO_2 carried away in the vacuum stream. Contact angle measurement can confirm whether or not the organic removal is completed.

When plasma interacts with the surface of polymers, four primary effects can occur: the removal of organic materials, cross-linking via activated species of inert gases, ablation and surface chemical restructuring. By adding polar functional groups to the surface structure, surface chemical restructuring dramatically increases surface energy and associated adhesion to other materials. Ablation roughens the surface, increasing the total contact area between the adhesive and the substrate surface.

Plasma etching is used to remove unwanted materials at the molecular level. It provides uniform etching and has been proven superior to wet chemical processes. In addition, this is an environmentally safe method for organic removal and surface modification.

Polymers were plasma-etched in a large plasma polymerization reactor. Capacitively coupled radio frequency (13.56 MHz) plasma source was used to generate plasma. Gases were introduced through a multipoint gas-feeding showerhead.

Contact angle measurements were done on bare and plasma-exposed flat polyethene test samples by Contact Angle Goniometer, and the results were compared. Because of their uneven shape, polymer samples provided by M/s Anabond were not tested for contact angle measurements. The contact angle of the bare polyethene sample was 48, whereas, after plasma treatment, it reduced to 34. Adhesion was found satisfactory in high-density polyethylene, polystyrene and acrylonitrile-butadiene-styrene polymer samples.

Textile Processing

Plasma treatment is emerging as a highly attractive alternative for surface modification of textile and technical textile. The drivers of this technology are the demand for new

production methods which meet the environmental and quality aspects. New enhanced-property materials replacing traditional materials are often no longer compatible with conventional cleaning and activation chemistry.

Plasma interaction with fabrics can lead to changes in wettability and surface texture. This leads, for example, to an increase in printing quality, dye uptake, dye adhesion etc. The improved characteristics include wettability, flame resistance, adhesive bonding, printability, electromagnetic radiation reflection, surface hardness, hydrophilic and hydrophobic tendency, dirt-repellent and antistatic properties.

The cold plasma process modifies the surface support favouring a great deal of free radicals on very stable polymers and increasing surface energy and wettability. The process allows, with only one operation, the cleaning of the support, the surface activation and, if necessary, the removal of moulding residues and the etching of the surface.

Three plasma treatment processes are commonly used: cleaning, activation, deposition and sterilization. Although all three processes are initiated using the energetic species and the UV radiation present in the plasma, the particular type of gas used and the process conditions combine to determine the substrate’s reaction.

Plasma action can change the surface's chemical, morphology and energetic characteristics. Mechanisms of importance here are cleaning, activation, etching, and probably polymerization, sterilization, and biocompatibility in the future.

Materials which can be treated are HDPE, nylon, PP, wool, and cotton. Unfortunately, the wide use of plasma treatment for textiles is essentially hindered by the absence of adapted continuous machines on the market and the cost of the machines. Nevertheless, for the more advanced technical textiles, this technique is finding its way into the market the textiles.

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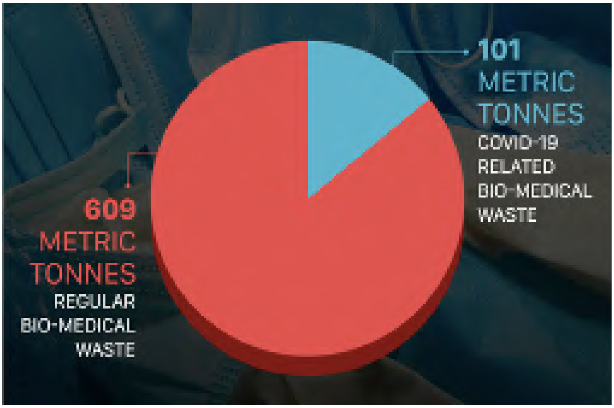
15. Plasma Pyrolysis of Bio-medical Waste

An international scandal involving a vast intra-European traffic in medical waste, originating from France and culminating in eventual redistribution in other European markets in the late 1980s, led to the resignation of the then French minister of health. As a result, the world was shocked to recognise the magnitude of the medical waste disposal problem. India is no stranger to such horror stories. Recycled syringes and quilts packed with used surgical cotton have a thriving market. Newspaper reports on rackets based on recycling medical waste back into the market abound. Photographs of hospital backyards filled with medical waste appear regularly. Pathogens of deadly diseases like hepatitis B find a ready and fertile breeding ground in the piles of undisposed medical waste. This is despite the existence of rules (Guidelines for Management of Healthcare Waste as per Biomedical Waste Management Rules, 2016) concerning the handling and remediation of biomedical waste.

The Medical Waste Problem

Public concern over the disposal and treatment of medical waste has resulted in increased regulations and court actions on a global scale. The fundamental reason is the phenomenal growth in the quantity of medical waste generated in the hospitals, attributed to the growing use of disposables as precautions against exposure to infectious diseases such as AIDS and the growth of medical and public health facilities. The recent COVID pandemic multiplied the medical waste problems many times. The generators include hospitals, clinics, and medical research facilities. A rule of thumb for medical waste production in affluent countries seems to be 1 kg per bed per 8-hour shift. India is all set to generate around 775 tons per day of biomedical waste in 2022, with current levels being 551 tons per day. United Nations Environment Programme (UNEP) study has estimated that due to the COVID pandemic, an increase of around 0.5 kg per bed per day of BMW is expected.

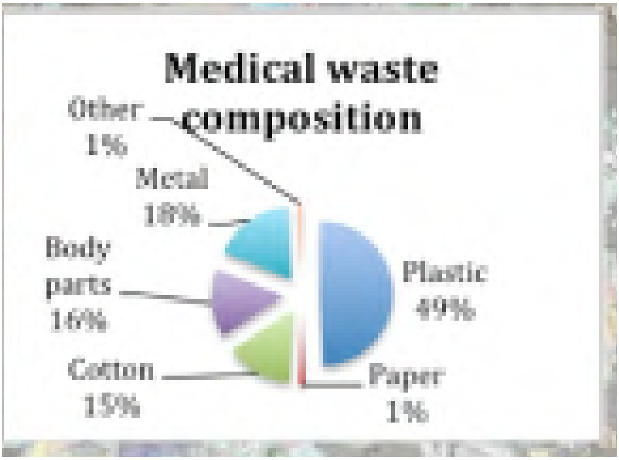


Medical Waste Generation

Conventional Remediation Techniques

Historically, landfilling was the most preferred means of disposal of medical waste. However, public opposition and positive correlation with groundwater contamination have resulted in this option steadily going out of favour. Burning the waste material in the open air can never be complete, with small quantities of many organic and chlorinated organic compounds and pathogens surviving and leading to the dispersal of dangerous diseases that can spread through the air. Therefore, incineration is the most popular method of medical waste disposal. About 85% of medical waste is incinerated, while only 6–15% is waste that requires special handling and disposal.

The fundamental problem of incineration is that combustion's chemistry determines heat generation. Efficient combustion demands airflow far above the stoichiometric requirement. The very high flow rate generates airborne pollutants and limits the attainable temperature. As a result, the effectiveness of incineration, measured in terms of the destruction and removal efficiency, is low. In addition, the performance of the emissions control equipment to meet the stringent requirement of safe disposal is poor.



The Dioxin Problem

PVC (Polyvinyl Chloride) plastic, which contains chlorine, constitutes many disposable products used in health care. When PVC products burn, they serve as a primary source of chlorine for dioxin formation. "Dioxin" refers to a family of compounds that can form when chlorine combines with organic material in a reactive environment. Dioxins and related chlorinated organic compounds are potentially toxic substances that produce a remarkable variety of adverse effects in humans and animals at low doses. These compounds are persistent in the environment and accumulate in magnified concentrations as they move up the food chain, concentrating on breast milk. Dioxin is carcinogenic, interacting directly with DNA through a receptor-based mechanism.

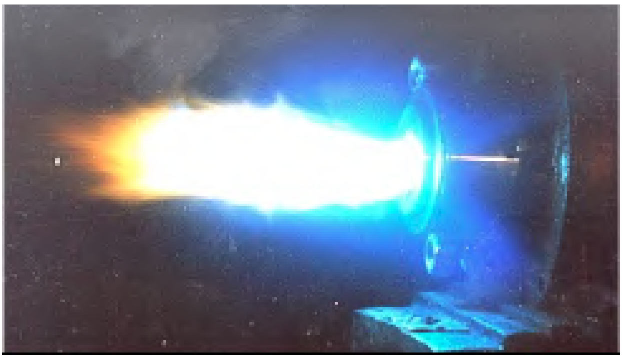
The TIFAC initiative

In the late 1990s, the Technology Information Forecasting and Assessment Council (TIFAC) approached Institute for Plasma Research (IPR) to develop a Plasma Mediated process for medical waste destruction. With dramatic developments in high-temperature plasma sources, we thought we could apply plasma heat to highly toxic waste, and the final products can be harmless gases. The large flux of ultraviolet radiation in thermal plasma can dehydrogenate organic chlorine. The reactors were to process gaseous, liquid, and solid materials. Plasma-based medical waste treatment is highly complex since it must contend with extreme temperatures and a corrosion-prone environment. The process depends on complex pyrochemistry resulting in toxic and dangerous products.

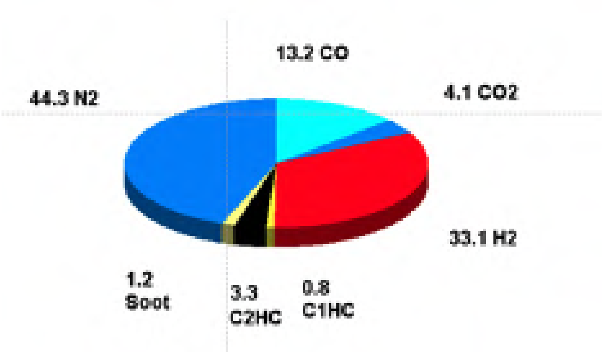
Furthermore, it deals with high volume, low packing density waste with a non-standard composition comprising various plastics, organic materials, and liquids. As a result, compliance with environmental emission standards is complex. In addition, there are capital and operating cost constraints imposed by inferior competitor technologies. Being an internationally competitive technology with very high commercial stakes, critical information on many crucial aspects was not readily available. No peer group with expertise in this field existed in India for problem-solving consultations. Under a development programme with intense time pressure, many problems will have to be solved concurrently with development.

The Plasma Torch

The workhorse of plasma-based waste destruction technology is the plasma torch. Plasma torches are electrical discharge plasma sources with the plasma extracted as a jet through an opening in the electrode andout of the confines of the cathode-anode space. The arc column's inherent thermal and electromagnetic instabilities are stabilised by forced gas flow along the current path. Interaction with a guiding wall or external magnetic fields also stabilises the plasma.



DC arc, RF and microwave plasma sources can be converted into plasma torches. Plasma temperatures can easily reach tens of thousands of degrees, and high enthalpy gas flows get generated in large volumes. The driver for developing plasma torches was the space race in the 1960s. Missiles re-entering the atmosphere create shock-ionised air plasma. Laboratory simulation of these conditions was necessary to develop materials capable of withstanding the searing heat of re-entry. Arc systems can generate re-entry conditions using clean, high enthalpy gases at high stagnation pressures. Many present-day plasma torches are derivatives of the plasma jet sources built for this application and now meet the need for intense heat sources



for waste treatment.

Conventional plasma torches require large gas throughput to stabilise the arc, resulting in product gas dilution and reduction in energy efficiency. We have innovated the graphite torch exploiting the gas generation in the pyrolysis of organic matter. An inline suction pump sucks the product gas and sends it through a filter to remove soot particles. It is then fed to the plasma torch. We had a 35 % gain in energy efficiency with this torch.It also increases electrode life by reducing the electrode erosion rate. We received a patent for the Endogenous Gas Feed concept in 2007.

Pyrolysis Process

Pyrolysis is the thermal disintegration of carbonaceous material into fragments of compounds in an oxygen-starved environment. The presence of charged and excited species renders the plasma environment highly reactive, catalysing homogeneous and heterogeneous chemical reactions. When the process is optimised, the most likely compounds to form are methane, carbon monoxide, hydrogen, carbon dioxide, and water. The high temperature and high enthalpy inhibit the formation of hydrocarbons. The product gas is high in hydrogen and carbon monoxide, with traces of methane, acetylene, and ethylene; therefore, it can be combusted very efficiently, resulting in carbon dioxide, nitrogen and water vapour being the only gaseous exhaust to the atmosphere.

The slag is a homogeneous, silico-metallic monolith with leachate toxicity levels orders of magnitude lower than current landfill regulations. Emission and leachate results convincingly demonstrate that plasma gasification is a far more environmentally friendly method of disposing waste than any competing technology. Plasma gasification provides more than a 95% volume reduction ratio of slag to input material. Other technologies offer an 80% reduction typically.

Prototypes

The prototype plant was built by Dr Ganesh Prasad (Plasma Physics) and Dr Sudhir Nema (Chemistry), both Scientists at FCIPT, using a conventional plasma torch and was installed at the Gujarat Cancer Research Hospital for field trials.Using the field experience, we built a series of prototypes to solve operational problems and improve reliability. We used an in-house developed graphite electrode plasma torch for ruggedness and energy efficiency. This used graphite electrodes with automated movement to keep plasma impedance constant.

A commercial version of a Plasma Reactor came after we installed the second field version at the Goa Medical College in 2000.

Fields Trials and Regulatory Approval

After the successful trial of the system in the Goa Medical College, the Department of Science and Technology sponsored a programme of demonstration of this technology by installing several plasma systems all over the country, including one at the Shri Chitra Institute in Trivandrum. A large number of systems enabled extensive field trials of this technology. The technology was transferred to several


The Commercial Pyrolysis System

manufacturers. About 1 KWh of power is required for 1 kg of waste. A 3 phase supply is adequate as the power source. A 25 KW unit is adequate for a 50 bed hospital.

The final battle that the development effort on pyrolysis technology had to fight was with the Regulatory Bureaucracy. The powerful incinerator lobby had put many obstacles in the path of CPCB declaring pyrolysis as an approved technology for medical waste destruction. However, we finally won the battle with the issue of a Gazette notification in 2016 endorsing Plasma Pyrolysis for medical waste destruction.

Conclusions

Plasma pyrolysis technology is one of the many societally beneficial applications developed by FCIPT. One important lesson we learnt was that while it was relatively easy to master technology development, it was complicated to fight the battle with entrenched forces that resisted the introduction of advanced technologies, citing various reasons.Even government departments sometimes become tools of these retrograde forces.

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16. Plasma Mediated Deposition of Films

The plasma environment facilitates many chemical reactions simultaneously. Reactions are heterogeneous in the presence of boundaries and substrates. Competition between ablation and deposition governs surface-related processes. With organic vapours, plasma polymerization and deposition occur. The material interacts with the gas phase active species and precursors during etching and deposition through the surface. Surface conditions such as contamination, the presence of inhibitors, barrier layers, the adsorption of gases etc., are important and affect the process kinetics and properties of the deposited films.

Film Deposition using Plasma

An interesting aspect of plasma chemistry is the synthesis of complex molecules from simple starting materials. Typical reactions are: isomerization, elimination of atoms or small groups, dimerization/polymerization and destruction of starting material. In addition, ion bombardment can be used to modify film characteristics.

Deposition takes place in four significant steps:

Electron-impact reactions between electron and reactant gases to form ions and radical reactive species Transport of the reactive products from the Plasma to the substrate surface concurrently with the occurrence of many elastic and inelastic collisions in both the plasma and sheath regions

Absorption of the reactive species on the substrate surface is usually followed by a reaction between the species and the surface. Finally, the reactive species and reaction products incorporate themselves on the substrate forming films or re-emit from the character back to the gas phase.

This technique is well established and is used to deposit thin organic and inorganic films (e.g. SiOx, TiN, TiCN, diamond coating etc.) on metals, glass, polymers and on various other materials to protect their surface from corrosion and to improve surface hardness and wear resistance property. Polymerization is the creation of huge molecules by joining many small linkable molecules called monomers. This process can happen in Plasma as well. However, Plasma can also polymerize materials, which do not usually form polymers under normal chemical route by fractionating gases that lack linkable sites into many new and reactive compounds that subsequently may polymerize.

Plasma Polymerized Glass Like Coatings

Glass-like coatings (GLCs) are polymerized thin films deposited using the plasma-enhanced chemical vapour deposition (PECVD) technique. These coatings consist of Si-O-Si bonds, which are highly coherent, uniform, and provide excellent corrosion resistance to the coated components. In addition, these coatings also provide a high-quality surface finish.

GLCs are highly coherent and have cross-linked structures. They are pinhole free and have good adherence to the substrates on which they are deposited. The coating thickness can be varied from 0.1 to 5 microns based on the requirement. Solvents like acetone, petroleum ether, water, dilute acid, and base do not affect the coatings.

Anti-tarnish Coating of Brassware

The plasma environment enhances the deposition and growth of thin films on metals and polymers by physical and chemical methods. These films can be designed to improve surface hardness, wettability, optical properties and corrosion protection. Plasma-enhanced chemical vapour deposition employs metal-organic monomers, which are decomposed in the Plasma and made to react with hot surfaces for the testimony of films.

Quartz-like polymerized silicon-based thin film coating involves dissociation of HMDSO leading to the formation of Si-O chains, which deposit as a quartz-like coating on substrates. The layer consists of highly coherent, cross-linked, pinhole-free Si-O-Si bonds and has good adherence to the substrates. Micron-thick SiO2 diffusion barrier films inhibit corrosion and provide the high quality surface finish. Coatings are immune to solvents like acetone, petroleum ether, water,

dilute acid and base and have undergone extensive industry acceptance tests.

The manufacturers of decorative brassware from Moradabad had problems competing in international markets with their epoxy-based tarnish-free coating. We developed a process for depositing quartz-like silica films on brassware. We have set up of Plasma Polymerization System to coat brass articles by SiOx at the Metal Handicraft Service Centre, Moradabad, under financial support from the Department of Science & Technology, Government of India.

Coatings on Automobile Reflectors

Aluminum-coated automobile reflectors lose their reflecting properties due to oxidation and corrosion when

exposed to a normal atmosphere. Conventionally, lacquer is coated to protect the surface from corrosion. However, lacquer coatings offer only a temporary reprieve. A material which is transparent, non-reactive, corrosion resistant and scratch resistant as glass. There are various methods for depositing glass coatings, and one such method to deposit glass-like coatings is plasma polymerization, which involves the deposition of these coatings by plasma polymerization.

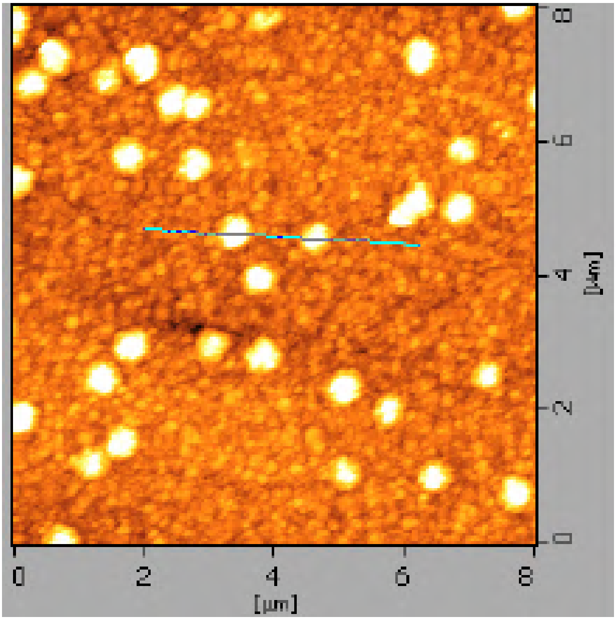
Silicon Oxynitride Films

High-quality carbon-free SiOxNy films have been grown at FCIPT by RF (13.56 MHz) Plasma-enhanced chemical vapour deposition (PECVD) on single crystal Si<100> wafers and textured Silicon solar cells, using a safe organic precursor, Hexamethyl-Disilazane (HMDSN). We have obtained process parameters which result in carbon-free (< 1.0 %) films of thickness ranging from ultra-thin (30 angstroms) to relatively thick (~ 3000 angstroms). We can be used for electronic and optical applications. In a joint project with BHEL, Electronics division, Bangalore, we have grown 'blue-violet' anti-reflection coatings on solar cells with uniform chemical composition (SiO1.35N0.5) and thickness (860 + 15 angstroms), and demonstrated an efficiency increase of ~ 1% (AM 1.5).

Another application of the silicon-based coating is to protect silver-coated metallic mirrors from drop in reflectance due to tarnishing. A thin dielectric film of Silicon Oxy-Nitride acts as a barrier layer for the silver surface when exposed to air. It does not allow atmospheric oxygen to tarnish the silver substrate. Another development undertaken for the manufacturers of automobile lamps was to synthesize Optical quality reflective coatings over complex shapes and large areas with reflectivity as high as 95% using Plasma Enhanced Chemical Vapour Deposition with safe monomers.

Hydrogenated Silicon Thin Films

Si: H thin films are actively studied for their use in various devices such as thin film solar cells, thin film transistor (TFT) displays and other devices such as photodiodes [1,2]. Several fabrication techniques have been used for the deposition of Si: H, and new developments are aimed at improving material quality and achieving higher deposition rates. PECVD is considered the most important of these techniques for extensive area depositions, allowing cheap substrates such as glass, stainless steel, and polymers for Photovoltaic modules. The advantage of Very High Frequency (VHF: 25–150 MHz) PECVD for higher deposition rates has been recognized based on the pioneering work at the University of Neuchâtel [3]. Curtins et al. showed that the deposition rate could be increased to 20 A°s without increasing power density, the frequency is raised from 25 to 70 MHz [3].

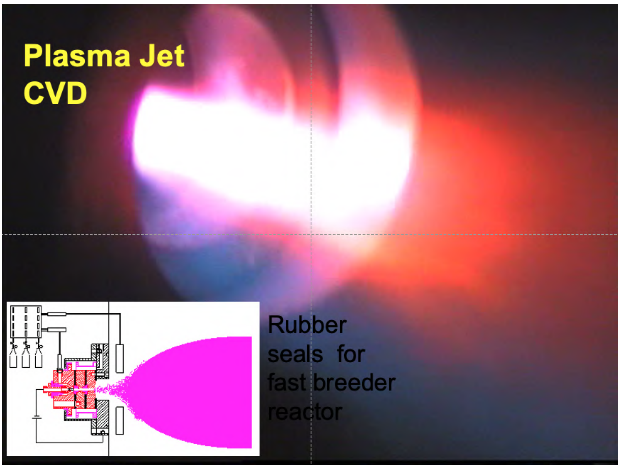


In a recent significant study, a novel multi-hole cathode (MHC) with VHF (60 MHz) PECVD has demonstrated the highest deposition rate of 77 A°s-1 at substrate temperatures of 200–400 C for device-grade micro-crystalline (mc)-Si: H thin films [4]. It is well known that Si: H films deposited by PECVD at a substrate temperature of around 250 C show the best optoelectronic properties, such as photoconductivity and photoresponse, for solar cell device applications. However, deposition of Si: H at low temperatures (40–150°C), well below typical processing temperatures of 200–350°C have also attracted interest [5,6] to grow devices on polyethylene.

Superhydrophobic Teflon-like coating

Superhydrophobic surfaces, with a water contact angle greater than 150o have attracted much interest for fundamental research and practical applications. Applications include the protection of glass substrates from contamination, self-cleaning surfaces, industrially applicable water repellent surfaces, etc. The hydrophobic nature is because of the increased surface area, and the trapped air below the droplet. In general, fluorocarbon compounds are found to be water and oil repellent due to their lower surface energies.

We have developed a process for converting Teflon tailings into superhydrophobic coatings. First, the Teflon tailings were pyrolyzed to generate fluorocarbon precursors. An expanding plasma arc (EPA), initiated at a near atmospheric pressure using a wall stabilized cascaded torch, allowed to expand into a low-pressure chamber was used to fragment these precursor molecules. The fragmented species react in the gaseous phase and form ultra-fine particles. Due to the EPA's high directionality and high drift velocity, these fine particles get quenched and deposited on the substrate.



The surface energy of fluorocarbon materials is intrinsically low and a smooth fluorocarbon coating can improve the contact angle up to 100–120o. However, in the present case, a chemically similar layer has improved the WCA up to 165o. This enhancement in WCA is basically because of the packed nanostructure of the coating. SEM shows that the coating consists of 80 nm to 200 nm nanostructures. The superhydrophobic nature is attributed to the deposition of low surface energy Teflon-like nano-structured coating. The gaps between these structures act as valleys while the structures themselves act as bumps giving rise to the surface roughness.

X-ray photoelectron spectroscope was used to study the chemical bond state of the coating. Carbon and fluorine are the main constituents of the XPS survey spectrum, with traces of oxygen and nitrogen. The deposited film is dominated by CF2 bonds (291.8 eV), and the deposited film has a chemical structure very close to Teflon, with little cross-linking. The low-intensity peaks observed at 284.0 eV and 282.2 eV in Fig. 7(a) are attributed to C–C and metal carbides, respectively. The higher concentration of CF2 groups in the coating is possibly due to the presence of low-energy electrons in the expanding Plasma.

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17. Bridging the Gap

In India, research institutions are well funded. Money is generally not a problem in pursuing research; the lack of ideas and human resources is. The situation in Indian universities is the converse. We have been very sensitive to this imbalance at the Institute for Plasma Research. My earlier association with Aligarh University strengthened this perspective, and I have taken many initiatives to correct this imbalance.

Satellite Research Projects

During the early days of the Plasma Physics Programme, it became apparent that capacity building in universities in plasma physics was essential to generate the human resource necessary for the development of future programmes. The first significant effort in initiating Universities into plasma physics research took place in 1984 when we organized a workshop on Plasma Physics Experiments in Universities under the sponsorship of the University Grants Commission. The basic idea was to collect faculty members from universities with some or no prior background in plasma physics and motivate them to start working on basic plasma physics experiments. There were 45 participants from universities and other organizations and about 28 from PPP.

The workshop led to the Thrust Area Programme committee of the Department of Science & Technology initiating a programme to fund universities on nucleating plasma physics experiments. This became known as the Satellite Research project, satellite to the main task at PPP. The DST's Science and Engineering Research Committee (SERC) subsequently entrusted me with the organization of this programme. I conceived a pro-active programme of engaging academic faculty to prepare proposals for DST funding. Many different university groups, which are at present active in plasma physics, can trace their genealogy back to this initiation.

Cross-Disciplinary Plasma Sciences

Later, with my growing interest in plasma processing, I conceptualized and managed the Cross-Disciplinary Plasma

Sciences Programmes for DST, which helped nucleate research groups in universities and promote collaboration between universities and research institutions. As Chairman of the SERC committee to implement this, I organized several inter-disciplinary workshops involving plasma, condensed matter and surface physicists, metallurgists, and chemists, coordinated the preparation of state-of-art reports, and developed procedures for evaluation of research proposals and funding them.

Research programmes linking plasma physics with other branches of physics, material science, chemistry, engineering and environmental sciences were identified and funded under this programme. The focus will be on basic scientific aspects, applications and technologies. Among the possible areas for CDPS activities, plasma-assisted processes in semiconductor manufacturing appear to be a promising and justified research activity.

The first Target Group Meeting (TGM) on "PLASMAS IN SEMICONDUCTOR PROCESSING" was held at the Institute for Plasma Research on the 4th and 5th of January 1999. Twenty participants and experts from various universities/research institutes participated, and 18 proposals were discussed . The proposals covered diagnostics and modelling of plasma source phenomena, plasma surface interaction and correlation of device characteristics with both source and surface interaction phenomena. Many of the recommendations had similar themes, and hence, possibilities of joint research were explored.

Development of cheap, indigenously built experimental systems was stressed and also the development of computer modelling is indicated as an active area. The participants regarded the CDPS programme as a new, unique, focused and proactive way of spreading basic research in various branches of plasma science.

The National Fusion Programme

With India's entry into the ITER project, a qualitative shift took place in our perception of fusion as a credible long-term option in the basket of futuristic nuclear technologies. While the specific details of the road map to energy from fusion will take time, preparations for acquiring the necessary competence in its scientific and technological skill and knowledge base must be initiated now, considering the long-time scales demanded by such endeavours.

With participation in ITER, creating a human resource base for the future requirement of trained manpower in fusion science and technology became essential. Therefore, while IPR prepares to meet the Indian commitment to ITER, it was thought imperative to conceptualize a long-term programme – a National Fusion Programme (NFP) - to acquire indigenous competence in all aspects of fusion science and technology. This will ensure that the country is ready to take up the construction of a demo reactor following the successful operation of ITER.

The programme is of a multidisciplinary, multi-institutional character, requiring expertise from various fields, ranging from the frontiers of fundamental science to advanced technologies. The research and development capability that will have to be nucleated in universities, academic institutions, national laboratories, and industries can be essential to realising the NFP. Specifically, we must generate a community of fusion scientists and engineers, set up programmes for 'Balance of ITER' technologies, partner with industries as contributors to fusion technology and develop human resources.

The Board of Research in Fusion Science and Technology (BRFST) was conceived as the agency which will execute these functions and advise IPR on financial assistance to universities, academic institutions, national laboratories, and industries. The charter of BRFST shall be to promote the nucleation and growth of research, development, and training of manpower in the field of fusion science and technology in universities and educational institutions through the award of research grants, support of training programmes, conferences and symposia and promotion of activities to increase

collaboration between academia and the Institute for Plasma Research.

In association with Ravi Kumar, I developed the National Fusion Programme concept and established the administrative framework of BRFST for funding universities and educational institutions in basic research and human resource development in fusion science and technology.

India will learn 10% of ITER since we shall supply the hardware. The 'Balance of ITER' will have to be learnt through an indigenous programme covering core fusion technologies like fusion materials, fusion neutronics, RF and microwave power systems, power engineering, data acquisition and control systems, plasma diagnostics, robotics, superconducting magnets, and cryogenic technology etc. The National Fusion Programme (NFP) aims to acquire indigenous competence in all these fields. The programme is multidisciplinary, and multi-institutional. In broad terms, we must generate a community of fusion physicists, set up programmes for 'Balance of ITER' technologies, partner with industries and develop human resources. NFP programme is designed to extend and complement the IPR efforts in all fusion science and technology areas. Internal fine-tuning of the proposals and having IPR personnel act as coordinators ensure this.

To identify potential partners in NFP, we conducted roadshows at major universities, IITs and NITs across the country, highlighting the areas where IPR required collaborations in R&D. Once an interested collaborator picked up a project that was of interest to them, the collaborator from IPR would hold discussions with them and NFP to formulate the project proposal. This yielded good results, and

faculty from over 40 institutions came forward and submitted research proposals in the same year, i.e., 2007.

A unique feature of NFP is its engagement with the industry to take up critical technology development efforts. The development of cryopanels using forming technology and the successful development of cryopumps and cryosorption materials are good examples of such collaboration's benefits.

National Fusion Programme is aimed at broad basing the Indian efforts in developing Fusion Science and Technology by involving universities, other educational institutions, and industries to work with national institutions. The consequential creation of a community of specialists in plasma physics and associated material and engineering technologies would be an essential initial condition if India were to launch a credible fusion reactor development programme.

In a short period of 10 years, BRFST and later, Plasma & Fusion Research Committee (PFRC) funded over 200 projects with a total budget of ~ Rs. 55 Crores in a variety of areas of R&D that were of prime interest to IPR research goals. The beneficiaries of these funds ranged from Universities, Colleges, R&D institutions of CSIR, and Institutes like IITs and NITs across the country.

18. Writing About Plasmas

I was born and lived my early life in Kottayam, which, much later, came to be known as the Aksharanagari, the city of letters, for becoming a place with 100 % literacy. It is the home of the CMS press, the earliest printing press established by Benjamin Bailey, a Christian Missionary, in 1821. In the 1950s, there were three Malayalam newspapers published from Kottayam. A unique Travancore institution that started in Kottayam in 1945 is the ‘Sahithya Pravarthaka Sahakarana Sangham’, Writer’s Cooperative, which published books and gave financial security and social status to writers. On my way from school, I would pay an occasional visit to the Co-operative’s Book Stall, with its shelves full of books that gave me great inspiration to follow the path of writing.

One teacher I was very fond of was Kanam E. J. Philip, our Malayalam teacher who was also a writer. Inspired by him, I started writing poetry. However, he made it clear that poetry had no future and that I should write stories like him. I kept in contact with him in the later years when he became an editor of the Malayala Manorama weekly.

Another incident strengthened the desire to write. The Malayalam drama we had to study was Antigone by Sophocles, taught by P. J. Thomas, a young teacher. He asked us to write an essay on Antigone as a heroine. I decided to depict Antigone with all mortal failings and argue that despite this, she transcended mortality by her stead-fast loyalty to her father. The teacher was very impressed by this and made very complimentary comments about this radical view.

With time, this dream faded, ever-present in the subconscious, but at no time showing signs of becoming a reality. With the existential struggles of doing well in studies, getting a PhD, and making a career, writing a book became an ever-receding mirage.

I believed that I possessed the basic skills. Years of diligent reading of the Hindu middle under my father's tutelage did bear fruit. Writing is essential for a scientist who needs to communicate his discoveries and insights to his peers. I read William Strunk's Elements of Style many times. All I needed to bring out a book was an appropriate subject.

In the 1990s, I started a newsletter - Plasma Processing Update - with the strong motivation to communicate the exciting knowledge about industrial applications of plasma physics, a field I was working on, to industries. The first issue of the Plasma Processing Update came out in 1994. The early issues were written almost entirely by me. However, with time came new enthusiasts from among the new staff. After two decades, this newsletter is still going strong, communicating to industries the developments in India on plasma processing and applications.

Plasma Sciences and the Creation of Wealth

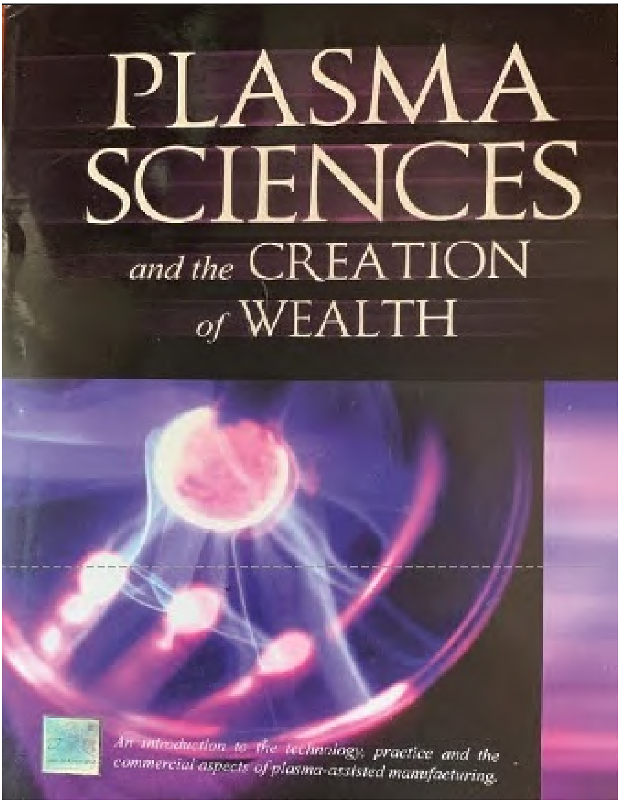
Around that time, I gave a talk titled "Plasma Science and the Creation of Wealth" at a meeting in Rajkot. After the conference, I was approached by one of the publishers in Rajkot, asking whether I would like to expand my address into a book. The dream, permanently lurking in the subconscious, suddenly emerged into the light, and I decided to start writing a book.

I had in mind a book that discusses the versatility of plasma as an enabling tool for wealth creation in industrial, manufacturing, environmental and engineering applications.

It should introduce the technology, practice and commercial aspects of plasma-assisted manufacturing. The agents of change in present-day society, entrepreneurs, business people, consultants and technocrats, were the target audience. But unfortunately, a book of this nature did not exist in the literature.

My 8-month stint with IAEA in Vienna boosted the writing effort. I acquired a laptop which came in very handy in preparing the book. The excellent library at IAEA and the easy internet access were great support. The draft of a book finally emerged.

It took me three years to complete the book, and Tata McGraw-Hill published it in 2005. This book discusses the versatility of plasma as an enabling tool for industrial, manufacturing, environmental and engineering applications. It introduces the technology, practice and commercial aspects of plasma-assisted manufacturing. The book did reasonably well,

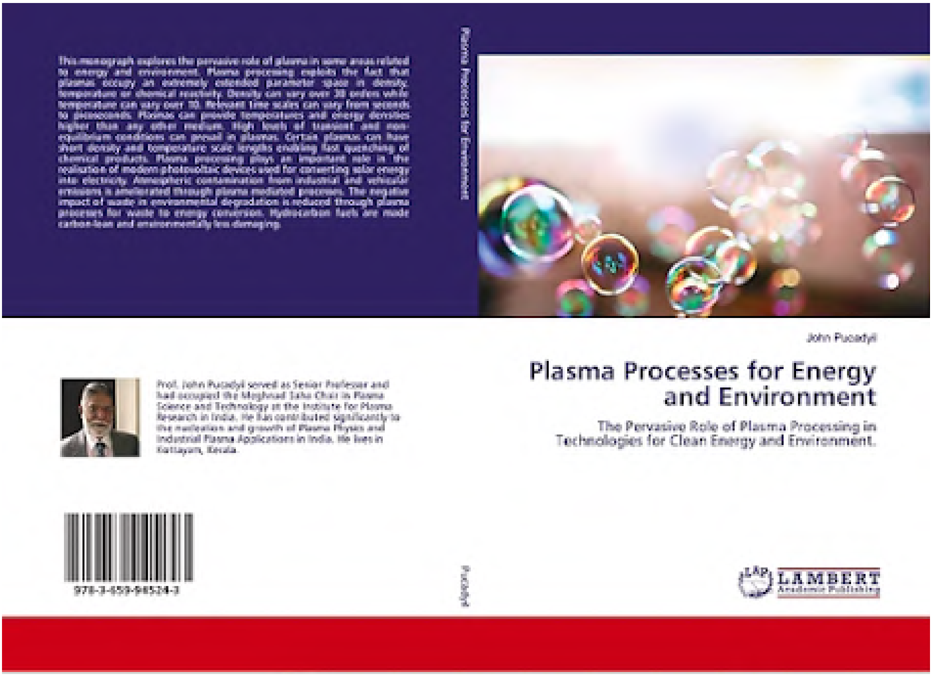


though I was disappointed by the publisher's lack of enthusiasm in promoting the book. Nevertheless, personal efforts succeeded in selling many copies. So it was a surprise when I found a copy of the text on the online Google Books.

Prof. Shouguo Wang from the Institute of Microelectronics, Beijing, approached me, indicating that he was interested in translating the book into Chinese. Originally the idea was to have the reputed publisher 'Science Press publish the book. However, Prof. Wang later decided to publish the book himself. Therefore, we agreed that The Chinese language version shall be an accurate translation of the original English version and shall mention all facts concerning the authorship of the original version. Through my Chinese colleagues in ITER, I learned that the book was published and a success. However, it took some time before I could settle all the terms with Prof. Wang.

Plasma Processes for Energy and Environment

In March 2016, I gave "Dr S. S. Ramaswamy Memorial Endowment Lecture" at the Entrepreneur Development Institute, Gandhinagar33rd DAE Safety & Occupational Health Professionals. The topic was Plasma Processes for Decarbonisation. This was published on their website. Shortly afterwards, Lambert Publishers from Germany approached me, asking whether I would like to expand the talk into a book. This was done within a year, and they published the book electronically in 2017. The book explores the pervasive role of plasma processes in making green energy and a clean environment possible. This was put up on the AERB website, and LAMBERT Academic Publishing approached me in



Germany with their interest in publishing the book. I added material on all plasma-based processes relevant to clean energy and a clean environment. This was electronically published, and all I had to do was to give them a pdf version of the book. The physical copies would be printed only when there is a demand for them. So, no stockpile of books as in conventional publishing. The cost of the book, however, was a steep Euro 36.

Walter Mosley says, “I think that everyone can write a book. … if they do, the writing of that book will change their lives.” Though he said this about writing fiction, I believe it can be generalized. Writing demands a certain kind of mental and emotional discipline. Then, when it comes out as a published book, it is a moment of extraordinary self-revelation.