Plasma Research Laboratory

Professor Jeffrey Harris - Head of Plasma Research Laboratory

The Plasma Research Laboratory investigates the physics of plasmas, the fourth state of matter, a subject of fundamental significance as well as of immense practical benefit to humankind.

http://wwwrsphysse.anu.edu.au/prl

Ionised gases—plasmas—make up 99% of the visible universe, and plasma phenomena are important in everything from stars and space exploration to the processing of electronic materials. Plasma physics is thus a highly interdisciplinary endeavour because of the range of physics areas it encompasses (fluid, atomic, electromagnetic, optical and surface physics) and the diverse technologies employed in plasma experiments (electronics, radio-frequency technologies, magnetics, lasers and microwaves, and spectroscopy).

Experimental plasma research in the Plasma Research Laboratory (PRL) centres on two types of systems:

The H-1 National Facility Heliac operated by the Laboratory's Toroidal Plasma Group is a large toroidal helical-axis stellarator device that is used to carry out fundamental research in the physics of plasma confinement for the production of electricity using fusion reactions like those that power the Sun. The heliac magnetic field is produced by a precision three-dimensional magnetic system. The plasma is produced by high-power radio and micro-waves, and its properties are measured by electric and magnetic probes, optical and microwave interferometry and scattering instruments. A particular focus of work on the heliac is the study of turbulent transport, flows, instabilities and magnetic configurations on plasma confinement. Technologies originated in research on the heliac are also being applied to plasma diagnostics for experiments around the world, instruments for industry and defence, and wireless communication and radar.

Helicon Plasma Sources, high-density linear magnetic plasma devices driven by radio-frequency waves, were originated by the Laboratory's Space Plasma and Plasma Processing Group, and now come in many configurations, from the large WOMBAT experiment to small systems that can be transported in a suitcase. They continue to serve as a focus for basic research in wave-plasma interactions, flows, and potential structure, as well as a basis for innovative devices for technological application. Current activities include the use of helicon plasma processing systems for the processing of electro-optic materials, the development of high-brightness ion sources, and the development of compact plasma thrusters for deep space travel.

The Laboratory also performs research in plasma theory, simulation, and visualisation, in collaboration with staff from the Department of Theoretical Physics and the Department of Computer Sciences in the Faculty of Engineering and Information Technology.

PRL staff are deeply involved in educating young scientists and engineers, through the supervision of post-graduate thesis research and fourth-year undergraduate research projects. We also regularly host students from around the world who come to take advantage of the Laboratory's special capabilities. Staff members of the Laboratory also contribute to undergraduate lecture and laboratory courses offered by the Department of Physics and the Department of Engineering in the ANU Faculties.

The Laboratory maintains extensive international research connections via collaborative research projects as well as externally sponsored research contracts. In 2002, the Laboratory hosted the 14th International Stellarator Workshop and co-hosted the 2002 Gaseous Electronics Meeting (GEM) and the 2002 International Conference on Plasma Physics (ICPP).

Toroidal Plasma Confinement

The centrepiece of toroidal confinement research in PRL is the H-1 Heliac Plasma National Research Facility. This facility is a three-field period helical axis stellarator, which has a major radius of 1 metre, mean minor radius of about 0.2 m and is characterised by a wide range of magnetic configurations. A variety of plasma conditions are accessible, from weakly magnetised argon plasma at 0.1 Tesla, to highly magnetised hydrogen plasma up to 1 Tesla, with temperatures in the range of tens of thousands to millions of degrees. Highlights of developments of the plasma generation and electron and ion heating systems, and the results of physics studies are highlighted below.

Development of the H-1 National Facility

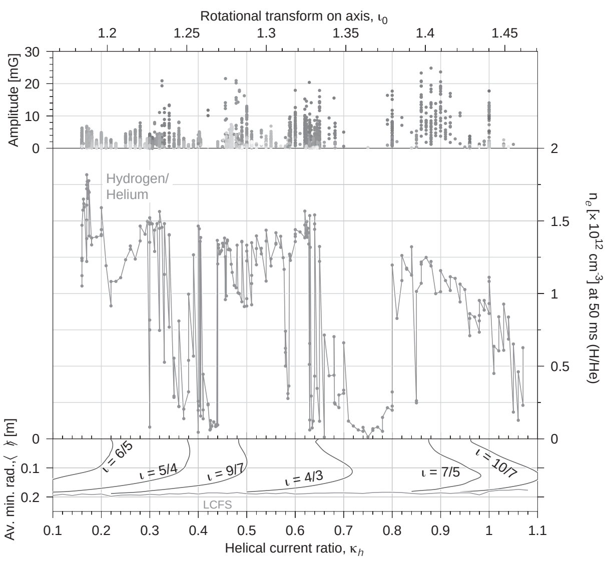
In 2002, two new facility milestones were met, and a record number of shots were fired, in between moving all the H-1 support laboratories and workshops and hosting/supporting two international conferences.

The electron cyclotron resonance heating (ECRH) system delivered more than 150 kW at 28 GHz into H-1 in April, producing the highest plasma energy to-date. Confirmation of temperatures awaits further data. The ECRH power supply capability has been extended from 10ms to 40 ms.

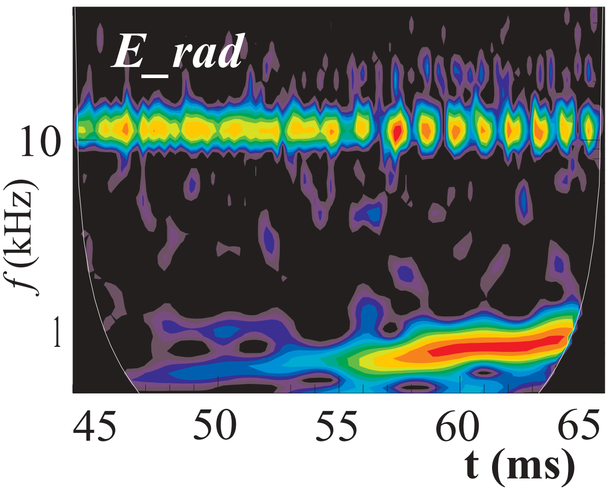
Another newly commissioned system has delivered 200 kW of radiofrequency (RF) power into H-1, achieving another milestone. Power at 0.5 Tesla to heat hydrogen plasma was increased to >120 kW. This complements the 7 MHz RF system used to create plasma and heat both ions and electrons.

Impurity studies show that for our cleanest plasma conditions, light impurities (carbon and oxygen) are dominant. These conditions are achieved with ECR heating, or RF heating near a low order resonance in rotational transform. A low temperature vacuum baking system (maximum of 90 °C) has been commissioned, and initial tests successfully demonstrated a marked acceleration of outgassing of H_2O, a major impurity. Gas control has been improved by installation of a five-way flow control system and a second puff valve.

Around 4600 plasma shots have been performed in 2002 of which half were in high field (0.5 Tesla) hydrogen/helium plasma. In order to diagnose higher temperature plasma, new remote diagnostics are being commissioned, such as correlation spectroscopy for fluctuation studies and a second multi-channel Doppler spectroscopy system (MOSS). New automated scanning software allows data to be taken more efficiently and reliably, and a new Rogowski loop and 20-coil external magnetic probe (Mirnov) array provides measurements of plasma current and



Dependence of density and magnetic fluctuations on rotational transform in the H-1NF heliac



The Figure shows the development of a zonal flow: low frequency (<1 kHz) spectral feature develops as a result of the non-linear interactions of the higher frequency fluctuations. Once developed, it starts modulating parent waves.

fluctuations. To simplify H-1 operation, installation of two additional PLC control systems has commenced.

Data Acquisition and Data Mining

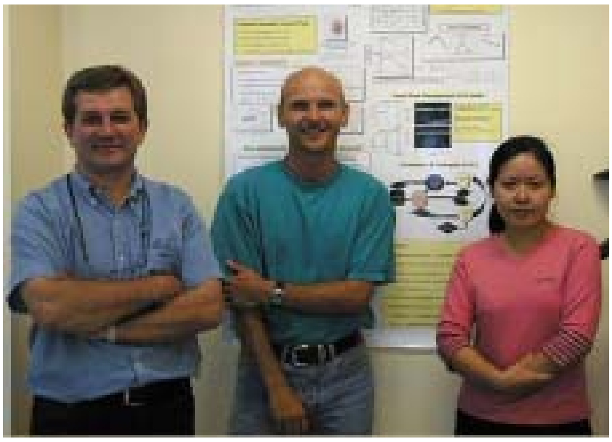
More than 50,000 plasma pulses have been recorded in total under "MDSPlus", and are being distilled into a "summary" database and an "electronic log book", small enough to fit on a business card. In 2002, these were integrated through a Web interface, and work commenced on data mining techniques to best exploit the data. Machine learning techniques showed promise in evaluating the quality of data, and association techniques were applied to explore signatures of magnetic fluctuations in hydrogen/helium plasma at higher fields.

Magnetic Configuration Studies

The main feature of the "flexible heliac" is the ability to change the shape of the magnetic confinement region (configuration) in several dimensions, such as shape, rotational transform ("twist per turn"), and the depth of the minimum in magnetic field ("magnetic well", related to stability). Studies of the confinement of hydrogen/helium plasmas heated with ion-cyclotron waves using very fine scale (steps <0.5%) scans of the rotational transform show that the density confined in the heliac is very sensitive to the presence of surfaces with rational values of the rotational transform inside the plasma volume. When the rotational transform profile crosses multiple low order rational (e.g., 4/3) surfaces, the density drops to very low values, as is illustrated in the figure on the left. Fluctuations in the magnetic field also show a fine structure that changes with rotational transform.

Plasma Turbulence and Transport Physics

The physics of plasma turbulence covers a broad spectrum of fundamental physics problems, such as turbulence development, self-organisation and self-regulation, as well as problems of the particle and energy loss in the toroidal plasmas crucially important for fusion research. The Group continues broad experimental studies into turbulence and transport contributing to both basic plasma physics and to fusion research.



Dr M. Shats, H. Punzmann and H. Xai with the poster summarising turbulence and transport highlights of the year

We reported the first observation of zonal flows in plasma in Shats M.G. and Solomon W.M. *Phys Rev. Lett.* **88**, 045001 (2002). Plasma zonal flows were theoretically predicted in 1979, found in computer simulations in 1998 and were observed in the H-1 heliac in 2001. Zonal flows are large-scale anisotropic structures, which are generated in the plasma by the turbulence via three-wave interactions. They affect their parent waves leading to the self-regulation of the plasma turbulence. Detailed studies of the effects of zonal flows on other turbulent structures and their role in saturating the turbulence levels have commenced. The analogy between plasma zonal flows and their relatives in planetary atmospheres will be further investigated.

Electric Fields in the Plasma and their Effect on Turbulence and Transport

Electric fields play a major role in plasma transport. They interact with plasma turbulence, can destroy turbulent vortices and accumulate fluctuation energy thus improving plasma confinement. Their generation and a complex interplay with the turbulence is a subject of the on-going collaboration with the University of California at San Diego.

Turbulent Structures and Plasma Self-Organisation

Plasma turbulence in toroidal configurations can self-organise into large turbulent structures or vortices. The presence of large vortices in the plasma leads to enhanced convective losses of particles across the confining magnetic field and deteriorates plasma confinement. When these structures are suppressed by shear flows, transport properties of the plasma are improved. Visualisation of turbulent vortices using novel diagnostics and signal analysis tools as well as studies into the mechanisms of the vortex generation are the main thrusts in this experimental area.

Plasma Diagnostics for Turbulence and Transport Studies

A number of diagnostics for studying the plasma turbulence has been developed and installed on the H-1NF. These include a four-channel heterodyne microwave (2 mm) scattering system, a 20-channel cross-correlation spectroscopy diagnostic combined with the 10-channel spectroscopy for particle transport analysis, and also Langmuir, Mach and magnetic probe arrays.

Development and Application of Advanced Signal Analysis Techniques

Modern methods of analysis of turbulent signals are powerful tools, which go beyond traditional linear, time-averaged spectral turbulence characterisation. Examples include time-resolved spectra using wavelets, higher order spectral analysis (bispectra, trispectra), statistical characterisation of turbulence, conditional analysis, etc.

Advanced Plasma Diagnostics

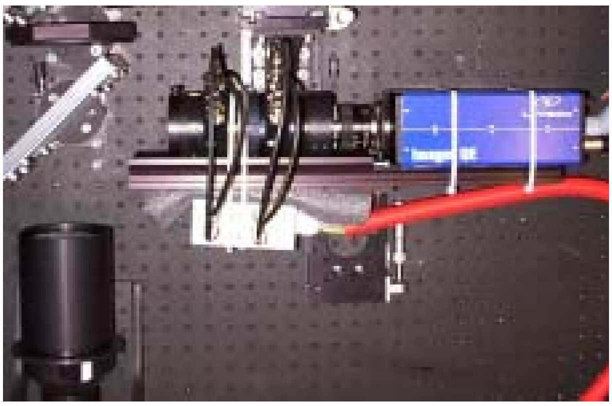
Remote Sensing and Inverse Methods

Understanding the physics of high temperature plasma confinement relies crucially on non-perturbing remote sensing tools. In recent years PRL has pioneered a number of radically new optical measurement systems that are now also being adopted at some of the world's premier fusion laboratories. Related systems are also finding application in industrial process control. To fully utilise the new measurement capabilities, the Group continues to develop the inverse mathematical methods that allow the unfolding and interpretation of the projection data.

A number of advanced imaging measurement systems based on the recently patented MOSS spectrometer (US patent #6462826, 2002) are now installed and operating routinely on H-1. The MOSS spectrometer is a modulated fixed-delay Fourier transform spectrometer based on solid electro-optic birefringent components. It is used for a wide variety of spectroscopic studies (e.g. polarisation and Doppler spectroscopy) of transition radiation from neutral atoms and ions. Growing interest from overseas groups led to the presentation of an invited talk at the German-Polish EURO Conference on Plasma Diagnostics for Fusion and Applications and to the sale of a custom imaging system to the Max Planck Institute for Plasma Physics in Germany. Another system is being developed for ion temperature measurements on the high-field tokamak Alcator C-MOD at MIT.

Ion Heating and Fuelling in H-1

The MOSS systems have been used for the study of plasma heating and force balance in low-field (0.1 T), low-temperature argon discharges. The discovery of a significant non-thermal contribution to the ion velocity distribution function, and its



The MOSS camera installed on the Wendelstein 7-AS stellarator in the Max Planck Institute for Plasma Physics in Germany localisation primarily to the plasma edge regions, suggests that ions are directly heated in H-1 through stochastic interaction with the radio-frequency sheath attached to the heating antenna. Time resolved behaviour of hydrogen and deuterium atom relative densities obtained by MOSS imaging spectroscopy have revealed the liberation of hydrogen from plasma-facing wall components as a major particle source.

Interferometry

The far-infrared (FIR) rapid-scan interferometer continues to operate reliably and has provided routine electron density profile information for a number of studies. It will be used together with the MOSS spectrometer and a calibrated directional gas injection system for particle control (under development).

Thermal Imaging

High-throughput, visible-near-infrared interferometric sensors for remote temperature measurement have been developed in 2002. Related to the MOSS spectrometer, the new filters are an attractive alternative to traditional radiometric systems and are also the subject of provisional patent protection. An ACT Knowledge Fund grant ($40,000) has been awarded for the development of an absolute spectro-radiometer based on these new devices for molten steel imaging at BHP-Billiton in Wollongong. The Remote-Sensing Group has also largely completed a contract ($99,000) with DSTO for the development of sensors for the infrared discrimination of rocket and engine infrared signatures.

Doppler Tomography and Inverse Techniques

We have established the conditions under which the inhomogeneous velocity distribution function can be retrieved from Doppler tomographic measurements. Inverse algorithms, which confirm these findings, have been developed. New Abel inversion methods based on general splines with non-linear optimisation of knot locations have been developed and used for inversion of the brightness, temperature and flow field projections obtained from the interferometer and MOSS systems. We are also collaborating with Chalmers University in Sweden on microwave probing systems and associated finite-difference time-domain inverse techniques for detection and localisation of human breast lesions.

Laser Induced Fluorescence

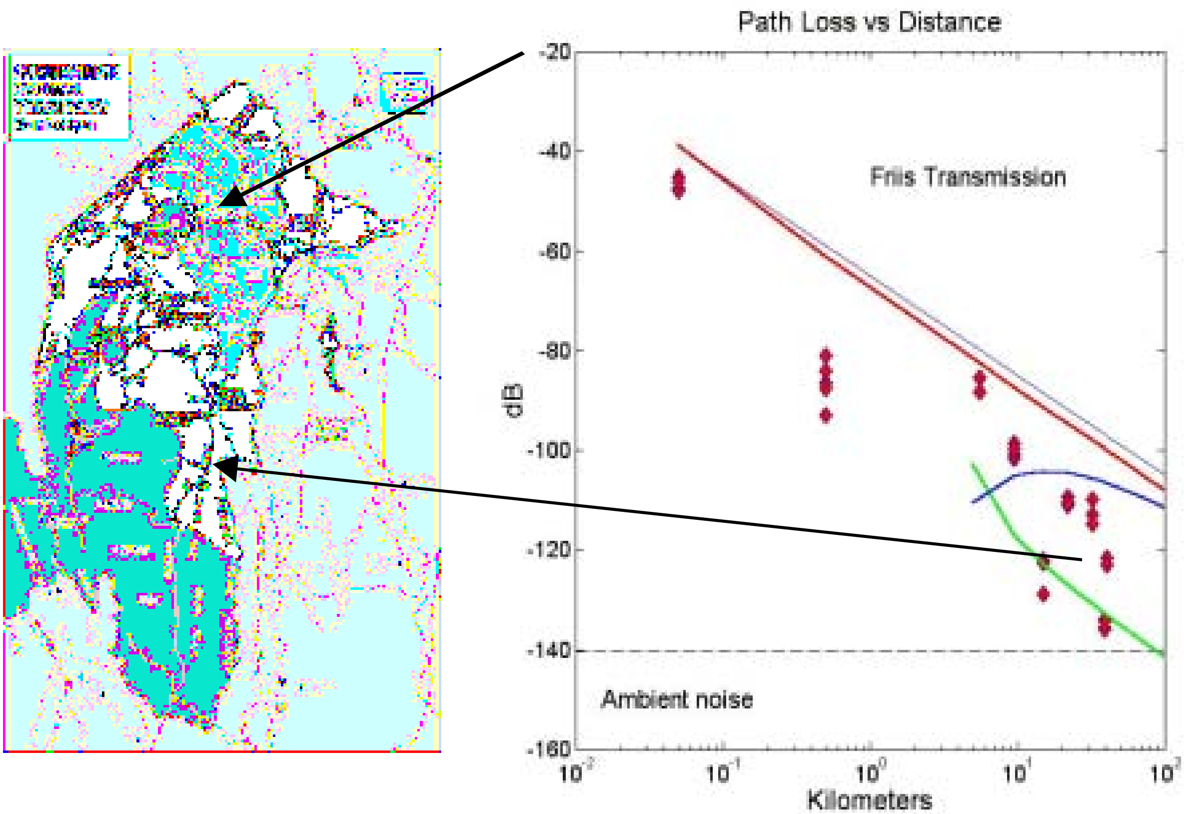
This collaborative project with the University of Sydney received ARC funding for three years commencing in 2000. The aim of the project is to develop techniques for measuring electric fields in plasmas using the laser excitation and fluorescence of metastable helium atoms in a pulsed helium beam.

Wireless Communications

The BushLAN Project

The BushLAN (Bush Local Area Network) project aims to develop technology to support moderate speed (100–200 kbps) VHF wireless data links over non-line of sight distances of 5–100 km to improve Internet connectivity in sparsely populated regions like regional Australia. These links would use vacant VHF TV channels. This technology is being explored by PRL and several industry groups, and was singled out for mention in the 2002 Australian Parliamentary Inquiry on Wireless Broadband Technology.

Earlier this year the BushLAN Group performed channel sounding experiments in the Australian Capital Territory using channels



Results of VHF channel test in the Australian Capital Territory

0 and 1 at frequencies around 50 MHz. The tests indicate that VHF wireless data transmission is feasible over significant distances at very low powers (40 km at 20 W). The figure below shows the path loss as a function of distance in the ACT. The transmitting antenna was located atop Mount Ainslie and the received signal was measured in various places as far south as Naas (40 kms). The straight line is the theoretically predicted path loss for line-of-sight. Hilly terrain would have blocked the signal were operation at microwave frequencies. These results indicate that transmission at > 250 kbps with a bandwidth of 250 kHz is possible, and have led to the development of a design for a low-cost digital transceiver unit for field network trials that is being prototyped in RSPhysSE with the support of a grant from the ACT Knowledge Fund.

In 2002, five students completed honours projects connected with BushLAN. Four more honours students and four post-graduate students are now starting more advanced BushLAN projects that include transceiver and software development, channel studies, and field trials of prototype systems with Etherwave Networks in Wollongong.

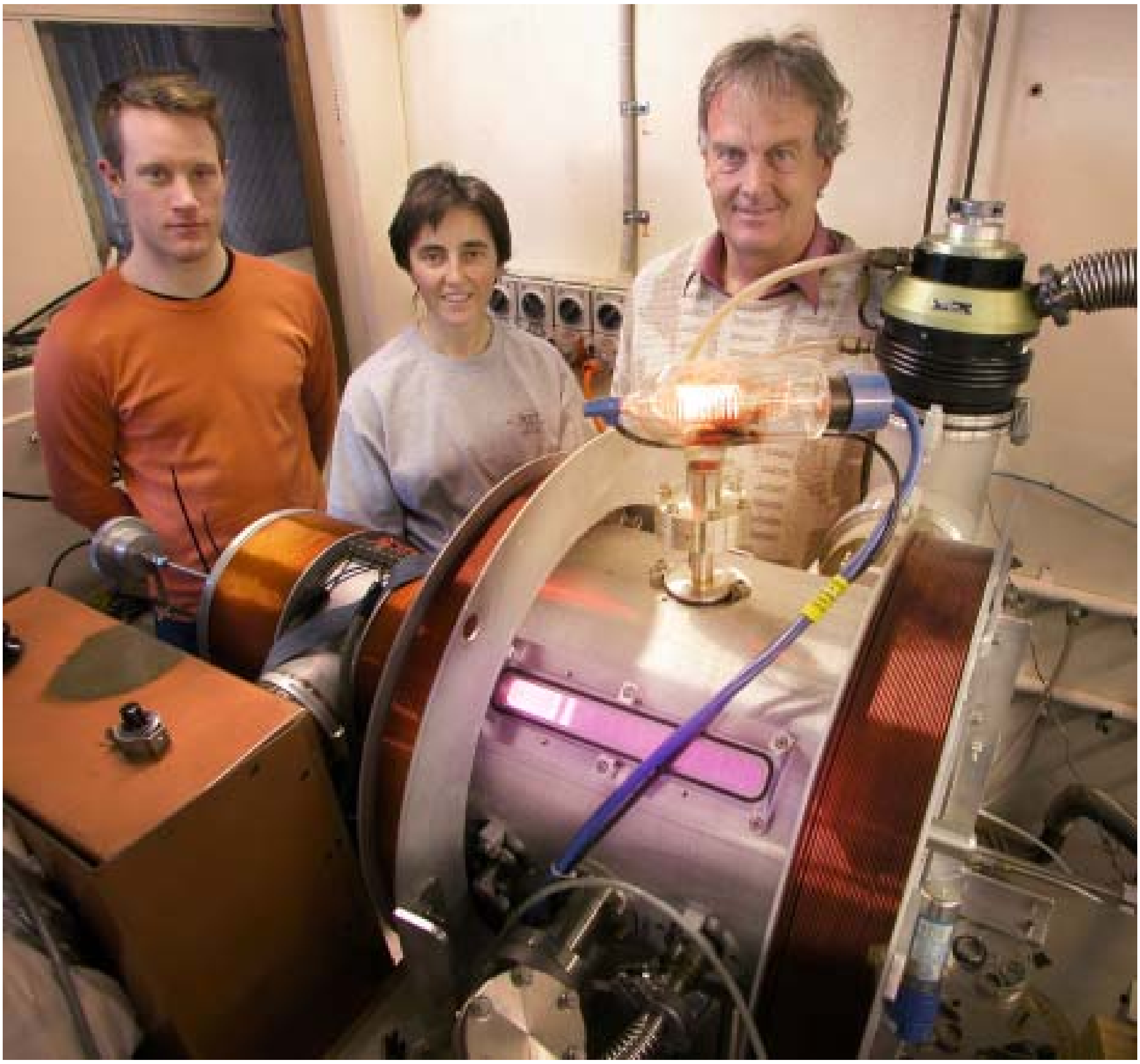
Plasma Lenses and Antennas

In other wireless work, Peter Linardakis is developing plasma RF switch concepts for mobile telecommunications in a PhD project sponsored by Motorola-USA. In 2002, he completed an exchange visit to the Motorola research laboratory in Illinois.

Dr Lise Caillault of the Office National d'Etudes et de Recherches Aerospatiales (France) is doing a post-doctoral project in the Laboratory on the use of plasmas to form microwave dielectric lenses in collaboration with the Australian Defence Science and Technology Organisation. She is looking at the effects of phase noise from the lens on radar applications.

Space Plasma and Plasma Processing

The Space Plasma (SP^3) group is primarily concerned with the basic physics of gaseous discharges and their application to a variety of industrial processes. The Group, shown below, is internationally recognised as leading the way in many developments, in particular, the plasma modification of surfaces, the development of high density plasma sources and the use of expanding plasmas for spacecraft thrusters.



Orson Suthereland, Dr Christine Charles and Professor Rod Boswell with the prototype plasma thruster

Dr Boyd Blackwell shows visitors the H1-NF during the "Machines that Ate Acton" tours

Plasma Thruster

A totally new phenomenon has been experimentally discovered in the SP^3 Laboratory, an electric double layer in an expanding plasma. This was found at low pressures where the simple Boltzmann expansion of a plasma breaks down and the plasma flow becomes supersonic. Although experiments are continuing, a patent has been applied for in the application of this effect to plasma thrusters for space craft and also to the alteration of surfaces. With this new research thrust, we are developing collaborations with NASA in Houston and a number of French groups.

Ion Beam Extraction

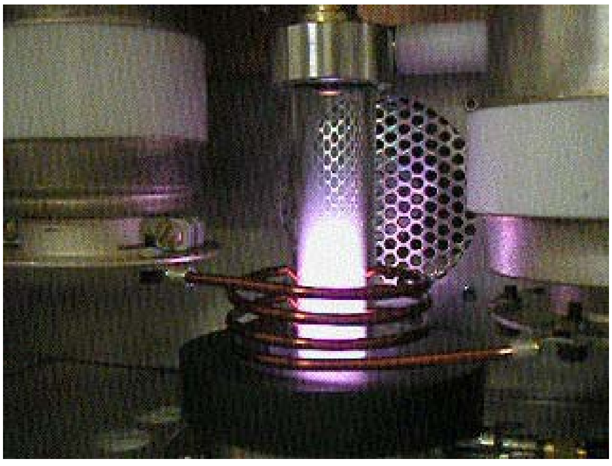
This year has seen the development of several new features in the ANU ion source project. Two significant collaborations have been undertaken. The laboratory hosted Dr M. Irzyk from France and Dr J. Keller from the USA. They have complimented the experimental work of plasma density and beam shape measurements with computer simulation studies. Major milestones have been achieved this year including significant gains in plasma density by increasing power, reducing source size, and optimising the magnetic field.

Cross-Field Diffusion in Helicon Plasmas

Helicon plasmas are known for their high density and high ionising efficiency. Much has been published on the possible wave mechanisms for accelerating the plasma electrons but virtually no concerted study has been made on the details of the plasma confinement. Recent experiments in the SP^3 Laboratory have shown that there appears to be a form of radial electrostatic confinement associated with the high density 'blue core' plasma.

Ion Heating in the Plasma Presheath

It is known that ion interaction with neutrals in the presheath of a plasma can define the actual length of the presheath.



Ion Beam Plasma Source

However, there have been few detailed experiments done on measuring the energy input to the perpendicular and parallel ion temperatures. We are collaborating with a group at UC Irvine on Laser Induced Fluorescence and Dr Helen Smith who uses particle-in-cell simulations to determine the evolution of these ion temperatures. The perpendicular temperature in particular is of crucial importance in defining the brightness of focussed ion beams.

Effect of Antenna Immersed in Laboratory Plasmas, e.g., H1 Heliac, Helicon

A plasma source excited by a double saddle helicon antenna has been modified by inserting a second electrically floating copper antenna in contact with the plasma through the glass end plate. For low helicon powers, the density decreases with time but for high powers, a copper free path is left in the glass adjacent to the helicon antenna due to re-sputtering of the deposited copper and no change in the plasma density is observed.

Particle-In-Cell Simulation of RF Breakdown in Plasmas

Experimental measurements and particle-in-cell simulations are used to investigate breakdown in radiofrequency plasmas. The RF "Paschen" curve requires significantly lower voltages and only the left hand side of the curve is affected by the secondary emission characteristic of the electrodes.

Helicon Source Modelling

A model of the energy balance based on the experimental data has been developed by initially modelling the plasma sheath along the double-saddle antenna of rather complex geometry. For the present capacitive coupling, the RF antenna voltage is mostly dropped across the sheath and the glass surface along the antenna charges negatively like the bias capacitor in an asymmetric discharge. Consequently, the main power deposition terms correspond to ion acceleration into the glass along the antenna and to the subsequent ion-induced secondary electrons, both contributing to the low power transfer efficiency of this capacitively coupled discharge.

Planar Optical Waveguides

The HARE Group has been working on the plasma deposition of germanium doped silicon dioxide for the fabrication of hydrogen-free planar optical waveguides with low loss in the 1200–1600 nm range. Photolithographic processes and HF etching were developed for waveguide fabrication and optical tests on thick deposited films. The preliminary results of the rib

Scott Collis of PRL demonstrates plasma phenomena to school students during the Australian Science Festival waveguides fabricated show low propagation loss (<1 dB/cm) at red light. To improve the rib waveguide fabrication morphology on the deposited films a plasma etching process has been developed. A Fourier Transform IR spectroscopy study combined with an experimental study of the stress lead to some insight into the bulk properties of the plasma deposited films.

Wall Charging in Helicon Plasmas

Wall charging is a contributing factor to plasma process drift in production lines especially when insulating materials are being deposited or etched. For our silicon dioxide plasma deposition process, the magnitude of the wall charging most likely depends on the effective capacitance formed by the silica layer and on the imbalance between the positively and negatively charged particles which impinge onto the sidewalls at the discharge initiation until equilibrium of fluxes is reached.

STAFF

Professor and Head of Department
Jeffrey Harris, MS MIT, PhD Wisc, FAPS, FAIP

Professors
Robert Dewar, MSc Melb, PhD Princ, FAIP, FAPS, FAS
Roderick Boswell, BSc Adel, PhD Flin, FAPS, FATS

Senior Fellows
Boyd Blackwell, BSc PhD Syd
John Howard, BSc PhD Syd
Michael Shats, MSc, PhD Gen Phys Inst Mosc (from October; Fellow until October)

Fellows
Gerard Borg, BSc PhD Syd

Research Fellows
Rowena Ball, BSc, PhD Macquarie (ARC Fellowship)
Christine Charles, Ingénieur INSA Rennes, PhD Orléans (jointly with APCRC)

Post-doctoral Fellows
Douglas Bulla, BSc MSc PhD Sao Paulo (jointly with APCRC)
Lise Caillault, DEA, PhD ONERA
Wei Tang Li, MSc China, PhD Syd (jointly with APCRC)

Adjunct Fellows
Mr Fenton Glass, BSc Qld
Mr Clive Michael, BSc
Mr Horst Punzmann, BSc Polytech Regensburg
Wayne Solomon, BSc Qld (ANUTECH)

Visiting Fellows
Joe Baker, MSc PhD Qld, OBE, FTSE
Andrew Cheetham, BSc PhD Flinders
Lawrence Cram, BSc BE PhD Syd
Roger Gammon, Btech PhD Brunel, FinstP, Cphys, MIE Aust, CP Eng, FAIE, FAIM
Sydney Hamberger, PhD DSc Lond, FAIP (Emeritus Professor)
Ian Hutchinson, PhD
Michael Izryk, PhD Orleans-CNRS
John Keller, PhD Rensselaer Polytechnic
Mike Lieberman, PhD Berkeley
Dennis Mather, BSc PhD UNSW, Dip Ed STC
Kazunobo Nagasaki, MSc PhD Kyoto
John O'Connor, BSc PhD DSc
Helen Smith, BSc Mon, PhD
Anthony Sproule, ME UTS, GradDipOR NSW IT

Head Technical Officer
Clinton Davies

Senior Technical Officers
Peter Alexander
Rob Davies, AssocDipMechEng CIT, BT Deakin
Ray Kimlin
John Wach, BAppSci CAE Ball, GradDipEl CCAE

Technical Officer
Costanzo Costa

Departmental Administrator
Helen Hawes, BA