

stellarator news

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Around the Labs

The LHD Divertor

The National Institute for Fusion Science (NIFS) is constructing a large superconducting heliotron device ($B = 4$ T, $R = 3.9$ m, $a \sim 0.6$ m, $l = 2$, $m = 10$, $\gamma_c = 1.25$, $\alpha_c = 0.1$), called the Large Helical Device (LHD), aimed at demonstrating the attractiveness of helical devices at more reactor-relevant plasma parameters [1,2]. The device is being built at Toki, a small town near Nagoya, and the experiment will start late in 1997.

One of the major features of the LHD device is to control the edge plasma and recycling by a closed helical divertor [3], with a goal of improving the energy confinement. We expect that the helical divertor designed for LHD will function similarly to those in

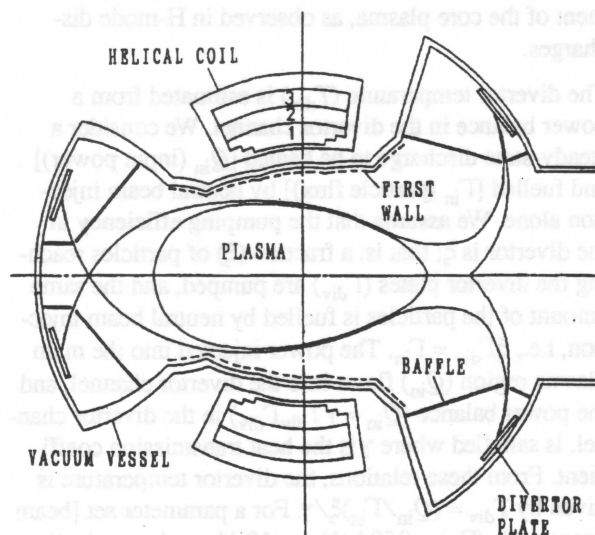


Fig. 1. Schematic view of the LHD helical divertor.

tokamaks, and we also plan to develop advanced divertor concepts. The LHD divertor configuration is being designed to be as flexible as possible to accommodate a wide range of divertor operational scenarios. To this end, we have designed a large vacuum vessel for the installation of closed divertor chambers of a reasonable size, as illustrated in Fig. 1.

Divertor Magnetic Topology

An edge magnetic configuration of the heliotron type is depicted in Fig. 2. A closed-surface region is surrounded by a stochastic region generated by overlapping of islands ($n = 10$), which naturally exist in the outer region. The field lines escaping from this region pass through thin, curved surface layers (hereafter called edge surface layers) before reaching the X-point and then the divertor plate. The existence of the edge surface layers is a peculiar feature of such a helical divertor. A surface layer consists of several layers, each of which again consists of multiple layers. Such a structure is generated by successive folding and stretching processes as the field lines rotate poloidally. The former process occurs because the radial position of the X-point changes with poloidal angle (by as much as approximately one-third

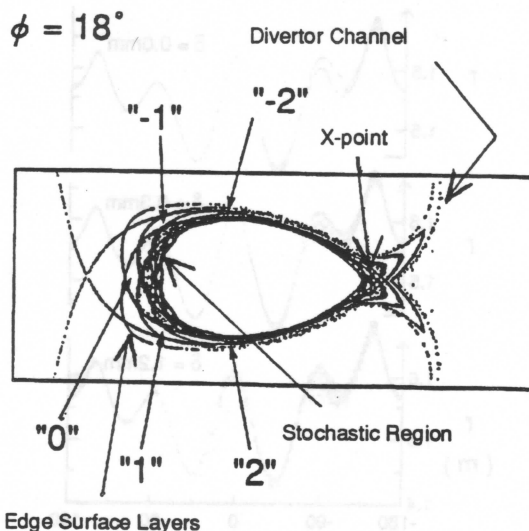


Fig. 2. The puncture plot of field lines from the stochastic region just outside the closed surface shows clearly an edge magnetic configuration of heliotron type.

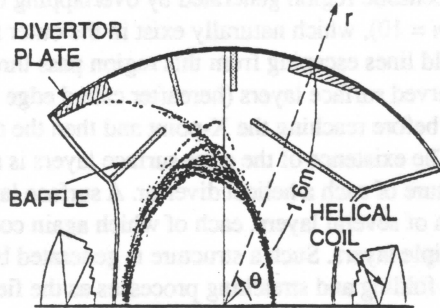
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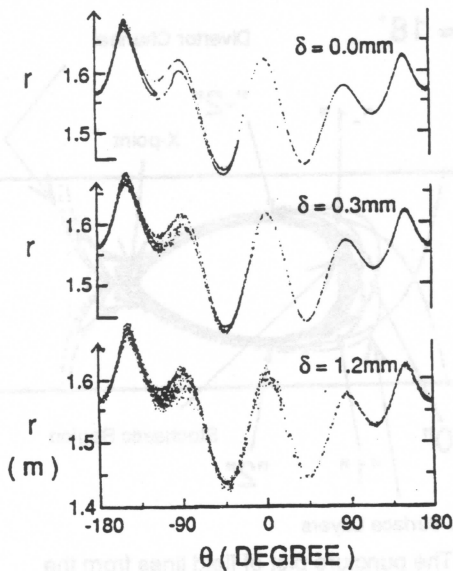
of the plasma radius). The latter is caused by high local rotational transform and shear at the edge on the larger major radius side of the torus.

Simulation of Perpendicular Transport Effects

To study the divertor plasma transport in such a complicated, three-dimensional (3-D) divertor magnetic structure, field lines are traced using a random walk process (at every 0.2-m step, positions of the field lines deviate by δ with random azimuthal directions on the plane perpendicular to the field lines) from the stochastic region until reaching a helical plane (defined by $\theta = -[5\phi + \theta_0 + 0.1 \sin(5\phi + \theta_0)]$ rotating with the helical coils [Fig. 3(a)]. In the real device, the divertor plates are located at $r = 1.55$ m near this plane. Puncture plots of the field lines in this plane are shown in Fig. 3(b). A strong poloidal asymmetry is seen in the plots. The fine structure of the edge surface layer is clearly



(a)



(b)

Fig. 3. (a) The LHD edge magnetic configuration. (b) Puncture plots of the field lines on a helical plane shown in (a) for three different random walk parameters.

seen when the field lines are traced exactly when $\delta = 0$. A random walk process with $\delta = 1.2$ mm corresponds to an effective perpendicular diffusion coefficient of $0.5 \text{ m}^2/\text{s}$ for a plasma with a temperature of 100 eV, a value that is smaller than a typically observed edge value. In this case, the fine structure is smoothed out completely. We expect that the distributions of the heat and particle fluxes on the plane for the LHD experiments are close to those with $\delta = 1.2$ mm. On the basis of this estimate, the maximum heat flux on the divertor plate with a field line incident angle of 30° is expected to be $\sim 5 \text{ MW/m}^2$ for a standard 20-MW LHD discharge.

Divertor operation with a high-density, cold divertor plasma can reduce impurity sputtering and enhance edge radiation, a promising boundary control technique that we plan to demonstrate in the LHD configuration. The vague boundary discussed above has poor confinement properties and thus may provide a cold, radiative edge volume, thus reducing the heat flux on the divertor plate. But this may prevent the formation of an H-mode edge temperature pedestal, which leads to an improvement of the core energy confinement. These considerations have led us to propose a high-temperature divertor plasma operation.

High-Temperature Divertor Plasma Operation

High-temperature divertor plasma operation has been proposed to improve the energy confinement in LHD. In this operation, the divertor plasma temperature is raised by efficient pumping in the divertor chamber. An elevated divertor temperature will lead to an improvement of the core plasma, as observed in H-mode discharges.

The divertor temperature (T_{div}) is estimated from a power balance in the divertor channel. We consider a steady-state discharge to be heated [Q_{in} (input power)] and fuelled [Γ_{in} (particle flux)] by neutral beam injection alone. We assume that the pumping efficiency in the divertor is ξ ; that is, a fraction (ξ) of particles reaching the divertor plates (Γ_{div}) are pumped, and the same amount of the particles is fuelled by neutral beam injection, i.e., $\xi \Gamma_{\text{div}} = \Gamma_{\text{in}}$. The power injected into the main plasma region (Q_{in}) flows into the divertor channel, and the power balance ($Q_{\text{in}} = \gamma T_{\text{div}} \Gamma_{\text{div}}$) in the divertor channel, is satisfied where γ is the heat transmission coefficient. From these relations, the divertor temperature is given by $T_{\text{div}} = (Q_{\text{in}}/\Gamma_{\text{in}})\xi/\gamma$. For a parameter set [beam energy ($Q_{\text{in}}/\Gamma_{\text{in}}$) $\sim 250 \text{ keV}$, $\gamma \sim 10$ (the value typically assumed for the case without secondary electron emission is ~ 8), $\xi \sim 0.2$], T_{div} becomes as high as 5 keV, which is significantly higher than the values observed at the pedestal of the H-mode discharges.

Collisionless Divertor Plasma

We have studied a high-temperature divertor plasma, namely, a collisionless divertor plasma in a one-dimensional model as illustrated in Fig. 4(a). An equal number of ions and electrons with a temperature T_0 are supplied into a divertor channel. Ions simply flow to the divertor plates. A negative electric potential is set up for the ambipolar flow condition, and electrons with parallel kinetic energy less than the potential amplitude are electrostatically trapped. The electron distribution functions in the divertor channel for two different collisionalities are calculated by a Fokker-Planck code and are shown in contour plots in the $v_{\perp} - v_{\parallel}$ space of Fig. 4(b). When the mean-free path becomes much longer than $(M/m)^{1/2} L$ (where M/m is the ion-electron mass ratio and L is the distance between the divertor plates), the trapped electrons are well confined by the potentials; their density becomes nearly equal to the ion density, even with a potential amplitude of $< kT_0$; and the average perpendicular energy of the trapped electrons is much greater than the average parallel energy, as is shown in the case on the right hand side of Fig. 4(b). On the other hand, for a marginally collisionless case [on the left-hand side of Fig. 4(b)], the potential amplitude is less than kT_0 , but the temperature distribution is almost isotropic.

Such a collisionless effect becomes important for the energy balance with secondary electron emission. When the divertor plasma is collisionless, the secondary elec-

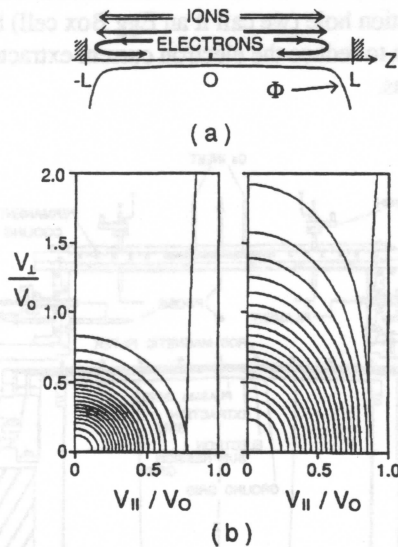


Fig. 4. (a) A one-dimensional model with a collisionless divertor plasma; (b) electron distributions in the model divertor (a) at two different collisionalities: $\lambda_c / L = 36$ for the case on the left-hand side and $\lambda_c / L = 360$ for the case on the right-hand side. Here V_0 and λ_e are the electron thermal velocity and the electron mean free path at a temperature of T_0 .

trons emitted from the divertor are first accelerated by the sheath potential and then barely trapped by the potentials. They eventually hit the divertor plate during the thermalization process. The parallel energy with which they hit the plates is nearly zero, and the perpendicular average energy is a fraction of the sheath potential. This is in contrast to the conventional collisional model where both average energies at which they strike the plates are equal to T_e . Thus the collisionless effect substantially reduces the cooling effect by secondary electrons and hence γ .

In this operation, the density profile is maintained by a combination of particle pumping and deep fuelling such as pellet or neutral beam injection. Thus the diffusion coefficient (D), and hence the particle confinement, become important in determining the energy confinement. This is desirable for energy confinement in LHD where the high neoclassical ripple-induced electron heat loss ($1/\nu$ regime) tends to suppress the temperature gradient. However, the effective D is not high because the ions are confined by $E \times B$ drift (ν -regime). A positive radial electric field appears in such a plasma regime, and hence a neoclassical outward impurity pinch may prevent impurity contamination in the core plasma.

Conceptual Design of the LHD Helical Divertor

One of the necessary conditions for divertor to function is that the scrape-off-layer plasma does not touch the first wall surrounding the main plasma. The distance between the coil center and the plasma edge on the small major radius side of the torus is fairly small, 315 mm. To increase clearance between the plasma and the wall, we decided to increase the coil current density to 53 A/mm². Because of the superconducting coil system, a radial space of 50 mm for the thermal insulation and a gap for the thermal displacement of the components is required, making the space there even tighter. After optimization of the system, the gap between the first wall and the plasma (the outermost edge surface layer) becomes 15 mm for the standard configuration, a gap wide enough for effective divertor functions. (Note that the very short connection length beyond the outermost edge surface of ~ 1 m makes the radial spreading of the plasma beyond this surface very small.)

The majority of the heat and particle fluxes from the core are guided to the divertor plates installed in the divertor chamber shown in Fig. 1. Divertor performance depends on how well the neutral particles recycled at the divertor plates are controlled. For this reason, the entrance width to the divertor chamber needs to be as small as possible. For high-density, cold-divertor plasma operation, a small entrance provides enhancement of recycling in the divertor while keeping recy-

cling at the main plasma edge minimal. For high-temperature divertor plasma operation, the pumping efficiency in the divertor chamber is the key parameter for successful operation, and the pumping efficiency is nearly equal to the ratio of the "equivalent" pumping surface area to the entrance area. For the LHD experiment, the required pumping efficiency is ~20%. We are considering a cryopump system for pumping the divertor and are also developing other pumping schemes with even higher efficiency.

The divertor plates are the major divertor component that handles the heat flux from the core plasma. Its conceptual design has been completed. In the LHD divertor configuration, the direction of the magnetic field is nearly poloidal, thus eliminating a problem of high heat concentration at the tile edges caused by small misalignment of the tiles. All of four divertor legs have a 3-D helical structure, and each divertor plate is designed as a helically running discrete-bar array. The angle between the field lines and the surfaces is designed to be around 30°. Each bar is made of a copper cooling channel, onto which several pieces of graphite or C-C composite armor are directly brazed. The cylindrical bar is 34–40 mm in diameter, 300–400 mm in length, and a total of 2040 bars is necessary for covering all the striking points of the four divertor legs. Pressurized-water cooling will be used to keep the surface temperature of the armor below 1200°C under the maximum heat flux of 5 MW/m².

In executing the LHD divertor experiment, we will first use a simple open helical divertor configuration to see the divertor plasma behavior in the 20-MW short-pulse discharges and to measure spatial distributions of the particle and heat flows. As an advanced experiment for confinement improvement by recycling control, we plan to use a local island divertor with $m/n = 1/1$ island, which will also be a good test bed for developing high-power, steady-state heat flux components. In the later phase of the LHD experiment, these experimental data will be utilized for the final design and installation of the closed divertor system, the major topic of this report.

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Present Status of R&D on Plasma Heating Systems for LHD

The development of the LHD plasma heating systems have proceeded steadily. The apparatus for the R&D of each heating system, in LHD, ECH, ICRF, and NBI, are now in place at the plasma heating laboratory of the new Toki Site. High-power testing of the components for each heating device is being carried out.

Negative Ion Source Development

The optimization of the negative ion source has been researched on a one-third-scale hydrogen negative ion source (Fig. 1). The source consists of a multicusp rectangular plasma source (37 cm in width, 62.5 cm in height, and 18.5 cm in depth), an acceleration electrode system with 800 extraction holes, and a rod magnetic filter. The extracted H^- ion current is measured by a 2-D calorimeter array placed at 1.6 m downstream from the plasma grid. The amount of Cs vapor seeded into the plasma source is controlled by changing the duration of the valve opening. The extracted hydrogen negative ion current is optimized with and without Cs operation.

Figure 2 shows the H^- ion current as a function of the arc power before and after Cs seeding. After Cs seeding, the H^- ion current is three times larger than without Cs operation. A total H^- ion current of 8.5 A has been obtained from 800 extraction holes of 9 mm in diameter. The effects of the small wall structure that surrounds each extraction hole (we call it an Egg Box cell) have been shown to reduce the electron current extracted with H^- ions.

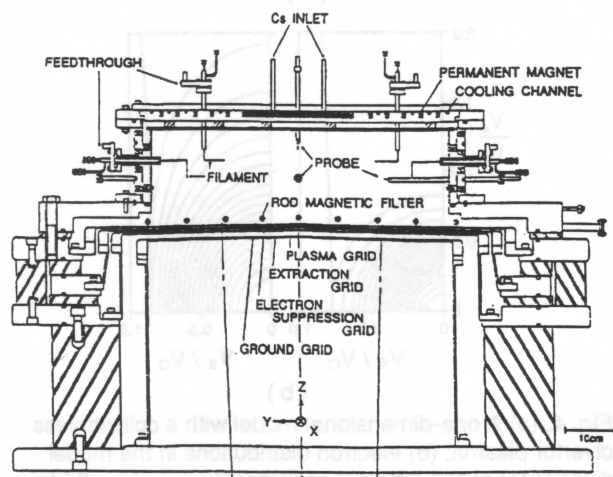


Fig. 1. The schematic diagram of the one-third-scaled negative hydrogen ion source.

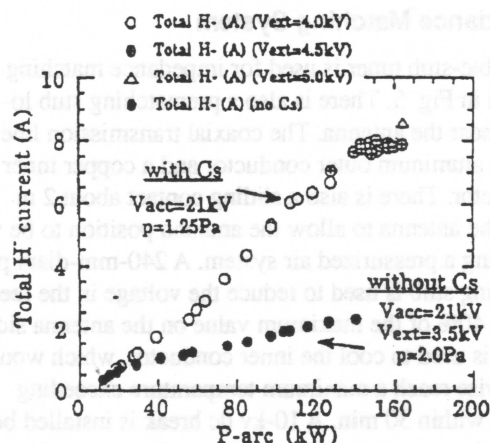


Fig. 2. Total H⁻ ion current as a function of the arc power with Cs (open circle) and without (closed circle).

Figure 3 shows the extraction current as a function of the arc power both with and without the Egg Box. Total H⁻ current is not changed in the two cases. Therefore the ratio of electron to H⁻ current can be reduced by a factor of 2 using the Egg Box cell.

Because the H⁻ ion current seems to be limited by the limitation of the capacity of the extraction experiment, the number of the extraction holes was reduced from 800 to 36, and the plasma confinement was modified by increasing the confinement cusp magnetic field and the number of filter rods. The extraction characteristics of the 36-hole grid system is shown in Fig. 3. The H⁻ ion current of 1.24 A has been obtained with an extraction voltage of 8.5 kV. This result indicates that the current density was attained up to 54 mA/cm². This current density satisfies the design value of 30 mA/cm² for LHD NBI injector.

Tsutomu Kuroda

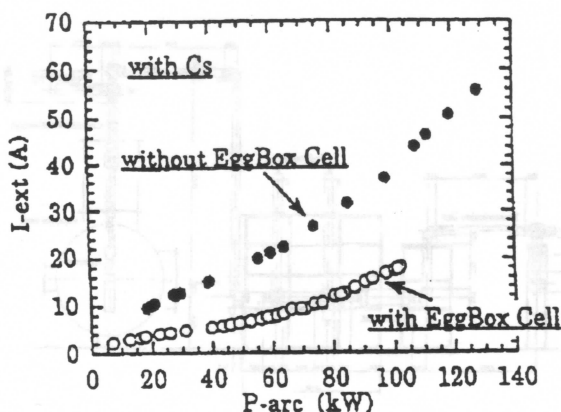


Fig. 3. Extraction currents as a function of the arc power with Egg Box cell (open circles) and without the Egg Box cell in the Cs-seeded operation.

ECH System

To develop a high-power CW gyrotron for LHD, we use the whispering-gallery-mode gyrotron (VGB-8008X), which was designed to extract the spent electron beam from the split waveguide. It was installed in the plasma heating laboratory (PHL) of the Toki site in December 1992. The test of the superconducting magnet for the gyrotron (with a capability of 55 kG) was also completed satisfactorily at the PHL. The system including the structure, the gyrotron, the SC-magnet, and the gyrotron tank is shown in Fig. 4. The structure for supporting the X-ray shielding and the transmission line components was set up. The power supply for the gyrotron has a series tube of type CQK400-4A and two tubes of type TH5188 for the deck modulator. The performance is as follows :

Beam voltage	20 to 81 kV
Beam current	50 A (< 10 s), 25 A (CW)
Cut-off time for fault	5 μ s
Anode voltage	-2 to 40 kV
Anode current	50 mA
Cut-off time for fault	< 2 μ s

The designed parameters of the gyrotron (VGB-8008X) are as follows :

Frequency	84 $\pm$ 0.5 GHz
Output mode	TE 15, 2
Pulse width	1 MW/10 s, 0.8 MW/CW
Beam parameters	80 kV $\pm$ 0.2 kV, < 62 A

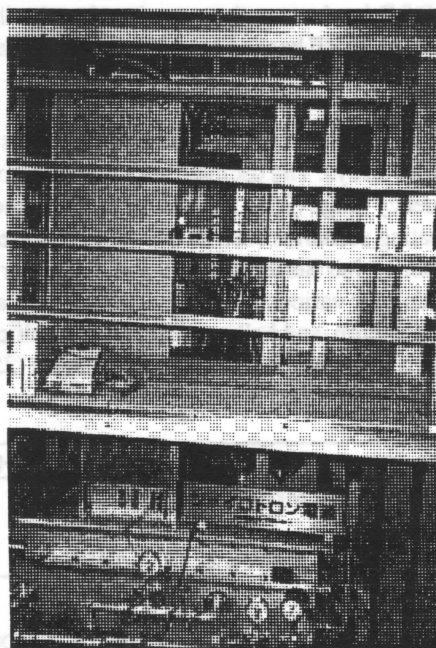


Fig. 4. The gyrotron and the oil tank. The collector of gyrotron is in the X-ray shielding box.

The gyrotron was tested at the factory for pulses up to 100 ms. The result shows that the output of the gyrotron is 0.9 MW for 1 ms and 0.5 MW for 100 ms. We started long-pulse tests at our new facilities at the end of February. When the test of VGB-8008X is completed, it will be replaced by a new gyrotron (VGB-8008S) with a built-in convertor.

As for the transmission lines development, the corrugated waveguide components such as the taper guide, the 90° elbow bend, the polarizer, the filter, and an 88.9-mm-diam switch were developed and inspected under low power with the aid of code analysis for radiation patterns. The corrugated waveguide components will be tested at high power using the gyrotrons. Up to now, the quasi-optical convertor with a wall deformation (for installation in the gyrotron) is being designed by using computer calculations. The result shows that the injected axiallysymmetric whispering gallery mode is converted to a locally concentrated profile near the wall. A study on methods for extraction of the millimeter beam from the waveguide is now under way.

Kunizo Ohkubo

ICRF Heating System

ICRF heating on the Large Helical Device features high power (up to 9 MW) with steady-state operation (30 min). We constructed an ICRF heating test system that consists of an RF oscillator, impedance matching circuit, prototype antenna, and test vacuum chamber at the Toki site. R&D has been under way since last April. We will discuss the ICRF heating subsystems individually.

RF Oscillator

We constructed an rf oscillator system that consists of two amplifier arrays. The oscillator has tunability over a wide frequency range (25 to 100 MHz) to accommodate various heating scenarios such as two ion-hybrid resonance, minority, ion Bernstein wave and higher harmonic heating for various plasma properties, such as hydrogen, deuteron, and helium (^3He). The specifications of the rf oscillator in two frequency ranges (25 to 60 MHz, 60 to 100 MHz) are as follows:

Frequency range	25–60 MHz	60–100 MHz
2-sec pulse	2 MW x 2	
10-sec pulse		1.5 MW x 2
30-min pulse	1.5 MW x 2	1 MW x 2

Thus far, 2-MW rf output has been achieved in short pulses, and long-pulse testing is under way.

Impedance Matching System

A double-stub tuner is used for impedance matching as shown in Fig. 5. There is also a prematching stub located near the antenna. The coaxial transmission line has an aluminum outer conductor and a copper inner conductor. There is also a sliding contact about 2 m from the antenna to allow the antenna position to be varied using a pressurized air system. A 240-mm-diam pre-matching stub is used to reduce the voltage in the feed line to 40% of the maximum value on the antenna side. Water is used to cool the inner conductor, which would otherwise reach a maximum temperature exceeding 200°C within 30 min. A 10-kv dc break is installed between the generator and tuners with rf leakage of less than -80 dB at 50 MHz.

Antenna

A prototype antenna has been fabricated and installed in a vacuum tank, which has a similar size to one section of the LHD as shown in Fig. 5. The size of the antenna is 40 cm wide and 70 cm long. An antenna strap, back plate, Faraday shield and side limiters are water cooled. A disk-shaped ceramic is used as a vacuum feed-through, which is cooled by a low rf-dissipation liquid. We can simulate a 2–3 MW, steady-state ICRF heating experiment by operating the whole system with no plasma load at 300 kW, CW. High-power handling and cooling system tests are now in progress.

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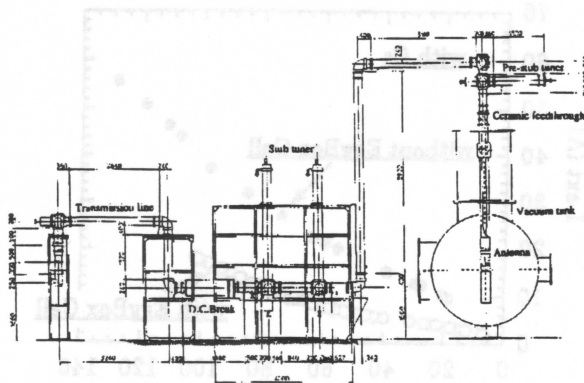


Fig. 5. Schematic drawing of ICRF heating system



Meetings

AINSE Plasma Science and Technology Conference and Elizabeth and Frederick White Workshop on Fundamental Problems in the Physics of Magnetically Confined Plasmas 12-15 July 1993 Canberra

A Plasma Science and Technology Conference, incorporating a workshop on Fundamental Problems in the Physics of Magnetically Confined Plasmas, will be held in Becker House, Australian Academy of Science, Canberra, from Monday July 12 to Thursday July 15, 1993. This will be the nineteenth plasma physics conference sponsored by the Australian Institute of Nuclear Science and Engineering. The workshop is sponsored by the Elizabeth and Frederick White Research Conference fund of the Australian Academy of Science.

Conference topics include

Experiments and Diagnostics

Physics of high- and low-temperature plasmas

Theoretical approaches

Numerical modelling

Fusion energy

Technological applications

Arc technology

Electronic device fabrication

Ionosphere, magnetosphere, sun

Plasma and the environment

Ozone layer

Overseas invited speakers

A. Bhattacharjee, Columbia University

J. Cary, University of Colorado, Boulder

L. Chen, Princeton University and University of California, Irvine

W. A. Cooper, Ecole Polytechnique Federale de Lausanne

J. Keller, IBM, Fishkill

J. L. Shohet, University of Wisconsin

A. Y. Wong, University of California, Los Angeles

Registration for participants from AINSE member universities is \$100, \$50 for students. Non-AINSE and late registration \$120, \$60 students. Registration includes the book of abstracts, refreshments, lunches, and the conference dinner.

Deadline: Abstracts for contributed papers and early registration 31 May 1993.

Accommodation and meals will be in Burgmann College and will be subsidized for participants from AINSE member universities registered by 31 May.

Further information and registration forms:

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