stellarator news

Published by Fusion Energy Division, Oak Ridge National Laboratory
Building 5700 P.O. Box 2008 Oak Ridge, TN 37831-6169, USA

Editor: James A. Rome Issue 99 July 2005
E-Mail: jar@ornl.gov Phone (865) 482-5643
On the Web at http://www.ornl.gov/sci/fed/stelnews

The 10-MW ECRH and current drive system for W7-X: first integrated tests with 0.9 MW, 30 min successful

Electron cyclotron resonance heating (ECRH) is the main heating system for the Wendelstein 7-X (W7-X) stellarator and the only one capable of continuous wave (CW) operation in the first stage of the experiment. The demonstration of the full-power CW capability of the ECRH system is therefore an important milestone in the ECRH project. Heating power of 10 MW is required to demonstrate the inherent steady-state capability of W7-X at reactor-relevant plasma parameters [1]. The standard heating and current drive scenario is X2 mode with low field side launch. High-density operation above the X2 cut-off density is accessible with O2 mode ($< 2.5 \times 10^{20}$ m^{-3}) and at even higher densities with O-X-B mode conversion heating [2,3]. EC current drive is a valuable tool to modify the internal current density distribution and to counteract residual bootstrap currents. Four front-steering plug-in launchers provide the necessary scanning range in toroidal and poloidal angles.

Because the ECRH system must operate with maximum reliability and availability, we have chosen a full modular design, which allows operation of each gyrotron and its required subsystems independent of all others. This design also minimizes cost because series production of identical modules is possible. It is evident from this concept that the demonstration of CW operation at full power with one module gives high confidence in the full system capability. The total ECRH power is generated by 10 gyrotrons operating at 140 GHz, each with 1-MW output power in CW operation.

The optical transmission system developed for W7-X, offers the most simple, reliable, and cost-effective solution. Radio-frequency (rf) power is transmitted to the torus (typically a distance of 60 m) by two open multibeam mirror lines, each combining and handling 5 (+2) individual rf beams (7 MW). The transmission system can handle a factor of 2–3 higher power, thus keeping the option open to replace the 1-MW gyrotrons by more powerful ones in a later state. It is worth noting that the transmission system already has the ECRH (24 MW) capability to meet the needs of ITER.

The development of the W7-X gyrotrons began in 1998 in Europe with Thales Electron Devices (TED) [4] and in the USA with CPI as industrial partner. Results from the two

In this issue . . .

The 10-MW ECRH and current drive system for W7-X: first integrated tests with 0.9 MW, 30 min successful
The components of the Wendelstein 7-X electron cyclotron resonance heating beamlines have been tested using a new gyrotron from CPI (USA). Although the system was not fully optimized for this tube, 0.9 MW was transmitted for 30 min. All measured parameters, in particular the gas pressure in the tube, the temperature in the collector wall, and the temperature of the most loaded mirrors, became stationary; the longest measured time to achieve this state is about 5 min. The quasi-optical multibeam waveguide system demonstrated its favorable transmission characteristics and the most loaded components showed an excellent performance under full-power CW conditions. 1

First non-neutral plasmas in the Columbia Non-neutral Torus
The Columbia Non-neutral Torus (CNT), a stellarator designed to study non-neutral plasmas and the effects of strong *ExB* drifts on confinement, has started its first campaign to create pure electron plasmas. Good confinement of significant amounts of electrons has been achieved, and it appears that the toroidal electron cloud satisfies the plasma criterion. 3

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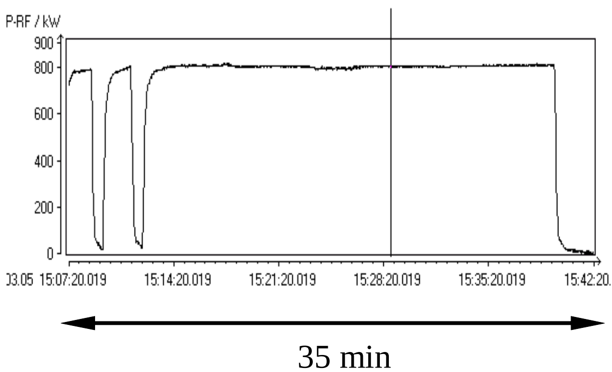
R&D tubes from TED were reported in the March 2004 issue of *Stellarator News*.

The final tests of the CPI gyrotron were recently completed at IPP, demonstrating source power of about 0.9 MW for a 30-min pulse duration, which is the target pulse duration for W7-X. The microwave beam was transmitted through seven single-beam mirrors of the transmission system into a commercial CW load from CCR [5] to perform integrated tests of the ECRH system. It is worth noting that none of the peripheral systems at IPP, such as main power supplies, central cooling system, body modulator, transmission line components, rf diagnostics, and the central control and data acquisition system, has ever seen CW-operation before and consequently all systems had to go through this qualification process together with the gyrotron. As the beam parameters were not known with the required accuracy at the beginning of tests, a provisional beam-matching optics (BMO) unit was used, resulting in transmission losses in the range 50–70 kW. The maximum power in 30-min pulses measured in the CCR load was 830 kW and represents the Gaussian mode content of the gyrotron beam. A typical time trace for an experimental sequence of two shorter (2-min) pulses and one longer 27-min pulse is shown in Fig. 1 (top).



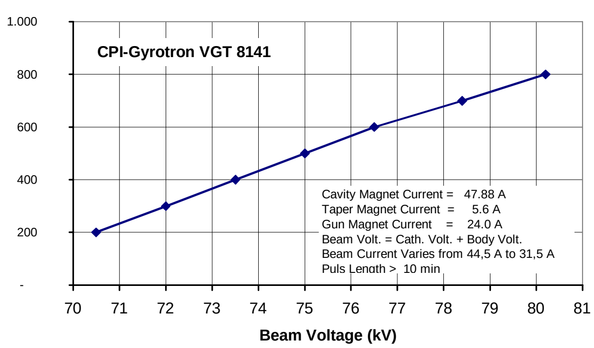


Fig. 1. Top: RF power as measured by the calorimeter vs time. Bottom: RF power vs beam voltage (with varying beam current). The measured power is the Gaussian fraction of the gyrotron beam.

All measured parameters, in particular the gas pressure in the tube, the temperature in the collector wall, and the temperature of the most loaded mirrors, became stationary; the longest measured time to achieve this state is about 5 min. The quasi-optical multibeam waveguide system demonstrated its favorable transmission characteristics, and the most heavily loaded components showed excellent performance under full-power CW conditions.

Problems arose from imperfect beam matching to a Gaussian beam and from side lobes hitting the beam duct concrete wall or uncooled elements such as the first mirror support. Additional water-cooled absorbing targets were installed at the measured hot spots. After some 30-min pulses, very reliable operation was achieved with all components behaving as expected. The beam pattern was measured at the end of the test period with high accuracy, and the design of a matched phase-correcting BMO is under way. It is expected that some fraction of the lost power will be recovered, which would increase the useful power in the Gaussian mode. Even more important, however, is the reduction of the power in hot spots from stray radiation, where even a few tens of kilowatts may cause significant heating of uncooled surfaces in CW operation. An example for a power scan is shown in Fig. 1 (bottom), which was obtained in 10-min pulses to save experimental time.

The project has now entered the phase of series installation and commissioning.

V. Erckmann for the W7-X ECRH teams at IPP,[1] FZK,[2] and IPF[3]

1. Max-Planck-Institut für Plasmaphysik, Teilinstitut Greifswald, Association EURATOM, Wendelsteinstr. 1, D-17491 Greifswald, Germany.
2. Forschungszentrum Karlsruhe, Association EURATOM-FZK, Institut für Hochleistungsimpuls- und Mikrowellentechnik, Postfach 3640, D-76021 Karlsruhe, Germany.
3. Institut für Plasmaforschung, Universität Stuttgart, Pfaffenwaldring 31, D-70569 Stuttgart, Germany.

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First non-neutral plasmas in the Columbia Non-neutral Torus

Introduction

The Columbia Non-neutral Torus (CNT) is a stellarator of unique design, dedicated to the study of non-neutral and electron-positron plasmas confined on magnetic surfaces. Such plasmas have unique properties and have not been studied experimentally before. The equilibrium for a low-density pure electron plasma confined on magnetic surfaces has been investigated theoretically and numerically in some detail [1–5]. Theory predicts the existence of stable equilibria with long confinement times, as long as hours in the case of a dense, cold, pure electron plasma. CNT is a two-period, ultralow-aspect-ratio stellarator whose magnetic field is created from only four circular coils: two internal, interlocked (IL) coils and two external poloidal field (PF) coils [6]. In the March 2005 *Stellarator News*, we introduced the CNT experiment and reported on the first magnetic surface mapping results [7]. The magnetic surface mapping experiments for the present configuration have now been concluded, showing very good agreement between numerical and experimental data, and confirmation of an ultralow aspect ratio, $A < 1.9$ [8].

Having confirmed the existence of large, high-quality magnetic surfaces with no significant island structures except at the plasma edge, we successfully filled the magnetic surfaces with approximately 10^{11} electrons, hence creating what we believe are the first stellarator non-neutral plasmas. We report here on these results.

Electron injection

Non-neutral plasmas have been created in CNT by injection of electrons from two different multifilament electron emitters. The first emitter consisted of four thoriated tungsten filaments mounted on a hollow ceramic rod, spaced approximately 8 cm apart to contact different magnetic surfaces. The filaments were operated independently in several ways. Heated, negatively biased filaments acted as sources of electrons, filling up the magnetic surfaces that they were inserted on through rapid parallel transport, and eventually filling the entire volume through cross-surface transport. Unbiased, heated filaments terminated to ground through 1-GΩ resistors played the roles of floating emitting probes. The potential on a floating emitting probe is close to that of the plasma, except when the plasma density is negligible. Also, we introduced large local electron sinks in some experiments by shorting the filaments directly to ground. On the rod in the first emitter, directly facing the plasma, were metallic bands used to connect the tungsten and copper wires. However, these metallic bands short-circuit the radial electric field. The second probe consists of eight platinum tips and four emitting tungsten filaments (from standard 12-V halogen light bulbs), mounted on a ceramic rod similar to the one used for the first probe. The amount of conductor directly exposed to the plasma is minimal, except for the 12 probe tips. We observed a roughly factor of two increase in confinement time using this second multifilament emitter, presumably because of the vastly reduced amount of exposed conductor material.

Confirmation that electrons fill the CNT stellarator

The first experiments in CNT focused on confirming that the plasma volume could be filled with a significant number of electrons. The data were taken over several seconds, so a steady state had been established between the electron emission and the electron losses. With three of the four filaments configured as floating emitting probes, the floating potential was measured at three different radial locations. The floating potential of an emitting probe is approximately $\phi_f = \phi_p - \alpha T_e / e$, unless the electron density is very low or the impedance to ground is not sufficiently high, in which case ϕ_f will be closer to zero [9]. Here, $\alpha \le 1$, at least in a neutral plasma [10]. An example of a potential profile measurement is shown in Fig. 1.

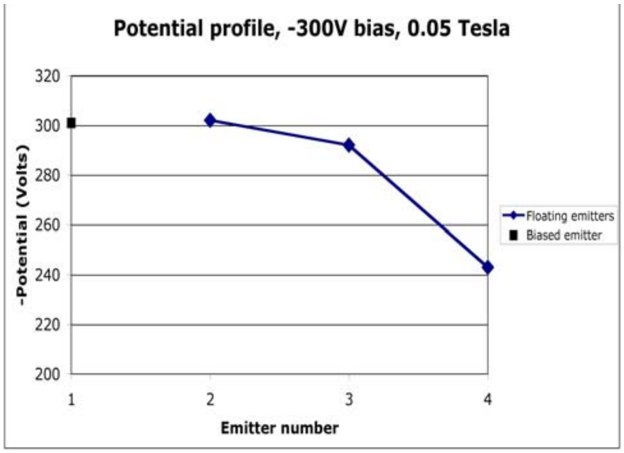

Fig. 1. A typical potential profile for a plasma created with a –300-V bias on the innermost emitter, which was placed near the magnetic axis. These emitters were spaced approximately 8 cm apart, with the fourth emitter inside but near the last closed flux surface.

The fact that the floating potentials are close to the filament bias potential demonstrates that the volume is filled with electrons. For the example shown in Fig. 1, the roughly –300-V potential on filaments terminated to ground through 1-GΩ resistors implies that they are collecting roughly 300 nA of negative current. This would not be possible if there were little or no space charge on the magnetic surfaces on which the floating emitting filaments are placed.

These measurements can be extrapolated to estimate the electrostatic potential difference between the magnetic axis and the last closed flux surface, assuming that the temperature is low enough that the floating potential profile approximates the plasma potential profile well. This difference, $\Delta\phi$, can then be used to estimate the total electron inventory. A simple circular cylindrical estimate, assuming constant electron density and a cylinder length of $2\pi R$, yields a total electron inventory

$$N = 8\pi^2\varepsilon_0 R\Delta\phi/e\,.$$

For a particular experiment with a neutral pressure of 5×10^{-9} torr and $B = 0.05$ T, a bias of −150 V was applied to the innermost emitting filament, yielding roughly $\Delta\phi \approx 80$ V and $N \approx 10^{11}$ electrons according to this estimate. The remaining 70-V potential difference is presumably occurring in the vacuum between the last closed flux surface and the grounded vacuum chamber and coils. A more sophisticated estimate was performed using the CNT 3-D equilibrium code [5] with an educated guess for the Debye length. This yielded $N \approx 1.3 \times 10^{11}$ electrons. For this particular experiment, the steady-state emission current from the biased emitter (the source of electrons) was 1.5 μA, that is, 10^{13} electrons per second, and hence the confinement time was approximately 10 ms. In the complete absence of a magnetic field, the filament emission current was in the milli-Ampere range. The electron inventory estimates presented here are believed accurate to within a factor of two, and consequently the estimates of the confinement time are no better than that. These results were obtained with the first emitter. As mentioned, the confinement time was observed to improve by roughly a factor of two with the second emitter.

Radial loss mechanisms

The theoretical prediction of the confinement time τ_p is $\tau_p \approx \tau_e(a/\lambda_D)^4$, where τ_e is the electron collision time, a is the average minor radius, and λ_D is the electron Debye length. Even for a relatively large Debye length, confinement is expected to be much better than the roughly 10 ms observed. We believe that the perturbing presence of the emitter rod and the probes mounted on it are the primary sources of electron losses, and consequently of the limited confinement time. For a typical bias voltage of –100 V, the floating emitting filaments typically collect on the order of 100 nA each, since they float at potentials on the order of –100 V and are terminated to ground through 1-GΩ resistors. Given that the emitting filament injects on the order of 1 μA at high magnetic field and low neutral pressure, the floating emitting probes are significant, but not dominant, sinks for the electron plasma. The emitter rod, which is a ceramic insulator, quickly charges up negative and self-shields, so direct losses to the emitter rod are likely not important in the steady state. However, the shielding electric fields that surround the negatively charged rod induce convective **E**×**B** patterns that have a significant component perpendicular to the magnetic surfaces and can therefore drive radial losses. This was tested experimentally by inserting a second rod, also a ceramic insulator of the same material and diameter but with no probes or filaments mounted. In different experiments with different insertion locations and slightly different magnetic configurations, we found confinement time reductions of 20–50%, clearly significant. In Fig. 2, we show a scan of the steady-state filament electron source rate, which is inversely proportional to the confinement time at fixed filament bias, as a function of magnetic field strength with one or two rods inserted. With two rods, the confinement time reduction is 50%, and the emission rate appears to be inversely proportional to B, as one would expect for **E**×**B**-driven losses. Thus it appears that the transport induced by the perturbing presence of material rods is dominant, and we therefore expect to see vastly improved confinement for plasmas without internal rods. We plan to achieve this by constructing an emitter that can be retracted within a fraction of a second. However, the near-term focus in CNT is on characterizing and understanding the plasma equilibrium in detail using internal probes, as discussed in the next section.

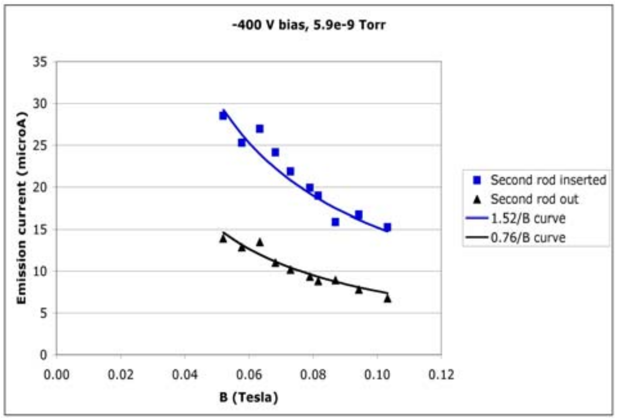

Fig. 2. The steady-state emission current as a function of magnetic field strength for two cases — one ceramic rod inserted deep into the magnetic surfaces (black) or two rods inserted (blue). The emission current follows an approximate $1/B$ scaling and is approximately a factor of two higher when the second rod is inserted, indicating a 50% reduction in confinement time.

Preliminary characterization of equilibrium parameters

As discussed earlier, we have achieved sufficient confinement that thermionic emission from a single filament near the magnetic axis suffices to fill the magnetic surfaces with electrons. The time for a parallel equilibrium to be established on a magnetic surface can be estimated as the time it takes a thermal particle to traverse the surface poloidally and toroidally, approximately $2\pi R/(\iota v_{th})$. For CNT as presently configured, the major radius $R = 0.3$ m; the rotational transform ι varies from 0.12 to 0.22 from axis to edge; and the electron thermal velocity v_{th} is within a factor of two of 10^6 m/s, assuming that the electron temperature is in the range of 2–20 eV. Thus, the parallel equilibration time is on the order of 10 μs. Since the electron confinement time is three orders of magnitude longer, parallel force balance has been firmly established; that is, the electron plasma is in equilibrium. The present phase of the CNT experiment aims to characterize the basic parameters of the pure plasma equilibria. Our preliminary findings are reported below.

As demonstrated in Fig. 1, floating potentials are readily measured, but it is somewhat more challenging to measure the electron temperature and the electron and ion densities, primarily due to the extremely low densities in CNT. For a typical plasma potential of –150 V, the electron density, based on space charge estimates, is in the range of 10^{12} m^{-3}, typical for pure electron plasmas confined in Penning traps, but very low compared to quasineutral plasmas. We have attempted to measure the ion content by biasing platinum tips highly negative relative to the plasma potential (attempting to collect ion saturation current). At vacuum levels of 1×10^{-8} torr or better, and at significant magnetic field (> 0.05 T), there is no detectable ion saturation current at the nano-Ampere level. Although analysis of these measurements is ongoing, we tentatively conclude that the plasma is indeed non-neutral, but we cannot yet conclude that the ion content is negligible. More accurate measurements are planned for the near future. We have also attempted to measure the electron temperature by obtaining a Langmuir characteristic on a platinum tip. Preliminary analysis indicates that temperatures are in the range of 5–15 eV, although some ambiguity remains. Thus, given that our volume-averaged densities are on the order of 10^{12} m^{-3}, the Debye length appears to be on the order of 1.5–3 cm. It is therefore small compared to the average minor radius of CNT (~16 cm), so the plasma criterion is satisfied.

Discussion

The first results from CNT are encouraging: the magnetic surfaces are of excellent quality and of the shape expected from numerical calculations, verifying that CNT is the lowest aspect ratio stellarator built to date. Significant numbers of electrons have been confined in CNT, filling the volume of the magnetic surfaces and producing space charge potentials on the order of a few hundred volts. The confinement times are much longer than the parallel equilibration time, indicating that a true magnetic surface equilibrium has been established, and, at sufficiently low neutral pressure and sufficiently high magnetic field, confinement appears to be not limited by instabilities or neoclassical losses, but by the presence of internal rods and probes. We are therefore optimistic that significantly better confinement can be achieved if the rods and probes are retracted. Work has begun to characterize the ion content, the electron temperature, and other plasma properties. It appears that the space charge cloud in CNT is predominantly, if not exclusively, made of electrons, and that the plasma criterion is satisfied. Hence, indications are that the first non-neutral plasmas have been created in CNT. Much more detailed diagnostic data are expected within the next few months, and we expect soon to be able to conclusively confirm the tentative findings reported here.

Confinement of electrons in previous stellarator experiments

CNT is not the first experiment to confine an electron cloud. In the Compact Helical System (CHS), similar volume-averaged electron densities have been obtained by injection of a ~1-keV electron beam from a stochastic region near the plasma edge [9, 11]. However, according to Ref. [11], the temperature in CHS was estimated to be on the order of 600 eV, so the Debye length appears to have been on the order of 10–20 cm, which is not small compared to the average minor radius in CHS (20 cm). Therefore, it does not appear that the plasma criterion was satisfied in those experiments, although this conclusion is dependent on the temperature estimate given. Also in a series of experiments at University of California Irvine (UCI) in the 1980s, electrons beams were trapped and accelerated in a stellarator configuration, the so-called stellatron. However, because of the large beam energy (several mega-electron volts) and energy spread (~20 keV) the stellatron experiments do not appear to have satisfied the plasma criterion either [12]. Nonetheless, both the CHS beam-injected electron experiments and the UCI stellatron experiments show evidence of plasma dynamics, specifically, collective oscillations. It is believed that, at least in the case of the CHS experiments, the instability is caused by a resonance with a finite ion population, created from ionization of background neutrals. In both the CHS and the UCI experiments, the neutral pressure was on the order of 10^{-7} Torr, compared to ~5×10^{-9} torr for the CNT experiments reported here. Although we currently focus our attention on creation and studies of small Debye length pure electron plasmas, we also plan to study higher temperature plasmas with a significant ion fraction, so that the physics of plasmas spanning the entire range from pure electron to quasineutral can be investigated.

Thomas Sunn Pedersen, on behalf of the CNT team
Dept. of Applied Physics and Applied Mathematics
Columbia University
204 S.W. Mudd, 500 W 120th Street
New York, NY 10027
Phone: 212 854-6528
CNT Web site:http://www.ap.columbia.edu/CNT

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International Energy Agency 15th International Stellarator Workshop (October 3–7, 2005)

followed by

IAEA Technical Meeting on Innovative Concepts and Theory of Stellarators (October 10–11, 2005)

1. Organization

The 15th International Stellarator Workshop and the Technical Meeting on Innovative Concepts and Theory of Stellarators will be organized by the Laboratorio Nacional de Fusión (Asociación EURATOM-CIEMAT para Fusión), which forms part of the Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas (CIEMAT), located in Madrid, Spain, in the frame of the International Energy Agency (IEA) Implementing Agreement on the Stellarator Concept and in cooperation with the International Atomic Energy Agency (IAEA).

The workshop Web page

http://www-fusion.ciemat.es/sw2005

contains all the information about deadlines, scientific program, timetable, and other organizational aspects. Please check it frequently for the latest updates.

2. Dates and Place

The Stellarator Workshop will be held at the Laboratorio Nacional de Fusión, CIEMAT, Av. Complutense 22, Madrid, Spain, from Monday October 3 to Friday October 7, 2005.

The IAEA Technical Meeting on Innovative Concepts and Theory of Stellarators will be held at the Laboratorio Nacional de Fusión, Ciemat, Av. Complutense 22, in Madrid, Spain, from Monday, October 10 to Tuesday, October 11, 2005.

Bus transportation from hotels to CIEMAT and vice versa will be provided to every registered participant.

3. Scope and Topics

Stellarator Workshop:

The Stellarator Workshop covers all aspects of fusion research of helical systems and related concepts. Specifically, the following topics will be covered:

- Recent experimental projects
- Transport and confinement improvement
- MHD equilibrium and stability
- Turbulence and transport
- Particle and power handling
- Divertors and impurity control/transport
- Plasma heating
- Diagnostics
- Configuration optimization
- New devices
- Reactor studies

IAEA Technical Meeting:

The aim of the IAEA Technical Meetings is to cover technical issues in the theory of stellarators; this meeting will concentrate on the progress of computational efforts. Overviews in this area of research should, however, be placed in the Stellarator Workshop.

4. Language

The official conference language is English.

5. Meeting Format

The International Program Committees of the Stellarator Workshop and of the IAEA Technical Meeting are in charge of the scientific content of the respective meetings. These two committees will nominate the invited speakers, accept papers, and select oral and poster contributions. The selection and acceptance will be done on the basis of submitted abstracts.

The programs of both the Stellarator Workshop and the IAEA Technical Meeting will be organized on the basis of invited talks and contributed papers to be presented as posters. A certain number of contributed papers will be selected for additional oral presentations.

Stellarator Workshop

The meeting will have 1 panel discussion (90 min), 4 review talks (45 min), 27 invited talks (30 min), 12 oral presentation sessions (20 min), and 3 poster sessions (2.5 hours long).

IAEA Technical Meeting

The meeting will contain invited and contributed papers (orals and posters) presented in sessions devoted to special topics with subsequent discussions. Plenary sessions will be followed by poster sessions to enhance topical discussions. It is expected that all talks will be ~20 minutes with ~5 minutes for discussion.

For further details, see the conference Web page.

Contacts

Stellarator Workshop Secretariat:

Dr. K. McCarthy
Laboratorio Nacional de Fusión, CIEMAT
Av. Complutense 22
28040 Madrid, SPAIN
Phone: 34-91-3466372 (6159)
Fax: 34-91-3466124
E-Mail: sw2005@ciemat.es
Home page:http://www- fusion.ciemat.es

IAEA TM Secretariat:

Guenter Mank - IAEA Scientific Secretary
IAEA, Section Head, Physics Section
Wagramer Str. 5
A-1400 Vienna, Austria
Phone: +43-1-2600-21756
FAX: +43-1-26007
E-mail: physics@iaea.org