stellarator news

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From the Editor....

Welcome to the rebirth of *Stellarator News*. This is an exciting time in the stellarator community because many new machines are about to start producing data in previously unreachable regimes of operation. I would like *Stellarator News* to serve as a source of information on recent developments in the world stellarator program that will be useful both to experts in the field and to the general fusion community.

If I can obtain articles via E-mail or on IBM (preferable) or Macintosh disks, I can produce this newsletter with a desktop publishing system with just a few evenings' work. My E-mail addresses (for various networks) are

ROME%ORN.MFENET@NMFECC.ARPA
ROME%ORN.MFENET@ANLVMS.BITNET
ROME@ORN.MFENET

MFENET is also reachable from HEPnet, GATnet, and SDSCnet. I can also accept plots in CGM, HPGL, MSwindows, Mac PICT, Lotus .PIC, GEM, AutoCad SLD, Tektronix, and PostScript formats. PostScript files are in ASCII and can more easily be sent over the networks. For a file to survive network transmission, you should keep each line to 72 characters or less, and there is often an upper limit on file size; end each file with the word "END" so that I know the whole file arrived. I will reply to each message so that you know it was received. I hope to maintain a bi-monthly publishing schedule, so please have your contributions for the next newsletter in before the end of the year.

In addition to experimental reports, I solicit short reports on theory development, news about people in the stellarator community, availability of computer programs, and announcements and summaries of meetings of interest.

Seventh International Workshop on Stellarators

The Seventh International Workshop on Stellarators will be held in Oak Ridge, Tennessee, April 10-14, 1989. It is jointly sponsored by Oak Ridge National Laboratory and the International Atomic Energy Agency.

The workshop will cover all topics applicable to stellarators and other helical confinement devices. Some topics of interest are:

- Experimental results
- Theory (Configurations, MHD, Transport)
- Diagnostics
- New devices, next-generation experiments, reactors

The number of oral presentations will be limited to emphasize overview talks, reviews of recent work, and topics of general interest. More detailed papers will be presented in poster sessions. Ample time will be set aside for free discussion and for more intense, focused, topical meetings.

A detailed announcement has already been sent to stellarator research groups. Extra copies can be obtained from the conference secretary, Jim Rome at ORNL.

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Around the Labs

Auburn To Build New Torsatron

The Auburn Torsatron is an l=2, M=10 device. The major radius is 58 cm and the vacuum vessel radius is 14 cm. The maximum magnetic field is 2 kG. During the past two years experimental work on the Auburn Torsatron has emphasized the study of magnetic surface mapping techniques. A secondary emphasis has been in the area of experimental studies of ICH. This ICH work is expected to continue through 1990 on the Auburn Torsatron.

A new machine is also under construction, the Compact Auburn Torsatron (CAT). This torsatron has a main helical winding having l=2, M=5. It also has an l=1, M=5 winding which carries approximately 30% of the current in the main l=2 winding. The maximum magnetic field will be 1 kG. The coil aspect ratio is approximately 2. The projected plasma aspect ratio is 5.5. The magnetic axis is circular to within a millimeter. This feature allows for a very cost-effective vacuum vessel. The l=1 coil will be wound directly on the vacuum vessel and the l=2 coil will be wound on the l=1 coil.

This machine was designed using the Cary-Hanson technique of magnetic surface optimization. The optimization parameters were the pitch modulation of the main helical coils and the location and relative currents in the VF coil sets. Calculations predict a rotational transform profile having a central transform of 0.3 and an edge transform of 0.8. The main focus of the machine will be the study of magnetic islands. Trim coils will be employed to induce and remove magnetic islands from near the plasma boundary. The fragility of the magnetic islands to various perturbations will be explored. Later in the experimental program the effect of magnetic islands on plasma properties will be studied.

Rex Gandy
Physics Department
Auburn University
Auburn, AL 36849

Wendelstein VII-AS Starts Plasma Operation

Experiments in Wendelstein VII-AS were started in May 1988 with an intensive study of the magnetic fields by mapping them under various operation conditions of the modular and external fields. A novel technique was used besides the classical ones of pulsed electron beam and pick-up probe: The magnetic surfaces in Wendelstein VII-AS were observed by a CCD camera and stored in the attached computer, using a static electron beam from a movable source and a movable thin rod with a fluorescent coating.

The agreement between measured and computed surfaces is excellent. For the standard case of Wendelstein VII-AS the ι-values are within about 1.5%. With superimposed TF fields the natural islands near the edge could be observed, e.g., at $\iota = 5/11$. The two islands introduced by an intrinsic perturbation appear to be of a tolerable dimension. The expected increase in aspect ratio was seen at elevated ι values.

Between July and late September 1988 further engineering tests brought the fields up beyond the level of 1.25 T, which value was planned during the first part of the initial operation period, and recently up to 2.7 T. Further implementation of the diagnostics was carried out; the mirrors for ECRH, an antenna for ICRH , and the limiters were mounted into the vacuum vessel.

First plasma was produced in Wendelstein VII-AS at the beginning of October 1988. Second harmonic ECRH was used at 1.25 T at various iota values from the standard case of $\iota = 0.39$ up to $\iota = 0.6$. The plasmas were characterized by an increasing density which is due to internal sources from the new vessel and its graphite-coated limiters. The discharge conditions were improved by the usual techniques. Two of the five turbo pumps broke down, but this damage could be fixed in a short time. Using one or two gyrotrons at 70 GHz for plasma build-up and heating, peak electron temperatures of 500 eV in hydrogen and 1 keV in helium were obtained , in transient plasmas at densities near cut-off.

More information will be given at the Oak Ridge Stellarator Workshop in November 1988 in the papers by H. Renner (*Initial Operation and Program of W VII-AS*), R. Jaenicke (*Measurement of Magnetic Surfaces in W VII-AS*), P. Grigull (*Conditioning of W VII-AS*), V. Erckmann and G. Mueller (*ECRH in W VII-AS*).

F. Rau and H. Renner
Max-Planck Institut für Plasmaphysik
D-8046 Garching bei München, FRG

ATF Ends Second Operational Period

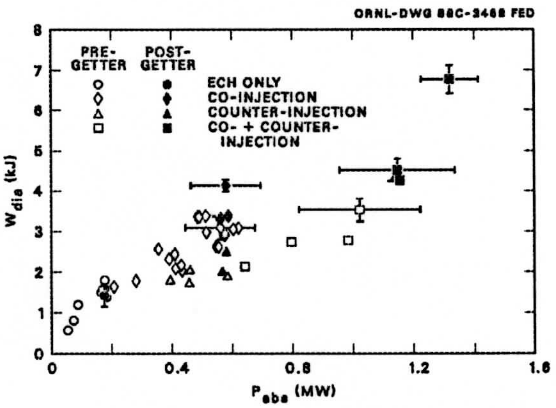
ATF has just completed the initial NBI experimental phase (end of May through end of September). This phase was preceded by field mapping experiments which indicated the presence of islands of about 6 cm width at ƚ = 1/2 and smaller islands at ƚ = 1/3 and 2/3. Studies of these results continued during the most recent run period; the cause (coil leads) and appropriate corrections were identified and those corrections are presently being made.

The experimental operation period stressed commissioning the diagnostics, heating, and wall conditioning systems. Initial operation emphasized wall conditioning using electron cyclotron resonance and glow discharge cleaning in conjunction with baking the vessel up to 150°C. Plasma operation showed evidence of substantial improvement in impurity levels as compared to the previous operation period. ECH plasmas lasting for up to 1 s were produced with no evidence of thermal collapse due to impurity buildup. Although ECH discharges were little affected by line radiation, the radiation was an important factor in the behavior of NB-heated discharges. Discharges underwent thermal collapse before the end of the beam pulse due to impurity radiation dominated by low Z impurities, particularly oxygen and carbon. Thomson scattering measurement showed a central electron temperature of 800 ±200 eV at $\bar{n}_e = 0.8\times10^{19}\mathrm{m}^{-3}$ with second harmonic 200 kW ECH at 53.2 GHz and 0.95 T. With 0.6 MW of NBI, both stored energy and line-averaged density increased, to 4 kJ and $2\times10^{19}\mathrm{m}^{-3}$ with $T_e(0) = 600 \pm 100$ eV. Radial temperature profiles indicated a cold plasma region in the outer 1/3 of the discharge, providing strong evidence that field errors are having a detrimental effect. Configuration scans showed that the optimal position of the axis occurred at a major radius of about 5 cm inside the standard radius ($R_0 = 2.1$ m), and these results can also be interpreted in terms of field error effects.

Besides the obvious problem of known field errors, impurity radiation was an important factor in limiting performance of NB heated plasmas, as clearly demonstrated by the chromium gettering experiment. In scaling experiments with one beam before gettering, global confinement time was found to decrease with heating power in a manner consistent with "LHS" and tokamak empirical scalings. With both beams injecting 0.7 MW each, however, little or no increase in stored energy was seen, implying more rapid confinement deterioration than anticipated. With modest chromium gettering in combination with gas puffing, performance improved substantially. The duration of the NBI phase was lengthened (to 100 ms) and the density $\bar{n}_e$ increased to $3.5\times10^{19}\mathrm{m}^{-3}$ by gettering before undergoing thermal collapse, and higher values of stored energy (up to 8 kJ) and volume-average beta (0.6%) were obtained using 1.4 MW of balanced injection.

Two other experimental studies were carried out. ICRF heating studies using a fast-wave antenna started in August. RF power of up to 94 kW at 29 MHz was applied for 0.1 s into 0.75 MW NB-heated discharges. The loading resistance for these shots was 0.6 ohm. The resistance is expected to go up substantially for a broader plasma profile, as expected when the field errors are corrected. Divertor scoping studies began with radial position scans of a graphite plate in the helical stripe region in order to determine the location and magnitude of the particle flux leaving the bulk plasma along the divertor stripe. The divertor stripe was observed to be tightly focused and to have a width of about 4 cm.

COMPARISON OF GETTERED AND UNGETTERED DISCHARGES



The field error repair is now in progress and will be checked with the electron-beam/fluorescent technique in November. Other improvements are also being made during this shutdown period, including more complete gettering and reinforcement of the vertical field coils for operation at 2 T. The experimental operation is scheduled to restart by the end of the year.

Masanori Murakami
Fusion Energy Division
Oak Ridge National Laboratory
P.O. Box 2009, Bldg 9201-2
Oak Ridge, TN 37831-8072

IMS EXPERIMENTS

The Wisconsin IMS device has machine parameters of l=3, 7 field periods, R_0=40 cm, a=4 cm, $\iota\!\!\!-(0)=0.0$, $\iota\!\!\!-(a)=0.6$, $B_0 = 3$–6 kG. Plasmas are produced using either a 7.25- or a 15.0-gHz rf source, with typical plasma parameters of $n_e = 10^{11}$–$10^{12}\ \mathrm{cm}^{-3}$, $T_e = 5$–15 eV, $T_i = 6$–10 eV.

The most noticeable feature of the IMS plasmas is a hollow density profile, the extent of the hollowness being influenced by both the radial location of the electron cyclotron resonance location and the application of moderate (~1%) vertical magnetic fields. Hollowness (peak n_e/central n_e) can be varied from 10 (extremely hollow) to almost 1 (centrally flat profile). Significant experimental emphasis has been placed on determining the possible role of poloidal electric fields and associated radial convection in producing these density profiles.

IMS has an inherent modular divertor structure of 63 discrete divertor bundles with 9 bundles per field period. Extensive work has been performed on mapping the locations of the emergent diverted plasma fluxes and investigating methods of influencing these modular divertor flows. Global flow redirection has been realized through the application of a vertical magnetic field, and local flow control has been demonstrated through the application of potentials to individual divertor neutralizing plates.

Plasma Potentials and Radial Convection

Diffusively dominated plasma transport would fill in a hollow profile on a timescale on the order of the confinement time. Inclusion of convection in the particle balance equation leads to solutions which closely match the experiment. To determine the possible role of electric fields in this convection, two-dimensional scans, at one toroidal location, of the plasma potential were measured using an emissive probe. Equipotential contours were then calculated and compared to the IMS magnetic surfaces.

For the profiles with small degrees of hollowness, the equipotential surfaces correspond well to the magnetic surfaces. For more hollow cases, however, the equipotential contours do not correspond so well. In these cases, a region of high potential was evident in one poloidal area. This provides a poloidal electric field, which, with variations in the magnetic field around the surface can cause the radial drift velocity on a surface to be non-zero. Numerical interpolation of the potential on a surface was used to calculate the a net radial convective velocity. The surface-averaged radial convective velocity for two density profiles with different degrees of hollowness are shown in the figure. Using these radial flow velocities in the particle balance equation provides an excellent match between the calculated and measured density profiles.

Divertor Flow Alteration

A vertical magnetic field which moves the magnetic surfaces major-radially inwards is predicted to focus the divertor pattern to the inboard side, and almost completely remove the outboard divertors. An oppositely directed magnetic field is predicted to increase the number of emergent field lines on the outboard side, and reduce the number on the inboard side, although the effect is not as pronounced as for the first case. This predicted global divertor refocussing has been verified by measurements of the divertor particle fluxes: the results are summarized in Table I. The code predicts an increase in the divertor connection length for both directions of vertical magnetic field, but the increase is more pronounced for the outwardly shifted surface case. A

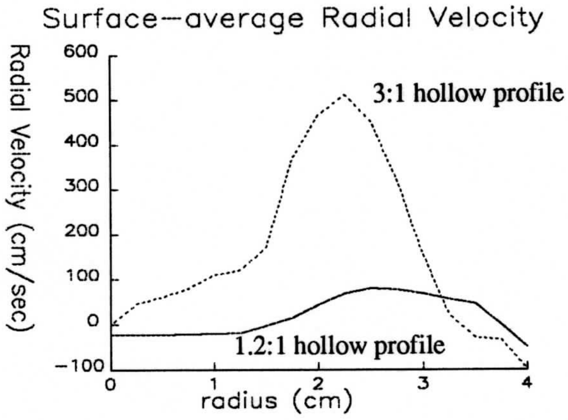


Table I

Divertor Poloidal Angle (0° = outboard)	Diverted plasma ion saturation current (mA)		
	B_v = Inward	No B_v	B_v = outward
Inboard @ 150	3.9	1.7	0.5
Inboard @ 211	1.7	0.7	0.3
Outboard @ 338	4.5	5.7	8.2
Outboard @ 28	5.3	6.1	7.3

toroidal current is predicted to increase the connection length but not significantly affect the divertor pattern.

Local changes in divertor flows have ben affected by applying potentials to individual divertor neutralizing plates. Floating potential measurements at the region just outside the separatrix where the divertor field lines originate, have shown that potentials up to the electron temperature propagate from the divertor regions into this region. Each divertor bundle has also been demonstrated to connect to a well defined region in this field line origin area. This potential then induces $\boldsymbol{E}\times\boldsymbol{B}$ flows either into or out of adjacent divertor-origin regions, and thus affects the divertor flows to a limited number of divertor regions. Measurements of divertor flows have corroborated this $\boldsymbol{E}\times\boldsymbol{B}$ driven divertor redirection hypothesis. Reversal of the IMS magnetic fields is seen to reverse the flux redistribution trends. These experimental results are summarized in Table II. θ is the poloidal angle measured from the outside of the torus, and ϕ is the toroidal angle.

F. Simon Anderson
Torsatron Stellarator Laboratory
University of Wisconsin
1415 Johnson Drive
Madison, WI 53706

Table II

Monitored divertor (adjacent origins)		Ion saturation current to divertor (mA)		
θ	ϕ	No Bias	Bias & +B	Bias & -B
+50V applied to divertor at θ=100°, ϕ=8.9°				
45.	-8.9	9.1	4.9	10.4
135.0	26.7	2.0	4.8	1.2
+50V applied to divertor at θ=340°, ϕ=8.9°				
0.0	26.7	8.0	2.0	14.4
300.0	-8.9	10.5	15.7	5.3

University of Colorado

Work at the University of Colorado has proceeded along two fronts. In collaboration with C. L. Hedrick and J. Tolliver of Oak Ridge, we have developed an averaged theory of particle orbits in stellarators with small rotational transform per field period. Numerical tests show that these invariants are very well conserved. The theory also predicts the probability that a particle makes a transition from the locally passing (toroidally trapped or blocked) state to the locally (ripple) trapped state at the end of the toroidal bounce. Numerical tests indicate that this transition probability is not very accurate when significant negative ambipolar potential is present. The source of the inaccuracy has been traced to a need for the calculation of higher-order terms in the dynamics near the separatrix. Calculation of these effects is under way.

John R. Cary
Department of Astrophysical, Planetary, and Atmospheric Sciences
University of Colorado, Boulder, Colorado 80309-0391

Meeting Reports

Summary of 2nd Workshop on Wendelstein VII-X

SCHLOSS RINGBERG, 13 - 16 JUNE 88

The 2nd Workshop on Wendelstein VII-X was held at Schloss Ringberg, Bavaria, from 13 to 16 June 1988. There were nearly 50 participants, mainly from IPP Garching; about 40 papers were given and intensively discussed. In his summary talk, H. Wobig pointed out that during the four days of the workshop considerable progress had been made towards the specification of the final concept of Wendelstein VII-X.

The formerly preferred configuration with four field periods (see e.g., *Proceedings of the Workshop on Wendelstein VII-X*, EUR 11058 EN, 1987) has been abandoned in favor of a Helias configuration with five field periods. This was initiated by results of recent stability analyses given in the papers by J. Nührenberg, H. Wobig and R. Scardovelli, which predict that β-limits are higher for five than for four field periods. According to the results of J. Nührenberg, Helias configurations at an aspect ratio of about 10 with five field periods can meet the goal of an average β of approximately 5% , as has been set for W VII-X, whereas in Helias configurations with the same aspect ratio and four field periods, the combined MHD ballooning and resistive interchange β-limit remains around average values of 2 - 3% for cases in which the option of a resonant divertor at the edge is available.

With five field periods and an aspect ratio of 10, the available space between plasma and a first wall is determined by local minimum distances of 2 - 3 cm for an average major radius of 5 m of the system. In view of the plasma wall interaction this has been considered as intolerable, and a modification of the overall geometric dimensions of Wendelstein VII-X has been proposed. The major radius has been increased to 6.5 m, and the magnetic field has been reduced from 4 to 3 T. This field reduction was used to keep the amount of superconducting material for the coils fixed, which is the most expensive component of the coil system.

There are several consequences of this modification: the maximum field at the coils is less than 6 T; therefore, the forces in the coils are slightly smaller than in a case with 4 T and a major radius of 5 m, although in the larger system, the current density has been increased. Thus, the distance between plasma and the first wall has increased to 12 - 14 cm which should lead to a smaller wall loading by high-energy particles. Although neoclassical transport losses for a fixed machine size at 3 T are larger than at 4 T, the expected plasma parameters are only slightly changed since the confinement time improves with the size of the device.

One of the main goals of Wendelstein VII-X, a stable operation with an average beta of approximately 5%, is not changed at all by the reduction of the magnetic field, since that experiment will be done at reduced fields of 2 - 2.5 T in all cases. The larger version of Wendelstein VII-X allows improved access for various heating schemes such as neutral beam injection and ion cyclotron heating, thus yielding the chance to apply more than 20 MW heating power in a later stage of the experiment.

Another result of the workshop concerns the question of normal conducting versus superconducting coils. After discussion of many arguments for and against each option there is a strong tendency in favor of a superconducting version of Wendelstein VII-X. Although a final decision will be made after a feasibility study has been performed by INTERATOM, it has been recognized during the workshop that a normal conducting modular coil system hardly offers a cost benefit, since the modular coils become rather voluminous. Even in view of an envisaged pulse length of only 10 s, and after taking into account extra costs for increasing the power supply of IPP, as well as the high running costs of a normal conducting coil system, the amount of financial investment in a normal conducting system appears to be comparable with that in a superconducting coil system. However, a detailed cost analysis has not been done so far.

The limitation of the pulse length to 10 s in the normal conducting option has been considered as a strong argument against this option. In view of the reactor potential of stellarators, any large experiment with the aim of demonstrating this potential should be able to run at true steady state with limits set only by the available heating power or its removal. Therefore the future planning of Wendelstein VII-X will be concentrated on the superconducting option.

A preliminary time schedule for the construction of Wendelstein VII-X with superconducting coils was presented by J. Sapper, who pointed out the milestones and tasks to be undertaken. Applications for EURATOM Preferential Support, Phases I and II, are foreseen for spring 1989 and mid 1990, respectively. A construction time of more than 6 years is estimated, beginning after

Phase II of the preferential support has been given. An important issue in this context is to build and test a prototype superconducting coil as soon as possible, thus providing necessary information for the construction of the whole coil system.

During the four days of the workshop the essential problems were addressed in presentations and discussions. Key issues were plasma equilibrium and stability in Helias configurations, transport and estimates of the bootstrap current, heating and predictions of the plasma parameters, coil systems and their vacuum fields. For the coil systems and vacuum fields, the issues were the attainable parameter range and the edge structure of the fields, the effect of perturbations and the required accuracy, as well as considerations of mechanical forces and the resulting stresses. The correlation between WVII-AS and W VII-X has been addressed in the paper by H. Renner, which describes the experimental program of WVII-AS and its possible impact on the design of Wendelstein VII-X .

Evidently, not all of the problems could be solved. Important issues like impurity accumulation and control, instabilities other than of the MHD type (drift modes, trapped particle modes) could be treated only occasionally. This simply happened because priority was given to the task of selecting the optimum type of field configuration. With the present knowledge this has been achieved by the choice of a 5-period Helias configuration with a major radius of 6.5 m and a field of B = 3 T.

The proceedings of the workshop are being published by EURATOM, Brussels, as Report EUR 11705 EN; an extended summary with a number of figures and tables is available in the Garching Report IPP 2/295 (August 1988). Further information on Wendelstein VII-X is given in the IAEA Nice Conference, paper C-I-4 , and in the 15th SOFT Utrecht, paper A-3-1.

F. Rau and H. Renner
Max-Planck Institut für Plasmaphysik
D-8046 Garching bei München, FRG

People

Major Changes in Management at ORNL

O. Bill Morgan, Director of the Fusion Energy Division (FED), has been promoted to the post of Laboratory Associate Director. He now has responsibilities for the ORNL divisions which deal with security, environment, health, finances, personnel, instrumentation and controls, and quality assurance.

Replacing Bill as FED Director is **John Sheffield**. John has been FED's Associate Director for Confinement since 1981. John worked at Harwell and Culham Laboratories from 1958 to 1966, and from 1966 until 1971 he was an assistant professor in the Center for Plasma Physics and Thermonuclear Research at the University of Texas in Austin. John returned to Culham until 1977 when he came to ORNL.

As a result of an eight-month national search, **Alvin W. Trivelpiece** has just been appointed Director of ORNL and a Vice President of Martin Marietta Energy Systems, Inc. Al will assume his position by the start of 1989. Al is currently Executive Director of the American Association for the Advancement of Science (AAAS) and before that was Director of the Department of Energy's Office of Energy Research. He is co-author of *Principles of Plasma Physics*, which was produced while he and Nick Krall were professors at the University of Maryland.