



stellarator news

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Initial operation of the TJ-I U torsatron

In April 1994 first electron cyclotron heated (ECH) plasmas have been produced in the TJ-I U torsatron. Flux surfaces have been mapped. Plasmas have been initiated and heated by means of 28-GHz electron cyclotron resonant heating (ECRH) with a 40-ms pulse length.

TJ-I Upgrade is a six period, $l = 1$ torsatron constructed at CIEMAT, Madrid [1]. Its major radius is 0.6 m, and the average plasma radius is 0.1 m. The magnetic field of TJ-I U is created by a five-coil system: one helical coil and two pairs of vertical field coils. The average magnetic field at the axis is 0.52 T with a magnetic ripple of 7.6%. The cross-section of the magnetic surfaces is toroidally asymmetric; they are elliptical for $\varphi = 0^\circ$ and slightly triangular for $\varphi = 30^\circ$. This last cross section is well-suited for ECRH power injection.

Before the first plasma experiments, the magnetic surfaces quality was extensively studied by means of magnetic surface mapping at reduced dc magnetic field values, up to 0.05 T. The technique used has been successfully applied previously in other stellarators [2]. It is based on imaging the spots produced by the impact of an electron beam, launched in the vacuum vessel along the magnetic field lines, against a fluorescent rod that sweeps the vessel cross section. The images are taken with an intensified charge-coupled device (CCD) camera and combined using an image integrator. The magnetic surfaces were measured at the toroidal plane $\varphi = 10^\circ$ for a large number

of values of the ratio between the helical and the vertical field coils currents. The results obtained show the existence of closed, nested magnetic surfaces in good agreement with the theoretical calculations, as can be seen in Fig. 1, so long as the value of the rotational transform is kept away from the low-order rational values present in the iota variation range. Otherwise, because the shear in this device is small, large islands can be observed.

ECRH plasmas have been created and heated using extraordinary waves at the second harmonic of electron gyro frequency. Microwave power is launched through an external port, perpendicularly to the toroidal direction. The heating system (MIG-2U complex) was designed and fabricated in Russia. It consists of high-voltage power supply, gyrotron, superconducting magnet, quasi-optical transmission line, instrumentation, control, interlock and cooling systems. The gyrotron generates up to 420 kW of microwave power at 28 GHz. It has almost linear polarization (99%) and a Gaussian distribution of microwave power on the output window. The measured waist of the gyrotron output beam is 23 mm at 3 db below the central power level. Because Gaussian beams provide a good match with the

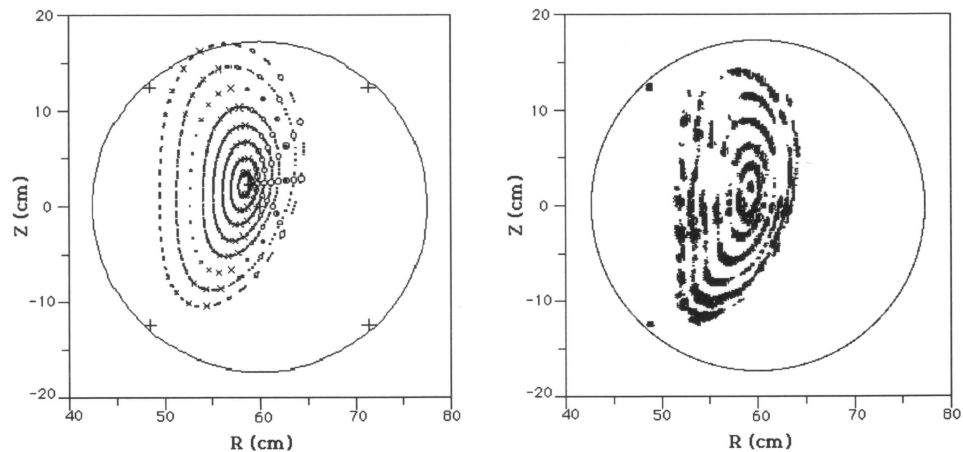


Fig. 1. Calculated and experimental magnetic surfaces in TJ-IU. Current ratio: $IVF/IHC = 0.451$. Rotational transform at axis: 0.251.

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mirror and lens waveguides, a quasi-optical line based on a mirror waveguide has been chosen for TJ-I U. It consists of four cylindrical mirrors coupled in pairs so that curvature radii of each pair lie in perpendicular planes. Total losses in the quasi-optical line do not exceed 10%. The Gaussian beam diameter (-3 db) on the TJ-1U window is 40 mm. The incident angle of the wave beam on the plasma column can be changed by the last mirror up to 3°.

First plasmas were obtained on April, 20, 1994. In the first discharges plasma density was dominated by outgassing from the wall produced by the gyrotron shot. After several tens of plasma shots alternated with glow discharge cleaning, the plasma density was controlled with external gas puffing. As can be observed in the plasma discharge shown in Fig. 2, line electron densities of about $0.4 \times 10^{13} \text{ cm}^{-3}$, near the cut-off limit, have been obtained. The density trace exhibits good time correlation with the signal from a microwave detector that indicates absorption of a fraction of the total microwave power present in the vacuum vessel (reference level about 0.4).

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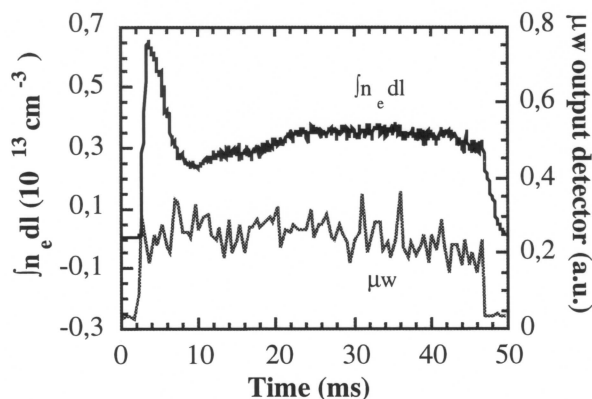


Fig. 2. Plasma shot showing integrated line electron density and microwave power in the vacuum vessel during the discharge.

ATF resumes operation

After nearly 18 months of downtime to repair a damaged helical field coil, the Advanced Toroidal Facility (ATF) torsatron at ORNL has resumed operation. While the operational period will be brief, it will perform a variety of experiments crucial to future fusion devices. Primary operation will be with 35- and 28-GHz ECH heating systems at 0.63 and 0.5 T.

A set of boronized carbon limiters will be tested to determine the feasibility of using such limiters as a supplemental source of boronization between major boronization cycles on the Large Helical Device (LHD) experiment at the National Institute for Fusion Science (NIFS) in Japan. Akio Sagara of NIFS has spent several weeks at Oak Ridge in preparation for this experiment.

A second set of experiments, lead by Masanori Murakami of ORNL, will attempt to explore transport and confinement scaling with dimensionless parameters. In a single long pulse discharge, p^* , the gyro-radius normalized to plasma radius, is modulated while fixing two other dimensionless parameters, collisionality and beta. The helical field will be varied in a periodic manner between 0.5 and 0.63 T while both the 28- and 35-GHz gyrotron powers and the plasma density are synchronously modulated.

The third set of experiments will explore the extension of the ATF pulse length. Initial results have been promising; already pulse lengths of up to 30 s at 0.63 T have been obtained. When the 28-GHz gyrotron system is fully operational, pulse lengths of more than 10 min should be achieved.

After these experimental runs are completed in June of this year, ATF will be "moth balled" Because insufficient funding is available for continued operation. It is hoped that in the not too distant future, funding for this program will be found and ATF can continue to provide important physics and engineering data for the fusion program.

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Around the Labs

Non-Maxwellian electron temperature distribution during ECR-heated discharges in W7-AS

The new single shot 20-point Thomson scattering system at W7-AS has been routinely operating since the beginning of 1993. A new feature has been found in the electron temperature profiles during ECR-heated discharges with heating power well above 200 kW, electron densities n_e less than about $8 \times 10^{19} \text{ m}^{-3}$, and with a toroidal magnetic field of B_0 about 2.5 T.

Close to the ECRH power deposition zone, the electron temperature deduced from the Thomson scattering spectrum appears to be much higher than the simultaneously measured electron cyclotron emission (ECE) temperature (see Fig. 1, upper two curves). The large error bars are due to the fact that there were only four spectral channels measuring a rather flat scattering distribution. In the meantime the corresponding polychromators have been extended to five spectral channels.

This phenomenon can be understood by assuming a Maxwellian electron distribution function with a superimposed superthermal tail. The Thomson scattering distribution reacts directly on the distorted distribution function, whereas the ECE signal does not (reabsorption). Thus a direct comparison of Thomson and ECE measurements allows one to separate the superthermal tail from the bulk Maxwellian distribution. The superthermal effect tends to decrease with increasing density as shown in Fig. 1 (lower two curves). At this density some small excess seems to remain in the Thomson signals. It can be influenced by changes in the magnetic configuration, for example, by varying the vertical magnetic field, rotational transform, and/or the magnetic mirrors. This effect does not depend on the heating mode (140 GHz, first harmonic, O-mode vs 70 GHz, second harmonic, X-mode). It does not occur at $B_0 = 1.27 \text{ T}$ and during purely neutral beam heated discharges.

To understand the driving mechanism one has to consider the geometry of the magnetic field. The new Thomson scattering system and the ECRH launching system are positioned in the same modular sector in adjacent local magnetic mirrors. Due to the scattering ge-

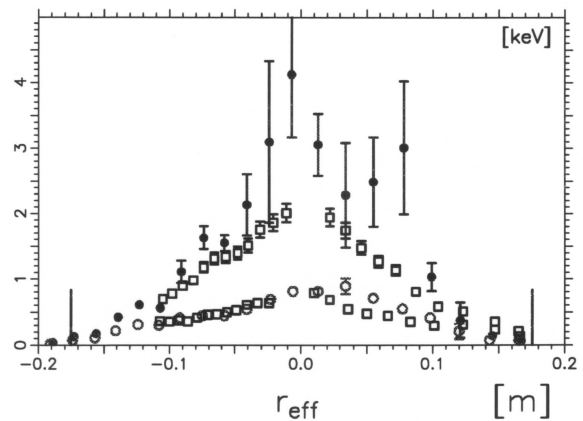


Fig. 1. Density dependence of the superthermal effect observed on W7-AS. For $n_e(0) = 8 \times 10^{19} \text{ m}^{-3}$ (lower two curves) agreement is found between Thomson scattering (open circles) and ECE (open squares). For $n_e(0) = 2 \times 10^{19} \text{ m}^{-3}$ (upper two curves) the Thomson profile (filled circles) appears to be much higher than the ECE profile (open squares) in the plasma center.

ometry, the high energy channels of the Thomson system can be influenced by the superthermal component of the electron distribution function, affecting the value of the deduced temperature. Superthermal effects of this kind have not been observed using the old Thomson scattering system located in a modular sector far from the ECRH launching system. In addition the scattering vector had an angle of about 45° with respect to the magnetic field, which indicates the electron distribution to be strongly anisotropic. Recently a bounce averaged Fokker-Planck code has been employed close to the plasma axis to study the superthermal component induced by ECRH and its dependence on the toroidal angle.

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ICRF Heating in CHS

The second phase of the ion cyclotron range of frequencies (ICRF) heating experiment in the Compact Helical System (CHS) was started at the end of October 1993 and will continue until the end of December 1994. In the first phase of the ICRF experiment (1991), we achieved successful heating results. However the increase in impurities during the RF pulse remained as a serious problem. Five new antennas were designed to reduce this effect and were installed in CHS for the second-phase high-power ICRF heating.

Suppression of impurities while maintaining good loading efficiency were key issues in the design of the Faraday Screen (FS) and the current conductor. Our antennas have carefully contoured FS and current conductors. Each strap of the FS was arranged to maintain a 1.5 cm clearance to the outermost magnetic field line plasma surface. The current conductor was also configured to keep a distance of 1.0 cm from the FS. Side guard limiters made of stainless steel were also arranged along the outermost magnetic surface. These limiters will be replaced by nonmetal limiters made of the carbon or the boron nitride if metal impurities become a serious problem.

Wall conditioning with titanium gettering is now being used, and boronization is scheduled to begin soon. This will cover surfaces of the FS and vacuum chamber with boron. Four single strap antennas were installed in the slant ports (P-ports) and the other one with a wide (~24 cm) single strap was installed in a vertically elongated position (U-port). Each antenna is center-fed from a 50-Ω coaxial line matched by a double stub tuner. The frequency is 26 MHz at $B_T \sim 1.7$ T. The transmitter power exceeds 1.5 MW. A Faraday-Cup energy analyzer is being prepared and will allow us to study the behavior of high-energy ions.

The gas puff is hydrogen minority and deuterium majority with various mixture ratios. The magnetic field strength is scanned (shot to shot) to adjust the location of the resonance layer. The radio frequency (RF) power is applied to the afterglow plasma of the ECH or neutral beam injection (NBI) heated plasma. In the case of an ECH afterglow target, a plasma with 600 J at $2 \times 10^{13} \text{ cm}^{-3}$ is sustained for 20 ms by the U-port ICRF antenna with 200 kW of radiated power for B_T around 1.7 T. The minority ratio measured by visible spectroscopy is about 10%. This value is the same as the mixture ratio of the gas puff. Similar results are obtained for the P-port antennas; however, at present, the performance of the U-port antenna is better than that of P-port antennas.

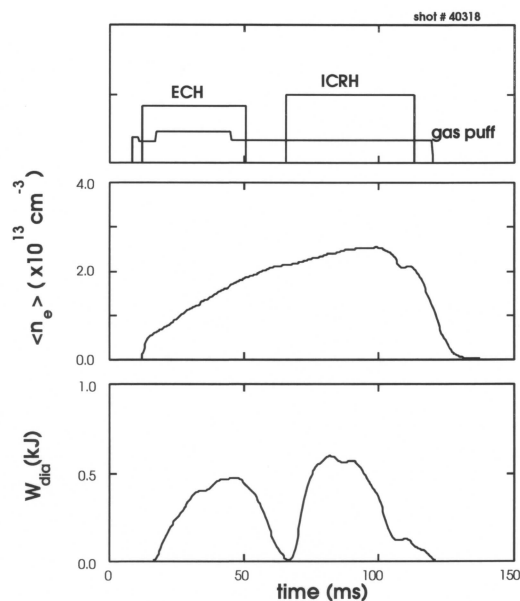


Fig. 1. Time behavior of the plasma parameters.

Figure 1 shows the time behavior of plasma parameters. RF power of 200 kW is applied after ECH is turned off. Only the U-port antenna is excited in this experiment. The stored energy increases and is sustained for about 20 ms. After 20 ms the radiation loss increases, and the stored energy decreases rapidly. Profiles of electron temperature and density measured with Thomson scattering are shown in Fig. 2. The electron temperature on the

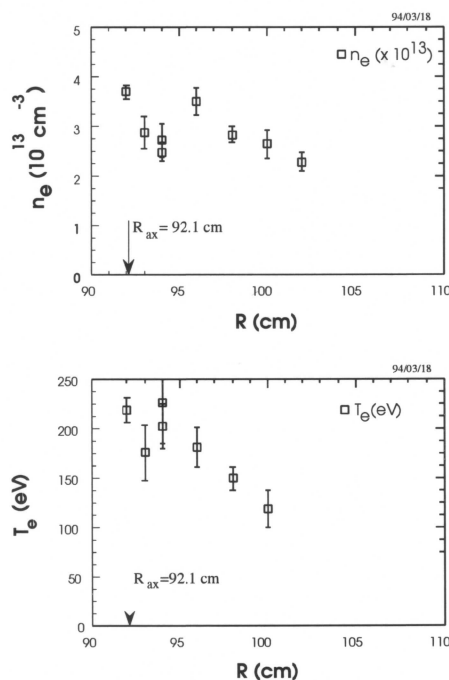


Fig. 2. Radial electron density and temperature profiles measured with Thomson scattering.

magnetic axis is about 200 eV. A two-component ion energy spectrum is obtained with the Neutral Particle energy Analyzer (NPA). Ion temperatures of the bulk and the tail components are about 190 eV and 770 eV, respectively. In addition electron heating is observed as seen in the first-phase experiments. Two-component heating is expected from the magnetic field structure.

Figure 3 shows the dependence of the stored energy and the line-averaged electron density on the magnetic field strength B_T . The maximum increase in the stored energy was 750 J for a plasma density of $2 \times 10^{13} \text{ cm}^{-3}$ with a total coupled RF power of 200 kW at B_T of about 1.7 T.

ICRF and NBI (~1 MW) combined heating has also been tried, and a small increase in the stored energy (~300 J) is observed. The minority ratio is about 30% in spite of the pure deuterium gas puffing. We are investigating methods to reduce the hydrogen content.

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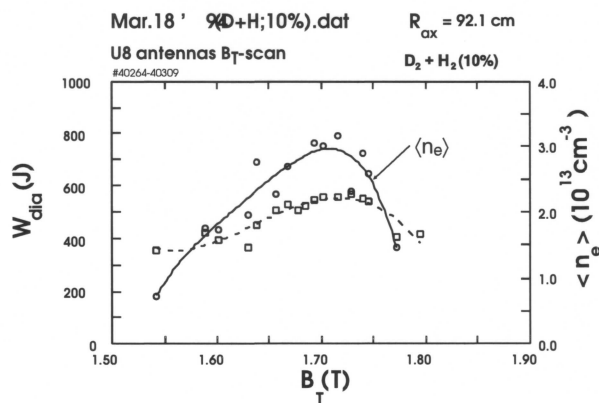


Fig. 3. Dependence of stored energy and line-averaged electron density on the magnetic field strength. The solid line with circles is the stored energy, and the dashed line with squares is the density.

Is it possible to determine plasma pressure and current density profiles in stellarators from the magnetic measurements?

Magnetic measurements to determine the shape and position of the plasma boundary, the current density, and plasma pressure profiles are widely used in modern experiments on tokamaks. Magnetic diagnostics are likely to form the basis for the plasma equilibrium control under the reactor conditions. To interpret the magnetic measurements in tokamaks, fairly accurate and fast algorithms have been developed (see, for example, [1]).

The three-dimensional (3D) nature of stellarators makes the problem of performing and interpreting the magnetic measurements extremely complicated. Even the solution of the direct equilibrium problem, strongly simplified by the assumption of the nested magnetic surfaces existing everywhere, takes about 2 orders of magnitude more time than in the case of axisymmetric magnetic traps [2,3]. That is why, among other factors, the complete measurements of the external magnetic fields in real stellarators and mathematically rigorous analysis of the magnetic data (including reconstruction of plasma pressure and current density profiles) based on 3D magnetohydrodynamic (MHD) equations seems to be unachievable in the near future. It should be remembered, however, that the problem of plasma profile reconstruction is not solved rigorously (from the mathematical point of view) even for the axisymmetric equilibria. In the axisymmetric case, a more pragmatic way of looking at this problem is used; it usually consists in considering a two-parametric set of functions, describing current density profiles, and determining those parameters which fit the experimental data.

The aim of this small notice is to call the reader's attention to some characteristic features of plasma equilibria that can be employed, in principle, for the identification of plasma profiles in stellarators. Where it is possible, I try to compare the situation to those in tokamaks.

Presently, it is commonly accepted that the magnetic measurements in stellarators are not sensitive to the plasma pressure profile. However, this statement is based mainly on the well-known analytical estimations of the change in the toroidal flux and the dipole component of the external magnetic field as well as on numerical analysis of experiments [2,3] for particular systems of magnetic loops. Notice, that for the moderate values of the total current the dipole component is also independent of the current distribution. It is well-known that for the purpose of plasma identification in tokamaks it is necessary to meas-

ure the higher (than dipole) moments of the poloidal magnetic flux.

The magnetic fields created by plasma currents in stellarators can be separated into two parts: axisymmetric and 3D. We have investigated the structure and values of the axisymmetric part of the external magnetic fields in Ref. [4]. Our analysis shows that in zero-net current regime of operation the dependence of the quadrupole component of the external magnetic field on the plasma pressure distribution for all magnetic systems considered is rather pronounced and can be utilized, in principle, for the determination of the plasma pressure profile. The dependence of the values of the other multiple harmonics on the plasma profiles increases with the poloidal number, while their values decrease. It may occur, in practice, that it is very hard to resolve them.

The problem of the identification of the current distribution differs from those in tokamaks because stellarators do not need large currents for heating. The typical problem is the determination of current density profiles for the moderate total currents (bootstrap current, currents generated by fast particles, etc.). Due to the small magnetic energy stored in these currents, they are not dangerous in themselves; but by modifying rotational transform they can trigger large-scale finite pressure instabilities. For high-beta experiments, the knowledge of current profile is of exceptional importance.

In Ref.[3] free-boundary plasma equilibria and signals from the set of magnetic diagnostic coils for the W7-AS device have been analyzed. It was shown that the diagnostic coil which significantly reduces the input of the dipole component of the external magnetic field is sensitive to the current distribution. However, the magnetic field harmonic content responsible for such effects were not investigated in the referenced paper. Early investigations [2,3] have given impetus to our work in this direction. At first, we analyzed the axisymmetric part of the external magnetic field. It was found that there is some hope of distinguishing strongly different current profiles by measuring the quadrupole component of the external magnetic field either in the case of large shear systems at high beta, or in the case of systems with an average elongation of the vacuum magnetic surfaces. Such elongation may be caused by the external quadrupole vacuum magnetic field, which is commonly used for combating the finite-beta changes in the plasma configuration, or by the special choice of modular coils (for example in W7-AS installation).

A self-consistent analysis of 3D equilibrium currents and magnetic fields in stellarators with a nearly planar geometrical axis was performed in Ref. [5]. A special semianalytical procedure has been proposed, and it was

shown that 3D fields offer much more promise for current distribution determination than axisymmetric components. In particular the input of the current terms in the change of the main harmonic of the 3D vacuum field is important up to the values of the parameter $\beta \sim \tau_j/N$, where β is the ratio of the plasma pressure to the pressure of the magnetic field, τ_j is the rotational transform created by the unidirectional current at the plasma edge, and N is the total number of field periods. At the same time, the dipole component of the external magnetic field, which is most generally employed for interpretation of the magnetic data in stellarators is a weak function of current density profile in the case of practical interest, that is, $\beta > \tau_j/A^2$. Here, τ is the total rotational transform and A is the aspect ratio. It was shown that the dependence of the external field value on the current density distribution in stellarators may be rather pronounced. This provides a way of determining the current density distribution by measuring the external 3D magnetic fields.

Finally, I shall discuss briefly the problem of the plasma boundary determination. In Ref. [6] we have investigated the problem of the influence of the plasma-induced magnetic fields on the shape and sizes of the plasma boundary. As would be expected, the plasma boundary destruction depends only weakly on the plasma pressure profiles and is essentially independent of the current density profile for the moderate total currents considered there. The axisymmetric components exert primary control over the plasma boundary. For one thing, the axisymmetric components may be larger than the 3D components generated by the plasma currents [2,5]; for another, the 3D components change quickly along the field lines and their influence on its resulting deviation is small. Among the axisymmetric components, the weakly pressure-dependent dipole component plays a dominant role because the influence of higher harmonics is more local and their amplitudes decrease with the multipolarity. The existing moderate pressure profile dependence increases as one passes from a shearless system to a system with large magnetic shear.

We analyzed [6] the problem of determination of the plasma boundary from the results of external magnetic measurements. Estimations of the accuracy of the magnetic measurements, which allow the sufficiently accurate identification of the plasma boundary by the method of field line tracing, are presented. It was shown that the requirements for the quality of the external magnetic field measurements in many cases may be less stringent than those in tokamaks. We must emphasize that this does not mean that it is equally easy to measure these fields. The most straightforward way, but evidently not the optimal one, is to use (for the measurements of the axisymmetric components of the external field) coils having a length

along the longitudinal coordinate equal to the period of the system and strongly localized in other directions. However, due to the constructional features of concrete devices it is unlikely that it is possible to accommodate such large probes in the vicinity of plasma boundary. This in turn automatically leads to the reduction in the accuracy of measurements as the amplitudes of higher harmonics decrease rapidly with the increase in the distance from the plasma boundary. A much more fruitful way, from our point of view, consists in the use of a number of local probes situated as close to the plasma boundary as possible. In so doing, the main problem obviously consists not in creating fast methods for data reduction (for this purpose, reduced equations proposed in [5] can be used or something different developed), but in understanding the value of the instrumental mistakes under real experimental conditions.

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FORMEX — A computer supported formulary

In the field of science, formulas describe — generally speaking — the functional relation between physical quantities. The particle velocity, for example, is a function of the particle energy ($v \sim E^{1/2}$), or the collision frequency is a function of the temperature ($\nu \sim T^{3/2}$). But very often formulas are used to evaluate numerical values in given units, or to prepare a plot of a physical quantity. The tedious work of evaluating several formulas many times and the trouble of adjusting the systems of units can be avoided by engaging a computer that runs through this business reliably and quickly. Commercially available spreadsheet programs are very suitable for this task. The formulary presented here has been compiled for specific needs in the field of plasma physics. It is the aim of this formulary to promptly evaluate all of the formulas after changing any of the input values and to clearly arrange the numerical results and the plot output.

The FORMEX formulary has been produced using the Excel® spreadsheet program, which is well-known and

in wide use. Some practical experience in handling Excel would be quite useful but is not required for operating the formulary. FORMEX consists essentially of a worksheet that contains a collection of 137 formulas. Some examples are shown in Table I.

All quantities necessary for the evaluation of a formula are listed next to the formula. Each input variable can be changed arbitrarily. A documentation is available to point out the derivation of the formula and reference its origin. The algorithm of how each formula performs the calculation is also displayed. A plot can be displayed to show how the evaluated quantity varies with the selected input variable. The numerical values of a complete set of the 23 input variables can be invoked by the name of an experiment (W7X, ASDEX Upgrade, LHD, ATF, JET and others). The formulary currently contains parameters for 17 experiments.

The formulary runs on the Macintosh as well as on the PC. It operates on the basis of Excel version 3.0 and any later version. Two Excel documents are necessary to run the formulary, the Excel worksheet *FORMEX* and the Excel macro sheet *FORMAK*. A *Read_me_first* instruction is also available. The operation of the formulary is menu controlled. The files are protected against faulty input and mistreatment to a large extent. To achieve this purpose, the files reside unchanged in any detail in the computer's memory. An extensive description of the FORMEX formulary has been documented in English in the IPP laboratory report IPP2/323 (January 1994). In FORMEX, German expressions are used for the formulas, the variables, and the comments. The menus and the commands that are necessary to operate FORMEX are written in English, however.

The formulary and its documentation can be copied from a diskette or transferred from a file server via the appropriate electronic net connection. Everyone on the Internet can get access to the anonymous FTP server FTP.IPPGarching.MPG.DE (user ID: *ANONYMOUS*, password: *E-Mail address*, directory: */pub/misc/formulas*), from where the files can be transferred (in binary!) without any restriction to a Macintosh or a PC. Inside IPP Garching, the *E3 Mac Server is accessible by AppleTalk connection.

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Table I: Example of FORMEX

Name of formula	Value	Name of variable	Value
Electron gyrofrequency	8.40E+10 Hz	Magnetic field	3.00 T
Ion gyrofrequency	2.29E+07 Hz	Magnetic field	3.00 T
		Ion mass	2.00
		Ion charge	1.00
Thermal ion velocity	6.92E+05 m/s	Ion temperature	5000 eV
		Ion mass	2.00
Beta total	4.474%	Magnetic field	3.00 T
		Electron temperature	5000 eV
		Electron density	1.0E+20 m ⁻³
		Ion temperature	5000 eV
		Ion density	1.0E+20 m ⁻³
Slowing down time	3.39E-02 s	Test ion energy	50000 eV
		Test ion mass	2.00
		Test ion charge	1.00
		Electron temperature	5,000 V
		Electron density	1.0E+20 m ⁻³
		Ion mass	2.00
		Ion charge	1.00
Equipartition time	1.36E-01 s	Electron temperature	5000 eV
		Ion mass	2.00
		Test ion charge	1.00
Electron-ion momentum exchange time	1.76E-03 s	Test electron energy	50000 eV
		Ion charge	1.00
		Ion density	1.0E+20 m ⁻³