Ciemat 703
Sp ISSN 614-087-X

ICRH STUDIES IN TJ-IU TORSATRON

CENTRO DE INVESTIGACIONES
ENERGETICAS, MEDIOAMBIENTALES Y TECNOLOGICAS

MADRID,1993

CLASIFICACION DOE Y DESCRIPTORES

700350
ICR HEATING
TORSATRON STELLARATOR
ANTENNAS
MHz LANGE
MHz RANGE 01-100
MHz RANGE 100-1000
THREE-DIMENSIONAL CALCULATIONS

Toda correspondencia en relación con este trabajo debe dirigirse al Servicio de Información y Documentación, Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas, Ciudad Universitaria, 28040-MADRID, ESPAÑA.

Las solicitudes de ejemplares deben dirigirse a este mismo Servicio.

Los descriptores se han seleccionado del Thesauro del DOE para describir las materias que contiene este informe con vistas a su recuperación. La catalogación se ha hecho utilizando el documento DOE/TIC-4602 (Rev. 1) Descriptive Cataloguing On-Line, y la clasificación de acuerdo con el documento DOE/TIC.4584-R7 Subject Categories and Scope publicados por el Office of Scientific and Technical Information del Departamento de Energía de los Estados Unidos.

Este trabajo se ha recibido para su impresión en Septiembre de 1.992

Depósito Legal nº M-479-1993
ISBN 84-7834-174-9
ISSN 614-087-X
NIPO solicitado

IMPRIME CIEMAT

INDEX

(1) KhFTI, Kharkov, Ukraine

(2) Asociación Euratom/CIEMAT, Madrid, Spain.

Plasma heating studies in TJ-IU using Fast Magnetosonic Waves in frequency range much greater than ω_{ci}

Dyakov V.E., Longinov A.V.
KhFTI(Kharkov, Ukraine)

Castejón F., Ascasibar E. and Rodríguez R. L.
Asociación Euratom/CIEMAT(Madrid, Spain)

INTRODUCTION

The electron heating by the application of fast magnetosonic waves (FW) in the $\omega >> \omega_{ci}$ frequency range has been demonstrated experimentally in stellarators [1,2]. However, theoretical study of this topic remains difficult since 3-D nonuniformity avoids the solution of wave equations. Such a nonuniformity pattern may modify considerably the feature of FW excitation, propagation and absorption in stellarators as compared with tokamaks. In particular, as it is shown in [3], the 3-D nonuniformity changes strongly the spectrum over longitudinal wave numbers $N_{||}=k_{||}c/\omega$, $k_{||}=\mathbf{k.B}/B$ compared with the antenna spectrum. This report studies some properties of this technique under the conditions of the TJ-IU torsatron [4] using the ray tracing code presented in [3].

RAY TRACING

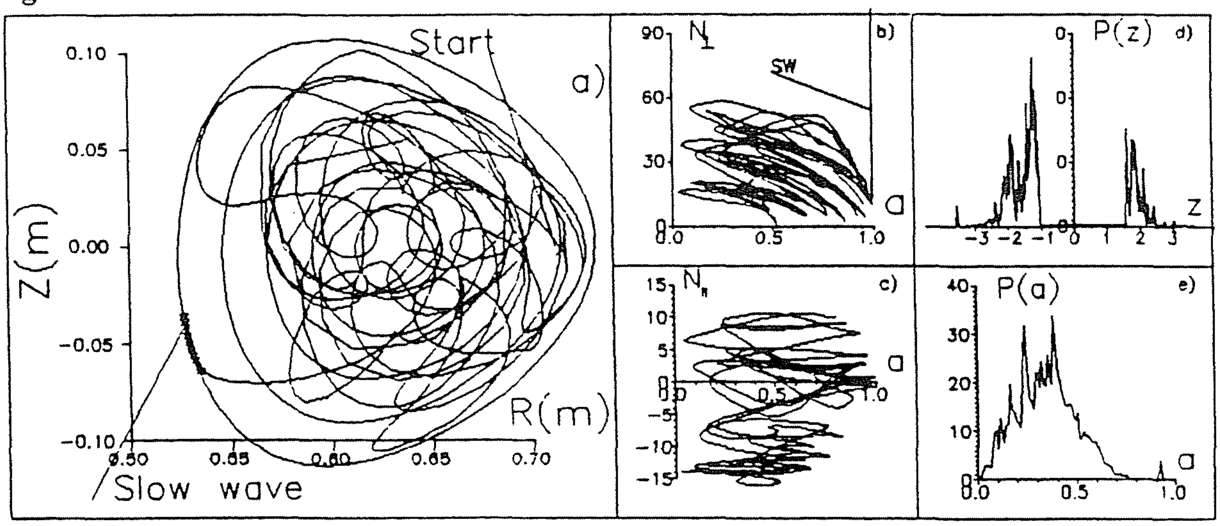
Flux coordinates (α,θ,ξ) are used to calculate the ray trajectories, where α is the label of the magnetic surface and θ, ξ are the poloidal and toroidal angles. The magnetic field and the flux surfaces have been calculated using VMEC code [5]. Standard parameters of the TJ-IU torsatron [4] have been used: the magnetic field on axis is B=0.5 T and parabolic density and temperature profiles have been considered: $n(\alpha) = n(0)(1-\alpha^2)$, $T(\alpha) = T(0)(1-\alpha^2)$. The FW antenna position is $\xi=30^o$ (see [6]), and we have taken $\beta\approx0.3$ %. The main conclusions drawn in this report are based on the analysis of about one hundred rays. Typical trajectories are given below for two regimes: the low frequency regime (f=50 MHz) and the high frequency one (f=150 MHz). Note that in the low frequency regime wave scattering due to nonuniformity along the magnetic field could modify the considered feature because the WKB approximation does not take this fact into account. The absorption ($Q=\mathrm{Im}\int\mathbf{k.dr}$) due to electron Cherenkov resonance as well as the spectral density of the absorbed power $P(\alpha,z)$ have been calculated, where $z=\omega/k_{||}v_{te}=v_{res}/v_{te}$ (v_{res} is the resonant electron velocity along the magnetic field). The spectral power density ($P(z)=\int P(\alpha,z)\,d\alpha$) and the power deposition profile ($P(\alpha)=\int P(\alpha,z)\,dz$) are given below.

LOW FREQUENCY REGIME (f=50 MHz)

Fig.1a shows the typical projections of the ray trajectory on the $\xi=30^o$ plasma cross-section. The longitudinal $N_{||}$ and transverse $N_\perp$ refractive indices are given along the trajectory versus the magnetic surface coordinate α. Figs.1d,e show the power deposition profile $P(\alpha)$ and the spectral density of the power deposition P(z). The ray path fills the cross-section of the plasma due to refraction and multiple scattering. 3-D nonuniformity of plasma and magnetic field entails the strong evolution of $N_{||}$. This is specially clear in the edge region, where FW has a small $N_{||} < N_{cr} \approx 1$, where N_{cr} is the Golant-Stix accessibility criterion [7]. In this case FW converts into the slow wave (SW) which is totally absorbed in the LH resonance at the plasma edge, so that a small portion of FW power is absorbed in the plasma centre. This effect may lower the electron heating efficiency. However this extremely disadvantageous effect is strongly weakened by the incomplete FW-SW conversion because of the strong nonuniformity (the WKB approximation breaks in this region). On the other hand, the FW-SW conversion may be sufficiently intense due to strong nonuniformity even at $N_{||} \geq N_{cr}$. Therefore, the lowering of the heating efficiency by FW-SW conversion due to this effect cannot be determined in the present frame. Another important consequence of strong change of $N_{||}$ along the ray path is that $|N_{||}|$ value may exceed considerably its initial value, thus the conditions of absorption by thermal electrons may be achieved, which enhances the absorption and diminishes the probability of forming superthermal electrons.

As it is shown in Fig.1d, where the spectral density of energy deposition is given, the power is absorbed by particles with sufficiently low z's up to $|z|=1.5$. Though the initial value $N_{||}$ is positive, for a given ray the electron absorption with $z<0$ ($N_{||}<0$) is even larger than that with $z>0$ (The ratio is about 1.8). This indicates the possibility of driving current, which is not related to the antenna spectrum. As it can be seen in Fig.1e, the absorption occurs in the centre of the plasma, for a<0.6. However, the power deposition profile is not peaked because the maximum is shifted considerably off axis ($\alpha=0.4$). This effect is common for all rays and is due to the fact that the paths have strong slowing-down in the region $0.3< \alpha <0.6$.

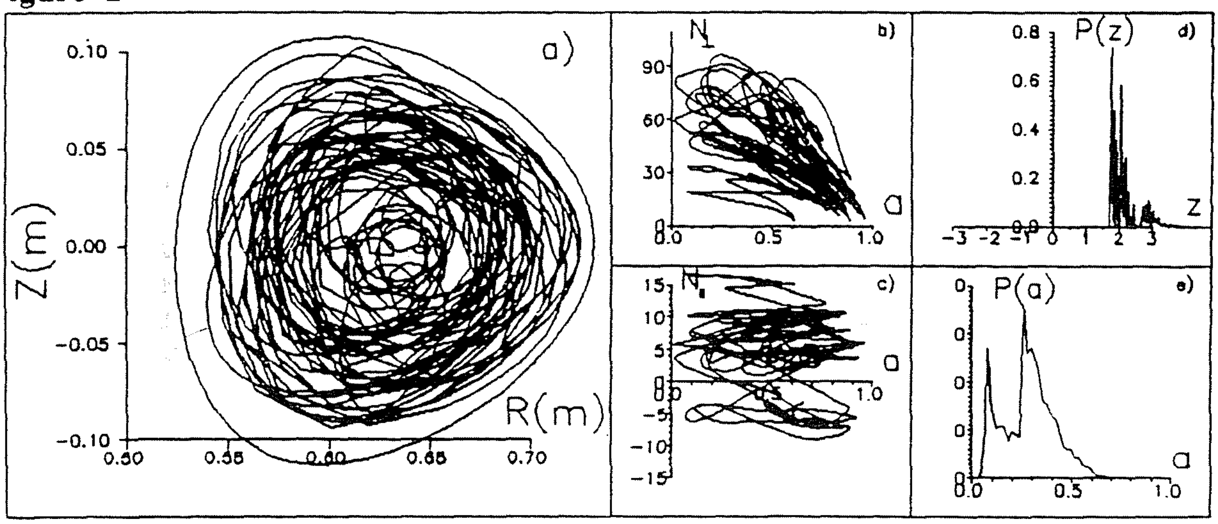
Figure 1



HIGH FREQUENCY REGIME (f=150 MHz)

The propagation of FW in the TJ-IU device is qualitatively similar to that in the low frequency regime. The most essential differences are the following: a) the possibility of FW-SW conversion near the edge is decreased considerably. However one cannot draw the only conclusion on dismissing this unfavourable effect, because the conversion will be stronger in the high frequency regime; b) energy deposition profile becomes more peaked. As an example we give the trajectory for parameters similar to the former case but T(0)=0.3 Kev, $n(0)=10^{13}$ cm^{-3} (β is the same), $\theta=0.4$. Fig.2 shows a strong variation of $N_{||}$ in this regime. However, in contrast to the preceding case, the appearing waves with $N_{\|}<0$ do not affect the spectral density P(z). The spectrum P(z) is practically asymmetric, the absorption being due to particles with $z\geq1.5$ (see Fig.2d). One sees in Fig.2e that absorption also occurs near the plasma edge. For equal β, the high temperature regime gives more peaked power deposition profile at both, low and high frequencies.

Figure 2



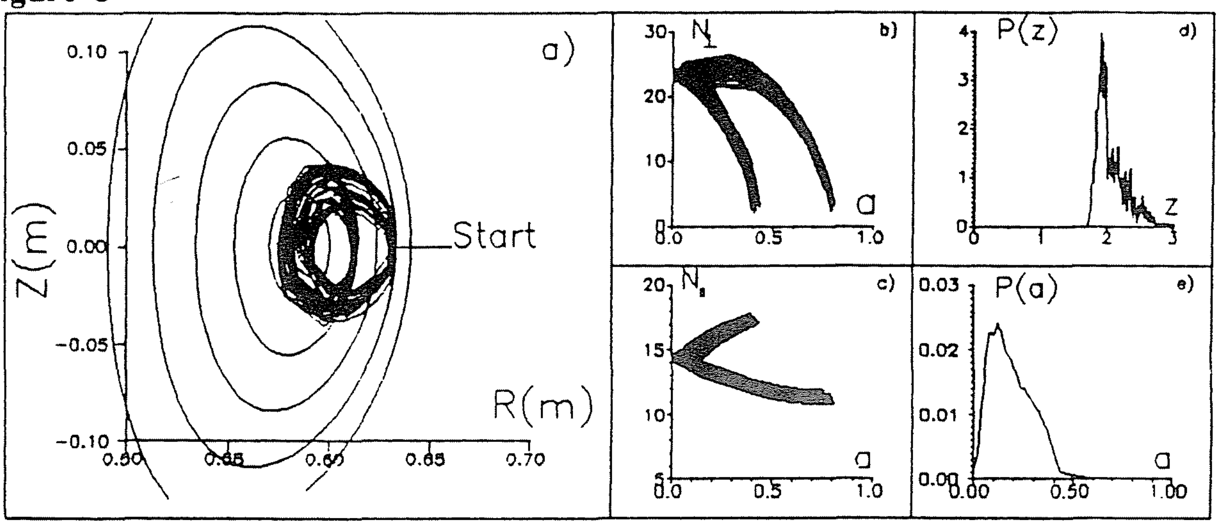
REGIME OF LOCALIZED MODES

Special solutions of the wave equation may exist in TJ-IU. Such solutions are characterized by the fact that $N_{\|}$, $N_{\perp}$ and ray coordinates are periodic functions of the toroidal angle ξ, with period $2\pi/m$ (m is the number of helical field periods). In this modes the broadening of the $N_{\|}$ spectrum caused by diffusion is less important and the spectrum becomes more localized and has a more correlated dependence on the radius. We will call these solutions localized modes. As an example we give the results for a ray describing the localized mode. All ray parameters but the starting point.correspond to those in Fig.1 Solutions corresponding to a localized mode occur for the launching point $\xi=\pi/12$, $\theta=0^{o}$. As one sees from Fig.3 the ray path is located in a bounded region of the plasma, in contrast to preceding cases. The periodic dependence of $N_{\|}(\alpha)$ and $N_{\perp}(\alpha)$ is observed in Fig.3b,c. The main properties of using this modes for plasma heating are: a) large value of $N_{\|}$ at the plasma edge ($N_{\|}\approx10$) what excludes FW-SW conversion at $N_{\|}< N_{cr}$ as well as the conversion due to mode coupling at $N_{\|}> N_{cr}$ decreases strongly; b) a higher slowing-down with respect to the conventional case is achieved, the maximum slowing-down occurring in the centre of the plasma. It leads to a peaked power deposition profile as well as to the FW absorption enhancement. The latter circumstance is important for the performance of the coupling system, under conditions when eigenmodes excitation may manifest. Fig.3d shows that the absorption with lower z occurs and a more peaked power deposition profile is achieved (Fig.3e), due to the increase of $N_{\|}$.

Calculation for higher β plasmas shows that a stronger damping happens and causes: a) a probability of edge power deposition due to mode conversion; b) the power deposition profile becomes more peaked; c) correlation of the $N_{\|}$ spectrum and antenna spectrum improves. Calculations for higher frequencies, f > 200 MHz show that such regimes perhaps cannot be used, at least in plasmas with $\beta<0.4\%$, because the $N_{||}$ lowering leads to a strong decreasing in damping.

The analysis of this paper is based on a linear approximation, disregarding the evolution of the distribution function under the action of RF field. For large powers coupled to the plasma, when a tail appears in the electron distribution function, the enhanced absorption may occur also in lower b plasmas. This effect is important at the initial stage because it allows to approach the high β regime in the end. However, this regime may be studied only by ray tracing techniques and solving the Fokker-Planck equation.

Figure 3



CONCLUSIONS

1. When the FW propagates in the TJ-1U torsatron, in the frequency range f=50 to 150 MHz, a strong broadening of the $N_{||}$ spectrum occurs (spectrum symmetrization and attainment of high $N_{||}$ values).

2. A considerable efficiency lowering for this heating technique is possible due to FW-SW conversion at the plasma edge.

3. Existence of localized modes is established. Their application provides a peaked power deposition profile and dismisses the negative effects connected with FW-SW conversion.

REFERENCES

1. Burchenko P. Ya.,Vasilenko E D., et al. Preprint **289**, 103, Khfti, Kharkov, (1966)
2. Okamura S., Fujiwara M., Hosokawa M., Ida K., Idei. H., et al. Proceedings of the 16th EPS Conference on Plasma Physics and Controlled Fusion, part II, 571. Venice, 1990.
3. Dyakov V.E., Longinov A.V., Pavlov S.S. IAEA Technical Commitee Meeting 7th Stellarator Workshop. Kharkov, USSR, p. 223. (1991)
4. E. Ascasíbar, et al. Fusion Technology 1990. North-Holland, vol 1, 577 (1991)
5. Hirshman S.P., Rij W.I., Merkel P. Comp.Commun.**43**, 143 (1986)
6. Longinov A.V. In this conference.
7. Golant V.E. Sov.Phys. Tech. Phys. **12**, 2492 (1971).

Plasma heating in TJ-I U torsatron by fast waves in the ICR range

A.V. Longinov, S.S. Pavlov
KhFTI, Kharkov. Ukraine

F. Castejón, L. Rodriguez, E. Ascasíbar
EURATOM-CIEMAT, Madrid. Spain.

1. Introduction

This report analyzes various plasma heating regimes using fast wave (FW) excitation in the ICRF range. Most promising scenarios for plasma production and heating in the TJ-I U torsatron [1] are found. The analysis is based on the 1-D model of excitation, propagation and absorption of electromagnetic waves that was applied previously for a similar aim to the U-2M stellarator [2].

In contrast to large systems, in the small TJ-I U stellarator, at the ICRF range, the vacuum wavelength exceeds considerably the plasma column radius, a_p ($B_0 = 0.5$ T, $a_p \approx 10$ cm). Under these conditions the density and magnetic field gradients enhance considerably the coupling between fast (FW) and slow (SW) waves outside conversion zones. Tunnelling penetration of waves through opacity zones at the plasma edge and near FW-SW conversion zones will also be enhanced.

2. Results

In this situation some heating scenarios that are well studied in connection with large devices may appear to be unacceptable. As an example we give the results of numerical calculations for plasma heating in TJ-I U at the $\omega = 2\omega_{ci}$ resonance:

Fig.1 shows the field components, E_z, E_φ and E_r (V/cm), energy dissipation due to ions, D_i, and electrons, D_e, (W/cm^3) and total power flux times $2\pi R$, P, (W/cm) versus major radius R, for the model with longitudinal slowing-down, $N_{||} = 20$, in a D-plasma with parameters: $n_e(0) = 5 \times 10^{12}$ cm^{-3}, $T_i = 800$ eV, $T_e = 400$ eV, $B_0 = 0.5$ T. As can be seen in this figure the main E_z component of the FW in the plasma interior exceeds considerably that on the current layer. This corresponds to the excitation in a plasma of almost resonant toroidal mode. In spite of that, the quality factor of the current layer, $Q = P_r/P_a$, (being P_r and P_a the reactive and active energy fluxes, respectively, on the current layer) for this toroidal mode is rather high (Q=92). The intensive SW excitation at the plasma edge from the inner side of the torus is the main unfavourable effect. This is indicated by E_r component oscillations and the enhancement of the longitudinal component, E_φ, in this region. The SW generation is due to FW-SW coupling caused by the plasma density non-uniformity. As a result, 90% of power coupled to plasma will be deposited at the plasma edge due to electron Cherenkov absorption. This fact can be seen from the behaviour of dissipation, D_e, and of the total energy flux, P, in this region.

In what follows we consider most promising heating scenarios, exhibiting their possibilities by excitation of separate toroidal modes. In all scenarios FW has been excited from the outer side of the torus in the plasma with parameters: $n_e(0) = 5 \times 10^{12}$ cm^{-3}, $T_i = 800$ eV, $T_e = 0.5\ T_i$, $B_0 = 0.5$ T. The B(R) dependence has been fixed as the corresponding to the $\varphi = 30°$ cross-section. This angle corresponds to the FW antenna location [3].

2.1. The $\omega < \omega_{ci}$ regime.

Fig.2 shows the calculations results for the toroidal mode with $N_{||} = 90$ slowing-down and frequency f = 5.6 MHz, in an H plasma. This regime is characterized by the FW excitation in the region where $\omega < \omega_{ci}$ and by the presence of the $\omega = \omega_{ci}$ resonance zone on the outer side of the torus and the Alfven resonance zone on the inner side. Due to high slowing-down, ($N_{||} = 90$), the FW cannot propagate in the whole plasma ($N_{\perp}^2 < 0$), as can be deduced from the exponential decreasing of the E_z component when it propagates into the plasma .In spite of this fact the antenna quality factor for such a mode is not very high (Q=110). However, in this case strong density non-uniformity also couples FW and Alfven SW efficiently despite of the FW excitation from the outer side of the torus. The enhancement of E_r and E_φ field components in the region $R \approx 60$ cm points to this end. As a result one heats ions (see D_i profile) whereas electrons are heated at the column centre (see D_e profile). Heating ions with sufficiently large longitudinal velocities, $v_{||}$, is an important feature. It weakens fast ion losses on banana and superbanana trajectories as can be deduced from the D_i profile asymmetry with respect to the $\omega = \omega_{ci}$ resonance point. Edge heating connected with SW generation is relatively weak . Less then 5% of the coupled power is deposited at the edge. If density is considerably decreased (one order of magnitude) the D_e profile is somewhat shifted relative to the centre (approximately over one third of the radius) and the quality factor remains approximately the same. Such a weak dependence on density is rather important for application of this regime at the plasma production stage in TJ-I U.

2.2. The $\omega = \omega_{ci}$ regime for a He minority in D-plasma or H-plasma.

This regime is of interest only at high concentrations of minority ions. Fig.3 shows calculation results for a He^3 minority heating regime (n_{He}/n_D=20%, $T_{He} = T_i = 800$ eV) in a D-plasma when one excites FW with $N_{||} = 20$ and frequency f = 4.1 MHz. One sees from the behaviour of the main FW field component , E_z, that here the condition for FW propagation in the plasma interior holds ($N_{\perp}^2 > 0$).The relatively high helium concentration exhibits the FW-SW coupling in the zone between the cyclotron resonances $\omega = \omega_{cHe}$ and $\omega = \omega_{cD}$. This is indicated by the E_r field growth in this zone. The SW affects strongly the FW polarization in the $\omega = \omega_{cD}$ resonance region. This causes the absorption due to bulk ions to exceed even one due to He^3 minority ions. Here, as in the previous case, a considerable asymmetry of absorption relative to the resonance point is found, being this fact favourable for confinement of fast particles. The quality factor of the antenna array is approximately the same as in the preceding regime (Q=110). This scenario does not practically contain the absorption at the plasma edge (<2%). The preferential heating of bulk ions is also an important advantage. This weakens the limitations on the power level coupled to plasma that are common for techniques with minorities [4] . This scenario is one of the most promising for bulk ion heating in TJ-I U.
Similar physical picture also occurs if one uses heating regimes with He minority in H-plasma. However the large distance between $\omega=\omega_{cHe}$ and $\omega=\omega_{cH}$ resonances leads to a less localized energy deposition profile.

2.3. Regimes with FW-SW conversion.

Under conditions of TJ-I U when the FW is excited from the weak magnetic field side one may accomplish regimes with FW-SW conversion and with the subsequent absorption by bulk ions and minority ions. SW absorption cuts off the tails of the distribution function of resonant particles. This is important from the point of view of enhancing power coupled to plasma and heating bulk ions, and of improving confinement of resonant particles. Below we consider two such regimes:

2.3.1. The $\omega = \omega_{ci}$ regime for He^3 minority in D-H plasmas.

Fig.4 shows calculation results of the heating scenario with He^3 minority (n_{He}/n_D = 5%, $T_{He} = T_i$ = 800 eV) in D-H plasma (n_H/n_D =50%, $T_H = T_i$) when the FW is excited with $N_{||}$ = 20 and the frequency is f = 4.1 MHz. The excited field behaviour , E_z, corresponds to the FW propagating in plasma ($N_\perp^2$ >0). However in this case, near the D-H ion-ion hybrid resonance region (R=70 cm), a strong generation of SW occurs and propagates into the plasma interior, being totally absorbed by helium minority ions. The behaviour of the kinetic flux shown in Fig.4 points to this effect. Besides, in contrast to the preceding regime, the absorption of D ions is insignificant. The electron absorption at the plasma edge is also absent, in fact. Apart from cutting tails of the distribution function of resonant particles the main advantage of this scenario is the low quality factor values (Q=13). Therefore this technique may become the most effective from the point of view of attaining high efficiency of RF power coupling to plasma.

2.3.2. The $\omega = \omega_{ci}$ regime for deuterons in D-H plasmas.

The previous scenario may also be used without the $H_e{}^3$ minority. Fig.5 shows calculation results of the D-H plasma heating regime (n_H/n_D = 50%, $T_H = T_i$ = 800 eV) with FW excitation with $N_{||}$ = 20 and frequency f = 3.75 MHz. One sees from Fig.5 that the dependencies of field components, fluxes and dissipations are similar to the ones of the previous regime. However in this case SW may achieve the cyclotron resonance zone for deuterons, where it will be absorbed. As in the preceding case a considerable asymmetry in absorption relative to the cyclotron resonance point appears, as well as, consequently, the reduction of fast ion losses. This scenario is also described by the rather low quality factor (Q=19).

It should be noted that for both scenarios with FW-SW conversion the 3D non-uniformity effect, that is not taken into account in these calculations, will make weak changes in the conversion efficiency. However due to the strong influence of the 3D non-uniformity on the SW propagation the picture of SW absorption may be changed strongly. This is specially important for the second regime because of the large distance between conversion and absorption regions.

3. Conclusions

The following conclusions can be drawn for TJ-I U conditions :

- Considerable edge energy deposition might occur and it must be taken into account while choosing scenarios and their parameters.
- Efficient application of FW-SW conversion is possible if FW is excited from the inner side of the torus.
- It is possible to accomplish regimes with electron or ion heating as well as simultaneous electron and ion heating.

References

1. E. Ascasíbar, L. Almoguera, J. Alonso, J. Botija, J. Moreno, A. P. Navarro, M. A. Ochando, A. Perea, J. Sánchez. Fusion Technology 1990. North-Holland, vol 1, 577 (1991)

2. Longinov A.V., Pavlov S.S., Proc. Eighth International Workshop on Stellarators. Kharkov (URSS), May 1991, p. 231.

3. Kolosenko E.I., Longinov A.V., Rodríguez R. L., Ascasibar E., Castejón F. "Antenna System For FW and IBW Excitation in the TJ-1U Torsatron": This conference.

4. Longinov A.V., Stepanov K.N., Proc. All-Union Meeting. Gorky, 1982. Inst. Prikl. Fiz. AN SSSR (1983), p.105.

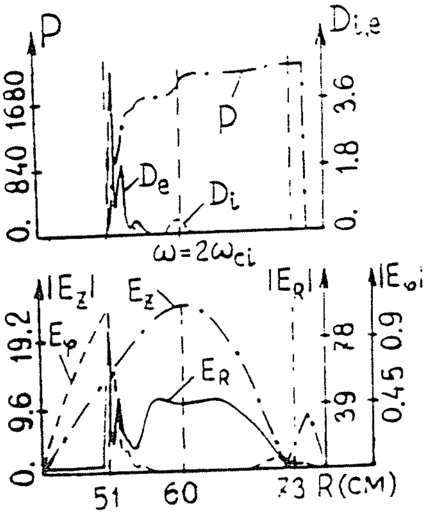


Fig. 1

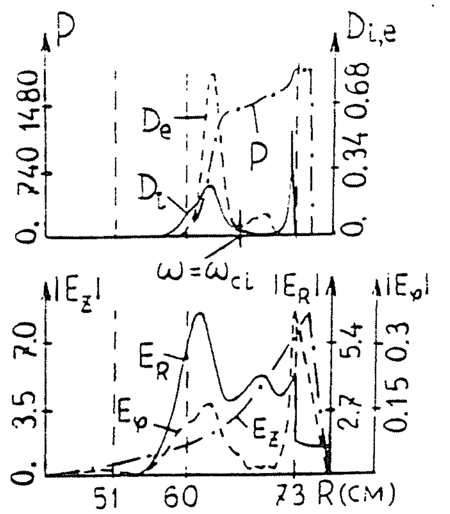


Fig. 2

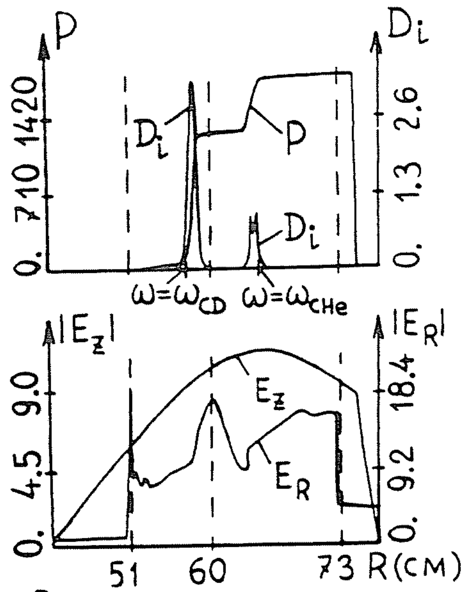


Fig. 3

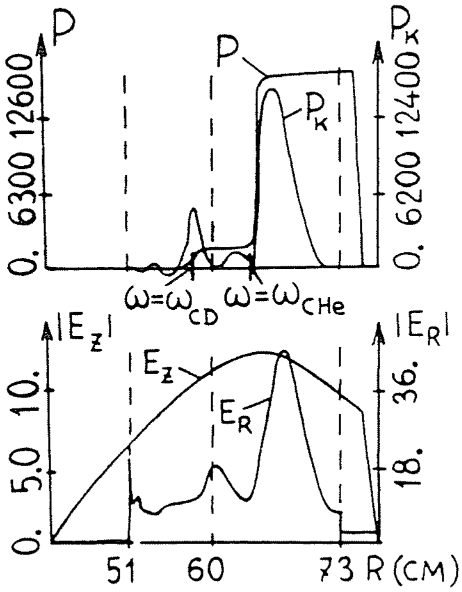


Fig. 4

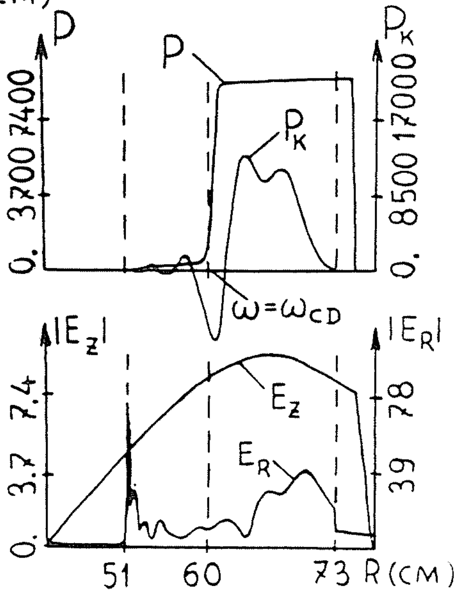


Fig. 5

Antenna System For FW and IBW Excitation in the TJ-1U Torsatron

Kolosenko E.I., Longinov A.V.(KhFTI, Kharkov, Ukraine)
Rodríguez R. L., Ascasibar E., Castejón F. (CIEMAT, Madrid, Spain)

Introduction

An antenna array for producing and heating plasma in TJ-1U torsatron has been developed [1] that couples RF power to plasma in $\omega \approx \omega_{ci}$ and $\omega >> \omega_{ci}$ frequency ranges. The main characteristic of such an array is that it can be used in different regimes allowing a broad frequency range including those for :

-Slow wave (SW) excitation in the $\omega < \omega_{ci}$ (2÷7 MHz) and $\omega \leq n\omega_{ci}$ (f=6÷30 MHz) ranges;

-Fast mode Alfven wave excitation ($\omega < \omega_{ci}$) or fast magnetosonic wave excitation in the $\omega \approx \omega_{ci}$ (2.5÷ 7.5 MHz) and $\omega >> \omega_{ci}$ (20 ÷150 MHz) ranges.

In figure 1 a general view of the antenna array location on the TJ-1U device (Major radius : R=0.6 m, minor plasma radius : a_p= 0.1 m, number of periods : M=6, number of helical coils : l=1) is shown.

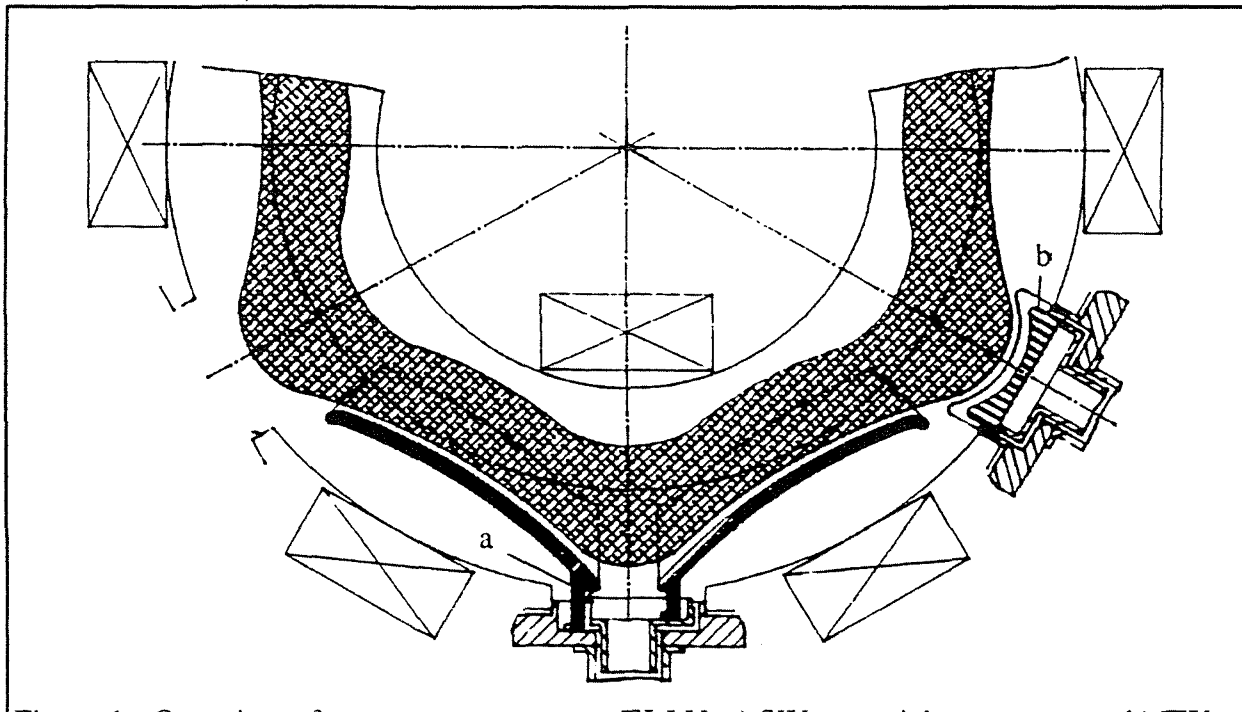


Figure 1 : Overview of antennas on torsatron TJ-I U. a) SW potential type antenna. b) FW or SW current type antenna.

Following this scheme two antennas located in adjacent horizontal ports of 261 mm inner diameter can radiate simultaneously. This enables us to choose the working regime : we can apply two different regimes (scenarii) simultaneously or applying only one we can control the oscillation spectrum excited in the plasma. In particular, we can generated some heating scenarii, or cancel the bootstrap current by driven currents.

Two types of antennas are provided : Fast wave (FW) and slow wave (SW) antennas.

FW antenna.

The FW antenna is a "fir-tree" type antenna [2]. Such an array has a low wave resistance that simplifies the electric strength problem.

Current layers

The antenna current surface is built in two layers (Fig.2a) to obtain a more efficient use of the window section in which the antenna is located. Two types of current layers are designed : Long wave (Fig.2b) and short wave (Fig.2c) ones. The current layer of the first type should be used mainly in the low frequency range.

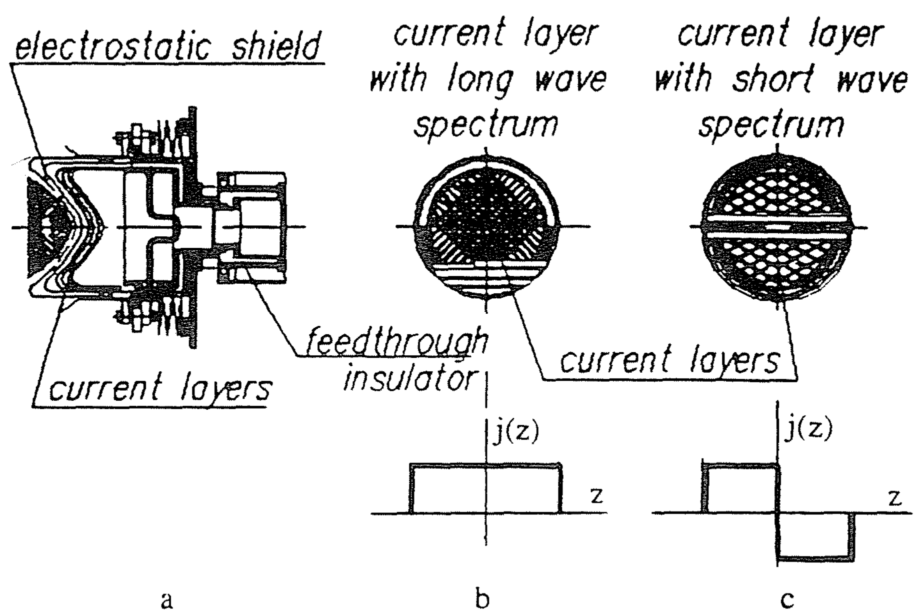


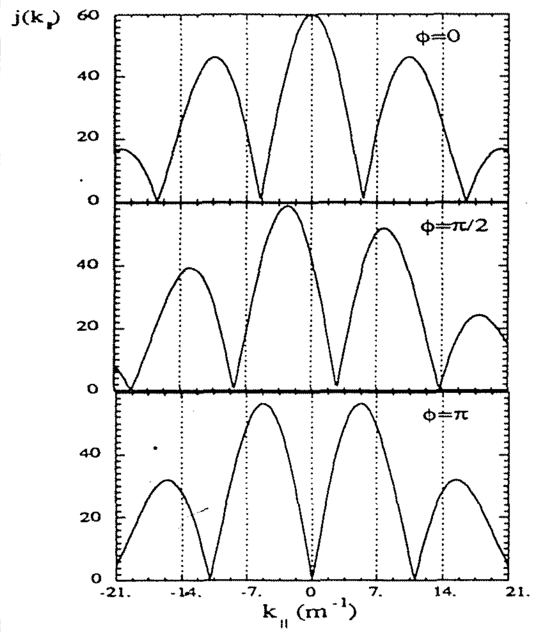
Figure 2 : Current type antennas

The current layer of the second type have to be used only in the high frequency range (f≈100÷150 MHz) to excite waves with sufficient slowing-down (N ≈10).

The current layer is placed under a double electrostatic shield, which surface facing plasma is covered with titanium nitride. The current layer is fed through a low wave coaxial line with a feedtrough insulator. These elements are common for all antenna types and one may transform one type to another by changing the current layer and the shield. A good adjustment of the antenna location with respect to the plasma surface is obtained using a bellow connection (up to the total extraction of the antenna out of the toroidal chamber.)

Spectrum emission control

To obtain different optimized heating scenarii, we consider the possibility of controling the spectrum direction following longitudinal wave numbers excited fy FW. For instance, an Alfven wave resonance mode needs a quite high slowing-down ($N_{||}$ ≈ 50÷120). Furthermore, to obtain a regime with current generation is necessary to use an asymmetrical spectrum.



f=2.5 MHz ($\omega<\omega_{ci}$)
Near xxx xxx $N_{\|}$
-200 -100

f=7.5 MHz ($\omega\sim\omega_c$)
Near xxxxxxxxx $N_{\|}$
-60 -30

f=50. MHz ($\omega>>\omega_{ci}$)
Near xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxx $N_{\|}$
Far xxxxxxxxxxxxxxx
-20 -10

f=150. MHz ($\omega>>\omega_{ci}$)
Near xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxx$N_{\|}$
Far xxxxxxxxxxxxxxxx
-6 -3

Figure 3 : Spectrum intensity using two FW antenna for three different phase shifts between them. xxx are working areas for antenna position related to the plasma.

To change spectra in our antenna system, two variing parameters can be used : In one case we vary the phase shift between currents in two antennas closed each to the other, and in another case we move the antenna near to the plasma edge.

In figure 3, the spectrum of the excited current on the antenna surface is shown for three different phase shifts. We can see from figure 3 that a big value of ratio of distance between antennas and antenna width produces a low sensitive to phase change spectrum in the short wave region. For this reason, the obtention of an asymmetrical spectrum (with a strong radiation direction) keeps difficult. Because of the possibility of moving antenna in the plasma edge, we can improve the radiation direction. Actually, since partial power radiated to the plasma is $P_k=j_k^2R_k$, where R_k is the plasma impedance for the k-th harmonic, when we take away antenna from plasma we obtain a strong decreasing of R_k for short wave harmonic. In this case spectrum into the plasma will be defined by long wave harmonics, with an improved asymmetry in the spectrum (in the radiating direction) that, as is shown in figure 3 can be high enough.

SW antenna.

Two types of SW antennas have been developed : Current type antenna and potential type antenna. The current type antenna is similar to the FW antenna, the only difference being the shield conductors and the current layer is turned 90° [3].

The potential type antenna is designed according to a "slot in the shield" scheme [4]. Its main advantage over the current type antenna is the considerably larger radiating surface ($\approx$10 times) and, consequently, a larger power input. Nevertheless its restricted displacement range with respect to the plasma surface presents a disadvantage.

Tuner.

A tuner (see Fig. 4) is provided to compensate the reactive component of the antenna impedance and to couple the antenna with the feeder in the broad range of frequencies (2.5÷150 MHz). It includes a set of circuit capacitors (an array of high voltage ceramic capacitors) as well as an adjustable inductor made in the form of a coaxial resonator with a plunger. An adjustable inductance is necessary to compensate the reactance of the potential type antenna as well as for tuning in frequency the current type antennas. Adjustment with the feeder is accomplished by two variable vacuum capacitors switched in series. The remote handling control and the antenna position adjustment are located at the tuner stand, as well as the dummy load that may be switched into the antenna circuit to decrease the effect of eigenmodes resonance excitation on working tuner.

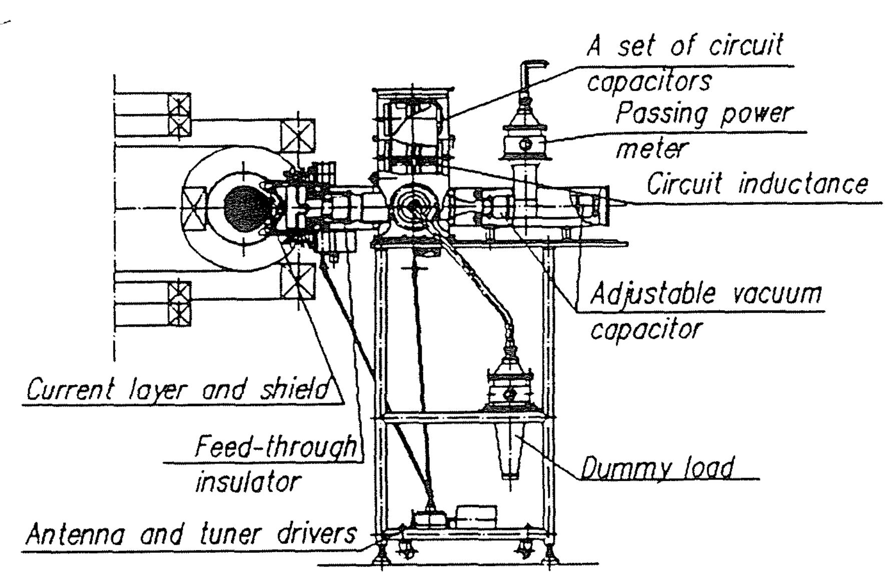


Figure 4 : General view of antenna with tuner

The preliminary analysis shows that with such an antenna array one may couple to the plasma of the TJ-1U device the RF power of P > 0.5 MW for FW antennas and P≈200÷300 kW for SW antennas.

References

1-1. E. Ascasíbar, L. Almoguera, J. Alonso, J. Botija, J. Moreno, A. P. Navarro, M. A. Ochando, A. Perea, J. Sánchez. Fusion Technology 1990. North-Holland, vol 1, 577 (1991).

2-A.V. Longinov, E.I. Kolosenko, G.A. Miroshinichenko et al. 13th Conf. on Contr. Fusion and Plasma Physics, Schliersee 1986, II, 201 (1986).

3-M. Ono et al. "Ion Berstein wave heating experiments on PLT". 11th Proc. Kyoto-(1986). IAEA-CN-47/F-I-3.

4-А.В.Лонгинов. Жур. Техн. Физики.. Том XXLII в 8 ,стр 15. (A.V. Longinov. "Electromagnetic wave exitation using longitudinal electric fields". Journal of Technical Physics. Vol XLII, № 8, p.1591.(1972).

CIEMAT-703

Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas.
Instituto de Investigación Básica. Madrid.-

"Estudios de ICRH en el torsatron TJ-IU."

CASTEJON, F., y otros (1993) 12 pp., 4 figs., 11 refs.

En este trabajo se presentan los estudios preliminares de calentamiento a la frecuencia ciclotrónica Iónica (ICRH) realizados para el torsatrón TJ-IU, en el rango de frecuencias f=3 - 150 MHz. Este amplio rango implica el uso de dos modelos teóricos diferentes. El primero de ellos es válido para alta frecuencia, donde la aproximación WKB es aplicable, mientras que el segundo resuelva la ecuación de onda completa en una dimensión.

Los cálculos para alta frecuencia se han realizado mediante un código de trazado de rayos que tiene en cuenta la geometría tridimensional del plasma y del campo magnético. Los resultados obtenidos mediante este modelo se presentan en el primer artículo de este informe. Los más importantes son el criterio para evitar el acoplamiento de la Onda Rápida (FW) con la Onda Lenta (SW) en la Resonancia Híbrida Inferior cerca del borde del plasma, y la existencia de los llamados Modos Localizados.

En el rango de baja frecuencia, la longitud de onda es del orden de magnitud del tamaño del plasma, lo cual hace que la aproximación WKB no sea válida. En este caso se usa un modelo unidimensional para resolver la ecuación de onda, que desprecia los efectos toroidales. Mediante este modelo se estudian los principales regímenes aptos para el calentamiento, los cuales se presentan en el segundo trabajo. Los estudios se han realizado para plasmas de hidrógeno, de deuterio o mixtos con o sin minoría

CIEMAT-703

Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas.
Instituto de Investigación Básica. Madrid.-

"Estudios de ICRH en el torsatron TJ-IU."

CASTEJON, F., y otros (1993) 12 pp., 4 figs., 11 refs.

En este trabajo se presentan los estudios preliminares de calentamiento a la frecuencia ciclotrónica Iónica (ICRH) realizados para el torsatrón TJ-IU, en el rango de frecuencias f=3 - 150 MHz. Este amplio rango implica el uso de dos modelos teóricos diferentes. El primero de ellos es válido para alta frecuencia, donde la aproximación WKB es aplicable, mientras que el segundo resuelva la ecuación de onda completa en una dimensión.

Los cálculos para alta frecuencia se han realizado mediante un código de trazado de rayos que tiene en cuenta la geometría tridimensional del plasma y del campo magnético. Los resultados obtenidos mediante este modelo se presentan en el primer artículo de este informe. Los más importantes son el criterio para evitar el acoplamiento de la Onda Rápida (FW) con la Onda Lenta (SW) en la Resonancia Híbrida Inferior cerca del borde del plasma, y la existencia de los llamados Modos Localizados.

En el rango de baja frecuencia, la longitud de onda es del orden de magnitud del tamaño del plasma, lo cual hace que la aproximación WKB no sea válida. En este caso se usa un modelo unidimensional para resolver la ecuación de onda, que desprecia los efectos toroidales. Mediante este modelo se estudian los principales regímenes aptos para el calentamiento, los cuales se presentan en el segundo trabajo. Los estudios se han realizado para plasmas de hidrógeno, de deuterio o mixtos con o sin minoría

CIEMAT-703

Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas.
Instituto de Investigación Básica. Madrid.-

"Estudios de ICRH en el torsatron TJ-IU."

CASTEJON, F., y otros (1993) 12 pp., 4 figs., 11 refs.

En este trabajo se presentan los estudios preliminares de calentamiento a la frecuencia ciclotrónica Iónica (ICRH) realizados para el torsatrón TJ-IU, en el rango de frecuencias f=3 - 150 MHz. Este amplio rango implica el uso de dos modelos teóricos diferentes. El primero de ellos es válido para alta frecuencia, donde la aproximación WKB es aplicable, mientras que el segundo resuelva la ecuación de onda completa en una dimensión.

Los cálculos para alta frecuencia se han realizado mediante un código de trazado de rayos que tiene en cuenta la geometría tridimensional del plasma y del campo magnético. Los resultados obtenidos mediante este modelo se presentan en el primer artículo de este informe. Los más importantes son el criterio para evitar el acoplamiento de la Onda Rápida (FW) con la Onda Lenta (SW) en la Resonancia Híbrida Inferior cerca del borde del plasma, y la existencia de los llamados Modos Localizados.

En el rango de baja frecuencia, la longitud de onda es del orden de magnitud del tamaño del plasma, lo cual hace que la aproximación WKB no sea válida. En este caso se usa un modelo unidimensional para resolver la ecuación de onda, que desprecia los efectos toroidales. Mediante este modelo se estudian los principales regímenes aptos para el calentamiento, los cuales se presentan en el segundo trabajo. Los estudios se han realizado para plasmas de hidrógeno, de deuterio o mixtos con o sin minoría

CIEMAT-703

Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas.
Instituto de Investigación Básica. Madrid.-

"Estudios de ICRH en el torsatron TJ-IU."

CASTEJON, F., y otros (1993) 12 pp., 4 figs., 11 refs.

En este trabajo se presentan los estudios preliminares de calentamiento a la frecuencia ciclotrónica Iónica (ICRH) realizados para el torsatrón TJ-IU, en el rango de frecuencias f=3 - 150 MHz. Este amplio rango implica el uso de dos modelos teóricos diferentes. El primero de ellos es válido para alta frecuencia, donde la aproximación WKB es aplicable, mientras que el segundo resuelva la ecuación de onda completa en una dimensión.

Los cálculos para alta frecuencia se han realizado mediante un código de trazado de rayos que tiene en cuenta la geometría tridimensional del plasma y del campo magnético. Los resultados obtenidos mediante este modelo se presentan en el primer artículo de este informe. Los más importantes son el criterio para evitar el acoplamiento de la Onda Rápida (FW) con la Onda Lenta (SW) en la Resonancia Híbrida Inferior cerca del borde del plasma, y la existencia de los llamados Modos Localizados.

En el rango de baja frecuencia, la longitud de onda es del orden de magnitud del tamaño del plasma, lo cual hace que la aproximación WKB no sea válida. En este caso se usa un modelo unidimensional para resolver la ecuación de onda, que desprecia los efectos toroidales. Mediante este modelo se estudian los principales regímenes aptos para el calentamiento, los cuales se presentan en el segundo trabajo. Los estudios se han realizado para plasmas de hidrógeno, de deuterio o mixtos con o sin minoría

de He^3. Finalmente, en el tercer artículo, se presentan los diseños de antena necesarios para estos regímenes de calentamiento. Se presentan dos modelos de antena para la excitación de SW, uno de ellos de tipo corriente y el otro del tipo potencial. Se ha diseñado además un tercer modelo para excitar FW, que es similar a la antena de corriente para SW, pero girada 90º.

CLASIFICACION DOE Y DESCRIPTORES: 7000350. ICR Heating. Torsatron Stellarator. Antennas. MHz Lange. MHz Range 01-100. MHz Range 100-1000. Three-Dimensional Calculations.

de He^3. Finalmente, en el tercer artículo, se presentan los diseños de antena necesarios para estos regímenes de calentamiento. Se presentan dos modelos de antena para la excitación de SW, uno de ellos de tipo corriente y el otro del tipo potencial. Se ha diseñado además un tercer modelo para excitar FW, que es similar a la antena de corriente para SW, pero girada 90º.

CLASIFICACION DOE Y DESCRIPTORES: 7000350. ICR Heating. Torsatron Stellarator. Antennas. MHz Lange. MHz Range 01-100. MHz Range 100-1000. Three-Dimensional Calculations.

de He^3. Finalmente, en el tercer artículo, se presentan los diseños de antena necesarios para estos regímenes de calentamiento. Se presentan dos modelos de antena para la excitación de SW, uno de ellos de tipo corriente y el otro del tipo potencial. Se ha diseñado además un tercer modelo para excitar FW, que es similar a la antena de corriente para SW, pero girada 90º.

CLASIFICACION DOE Y DESCRIPTORES: 7000350. ICR Heating. Torsatron Stellarator. Antennas. MHz Lange. MHz Range 01-100. MHz Range 100-1000. Three-Dimensional Calculations.

de He^3. Finalmente, en el tercer artículo, se presentan los diseños de antena necesarios para estos regímenes de calentamiento. Se presentan dos modelos de antena para la excitación de SW, uno de ellos de tipo corriente y el otro del tipo potencial. Se ha diseñado además un tercer modelo para excitar FW, que es similar a la antena de corriente para SW, pero girada 90º.

CLASIFICACION DOE Y DESCRIPTORES: 7000350. ICR Heating. Torsatron Stellarator. Antennas. MHz Lange. MHz Range 01-100. MHz Range 100-1000. Three-Dimensional Calculations.

CIEMAT-703

Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas.
Instituto de Investigación Básica. Madrid.-

"ICRH studies in TJ-IU torsatron."

CASTEJON, F., y otros (1993) 12 pp., 4 figs., 11 refs.

Preliminary studies for Ion Cyclotron Resonance Heating (ICRH) in the frequency range f=3-150 MHz are presented for TJ-IU torsatron. This wide range implies the use of two different theoretical models. The first valid for high frequency, where the WKB approximation is applicable, and the second one which solves the full wave equation in one dimension.

The high frequency calculations have been made using a ray tracing code and taking into account the magnetic field and plasma 3-D inhomogeneity. The results obtained in this case are presented in the first paper of this report, being the most important the criterion to avoid Fast Wave (FW)-Slow Wave (SW) coupling at Lower Hybrid Resonance, near the plasma edge, and the existence of so called Localized Modes.

For the low frequency range wave-length is of the size of the plasma radius, therefore, the WKB approximation cannot be used. In this case a 1-D model is used which disregards totoidal effects, to study the main available heating scenarios which are presented in the second work of this report. The studies are made for hydrogen, deuterium and mixed plasmas with and without He^3 mority.

Finally, the antenna designs to reach these several scenarios are presented in the third paper. Two different antenna models are provided for SW excitation, one of the

CIEMAT-703

Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas.
Instituto de Investigación Básica. Madrid.-

"ICRH studies in TJ-IU torsatron."

CASTEJON, F., y otros (1993) 12 pp., 4 figs., 11 refs.

Preliminary studies for Ion Cyclotron Resonance Heating (ICRH) in the frequency range f=3-150 MHz are presented for TJ-IU torsatron. This wide range implies the use of two different theoretical models. The first valid for high frequency, where the WKB approximation is applicable, and the second one which solves the full wave equation in one dimension.

The high frequency calculations have been made using a ray tracing code and taking into account the magnetic field and plasma 3-D inhomogeneity. The results obtained in this case are presented in the first paper of this report, being the most important the criterion to avoid Fast Wave (FW)-Slow Wave (SW) coupling at Lower Hybrid Resonance, near the plasma edge, and the existence of so called Localized Modes.

For the low frequency range wave-length is of the size of the plasma radius, therefore, the WKB approximation cannot be used. In this case a 1-D model is used which disregards totoidal effects, to study the main available heating scenarios which are presented in the second work of this report. The studies are made for hydrogen, deuterium and mixed plasmas with and without He^3 mority.

Finally, the antenna designs to reach these several scenarios are presented in the third paper. Two different antenna models are provided for SW excitation, one of the

CIEMAT-703

Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas.
Instituto de Investigación Básica. Madrid.-

"ICRH studies in TJ-IU torsatron."

CASTEJON, F., y otros (1993) 12 pp., 4 figs., 11 refs.

Preliminary studies for Ion Cyclotron Resonance Heating (ICRH) in the frequency range f=3-150 MHz are presented for TJ-IU torsatron. This wide range implies the use of two different theoretical models. The first valid for high frequency, where the WKB approximation is applicable, and the second one which solves the full wave equation in one dimension.

The high frequency calculations have been made using a ray tracing code and taking into account the magnetic field and plasma 3-D inhomogeneity. The results obtained in this case are presented in the first paper of this report, being the most important the criterion to avoid Fast Wave (FW)-Slow Wave (SW) coupling at Lower Hybrid Resonance, near the plasma edge, and the existence of so called Localized Modes.

For the low frequency range wave-length is of the size of the plasma radius, therefore, the WKB approximation cannot be used. In this case a 1-D model is used which disregards totoidal effects, to study the main available heating scenarios which are presented in the second work of this report. The studies are made for hydrogen, deuterium and mixed plasmas with and without He^3 mority.

Finally, the antenna designs to reach these several scenarios are presented in the third paper. Two different antenna models are provided for SW excitation, one of the

CIEMAT-703

Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas.
Instituto de Investigación Básica. Madrid.-

"ICRH studies in TJ-IU torsatron."

CASTEJON, F., y otros (1993) 12 pp., 4 figs., 11 refs.

Preliminary studies for Ion Cyclotron Resonance Heating (ICRH) in the frequency range f=3-150 MHz are presented for TJ-IU torsatron. This wide range implies the use of two different theoretical models. The first valid for high frequency, where the WKB approximation is applicable, and the second one which solves the full wave equation in one dimension.

The high frequency calculations have been made using a ray tracing code and taking into account the magnetic field and plasma 3-D inhomogeneity. The results obtained in this case are presented in the first paper of this report, being the most important the criterion to avoid Fast Wave (FW)-Slow Wave (SW) coupling at Lower Hybrid Resonance, near the plasma edge, and the existence of so called Localized Modes.

For the low frequency range wave-length is of the size of the plasma radius, therefore, the WKB approximation cannot be used. In this case a 1-D model is used which disregards totoidal effects, to study the main available heating scenarios which are presented in the second work of this report. The studies are made for hydrogen, deuterium and mixed plasmas with and without He^3 mority.

Finally, the antenna designs to reach these several scenarios are presented in the third paper. Two different antenna models are provided for SW excitation, one of the

current type and the other one of potential type. A third antenna is designed to excite FW which is similar to the current type antenna for SW, but rotated 90º.

DOE CLASSIFICATION AND DESCRIPTORS: 700350. ICR Heating. Torsatron Stellator. Antennas. MHz Lange. MHz Range 01-100. MHz Range 100-1000. Three-Dimensional Calculations.

current type and the other one of potential type. A third antenna is designed to excite FW which is similar to the current type antenna for SW, but rotated 90º.

DOE CLASSIFICATION AND DESCRIPTORS: 700350. ICR Heating. Torsatron Stellator. Antennas. MHz Lange. MHz Range 01-100. MHz Range 100-1000. Three-Dimensional Calculations.

current type and the other one of potential type. A third antenna is designed to excite FW which is similar to the current type antenna for SW, but rotated 90º.

DOE CLASSIFICATION AND DESCRIPTORS: 700350. ICR Heating. Torsatron Stellator. Antennas. MHz Lange. MHz Range 01-100. MHz Range 100-1000. Three-Dimensional Calculations.

current type and the other one of potential type. A third antenna is designed to excite FW which is similar to the current type antenna for SW, but rotated 90º.

DOE CLASSIFICATION AND DESCRIPTORS: 700350. ICR Heating. Torsatron Stellator. Antennas. MHz Lange. MHz Range 01-100. MHz Range 100-1000. Three-Dimensional Calculations.