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CHARACTERISTICS OF ION BERNSTEIN WAVE
HEATING IN JIPPT-II-U TOKAMAK

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Characteristics of Ion Bernstein Wave
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ABSTRACT

Using a transport code combined with an ion Bernstein wave tokamak ray tracing code, a modelling code for the ion Bernstein wave heating has been developed. Using this code, the ion Bernstein wave heating experiment on the JIPPT-II-U tokamak has been analyzed. It is assumed that the resonance layer is formed by the third harmonic of deuterium-like ions, such as fully ionized carbon, and oxygen ions near the plasma center. For wave absorption mechanisms, electron Landau damping, ion cyclotron harmonic damping, and collisional damping are considered. The characteristics of the ion Bernstein wave heating experiment, such as the ion temperature increase, the strong dependence of the quality factor on the magnetic field strength, and the dependence of the ion temperature increment on the input power are well reproduced.

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I. INTRODUCTION

Ion Bernstein wave heating in tokamaks is based on the consideration that the finite-Larmor-radius waves in the range of the ion cyclotron frequency excited from the low field side of the torus can propagate towards the plasma center without suffering significant absorptions until the waves reach the cyclotron resonance region, where strong absorption takes place. The effectiveness of this heating method is emphasized in the literature.^{1,2} In Ref. 2, ray tracing calculations show that ion Bernstein waves (IBW) are accessible in reactor-grade tokamak plasmas for a wide range of launched $n_{\parallel}$ (refractive index parallel to the magnetic field). Reference 1 also shows that the fusion plasma can effectively absorb the IBW even at relatively high cyclotron harmonics, since the wavelength of IBW perpendicular to the magnetic field $\lambda_{\perp}$ is comparable to the ion-Larmor-radius ρ_i : $k_{\perp}\rho_i \approx \mathcal{O}(1)$, where $k_{\perp} = 2\pi/\lambda_{\perp}$.

The properties of IBW such as excitation, propagation, dispersion relation, absorption, heating, and parametric excitation have been studied extensively using the ACT-1 (Advanced Concepts Torus-1) apparatus at the Princeton Plasma Physics Laboratory.³⁻⁶ In heating experiments carried out in ACT-1, a quality factor of $\Delta T_{i\perp}\bar{n}_e/P_{rf} = 10 \text{ eV} \cdot 10^{10} \text{ cm}^{-3}/\text{Watts}$ was obtained for $\bar{n}_e = 10^{10} \sim 10^{11} \text{ cm}^{-3}$, where $\Delta T_{i\perp}$, $\bar{n}_e$, and P_{rf} are the increments in perpendicular ion temperature, average electron density, and heating input power, respectively.

The ACT-1 is a simple torus without rotational transform. For a tokamak heating experiment, IBW heating was first applied to the JIPPT-II-U tokamak.⁷ The frequency f for the IBW heating was 40 MHz, which corresponds to three times the deuterium cyclotron frequency at the magnetic field B_c of 1.75 T ($\omega = 3\Omega_D$). When the toroidal magnetic field B_c is set to be around 1.8 T ($R = 91 \text{ cm}$) at the vacuum vessel center, the resonance region (where $\omega = 3\Omega_D$ is satisfied) is located in the neighborhood of the plasma center ($R = 93 \text{ cm}$), whereas the hydrogen cyclotron resonance and its harmonic resonance regions are situated outside the plasma. If deuterium ions are added to a bulk hydrogen plasma as a minority species, only the deuterium ions can resonate with IBW. Deuterium ions are accelerated by cyclotron damping in the resonance region, and bulk hydrogen ions are subsequently heated through ion-ion collisions. In the JIPPT-II-U experiment, hydrogen was a majority ion

species and helium was used as a minority species instead of deuterium. (The cyclotron frequency of fully ionized helium ions is the same as that of deuterium.) The toroidal magnetic field at the center B_0 was varied from 1.6 to 2.0 T. An rf power of ≤ 80 kW was injected into the plasma. An optimized quality factor, $\Delta T_{i\perp} \cdot \bar{n}_e / P_{rf} = 11 \text{ eV} \cdot 10^{13} \text{ cm}^{-3} / \text{kW}$, was obtained, an excellent result. It was shown that the quality factor depended strongly on B_0 . The content of helium was varied up to 40%, however, the dependence was found to be weak. In the present paper, we shall attempt to analyze the experimental results from JIPPT-II-U, using a tokamak transport code combined with a ray tracing code for IBW power deposition.

II. NUMERICAL MODEL

A. Transport code

A transport code BALDUR⁸ and a ray tracing code for IBW² are combined in order to analyze the experimental results from JIPPT-II-U. As mentioned in the Introduction, the ion species consist of H^+ , He^{++} , C^{+6} , and O^{+8} , but minorities are treated only in the ray tracing code, neglecting their effects on the transport equations except for the effective ionic charge Z_{eff} . Wave absorption along the rays is calculated for all the species in the ray tracing code, and the summation of these calculations is regarded as the input power from the waves to bulk electrons and ions in the transport code. Transport coefficients are chosen to satisfy the experimental data just before the rf onset; $n_{e0} = 2.2 \times 10^{13} \text{ cm}^{-3}$, $\bar{n}_e = 1.45 \times 10^{13} \text{ cm}^{-3}$, $T_{e0} = 700 \text{ eV}$, $T_{i0} = 300 \text{ eV}$, $V_L = 1.5\text{--}2.0 \text{ V}$, and $Z_{eff} = 2.5\text{--}3.0$, where n_{e0} and $\bar{n}_e$ are central and line-averaged electron density, T_{e0} and T_{i0} are electron and ion temperatures at the plasma center, V_L is the one turn voltage, and Z_{eff} is deduced from the conductivity given by Hirshman *et al.*⁹ The plasma current I_p and line-averaged density $\bar{n}_e$ are programmed to simulate the experimental data as in Fig. 1. It is assumed that in addition to recycling neutral atoms emitted from the wall or limiter having energy of 15 eV, neutrals of 2 eV are puffed to simulate the experimental time evolution of the line density. The electron thermal conductivity χ_e is estimated to be $\chi_e = (2\text{--}3) \times 10^{17} / n_e$, and the particle diffusion coefficient D is assumed to be $D = 1/5 \chi_e$. The neoclassical ion thermal conductivity¹⁰ is enhanced by a factor of three. In the region where the safety factor q drops below unity, χ_e is enhanced to flatten the electron temperature profile.⁸ These values reproduce the ohmic

parameters quite well. We assume that the transport coefficients thus determined do not change during the rf injection.

Radiation losses are not included in the present calculation. Line radiation losses are not negligible in the peripheral region, but the electron-ion coupling is not strong, since the average relaxation time between electrons and ions τ_{e-i}^E is approximately 10 ms. In the case of IBW heating, almost all the wave energy flows into the ions for the parameters of the JIPPT-II-U experiment. Accordingly, the energy balance for electrons is not very important in the present problem. At the plasma center where the wave energy is deposited, $n_{e0} = 2 \times 10^{13} \text{ cm}^{-3}$, $T_{e0} = 700 \text{ eV}$, and $\tau_{e-i}^E = 20 \text{ ms}$, so the electron-ion coupling is weakened further.

B. Ray tracing code

In the JIPPT-II-U experiment, a Nagoya Type-III coil¹¹ was installed to excite ion Bernstein waves. This coil, Faraday-shielded in the poloidal direction, simulates an E_z -waveguide antenna. The coil width in the toroidal direction l is 50 cm, and in the poloidal direction the width d is 17 cm. An rf current with a frequency of 40 MHz is fed from the feedthrough and one end of the coil is grounded to the torus wall. We assume that the power spectrum of the coil can be expressed as

$$P(k_p, k_t) = A(k_p, k_t) \frac{\sin^2(k_p d/2)}{(k_p d/2)^2} \frac{\sin^2(k_t l/2)}{(k_t l/2)^2}, \quad (1)$$

where A is the coupling constant, and k_p and k_t are the poloidal and toroidal wave number, respectively. We consider the spectrum localized in the range where $k_p < 2/d$ and $k_t < 2/l$. This restriction for k_p and k_t corresponds to $n_p = ck_p/(2\pi f) < 15$ and $n_t = ck_t/(2\pi f) < 5$, where n_p and n_t are the poloidal and toroidal refractive indices, respectively. The parallel refractive index is $n_{||} = n_t(b_t/B) + n_p(B_p/B)$. In the calculation, 30 rays selected from the spectrum satisfying $|n_{||}| < 5$ are launched from the antenna current maxima. The power of each ray is determined from Eq. (1), assuming that A is unity for simplicity.

For a short time step, assuming that the plasma profiles are not changed, each ray launched from the antenna is followed solving the ray equations.¹² The local dispersion relation is given by

$$D(k, \omega) = K_{xx} + \frac{|K_{xy}|^2}{n^2} + \frac{n_1^2 K_{zz}}{n_1^2 - K_{zz}} \quad (2)$$

where K_{xx} , K_{xy} , and K_{zz} are elements of the dielectric tensor.¹ We consider here electron Landau damping (ELD), ion cyclotron damping (ICD), electron-ion collisions, and ion-ion collisions as damping mechanisms of the wave. The wave power P attenuates along a ray due to ELD, ICD, and electron-ion collisions;

$$P(X + \Delta X) = P(X) \exp\{-2 \operatorname{Im} k_{\perp} \cdot \Delta X_{\perp}\} \quad (3)$$

where X is the path length along the ray, ΔX is its small interval, and $\Delta X_{\perp}$ is the perpendicular component of ΔX . In Eq. (3), $\operatorname{Im} k_{\perp}$ is the damping rate of the wave amplitude, which is given by

$$\operatorname{Im} k_{\perp} = (\operatorname{Im} k_{\perp})_{\text{ELD}} + (\operatorname{Im} k_{\perp})_{\text{ICD}} + (\operatorname{Im} k_{\perp})_{e-i} \quad (4)$$

with

$$(\operatorname{Im} k_{\perp})_{\text{ELD}} = - \left[\frac{n_1^2 n_2^2 \operatorname{Im} K_{zz}}{(n_1^2 - K_{zz})^2} \right] / \left(\frac{\partial K_{xx}}{\partial k_{\perp}} \right) \quad (4a)$$

$$(\operatorname{Im} k_{\perp})_{\text{ICD}} = - \operatorname{Im} K_{xx} / \frac{\partial K_{xx}}{\partial k_{\perp}} \quad , \text{ and} \quad (4b)$$

$$(\operatorname{Im} k_{\perp})_{e-i} = - \left[\sum_i \frac{v_{ei}}{\omega} \frac{n_1^2 n_2^2 K_{zz}}{(n_1^2 - K_{zz})^2} / \left(\frac{\partial K_{xx}}{\partial k_{\perp}} \right) \right] \quad (4c)$$

where (4a), (4b), and (4c) are damping rates of the wave by ELD, ICD, and electron-ion collisions. Equation (4c) is obtained by replacing the electron mass m_e by $m_e(1 + i v_{ei}/\omega)$, where v_{ei} is the electron-ion collision frequency.

Suppose that the wave power P attenuates due to the ion-ion collisions according to

$$P(X + \Delta X) = P(X) \exp\left(- \sum_i \Gamma_i \Delta t\right) \quad (5)$$

where Γ_i is the damping rate of P due to the collisions of the i-species, and $\Delta t = \Delta x_{\perp} / v_{g\perp}$ ($v_{g\perp}$ is the perpendicular group velocity). We assume that Γ_i has a form of

$$\Gamma_i = \sum_j \nu_{ij} \frac{E_i}{W_0} \frac{(k_{\perp} \rho_i)^2}{A + (k_{\perp} \rho_i)^2}, \quad (6)$$

where ν_{ij} is the collision frequency between i- and j-species ions, W_0 is the wave energy density of IBW, and E_i is the fraction of W_0 to which the i-species ions contribute. In Eq. (6), $A = 1$ when $i = j$, and $A = 0$ if $i \neq j$. In the electrostatic approximation, W_0 is

$$W_0 = \frac{1}{8\pi} K_{zz} E_{\parallel}^2 \left[\frac{\omega}{2} \frac{\partial K_{xx}}{\partial \omega} / K_{xx} + 1 \right], \quad (7)$$

where $E_{\parallel}$ is the parallel component of electric field, the first term on the right-hand side is due to ion motion, and the second is attributed to electrons. The first term is much greater than the second by two to three orders of magnitude: the IBW is mainly supported by coherent ion motion. In Eq. (6), the term E_i/W_0 represents the fractional loss of wave energy by collisions contributed by i-species ions. The term containing A takes into account the fact that like particle collisions are not as effective at randomizing the coherent motion if the ion-Larmor radius is much smaller than the wavelength. The deposited power calculated by Eqs. (3) and (5) is distributed to each radial zone in order to give the input power for BALDUR.

Since $\lambda_{\perp} = \rho_i$ ($k_{\perp} \rho_i \approx 0(1)$ for IBW), the WKB approximation is usually well satisfied for tokamaks. It breaks down at the reflection region; however, since the region is very thin, the actual numerical error due to reflection should be quite small.

Typical examples of IBW ray tracing calculations for the JIPPT-II-U experimental parameters are shown in Fig. 2. Figure 2(a) shows the wave number $k_{\perp}$ plotted as a function of plasma radial position, where the solid curve is the real and the dashed curve is the imaginary part of the dispersion relation. In the figure, the locations of respective resonances are also shown. In Fig. 2(b), the radial projection of the corresponding wave electric field is shown. The wave can be seen to be completely absorbed by the $3\Omega_{He}$ resonance. The ray trajectories for various values of launched $n_{\parallel}$ (as

labeled) are shown in Fig. 2(c). The rays for all n_i propagate on radially inward paths, intersecting the resonance near $r=0$. The oscillatory motion in the poloidal (and toroidal) direction is due to the rotational transform of the tokamak geometry. In Fig. 2(d), the wave power normalized to the initially launched value is plotted as a function of radial position for various values of n_i (upper graph) and for various minority ion concentrations (lower graph). In the graph, we have included a special case where no helium but a small amount of fully ionized carbon ions ($n_C = 3 \times 10^{10} \text{ cm}^{-3}$) exists in the plasma. We should note here that fully ionized carbon also has the same deuterium-like resonance frequency. The wave again damps efficiently at the resonance, indicating that IBW heating can occur even without helium ions. The same calculations, however, predict that other possible resonances of the partially ionized impurities which can occur in the wave path should cause no significant power absorption.¹³ Therefore, we conclude from our analysis that the primary wave power deposition occurs near the plasma center by a deuterium-like resonance for a wide range of n_i -spectrum and for a good range of ion concentrations.

III. NUMERICAL RESULTS

Parameters for numerical calculations are: $R_0 = 93 \text{ cm}$, $a_L = 23 \text{ cm}$, $B_0 = 1.6\text{--}2.0 \text{ T}$, $P_{rf} = 0\text{--}80 \text{ kW}$, and $f = 40 \text{ MHz}$, where R_0 , a_L , B_0 , P_{rf} , and f are major radius, limiter radius, toroidal magnetic field at $R = 91 \text{ cm}$, rf input power, and the wave frequency, respectively. Since IBW heating depends strongly on B_0 , we include the Shafranov shift of the magnetic axis during rf heating. For simplicity, we assume that the magnetic axis lies at $R = R_0 + \Delta_S$, and the effective plasma radius (distance from the launching position to the magnetic axis) is $a = a_L - \Delta_S$, where Δ_S is the Shafranov shift. The tokamak plasma with Z_{eff} of 2-3 contains carbon and oxygen concentrations of over 5%.¹⁴ We assume that the ratio of ion species contribution to n_e are $\bar{n}_H^0 = 78.6\%$, $\bar{n}_{He}^0 = 0.005\%$, $\bar{n}_C^0 = 0.9\%$, and $\bar{n}_O^0 = 2\%$ at the plasma center ($r=0$), where $\bar{n}_H^0$, $\bar{n}_{He}^0$, $\bar{n}_C^0$, and $\bar{n}_O^0$ are the hydrogen, helium, carbon, and oxygen ions content ratios, respectively. The distribution of concentration $g_i(r)$ is determined by $\sum_i Z_i g_i(r) = 1$, where Z_i is the ionic charge of the i -species.

Figure 3 shows the time behavior of hydrogen ion temperature when $B_0 = 1.8$ T and $\Delta_S = 1.3$ cm. The input power P_{rf} decreases linearly from 80 to 60 kW. The solid line is the simulation results on which the highest values of $T_i(r)$ are plotted. In the case of Fig. 3, the plotted T_i corresponds to the central ion temperature T_{i0} . Open circles and triangles are experimental data from charge exchange signals (averaged over 20 shots). The central ion temperature increases from 300 to 800 eV in ~ 10 ms during rf injection, with $P_{rf} = 70$ kW on average. The ray tracing calculations indicate that the wave power is delivered to hydrogen, helium, carbon, and oxygen ions roughly in proportion to their particle numbers. This result is attributed to the fact that as the wave approaches close to the resonance layer, v_{g1} becomes so small that the wave stays for a sufficiently long time just in front of the resonance layer to suffer from ion-ion collisions, as well as from ion-cyclotron damping. The heat deposition to electrons is quite small in the ray tracing calculation. An increase in central electron temperature is seen at the end of rf injection. However, the increment is at most 100 eV. It is clear that the increment is mainly due to energy relaxation between electrons and ions.

Figure 4 shows the dependence of the heating quality factor $\Delta T_i \bar{n}_e / P_{rf}$ (eV $\times 10^{13}$ cm $^{-3}$ /kW) on the magnetic field strength B_0 at $R = 91$ cm. The result is obtained by scanning B_0 from 1.6 to 2.0 T, keeping the other calculation parameters the same as in Fig. 3. The increment ΔT_i is the difference between the highest value of $T_i(r)$ during the heating and the central ion temperature without rf injection. The increment is averaged over the period of rf injection. The experimental results are also shown for various He concentrations. The agreement between the calculation and experiment is remarkable. It is noted that the dependence on He concentration is not seen in the experiment. It may be reasonable that the resonance layer is always formed by the existence of fully ionized carbon and oxygen ions near the plasma center.

Figure 5 shows the dependence of ΔT_i on P_{rf} when $B_0 = 1.8$ T and P_{rf} is varied up to 80 kW. The solid line is obtained for the case when $\Delta_S = 1.3$ cm, and the broken line is the case without the Shafranov shift. The strength of the magnetic field on the magnetic axis (corresponding to the plasma core center) is 1.775 T for the former case, and 1.8 T for the latter. When

compared to the experimental results, it can be seen that the solid line ($\Delta_S = 1.3$ cm) agrees with the experiment when P_{rf} is high, and the broken line recovers the experiment for lower input power. This tendency seems reasonable, since the Shafranov shift increases as the temperature increases.

IV. DISCUSSION AND CONCLUSION

A remarkable feature of IBW heating is the strong dependence of heating efficiency (quality factor) on the magnetic field strength as seen in Fig. 4. This strong dependence is attributed to the sharp localization of the deposition profile. An example of the deposition profile corresponding to Fig. 3 is shown in Fig. 6. It is seen that the power density deposited is localized in a region with a width of 2 cm. The ray tracing calculation in the case when $B_0 = 1.9$ T also shows a power density profile peaked around $r = 6.5$ cm with a width of 2-3 cm. We assume here, for simplicity, that all the power of the IBW P is deposited in the region between r and $r + \Delta r$, and that in this interval the average ion temperature increment is $\Delta T(r)$ and the ion energy confinement time is $\tau_i(r)$. Then, we obtain

$$\frac{n_i(r)\Delta T(r)}{\tau_i(r)} = \frac{P}{V} \quad (8)$$

where V is the volume of the zone; $V = 2\pi^2 R[(r+\Delta r)^2 - r^2]$. If all the power density is localized around $r = r_0$, and $r = r_1$ for the case when $B_0 = 1.8$ T and 1.9 T, respectively, Eq. (8) yields

$$\frac{\Delta T(r_1)}{\Delta T(r_0)} = \frac{\tau_i(r_1)}{\tau_i(r_0)} \frac{n_i(r_0)}{n_i(r_1)} \frac{\Delta r}{2r_1} = 0.17 \frac{\tau_i(r_1)}{\tau_i(r_0)} \quad (9)$$

where we assumed that $r_0 = 0$, $r_1 = 6.5$ cm, $\Delta r = \Delta r_0 = \Delta r_1 = 2$ cm, and $n_i(r) = 2 \times 10^{13} (1 - r^2/a^2)$. In Eq. (9), $\tau_i(r_1) < \tau_i(r_0)$, since the neoclassical conduction loss is dominant in the ion energy balance in the region where $r \leq 10$ cm. On the other hand, the experiment shows that $\Delta T(r_1)/\Delta T(r_0) = 0.15$, which is consistent with Eq. (9). Therefore, we may conclude that the strong dependence of heating efficiency on the magnetic field is nothing but the sharp localization of power deposition. However, it should be noted that this strong dependence takes place for the maximum value of $T_i(r)$. For the averaged ion temperature over the radius $\bar{T}_i$, there is no such notable difference between the two cases as is seen in Fig. 7.

In conclusion, we have constructed a tokamak IBW modelling code using an IBW ray tracing and the BALDUR plasma transport code. In the transport code, a one-ion-species energy balance equation was solved. The present numerical results reproduce many of the IBW heating characteristics observed in the JIPPT-II-U experiment. Implicitly, this modelling code assumes that the equilibration time between the heated ion species and the bulk ion species is shorter than the ion energy confinement time. Therefore, this code should be useful for predicting IBW heating for future experiments on larger tokamak devices. An example of the present modelling code for the INTOR IBW heating study is presented in Ref. 15. For smaller devices, however, further refinement of the code may be necessary to explain more detailed features of the heating. In particular, $T_{\perp}$ and $T_{\parallel}$ (perpendicular and parallel temperature to the magnetic field) of the heated species, as well as T_i of different ion species, need to be considered. For the JIPPT-II-U IBW experiment, a variation of the present code was written to include multi-ion, two temperature ($T_{\perp}$ and $T_{\parallel}$) features. This modified code, however, uses simpler transport equations which solve only for a steady-state solution. This code was used successfully to explain the difference between $T_{\perp}$ and $T_{\parallel}$ observed in the experiment.⁷ In the future, it should be of interest to incorporate this more detailed ion energy balance, as well as possible nonlinear absorption mechanisms,^{16,17} into the present IBW modelling code.

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"BALDPLIM", a version of BALDUR developed at PPPL, was used for the calculations.

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Figure Captions

- FIG. 1. Programmed plasma current I_p and line-averaged density $\bar{n}_e$. During rf injection (from 95 to 124 ms), cold neutrals are fed in addition to recycled neutral atoms. After 124 ms, a recycling ratio of 0.9 is chosen so as to simulate the decay of $\bar{n}_e$.
- FIG. 2. Typical IBW heating configuration. (a) IBW dispersion relation. The solid curve is real k_1 and the dashed curve is imaginary k_1 . Respective resonances are shown (5% He). (b) Radial projection of the IBW electric field (5% He). (c) Ray trajectories for various launched n_1 (as labeled). (d) Power deposition profiles for various launched n_1 (upper graph) and for various minor concentrations (lower graph). $B_0(R = 91 \text{ cm}) = 1.8 \text{ T}$, $n_0(\text{center}) = 2.0 \times 10^{13} \text{ cm}^{-3}$, $n(\text{edge}) = 0.01 n(\text{center})$, $T_e(\text{center}) = 700 \text{ eV}$, $T_i(\text{center}) = 300 \text{ eV}$, $T_e(\text{edge}) = 30 \text{ eV}$, $q(\text{center}) = 1.0$, $q(\text{edge}) = 4.0$ and $f = 40 \text{ MHz}$.
- FIG. 3. Time behavior of the maximum values of $T_i(r)$. The solid line is the calculation result with rf injection, and the broken line is the result without the injection. Open circles and triangles are experimental data from charge exchange raw signals averaged over 20 shots.
- FIG. 4. The dependence of the quality factor on magnetic field strength. The solid line is the calculation result. Open circles are experimental measurements. The helium concentration is varied up to 40% in the experiment.
- FIG. 5. The dependence of ΔT_i on P_{rf} . The solid line is the calculation result with Shafranov shift $\Delta_S = 1.3 \text{ cm}$. Broken line is for the case when $\Delta_S = 0$.
- FIG. 6. Deposition profiles. (a) Power deposited in each radial zone in arbitrary units. (b) Power density profile in Watts/cm³. P is deposited in each radial zone with volume of V.
- FIG. 7. Time behavior of averaged ion temperature over radius. Solid line is the case when $B_0 = 1.8 \text{ T}$ and broken line is the case when $B_0 = 1.9 \text{ T}$.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

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