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BENCHMARKING OF THE NBI BLOCK IN ASTRA CODE VERSUS THE OFMC CALCULATIONS

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Benchmarking of the NBI Block in ASTRA Code Versus the OFMC Calculations

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The description of the Neutral Beam Injection block in the 1.5D ASTRA code is presented including the neutral beam absorption, first orbit analysis and fast ion slowing down. Benchmarking in the ASTRA code is carried out using the OFMC calculations for the JT60-U experimental parameters. The benchmarking reveals that the NBI solver of the ASTRA code provides satisfactory accuracy of the absorbed power and generated current calculations. Taking account of ripple losses and the multistep atomic processes for the high energy NBI enables calculation of both the transversal NBI in the rippled field and the tangential negative beam injection in the JT60-U experiments. The fast and self-consistent treatment of all plasma parameters in a MHD equilibrium makes the ASTRA code extremely convenient for the experimental data analysis and plasma transport simulations in the JT60-U experiments.

Keywords: Neutral Beam Injection, Tokamak, ASTRA Code, OFMC Code, Fokker-Planck Equation, Ripple Losses, Negative Beam Injection

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ＡＳＴＲＡコードのＮＢＩ部とＯＦＭＣ計算とのベンチマーク

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1.5次元ＡＳＴＲＡコードの中性粒子入射（ＮＢＩ）部について、中性ビームの吸収、一次軌道解析及び高速イオンの減速を中心に記述する。JT-60Uの実験パラメータを用いて、ＡＳＴＲＡコードとＯＦＭＣ計算とのベンチマーク検査を行った。このベンチマークの結果から、ＡＳＴＲＡコードのＮＢＩ部は十分な正確さで吸収力パワーと駆動電流を計算できることが判明した。高エネルギー粒子に関するリップル損失と多段階原子過程を考慮することにより、JT-60U実験におけるリップル磁場中の垂直NB入射及び負ビームの接線入射について共に計算可能となった。ＡＳＴＲＡコードは、ＭＨＤ平衡とプラズマパラメータを無矛盾的に高速計算するので、JT-60U実験の実験解析や輸送シミュレーションに非常に有効である。

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1. INTRODUCTION

The neutral beam heating and current drive block of the ASTRA code [1] simulates three types of processes connected with the neutral beam absorption and the hot ion-plasma interaction:

the birth of hot ions due to ionization and charge exchange of the hot neutrals accompanied by the birth of electrons and warm neutrals ("neutral beam halo"), taking account of the multistep ionization processes which are important in the case of the high energy negative NBI ;

the drift motion of the hot ions accompanied by trapping of the hot ions in the plasma or hot ion losses due to intersection of the drift trajectory with the wall ("orbital losses"), trapping into the ripples ("ripple losses") and trapping into the magnetic wells;

the thermalization of the fast ions due to Coulomb collisions with plasma electrons and ions accompanied by energy and momentum transfer to the plasma and generation of toroidal current.

Some simplifications allowed us to make the block less time consuming whilst maintaning satisfactory accuracy.

2. NBI SIMULATION IN THE ASTRA CODE

2.1 FAST PARTICLES ABSORPTION

The neutral beam penetration into the plasma is described in the approximation of "pencil" beams with the energy distribution in terms of the "footprint" [2,3], i.e. by the prescription of the input power distribution in the meridian orthogonal cross section. The power distribution in this cross section is calculated using the real beam geometry and from the fast ion source power distribution.

In the ASTRA code the NB-plasma interaction is described in a realistic geometry of the magnetic surfaces calculated self-consistently with the plasma parameter distribution from the equilibrium solver including the anisotropic hot ion pressure. For the solution of the Grad-Shafranov equation we use L.E. Zakharov's simplified 3M technique [4] with the following magnetic surface parametrization:

$$R = R_0 + \Delta(a) + a\,(\cos\vartheta - \delta(a)\sin^2\vartheta), \qquad (1)$$
$$Z = k(a)\,a\sin\vartheta,$$

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$$R = R_0 + \Delta(a) + a\,(\cos\vartheta - \delta(a)\sin^2\vartheta), \qquad (1)$$
$$Z = k(a)\,a\sin\vartheta,$$

where

ϑ is a parameter;

a is the surface minor radius;

Δ is the "Shafranov's shift";

k is the elongation;

δ is the triangularity.

In the NBI block of the ASTRA code more accurate formulae for the NB stopping cross section were used [5] taking account of the multistep processes (excitation + ionization) in multispecies plasmas for the range of parameters expected in a fusion reactor and negative-ion-based high energy NBI of JT60-U:

E = 100-10000 keV/nucl, $n_e = 10^{18}$ -10^{22} m^{-3} , T_e = 1 - 50 keV.

For the moderate beam energies E < 100 keV/n there are used the following expressions:

for beam ionization by proton and electron impact and charge-exchange cross-sections [6],[7]:

$$\sigma_{pi}\, v_b = 43.73\, \sqrt{E}\; 10^{-34.833 + y\,(8.156 - 0.8712\, y)}, \quad \text{for } E < 150 \text{ keV},$$

$$y \equiv 3 + \lg E,$$

$$\sigma_{pi}\, v_b = 1.575\; 10^{-12}\, (2.22 + \lg E\,)/\sqrt{E}, \text{ for } E > 150 \text{ keV};$$

$$<\sigma_{ei}\, v_e> = 6.1\; 10^{-14}\, \frac{\exp(-y)}{y + 0.73\sqrt{1+y^{-1}}} \quad \text{for } T_e < 0.02 \text{ keV},$$

$$y \equiv 0.0136/T_e\,,$$

$$<\sigma_{ei}\, v_e> = 10^{-11.231 - 0.5151\, y - 2.563/y}, \quad \text{for} \quad T_e > 0.02 \text{ keV},$$

$$y \equiv 3 + \lg T_e\,;$$

$$\sigma_{cx}\, v_b = 9.6\; 10^{-15} \sqrt{y}\, (1 - 0.155 \lg y)^2\, (1 + 0.1112\; 10^{-14}\, y^{3.3}\,)^{-1},$$

with $y \equiv 1000\, E$

for the rate of the ionization by impurities [5]:

$$\sigma_z\, v_b = 7.457\; 10^{-20}\, Z\, v_b \left(\frac{1}{1+0.08095 E_z} + 2.754 \frac{\ln(1+1.27 E_z)}{64.58 + E_z}\right),$$

with σv [m^3 /s], $E_z = E/Z$ [keV/n].

The total beam stopping cross section for mediate energies is calculated as:

$$\sigma_{tot} = (n_p\, \sigma_{pi} \; + n_z\, \sigma_z + n_i\, \sigma_{cx}\,)/n_e + <\sigma_{ei}\, v_e >/v_b\ ,$$

where: $v_e = (2\ T_e\ /m_e\ )^{1/2}$ is the electron thermal velocity, v_b [m/s] is the fast neutral velocity, <..> denotes the Maxwellian averaging.

2.2 FAST PARTICLES TRAPPING

The fast ion trapping analysis is carried out in the drift approximation taking account of the toroidal and the Larmour phase symmetries. The ion motion is considered in variables which describe the inclination of the orbit with respect to the toroidal magnetic field as well as the fast particle energy:

with $\xi = (\boldsymbol{v},\boldsymbol{B})/|\boldsymbol{vB}|$, $\quad v = |\boldsymbol{v}|$

We also use the variable $\psi(\rho) = \Psi(\rho)\text{-}\Psi(0)$ which describes the relative poloidal flux with respect to the magnetic axes and is an increasing function of the distance from the magnetic axes in tokamak plasmas (we use a positive value of ψ).

We also use conservation of the toroidal and magnetic moments as well as fast ion energy on the first pass along the trajectory. Taking account of:

the generalized toroidal momentum:

$$R\, M_b\, v\, \xi\text{-}\ e_b\, \psi/2\pi c = R_b\, M_b\, v_b\, \xi_b\ \text{-}\ e_b\, \psi_b\ /2\pi\, c = \text{const},$$

the energy:

$M_b\, v^2/2 = E_b = \text{const},$

the magnetic moment:

$v_\perp^2\, /B = \text{const},$

one can obtain the integral of motion:

$$\psi/2\pi B_0\ \pm r_b\, R\, (1\text{-}R_{cr}/R\ )^{1/2} \equiv C(\psi,R) = \text{const} = C_b\ ,$$

with

$(v_b\ ,\xi_b\ ,\psi_b\ )$ - coordinates of the appearance of the hot ion, index "b" corresponds to the point of the hot ion birth;

$B = B_0 R_0\ /R\ ,$

(-) corresponds to the co direction of the hot ion motion to the plasma current (co injection);

(+) - counter motion;

$r_b \equiv v_b \sqrt{M_b}\, c/eZ_b B$-is the ion gyro-radius for $\boldsymbol{v} \perp \boldsymbol{B}$;

$R_{cr} \equiv R_b - R_t^2/R_b$;

R_t is the tangential radius of the specific "pencil" beam.

For simplicity we neglect the dia(para) magnetic corrections in the radial dependence of $B = B_0R_0/R$ as well as the electrical potential. In general it is possible to take them into account following a similar calculation, But in presence of the electrical potential (which is difficult to measure experimentally) the trapping analysis becomes more complicated and time consuming.

The hot ions with $R_{cr} < R_0 - a$, keep the sign of ξ (the direction of the toroidal motion) on the whole trajectory. Thus it is necessary to analyze only whether the particle leaves the bulk plasma (reaches the separatrix, limiter or wall).

If $R_{cr} > R_0 - a$, it is also necessary to know whether the particle reaches the point $R = R_{cr}$, (whether it is trapped in the magnetic well) or it remains untrapped $R > R_{cr}$.

The analysis of trapping in the magnetic well can be done in the following way. Using

$$\psi_{cr} \equiv \psi\,(R_0 + \Delta(0) - R_{cr}), \qquad \psi_a \equiv \psi(a),$$

$$R_+ \equiv R_0 + a\,, \qquad R_- \equiv R_0 - a,$$

one can reduce the condition of trapping in the magnetic well to the simple condition:

$$(\psi_{cr}-C_b)(\psi_a-C_b) \le 0.$$

and the condition of ion loss from the bulk plasma to following two:

$$C(\psi_a,R_+) - C_b < 0, \qquad \text{for the co motion,}$$

$$C(\psi_a,R_-) - C_b < 0 \qquad \text{for the counter motion.}$$

For the case of large gyroradius the loss expressions should be corrected taking account of r_b:

$$\psi_a \equiv \psi(a - r_b\, v_{\perp +}/v_b)\;,$$

$$R_+ \equiv R_0 + a - r_b v_{\perp +}/v_b\,, \qquad R_- \equiv R_0 - a + r_b\, v_{\perp +}/v_b\,,$$

The first orbit analysis is carried out to eliminate the fast ions with orbits crossing the plasma boundary from the fast ion source S_b. We also exclude the trapped ions from the fast ion current in the steady state Fokker-Planck solver (see below). In the case of the full scale Fokker- Planck solver this trapping is taking into account in the proper integration over the pitch angle (see below).

Keeping in mind the large rippling of the magnetic field and large fraction of the trapped particles for the case of the perpendicular injection in the JT60-U we introduce also the ripple loss analysis following the consideration of ref. [11]. According to [11] the dominant part (80 - 90 %) of the energy losses is caused by the direct trapping of the hot ions into the ripple loss cone. Thus we restrict our consideration of the ripple losses by the direct trapping of the "banana" particles into the magnetic wells (and do not consider passing particles and collisional and diffusion into the loss cone). Following [11] the criterion of the loss cone is $\eta > \eta_0$, $\partial\eta/\partial z < 0$, where:

$\eta \equiv B_R/B_\varphi N\,\delta$,

B_R and B_φ are the R- and toroidal component of the magnetic field,

N is a number of the toroidal field coils (= 18 in the JT60-U),

$\delta = (B_{max} - B_{min})/\,(B_{max} + B_{min})$ is the amplitude of the ripple.

To calculate the ripple depth δ in the JT60-U we use the Yushmanov's analytic expression valid for the tokamaks with circlar coils:

$$\delta = \delta_n\, I_0(Na/(R_0 - L_0))$$

where I_0 is a modified Bessel function,

$$a = \{2\,(R_0 - L_0)(\,R - (R^2 - r^2 - L_0^2 - 2rL_0\cos\vartheta)^{1/2})\}^{1/2},$$

$$R = R_0 + r\cos\vartheta, \quad z = r\sin\vartheta.$$

The other parameters were chosen to fit the JT60-U ripple depth

$$L_0 = 0.84,\ \delta_n = 0.00025\,,\ R_0 = 3.3.$$

The "banana" hot ions with the "banana" tips in the loss cone leave the plasma very quickly due to the fast drift. We exclude these particles from further calculations. According to [11] this approach enables us to calculate the NBI power to ions and elecrtons with accuracy of 3-4%

After the first orbit analysis, the fast ions are considered in the thin orbit approximation. The coordinates of the trapped particle (v_b ,ξ_b ,ψ_b) correspond to the point of ionization. .

2.3 FAST ION DISTRIBUTION

The fast ions thermalization in the NBI block of the ASTRA code is calculated by solving the linearized Fokker-Planck equation (n_b/n_e<<1) in the coordinates (v,ξ,r) for the gyro- and magnetic surface averaged distribution function f of the fast ions. The radial variable (the square root of the normalized toroidal flux $r=\rho/\rho_a = (\Phi/\Phi_a)^{0.5}$) is included only as a parameter in the coefficients of the Fokker-Planck equations and particle sources and sinks:

$$\frac{\partial f}{\partial t} = \frac{v_b^3}{\tau_0}\sum_\alpha \frac{Z_\alpha^2 n_\alpha}{n_e v^2}\left(\frac{\partial}{\partial v}\frac{T_\alpha}{M_\alpha v}\frac{b_\alpha}{\kappa_\alpha}\frac{\partial}{\partial v}(\kappa_\alpha f) + c_\alpha \frac{\partial}{\partial \xi}(1-\xi^2)\frac{\partial f}{\partial \xi}\right) - \nu f + S_b \tag{3}$$

where:

$\alpha = i,e,$

Z_α, $n_\alpha(r)$, $T_\alpha(r)$, M_α are charge, density, temperature and mass of the proper plasma components;

$S_b\,(v,\xi,r)$ is the fast ion source:

$\nu(v,\xi,r)f$ - describes the volume losses of the hot ions due to charge exchange;

$u_\alpha \equiv v/v_\alpha$, $\quad v_\alpha \equiv (2\,T_\alpha/M_\alpha)^{1/2}$, $\kappa_\alpha \equiv \exp(M_b\, v^2/2T_a)$

$$b_\alpha \equiv \frac{4}{\sqrt{\pi}}\int_0^{u_\alpha}\exp(-x^2)x^2 dx$$

$$c_\alpha \equiv \frac{1}{\sqrt{\pi}}\left(\exp(-u_\alpha^2) + (2u_\alpha^{-1} - u_\alpha^{-3})\int_0^{u_\alpha}\exp(-x^2)x^2 dx\right)$$

$$\tau_0 \equiv E_b^{3/2}\, M_b^{1/2}/\sqrt{2}\pi\, Z_b^2\, e^4\, n_e \ln\Lambda$$

The boundary conditions on the fast particle flux in velocity space are prescribed at infinity: $\Gamma_{v=\infty}=0$ (in the ASTRA $E_\infty=E_b$ 16/9) and provide the absence of artificial numerical sources and sinks. The boundary condition at v = 0, as well as these at ξ = 1, ξ = -1, are excluded by using a special shifted flux mesh [2]. The supra thermal part f_b of the fast ion distribution function f is determined the following way:

$$f_b\,(v,\xi,r) = f(v,\xi,r) - f(0,\xi,r)\exp(-(v/v_i)^2), \tag{4}$$

with $v_i \equiv (2\ T_i\ /M_b)^{1/2}$ - the thermal velocity of the Maxwellian ions.

All distributions connected with the interaction of the fast ions with plasma are determined using the solution of (3) calculated on the different magnetic surfaces:

The fast ion current is calculated taking into account the trapping into the magnetic wells:

$$j_{\|fi} = e_b \int \left(\int_{\xi_t}^{1} \xi f_b d\xi + \int_{-1}^{-\xi_t} \xi f_b d\xi \right) v^3 dv \qquad (5)$$

with the boundary of the trapping in the magnetic wells $\xi_t = (2\varepsilon/(1+\varepsilon\ ))^{1/2}$, and $\varepsilon = a/R$. For the high beta case in the tight aspect ratio tokamaks one should improve this expression taking the magnetic field from the equilibrium:

$\varepsilon = (B_{max} - B_{min})/(B_{max} + B_{min})$.

The density of driven current is calculated taking account of the electron Okhawa current together with the neoclassical corrections [9]

$$j_{\|b} = (1 - F_{te}/Z_{eff})\ j_{\|fi}\ , \qquad (6)$$

where

$$F_{te}(Z_{eff}, \varepsilon) = (Z_{eff}^2 + 1.41 Z_{eff} + (Z_{eff}^2 + 0.45\ Z_{eff})g)/(Z_{eff}^2 + 1.41 Z_{eff} +$$

$$+ (2\ Z_{eff}^2 + 2.66 Z_{eff} + 0.75)g + (Z_{eff}^2 + 1.24\ Z_{eff} + 0.35)g), \qquad (7)$$

and the expression for the toroidal correction [9] which is valid in contrast with [10] for arbitrary aspect ratio up to $\varepsilon = 1$:

$f_t = \sqrt{\varepsilon}\ \ (1.46 - 0.46\ \varepsilon)$, where $g = f_t/(1-f_t)$ describes the fraction of the trapped particles.

All other distributions (fast particle density n_b, pressure $p_{b\perp}$, $p_{b\|}$, power transfer to ions and electrons P_{bi}, P_{be}) are calculated in the usual way by means of f_b)

This technique is used to simulate the dynamics of present day NBI heating and current drive experiments, where the beam slowing down time is comparable with the energy confinement time and the beam energy is comparable with the ion temperature.

For plasma parameters typical of future reactors $E_b \cong 1000$ keV >> $T \cong 10$ keV, $n_e \cong 10^{20}$ m^{-3}, the velocity space diffusion can be omitted. The Coulomb slowing down time is less than the charge exchange time as well as the energy confinement time:

$$\tau_{cx} >> \tau_E > \tau_s = 3.7\, M_b / M_p\, (T_e / 10\ \mathrm{keV})^{1.5} / (n_e / 10^{19}\ \mathrm{m}^{-3})\ [\mathrm{s}] \tag{8}$$

and Eq. 3 can be reduced to the steady state equation:

$$v \frac{\partial}{\partial v}(v^3 + v_c^3) f_b + 0.5\, Z_2\, v_c^3 \frac{\partial}{\partial \xi}(1 - \xi^2) \frac{\partial f_b}{\partial \xi} = - v^3\, \tau_s\, S_b\,, \tag{9}$$

where:

$v_c = (3\sqrt{\pi}\, m_e\, Z_l / 4M_b)^{1/3}\, v_e,$

$Z_l = (\sum n_i Z_i^2 / M_i) M_b / n_e,$

$Z_2 = \sum n_i Z_i^2 / n_e Z_l\,,$

$\tau_s = (M_b / Z_b e^2)^2\, v_c^3 / 4\pi Z_l\, n_e \ln \Lambda$ is the Coulomb collisional time

This equation (9) can be solved analytically [8].

$$f_b = \frac{v_b^3 \tau_s}{x^3 + x_c^3} \sum_{l=o}^{\infty} S_l P_l(\xi) \left(x^3 \frac{1 + x_c^3}{x_c^3 + x^3} \right)^{l(l+1)Z_2/6} \tag{10}$$

where

$v_b = (2\, E_b / M_b)^{1/2}$;

$x = v / v_b\,,\ x_c = v_c / v_b$

$P_l\ (\xi)$ are the Legendre polynomials:

$\int_{-1}^{+1} P_l\, P_k\, d\xi = \delta_{lk} / (l + 1/2)$;

$S_l = (l + 1/2) \int_{-1}^{+1} S\, P_l\, d\xi.$

Using the expression (10) for the steady state fast ion distribution function, it is easy to determine all the variables which are necessary to solve the plasma transport and equilibrium equations in ASTRA analytically:
the fast ion current density is calculated taking account of fast ion trapping:

$$j_{\|fi} = \int e_b\, v_{\|}\, f_b\, d^3 v = 2\, e_b\, S_1\, \tau_s\, v_b\, F_1 (1/x_c, y)\, h_t/3, \tag{11}$$

where:

$y = Z_2 / 3 \approx 0.8\, Z_{eff}\, M_p / M_b$,

$$F_l(x,y) = x^{-1}(1+x^{-3})^y \int_0^x (1+u^{-3})^{-1-y}\, du \cong x^3/(4+3y+x^2(x+1.39+0.61y^{0.7}))$$

(12) see [10]

$h_t = 0$ for the fast ions trapped in the magnetic well,
$h_t = 1$ for passing ions;

The NBI driven current density is calculated as before (see Eq. 6).
The parallel pressure of the suprathermal ions:

$p_{b\parallel}=\int M_b\, v_\parallel^2 f_b\, d^3v=2\tau_s E_b\{S_0\,(1-2F_{NB2}\,(x)/x^2)/3+4S_2F_{NP}(x,Z_2\,)/15\}$,

the transverse pressure of the suprathermal ions:

$p_{b\perp} = \int M_b\, v_\perp^2 f_b\, d^3v/2 = 2\,\tau_s\, E_b\,\{S_0\,(1-2F_{NB2}(x)/x^2)/3 - 2\,S_2\, F_{NP}\,(x,Z_2)/15\}$,

where:

$x = 1/x_c$

$F_{NB2}(x) = \int_0^x (u^3+1)^{-1}\, u\, du = [\arctan((2x-1)/\sqrt{3}) + \pi/6]/\sqrt{3} - [\ln((1+x)^2\,/(1-x+x))]/6;$

$F_{NP}\;(x,y) = x^{-2}\,(1+x^{-3}\,)^y \int_0^x (1+u^{-3})^{-1-y}\, u\, du.$

All other distributions (fast particle density n_b,, power transferred to the Maxwellian ions and electrons P_{bi}, P_{be}) are calculated from (10) the same way as in Ref. [10].

the fast ion density:	$n_b = 2\,S_0\,\tau_s\,\ln(1+x_c^{-3}\,)/3$
the ion heating:	$P_{bi} = 4\,E_b\,S_0\,F_{NB2}\,(x)\,/x^2$
and the electron heating:	$P_{be} = 2\,E_b\,S_0\,(1-2\,F_{NB2}(x)/x^2)$.

where the neutral beam absorbed power is:

$$P_b=2\,E_b\,S_0 \tag{13}$$

In the case of the fast solver only a few terms of the source expansion are used: S_0, S_1 , S_2. Thus, only these three terms, rather than the fast ion distribution function, are calculated by the fast Fokker-Planck solver. Thus this technique could be used for relaxed fast ion distribution without charge exchange losses.

3. BENCHMARKING OF THE ASTRA NBI SOLVER

The NBI solver of the ASTRA benchmarking versus the OFMC calculations was carried out for the same JT60 - U experimental parameters of the NBI L-mode discharges E021796, E021795. In both cases the perpendicular neutral beam injection was used. The results of comparison are performed in figs.1,2.

In these shots with large fraction of trapped particles the effect of the magnetic field rippling plays an important role. The calculations of the NBI absorption without taking account of the ripple losses noticeably overestimate the bulk plasma NBI heating at the periphery (figs.1a, 2a). The simple technique described above enables to take into account the ripple losses and provides acceptable accuracy in comparison with the OFMC calculations (figs.1b, 2b).

In the case of the nearly perpendicular injection of both JT60-U shots the value of the NBI driven current is negligible. Thus the accuracy of the NBCD calculations of the ASTRA NBI solver was verified by comparison with a few different codes for the shots with the tangential NBI. The results of comparison with PENCIL (JET), ONETWO (GA) and TRANSP (PPPL) codes are performed in fig.3. The agreement of the ASTRA NBI solver calculations with all others could be considered as satisfactory too.

4. CONCLUSIONS

The benchmarking reveals that the NBI solver of the ASTRA code provides satisfactory accuracy of the absorbed power and generated current calculations. Taking account of the ripple losses and multistep atomic processes for the high energy NBI enables calculation of both the transversal and negative beam injection in the JT60-U experiments. The fast treatment of all plasma parameters selfconsistently with the magnetic equilibrium makes the ASTRA code extremely convenient for the experimental data analysis and plasma transport calculations in the JT-60U experiments.

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In these shots with large fraction of trapped particles the effect of the magnetic field rippling plays an important role. The calculations of the NBI absorption without taking account of the ripple losses noticeably overestimate the bulk plasma NBI heating at the periphery (figs.1a, 2a). The simple technique described above enables to take into account the ripple losses and provides acceptable accuracy in comparison with the OFMC calculations (figs.1b, 2b).

In the case of the nearly perpendicular injection of both JT60-U shots the value of the NBI driven current is negligible. Thus the accuracy of the NBCD calculations of the ASTRA NBI solver was verified by comparison with a few different codes for the shots with the tangential NBI. The results of comparison with PENCIL (JET), ONETWO (GA) and TRANSP (PPPL) codes are performed in fig.3. The agreement of the ASTRA NBI solver calculations with all others could be considered as satisfactory too.

4. CONCLUSIONS

The benchmarking reveals that the NBI solver of the ASTRA code provides satisfactory accuracy of the absorbed power and generated current calculations. Taking account of the ripple losses and multistep atomic processes for the high energy NBI enables calculation of both the transversal and negative beam injection in the JT60-U experiments. The fast treatment of all plasma parameters selfconsistently with the magnetic equilibrium makes the ASTRA code extremely convenient for the experimental data analysis and plasma transport calculations in the JT-60U experiments.

ACKNOWLEDGMENTS

The authors express their gratitude to Dr. M. Azumi and Dr. T. Hirayama for continuous encouragement of this work .

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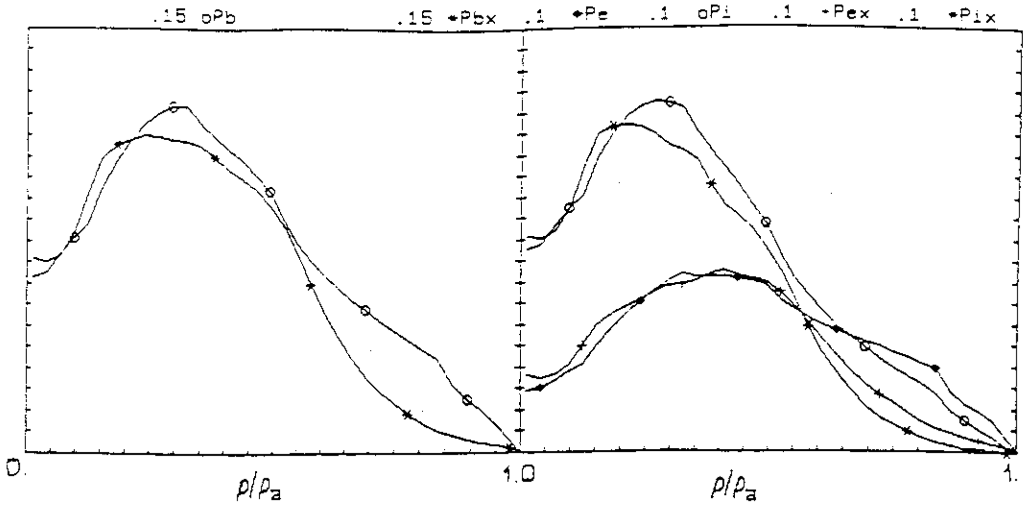

FIG.1 a NBI without ripple losses

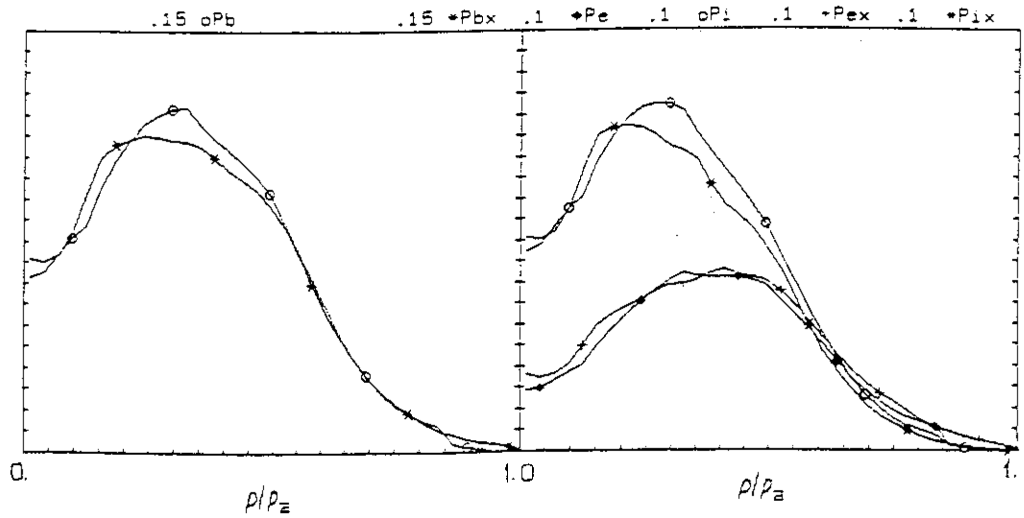

FIG.1 b NBI with ripple losses

FIG. 1 The benchmarking of the ASTRA NBI solver versus the OFMC calculations for the NBI L-mode JT60-U discharge E021795 (a) without (b) with taking account of the ripple losses in ASTRA calculations

at the right part:

(-o-) Pi is the radial distribution of the power absorbed by ions from the ASTRA NBI calculations,

(-◆-) Pe is the power absorbed by electrons (ASTRA),

(-*-) Pix is the power absorbed by ions (OFMC),

(-+-) Pex- is the power absorbed by electrons (OFMC),

at the left part:

(-o-) Pb = Pe + Pi (ASTRA)

(-*-) Pbx = Pex + Pix (OFMC)

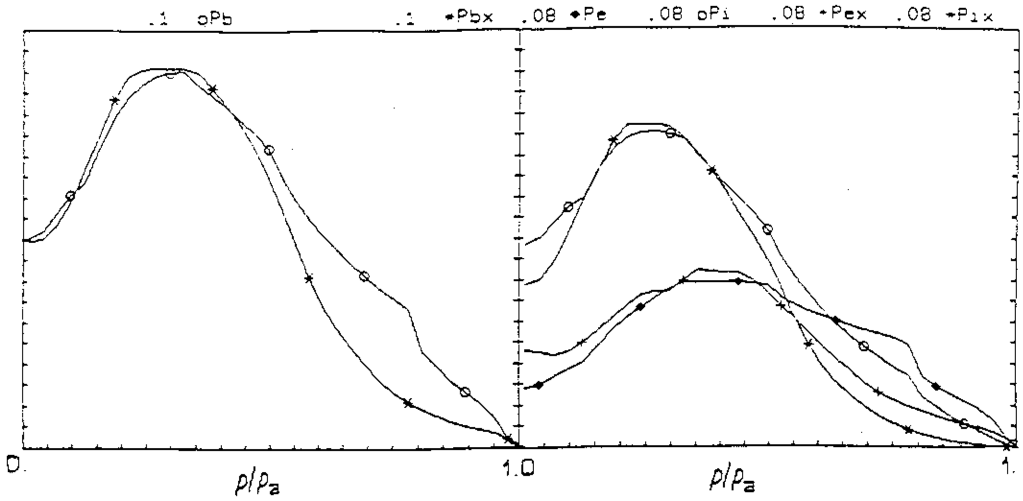

FIG.2 a NBI without ripple losses

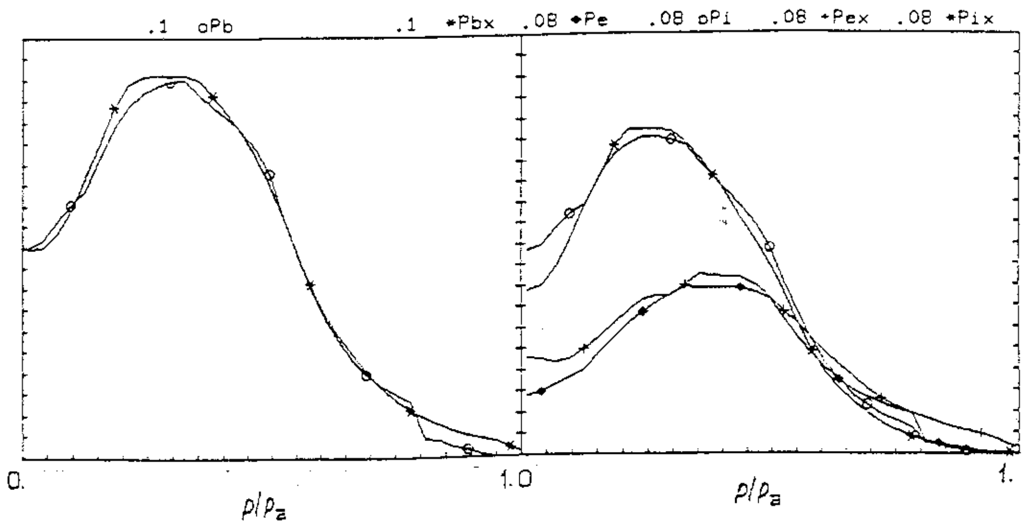

FIG.2 b NBI with ripple losses

FIG. 2 The benchmarking of the ASTRA NBI solver versus the OFMC calculations for the NBI L-mode JT60-U discharge E021796 (a) without (b) with taking account of the ripple losses in ASTRA calculations

at the right part:

(-o-) Pi is the radial distribution of the power absorbed by ions from the ASTRA NBI calculations,

(-◆-) Pe is the power absorbed by electrons (ASTRA),

(-*-) Pix is the power absorbed by ions (OFMC),

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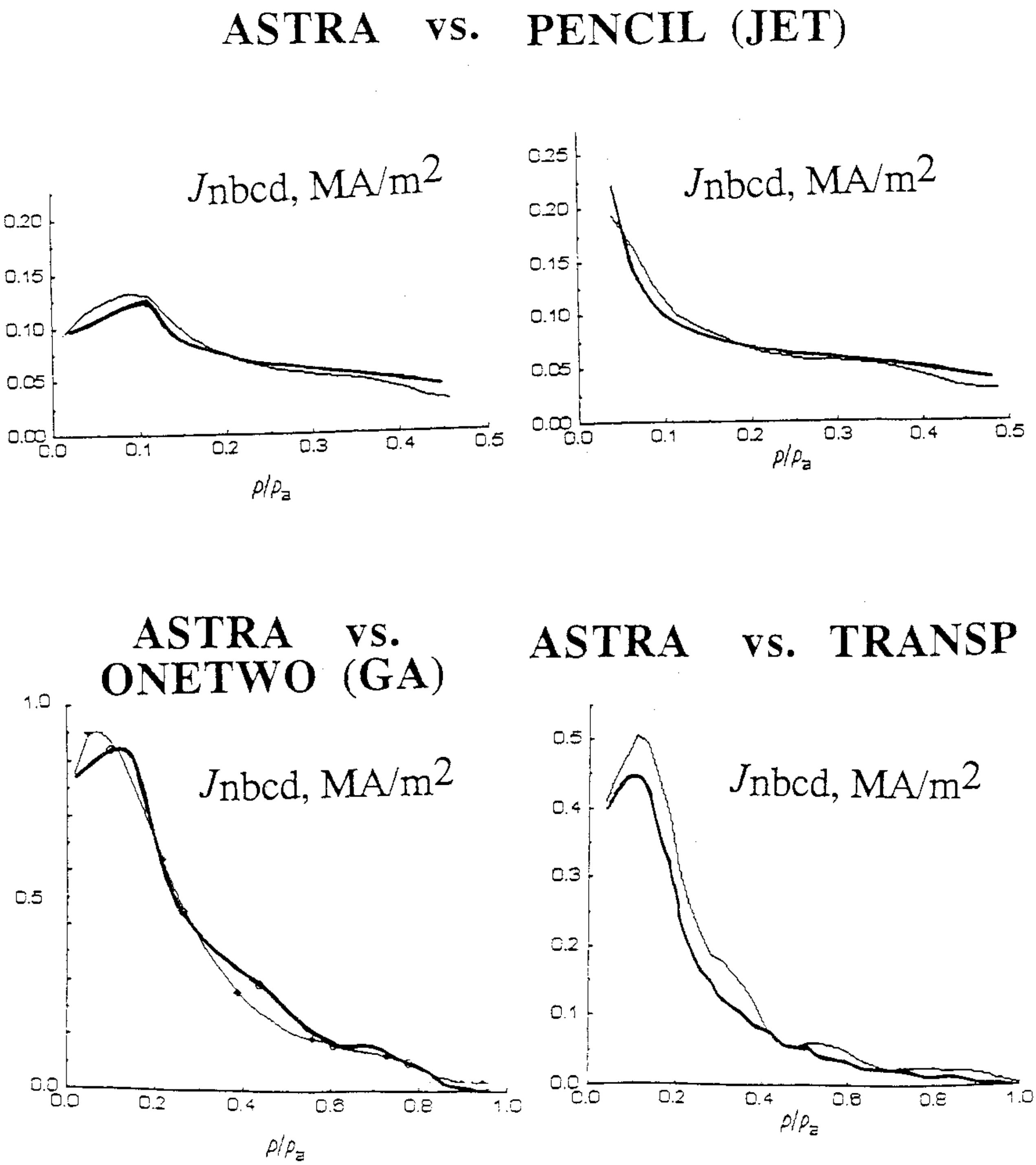

FIG.3

The benchmarking of the ASTRA NBI solver versus the PENCIL, ONETWO and TRANSP codes for the NBCD in the case of tangential injection.
(**—**) Solid curves correspond to the driven current density profile calculated by ASTRA NBI solver, (—) thin curves to the other codes.