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COMPARISON OF NBI CURRENT DRIVE THEORY WITH EXPERIMENT AND REQUIREMENTS FOR EXTRAPOLATION TO NEXT STEP DEVICES

—CONCEPTUAL DESIGN STUDY OF FY86 FER—

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Comparison of NBI Current Drive Theory with Experiment and Requirements for Extrapolation to Next Step Devices
- Conceptual Design Study of FY86 FER -

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The exactness of the present beam current drive theory was investigated by comparing between a numerical simulation and an experimental value. Ambiguities in the present beam current drive theory are also discussed. In order to estimate the potential of the NBI current driver in next generation tokamaks, the current-drive efficiency is calculated with INTOR parameters. Drive efficiency is nearly at the level of the r.f. current driver.

Keywords: NBI Current Drive, INTOR, Comparative Evaluations, Efficiency

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NBI電流駆動の理論と実験の比較および次期装置に適用するための要求
一次期大型装置設計（FY 86　FER）

日本原子力研究所那珂研究所臨界プラズマ研究部
岡野　邦彦*・山本　新・杉原　正芳

（1987年7月8日受理）

現在使われているビーム入射電流駆動に関する理論の精度を，その理論に基づく数値シミュレーションと，トカマク実験によって得られた測定結果とを比較することにより確かめた。また，現在の理論に残されている不確定な要素が何かについても言及した。次期装置の電流駆動装置としてNBIを採用した場合の性能を評価するため，INTORの標準装置パラメータを使い電流駆動効率を見積った。それによると効率は，他のRF電流駆動装置の場合とほぼ同等であることがわかった。

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1. Introduction

Non-inductive current-drive would be one indispensable technology to make the tokamak system a more attractive reactor candidate. Although lower hybrid wave current-drive is most successful to date, the recent beam current drive experiments in JET [1] and TFTR [2], where over half mega ampere currents have been driven, imply the large potential for the NBI (neutral beam injection) current drive method.

After the first beam current drive proposal by Ohkawa [3], many researchers have developed physical models. The first part of this study discusses the exactness of the present beam current drive theory by comparing between the result by the beam current drive analysis code and the DITE beam current drive experiments [4]. The following parts present results of investigations on the ambiguities remaining in the present model and the NBI current driver potential for the next generation tokamak.

Most part of this report was presented at the INTOR-related IAEA Specialists' meeting on non-inductive current drive, which was held from 15 to 17 September 1986 at Max-Planck Institute in Garching.

2. Beam Current Drive Analysis Code

The beam current drive analysis code DRIVER-3 is an upgraded version used in the earliest paper on the current profile and its control by beam + ICRF current driver [5]. The present code gives the current profile and the current drive efficiency in a non circular 3-D toroidal geometry. A beam power deposition code includes cross-sections of electron ionization, charge exchange, hydrogen and impurity impact ionization. The circulating fast ion current on each magnetic surface is estimated by a 2-D fast ion Fokker-Planck equation [6,7], which includes charge exchange loss and Alfvèn wave effect [8], as well as the slowing down, pitch angle diffusion and energy diffusion. The backstreaming electron current is determined in accordance with the finite aspect ratio calculation by Start & Cordey [9].

A quasi 1-D transport code with a simplified NBI current drive calculation [10] is also used to analyse some transient phenomena.

3. Comparison with Experiment

Clark et al. compared the NBI current drive experiment of DITE with a Fokker-Planck calculation [4], and have obtained a fairly good agreement. The authors also compared their Fokker-Planck calculation with the DITE experiment. Using the DITE experimental parameters of Discharge A in Ref. [4], the driven current estimated by the authors' code is 28 - 29 kA, when the observed current in DITE was about 33 kA (Table 1).

In this calculation, beam parameters, like the beam energy, power, and power ratio for molecular ions (H_2^+, H_3^+) and the plasma condition like the temperature profile, the density profile, Z_{eff} etc., are set up to be same as the experimental measurement. The 12 % current deviation, between the DITE measurement and the Fokker-Planck calculation, is much less than the error estimated in the experiment. Therefore, it can be concluded that the present beam current drive analysis code is fairly reliable to estimate the driven currents in tokamaks.

4. Present Model Ambiguity

The present NBI current drive theory ambiguity can be estimated as follows: First, the backstreaming electron current can be reduced by a neo-classical trapped electron effect. The existence of trapped electrons was not clarified in the DITE experiment, because the neo-classical effect in the total driven currents was small (15 %), owing to the high Z_{eff} (= 4.0). In the next step devices with a lower Z_{eff}, the neo-classical effect is important. Without the neo-classical effect, a large part of the beam driven current would be cancelled, due to the backstreaming electron current. Second, with several hundred keV injection, the fast ion velocity can exceed the Alfvèn velocity. Then, the Alfvèn waves may be generated and absorb the fast ion energy. The beam ions would be rapidly slowed to the Alfvèn velocity[1,4]. The Alfvèn wave effect existence is ambiguous, because there has been no experiment with such high energy injection reported to date.

The current drive efficiencies I_p/P_b (Amp/Watts) and Q value (= fusion power/driver power) for INTOR are plotted in Fig. 1. The INTOR parameters used here are listed in Table 1. In Fig. 1, the solid line values are calculated with the finite aspect model of neo-classical trapped electron effect [9]. The broken line values are the case without trapped electrons. If the present neo-classical model is valid, the Z_{eff} dependences of I_p/P_b and Q value are very weak, in the $1.5 < Z_{eff} < 3.0$ range. On the other hand, without the trapped electron correction, the efficiency and Q value are greatly reduced, and high Z_{eff} operation will be required to obtain an acceptable drive efficiency.

The drive efficiency degradation in INTOR, due to the Alfvèn wave effect, is shown in Fig. 2. In this calculation, it is assumed that the injected beam ions are immediately slowed down to the Alfvèn velocity, after trapped in the plasma. The beam energy with the Alfvèn velocity, E_A, is about 500 keV when $\overline{T}_e = 20$ keV, $\overline{n}_e = 0.93 \times 10^{20}$ m^{-3} and $\overline{n}_i = 0.87 \times 10^{-20}$ m^{-3} ($Z_{eff} = 2.0$). Therefore, the current drive efficiency for over 500 keV beams is greatly reduced by the A.W.I. (Alfvèn wave instability), while there is no degradation when $E_b < 500$ keV. As the over 500 keV beam is indispensable to drive currents with reasonable beam power in future large tokamaks, the A.W.I. investigation is a very critical issue.

5. A.W.I. study in Present Tokamak

An experimental approach to the A.W.I. study is not easy, because E_A is proportional to $A_b B_t^2/\sum_i(A_i n_i)$. That is, the A.W.I. experiment will require high density, high beam energy with moderate toroidal field. The achievement of these conditions is usually very severe, owing to the critical beta limit.

Marginal operation conditions which must be met to study the A.W.I., are plotted in Fig. 3, where the vertical axis is $E_A/A_b\cdot(B_t/5T)^2$ and the horizontal axis is ion density. When the 160 keV D^0 beam is available with $B_t = 2.5$ Tesla, the marginal operation point is shown by solid circle in the figure. The JET group is planning such beams. The marginal plasma parameters for JET to investigate A.W.I. are listed in Table 3. With $\overline{n}_e = 10^{20}$ m^{-3}, $\overline{T}_e = 4.0$ keV and $I_p = 4$ MA, β_t attains a beta limit ($\beta_t = 4.0\ I_p/a\cdot B_t = 5.1$ %). The 20 MW injection of 160 keV D^0 beam into such plasma will generate the 340 kA beam driven current without A.W.I. As the beam ion velocity exceeds the Alfvèn velocity in the plasma central region, if A.W.I. occurs, the driven currents should be reduced. However, the small current change (< 340 kA, in total 4 MA current) may be undetectable. In such a case, the direct measurement of fast ion velocity distribution will be required.

The result of quasi 1-D transport analysis with the above JET parameters is shown in Fig. 4, where the energy confinement time τ_E is assumed to be a half of the value by the INTOR/ALCATOR scaling in accordance with an L-mode discharge. The plasma beta attains the beta limit in 3 seconds after 20 MW beam has been switched on. This period of several seconds before beta limit seems to be sufficiently long to enable studying the A.W.I.

6. Steady State Operation of INTOR

The estimated current drive efficiency I_p/P_b (amp/watts) and Q-value for INTOR are plotted in Fig. 5 as functions of T_e. The dotted lines show a very pessimistic case, where the Alfvèn wave effect and no trapped electron effect are considered as well as the charge exchange loss with $n_0/n_e = 0.5 \times 10^{-5}$. The solid lines are an optimistic case, with full neoclassical effect, no Alfvèn wave and no charge exchange. The parameters used here are listed in Table 2. Beam energy $E_b = 500$ keV and $R_{tang} = 4.7$ m (minimum major radius of beam line). This beam energy is lower than the optimum value which gives a maximum current drive efficiency, but is more realistic for the INTOR design when considering the beam technology development in the near future [11]. In the optimistic case in Fig. 5, the current drive efficiency attains 0.1 (amp/watts) with $\overline{T}_e = 23$ keV and Q over 6 is achievable. In the pessimistic case, these values are reduced by 30 to 40 % and $Q_{max} = 4.2$. The most important loss mechanism in this case with $E_b = 500$ keV, is the lack of trapped electron effect. The charge exchange and Alfvèn wave effect are small in this case. However, with the increase in E_b, the Alfvèn wave effect becomes important, as shown in Fig. 2. If the Alfvèn wave instability is not suppressive, there is no expectation for efficiency improvement by increasing E_b over 1 MeV.

Throughout the calculation for Figs. 1, 2 and 5, broad profiles of temperature and density were used; $T = T_0(1 - x^2)$,

$n = n_0(1 - x^2)^{0.3}$, $x = r/a$. Each neutral-beam power in multi beam-lines is automatically controlled in order to maintain a preset desired current profile; $j = j_0(1 - x^2)^{0.5}$ (Fig. 6). Flexible current-profile controllability by NBI makes such treatment possible. Note that the fusion power and the current drive efficiency depend on these profiles. The present profiles are chosen to give some consistency with the high beta plasma equiliblia in the first stability regime, which would require a broad pressure profile as well as a broad current profile.

Finally, it should be note that the energy balance between the injection power and the loss power from the plasma is not discussed in the present Q calculation. As shown in Ref. [11], including the energy balance calculation with an transport model may result in a lower Q value than that of the present calculation, owing to the operating parameter range restricted by the energy balance condition.

7. Conclusion

The agreement between the simulation and the DITE experiment is fairly good. The main ambiguities in present model for the extrapolation to larger devices are the existence of trapped electron effect and the Alfvèn wave instability. The former will be clarified by the experiments on TFTR and JET. If a 160 keV D^0 beam is available, the latter can be investigated by JET.

The NBI current drive efficiency in INTOR, which is predicted by the present model, is about 0.1 Amp/Watts. This value is a level of other r.f. current drivers.

Acknowledgement

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References

[1] Cordey J. G., 'Beam Current Drive in JET', in INTOR Rerated Specialist's Meeting on Non-Inductive Current Drive, Garching (1986), to be published.

[2] Grisham L., 'Currents Driven During Beam Heating on TFTR', ibid.

[3] Ohkawa T., Nucl. Fusion 10 (1970) 185.

[4] Axon K. B. et al., Proceeding of 9th IAEA Int. Conf. on Plasma Physics and Controlled Fusion Research, Vol. 1, (1981) 413.

[5] Okano K., Inoue N. and Uchida T., 'Control of Current Distribution by ICRF-Enhancement of Beam-Driven Current', Plasma Phys. and Controlled Fusion 27 (1985) 1069.

[6] Gaffey J. D., Jr., J. Plasma Phys. 16 (1976) 149.

[7] Mikkelsen D. R. and Singer C. E., Nucl. Technol./Fusion 4 (1983) 237.

[8] Berk H. L. et al., Nucl. Fusion 15 (1975) 819.

[9] Start D. F. H. and Cordey J. G., Phys. Fluids 23 (1980) 1477.

[10] Masuzawa M. et al., 'Plasma Current Ramp-up by Neutral Beam Injector', to be published.

[11] Yamamoto, S. et al., in the 11th IAEA Int. Conf. on Plasma Physics and Controlled Fusion Research, Kyoto, 1986, IAEA-CN-47/H-I-3.

Table 1 Comparison between theory and DITE experiments [4]

Comparison with DITE Experiment

Discharge A ($H^{\circ} \rightarrow He^{++}$)

	Experiment	Fokker-Planck
density (m^{-3})	$n_{eo} = 4.0 \times 10^{19}$ $\overline{n_e} = 1.5 \times 10^{19}$	←
temperature (kev)	$T_{eo} = 0.67$	$T_e = T_{eo} (1 - r^2)^2$
P_b (MW)	0.9	← $H_1 : H_2 : H_3 = 7 : 1.5 : 1.5$
Z_{eff}	4.0	← (Fe 0.7 %)
I_{drive} (KA)	33	29.2 ($n_o = 0$) 27.7 ($n_o = 10^{15} m^{-3}$)

Table 2 INTOR parameters used in this study

INTOR

$R = 5$ m, $a = 1.2$ m
$\kappa = 1.6$, $\delta = 0.2$
$B_t = 4.96$ T,
$I_p = 6.4$ MA ($q_\psi = 2.0$)
$\beta_t = 5.92$ % ($\beta_t = 5.5 I_p / a B_t$)
$E_b = 500$ keV, D^0 BEAM

* TEMPERATURE & DENSITY PROFILES

$T_e = T_{eo}(1-r^2)$ (PARABOLIC)
$n_e = n_{eo}(1-r^2)^{0.3}$ (VERY FLAT)

Table 3 JET parameters required for A.W.I. study

JET

$R = 2.96$ m
$a = 1.25$ m, $\kappa = 1.6$
$R_{tang} = 1.85$ m

$n_e = 10^{20}$ m^{-3}
$T_e = 4.0$ keV
$B_t = 2.5$ T
$I_p = 4.0$ MA

} Beta-t = 5.1 % (TROYON'S LIMIT)

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* 160 keV D^0-BEAM 20MW

$I_{drive} = 340$ kA
$I/P = 0.017$ AMP/WATTS
$I_{drive}/I_p = 8.5$ %

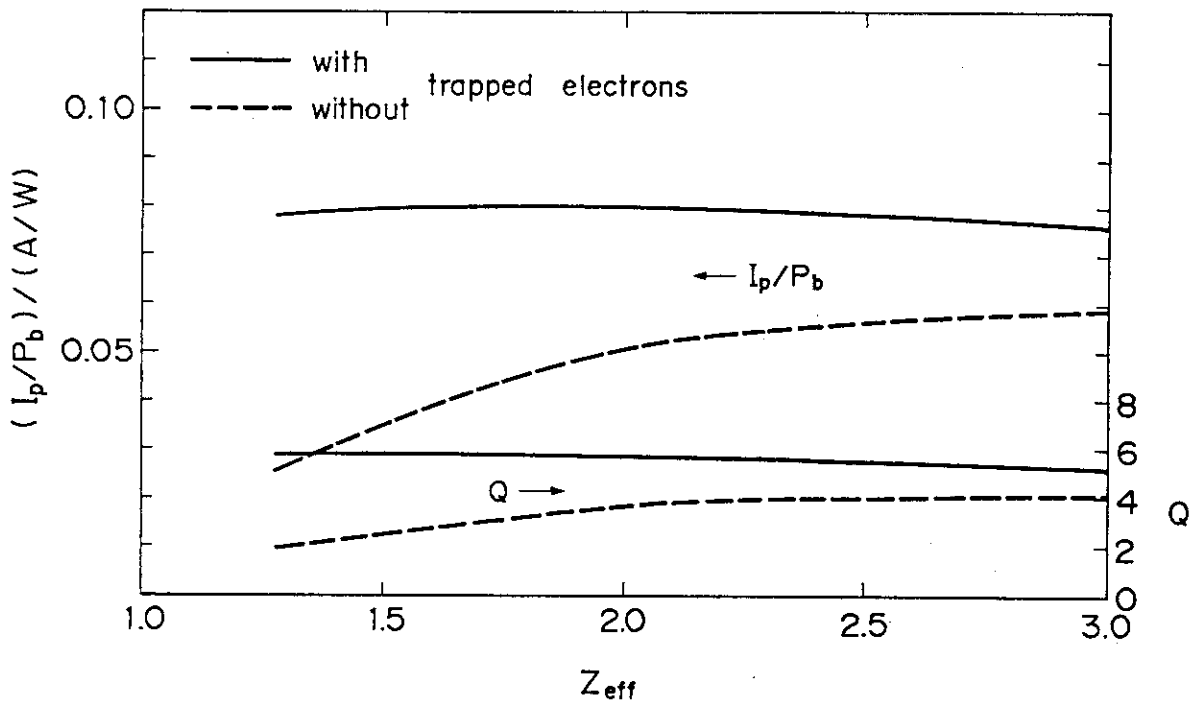

Fig. 1 Current drive efficiency with/without trapped electron effect

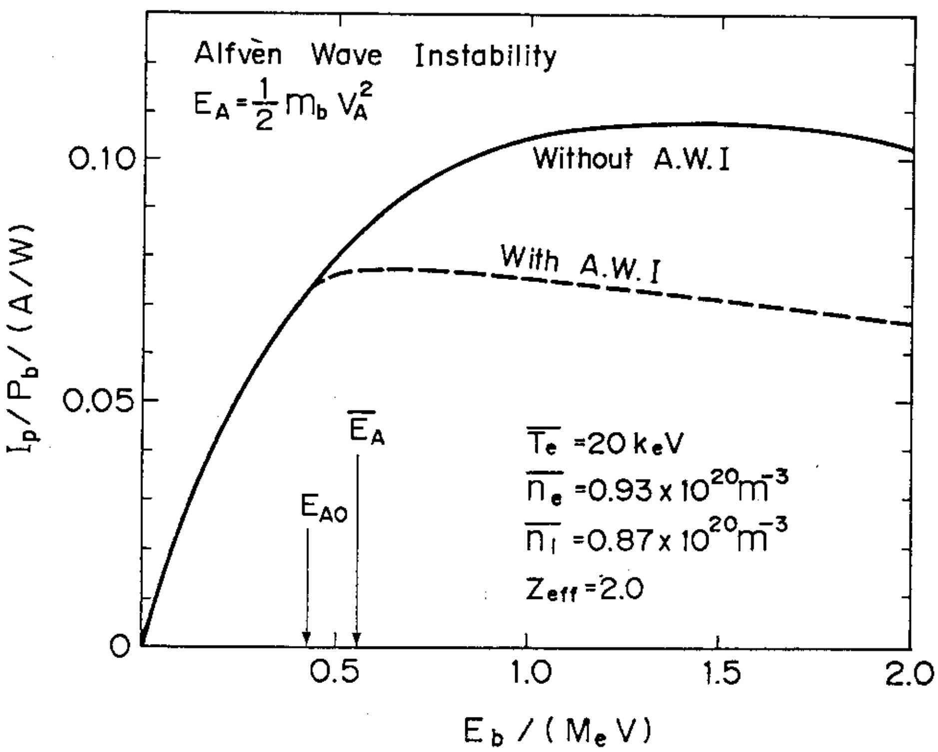

Fig. 2 Drive efficiency degradation due to Alfvèn wave instability (A.W.I.)

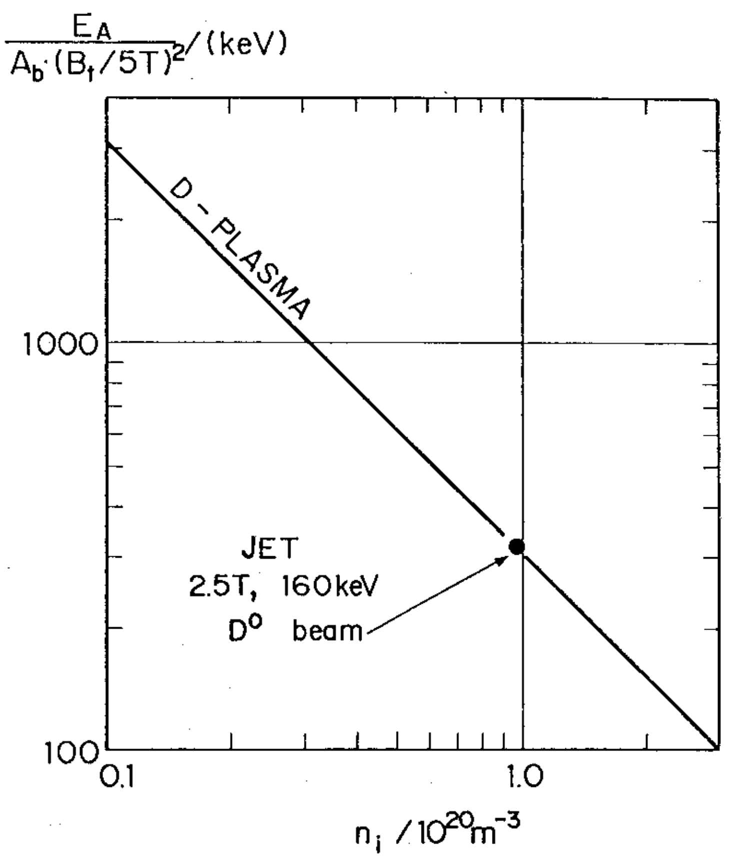

Fig. 3 Marginal operation parameter for A.W.I. study

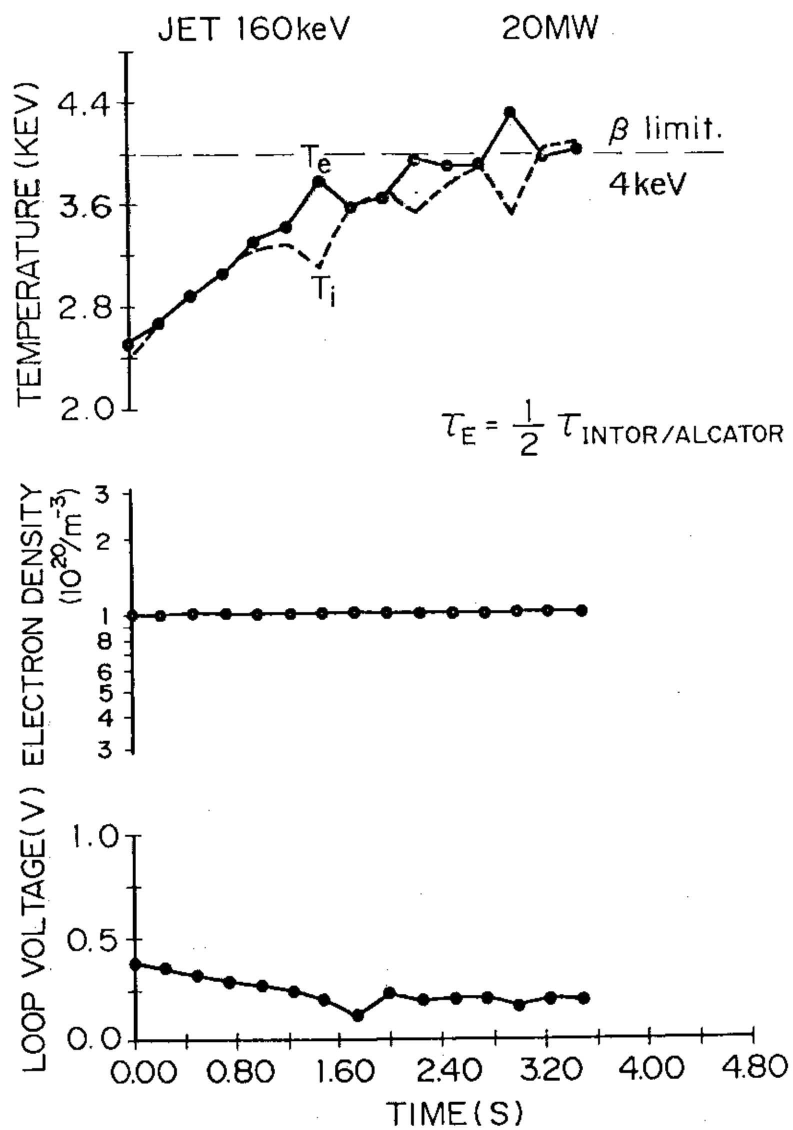

Fig. 4 Transport analysis during A.W.I. study in JET, with 20 MW 160 keV D^0 beams

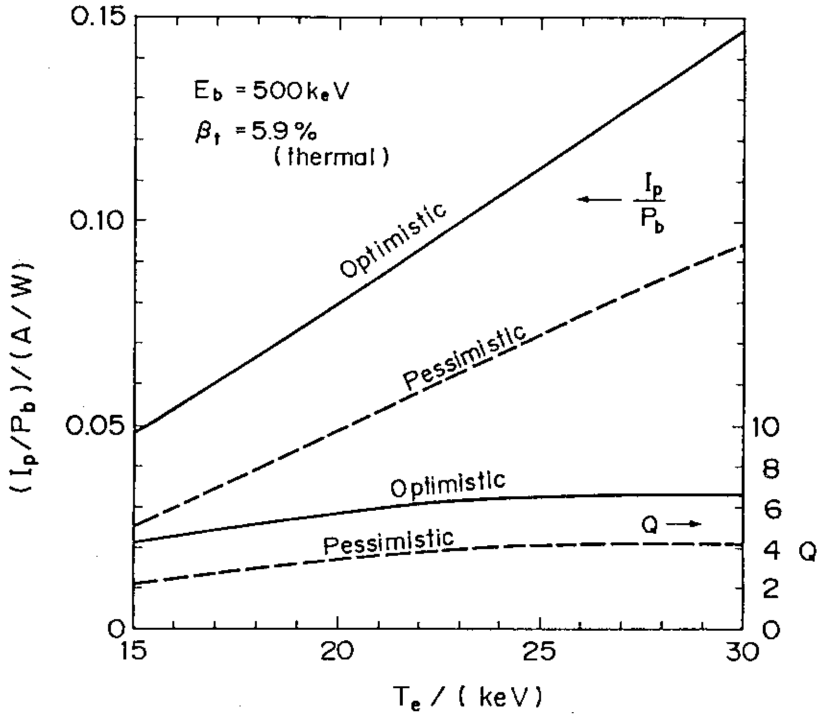

Fig. 5 Current drive efficiency and Q value for INTOR

*Optimistic case: Full trapped electron effect no A.W.I. and negligible charge exchange with Z_{eff} = 1.8 (to maximize Q)

*Pessimistic case: No trapped electron effect with A.W.I., charge exchange loss ($n_e/\bar{n}_e$ = 5 x 10^{-6}) and Z_{eff} = 2.5 (to maximize Q)

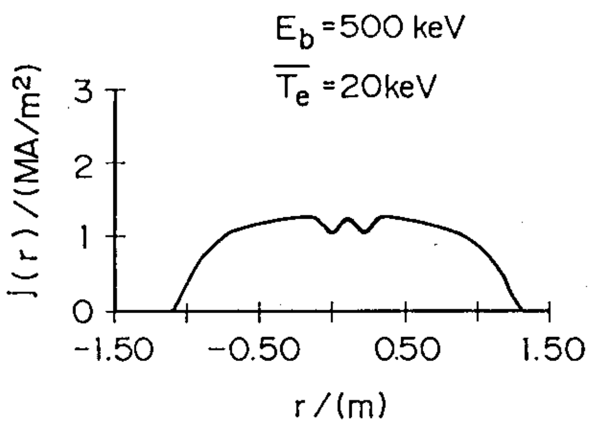

Fig. 6 Example of driven current profile

$J(r) \propto \{1 - (r/a)^2\}^{0.5}$