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TRANSPORT CODE STUDIES OF INTOR
AT PPPL

BY

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**PLASMA PHYSICS
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TRANSPORT CODE STUDIES OF INTOR AT PPPL

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1. SUMMARY

This report summarizes transport modeling studies carried out with the BALDUR one-dimensional transport code for the International Tokamak Reactor INTOR. The work described here uses a reference set of machine parameters agreed upon by the U.S. INTOR Concept Advisory Group in April 1979. The plasma transport model used is based on suggestions reported from the Energy and Confinement Group in the minutes of the February 1979, INTOR Workshop in Vienna. The reference transport model was further defined in March 1979, by the Modeling Subcommittee of the Energy and Particle Confinement committee, which is one of the team of experts participating in the U.S. INTOR study.

This report has been written to provide an accessible compilation of INTOR plasma simulation results, and to be included as part of the documentation provided by the Modeling Subcommittee. In Sec. 2 of this report, we describe the reference transport model and results of plasma simulations using this model. Particular attention is paid to the length of the heating pulse needed for ignition, and the value of the plasma pressure at ignition. The particle fluxes through the plasma boundary are also reported. In Sec. 3, we report the results of varying the assumptions in the reference machine design and transport model. Particular attention is paid to the problem of variations in the assumed plasma confinement, since this is a major source of uncertainty in reactor design. In Sec. 4 the conclusions of this study are summarized.

2. REFERENCE MODEL

In this section we describe results from a single standard set of machine parameters and a standard transport model. The machine parameters are listed in Table 1, and the transport model is described in Table 2. However, it was not expedient to use a unique method of programming the plasma parameters, so the results from three different plasma startup scenarios are presented. These scenarios are described in Table 3.

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TABLE I: MACHINE PARAMETERS

DIMENSIONS

Major Radius (m)	4.8
Minor Radius (m) (equivalent circle)	1.47
Ellipticity	1.5
B_T on Axis (T)	5.6
Plasma Current (MA) (equivalent circle)	3.75
Toroidal Field Ripple (%)	0

HEATING

Power (MW)	60
Neutral Beam Energy (keV)	150
Injected Species	D ⁰
Energy Mix at Full:1/2:1/3 energy	
by Atomic Current	0.60:0.24:0.16
by Power	0.78:0.09:0.04
Beam Tangency Radius (m)	1.63

FUELING Beam fueling
plus Gas puffing

TABLE II: REFERENCE TRANSPORT MODEL

Diffusivities (cm ² /s)	
χ_e	$5 \times 10^{17}/n_e + \text{neoclassical}$
χ_i	$3 \times \text{neoclassical}$
D_{Hydrogen}	$1.25 \times 10^{17}/n_e$ $+ 3 \times \text{neoclassical}$ $+ \text{Ware pinch}$ $+ (500 r^3/a^3 \text{ for long pulse model})$
$D_{\text{Impurities}}$ Standard model Long pulse	Fixed n_{Oxygen}/n_e $\left\{ \begin{array}{l} 1.25 \times 10^{17}/n_e \\ + 3 \times \text{neoclassical} \\ + 500 r^3/a^3 \end{array} \right.$
Recycling Coefficient	
Hydrogen	0.9
Impurities	1.0
Fast Ions	
Beam Ion Treatment	Fokker-Planck
Beam Charge Exchange Loss	None
Alpha Heating	Delayed from birth
Fraction of α -Heating to Ions	Steady-state fraction

TABLE III: STARTUP SCENARIOS

Scenario	Density*	Gas Puffing*	Impurities
1. Constant Density [†] (to define ignition and optimize n_e)	$\langle n_{e14} \rangle$ (t)	fraction T (t)	Oxygen $Z_{eff}(r) = 1.5$
	1.4 (0)	0.7 (0)	
		0.7 (t_{off})	
		0.5 ($t_{off} + 1$)	
	1.4 (14)	0.5 (14)	
2. Standard Variable Density Startup (used as a reference scenario for com- parison with varia- tions)	0.7 (0)	0.9 (0)	Oxygen $Z_{eff}(r) = 1.5$
	0.7 (0.5)	0.9 (0.5)	
	1.4 (7.5)	0.7 (7.5)	
		0.5 (8.5)	
	1.4 (10)	0.5 (10)	
3. Long Pulse (to study helium accumulation and energy and particle fluxes)	0.7 (0)	0.9 (0)	$\langle n_{Oxygen} \rangle =$ $1.4 \times 10^{12} \text{ cm}^{-2}$ Helium Accumulates
	0.7 (0.5)	0.9 (0.5)	
		0.7 ($t_{off} = 5.8$)	
		0.5 ($t_{off} + 1$)	
	1.4 (7.5)		
	1.4 (25)	0.5 (25)	

* Density and tritium fraction in puffing gas are interpolated linearly between times in seconds shown in parentheses. Beam heating starts at $t = 0.5 \text{ s}$.

[†] Density and beam turnoff time t_{off} are varied between various constant-density runs.

2.1 Defining Ignition

The first problem we addressed was finding a useful definition of ignition, since the main thrust of this work is to investigate the influence of various assumptions in the machine design and transport model on the requirements for ignition. The most straightforward definition of ignition is obtained by removing auxiliary heating at various times and following the evolution of the plasma pressure. If the pressure is nondecreasing after a long period of smoulder (e.g., after one particle confinement time, about 6 seconds) then the plasma can be said to have ignited. This definition of ignition is unambiguous if the accumulation of alpha-particle ash is neglected; otherwise, the ash-removal mechanism must also be specified and investigated.

A series of plasma simulations designed to define ignition in a startup scenario with constant plasma density is illustrated in Fig. 1a. Buildup of a small fraction of helium ash is neglected in these calculations.

Since it is inconvenient to repeat such calculations for a large variety of machines and transport models, we have searched for an approximate but simpler definition of ignition. The criterion we have chosen is that the rate of increase in energy of the thermal particles in the inner half of the plasma volume should exceed the rate of auxiliary heating in the inner half of the plasma volume. We consider only the inner half of the plasma volume rather than the whole plasma because strong edge heating, which occurs in the startup scenarios considered here, is ineffective in producing ignition. Therefore, it is primarily the conditions in the plasma core which are relevant to ignition. That this simple definition of ignition is adequate for the case shown in Fig. 1a is illustrated in Fig. 1b. In Fig. 1b we plot the difference between the rate of energy gain and the auxiliary heating inside the radius $r = 0.7a$ as a function of time. This difference is approximately equal to zero at the ignition point, which is defined by the dot in Figs. 1a and 1b.

The above definition of ignition has been used in all of the studies reported here. It has been checked against the more rigorous criterion described above only for the long pulse simulations described below in this section, which have variable plasma density during startup. The heating pulse required for ignition in this case agreed to within 1% using the two definitions of ignition. Such excellent agreement cannot be guaranteed for all of the cases reported here. It must nevertheless be apparent that our simpler criterion for ignition is, at the least, a reasonable qualitative comparator for various machine parameters and transport models. We shall, therefore, routinely report the heating pulse required to attain ignition (by this simple definition) as a measure of confinement and alpha heating in various startup scenarios. We shall also report the value of the volume-averaged total kinetic pressure to magnetic pressure ratio $\langle\beta\rangle$, since theory suggests that this may put a limit on achievable plasma parameters. As an example, Fig. 2 shows the heating pulse t_{ig} and pressure ratio $\langle\beta\rangle_{ig}$ at ignition for a variety of plasma densities and for 150 keV and 200 keV neutral beam injection. The study depicted in Fig. 2 was done in order to define the optimal plasma density for heating to ignition. Not unexpectedly, it was found that the minimum $\langle\beta\rangle$ for ignition occurs well above a volume average plasma electron density of $\langle n_e \rangle = 10^{14} \text{ cm}^{-3}$ but that the minimum in $\langle\beta\rangle_{ig}$ is very shallow.

2.2 Standard Variable-Density Startup

Since the heating pulse required for ignition is much lower at lower plasma density, it was decided to approach the ignited burn with a variable-density

startup scenario, where $\langle n_e \rangle$ is raised from 0.7 to $1.4 \times 10^{14} \text{ cm}^{-3}$ over a specified period. The time over which the density was increased was chosen to be 7 sec in order to achieve ignition at 10^{14} cm^{-3} in the reference model.

The results for the variable-density reference model will now be described in some detail, since this is the model about which the variations to be described below in Sec. 3 were made. The values of t_{ig} and $\langle \beta \rangle_{ig}$ for this reference model are given by the points marked * in Figs. 2a and 2b. The evolution of $\langle n_e \rangle$, the central electron density n_{e0} , the density-averaged temperatures $\langle T_e \rangle_n$ and $\langle T_i \rangle_n$, the peak temperatures T_{e0} and T_{i0} , and various contributions to the pressure ratio $\langle \beta \rangle$ are shown in Fig. 3. The density, temperature, and beam-heating profiles just before ignition are shown in Fig. 4.

2.3 Burn with Helium Accumulation

In order to illustrate the particle and energy fluxes which might occur in an extended thermonuclear burn, we have slightly modified the standard variable-density startup. The modifications include turning off the beams after 5.3 sec of heating and accumulating all of the fusion-generated helium ions. The oxygen and helium impurities are transported according to the empirical diffusion model described in Table 2. (A small anomalous contribution of the form $500 r^3/a^3 \text{ cm}^2/\text{sec}$ is added to the particle diffusion coefficient to help overcome numerical problems with the large gradients near the edge of the plasma.) The length of the heating pulse in this simulation is chosen so that the pressure ratio (Fig. 5a) and the fusion power rise only very gradually in the 19 sec of burn. The parameters of interest for this long pulse simulation are the helium production and the net tritium and total hydrogenic particle outflux (Fig. 5b), and the power outflux in the form of neutrons, plasma particles, charge exchange neutrals, and radiation (Fig. 6). Also shown in Fig. 5b is the total amount of iron which would be sputtered by charge exchange neutrals if the first wall were made of stainless steel, as an indication of the magnitude of one possible impurity generation mechanism. It should be kept in mind that many of these results may be highly dependent on the transport model used and on the boundary conditions and hydrogen and impurity recycling coefficients assumed. An investigation of these problems was beyond the scope of the present study, however.

2.4 Density Programing

The INTOR standard 60 MW D⁰ beams represent a current of 518 A (including the half and third energy components). This current represents a flux of 3.23×10^{21} particles/sec or a rise rate of the volume averaged density of $1.348 \times 10^{13}/\text{cm}^3 \text{ sec}$. For five seconds of injection, this will raise the volume averaged density by $6.75 \times 10^{13}/\text{cm}^3$. Since this source is all D⁺ and is somewhat peaked at the center (certainly more peaked than the source from gas puffing and plasma recycling) it can seriously dilute the tritium at the center.

In our calculations, this effect has been reduced by recycling only 90% of the plasma (D and T) particle loss (~10% is pumped by a divertor, gettering, etc.) as neutrals and by gas puffing tritium at the plasma edge at a rate designed to keep the volume average density at a programed level. The tritium source (gas puffing) is at the edge and the deuterium source (60 MW beams) is at the center. For the standard variable density startup case, the relative fraction of tritium $[n_T/(n_D + n_T)]$ in the center goes from 0.9 at $t=0$ (in the variable density startup) to 0.37 after 5 secs of beam injection. Injection for longer times continues to reduce the central tritium fraction. After the beams are turned off, a 50% D - 50% T mixture is puffed in at a rate programed to keep the volume averaged

density constant. Without the partial recycling and tritium gas puffing during beam heating, either the density will rise at a rate $\sim 1.4 \times 10^{13}/\text{cm}^3 \text{ sec}$ (faster at the center), or there will be very little T at the center.

The code includes separate equations for deuterium and tritium transport as well as a two species neutral gas treatment. Neutral sources due to recycling, gas puffing, neutral beam deposition by charge exchange, and hydrogen recombination are computed.

3. VARIATIONS FROM STANDARD MODEL

In this section we report the results of varying the standard transport model and machine parameters. First we show the large variations in $\langle \beta \rangle_{ig}$ and t_{ig} which occur for the reference machine design if the electron thermal diffusivity is allowed to vary over the minimum range of values which can reasonably be extrapolated from existing experiments. Then we illustrate the smaller variations which result from what we think to be reasonable variations in other parameters such as the ion thermal diffusivity, plasma current, low-Z impurity content, and neutral beam energy. The most obvious uncertainty in the plasma physics which is likely to have a major effect on the size and cost of INTOR is the electron thermal diffusivity, so we have included a brief examination of how the machine parameters might be varied in response to improved measurements of this quantity. The effect of toroidal field ripple is also discussed.

3.1 Electron Thermal Diffusivity

Figure 7 shows the variation of $\langle \beta \rangle_{ig}$ and t_{ig} with electron thermal diffusivity, χ_e . In Fig. 7 the scaling of χ_e is kept proportional to $1/n_e$ but the magnitude of the diffusivity is varied. The point * in Fig. 7 shows the results for a case identical to the standard variable-density startup scenario except with $\chi_e = 5 \times 10^{17}/(n_e T_e^{0.75})$ (with T_e in keV).

3.2 Variation of Miscellaneous Parameters

Table 4 shows the effect of various changes from the standard variable-density startup model. The first two entries after the standard model show the effects of varying the neoclassical ion transport either directly or by increasing the plasma current by 25%. The long pulse model shows the effects of increasing the low-Z impurity levels (from 0.9% oxygen and no helium at ignition in the standard model to 1.2% oxygen and 1.4% helium at ignition in the long pulse model).

The fifth entry in Table 4 shows that 10 MW of power from a 400 keV negative ion source can be substituted for 20 MW of positive ion power (with the standard energy mix for the positive ion source given in Table 1). This substitution causes little change in the startup scenario. However, an attempt to reduce the power to 10 MW/400 keV + 30 MW/(150, 75, 50) keV gave no ignition after 7 sec of neutral injection.

The last two entries in Table 4 show the effect of making a substantial change in the radial dependence of the electron thermal diffusivity χ_e . A detailed analysis of the energy balance in the beam-heated experiments on FLT (see the

report of the INTOR, Energy and Particle Confinement team) has indicated that the electron thermal diffusivity should be a more strongly increasing function of r/a than would be given by a n_e^{-1} dependence alone. A reasonable fit to the PLT data is given by $\chi_e = 1 \times 10^{17} / [n_e (1 - r^2/a^2)^{3.5}]$. Compared with our standard model, namely $\chi_e = 5 \times 10^{17} / n_e$, this corresponds to a smaller diffusivity in the central part of the plasma, and a much larger diffusivity in the outer part. The last two entries in Table 4 are the results of computations run with this "PLT model" for χ_e , namely the standard variable-density startup scenario, and the variant of it where 20 MW of standard beams are replaced with 10 MW at 400 keV. We see that the times to reach ignition are somewhat longer than with the standard model for χ_e , due to the relative ineffectiveness of the heating power that is deposited in the outer part of the plasma. We also see that the $\langle \beta \rangle$ value at which ignition occurs is lower than with the standard model. However, with the new χ_e model, the temperature profiles are much narrower than with the standard model giving rise to larger pressure gradients so that, from the point of view of MHD stability, the lower $\langle \beta \rangle$ values may not be any easier to attain.

TABLE IV: VARIATIONS FROM STANDARD MODEL

Model	t_{ig} (s)	$\langle \beta \rangle_{ig}$ (%)
Standard	4.4	3.8
$\chi_i = 1 \times$ neoclassical	3.5	3.2
$I_{eq} = 4.69$ MA	3.8	3.4
Long Pulse Model $\langle n_{Oxygen} \rangle = 1.4 \times 10^{12} \text{ cm}^{-3}$ + He accumulation	5.6	4.4
High Energy Beam 10 MW/400 keV + 40 MW/(150, 75, 50) keV	5.3	3.7
PLT Model $\chi_e = 10^{17} / [n_e (1 - r^2/a^2)^{3.5}]$	5.0	2.4
PLT Model with High Energy Beam 10 MW/400 keV + 40 MW/(150, 75, 50) keV	5.7	2.3

3.3 Varying the Minor Radius with χ_e

Given that we do not presently understand electron energy transport in tokamaks, but that measurements of this transport in plasmas much nearer the reactor regime is imminent, it seems a revision in the standard transport model is likely to occur before the final design of an INTOR-type machine is implemented. Slightly worse energy confinement than that assumed in the standard model would force a larger minor radius to achieve ignition at modest $\langle\beta\rangle$, and better confinement might allow a smaller and less expensive machine. As a simple illustration of the plasma physics consequences of such revisions, we have run three simulations with nominally identical energy confinement time, i.e., with $a^2 \propto \chi_e$. We have kept the inner edge of the plasma at fixed major radius (although this might in fact vary slightly in optimized designs) and scaled the plasma major radius and toroidal field accordingly, as listed in Fig. 8. The angle of the beam centerline with the magnetic axis was kept constant. The beam energy was kept constant at 150 keV (as might be appropriate if the beam development program were committed to positive ion sources).

The injection power was scaled with the plasma volume, the idea being to calculate t_{ig} for each simulation to see if this is an appropriate scaling. The results of this investigation, given in Fig. 8, show the desired result that $\langle\beta\rangle_{ig}$ is nearly constant, indicating the appropriateness of the minor radius scaling used. However, the results for t_{ig} indicate that the smallest machine may be slightly underequipped with neutral injection power. These results do not represent a survey of optimized machine designs, which are more appropriately found with zero-dimensional codes. These results are meant to provide a single set of one-dimensional, self-consistent calculations specific to INTOR.

4. EFFECT OF FIELD RIPPLE

The calculations discussed above have all neglected any contribution to the ion thermal conductivity χ_i from field ripple. For INTOR parameters, the most important contribution to χ_i from field ripple arises from those ions that are actually trapped in the local ripple wells. An expression for this contribution, denoted χ_i^{RT} , has been given in the report of the INTOR Energy and Particle Confinement team for the case where the peak-to-average field ripple $\delta(r, \theta)$ can be approximated by

$$\delta(r, \theta) = [\delta_0 + (\delta_a - \delta_0) r^m / a^m] \exp(-\beta \theta^2) \quad .$$

We have employed this expression for χ_i^{RT} in our transport code, and performed calculations for INTOR with various sets of ripple parameters. Other effects of field ripple, such as contributions to χ_i from ripple induced radial drifts of toroidally-trapped particles, or ripple losses of beam ions or alpha-particles, are neglected in our calculations. Although these effects are not believed to be as important as the ripple-trapping contributions to χ_i , they are not well understood at this time, and their neglect implies that our calculations tend to underestimate the adverse effects of field ripple.

For our calculations with field ripple, we have chosen the long pulse case with helium accumulation, discussed in Sec. 2.3, in view of the interest in the question of whether field ripple can provide control of the temperature in a long-pulse ignited burn.

For a case with 4% peak-to-peak ripple ($\delta_a = 0.02$, $\delta_o = 0.002$, $\beta = 0.4$, $m = 2$, $N = 12$) roughly corresponding to the 12 coil INTOR reference design concept (TF coil bore of 6m/9m), the plasma falls far short of reaching ignition. For 2% peak-to-peak ripple, ignition is marginal, and depends quite sensitively on details of the programed gas puffing, especially the fraction of tritium in the gas. For the long pulse case discussed in Sec. 2.3, we have succeeded in achieving ignition only by eliminating the oxygen impurities, thus increasing the density of the reacting ions.

Figure 9 shows results for this case, where the specific parameters of the 2% peak-to-peak ripple roughly correspond to a 14-coil INTOR design ($\delta_a = 0.01$, $\delta_o = 0.0006$, $\beta = 0.3$, $m = 2$, $N = 14$). We see that ignition has clearly been achieved, in the sense that the temperatures are maintained for some considerable time after the beams are turned off at 5.8 secs. However, no thermal runaway occurs; the thermal losses due to ripple trapping limit the central ion temperature at about 30 keV. Eventually, the central temperatures decline, quite abruptly, as the helium buildup leads to a reduction in the densities of the reacting deuterons and tritons. The burn pulse is thus limited to about 25 secs.

5. CONCLUSIONS

The conclusions of this investigation of one-dimensional transport simulations of the INTOR design are straightforward. First, the reference design should ignite at modest pressure ($\langle\beta\rangle = 4\%$) and with the specified heating pulse and power. Second, assuming adequate impurity control (!), the major uncertainty in the actual INTOR plasma parameters arises from possible variations in the electron thermal diffusivity χ_e . Future measurements of χ_e may suggest revisions of the machine parameters as discussed above. Finally, the self-consistent set of particle and energy fluxes derived for the above long pulse scenario may be of use as a rough guide in assessing of pumping and cooling requirements for the INTOR reference concept.

Field ripple has been identified as a serious limitation on the capability of INTOR, and our computations show that the peak-to-peak ripple at the edge of the plasma must be held below 2% if ignition is to be achieved. In this case, field ripple does seem to be capable of providing control of the ion temperature in a long pulse ignited burn.

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FIGURE CAPTIONS

Fig. 1 Evolution of INTOR plasma parameters at $\langle n_e \rangle = 1.4 \times 10^{14} \text{ cm}^{-3} = \text{constant}$. (a) Volume average pressure ratio with beam heating turned off at $t_{\text{off}} = 7.2, 7.6, \text{ and } 8.0 \text{ s}$. (b) $\Delta P_{0.7} = [(\text{rate of increase of thermal plasma energy}) - (\text{auxiliary heating})]$ inside $r = 0.7 a = 1.0 \text{ m}$ for $t_{\text{off}} = 8.0 \text{ s}$. (All figures are labeled in the lower right-hand corner with numbers which identify the relevant computer simulations.)

Fig. 2 (a) Volume-average pressure $\langle \beta \rangle_{ig}$ and (b) heating pulse t_{ig} for ignition at constant density with 60 MW of 150 keV and 200 keV beam injection, and variable density with 150 keV beams (*).

Fig. 3 Evolution of plasma parameters in standard variable-density startup scenario with beam heating from 0.5 to 5.0 s: (a) central and volume-average electron density; (b) central and density-weighted average ion and electron temperatures; (c) volume-averaged total pressure ratio β and contributions from thermal electrons β_e , thermal ions β_i , fast α particles β_α , and fast beam ions β_b .

Fig. 4 Radial profiles 0.3 s before ignition for standard variable-density startup parameters listed in Table 3. (a) Density n_e of electrons, n_D of deuterons and n_T of tritons, (b) ion and electron temperatures, (c) instantaneous power density from beam heating of thermal particles.

Fig. 5 Evolution of plasma parameters for long pulse parameters listed in Table 3. (a) Volume-average pressure ratio, (b) particle balance, including [(integrated fueling) - (change in number of particles in plasma)] for tritons ($N_{T, \text{Wall}}$) and all hydrogenic ions (N_{Wall}), total number N_{plasma} of hydrogenic ions in plasma, integrated helium production N_{He} , and integrated number N_{Fe} of iron atoms sputtered by charge-exchange from a stainless steel wall (these iron atoms are assumed here not to enter the plasma). Right-hand ordinates show conversion to units of kilo-Curies ^3H , and torr-liters of H_2 at 0°C .

Fig. 6 Power outflux for long pulse parameters listed in Table 3. Right-hand scale gives neutron power P_{Neutrons} and left-hand scale gives power outflux in thermal plasma P_{plasma} , radiation P_{rad} , and charge-exchange neutrals P_{cx} .

Fig. 7 Ignition requirements for standard variable-density startup scenarios identical to that listed in Table 3 but with variable electron thermal diffusivity χ_e . Results for $\chi_e = 5 \times 10^{17} / (n_e T_e^{0.25} \text{ keV})$ are given by the points labeled *. (a) Volume-average pressure ratio and (b) heating pulse at ignition.

Fig. 8 (a) Volume-average pressure ratio and (b) heating pulse required for ignition for standard variable-density startup parameters listed in Table 1-3, with modifications as indicated at the bottom of the figure.

Fig. 9 Long pulse case with 2% peak-to-peak ripple and helium accumulation. No oxygen impurities; $Z_{eff} = 1 + \text{helium contribution}$. Beams are off at 5.8 secs. (a) Central deuterium, tritium, and helium densities. (b) Central electron and ion temperatures.

DEFINITION OF IGNITION

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

$\sigma_{eq}(m)$	1.14	1.47	1.74
$R(m)$	4.53	4.80	5.02
$B(T)$	5.30	5.00	4.78
$I_{eq}(MA)$	2.37	3.75	4.44
$P_b(MW)$	34	60	88

Fig. 8

Fig. 9

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