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WITH INTOR-LIKE PARAMETERS

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Ignition in a Tokamak Reactor with INTOR-Like Parameters

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ABSTRACT

The requirements for ignition in a tokamak reactor with INTOR-like parameters were studied using a one-dimensional transport code. With "empirical" electron energy diffusivity χ_e , ignition was obtained with 60–75 MW of neutral beam injection at a volume average pressure ratio $\langle\beta\rangle = 4–5\%$ under a variety of conditions. Changing χ_e gave ignition at the same $\langle\beta\rangle$ if the plasma minor radius varied as $a \propto \chi_e^{1/2}$. The maximum impurity concentration which allows ignition was found to be comparable to that for the much simpler case of a homogeneous plasma with radiative losses only. In long pulse simulations with efficient helium pumping, the maximum toroidal field ripple which allowed ignition was 2.0% (peak to peak) at the plasma edge. Ignition was maintained with over 99% recycling of helium ash using 5% less than maximum ripple.

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1. INTRODUCTION

The requirements for obtaining ignition in an experimental tokamak have been the subject of a number of studies in the past four years [1,2,3,4,5]. This work has recently been extended in support of the 1979 International Tokamak Reactor (INTOR) Workshop [6]. The INTOR study has included plasma simulations using a variety of transport codes. A summary of some of these results and of a comparison of different transport models is available in the U.S. contribution to the INTOR Workshop [7]. An evaluation of ignition requirements [8] for the recent ORNL-TNS design [1] is also of particular interest because the parameters of this design closely resemble those chosen as a reference design by the INTOR Workshop participants.

The ORNL-TNS study provides a starting point for the work reported here. This TNS tokamak was heated to ignition using neutral beams with a full energy component at 100 - 150 keV. It was found that there is considerable advantage in gradually raising the opacity of the plasma to fast neutrals (i.e., raising the minor radius [4,9] or density [8]) during heating to ignition. Here, we adopted the variable density startup approach for computational convenience. In the TNS study this was modeled by a one-fluid code which solved the 1-D transport equations in a sequence of 2-D flux-conserving equilibria. We took the complementary approach of using BALDUR [10], a multiple fluid code which solves the 1-D transport equations assuming concentric circular flux surfaces.

First, we briefly describe our transport and plasma model, our criterion for ignition, and the requirements for fueling and heating INTOR-like plasma to ignition in the multifluid model. Then, we describe the effects on ignition requirements of varying energy confinement, impurity influx, toroidal field ripple, synchrotron radiation, and the rate of removal of helium ash.

The results reported here should be of direct use in the next round of design of INTOR and the related Engineering Test Facility (ETF) in the U.S. They may also provide useful insights for studies of advanced operations in tritium-rated experiments such as T-20, JET, and TFTR and in conceptual studies of fusion power reactors.

2. MODELS

In this section we describe a reference set of machine parameters and plasma transport coefficients and outline the assumptions used in the transport model. We then describe the reference startup scenario. Variations from this standard model are noted as the results are presented in Section 3 below.

2.1 Machine-related parameters

Our reference machine parameters are based on an early set of suggestions from the U. S. INTOR Concept Advisory Group [11]. They are listed in Table I. In our model, the plasma elongation affects only the deposition profile of fast neutrals, which is computed for confocal ellipses with semimajor axes in the ratio $\kappa = b/a$. The deposition within these flux surfaces is then mapped

to circles by multiplying the semiminor radii by $\kappa^{1/2}$, and the remaining calculations assume a circular plasma of radius $a_{eq} = a\kappa^{1/2}$.

2.2 Transport coefficients

Our reference transport coefficients are based on a standard set which was adopted by the U. S. INTOR Energy and Particle Confinement Committee in order to have an easily described transport model which is compatible with experimental data from existing tokamaks of moderate size. Our reference transport coefficients are listed in Table II.

To the standard INTOR set we have sometimes added ion thermal diffusivity due to toroidal field ripple, including ripple trapping [12] and the recently derived ripple-plateau diffusion [13]. Banana-drift diffusion [14] was thought to be negligible and is ignored, but recent results suggest it should be included for an accurate estimate of ripple limits [15]. We assumed 12 toroidal field coils and took the ripple to be $\delta(r, \theta) = [\delta_0 + (\delta_w - \delta_0)r^2/r_w^2] \exp(-0.3\theta^2)$ where $\delta_0 = \delta_w/8$, with a nominal peak-to-average $\delta_w = 1.1\%$ (2.2% peak-to-peak) where $r_w = a + 9$ cm is the minor radius of the vacuum vessel. This prescription for the ripple approximately matches that suggested by the U. S. INTOR Energy and Particle Confinement team [7,15].

A 9 cm scrapeoff region was added to the plasma for ripple transport and helium recycling calculations. In the scrapeoff region, loss terms were added to account for flow of plasma particles and energy along the field lines. The loss terms are

equal to a factor alpha times the particle or energy content, divided by $\tau_{||} = [(\pi q_a R)/(T_e + T_i)/m_i]^{1/2}$. Here q_a is the safety factor at the plasma/scrapeoff boundary, R is the major radius, T_i is the local ion temperature, m_i is the mean ion mass. $\alpha = 1$ for particles, $\alpha = 2$ for ion energy, and $\alpha = 5.8$ (no secondary electron emission) for electron energy [16]. A specified fraction of the hydrogen and helium is recycled from the wall whether it flows out to the wall or is counted as a loss due to parallel flow. For the examples shown here, the energy of incoming hydrogenic neutrals is 40 eV (short pulse impurity influx) and 100 eV (long pulse), and of helium neutrals is 40 eV, energies chosen to be appropriate to wall reflection and a hot divertor channel respectively.

A small term of the form $D = 500(r/a)^3 \text{ cm}^2/\text{s}$ was added to all of the particle diffusion coefficients when studying impurity limits, since a term of this type had previously been found helpful in avoiding numerical problems in the zones near the edge of the plasma. It will be noted below whenever this term and/or the ripple diffusion are omitted.

2.3 Computational model

The BALDUR transport model has recently been documented [10]. The specific aspects of this model used in the present work are documented in an appendix added to this preprint of this paper. A brief summary of the aspects of this model most relevant to INTOR simulations is as follows: (1) The geometry is modeled as a right circular cylinder with length $2R$ and periodic boundary conditions

at the end of the cylinder. (2) Up to four separate particle density equations are solved. The source for hydrogen ions is computed with a Monte Carlo model [18]. Impurities are treated as ions with a charge given by the average charge which would be obtained in coronal equilibrium [19]. The source for helium ions is a volume source due to fusion and due to ionization of incoming neutrals recycled from the wall with a specified recycling coefficient. The source of other impurities is determined by specifying the initial concentration and the flux through the boundary of the plasma. (3) Two separate energy transport equations are solved for the ion and electron energy. Sources and sinks include electron-ion equilibration, heating by fast alphas and injected particles, ohmic heating, coronal equilibrium radiation [19], ionization, and charge exchange with the cold neutral spectrum computed with the Monte Carlo neutral routine. (4) The injected fast ions are followed by solving the Fokker-Planck equation, with drag and pitch angle diffusion only, in a cylindrical geometry. The fast ion source is computed with the Monte Carlo beam deposition routine FREYA. The neutral gas transport includes gas puffing neutrals, recycled neutrals, recombination neutrals and neutrals formed by the charge exchange of the neutral beam with the plasma. The alpha heating for the short pulse simulations described below was computed with a similar but simpler time-dependent model taking into account delayed heating of electrons and ions [10]. For the long pulse simulations described below, we used a Monte Carlo model of alpha heating which includes the effects due to the finite size of the alpha orbits

[20]. (5) In solving for the toroidal plasma current, the resistivity is enhanced inside the surface where the safety factor $q \leq 1$ [10]. This is the only effect of MHD fluctuations modeled in the code for the applications described here.

2.4 Reference startup scenario

An analysis of the requirements for ignition clearly requires an attempt to optimize the startup scenario. We approached this optimization in three steps. First, we used simple conditions (no impurities, no ripple, nearly constant electron density) to search for the optimum plasma density for ignition. As explained below, this led us to conclude that it was in fact best to increase the density during startup.

Our second step was to program the fraction of tritium in the fueling gas. The conclusion of this step defined our basic startup scenario. In some cases a specified influx of impurities was added to simulate contamination originating outside the plasma.

When we wanted to study quenching of ignition by helium ash, we needed to simulate longer discharges and encountered a thermal instability leading to high plasma temperatures. Since we wanted to study toroidal field ripple and expected it to facilitate achieving a steady burn, our third step was to determine the maximum ripple which allowed ignition. We could then vary the recycling of helium at the plasma boundary and determine the pumping requirements needed to avoid quenching ignition due to the accumulation of helium ash.

The results of these studies on optimizing startup illustrate some important physical processes relevant to the requirements for ignition, so we now discuss these studies in detail.

2.4.1 Plasma density

A study of the requirements for ignition in INTOR at constant volume-averaged electron density $\langle n_e \rangle$ [17] showed that the volume average pressure ratio $\langle \beta \rangle$ decreased slowly with increasing $\langle n_e \rangle$ when $\langle n_e \rangle \sim 10^{14} \text{cm}^{-3}$. Assuming that it is desirable to reduce the required $\langle \beta \rangle$, this suggests igniting the plasma at $\langle n_e \rangle \geq 10^{14} \text{cm}^{-3}$. However, the required heating pulse length t_{ig} rose dramatically with increasing $\langle n_e \rangle$ due to poor penetration of the injected neutrals into high density plasmas. Therefore, we chose a compromise approach of increasing $\langle n_e \rangle$ from 0.7×10^{14} to $1.4 \times 10^{14} \text{cm}^{-3}$ in 7 s. This gave ignition at $\langle n_e \rangle \approx 10^{14} \text{cm}^{-3}$ at modest $\langle \beta \rangle \approx 4\%$ with t_{ig} less than that required for startup at constant density. These results were not surprising, since it had been recently found elsewhere that the total injected energy required for ignition is reduced by variable density startup [7].

It should be noted that throughout these studies we have used an approximate criterion for ignition; namely, that the rate of increase in plasma energy should exceed the externally applied heating in the inner half of the plasma volume. If this is the case, then one might expect the energy content of the plasma core to increase after turning off the heating, i.e., one might expect ignition. Figure 1 shows that this is the case for startup with constant $\langle n_e \rangle = 1.4 \times 10^{14} \text{cm}^{-3}$. $\Delta P_{0.7}$ is the difference between

the rate of thermal plasma energy increase and the heating by fast ions in the inner half volume of the plasma (i.e., inside $r = 0.7a$). The outer half of the plasma volume is excluded in applying this criterion because the fraction of the alpha heating (which determines ignition) deposited there is negligible (~10%) and because the plasma core can "smolder" to ignition [21] even if the energy balance at the edge is temporarily unfavorable. Figure 1 shows that $\Delta P_{0.7} = 0$ almost exactly at the point where turning off the beams leads to a steady burn with $\langle \beta \rangle$ approximately constant. This definition of ignition has also been successfully checked for different discharges with variable density startup and oxygen and helium [17], but has not been exhaustively repeated for all of the results presented here. However, it should be apparent that this simple ignition criterion is at least a reasonable qualitative comparator for quickly determining the relative merits of various machine configurations, which is the main goal of the present study.

2.4.2 Species mix

It was known from studies of TFTR [22,23] that beam fueling can lead to buildup of deuterium in the center of the plasma and a consequent decline in fusion output. Since BALDUR follows the diffusion of both deuterium and tritium particles, we were able to observe this problem in simulations of INTOR. The problem was corrected by starting with a large (but realistic) initial tritium fraction of 90% and by linearly decreasing the fraction of tritium in the neutral gas influx at the edge of the plasma (from 90% to

70% during beam injection and then to 50% after an arbitrarily chosen time of one second after the end of beam injection). This strategy resulted in a D:T mix which was sufficiently good to give at least 85% of the fusion power which would have been obtained at ignition with the optimum D:T mix.

With prescribed $\langle n_e \rangle$, the addition of impurities can also lower the fusion yield directly by decreasing the concentration of hydrogen species in the plasma. If high Z impurities are included, there can also be significant losses due to radiation. These effects had previously been computed in a steady state model (without transport) with constant impurity fractions [24]. In the case of our more complete startup calculations, the assumption of constant impurity fraction had to be dropped in favor of the more physically reasonable assumption that the impurity influx initially increases as the plasma is heated. (Although assuming constant impurity fraction was computationally simpler, it often led to radiative collapse during ohmic heating.) To define a simple model which would allow investigation of the limits on ignition set by accumulation of impurities (other than helium ash), we did the following: The initial fraction of impurities during ohmic heating was set to a small value, arbitrarily chosen to be 1% of the final level attained after $\langle n_e \rangle$ rises to $1.4 \times 10^{14} \text{cm}^{-3}$. During beam heating, the impurity influx was set to initially rise linearly. The assumption here is that the impurity generation may be expected to increase with increasing plasma energy and that the plasma energy will rise linearly in the early part of beam heating when thermal inertia dominates the energy balance. At least in the case

of charge exchange sputtering off a stainless steel wall, it has been confirmed that this expectation is approximately verified [25]. Eventually, however, the impurities will probably begin to be lost via the divertor and cease to accumulate. To model this, we have abruptly terminated the impurity influx at a time $\tau_p = a^2/(4D)$ after the beginning of heating. For our model, $D \equiv D_{\text{impurities}} \approx D_{\text{hydrogen}}$ and we take $\tau_p = 3$ s corresponding to $\langle n_e \rangle \approx 10^{14} \text{ cm}^{-3}$. Elsewhere we have used slightly more sophisticated models of impurity influx [26], but the model used here is adequate for an approximate determination of impurity limits. In particular, since an impurity source due to the wall sputtering gives extremely large impurity fluxes (greater than justified by current experiments), the simpler model was used in the absence of a complete treatment of the complicated interactions between the plasma and its material boundary.

We have now described the full sequence of events in a standard short pulse (e.g., 10 s) startup scenario. A summary of these events is given in Table III. Figure 2 shows the evolution of various plasma parameters for a simple case with 60 MW beam injection, no charge exchange loss of circulating fast ions, no ripple, and the $500r^3/a^3$ term omitted from the hydrogenic particle diffusivities. In this case only we modeled impurities as oxygen with $Z_{\text{eff}}(r, t) \equiv 1.5$.

3. IGNITION REQUIREMENTS

After defining the standard startup scenarios above, we looked at variations in the transport model and machine parameters to see which parameters would allow an ignited burn.

3.1 Miscellaneous parameters

In order to reduce the number of parameters to be varied, we first showed that a number of factors have little effect on ignition requirements and could consequently be left at their reference values for the duration of the study. In particular, a change of less than 1 part in 5 in the value of $\langle \beta \rangle$ at ignition and 1 part in 4 in t_{ig} resulted from (1) setting $\chi_i = 1 \times$ neoclassical; or (2) increasing the plasma current by 25%; or (3) replacing 20 MW of standard beams by 10 MW at 400 keV (full energy only) [17]. Changing the electron thermal diffusivity to a value of comparable magnitude but with a different profile, $\chi_e = 10^{17}/[\ln_e(1 - r^2/a^2)^{3.5}]$ cm²/s [17], gave comparable t_{ig} but $\langle \beta \rangle$ at ignition 1/3 lower than in the standard model. However, the pressure profiles were more peaked with this χ_e , so this was not considered a significant improvement and this model was not further investigated.

3.2 Magnitude of χ_e

We kept the same scaling $\chi_e \propto 1/n_e$ and multiplied χ_e by a constant factor, keeping all other parameters as for the results shown in Fig. 2. The resulting values of $\langle \beta \rangle$ at ignition are shown in Fig. 3a for a factor of 2 variations in the magnitude of

χ_e . We believe that this is the absolute minimum range of χ_e which can sensibly be extrapolated from existing data to the reactor regime. To further illustrate this point, we note that a relatively weak dependence on T_e , namely, $\chi_e = 5 \times 10^{17}/(n_e T_e^{0.25})$ with T_e in keV, gives the result designated by a * in Fig. 3. It would clearly be unreasonable to claim from existing data that such a weak temperature dependence, either favorable or unfavorable, could be excluded in the high temperature (20 keV on axis) and high density (10^{14}cm^{-3}) regime of interest here.

Given that our reference scenario is near the boundary of stability to axisymmetric MHD modes [25], it might be necessary to alter the INTOR design if χ_e proves to be larger than the value assumed in the reference scenario. Conversely, if there are no other problems and χ_e is less than the value assumed in the reference scenario, then it may be possible to make the machine smaller and less expensive. To illustrate this point, we have run simulations varying the magnitude of χ_e and also varying the minor radius to keep nominally identical confinement time; i.e., with $a^2 \propto \chi_e$. To scale other machine parameters appropriately, we kept the inner edge of the plasma at fixed major radius (although this might in fact vary slightly in optimized designs), and we scaled the plasma major radius and toroidal field appropriately to keep a fixed maximum field at the toroidal field coils. The beam injected power was scaled with the plasma volume, the angle of the beam centerline with the magnetic axis was kept constant, and the beam energy was kept constant (as might be appropriate if the beam development program were committed to positive ions sources). The

variable parameters for the three simulations denoted by the dots in Fig. 4 are listed at the bottom of Fig. 4. The results show that this scaling is approximately appropriate to maintain a constant $\langle \beta \rangle$ at ignition. However, the savings accrued assuming $a^2 \propto \lambda_e$ may be slightly overestimated for small λ_e , especially given that the aspect ratio would be slightly larger and the β limit may be slightly smaller in such a case [25].

The importance of giving adequate consideration to possible variations in anomalous thermal diffusivity during the design of ignition experiments cannot be overstated, especially since this problem has been given little or no attention in previous design studies [2,3,4,5]. This is particularly important when the experiment might be considered a failure if it does not reach ignition. This would be the case for INTOR (or ETF), especially since the use of the experiment as a materials test facility is centered on the assumption of ignition and adequate consideration has not been given to the performance or problems expected if the device is to be run as a continuously beam-driven machine. Figure 3 shows that, unless further significant positive data is available on energy confinement or β limits by the time the design for an INTOR-type ignition experiment is frozen, it would be very risky not to include a substantial increase in the plasma radius over the initial design value. (Should favorable data subsequently become available, the additional plasma volume would undoubtedly be of great use in expanding experimental flexibility.) Similar comments apply to copper coil ignition experiments.

3.3 Impurity influx

The evolution of INTOR plasmas was followed to final states with various concentrations of various impurities. In order to ensure that ignition would be limited by impurity influx rather than by too little beam power, we raised the injection power to 75 MW. In these calculations we again ignored charge exchange loss of beam ions, assumed negligible ripple, and used the temporal sequence during startup indicated by the leftmost set of numbers in Table III.

The evolution of the density-weighted volume average electron temperature $\langle T_e \rangle_n$ in plasmas approaching various final Ni concentrations is shown in Fig. 5a. For such metallic impurities, there is a well-defined limit beyond which T_e does not increase sufficiently to strip the impurities to helium-like charge state. In such cases the high radiative losses ensure that ignition (denoted by the dots in Fig. 5) never occurs.

The ignition criterion shown in Fig. 4b also illustrates the abrupt transition between ignition and fizzle for various rates of Ni influx. One caveat that should be mentioned concerning these results is that for nearly marginal impurity levels (e.g., 0.15% Ni) the electron temperature in the outermost computational zone (outer few centimeters) drops precipitously after the beam heating is removed. This leads to a regime where not even the atomic physics for the relatively simple coronal equilibrium model used here is available. Although the plasma core is clearly ignited in such cases, it remains an open question whether a long ignited burn

could be maintained with impurity concentrations slightly below the ignition limits reported here.

We were interested in the values of $\langle \beta \rangle$ at ignition and the length of the heating pulse required for ignition. These are shown as a function of final Ni and Mo concentration in Fig. 6. t_{ig} is rapidly approaching ∞ when the impurity concentration is such to require $t_{ig} = 7$ s. We therefore define the impurity concentration which requires $t_{ig} = 7$ as the "impurity limit."

The impurity limit is given as a function of atomic number by the solid line in Fig. 7. Also shown (as the dashed line) is the impurity concentration which prevents ignition in an infinite homogeneous plasma at $T_e = 10$ keV with equal amounts of deuterium and tritium [24]. (The value of $\langle T_e \rangle_n$ at ignition ranged from 9 to 13 keV for the INTOR cases we computed.)

We also checked the possibility that increasing the minor radius by a factor of $1.5^{1/2}$ would raise the maximum allowed Ni impurity fraction. The toroidal field was kept constant and other parameters scaled appropriately as noted in [25]. Although $\langle \beta \rangle$ at ignition was reduced by $1/3$ to $1/2$ for various final Ni concentrations, the impurity limit only increased from 0.18% to 0.20%. Given the strong nonlinearity of "burn out" and impurity radiation near the impurity limit, this latter result is not surprising.

3.4 Ripple and helium recycling

Helium pumping requirements and the effects of toroidal field ripple on the ignited burn were studied with a series of long pulse simulations. The long pulse simulations were derived from the standard short pulse by addition of thermal ripple losses, charge exchange loss of fast beam ions, helium accumulation and recycling, and a 9 cm scrapeoff region. To obtain conditions which would give a steady burn, we chose 5.3 s of heating with 50 MW of beam. The variable density startup scenario was changed to accommodate the larger gas puffing rate needed to penetrate the scrapeoff; we chose a scenario in which the time needed to reach $\langle n_e \rangle = 1.4 \times 10^{14} \text{ cm}^{-3}$ was only slightly longer than for the short pulse simulations. The pulse length was extended to 20s to study helium accumulation. The long pulse burn scenario is summarized in Table III, and the BALDUR input parameters are described in detail in an appendix added to this preprint of this paper.

The first study carried out with long pulse simulation determined the critical toroidal field ripple which allowed an ignited burn ($\Delta P_{0.7} > 0$ at $t = 15\text{s}$). The critical ripple was computed by multiplying the standard ripple amplitude $\delta(\rho) = [0.14 + 0.95(r/r_w)^2] \exp(-0.3\theta^2)$ by various constant factors. The maximum peak — peak ripple at the plasma edge which allowed an ignited burn was $2\delta_w = 2.3\%$ when approximately 100% of the helium outflux was pumped. This corresponds to $2\delta = 2.1\%$ at $r = a$.

We then chose a standard ripple with $2\delta = 2.0\%$ at $r = a$ to investigate the required helium pumping fraction P_{He} . Here P_{He} is the fraction of total helium outflux up to time $t = 15\text{s}$ which is

not returned to the plasma. The results for $P_{He} = 0.6\%$ are shown in Fig. 8. Figure 8 shows a prolonged smolder followed by thermal runaway. The helium fraction $\langle f_{He} \rangle \equiv \langle n_{He} \rangle / \langle n_e \rangle$ is small until unrecycled helium accumulates in the plasma core during thermal runaway.

It may be adequate to pump away a very small fraction ($\sim 1\%$) of the helium outflux. This is illustrated in Fig. 9, which shows the helium fraction $\langle f_{He} \rangle$ as a function of the pumping fraction P_{He} . This result should not be surprising, since the time to recycle helium near the edge of the plasma is orders of magnitude smaller than the time required to poison the thermonuclear core by accumulation of helium ash. However, the quantitative results presented here should be interpreted with care, since they result from order-of-magnitude one-dimensional approximations to a complicated two-dimensional flow. A more detailed study of the intriguingly optimistic helium pumping requirements derived here is clearly desirable.

Finally, we note that synchrotron emission was not included in the standard long pulse scenarios because its effect was very small. For example, including 0.4% loss of local synchrotron emission only reduced the maximum ripple allowed with efficient helium pumping to $2\delta = 1.9\%$ at $r = a$. The 0.4% loss was estimated from Trubnikov's prescription [27], using the values $n_e = \langle n_e \rangle = 1.4 \times 10^{14} \text{ cm}^{-3}$ and $T_e(r = 0.7a) = 10 \text{ keV}$ at $t = 15\text{s}$ from the burn shown in Fig. 8 and assuming no reflection of the radiation at the wall.

4. CONCLUSIONS

The study outlined here represents an in-depth analysis of the requirements for ignition in an example typical of the next generation of ignited tokamaks with superconducting toroidal field coils, within the limits of what can be achieved with a sophisticated 1-D transport code with coronal equilibrium atomic physics and cylindrical magnetic geometry. We suspect that the following results are general to beam injected ignition experiments in tokamaks.

The D:T mix in the filling and fueling gases must be programmed during startup to give an optimal mix when approaching ignition. To assure ignition at a given $\langle\beta\rangle$, the plasma minor radius must be sized according to the scaling $a \propto \chi_e^{1/2}$, where χ_e is the largest anomalous thermal electron diffusivity which can reasonably be extrapolated from the existing experimental data base (assuming, of course, that ignition in a device of such size could lead to a useful fusion reactor). The maximum impurity fraction which allows ignition is within a factor of two of that computed for an optically thin homogeneous plasma without transport losses. Accumulation of 1/2 of the maximum allowed impurity fraction does not have a significant effect on the value of $\langle\beta\rangle$ at ignition for moderate or high Z impurities. The effects of toroidal field ripple must be carefully investigated with an appropriate transport calculation during the design of the machine, and the ripple must be reduced by increasing the toroidal field coils in size or number (or by adding ripple-compensating coils) until ignition is attainable. Finally, there are indications that quenching of

ignition by fusion ash might be avoided by pumping a relatively small fraction of the helium flowing out across the plasma boundary. These results should provide a useful background both for the interpretation of results on INTOR and ETF with more sophisticated transport codes in the future, and for the continuing design effort on these and other ignition experiments.

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APPENDIX: COMPLETE SPECIFICATION OF MODELING PARAMETERS

Table A.I gives a complete list of the parameters required to obtain the results in the text with the BALDUR transport code. In the first part of Table A.I, the values for short pulse simulations are given in parenthesis when they differ from values for long pulse simulations. A dash indicates an aspect of the BALDUR model not used. Units are cys if not indicated. Table A.II gives a brief summary of the physics included in the BALDUR versions used. A misprint in the published <ov> used [A1] was corrected for the long pulse studies. The effect of this error on the short pulse studies is negligible (cf Table A.II).

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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)	5.0
Plasma Current (MA) (equivalent circle)	3.75
Toroidal Ripple (peak - peak, %)	
$r = 0$	0.3
$r = a$	2.0

HEATING

Power (MW)	60 - 75
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	0.78:0.16:0.06
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	$3 \times \text{neoclassical}$ (+ ripple for long pulse)
D_{Hydrogen}	$1.25 \times 10^{17}/n_e$ + $3 \times \text{neoclassical}$ + Ware pinch (+ $500 r^3/a^3$ for impurity influx studies)
$D_{\text{Impurities}}$	$1.25 \times 10^{17}/n_e$ + $3 \times \text{neoclassical}$ (+ $500 r^3/a^3$ for impurity influx studies)

Recycling Coefficient

Hydrogen	90%
Helium	0 - 99.6%
Impurities	1.0 (+ linearly increasing influx when $t_{\text{on}} < t < \tau_p + t_{\text{on}}$)

TABLE III. STARTUP SEQUENCE

TIME	MEANING	VALUE (s)		$\langle n_e \rangle$ (10^{14} cm^{-3})	P_b (MW)	%T PUFFED
		Short Pulse	Long Pulse			
t_0	t_{start}	0.0	0.0	0.7	0	0.9
t_1	t_{on}	0.5	0.5	0.7	60 - 75	0.9
t_2	$\tau_p + t_{\text{on}}$	3.5	-	↓	"	↓
t_3	t_{off}	7.5	5.8		→ 0	0.7 ↓
t_4	$t_{\text{off}} + 1$	8.5	6.8		0	0.5
t_5	$t_{\langle n_e \rangle \text{max}}$	7.5	8.	1.4	0	"
t_6	t_{stop}	10	20	1.4	0	"

TABLE A.1: TRANSPORT MODELS FOR LONG (AND SHORT) PULSES

1. Diffusivities	= Form	X	χ_e	Factor χ_i	D_H	D_I
Empirical	$1/n_e$		5×10^{17}	--	1.25×10^{17}	1.25×10^{17}
Constant	1.		--	--	--	--
Radial algebraic	$(r/r_{wall})^3$		--	--	586.(500.)	586.(500.)
Neoclassical	Hinton-Hazeltine		1.	3.	3.	3.
	Hawryluk-Hirshman		--	--	--	--
Ripple	Trapping		--	1.(0.)	--	--
	Banana-plateau		--	1.(0.)	--	--
	Banana-drift		--	--	--	--
PLT	$10^{17} \cdot n_e^{-1}$		--	--	--	--
	$(1-r^2/r_{wall}^2)^{-3.5}$		--	--	--	--
Other						
Bohm limit, gradual	$X \rightarrow X/[1 + X/(f_B D_{Bohm})]$	f_B	=	150.(-)	150.(-)	100.(-)
	$X = \chi_e, \chi_i, D_H, D_I$					
Exact Bohm limit in scrape-off	D_{Bohm}		--	--	--	--
Scrapeoff limit						
	$X \rightarrow X_{scr} + \Delta_{fit}(X_{scr} - X_{fit})$	X_{scr}	=	--	--	--
	for $r_{fit} < r < r_{lim}$					
	$X \rightarrow X_{scr}$ for $r_{lim} < r$					
	$X_{scr} = \chi_e, \chi_i, D_H, D_I$					
	$\Delta_{fit} = (r - r_{fit})/(r_{lim} - r_{fit})$					
	$r_{fit} = .85 r_{lim}$					

TABLE A.I: TRANSPORT MODELS (Continued)

2. Other Transport Parameters					
Parameter	BALDUR Input Variable	Units	Long Pulse	Value	
				Long Pulse	Short Pulse
Energy loss per hydrogenic ionization	EIONIZ	keV		.04	
Fraction of charge exchange events giving loss of fast ion	HFUTZ(1)	--	1.		0.
Fraction of local cyclotron emission lost from plasma	CFUTZ(100)	--	0.,.004		0.
Factor in wave-pinch hydrogenic diffusion and electron conductivity	CFUTZ(19)	kG		1.	
Connection length in scrapeoff	CFUTZ(127)	cm	4500.		--
3. Machine Parameters					
Major radius	RMAJOR(1)	cm		480.	
Minor radius of wall (equivalent circle model)	RMINOR(1)	cm	155.		147.
Minor radius of plasma (excluding scrapeoff)	RADIUS(N) N=CFUTZ(120)-2	cm		147.	
Toroidal field on axis	BZ	kG		50.	
Peak-average ripple					
$\delta = [\delta_o (\delta_a - \delta_o)(r/a)^n]e^{-\beta\theta^2}$					
δ_a	CURRENT(11)	--	.011		0.
δ_o	BPOID(11)	--	.001375		0.
n	RMAJOR(11)	--	2.		--
β	CFUTZ(144)	--	.3		--
Ellipticity (for beam deposition)	ELLIPT	--		1.5	

TABLE A.I: TRANSPORT MODELS (Continued)

4. Beam Parameters				
Parameters	BALDUR Input Variable	Units	Long Pulse	Value Short Pulse
Time beams on	HTON(1)	s		.5
Time beams off	HTOFF(1)	s	5.8	5.-10.5
Full beam energy	HEBEAM(1)	keV		150.
Total beam atomic current	HIBEAM(1)	kA	.518	.518,.648
Fractional atomic currents				
Full energy	HFRAC(1,1)	--		.6
1/2 energy	HFRAC(2,1)	--		.24
1/3 energy	HFRAC(3,1)	--		.16
Beam species	HHBEAM(1)	--		-2(=D ⁰)
Port major radius	HRMAJ(1)+ HRMIN(1)	cm		720.
Angle to normal at port	HANGLE(3,1)	degrees		13.2
Port shape	NHAPER(1)	--		2(=circular)
Port width	HAPER(1)	cm		40.
Port height	HAPERV(1)	cm		--
Source, shape	NHSHAP(1)	--		2(=circular)
Source width	EWIDTH(1)	cm		10.
Source height	HEIGHT(1)	cm		--
Length (source-port)	HLENGTH(1)	cm		800.
Horizontal divergence	HDIV(1)	degrees		.3
Vertical divergence	HDIVV(1)	degrees		.7
Horizontal focal length	HFOCL(1)	cm		∞
Vertical focal length	HFOCLV(1)	cm		∞

5. Boundary Conditions and Volume Sources of Particles

Parameters	BALDUR Input Variable	Units	Long Pulse	Value	Short Pulse
Hydrogenic species	NGAS(1)	--		$-2(\approx D^+)$	
	NGAS(2)	--		$-3(\approx T^+)$	
Impurity atomic number	NIMP(1)	--	2		$6-72^*$
Total toroidal current	CURRENT(1)	kA		3750.	
Specified boundary values					
T_e	TE1	keV		.0005	
T_i	TIO	keV		.0005	
n_D	DENGA1(1)	cm^{-3}	--		0.5×10^{13}
	DENS(50)*FRACTH(1)	cm^{-3}	9.3×10^9		--
n_T	DENGA1(2)	cm^{-3}	--		1.5×10^{13}
	DENS(50)*FRACT	cm^{-3}	8.3×10^{10}		--
n_{He}	DENS(50)*FRACT(1)	cm^{-3}	9.3×10^8		--
Specified impurity influx, Specification times					
	TIMP(3)	s	--		3.501
	TIMP(4)	s	--		3.5
	TIMP(5)	s	--		3.501
Influx rates					
	FLIMP(1,3)	$\text{cm}^{-2} \text{s}^{-1}$	--		0.
	FLIMP(1,4)	$\text{cm}^{-2} \text{s}^{-1}$	--		$0-4.2 \times 10^{14}$
	FLIMP(1,5)	$\text{cm}^{-2} \text{s}^{-1}$	--		0.
Is helium volume source included?	CFUTZ(70)	--	1. (Yes)		no
Desired recycle fraction					
Helium to wall	CFUTZ(71)	--	.2-1.		--
Helium lost in scrapeoff	CFUTZ(72)	--	.2-1.		--
Incoming neutral helium energy	CFUTZ(73)	keV	.04		--

*Standard case has $Z_{eff} = 1.5$, $n_e/n_i = 1.078$, if no impurity influx is prescribed.

TABLE A.I: TRANSPORT MODELS (Continued)

5. Boundary Conditions and Volume Sources of Particles (cont.)					
Parameters	BALDUR Input Variable	Units	Long Pulse	Value	Short Pulse
Hydrogenic recycle fraction	GRECYC	--		.9	
Energy of incoming hydrogenic neutrals	TCOLD	keV	.1		.04
Type of n_e monitor for gas puff	NPUFF	--		2(=vol.ave.)	
Maximum influx rate	GFLMAX(1-6)	$\text{cm}^{-2} \text{s}^{-1}$		$2-4 \times 10^{16}$	
Times to change puffing (+ trivial changes when HTOFF $\geq$ 6.5 s)	GFTIME(3)	s		.5	
	GFTIME(4)	s		HTOFF(1)	
	GFTIME(5)	s		HTOFF(1)+1.	
	GFTIME(6)	s	13.5		7.5
Target $\langle n_e \rangle$	DENMON(3)	cm^{-3}		0.7×10^{14}	
	DENMON(6)	cm^{-3}	2.0×10^{14}		1.4×10^{14}
Deuterium fraction in gas puff	GFRACT(3)	--		.1	
	GFRACT(4)	--		.3	
	GFRACT(5)	--		.5	

TABLE A.I: TRANSPORT MODELS (Continued)

6. Numerical Methods Parameters				
Parameters	BALDUR Input Variable	Units	Long Pulse	Value Short Pulse
Degree of implicitness for predictor-corrector iteration	THETAP	--		0.5
Is extrapolation used?	NLEXTR	--		0(=no)
Maximum timestep	DTMAX	s	.05	.5
Initial timestep	DTINIT	s	1×10^{-6}	1×10^{-4}
Maximum error in any zone	DELMAX	--	.2	.05
Number of zones	NZONES	--		50
Zone centers	RADIUS(1-50)	cm	5., 10.,	--(Equal spacing in minor radius
15., 20., 25., 30., 35., 40., 45., 50., 55., 60., 64., 68., 72., 76., 80., 84., 88., 92., 96., 100., 104., 108., 112., 116., 120., 124., 128., 132., 136., 140., 142., 143.5, 144.5, 145.5, 146., 147., 147.5, 148., 148.5, 149., 149.5, 150., 150.5, 151., 152., 153., 154.				
Number of Monte Carlo neutral particles followed	NIPART		500	1000
Number of timesteps between neutral profile calculations	NGPROF		4	10
Number of particles in Monte Carlo beam deposition profile	NIPART			40,000
Maximum number of timesteps between beam profiles	NIPROF			20
Change in n allowed before new beam deposition profile	HNCHCK			.1
Change in T allowed before new beam deposition profile	HTCHEK			.3

TABLE A.II: VERSIONS OF BALDUR USED IN INTOR STUDIES

Version:	XNEWLOKI
Loading Date:	April 3, 1979
Loaded By:	Daniel Heifetz, PPL

Physical Features:

1. Energy sources

- 1.1 Beams: Time dependent slowing down by local Fokker-Planck.
- 1.2 Alphas: Delayed local heating with steady-state fraction (recomputed every NIPROF = 20 timesteps) to ions and electrons. First orbit losses. Uncorrected Hively $\langle \sigma v \rangle = S_5^* [Al]$.
- 1.3 Ohmic heating: Poloidal flux diffusion (enhanced η when $q < 1$).
- 1.4 Radiative losses: Coronal equilibrium average ion model and specified fraction of local synchrotron emission.
- 1.5 Hydrogenic ionization and charge exchange: Monte Carlo neutrals with birth spectrum given by T_i (Aurora package).

2. Particle sources

- 2.1 From "thermal" neutrals: Monte Carlo neutral transport; feedback control of gas puffing.
- 2.2 Pellet injection: Not used.
- 2.3 Beam fueling: Fast ions converted to thermal ions at $1.5 T_i$; thermal ions lost by charge exchange with beam neutrals are added ¹ to "thermal" neutrals.
- 2.4 Helium: Fusion source particles added to thermal helium after slowing down.
- 2.5 Other impurities: Specified influx from wall.
- 2.6 Electrons: Charge neutrality (including fast ions).

Use: Short pulse with and without specified impurity influx.

TABLE A.II: VERSIONS OF BALDUR (Continued)

Version: LNCHHFLX

Loading Date: February 13, 1980

Loaded By: Fred Seidl, PPL

Physics Features (in addition to those in XNEWLOKI)

Alphas: Monte carlo particles launched continuously and slowing down along first orbit. Correct (-) sign in a_5 coefficient in $\langle \sigma v \rangle = S_5 * [Al]$. (Correction gives $<10\%$ decrease in $\langle \sigma v \rangle$ for $T_e < 25$ keV.) Other Monte Carlo alpha treatments not used.

Helium: Volume source of helium recycled from wall and scrapeoff.

Transport: Ion thermal losses include revised banana-plateau, no banana drift.

Use: Long pulse with helium recycling and ripple.

(PPPL-803653)
Fig. 1. Evolution of (a) $\langle \beta \rangle$ for $t_{\text{off}} = 7.2, 7.6$, and 8.0 s, (b) energy balance parameter $\Delta P_{0.7}$ for $t_{\text{off}} = 8.0$ s. Dots denote ignition.

(PPPL-803659)
Fig. 2. Evolution of plasma parameters for standard short pulse startup except with $t_{\text{off}} = 5.0$ s, (a) central and volume-averaged n_e ; (b) central and density-weighted volume-averaged electron and ion temperatures; (c) volume-averaged total pressure ratio and contributions from thermal electrons β_e , thermal ions β_i , fast α particles β_a , and fast beam ions β_b .

(PPPL-792140)
Fig. 3. (a) $\langle \beta \rangle$ at ignition and (b) heating pulse t_{ig} to ignition with various x_e , and with $x_e \approx 5 \times 10^{17} / (n_0 T_e, keV; 0.25)$ (*).

(PPPL-792138)
Fig. 4. (a) $\langle \beta \rangle$ at ignition and (b) t_{ig} for various x_e with other parameters as indicated at bottom of figure.

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

(PPPL-803658)

Fig. 5. Evolution of (a) $\langle T_e \rangle_n$ and (b) energy balance parameter for discharges approaching various final volume average Ni concentrations.

(PPPL-803657)

Fig. 6. (a) $\langle \beta \rangle$ at ignition and (b) heating pulse length for ignition vs final impurity concentrations.

(PPPL-803665)

Fig. 7. (a) Impurity limit on ignition in homogeneous plasma without transport loss (dashed line), maximum final impurity concentration (as defined in text) for INTOR (solid line).

(PPPL-803663)

Fig. 8. Evolution of volume-averaged pressure ratio, electron density, and He fraction for standard long pulse with $2\delta = 2.0\%$ at $r = a$, and $p_{He} = 0.6\%$.

(PPPL-803664)

Fig. 9. Helium fraction vs pumping fraction for long pulse scenarios at $t = 15$ s.