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DISCHARGE (CIT-2L)

By

D.P. Stotler and G. Bateman

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PRINCETON UNIVERSITY
PRINCETON, NEW JERSEY

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Simulation of a Compact Ignition Tokamak Discharge (CIT-2L)

D. P. Stotler and G. Bateman
Plasma Physics Laboratory, Princeton University
Princeton, NJ 08544

A reference simulation of a compact ignition tokamak (CIT) limiter discharge is carried out using the 1-1/2-D BALDUR transport code. The parameters for the discharge are as in the CIT-2L design; these parameters are described here, and the results of the simulation are discussed. It is found that plasma ignition can be reached and sustained within the specified constraints.

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I. Original Scenario

The simulation described here is based upon a scenario for a compact ignition tokamak (CIT) discharge developed by Singer *et al.*¹ More detailed information on CIT can be found there and in references therein. Many of the features of the present scenario are the same as in the original; we discuss them first.

The equilibrium geometry for the limiter configuration of CIT, CIT-2L, is that of an elongated, axisymmetric tokamak. Parameters used are as follows. The major radius, R_0 , is 1.32 m; the half-width of the plasma, a is 0.43 m. The outermost flux surface is assumed to have an elongation, $\kappa_a = 2.0$, and a triangularity, $\delta_a = 0.4$. The flat top values for the toroidal magnetic field and plasma current are $B_0 = 10.4$ T and $I = 10.0$ MA, respectively.

B_0 and I are ramped up from small initial values during the first 6 seconds of the discharge. I is increased in an almost linear fashion; B_0 comes up faster at the beginning of the ramp so that B_0^2 rises linearly (these are as shown in Fig. 1). The combination of this ramping scheme with properly timed auxiliary heating and pellet injection leads to a relatively small sawtooth inversion radius (typically a quarter of the minor radius) so that sawteeth do not have a major impact on the level of ignition achieved.

Auxiliary heating is assumed to occur through the He^3 cyclotron resonance. It is for this reason that He is introduced into the plasma. A total of 20 MW of power are input; 75% goes to the ions, 25% to the electrons.

The transport coefficients are based upon both semiempirical scalings and theoretical calculations.¹ The electron thermal diffusivity, χ_e , is proportional to T^t , where t is the confinement degradation parameter. The complete expression is given in Ref. 1. The particle flux for species a is written in the form

$$\Gamma_a = -D_a \frac{\partial n_a}{\partial \rho} + \Gamma_a^{neo},$$

where $D_a = 0.2\chi_e$, n_a is the species density, and ρ is the radial coordinate. The banana - plateau neoclassical ion fluxes calculated by Hawryluk *et al.*² form the largest contribution to Γ_a^{neo} . The ion thermal diffusivity is taken to be

$$\chi_i = 0.5\chi_e + \chi_i^{CH},$$

where χ_i^{CH} is the result of the calculation by Chang and Hinton.³ A convective energy flux of $c_j T_j \Gamma_j$ is included in the energy transport equation for both electrons and ions; the constant $c_j = 3/2$ in both cases.

Our simulation differs from the original in the gas composition and the timing of the auxiliary heating. We first describe the scheme used by Singer *et al.*¹ The initial gas in the tokamak was assumed to be deuterium with about 1% He added. After injection of a small deuterium pellet, more He was influxed to bring the impurity concentration up to about 8%. All of the tritium entered through two large tritium pellets later in the discharge. The volume-averaged electron density was held fixed at $\langle n_e \rangle = 8 \times 10^{20} m^{-3}$ during the plasma burn period. Carbon was influxed while the auxiliary heating was on to yield a volume-averaged effective charge of $\langle Z_{eff} \rangle \simeq 1.5$ during the burn period.

The timing of the various events in the original scenario was as follows. The initial time of the simulation was taken to be 0 sec; at this point densities and fields are at small but nonzero values. The magnetic field and plasma current ramps began at 0.2 sec. At about 1.4 sec, a small deuterium pellet was injected to reach $\langle n_e \rangle = 1 \times 10^{20} m^{-3}$. Auxiliary heating began at 2.7 sec; the small amount of gas in the machine was rapidly heated to very high temperatures. The two large tritium pellets were injected at about 4.4 and 5.0 sec. After the plasma temperature recovered from this sudden increase in density, fusion power production began. The toroidal magnetic field and plasma current reached their peak values at 5.6 and 6.2 sec, respectively. The auxiliary heating was then shut off at 6.8 sec.

The simulations in which the confinement degradation parameter, t , was set to one showed a transient ignition over a period of one to two seconds. Due to the fact that the only tritium in the system entered via the two large pellets, the burn period did not last very long. The energy confinement times remained close to their adopted empirical scaling¹ which is based upon the one proposed by Kaye and Goldston.⁴ Singer *et al.* also performed simulations with $t = 2$; they found it difficult to reach ignition in this case. Furthermore, they concluded that the level of ignition was very sensitive to the volume-averaged electron density, the effective charge, and upon the characteristics of the sawteeth. Poor confinement was associated with sawteeth having broad mixing radii.⁵

II. Alterations

We now describe the alterations we made to the original scenario to optimize the ignition. In order to get a better idea of how the ignition proceeds, the amounts of tritium and deuterium are balanced in the initial gas and in all subsequent gas puffing and pellet injections. Changes may be made to this later to minimize the tritium inventory required.

The primary difference is in the timing of the pellet injection. Note that in the work by Singer *et al.*, the auxiliary heating was being applied for about 1.7 sec to a plasma with a density of about one-eighth of the final density. Furthermore, the two large pellets were injected into a very hot plasma so that their penetration was shallow, even at injection speeds of 2 km/sec.

We suggest injecting the pellets around the start of the auxiliary heating. In this manner, much better penetration is achieved, and less heating is needed to reach ignition. In particular, we choose as the injection times of the two large pellets 2.4 and 2.9 sec.

Since impurities accumulate rapidly near steep density gradients, according to the neoclassical particle transport model used here,² great care must be exercised to avoid sharp peaks in the density profile. In the simulation, these can arise either from pellets penetrating to the magnetic axis or from extensive gas puffing at the edge. The pellet sizes are chosen to be large enough so that gas puffing is needed only to maintain and not raise the plasma density. An upper limit of 2 km/sec is placed upon the pellet speed so as not to exceed presently expected capabilities for the CIT pellet injector. However, smaller velocities are necessary, at least for the first two pellets, to prevent them from penetrating to the plasma center and leading to excessive impurity accumulation. If needed, these problems also can be avoided by injecting the pellets away from the midplane.

The auxiliary heating can be turned off at 5.3 sec without altering the rest of the burn period significantly (namely, by this time the power into the plasma from fusion α -particles exceeds 20 MW). The time evolution of the volume-averaged density is shown along with the magnetic field and current ramps (these two are as in the original scenario) and the levels of impurity influx in Fig. 1.

We corrected some problems with the impurity influx in the simulation

so that it now follows more closely the desired specifications. The He concentration in the initial gas and the He influx rate are adjusted so that $n_{He}/n_e = 0.05$ during heating, enabling the minority heating scheme to work efficiently. The carbon influx is similarly adjusted to reach $Z_{eff} \simeq 1.4$ during the ignition period.

Since Singer's work on this problem, the BALDUR code has been upgraded to provide enhanced transport wherever the local value of the plasma pressure gradient exceeds the critical value for the onset of ideal high- n ballooning modes. The thermal and particle diffusivities are sharply increased when this limit is reached, restoring the pressure gradient to a marginally stable value. Physically reasonable limits are placed on the magnitude of the resultant diffusivities.

The ignition margin in this revised scenario is somewhat higher than in the original. As a result, the flat-top volume-averaged electron density can be reduced to $\langle n_e \rangle = 6.5 \times 10^{20} m^{-3}$, which is at or just below the most pessimistic calculations of the Murakami density limit for CIT. The lower density is achieved by using smaller pellets than before.

III. Simulation Results

We now give a detailed description of the simulation produced with the 1-1/2-D BALDUR code. Specific comparisons with the original scenario can be made by referring to Ref. 1.

A. Temperature evolution

In Figs. 2 and 3, we show three-dimensional plots of the ion and electron temperatures, respectively, as functions of time and radial half-width. The peak values are consistent with an ignited plasma. In fact, the maximum volume-averaged temperature is about 9 keV. While this is true for both electrons and ions, the central temperatures of the two species differ somewhat. The time dependences of the central electron and ion temperatures are depicted separately in Fig. 4. In particular, we note about a 2 keV difference in the maximum values attained. It is believed that this is due to the fact that most (almost 3/4) of the α -particle heating, which is highly peaked in the center, goes into the electrons. The peaking of the

α -particle distribution is demonstrated in Fig. 5 where we plot the α contribution to β as a function of half-width and time. During the early part of the discharge when the power into the plasma comes from mostly ohmic or auxiliary heating, the temperatures near the magnetic axis are almost exactly equal. They do not begin to diverge until the auxiliary heating is turned off and α -heating becomes significant. Throughout the ignition period, the temperature difference remains close to 2 keV. As P_α falls during shutdown, so does the temperature difference.

Another contributing factor is that the ion energy loss (conduction and convection) is considerably greater than the electron energy loss within about 10 cm of the magnetic axis. This is primarily due to the fact that χ_i , comprised mostly of neoclassical effects, is almost an order of magnitude larger than χ_e in this region. However, when integrated over the volume of the plasma, the electron and ion losses are approximately equal.

The relatively small α input power and the higher losses conspire to give the ions a lower equilibrium temperature than the electrons. The magnitude of the electron - ion coupling determines how large the difference between the two actually is.

The temperatures do not reach their peak values until about two seconds after the auxiliary heating is turned off. In this respect, they follow the time evolution of the volume-integrated α -power as shown in Fig. 6. Both of these effects are characteristic of an ignited plasma.

B. Density evolution

In Fig. 7, we show the evolution of the total ion density as a function of time and radial half-width. The electron density is similar since BALDUR computes the electron density from quasineutrality. The effects of the three pellets are clearly evident as off-axis peaks in the radial density profile. In each instance, a centrally peaked profile is achieved soon afterwards. This effect has been observed experimentally as well. Since there is no inward pinch in this simulation, the central density drops steadily with time following pellet injection, as shown in Fig. 8; a steady-state profile is not reached before shutdown begins. Using such flat density profiles is a pessimistic procedure since more peaked ones would increase the level of ignition for the same parameters.

From Fig. 9, we see that the volume-averaged ion density falls off late in the run. This is a result of not only burnup of deuterium and tritium, but of the continued carbon influx. It is the volume-averaged electron density that is held fixed by the code, so that the introduction of one carbon atom entails a loss of five hydrogen ions.

C. Sawteeth

As in the original scenario, sawteeth are relatively unimportant in this simulation due to the small mixing radius resulting from the combination of field ramps and properly timed off-axis heating and pellet injection. This radius increases from about 12 cm during auxiliary heating and the early stages of ignition to more than 20 cm late in the discharge. The broadening of the sawtooth mixing radius is evident in the evolution of the current density shown in Fig. 10. The effects of the sawteeth on the temperature profiles are apparent in Figs. 2 and 3. The safety factor, q , increases monotonically with radius at all times. Hence, double tearing modes should not be a problem in this scenario. On axis, q gets as low as 0.9 during the ignition period; at the edge, it is typically 2.7. It should be pointed out that the sawtooth model used here requires a period as an input parameter. In both this and the original scenario, the sawtooth period was taken to be 0.3 sec. The results should not be sensitive to the particular value employed due to the small mixing radius, but future simulations will be carried out with smaller periods to verify this.

D. Ballooning modes

For the most part, the profiles obtained during this simulation are stable with respect to high- n ballooning modes. Most of the ballooning activity occurs in the low shear, low q region near the magnetic axis; under these conditions the critical pressure gradient is the lowest. Late in the run ($t > 7.5$ sec), the size of this region grows until shutdown begins. For instance, at $t = 8$ sec, it is about 8 cm wide and centered at a half-width of about 14 cm.

Presently, work is under way to examine these profiles for the stability of Mercier and low- n pressure-driven modes. The Mercier modes can be more

restrictive than the ballooning modes in regions where $q < 1$. However, the pressure profile in our simulation is very nearly flat near the center so that this may not be a problem. The low- n pressure-driven modes, or the "infernal modes" as they have been called, can be more unstable than their higher- n counterparts in regions of low shear. Again, it is hoped that the pressure profile is flat enough in the low shear regions that these modes are stable.

E. Ignition parameters

A more quantitative measure of the level of ignition than the time evolution of the temperature can be obtained by examining the detailed power balance of the plasma. The time dependences of the ohmic, auxiliary, and α -heating power, integrated over the entire plasma volume, are shown in Fig. 6. Just after the auxiliary power is turned off, the power balance shows a net loss of about 2.4 MW. However, this turns into a net gain by about $t = 6$ sec. As the α -power continues to rise with the plasma temperatures (and, hence, the losses), this net gain remains between 1 and 2 MW. By $t = 8$ sec, the α -power begins to drop, and the power balance indicates a net loss, signaling the end of the ignition period. It should be noted that considering the net power balance only over some portion of the interior of the plasma will lead to alterations in the beginning and ending times of ignition, but not by much more than 0.5 sec. Thus, it appears that we have about two seconds of self-sustained (alpha plus ohmic) plasma burn.

The end of the ignition period could be due to a combination of several effects. One is the increasing size of the ballooning-unstable region mentioned in Sec. D. We note that both τ_E and the central temperatures begin dropping at the same time. There is evidence that the drop in τ_E between $t = 7.5$ and 8 sec is consistent with ballooning-enhanced transport; the same can be said for the decreasing central temperature. On the other hand, however, the central density is still decreasing. This can lower the total α -power production directly if the central temperature is not increasing. Furthermore, by $t = 8$ sec the sawtooth mixing radius has grown to more than 23 cm, so that the effects of sawteeth may also play a part in terminating the ignition. Finally, the volume-averaged density begins to drop at about $t = 8.5$ sec to begin the shutdown phase; this clearly causes

a drop in the α -power.

The peak α -power of 40 MW is well below the maximum design specification of 60 MW. Furthermore, the peak volume-averaged toroidal β is about 4% (see Fig. 11), considerably less than the reference Troyon value for the CIT device (about 6.3%). The fact that we are finding ballooning activity at β values below the Troyon limit indicates that our pressure profiles are different from the optimized ones used in theoretical work.

The value of Z_{eff} during ignition is increasing in time due to the continuing influx of carbon and the fusion production of He from deuterium and tritium. Just after the heating is turned off, $\langle Z_{eff} \rangle \simeq 1.2$; by $t = 7.5$ sec, it has increased to 1.4. It is possible that these values are overly optimistic.

The energy confinement times in this simulation are very good. From about the time the last pellet is injected until the shutdown begins, $\tau_E \sim 0.4 - 0.5$ sec, as shown in Fig. 12. Typically, $\tau_E/\tau_{KG} \sim 1.1 - 1.2$ (see Fig. 13) during the run. The empirical confinement time scaling, τ_{KG} , is as described in Ref. 1. These values of τ_E are somewhat larger than previous estimates of CIT L - mode confinement times. We can argue that τ_{KG} is higher than in earlier calculations due to the lower α -power and increased major radius (1.32 m as opposed to the value 1.22 used previously). Nonetheless, this confinement scaling is a bit optimistic for an L - mode discharge. More pessimistic scalings (e.g., setting the confinement degradation parameter, t , equal to two) were considered by Singer et al.¹; they concluded that it is very difficult to obtain ignition under these circumstances.

IV. Future Modifications

Further work will be done on this scenario to bring it into line with realistic engineering constraints on the system. In particular, the plasma will grow from a small circular cross section and will not reach full size and elongation until the end of the current and magnetic field ramps. In this way, the edge safety factor will be about 2.7 - 3. throughout the run. Unfortunately, this may affect the way the current profile is set up and significantly increase the sawtooth mixing radius. In addition, the burn pulse should last for about ten energy confinement times, or about twice the value discussed here. This could be achieved to some extent just by delaying the shutdown, although extending the length of time over which

the plasma temperature is increasing may be more difficult with L - mode confinement.

Also, the increased interest in H - mode confinement and the consequent need for a divertor geometry suggests running the simulation again with parameters typical of the CIT divertor option as opposed to the ones above that characterize the limiter mode of operation. The main difference is that only 9 MA of plasma current are needed. Typically, H - mode discharges are modeled by doubling the L - mode confinement time or, equivalently, dividing the given L - mode transport coefficient by two.

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Figures

FIG. 1. Required values of toroidal magnetic field (B), plasma current (I_p), volume-averaged electron density ($\langle n_e \rangle$), and impurity influxes in the revised scenario. Units for the first three are as labeled; carbon and helium fluxes are in arbitrary units.

FIG. 2. Ion temperature in keV as a function of half-width and time.

FIG. 3. Electron temperature in keV as a function of half-width and time.

FIG. 4. Calculated electron and ion temperatures at the magnetic axis as a function of time.

FIG. 5. Contribution of α -particles to β as a function of half-width and time.

FIG. 6. Time evolution of the volume-integrated ohmic, auxiliary, and α -power in MW.

FIG. 7. Ion density in m^{-3} as a function of half-width and time.

FIG. 8. Central ion and electron densities as a function of time.

FIG. 9. Volume-averaged electron and ion densities as a function of time.

FIG. 10. Toroidal current density in MA/m^2 as a function of half-width and time.

FIG. 11. Volume-averaged toroidal β as a function of time; separate curves are shown for α -particle, electron, ion, and total β .

FIG. 12. Energy confinement time as a function of time.

FIG. 13. Ratio of the energy confinement time, τ_E , to the Kaye - Goldston - like scaling law, $\tau_{E,KG}$, as a function of time.

Fig. 1

#86P0339

Fig. 2

Fig. 3

Fig. 4

#86P0334

Fig. 5

Fig. 6

#86P0338

Fig. 7

Fig. 8

Fig. 9

#86P0336

Fig. 10

Fig. 11

Fig. 12

Fig. 13

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