Ignition and Fuelling Scenarios Based on the Injection of Pellets in Thermonuclear Plasmas

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Some of the potential of pellet injection for future fusion machines is demonstrated by means of reactor scenario calculations performed with the help of the BALDUR /1/ 1-D tokamak transport code, which incorporates an extensive Monte Carlo treatment of the neutral particles and a divertor model. The code is supplemented by a pellet ablation routine that is based on the so-called neutral gas shielding model /2/. The parameters of the recipient plasma are assumed to be identical with the standard INTOR parameters /3/. The present calculations are part of an extensive assessment performed for NET (Next European Torus) /4/.

Density Ramp-up and Ignition by Pellet Injection

Early analyses of ignition scenarios in NB-heated tokamaks (see, for example, Watkins et al. /5/, Holmes et al /6/, and Houlberg et al. /7/) have shown that optimum path to ignition in the n,T space always starts with a low-density high-temperature plasma state. The calculations of Watkins et al. show that, irrespective of the scaling laws assumed by them (Alcator-Intor, Coppi-Mazzucato, Ohkawa, and a radially dependent version of Alcator-Intor scaling), the minimum ß for ignition is always associated with low densities ($n_i \lesssim 10^{20}\ m^{-3}$). The calculations of Houlberg et al. /7/ indicate the importance of the NB penetration depth, i.e. heating profile, on the optimum ignition power characteristics.

The purpose of the present ignition scenario calculations is to assess the potential of density ramp-up by pellet injection in planned fusion machines such as NET, based on the INTOR design and plasma parameters. Special attention has been paid to the possibility of reducing the beam energy envisaged for INTOR (175 keV) by simultaneously increasing the envisaged beam power (from 75 MW to 100 to 110 MW). Three beam energy levels were considered: 120 keV, 100 keV, and 80 keV, respectively). The respective power fractions associated with the 1/1, 1/2, and 1/3 energy components were assumed to be: 0.59 : 0.22 : 0.19 (120 keV), 0.62 : 0.21 : 0.17 (100 keV), and 0.64 : 0.20 : 0.16 (80 keV) /8/. In all cases, the scenario started with plasma in the so-called "hot ion mode" (in low-density NB-heated plasmas the energy is preferentially coupled into the plasma ions and thus the ion temperature may substantially exceed the electron temperature in the heat deposition zone). As soon as the minimum ß value necessary for ignition has been reached, a pellet of preselected size was injected into it, thus adiabatically ramping the plasma density up to the value necessary for ignition (i.e. for a self-sustained alpha reaction rate). The values of β_{ign} and n_{ign} were previously determined from standard INTOR start-up phase calculations (E_{bi} = 175 keV, P_{bi} = 75 MW) with marginal ignition ($_{bi}$ = 4 s) and were found to be: β_{ign} = 2.5 and n_{ign} 9.5×10^{19} m^{-3}, respectively. Details of these calculations can be found in /9/.

The pellet velocity assumed (approx. 2400 m/s after correction for the ellipticity of the plasma cross-section) corresponds to values not very far from the presently obtainable ones. The ablation rates yielded by the neutral gas shielding theory /2/ were used without corrections for possible magnetic shielding effects. Thus the actual pellet penetration depths may be larger under reactor conditions than those calculated here /4/. (This may again further relax the requirements on the NB and pellet injector systems.) Since the intense deuterium beams make the discharge rather tritum-lean in the reactor zone, only tritium pellets were used for ramp-up purposes.

It should be noted that the results of reactor scenario calculations such as those described here strongly depend on the scaling laws (transport models) used. The present calculations are limited to Alcator-Intor scaling, on which the standard INTOR and NET calculations are based.

The NB heat pulse data and pellet sizes required for ignition by means of density ramp-up via pellet injection can be summarized as follows:

Particle energy	Total beam current	Beam pulse duration	Pellet radius	Pellet injection time
120 keV	1.25 kA	2.16 s	0.37 cm	2.15 s
100 keV	1.40 kA	2.68 s	0.34 cm	2.67 s
80 keV	1.70 kA	3.00 s	2 x 0.29 cm	1 s 2.99 s

The pellet injection times shown are counted from the start of the beam pulse. In the first two cases considered, the starting plasma density was 4×10^{19} m^{-3}, while in the third case it was reduced to 1×10^{19} m^{-9}. Because of the rather large beam current associated with the 80 keV case and the corresponding rather tritium-lean discharge, it was found necessary to inject a tritium pellet already in the early discharge phase, thus ensuring an acceptable D-T mixture in the reaction zone to the end of the NB heating pulse.

In conclusion, the potential of density ramp-up in NB-heated plasmas by pellet injection may be summarized as follows:

a) The injection scenario can be started with plasma densities sufficiently low to ensure deep beam penetration, central particle deposition and thus peaked temperature and density profiles. Advantage may be taken of the hot ion mode in this case.

b) While in the case of density ramp-up by gas puffing the ramp-up time is finite and the beam may be blocked off at the plasma periphery before the heating pulse is off, density ramp-up by pellet injection is practically instantaneous and unimpaired beam penetration may be granted during the entire heating phase.

c) Pellet injection transports fresh fuel to the reaction zone on a time scale that is much shorter than the diffusion time characterizing the method with gas puffing. Hence the timing of the moment of density ramp-up with respect to the heat pulse is less complicated in the case of pellet injection than in the second case.

d) Transition from NB-driven fusion to self-sustained alpha particle production may be possible at lower beam energies and shorter beam pulses (with increased beam currents) than in the case of gas puffing.

Continuous Fuelling by Pellet Injection

In a series of calculations performed for NET, the optimum combinations of pellet sizes, pellet velocities, and pellet frequencies applicable to reactor fuelling were investigated by injecting a string of 10 pellets ("continuous" fuelling) into an already ignited standard INTOR plasma. Before and after pellet injection, the density was kept at a constant level by gas puffing. The same transport scaling laws were assumed here as in the case of the ignition scenarios (Alcator-Intor) with an addendum: a "soft beta limit" was applied to obtain steady-state burning conditions. Details of these calculations can be found in /9/ as well.

The results obtained have shown that the response of the recipient discharge to the injection of a continuous string of pellets, i.e. the change of the temperature and density distributions, the onset of favourable or unfavourable profiles and the resulting changes of the particle and energy confinement times are functions of the pellet mass-velocity-frequency combinations applied. Hence, for determining the optimum injection characteristics, systematic scanning of these parameters was performed on the basis of the following considerations: First, deep pellet penetration produces favourable density profiles, improves the confinement time, and increases the alpha production rate. Hence for a given velocity the pellet mass should be large enough to ensure deep penetration and yet small enough not to cause large-amplitude density fluctuations. Second, the pellet frequency required for continuous fuelling depends on the particle confinement time associated with the modulated density and temperature profiles developing during continuous pellet fuelling. Care should be taken that the frequencies chosen and the respective injection periods are different from the characteristic response time associated with burn control ($\gtrsim 1$ s). Third, the particle exhaust flux should be large enough to ensure the rate required for helium pump-off.

In conclusion, reactor fuelling scenario calculations have shown, that fuelling by pellet injection at technically feasible pellet velocities is superior to fuelling by gas puffing alone: a) It produces favourable density and temperature profiles, thus increasing the particle and energy confinement times; b) it increases the central and average β_T values and may cause a substantial increase of the thermal alpha power production; c) the particle exhaust flux corresponding to pellet fuelling is somewhat reduced compared with edge fuelling but is still more than sufficient for effective helium pump-off.

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