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COMPACT TOROID REFUELING OF REACTORS

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ABSTRACT

The feasibility of refueling fusion reactors and devices such as the International Thermonuclear Engineering Reactor (ITER) with high-velocity compact toroids is investigated. For reactors with reasonable limits on recirculating power, it is concluded that the concept is not economically feasible. For typical ITER designs, the compact toroid fueling requires about 15 MW of electrical power, with about 5 MW of thermal power deposited in the plasma. At these power levels, ideal ignition ($Q = \infty$) is not possible, even for short-pulse burns. The pulsed power requirements for this technology are substantial.

It has recently been suggested that deep fueling of fusion-grade plasmas could be achieved through injection of high-velocity (500- to 1500-km/s) compact toroids (CTs) [1]. In a fusion reactor, the external power required by the fueling system should be a small fraction of the thermal output power of the device. Parasitic or recirculating power loads cause a direct increase in the cost of electricity, and generic reactor studies limit such loads to about 10 to 15% of the output electrical power of a fusion device (3 to 5% of the thermal power) [2,3]. Recirculating power requirements include control systems, real-time fuel reprocessing, heat transfer systems, plasma profile control, plasma current drive, and fueling. If the fueling system served no other function, a reasonable upper limit on its electrical power requirements would be 3% of the electrical output power or about 1% of the output thermal power. Higher levels are not practical since about 10% of the electrical output would be required for the current drive system for a tokamak-based reactor and 3 to 5% would be required for control, heat transfer, fuel reprocessing, and heat loads. Thus,

$$P_{\mathrm{ct}}/P_{\mathrm{DT}} < \gamma \quad (\gamma \sim 0.01)$$

where P_{ct} is the plug power required by the compact toroid fueling and current drive system and P_{DT} is the output thermal power,

$$P_{\mathrm{DT}} = n^2 \langle \sigma v \rangle / 4Q$$

with $Q = 2.82 \times 10^{-12}$ J/fusion for the deuterium-tritium (DT) fusion reaction. The CT plug (electrical) power is

$$P_{\mathrm{ct}} = (1/\eta)(0.5) m S v_{\mathrm{ct}}^2$$

where η is the efficiency of the CT system, m is the mass per injected particle, S is the fueling rate (in particles per second), and v_{ct} is the final (highest) velocity of the accelerated CT. The formation energy of the CT has been neglected since the random kinetic energy of the toroid is of order 10–100 eV [1]. Thus,

$$\frac{(1/\eta)(0.5) m S v_{\mathrm{ct}}^2}{n^2 \langle \sigma v \rangle / 4Q} < \gamma \tag{1}$$

The fractional burnup is defined as

$$F_{\mathrm{b}} = \frac{2(n^2 \langle \sigma v \rangle / 4)}{S} \tag{2}$$

The fractional burnup is in the range of 5% for steady-state reactors; higher values result in unreasonable alpha particle densities, which could quench the fusion reaction and limit background ion pressures.

Equations (1) and (2) can be rearranged to give

$$\frac{(1/\eta)(0.5)mv_{\rm ct}^2}{(F_{\rm b}/2)Q} < \gamma \tag{3a}$$

or

$$v_{\rm ct} < \left(\frac{\gamma\eta Q F_{\rm b}}{m}\right)^{1/2} \tag{3b}$$

With reasonable values of $\eta = 0.3$ and $m = 2.5(m_{\rm p})$, a constraint on $v_{\rm ct}$ is obtained:

$$v_{\rm ct} < (1.4 \times 10^6)(F_{\rm b})^{0.5} \text{ m/s} . \tag{4}$$

For $F_{\rm b} = 0.05$, a limit of $v_{\rm ct} < 3.2 \times 10^5$ m/s is found. A tritium particle traveling at this speed has an energy over 1 keV.

To determine next an upper limit on the density of the CT, the formation process is considered. In Fig. 1, a plot of $T_{\rm ct}$ vs $n_{\rm ct}$ is shown with a curve giving the $\beta = 0.2$

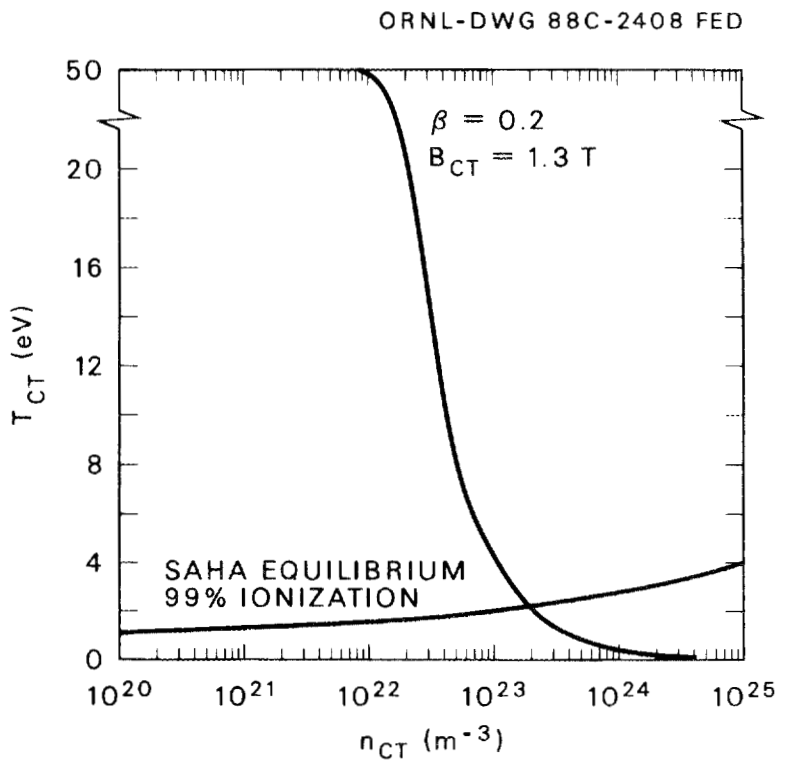

Fig. 1. $T_{\rm ct}$ vs $n_{\rm ct}$ with $\beta = 0.2$.

limit for reasonable $B_{ct} = 1.3$ T [1]. Also shown is the limit in T-n space given by the Saha equation with the constraint of high (99%) ionization of a hydrogen plasma. It can be seen from Fig. 1 that CT densities will probably be limited to about 1×10^{22} m^{-3} for T_{CT} in the range of 25–100 eV [1]. Lower values of T_e, in the range of 5–10 eV, have been inferred from past CT experiments [4], but this is largely due to significant levels of impurities, usually carbon and oxygen. Measured values of beta in plasma-gun-generated CT experiments are typically 0.1 [4], with $\langle n \rangle$ of order (1–5) $\times 10^{14}$ cm^{-3} [4–6]. Thus, the assumed values of $\beta = 0.2$ and $\langle n \rangle \simeq 10^{16}$ cm^{-3} are optimistic, given the performance of CTs to date. As noted in Ref. [4], not all of the fill gas used to form the CT plasma is used (i.e., the CT plasma density depends only weakly on the gas-valve filling pressure); this situation must be improved for fueling of DT devices in which tritium inventory is a concern.

Given these limits on n_{ct} and v_{ct}, the magnetic field that a CT can penetrate can be calculated from

$$0.5\rho_{ct}v_{ct}^2 \geq B^2/(2\mu_0) \ , \tag{5}$$

where $\rho_{ct} = m\langle n_{ct} \rangle$. Equations (3a) and (5) can be rearranged to give

$$B \leq [\mu_0 \gamma \eta \langle n \rangle Q F_b]^{1/2} \tag{6}$$

The highest field that the CT could penetrate is about 2.3 T for $F_b = 0.05$. This field level is too low to allow CT fueling of reactor devices. The situation could be improved somewhat if the CTs could be formed at higher beta values or higher internal fields, but it will be difficult to attain performance at a level that would allow penetration of 5- to 6-T fields, as specified for on-axis fields in most fusion reactor designs.

If the CT fueling system can also drive current at design values, then more recirculating power can be allocated to the fueling/current drive system. A reasonable limit would be:

$$P_{ct}/P_{DT} = \gamma < 0.04$$

This constraint would raise the limiting value of v_{ct} and allow CT penetration to fields of 4.6 T. Even at these fields, fueling in the central core of a reactor plasma is still difficult to achieve. Finally, note that a 3600-MW(t) reactor operating at 5% fractional burnup would require a particle refueling rate of 5.14×10^{22} s^{-1} [from Eq. (2)]. At an average CT density of 10^{22} m^{-3} and volume of 0.05 m^3, this would demand a CT injection rate of about 100 Hz. At average power levels of order 30–40 MW, this repetition rate is not practical with existing pulsed power capacitor technology (although other options are sketched in Ref. [1]).

Compact toroid refueling of devices on the scale of the International Thermonuclear Engineering Reactor (ITER) has a different set of constraints because ITER produces no net electrical power. Penetration of 6-T magnetic fields at a CT density of 1×10^{22} m^{-3} requires velocities of at least 8.3×10^5 m/s.

For the ITER device, $F_b = 0.1$ and the output fusion power is of order 500 MW. With these values in Eq. (2), $S = 3.6 \times 10^{21}$ particles per second. For the minimum velocity derived here and a 50-50 mix of DT fuel, the thermal power to the plasma from the CTs is about 5.2 MW. The electrical power for the fueling system would be at least 15 MW. A tritium particle accelerated to this speed would have an energy of about 9 keV. Again, at an average CT density of 10^{22} m^{-3} and volume of 0.05 m^3, this would require an injection rate of about 7 Hz with about 2.33 MJ per pulse.

The 5 MW of thermal power into the ITER device is in a very localized region with a volume on the order of the CT volume. The resulting power density is one to two orders of magnitude larger than the fusion power density.

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