Fusion Burn Control with Isotopic Fueling *

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One of the gaps in knowledge for harnessing and controlling fusion power is the demonstrated ability to control the fusion burn by adjusting the fuel isotopic mix. The method of isotopic fueling [1] that uses pellets of the different isotopes has been proposed, but never used in practice and will be first attempted on ITER. Research to develop this or related techniques is needed during ITER and beyond for DEMO.

The fusion output power from a burning DT plasma is given by

$$P_{DT} = E_{DT}\,\gamma\,(1-\gamma)\,n_i^2\,\langle\sigma v\rangle_{DT}, \tag{1}$$

where E_{DT} is the energy release per DT reaction (17.6 MeV), γ is the tritium fraction T/(D+T), n_i is the total hydrogenic ion density assumed to be predominantly deuterium and tritium, and $\langle\sigma v\rangle_{DT}$ is the DT reaction rate coefficient. We ignore the DD fusion reactions since its reaction rate coefficient is two orders of magnitude lower than the DT reaction rate in the temperature range that ITER will operate. In this ion temperature range (5 – 30 keV) the DT reaction rate coefficient scales roughly as $\sim T_i^{2/3}$, thus the fusion power P_{DT} scales as

$$P_{DT} \sim \gamma\,(1-\gamma)\,n_i^2\,T_i^{2/3}\,. \tag{2}$$

This is shown clearly in Fig. 1 to be a parabolic function of the tritium fraction γ, which makes it an important aspect in the control of the fusion power output. As long as γ can be maintained above 0.4 and below 0.6, the fusion power will be within 5% of its maximum for a given total density and ion temperature.

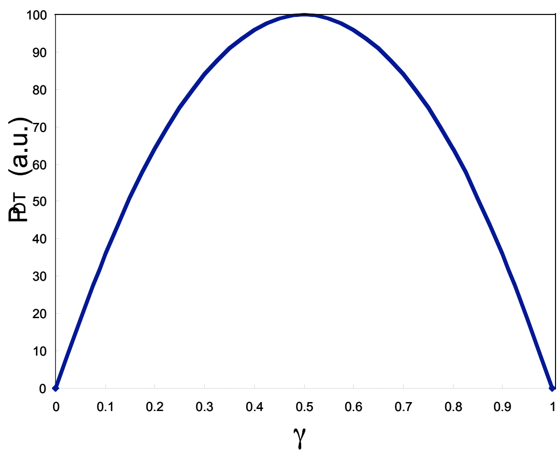

Fig. 1 Fusion power from DT as a function of the tritium fraction for a given total density and ion temperature.

By fueling with an 50:50 mix of DT it may be possible to maintain a plasma with a nearly 0.5 tritium fraction in the plasma burning core. However, the particle transport properties of the isotopes may well be different in a burning plasma as expected by neoclassical transport theory [2] , which would lead to a non optimal isotope mix in the burning core.

The isotopic ratio will be measured to some extent in the ITER burning plasmas by several diagnostics [3]. The neutral particle analyzer (NPA) will be able to determine

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the tritium fraction in the edge and scrape off layer with a 100 ms integration time, but will not be able to determine the ratio in the core due to fast particles from the deuterium neutral beams. The charge exchange recombination spectroscopy systems (CER) may have some capability to determine γ in the core from the Balmer alpha emission lines, but this is a difficult measurement. The diagnostic residual gas analyzer (RGA) systems will be able to determine the γ in the divertor pumping ducts with a time response of several hundred ms. Some possible additional diagnostics that are not yet finalized for ITER that can help with the tritium fraction determination are an analyzer based on the Penning gauge (PG) diagnostic [4] located under the divertor and a time of flight neutron spectrometer (TOF NS) [5]. The PG related diagnostic would enable fast (10 ms) and accurate (better than 5% accuracy) measurement in the divertor and the TOF NS will enable a determination of T/D in the reacting core with a 1 sec integration time with reasonable accuracy ~10%.

ITER will have two pellet injection systems available for initial operation [6]. As described above, these systems will utilize a screw extruder that will hold the DT fuel for at least 30 seconds before the pellets are formed and accelerated. Therefore it is not possible to modify the T/D ratio in the pellets on any reasonable time scale with one injector. It is possible to operate the two injectors with very different isotopic ratios, one at 90%T,10%D (maximum T concentration possible from the tritium plant) and the other with primarily D. This will enable the modification of the input pellet isotopic ratio by controlling which injector injects pellets on a real time basis depending on the measured isotopic concentration in the plasma core. The time scale for injecting a pellet will be on the order of 100 ms from the command to inject (30 meters distance with a pellet velocity of 300 m/s). The T/D measurements from the plasma typically have a 100 ms integration time; therefore it will be possible to change the fueling isotopic ratio on the same time scale that it can be measured. This control scheme is shown schematically in Fig. 2.

The predicted density perturbations from the pellets in ITER and certainly also for DEMO are not expected to reach the center of the plasma due to the high plasma electron temperature which will rapidly ablate the pellets. Therefore, the change of the isotopic mix in the plasma burning core will rely on the transport of fuel ions by diffusion and convection. If the tritium transport in ITER and DEMO behaves as it did in the JET particle transport experiment [2], which was determined to have a fairly strong anomalous inward pinch in the outer 30% of the minor radius of the plasma, then it should be possible for the isotopic pellet fueling scheme to be effective in controlling the optimal DT mixture in the burning core. This will likely be an active area of research on ITER and should be a high priority to the US since it is providing key components in the fuel cycle for ITER.

The fuel burnup in ITER with 500 MW of fusion power generated is expected to be ~0.3% of the maximum anticipated DT fueling rate (120 Pa-m^3/s) . This low fuel burnup is simply a function of the fusion reaction rate and achievable densities in the plasma. DEMO will likely have a similar burnup fraction of the incoming fuel. This low fuel burnup fraction means that the fuel cycle must recirculate the fuel many times before it is actually consumed in the fusion reactions. This has significant design implications on the fuel cycle components and must be taken into account in any future fusion reactor.

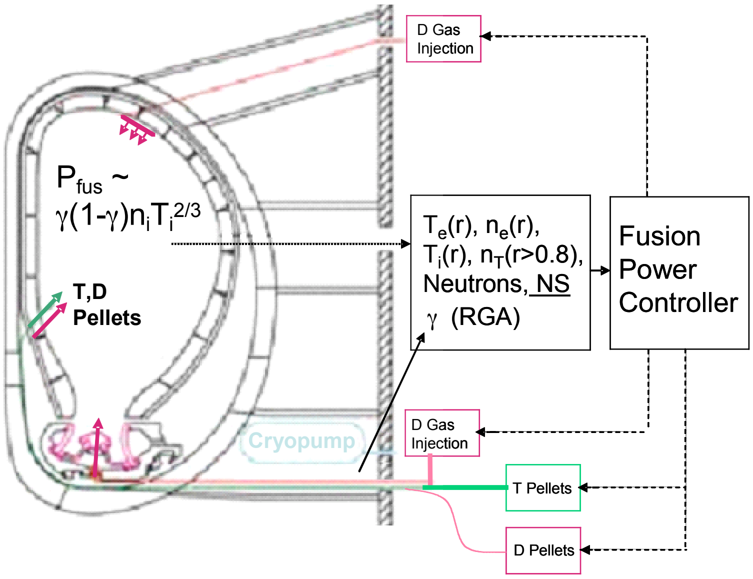

Fig. 2 Block diagram for control of DEMO fusion power and density utilizing the fueling system.

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