ECH Ignition of DD in Mirror/Cusp Geometry

T. K. Fowler
Dept. of Nuclear Engineering
University of California, Berkeley

Abstract

It is shown that Electron Cyclotron Heating (ECH) could ignite pure DD fuel in simple mirrors and cusps.

1. Introduction

The recent demonstration of breakdown and heating by ECH in the University of Wisconsin WHAM mirror experiment points the way toward igniting DD in mirror/cusp configurations.

While ignition depends on both temperature T and confinement number $n\tau$, in a stable mirror or cusp $n\tau$ is due to collisions only, and collisional $n\tau$'s depend only on T. Then ECH could ignite mirrors and cusps at low density. The $n \approx 10^{18}/m^3$ in earlier ECH mirror/cusp experiments would suffice (ELMO [1], RFC-XX [2]). At a density of $10^{18}/m^3$, ECH power 1 kW/liter = 1 MW/m^3 was sufficient to breakdown gas and heat the plasma in ELMO and RFC-XX [1, 2]. At reactor scale ([3], Table 2), 1 MW/m^3 gives about 40 MW ECH per mirror, the same as high-field (12 T) tandem mirror DT and DD reactor models in [3] and similar to total RF in the ITER tokamak. Neither tandem mirror end plugs nor ion heating by neutral beams are required. ICH ignition may also be possible [2].

Example geometries are the WHAM simple mirror [4] and the Novatron mirror-cusp [5]. The Novatron is MHD stable but requires attention to losses at $B = 0$ on axis inherent in cusp geometry (also for $\beta = 1$ [3]). A simple mirror could be stabilized by "sloshing electrons" [6, 7], or other means. In both geometries, adding a long solenoid length L between mirrors yields a DD fusion power gain $Q \propto L$ (as in a tandem mirror). The Q could be increased by storing tritium decaying to ^{3}He re-injected into the reactor (Cat. DD, [3], App. A).

2. DD Ignition

We substitute RF plugging for tandem mirror end plugs. RF plugging by a ponderomotive potential Φ was demonstrated in RFC-XX [2]. The ECH Φ that confines electrons generates an electrostatic potential $\phi \approx \Phi$ confining ions.

First ignoring radial loss, we apply the Pastukhov approximation ([3], Eq. (17a)), giving ion end loss confinement time $\tau_{\text{end loss}} \propto \tau_{ii} (\phi/T_i) \exp (\phi/T_i) \approx \tau_{ii} (\Phi/T_i) \exp (\Phi/T_i)$. Then igniting a DD reactor is described by:

$$d(nT_i)/dt = n^2(T_e - T_i)/(n\tau)_{ei} + 1/2n^2 (\sigma v E)_{nuc} - n^2 (T_i/n\tau_{\text{end loss}}) \tag{1}$$

$$(\sigma v)_{DD} \approx 1.8 \times 10^{-25} (T_i /5 \text{ keV})^2 , \quad 5 - 50 \text{ keV} : \quad \text{SI/keV} \tag{2}$$

$$(n\tau)_{ei} = [50(n\tau)_{ii}(T_e/T_i)^{3/2}] \tag{3}$$

$$n\tau_{\text{end loss}} = (n\tau)_{ii} (\Phi/T_i) \exp (\Phi/T_i) \tag{5}$$

$$\Phi = (1/4\, m_e) (eE/\omega)^2 = \tfrac{1}{4} m_e c^2 (E/B)^2 \; ; \; \omega = (eB/m_e c) \tag{6}$$

$$\partial/\partial z\, n(T_i + T_e) \approx - n \nabla\Phi \tag{7}$$

Eq. (1) describes ignition of DD fuel ($E_{nuc} \approx 20$ MeV). The DD cross-section $(\sigma v)_{DD}$ in Eq. (2) is fitted to Table C1 in [8], rising to 10^{-23} at 150 keV. The Φ in Eq. (6) comes from [9]. We apply ECH near the two mirror throats, giving a small heating volume V_{Se} (turnaround volume for sloshing electrons [6]).

ECH heating to ignition requires that electron heating exceed end loss, $n^2(T_e - T_i)/(n\tau)_{ei} > n^2 (T_i/n\tau_{\text{end loss}})$ giving $(\Phi/T_i) \exp (\Phi/T_i) > 60$, requiring $(\Phi/T_i) > 3$. Ignition requires that fusion power exceeds end loss, $1/2n^2 (\sigma v E)_{nuc} > n^2 (T_i/n\tau_{\text{end loss}})$, giving $(\Phi/T_i) \exp (\Phi/T_i) > 25$, requiring $(\Phi/T_i) > 2.5$. Applying this to DD reactors in ([3], Table 2; $T_i = 150$ keV), ignition occurs if $\Phi \approx \phi > 3\, T_i \approx 450$ keV, while for tandem mirrors in [3] the required potential $\phi = 1100$ keV.

3. Buildup Time

Because the magnetic field B and heating volume V_{Se} are fixed, maintaining E giving 1 MW/m^3 can maintain constant ponderomotive potential $\Phi \propto (E/B)^2$ while ECH and fusion power heat the fuel as n increases.

As an example, we apply RF plugging to the "Next Generation" Cat DD reactor, [3] Table 2, with mirror B = 12 T already achieved in WHAM; Center Cell B = 2.4 T. We take the ECH power constant at 40 MW per mirror needed for breakdown. With Center Cell B = 2.4 T, R = 4 m, length L = 270 m, the plasma energy is $\beta\ (\pi\ 4^2\ 270)[(2.4)^2/2(4\pi/10^7)] = \beta\ 3 \times 10^{10}$ J. Then buildup by ECH alone requires a time $t = \beta\ (3 \times 10^{10}/(2 \times 40 \times 10^6)) = \beta\ 375$ s = 6 minutes. As fusion turns on, this becomes about a minute to build up at $\beta = 1$ at steady density $n = 2.4 \times 10^{20}/\mathrm{m}^3$.

Besides ECH, the control knob is the neutral feed rate I_0, giving:

$$dn_0/dt = I_0 - n\, n_0\, \sigma v_{\mathrm{Ionization}} \tag{8a}$$

$$dn/dt = n\, n_0\, \sigma v_{\mathrm{Ionization}} - (n^2/(n\tau)_{ii}\, (\Phi/T_i) \exp(\Phi/T_i)) \tag{8b}$$

$$dn/dt \approx I_0 - (n^2/(n\tau)_{ii}\, (\Phi/T_i) \exp(\Phi/T_i) \tag{8c}$$

4. Stability

While stable ECH heating has been achieved [1,2], stability of ECH RF plugging is not guaranteed; and sloshing electrons are subject to trapped particle modes ([3], Sect. 4.2). Regimes stable to MHD and trapped particle modes are discussed in [6, 7]. We refer to the literature for use of multiple ECH frequencies to cover the cross-sectional area (V_{Se}/L_{Se}) uniformly [1, References therein].

5. Radial Transport/SYMTRAN

We consider Electron Temperature Gradient (ETG) radial transport that explains tokamaks, giving a transport coefficient χ_{ETG} fitted to Tore SUPRA tokamak data (SI/keV units) [10, 11]:

$$\chi_{ETG} = 0.2\,(T_e^{3/2}/B^2)[\,d/dR \ln T_e \;-\; d/dR \ln n] \qquad (9a)$$

$$\rightarrow 0.2\,(T_e^{3/2}/B^2R) \qquad \text{for constant n} \qquad (9b)$$

$$\tau_{ETG} \rightarrow R^2/\chi_{ETG} \qquad (9c)$$

The SYMTRAN simulation of a tandem mirror reactor in [10] found that competition between $d/dR \ln T_e$ and $d/dR \ln n$ in Eq. (9a) adjusted T and n profiles to give results otherwise determined by end losses. The main effect of ETG was to reduce the burning plasma energy averaged over the radial profiles. A new SYMTRAN could model ignition in Section 2.

6 . Charge Exchange

ELMO ion heating was killed by charge exchange [1]. Mirrors are their own best vacuum pump, by ionization at the surface transported to the expander (better than a tokamak divertor). This can add to ECH heating requirements, lowering fusion gain Q (by a factor 2 in [3], Table 2). Charge exchange in mirrors is discussed in [12].

7. Radiation

With attention to vacuum chamber design to contain Bremstrahlung ([3], Fig. 4), the remaining concern is synchrotron radiation. Ref. [3], Eq. (3b) gives:

$$(P_{SYN}/V_{CC}) = (3200/\sqrt{T_e})\, n_{20}^2 = 0.02 \text{ MW/m}^3 \quad \text{startup} \qquad (10)$$

for Center Cell volume V_{CC}; T = 250 keV [3]; and $n_{20} = 0.01\ (10^{20}/m^3) = (10^{18}/m^3)$ during low-density ignition. Again, wall reflection must limit synchrotron radiation loss as n increases ([8], Chap. 3).

8. Mirror/Cusp Reactors

Examples in [3], Table 2, apply, but without the P_{NBI} =17 MW per end plug. As noted in Sect. 3, Next Generation cases apply, the required mirror B_{mirror} = 12 tesla already being available in WHAM. The example DT reactor has a length 55 m producing 1170 MW-electric. The Cat. DD example discussed in Sect. 3 has a length 270 m producing 510 MWe; but, since tritium breeding is not required, the Center Cell is simpler and cheaper per meter of length, with B = 2.4 T and radius only 4m plus coils [6]; [3,App. A]. Sheffield & Sawan have examined a DD tokamak suppressing DT neutrons, requiring current 88 MA, much larger than the ITER current [13].

References:

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Notes: Mirror RF Plugging TKF 8 – 1 – 24

RF plugging is produced by a standing wave in a cavity near the mirror throat. The electric field in a standing wave is determined by the source (gyrotron). With perfectly conducting walls, no energy is lost unless there is a “load” absorbing waves. So E in the standing wave is independent of the power delivered to the cavity (zero if no “load”). We must check separately whether the required ponderomotive E is large enough to break down gas and heat the resulting plasma.

For ECH plugging, the electric field E yielding a desired ponderomotive plugging force depends on the electron temperature. The ponderomotive force requires (for mirror field B):

$$\Phi = \tfrac{1}{4} m_e c^2 (E/B)^2 \qquad \text{Ponderomotive Potential} \tag{1}$$

$$\partial (nT_e)/\partial z = n\, \partial\Phi/\partial z \tag{2}$$

$$\Phi = T_e \tag{3}$$

$$E/B = (T_e / \tfrac{1}{4} m_e c^2)^{1/2} \tag{4}$$

For RF plugging replacing tandem mirror end plugs in our DD reactor example,[1] we obtain (for $T_e = 250$ keV; $T_i = 150$ keV; $m_e c^2 = 511$ keV; $B = 12$ Tesla $= 1.2 \times 10^5$ gauss; $P_{ECH} = 2 \times 40$ MW $= 80$ MW $= 8 \times 10^{14}$ erg/s; esu/keV units):

$$E = (4 \times 250/511)^{1/2} B = 1.4\, B \tag{5}$$

$$\nabla(c\, E\, B/4\pi) = 1.4\, \nabla(c\, B^2/4\pi) = 5 \times 10^{19}\, \nabla = 8 \times 10^{14} \tag{6}$$

From this, with $B = 2.4$ T, $R = 4$ m center cell: $\nabla^{-1} = (5 \times 10^{19}/8 \times 10^{14}) = 6 \times 10^4$ m $>>$ R_{Se} (resonance heating zone) $= R_{CC}\, (B_{\text{Center cell}}/B_{\text{mirror}})^{1/2} = 4\, (2.4/12)^{1/2}$ m $= 1.8$ m to heat the plasma, giving $\nabla R << 1$ in the heating zone. Thus RF plugging rather than heating determines the required gyrotron E, while propagation $\nabla E^2 << E^2/R_{Se}$ automatically matches ECH gyrotron power to the 40 MW per mirror known to produce “runaway” break down of gas to create an initial plasma density $n = 10^{18}/\text{m}^3$ (“runaway” Ref. 1 Sect 3.2).

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