Prospects for an Axisymmetric Advanced Fuel Tandem Mirror

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Abstract. We describe a new axisymmetric tandem mirror concept which incorporates advances in physics understanding, recent experimental results and developing technologies. The tandem mirror concept consists of two small high magnetic field axisymmetric mirrors at the ends a solenoidal central cell which axially confines a high beta fusion plasma. High energy neutral beam Injection and high frequency electron cyclotron heating power are applied to the end cells which operate at higher density and temperature to provide both magnetic mirror as well as electrostatic axial plasma confinement of the ignited central cell plasma. Designs fueled with DT and, cat-DD are considered indicating a wide design space warranting further analysis as well as experimental investigations.

INTRODUCTION

This paper describes a new version [1] of the tandem mirror concept [2,3] stimulated by work of our late colleague Richard F. Post [4] as well as by results from the Gas Dynamic Trap (GDT) experiment [5,6], from earlier mirror experiments [7], theoretical insights [8], and technology advances (high-field superconducting magnets, high-energy neutral beams, and high-power high-frequency microwave gyrotrons). The confluence of these elements enables the possibility of a high-Q fusion concept capable of burning advanced fuels that predominately produce charged reaction products subject to magnetic confinement and direct energy conversion rather than neutrons which damage and activate vessel materials.

Figure 1 illustrates key features of the new concept, a variant of Post's Kinetic Stabilized Tandem Mirror (KSTM) [4]. A long high-beta low-magnetic-field solenoid is capped by short high magnetic field end cells at a positive potential. The potential peaks, which confine lower energy central cell ions, are generated by neutral beam and electron cyclotron power sources in the end cells to sustain higher density and temperature end cell plasmas.

Earlier tandem mirrors [7-11] commonly provided MHD stability with minimum-B end cells which unfortunately introduced neoclassical radial transport. Now it is recognized that there are many other ways to provide axisymmetric MHD stability [12]. The KSTM concept utilizes plasma pressure in regions of stable magnetic field curvature such as in the end expander. The advantage of axisymmetric mirror cells is that they enable higher mirror ratios to increase axial confinement. Also, relative to minimum-B end cells, axisymmetric cells can be smaller and thereby reduce auxiliary power requirements to electrostatically confine the central cell plasma.

Early tandem mirror experiments operated at low electron temperatures (<250 eV). Popular belief was that open-ended mirror configurations would be limited to such low temperatures. However both theory and, now recently, experiments indicate there is no such limitation. Experiments on GDT using ECH power [6] have reached 1 keV electron temperature, well above the perceived limitations.

ITER R&D and other work has valuable impact on tandem mirror concepts. Advances in high-field high-temperature superconducting magnetics, improve the fusion power gain, Q. Neutral beams of 1 MeV developing for

ITER are ideal for tandem mirror systems as are 170 GHz – 1 MW level ECH sources. In this study we consider the impact of such technologies as well as more futuristic developments.

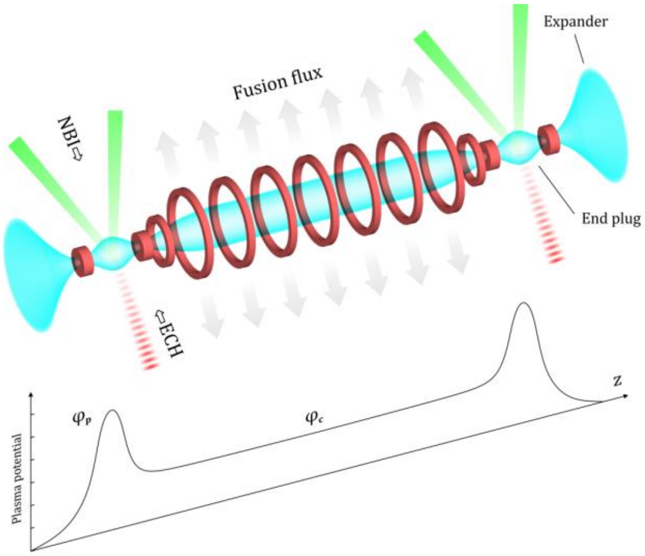

FIGURE 1. Schematic of a tandem mirror magnetic geometry and axial potential profile.

Due to the high ECH power in the much smaller high- density end cells the electron temperature T_{ep} exceeds that in the central cell. The confining potential (Φ_i) illustrated in Fig. 1 is $\Phi_i = \Phi_p - \Phi_c = T_{ep} \ln (n_p/n_c)$ Here n_p and n_c are the plug and central cell densities and T_{ep} is the plug electron temperature. A new result in this paper shows that strong heating of electrons in the end plugs decouples the end and central cell electron temperatures facilitating burning advanced fuels, without the need for externally imposed thermal barriers. Since magnetic mirror system performance favors high temperature plasmas, (e.g. above 100 keV) it is natural to consider advanced fuel options.

Recent advances in high-field superconducting technology together with the development of MeV neutral beams as well as megawatt level high-frequency gyrotrons provide motivation to consider Generation II tandem mirror fusion concepts which could burn a range of fuels such as DT or DD. We envision an ignited plasma confined in a simple solenoid with small high-field axisymmetric mirror cells at both ends providing high mirror ratios for axial confinement. Our considerations incorporate physics results from experiments, new theoretical understanding and advances from the GDT facility in Novosibirsk Russia. While axisymmetric MHD stability can be provided by several methods, we consider here kinetic stabilization by plasma pressure in the good curvature region beyond the outermost mirrors. MeV level neutral beams and high power ECH provides the positive end cell electrostatic plasma potential that axially confines central cell plasma. We have evaluated the requirements to achieve fusion power gains of Q = 10 to 20 for central cell lengths (L_c) from 55 to 270 m (depending on the magnetic field strength, the design dimensions and the fusion fuel). Our evaluations indicate the existence of an encouragingly wide design space warranting more comprehensive modeling and experimental investigations to find optimized design parameters.

Physics Design

The KSTM concept envisioned here incorporates several physics considerations. Based on achieving a plasma beta of 60% in GDT [6] we assume MHD stability. To avoid micro-instabilities we design the end cells with a mirror ratio RM = 2 to3 with skew neutral beam injection to diminish the propensity of Alfven Ion Cyclotron (AIC) modes. The end cell plasma radius exceeds 25 gyro-radii to insure stability of Drift-Cyclotron-Loss-Cone (DCLC) modes [13]. The magnetic field beyond the end cells is flared and diminished by a factor exceeding $(m_i/m_e)^{1/2}$ to decouple the electron temperature from the cold end walls [8]. Synchrotron radiation losses are controlled by enclosing the end cells in microwave cavities with minimal opening for neutral beams and microwave input power. Direct energy conversion is incorporated [14]. We have consider here two fuel combinations: DT, and Catalyzed DD (by reinjecting T produced by DD or, reinjecting 3He obtained by decay of T in storage).

Since the energy input to the end plugs is mainly the ECH power, we determine Q as:

$$Q=(P_{fusion}/2P_{ECH}) =(L_c /2L_p)(R_c/R_p)^2(F) \tag{1}$$

$$F=f_c\,(n_1n_2/n_c^2)(n_c/n_p)(\sigma v\,(E_{fus}/T_{ep})\,n\tau_{ee}\,) \tag{2}$$

Here L is the cell length and R the radius. The factor F characterizes the fuel and plasma. High Q is achieved with: 1.) a long central cell (L_c) relative to each end plug length (L_p), 2.) A high magnetic field in the end plug (B_p) relative to the central cell (B_c) to decrease the plug size, and 3.) a combination of factors F depending on the fuel and plasma being considered. Solving particle and power balance equations with T_{ic}=150 keV and setting $T_{ep} - T_{ec} \approx T_{ep}$ we find for plasma betas of 90% the design values given in the Table below.

Preliminary Estimates of Tandem Mirror Power Reactor Parameters

Technology	Existing	Next Generation		Futuristic
Fuel	DT	DT	Cat. DD*	Cat. DD*
Q	10	20	10	20
Fusion Power, MW	980	3990	2000	7680
Net Electric, MW_e/η_{eff}	215/22%	1280/32%	590/29%	3000/39%
% Neutron Power	80%	80%	6%	6%
L_C, m	215	55	270	65
Neutron wall load, MW/m^2	0.15	2.3	0.02	0.3
B_{mirror}, T	> 12	> 24	> 24	> 48
B_p/B_c, T	6/1	12/1.9	12/1.9	24/5
F, 10^{-4}	50	50	5	5
R_p/R_c, m	0.65/4	0.3/4.0	0.3/4.0	0.15/4.0
$(E_{mag})_{vac}$, GJ	7	19	19	31
P_{ECH}, MW	23	46	46	91
P_{NBI} , MW	18.6	18.3	18.3	18.3

The Table column titled “Existing Technology” deploys developing ITER level technologies: 18 T circular magnets, 1 MeV neutral beams, and 170 GHz gyrotrons. A Q=10 ignited DT plasma with a radius comparable to that of ITER be 230 m long (about 5 times the circumference of the Q=10 ITER design) but with 5 times less magnetic stored energy (E_{mag}). Such a device with DD could also provide a JET-level Cat.DD demonstration of the application of advanced fuels.

The Table column labeled “Next Generation” assumes a doubling of the peak magnetic field and a doubling of the ECH frequency to 340 GHz. Burning DT it would be ITER size but produce 10 times more fusion power and have

Q=20. At 5 times longer length and burning Cat.DD fuel it would produce 2 GW fusion power at Q=10. The futuristic column illustrates the gain in doubling the magnetic field even further: an ITER size Q=20 advanced fuel ignited plasma producing 3 GW electric.

SUMMARY

In this paper we point out that an axisymmetric tandem mirror driven with high ECH powers can sustain ignited advanced fuels that produce significantly fewer neutrons that damage ad activate materials used to construct future fusion reactors. The new linear tandem mirror concept described in this paper with Q =10 can be obtained with 24 T mirror magnetic field requiring a two-fold advances in magnet and gyrotron technologies in a 24 m system length. The attractiveness of this concept motivates further analysis, optimization, as well as experiments. Related ideas regarding advanced fuel tandem mirrors were published by G.I. Dimov [15].

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