Very High Efficiency Fusion Reactor Concept

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ABSTRACT

Very high fusion reactor net efficiencies (> 65%) are shown to be feasible through a new mode of advanced fuel tandem mirror operation. Inducing nonadiabaticity for fusion products not needed to sustain the plasma against losses enhances their end loss rate, leading to a narrow end loss energy spectrum and resultant very high efficiency direct electrostatic conversion. Magnetic field gradients required for nonadiabaticity are estimated, an approximate power balance is calculated, and a reference case is generated. Operation of D-^{3}He reactors in this mode is particularly interesting due to the recent discovery of a substantial ^{3}He resource on the lunar surface.

The possibility of electrostatic direct conversion of particle energy into electricity has long been recognized as a benefit of open magnetic confinement systems. Previous work has investigated the efficiencies attainable by direct conversion of escaping electrons, fuel ions, and thermalized charged fusion products. Due to the thermal spread of the escaping particles, realistic direct converter efficiencies are limited to about 65% [1]. This report discusses the benefits of enhancing the scattering rate of a class of fusion products, leading to almost immediate end loss for that part of the fusion product energy not required to sustain the plasma. The resulting, narrow energy distribution of the end loss fusion products can give very high direct converter efficiency (> 90%) [2].

The geometry under discussion is that of the thermal barrier tandem mirror [1,3,4]. The new operating mode has major implications for plasma power balance, but does not alter the essential configuration. Representative magnetic field, electrostatic potential, and density profiles for the reference case are shown in Fig. 1; end cell density values are scaled from MINIMARS [4], not calculated here.

The D-^{3}He fuel cycle most obviously shows the advantages of this mode of operation, and this report will concentrate on that cycle, although the equations will be written in general form. Some benefit might be realized for a D-T cycle but, with only 20% of the fusion reaction energy in charged particles, the overall effect would be small.

This paper will discuss the two main physics questions involved: fusion product end loss and plasma power balance. There are also a variety of engineering questions to be resolved, which are not discussed here. It is, however, worth pointing out that the recent discovery of a substantial resource (10^9 kg) of ^{3}He on the lunar surface [5] creates the potential for a D-^{3}He

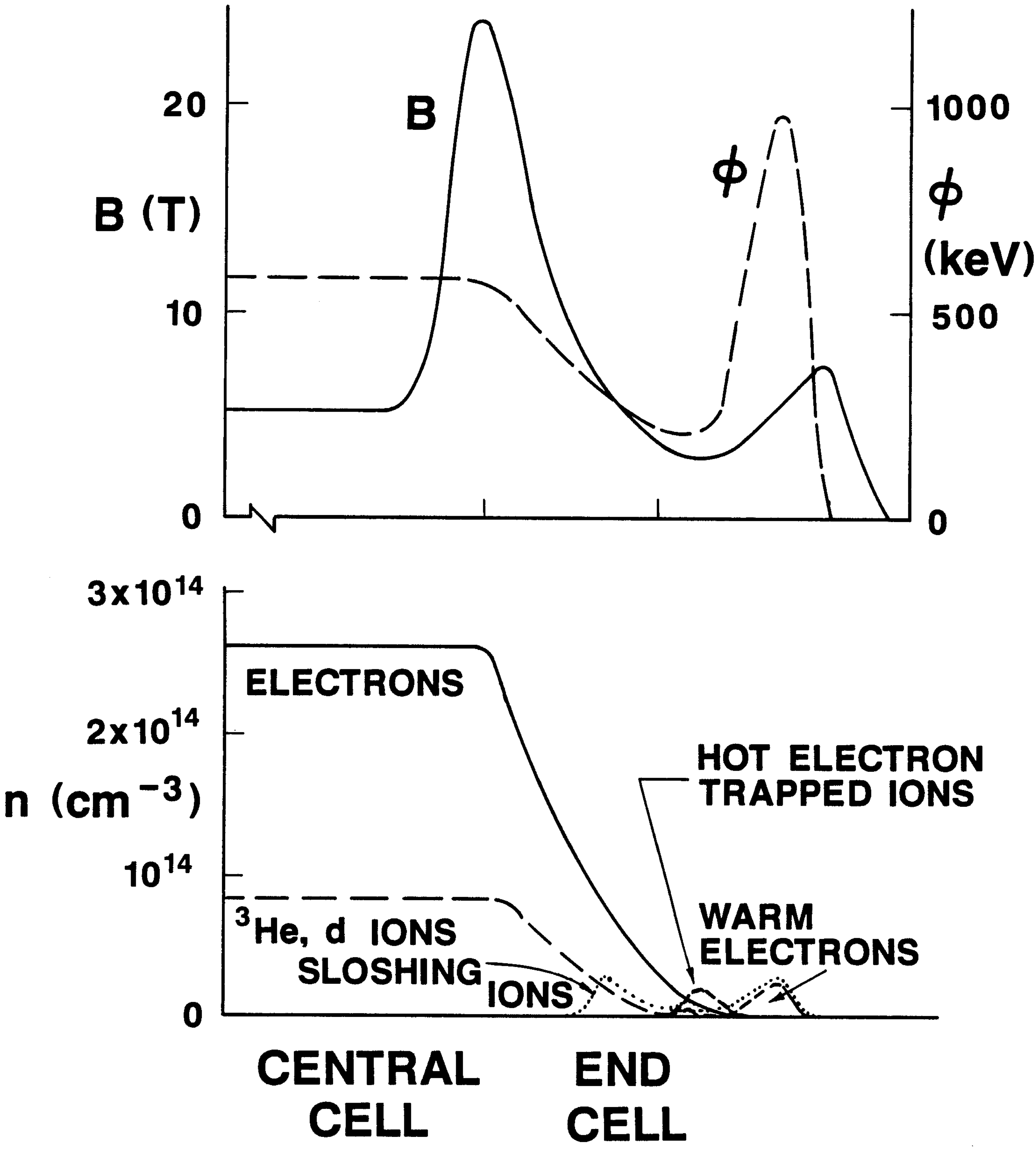

Fig. 1. Representative magnetic field, electrostatic potential, and density profiles for the reference case.

fusion economy. Also, the D-^{3}He cycle is attractive for specialized applications, such as space power or space propulsion.

Units used are cgs with energies in eV and powers in watts.

Fusion product end loss may be enhanced by breaking fusion product adiabaticity, the conservation of magnetic moment $\mu \approx v_\perp^2/2B$, while retaining fuel ion adiabaticity. There is a well-developed theoretical basis with some supporting experimental evidence for estimating the magnetic field gradient and ion energy at which strongly enhanced scattering occurs [6,7]. The magnetic field gradient required to cause sufficiently fast loss of fusion products may be estimated using the analysis of Refs. 6 and 7. Ion diffusion is stochastic for K > 1, where K is the Chirikov mapping parameter [8], given here by

$$K = \frac{3\pi^2}{16} \frac{r_o}{L_B} \left(\frac{\Omega_o L_B}{v}\right)\left(\frac{\lambda^2 + 3}{\lambda^2}\right) \exp\left[- \frac{\kappa(\lambda)\ \Omega_o L_B}{v}\right] \qquad (1)$$

where $\lambda = (v_\perp/v)_0$, the subscript o signifies a midplane value, v is the ion velocity, $v_\perp$ is the velocity perpendicular to B, Ω is the ion cyclotron frequency, r is the radial position, and

$$\kappa(\lambda) = \frac{1}{4\lambda^2} \left[\left(\lambda + \frac{1}{\lambda}\right) \ln \left(\frac{1 + \lambda}{1 - \lambda}\right) - 2\right] . \qquad (2)$$

The magnetic field, B, is assumed to be fit adequately by a quadratic axial profile with scale length L_B near the midplane. The more sophisticated tanh function analysis of Ref. 7 should lead to a similar L_B, since the main physics effect is a phase shift, provided the narrow range of parameters giving $\Delta\mu \ll \mu$ is avoided.

Gross stochasticity, as defined by K > 1, implies a large change in μ ($\Delta\mu/\mu \sim 1$) on each pass through resonance, i.e. each transit of the tandem mirror central cell [7,8]. For typical D-^{3}He tandem mirror reactor parameters, the ion-electron drag time is about 10^5 central cell ion transit (bounce) times, and a stochastic fusion product ion with $\Delta\mu \sim \mu$ will random walk $\mu_{total} \sim N_{bounce}^{1/2} \Delta\mu \sim 300\ \mu$ and almost certainly scatter into the mirror loss cone before giving significant energy to the fuel ions. The analysis used here thus overestimates the required steepness of the magnetic field gradient and represents an upper bound.

For a D-^{3}He reactor, as shown below, about half of the fusion product energy is required to sustain the plasma. Making half of the fusion products stochastic requires an effective loss cone angle of 60° or λ = 0.87. Substituting this value into Eqs. (1) and (2) and solving K = 1 for L_B gives

$$L_B \simeq 0.9 \frac{v}{\Omega_0} \ln \left(\frac{15}{16} \pi^2 \frac{r_0 \Omega_0}{v}\right) . \qquad (3)$$

For the 14.7 MeV protons from the D-^{3}He reaction, a typical plasma radius of 25 cm, and B_0(plasma) = 2.5 T, $L_B \simeq 47$ cm. For this case, $\Delta\mu/\mu \sim 0.5$. Note that L_B is the scale length near the bottom of the well which, for a 60° loss cone, corresponds to a mirror ratio of 1.33 and leads to a required magnetic field gradient of about 2 T/m. This is well within technological feasibility (similar to fields already achieved for MFTF-B).

To calculate plasma and plant power balance, a simplified analysis which concentrates on the central cell is used. End cell power and other effects may be parameterized without changing the essential physics. Electrons plus two fuel ion species are used in the model, and the fusion ash is treated as a single species with a suitably weighted charge and mass when multiple reaction products are present, as in the D-^{3}He case. The fraction of fusion power going to the direct converter, f_{DCfus}, is assumed to be set by choosing a suitable gradient in the central magnetic field. A computer code, PBRA, has been written to solve the equations discussed here. In general, the physical effects modeled by these equations have a well-developed theoretical basis with some early experimental indications of their validity. However, experimental work on thermal barrier tandem mirrors is just beginning.

Central cell electron power balance may be written

$$\frac{n_{ec}^2}{(n\tau)_{ec}} (\phi_e + T_{ec}) V_c + P_{brem} + P_{synch} = f_{efus} P_{fus} + P_{ec}$$

$$+ n_{ec} \nu^{ec/i1} (T_{i1} - T_{ec}) V_c + n_{ec} \nu^{ec/i2} (T_{i2} - T_{ec}) V_c \quad (4)$$

where n_{ec} is the central cell electron density; $(n\tau)_{ec}$ is the central cell electron $n\tau$ value, given by the Pastukhov formula [9,10]; ϕ_e is the electrostatic potential confining electrons; T_{ec} is the central cell electron temperature; V_c is the central cell volume; f_{efus} is the fraction of fusion power going to electrons; P_{fus} is the total fusion power; P_{ec} is central cell auxiliary electron heating, if present; $\nu^{ec/i1}$ is the energy transfer rate between electrons and ion 1 [11]; $\nu^{ec/i2}$ is the energy transfer rate between electrons and ion 2; T_{i1} is the temperature of ion 1; T_{i2} is the temperature of ion 2; and P_{brem} is the bremsstrahlung power, given by $P_{brem} = 1.1 \times 10^{-13} Z_{rel} n_{ec}^2 T_{ec}^{1/2} V_c$ where Z_{rel} is a relativistic correction [12]. P_{synch} is the synchrotron radiation power. Assuming a volume-averaged beta of 60% and a wall reflectivity of 90%, synchrotron radiation is small (< 10% P_{brem}) and is neglected [13,14].

Ion 1 power balance gives

$$\frac{n_{i1}n_{ec}}{(n\tau)_{i1}}(z_{i1}\phi_1 + T_{i1})\,V_c + \frac{n_{i1}}{n_e}\,I_{tr1}(\tfrac{3}{2}\,T_{i1}) + n_{i1}\nu^{i1/ec}\,(T_{i1} - T_{ec})\,V_c$$
$$= f_{1fus}P_{fus} + f_{1ICRF}P_{ICRF} + n_{i1}\nu^{i1/i2}\,(T_{i2} - T_{i1})\,V_c \qquad (5)$$

where n_{i1} is the ion 1 density; $(n\tau)_{i1}$ is the ion 1 $n\tau$ value, given by the Pastukhov formula; z_{i1} is the ion 1 charge; I_{tr1} is the barrier trapping current for ion 1; $\nu^{i1/ec}$ and $\nu^{i1/i2}$ are energy transfer rates [11]; f_{1fus} is the fraction of fusion power going to ion 1; f_{1ICRF} is the fraction of ICRF power going to ion 1; and P_{ICRF} is the total ICRF heating power. An analogous equation holds for ion 2.

Quasineutrality may be written as $n_{ec} = z_{i1}n_{i1} + z_{i2}n_{i2} + z_{ash}n_{ash}$ where n_{ash} is the fusion ash density and z_{ash} is a suitably averaged fusion ash charge. Particle balance for the whole device is given by

$$\frac{n_{ec}^2}{(n\tau)_{ec}} = (z_{i1} + z_{i2})\,n_{i1}n_{i2}\langle\sigma V\rangle_{fus} + \frac{z_{i1}I_{tr1} + z_{i2}I_{tr2}}{V_c} + \frac{n_{i1}n_{ec}}{(n\tau)_{i1}} + \frac{n_{i2}n_{ec}}{(n\tau)_{i2}} \qquad (6)$$

where $\langle\sigma v\rangle_{fus}$ is the fusion reaction rate.

The central cell magnetic field, B_c, is found by choosing a value for β_c $\equiv$ plasma pressure/magnetic field pressure:

$$B_c = \left[\frac{n_{ec}T_{ec} + n_{i1}T_{i1} + n_{i2}T_{i2} + n_{ash}T_{ash}}{2.5 \times 10^{10}\ \beta_c}\right]^{1/2} . \qquad (7)$$

A simple measure of the benefits to be gained using this mode is the overall plant net efficiency, η_{net}. A reasonable model for plant power flow is used to approximately evaluate η_{net}. The net power produced may be written

$$P_{net} = \eta_{th}(f_{nfus}P_{fus} + P_{brem} + P_{synch}) - \eta_{inj}^{-1}(P_{ICRF} + P_{end} + P_{ec})$$
$$+ \eta_{end}(P_{eloss} + P_{1loss} + P_{2loss} + P_{end} + P_{ICRF}) + \eta_{DC}f_{DCfus}P_{fus} \quad (8)$$

where η_{th} is the thermal efficiency, f_{nfus} is the fusion power in neutrons, η_{inj} is the injection efficiency, η_{DC} is the direct conversion efficiency for fusion products lost before they thermalize, η_{end} is the conversion efficiency for the remaining end loss power, P_{end} is the power required to sustain the end cells, and the terms subscripted "loss" are the end loss powers given by the first terms of Eqs. (4) and (6). The net plant efficiency is P_{net}/P_{fus}. The plant power flow resulting from this analysis is shown in Fig. 2.

Solving Eqs. (4)-(8) leads to the D-^{3}He reference case shown in Table 1. The associated plasma power flow and plant power flow are shown in Figs. 2 and 3. The reference case assumes an estimated value of 25 MW of central cell ICRF power for MHD stabilization to allow high beta and axisymmetry [15]. Complete wall [16] or magnetic divertor [17] stabilization would eliminate this power entirely, but future understanding of RF stabilization may lead to even higher ICRF power requirements. The $\overline{\beta}$ value of 0.6 is consistent with present tandem mirror reactor theory [4]. The high total end cell potential requires neutral beams with energies greater than 1 MeV; non-hydrogen beams are one possibility [18].

The reference case shows that, even at relatively low power levels, a net plant efficiency of at least 65% appears to be feasible for a D-^{3}He reactor in this mode. Presently operating power plants and detailed conceptual designs of D-T fusion reactors achieve net plant efficiencies of 33% to 45%. Thus, there is a strong incentive to investigate the broken adiabaticity mode of operation. Possible applications might be a "clean", high efficiency, fusion

Table 1. Reference Design Parameters for a Fusion Reactor in the Broken Adiabaticity Mode

Parameter	Value
Net efficiency	65%
Net power	600 MW_e
Fusion power	930 MW
Q (plasma)	17
Central cell ICRF power	25 MW
End cell power	30 MW
Barrier pumping power loss	15 MW
Central cell	
Volume	2.9×10^8 cm^3
Volume-averaged beta	0.6
Magnetic field (on axis)	4.0 T
Helium-3 temperature	97 keV
Deuterium temperature	100 keV
Electron temperature	75 keV
Electron density	2.6×10^{14} cm^{-3}
^3He to D density ratio	1
Assumed fusion ash density	8.7×10^{12} cm^{-3}
Ion confining potential	400 keV
Deuterium $n\tau$	8.4×10^{15} cm^{-3} s

PLASMA POWER BALANCE

600 MWe Ra Mode d – ^{3}He Reference Case

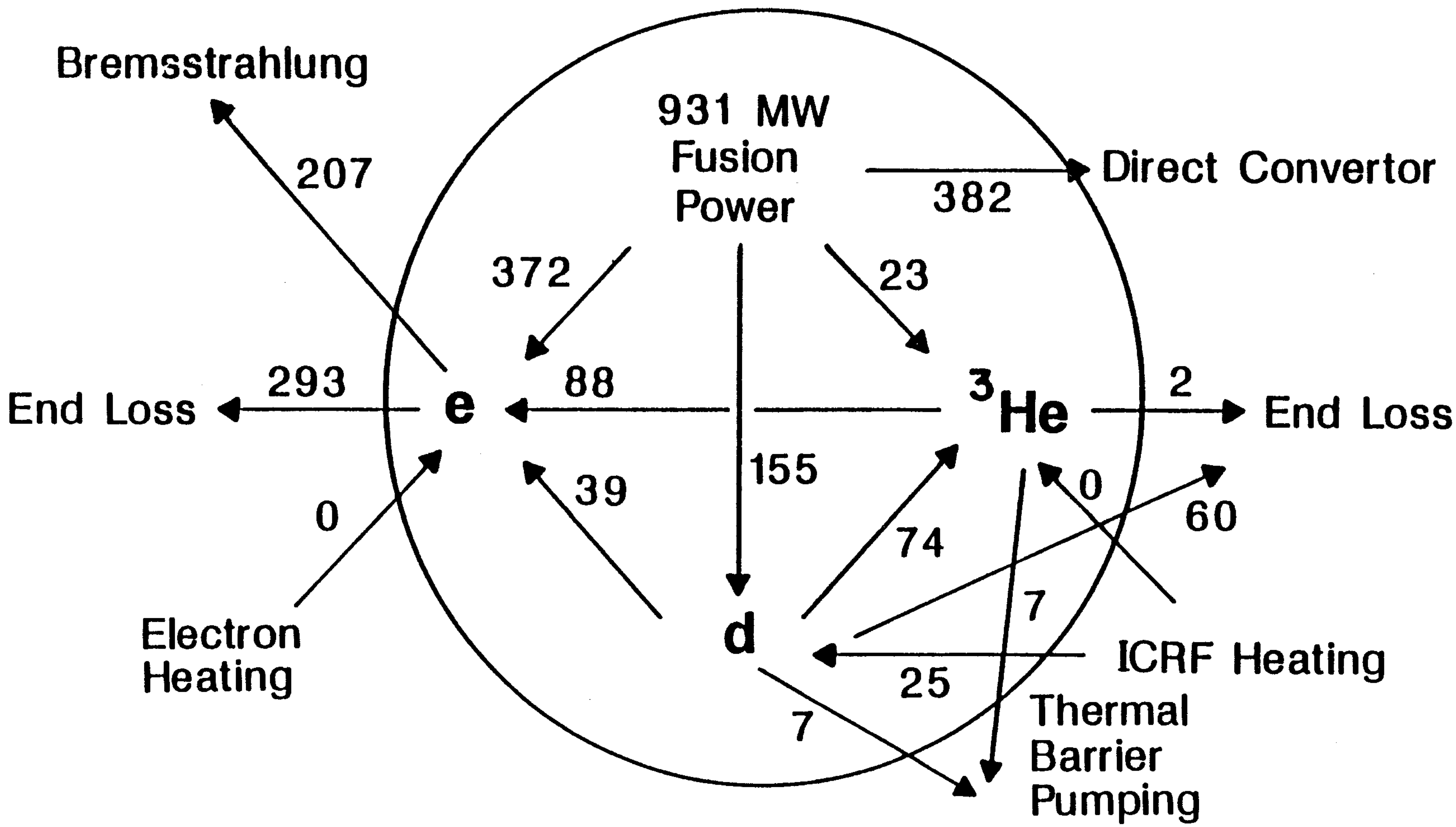

Fig. 2. Reference case plasma power balance.

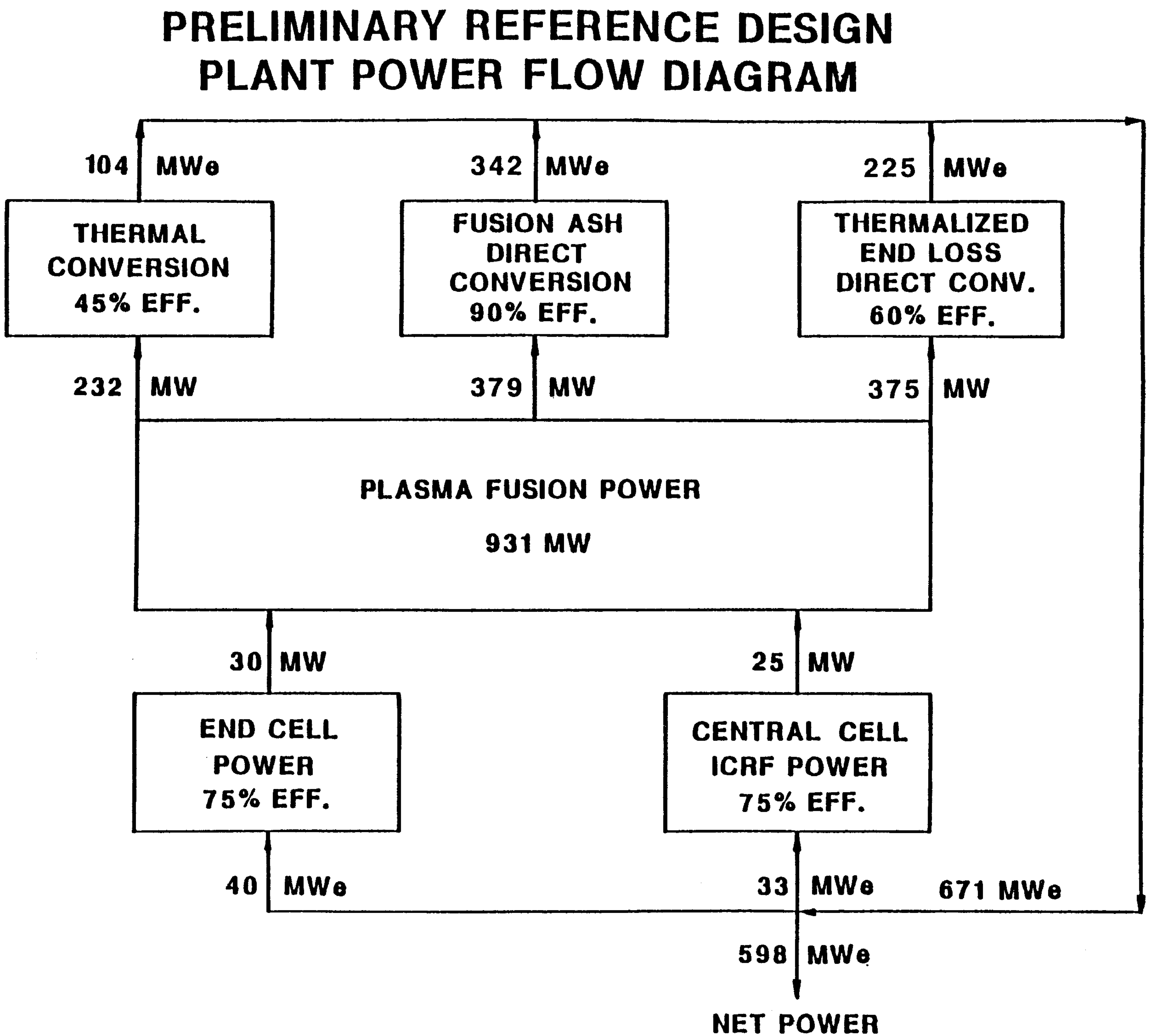

Fig. 3. Reference case plant power flow.

demonstration device or a low mass, high power reactor in space. Should it prove feasible to utilize the lunar ^3He resource [5], a D-^3He fusion economy can be envisioned.

In summary, the magnetic field gradients required to break adiabaticity have been shown to be technologically realistic. Although the end cell physics needs to be assessed in detail, the simple power balance calculations given here indicate that this mode of operation leads to a very high net plant efficiency. Other physics questions include a more sophisticated nonadiabaticity calculation and the analysis of whether the anisotropic fusion product pressure can drive instabilities [19]. Further work is also required to assess the engineering and cost implications of the mode for both specialized applications and a fusion economy.

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