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# A fusion power plant without plasma-material interactions

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**Abstract**

A steady-state fusion power plant is described which avoids the deleterious plasma-material interactions found in D-T fueled tokamaks. It is based on driven p-$^{11}$B fusion in a high-beta closed-field device, the field-reversed configuration (FRC), anchored in a gas-dynamic trap (GDT). The plasma outflow on the open magnetic-field lines is cooled by radiation in the GDT, then channeled through a magnetic nozzle, promoting 3-body recombination in the expansion region. The resulting supersonic neutral exhaust stream flows through a turbine, generating electricity.

## I. Plasma-material interactions in DT tokamaks

Fusion has been proposed as a means for providing a clean, safe, and inexhaustible source of energy. Research efforts have been concentrated on the D-T reaction in tokamaks, because the temperature and density required for ignition are the lowest of all fusion fuels and the tokamak configuration was the first to provide good confinement. Progress has been considerable. Plasma temperatures and densities in the scientific breakeven regime have been achieved in tokamaks.[1,2]

However, the ITER design activity[3] has shown that several major plasma-material interaction (PMI) problems occur in DT-fueled tokamaks, complicating extension of this configuration to a power plant. These are:

1) damage and activation of plasma-facing components (PFCs) and structural materials by neutron bombardment;
2) high tritium inventory (> 100 g) in PFCs, due to codeposition and implantation processes;
3) high erosion rates (0.25 m/burn-yr) of PFCs by sputtering;
4) high steady-state and intermittent heat fluxes (> 5 MW/m$^2$) to divertor components due to plasma bombardment;
5) very high (> 10$^5$ MW/m$^2$) plasma heat fluxes to PFCs during disruptions;
6) ablation of materials by disruption-generated runaway (> 30 MeV) electrons;
7) high (> 10$^7$ Nt) forces on structures due to vertical displacement events; and
8) difficult *in-vessel* component repair because of complex geometry and radioactivity.

It has long been recognized[4] that other fusion reactions, such as p + $^{11}$B $\rightarrow$ 3 $^4$He and D +$^3$He $\rightarrow$ $^4$He + p, are attractive alternates to D-T because the fuel is not radioactive and the fusion events produce far fewer neutrons. They also eliminate the need for meter-thick neutron shielding and T breeding from Li. Thus, several of the PMI problems listed above immediately disappear. In this paper we describe how all the above-listed PMI problems are avoided if the goal of D-T ignition is changed to energy amplification in p-$^{11}$B. This solution requires that a high-β, closed-B confinement device, the field-reversed configuration (FRC),[5] have as good confinement as achieved in tokamaks. A research program to this end has already been described.[6] The required parameters are listed in section III.

Advances in plasma physics, many achieved in tokamak research, have made this approach more realistic than previously envisioned.

## II. Choice of fuel, plasma density and temperature

The advanced fuel mixture chosen is p-$^{11}$B because of a lower neutron yield and greater availability compared to D-$^{3}$He. The penalty paid is a lower fusion cross section. p-$^{11}$B does require operation at high density ($n_e \sim 0.3\text{-}1 \times 10^{15}$ cm$^{-3}$) and temperature ($T_i \sim 100\text{-}300$ keV). At these parameters, the fusion power density is 1 to 10 W/cm$^{-3}$. The magnetic field at $\beta = 1$ is 10 T. Early calculations[4] showed that a large Bremsstrahlung energy loss from the hot dense plasma limits Q, the ratio of fusion power to auxiliary heating power $P_f/P_a$, to about 3. Recent calculations show higher gains, Q > 4, are possible, particularly if colliding polarized flows of superthermal fuel ions can be generated within the plasma.[7] The application of α–channeling[8] to heat fuel ions could increase Q above 4 in the low-$T_i$ FRC range, *ca.* 150 keV. As seen in figure 1, the minimum Q necessary for there to be power available for sale is about 2.

It should be noted that D-T tokamak experiments have already achieved (simultaneously) temperatures and densities within factors of 2 and 5 respectively of those needed in p-$^{11}$B reactors.[1] High densities alleviate PMI problems found in tokamaks. Another positive feature of the higher densities and temperatures, as described elsewhere,[4-7] is a smaller reactor size compared to tokamaks, with possible improvements in economic attractiveness.[9]

What is certain is that p-$^{11}$B fuel eliminates radioactivity, activation, and neutron damage problems. If fusion is to live up to its fullest potential, scientific research must find a suitable plasma confinement configuration for p-$^{11}$B fuel.

## III. Choice of configuration: equilibrium, confinement, steady-state operation, and stability

The tokamak configuration has been the research platform on which the preponderance of fusion results have been obtained. But the tokamak, and likely the stellarator, are unsuitable for burning p-$^{11}$B because of the density limit, poor geometry for heat removal, and short lifetime of PFCs. Other confinement configurations have been investigated, such as mirror machines (MM), gas dynamic traps (GDT),[10] spheromaks, and field-reversed configurations (FRC).[4] The purely linear machines, such as MMs and GDTs, suffer from end losses. The novel toroidal configurations with closed field lines but no toroidal magnetic field coils, e.g., FRCs and spheromaks, have stability problems. Each *isolated separate* device has short PFC lifetimes, primarily due to sputter erosion by plasma ions.

To overcome the shortcomings noted in the above paragraph, we are proposing the hybridization of a GDT with an FRC and a magnetic nozzle, see Figure 2, into a hybrid fusion reactor configuration (HBFRC). An FRC is preferred over the spheromak as the core of the HBFRC because: a) an FRC has no toroidal magnetic field $B_T$, hence higher $\beta$ and lower synchrotron radiation losses than a spheromak; b) without toroidal field, an FRC is not likely to generate MeV runaway electrons during disruptions of the plasma current; and c) the lack of toroidal field may eliminate certain instabilities.

Fusion of p with $^{11}B$ takes places within the FRC. The ~3 MeV alpha particles formed heat the p-$^{11}B$ fuel and must maintain the ion temperature above ~ 100 keV. If alphas transfer their energy to electrons according to classical slowing down, Bremsstrahlung prevents ignition. Under these conditions the FRC ions must be heated to maintain the burn. In this conceptual design, ICRF heating (~ 100 MHz) is chosen because of high energy conversion efficiency, applicability to $\alpha$-channeling, and ability to create ion distributions with tails extending to several hundred keV.[11] These tails may improve stability and fusion power.

Because Bremsstrahlung power losses are unavoidable, plasma transport losses must be small, < 0.3 $P_f$, to achieve the necessary high temperatures.[4] The closed field line structure of the FRC must provide the requisite energy confinement. There is insufficient data to extrapolate energy confinement from previous FRCs to a reactor-scale plant. From experiences on tokamaks, theoretical predictions are also not deemed sufficiently accurate. We note that L-mode scaling, developed from only tokamak data, contains no toroidal field dependence. Without defense, we apply L-mode scaling to a 1 m radius FRC with p-$^{11}B$ fuel, 50 MA plasma current, $\kappa$=5, $T_i$ = 100 keV, $n_e = 10^{15}$ cm$^{-3}$, and $P_f$ = 100 MW, finding $\tau_E$ ~ 20 s (or $\chi$~ 0.05 m$^2$/s) . This gives a transport $n\tau T$ of 2 x $10^{18}$ keV cm$^{-3}$ s.

Most previous FRCs have operated in a pulsed mode. Sustainment of the current is necessary for steady-state operation. By use of the rotomak technique,[12,13] the plasma current would be driven continuously through the application of a rotating magnetic field (f ~ 500 kHz, B ~ 100 G, P ~ 5 MW). Experiments to drive 1 MA are in progress.[14] This current-drive technique induces a time-dependent magnetic shear and a radial component in B. The latter will cause radial particle transport, driving additional current, as described by the Onsager reciprocity relations.[15] The combination of high frequency ICRF and the lower frequency rotomak RF fields may allow $\alpha$-channeling *via* the two-wave process.[16]

An isolated FRC is subject to tilt[17] and interchange[18] modes. But experiments show that ideal MHD theory is overly pessimistic.[19] Equilibria which are not subject to these instabilities have been obtained.[20] Energetic beams have been discussed as one method to prevent the tilt mode.[21] To help suppress these instabilities over a wider operational space we suggest a new approach, that the FRC be held within the linear geometry of the GDT. The outflowing plasma in the good curvature region of the nozzle stabilizes the GDT against interchange and tilt modes. The GDT confinement promotes build-up of a larger plasma pressure outside the FRC separatrix, also a stabilizing influence on the FRC against interchange modes. The GDT plasma itself is a "stiff" conductor, providing a stabilizing surface on the FRC separatrix. The neutralization of the plasma as it exits the GDT nozzle, described in the next section, is an important element necessary for the GDT to provide stability because it prevents plasma from intersecting conducting surfaces.[22]

The rotomak will further aid stabilization. Additional stability might be provided by rotation,[23] created, for example, by self-generated radial electric fields[7] or by Ioffe bars.[24]

## IV. Reduction of plasma-material interactions

As noted earlier, the choice of non-radioactive, aneutronic fuel has eliminated three of the eight problems listed in section I. Moreover, the lack of neutrons allows use of many recently developed high-technology materials, e.g., ceramics and composites, not permitted as PFCs in a D-T tokamak. In this section we describe how the magnetic nozzle causes the exhaust plasma to recombine, eliminating ion sputter erosion of and excessive heat loads on the PFCs. The remaining three PMI problems are associated with disruptions. The HBFRC mitigates these too, as described later.

The length of the GDT region is set to allow the electrons to cool by boron radiation as they flow towards the nozzle. An adequate length, assuming coronal radiation, is less than 5 m. The minimum length depends on $P_f$ and $n_e(s)$, the separatrix density. This small length, compared to a tokamak scrape-off layer (SOL), is possible because of the large volume, high density, and high $Z_{eff}$ of the GDT, compared to a tokamak's SOL. In the GDT a Marfe-like[25] structure will develop as the electron temperature falls from ~ 1 keV near the separatrix to ~5 eV, the low-temperature peak of the B-radiation rate.[26] Concomitantly, the plasma density rises above $10^{15}$ $cm^{-3}$ to reduce pressure drop. At the nozzle throat the magnetic field is 30 T. Throughout the GDT the bulk ions remain near 1 keV, considerably warmer than the electrons, because of the low collisionality. A hot ion component also exists in the GDT because of prompt $\alpha$ losses.

Within the GDT the pressure is nearly constant at $p_0$ and the flow essentially stagnated. Acceleration to sonic flow, M = 1, occurs in the nozzle. A double layer develops within the plasma at this position. The flow through the nozzle double layer is about 6 x $10^{22}$/s. Because the ions are warm, the total power through the nozzle is about 10 MW, 20% of $P_f$.

The ambipolar expansion of the plasma out of the magnetic nozzle further cools the outflowing plasma stream. The high density and low temperature at the nozzle exit promote 3-body volumetric recombination.[27,28,29,30] As the plasma expands out from the nozzle, becoming both cooler and more tenuous, the rate of recombination, R, changes, initially falling as the flow accelerates, then rising as the flow speed asymptotes. Beyond this point R depends on distance x from the nozzle approximately as $x^{9\gamma-15}$, where $\gamma$ is the ratio of specific heats. $\gamma$ = 5/3 for an ideal gas and 2 for a collisionless magnetized plasma. The expanding plasma will have $\gamma$ in this range. Hence significant recombination will occur as the plasma expands from the nozzle, until the plasma density has dropped.

The warm ions exiting the nozzle have a mirror loss cone distribution. The overall result is a conversion of the exiting plasma stream into a supersonic directed neutral gas jet. The gas pressure surrounding the expanding stream is in the 0.01-1.0 Torr range, in approximate balance to the pressure of the supersonic jet. Pressure recovery occurs downstream as the ambient neutral gas is entrained in the flow and heat conducted to the wall. This supersonic gas stream does not cause sputtering. It allows for efficient energy conversion by a high-temperature turbine. The plasma in the nozzle prevents the backflow of the ambient gas into the reaction chamber, similar, in principle, to the plasma window developed for synchrotron light sources.[31] Nozzles on plasma arc jets routinely survive thousands of hours of operation with comparable power flows.[32]

About 80% of the fusion power is released as Bremsstrahlung[33] and line radiation in the FRC and GDT. It would be recoverable by the high efficiency (~60%) techniques proposed by MSNW and described by Dawson.[4] In these, helium gas flows through $B_4C$ heat exchanger tubes which contain corrugated sheets of refractory medium-Z material. $B_4C$, an insulator, is nearly transparent to 100 keV X-rays; the medium-Z materials absorb the X-rays within a few millimeters. The Bremsstrahlung heats the medium-Z materials to about 2000 K. A gas coolant extracts this energy and is used to drive a high efficiency thermal cycle.

Vertical displacement events are absent in the FRC because of the nozzle magnets. Disruptions of the current may nonetheless occur if stability is lost. If a tilt mode developed and the plasma contacted the $B_4C$ tubes, no currents would flow through the structure since they are insulators, eliminating halo currents which occur in tokamaks. Impurities would be released from the $B_4C$, increasing the radiative losses and causing a thermal collapse. The intense heat load would be predominantly as x-ray radiation which causes less material damage than charged particles. The X-rays would be absorbed by the medium-Z (and $B_4C$) material volumetrically, raising the temperature about 200 K above its operating value.

The entire FRC current is in the diamagnetic direction hence runaway electron generation is unlikely. (The high density of an FRC also makes runaways unlikely.) Whatever fast electrons are generated by transients and which reach open field lines will flow into the high pressure gas-filled region beyond the nozzle where they are stopped by the ambient neutral gas.

The advantages of this non-radioactive double-ended linear configuration for construction, assembly, maintenance, and energy conversion are clear. A single-ended configuration could be used for propulsion.

## V. Closing remarks

The hybrid fusion reactor configuration (HBFRC) device described above is based on a synthesis of physics results gained through tokamak, FRC, GDT, and basic plasma science research as well as fluid mechanics and aerospace technology. Examples are Marfes, 3-body recombination, shear stabilization, ICRF heating and non-inductive current drive. The HBFRC's linear configuration, its lack of radioactivity, and its resolution of vexing PMI problems, make it an attractive power plant from an engineering perspective. Joint experimental and theoretical research is needed to test the HBFRC. Studies of stability, energy confinement, Bremsstrahlung and synchrotron generation and absorption, radiative cooling, nozzle phenomena, plasma formation, fueling, ash exhaust, current drive, magnetic coil and heat exchanger technology, and energetic particle effects are necessary.

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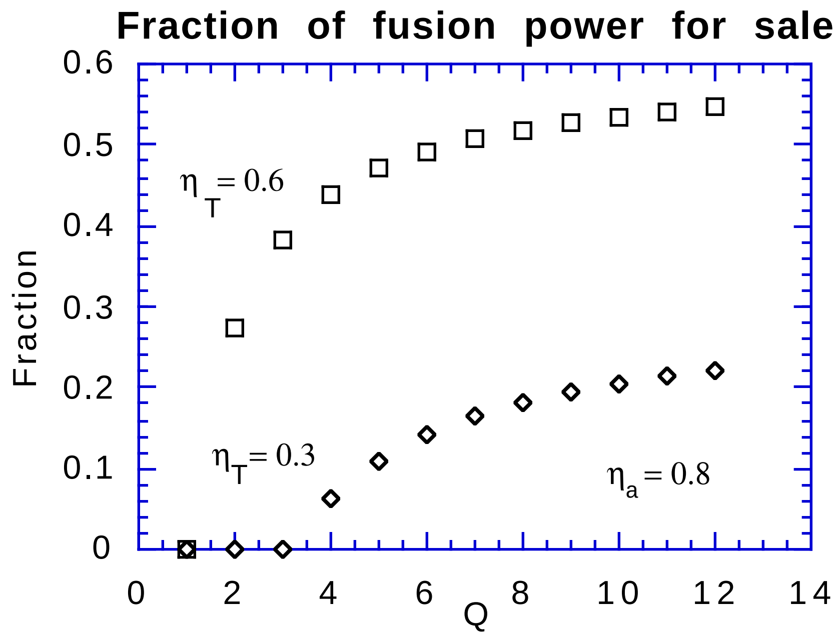


Figure 2. Fraction of fusion power for sale. $\eta_a$ is the efficiency of the auxiliary heating power system, $\eta_T$ the conversion efficiency of the units (turbine or MSNW) which generate electricity.

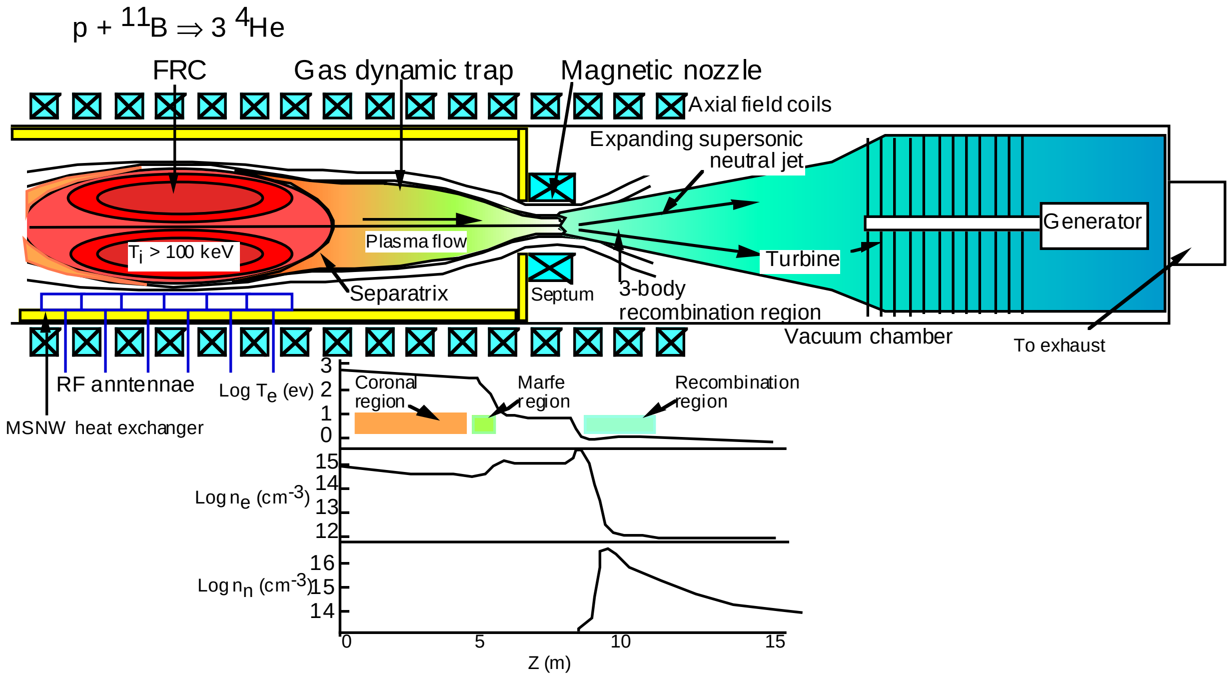


Figure 2. Schematic of a Hybrid Fusion Reactor Configuration (HBFRC). The left-hand side components of the device, e.g., nozzle and turbine, are not shown.

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