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TITLE  THE REVERSED-FIELD PINCH AS A POLOIDAL-FIELD-DOMINATED, COMPACT, HIGH-POWER-DENSITY FUSION SYSTEM

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THE REVERSED-FIELD PINCH AS A POLOIDAL-FIELD-DOMINATED, COMPACT, HIGH-POWER-DENSITY FUSION SYSTEM

Robert A. Krakowski

The reversed-field pinch (RFP) and the other confinement approaches being addressed by this panel [e.g., spherical-torus tokamak (STT), spheromak (SPH), field-reversed configuration (FRC), and dense z-pinch (DZP)] have two characteristics in common: a) they have a promising but less developed database than the “conventional” tokamak, and b) to varying degrees the confining magnetic field just outside the plasma is generated primarily by toroidal or axial currents flowing within the plasma. This ever increasing poloidal-field domination (PFD) as one moves in the direction STT → RFP → SPH → FRC → DZP leads to significantly improved reactor projections. These attractive projections result primarily from: a) the potential for lower optimum cost occurring for higher power density and reduced system size; b) reduced coil requirements as expressed in terms of size, fields, cost and technology; and c) an overlaying of important plasma support functions with potentially reduced technological requirements, operational complexity, and cost.

Before the degree to which PFD confinement schemes improve reactor prospects can be assessed, a working definition of an “attractive” fusion reactor would be useful. Such a definition of an “attractive” fusion reactor, however, cannot be made unambiguously because of a combination of requirements: a) acceptable product cost (e.g., cost of electricity and total capital cost, including system complexity as translated into reactor longevity, maintainability, reliability and availability), b) acceptable safety (e.g., nuclear afterheat, power density, passive cooling geometry, disruption control, etc.) and environmental (e.g., resources, long-term waste, etc.) constraints, and c) acceptable total cost of development (e.g., actual integrated cost, opportunity costs risk, time, etc.). Furthermore, energy alternatives against which fusion must compare (e.g., cleaner fossil, safer fission) are presenting a tougher competition, particularly as the time horizon for commercial fusion is pushed further out; the definition of “attractive” under these circumstances becomes a moving as well as a multi-faceted target.

The attractiveness of the fusion end product can be enhanced in a number of ways: a) reduced cost and power of the entry level device; b) availability of a range of unit sizes; c) reduced complexity and combined plasma support systems; d) more efficient plasma confinement (reduced peak to average magnetic field, high engineering beta); e) reduced sensitivity of R&D and product cost to the main plasma parameters; f) more of the burden of confinement and profile control placed on the plasma and less on cumbersome and sometime interfering external systems. The compact systems that form the topic being addressed by this panel offer the exciting potential of achieving many of these essential element of reactor “attractiveness.” Furthermore, all of these concepts address directly the main problem facing reactor projections of the conventional tokamak: low fusion power core (FPC; i.e., plasma chamber, first wall, blanket, shield, coils, and related structure).
power density resulting in large size and cost. The reduction in (or elimination of) external coil requirements also reduces cost, leads to a more open and maintainable system, (with “single-piece” FPCs becoming a possibility). Under certain conditions the efficient use of copper- or aluminum-alloy coils to confine a high-power-density plasma also becomes an option. Lastly, the combined functions of confinement, heating (large current density and strong ohmic power density), current drive (magnetic helicity injection), impurity control (natural divertor in SPH or FRC, toroidal-field divertor in RFP, pulsed operation for DZF, double-null poloidal divertor in a naturally elongated STT), and possible combination of fueling and magnetic helicity injection can contribute immensely to the reduction of FPC size, complexity, and cost.

In summary, the PF13 systems promise eased reactor engineering and improved economics. These benefits derive primarily from lower optimum costs occurring at increased plasma fusion power density (50-100 MW/m³ compared to ~2 MW/m³ for ITER^2 and 5 MW/m³ for Starfire^3) and first-wall neutron loading (~5 MW/m²). Potential uncertainties associated with this parameter regime of competitive economics are: a) increased first-wall afterheat power density and diminished inherent safety against damage resulting from an inadvertent loss of coolant or coolant flow, and b) increased particle and power fluxes emanating from the plasma. The degree to which this downside of higher power density manifests itself on a practical engineering design depends strongly on: a) FPC materials and configurational choices, and b) the degree to which the plasma heat loss can be spread uniformly over the first wall (versus concentrated on a divertor plate) as well as the degree to which the temperature of particles leaving the plasma and the related divertor-plate erosion can be reduced. Operation in the regime of a high-density, PF13 plasmas, like that of the RFP, generally favors reduced temperatures at the divertor plate and increased radiative loss over convective transport from the bulk plasma, thereby offering relief from these downside issues.4,5

Against the background provided by these general remarks, the reversed field pinch (RFP) is described as a specific example of a PF13 fusion reactor system. Table I gives typical parameters for the main RFP experiments as well as for devices under construction and those projected further into the future. The toroidally axisymmetric RFP typically has a plasma aspect ratio of A = 6, is heated solely by strong plasma currents (jφ = 20 MA/m²), achieves temperatures of ~1 eV/kA, and can be operated with experimental discharge times that are much greater than the time required for the large on-axis toroidal field (comparable to the edge-plasma poloidal field) to diffuse resistively to the low (10 times less than the on-axis toroidal field), reversed toroidal field that exists external to the plasma. The poloidal currents flowing in the outer regions of the plasma are driven by a mean poloidal electric field that in turn is generated by plasma fluctuations created in the process of maintaining the RFP plasma/magnetic field configuration in a near minimum energy state.5 The turbulence associated with this “relaxation” process leads to enhanced transport, which, while considerably greater than a tokamak of comparable size and current, nevertheless scales to an ignited DT reactor (Table I, lφ = 15 20 MA, v_p = 0.6 m, jφ = 15 MA/m²)^5,7. Figure 1 gives the usual Lawson diagram as a summary of RFP
status relative to the tokamak; other compact systems as well as projected performance from RFP devices presently under construction are also given.

The higher-power-density reactor projected for the RFP (re: TITAN, Table 1) would be less expensive than the most optimistic tokamak reactor and is expected to be very competitive with fission power. Figure 2 gives a cost comparison between the RFP and a number of advanced tokamak power plants. The favorable cost position of the RFP results both from a reduced FPC cost (higher mass power density), more efficient (projected) current drive, and reduced (resistive, low-field) coil masses, technology, and costs. Since these RFP reactor designs operated with neutron wall loadings in the range 10-20 MW/m², compared to 3-4 MW/m² for the optimized (but higher costing) tokamak reactor, the tokamak may be able to take certain credits for a favorable safety assurance rating. The maximum advantages with regard to the full impact of cost credits for high level of Safety Assurance (i.e., reduced cost by not requiring “N-stamped” components) are also shown in Fig. 2. The cost impact for the tokamak reactor if the existing database is used is also shown on Fig. 2. The integrated results and comparisons given on Fig. 2 illustrate the desirability of achieving high mass power density through high plasma power density, reduced coil mass and cost (low toroidal field), and combined heating, confinement, and current-drive systems that may require less-advanced technology. Detailed design studies have shown that through careful choice of materials and (cooler) configuration both the economics of high power density and inherent safety may be available tofusion through the RFP.

In conclusion, the RFP represents an important step away from the limitations and problems of the toroidal-field-dominated tokamak and towards a configuration wherein the onus of confinement, heating, and sustainment is put more on the plasma and less on complex, expensive, and sometimes interfering external support systems. The increased power density and associated reduced cost in a simplified system are essential elements of enhanced reactor attractiveness for this PFD system. These advantages can be further enhanced if the stiff toroidal-field “back bone” that is responsible both for the tokamak physics successes and its reactor problems is completely eliminated (e.g., the spherical). Given that the problem of plasma stability and energy confinement can be solved in these configurations with reduced externally imposed toroidal fields, one moves closer to an ideal magnetic-confinement fusion reactor. Lastly, those systems which confine only by poloidal field (e.g., the DZP and its toroidal counterpart, the FRC) offer the potential of even more compact, high beta systems that unlike the tokamak SST – RFP – SPH evolution, project efficient approaches to pulsed magnetic confinement systems that offer unique and inexpensive solutions to many of the technical problems now facing the commercialization of fusion. In view of the present commercial prognosis of the conventional tokamak and the physics required to project an economic end product, more energetic and resource should be put behind the important options which even at 5% of the US fusion budget are providing the lion’s share of hope and optimism for a realistic solution to the problem of commercializing fusion power.
REFERENCES


### TABLE I. MAIN PARAMETERS FOR EXISTING (E), PLANNED (P), AND CONCEPTUAL (C) RFP DEVICES

<table>
<thead>
<tr>
<th>Device</th>
<th>Status</th>
<th>Laboratory</th>
<th>$R_c$ (m)</th>
<th>$r_p$ (m)</th>
<th>$I_0$ (MA)</th>
<th>$J_0$ (MA/m$^2$)</th>
<th>$T_e$ (keV)</th>
<th>$n$ ($10^{20}$/m$^3$)</th>
<th>$\beta_0$</th>
<th>$\chi E (m^2/s) \equiv (3/16) r_p^2/\tau_E$</th>
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<tr>
<td>ZT-P</td>
<td>E</td>
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<td>0.45</td>
<td>0.068</td>
<td>0.095</td>
<td>6.5</td>
<td>0.25</td>
<td>1.5</td>
<td>0.3</td>
<td>43.4</td>
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<td>TPE-1R(M)15</td>
<td>E</td>
<td>ETL Japan</td>
<td>0.70</td>
<td>0.135</td>
<td>0.135</td>
<td>2.4</td>
<td>0.65</td>
<td>0.18</td>
<td>0.2</td>
<td>15.5</td>
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<tr>
<td>TPE-1R(M)</td>
<td>E</td>
<td>ETL Japan</td>
<td>0.50</td>
<td>0.09</td>
<td>0.13</td>
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<td>0.60</td>
<td>0.3</td>
<td>0.1</td>
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<td>Padova Italy</td>
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<td>0.125</td>
<td>0.15</td>
<td>3.0</td>
<td>0.08</td>
<td>1.0</td>
<td>0.1</td>
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<tr>
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<td>0.20</td>
<td>0.7</td>
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<td>OHTE RFP</td>
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<td>4.5</td>
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<td>ZT-40M</td>
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<td>0.1-0.2</td>
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<td>ZTH</td>
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<td>0.40</td>
<td>4.0</td>
<td>8.0</td>
<td>0.5-5.0</td>
<td>0.3-5.0</td>
<td>0.10</td>
<td>2.4($b$)</td>
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<tr>
<td>FTF RFP</td>
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<td>1.80</td>
<td>0.30</td>
<td>10.4</td>
<td>37.0</td>
<td>10-20</td>
<td>6.0-9.0</td>
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<td>0.4($b$)</td>
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<tr>
<td>TITAN</td>
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<td>UCLA-led Study</td>
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<td>16.0</td>
<td>10-20</td>
<td>9.0</td>
<td>0.2</td>
<td>0.3($b$)</td>
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*a* Existing (E), Planned (P), Conceptual (C)

*b* Extrapolation based on a $\tau_E \propto I_0$ scaling, leading to $\chi E \simeq 3.8, I_0$. 

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Figure 1. Present status and future directions in RFP confinement relative to other compact, high-power-density systems, as well as the tokamak. While the confinement time of RFPs is considerably below tokamaks of comparable size and current, the strong scaling of confinement time with plasma current and the absence of safety-factor restrictions on current for the RFP projects adequate confinement: for a) DT ignition in an a = 0.3-0.4m I_θ = 8-10 MA device; and b) an economic reactor with a = 0.6 m and I_θ = 15-20 MA.
Figure 2. Dependence of cost of electricity on FPC mass power density for a range of 1200-MWe (net) fusion power plants showing the minimum-cost designs. The first-wall neutron loading for the tokamak varies only over a narrow range (3-4 MW/m²), whereas that for the poloidal-field-dominated RFP shows a much stronger variation (5-20 MW/m²). Each curve is generated by varying the maximum magnetic field at the toroidal-field coil while holding constant main plasma parameters. In the case of the tokamak reactor, which enforces a relationship between superconducting coil current density and coil field, the cost first diminishes with increased field because of the increase in plasma power density. At an optimum coil field, further increases in field cause reduced current density to increase coil mass and overall cost. The decrease in RFP cost as coil field is increased from initially low values also results from increased power density. At some point, however, the neutron wall loading becomes large for the RFP and cost is driven upward because of the rate of blanket “burn-up” and the decreasing availability resulting from more frequent changeout of the constant-radiation life blanket. The tokamak basecase uses the following relation between coil current density, $j_\phi$, (MA/m²) and peak field at the coil, $B_\phi(T)$: $j_\phi = 966B_\phi/11[1 + (B_\phi/12)^{1.5}]$, whereas the advanced coil option scales as: $j_\phi = 35(12/B_\phi)^{0.8}/[1 + (B_\phi/12)^{1.8}]$. 

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