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A "COMPACT" REVERSED-FIELD PINCH (CRFP) REACTOR DESIGN†

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1. INTRODUCTION

Many fusion reactor design studies have resulted in large and complex nuclear "islands", making maintenance difficult, integration into smaller electrical networks impractical, and posing financial problems due to the large capital costs involved. Consequently, a new class of concepts, termed compact tori (CT), have evolved that could potentially lead to smaller, less complex systems[1]. These concepts include Field Reversed Mirrors, Field Reversed Theta Pinches, and Spheromaks. They all share, to a varying extent, the common features of a closed toroidal configuration and a high- β field that is largely created by internal plasma currents. The Reversed Field Pinch (RFP) has a magnetic configuration that is similar in many respects to these CT. Consequently it too can be viewed as a candidate for a "compact" system. While a relatively large major radius (and large aspect ratio) will be retained, the plasma chamber itself and the surrounding structure can enjoy a "compactness" and still provide easy access.

2. PRIOR RFP CONCEPTUAL REACTOR CHARACTERISTICS

RFP conceptual reactor studies have been carried out at both the Culham Laboratory and the Los Alamos Scientific Laboratory[2-5]. These reactor concepts typically have a major radius of ~ 12 - 15 m and a minor radius of ~ 1.5 - 1.75 m. Thermal power levels are of the order of 2000-3000 MW. As such, these reactors are relatively large. This does not infer that they may not ultimately be attractive, however. Indeed, the RFP has a series of notable features that provide important advantages. Thus, the ability to heat to ignition with ohmic heating results both in a cost savings and simplicity compared to approaches requiring auxiliary heating via neutral beams or RF. The relatively high β provides a good power density and offers the possibility of eventually extending the concept to advanced fuels like catalyzed-deuterium. The lack of an aspect ratio constraint on stability allows a large aspect ratio design which in turn, by virtue of the open central region, simplifies maintenance and allows modular construction.

The goal set for the present study then was to examine the feasibility of a smaller RFP reactor in the 100 MWe range that would still retain many of the advantages cited above for the larger units. Such a reactor, labeled a Compact RFP (CRFP), would provide a flexibility in size that may be essential for early exploration of fusion power, by providing a route to a lower capital cost device suitable for a near term demonstration plant.

3. CRFP STUDIES

Scaling down the dimensions of the large RFP designs by roughly a factor of two provides a plasma volume compatible with the goal of a 100 MWe output. In order to examine the transport and stability properties of an RFP burn in a plasma of this size, we employed the 1-D dynamic burn code developed earlier for RFP studies and described elsewhere[6]. This code includes both global and local stability checks. Violation of the former results in burn termination while local violations are assumed to result in turbulent transport.

Continuity balances and alpha heating are treated in a conventional manner. Results from these calculations are presented in table I along with comparison parameters for the EAST RFP reactor (RFPR) reference design. It is observed that, while the volume of the CRFP is decreased by a factor of 8 compared to the RFPR, its net electrical output is only reduced by a factor of 7.5. Consequently, the CRFP enjoys a slight advantage in power density although its Q_p -value has dropped from 14.4 to below 10, indicating an undesirable increase in re-circulating energy. The output power of 100 MWe satisfies the original goal of a "small" reactor, however. Indeed, a further decrease in size causes a rapid decrease in Q_p due to radial energy losses via thermal conduction. (As in the RFPR, an energy confinement time of $\tau_E \sim 200 \tau_{\text{ohm}}$ was employed.) Indeed, to avoid excessive losses in the CRFP, it was necessary to increase magnetic field by a factor of 1.2 in order to increase the density.

Table I
Comparison of CRFP Parameters with RFPR

PARAMETER	RFPR	CRFP
First wall radius, r_w (m)	1.5	0.75
Major radius, R(m)	12.7	6.35
Burn time, τ_b (s)	21.6	10.3
Cycle time, τ_c (s)	26.6	15.3
Toroidal field on centerline, $B_{\phi 0}$ (T)	6.93	8.5
Toroidal current, I_{ϕ} (MA)	20.0	12.0
Average plasma density, $n(1/m^3)$	$2.0(10)^{20}$	$3.8(10)^{20}$
14.1 MeV fusion neutron energy, W_N (MJ/m)	676.5	173.0
Total thermal power, P_{TH} (MWt)	3000	628
Net electrical power, P_E (MWe)	750	100
$Q_p = (\text{fusion energy})/(\text{ohmic \& field energy})$	14.4	9.7

The CRFP burn time was shorter than for the RFPR as indicated by the respective burn-up fractions. Gross MHD stability was maintained throughout the burn, but Suydam's criterion was violated on centerline, leading to a turbulent core region that results in enhanced transport. However, as found in the RFPR[G], the turbulence does not result in a major deterioration in the energy balance since the outer radius zone remains quiescent.

An indication of the relative size of the CRFP can be gained from fig. 1. Its relative location between the RFPR and Zeta reinforces the earlier suggestion that a device of this type would be potentially attractive as an early demonstration device.

4. PROBLEMS AND IMPROVEMENTS

Due to the capital intensive character of fusion devices, to be competitive economically, any reactor in the 100 MWe range must, of necessity, offer high performance and modular construction (i.e., mass production of key components). It appears that the same

Fig. 1. Relative sizes of RFP experiments and reactors.

design considerations employed in the RFPR can lead to satisfaction of the latter requirements. On the other hand, the low energy multiplication (Q_p) and associated large recirculation power requirement suggests an undesirable expense. Previous work[7] has indicated that significant improvements in Q_p might be obtained by refueling. Since batch burns (non-refueled) are extinguished by fuel depletion, refueling the plasma increases the burn time, the amount of fusion energy produced per pulse, and consequently Q_p . However, refueling introduces new problems of fuel penetration and stability. Since the degree of anomalous mixing between the refuel ions and the plasma is unknown, two extremes, representing complete mixing (gas refueling) and no mixing (pellet injection with in-situ particle deposition), are considered for the CRFP.

4.1 Gas Refueling

Tokamak experiments[8] indicate that anomalous mixing between the cold refuel gas and the plasma occurs on a fast (μsec) time scale. Consequently, for the gas refueling simulations the refuel ions were assumed to immediately redistribute themselves along the plasma density profile. This is done by introducing a fuel source rate of the form:

$$S(r) = S_0 J_0(\alpha r), \quad \alpha = 2.405/r_w. \quad (1)$$

Results indicate that the burn time is approximately doubled over the batch burn CRFP and Q_p is increased by about 75% (see table II, Case A). Once again, gross MHD stability is maintained through the entire burn.

4.2 Pellet Refueling

If the refuel ions do not anomalously mix with the background plasma, it is necessary to inject the refuel ions in order to refuel the interior of the plasma. Pellet injection appears to be the most energy economic manner to do this. For these simulations, the ablation model of Parks, et al.[9] was used to determine the refuel deposition profile. The refuel ions and electrons were assumed to immediately equilibrate with the background where they are deposited.

Table II
Summary Description of Design Parameters

PARAMETER	GAS REFUELED CRFP (CASE A)	PELLET REFUELED CRFP (Case B)
First wall radius, r_w (m)	0.75	0.75
Major radius, R (m)	6.35	6.35
Burn time, τ_B (s)	21.0	18.1
Cycle time τ_C (s)	26.0	23.1
Toroidal field on centerline, $B_{\phi 0}$ (T)	8.4	8.4
Toroidal current, I_ϕ (MA)	13.2	13.2
Average plasma density, N ($1/m^3$)	$2.7(10^{20})$	$2.7(10^{20})$
14.1 MeV fusion neutron energy, W_N (MJ/m)	333.0	256.5
Total thermal power, P_{TH} (MWt)	820	706.0
Net electrical power, P_E (MWe)	240	160.0
Q_p = (fusion energy)/(ohmic & field energy)	17.2	13.2
Pellet radius (cm)	-	0.195
Pellet velocity (m/sec)	-	$6.2(10^4)$
Pellet injection rate (sec^{-1})	-	0.5
Effective refuel rate (m-sec) ⁻¹	$3.1(10^{19})$	$2.8(10^{19})$

Results indicate that the pellet-refueled CRFP mode performs better than the batch-burn mode but not as well as the gas-refueled mode. The difference is principally due to the pellets not reaching the plasma axis where the temperature is highest. Pellet refueling increased Q_p by about 30% over the batch burn mode (see table II, Case B).

5. CONCLUSION

These results indicate that a CRFP operating in the range of 100 MWe should be feasible. While the large aspect ratio leads to a 6.4-m major radius, the design still retains many attributes of conventional compact tori, such as simplicity and ease of access. The relatively low Q_p with batch burns might be satisfactory for a demonstration unit. However, to obtain power-plant "grade" Q_p , either refueling (possibly by pellets) or larger size plasmas appear necessary.

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