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ABSTRACT

Application of a magnetized coaxial plasma gun for start-up of a field-reversed-mirror reactor is considered. The design is based on preliminary scaling laws and is compared to the design of the start-up gun used in the Beta II experiment.

INTRODUCTION

Several recent conceptual designs of fusion reactors have been based on field-reversed mirror plasmas (1,2,3). In the designs of Refs. 1 and 2 the field-reversed plasma density, energy, and current are sustained in steady state by neutral-beam injection, while in Ref. 3, field-reversed plasma rings are fed in at one end of the reactor, burn as they move down the reactor core, and are exhausted at the discharge end of the reactor.

A necessary precursor to the plasma burn, be it sustained in steady state or transient, is the creation of the field-reversed-mirror plasma. In Ref. 1 a number of possible start-up scenarios were qualitatively described: "slow buildup" with neutral beams, "fast" ion injection with an intense, pulsed, ion-neutral source (IPINS), a reversed-field theta-pinch, rotating electron or ion beams, conical theta-pinch guns, and a magnetized coaxial plasma gun.

Subsequent to the publication of Ref. 1, the magnetized coaxial plasma gun was chosen as the preferred field-reversal start-up method for the Beta II experiment at Lawrence Livermore Laboratory. Initial experimental results on the Beta II device (4,5) have demonstrated production of field-reversed flux and have extended the pioneering work of Alfvén and co-workers (6) to a field-reversed flux useful for starting up present-day field-reversed plasma experiments. Experiments on Beta II are proceeding to the next stage of axial translation and mirror trapping of field-reversed plasma, to be followed by

neutral-beam injection. In this report we consider the design (based on preliminary scaling laws) of a coaxial plasma gun for start-up in the field-reversed-mirror pilot reactor of Ref. 2.

THE MAGNETIZED COAXIAL PLASMA GUN

The basic arrangement for formation of field-reversed plasma rings with a coaxial plasma gun is shown schematically in Fig. 1a. The plasma gun is a cylindrically-symmetric, annular-breeched device in which a ring-shaped plasma is formed and accelerated by discharge current flowing radially across the anode-cathode gap. If the gun's external solenoid windings and the solenoid windings inside the center electrode are properly designed, the central, axial magnetic flux can be constrained largely within the center electrode. The field lines emerge radially at the ends of the center electrode and return outside the body of the gun, forming a magnetic-cusped field at the muzzle end of the gun.

While the axial magnetic field in the anode-cathode gap may be quite small, a toroidal field will be imbedded in the plasma during acceleration owing to the large, axial current flowing in the center electrode. As the plasma leaves the gun it encounters the radial-field component of the magnetic cusp, as shown in Fig. 1b. Inertia and $J \times B$ acceleration, together with high conductivity, cause the plasma to "push" the radial field, thus capturing magnetic flux as it passes through the cusp. Behind the ring the extended field lines break and reconnect so that the ring emerges downstream from the cusp—with its "captured flux"—as an annular plasma confined by an axially field-reversed, closed magnetic field. The plasma ring may subsequently drift into a magnetic-mirror trough where it could be trapped and a fusion plasma burn initiated, as shown in Fig. 1c. Moreover, upon leaving the gun, the plasma could also be made to enter a region of increasing axial field for the purpose of heating the fusion fuel by magnetic compression prior to confinement in an axial-mirror well.

GUN START-UP IN THE BETA II EXPERIMENT

The construction of a magnetized coaxial plasma gun for starting up a field-reversed plasma in Beta II was proposed in August 1978 (7). The goals of the experimental program on Beta II were stated to be: (a) formation of the

Fig. 1. Formation of field-reversed plasma by magnetized coaxial plasma gun during (a) acceleration; (b) elongation; and (c) reconnection.

field-reversed plasma, (b) translation and magnetic mirror trapping of the plasma, and (c) neutral-beam sustenance of the plasma.

Achievement of the first goal was reported in November 1979 (4). Internal, magnetic-probe measurements have demonstrated production of field-reversed plasma for a variety of experimental conditions. For one set of data the equilibrium guide field was $B_0 = 4.8$ kG and a probe signal $\frac{\Delta B}{B_0} = 3.1$ was recorded corresponding to a reversed field $B_z = -10$ kG. The radius of field-reversed plasma was in the range 10 to 15 cm.

Continuing experiments on Beta II will attempt to trap the field-reversed plasma in a magnetic mirror. Here, the emphasis will be on quasi-static methods which will be applicable to the superconducting magnet environment of a fusion reactor.

GUN START-UP FOR THE FIELD-REVERSED-MIRROR PILOT REACTOR

The field-reversed-mirror pilot reactor (2) is shown in Fig. 2. The field-reversed DT plasma is at the center of the reactor. A cylindrical blanket and shield surround the plasma. Surrounding the blanket and shield is a set of niobium-titanium superconducting magnets which provide the required background magnetic field. Neutral-beam injectors fuel and sustain the energy of the plasma. The large tanks at the ends of the reactor house direct energy converters and vacuum-pumping systems for the plasma leakage. The coaxial plasma gun for start-up is located at one end of the reactor, inside the direct-converter tank.

During start-up the poloidal-field generator coils of the gun would be pulsed. The gun would be positioned so that the fringe field of the reactor acts as an increasing guide field to remove, by self-compression, nearly all the kinetic energy of the ring. After self-compression the ring would drift (at low kinetic energy) into the neutral-beam region where the equilibrium position would be established by weak time-varying fields, by a nearby dissipative structure to damp the ring motion, or possibly by dissipation within the ring itself.

During the plasma burn (gun coils off), charged particles diffusing out of the field-reversed plasma region will stream along open magnetic-field lines to the direct converters. To permit uninhibited passage of the escaping plasma stream to the direct converters, the gun uses a hollow center electrode with an inside radius that exceeds the radius of the magnetic-field-line bundle carrying plasma.

Fig. 2. Field-reversed-mirror pilot reactor.

GUN SCALING FOR THE FIELD-REVERSED-MIRROR PILOT REACTOR

The predicted performance of a field-reversed-mirror plasma depends strongly on the parameter S , the ratio of plasma mirror radius, a , to the ion gyroradius, ρ_i . Stability of the plasma is believed to require that S be a small number, probably 10 or less. For the field-reversed-mirror pilot reactor, both $S = 5$ and $S = 7$ were considered, and the reactor was designed to accommodate either plasma. The steady-state-fusion plasma ring is maintained by neutral beams inside the reactor and is assumed to be a spherical Hill's vortex with the characteristics given in Table 1.

Table 1. Plasma parameters for field-reversed-mirror pilot reactor.

Parameters		$S = 5$	$S = 7$
T_i , keV	=	67	102.8
T_e , keV	=	35	59.7
U_{ions} , MJ	=	0.49	2.64
$U_{electrons}$, MJ	=	0.26	1.53
$U_{thermal}$, MJ	=	0.75	4.17
$U_{magnetic}$, MJ	=	0.056	0.31
$I_{toroidal}$, MA	=	4.59	8.05
$\psi_{poloidal}$, Wb	=	0.237	0.755
N_{ions}	=	3.08×10^{19}	1.08×10^{20}
B_{vacuum} , T	=	4.79	4.58
R_{final} , m	=	0.123	0.224

In Table 1, $U_{magnetic}$ was evaluated by using the fact that, for a spherical Hill's vortex,

$$g = U_{thermal} / U_{magnetic} = 27/2 .$$

The toroidal current,

$$I_{toroidal} = \frac{20\sqrt{2}}{3\pi} \frac{\psi_{poloidal}}{\mu_0 R_{final}} ,$$

and the poloidal flux, ψ_{poloidal} , were evaluated by noting that, for the spherical Hill's vortex,

$$u_{\text{thermal}}^{\text{plasma}} = \frac{32\sqrt{2}}{7\pi} \frac{\psi_{\text{poloidal}}^2}{\mu_0 R_{\text{final}}}.$$

Because coaxial plasma guns typically accelerate plasma to 1-10 keV energy, it is unlikely that the injected ring can be made to have the desired steady-state temperatures (for $S = 5$ (7), $T_i = 67$ (103) keV and $T_e = 35$ (60) keV). Further, if a scaled-up gun performs like present laboratory-scale guns, a substantial toroidal field, B_θ , will be embedded in the ring during production. We have developed an injection scenario which is based on the presence of a toroidal field and which addresses the mismatch of injected and steady-state ring parameters (8). Assuming that the gun produces a relatively low-temperature and low- β plasma, the approximate equilibrium requirement (Bennett relation),

$$I_{\text{toroidal}}^2 = ne (T_e + T_i) r_p^2 + \frac{B_\theta^2}{2\mu_0} r_p^2,$$

can be satisfied initially by the toroidal-field-pressure term above. After the ring has been positioned in the beam region, the plasma-pressure term above can be increased by neutral-beam heating while B_θ is allowed to decay resistively. In this way the ring size and equilibrium requirements remain approximately constant during heating.

Self-compression of the ring as it drifts along the guide field into the neutral-beam region can be estimated by noting that the poloidal flux ψ_p is conserved in the high conductivity limit. We assume that during self-compression, and with embedded toroidal field, the ring remains approximately a spherical Hill's vortex with plasma thermal energy and toroidal field energy related by the constant ratio, g . With these assumptions, we may write the energy balance before and after compression as

$$U_{\text{thermal}}^o \left(1 + \frac{1}{g}\right) + U_{\text{kinetic}}^o = U_{\text{thermal}}^f \left(1 + \frac{1}{g}\right) + U_{\text{kinetic}}^f,$$

where the superscripts "o" and "f" refer to initial and final conditions, respectively. If the magnetic flux inside the ring is conserved during compression, then the condition under which a ring comes to rest as it moves into a stronger magnetic field, B^f , is given by

$$U_{\text{kinetic}}^0 = U_{\text{thermal}}^f \left(1 + \frac{1}{g} \right) [1 - (B^0/B^f)^{1/2}] .$$

This condition for stopping the ring leads to the expression for the fraction of total ring-plasma energy that is at first axially-directed kinetic energy:

$$f = \frac{U_{\text{kinetic}}^0}{U_{\text{kinetic}}^0 + U_{\text{magnetic}}^0 + U_{\text{thermal}}^0} = [1 - (B^0/B^f)^{1/2}] .$$

The axial magnetic-field strength is plotted in Fig. 3 as a function of Z , the distance into the direct converter for both the $S = 5$ and the $S = 7$ cases. The radial distance from the machine's axis to the flux lines that lie just outside the separatrix, R_{flux} , is plotted in Fig. 4, also as a function of Z . We have used the analytic assumptions above and the data shown in Figs. 3 and 4, to plot the initial radius, R^0 , of a plasma ring formed at a distance Z into the direct-converter region that comes to rest at the reactor mirror well; Figs. 5 and 6 show the plots for the $S = 5$ and $S = 7$ cases, respectively. Also shown in Figs. 5 and 6 is the behavior of the function "f."

Fig. 3. Axial magnetic-field strength on reactor axis.

To permit uninhibited passage of the escaping plasma stream to the direct converters, our gun design incorporates a hollow center electrode having a radius which exceeds R_{flux} for the $S = 7$ case. Since the gun may

Fig. 4. Magnetic field lines at plasma limit.

well have a length of 1-2 m, the bore of the hole at the rear of the center electrode must be large enough to miss the exiting plasma stream. Therefore, if the hole in the center electrode is right-cylindrical, the plasma rings formed in the gun will be larger than equilibrium radius for either plasma case (see Figs. 5 and 6). The radial pressure imbalance is sustained by the center electrode and as the rings leave the muzzle of the gun they shrink in radius to the equilibrium value, R_0 . Experimental determination of the value of "f" achievable in these guns would then dictate the axial location and radial size of the gun. For example, if $f \approx 0.5$, the muzzle of the gun would have to be located at roughly $Z = 3.8$ m, with the hole in the center electrode having a radius greater than 50 cm to avoid intersecting the $S = 7$ plasma stream at its widest point.

A current model of the gun operation (8) has the acceleration of plasma taking place largely after the current-sheath-rundown phase. At the end of rundown of the current sheath it is believed that 99% of the gas has been pushed radially outward against the outer electrode while the remaining 1% of the gas is trapped as a low- β plasma in the high- B_0 field region near the

Fig. 5. Initial plasma radius and energy function f , $S = 5$ plasma.

Fig. 6. Initial plasma radius and energy function f , $S = 7$ plasma.

center electrode. The subsequent acceleration into a vacuum takes place as a *magnetosonic rarefaction wave propagates towards the gun breech*. The expansion converts the internal energy, $\sim B_0^2/2\mu_0$, into streaming-plasma kinetic energy. The low-mass, low- β plasma is promptly ejected as a high-energy component (HEC). This is followed by ejection of a low-energy plasma component over a long period of time. The two plasma components each have about one-half the input energy of the gun, and for an operating 200-kJ gun (9) the HEC forms a "slug" of plasma with a length about equal to that of the gun.

In the gun application considered here, a poloidal fringe field inhibits the free expansion of plasma beyond the muzzle. If the poloidal-field pressure is small compared to the stagnation pressure of the HEC, nearly free expansion occurs, and if field reconnection takes place behind the HEC "slug" roughly 50% of the gun energy would be trapped in the ring (mostly as kinetic energy). This energy could be converted into plasma pressure and magnetic energy by self-compression as the ring drifts along an increasing guide field. For this case the overall energy efficiency of ring production might be $\sim 50\%$.

Numerical calculations in progress (10) suggest that if the poloidal-field pressure approaches the HEC stagnation pressure, the kinetic energy of the HEC can be reduced and probably made small. For this case, if the HEC expands to a length $\approx l_g$, reducing B_0 by 2 (existing guns tend to self-crowbar after rundown and thus conserve toroidal flux) before reconnection occurs, three-fourths of the HEC energy would be trapped in the ring to give an overall efficiency of 37.5%. For this case the energy would be mostly magnetic since the HEC is low- β .

The foregoing discussion suggests that the overall energy efficiency of ring production can be in the range 30-50%. In this report the efficiency will be assumed to be 25%.

Marshal has considered scaling laws for coaxial guns (8). Basing his argument on the mechanisms discussed earlier (for which the output energy of the gun is equal to the magnetic energy stored in the gun at completion of rundown), he finds

$$U = \frac{1}{2} L_g I^2 = 12.53 l_g(\text{cm}) V(\text{volts}) r_1(\text{cm}) \sqrt{\rho(\text{gm cm}^{-3})} \text{ J ,}$$

where l_g is the gun length, V the terminal voltage, r_1 the center electrode radius, and ρ the filling-gas density.

Forming an $S = 5$ plasma ring having $U_{\text{Total}} = 6.75 \text{ MJ} + 0.056 \text{ MJ}$ and the assumed efficiency $\eta = 25\%$ would require a gun energy of $U_{\text{gun}} \sim 3.2 \text{ MJ}$. Taking $\rho = 1.17 \times 10^{-7} \text{ g/cm}^3$ (1-Torr D_2), the above scaling law gives $l_g V r_1 = 7.47 \times 10^8 \text{ V} \cdot \text{cm}^2$. For the $S = 7$ case ($U_{\text{total}} = 4.48 \text{ MJ}$), the scaling law gives $l_g V r_1 = 4.18 \times 10^9 \text{ V} \cdot \text{cm}^2$. An arbitrary choice of $f \approx 0.5$ locates the gun (as discussed above) at $Z \sim 3.8 \text{ m}$. To accommodate an adequate hole in the center electrode (see Figs. 5 and 6), we choose the center electrode radius to be $r_1 = 85 \text{ cm}$. (The choice of the inner radius of the outer electrode is somewhat arbitrary, but $r_2 \approx r_1 + 30 \text{ cm} \approx 115 \text{ cm}$ would probably be reasonable.) Because r_1 exceeds the ring's equilibrium radius in the magnetic field just beyond the end of the gun, the ring compresses immediately after leaving the gun muzzle, as we have explained above. A gun length $l_g \approx 150 \text{ cm}$ would permit the $S = 7$ plasma effluent also to clear the rear end of a right-cylindrical hole in the center electrode. A gun having these dimensions is shown schematically in Figs. 5 and 6. From the expression above, we obtain a gun terminal voltage $V \approx 59 \text{ keV}$ to initiate the $S = 5$ plasma, while the $S = 7$ plasma would require $V \approx 330 \text{ keV}$. A comparison of these predicted reactor-gun characteristics with the characteristics of the gun designed for the Beta II experiment appears in Table 2.

Table 2. Comparison of Beta II gun and reactor gun.

	Plasma gun		
	Beta II gun	S = 5	S = 7
Center electrode radius, R_1 , cm	7.5	85	85
Outer electrode radius, R_2 , cm	15	115	115
Length, l_g , cm	150	150	150
Voltage, V, kV	40	59	330
Output energy, U_g , MJ	0.2	3.2	17.9
Flux in center electrode, ψ_{poloidal} , Wb	0.07	0.24	0.755
Poloidal B in center electrode, B_p , T	4.0	0.104	0.33
Guide field at gun muzzle, T	0.2 - 0.4	1.1	1.05

CONCLUSIONS

From the preliminary calculations given above, it appears that a coaxial plasma gun might scale reasonably to reactor-grade operating conditions. Ongoing experiments and numerical simulations should shed some light on the validity of the scaling laws described above.

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