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**PLASMA EXPANDER FOR VENETIAN BLIND
DIRECT CONVERTERS**

Richard R. Smith

April 6, 1973

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PLASMA EXPANDER FOR VENETIAN BLIND DIRECT CONVERTERS

Abstract

Characteristics and advantages of a plasma expander with a field simulating that of a magnetic monopole were investigated. Such a field, with $B \propto 1/r^2$, exactly conserves an ion's magnetic

moment. The expander is especially suitable for a "Venetian Blind" direct recovery unit. A monopole field can be approximated with coils arranged on the surface of a 30° cone, except at the apex and base of the cone.

Introduction

Moir and Barr¹ recently proposed a direct converter that differs from the one proposed by Post.² This so-called "Venetian Blind" converter is intended to expand the plasma from the reactor in a field decreasing inversely as the square of the distance from the reactor (rather

than a field decreasing inversely as the distance), thus making a higher ratio of expansion possible over a shorter distance. The collector has a lower maximum theoretical efficiency but can handle much higher space charge and thus operate at a substantially lower reactor temperature.

Plasma Expansion in a Magnetic Field with $B \propto 1/r^2$

In the expander designed for a Post-type converter, the field lines form a flat fan with an intensity decreasing as $1/r$ from the fan's vertex. It was found from computer simulations³ that one could define a parameter

$$\epsilon = \left| \frac{2\pi m V_{\parallel}}{qB} \right| \frac{1}{B} \frac{dB}{ds}$$

that had to be less than 3 during the trajectory, to ensure a sufficiently constant magnetic moment. Guided by the experience with the fan-shaped expander, we anticipated that the $1/r^2$ expander would have problems towards the end of the

trajectory, where ϵ would be proportional to r and grow large.

It is possible to rigorously prove the constancy of the magnetic moment in a $1/r^2$ field.⁴ In spherical coordinates the field is that of a monopole:

$$\vec{B} = B_0 r_0^2 \frac{\vec{r}}{r^3}$$

From the equation of motion we get

$$\vec{v} = r_0^2 \Omega \frac{\vec{v} \times \vec{R}}{r^3},$$

where Ω is qB_0/m . One finds that the angle θ between the position vector of the

particle and the Z axis is equal to $\tan^{-1}(V/r_0\Omega)$; that $r^2 = r_0^2 + V^2t^2$; and that $V_{\perp} = -r_0V/r$. From this it follows that the magnetic moment μ , defined as $(m/2)(V_{\perp}^2/B)$, is constant.

Thus one must not be too zealous in applying a criterion for adiabaticity based

on a simple gradient of the field, such as (see Ref. 5)

$$\frac{V_{\perp}}{B} \frac{\partial B}{\partial z} \leq \frac{\Omega}{N},$$

where $\Omega = zeB/M$ and N is an empirical constant such as 20, because such a criterion predicts nonadiabaticity for a monopole field.

Simulation of $1/r^2$ Field

Once the constancy of μ in a $1/r^2$ field is seen, it is of interest to examine the difficulty of realizing such a field with coils. An expander consisting of two cones was designed by using the MAFCO magnetic field code.⁶ The first cone was small and represented the neutron trap that expands the plasma from 150 kG to about 50 kG. The second cone had a vertex half-angle of 15° and constituted the bulk

of the device. In this second cone the field lines were to seem to diverge from a common point. The currents in the circular loop constituting the cone of coils were chosen proportional to $1/(z + z_0)^2$, where the cone axis is along z and z_0 is the distance from the origin to the desired field line focus. The currents must be increased somewhat as one approaches the end of the expander.

Fig. 1. Perspective view of coil configuration used in simulation of a Venetian Blind plasma expander.

Figure 1 is a perspective drawing of the coil configuration. Figure 2 shows a plot of the field line parallel to the cone and passing through $z = 0$, $R = 94$ cm. The field line is nearly straight, out to the region of the collector elements at $z = z = 65$ m. This line enclosed the desired flux of 150 Wb and thus was the guiding center line farthest from the axis that had to be considered. The coils are spaced 1 m apart, from -18 m to +80 m. Table 1 shows the coil location z , radius A in centimeters, and current I in amperes. A 150-kG mirror coil is assumed to contribute to the field.

Figure 3 shows the magnetic field contours in the $1/r^2$ region. While it is not clear if the contours down to 200 G are concentric circles as they would be in a $1/r^2$ field, they are at least concave to the left. The bend in the field lines at $z = 0$ is of no importance to the constancy of the magnetic moment, because the field strength is quite large there and the field variation in one pitch length is small. Thus we conclude that it is not difficult to simulate a $1/r^2$ field.

There is an additional advantage of a $1/r^2$ expander over a fan-shaped $1/r$ device.

Ion Trajectories in the Expander

Having determined that the expander magnetic field simulates that of a monopole, the orbits of several representative ions were examined in detail. Figure 4 shows μ versus t for a 14.7-MeV proton launched from $z = 0$ with its guiding center on the limiting field line of Fig. 2. The magnetic moment dips at the end of the orbit because the ion is slipping off its

Fig. 2. Field line parallel to coils. Note scale distortion on this and succeeding figures.

In the latter case the field lines are spread much more in one direction than in the other. Thus the angle between the local field and the motion of the guiding center will vary periodically for the fan expander but not for the conical or monopole expander. Such a periodic modulation would not average to zero because of the changing field strength and gyrofrequency, and such "bumpiness" could affect the ion's perpendicular energy.

bending field line, and the velocity happens to become nearly parallel to $\vec{B}$ for the particular choice of initial orbit conditions. Such a proton launched on the limiting field line fits inside the expander walls.

Five 300-keV tritons were launched at $z = 0$ on the z axis on the four field lines shown in Fig. 5. These lines passed through $r = 20, 40, 60$, and 80 cm. The

Fig. 3. Contour plot of magnetic field.

pitch length in the region of the collector structure, i.e., near $z = 6500$ cm, exceeds 30 m and is too large for the orbits to follow the field lines at the end of the expander. This is shown in Fig. 6a, a projection of the orbit launched on the axis onto the vertical plane. The time-dependence of the magnetic moment during this orbit is shown in Fig. 6b. An end-on

view of this orbit is shown in Fig. 6c. Figures 7a and 7b show x versus z and μ versus t for the orbit launched at $z = 0$ $r = 80$ cm. The magnetic moment of all five cases had acceptably small variations near the beginning of each orbit. The changes in μ at the ends of the orbits are due to the field lines bending. This effect is most pronounced for the trajectories

Table 1. MAFCO input data.

x	y	Coil location (z), cm	Radius (A), cm	Alpha	Beta	Current (I), A
0.	0.	-1800.00	152.00	0.	0.	12800000.00
0.	0.	-1700.00	156.00	0.	0.	12400000.00
0.	0.	-1600.00	161.00	0.	0.	11800000.00
0.	0.	-1500.00	165.00	0.	0.	11100000.00
0.	0.	-1400.00	169.00	0.	0.	10700000.00
0.	0.	-1300.00	173.00	0.	0.	10100000.00
0.	0.	-1200.00	178.00	0.	0.	9880000.00
0.	0.	-1100.00	182.00	0.	0.	9460000.00
0.	0.	-1000.00	186.00	0.	0.	9040000.00
0.	0.	-900.00	190.00	0.	0.	8930000.00
0.	0.	-800.00	195.00	0.	0.	8260000.00
0.	0.	-700.00	199.00	0.	0.	7980000.00
0.	0.	-600.00	203.00	0.	0.	7560000.00
0.	0.	-500.00	208.00	0.	0.	7200000.00
0.	0.	-400.00	212.00	0.	0.	7150000.00
0.	0.	-300.00	216.00	0.	0.	7030000.00
0.	0.	-200.00	220.00	0.	0.	6450000.00
0.	0.	-100.00	229.00	0.	0.	5710000.00
0.	0.	0.	229.00	0.	0.	5280000.00
0.	0.	100.00	256.00	0.	0.	2630000.00
0.	0.	200.00	283.00	0.	0.	1610000.00
0.	0.	300.00	310.00	0.	0.	1090000.00
0.	0.	400.00	336.00	0.	0.	823000.00
0.	0.	500.00	363.00	0.	0.	646000.00
0.	0.	600.00	390.00	0.	0.	520000.00
0.	0.	700.00	417.00	0.	0.	426000.00
0.	0.	800.00	444.00	0.	0.	337000.00
0.	0.	900.00	470.00	0.	0.	302000.00
0.	0.	1000.00	497.00	0.	0.	260000.00
0.	0.	1100.00	524.00	0.	0.	226000.00
0.	0.	1200.00	551.00	0.	0.	197000.00
0.	0.	1300.00	578.00	0.	0.	174000.00
0.	0.	1400.00	604.00	0.	0.	155000.00
0.	0.	1500.00	631.00	0.	0.	139000.00
0.	0.	1600.00	658.00	0.	0.	125000.00
0.	0.	1700.00	685.00	0.	0.	113000.00
0.	0.	1800.00	712.00	0.	0.	103000.00
0.	0.	1900.00	738.00	0.	0.	94400.00
0.	0.	2000.00	765.00	0.	0.	86500.00
0.	0.	2100.00	792.00	0.	0.	76400.00
0.	0.	2200.00	819.00	0.	0.	73500.00
0.	0.	2300.00	846.00	0.	0.	66200.00
0.	0.	2400.00	872.00	0.	0.	63300.00
0.	0.	2500.00	899.00	0.	0.	58900.00
0.	0.	2600.00	926.00	0.	0.	55100.00
0.	0.	2700.00	953.00	0.	0.	51500.00
0.	0.	2800.00	980.00	0.	0.	48100.00
0.	0.	2900.00	1006.00	0.	0.	45300.00
0.	0.	3000.00	1033.00	0.	0.	42200.00
0.	0.	3100.00	1060.00	0.	0.	40500.00

Table 1. (Continued).

x	y	Coil location (z), cm	Radius (A), cm	Alpha	Beta	Current (I), A
0.	0.	3200.00	1087.00	0.	0.	39300.00
0.	0.	3300.00	1114.00	0.	0.	38500.00
0.	0.	3400.00	1140.00	0.	0.	36500.00
0.	0.	3500.00	1167.00	0.	0.	34700.00
0.	0.	3600.00	1194.00	0.	0.	32900.00
0.	0.	3700.00	1221.00	0.	0.	31400.00
0.	0.	3800.00	1248.00	0.	0.	29900.00
0.	0.	3900.00	1274.00	0.	0.	29200.00
0.	0.	4000.00	1301.00	0.	0.	28500.00
0.	0.	4100.00	1328.00	0.	0.	27090.00
0.	0.	4200.00	1355.00	0.	0.	25800.00
0.	0.	4300.00	1322.00	0.	0.	24700.00
0.	0.	4400.00	1408.00	0.	0.	23700.00
0.	0.	4500.00	1435.00	0.	0.	23000.00
0.	0.	4600.00	1462.00	0.	0.	22100.00
0.	0.	4700.00	1484.00	0.	0.	21500.00
0.	0.	4800.00	1516.00	0.	0.	21000.00
0.	0.	4900.00	1542.00	0.	0.	20200.00
0.	0.	5000.00	1569.00	0.	0.	19500.00
0.	0.	5100.00	1596.00	0.	0.	19000.00
0.	0.	5200.00	1623.00	0.	0.	18200.00
0.	0.	5300.00	1650.00	0.	0.	17700.00
0.	0.	5400.00	1676.00	0.	0.	17100.00
0.	0.	5500.00	1703.00	0.	0.	16400.00
0.	0.	5600.00	1780.00	0.	0.	16000.00
0.	0.	5700.00	1757.00	0.	0.	15400.00
0.	0.	5800.00	1784.00	0.	0.	15200.00
0.	0.	5900.00	1810.00	0.	0.	14600.00
0.	0.	6000.00	1837.00	0.	0.	14400.00
0.	0.	6100.00	1864.00	0.	0.	13900.00
0.	0.	6200.00	1891.00	0.	0.	13600.00
0.	0.	6300.00	1918.00	0.	0.	13200.00
0.	0.	6400.00	1944.00	0.	0.	13000.00
0.	0.	6500.00	1971.00	0.	0.	12700.00
0.	0.	6600.00	1998.00	0.	0.	12300.00
0.	0.	6700.00	2025.00	0.	0.	12200.00
0.	0.	6800.00	2052.00	0.	0.	12100.00
0.	0.	6900.00	2078.00	0.	0.	11900.00
0.	0.	7000.00	2105.00	0.	0.	11900.00
0.	0.	7100.00	2132.00	0.	0.	11700.00
0.	0.	7200.00	2159.00	0.	0.	11700.00
0.	0.	7300.00	2186.00	0.	0.	11500.00
0.	0.	7400.00	2212.00	0.	0.	11200.00
0.	0.	7500.00	2239.00	0.	0.	11100.00
0.	0.	7600.00	2266.00	0.	0.	11000.00
0.	0.	7700.00	2293.00	0.	0.	11500.00
0.	0.	7800.00	2320.00	0.	0.	12100.00
0.	0.	7900.00	2346.00	0.	0.	12200.00
0.	0.	8000.00	2373.00	0.	0.	12300.00

Fig. 4. Magnetic moment versus time for a 14.7-MeV proton. Encounter with collector structure is at Δ (6500).

Fig. 5. Field lines passing through $z = 0$, $R = 20, 40, 60$, and 80 m.

nearest the coils. The approximate time at which the ion encounters the collector structure is indicated by Δ on Figs. 4, 6b, and 7b.

Table 2 summarizes the properties of these orbits at $z = 6500$ cm: θ_1 is the

Fig. 6a. Orbit of a 300-keV triton launched with guiding center on the z axis.

Fig. 6b. Magnetic moment versus time for orbit in Fig. 6a.

angle between the guiding center field line and the z axis; θ_2 is the same angle at $z = 5500$ cm; and θ_3 is the expected angle between the guiding center field line and the z axis if the field lines had diverged from a common point and if the line passing through $z = 0$, $r = 94$ cm has an angle of 15° . The angle between $\vec{V}$ and the guiding line is ϕ_1 , and ϕ_2 is that angle if the line had not started to bend. The x , y , and z components of velocity are u , v , and w . From comparing θ_1 and θ_2 we see that the

Fig. 6c. End-on view of orbit in Fig. 6a.

field lines behave as expected up to $z = 5500$ and then start to bend outwards slightly. This could be corrected by continuing the windings past $z = 80$ m or by adjusting the coil currents. The angle ϕ_2 is important in calculating the efficiency of the Venetian Blind converter, because it gives the spread in entrance angle. For these orbits this spread is evidently bounded by $\pm 3^\circ = \pm 0.05$ radians. From Fig. 4 in Ref. 2, this should not be a severe problem.

Fig. 7a. Orbit of a 300-keV triton launched to follow a field line through $z = 0$, $R = 80$ cm.

Fig. 7b. Magnetic moment versus time for orbit in Fig. 7a.

Table 2. Parameters of five orbits.

Orbit	θ_1 , deg	θ_2 , deg	θ_3 , deg	ϕ_1 , deg	ϕ_2 , deg	U , cm/sec	V , cm/sec	W , cm/sec
1	0	0	0	2.1	2.1	0.118×10^8	0.097×10^8	4.375×10^8
2	3.6	3.5	3.3	1.6	2.5	0.354	0.134	4.361
3	7.8	6.3	6.5	2.8	2.7	0.582	0.182	4.335
4	11.2	9.5	9.7	3.0	3.1	0.779	0.220	4.302
5	14.8	12.8	12.8	4.0	2.9	0.946	0.215	4.269

Conclusions

We have seen that there are two advantages of expanding a plasma in a $1/r^2$ field rather than in a $1/r$ fan-shaped field: more expansion per unit length and better preservation of magnetic moment, as a result of the straightness of the field lines. It is relatively easy to approximate the

field of a magnetic monopole throughout most of a conical expander with a full angle of 30° at the apex. When magnetic fields, dimensions, and ion trajectories appropriate to a Venetian Blind direct energy recovery unit (Ref. 4) are used, the computed orbits are close to those desired.

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