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STUDIES OF ACCELERATED COMPACT TORUSES

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1. ACCELERATION OF MAGNETIZED PLASMA RINGS

INTRODUCTION

In an earlier publication[1] we considered acceleration of plasma rings (Compact Torus). Several possible accelerator configurations were suggested and the possibility of focusing the accelerated rings was discussed. In this paper we consider one scheme, acceleration of a ring between coaxial electrodes by a B_θ field as in a coaxial rail-gun. If the electrodes are conical, a ring accelerated towards the apex of the cone undergoes self-similar compression (focusing) during acceleration. Because the allowable acceleration force,[1] $F_a = \kappa U_m/R$ where $(\kappa < 1)$, increases as R^{-2}, the accelerating distance for conical electrodes is considerably shortened over that required for coaxial electrodes. In either case, however, since the accelerting flux can expand as the ring moves, most of the accelerating field energy can be converted into kinetic energy of the ring leading to high efficiency.

EQUATIONS OF MOTION

We consider a ring betwen electrodes as shown in Fig. 1. Since the ring approximately conserves flux both $\psi_{poloidal}$ and $\psi_{toroidal}$ remain constant during acceleration, and since $p << B^2/2\,\mu_0$, so that $B_T \approx B_p$, it is readily seen that the aspect ratio a/R remains constant as R changes. We note that the net accelerating force on the ring is due to the B_θ field behind the ring, $F_{B\theta} = (dL_g/d\rho)\ (I^2/2)$, and the component of the equilibrium force along the cone, $\overline{F}_{eq}\cdot\hat{\rho} \approx U_m/\rho$. The ring motion is given by,

$$M_r\ddot{\rho} - F_{drag} = U_m/\rho - L_g'\ I^2/2 \qquad (1)$$

where U_m and M_r are the ring's magnetic energy and mass respectively. F_{drag} is computed from the eddy current dissipation in the electrode surfaces. Approximately, $F_{drag} = (2\delta/\Delta^2)\ U_m$ where δ is the skin depth allowing for velocity-dependent and diffusive penetration of the ring fields. The electrode resistively η used to compute δ is corrected for nonlinear diffusion.[2]

Equation (1), the driving circuit equation

$$V_0 - \int \frac{I\ dt}{c} = \frac{d}{dt}\left[(L_x + L_g)\ I\right] \qquad (2)$$

and the energy equation,

$$\dot{U}_m = \dot{U}_m\Big|_{\text{compression}} - \dot{U}_m\Big|_{\text{skin loss}} - \dot{U}_m\Big|_{\text{plasma resistance}}$$

are solved numerically for the ring motion.

RESULTS AND SUMMARY

A number of problems have been studied using parameters approximating CT rings which have been produced by plasma guns, and using parameters appropriate to various high-energy, high power electromagnetic pulse sources (Python, SHIVA-STAR, etc.). Here we summarize one case, a ring accelerated in two phases by the SHIVA STAR capacitor bank.[3] Phase I consists of adiabatically compressing the ring in an $\alpha = 90^0$ cone. Phase II allows the compressed ring to turn the corner and accelerate along an attached small-angle cone thus converting the stored magnetic energy into ring kinetic energy. The results are given in Table 1.

If the ring at the maximum kinetic energy (4.4 MJ) were allowed to strike a target, the deposition power would be roughly 1.2×10^{16} W ($\tau \approx 0.3$ ns) with a power density of 5.3×10^{15} W/cm^2. Only the ring mass is specified here, the choice of ion species being left to further optimization.

2. APPLICATIONS OF ACCELERATED COMPACT TOROIDS

It has recently been suggested[4] that magnetic acceleration of low-β plasma rings, similar to those produced in existing experiments, could fill some of the wide gap in parameter space that lies between the extremes of conventional particle acceleration and magnetic acceleration of metallic slugs or magnetized pellets. Many applications can be conceived that exploit the newly-accessible regimes, some of which also make use of the special magnetic or confinement properties of the rings. Listed below are some of the possible applications, ordered in increasing energy (but not necessarily decreasing credibility). Low energy is defined as U = input energy $\simeq U_M$ = initial magnetic energy. Medium energy is $U > U_M$ and high energy is $U >> U_M$. We invite the reader to add to the list.

LOW ENERGY

Magnetic fusion applications dominate the low energy uses.

1. Current drive. Most toroidal confinement devices employ parallel current, giving a net helicity to the fields. The additive property of helicity allows for current maintenance through providing an external helicity source, i.e., plasma rings, to match the ohmic losses. High values of Q are estimated for current drive by plasma ring injection although the resulting disturbance of magnetic surfaces may cause unacceptable heat loss.
2. Fueling and heating. Dense rings moving faster than their internal Alfvén speed but slower than the Alfvén speed of the fusion reactor medium should cross field lines readily. The ultimate annihilation of rings by tilting and reconnection deposits a "cargo" of energetic particles or fuel.

MEDIUM ENERGY

1. Neutron Source. Accelerated rings can be focussed radially (e.g., by conducting cones) causing an increase in the field intensity and adiabatic heating. If the rings are designed to reach fusion temperatures they can provide a high fluence (due to the high density) pulsed neutron source.
2. High field moving ring reactor. More stringent conditions on the rings, e.g., larger values of I, the circulating current, can lead to net power production. Small rings ($R \sim 20$ cm) operating near stress limits ($B_{wall} \sim 500$ kG) can have reasonable Q's and lower energy/ring than traditional fusion schemes ($\sim 5 \times 10^7$ J). The price paid is a high peak wall loading, although the duration of the peak at any location can be controlled by the ring velocity. The simple topology (a hollow conducting tube surrounded by tritium breeding material), the absence of nearby coils, and the small diminsions may make frequent replacement acceptable.

HIGH ENERGY

1. Fast switching/power amplification. Energy stored in a relatively slow medium, e.g., highly capacitive or inductive capacitor banks and high-explosive generators, can be converted at high efficiency into either inductively stored energy behind the ring or kinetic/magnetic energy of the ring itself. The energy is switched to a load in a time of order L/V (L = length of ring, V = velocity of ring). Rings compressed to dimensions less than a centimeter appear possible with speeds a significant fraction of c, giving

switching times of a fraction of a nanosecond. If the energy is stored in the ring itself, then the deposition time is also of order L/V.

2. Inertial fusion driver. Given the power amplification feature mentioned above, the use of accelerated rings as efficient drivers for inertial fusion is a possibility. Rings moving $\sim 10^8$ cm/s with dimensions <1 cm and kinetic energies $\sim$10 MJ would match the power requirements for inertial fusion. The compactness of the accelerator (lengths $\sim$ 10 m) is an advantage in addition to the efficiency, making this a reasonable candidate for fusion powered rocket propulsion.

3. Synthesis of transuranic elements. A low mass ring containing $\sim$1 coulomb of protons and salted with a few percent of high mass nuclei could be accelerated to a kinetic energy $\sim$10 MJ with about 10 MeV/nucleon. Such rings would be suitable for transuranic elements synthesis at a much higher particle flux than obtainable from conventional accelerators.

4. High flux ion source. A ring with $\sim$1 MeV/nucleon could serve as a high flux source of ions for an accelerator. A small fraction of the ions released by the destructive deceleration of the ring could be collimated then accelerated by conventional means to high energies.

5. Attainment of super-high magnetic fields. An interesting feature of moving rings undergoing focusing in a conducting channel is that the extent to which the magnetic field penetrates the wall is a function of velocity, Δ = skin depth = $\sqrt{\eta L/V}$ where η is the resistivity. Even if the fields [which scale as $(R_0/R)^2$] are strong enough to

modify the wall resistivity by ohmic heating ($B > 1$ MG) the velocity can be chosen large enough to give negligible wall penetration. At fields high above the stress limits ($B > 10$ MG), the passage of the rings launches a radial shock wave at a velocity $u \sim B/\sqrt{4\pi\rho_{wall}}$. Again, at high ring velocity, $V \gg u$, the ring outraces the receding wall and continues to focus. The limit may be reached when the wall is shocked to plasma temperatures and the resulting radiation precedes the ring and destroys the tube ($B \sim$ several hundred MG). Further focusing may be possible by passing the ring through material of increasing density. The dynamic pressure following the resulting bow shock is matched by magnetic pressure in the ring leading to field strengths $\sim 10^9$ Gauss.

6. Inertial fusion by sudden ring deceleration. If very high magnetic fields are obtainable, the ring density, ρ, (proportional to B^2 for fixed T, β) becomes high, eventually exceeding solid densities. The ring itself is then suitable as a "target" for inertial fusion. The ring is ignited by sudden deceleration in a dense medium, launching an internal shock wave that heats the ring to fusion temperatures. The advantage of this method is that the energy input required for a given Q decreases with increasing density. Energies per pulse as low as 1 MJ may be possible at reasonable Q's.

REFERENCES

1. C. W. Hartman, J. H. Hammer, Physical Review Letters 48, No. 14, 929 (1982).

2. "Pulsed High Magnetic Fields," H. Knoepfel, N. Holland Pub. Co., 1970, p. 73.

3. SHIVA-STAR is a 9.3 MJ Upgrade of SHIVA-II, see W. Baker, et al., paper ID5-6 Proc. 1982 IEEE Int. Conf. on Plasma Science, May 1982, Ottawa, Canada.

4. C. W. Hartman, J. H. Hammer, Physical Review Letters 48, No. 14, 929 (1982).

Table 1.

Phase I Initial State

t = 0

L_x	Δ_0	R_0	M_r	U_{mo}	T_ϵ	B_{ave}	U_{cap}
nH	cm	cm	gm	10^5 J	eV	MG	10^5 J
40	15	50	1(-4)	0.4	10	1.3(-2)	93.3

Phase I Final State

t - 10.0 μs

R	L	I	U_{cap}	U_L	U_m	U_{mlost}	B_{ave}
cm	nH	DMA = 10^7 A	10^5 J	10^5 J	10^5 J	10^5 J	MG
5.7	66.7	1.4	19.5	69.2	1.9	1.2	0.77

Phase II Maximum Kinetic Energy State

t = 10.58 μs

R	U_m	U_k	V_{ring}	E_k	Δ	B_{ave}	L_{acc}
cm	10^5 J	10^5 J	cm/μs	eV/nucleon	cm	MG	cm
1.1	9.2	44.0	930.0	4.4×10^6	0.33	20.0	400

FIGURE CAPTIONS

Fig. 1. Geometry and circuit. Here $L_g = \mu_0/2\pi\ (\rho_0 - \rho)\ \ln \left\{\tan \frac{\alpha \hat{2}}{2} / \tan \frac{\alpha \bar{1}}{2}\right\}$.

Hartman, Eddleman, Hammer - Figure 1