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RESULTS FROM THE RACE COMPACT TORUS ACCELERATION EXPERIMENT

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Introduction

RACE[1] (for Ring ACceleration Experiment) is a proof-of-principle experiment aimed at demonstrating acceleration of magnetically confined compact torus plasma rings to directed kinetic energies well in excess of their magnetic and thermal energies. If successful, a compact torus accelerator could have many applications such as an inertial confinement fusion driver, x-ray generator, fast opening switch, high power RF source and a fuel injector for large Tokamaks.

In the course of the first year of operation (first shots were in early May 1986) we have observed: successful formation of rings in the RACE geometry; acceleration of rings with large forces, $F_{accelerate} \sim F_{equilibrium}$ without apparent degradation of the ring structure; peak velocities of $\approx 2.5 \times 10^8$ cm/sec; acceleration efficiency of $>30\%$ at speeds of 1.5×10^8 cm/sec inferred from trajectory and capacitor bank data; kinetic to magnetic energy ratios ~10 were observed. Experiments in the near future will be aimed at confirmation of the mass/energy measurements by calorimetry and direct density measurements. The first trials of a focusing cone at the end of the accelerator will begin in July 1987. Significant focusing of rings is predicted since the kinetic energy is much larger than the magnetic energy.

Apparatus

The RACE apparatus consists, in part, of a magnetized coaxial plasma gun as shown in fig. 1 (a modification of the gun from the Beta II experiment[2]) that is 50 cm. long with an outer/inner diameter of 35 cm/20 cm. The gun has both inner and outer solenoids which can be energized by a 5 kV, 250 kJ electrolytic capacitor bank. Gas is fed into the gun with eight electromagnetically driven gas valves having a total plenum volume of .5 cc. The gases used are hydrogen, helium, argon or mixtures thereof. The gas is broken down and ejected from the gun by discharging a 60 kV, 200 kJ low inductance capacitor bank between the inner and outer gun electrodes. As in similar magnetized gun experiments, firing the gun results in emergence of a spheromak-type compact torus near the gun muzzle. In RACE, the ring is formed in the inter-electrode region at the beginning of the accelerator section (see fig. 1). The coaxial accelerator electrodes are 6 meters long with an outer/inner diameter of 50 cm./20 cm., and are housed in a vacuum vessel 1.5 meters in diameter. The accelerator is essentially a coaxial rail gun with the ring acting as a moving short, accelerated by $\underline{J} \times \underline{B}$ forces when the 260 kJ, 120 kV accelerator bank is discharged. The accelerating B_θ field is fed through an annular slot between the inner gun and inner accelerator electrode as shown in fig. 1.

The diagnostics consist of current and voltage monitors for the banks, visible light and VUV detectors, a framing camera and an array of B-loop probes arrayed circumferentially (for symmetry) and axially (for trajectory). Except for early studies examing radial profiles and verifying the compact torus topology of the fields, the B-loops have been located near the outer accelerator electrode. Recently deployed diagnostics include a He-Ne interferometer, Faraday cups and small scale calorimeters.

For the next run cycle (beginning 7/87) the last 2m of cylindrical accelerator electrodes will be replaced by a 2m section of conical, coaxial electrodes to test the theoretical predictions of ring focusing[3] and reach higher energy densities.

Experimental Results

The first experiments with all stainless-steel electrodes and H_2 gas injection demonstrated formation of CT rings suitable for acceleration having total magnetic energy of 5-10 kJ and ring lengths of 50-100 cm. Acceleration was observed to $v_{ring} \approx 4 \times 10^7$ cm/sec with a ring mass of 5×10^{-4} gm. and a kinetic energy of ≈40 kJ (out of 100 kJ of accelerator bank energy) inferred from trajectory analysis. Subsequent experiments have been conducted with tantalum liners on the gun electrodes, copper cladding of the inner accelerator electrode and glow discharge cleaning. Electrode contributions to the ring mass have been reduced, resulting in acceleration up to $v \approx 2.5 \times 10^8$ cm/sec for some cases. Formation of lower mass rings is a sensitive function of gun parameters, particularly of gas valve timing. If the gas valves are fired such that the gas just reaches the opposing gun electrode when the gun is fired, a distinct low mass ring can be formed with little trailing effluent. When the gas is allowed too long a time to extend into the gun region, a protracted "tail" may be observed with the magnetic probes that can interfere with acceleration.

To infer ring mass and energy from the observed trajectory, a point model[3] of ring acceleration is used which treats the ring as a localized, constant mass with zero resistance. The ring is assumed to obey a force equation where ring inertia is balanced by the magnetic accelerating force and the resistive drag of the metal electrodes. A circuit equation is simultaneously solved with a time varying inductance determined by the ring position:

1) $(L\ddot{I}) + I/C = 0$

2) $L = L_x + \mathcal{L}'\ell$

3) $M\ddot{\ell} = F_{TOT} = \frac{\mathcal{L}' I^2}{2} - F_{DRAG}$

where I is the current, L is the total inductance, L_x is the external inductance, $\mathcal{L}'$ is the inductance per unit length of the accelerator, C is the accelerator bank capacitance, M is the ring mass, and ℓ is the ring axial position

One free parameter (M) is adjusted to obtain the best agreement with the observed trajectory. A comparison of the model (solid & dashed curves) with experimental data (horizontal bars) is shown in fig. 2 for several masses ($M = 1.75 \times 10^{-5}$gm ± 30%). The end points of the horizontal lines indicate the times when B_z, the axial field at the outer electrode, drops to 1/2 of the peak B_z at varios probe locations. For the shot shown in fig. 2 (#1076) the peak velocity was $v \approx 1.4 \times 10^8$ cm/sec with an inferred mass $M \approx 1.8 \times 10^{-5}$ gm. and kinetic energy of 18 kJ (out of 50 kJ accel bank energy).

A cross-check on the point model calculations is obtained from the accelerator bank current and voltage data and a probe that measures voltage at the accelerator muzzle. The muzzle voltage gives a measure of the ring resistance which is usually found to be small, in accord with the assumption of the model. Neglecting resistance, the accelerator inductance can be found from the measured voltage and current:

4) $L_{acc} = \frac{\int V dt}{I} - L_{ext}$

The axial position of the moving short circuit is then given by:

5) $\ell = L_{acc}/\mathcal{L}', \ \mathcal{L}' = 2 \ \ell n \ \frac{r_{outer}}{r_{inner}}$ nH/cm.

Figure (3) shows a comparison of the ring position from probe data (horizontal bars) with the current sheet position, ℓ, determined from voltage and current data (solid curve), indicating that for shot 1076, the ring does form the current path between electrodes, as opposed to current flowing through any trailing matter evolved from the gun or accelerator electrodes.

From the current and voltage data the energy input to the accelerator can be calculated:

6) $E = \int VIdt.$

Again neglecting resistance, the work done on the moving current sheet can be found, which should equal the kinetic energy of the ring if the drag force is small (the resistive drag due to the electrodes is generally very small at typical ring velocities in RACE):

7) $$\begin{aligned} E_{kinetic} &= \int^{t} VIdt - L(t)I^{2}/2 \\ &= \int^{t} VIdt - I\int^{t} Vdt/2. \end{aligned}$$

For shot #1076, as shown in fig. 4, the kinetic energy defined in eq. 7 and based on measured accelerator voltage and current (solid curve) is in good agreement with the point model prediction (dashed curve), where $M = 1.8 \times 10^{-5}$ gm was used.

When the accelerator muzzle voltage is not negligible, it is straightforward to correct for finite ring resistance by subtracting the resistive voltage drop from the total voltage drop.

Not all shots show the clear evidence of coupling to the accelerator seen in #1076. A "re-strike" is sometimes observed, particularly when the accelerator voltage is raised too high for fixed gun and solenoid voltages. The current sheet position, as determined by eq's 4,5 may track the ring for a portion of the accelerator length and then make a sudden jump back to the vicinity of the accelerator feed slot. The cause of the re-strike is not yet understood although it may be related to the "blow-by" effect when the accelerating field exceeds the ring field and blows by the ring, creating large inductive voltage spikes.

References:

1) C.W. Hartman and J.H. Hammer, "Acceleration of a Compact Torus Plasma Ring, A Proposed Experimental Study," LLL-PROP-191, April 15, 1984.
2) W.C. Turner, et.al., Phys. Fluids 26 (7), July 1983.
3) C.W. Hartman, J.H. Hammer, J. Eddleman, Proceedings of the Seventh Symposium on the Physics and Technology of Compact Toroids in the Magnetic Fusion Program, Santa Fe, N.M., May, 21-23, 1985.

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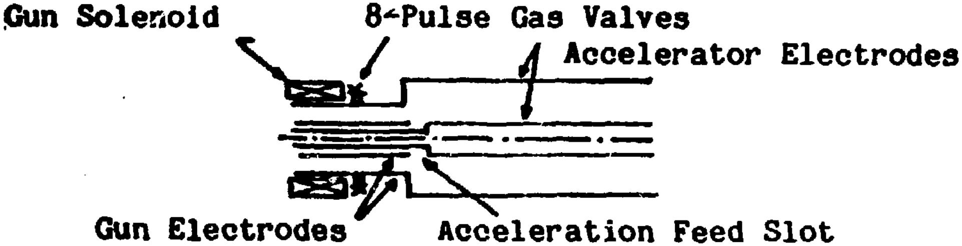

Race Gun and Accelerator Electrodes

FIGURE 1

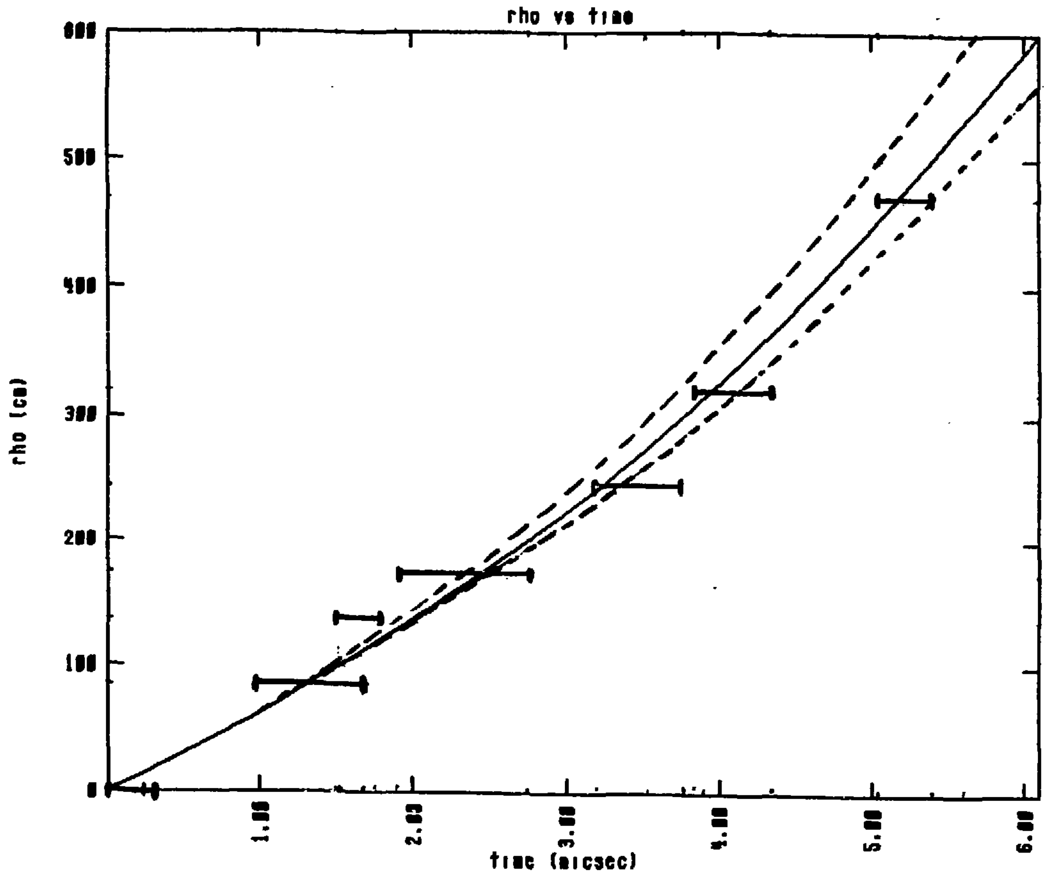
rho vs time
rho (cm)
0
100
200
300
400
500
600
1.00
2.00
3.00
4.00
5.00
6.00
time (micsec)

FIGURE 2

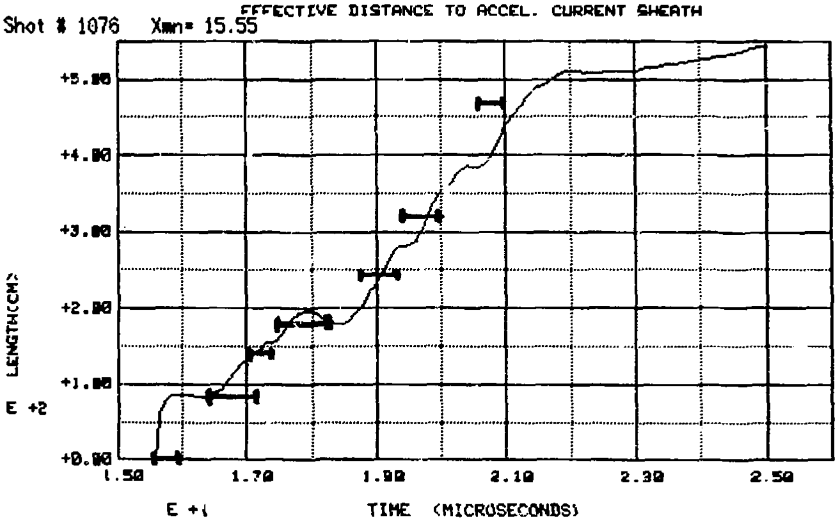
EFFECTIVE DISTANCE TO ACCEL. CURRENT SHEATH
Shot # 1076 Xmn= 15.55
+5.00
+4.00
+3.00
+2.00
+1.00
+0.00
LENGTH(CM)
E +2
1.50
1.70
1.90
2.10
2.30
2.50
E +(
TIME (MICROSECONDS)

FIGURE 3

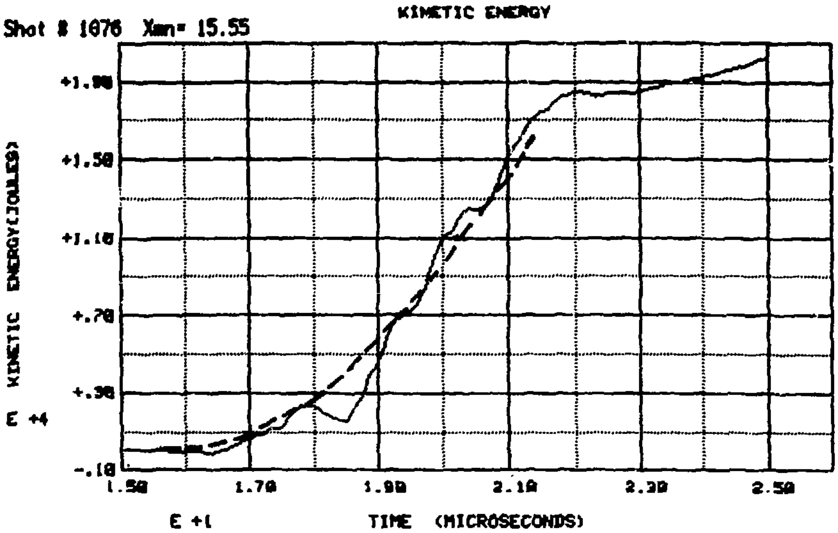
KINETIC ENERGY
Shot # 1076 Xmn= 15.55
+1.90
+1.50
+1.10
+.70
+.30
-.10
KINETIC ENERGY(JOULES)
E +4
1.50
1.70
1.90
2.10
2.30
2.50
E +1
TIME (MICROSECONDS)

FIGURE 4