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High Energy Density Fusion Using the Compact Torus*

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My remarks are concerned with employing the Compact Torus magnetic field configuration to produce fusion energy. In particular, I would like to consider high energy density regimes where the pressures generated extend well beyond the strength of materials. Under such conditions, where nearby walls are vaporized and pushed aside each shot, the technological constraints are very different from usual magnetic fusion and may admit opportunities for an improved fusion reactor design.

Possible high energy density fusion regimes are shown in Fig. 1, a Lawson-like plot of $n\tau$ vs n. Here $n\tau$ for energy confinement is plotted vs n (or B^2) for various loss processes and compared with $(n\tau)_\alpha$, the required $n\tau$ to achieve α-particle heating. Figure 1 considers spherical plasma scaling for intial plasma-field energies of 10 and 100 MJ. As $(n\tau)_{loss}$ increases above $(n\tau)_\alpha$ α-particle heating can provide ignition and energy gain.

Figure 1 shows that in the range $n \approx 10^{21} - 10^{22}$ cm^{-3} or so, $(n\tau)_{walls}$ can exceed $(n\tau)_\alpha$ sufficiently to have a $Q = E_{fusion}/E_{in}$ of a few 10's for a few 10's of MJ initial energy. Magnetic fields are still required in this regime since field-free electron conduction losses, $(n\tau)_{el.cond.}$, are too large, however, plasma energy transport at the Bohm rate, $(n\tau)_{Bohm}$ is small. In this range of density the magnetic field can provide confinement (MC, $\beta = 1$ is assumed here), or insulation against electron heat conduction (MI). Possible configurations are the Z-pinch and compact torus which can operate in either the MC or MI modes. (It should be noted that for the Z-pinch (MC), $(n\tau)_{walls}$ can be increased over the spherical scaling shown by the aspect ratio L/a). Detailed calculations(1) of a compact torus in the MI regime have shown ignition and energy gain for initial energies of a few 10's of MJ with an energy gain of $\simeq$ 30. Non axisymmetric fuel injection(2) appears possible in this regime which can increase Q to 100 or more.

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The possibility of a high energy density fusion reactor with destructible walls has been noted for sometime[3,4]. What is new, is the possibility of forming high energy density compact toruses at high efficiency and on the timescale appropriate for the application discussed here. To form appropriate compact toruses consider the compact torus accelerator[5] under development at LLNL shown schematically in Fig. 2. Here, a compact torus formed by a magnetized Marshal gun, is injected between coaxial electrodes and accelerated as in a coaxial rail gun. The compact torus can undergo slow magnetic compression for inductive energy storage before acceleration and, after acceleration, can be focussed to high energy density by injection into a focus cone. With precompression the driver power requirements are modest, matching to low voltage, high capacitance banks. After focusing to cm dimensions the time scale is reduced from $\simeq$10 microseconds acceleration time to $\simeq$ 10 nanoseconds for injection into the confinement region. The short focus time allows high energy densities to be achieved (B $\simeq$ 10-100 MG, $E_{kinetic}$/ion $\simeq$ 10-100 keV) with large total energy ($U_K \simeq$ 10-100 MJ) at an overall efficiency of 30-50%. The focused ring would then be injected into a spherical chamber for confinement and burn.

We have examined numerically the possibility of achieving the required energy density and total compact torus energy with the compact torus accelerator. Figure 3 shows scaled compact torus accelerators ranging from the present plasma ring accelerator experiment, RACE, to a 100 MJ system. For the 100 MJ system a compact torus ring with 2×10^{-3} gm mass is predicted to focus to R = 1 cm with a kinetic energy of 40 MJ and a velocity of 6×10^{8} cm/sec. The focused ring would be injected into a spherical chamber and refueled by encounter with a DT pellet. A transition to $\beta \geq 1$ is assumed to take place followed by refuelled burning as the walls are pushed outward and vaporized.

The primary electrical cost of a 100 MJ accelerator (the accelerator bank) has been estimated based on a 500 kV bank. Using off-the-shelf capacitors, the cost of a low repetition rate (1 pulse/day) bank was 35 M$. Increased repetition rate and bank lifetime along with replaceable accelerator electrodes might increase the device cost to the 200 M$ range.

This work has been done in collaboration with James Hammer and Grant Logan, Lawrence Livermore National Laboratory, Livermore, CA.

FIGURE CAPTIONS

Fig. 1. Energy loss $n\tau$'s and α-particle heating $(n\tau)_\alpha$ plotted vs n (or B^2, β = 1) for a spherical plasma encased in a ρ = 10 gm/cm^3 density solid and for 10 and 100 MJ initial plasma-field energy. The regime of interest for either Magnetic Confinement or Magnetic Insulation is shown.

Fig. 2. Schematic drawing of the RACE (for Plasma Ring ACceleration Experiment) apparatus with a focusing cone. The magnetized Marshall gun is 0.8 m long and the coaxial acceleration electrodes are 6 m long, 50 cm OD, and 20 cm ID. A typical compact torus plasma ring, shown under acceleration, is 0.5-1.0 m long, contains 10-20 μgm of plasma, has 2 KJ magnetic energy and is accelerated to 1-2 x 10^8 cm/sec velocity.

Fig. 3. Scaled Compact Torus Accelerators with pre-compression for acceleration bank energies from 0.26 MJ (RACE) to 100 MJ.

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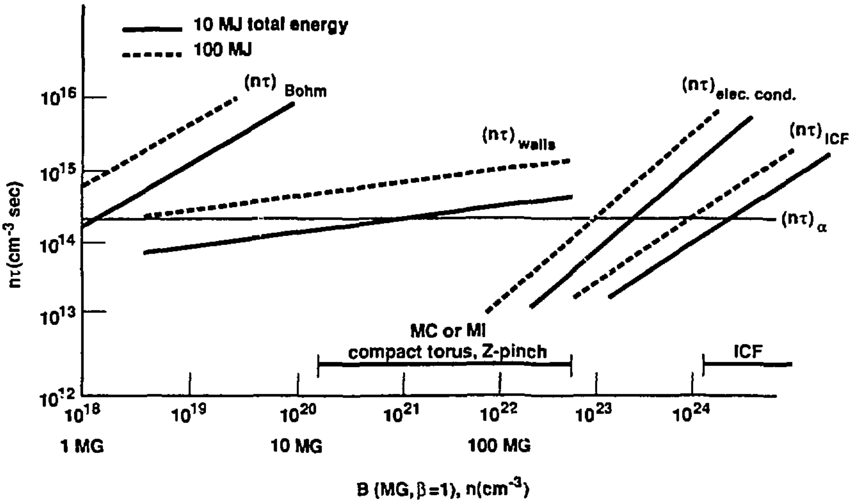

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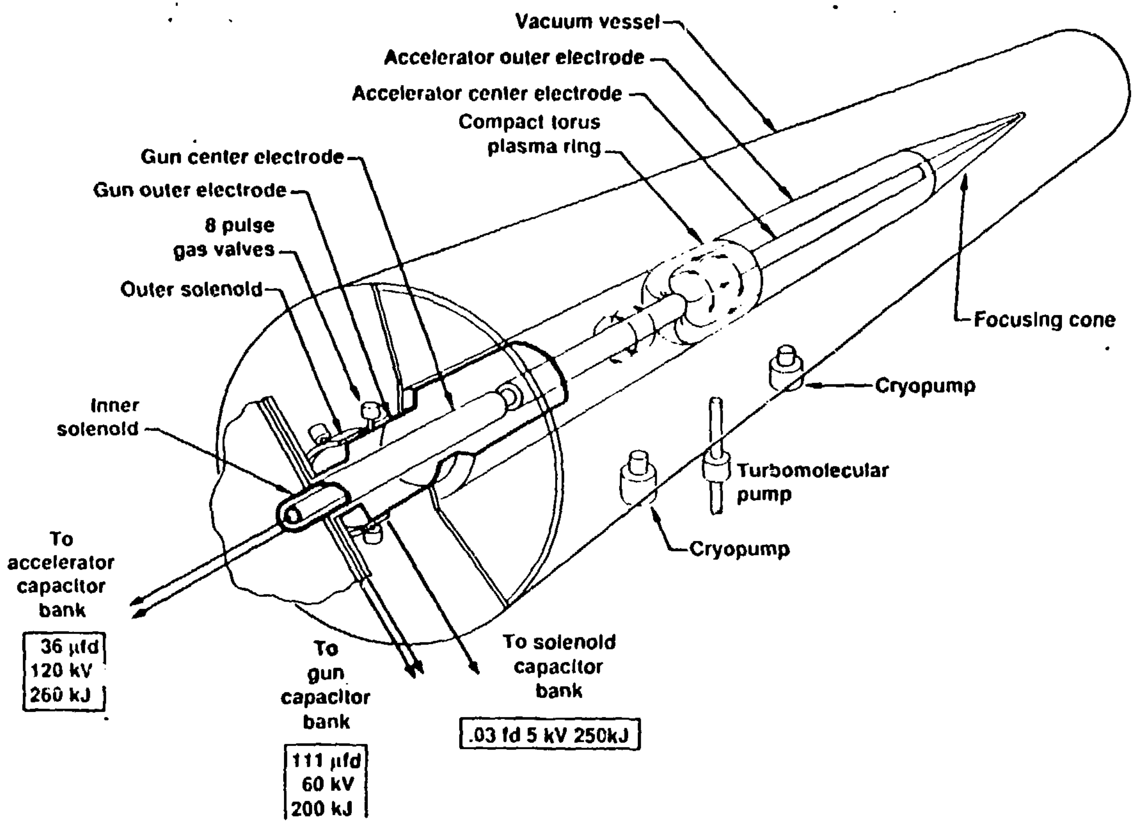
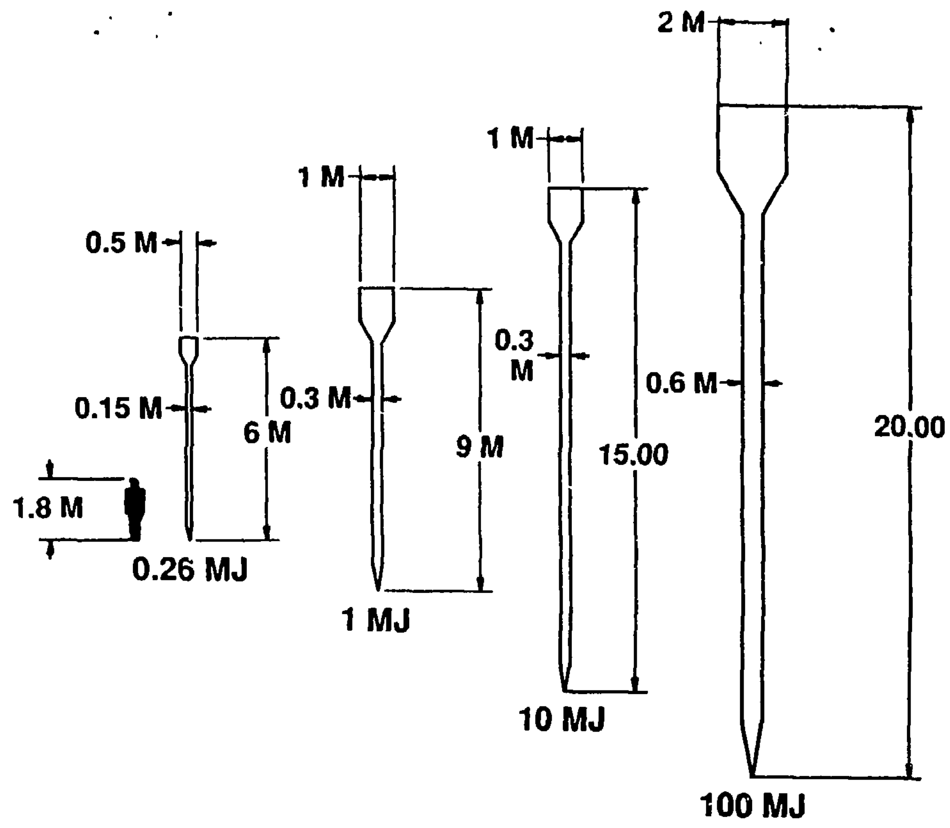


Vacuum vessel
Accelerator outer electrode
Accelerator center electrode
Compact torus
plasma ring
Gun center electrode
Gun outer electrode
8 pulse
gas valves
Outer solenoid
Inner
solenoid
Focusing cone
Cryopump
Turbomolecular
pump
Cryopump
To
accelerator
capacitor
bank
36 μfd
120 kV
260 kJ
To
gun
capacitor
bank
111 μfd
60 kV
200 kJ
To solenoid
capacitor
bank
.03 fd 5 kV 250kJ



0.5 M
0.15 M
6 M
1.8 M
0.26 MJ
1 M
0.3 M
9 M
1 MJ
1 M
0.3 M
15.00
10 MJ
2 M
0.6 M
20.00
100 MJ