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CHARGED PARTICLE DRIVER FOR ICF USING AN ACCELERATED, FOCUSED COMPACT TORUS

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Abstract

We report the status of evaluating an accelerated and focused compact torus as a driver for ICF. We are studying the acceleration and focusing aspects experimentally in the RACE facility, a recently completed ring generator coupled to a 260 kJ acceleration bank. Compact torus and ICF target interaction is being investigated with PIC codes and LASNEX, a 2D magneto-hydrodynamics code. Final conditions required of the CT are discussed as well as coupling issues such as superthermal electron production. We conclude with an economic evaluation of a few 100 MW reactor driven by a compact torus.

Introduction

A reactor scale ICF driver must deliver several megajoules of energy to a fusion capsule to achieve sufficient yield and competitive cost with other methods of electrical production. However, both lasers and ion beam sources posed as potential drivers are still prohibitively expensive despite gains in cost reduction. An alternative method of producing the required energy is to accelerate and then focus a compact torus (CT) configuration to conditions matching that of proposed ion beam sources. The CT consists of a plasma ring with poloidal and embedded toroidal magnetic fields, as shown in Fig. 1. The advantage of such an approach is the predicted high efficiency (50%) of delivering stored energy from a capacitor bank to kinetic energy of the CT, and the low cost of the generation and acceleration facility. Accelerations to velocities in excess of 1.0×10^9 cm/s appear possible with light (10µg) CTs and total kinetic energies approaching 5 MJ should be achievable with existing capacitor banks. Two major issues must be addressed; first, one must experimentally demonstrate acceleration and focusing of CTs, and second, the coupling of the CT to an ICF target must be studied to ensure proper energy delivery. This paper will discuss the status of both these aspects in our investigation of CTs as a driver for ICF.

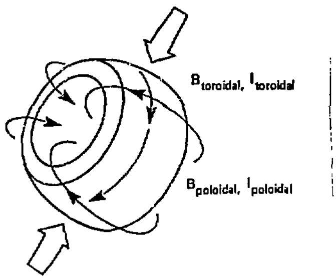

Fig. 1. Compact torus configuration.

Approach

Compact toroid configurations have been studied for several years for magnetic fusion applications [1-5]. The approach uses the CT as the fusion fuel, with the intent of achieving thermonuclear burn and ultimately as an economic power source. In our system, the CT serves only as a power multiplier, and the ions in the CT are

Table 1
Typical Ring Parameters

$n \approx 2\times10^{13} - 2\times10^{15}$ ions/cm^3
$N \approx 6\times10^{17} - 6\times10^{19}$ ions (H + C, O)
$R \approx 20$ cm
$B \approx 5 - 10$ KG
$U_{magnetic} \approx 5 - 10$ kJ
$T \approx 10$ eV $- 150$ eV
$\beta \approx 0.1 - 0.002$
$\tau_{lifetime} \approx 100 - 800$ µsec

unaffected by the field, cross into the target. The electrons have a much smaller Larmor radius and may remain tied to the magnetic field. An estimate of this can be made from the field values calculated at the final focus, approximately 20 MG. This gives a radius of <.1 μm for electron energies of 2.5 keV (3.0×10^9 cm/s). The electrons can form a strong electric field that can slow down the ions. The field is self limiting however, by the space charge of the electrons and a balance between electrostatics and magnetic pressure. The net effect of this field is to shorten the range of the ions. To reduce this electric field, one should minimize the magnetic field at the time of stagnation.

Another coupling issue relates to the generation of superthermal electrons caused by the rapid compression of the large magnetic field. A worst case estimate can be made by taking the total magnetic field before impact and converting it to kinetic energy of the electrons. With a magnetic field energy of 1 MJ in our 10 MJ case, and a 10 μg ring, we see that energies of 1 MeV are possible. At this energy, the electrons have a range of .5 g/cm^2, more than ten times the range of the ions, and could cause serious preheat problems. This view is overly pessimistic, as all the magnetic field would not be converted; a better approach is to calculate self-consistently the voltage created as the CT stagnates. We are presently putting the proper field equations in our PIC code, CONDOR, and will calculate the fields created at the time of stagnation. The obvious solution is to reduce the magnetic field at the point of stagnation and this can be accomplished in two ways. One can use a larger radius, i.e. not focusing so tightly, and this would result in a lower magnetic field energy. A second approach would be to limit the acceleration, reducing the final velocity, and thereby reducing the magnetic field. A combination of both these approaches, allowable if one used hydrogen as the CT ion species, would lower the total energy imparted to the electrons, reducing deleterious preheat effects.

With the CT reduced to a beam, we now treat the actual coupling to the target. The energy of the CT must be delivered to the target in a spot size of 1 cm or less and should have an ion range of .01 to .1 gm/cm^2. The range constraint arises from coupling requirements to the target. Sufficient range is needed to penetrate the target and deposit the majority of energy in the target. The velocity goal arises from the minimum ion range, and 3.0×10^9 cm/s translates to 4.6 MeV/amu. Ranges for this energy are shown in Fig. 4 for helium and uranium. The range curves are provided by Bangerter et al. and are revised from previously used values [6]. One can see that the heavier ions have a shorter range for the same energy, resulting in higher energy deposition. If the velocity is less than the desired 3.0×10^9 cm/s, then a lower mass ion must be used to meet the minimum range. Also shown on Fig. 4 is a curve for hydrogen at 1.5×10^9 cm/s.

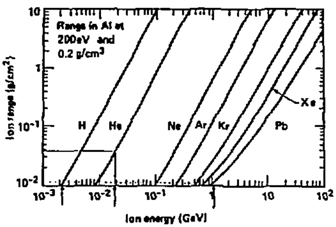

Fig. 4. Range curves for ions. Examples are noted for 2.2 MeV H, 18 MeV He and 1.1 GeV Pb.

If the proper range can be achieved, the gain of the target can be estimated from published gain curves. We have used curves, shown in Fig. 5, for single shell targets that have been constructed from many one and two-dimensional simulations [7]. These curves must be used with care, as they are only best estimates of expected target performance and more accurate values must await high power experiments. Nevertheless, the gain indicated implies 5 MJ will yield an output sufficient to be considered for reactor scale systems.

The key value to this approach lies in the high efficiency of the source and the apparent low cost of the driver. Meier and Hogan have done a preliminary estimate of the economics of a heavy ion beam reactor system, including power unit costs, repetition rate, driver and target factory costs and annual operation and maintenance. They find that the driver is a major factor in dictating the cost of electricity [8]. Using not the fuel, but rather act as a charged particle beam to drive a fusion capsule. To achieve this goal, the CT weighing a fraction of a milligram must be accelerated to velocities exceeding 1.0×10^9 cm/sec and then focused to a spot size approximately 1 cm in diameter. The generation of CTs has already been shown at the RACE experiment and elsewhere; Table 1 indicates the parameter range of rings formed by various experimental groups. The CT is created by injecting gas between coaxial electrodes and then discharging the gun bank, ionizing the gas. An embedded toroidal field is created by the discharge, and the ionized gas is moved down the breach by the self forces of the bank current. The preemplaced solenoidal field is pushed out in front of the ring, reconnecting behind to form the CT configuration as the ring leaves the gun. After ring formation, the acceleration bank is fired, creating a $J \times B$ force that can either compress or accelerate the CT. In Fig. 2, a compression stage is shown, and the force from the capacitor bank is almost balanced by the radial component of the ring's restoring force against the conical electrodes. This compression stage allows the capacitor bank to build to maximum current while the CT is forced down the conical structure. The length of the compression stage is chosen so that the acceleration bank has reached peak current just as the CT reaches the end of the cones. Most of the bank's energy is now stored inductively behind the CT, and this provides the accelerating force in the straight section of coaxial electrodes. Since the CT mass is small, very high velocities can be obtained in short lengths, and it is during this phase that most of the stored energy is converted into CT kinetic energy. A second conical section is placed at the end of the structure to compress the CT to its final radius.

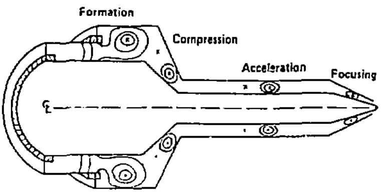

Fig. 2. Ring generator, acceleration and focusing phases.

Acceleration and focusing will be tested in the RACE facility, (Ring Acceleration Experiment). Calculations indicate that approximately 50% of the bank's energy can be coupled to kinetic energy of the ring. With a bank of 10 MJ, such as the Shiva Star at AFWL, this translates to 5 MJ of kinetic energy. The RACE experiment is more modest in scope, with 260 kJ stored in the capacitor bank. The geometry and associated banks are shown in Fig. 3. To date, RACE has formed rings from argon and hydrogen, and ring lifetimes have been noted to 60 µs. Magnetic fields of the CT were sampled at 23, 43, and 210 cm from the gun, and timing and absolute values correlate with a drifting CT. The acceleration bank is now connected to the facility, and the first tests of ring acceleration have commenced. Velocities $\geq 10^8$ cm/s have already been achieved. Velocities expected from the RACE facility range from .7 to 6×10^8 cm/s with ring masses of 5 to 500 µg. Higher velocities may also be attained with even lighter rings, but at a large loss of efficiency in energy transfer.

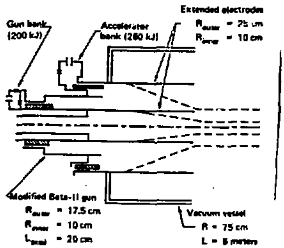

Fig. 3. RACE dimensions and capacitor bank stored energies.

To be useful as a fusion driver, the accelerated and focused CT must meet similar conditions to that of charged particle fusion. The key to this approach is the delivery of adequate energy and power in a form usable to an ICF capsule. Total energy required ranges from 1 to 10 MJ at power levels of 100's of TW. In addition, the CT must be stripped from its magnetic field so that it can be treated as an ion beam. This condition can be met if the kinetic energy of the CT greatly exceeds its magnetic energy. In this case, the ions,

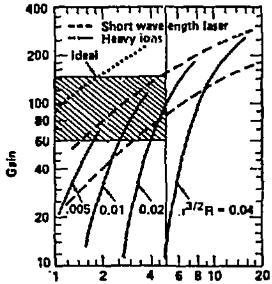

Fig. 5. GAM curves highlighted for several ion ranges at 5 MJ. R is the ion range; r is spot radius (cm).

their numbers, one finds a driver cost of 100 to 200 M$ might allow a reactor to be built in the 100's of MW size instead of the currently proposed 1+ GW systems. A specific example shows that a 400 MW CT system matches the cost of electricity, with all capital and operating costs folded in, equal to that of a 1 GW heavy ion driver. Additional work by Tobin indicates such a price may be realistic for a 5 MJ system with a 3 Hz rep rate [9]. However his system suggests the need for continual replacement of electrodes, and we must evaluate the cost of this additional requirement. Still, the reduction in costs of either the power plant or CT driver could drop this power level even lower. Given the simple technology involved in accelerating CTs, such a low cost might be possible, thus allowing smaller reactor scenarios.

Summary

We are presently studying the feasibility of accelerating and focusing CTs as a possible ICF source. Our experimental facility is complete, and we have generated rings with both hydrogen and argon. Experiments have started to study acceleration, a crucial test for the viability of CTs as an ICF driver. Calculations are being performed on the coupling of accelerated CTs to a fusion capsule, and indications are that power, energy, and range constraints can be easily met. The issue of hot electrons remains unresolved, with the simplest solution being the minimization of magnetic field energy in the acceleration scheme. With proper kinetic energy and spot size delivered to a CT, a small, economical reactor appears as a very real possibility.

Acknowledgment

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