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C. W. Hartman, D. B. Reisman, H. S. McLean, J. Thomas

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Charles W. Hartman(1), David B. Reisman, Harry S. McLean, and John Thomas(2)
Lawrence Livermore National Laboratory

Abstract

A fusion reactor is described in which a moving string of mutually repelling compact toruses (alternating helicity, unidirectional Btheta) is generated by repetitive injection using a magnetized coaxial gun driven by continuous gun current with alternating poloidal field. An injected CT relaxes to a minimum magnetic energy equilibrium, moves into a compression cone, and enters a conducting cylinder where the plasma is heated to fusion-producing temperature. The CT then passes into a blanketed region where fusion energy is produced and, on emergence from the fusion region, the CT undergoes controlled expansion in an exit cone where an alternating poloidal field opens the flux surfaces to directly recover the CT magnetic energy as current which is returned to the formation gun.

The CT String Reactor (CTSTR) reactor satisfies all the necessary MHD stability requirements and is based on extrapolation of experimentally achieved formation, stability, and plasma confinement. It is supported by extensive 2D, MHD calculations. CTSTR employs minimal external fields supplied by normal conductors, and can produce high fusion power density with uniform wall loading. The geometric simplicity of CTSTR acts to minimize initial and maintenance costs, including periodic replacement of the reactor first wall.

Key words compact torus, fusion reactor

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Introduction

The compact torus has the unique aspect of self-generated magnetic confinement in a closed configuration, requiring only ancillary fields to provide equilibrium. Two consequences emerge, the high conductivity of a fusion-temperature plasma allows for slow decay of the magnetic energy, and the self-contained field configuration allows for mobility of the CT. In this paper we incorporate both consequences into a fusion reactor concept based on a moving string of mutually repelling CTs. Employing a string of CTs enables MHD stability to be maintained and allows uniform heat loading of the first wall. The possibility of a liquid first wall also presents itself.

The CTSR is shown in Fig. 1. CTs are formed in sequence at a coaxial input and move down a compression cone into a straight cylinder where heating and fusion take place. In the interest of simplicity, we limit the burn time to the time for the magnetic energy to decay of order 10%.When the CTs emerge from the fusion region the burn is quenched by expansion in an exit cone where direct recovery of the magnetic energy occurs. The recovered current is then returned to the input.

CT Formation and Direct Recovery

Direct recovery of the magnetic energy is the inverse of formation for CTs of the Spheromak type[1]. Both formation and recovery employ in this reactor description nonconventional operation of the magnetized coaxial plasma gun[2,3] where, instead of usual static poloidal field and pulsed gun current, the gun current is maintained constant and the poloidal field is oscillated to form and recover entering and exiting CTs. (As an alternative, two guns for formation and recovery with oppositely directed static poloidal flux and alternately switched gun current has been calculated and can be considered as a back up). To allow the poloidal flux to be time varying and, at the same time conduct the steady gun current, it is necessary to provide a 3D electrode configuration in the form of a squirrel cage, i.e. conducting bars for electrodes where the poloidal flux is introduced. Continuation of the poloidal flux between the bars outside the inter electrode region allows a plasma source to introduce fuel during formation and acts as a diverter during recovery.

A Trac2[4] computation of CT formation and an initialized CT's displacement into a compression cone is shown in Fig.2. Although there is some experimental confirmation of the Trac2 model , this computation must be considered as heuristic since it is 2D and, constrained by the code limitation which allows only a static poloidal flux can be used. Additional helicity injection effects may occur which can , most importantly, amplify the CT toroidal current by factors of 3-5[5] reducing the recirculating current by the same factor. Helicity effects may also play an inverse role during recovery. Fig. 3 shows flux contours for a single domain computation of both recovery and formation. An initialized CT moves into a counter directed poloidal flux region which opens the CT flux surfaces releasing Bt into the feed back link to the formation gun to produce another CT. In this static field problem no attempt was made to control the kinetics of reconnection so the recovery-formation was about 50% efficient. With a time varying poloidal opening field recovery can be nearly adiabatic and much higher efficiencies can be expected, approaching that of electrical machinery.

CT Compression

Following relaxation of the CT to a minimum energy Taylor state[6], it enters a conical electrode region and is compressed in radius. Stable compression with a Bt field has been achieved in the Compact Torus Accelerator[7] and good agreement with Trac2 calculations has been obtained[5]. In the case of the CTSR it is important to maintain a balance of the repulsive forces of each CT as the string moves down the cone. To solve this problem with Trac2 we initialize a string of CTs in the cone, all with the same poloidal flux rAt, and adjust the interelectrode width and CT length so that each CT has the same magnetic energy. The resulting motion in the cone preserves the force balance, reduces the CT radius, and reconfigures the CT at constant energy with increased field since RBt=constant. A further constraint is that the compressed CT must have Lct< 1.6Rct for stability[9].

Employing a compression cone has several advantages, CT formation and relaxation take place at large radius and low magnetic field where ohmic dissipation is more easily controlled, and neutron shielding is more easily employed. Since the ratio toroidal flux/poloidal flux increases during compression, tearing mode activity probably will occur resulting in reduced energy confinement during this phase. A number of variations of formation and compression are possible, including omitting the compression phase entirely and forming the CT at the final radius with a radial gun.

Plasma heating to fusion temperature

When the CT is compressed to the final radius with no center conductor and is in the minimum magnetic energy state, the plasma has to be heated to fusion temperature as the CT moves into the blanketed fusion region. At low temperature, ohmic heating is dominant but decreases rapidly as the plasma becomes hotter. For an example CT to be discussed in detail later, with Bave=100 kG, R=1m, L=1.6m, initially, at Ti =.2keV, Pohmic=440 MW, and after 0.1sec Ti=4keV, Pohmic=14 MW. Further heating to 15keV as the CT moves a few meters requires roughly 50-100 MW of additional heating some of which will come from alpha particles.

CT fusion estimates and reactor power flow.

We base our estimates of the fusion reactor power gain,
G= Pfus/(Ploss +(1-f)Pmag.). Where Pfus is the total fusion power, Ploss includes ohmic losses including losses due to CT drag, and Pmag is the power flow of the magnetic energy of the exiting CTs which is directly recovered with efficiency f. Estimates of G are given for an example CT shown in Fig.4.

The CT is initialized in a Taylor state with uniform Te=Ti=15keV, rhomax=3.e-9 gm/cm3, rhomin= 1.e-12 gm/cm3 50/50 DT, and at the “o” point, Bt=100KG. The plasma pressure is determined by the “o” point beta= 0.1[10].Trac2 calculated parameters are summarized below.

PARAMETERS of EXAMPLE CT

R=100 cm
L=160 cm
Um=100 MJ
Uplasma=11.3 MJ
rAtmax= 12.8 KG-m2/radian
Bz(R=100cm) = -58 KG
Bz(R=0 cm) = 162 KG
Pfusion= 96 MW
Palphas = 20 MW total
Palphas = 190 w/cm2 on outer wall
Tdecay = 5.0sec 10% of Um
nTdecay= 3.6e15 cm-3 sec
nTalphahtg = 4.e14 cm-3 sec

If a sustained burn can be maintained as initialized for Tdecay, the total fusion energy produced is 480 MJ = 4.8Um, limiting G to low values. Direct recovery, which may have 90% efficiency, can increase G 10-fold. We do not address in this paper issues related to burn sustainment and energy loss when beta exceeds the limiting stable beta.

A fusion reactor example.

Consider a reactor with 1000 MWt total fusion power. A string of 10 CTs, as described above, would produce the total power in a reactor region length Lrr = 16m. Limiting the flow-through time to10%Um decay, Tdecay = 5. sec, the string velocity is 3.2 m/sec.The magnetic power of the CTs is Pmag= UmVct/Lct = 200 MW. If Pmag is directly recovered with f=0.9 a maximum possible gain, G = 50 is predicited. Lower f and ohmic and other losses will probably reduce G by 10-20%. We have not included drag losses since there are a number of possibilities of modifying drag or eliminating it by employing either a liquid Li first wall with axial flow or a solid wall with flowing Li backing.

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(1) LLNL retired
(2) privately employed

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chartman2@comcast.net
268 Wayne Avenue, Alamo, CA. 94507

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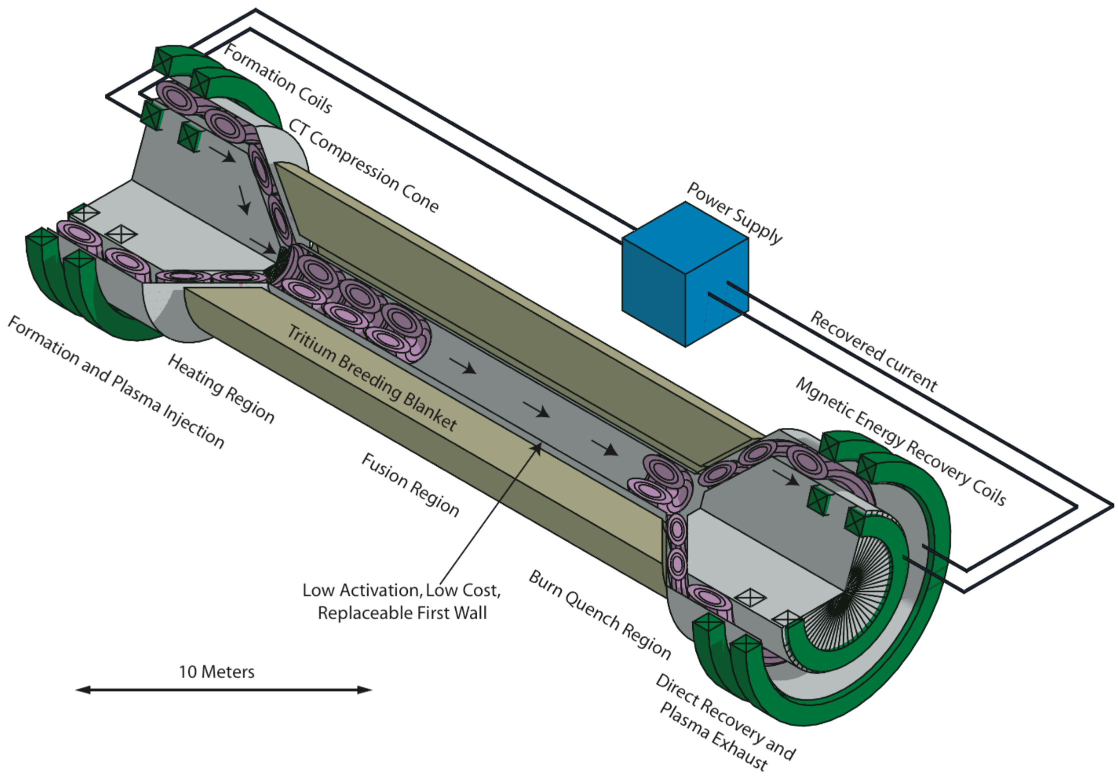

Fig. 1 The compact torus string reactor, CTSR, 1000MWt. CTs with alternating helicity and unidirectional Bt are formed between coaxial electrodes, Ri=3m, Ro=4m with constant gun current and alternating poloidal flux. The CTs are compressed to the final radius, at constant magnetic energy, the plasma is heated to thermonuclear temperature, and then pass through a fusion region. On exiting the fusion region the CTs expand in radius at constant magnetic energy and the magnetic energy is recovered as current which is returned to the formation gun.

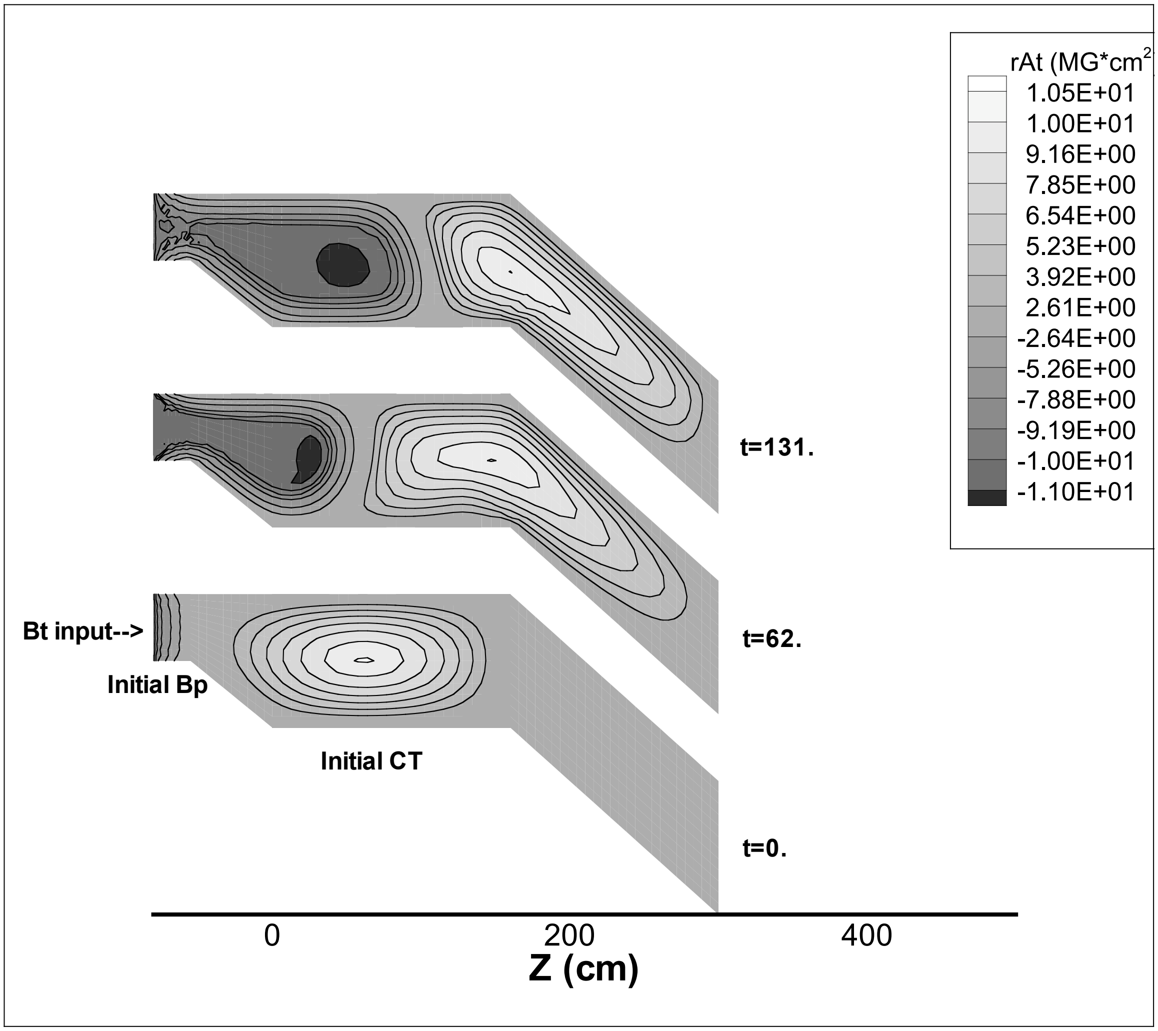

Fig 2 Sequence of rAt contour plots illustrating CT formation. The initial CT is displaced into the compression cone shown in Fig 1.

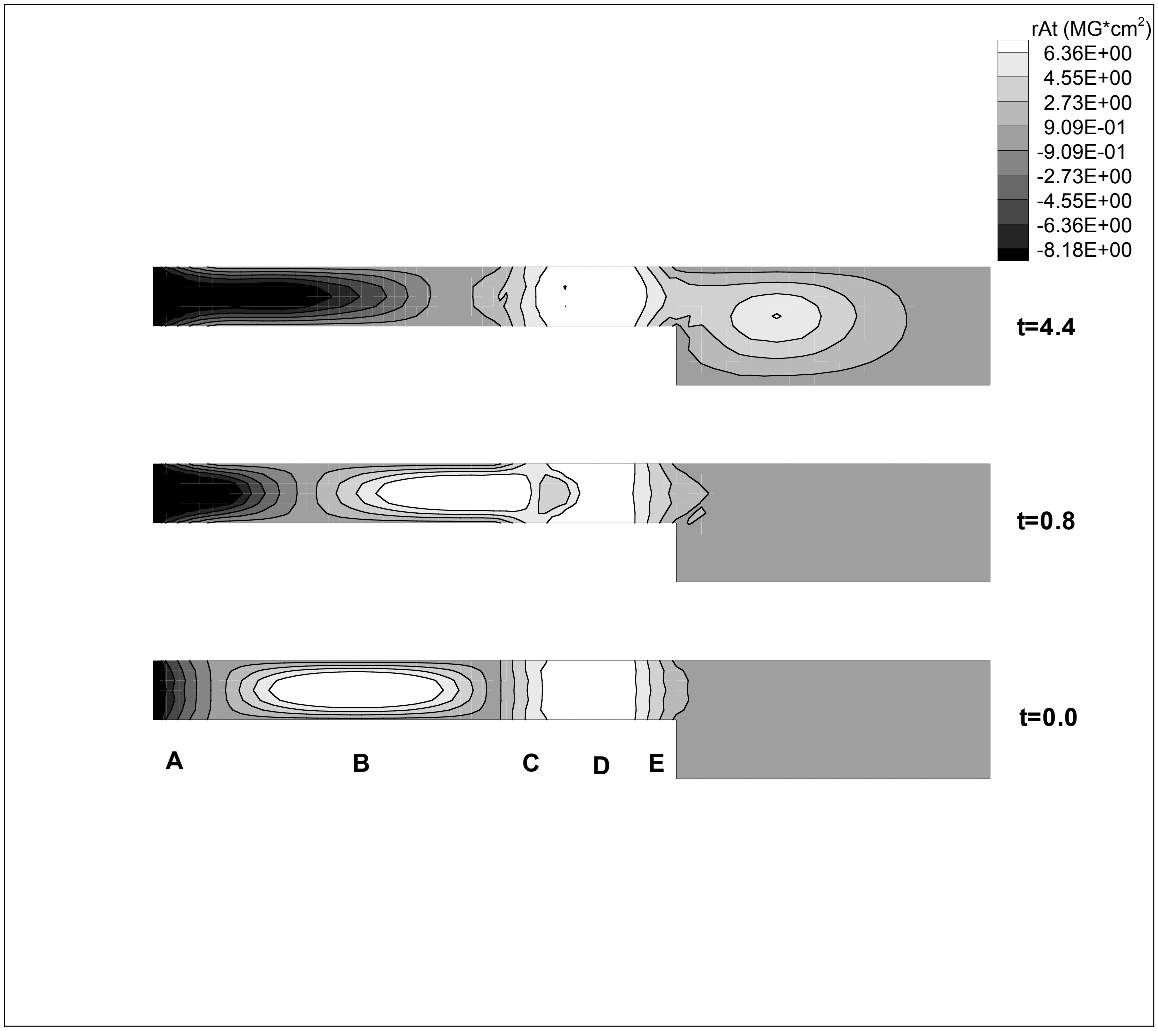

Fig 3 A single domain computation of direct conversion. Region A, with initialized Bp and injected Bt, serves to simulate a CT trailing the initialized CTB. Region C has poloidal flux, counter-directed to the incoming CTB flux which opens the surfaces releasing Bt. D returns the Bt flux released to the input of the formation gun with flux E forming a CT. Time t is in microseconds.

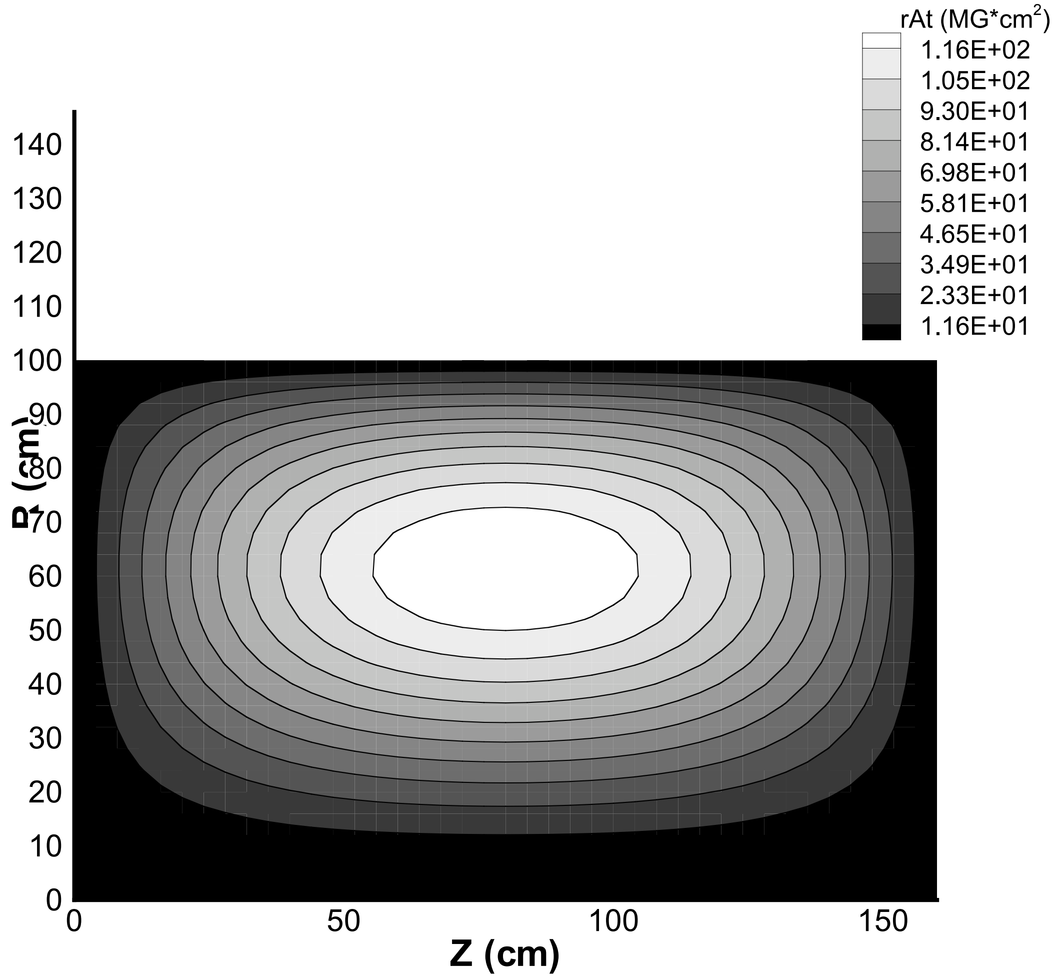

Fig. 4 Poloidal flux per radian (rAt) contours for the CT example used to estimate the fusion reactor power and gain. The dipole current is 25 MA and the magnetic energy is 100 MJ.