# Development of Merged Compact Toroids for Use as a Magnetized Target Fusion Plasma

**Stephen Howard · Michel Laberge · Lon McIlwraith · Doug Richardson · James Gregson**

**Abstract** We report on the development of compact toroid (CT) accelerators to create the target plasma for magnetized target fusion (MTF) devices. Due to the requirements of high initial density of $\sim 10^{17}$ cm$^{-3}$, strong internal fields of 5–10 T, and base temperatures of >100 eV, a design based on conical compression electrodes is an effective avenue to pursue. Progress is being made at General Fusion Inc, (Vancouver, Canada) to develop a pair of large CT accelerators for generating an MTF target plasma. In this design, tungsten coated conical electrodes (with a formation diameter of 1.9 m, a radial compression factor of 4, and overall accelerator length of 5 m) will be used to achieve ohmic heating and acceleration of the CT, yet with low wall sputtering rates. A pair of these accelerators can be synchronized and shot at one another, producing a collision and reconnection of the two CTs within the center of an MTF chamber. Depending on the choice of relative helicities, the two CTs will merge to form either a spheromak-like or an FRC-like plasma.

**Keywords** Magnetized target fusion · Compact toroids · Acceleration · Spheromak · FRC

## Introduction

General Fusion Inc. is working to develop a low cost MTF concept based on spherical focusing of high pressure acoustic pulse in liquid metal, which is used to compress a high density self confined plasma [1, 2]. For this fusion concept the target plasma is required to have the following properties before MTF compression: a density of $n > 10^{17}$ cm$^{-3}$, a temperature of $T_e \sim T_i \sim 100$ eV and be well magnetized B $\sim$ 5–10 T. These parameters are required to satisfy the Lawson criteria during a spherical compression from 20 cm initial radius to 2 cm radius at peak compression with a dwell time of 7 μs (FWHM of pressure). Peak plasma conditions during an MTF pulse will be $n = 10^{20}$, $T = 10$ keV, B $\sim$ 500–1,000 T.

The General Fusion (GF) approach for generating the self confined target plasma is to use a conical focusing coaxial CT accelerator (injector) with a radial 4x compression similar to the MARAUDER device [3, 4] see Fig. 1. For our system a formation density of $n = 2.5 \times 10^{15}$ gives target density of $10^{17}$ cm$^{-3}$, while a formation magnetic field $B = 0.8$ T gives target value of $B = 9$ T (ideal MHD). Merging of a pair of fast CTs will give the required temperature from thermalized ion kinetic energy. With our design we will also be able to investigate the use of snow-plow buildup of density during the acceleration process [5]. The performance of the injector will be characterized by a comprehensive deployment of diagnostics. The facility being constructed will operate two CT accelerators, synchronized to create a head-on collision of CTs in the center of the target chamber (see Fig. 2). Depending on the choice of relative helicities of the two CTs the final magnetic configuration of the target plasma can be made to be either spheromak-like or FRC-like. For a CT composed of equal parts of D–T the net mass of the merged CT plasma will be in the range of 10–15 mg.

ICC 2008 Reno NV, June 25th, IP: 021.

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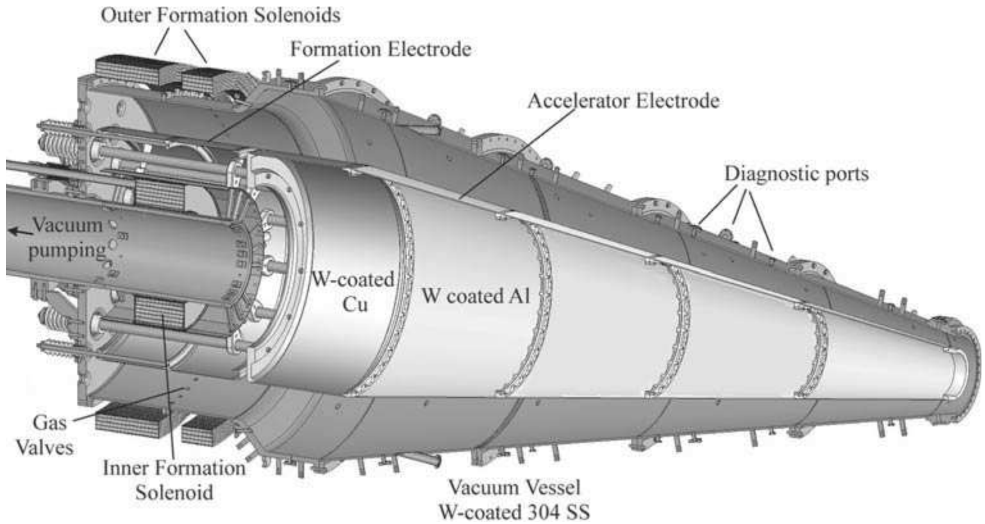


**Fig. 1** Cross-section of injector, with length of 5 m, maximum radius of vessel is 0.95 m. Formation and acceleration power is applied through a set of discrete feedthroughs in the back plate. Center electrode is self-supported by the cantilevered feedthrough rods

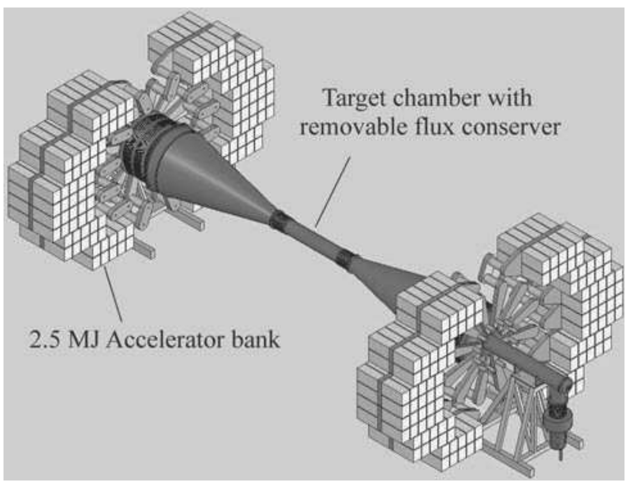


**Fig. 2** Layout of the CT merging experiment shown with accelerator capacitor banks and parallel plate transmission lines

## Merged Compact Toroids for use as MTF Fuel Plasma

There are a number of reasons why it is attractive to use merged CT plasmas as the target for a fusion compression device. First, since the pair of CTs can be made to have close to zero total momentum, the merged plasma is relatively easy to catch within an imploding liner. It has the additional benefit of having a natural pre-MTF heating through the thermalization of ion kinetic energy from acceleration, and by reconnection of B fields. Having the total particle inventory of the target plasma come from two injectors will lessen the burden on each individual injector, requiring lower formation density by a factor of 2. Dividing the inventory between two injectors is also expected to produce lower impurity levels than a device with just a single coaxial injector due to having less radial electrical current density passing through the electrode wall, hence lower sputtering.

Working with a merged CT system has the advantage that we will be already set up to try MTF compression on two distinct configurations: the spheromak configuration produced by a co-helicity merge, and an FRC produced by a counter-helicity merge. Changing between these two modes would be implemented by a polarity reversal on one of the two injectors in either the formation solenoid current, or the railgun current. Thus the same set-up can be made to test both plasma configurations.

The process of accelerating the CT plasma is expected to have the additional benefit that any high Z impurities ejected from the wall tend to be poorly entrained in the accelerating plasma, remaining at low velocity within the back of the trailing plasma. The main hydrogen CT plasma tends to significantly outrun these impurities if sufficient acceleration is achieved.

In order to fully assess the merits and viability of merged CTs as an MTF fuel plasma there are a number of fundamental plasma physics issues that will need to be studied on a device that is capable of producing fusion relevant conditions. This task will be undertaken with this first injector pair firing into a static target chamber (Fig. 2). A second pair of injectors are planned for the subsequent test reactor experiment, in which an optimized target plasma will be compressed to fusion conditions by a spherically focused shock wave in a PbLi liner fluid. The main purpose of the first injector pair is to demonstrate the required pre-compression parameters, and to study the necessary physics issues. The plasma dynamics of CT merging as well as the stability of the final state are currently being investigated in parallel by ongoing experiments such as SSX, [6, 7] however the GF injector pair will operate at significantly higher density, temperature and magnetic field strength. The cross-experiment comparison between the lower and higher density merging experiments is likely to provide insight into the relevant scaling laws. The key parameter that is expected to characterize the reconnection process is the collisionality parameter $\delta/\lambda_{\mathrm{mfp}}$, [8] where $\delta$ is the thickness of the reconnection layer and $\lambda_{\mathrm{mfp}}$ is the mean free path length. The low density experiments operate more toward a fast collisionless reconnection process $\delta/\lambda_{\mathrm{mfp}} << 1$, while the higher density experiments in the collisional regime $\delta/\lambda_{\mathrm{mfp}} > 1$ are expected to more closely follow a classical reconnective rate determined by the Spitzer resistivity [9]. The GF runs are planned to include a sequence of low-density shots as well, in order to provide sufficient overlap with other available data.

As with any MTF scheme using a material liner implosion, a critical issue is impurity transport from the wall. This will be addressed in a preliminary way with these first set of experiments by measurements of the impurity generation and transport from direct contact of the merged CT plasma against a wall surface composed of relevant sample materials. For diagnostic clarity, localized samples of Pb and/or Li acting as limiters, will be inserted into the plasma edge within the target chamber, and the resulting transport of impurities into the stationary merged plasma will be measured spectroscopically, and possibly by other methods (deposition probes, residual gas analysis, etc). Additionally, the target region flux conserver can be coated with test materials to assess the net impact on plasma lifetime. This will determine the impurity levels present in the initial plasma before compression, however scaling models will be needed to extend these rates to harsher conditions during the peak of the MTF pulse.

In order to develop a comprehensive model of the merging process and resulting plasma conditions, there is a clear need to make the most of experimental data by coupling it with a parallel simulation effort. The approach is to use a well validated code such as NIMROD, further benchmarked against actual data from the GF injector, as an advanced analysis tool for understanding the experimentally obtained data. Surface magnetic data and optical data from the interior would be used to constrain the simulation, and the output could be used to visualize the dynamics of the plasma process as implied by the diagnostic evidence. Through this approach we hope to have a robust model of system that can then be run with imploding walls in order to predict how the system will behave as an MTF device before the capital is expended to actually build the prototype implosion system.

## Injector Design

The injector design has taken into account numerical models for breakdown, ohmic heating, density accumulation through snowplow, as well as spheromak formation and equilibrium models. The necessary overall scale of the injector has been determined primarily by the consideration of current density to the wall and achievable formation density, as implied by the performance of previous coaxial gun experiments. The overall design choic
injector can be mostly described as a hybrid of previous coaxial devices (refer to Fig. 3). The shape and proportions of the vessel is similar to the MARAUDER [4] device, with an outward radial expansion step in the outer wall to allow magnetic relaxing and closure of flux surfaces before the acceleration pulse is applied (see Fig. 1). SSPX also shares this outward radial expansion feature, and has a similar volume to the expansion region of the GF injector where the newly formed CT is at its largest. RACE versions 1 and 2 [10] also had an outward expansion step. In contrast RACE version 3 [11], CTIX [5] and CTF II [12] use an inward radial expansion at the edge of the formation region to facilitate CT magnetic closure, however this has the disadvantages effect of reducing the surface area of the inner electrode and thereby unnecessarily increasing the electrical current density through the wall for the given amount of required railgun current. Simple practical considerations have lead us to choose the arrangement of how electrical power is applied to the electrodes, going with a single grounded outer electrode as in RACE and CTF II, with distinct formation and acceleration inner electrodes. MAURADER and CTIX use a single inner electrode, but with a segmented outer electrode with high-voltage ceramic breaks between the formation and acceleration sections, and with the outer accelerator electrode being brought up to high voltage. This significantly complicates the deployment of diagnostics on the injector surface as well as connecting it in the future with the MTF reactor vessel. The GF injector will be similar in scale to proposed ITER refueling injector [13], and could be used in a medium density mode ($10^{16}$ $\mathrm{cm}^{-3}$) for that application if that was ever desired. If possible, the GF injector will make use of passive inductive switching of the main acceleration current, as demonstrated by CTIX [5], since this provides a reliable and low cost route to high repetition rate.

Due to the large size of the formation region, we have not been able to find a manufacturer with the capability to make a sufficiently large annular ceramic insulator for separating and mechanically supporting the electrode structures, as is the standard design approach in previous, smaller devices. Instead, the GF design uses a set of discrete high power ceramic feedthroughs located on the back plate, with brazed ceramic-metal seals instead of the standard polymer O-ring seals. Considering the importance of a high quality vacuum in this system we are avoiding polymer seals entirely throughout the vessel, and will bake the vessel at high temperature (400°C).

The CT is formed using a standard magnetized Marshal gun approach, resulting in a spheromak-like configuration

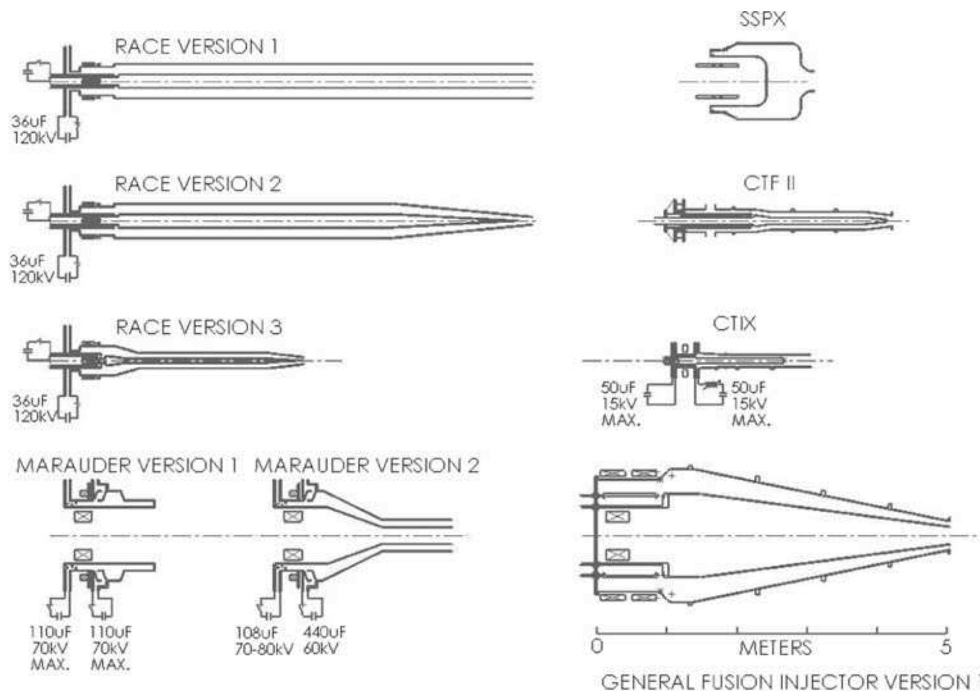


**Fig. 3** Comparisons with relevant coaxial-gun devices. RACE version 1, 2 [10] and version 3 [11] are notable for achieving 30% electrical to KE efficiency (v.1), a radial compression factor of 2 (v. 2), and plasma densities n $\sim 10^{16}$ cm$^{-3}$ with version 3. MARAUDER [3, 4] achieved highest CT mass (2 mg), and radial compression factor of 3, while also developing the physics of self-similar compression during acceleration [16]. SSPX produces stationary spheromaks, but has similar formation parameters to the GF injector, and has achieved $T_e = 500$ eV, $\delta B/B \sim 1\%$, and long lifetimes. CTF II [12] and CTIX [5] are smaller injectors that have demonstrated CT refueling of tokamaks, with CTIX's main contribution being high rep-rate achieved via passive inductive switching of accelerator power

with both toroidal and poloidal magnetic fields. Typically spheromak formation involving poloidal flux amplification [14, 15] which is expected to scale in proportion with $\lambda_{gun} = \mu_0 I_{gun}/\varphi_{gun}$, the formation gun current divided by the gun magnetic flux. Given the scaling established by SSPX [15], the GF design would yield roughly a factor of 2 flux amplification. However we have designed the solenoids and power supply so that it is capable of introducing all of the poloidal flux directly, in case collisional effects result in sub-optimal flux amplification when attempting to reach high-density formation states. The Taylor state minimum eigenvalue is $\lambda_0 = 9.972$ m$^{-1}$ for the expansion region is nearly the same as that of SSPX [15] with $\lambda_0 = 10$ m$^{-1}$.

The compact toroid is low $\beta$, typically <10% and the acceleration dynamics are dominated by the work done to increase the magnetic potential energy of the CT, $U_B(z)$. For a self-similar compression the magnetic energy is inversely proportional to the radial position of the CT, $U_B(z) = U_{B0}\, r_0/r(z)$ [16]. Electrode geometries other than self-similar can be handled as well, in order to include the expansion and target regions in the same model. To do so we use the approximation of ideal conservation radial, axial, and toroidal magnetic flux to calculate the magnetic field strength of each component as the CT propagates into variable geometry electrodes. For simplicity we only use mean values for each component and use the volume $V_{CT}(z)$ of the entire CT, then the magnetic energy is $U_B(z) = V_{CT}(z)(B_r^2(z) + B_z^2(z) + B_\theta^2(z))/2\mu_0$. The additional assumption that the axial extent $\Delta_Z(z)$ of the CT is directly proportional to inter-electrode gap distance $\Delta_Z(z) = \Delta_{Z0}\ (r_{out}(z) - r_{in}(z))/\Delta_{r0}$, is all that is needed to make the dynamics be fully determined. Direct proportionality exactly holds for the CT axial extent in self-similar compression, and correctly describes the general tendency for the CT to expand or contract to fill the geometry of the vessel.

Acceleration of the CT is accomplished if the railgun force exceeds the gradient of $U_B(z)$. In a conical geometry $U_B(z)$ becomes very large as it nears the end of the accelerator, so it is possible for the CT to bounce back if not enough pushing force is applied. Positive acceleration only occurs if current exceeds a minimum equilibrium value. Equilibrium current increases with axial position, yet it is permissible for the time dependent railgun current to fall below the equilibrium value if there is already enough CT kinetic energy to coast uphill through the remaining extent of the compression region. For reasons of minimizing current density through the wall, it is therefore best to drive hard in the beginning of the acceleration section where the electrode radius is largest, building enough kinetic energy to coast through the peak compression region. The alternative strategy of maintaining constant rates of acceleration by driving at or above the equilibrium current for the entire duration may not be practical considering that the high value for equilibrium current near the muzzle of the accelerator is likely to cause significant ablation of the smaller diameter electrode surface, and thereby contaminate the plasma. We are also taking the basic precaution against surface sputtering by using a dense tungsten coating on all electrode surfaces, which appears to be a successful approach on similar scale devices.

Using this 1-D model of acceleration dynamics coupled with a dissipative LRC circuit model of the accelerator bank and transmission line, it was possible to explore parameter space and finalize a design for the electrode geometry and drive circuit. For an initial CT magnetic energy of $U_{B0} = 250$ kJ, and a final energy after compression of $U_{Bfinal} = 1$ MJ, we found a design that gave good performance with an accelerator bank of 2.5 MJ run at 40 kV.

## Dynamics of CT Merging

Within the scope of this project, a number of currently open questions regarding reconnection dynamics in non-trivial geometries will be addressed experimentally and theoretically. One basic observation is that unconstrained CTs injected through free space into a vacuum magnetic field (or even a low $\beta$ plasma) will tend to rapidly align with the external field and then reconnect. A special case is the tilting mode in FRCs where reconnection with the guide field results in the total loss of the plasma. For refueling a tokamak by high-speed injection of a CT, tilting-facilitated reconnection is the desired fuel deposition process. However, direct loss on open field lines is disastrous for any scheme that uses the compact toroid as the main fusion plasma. In the approach being taken at GF with merged CTs, the absence of a guide field eliminates the risk that the main plasma can be lost directly onto open field lines. Once contained within the imploding spherical flux conserver, a spheromak or FRC plasma will only have internal modes to place confinement at risk. Despite this, when CTs come off the end of the accelerating center electrode, natural tilting is possible, and this may affect the outcome of the merging process in yet unknown ways.

When pre-merge tilting of the CTs is taken into account, there are several possible routes that the merging process might follow. We will briefly consider as an illustrative example the case of a co-helicity merge to form a spheromak target plasma, in which both incoming CTs have tilted off machine axis with a relative angle $\Delta\theta$ between their poloidal magnetic moments of $\Delta\theta \sim \pi/2$. In this case it may be possible for the system to be attracted toward a local minimum of magnetic energy such as shown in Fig. 4a with $\Delta\theta = \pi$, which may be distinct from the desired global energy minimum shown in Fig. 4b of $\Delta\theta = 0$. If the sort of genus-2 topology as in Fig. 4a persisted for significant fraction of the compression time, it may degrade confinement due to poor flux surfaces or due simply to having shortened scale lengths. However, it may be more likely that a very large $\Delta\theta$ is actually permissible and the system will always rapidly realign into the global minimum merging configuration such as Fig. 4b, which would agree qualitatively with results from tokamak injection studies.

One can also ask the question of whether or not CT re-alignment can happen faster than bulk reconnection? If there was either a very slow rate of re-alignment or a very

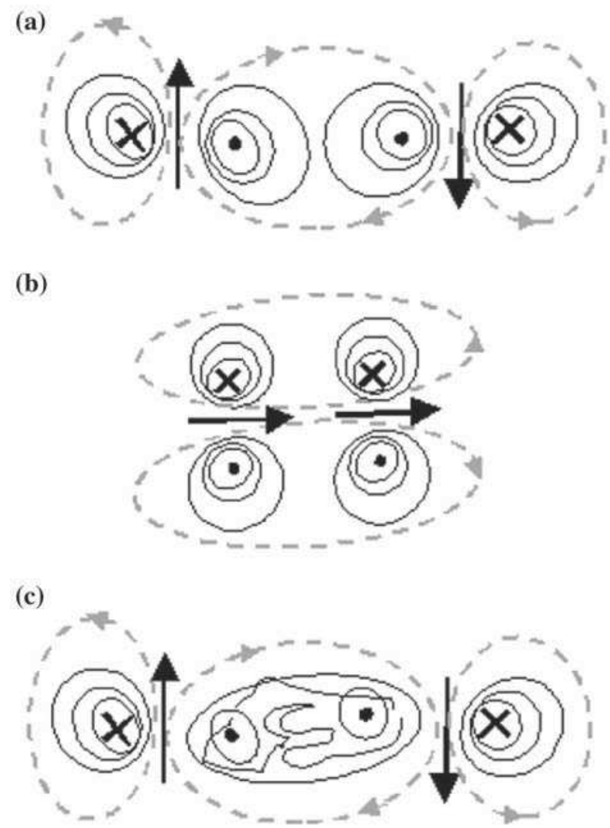


**Fig. 4** When tilting of the CTs is taken into account, there are several possible routes that the merging process might follow. As an example we show the case of co-helicity merging to form a spheromak final state. First, it may be possible for the system to be attracted toward a local minimum of magnetic energy such as shown in (**a**), which could be distinct from the desired global energy minimum shown in (**b**). In addition, it is at least hypothetically possible that the rate of realignment might be slower that the bulk reconnection of CT core, which could result in field line topology such as shown in (**c**), where flux surfaces may be broken in a highly non-axisymmetric fashion, with field lines that meander in figure-eight patterns through both CTs

rapid rate of bulk reconnection, then colliding CTs with a relative tilt angle would reconnect in a non-axisymmetric fashion localized to the region of first contact as shown in Fig. 4c. Once this happened, the field lines would meander in figure-eight patterns through both CTs and it is unclear how it would relax into an adequately stable self-confined configuration.

Although merged CT plasmas have several advantages, if it turns out that their dynamics cannot be tamed sufficiently to produce energy confinement lifetimes that are good enough for MTF, then we can always fall back to the simpler arrangement of using a single plasma source. With the current hardware for this project a single spheromak target plasma could be tested immediately. The remaining alternative would be to construct a completely different system for forming and translating an FRC into the target chamber.

The upcoming experiments with merged CTs are expected to demonstrate coaxial injector technology at a large scale, but more importantly they should provide new data for reconnection physics at the higher density that is needed to understand the dynamics and stability during MTF compression.

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