300 KM/S PLASMA ACCELERATOR FOR FUELLING

R. RAMAN*, J. THOMAS[1)], D.Q. HWANG[1)], G.D. CONWAY[2)], A. HIROSE[2)],
F. MARTIN[3)] AND P. GIERSZEWSKI

Canadian Fusion Fuels Technology Project
2700 Lakeshore Road West
Mississauga, Ontario, L5J 1K3, Canada

[1)]Department of Applied Science
University of California, Davis
Livermore California 94550

[2)]Department of Physics, University of Saskatchewan
Saskatoon, Saskatchewan, S7N 0W0, Canada

[3)]Centre Canadien de Fusion Magnétique
Varennes, Québec, J3X 1S1, Canada

*Present address: Dept. of Physics, Univ. of Saskatchewan, Saskatoon, Saskatchewan, S7N 0W0, Canada

ABSTRACT

The Compact Toroid Fueller (CTF), at the University of Saskatchewan, will inject high-speed, dense Spheromak plasmoids into the STOR-M tokamak and the Tokamak de Varennes (TdeV) to examine the feasibility of this approach as a fueller for future tokamak reactors. Compact Toroid (CT) formation and acceleration at the RACE device at the Lawrence Livermore National Laboratory has shown that CT-plasmoid velocities sufficient for center fuelling fusion reactors can be achieved by magnetized coaxial accelerators. The CTF injector will test theories on CT-tokamak interaction and fuelling by the injection of CT-plasmoids into the STOR-M and TdeV tokamaks. Among the questions to be addressed are the repetition-rate requirements for future injectors, the bootstrap current enhancement factor, CT fuel confinement times, impurity effects, plasma heating, injector electrical efficiency and gas load to the tokamak following CT injection.

1.0 INTRODUCTION

For long-pulse or steady-state operation of a tokamak, on-line fuelling is needed. Continuous fuelling by gas puffing external to the plasma is a standard technique in all tokamaks. However, this gas will not efficiently penetrate into the central core of a burning plasma, where the bulk of the fusion reaction occurs. Most of the puffed fuel would be swept away in the scrape-off layer, resulting in very low burnup rates. In fact, it is necessary to penetrate well beyond the magnetic separatrix. Although the optimal penetration depth is not yet clear, it is highly desirable to be able to penetrate to the plasma core to minimize tritium throughput, to improve startup ignition, and to provide full and flexible control of the plasma density profile. Two types of "centre fuelling" schemes exist today. These are (a) frozen pellet injection and (b) neutral beam injection. For central penetration of an ITER class reactor, frozen pellet velocities of up to 100 km/s may be needed [1]. Conventional pneumatic injectors have attained velocities of up to 3 km/s [2] while 10 km/s appears possible with advanced systems. This is still an order of magnitude less than desired. The low inertial strength of frozen pellets further exacerbates the problem by limiting the acceleration pressure and consequently requiring impractically long (length >> tokamak dimensions) acceleration sections for reactor centre fuelling. The alternate approach, neutral beams are designed for plasma heating and (while successfully used for fuelling present-day tokamaks, e.g. JET tritium shots) are too inefficient for fuelling purposes.

Recent work by Perkins [1] and Parks [3] indicates that central fuelling of reactor grade tokamak plasmas may be possible by Compact Toroid (CT) injection—specifically, by Spheromak injection. The Spheromak is a compact toroidal plasma configuration with toroidal and poloidal magnetic fields of approximately equal strength. With serious studies in the 1980's, Spheromaks were considered to have the potential for generating fusion reactor grade plasmas. The major experiments were conducted at Los

Alamos National Laboratory (LANL, CTX device) [4], Princeton University (S1 device) [5], Univ. of Maryland (MS device) [6], and at Osaka University (CTCC device) [7]. At LANL, the CTX [8] device demonstrated the formation of relatively clean Spheromaks as indicated by the electron temperature of about 70 eV, which exceeds the oxygen radiation barrier temperature. The corresponding flux confinement time was about 100 μs. At the Lawrence Livermore National Laboratory's (LLNL) Ring Accelerator Experiment (RACE) [9], Spheromak translational velocities of up to 2500 km/s have been demonstrated for low mass CT's (<< 10 μg), while velocities of about 1400 km/s have been achieved with CT's weighing about 20 μg. The net acceleration efficiency defined as CT kinetic energy divided by the initial capacitor bank energy, was ≥ 30%. CT formation efficiencies are generally ≥ 10% for an unoptimized system [10]. The overall system efficiency (unoptimized, formation plus acceleration) is ≥ 20%. The rather high efficiencies achieved in this scheme combined with the plasma parameters achieved to date, which exceeds the modest requirements for tokamak fuelling [1,3], makes this a highly desirable fuelling scheme.

Preliminary experiments by Brown and Bellan [11,12] have shown that it is possible to perturb the density and current of a tokamak by CT injection. However, in their experiment the target tokamak (Encore, major radius = 38 cm) was small in relation to the injected CT ($N_{CT} \sim 6 \times N_{tokamak}$, where N is the total particle inventory), the effect of CT impurities on the target tokamak was not studied, and they did not inject accelerated CT's into the tokamak.

The CTIX device at UC-Davis/LLNL [13] generates accelerated CT's with a mass of up to 15 μg and velocities of up to 200 km/s. The immediate goals of this program are to study the interaction dynamics of the CT with a vacuum magnetic field.

For CT fuelling to be viable, accelerated CT injection into a medium-sized, well-diagnosed tokamak ($N_{CT} \leq 0.3 \times N_{tokamak}$), with acceptable levels of impurity needs to be demonstrated. The goal of the Compact Toroid Fueller (CTF) injector is to perform such a proof-of-principle experiment at the Tokamak de Varennes (TdeV) facility (major radius = 86 cm). Initial commissioning and testing of the injector will be done on the STOR-M tokamak (major radius = 45 cm).

The main physics goals will be to determine:

(a) the maximum fuel mass that can be injected without causing a tokamak disruption. This information will be used in future injectors to determine the rep-rate requirements;

(b) the density deposition profile within the tokamak as a function of CT parameters (size, speed, field strength);

(c) CT impurity, levels and methods to limit their level, and effect of CT impurities on the tokamak;

(d) the injection of CT's with hydrogen, deuterium and helium plasmas to simulate tritium-CT injection;

(e) the particle confinement time of the CT fuel during centrally-fuelling discharges. This will be done to estimate the fuel burn up fraction that can be expected during CT-tritium fuelling of future reactors;

(f) the extent of additional plasma heating due to the substantial kinetic energy of the CT; and

(g) the extent of enhancement in bootstrap current due to CT fuelling. Since the bootstrap current is proportional to pressure gradient dp/dr, this effect would be expected to be much higher than during pellet fuelling. The density deposition profile will be determined that maximizes this effect.

The technology goals are:
(a) measure CT injection electrical efficiency;
(b) measure and minimize CT impurities; and
(c) measure and minimize residual gas loads on tokamak.

2.0 CT FORMATION AND ACCELERATION

2.1 Injector Requirements

Table I lists the representative TdeV parameters [14] and Table II is a list of the desired CT parameters. For a proof-of-principle experiment, a 5 – 30% perturbation of the TdeV particle inventory is desired. The necessary inventory of particles should be contained in a CT small enough to pass through a port on TdeV and small compared to the minor diameter of the tokamak. This limits the CT diameter to be less than 15 cm. Given these parameters for the CT mass and size, the Perkins/Parks model predicts central fuelling for CT velocities of approximately 40 to 60 cm/μs, the primary requirement being that the CT kinetic energy exceed the displaced toroidal magnetic field energy of the tokamak. In general, the temperature of the CT plasmas would be limited to about 10 eV as energy loss from these plasmas would be dominated by line radiation from trace carbon and oxygen impurities. Even if compressed to high densities, on time scales relevant to this experiment, the temperature is not expected to rise above 20 eV since less than 1% of oxygen is needed to clamp the temperature at about the oxygen radiation barrier temperature (for $n_e > 10^{15}$ cm^{-3}). However, because of the high translational velocities, the energy per ion is substantial (e.g. 2.5 kev per ion).

Table I: TdeV Machine and Plasma Parameters

Major radius (R)	86 cm
Minor radius (a)	27 cm
Plasma volume (Vol)	1.27×10^6 cm^3
Average density ($<n_e>$)	$1.85 - 7.4 \times 10^{13}$ cm^{-3}
Peak density (n_e peak)	$2.7 - 8.3 \times 10^{13}$ cm^{-3}
Particle inventory (N_{tol})	$2.3 - 94 \times 10^{18}$ particles
Toroidal field on axis (B_ϕ)	1.5 T
Electron temperature (T_e)	700 eV
Z_{eff}	1.4 – 1.5
Plasma thermal energy (E)	5 kJ
Helicity	~ 0.15 Wb^2

Table II: Desired CT Parameters

Particle inventory (N_{CT})	$2.3 - 28 \times 10^{18}$ particles
Plasma density (n_{CT})	8.3×10^{14}–1×10^{16} cm^{-3}
% fuelling (of TdeV inventory)	5 – 30%
Mass (m_{CT})	3.8 – 47 μg
Outer radius (r_{out})	7.5 cm
Inner radius (r_{in})	3.5 cm
Length (L_{CT})	20 cm
Volume (Vol_{CT})	2764 cm^3
Average magnetic field ($<B_{CT}>$)	1 T
Magnetic energy (W_{CT})	1 kJ
Translational velocity (Vel_{CT})	10 – 100 cm/μs
Plasma beta (β)	< 5%
Electron temperature ($T_{e,CT}$)	< 20 eV
Plasma thermal energy	22 – 270 J
Plasma kinetic energy	19 – 23,380 J
Equivalent energy per ion	25 – 2609 eV
Helicity	~ 10^{-5} Wb^2
Magnetic binding energy per ion	0.5 – 6 keV

2.2 The CTF Injector

Figure 1 shows the main features of the CTF injector. The injector consists of four regions. These are the formation, pre-compression, acceleration and focusing regions.

The Formation Region: This region contains the Stainless Steel (SS) 304 formation electrodes, and the Oxygen Free High Conductivity (OFHC) copper entrance region electrodes. The SS electrodes consist of two 71 cm long coaxial electrodes with diameters of about 16.8 cm (OD) for the inner electrode and 24.8 cm (ID) for the outer electrode. To the far left of these electrodes, a 22 cm diameter, 10 cm long alumina cylinder provides the electrical break between the inner and outer formation electrodes. The SS flanges on either side of the dielectric are connected to an 800 μF, 10 kV capacitor bank system with the inner electrode being the cathode and the outer electrode (the anode) being the ground. Figure 1 also shows the associated electrical schematic. Inside the inner electrode is a solenoid powered by a 3 kV, 1500 μF capacitor bank capable of generating up to 6 mWb of magnetic flux. The formation electrodes are made out of 304 SS as these need to be resistive enough to allow the solenoid flux to penetrate through them. The outer electrode has two eight inch ports. The bottom port is connected to an (Edward's) 1000 ℓ/s turbo molecular pump. The top port contains ionization and convectron gauges, as well as provisions for in-situ residual gas analysis during glow discharge cleaning. To the right of these ports are eight pulsed gas injection valves spaced equally azimuthally. The valves are powered by a 55 μF, 6 kV capacitor module. The valves (designed by the UC-Davis, CTIX group) are fast acting and provide up to 10^{19} particles per pulse per valve. The large number of valves provides a uniform gas distribution in the annulus between the electrodes on as short a time as possible. Approximately 15 cm is provided on either side of the gas valve to trap an adequate amount of particles in the CT (for high mass CT's). Since the neutral hydrogen transit time is about 0.1 cm/μs, approximately 150 μs is available from the time the gas exits the valve nozzle to when the formation gun may be discharged (to maximize trapped particles). Alternatively, to form low mass CT's, the formation gun would be discharged at the instant the gas front reaches the inner electrode (about 16 μs after the gas exits the nozzle). Further to the right of the SS electrodes is the 14 cm long OFHC copper entrance nozzle. In general, the nozzle should be flux conserving and have a length equal to a few times the inter-electrode gap distance. These attributes serve three purposes. First, they isolate the forming CT from the resistive SS electrodes. Second, they provide a flux conserving region in which the solenoidal flux can stretch and easily detach at the nozzle exit, due to a sharp jump in the inner electrode radius. Third, they isolate the solenoid flux from the acceleration flux.

CT Formation: Figure 2 outlines the steps involved in CT formation and acceleration. First, the solenoid would be energized (t = 0). This would cause the solenoidal flux to penetrate the SS electrode and create a "foot print" on both electrodes. "Foot prints" are the regions where the flux enters and leaves a surface. Around the time of peak solenoid flux (t ~ 1 ms) the gas valves would be pulsed. This causes neutral hydrogen gas to fill the annulus between the electrodes. At some time Δt past the time of gas valve trigger, the formation capacitor bank discharge would be initiated and thereby ionize the gas. The current density (J) between the electrodes coupled with the toroidal field (B_{tor}) it generates, results in a force (J × B) that accelerates the plasma toward the entrance region. The solenoidal flux (the poloidal flux) will, due to field line tension, offer resistance to the flowing plasma. If the gun current (I_g) exceeds a critical valve (I_{crit}), then the gun J ×B force exceeds the restraining tension and a CT is formed. The CT that forms in the flux conserver will decay as the internal currents are dissipated due to plasma resistivity. The estimated plasma lifetime in CTF is about 33 μs.

Once formed, the CT may be non-axisymmetric. However, since the Spheromak equilibrium in an oblate flux conserver requires it to be axisymmetric, an initially non-axisymmetric CT will relax to become axisymmetric after a relaxation period. This relaxation time is on the order of a magnetic reconnection time and is estimated to be about 3 to 7 μsec in CTF.

In order to decouple the CT formation phase from the acceleration phase, it is important that the plasma lifetime exceed the sum of the helicity injection time plus the CT relaxation time. The formation bank's first quarter cycle time in the present injector configuration is about 14 μs, so that by proper adjustment of the solenoid flux, the helicity injection phase may be limited to as low as 5 μs. Thus, in CTF, it is anticipated that the acceleration phase will be initiated about 10 – 15 μs after the helicity injection into the source chamber begins.

CT Acceleration: CT acceleration occurs in the precompression, acceleration and focusing regions of the device. The precompressor is the region that separates the formation section from the accelerator and serves two purposes. First, it allows for the formation of a relatively large Spheromak which can then be reduced to the required final size. Since the flux confinement time of these plasmoids scales as r^2, it is advantageous to form as large an initial Spheromak as possible. As the Spheromak is compressed to its final dimensions, its lifetime will correspondingly decrease. However, since the acceleration phase lasts for less than 10 μs, the compressed CT will exit the accelerator before excessive flux loss occurs. Furthermore, during the precompression phase, which may last as long as 5 μs, the magnetic energy density in the Spheromak will actually increase due to compression. Second, the precompressor allows the separation of the formation and acceleration processes and allows time for the source plasmoid to relax before acceleration. This has the advantage that, should the formation process produce a nonaxisymmetric plasmoid, the relaxed and hence accelerated CT will likely be axisymmetric. Also, since in this gun geometry the acceleration phase is independent of formation, the accelerator bank timing is less critical (as compared to dynamic formation and acceleration). This should result in a more reproducible CT.

In this injector, the precompressor reduces the inner and outer radii of the source Spheromak from 5 and 12 cm to about 3.5 and 7 cm, respectively, in the accelerator. This compression is obtained by discharging the accelerator bank across the inner formation electrode (biased positive) and the inner acceleration electrode (biased negative) as shown in Figure 1. The resulting J × B force will compress the CT against the cone of the precompressor while eddy currents in the cone wall provide the restraining force. With increasing current in the circuit, the CT is compressed until small enough to enter the accelerator region. Once in the straight accelerator, there is no restraining force and the CT accelerates very rapidly. The transit time along the one meter accelerator section is expected to be ≤ 4 μs (much less for low mass CT's).

In this injector, a final focusing section has been added. Its purpose is to allow proper interfacing with the tokamak. Here part of the CT kinetic energy is used to further compress the CT to enable it to pass unobstructed through the 6 inch gate valve that separates the injector from the TdeV tokamak.

The precompressor, accelerator and focusing regions were optimized using the TRAC code developed by J. Eddleman [15] at LLNL. TRAC is 2-D ideal MHD Lagrangian code that tracks the group motion of the CT through the different phases of precompression, acceleration and focusing. The code has shown good agreement with the results of the RACE experiment [15]. The code allows for arbitrary variation of the accelerator/precompressor geometry as well as the external circuit parameters. Based on simulations, a 100 μF, 40 kV capacitor bank with an external inductance of ~ 150 nH was chosen as the CT injector accelerator bank. TRAC simulations indicate that CT's with a mass of about 30 μg can be accelerated to velocities up to about 1000 km/sec.

3.0 IMPURITY CONTROL

An essential requirement for any fuelling device is that the injected fuel should entrain minimal levels of impurity. After considerable effort, CTX at LANL generated CT's with low levels of impurity, as indicated by the relatively high electron temperature and long plasma lifetime. This was only achieved after plasma spray coating the electrodes with tungsten, extensive glow discharge cleaning, and a "density pump-out" wait time (~ 0.1 – 0.5 ms). During this period, the CT lost sufficient mass such that the level of impurities was no longer large enough to cause the CT to be radiation dominated through oxygen (due to reduced electron density). This is because, for a coronal steady-state plasma (as would be approximately the case in CTX after ~ 100 μs), the radiated power for a given impurity fraction is directly proportional to the square of the electron density. Thus, a 50% density drop lowers the radiated power by a factor of four.

In Spheromaks used for fuelling, one cannot wait the required pump-out time since: (a) we would like to maximize the number of fuel particles in a given sized CT;

and (b) it is the actual impurity content that is of significance. Actually it is preferred if the CT were to be radiation dominated and the impurity fraction was acceptable. This is because, for a radiation-dominated plasma, the plasma temperature would be low which means that more fuel particles can be contained (due to finite β limitations). Fortunately, it is easy to meet the first condition with less than 1% oxygen being needed to clamp the temperature at the oxygen radiation barrier level (for $n_e \geq 10^{15}$ cm^{-3}). A limit on the acceptable level of impurity (if oxygen) for TdeV may be obtained, for a proof-of-principle experiment, by limiting the CT $Z_{effective}$ to be between 2 and 3. Assuming that the oxygen is fully stripped (conservative), this means that up to 2% oxygen may be contained in the CT to result in a Z_{eff} of 2 and 5% for a Z_{eff} of 3. Thus, for the present experiment, between 2 to 5% of oxygen may be an acceptable level.

While thus far in accelerated CTs the absolute impurity fraction has not been measured, in the RACE experiment the dominant impurity lines seem to be those of oxygen. In RACE, the intensities of high-Z elements are either absent or negligible in comparison to oxygen lines. One explanation offered by C. Hartman of the RACE group is that the heavy particles (tungsten, iron, etc.) are not entrained in the high velocity CT and simply fall back on to the electrode surface once the CT acquires sufficient velocity. In fact, RACE reports the collection of heavy metal dust on the electrode surface after many months of operation. The observation that CTs preferentially collect low-Z particles may be an unexpected and desirable feature of this type of CT fueller.

Impurities in the CTF injector will be controlled by plasma spray coating the electrode surfaces with low porosity (high density, ~ 95% theoretical density) tungsten followed by extensive glow discharge cleaning. While the tungsten-coated electrodes in RACE result in relatively clean plasmas (as far as high-Z elements are concerned), the RACE electrodes are somewhat porous. C. Hartman estimates the theoretical density of the tungsten coat on the RACE electrodes to be ~ 85%. This makes it difficult to form low mass CTs since the CT collects gas from the walls. Therefore high density coating should, besides producing clean CTs, allow the injector to operate in the low CT mass regime.

Finally, while oxygen appears to be the dominant impurity in single-shot injectors, it is expected to be less of a problem in multiple-pulse injectors. At a pressure of about 10^{-4} Pa, the time it takes to form an impurity monolayer on the electrode surfaces is a few seconds, therefore, for an injector rep-rated at a few Hz, there should be inadequate time for a monolayer of oxygen to form between discharges, so the electrodes should progressively clean up. However, future research is needed to investigate the specific effects of a rep-rated CT gun operation.

4.0 DIAGNOSTICS

CT Diagnostics: Accelerated CT experiments to date have not measured the absolute impurity fraction. Since this is extremely important for tokamak fuelling, in CTF, the Silicon Implantation Materials Method System (SIMMS) technique will be used for the absolute measurement of high-Z impurities. This involves the capture of a portion of the translating CT plasmoid and quantitative measurement of all the particles contained in that sample. During the initial testing phase of CTF, spectroscopic measurements in the visible region will be performed for both the formation and acceleration sections to determine the relative intensities of various impurity lines. Based on RACE results, oxygen is expected to be the dominant impurity. The spectrometer will be absolutely calibrated at a wavelength near the appropriate oxygen wavelength to determine the absolute oxygen fraction in the CT. A spectrometer (monospec 18) in conjunction with an intensified CCD (Princeton Instruments) detector array will be used for coarse survey work while a high resolution spectrometer (SPEC 1702) fitted with the same CCD detector will be used for detailed measurements of oxygen (or other) lines.

Eight, two-axis magnetic probes will be used at different azimuthal axial locations to measure the poloidal and toroidal magnetic field components on the outer electrode surfaces. These probes will also provide information on the symmetry and magnetic confinement times of the CT in the formation flux conserver. In the accelerator, they will provide the CT velocity and field decay rates during acceleration.

Also, a single-channel, two-beam Mach-Zender interferometer will be used at two-axial locations on the accelerator to determine the CT mass and velocity.

5.0 CONCLUSIONS

The CTF injector is designed to increase the TdeV particle inventory by about 5 to 30%. This will be achieved with the injection of a CT-Spheromak plasmoid travelling at a velocity of up to 1000 km/s and trapped magnetic field of about 1 Tesla in a CT volume 1 to 3 liters. The large magnetic binding energy of the Spheromak should aid in maintaining its structure during the CT-tokamak interaction phase. Plasma spray coating the electrode surfaces with dense tungsten (~ 95% theoretical density), followed by extensive glow discharge cleaning should allow the generation of relatively clean low and high mass CTs. With future rep-rated operation, this type of injector is expected to naturally clean up.

The physics studies at TdeV are expected to answer many questions in regard to CT fuelling. Among these are the rep-rate requirements of future injectors, the bootstrap current enhancement, CT fuel confinement times, impurity effects and plasma heating.

ACKNOWLEDGEMENTS

The technical assistance provided by the CTIX and RACE groups is gratefully acknowledged. In particular, we would like to thank H. McLean, J.L. Eddleman, D. Ravenscroft, C. Hartman, A. Molvik, J. Hammer. Special thanks to J. Ratzlaff and T. Jarboe for the useful technical discussions.

REFERENCES

1. HO, S.K., PERKINS, L.J. and HAMMER, J.H., Nuclear Fusion **28**, no. 8 1365 (1988).

2. HAWKE, R.S., J. Vac. Sci. Technol. A. **1**, 969 (1983).

3. PARKS, P.B., Phys. Rev. Lett. **61**, no. 12, 1364 (1988).

4. FERNANDEZ, J.C., BARNES, C.W. and JARBOE, T.R., et al. Nuclear Fusion **28**, no. 9, 1555 (1988).

5. YAMADA, M., Nuclear Fusion **25**, no. 9, 1324 (1985).

6. CHIN-FATT, C., DeSILVA, A.W. and GOLDENBAUM, G.C., et al., "The Present Status of MS", Eight CT Symp., U. of Maryland, June 1987.

7. MAGATA, M., et al., "Shear Stabilizing Experiments of Gun-Spheromak Plasmas", Proc. 10th Int. Conf. on Plasma Physics and Controlled Nuclear Fusion Research, London, September 12-19, 1984, IAEA, Vienna (1985).

8. JARBOE, T.R., HENNIS, I. and HOIDA, H.W., et al., Phys. Rev. Lett. **45**, no. 15, 1264 (1980).

9. HAMMER, J.H., HARTMAN, C.W. and EDDLEMEN, J., et al., Phys. Rev. **61**, no. 25, 2843 (1988).

10. TURNER, W.C., GOLDENBAUM, G.C. and GRANNEMAN, E.H.A., et al., Phys. Fluids **26**, 1965 (1983).

11. BROWN, M.R. and BELLAN, P.M., Phys. Fluids B **2** (6), 1306 (1990).

12. BROWN, M.R. and BELLAN, P.M., Phys. Rev. Lett. **64**, no. 18, 2144 (1990).

13. THOMAS, J.C. HWANG, D.Q., EVANS, R., HILLYER, T., ROGERS, J.H. and RAMAN, R., Bull. Amer. Phys. Soc. **36**, no. 9, 2490 (1991).

14. DÉCOSTE, R., et al., Bull. Amer. Phys. Soc. **35**, no. 9, 1947 (1990).

15. EDDLEMAN, J., HAMMER, J.H., HARTMAN, C.W., McLEAN, H.S. and MOLVIK, A.W., Bull. Amer. Phys. Soc. **35**, no. 9, 2058 (1990).

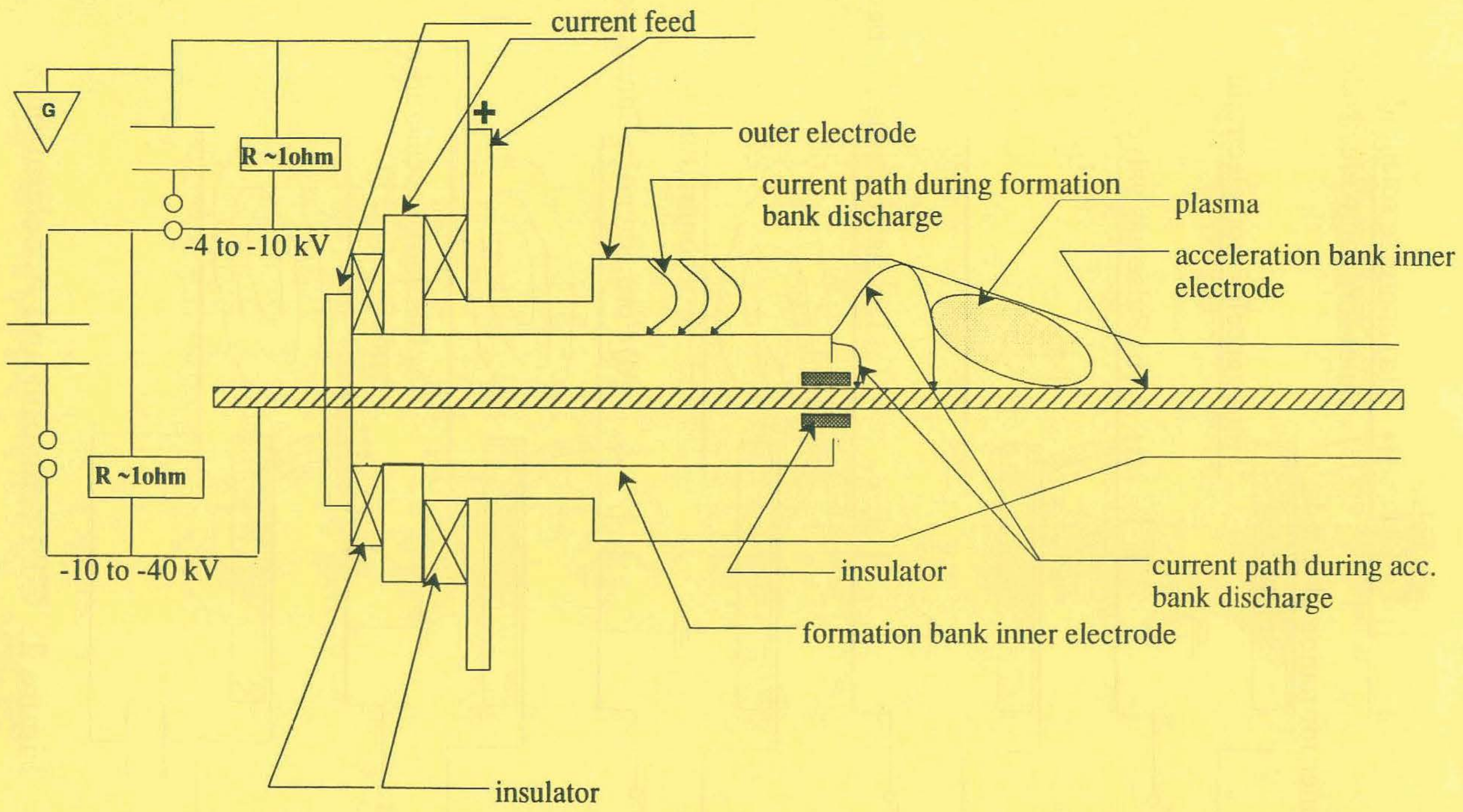

Figure 1: Main Features of the CTF Injector

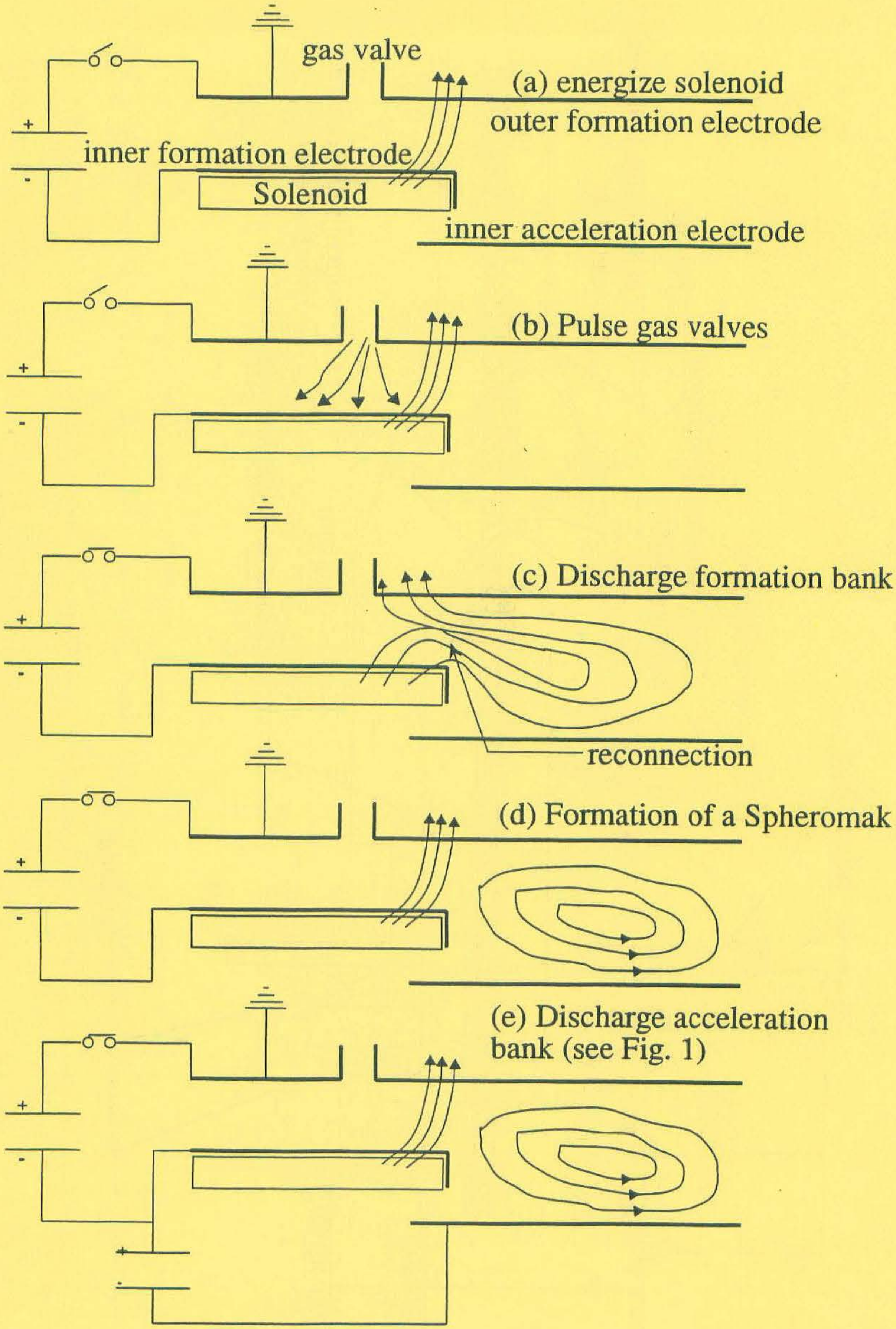

Figure 2: CT Formation and Acceleration