THE USE OF COMPACT TOROID INJECTION FOR TOKAMAK CENTRAL FUELLING AND RUNAWAY ELECTRON (RE) MITIGATION DURING DISRUPTION EVENTS

Collaboration between UC Davis and Sandia National Lab, Livermore

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1 Tokamak fuelling using high velocity compact torus (CTs)

Compact toroids (CTs) are self-organized magnetized plasmoids in a nearly force-free Taylor state. In the laboratory, CTs can be formed using coaxial electrodes and a solenoid magnetic field coil. The resultant CT equilibrium is sufficiently robust that it can withstand extremely large acceleration (> 10^9 g) and can achieve high final velocity (~ 1000 km/s) in a short distance (< 5 m) and a fast time period (< 100 μs). The final high velocity gives the CTs the kinetic energy density to penetrate the confining magnetic field of a tokamak. In other words, the penetration condition is

$$\rho_{CT} V_{CT}^2 \geq \frac{B_{tok}^2}{\mu_0}$$

where, ρ_{CT} is the CT mass density and B is the tokamak confining magnetic field. Plotting the above, the penetration condition in mass density vs. V_{CT} is given in Figure 1.

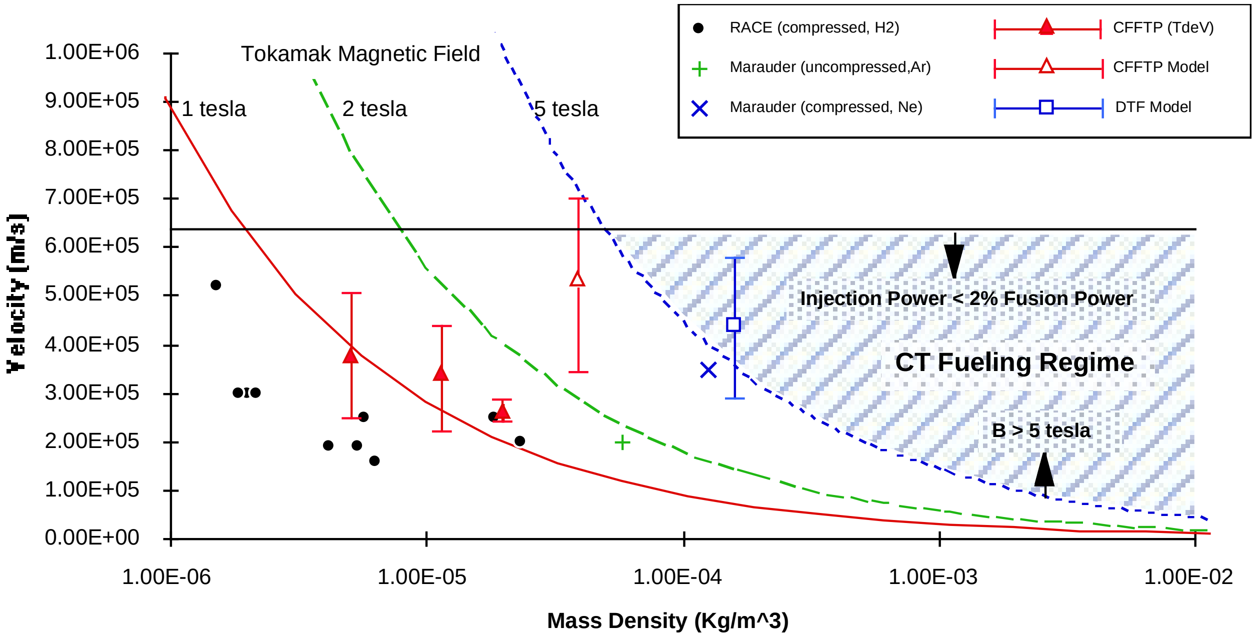
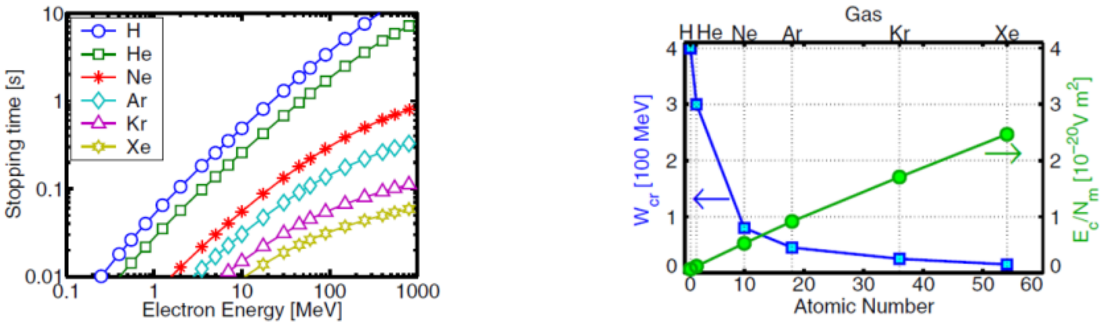


Figure 1: CT penetration into tokamak magnetic field and penetration condition. The highest achieved CT parameters, capable of reaching the center of a 5 T field, have been achieved on the USAF Marauder device.

Because injected particles in a CT are in the plasma state, the formation of the CT is not restricted to hydrogenic species. As shown in the various large accelerator experiments such as RACE and

Marauder, high-Z CTs, including CTs of noble gases, can be formed and accelerated. In addition, recent results from the CTIX experiment at UC Davis have demonstrated that non-hydrogen CTs can be produced through gas injection in the acceleration stage of the accelerator, thus opening the possible dual use of the single accelerator for the hydrogen species fueling and runaway electron mitigation using high-Z noble ion species via bremsstrahlung radiation cooling of the runway electrons as a result of a disruption event.[1] The simulated effect of high-Z ion species on the RE is shown in [1] and graphs below. Unlike gas or pellet injection, the high-velocity high-Z CTs (> 100 km/sec) offer the potential to mitigate the RE damage through bremsstrahlung cooling the RE, in addition to the collisional stopping mechanism, as described in Rosenbluth's model.[2] This mitigation technique is needed, in addition to disruption prevention methods, in the event of unforeseen component failure during tokamak operation.

The ability of an accelerated CT to reach the magnetic axis of a tokamak offers the advantage of affecting the RE production at its point of origin. In addition the formation of high-Z CTs can place the high-Z ions on the magnetic axis and bremsstrahlung cool the RE during its formation phase. Furthermore, the high speed CT allows fast mitigation of the RE and thus limiting its damage to tokamak components using the same injector that operated as a fueler.



(a) (b)

Figure 2 (from figures 3 & 4 of [1]): (a) the time it takes to cool down energetic electrons to 10 keV for different gases with density of $\boldsymbol{n}$ = 10^{20} m^{-3}. For example, for the xenon case the cool down time for RE at 100 MeV is ~ 30 msec.(b) Critical energy, $\boldsymbol{w_{cr}}$, over which the radiative stopping power of the RE is dominant over collisional stopping power and the critical electric field, $\boldsymbol{E_c}$, below which the RE population is not enhanced.

The comparison between collisional stopping of the RE (Rosenbluth density) and bremsstrahlung cooling is given in Figure 3. As shown, the cross-over RE energy between collisional and bremsstrahlung effects is at 15 MeV for Xe ions in the compact toroid. Most present medium sized tokamaks such as J-TEXT[3] have RE in this range. The noble gas compact toroids can be produced using either a noble working gas in the formation section or by injection of a noble gas in the acceleration region of the injector as demonstrated below for He. As the tokamak energy increases, the RE energy as a result of the disruption will increase allowing other noble gases to be effective in bremsstrahlung cooling. At or above 100 MeV (the expected range in ITER), Ar, Ne or even He will all be effective in bremsstrahlung cooling the RE.

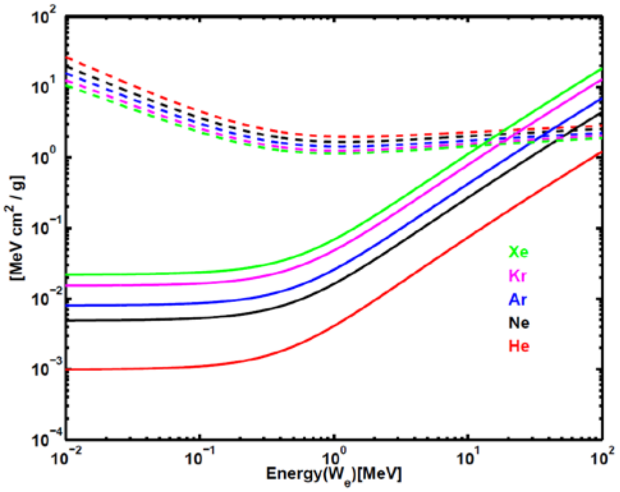
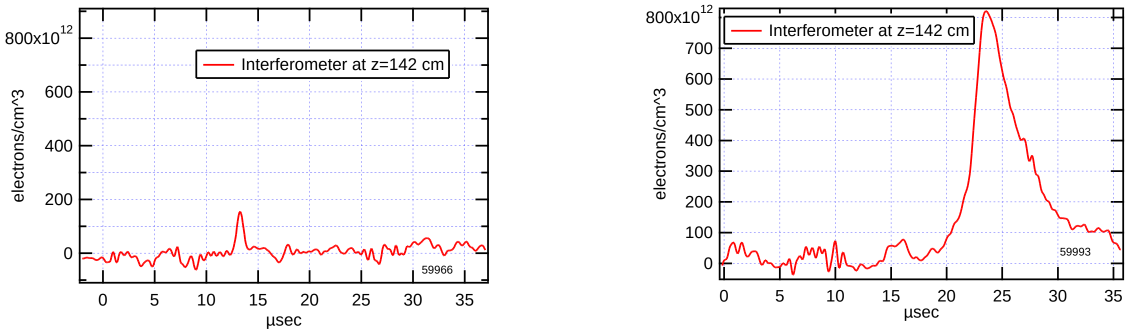


Figure 3: Comparison of stopping power of RE in various noble gas media by collisional (dashed lines) and bremsstrahlung cooling (solid lines).[1]

2 Acceleration section gas injection results on CTIX

An important technique which has been pioneered on CTIX is the use of snowplow accretion of neutral gas to increase the density and kinetic energy of CT plasmas. Using the snowplow method, an initial CT plasma of moderate density gains mass as it passes through gas puffed into the accelerator region prior to plasma formation. While the accretion and ionization of neutral gas by the moving CT builds density, the temperature and velocity of the CT are maintained by energy input from the accelerator formation bank. The snowplow method allows variable transfer of capacitor energy to CT kinetic energy, yielding higher energy efficiency. In addition, since formation can be performed with a standardized gas, typically hydrogen, snowplow accretion can performed with a wide variety of gases, depending on the application.

Figure 4 shows the results of accelerator injection experiments performed using helium as the injected gas with an initial hydrogen plasma. In this example, CT density increase of a factor of seven was obtained.



(a) (b)

Figure 4: CTIX plasma density in acceleration region (a) without gas puffing (b) with helium gas puffing.

Recently, accelerator-puffing experiments have been begun using inert gases of higher atomic number such as argon and krypton, which would be similarly employed in disruption-mitigation applications. Preliminary results demonstrate efficient accretion of relatively small Kr gas puffs (10-20%

of CT mass), and detection of Kr on downstream silicon targets by Rutherford backscattering. These experiments will continue, using gradually increasing injected-gas mass fraction, along with higher acceleration voltages to maintain CT velocity.

3 Injector material study

For CT injection to be attractive as a fueling technology, the generation of impurities from the electrode surfaces and transport into the tokamak plasma must be controlled. This can be accomplished through the careful design of the electrode surfaces, use of refractory materials, and implementation of robust conditioning techniques. The Sandia National Laboratory is collaborating with the CTIX program to document the formation and acceleration of these impurities, and eventual replacement of the electrode surfaces. We have built on our previous studies of impurity generation and acceleration in passively switched CTIX plasmas through similar measurements on the initial experiments for active switching. This study uses silicon collector probes at the exit of the accelerator to examine the impurity content, and in some cases, uses modeling to estimate the velocity of the various impurity species. Initial results from active switching demonstrate a factor of two reduction in the amount of impurities exiting CTIX under typical operating conditions (-7 kV formation and +9 kV acceleration voltage). Previous measurements have shown that these metals are not distributed throughout the CT; they exit at a lower velocity, more characteristic of the un-magnetized trailing plasma that follows the primary CT.

4 J-TEXT collaboration leading to testing of CT injection on long pulsed tokamaks

In order to introduce a new technique for RE mitigation on a major long-pulse tokamak such as EAST, K-STAR, Tore Supra, etc., testing on an intermediate-size tokamak with a full set of disruption diagnostics will be necessary to demonstrate the capability of the technique. In this regard, we have identified the J-TEXT tokamak[3] (Wuhan, China) which has been upgraded recently and has disruption and neoclassical tearing modes studies as some of its program goals. In particular, J-TEXT is equipped with the diagnostics to study the runaway electrons resulting from disruption.[4]

Of the four RE mitigation techniques, both MGI and KPI have been tested on mid-sized short-pulse tokamaks. Edge resonant magnetic field perturbation has been investigated in Textor[5] with enhanced RE loss observed. Our research has proposed an international collaboration to investigate and quantify the effects on RE by injection of a high-Z CT into a tokamak disruption on J-TEXT. The US team will design and fabricate the CT injector capable of penetration of J-TEXT parameters. The J-TEXT team will provide the tokamak operation and diagnostics of this collaboration.

In addition to the bremsstrahlung cooling, the internal magnetic field of the CT offers the possibility to perturb the axial tokamak magnetic field and local reconnection process and further suppress RE production. At the stopping location of the CT, the external tokamak field must balance the internal CT magnetic pressure, thus leading to nearly 100% magnetic perturbation. Similar edge magnetic field perturbation has demonstrated this method can spoil the RE confinement and limit the final RE energy.[5]

5 References

1. Bakhtiari, M., G.J. Kramer, M. Takechi, H. Tamai, Y. Miura, Y. Kusama, and Y. Kamada, *Role of Bremsstrahlung Radiation in Limiting the Energy of Runaway Electrons in Tokamaks.* Physical Review Letters, 2005. **94**(21): p. 215003.
2. Rosenbluth, M.N. and S.V. Putvinski, *Theory for avalanche of runaway electrons in tokamaks.* Nuclear Fusion, 1997. **37**(10): p. 1355.
3. Zhuang, G., Y. Pan, X.W. Hu, Z.J. Wang, Y.H. Ding, M. Zhang, L. Gao, X.Q. Zhang, Z.J. Yang, K.X. Yu, K.W. Gentle, H. Huang, and J.T. Team, *The reconstruction and research progress of the TEXT-U tokamak in China.* Nuclear Fusion, 2011. **51**(9): p. 094020.
4. Chen, Z.Y., Z.P. Chen, Y. Zhang, W. Jin, D. Fang, W.G. Ba, Z.J. Wang, M. Zhang, Z.J. Yang, Y.H. Ding, G. Zhuang, and J.-T. Team, *Study of the generation and suppression of runaway currents in provoked disruptions in J-TEXT.* Physics Letters A, 2012. **376**(24-25): p. 1937-1941.
5. Lehnen, M., S.A. Bozhenkov, S.S. Abdullaev, M.W. Jakubowski, and T. Team, *Suppression of runaway electrons by resonant magnetic perturbations in TEXTOR disruptions.* Physical Review Letters, 2008. **100**(25).