A PROPOSAL FOR USING COMPACT TORUS INJECTION ON TOKAMAKS FOR BOTH CENTRAL FUELING AND FOR THE MITIGATION OF RUNAWAY ELECTRONS 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 (>1 x 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

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

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.

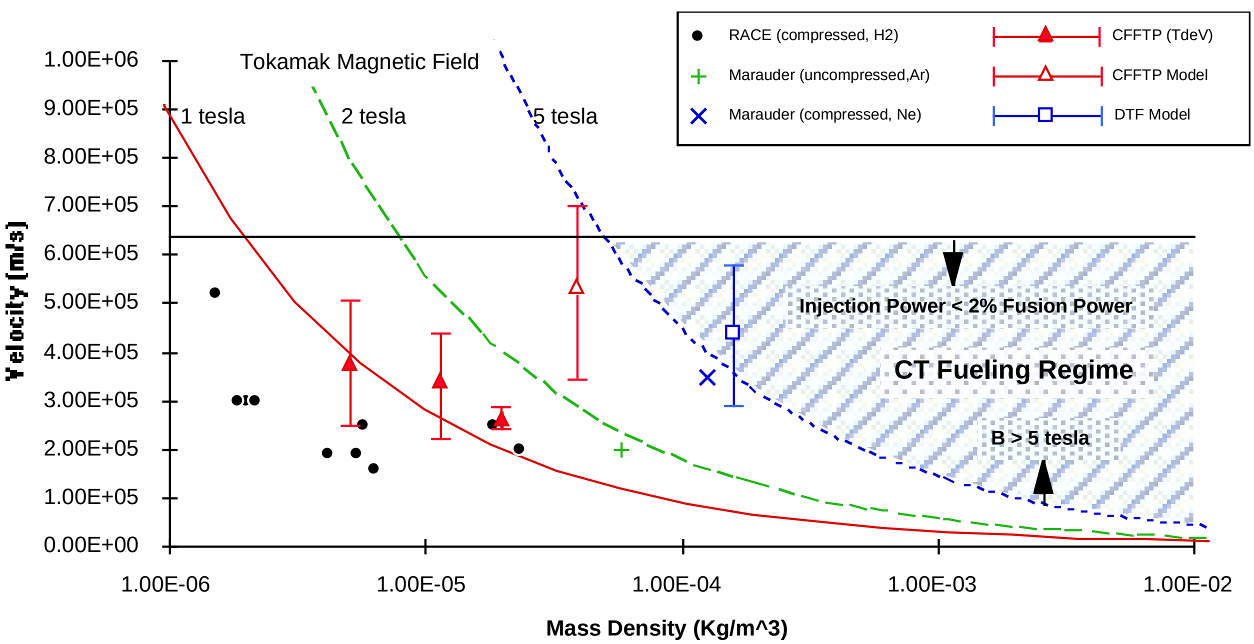
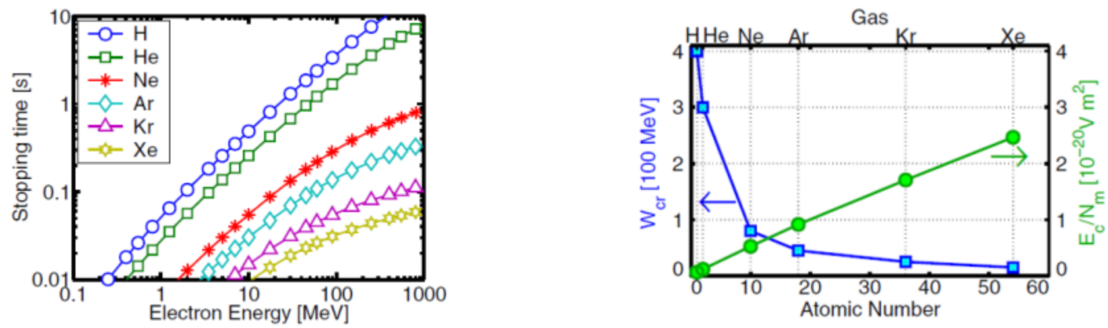


Figure 1: CT penetration into tokamak magnetic field and penetration condition. The highest achieved CT parameters, capable of reaching the center of a 5 T field, have been achieved on the USAF Marauder device.

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



(a) (b)

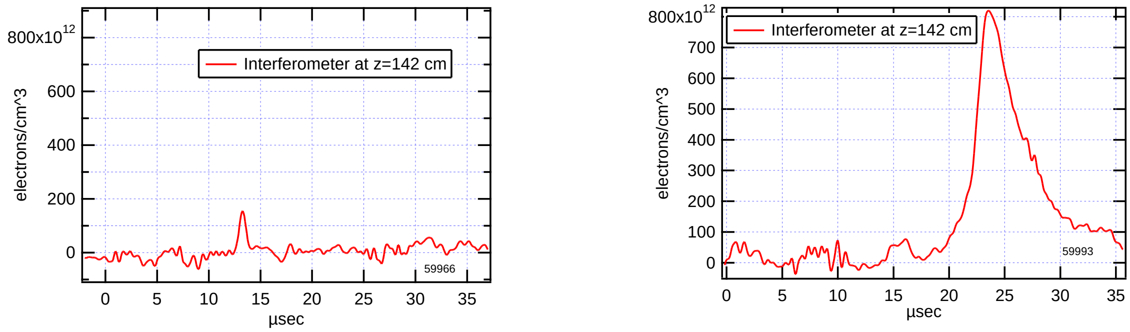
Figure 2 (from figures 3&4 of [1]): (a) the time it takes to cool down energetic electrons to 10 keV for different gases with density of $n=10^{20}$ m^{-3}. For example, for the xenon case the cool down time for RE at 100 MeV is ~ 30 msec.(b) Critical energy, w_{cr}, over which the radiative stopping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

The experimentally verified tokamak disruption sequence consists of (1) thermal quench, (2) current quench, and (3) inductive runway electron (RE) production. Due to magnetic confinement, RE energy can reach up to 100 MeV on the magnetic axis of the tokamak. Another important disruption parameter is the time scale of the event, which is in the microsecond range, much shorter than the discharge period of milliseconds to seconds. For RE mitigation, the method must have time response capable of delivering the particles to the magnetic axis in microsecond range. At the CT velocity of 1000 km/s, the high-Z CT will transverse the meter-long minor radius in much less than a millisecond.

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 3 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 3: 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, such as would be used in disruption-mitigation applications. Preliminary results presented at APS DPP 2011 demonstrated 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. Sandia is collaborating with the CTIX program to document the formation and acceleration of these impurities, and eventual replacement of the electrode surfaces. In 2011, 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 presented at the APS DPP 2011 demonstrated a factor of two reduction in the amount of impurities exiting CTIX under nominal 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 Proposed Injection 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 HL-2A tokamak which has been upgraded recently and has disruption and neoclassical tearing modes studies as some of its program goals. In addition, this facility has a full set of energetic electron x-ray diagnostics capable of measuring the RE characteristics (Figure 4).[2, 3] The proposed collaboration is to set up a RE mitigation experiment on HL-2A using high-Z compact toroid injection.

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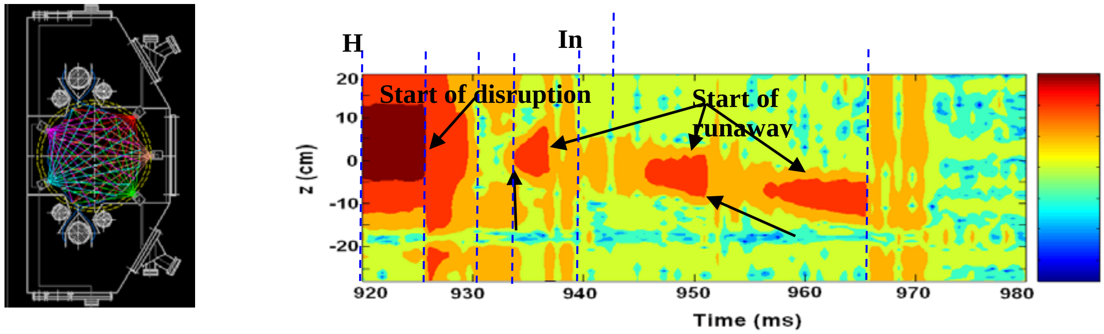

(a) (b)

Figure 4: (a) Soft x-ray camera system of HL-2A (b) sample of the RE measurement

5 References

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3. Liu, Y., *Presentation at Tsinghua University and private communication*, 2011.