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Prospects for Field-Reversed Configuration Formation & Compression on Z*

B.J. Sporer[1], S.A. Slutz[2], A.P. Shah[1], G.V. Dowhan[1], T.J. Smith[1,2], G.A. Shipley[2], N.M. Jordan[1], and R.D. McBride[1]
[1]University of Michigan
[2]Sandia National Laboratories
bsporer@umich.edu

Motivation:

Field-reversed configurations (FRCs) have emerged as an attractive plasma target for magneto-inertial fusion (MIF) with formation & compression on the multi-microsecond timescale [1] [2]. A recent analytical exploration by Slutz et al. [3] has indicated the potential for impressive fusion gain via compression of high-energy-density, centimeter-scale FRCs on the sub-microsecond timescale of the Z-machine. This could be done on a platform similar to MagLIF, using bias coils *and* an AutoMag-type [4] liner to produce the requisite field reversal. Validity of the analytic solution was confirmed with a 2D LASNEX simulation (see Fig. 1) that suggested 538 kJ of DT fusion yield with a prescribed 500 kJ of liner kinetic energy. Such kinetic energy is attainable in MagLIF experiments on Z [5], and even more energetic liners may be attainable for FRC implosions considering the larger liner dimensions and longer implosion times desired.

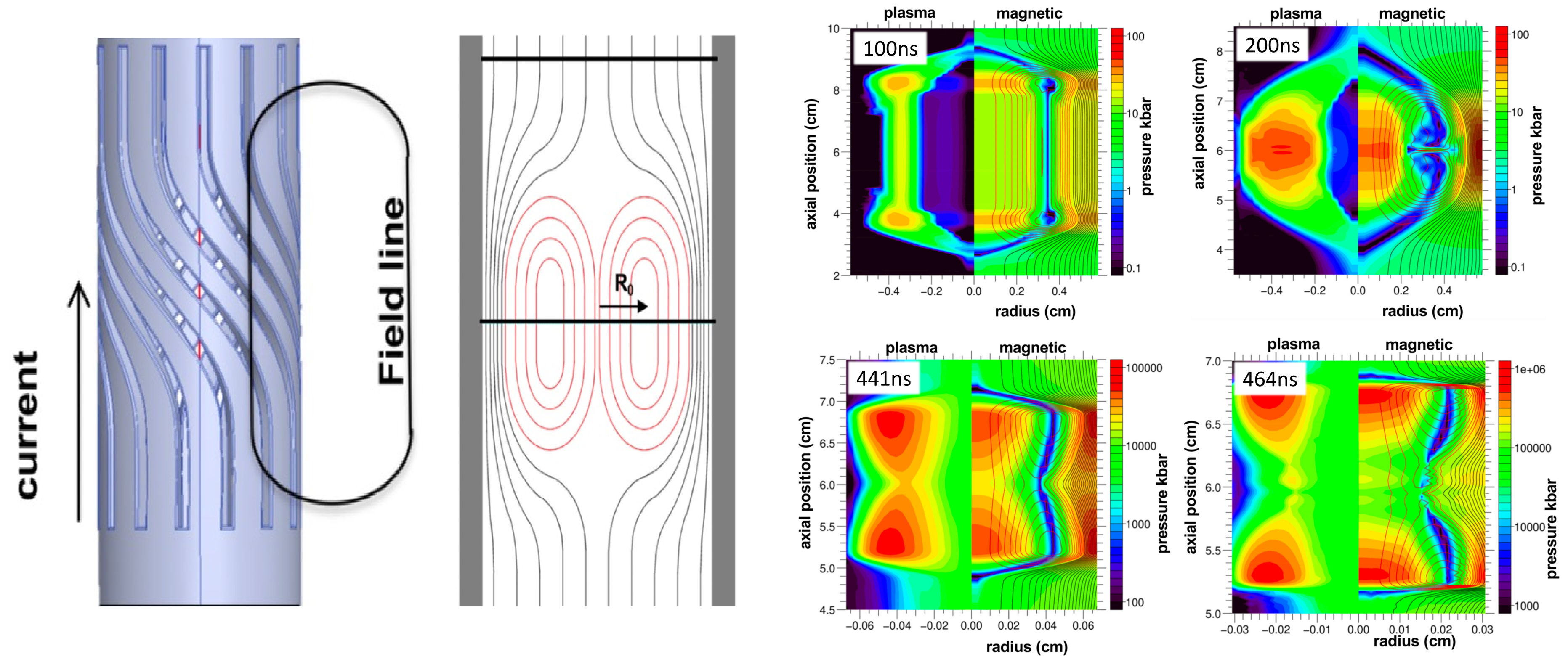

Figure 1: Plasma and magnetic pressure contours (right) from a LASNEX simulation of FRC formation & compression, as imagined in an AutoMag liner on Z (left). Reproduced from Ref. [3].

Stability and Decay of FRCs:

FRCs are known to exhibit three macro-instabilities: resistive tearing, rotational/wobble, and tilt. The former could possibly explain the bifurcation at later times in the Fig. 1 simulation, while the latter two can only be captured in 3D. It is proposed that rotational modes may be stabilized by the fringe azimuthal fields inherent to the helical AutoMag concept. Robustness to tilt instability is typically assessed by the S or S^* parameters [6] [7]. FRCs with $S^*/E > 3$ (where E is the FRC elongation) are typically tilt unstable with few exceptions [7], though it is unclear if this semi-empirical rule-of-thumb holds at this newly proposed energy density. A series of experiments to compress FRCs on Shiva Star at AFRL produced FRCs with $S^*/E \approx 2-3$, which appeared to decay resistively rather than through instability [8].

Formation Platform on MAIZE at UM:

As depicted in Fig. 2 top, a platform is being developed on the 1-MA class MAIZE linear transformer driver (LTD) at UM to study high-field FRC formation and stability. Helical load hardware is used to emulate the fields of an AutoMag liner. Pre-ionization (PI) is provided by an axial discharge between two electrodes at the ends of the quartz tube containing deuterium gas. If (and only if) both bias field and PI are applied, ring-like structures can be seen forming in axial fast-framing images (Fig. 2 bottom & Fig. 3 left). We suspect these are rudimentary FRCs, and we are developing excluded flux B-dot diagnostics to further characterize the plasma structure. Some preliminary excluded flux results are shown in Fig. 3.

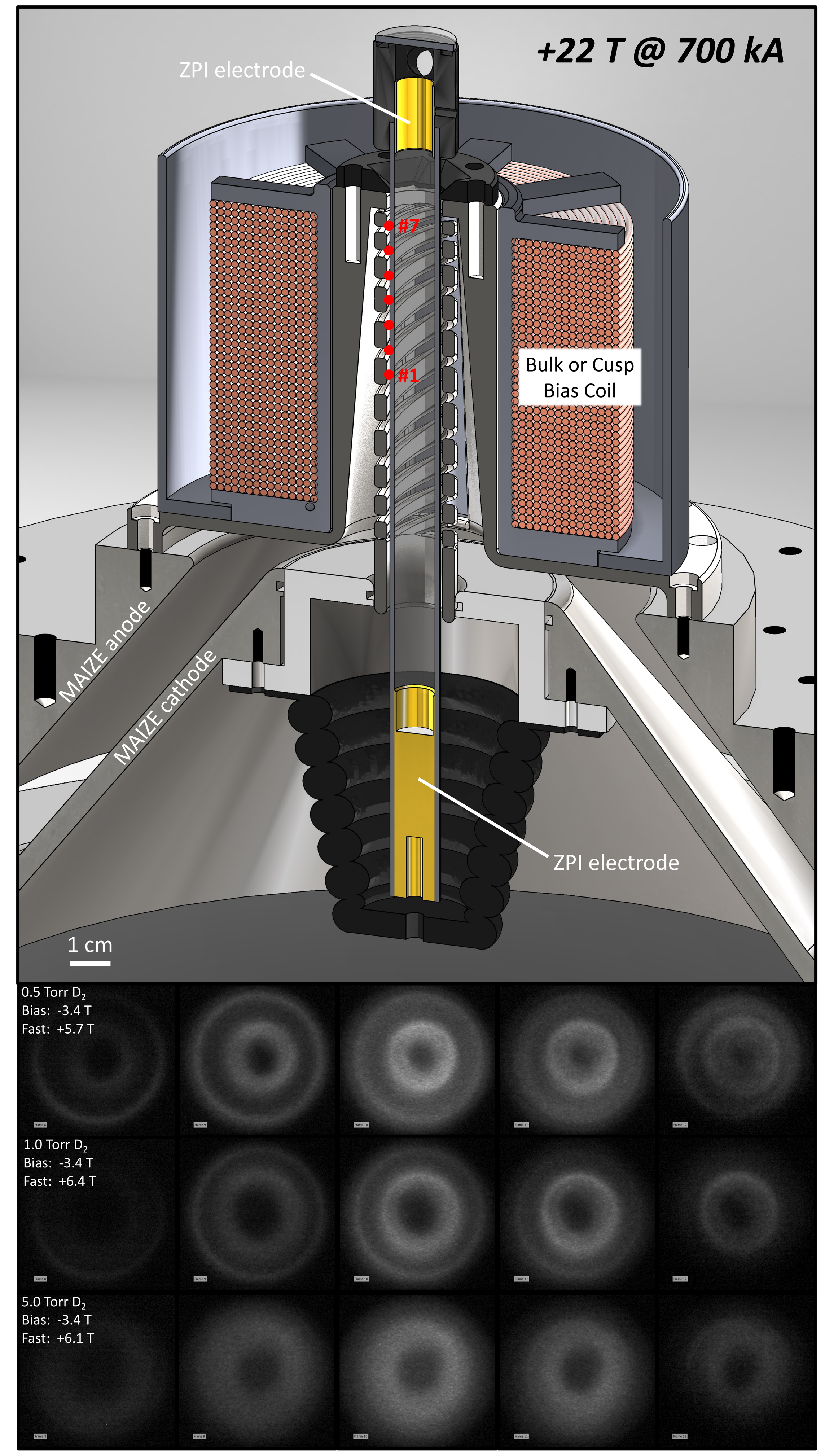

Figure 2: High-field FRC formation platform on MAIZE (top). Axial locations of excluded flux B-dots are marked. FRC-looking objects (bottom) have been imaged on this platform at 200 kA.

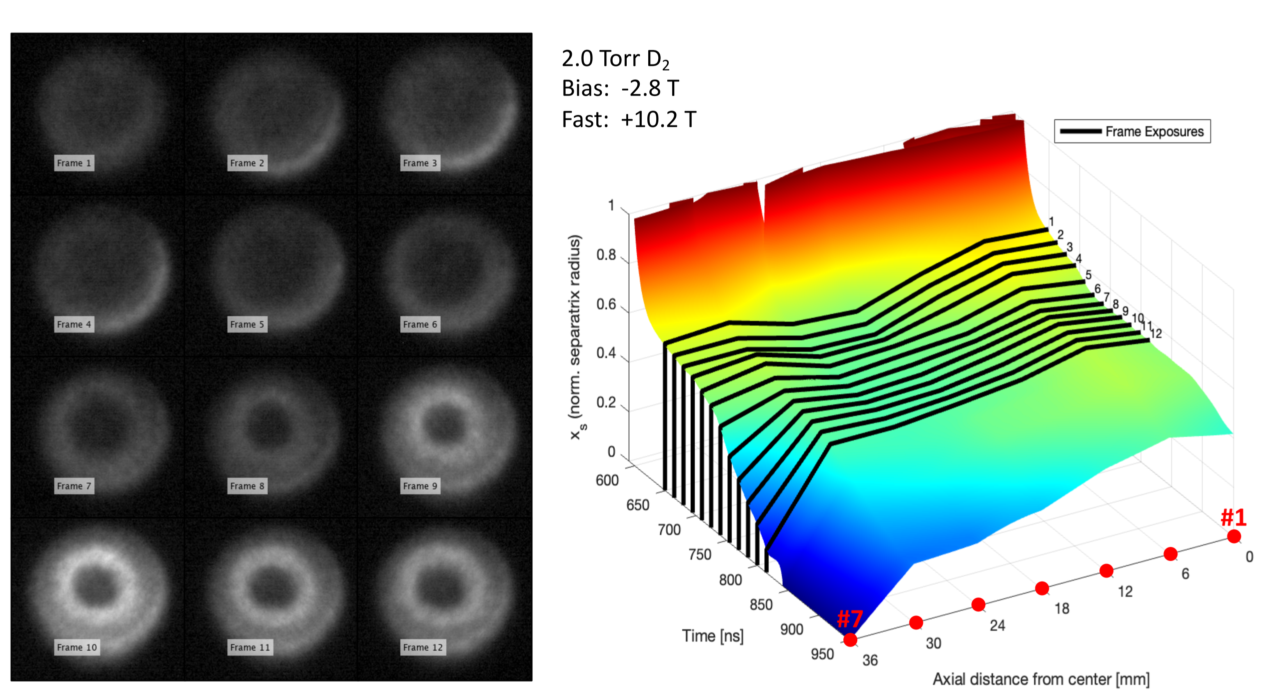

Figure 3: Normalized separatrix/excluded flux radius x_s calculated from B-dot signals (see Fig. 2 top for B-dot locations) as a function of space and time (right), along with fast framing images from the shot (left). This shot seems to show signatures of FRC axial contraction.

Z-discharge Pre-Ionization (ZPI):

An advantage over traditional MagLIF, plasma pre-heat of an FRC is provided by field reconnection and self-compression during the formation phase. But an external source of pre-ionization is still needed for efficient retention of the bias field in the plasma during field reversal. Back-of-the-envelope calculations show a temperature of at least a few electron-volts is desired. Due to machine-related constraints, efforts on MAIZE have used Z-discharge PI, in which an axial current is passed through the gas just prior to field reversal. A ZPI pulser storing 75 J at 25 kV was constructed for this purpose. A typical ZPI voltage & current trace is shown in Fig. 4. Spectra have been taken at various times throughout the pulse and at various D_2 fill pressures in an attempt to characterize ZPI plasma temperature. I am working to reproduce the observed spectra using the NIST LIBS database. The gas fill system will also be modified in future campaigns to improve purity.

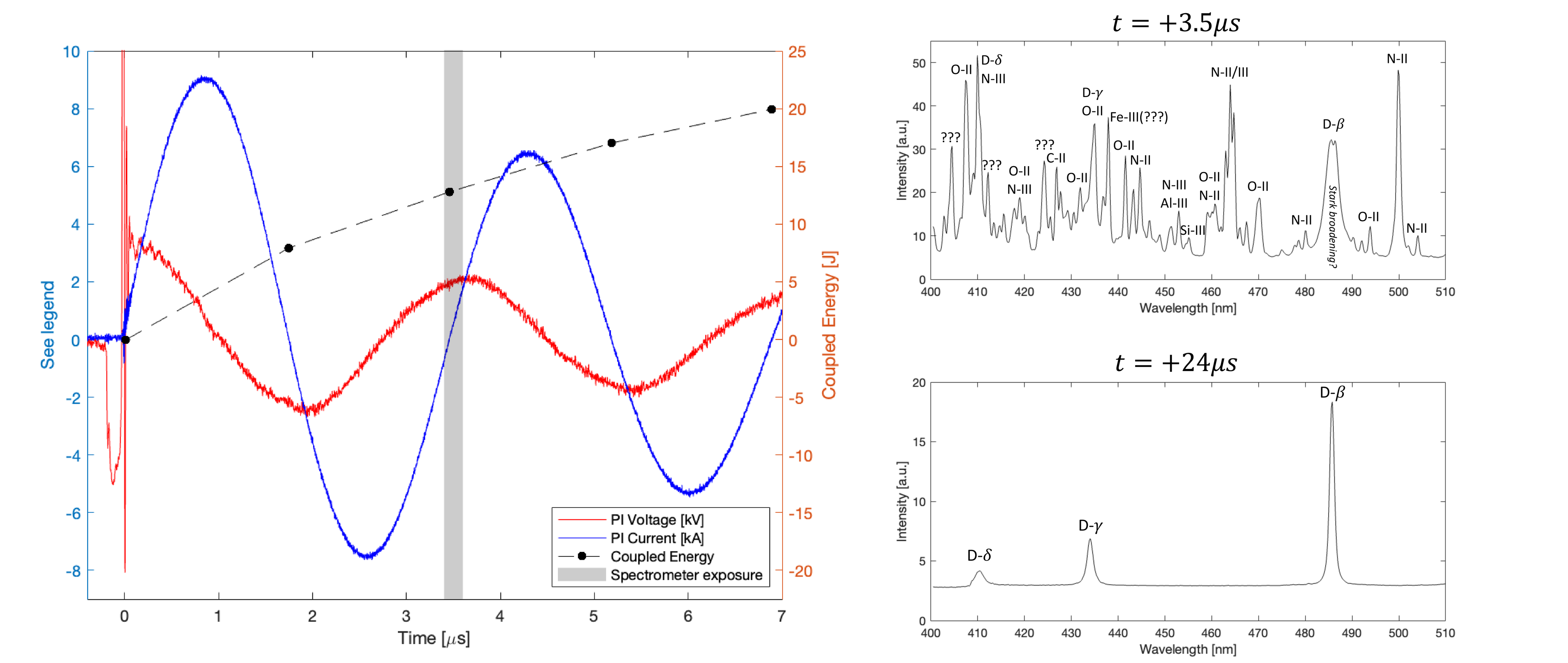

Figure 4: ZPI voltage & current trace into a 1 Torr D_2 gas fill. Also shown are two spectra, one taken at the second zero-current of the pulse (when MAIZE is typically fired), and another taken much later, when ZPI oscillations have died down.

Simulation Plans:

FRCs present a unique challenge for simulation. Kinetic/viscous effects, charge separation, anomalous resistivity, and 3D effects all play an important role in FRC formation, stability, and decay. We have considered HYDRA, GORGON, PERSEUS, and CHICAGO to simulate various aspects of these high-energy-density FRCs. Hall physics in PERSEUS may allow resolution of anomalous resistivity and charge separation from first principles. CHICAGO may allow inclusion of kinetic stabilization effects, as well as be appropriate for gas breakdown physics in the ZPI stage. I am beginning with simple 2D equilibrium studies in GORGON, using an input developed by Chris Jennings at Sandia.

References:

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