Characterization of Plasma Stability during MTF Compression

An INFUSE-supported collaboration between PPPL & General Fusion

Aaron Froese, General Fusion
INFUSE Workshop February 27-28, 2024
Princeton, New Jersey

generalfusion PPPL INFUSE

GENERAL FUSION OVERVIEW

FOUNDED IN
2002

Headquartered in
Vancouver, Canada

155
employees

147
patents

26
Ph.D.'s

15
plasma
compressions

Research Strategy

Pursue the fastest, lowest risk path to commercial fusion via Magnetized Target Fusion (MTF)

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PI3 Coaxial
Helicity Injector

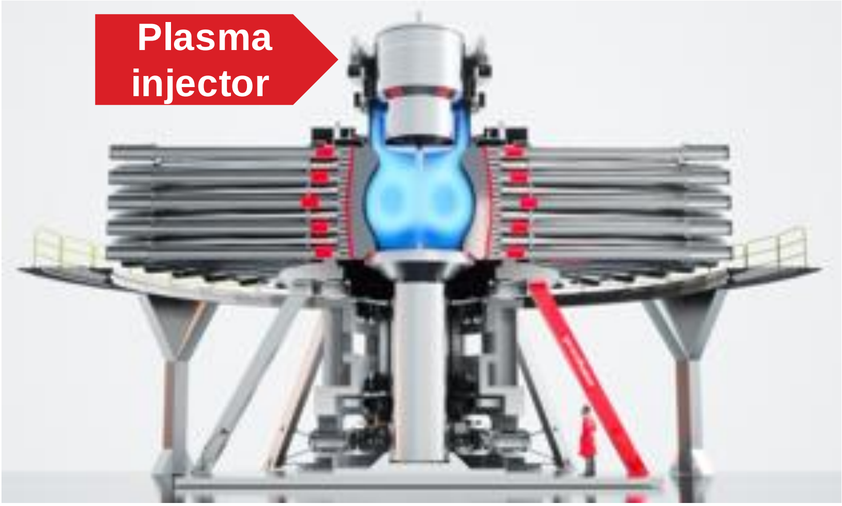
Magnetized Target Fusion

General Fusion's Fusion Demonstration Plant Concept

Compression system

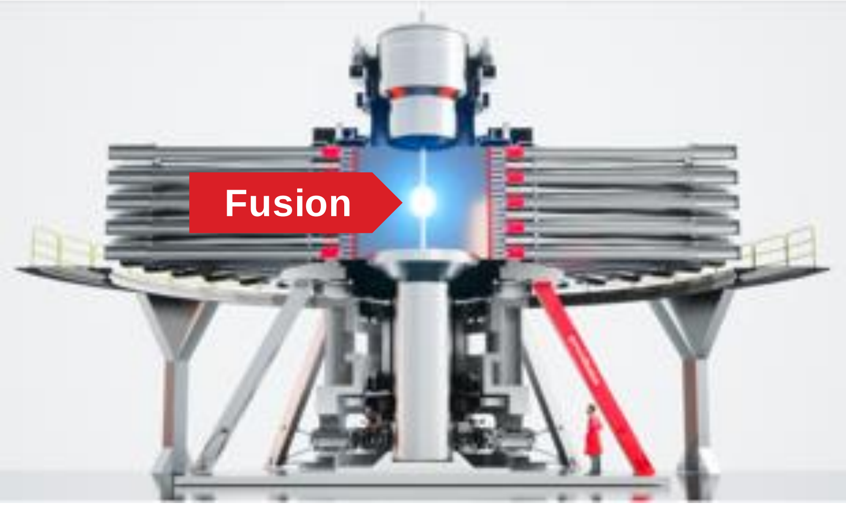
Create a vacuum cavity surrounded by liquid lithium and compress it with pistons

Plasma injection



Inject an MHD stable magnetized plasma toroid into the collapsing cavity

Plasma compression



Compress the plasma with the liquid lithium faster than the energy confinement time

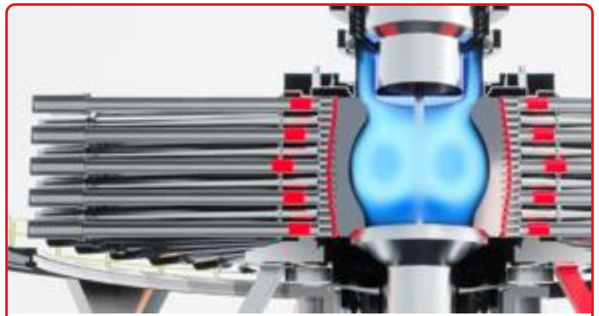
Source: https://www.youtube.com/watch?v=R1FnYiV8qzo

Advantages of General Fusion's Magnetized Target Fusion Concept

Neutron Shielding

Lithium liner protects structural components from fusion neutron damage

✓ **Power Plant Longevity**



Fuel Production

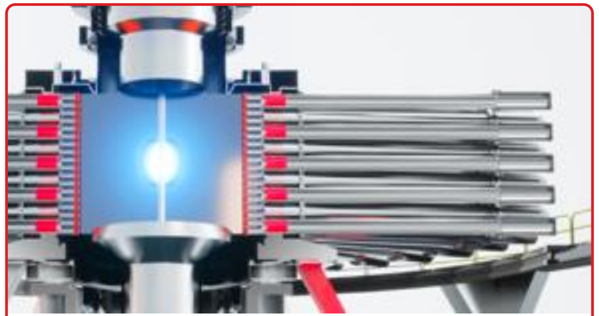
Lithium liner with 4π coverage breeds enough tritium to be self-sufficient

✓ **Affordable Fuel Supply**

Electricity Production

Lithium must be pumped to create cavity. Flow can easily be directed through a heat exchanger to extract fusion heat.

✓ **Industrialized Process**



Cost-Effective Drivers

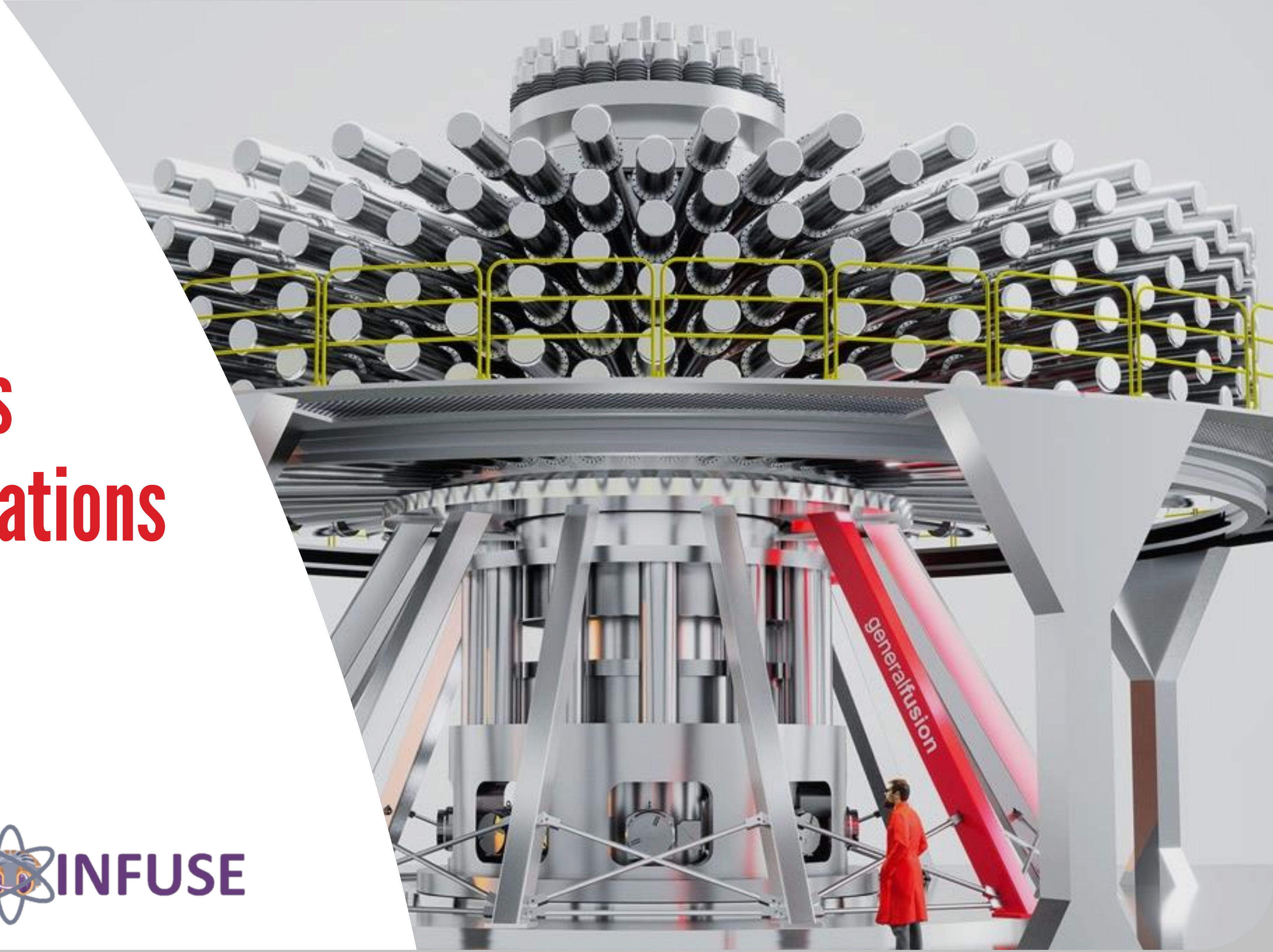
Most energy input is from inexpensive piston drivers, avoiding high-power lasers or large superconducting magnets

✓ **Competitive Plant Capex**

Magnetized Target Fusion (MTF) with liquid metal walls addresses the four major long-standing barriers to commercial fusion

Source: National Academy of Sciences: *Bringing Fusion to the U.S. Grid*, Roland Berger and Management estimates.

General Fusion's INFUSE Collaborations



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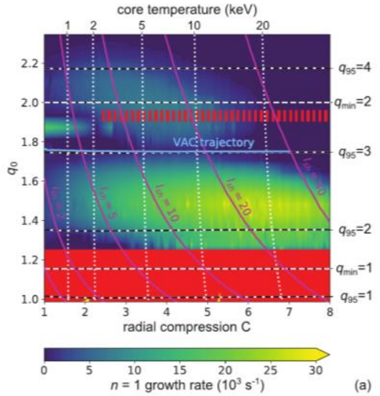
INFUSE

Summary of Past and Active INFUSE Projects

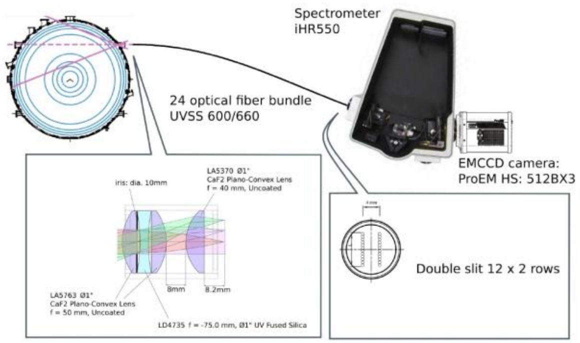


Advanced Stability Analysis - Complete

Apply advanced computational stability analyses to model equilibrium states representing the Fusion Demonstration Plant (FDP)

Effects of plasma rotation on stability are studied using the NIMROD, M3D-C1, and NIMROD codes under development at Princeton Plasma Physics Laboratory

Princeton Plasma Physics Lab

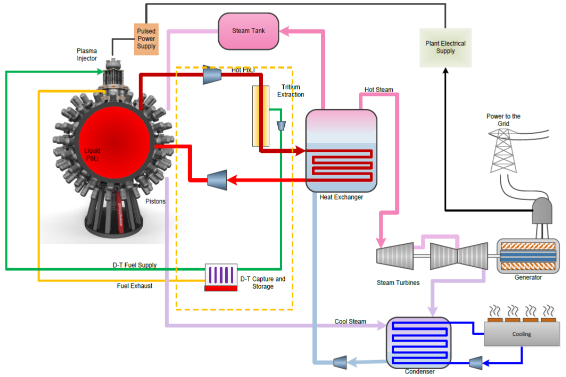


Ion Temperature Diagnostic Improvement

Improve ion temperature measurements on lab-scale devices and develop expertise and technology for ion temperature measurements in future plasma systems.

Characterize the ion temperature of uncompressed plasmas to inform the design of the Fusion Demonstration Plant (FDP)

Oak Ridge National Lab

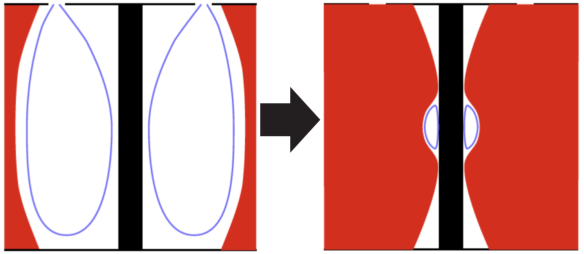


Tritium Fuel Cycle Modelling

Model the total inventory of tritium in General Fusion's future Commercial Pilot Plant (CPP).

Understanding tritium inventory is a necessary step to design, license, construct, and operate larger and increasingly integrated fusion machines.

Savannah River National Lab



Kinetic Monte Carlo MHD Simulation

A model of the MTF plasma must be able to handle continually varying geometry and, to be predictive, it must faithfully include the real imperfections arising in the process.

Develop the ability to accurately run MHD models considering long-mean-free-path effects with asymmetry on the order of 10%

Oak Ridge National Lab

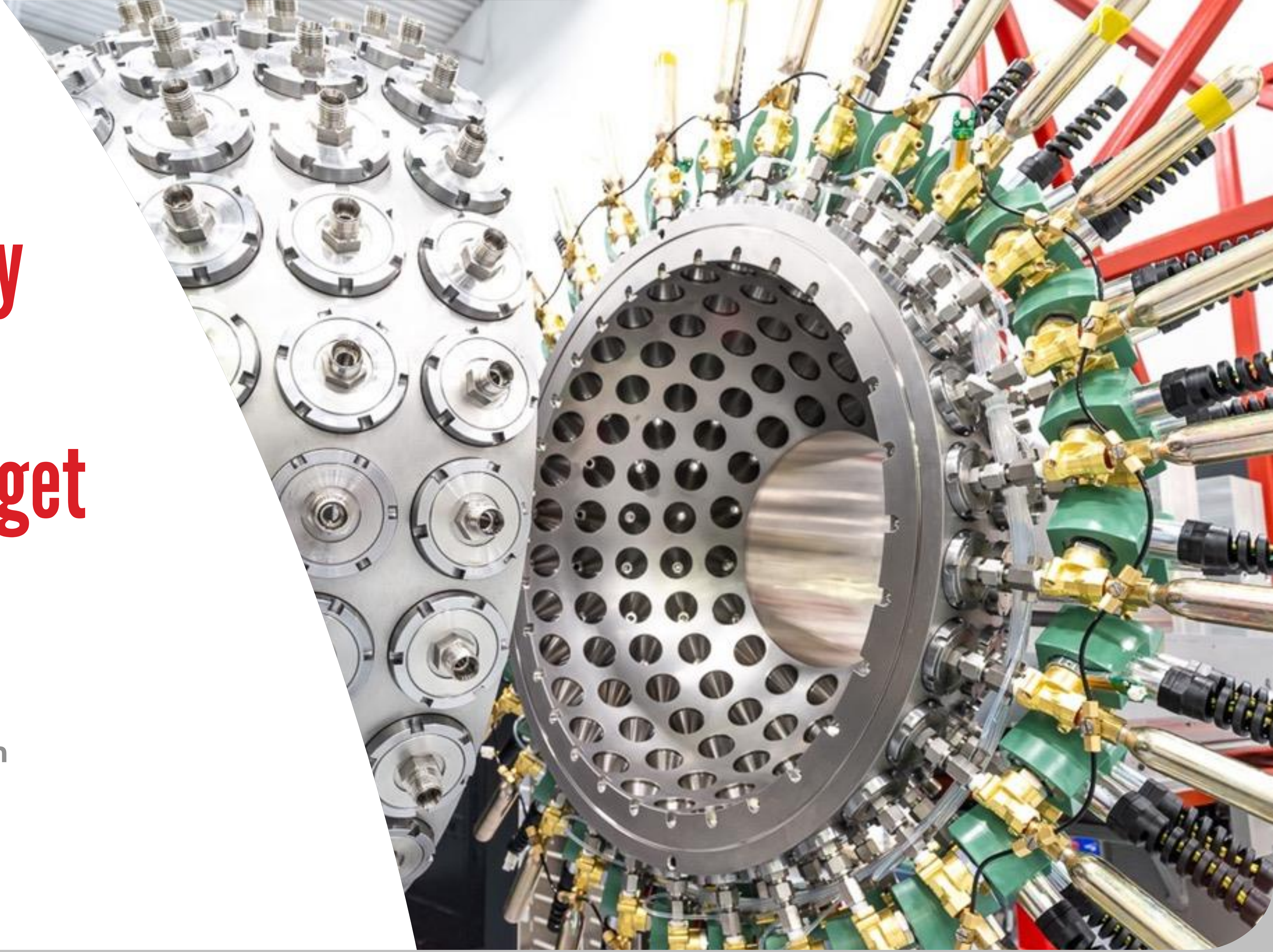
General Fusion benefits from INFUSE projects in a wide range of technical subjects

Our Tips for Success with INFUSE

- The award period is short (typically 1 year).
  - Ensure the proposed research is self-contained and achievable in the given time frame.
  - Ensure you are ready to start the work as soon as the CRADA is complete.
  - Select a PI that will have time to devote to the project.
  - The company needs and PI interests should align as much as possible.
- On the time scale of start-up companies, it takes a long time for the CRADA to be approved.
  - We waited about 1 year for each of our CRADAs.
  - Ensure other parts of the project are not impeded by the wait.
  - Where possible, partner with groups rather than individual PIs. (This applies to both the company and laboratory sides.)
- Plan for potential publications and associated costs
- Build on your new capabilities and relationships

Plasma Stability Analysis for Magnetized Target Fusion

Aaron Froese, General Fusion
Chang Liu, PPPL
Dylan Brennan, General Fusion



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Stability Analysis Methods and Geometry

Method

MTF compression scenarios are approximated as a series of quasi-static Grad-Shafranov equilibria

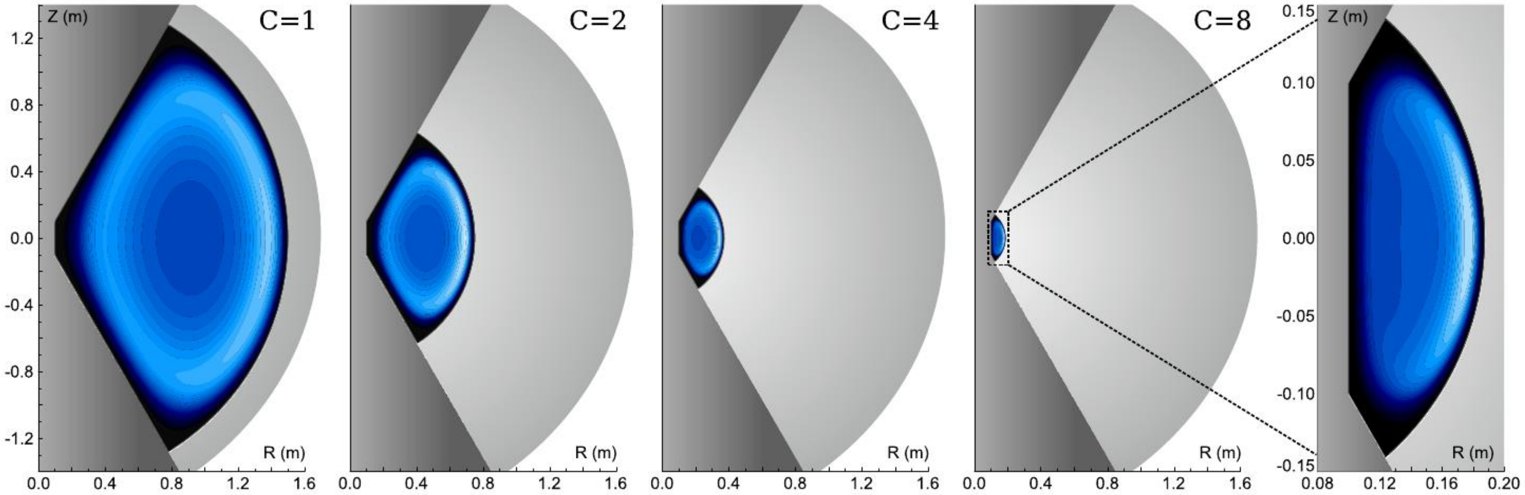
The safety factor profile, entropy density profile, and angular momentum profile are conserved.

The stability of each equilibrium is analyzed with multiple codes for validation.

Linear analysis is done with GPEC (RDCON & RMATCH).

Nonlinear MHD simulations are performed with NIMROD and M3D-C1.

Compression Geometry



CORSICA equilibria showing compression of plasma by converging liquid metal flow. Contours indicated normalized parallel density, $J_{||}/B$. Light gray is liquid metal, dark gray is solid metal

Linear Stability Analysis Using GPEC

PI: Aaron Froese

Linear analysis is faster than MHD simulations and allows us to explore the parameter space quickly.

RDCON (A.H. Glasser. Phys. Plasmas, 23:072505, 2016)

A linear layer model is evaluated with Resistive DCON. It can identify:

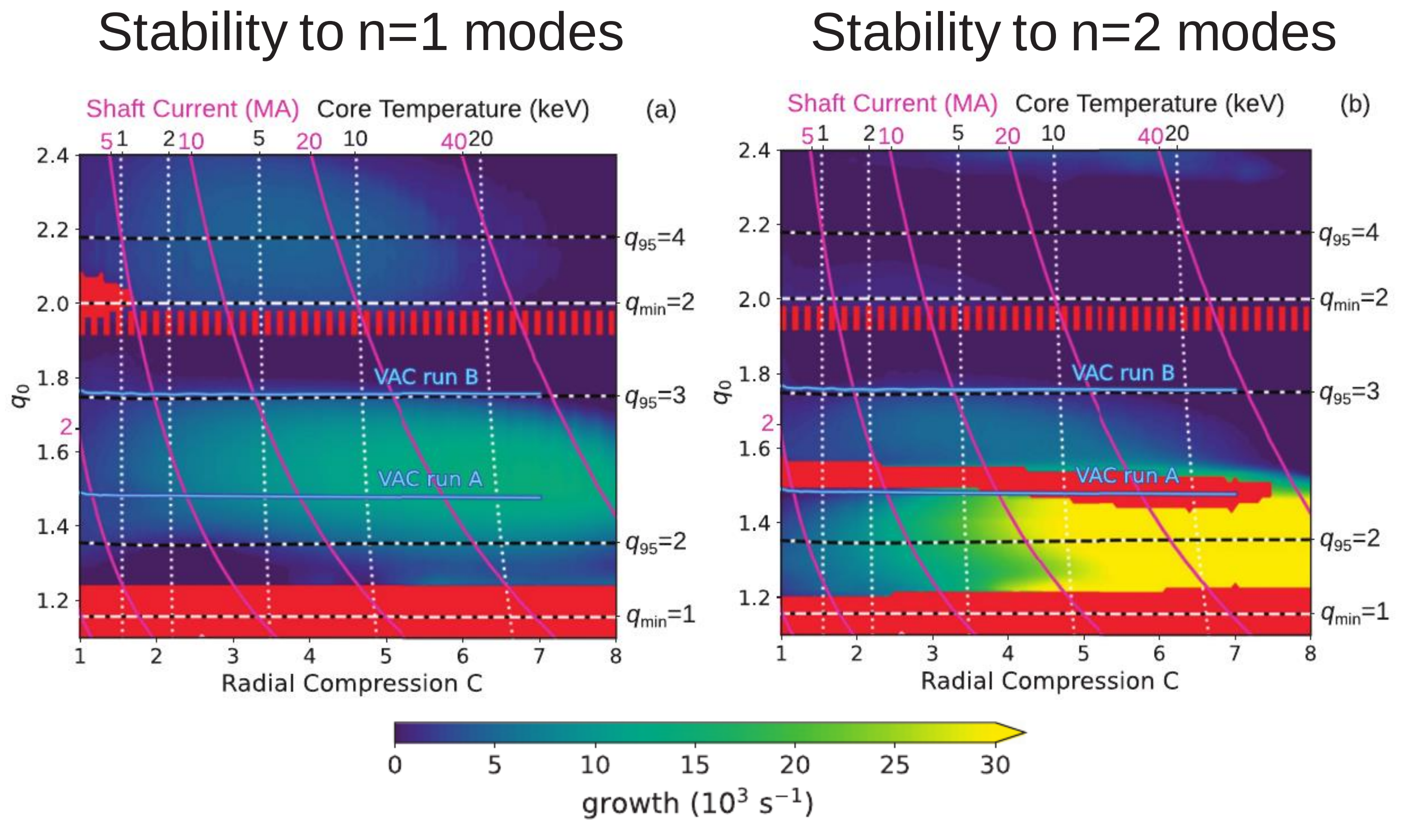
- Mercier stability
- Ballooning stability
- ideal MHD stability
- resistive tearing and interchange stability

RMATCH (Glasser, Wang, Park, Phys. Plasmas, 23:112506, 2016)

- global resistive growth rates
- effects of toroidal rotation

Cole06_EFP (Cole, Fitzpatrick, Phys. Plasmas 13:032503, 2006)

- error field penetration



Source: D. Brennan, et al. 2020 Nucl. Fusion **60** 046027

Stability results from an RDCON analysis of an LM26-style geometry. Red indicates ideal instability, green/yellow is resistive instability, dark blue is stable.

Contact Aaron Froese: aaron.froese@generalfusion.com

Soft Beta Limits with M3D-C1

PI: Chang Liu

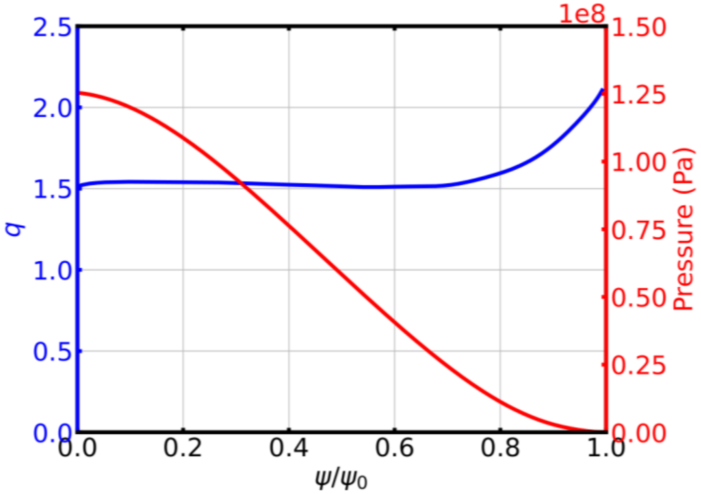
Linear simulations

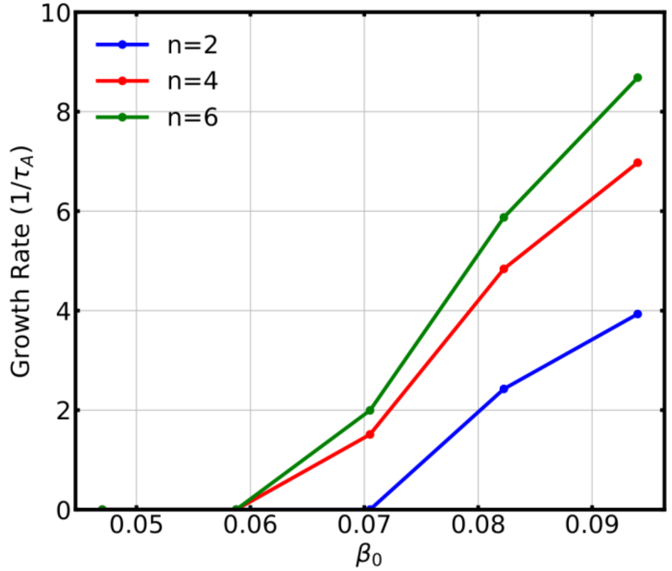
Pressure-driven MHD modes in MTF can lead to crash of core temperature

Pressure-driven MHD modes in NSTX can be excited in high-beta cases, which lead to strong thermal transport and limit the core temperature (Jardin PRL 2021).

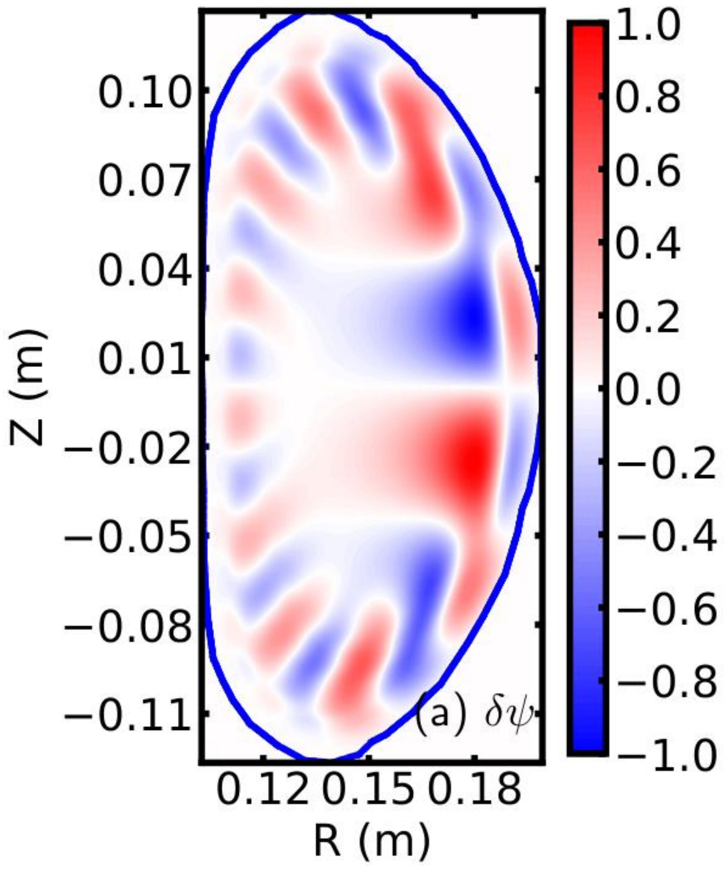
For a highly compressed MTF plasma (C=8), we tested multiple pressures with linear M3D-C1 simulations.

For core beta $\beta_0 > 6\%$, n=4 and n=6 interchange modes appeared.





m/n=9/6 Interchange Mode Structure



Source: CRADA 2707 Final Report

M3D-C1 identifies several unstable interchange modes for a highly compressed (C=8) plasma where core beta > 6%.

generalfusion

Contact Chang Liu: cliu@pppl.gov

Soft Beta Limits with M3D-C1

PI: Chang Liu

Nonlinear simulations

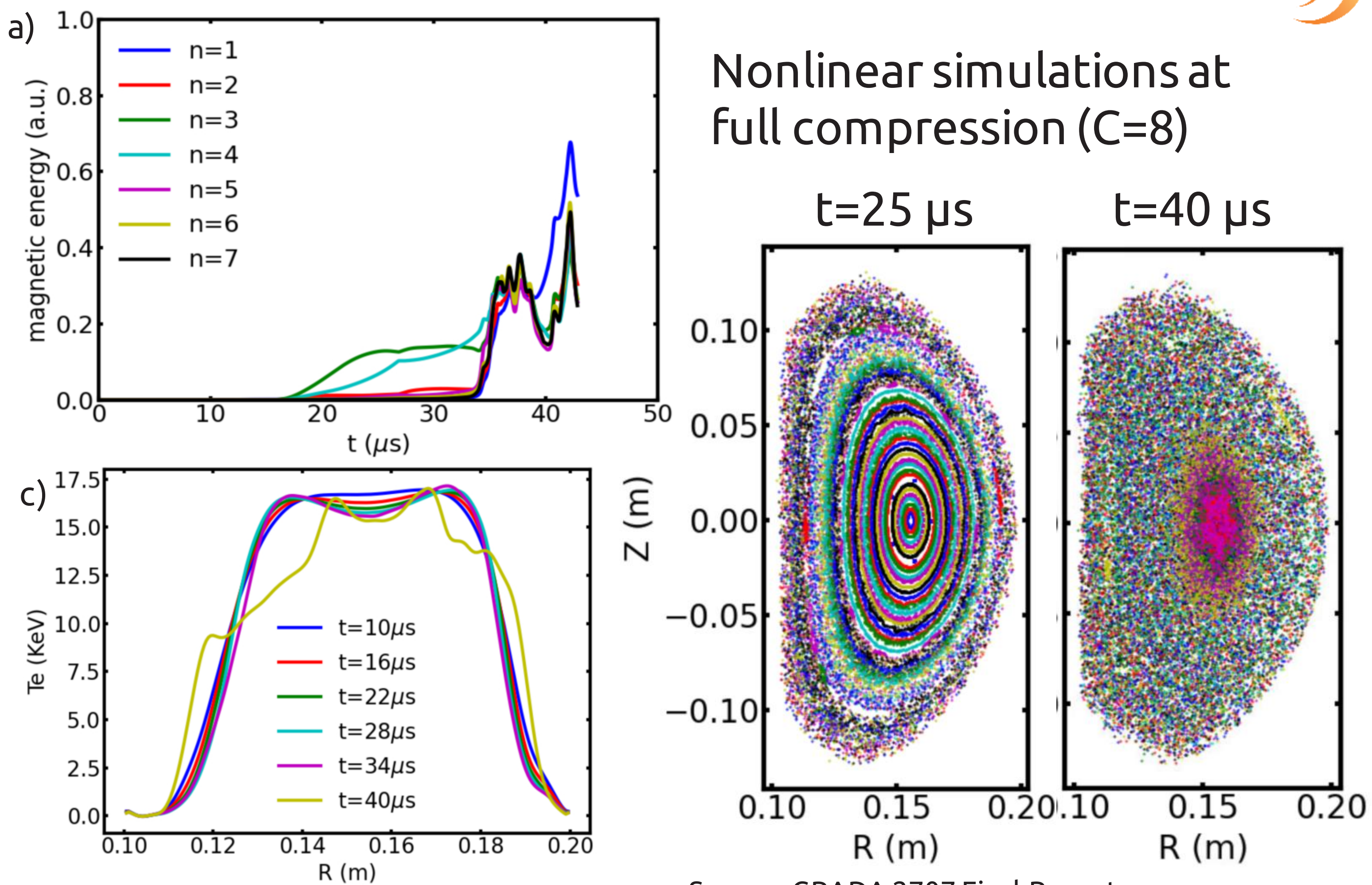
In M3D-C1 nonlinear simulations with core $\beta_0 = 0.2$, there were two stages of MHD mode excitation.

Stage 1 (before 35 μs)

- n=3,4 modes are excited and reach initial saturation, breaking the flux surfaces in the outer region.
- The temperature profile experiences minimal change.

Stage 2 (after 35 μs)

- All modes are excited and most flux surfaces are disrupted.
- Thermal transport is extreme and the temperature profile begins to collapse.



Nonlinear simulations at full compression (C=8)

Source: CRADA 2707 Final Report

a) Evolution of MHD mode energy from M3D-C1 nonlinear simulation
b) Magnetic flux surface breakdown at t = 25 μs and 40 μs
c) Plasma temperature profile evolution in M3D-C1 simulation

Contact Chang Liu: cliu@pppl.gov

Error Field Penetration with NIMROD

PI: Dylan Brennan

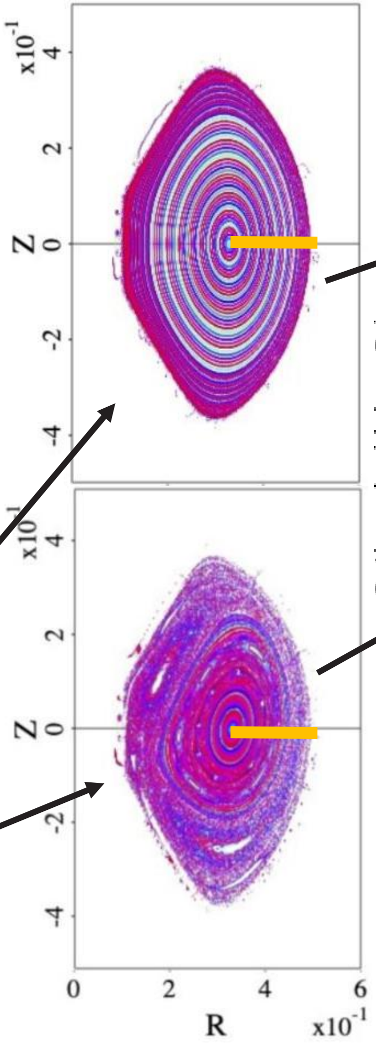
Deformation of the boundary

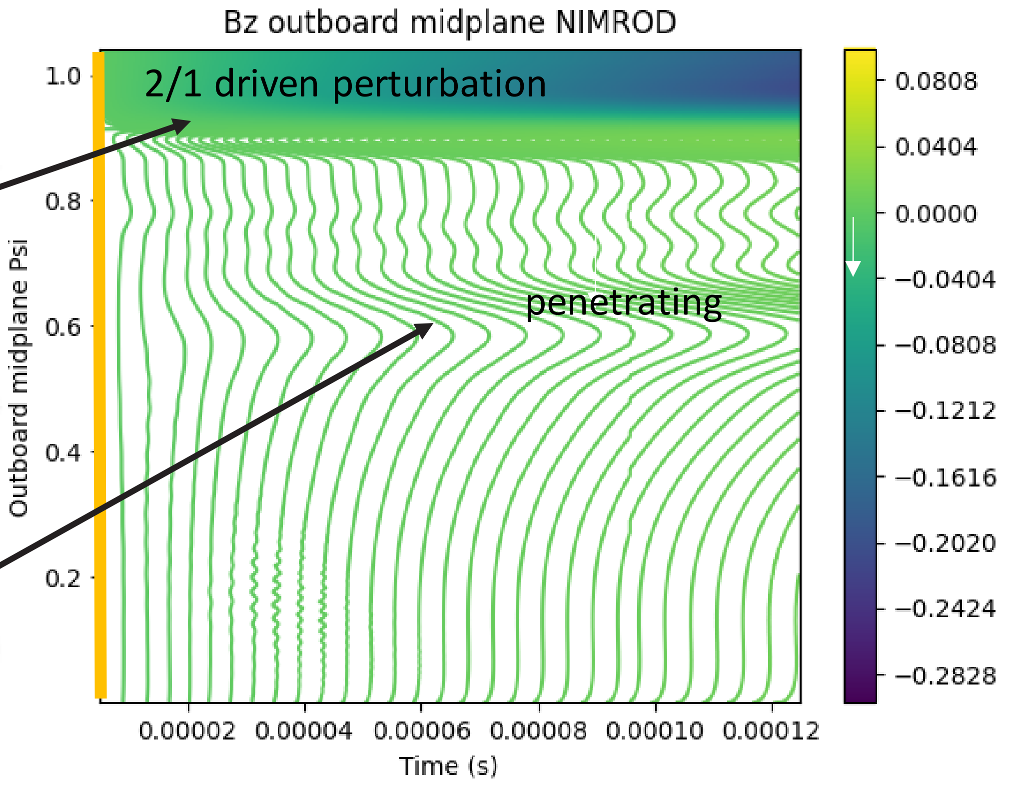
Perturbation of the lithium walls during compression produces error fields in the plasma.

We study the penetration threshold with NIMROD in equilibrium states by ramping m/n=2/1 Resonant Magnetic Perturbation (RMP) fields slowly over time.

Below the penetration threshold, only the flux surfaces near the wall are perturbed, but they shield the core surfaces.

Above the penetration threshold for these fields, large magnetic islands can be driven, causing disruption.





Plasma response is indicated by contours that deviate from vertical.

Source: CRADA 2707 Final Report

Resonant Magnetic Perturbation (RMP), mainly 2/1, is applied at boundary and ramped up in time. Poincare plots of magnetic fields are shown before and after error fields penetrate.

Contact Dylan Brennan: dylan.p.brennan@gmail.com

Island Width Remains Small Until Plasma Cannot Shield Error Field

PI: Dylan Brennan

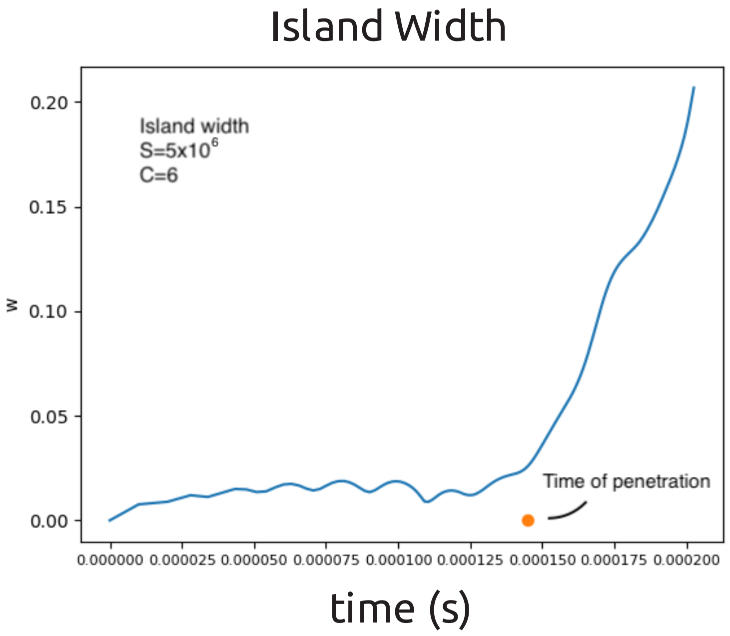
Penetration Threshold

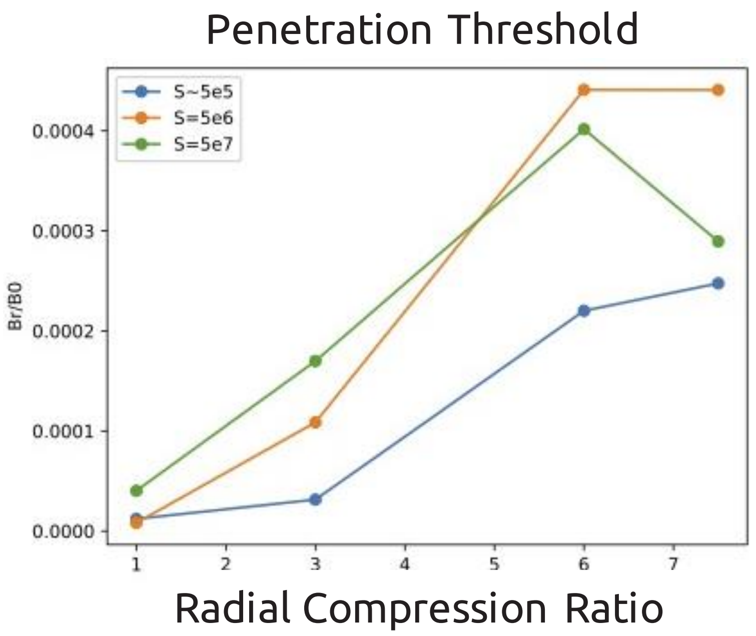
Initially, a small island saturates around the linear layer width.

As error field increases, it penetrates the plasma and a large magnetic island appears (left plot), causing stochasticity and thermal deconfinement

Penetration thresholds from NIMROD simulations (right plot) show that:

- Higher resisitivity (Lundquist S) has higher threshold, which is not explained. We expect lower threshold due to the decreased resistive layer widths.
- Cases at higher compression have greater thresholds. May be partially due to higher S and higher rotation, but results not well understood.





Source: CRADA 2707 Final Report

Island width calculated from NIMROD shows when error fields penetrate the plasma. The penetration threshold depends on compression and resistivity.

RESEARCH IMPACT

Fusion Energy Impact

- Accurate predictions of plasma stability, soft-beta limits, and error field penetration are important for all fusion designs.
- These methods can be applied to extended-MHD simulations of other fusion devices: conventional tokamaks, stellarators, and novel concepts.
- NIMROD, M3D-C1, and GPEC are widely used. All improvements to the software are shared with the research community.
- We have two peer-reviewed papers on this topic and are working on a third, with more expected.
    - D. Brennan et al. *A stable corridor for toroidal plasma compression.* 2021 Nucl. Fusion **61** 046047
    - D. Brennan, et al. *Stable compression of a spherical tokamak plasma.* 2020 Nucl. Fusion **60** 046027

Market Impact

- Success with this research will provide new insight into magnetic compression and heating of MTF plasmas while avoiding MHD instabilities.
- This work will enable predictive simulations of MTF experiments that use compact toroid targets, such as General Fusion's magnetized target fusion prototype LM26.
- Experimental verification of these analyses will prove their practicality for designing successful fusion devices.

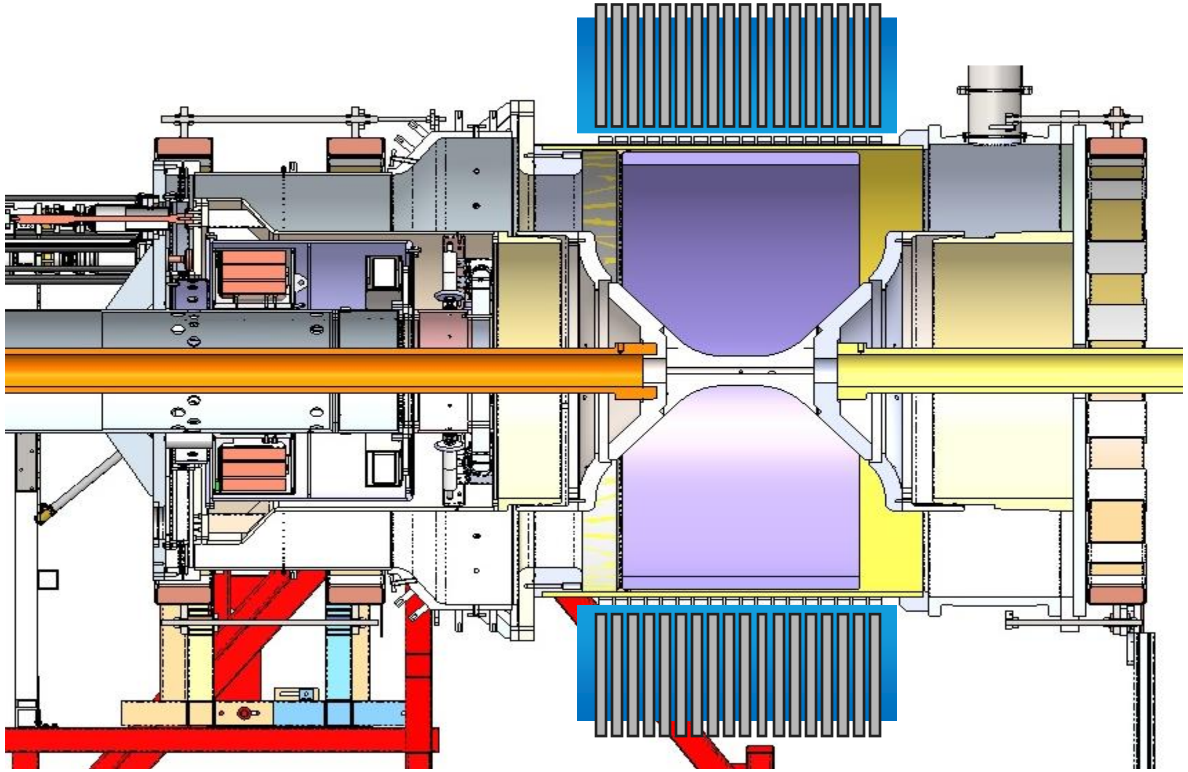
7:00

LM26 PLASMA COMPRESSION PROTOTYPE

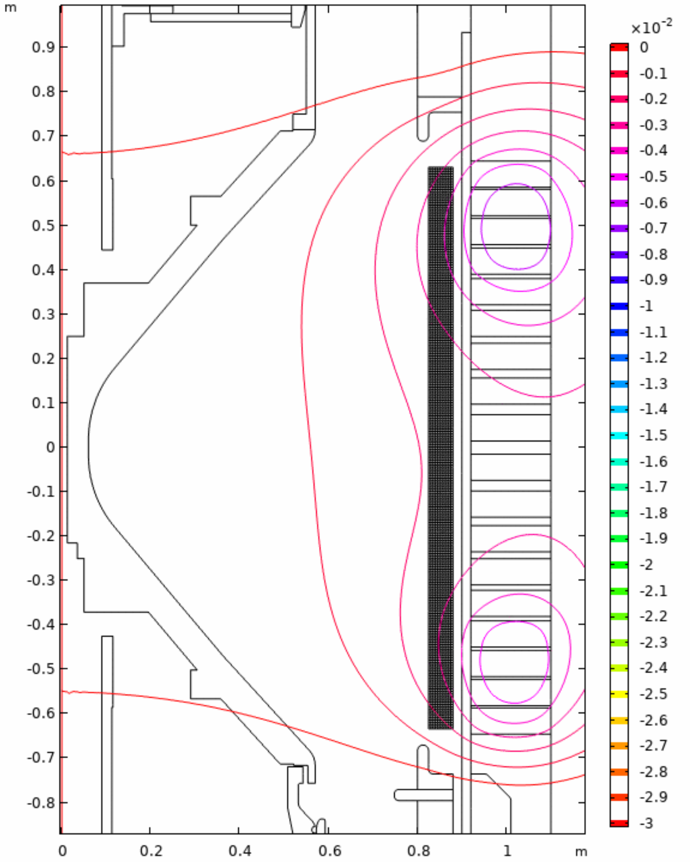
Goal: Demonstrate plasma toroid compression by a sufficiently large factor (at least 4x), with sufficiently hot initial conditions, while maintaining stability and good plasma composition.

- Plasma toroid will be generated using PI3 coaxial helicity injector
- Solid lithium liner will be compressed with theta-pinch coils for high rep rate (1-2 times per week)

LM26 Parameters
R_{coil} = 95 cm
N_{turn} = 18
solid lithium liner
M_{Li} < 300 kg
B_{coil}(peak) = 12 T
E_{cap} = 18 MJ
τ_{comp} = 2-2.6 ms

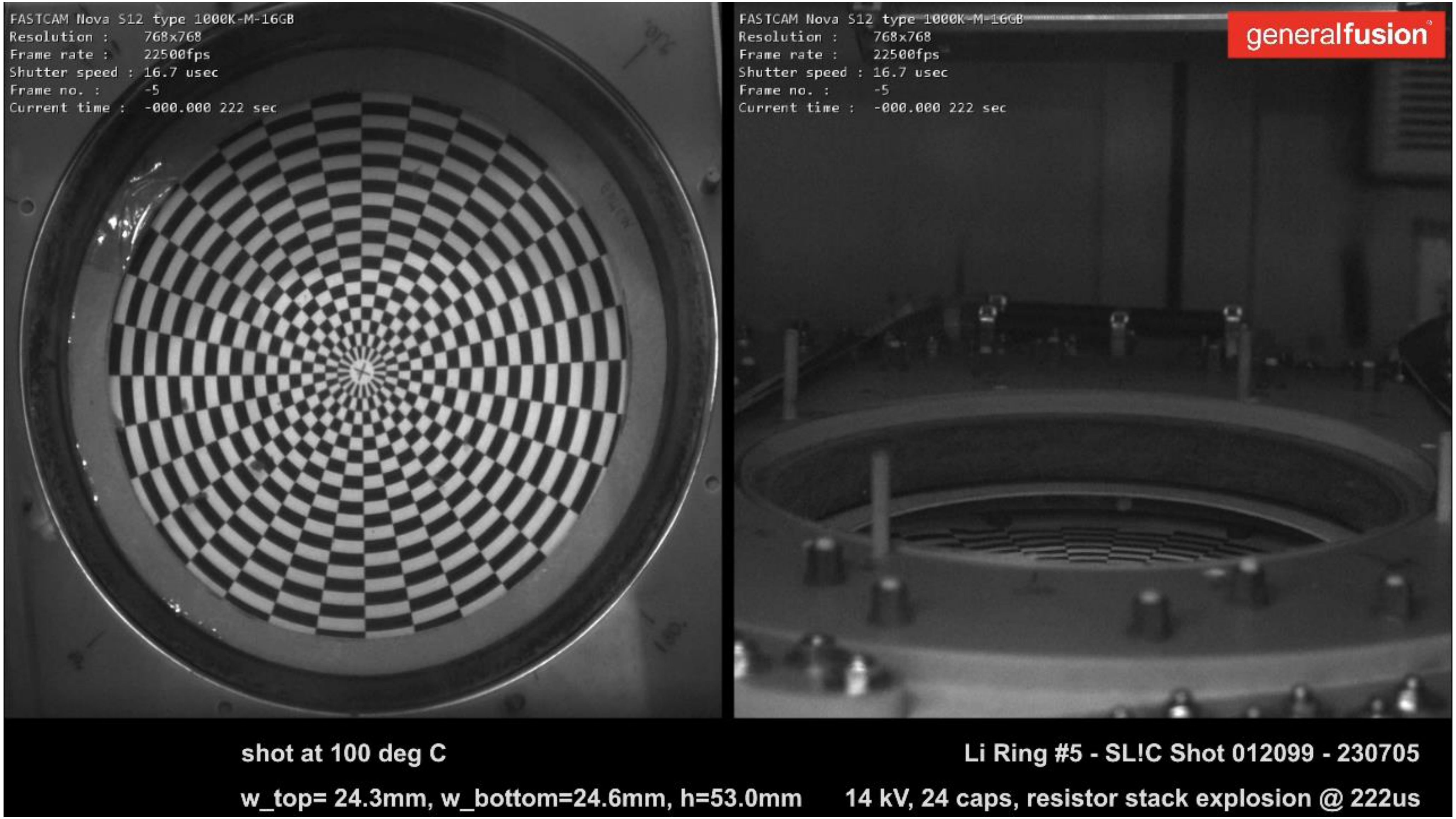


SolidWorks Schematic for LM26



COMSOL model of lithium compression

SOLID LITHIUM RING COMPRESSOR (JULY 2023)

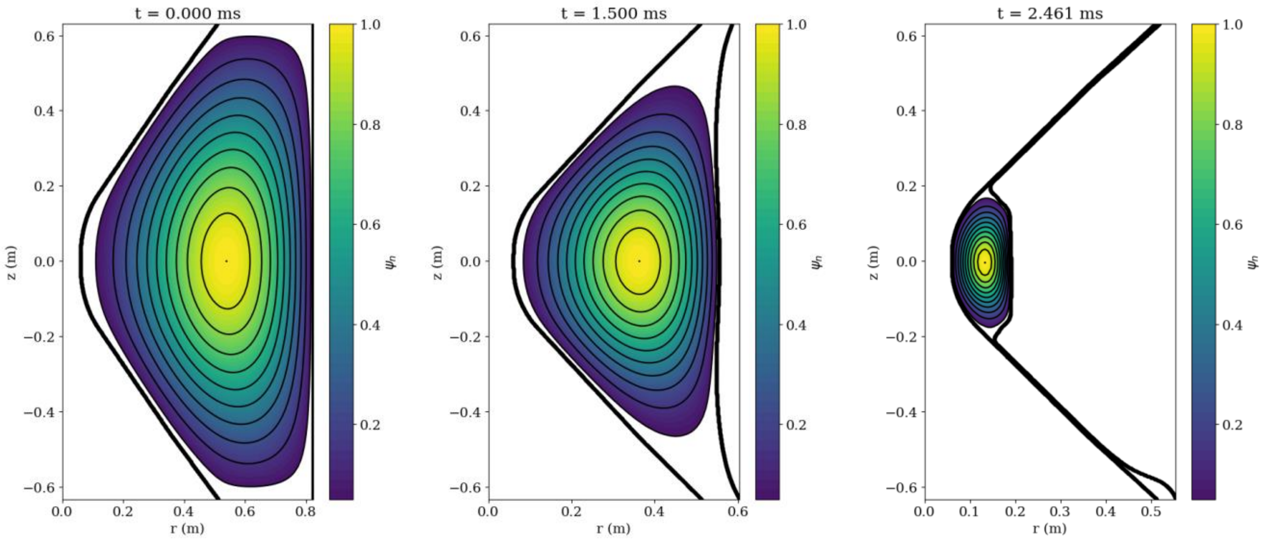


- A solid lithium ring is compressed with theta pinch coils in 1.1 milliseconds.

Future Plans for this Research

- The LM26 compression geometry will be very different from the more self-similar idealized geometry we have modelled in the past.
  - We will implement the predicted LM26 geometry in CORSICA, NIMROD, and M3D-C1
- Flux from the driving coils will diffuse through the solid lithium, pushing the plasma away from the liner surface.
  - We will include applied poloidal fields and evaluate stability of external modes with GPEC.
- We will use M3D-C1 to find soft-beta limits in unstable regions, including kinetic effects (with M3D-C1-K)
- We will use NIMROD RMP models to calculate, explain, and maximize penetration thresholds
- We need these results from M3D-C1 and NIMROD and GPEC to compare with the LM26 experiment.

LM26 Predicted Geometry



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