Expected MHD Stability and Error Field Penetration in LM26 Magnetized Target Fusion Experiment at General Fusion

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66th Annual Meeting of the APS Division of Plasma Physics, Atlanta, Georgia, October 7-11, 2024 PP12.68

INTRODUCTION TO LM26

Lawson Machine 26 (LM26) is a magnetized target fusion (MTF) demonstration machine with the goal of **producing significant plasma heating via compression**.

Operation

1. The toroidal plasma is generated by coaxial helicity injection (CHI).
2. Plasma confined inside a solid lithium liner, with an aluminum shaft.
3. Liner inductively compressed in less than 3 milliseconds.
4. The plasma will heat if the energy confinement time is longer than the compression time.
5. **Plasma must remain MHD stable throughout the whole compression to maintain confinement.**

Status

- Design of the first stage is complete.
- Simulations of the machine operation and performance are mature.
- Construction of the 18 MJ power supply is underway
- Large components of the flux conserver are being manufactured.
- PI3 CHI injector is being disassembled to be reconfigured as LM26.
- First plasma is scheduled for Q1 2025.
- Goal is to reach 10 keV by 2025.

QR code for video of LM26 Concept www.youtube.com/watch?v=3i3hPtWOQL0

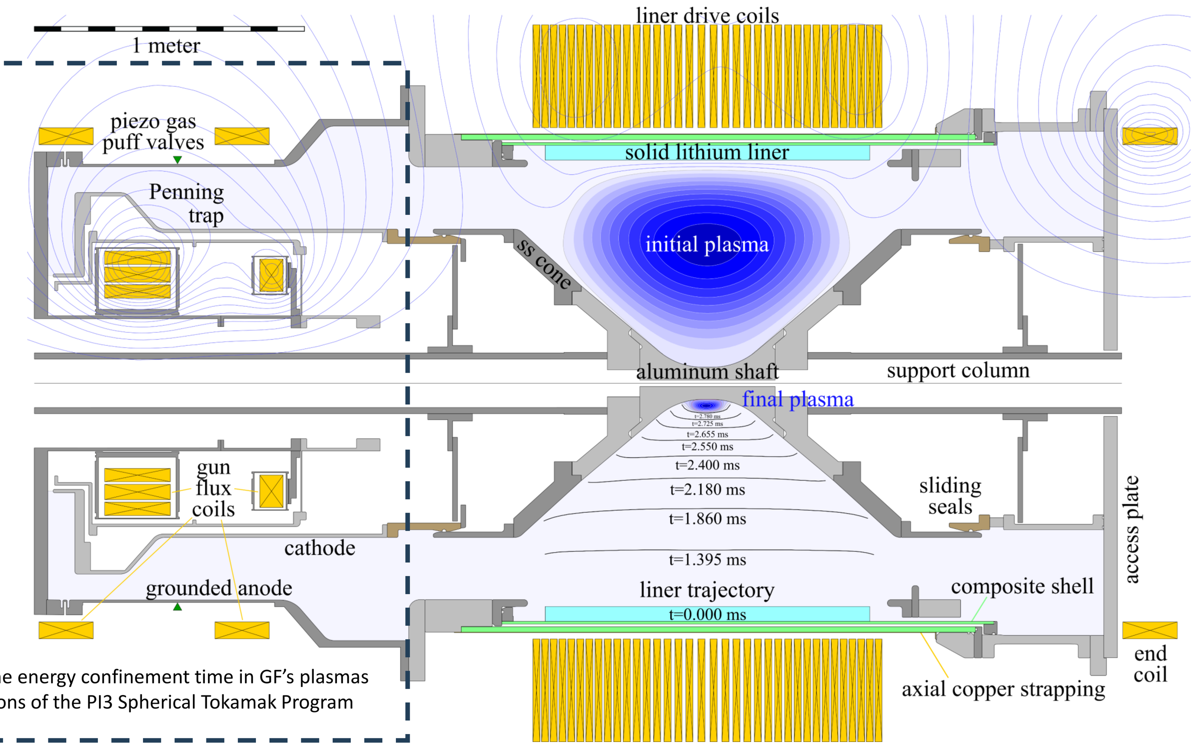
Plasma Compression Experiment Design

Plasma Injector 3 (PI3)

- Largest coaxial helicity injector ever built.
- In operation since 2018 with an almost spherical aluminum flux conserver.

Poloidal flux Ψ_{CT}	0.05 – 0.25 Wb
Plasma current I_p	0.1 – 0.6 MA
Shaft current I_{sh}	1.0 – 1.2 MA
Plasma density n_e	1 – 4x10^{19} m^{-3}
Temperature T_e	100 – 500 eV
Temperature T_i	300 – 1000 eV
Confinement time τ_E	5 – 15 ms

Related talks and posters:
GO05.00012: Andrea Tancetti (Tues 11:42–11:54 AM) Calculation of the energy confinement time in GF's plasmas
JP12.00111: Patrick Carle (Tues 2:00– 5:00 PM) Physics Conclusions of the PI3 Spherical Tokamak Program



Capacitor Banks	Voltage (Typical/Max)	Capaci-tance	Energy (Typical/Max)
I_{shaft} Peaking Bank	8 / 10 kV	30 mF	1.0 / 1.5 MJ
I_{shaft} Sustain Bank	7 / 11 kV	48 mF	1.2 / 2.9 MJ
Pre-form Bank	20 / 25 kV	0.2 mF	40 / 62 kJ
Formation Bank	22 / 25 kV	2.5 mF	600 / 780 kJ
Compression Bank	10.5 / 10.5 kV	329 mF	18 / 18 MJ

LM26 Plasma Geometry	Initial Value (time = 0 ms)	Final Value (time = 2.76 ms)
Liner inner radius D/2	80 cm	10 cm
Major radius R	45 cm	8 cm
Minor radius a	35 cm	2 cm
Elongation κ	1.6	1.6
Triangularity δ	-0.2	0.5

COMSOL MODEL VALIDATION WITH EXPERIMENT

Steps for Model Implementation

1. Lithium material characterization
2. Validate with lithium ring compression experiments
3. Validate lithium cylinder compression on cones
4. Trajectory prediction in full-scale LM26 geometry

COMSOL Multiphysics rapidly iterates electromagnetic compressor designs

Physics:

- Moving Mesh
- Solid Mechanics (linear)
  - Plasticity Material Model
  - Contact Mechanics (Penalty)
- Magnetic & Electric Field (quadratic)
- Coil excitation from electrical circuits
- Heat Transfer (quadratic)

Solver:

- BDF 2nd order implicit scheme
- Fully coupled
- Automatic remeshing

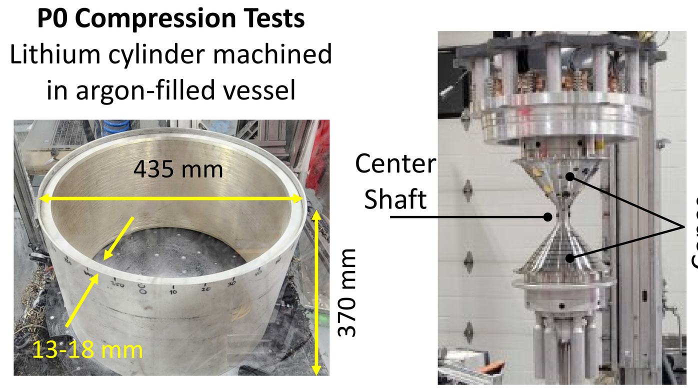
Johnson-Cook Material Model, calibrated with COMSOL and PolymerFEM MCalibration

$$\sigma = \left(\sigma_y + B\varepsilon_p^n\right)\left(1 + C\ln\frac{\dot{\varepsilon}}{\dot{\varepsilon}_{ref}}\right)\left(1 - T^{*m}\right)$$

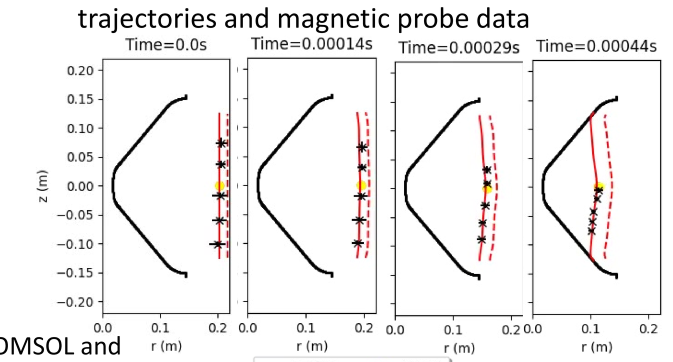
- σ_y: Yield stress at reference conditions, 0.76 [MPa]
- B : Strain hardening constant, 2.96 [MPa]
- n : Strain hardening coefficient, 0.31
- C : Strengthening coefficient of strain rate, 0.12
- ε_p: Plastic strain, reference rate $\dot{\varepsilon}_{ref} = 0.002$ s^{-1}
- T*: temperature (T-294)/(Tmelt-294), Tmelt=453K
- m : Thermal softening coefficient, 1.27

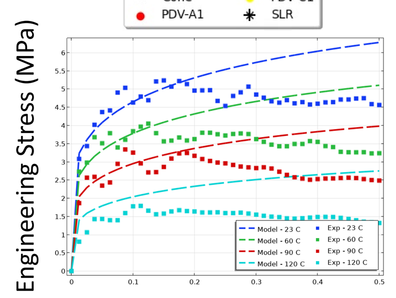
P0 Compression Tests

Lithium cylinder machined in argon-filled vessel

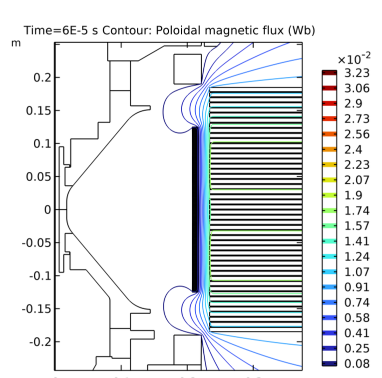


- Simulation models agree well with measured trajectories and magnetic probe data



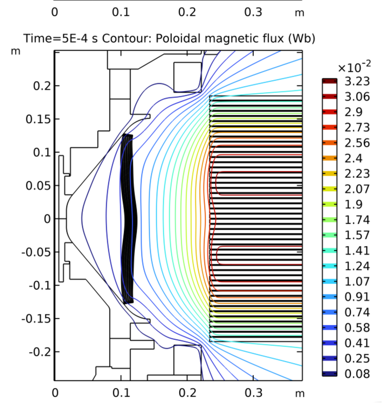


Comparison of Material Model and Experimental Data at 100 s^{-1}

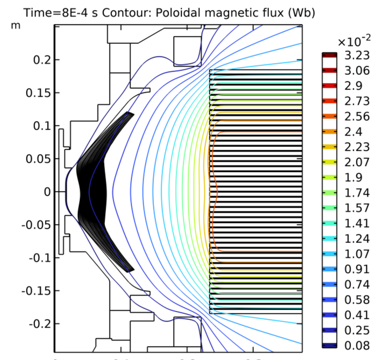


Simulation of Prototype Zero (P0), liner acceleration experiment

Liner begins moving after 60us.



After 0.5 ms, the liner strikes the metal cones. Some flux has passed through the lithium.



Max compression is reached at 0.8 ms. Cavity radius has been reduced by a factor of about 5.

Dick J.-S., et al. PVP2024-121787 Proc. ASME PVP Conf. [submitted]

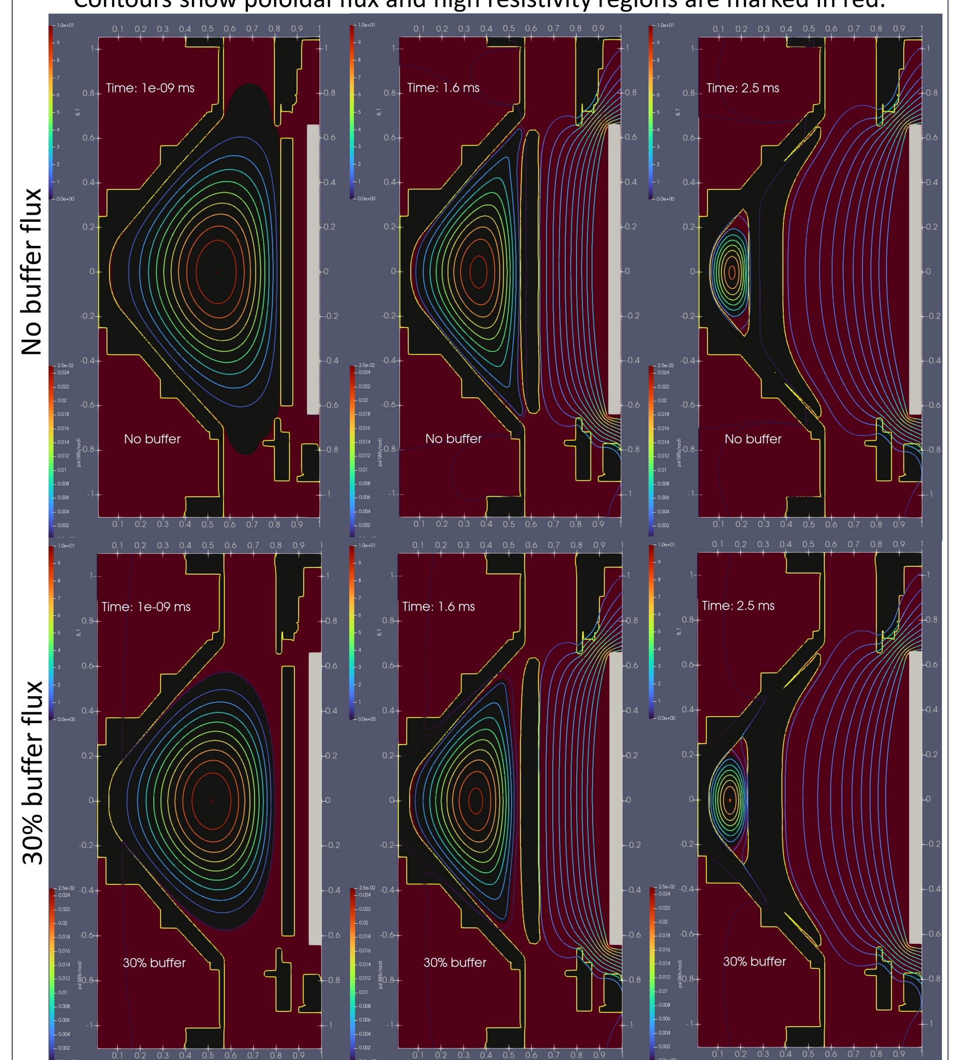
OPENFOAM MHD MODEL VALIDATION

The OpenFOAM MHD solver developed at General Fusion [V Suponitsky et al. Fluids 2022, 7(7), 210] was extended to simulate EM compression of the liner driven by the external circuit and diffusion of the magnetic fields into multiple solid materials. Solid lithium is modelled as a high viscosity liquid (creeping flow). This approach is robust at capturing the dynamics of the liner in the regimes of interest when compared to the experimental results and COMSOL modeling.

The solver is used to simulate: (1) small ring compressor, (2) P0 experiments with emphasis on toroidal flux trapping and flux diffusion into the cones, and (3) compression of a simplified magnetized plasma in LM26, which involves interaction between plasma magnetic fields, buffer fields, and driving fields. A single-temperature plasma model is also implemented and can be further extended in the future.

LM26 plasma compression simulations with 0% and 30% buffer flux

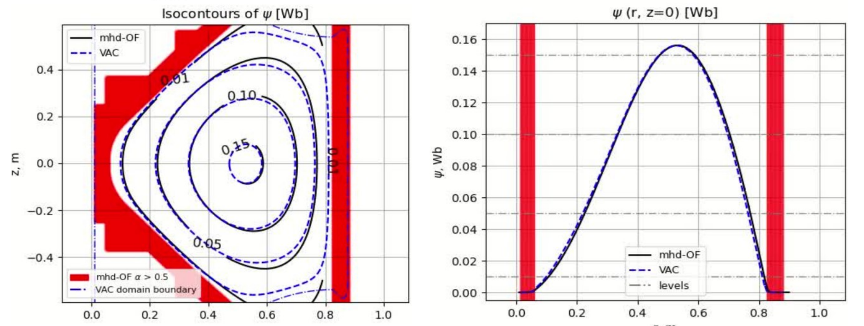
Contours show poloidal flux and high resistivity regions are marked in red.



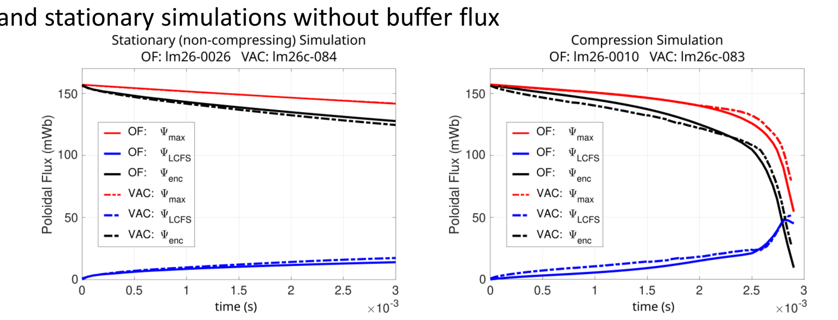
- Plasma region bounded by LCFS, with high resistivity (red) outside
- Buffer field controls shape of the plasma and diffusion into liner and cones
- With buffer flux plasma is limited on the cones. Choice of materials plays an important role in reducing flux diffusion.

Comparison between MHD-OpenFOAM solver and layered VAC

- Liner trajectory and poloidal and toroidal fields at inner and outer liner surfaces, and inner surface of the cones extracted from OpenFOAM and provided as inputs to VAC MHD sim. Resistivity of the plasma was kept constant in both OpenFOAM and VAC.
- Initial plasma parameters: peaked lambda profile, uniform pressure profile, I_{shaft} = 1.5 MA, $\bar{\psi}_{max}$ = 0.157 Wb



Initial flux surfaces and equatorial profile of poloidal flux for compression and stationary simulations without buffer flux

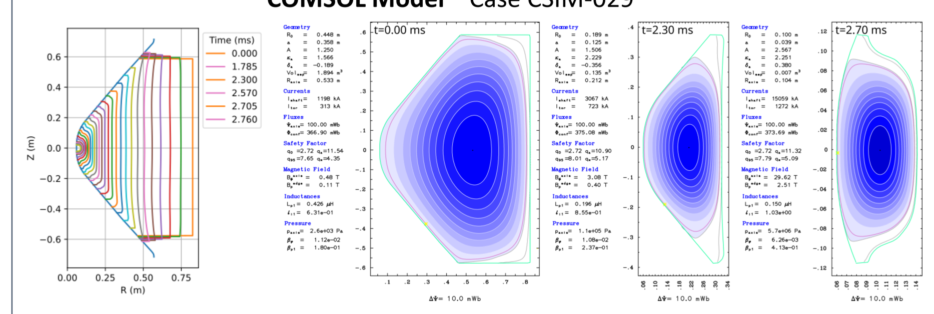


Time evolution of poloidal flux at axis ($\bar{\psi}_{max}$), LCFS ($\bar{\psi}_{LCFS}$), and closed flux ($\bar{\psi}_{enc}$) for stationary (non-compressing) and compression cases.

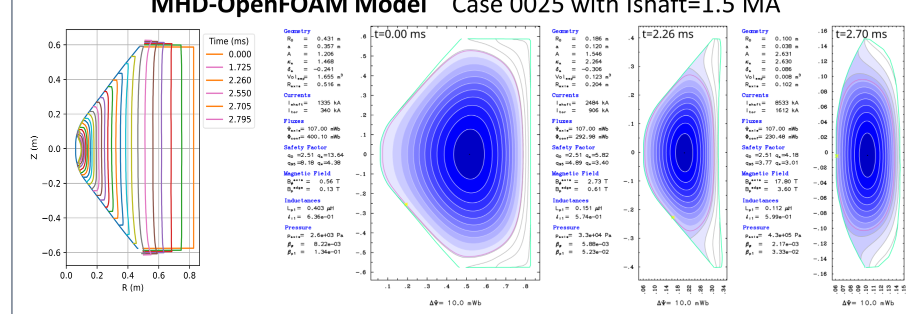
MHD STABILITY DURING COMPRESSION

The plasma will heat to fusion conditions only if compressional heating is greater than transport losses, i.e., if the energy confinement time is longer than the compression time. To maintain sufficient energy confinement time, the plasma must be kept MHD stable. Using the liner geometries predicted with COMSOL and OpenFOAM, we model the plasma evolution with CORSICA by conserving the safety factor (q) and specific entropy profiles. Then we evaluate the ideal and resistive MHD stability using RDCON [A Glasser et al. 2016 Phys. Plasmas 23 112506]. With this technique, we have previously calculated MHD stable trajectories in a simplified compression geometry [D Brennan et al. 2020 Nucl. Fusion 60, 046027; D Brennan et al. 2021 Nucl. Fusion 61, 046047].

COMSOL Model Case CSIM-029

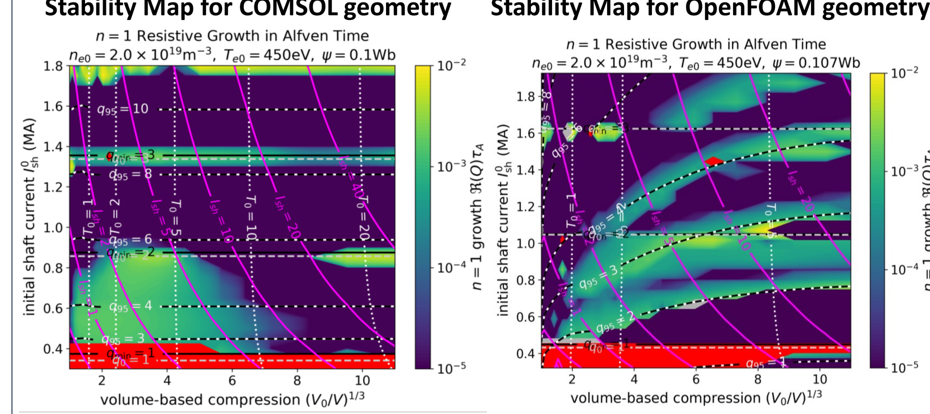


MHD-OpenFOAM Model Case 0025 with Ishaft=1.5 MA



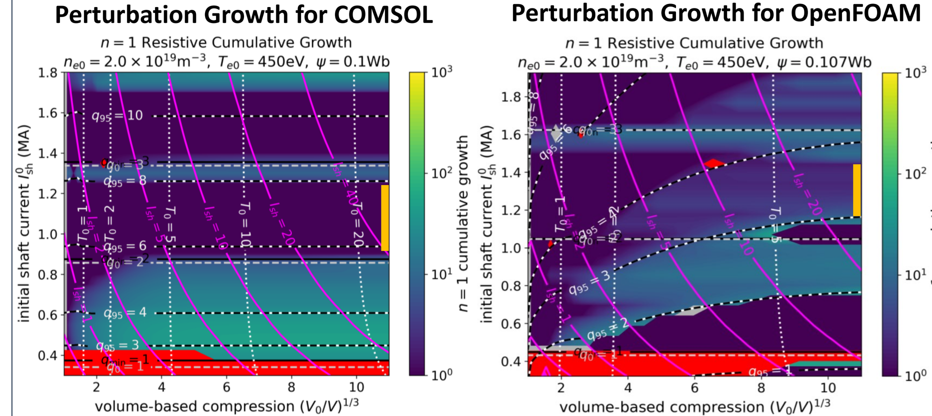
- We introduce the same plasma in both trajectories, with only the geometry and poloidal flux boundary conditions taken from COMSOL and OpenFOAM.
- Case CSIM-029 has small (~4 mWb) flux diffusion through liner from drive coils.
- Case OFSIM-0025 uses an isothermal MHD plasma and models flux diffusion from the plasma into the flux conserver.
- Despite these differences, the liner trajectories and poloidal flux boundary conditions are very similar until late compression (> V/V$_0$ = 5^3).

Stability Map for COMSOL geometry / **Stability Map for OpenFOAM geometry**



- Horizontal trajectories show properties of plasmas that have conserved safety factor (q) and specific entropy profiles
- Red regions = ideal MHD unstable (very fast growth)
- Yellow/Green regions= resistively unstable (fast/slow)
- Deep blue regions = stable
- Magenta = shaft currents (I_{sh}) given in MA
- The growth rates above are integrated along each horizontal trajectory by the time spent at each volume to get plots of cumulative growth below.

Perturbation Growth for COMSOL / **Perturbation Growth for OpenFOAM**

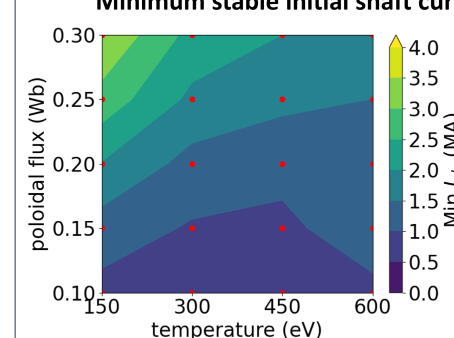


- We assume that the plasma can tolerate perturbation growth of 10 times before final compression and use that as a threshold to find stable corridors.
- Under this criterion, both COMSOL and OpenFOAM trajectories agree that plasmas remain stable until full compression when q_{min}=2.3-2.7 (orange line).
- Flux and q conservation cause a peaked edge current as geometry changes.
- Edge q decreases in OpenFOAM model because flux surfaces diffuse into shaft.
- **Self-consistently modeling the plasma and liner, as with MHD-OpenFOAM, improves accuracy, but is not necessary to establish requirements on plasma.**
- Resistive stability is sensitive to the edge current, which opens compression corridors stable to n=1 and n=2 [D.Brennan et al, Nucl. Fus. 61, 046047 (2021)].

REQUIREMENTS FOR PLASMA STABILITY

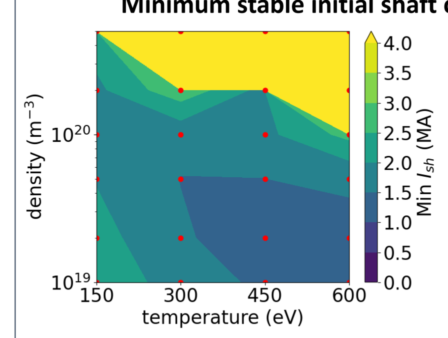
MHD stability can usually be achieved by increasing shaft current and, hence, the toroidal field and safety factor q. However, generating shaft current requires large, expensive capacitors. We want to know the minimum necessary shaft current that will maintain stability through to the end of the compression trajectory. For a single COMSOL compression trajectory (CSIM-029), we scan plasma parameters and find a wide range under which the plasma remains stable with less than 1.5 MA initial shaft current, the amount under construction.

Minimum stable initial shaft current vs Poloidal Flux and Temperature



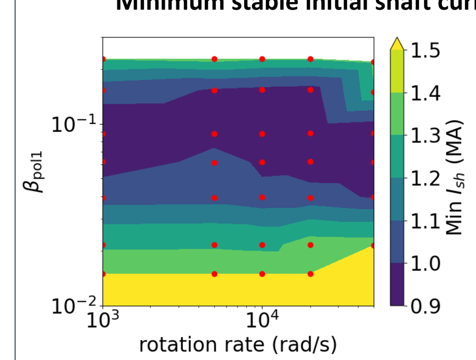
- For these cases, the poloidal flux is conserved during compression, but the density and temperature increase 20% slower than adiabatically by $n/n_0 = (T/T_0)^{3/2} = (V/V_0)^{-0.8}$
- For a shaft current of 1MA, the plasma must have less than 150 mWb of poloidal flux and a starting temperature 300-500 eV.

Minimum stable initial shaft current vs Density and Temperature



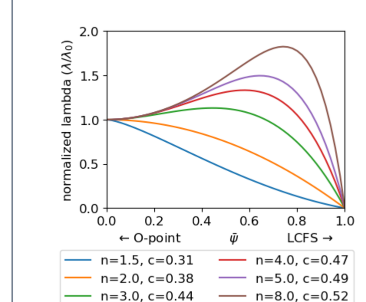
- Beta limits are exceeded in top right
- Glasser stabilization (stabilization due to pressure and favourable curvature) is reduced in bottom left.
- Resistivity is less on the right, so bottom right is most stable and less shaft current is required there.
- In yellow regions, the shaft current required to achieve stability exceeds the maximum value tested.

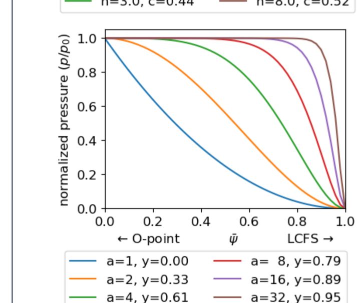
Minimum stable initial shaft current vs Poloidal Beta and Rotation



- Similar to above, beta limits are exceeded at the top
- Glasser stabilization (stabilization due to pressure and favourable curvature) is reduced at the bottom.
- Rotation has a negligible effect on stability
- On all contour plots, stability maps are created at the red points. Contours are interpolated from those points

Minimum stable initial shaft current vs Plasma Profiles





- Here we examine the effect of the pressure profile and current density profiles.lambda profile.
- The current density is controlled by selecting a lambda (≡ dF/dψ) profile of the form:

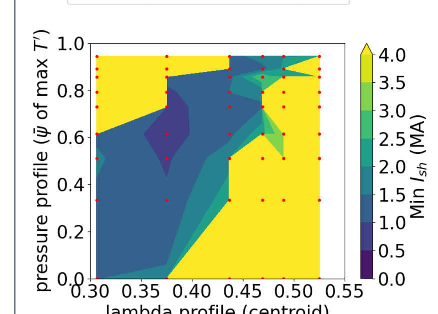
$$\lambda = \lambda_0\left(1 + 2\bar{\psi}^2 - 3\bar{\psi}^n\right)$$

where increasing n makes the profile more hollow and reduces internal inductance.

- The centroid c of the lambda profile indicates the $\bar{\psi}$ location of the current density.
- The density is uniform at 2e19 m^{-1}.
- The temperature profile is specified by

$$T\left(\bar{\psi}\right) = T_0\left(1 - \bar{\psi}^a\right)^b$$

where a makes the profile wider and squeezes the gradient nearer to the LCFS and $b = 2$ for simplicity.



- The lambda profile and pressure profile must be matched to one another.
- Hollow lambda profiles are stable, but only when the pressure gradients are very close to the LCFS.
- Likewise, peaked lambda profiles are stable when paired with peaked pressure profiles.

- The optimum (where the lowest initial shaft current is required) has lambda centroid 0.38 and a temperature profile with maximum gradient at $\bar{\psi}$=0.6.
- The profiles at this minimum are

$$\lambda = \lambda_0\left(1 - \bar{\psi}^2\right) \qquad T\left(\bar{\psi}\right) = T_0\left(1 - \bar{\psi}^4\right)^2$$

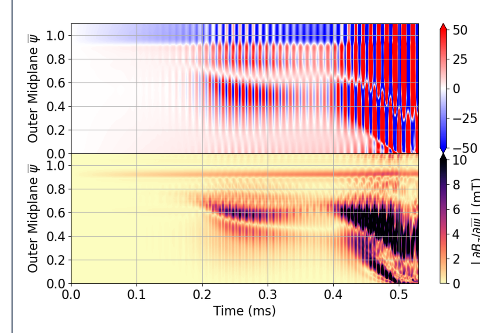
which are a peaked lambda profile and a broadish pressure profile.

- **Extensive ideal MHD stability scans with RDCON were used to find highly stable geometric and plasma parameters, which are easily achievable using the hardware under construction.**

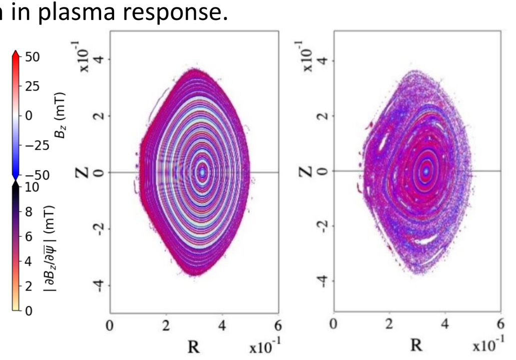
ERROR FIELD PENETRATION

Geometric perturbations in the liner surface will grow during compression and be experienced by the plasma as increasing magnetic perturbations, or error fields. Error field penetration (EFP) is an important problem in the stable regions and can drive resonant perturbations in the plasma.

- We take a two-pronged approach:
  - Reduced model of Cole and Fitzpatrick [A Cole, R Fitzpatrick 2006 Phys. Plasmas 13 032503] applied to equilibria
  - NIMROD simulations with RMP boundary imposed
- The goal is to characterize the penetration thresholds and find the conditions (e.g. resistivity, viscosity, rotation, etc.) that shield the highest error fields.
- We analyze in a static equilibrium geometry, which is justified because the compression time is much longer than Alfven time and RMP ramp time.
- Resonant magnetic perturbation (RMP) of 2/1 mode imposed on Br at boundary drives a wider spectrum in plasma response.

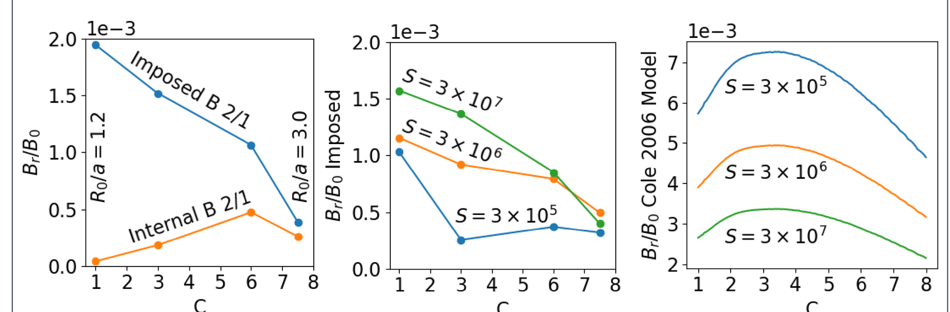


Bz on outer midplane of NIMROD plasma showing penetration at 0.2 ms.

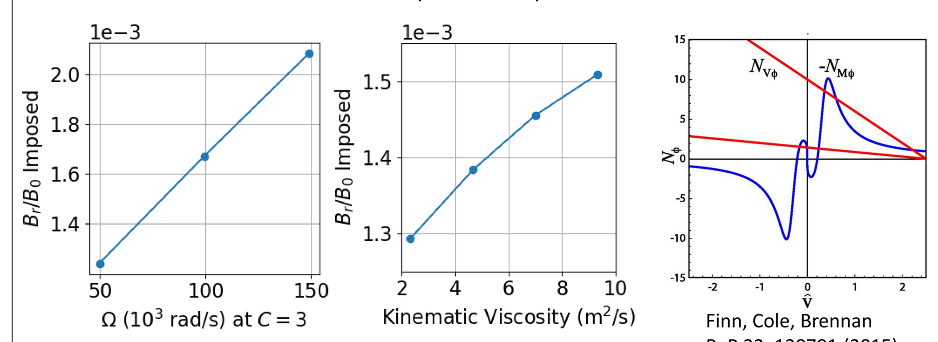


Poincare plot of flux surfaces before and after error field penetration

- Prior to penetration, initial islands can propagate, as described by Fitzpatrick model [PoP 21, 092513 (2014)] and observed by Howell [NIMROD Mtg 5/23].
- Penetration point is deduced where the island width rapidly grows past the layer width, such as at t=0.2 ms in Br phase plot above.



- NIMROD simulations are based on equilibria taken from a compression sequence. In addition to constraints on entropy and q, the toroidal flow Ω increases by angular momentum conservation.
- Aspect ratio, shaping, and Ω affect the plasma response spectrum (ratio of 2/1 inside), but fixing Lundquist number (S) isolates those effects.
- EFP limits from NIMROD start at O(10^{-3}) and decrease with increasing with C and S, unlike analytic model [Cole & Fitzpatrick, Phys. Plas. 13, 032503 (2006)] where high S cases have lower limits and effect of C is non-monotonic.
- NIMROD results at lower Lundquist number S = 5 × 10^5 are not fully in the asymptotic regime and deviate significantly from analytic model.
- Increases in S and Ω are most impactful on penetration thresholds.



Finn, Cole, Brennan PoP 22, 120701 (2015)

- Limits increase with viscosity and/or rotation, as expected
- Increasing rotation Ω shifts the Nνφ curve up and to the right with fixed slope.
- Increasing viscosity increases the slope of the Nνφ line.
- Both lead to a higher point where the Nνφ curve slips into a locked state.
- This gives some confidence that the NIMROD and Finn, Cole, Brennan [PoP 22, 120701 (2015)] results are scaling correctly.

Future Error Field Penetration Work

- Understand discrepancies between NIMROD and Cole 2006 analytic model.
- Penetration limits ~1e–3 pre-compression decrease to ~1e–4 as S increases.
  - How important are experimentally observed rotation shears?
  - How important is the shaping and stability to the EFP limits?
  - Are two fluid effects important?
- Kinetic ions interactions and kinetic layer regimes all open questions
- Flux soak into wall affects the equilibrium and EFP limits and will be included
- Instability interaction with the liquid wall also being investigated