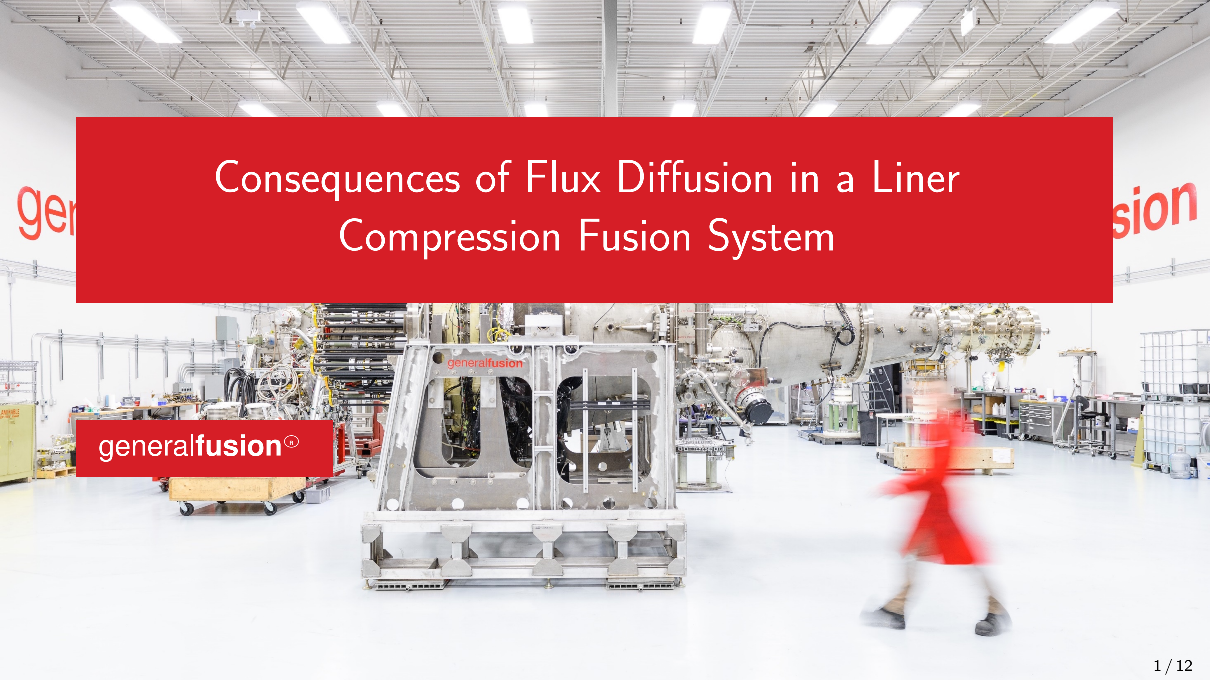
Consequences of Flux Diffusion in a Liner Compression Fusion System



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Consequences of Flux Diffusion in a Liner Compression Fusion System

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Special thanks to:
Ivan Khalzov

Slow-liner Magnetized Target Fusion (MTF)

Linus concept (Naval Research Laboratory, 1970s)

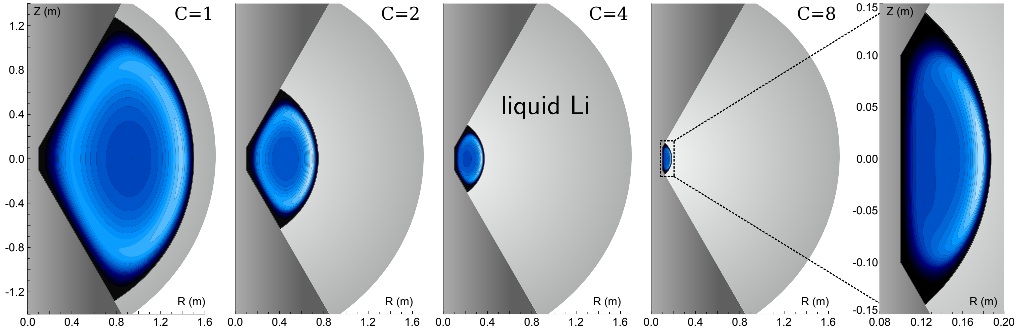
- Compression of a magnetized DT plasma by a conducting liquid metal liner
- Mechanical or pneumatic acceleration of liquid metal
- Initial plasma size of order meters
- Compression time of order milliseconds

References

- Robson A.E. (1982) “The Linus Concept”. In: Brunelli B., Leotta G.G. (eds) Unconventional Approaches to Fusion. Springer, Boston, MA.
- Michel Laberge, “Magnetized Target Fusion with a Spherical Tokamak”, Journal of Fusion Energy **38** (2019) 199–203.

Fusion Demonstration Plant (FDP)

- General Fusion is designing a 70% scale machine
- Spherically converging liquid lithium liner compressing deuterium plasma
- Initial $R_{\text{fc}} = 1.5\,\mathrm{m}$. Final $R_{\text{fc}} = 0.2\,\mathrm{m}$. Radial compression ratio $C \approx 8$.
- Compression time $t_c \approx 3.8\,\mathrm{ms}$
- MHD simulations are based on the following geometry:



MHD simulation of plasma compression by resistive liner

Code used for 2D and 3D MHD simulation

- Versatile Advection Code (VAC) by Gábor Tóth [University of Michigan]
- Finite-volume cell-centered code, curvilinear grid
- Additional features introduced at General Fusion for MTF simulation

Physics included in the simulation

- Compression: predetermined time-dependent meshes for plasma and metal
- Resistive MHD in plasma with T-dependent resistivity
- Physical parallel heat transport
- Constant cross-field transport: $\chi_\mathsf{i} = 4\,\mathrm{m}^2/\mathrm{s}$, $\chi_\mathsf{e} = 9\,\mathrm{m}^2/\mathrm{s}$
- Resistive MHD in metal, prescribed flow, flux diffusion and advective flux shearing

Understanding MHD effects in the liner

Evolution of poloidal flux field $\psi(r, z)$ has diffusive and advective nature:

$$\frac{\partial \psi}{\partial t} = D\Delta^* \psi - \mathbf{v} \cdot \nabla \psi$$

Diffusive nature

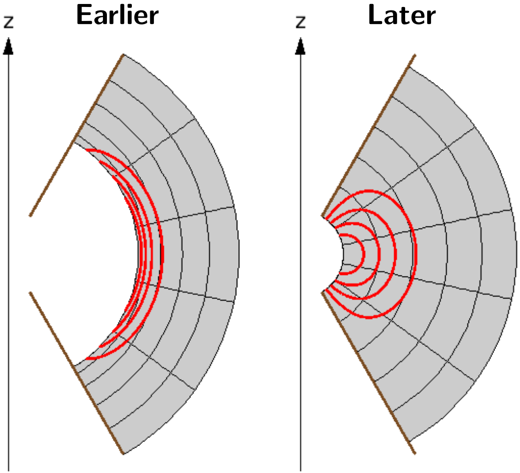
- Resistivity of liquid lithium: $\eta \approx 2.8 \times 10^{-7}\,\Omega\,\mathrm{m}$ gives $D = \eta/\mu_0 \approx 0.22\,\mathrm{m}^2/\mathrm{s}$

Advective nature

- Liquid metal drags ψ with the liquid velocity $\mathbf{v}$
- This results in flux spreading in converging liquid metal flow[1]

[1] Insight due to Ivan Khalzov (General Fusion)

Magnetic flux spreading in collapsing liner



Here we are showing the advective effect

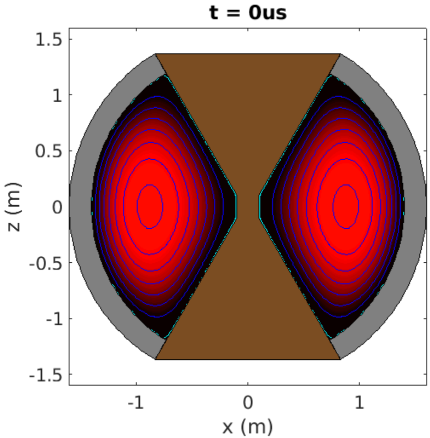
- Cell volume preserved
- Cell thickness increases
- Soaked flux lags interface (flux shearing)
- Increases B contrast with plasma
- Enhances soak from plasma when $D \neq 0$

red contours: poloidal flux in liquid

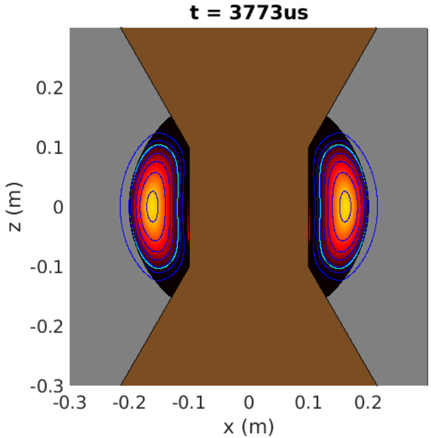
MHD simulation snapshots, initial and final time

Gray: liquid lithium. Copper: solid center conductor. Heat map: plasma temperature.
Dark contours: $\psi(r,z)$, bright contour: separatrix (LCFS).

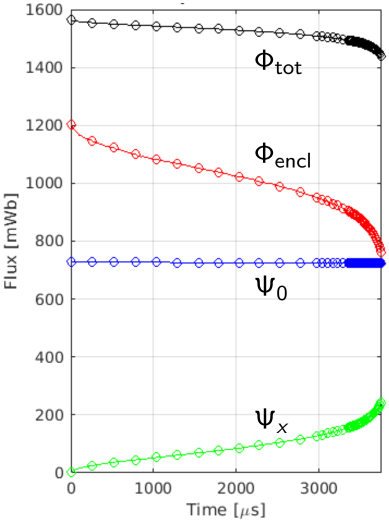
$T_\mathrm{i} = T_\mathrm{e} = 0.4\,\mathrm{keV},\ C = 1$



$T_\mathrm{i} = 12\,\mathrm{keV},\ T_\mathrm{e} = 7\,\mathrm{keV},\ C \approx 8$



Magnetic fluxes versus time during compression



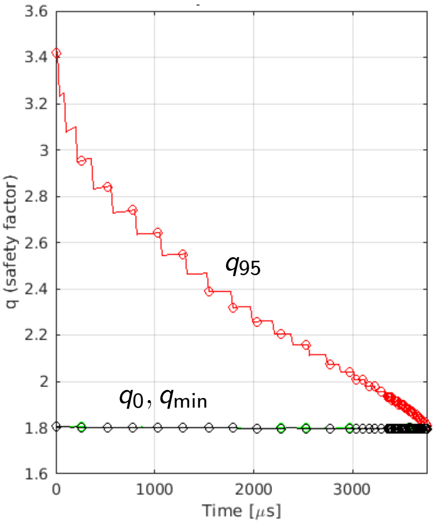
Poloidal flux, in webers, $\Psi(r,z) \equiv 2\pi\psi(r,z)$

- **Blue**: $\Psi_0(t)$ is poloidal flux linked by magnetic axis, nearly constant due to good plasma conductivity
- **Green**: $\Psi_x(t)$, poloidal flux linked by separatrix (i.e., soaked into the liner)
- Poloidal flux enclosed in the plasma is $\Psi_0 - \Psi_x$

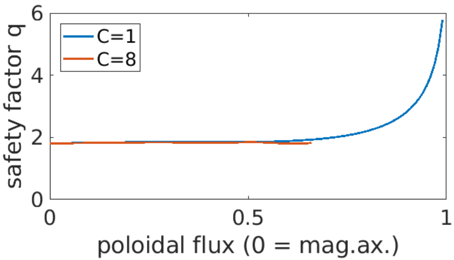
Toroidal flux $\Phi \equiv \int B_\varphi(r,z)\,dr\,dz$

- **Black**: toroidal flux $\Phi_{tot}(t)$ in the entire plasma domain
- **Red**: toroidal flux $\Phi_{encl}(t)$ enclosed by the separatrix

Safety factor characteristics versus time during compression



- q profile in interior of plasma does not evolve much because $t_c \ll \tau_B$
- high q flux surfaces lost into the wall
- remaining plasma is lower magnetic shear
- final state nearly single-helicity



Conclusions

Successful 2D MHD compression simulations with flux soak

- Approximately 30% of poloidal flux soaks into wall (agrees with 1D code)
- Remaining q profile has low shear, low q_{95} (trimmed initial profile)
- Final $T_\mathrm{i} = 12\,\mathrm{keV}$, $T_\mathrm{e} = 7\,\mathrm{keV}$ at $C \approx 8$

Interesting effects of flux soak for slow-liner MTF

- Unusual q profile, potentially reversed shear, nearly-single helicity (depending on initial q profile)
- Loss of plasma and current to wall may enhance plasma-wall interaction
- Next steps: stability analysis and 3D simulation

General Fusion talks and posters at APS DPP 2020

Mon, 2-5pm: **CP19.22**	Aaron Froese, D. Brennan, S. Barsky, M. Reynolds, Z. Wang, M. Laberge *Effects on Stable MHD Region of a Magnetized Target Plasma Compression*
Tues, 9:30-12:30: **GO13.8**	Stephen Howard, A. Mossman, W. Zawalski, D. Froese *Plasma-wall interaction on the SLiC spherical tokamak device with large-area, dynamic liquid lithium free surface*
Tues, 2-5pm **JO09.6**	Meritt Reynolds *Consequences of Flux Diffusion in a Liner Compression Fusion Reactor*
Tues, 2-5pm: **JP19.11**	Cody Moynihan, S. Stemmley, A. de Castro, J. Zimmermann, D. Ruzic *Design and Initial Results from the Dynamic Lithium Corrosion Test Bed*
Mon, 2-5pm: **CP19.21**	Paria Makaremi-Esfariani, Peter de Vietien *Coupled CFD/MHD Simulations of Plasma Compression by Resistive Liquid Metal*
Wed, 2-5pm: **PP12.15**	Ivan Khalzov, Ryan Zindler, Michel Laberge *2D Lagrangian Code for Resistive Evolution of Plasma Equilibrium and Its Application to MTF Studies at General Fusion*
Fri, 9:30-12:30: **ZP07.11**	Kelly Epp *et al.* *Confinement Physics on Plasma Injector 3*