Tokamak Energy

Recent Progress and Plans for Lithium Technology

8th December 2022

Naomi Mburu

FPA 2022, 7th December – 8th December, 2022

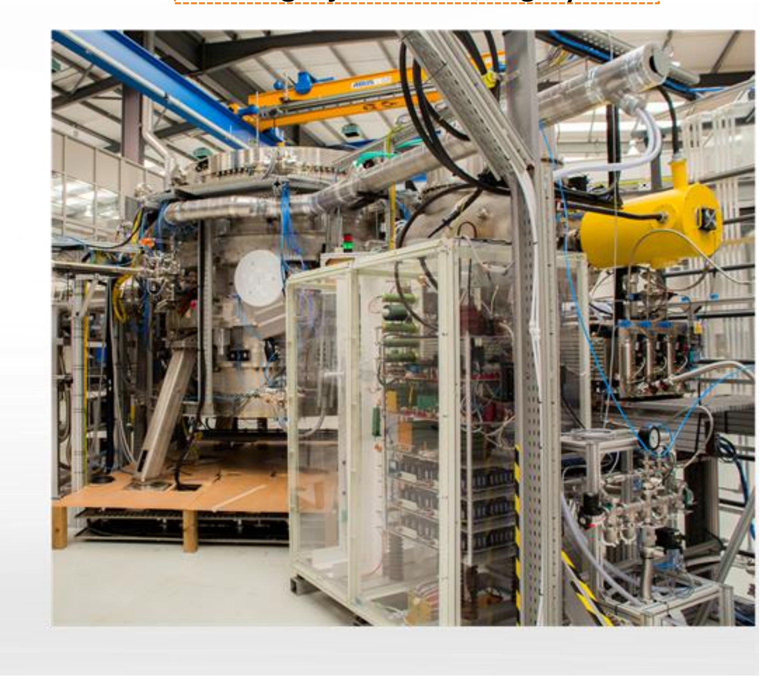
Grand Hyatt Hotel, Washington D.C.

Tokamak Energy Limited

- Established in 2009 in Oxfordshire, UK. US subsidiary expanding
- 220+ employees
- Over $200M investment plus $50M from UK/US governments
- World leading high temperature superconducting magnet facility

Key Technologies

Spherical Tokamaks
Squashed shape, compact
Highly efficient, *high* β

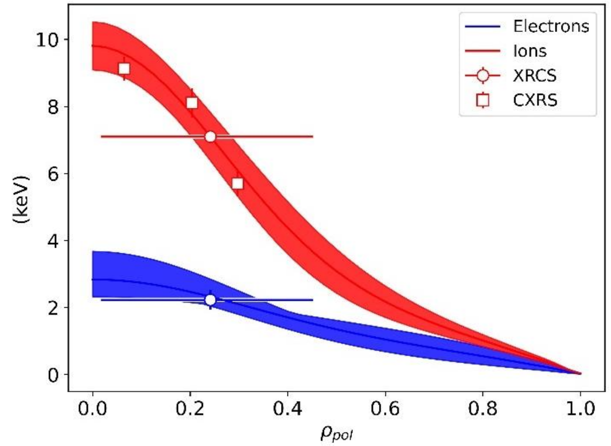


ST40

High Temperature Superconductors
High field
Quench protection simplified
Lower cryogenic cooling requirements

Li technologies
As a path to low recycling regime and sustainable divertor solution

Achievement of ion temperatures in excess of 100 million degrees Kelvin

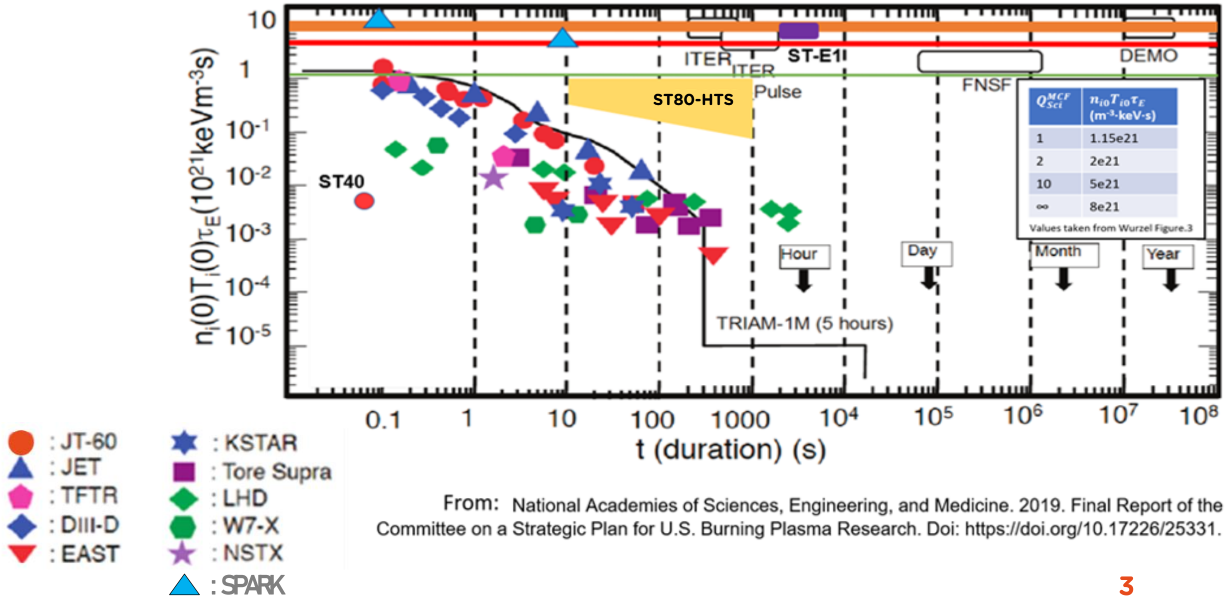


S. McNamara, submitted for publication, 2022

- Highest temperature ever achieved in a spherical tokamak
- Highest triple product achieved of any private fusion company
- Achieved in 5 years for <$70m

What's Next? ST80-HTS Mission

- First high field spherical tokamak using high temperature superconducting (HTS) magnets
- Demonstrate long pulse (~15 min) operation with high duty cycle

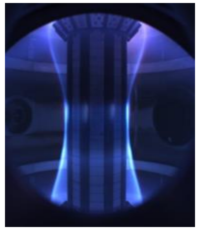


From: National Academies of Sciences, Engineering, and Medicine. 2019. Final Report of the Committee on a Strategic Plan for U.S. Burning Plasma Research. Doi: https://doi.org/10.17226/25331.

The realisation of commercial fusion

ST40

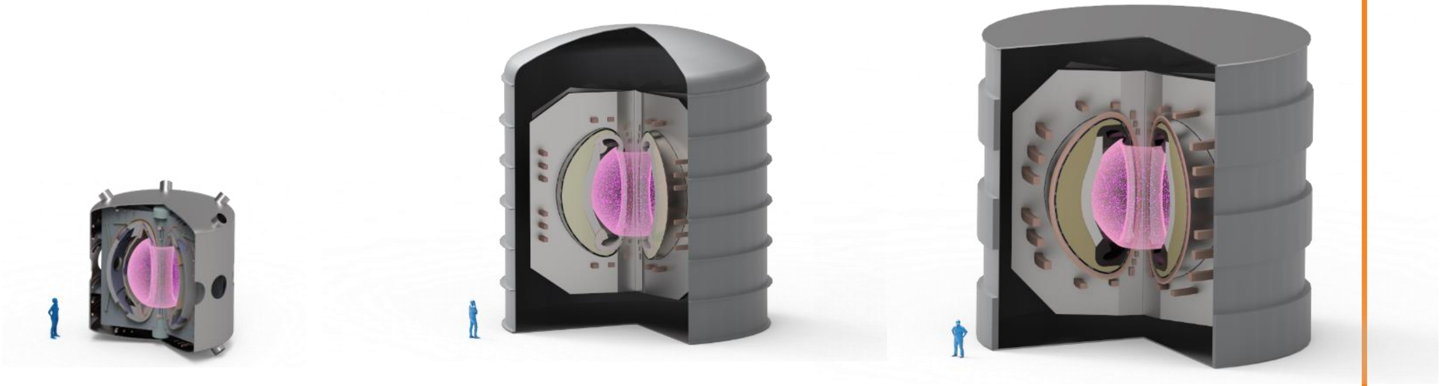
Further validation of ST benefits



HTS

HTS magnet scale up and demonstration of full ST magnet configuration

ST80-HTS | **Fusion Pilot Plant (ST-E1)** | **Commercial Deployment**



High performance ST with HTS magnets

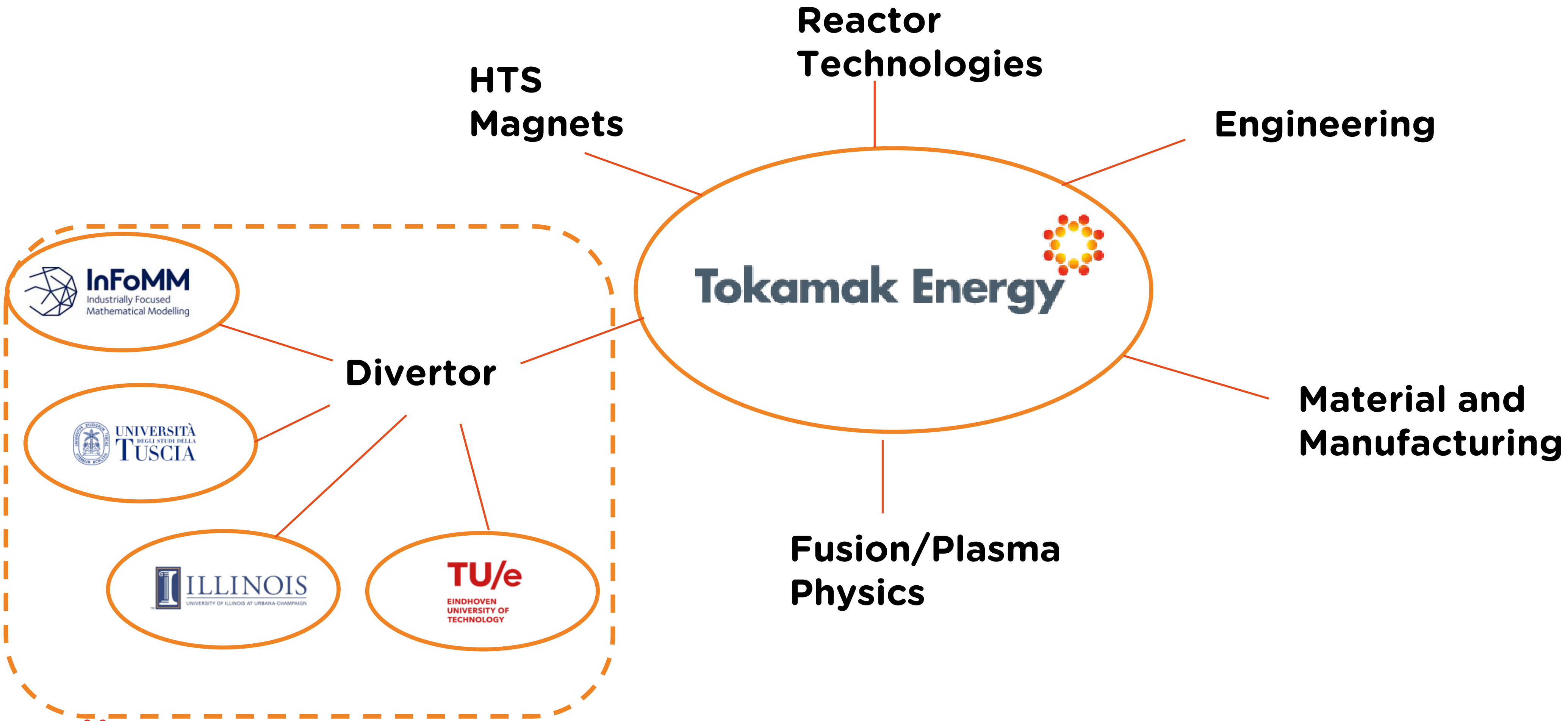
Demonstrates technical & commercial capability

Designed for a rapid, global rollout

Mid 2020s → Early 2030s → Mid 2030s

Supporting Technology Development

With a little help from our friends…



Could Lithium be the path to a robust, steady state divertor and first wall design?

In Short, Yes !

But first, let's discuss why traditional, solid plasma facing components (PFC's) fail

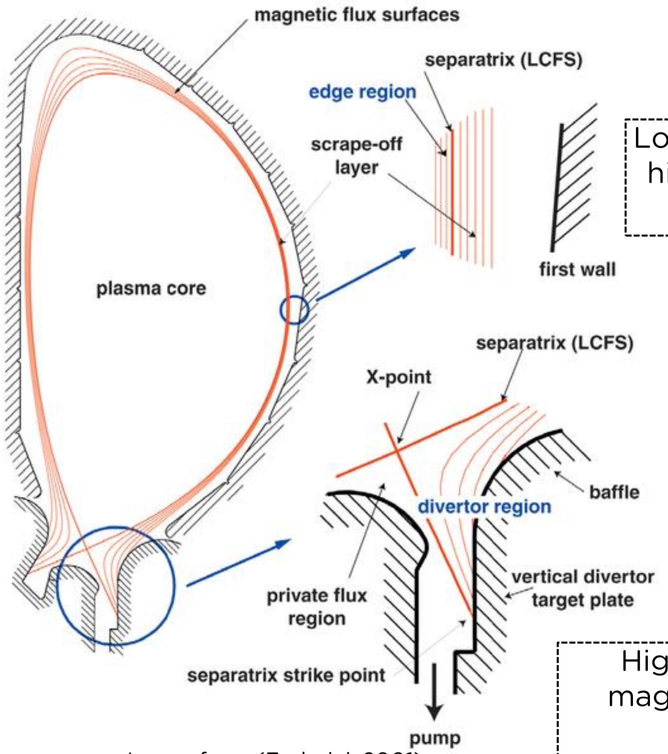
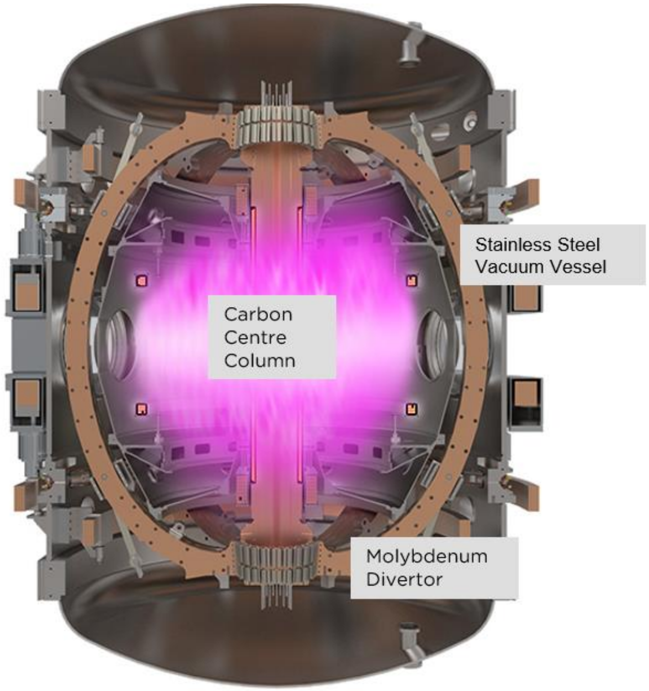


Image from (Federici, 2001)

Lower heat fluxes and high magnetic fields on the first wall

High heat fluxes and magnetic fields on the divertor

First Wall and Divertor Region are of primary interest for LM PFC development



ST40 Spherical Tokamak at Tokamak Energy

A recent study showed that Plasma Wall Interactions accounted for 38% of plasma disruptions on the EAST Tokamak (Gao, 2020)

Sources:
Gao, B., Ding, R., Xie, H., Zeng, L., Zhang, L., Wang, B., ... & Chen, J. (2020). Plasma-facing components damage and its effects on plasma performance in EAST tokamak. *Fusion Engineering and Design*, *156*, 111616.
Younkin, T. (n.d.). PSI SciDAC. In Integrated Modeling of the Plasma-Surface Interaction For Erosion and Impurity Migration In ITER.
Matthews, G. F., Bazylev, B., Baron-Wiechec, A., Coenen, J., Heinola, K., Kiptily, V., ... & Contributors, J. E. T. (2016). Melt damage to the JET ITER-like Wall and divertor. *Physica scripta*, *2016*(T167), 014070.
Baldwin, M. J., & Doerner, R. P. (2008). Helium induced nanoscopic morphology on tungsten under fusion relevant plasma conditions. *Nuclear Fusion*, *48*(3), 035001.
Federici, G., Skinner, C. H., Brooks, J. N., Coad, J. P., Grisolia, C., Haasz, A. A., ... & Whyte, D. G. (2001). Plasma-material interactions in current tokamaks and their implications for next step fusion reactors. *Nuclear Fusion*, *41*(12), 1967.

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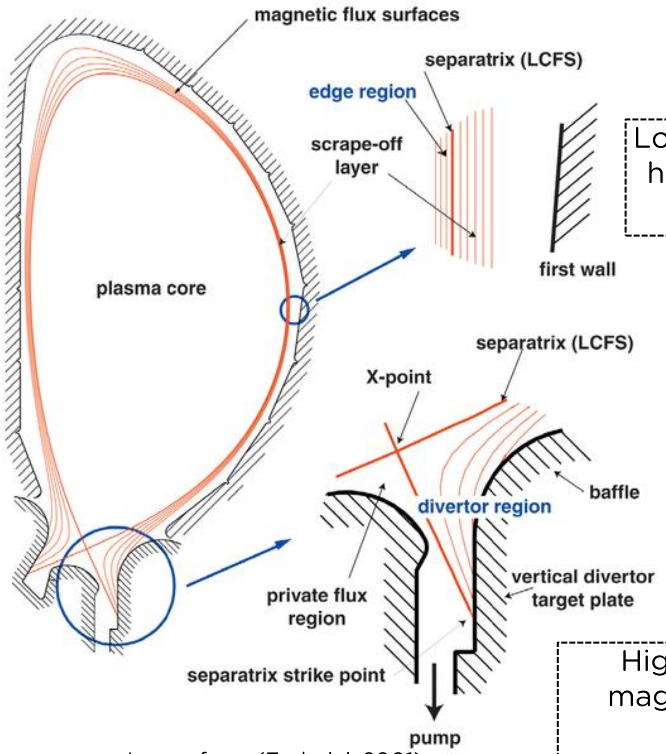
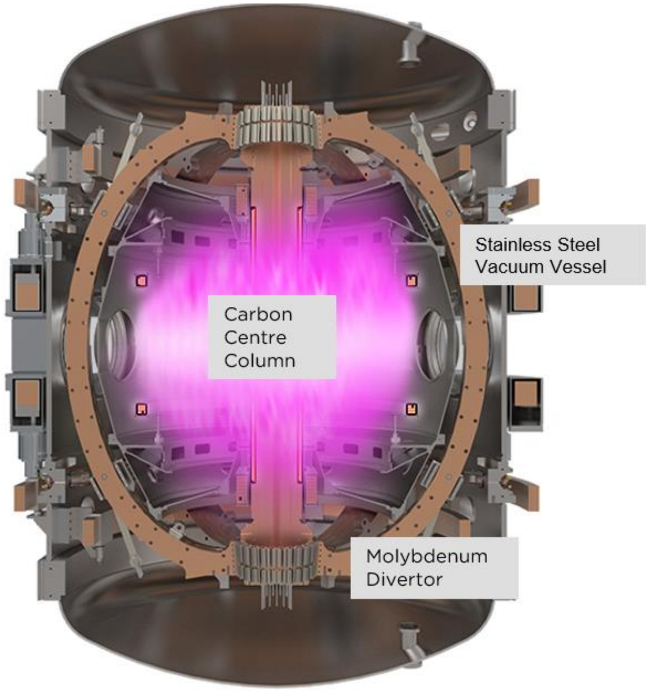


Lower heat fluxes and high magnetic fields on the first wall

High heat fluxes and magnetic fields on the divertor

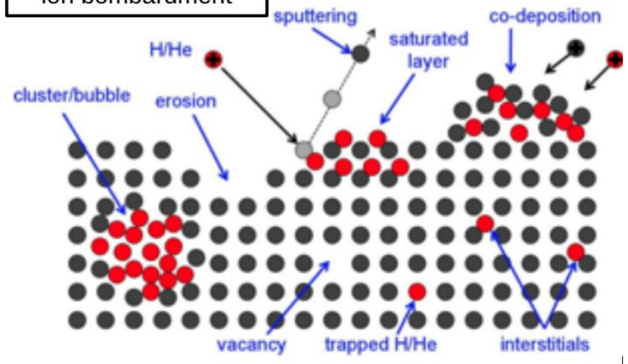
Image from (Federici, 2001)

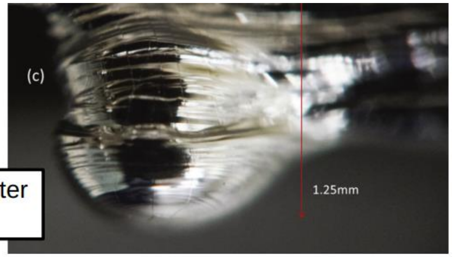
First Wall and Divertor Region are of primary interest for LM PFC development



ST40 Spherical Tokamak at Tokamak Energy

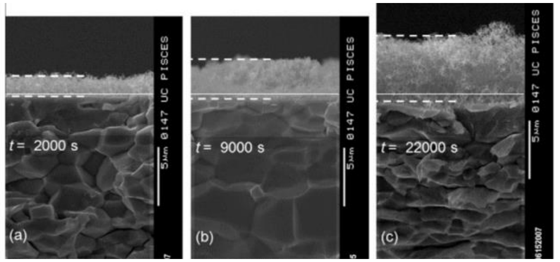
Material damage from ion bombardment





Molten tungsten after disruption

Tungsten fuzz growth after He ion bombardment



Images from: (Matthews, 2016) (Baldwin, 2008), (Younkin, SciDAC)

Sources:
Gao, B., Ding, R., Xie, H., Zeng, L., Zhang, L., Wang, B., ... & Chen, J. (2020). Plasma-facing components damage and its effects on plasma performance in EAST tokamak. *Fusion Engineering and Design*, *156*, 111616.
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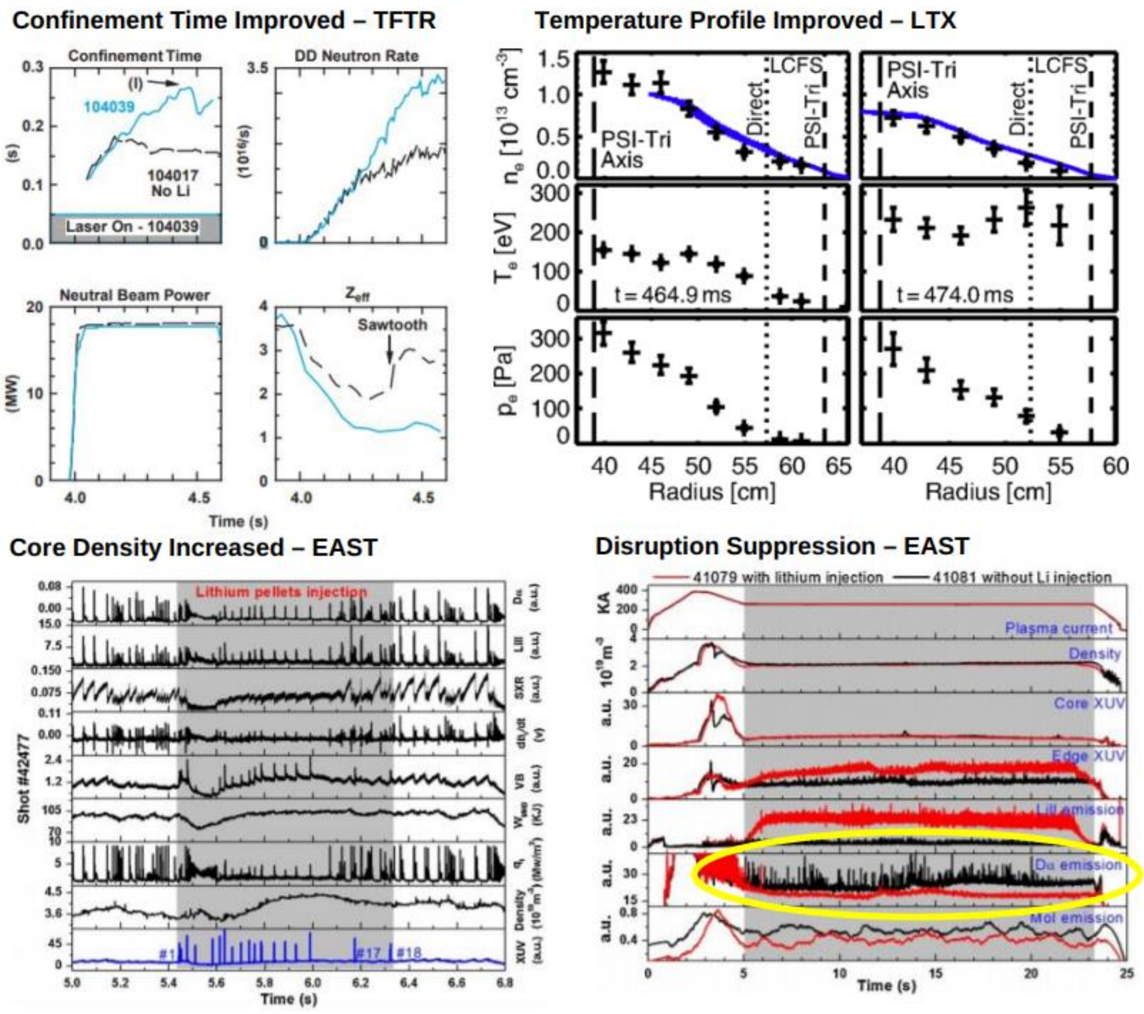
Why use Liquid Metal (LM) PFC's?

Benefits of Liquid Lithium Wall

- Mitigates surface damage during normal operation
- Constantly refreshing, and low recycling
- Prevents high-Z substrate materials from entering core
- Prevents fuel recycling from cooling the core
- Getters impurities and potential to improve helium ash recovery

Improved Plasma Performance

- Increased confinement time
- Increased core temperature
- Increased core density
- Reduction in ELM magnitude and frequency using a powder dropper



Images from (Mansfield, 2001) (Boyle, 2017) (Hu, 2014)

Sources:
Mansfield, D. K., Johnson, D. W., Grek, B., Kugel, H. W., Bell, M. G., Bell, R. E., ... & Wurden, G. A. (2001). Observations concerning the injection of a lithium aerosol into the edge of TFTR discharges. *Nuclear fusion*, *41*(12), 1823.
Boyle, D. P., Majeski, R., Schmitt, J. C., Hansen, C., Kaita, R., Kubota, S., ... & Rognlien, T. D. (2017). Observation of flat electron temperature profiles in the lithium tokamak experiment. *Physical Review Letters*, *119*(1), 015001.
Hu, J. S., Ren, J., Sun, Z., Zuo, G. Z., Yang, Q. X., Li, J. G., ... & Ruzic, D. N. (2014). An overview of lithium experiments on HT-7 and EAST during 2012. *Fusion Engineering and Design*, *89*(12), 2875-2885.

How do Magnetic Fields and Heat Fluxes Affect LM Flow?

Magnetohydrodynamics (MHD)

- ❖ Transverse magnetic fields induce current in flowing liquid metal, which generate an MHD drag effect

F = J x B

MHD and TEMHD Effects

- ❖ TEMHD propels LM flow
- ❖ MHD produces drag

Thermoelectric Magnetohydrodynamics (TEMHD)

- ❖ Seebeck Effect generates thermoelectric current at the junction between the liquid metal and solid sidewall, when a temperature gradient is present

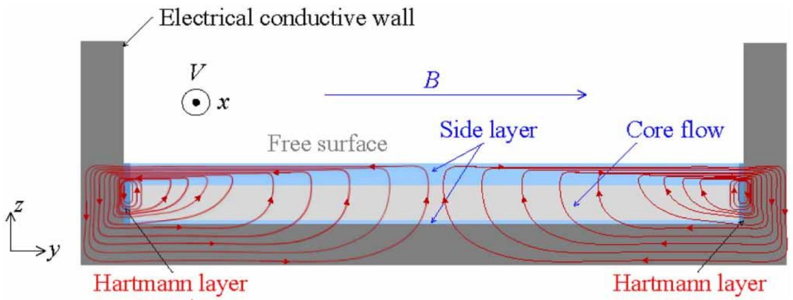


Image from (Yang, 2020)

What we care about is this Hartman Layer activity, which induces a drag effect on the liquid metal

TEMHD Dominates

MHD Dominates

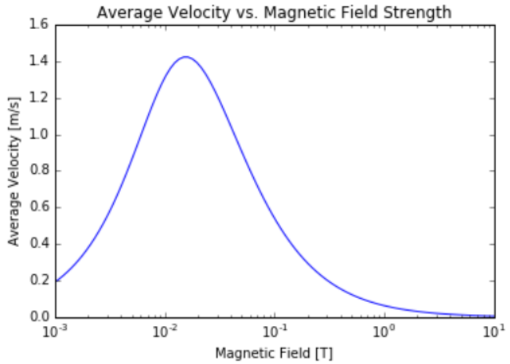


Figure 2.5 – Semi-logarithmic plot of the average TEMHD flow velocity versus magnetic field.

Image from (Szott, 2020)

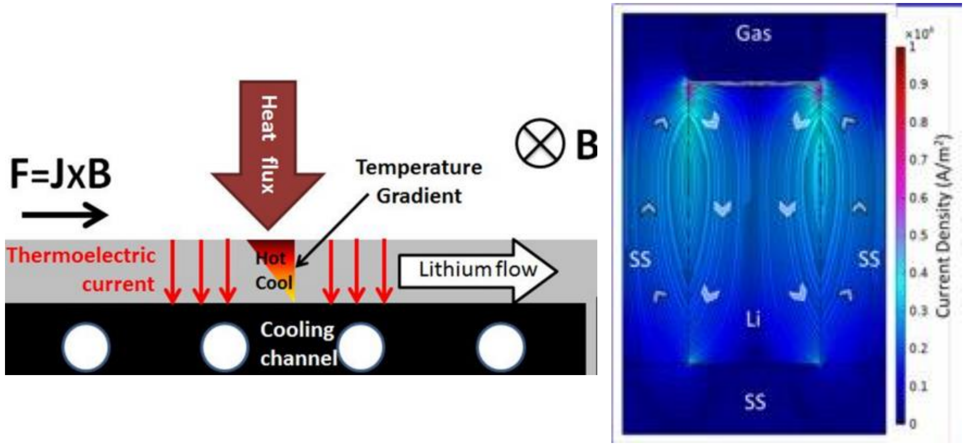


Image from (Xu, 2015)

Yang, J. C., Qi, T. Y., Ren, D. W., Ni, M. J., Liu, B. Q., Hu, J. S., & Li, J. G. (2020). Magnetohydrodynamic effects on liquid metal film flowing along an inclined plate relating to plasma facing components. *Nuclear Fusion*, *60*(8), 086003.
Szott, M. (2020). Advanced Geometries For Dryout Mitigation In Temhd-Driven Liquid Lithium Systems (dissertation). Retrieved from https://www.ideals.illinois.edu/items/115559.
Xu, W. (2015). Experimental And Numerical Analysis Of Thermoelectric Magnetohydrodynamic Driven Liquid Lithium Flow In Open Channels For Fusion Applications (dissertation). Retrieved from https://www.ideals.illinois.edu/items/79861.

Our Progress with Lithium PFC's

Where are we with Lithium Technology Development?

What we know

1. Lithium can reduce surface damage and plasma recycling
2. Lithium can absorb and desorb hydrogen isotopes (tritium recovery)[1] and impurities
3. Lithium PFCs can improve plasma performance

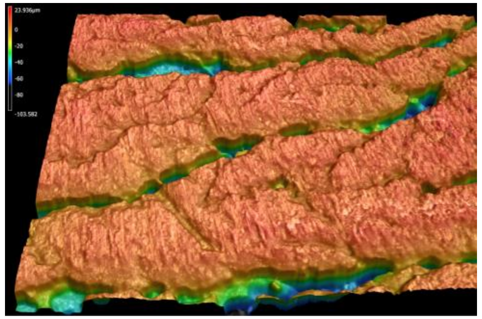
What we don't know

1. How plasma interacts with lithium coated PFC's (UIUC)
2. How to construct a closed loop, flowing lithium loop in a fusion environment (UIUC)
3. How to generate uniform, evenly spread liquid metal flow (Tuscia)
4. How to prevent dryout and droplet formation for thin liquid metal films (Eindhoven)
5. Dynamics of thin film LM flow in a fusion environment (Oxford)
6. Experimental quantification of liquid metal response to magnetic fields (Me @ Oxford)
7. Timescales and saturation points for lithium absorption/desorption of hydrogen (FLARED Infuse)

[1]Christenson, M., Panici, D., Moynihan, C., Wendeborn, J., Anderson, J., & Ruzic, D. N. (2019). A study on hydrogen absorption and dissolution in liquid lithium. *Nuclear Fusion*, *59*(2), 026011..

Snapshots of Our Liquid Metal Research Portfolio (US)

Lithium compatibility with ST40 Divertor Materials

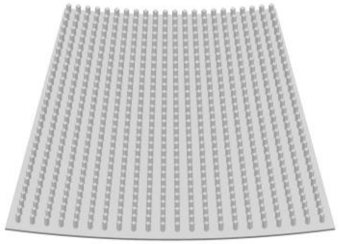


Molybdenum plate analyzed from ST40

Cody Moynihan, Steven Stemmley

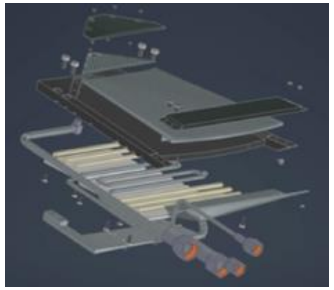
ILLINOIS
UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

Advanced TEMHD Geometries and Integration to Divertor Region



Angled Twisted Posts

Szott,, M. Doctoral Thesis, 2020.

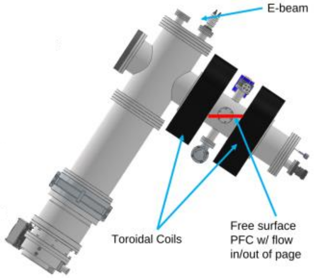


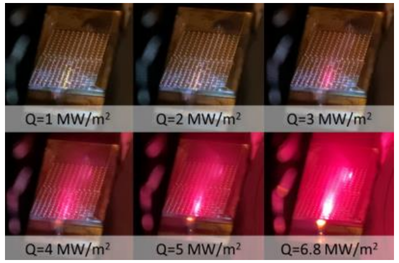
ST40 Divertor Plate Assembly

Matthew Szott, Cody Moynihan, Steven Stemmley

ILLINOIS
UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

Experimental Investigation of TEMHD Effects





SLiDE facility can test TEMHD Effects at 6.8 MW/m2 and up to 0.08T toroidal field

Steven Stemmley, Cody Moynihan

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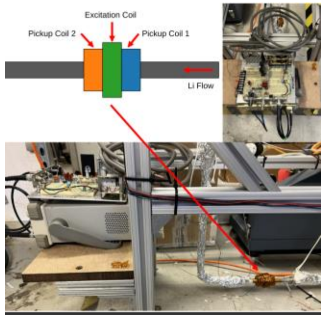
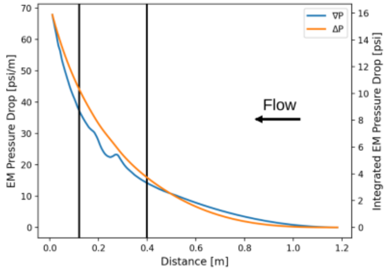
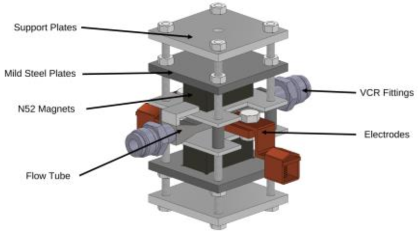
Lithium Pump, Flowmeter and Reservoir Development



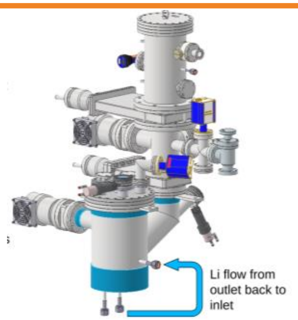
Electromagnetic Flowmeter



ST-40 Pumping Requirements



Conduction Pump



Lithium Loading Lock and Reservoir

Steven Stemmley, Cody Moynihan

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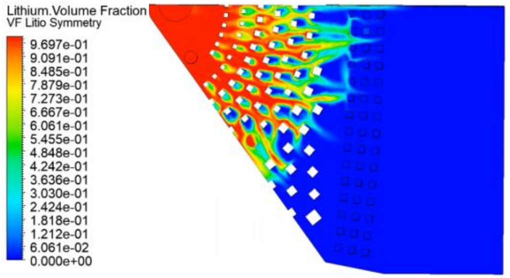
Snapshots of Our Liquid Metal Research Portfolio (Europe)

Modelling of the distributor within ST40's flowing liquid lithium divertor

Distributor Region

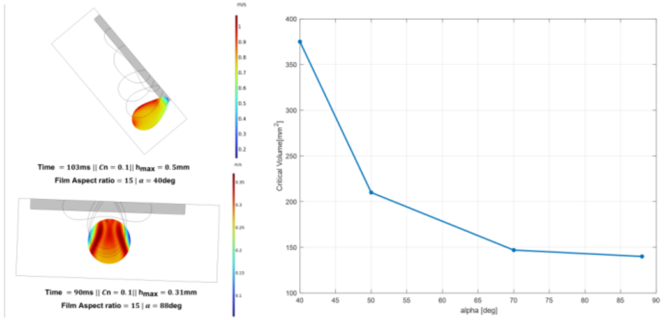


Cuneo, D. Masters Thesis, 2022.

Davide Cuneo

Università degli Studi della Tuscia

Computational Exploration of film rupture and droplet formation



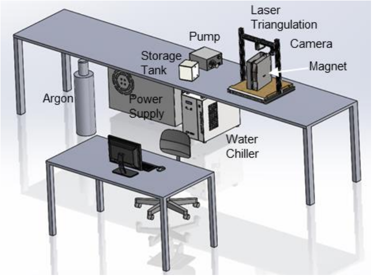
Mingozzi, S. Masters Thesis, 2022.

Simone Mingozzi

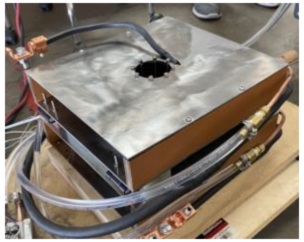
TU/e Eindhoven University of Technology

Experimental Quantification of LM Response to Magnetic Fields/TEMHD

$$\Delta h = f(B,\ Q,\ \alpha)$$



Oxford's First Liquid Metal Flow Experimental Facility



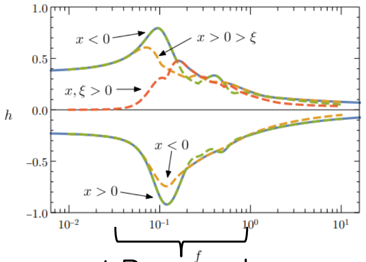
1T, Adjustable Electromagnet

Naomi Mburu

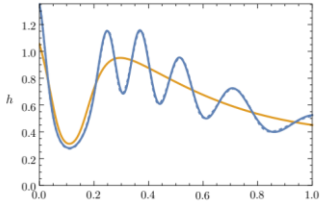
Oxford Thermofluids Institute · PPPL Princeton Plasma Physics Laboratory

Dynamics of thin film LM flow in a fusion environment

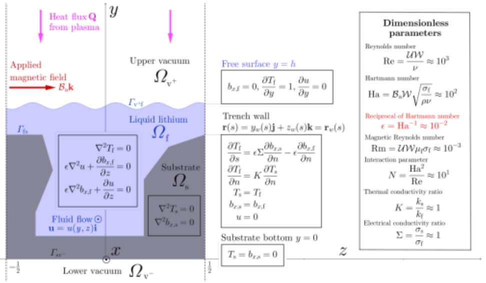
Pressure Sweeping Effects



Resonant Range where dangerous thinning may occur



Comparing Unsteady (Blue) and Steady (Orange) state free surface flow



Computational Modelling of TEMHD Flow in COMSOL

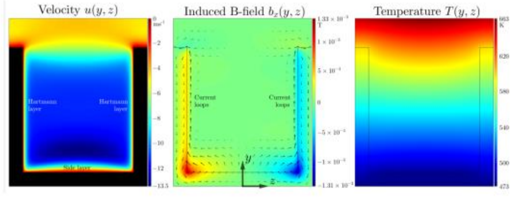


Figure 4 – Representative plots of numerical solutions to the 2D trench problem posed above.

Lunz, D. Doctoral Thesis, 2022.

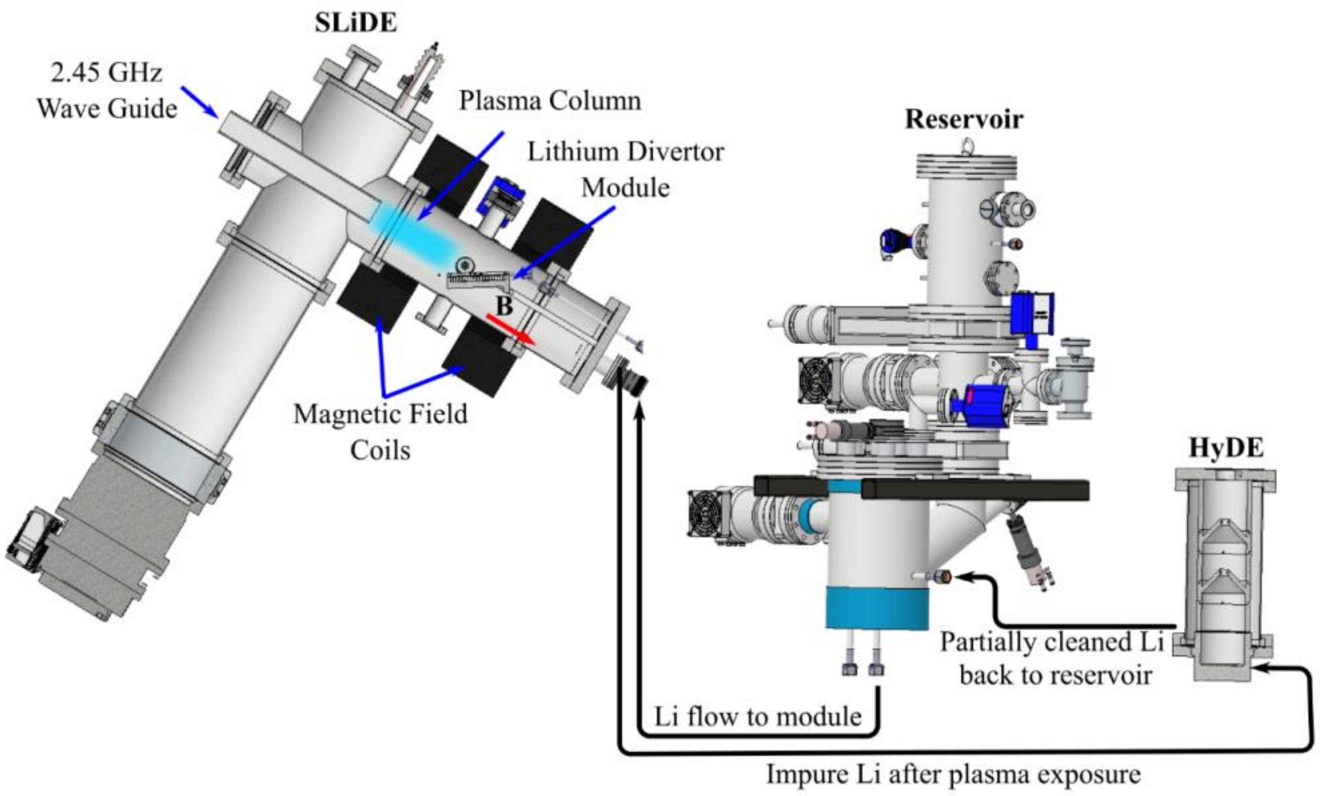
Oliver Bond, Davin Lunz

InFoMM Industrially Focused Mathematical Modelling

What is on the horizon?

FLARED: Flowing Lithium's Adsorption and Release Experiment for Deuterium

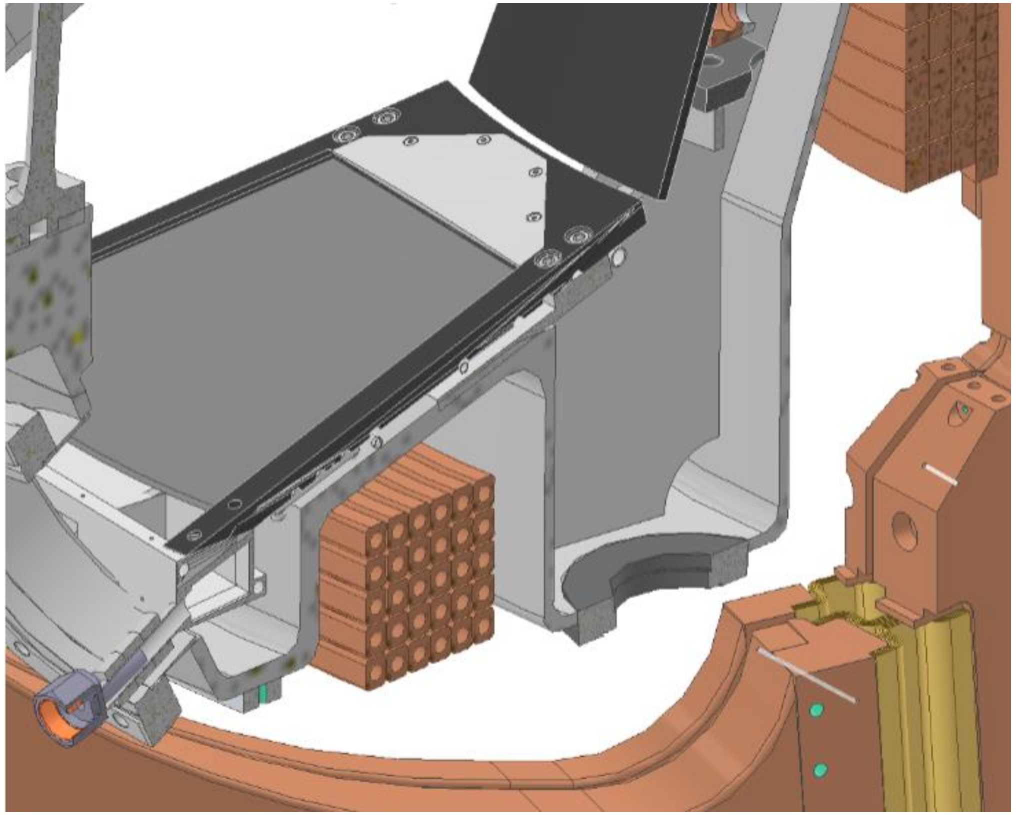
A US DOE INFUSE project with the University of Illinois, Urbana Champaign
Deuterium used as a proxy for tritium



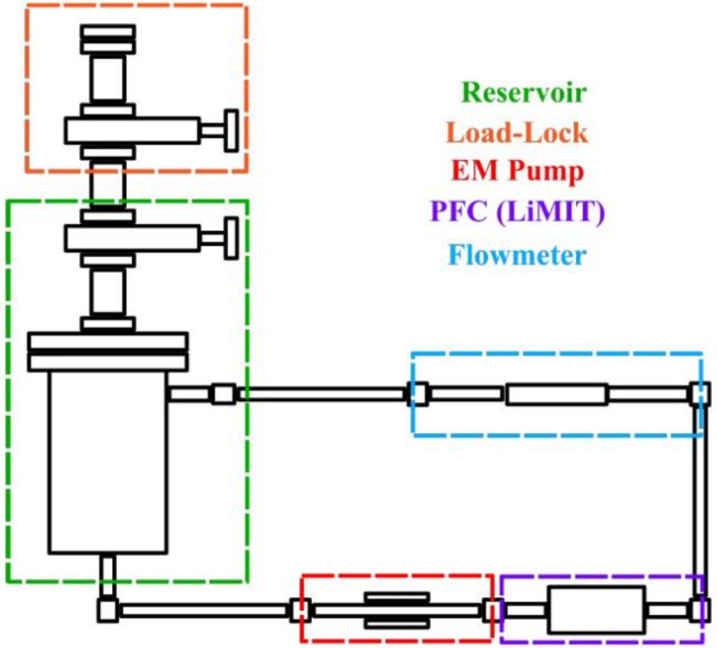
How much tritium does liquid lithium pump?

How quickly can unburnt tritium be recovered from liquid lithium?

Feasibility Studies for a Flowing Liquid Lithium Loop for ST40



CAD of flowing liquid lithium plate suitable for installation on ST40



Components under development

The road ahead to fusion is lined with Lithium!

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