DIII-D Strategic Planning Meeting

Jim Pickles

Concept

Tokamak Energy

250+

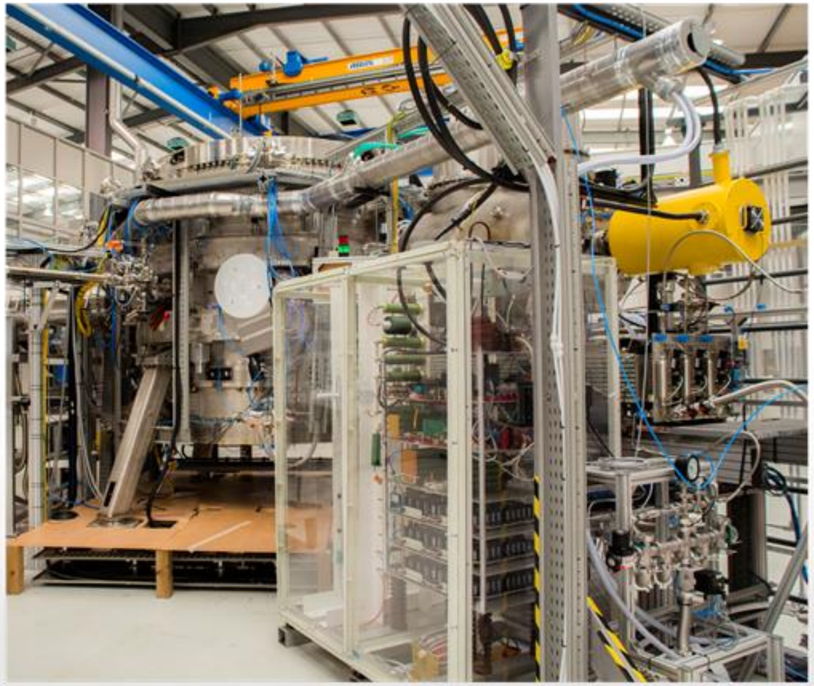
World-class scientists, engineers
and commercial specialists

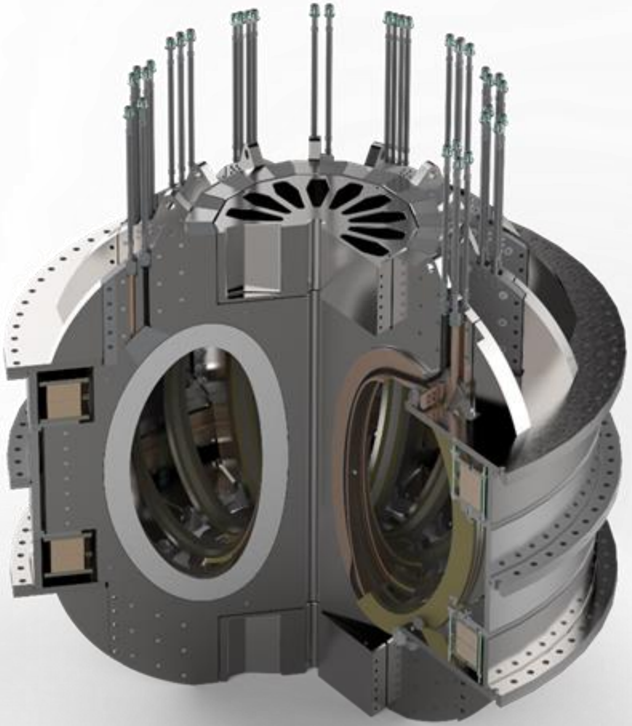
$250M raised to date

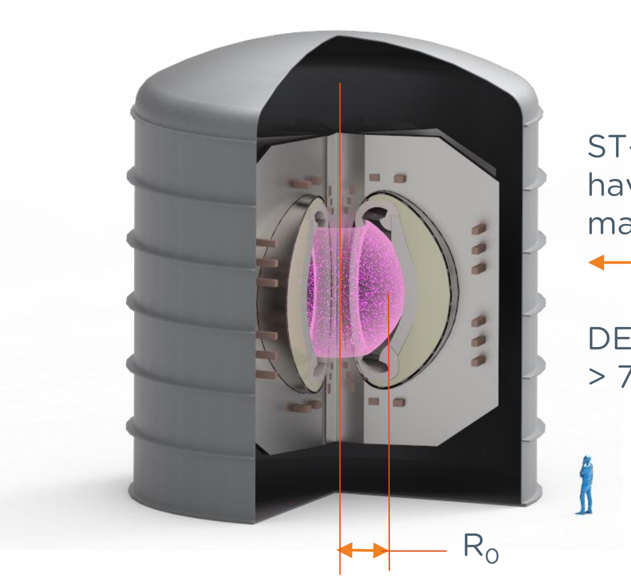
Financial backing from private
capital and government grants

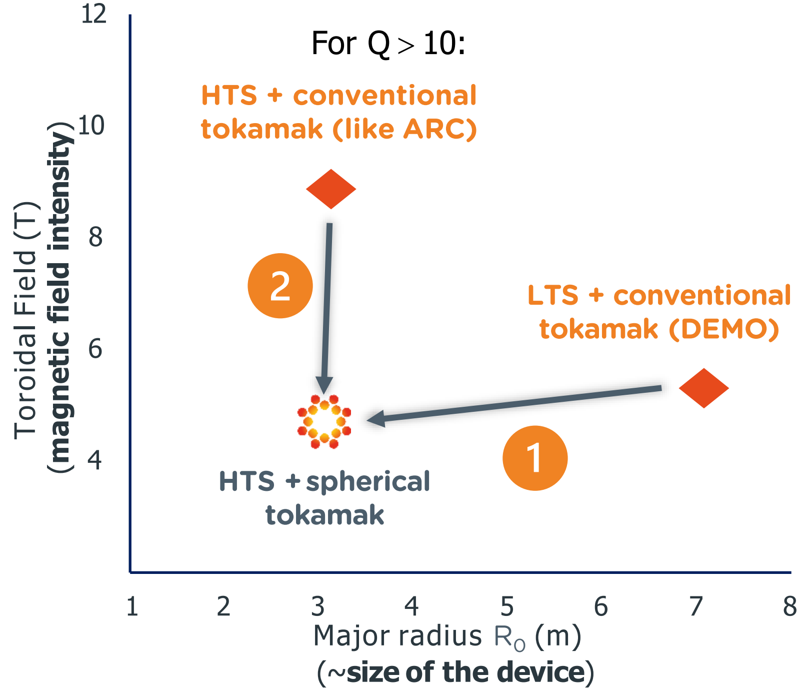
Goal

On track to bring commercial
fusion to market in the 2030s









'Q' is the ratio of fusion energy to energy used to heat the plasma.
Commercial viability for net electricity generation needs Q > 10

Our differentiator:

Compact, Low Cost Fusion

Spherical Tokamak with HTS offers energy producers a compact, highly efficient and low cost fusion solution.

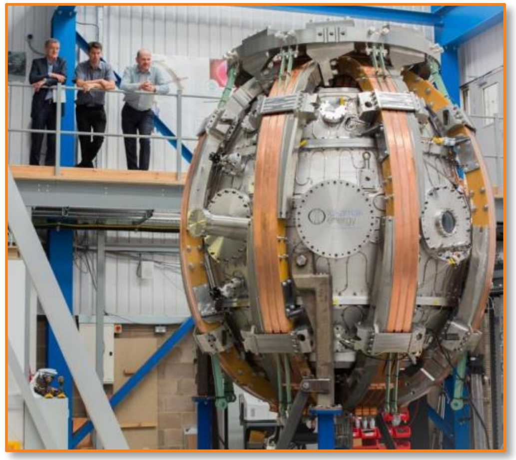
1 Compact Spherical Tokamak

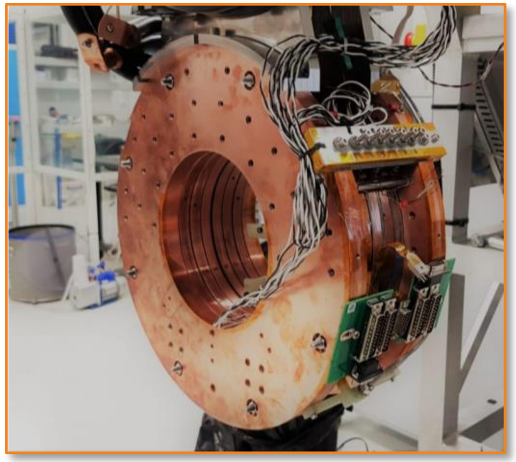
- Spherical tokamak is **more efficient than conventional tokamaks** for two reasons**:**
  - High "beta" = lower magnetic field needed to reach fusion conditions
  - High "bootstrap fraction" = reduced recirculated power required to drive plasma current
- Enables a smaller reactor for the same energy output
  - Approximately half the linear dimensions of a conventional Low Temperature Superconductor (LTS) tokamak with higher Q (~25) - **lower CapEx & lower OpEx**

+

2 High Temperature Superconducting (HTS) magnets

- HTS magnets enable stronger magnetic fields and smaller devices
  - Size of ITER & DEMO are set by use of LTS magnets
  - ST needs lower magnetic field in plasma for same performance as a conventional tokamak using HTS = **less HTS** - **lower CapEx**
- HTS also operates at 4x higher temperature than LTS - reduces recirculated power used for cooling the magnets - **lower OpEx**





The right partner for fusion

We are the best positioned private company to bring commercial fusion to market

Founded in 2009 as a spin-out from the renowned Culham Centre for Fusion, we're the **only private company with 10 years' experience** designing, building and operating tokamak devices. We continue to set the pace for commercial fusion: delivering industry-leading results for fusion performance and component technologies.

2017
Designed, built and operate the world's **highest-magnetic field** spherical tokamak (ST40)

2020
Achieve **world-record over 24 T field at 20 K** using our patented HTS magnet technology

2022
First private fusion company to achieve **100M °C** plasma ion temperature in a tokamak

2022
Achieved the **highest plasma 'triple product'** by any private fusion company

The pathway to commercial fusion

We offer a credible pathway to bring fusion to market in the 2030s.

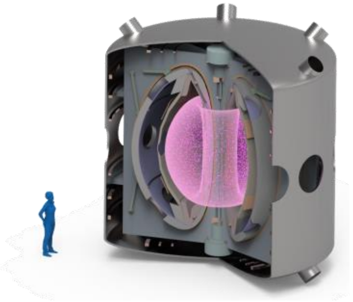
Advanced Prototype

2026

ST80-HTS

ST80-HTS will demonstrate multiple advanced technologies required for commercial fusion energy

Location: UK



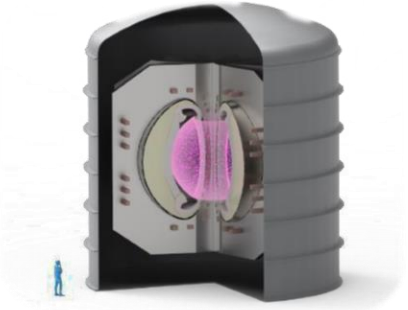
Fusion Pilot Plant

Early 2030s

ST-E1

ST-E1 will be a commercial-scale fusion pilot plant producing up to 200 MW of net electrical power

Location: TBC (early adopter market)



We are seeking strategic delivery partners for the next phases of our commercialization program

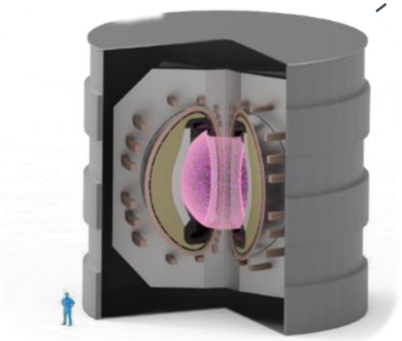
First of a Kind Commercial Plant

Mid 2030s

FOAK

First of a Kind (FOAK) will be a commercial fusion power plant generating 500MWe

Location: TBC (early adopter market)



Technology gaps

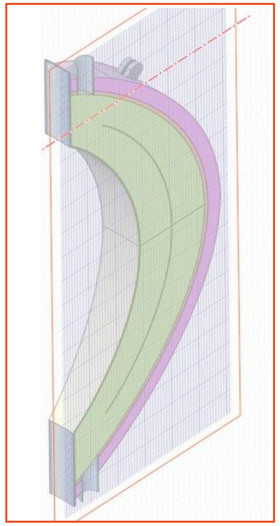
Breeding Blankets and Fuel Cycles

Breeding Blankets

Naturally Enriched Liquid Lithium Breeding blankets

Conceptual design of a liquid lithium breeding blanket

Detailed design of breeding blanket, fabrication of prototype module, tools and manufacturing processes

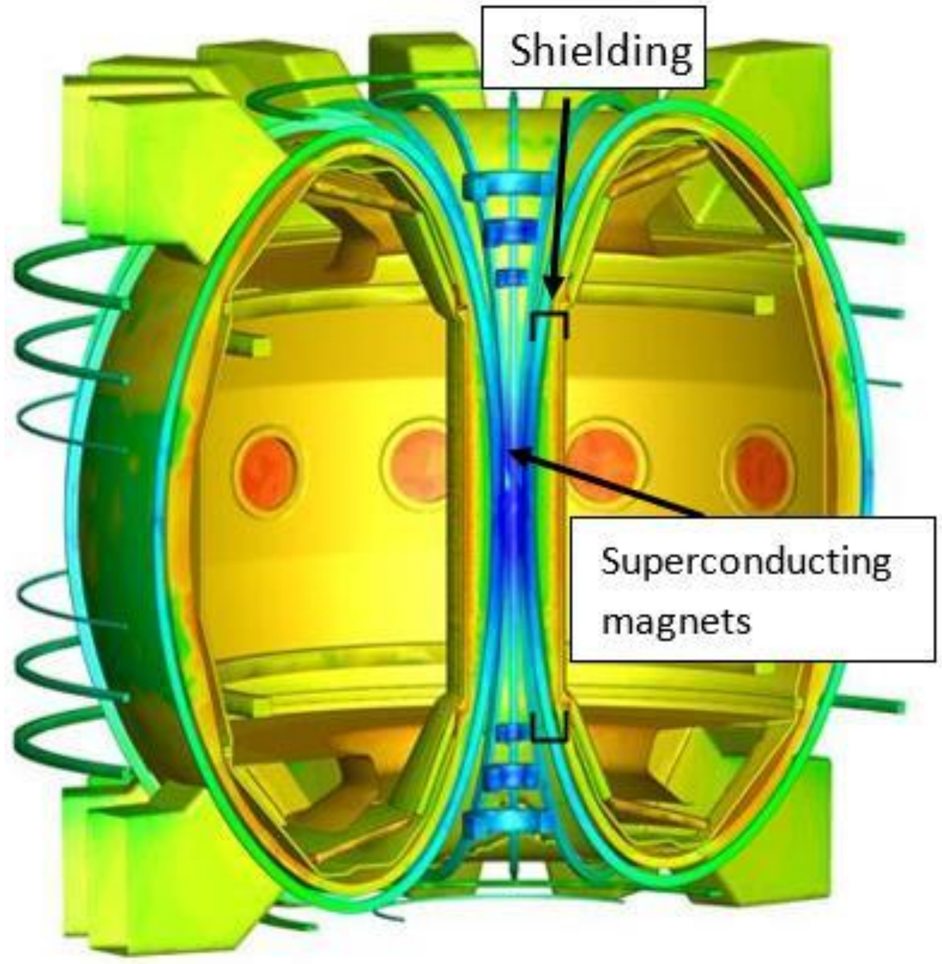


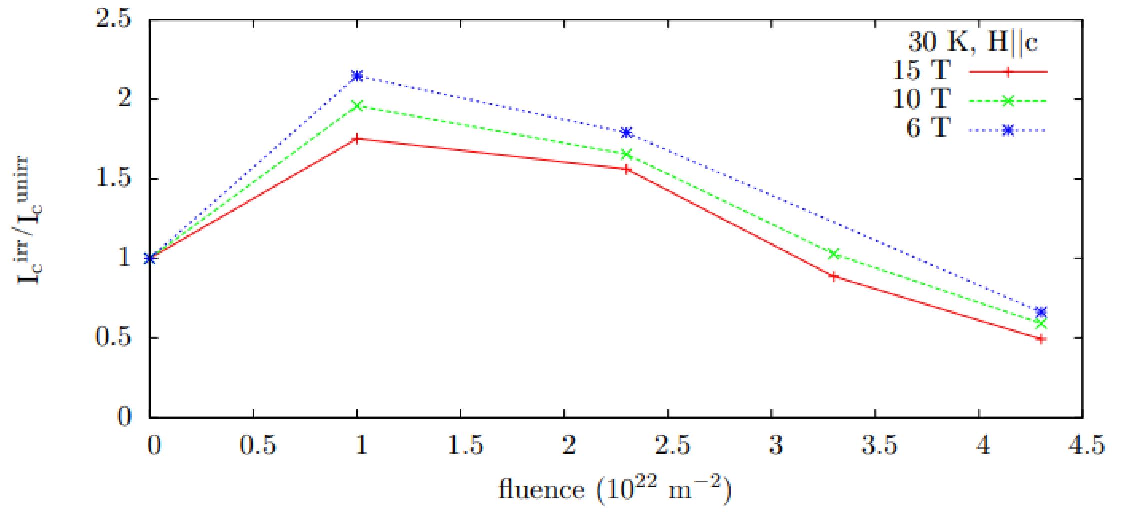
Testing of performance in breeding blanket testing facility

- Naturally enriched liquid lithium breeding blanket concept
- **Vanadium alloy and/or CNA based design**

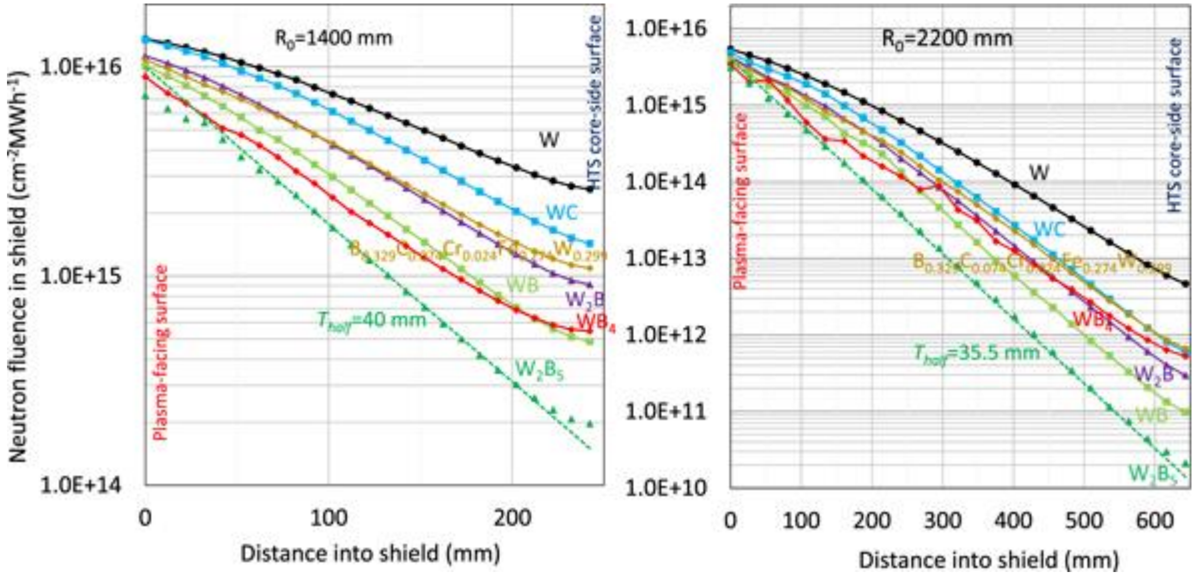
Advanced Radiation Shielding

Compact Spherical Tokamaks Require high-performance radiation shielding which could also be relevant for other neutronic fusion concepts





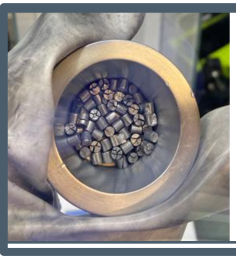
D. Fischer, *Effect of neutron radiation damage on coated conductors for fusion magnets*, 2019

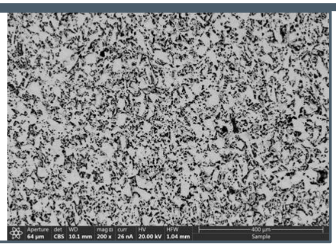


Colin G. Windsor *et al* 2021 *Nucl. Fusion* **61** 086018

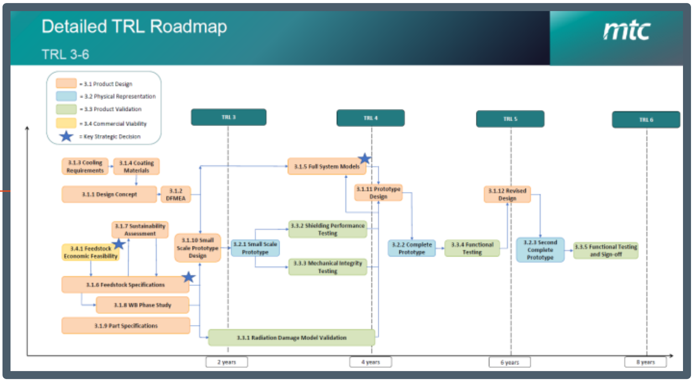
Key enabling technology: Advanced Radiation Shielding

Work Package	Status
A. Identify Advanced Shield materials	Complete
B. Synthesize and characterize WB_x and HfH_x	In progress
C. Radiation Damage Modelling	In progress
D. Detailed TRL & MRL tactical roadmap	Complete
E. Experimentally validate Radiation Damage models	Ready to commence
F. Integrated concept design	Ready to commence
G. Demonstrate shield performance – prototype test (TRL6)	Ready to commence
H. Supply chain gear up	In progress





INFUSE Innovation Network for Fusion Energy



- We have undergone work on producing a roadmap to develop a pathway to industrial scale manufacturing of our shielding technologies
- Additionally, we are looking into novel composite materials which would not only have a shielding function, but also a structural function for regions where spatial constraints require both functions

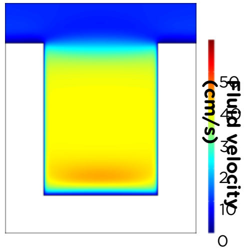
Shield testing in DIII-D (e.g. novel composites)?

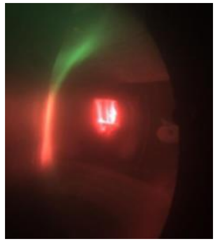
Plasma Facing Components

Liquid lithium divertor in more detail

- If using lithium, then T removal is important. **Conclusion:** lithium must be flowing.

Thermoelectric MHD (TEMHD; self-flowing)





O. Bond,
University of Oxford & TE

O'Deaet, et. al.,
Nuc. Fusion,
2022
(under review)

Fast flowing

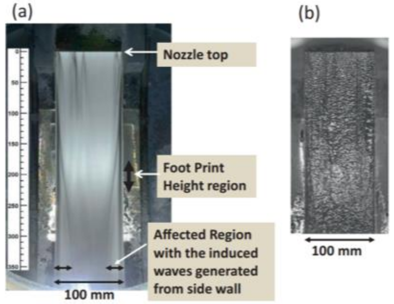
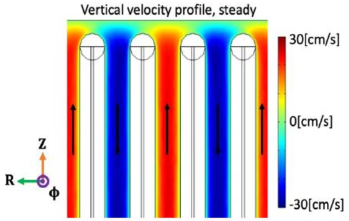


Fig. 5. Li target images at 20 m/s at 300°C taken by (a) a video camera for two seconds and (b) a high speed video camera for 10 μs.

E. Wakai, et. al.,
Nucl. Mater. Energy, 2016

Divertorlets



R. Maingi,
ISLA-7, 2022

- **Advantages:** self-propelled flow
- **Disadvantages:** flow is not fast enough to transport heat down stream

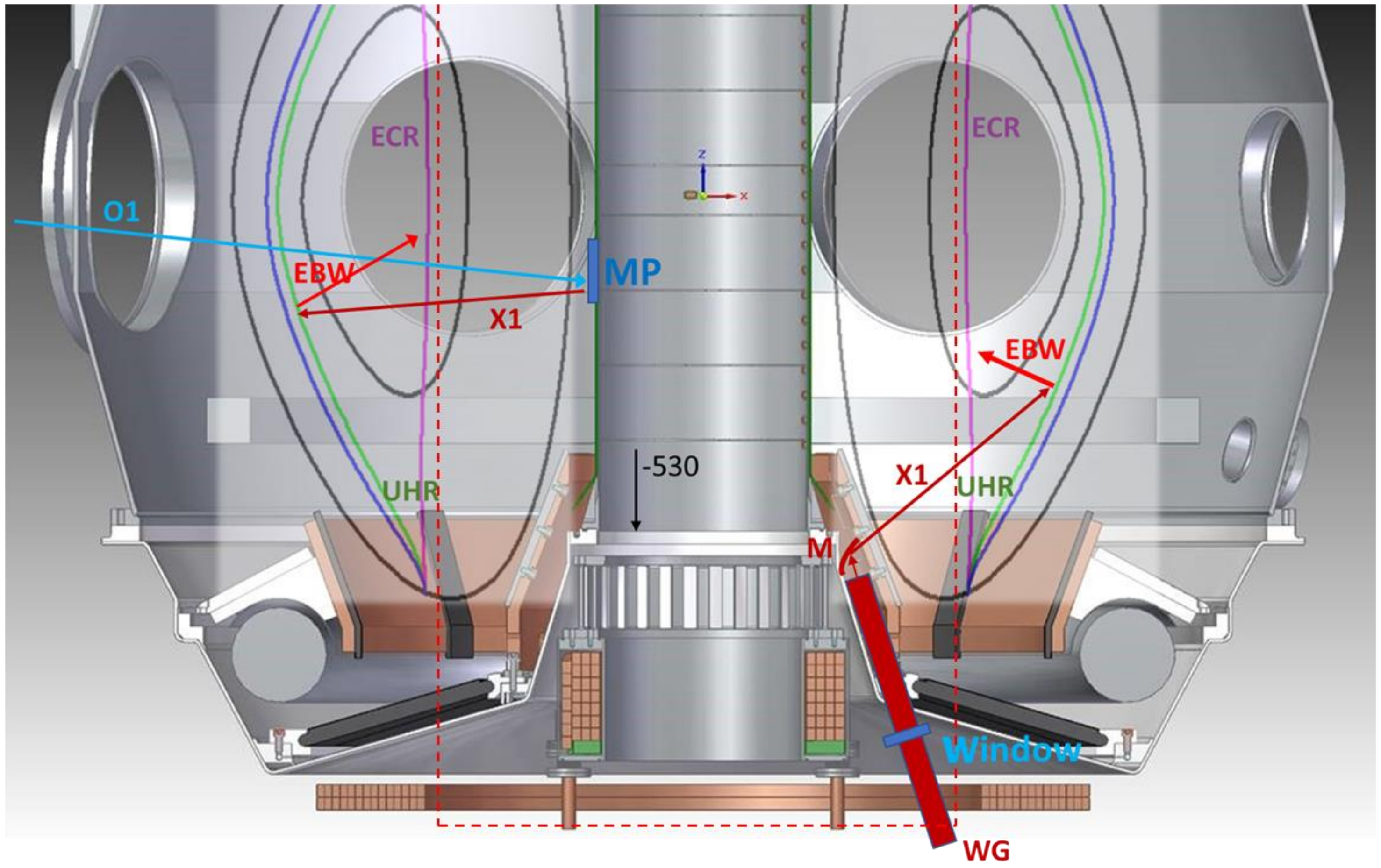
- **Advantages:** potentially can withstand higher power loading than solids
- **Disadvantages:** pumps are technologically challenging and may require a lot of power

- **Advantages:** continuous replenished surface and lower power than fast flowing
- **Disadvantages:** free surface needs to be flat, electrodes technologically challenging

Very interested in regenerative PFCs, especially different methods of Lithium flow in a plasma environment

Startup

Direct HFS X1 Launch and with Mirror-Polariser



Poloidal cross-section of ST40 with 2 options of EBW excitation: O-X-B with mirror-polariser (left) and X1 direct HFS launch (right). Fundamental EC resonance is indicated by the dashed red line.

- 2 options of HFS X1 launching are under development on ST40
- Direct HFS X1 launch is ideal for EBW plasma start-up based on X1-EBW mode conversion
- Direct X1 launch has a highest density limit but cannot provide central heating and CD
- Alternative option is based on LFS launch of O1 mode with subsequent O1-X1 MC on a mirror-polariser (MP) at the central post
- The later scheme can provide central H&CD but accessibility is limited by O-mode cut-off
- Both steerable LFS launchers will allow beam focusing at MP for both frequencies 140/105 GHz and will support co- or counter- CD if RF beam reflected below or above midplane
- Design of HFS launchers and steerable LFS launchers is in progress in collaboration with **ORNL under INFUSE grant**

DIII-D synergy: EBW start-up experiments (Vladimir Shevchenko)

Materials

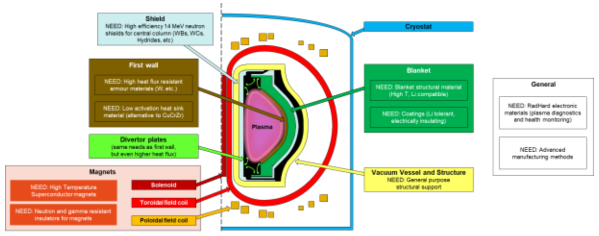
Materials Strategy

Identify critical challenges, Collaborate, Validate in real environments

	Plasma	Neutrons	Load	Heat	Chemical	Tritium
Environmental challenge Complex and aggressive	Plasma erosion Sputtered armour material poisons plasma	Atomic displacement; Solid transmutation; Gaseous transmutation **Each atom displaced >20 times / year** **Brittle transmutants and gas bubble formation impacting material properties** **Orders of magnitude worse than fission environment**	Physical load; Magnetic load Blanket modules weighing several tonnes Magnetic forces strong enough to lift battleships	Heat flux; Temperature Plasma temperatures > 100 M °C **Heat fluxes > 20 MW/m²**	Chemical / corrosion Coolants are highly corrosive	^{3}H Tritium permeation Lose valuable tritium into structure
Synergies challenge Strong and unpredictable	INTERACTION STRONG INTERACTION STRONG INTERACTION UNPREDICTABLE INTERACTION INTERACTION			INTERACTION		
Simulation challenge Lack of simulation options		**No way to simulate experimentally (in the absence of a Fusion Prototypic Neutron Source),** **No predictive computer models**			**Hard to model or simulate experimentally**	
	Synergistic effects particularly challenging to simulate					
		Critical challenge		**Critical challenge**	**Critical challenge**	

Key challenge is materials testing in a truly representative environment…

Testing campaign focused on key parameters for safe operation



Testing and surveillance campaign in future TE devices

Materials testing in DIII-D: Vacuum, plasma, magnet interactions?

Specific materials needs

Materials need to be low-activation, and neutron-tolerant and must be capable of performing at high temperatures (with overlapping operational temperature windows)

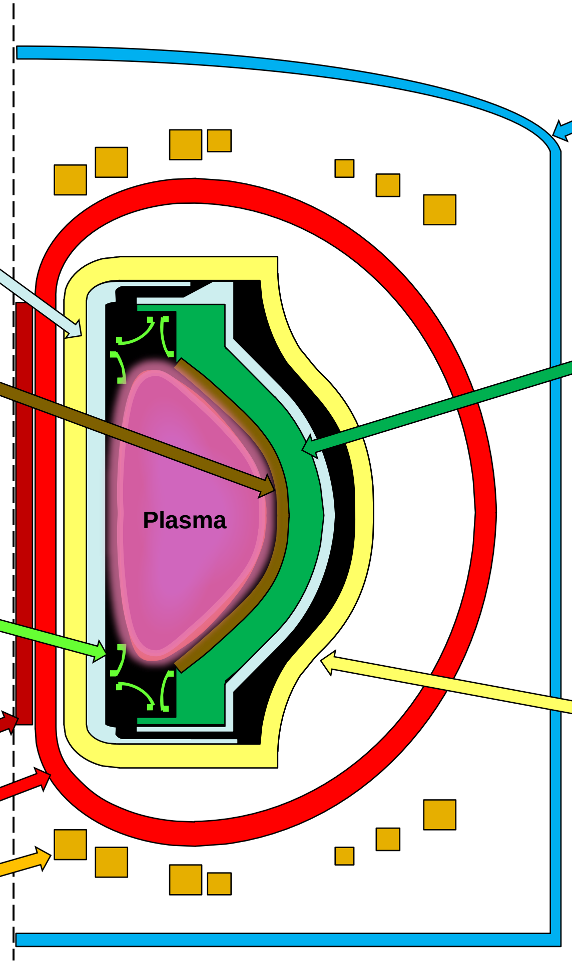
Shield
NEED: High efficiency 14 MeV neutron shields for central column (WBs, WCs, Hydrides, etc)

First wall
- NEED: High heat flux resistant armour materials (W, etc.)
- NEED: Low activation heat sink material (alternative to CuCrZr)

Divertor plates
(same needs as first wall, but even higher heat flux)

Magnets
- NEED: High Temperature Superconductor magnets
- NEED: Neutron and gamma resistant insulators for magnets

Solenoid
Toroidal field coil
Poloidal field coil



Cryostat

Blanket
- NEED: Blanket structural material (High T, Li compatible)
- NEED: Coatings (Li tolerant, electrically insulating)

Vacuum Vessel and Structure
NEED: General purpose structural support

General
- NEED: RadHard electronic materials (plasma diagnostics and health monitoring)
- NEED: Advanced manufacturing methods

Summary

Summary of areas of interest

Shielding
- Testing of novel shield materials (e.g. composites)

PFCs
- Regenerative PFCs, especially different methods of Lithium flow in a plasma environment

Startup
- Electron Bernstein Wave start-up experiments

Materials
- Materials testing in application (vacuum, plasma, magnet interactions)

Control, diagnostics & actuators
- Focus on developing pilot plant relevant control, diagnostics & actuators
- Developing compatible scenarios (e.g. with reduced diagnostics, and FPP relevant actuators)

End