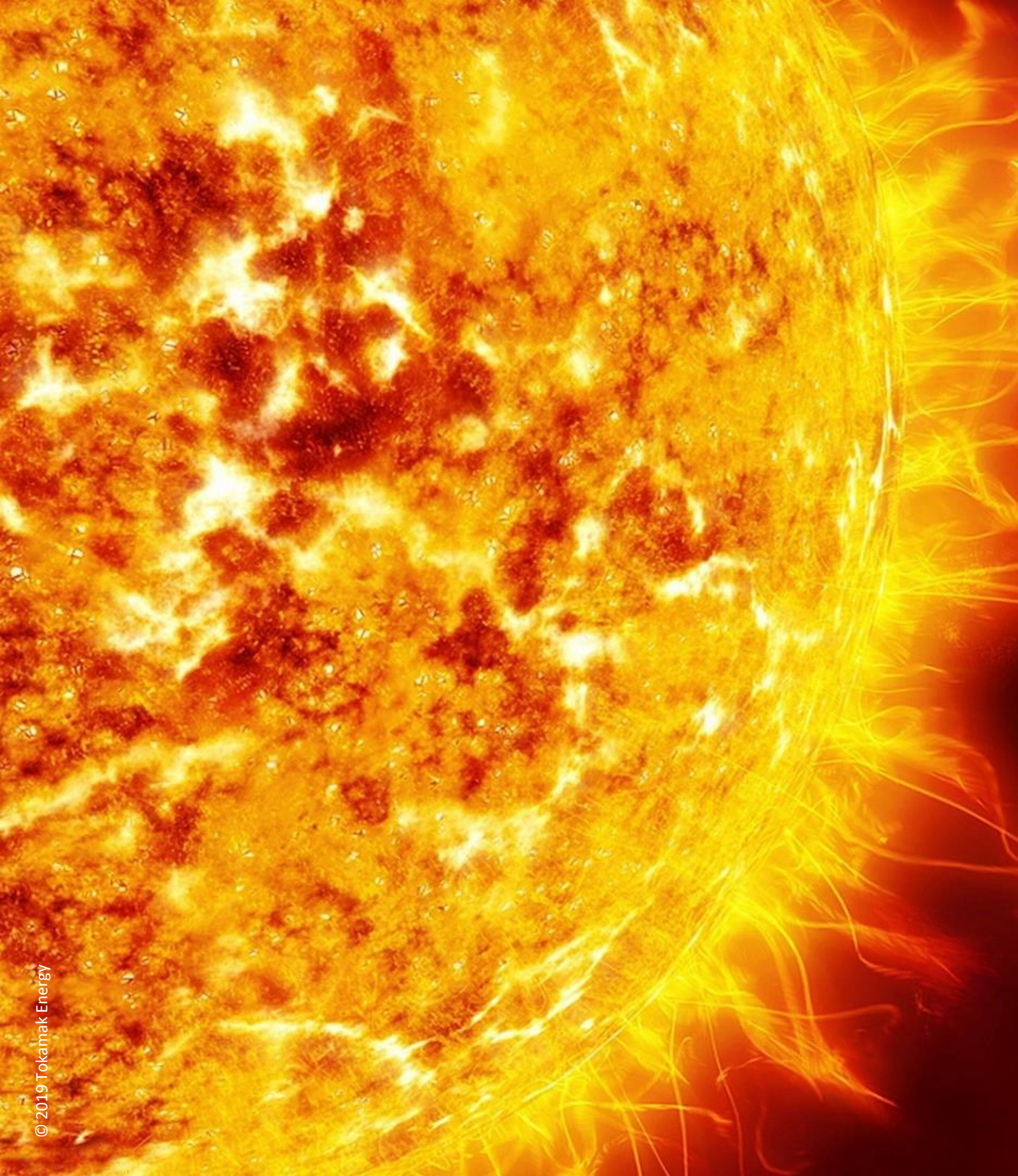

tokamak energy

a faster way to fusion

Tokamak Energy and the high-field spherical tokamak route to fusion power

Dr Steven McNamara
& the Tokamak Energy Team

Overview

tokamak energy
a faster way to fusion

- Introduction to Tokamak Energy
- The high field ST approach to fusion
- ST40: Overview and research programme
- HTS magnet development: Progress and future plans

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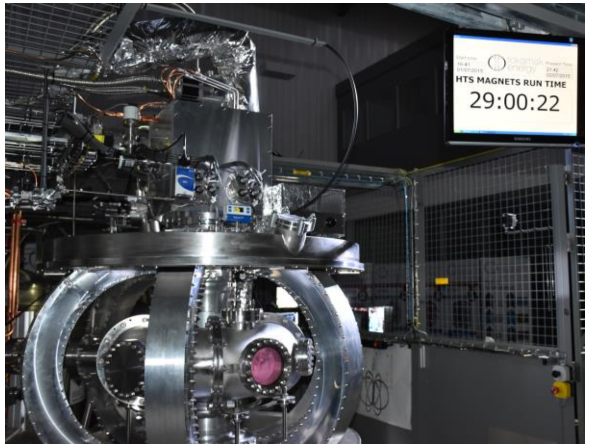
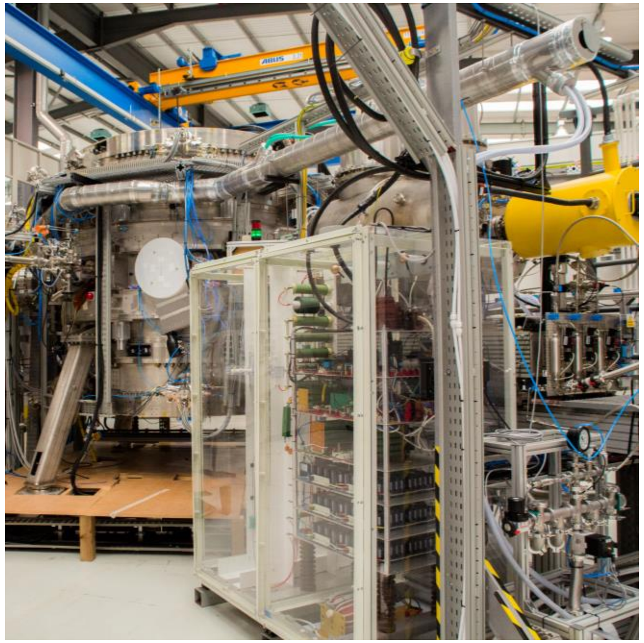
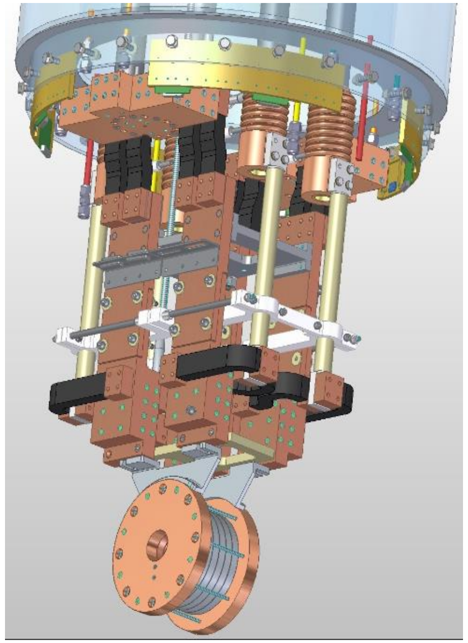
Tokamak Energy

tokamak energy
a faster way to fusion

- Established in 2009 with a mission to develop a faster way to fusion energy
- Private company with over £50M investment
- Engineering centre in Milton Park, Oxfordshire, UK
- Team of over 80 scientists, engineers and technicians
- Designed, built and tested 3 prototype tokamaks since 2012
- World leading high temperature superconducting magnet laboratory



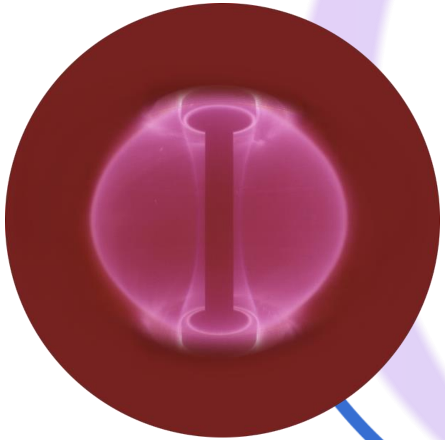




Promising physics and emerging technologies

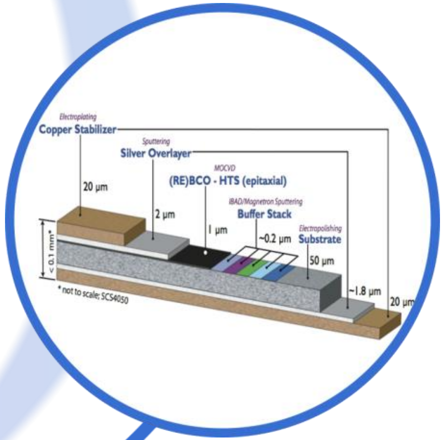
Spherical Tokamak

Improved geometry, highly efficient



High Temperature Superconductors (HTS)

High current at high field



FUSION POWER

Smaller, cheaper, faster...... with distinct competitive advantage

Overview

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Economically attractive

- Cost of electricity

$$CoE = \frac{Op\ costs + Depreciation\ costs}{Net\ elec\ produced}$$

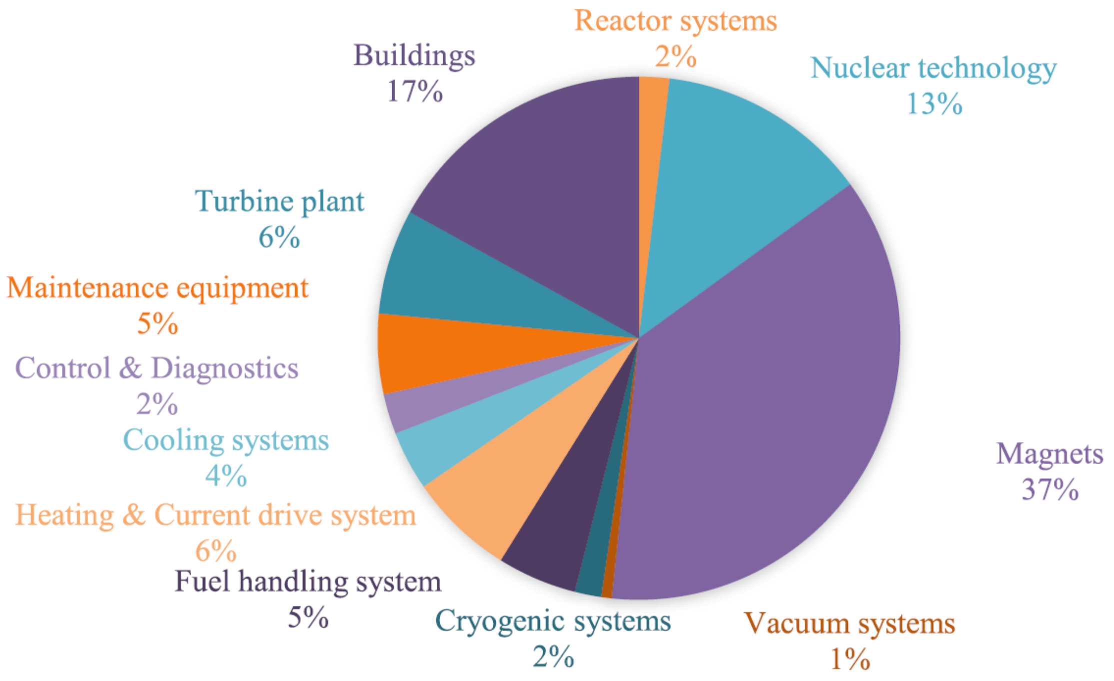
Economically attractive

- Cost of electricity

$$CoE = \frac{Op\ costs + Depreciation\ costs}{Net\ elec\ produced}$$

- Beta is a measure of how efficiently the toroidal field is utilised

$$\beta_T \beta_p = 25 \frac{1+\kappa^2}{2}\left(\frac{\beta_N}{100}\right)^2$$



Entler, S, et al. "Approximation of the economy of fusion energy." *Energy* 152 (2018): 489-497.

Economically attractive

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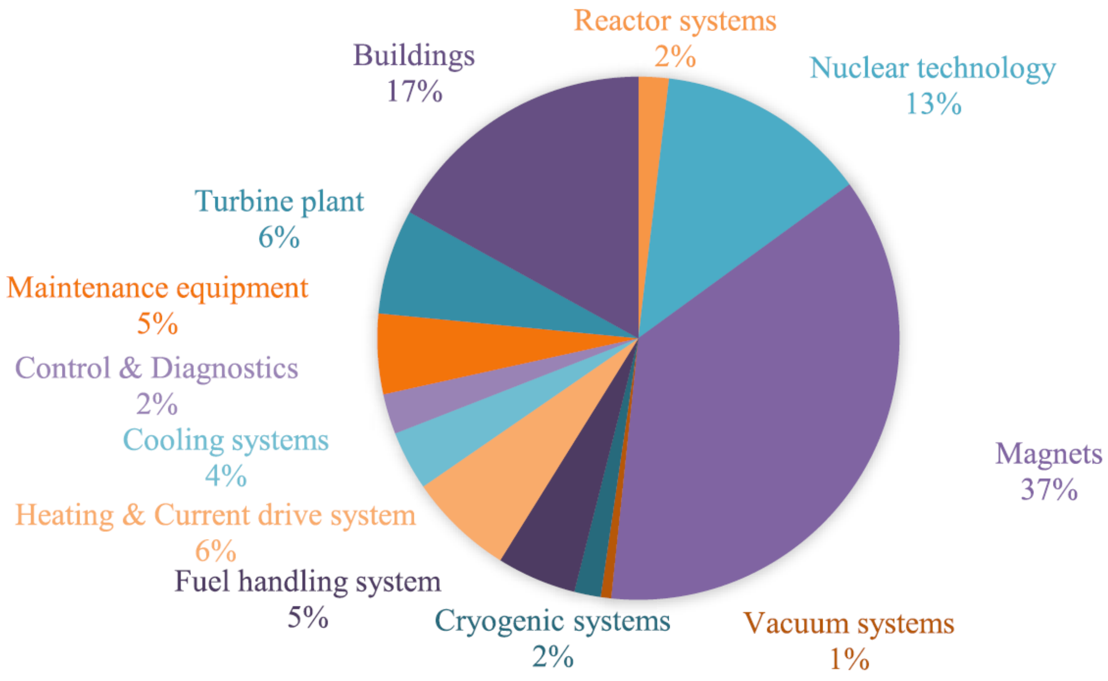
$$\beta_T \beta_p = 25 \frac{1+\kappa^2}{2} \left(\frac{\beta_N}{100}\right)^2$$

- Bootstrap fraction determines current drive requirements

$$f_{bs} \sim \sqrt{\epsilon} \beta_p$$



Fusion power	3255	MW
Thermal power[a]	4149	MW
Gross electric power	1660	MW
Net electric power	953	MW
Plant self-consumption[b]	707	MW
Plant availability fraction	75	%

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Economically attractive

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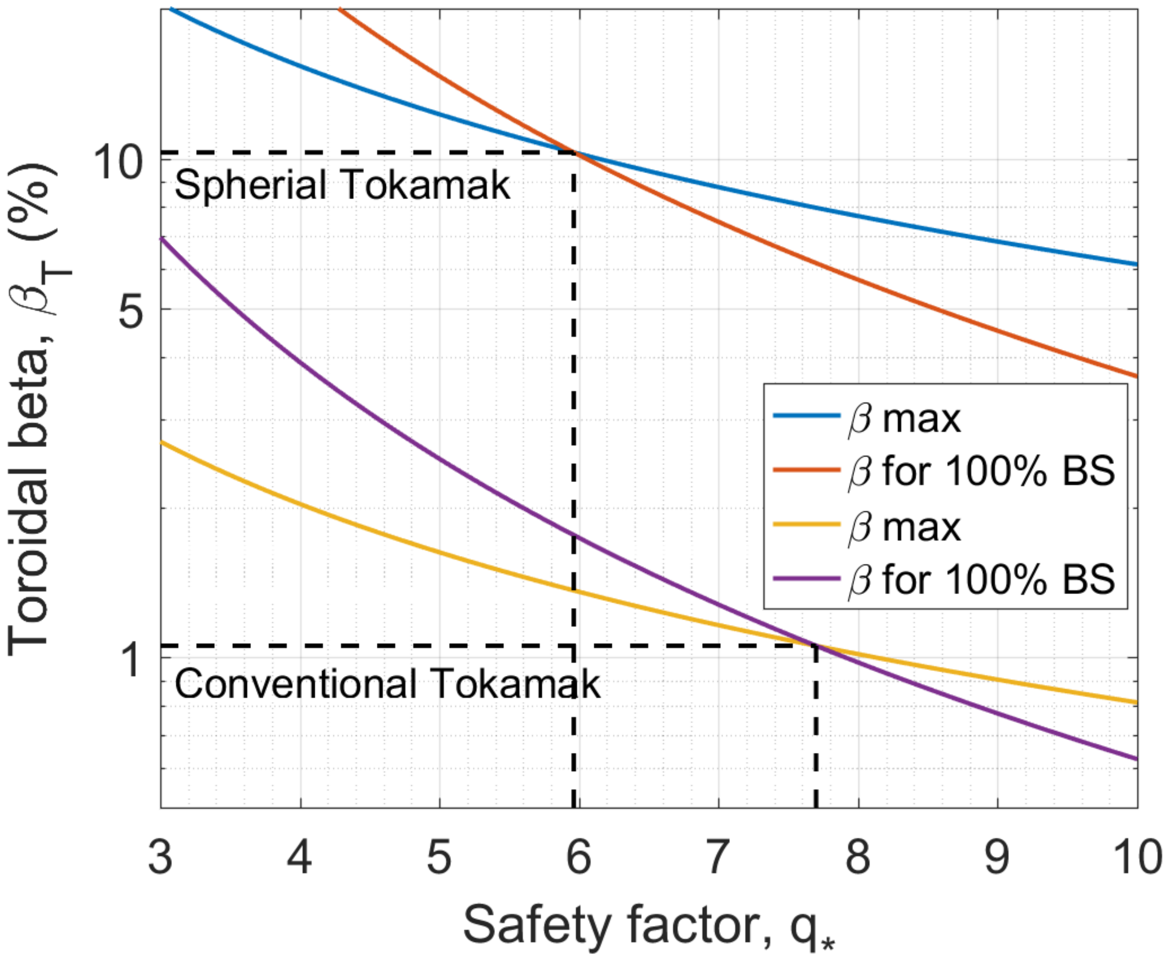
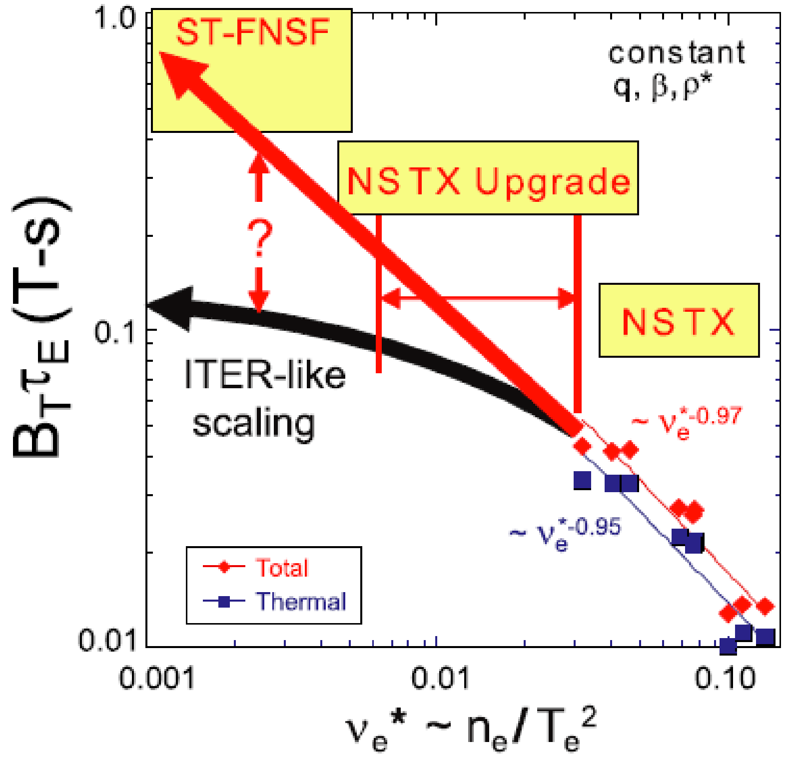


Favourable confinement

- MAST, NSTX and GLOBUS-M (M2) have found that energy confinement in STs has a stronger dependence on toroidal field compared to large aspect ratio devices



$$\tau_E(IPB98) \sim I_p^{0.93} \boldsymbol{B_T^{0.15}}$$

$$\tau_E(NSTX) \sim I_p^{0.57} \boldsymbol{B_T^{1.08}}$$

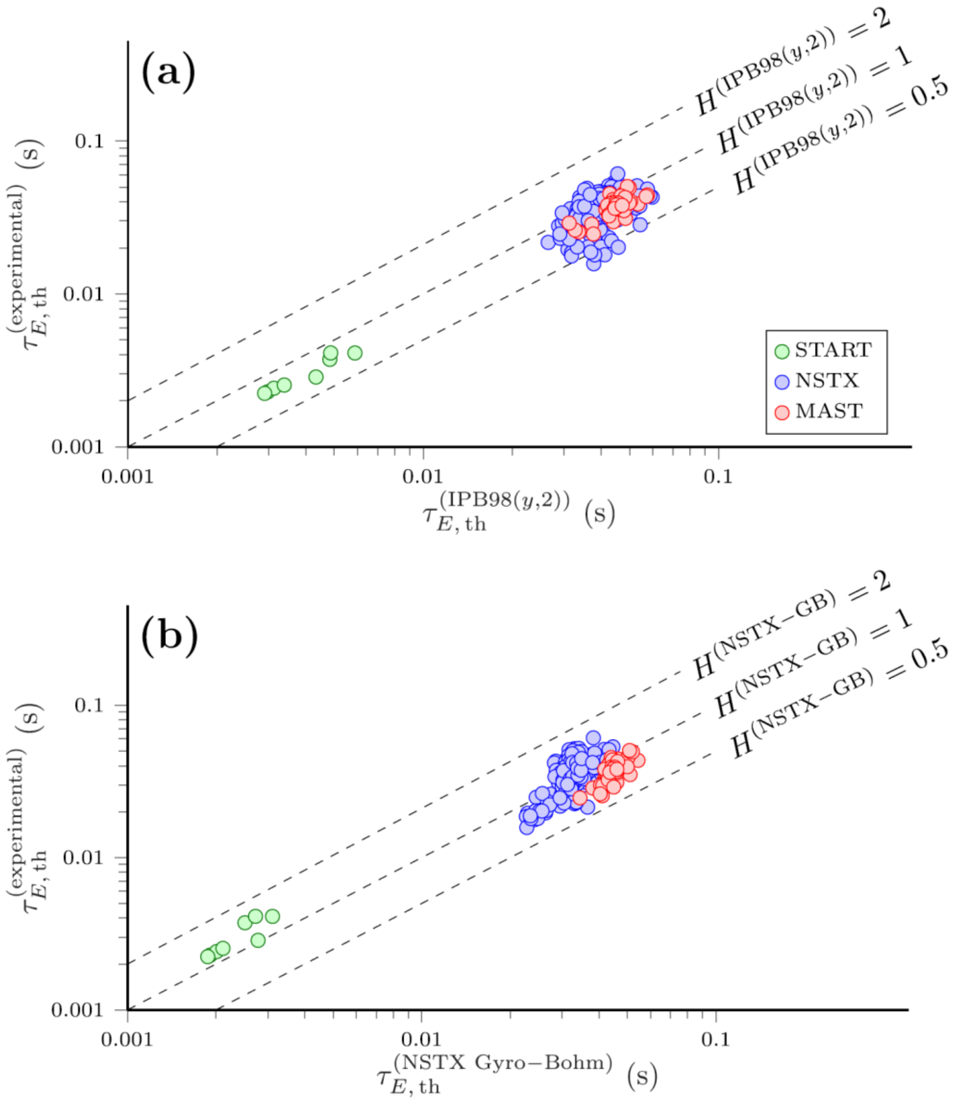
Favourable confinement

- MAST, NSTX and GLOBUS-M (M2) have found that energy confinement in STs has a stronger dependence on toroidal field compared to large aspect ratio devices
- Tokamak Energy have extended ST scaling to include a size dependence

$$\tau_{E,th}^{(\mathrm{ST,\,gyro-Bohm})} \propto \omega_{c_i}^{-1}\rho_*^{-3}\nu_*^{-0.53}\beta^{-0.17}q^{-0.35}$$

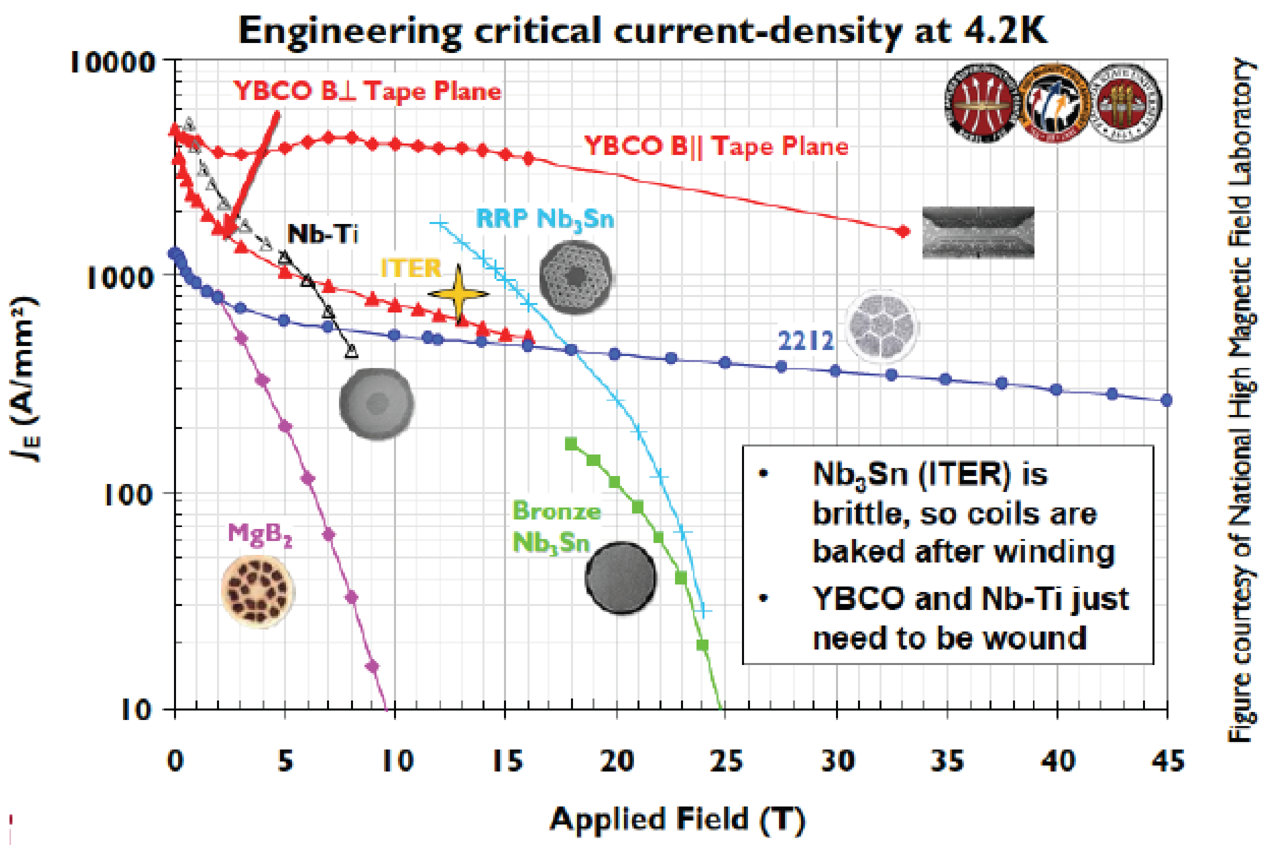
$$\tau_{E,th}^{(\mathrm{ST,\,gyro-Bohm})} = 0.21 I_p^{0.54} B_T^{0.91} P_L^{-0.38} n_e^{-0.05} R^{2.14}$$

- When extrapolating to reactor regimes this leads to a significant improvement in performance



Buxton P. F., Connor J. W., Costley A. E., Gryaznevich M., & McNamara S. "On the energy confinement time in spherical tokamaks: implications for the design of pilot plants and fusion reactors." *PPCF* 61(3) (2019)

The game changer:
High Temperature Superconductors (HTS)



- HTS tape is now available at commercially relevant scales from a number of manufactures
- 2nd generation "2G" HTS made from REBCO:
  - ✓High temperature
  - ✓High magnetic field
  - ✓High current density

Approaches to fusion power

$$nT\tau_E \propto \frac{H^2}{q^3} R_0^2 B_T^3 \left(\frac{\kappa^{7/2}}{A^3}\right)$$

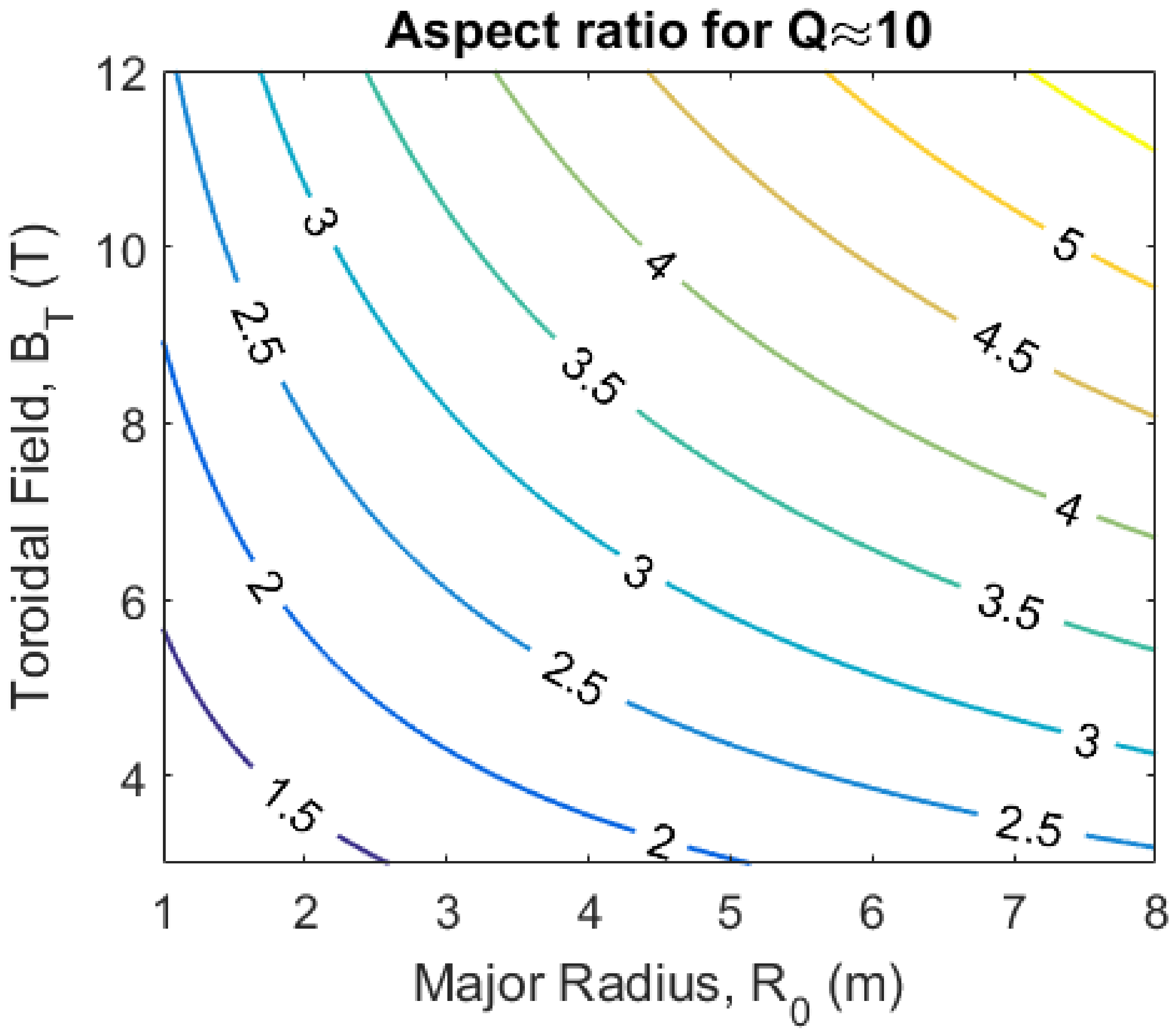
- Simplified confinement scaling

$$\tau_E^{\mathrm{IPB98}(y,2)} \propto H I_p P_L^{-1/2} n^{1/2} R^2 A^{-1/2} k^{3/4}$$

- Impose Greenwald and kink limits

$$n \propto I_p A^2 R^{-2}$$

$$I_p \propto R_0 B_T \kappa q^{-1} A^{-2}$$

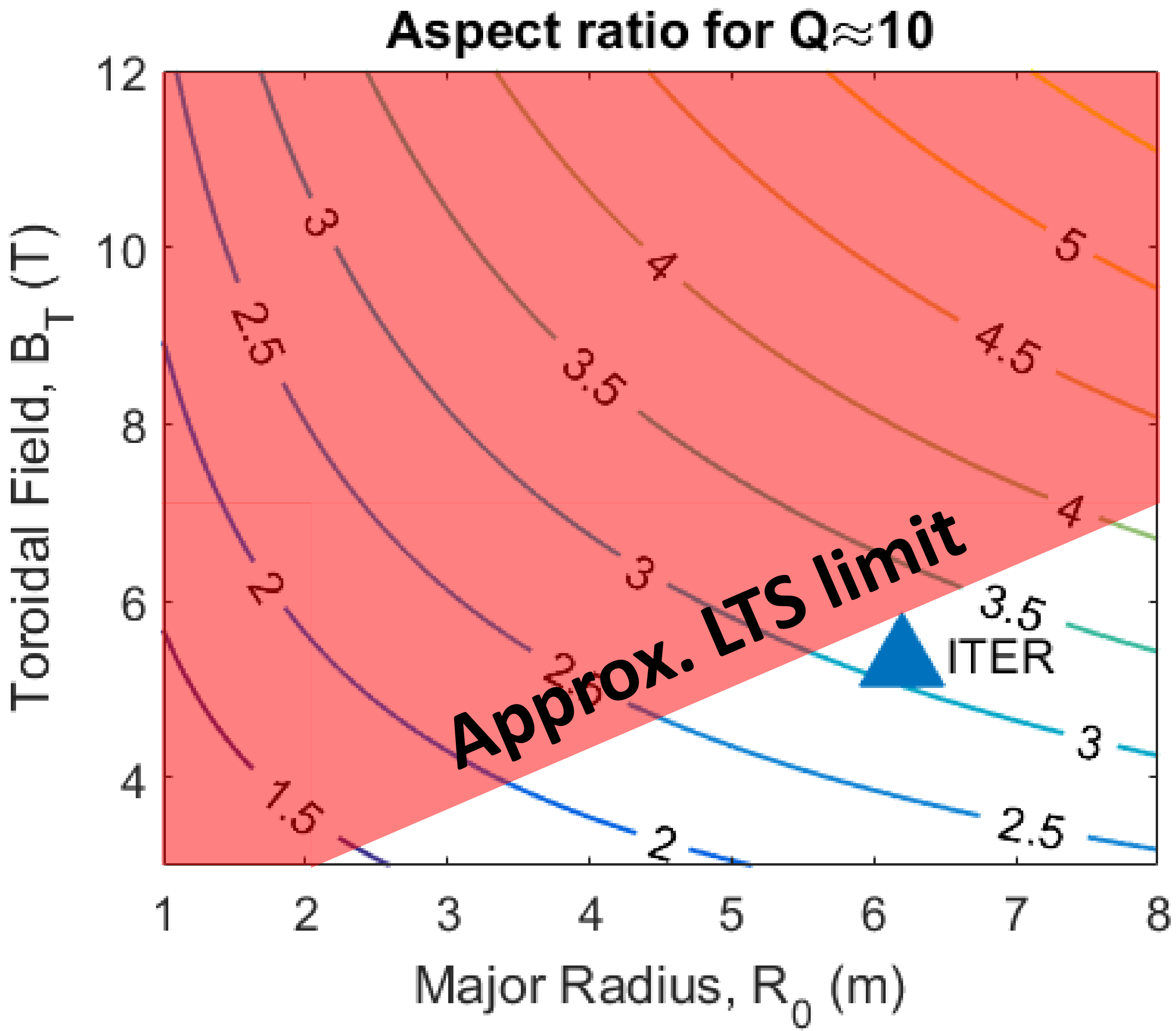


Costley, A. E. "Towards a compact spherical tokamak fusion pilot plant." *Phil. Trans of the RS A* 377.2141 (2019)

Approaches to fusion power

$$nT\tau_E \propto \frac{H^2}{q^3} \boldsymbol{R_0^2} B_T^3 \left(\frac{\kappa^{7/2}}{A^3}\right)$$

china eu india japan korea russia usa



Approaches to fusion power

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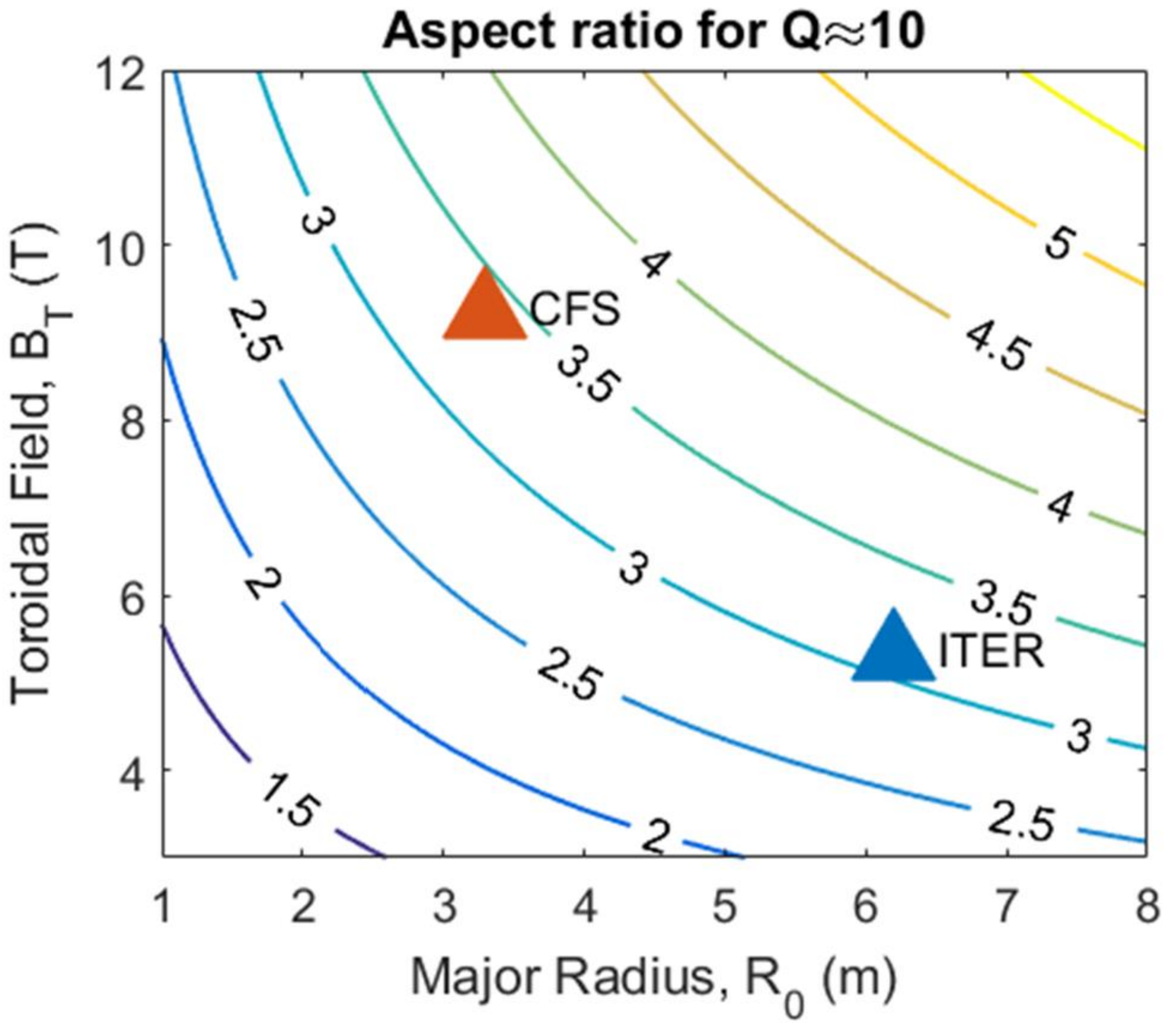
COMMONWEALTH FUSION SYSTEMS

Massachusetts Institute of Technology



Approaches to fusion power

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a faster way to fusion

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iter
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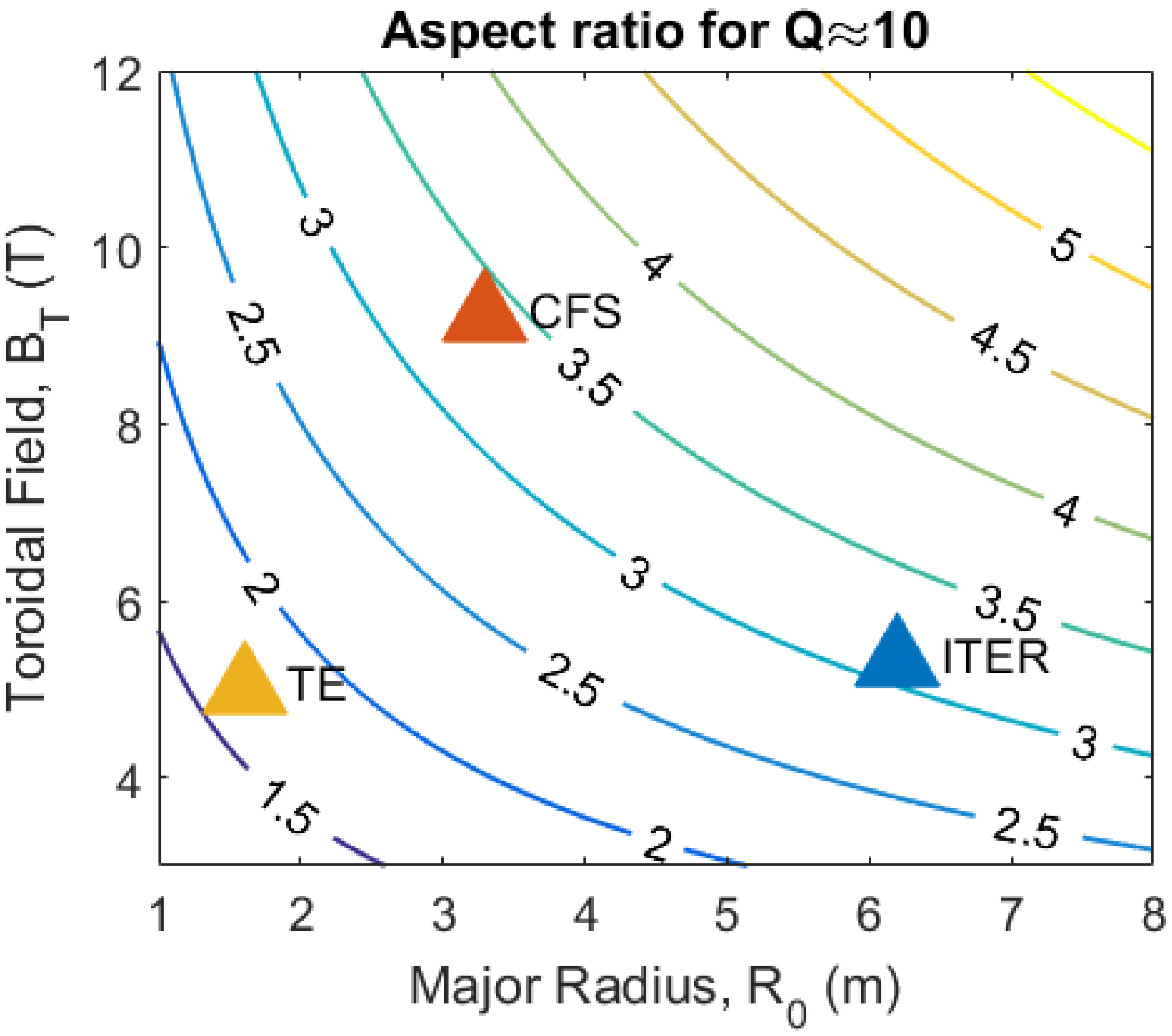

A Faster Way to Fusion

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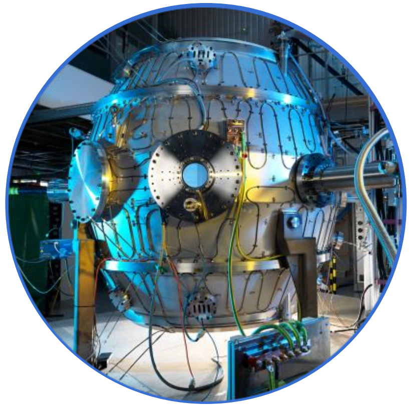
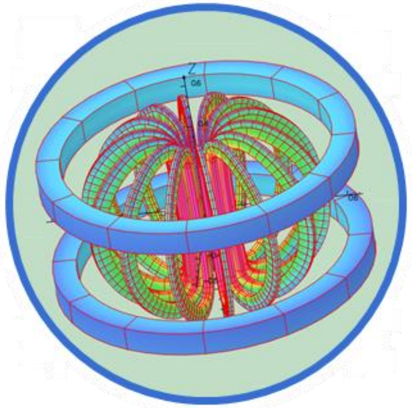
Research & Development



ST40

Verify the high field ST approach

Energy gain conditions

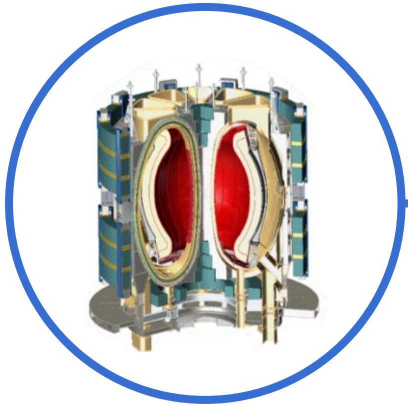


HTS Magnet Demo

Large scale HTS magnet

Magnet design and construction

Engineering & Demonstration



ST-F1

Fusion Power Demonstration

All HTS Magnets

Industrial scale heat production

Commercial Roll Out

ST-E1

Commercial scale module

Electricity production (to the grid)

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ST40: Expanding the high field ST physics basis

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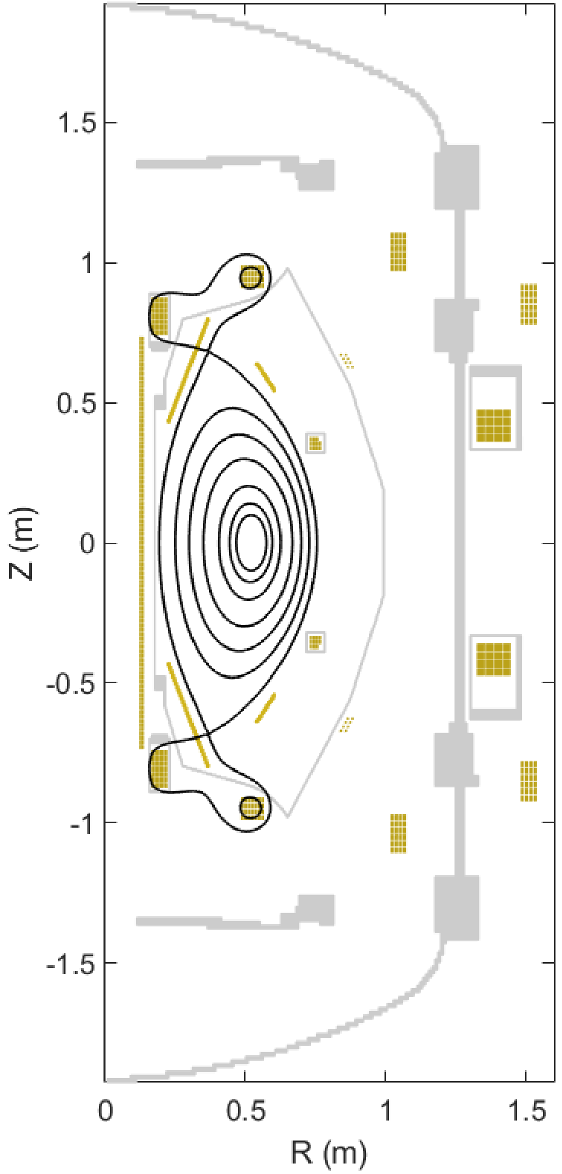
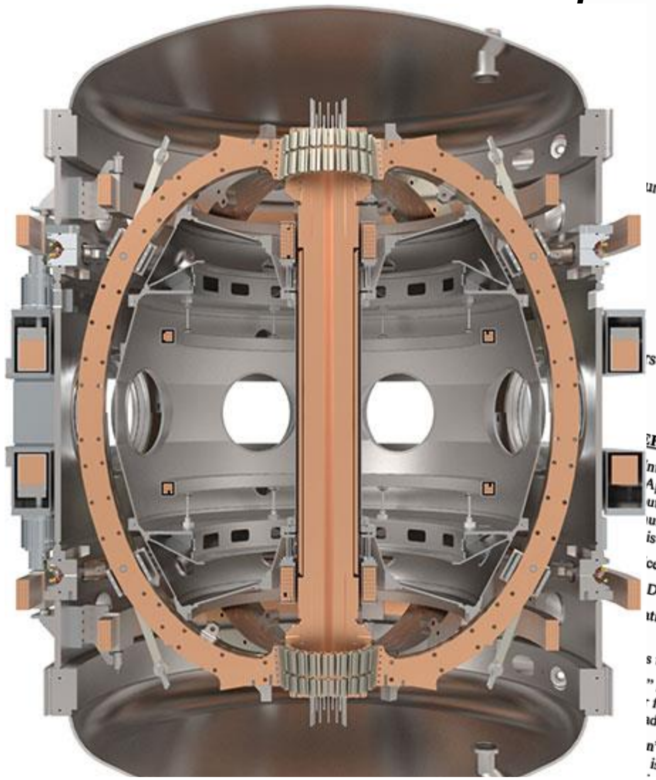
- Design parameters:
  - Toroidal field, $B_T = 3\mathrm{T}$
  - Plasma current, $I_p = 2\mathrm{MA}$
  - Major radius, $R = 0.4 - 0.5\mathrm{m}$
  - Aspect ratio, $A = 1.6 - 1.9$
  - Elongation, $\kappa \geq 2.3$
  - Up to 4MW of auxiliary heating from NBI and ECRH/EBW

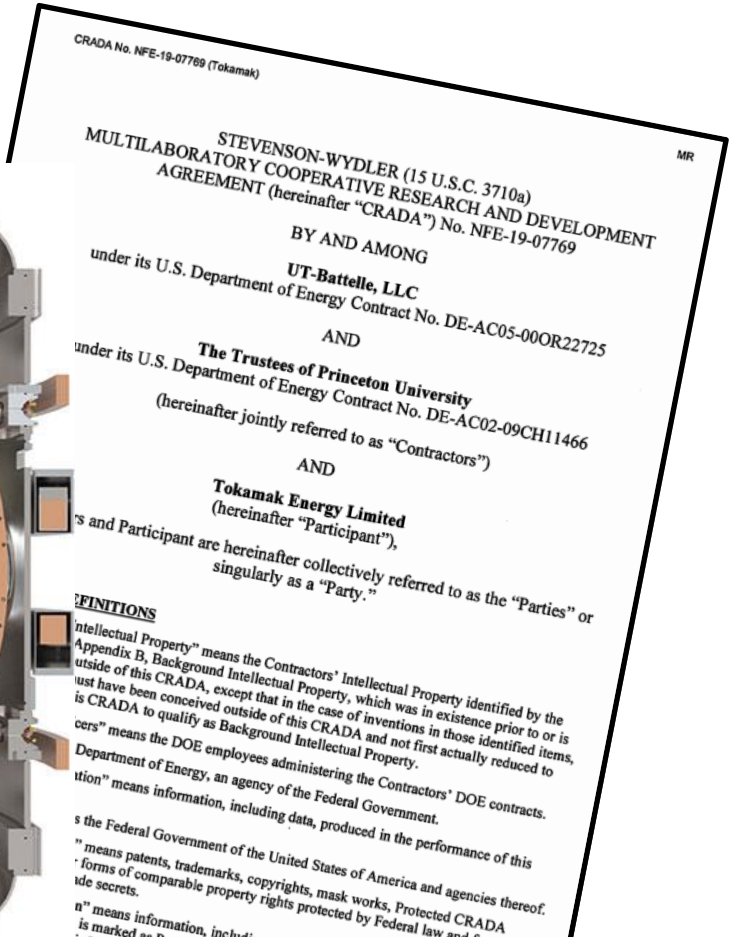
- Extending the high field ST physics basis:
  - Investigate confinement at high field
  - Characterise divertor performance
  - Demonstrate solenoid-free start-up methods
  - Develop reactor relevant operating scenarios



A first-of-a-kind collaboration

ST40




CRADA No. NFE-19-07769 (Tokamak)

MR

STEVENSON-WYDLER (15 U.S.C. 3710a)
MULTILABORATORY COOPERATIVE RESEARCH AND DEVELOPMENT
AGREEMENT (hereinafter "CRADA") No. NFE-19-07769

BY AND AMONG

UT-Battelle, LLC
under its U.S. Department of Energy Contract No. DE-AC05-00OR22725

AND

The Trustees of Princeton University
under its U.S. Department of Energy Contract No. DE-AC02-09CH11466

(hereinafter jointly referred to as "Contractors")

AND

Tokamak Energy Limited
(hereinafter "Participant"),

s and Participant are hereinafter collectively referred to as the "Parties" or singularly as a "Party."

FINITIONS

ntellectual Property" means the Contractors' Intellectual Property identified by the Appendix B, Background Intellectual Property, which was in existence prior to or is utside of this CRADA, except that in the case of inventions in those identified items, ust have been conceived outside of this CRADA and not first actually reduced to is CRADA to qualify as Background Intellectual Property.

cers" means the DOE employees administering the Contractors' DOE contracts.

Department of Energy, an agency of the Federal Government.

ation" means information, including data, produced in the performance of this

s the Federal Government of the United States of America and agencies thereof.

" means patents, trademarks, copyrights, mask works, Protected CRADA forms of comparable property rights protected by Federal law and ide secrets.

n" means information, includi is marked as

- This month ORNL, PPPL, and Tokamak Energy signed a CRADA covering a ~ 3 year collaborative research program
- FES awarded a total of \$3.9M to ORNL and PPPL to carry out open public research on ST40
- The collaborative research intends to study world leading high toroidal magnetic field (up to 3T) spherical tokamak plasmas to explore:
    - ST energy confinement scaling's w.r.t. high B_T & I_P
    - λ_q at B_{pol} nearly 2 x greater than NSTX-U and MAST-U
    - Maximum achievable ST pedestal pressures by temporarily relocating the NSTX-U Thomson pulse-burst laser system to ST40
    - And more! (RF, T-CHI, MHD, fast particles …)

Oak Ridge National Laboratory

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PPPL

ST40: Construction, commissioning and first results

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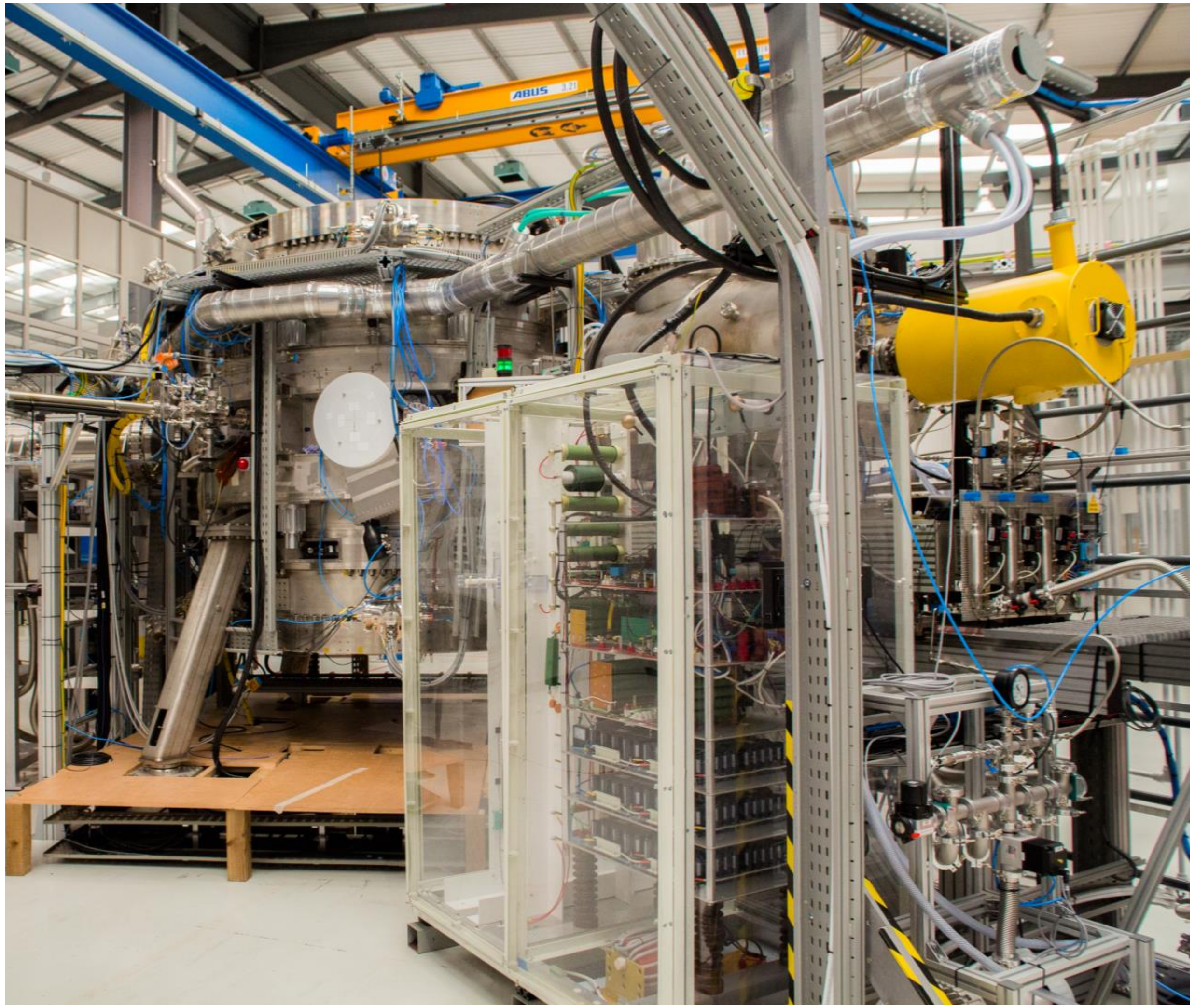
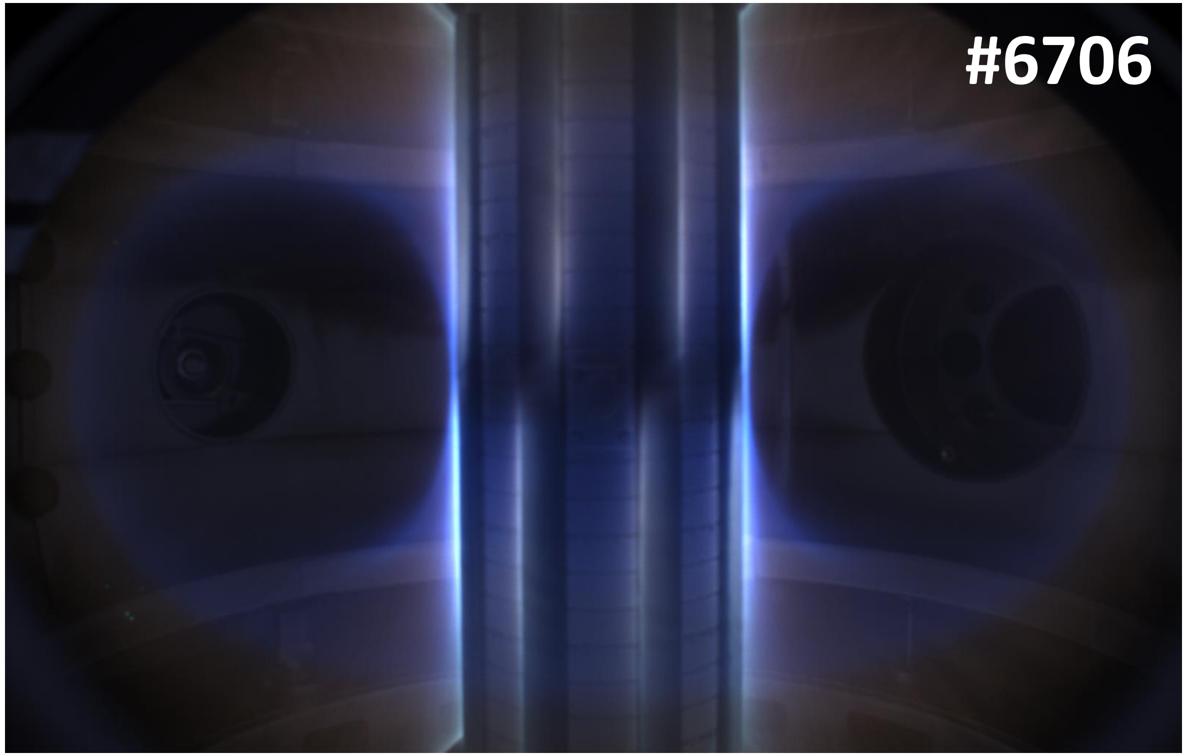


- See Mikhail's talk straight after this one!



ST40: Upgrade and research programme

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☑ Complete!

Programme 1	Programme 2	Programme 3	Programme 4
Completed October 2019	In progress, ending early 2020	Starting late 2020	2022 - …
System & diagnostic commissioning		Upgraded vacuum vessel and in-vessel components	Liquid metal divertor upgrade

Ohmic plasmas

Neutral beam heated plasmas

RF heated plasmas

Solenoid free start-up: merging compression

Solenoid free start-up: EBW/ECRH

Confinement and transport studies

SOL and divertor characterisation

ST40: P1 & P2 Diagnostics

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Diagnostic Neutral Beam Injector (DNBI)

NIR Retro-reflector

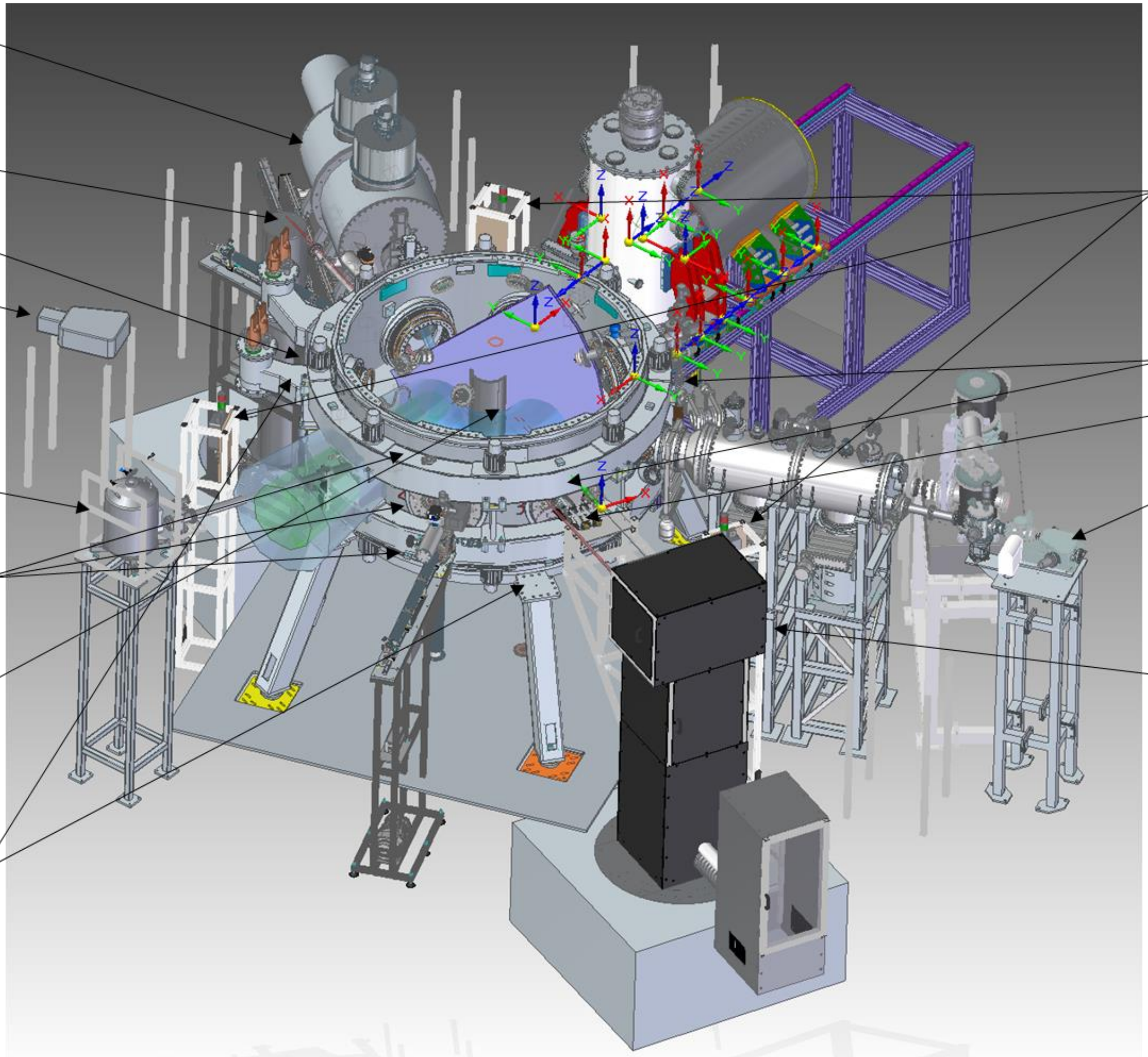
UV/Visible Doppler (Avantes) (Princeton) Spectrometers

Soft X-ray (Canberra) Spectrometer

Foil Filtered Soft X-ray Linear Arrays/Cameras

Panoramic (Ocean) Spectrometer

Line Emission Monitors



Hard X-ray & Gamma Detectors

Fast Visible & H-alpha Cameras

Infrared Camera

Neutral Particle Analyser (NPA)

Vibration Isolated Diagnostic Tower provides support for:

- SMM Interferometer
- NIR Interferometer
- ECE Radiometer

ST40: P3 Additional diagnostics

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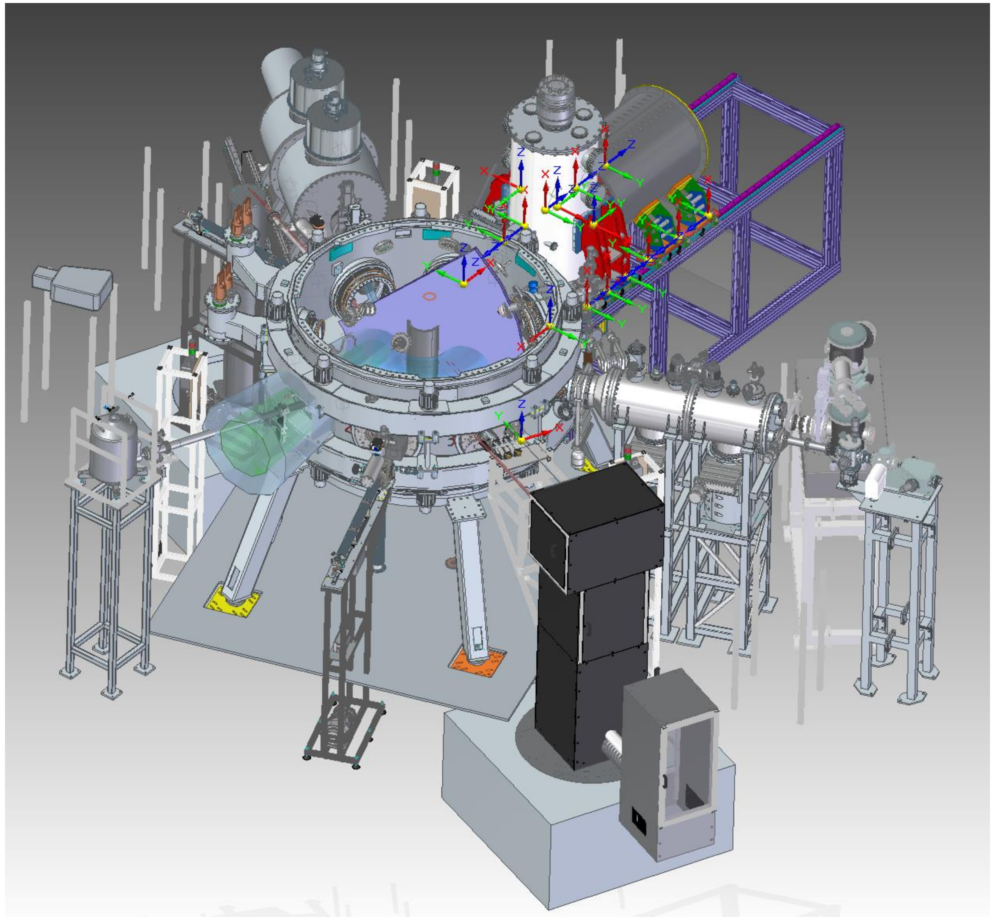

- Burst pulse Thomson Scattering system on loan from NSTX
- Divertor IR cameras
  - High resolution in lower divertor
  - Lower resolution in upper divertor
- Langmuir probes
- Toroidal array of fast magnetics
- Neutron diagnostics

ST40: 2020 vacuum vessel upgrade

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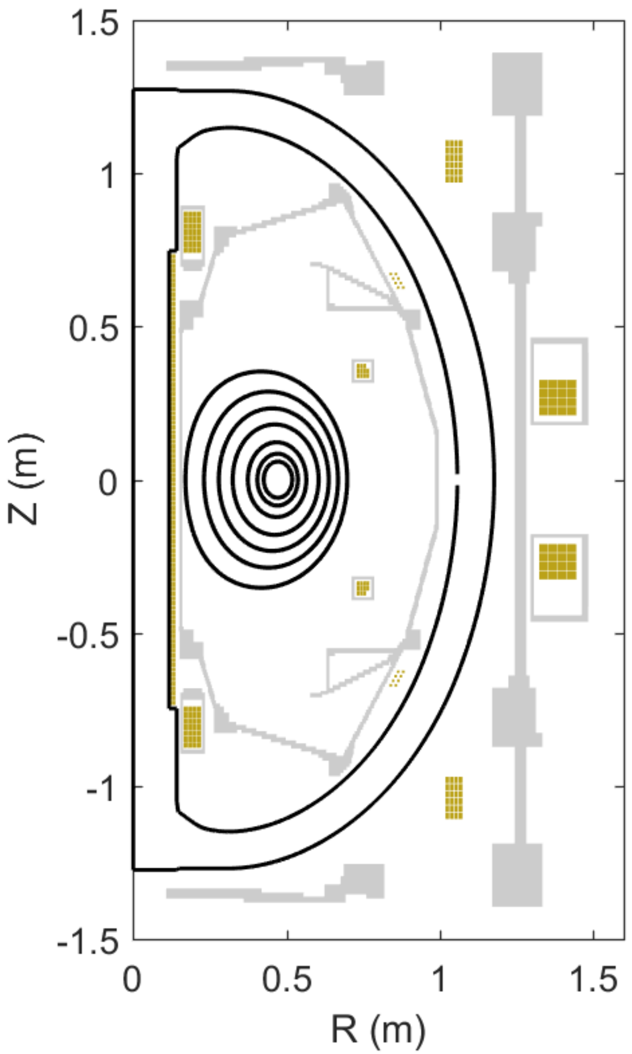
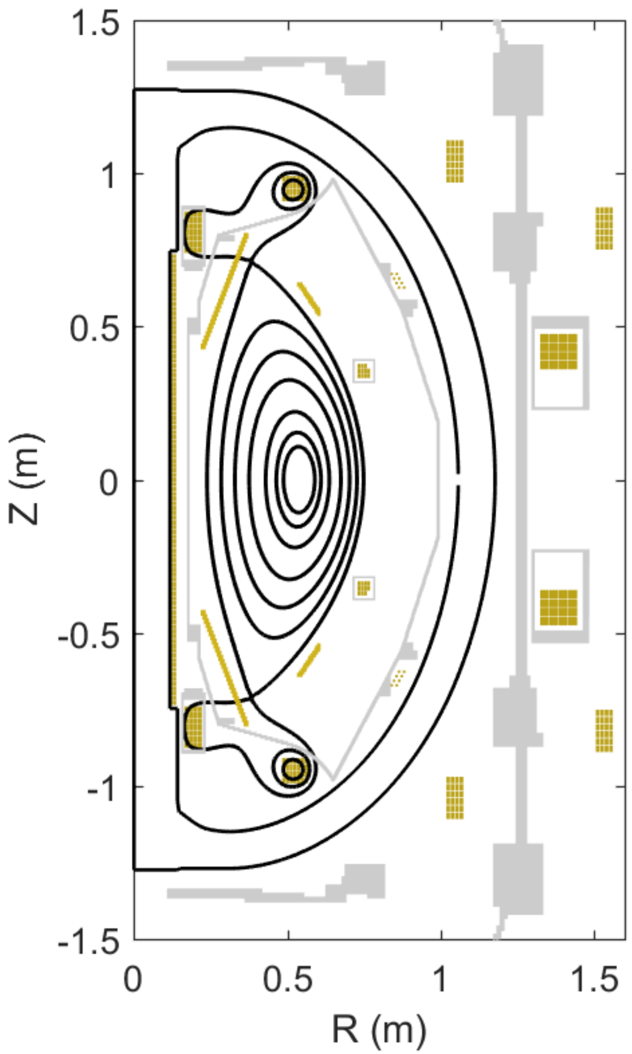
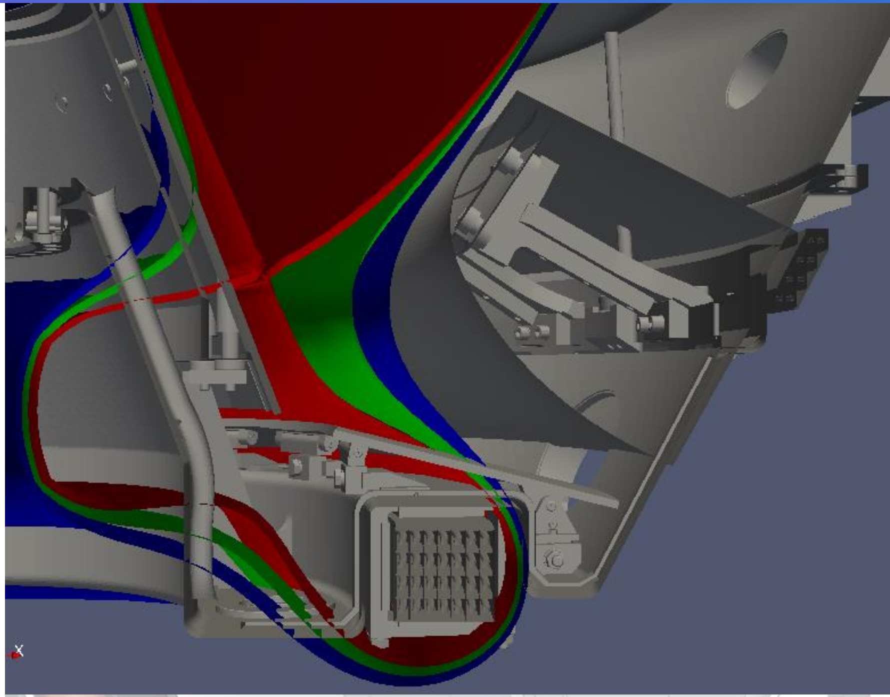
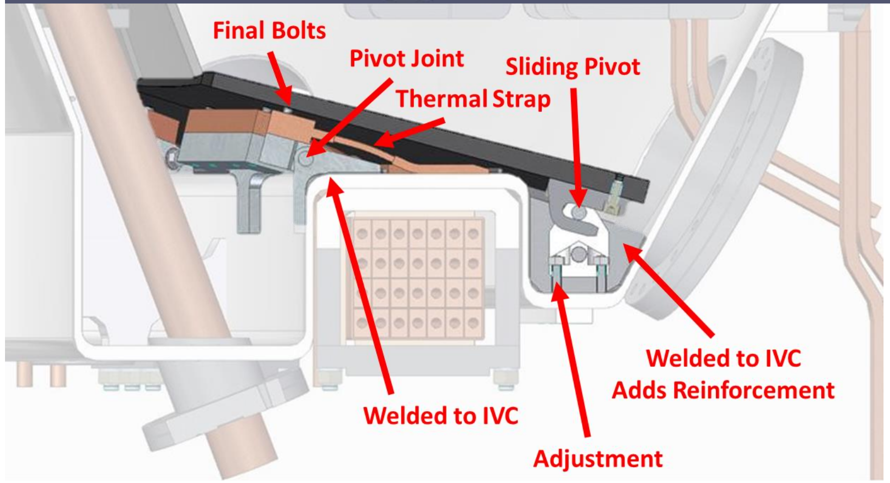
Programme 1 & 2



Programme 3

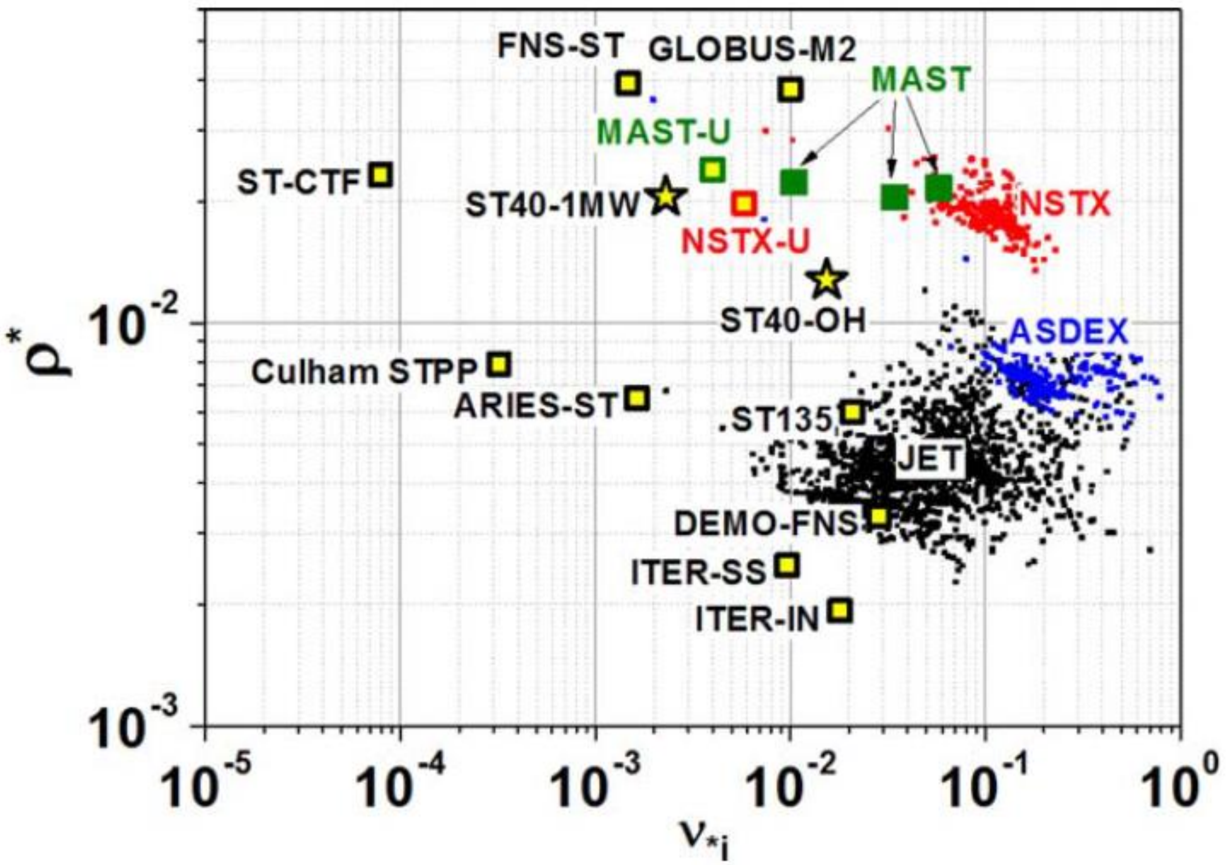




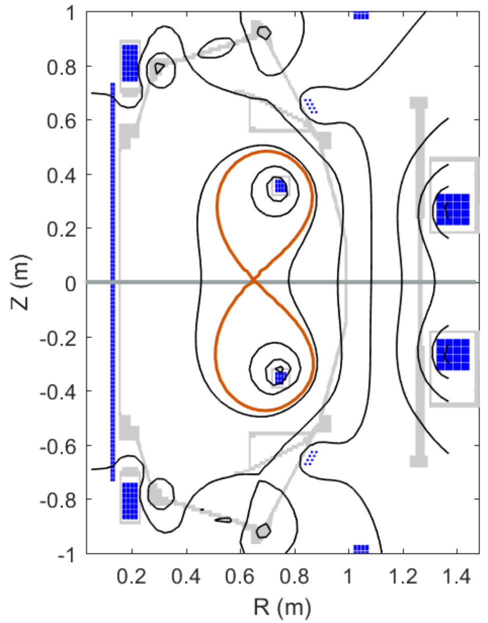


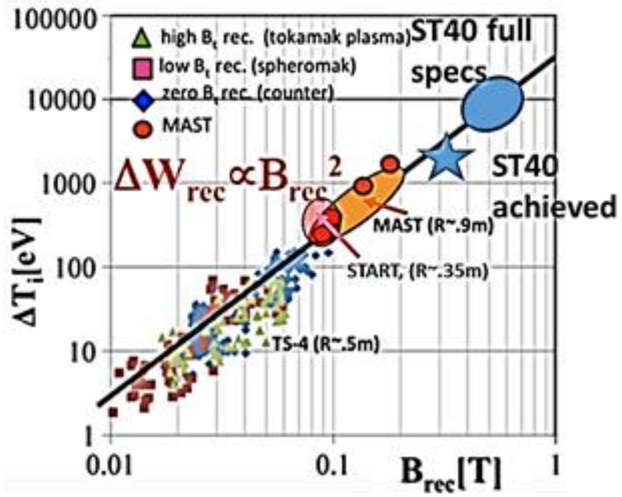
Energy confinement studies

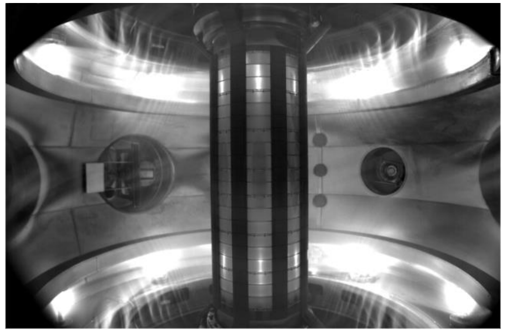
- ST40 can extend confinement database to low collisionality in OH and NBI heated regimes
- Research topics:
  - Core and pedestal confinement scalings
  - Ion scale turbulence supersession in new regimes
  - Dominant anomalous transport mechanisms

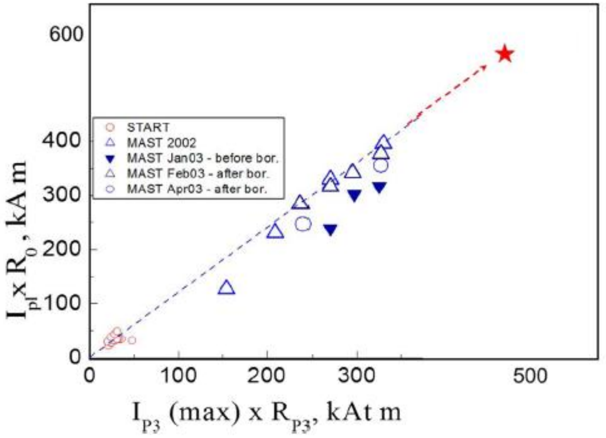


Developing solenoid free start-up methods









- Merging Compression (MC)
  - ☑ Direct access to burning plasma regime
  - ☒ In-vessel, high voltage, coils
- Double Null Merging (DNM)
  - ☑ Direct access to burning plasma regime
  - ? Ex-vessel coils but still inside TF
- RF assisted start-up (EBW/ECRH)
  - ☑ Remote hardware
- Transient CHI
  - ☑ Suitable target plasma (low li, moderate Ip)
  - ☒ In-vessel electrodes
  - ? Impurities?

Developing solenoid free start-up methods

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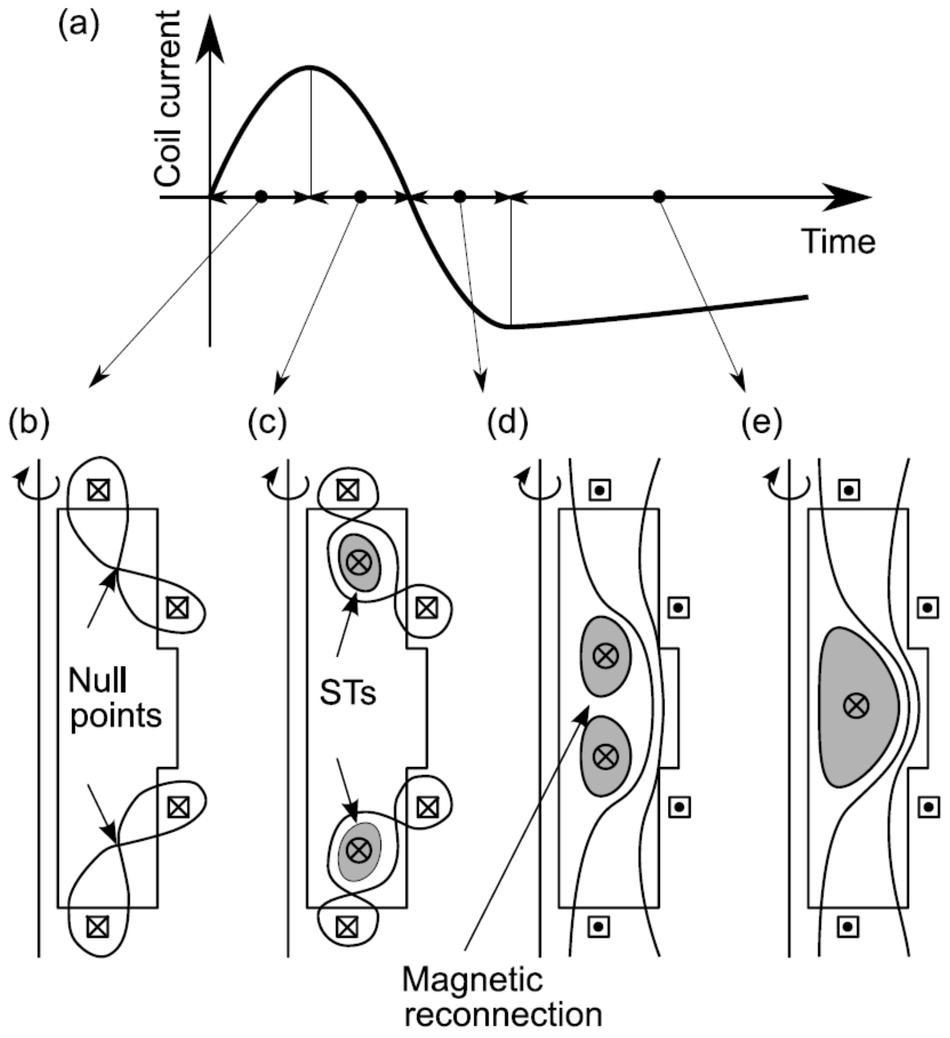

Yamada, T, et al. "Merging Startup Experiments on the UTST Spherical Tokamak" *Plasma and Fusion Research* Vol 5, S2100 (2010)

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Developing solenoid free start-up methods

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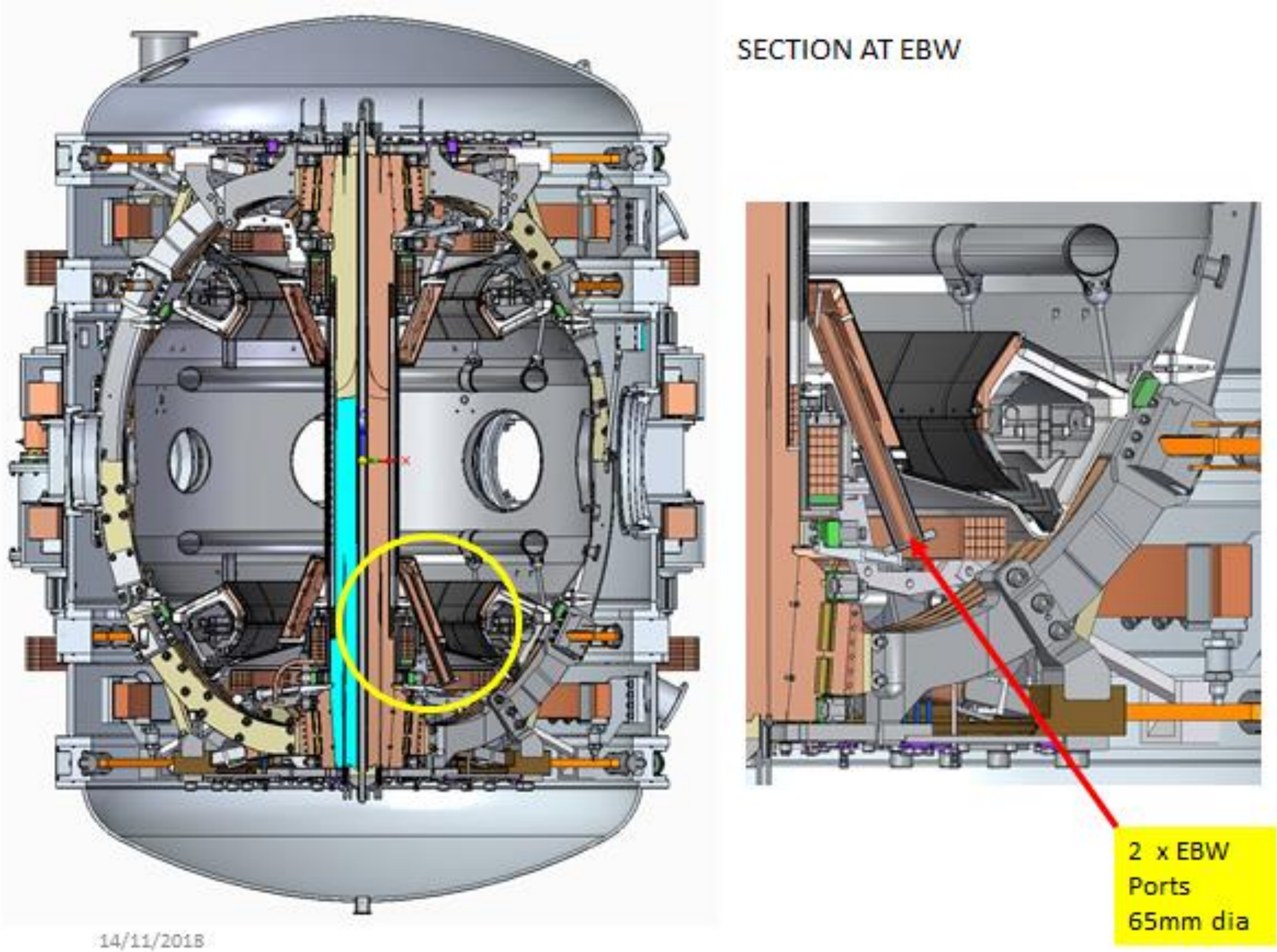

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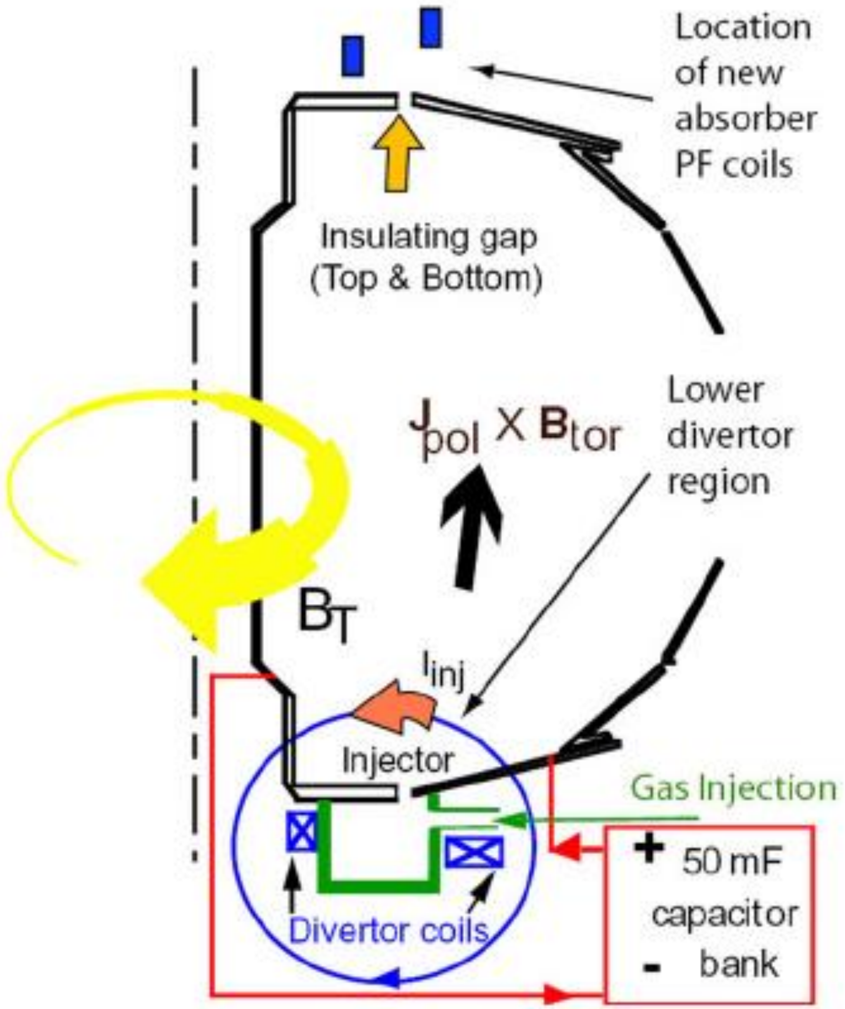

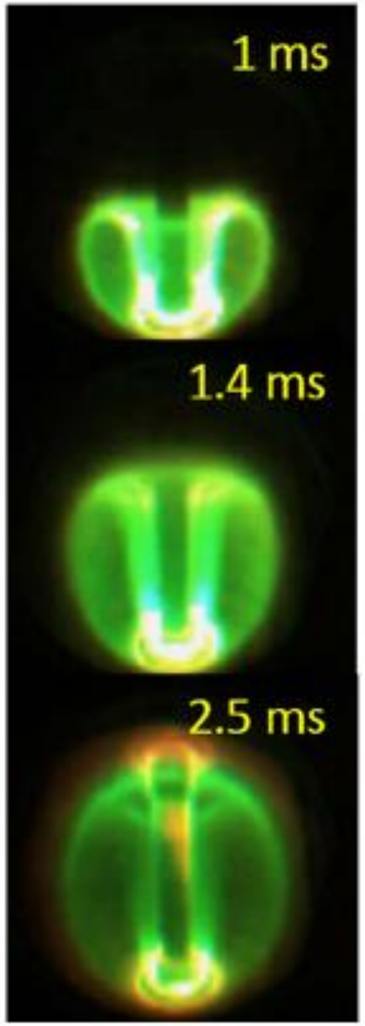

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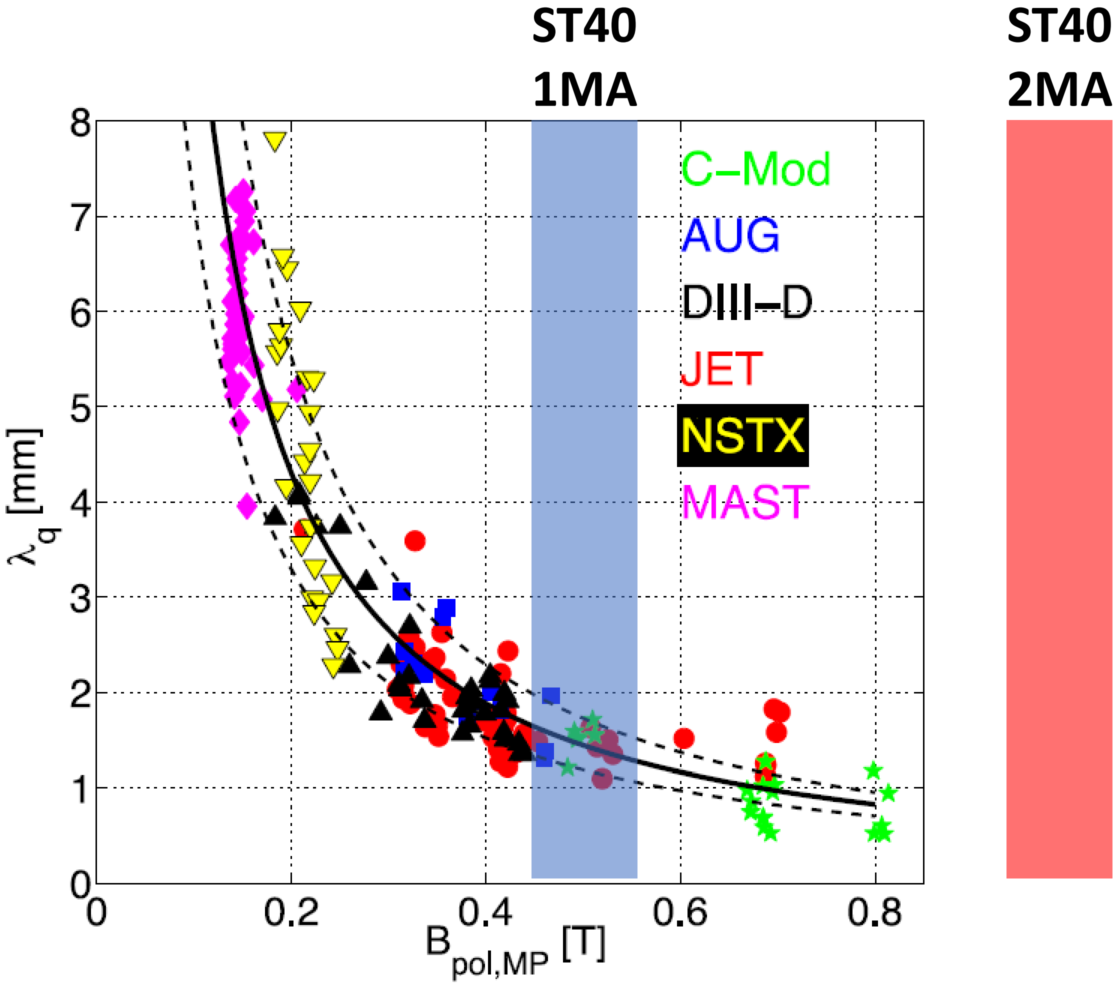
  - ☑ Remote hardware
- Transient CHI
  - ☑ Suitable target plasma (low li, moderate Ip)
  - ☒ In-vessel electrodes
  - ? Impurities?

Divertor performance

- ST40 is uniquely placed to study SOL width, λ_q, at high B_{pol}
- Access to heat loads of up to $40 MW/m^2$
- Partially closed LFS divertor
- High resolution IR camera in lower divertor to study heat loads
- Lower resolution IR camera in upper divertor to study up/down power balance



T. Eich et al., NF 2013; PRL 107, 215001 (2011)

Liquid metal development

- Tokamak Energy have partnered with three leading laboratories:

InFoMM
Industrially Focused Mathematical Modelling

- Theoretical modelling of flowing liquid lithium
- Developing ‘true’ free surface models

CPMI
Center for Plasma-Material Interactions
University of Illinois at Urbana-Champaign

- Developing the flowing liquid lithium divertor plate for ST40

OXFORD THERMOFLUIDS INSTITUTE

- Developing a diagnostic to measure the depth of the flowing liquid lithium

Developing a flowing liquid lithium divertor for ST40

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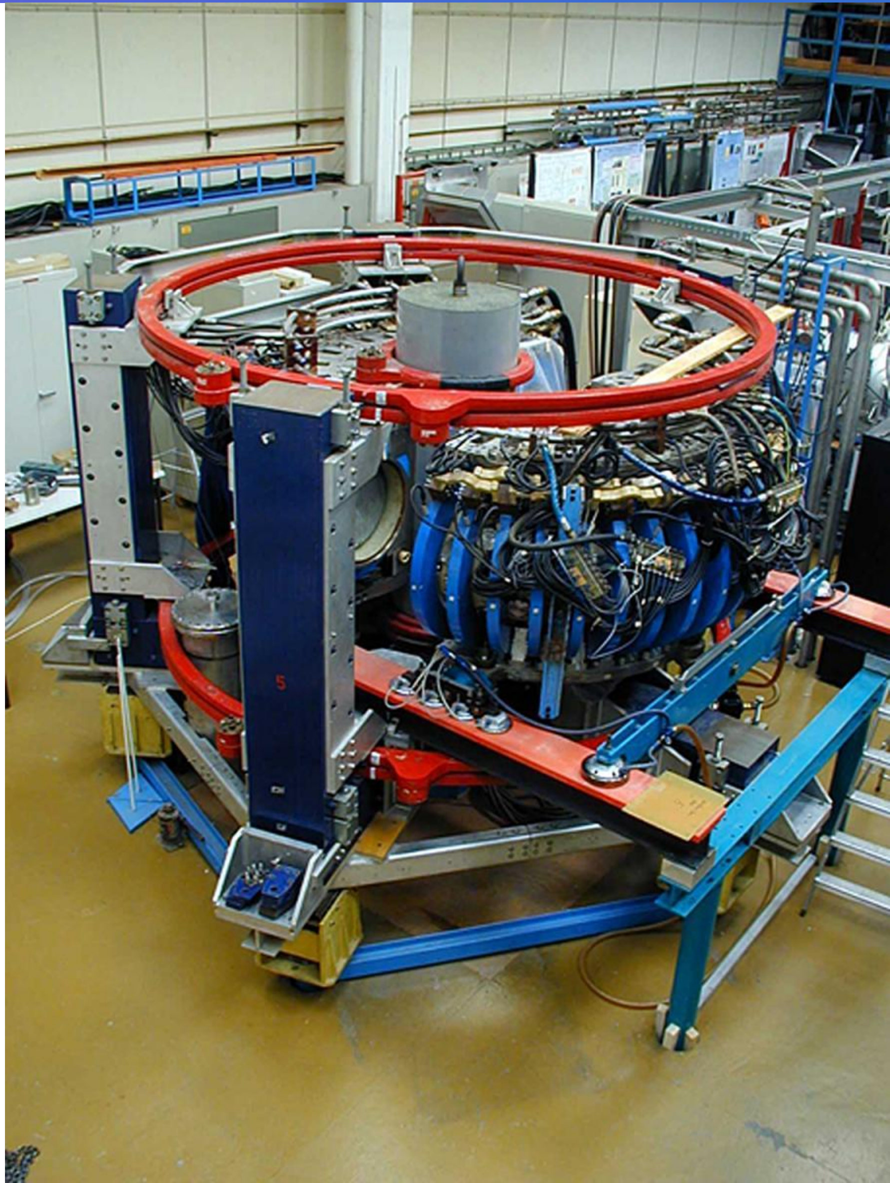
CPMI
Center for Plasma-Material Interactions
UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

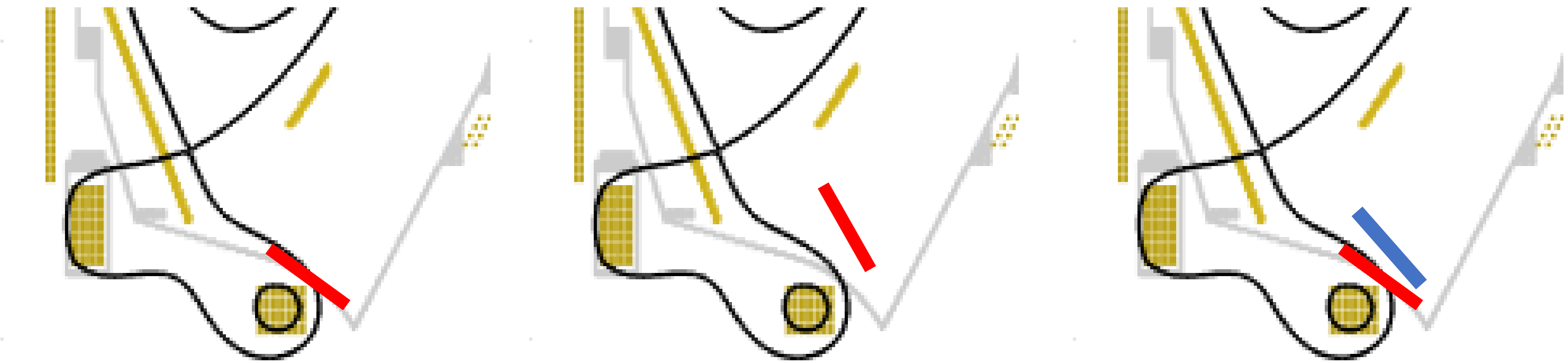
- Developing a flowing liquid lithium divertor plate for ST40
- 3 year project, has been running for nearly 1 year
- Planning to test ST40 prototype in HIDRA
- Initial testing in vacuum at different orientations (to check the analytic model)
- Later testing with plasma



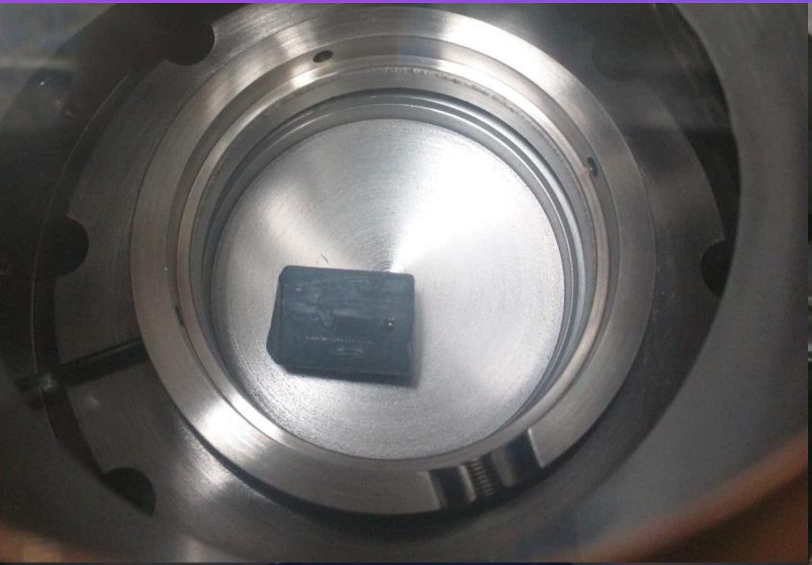
Programme 4: Divertor concepts

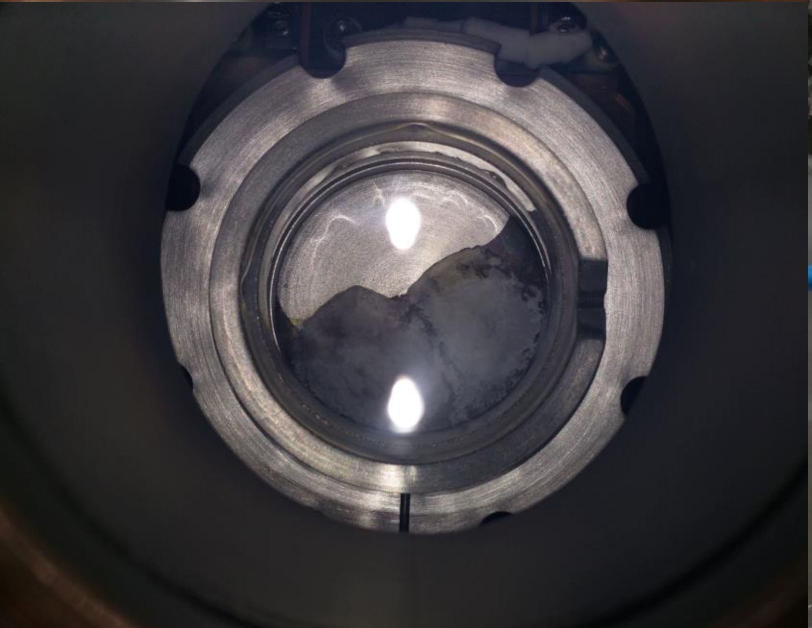
- We are exploring a range of divertor concepts

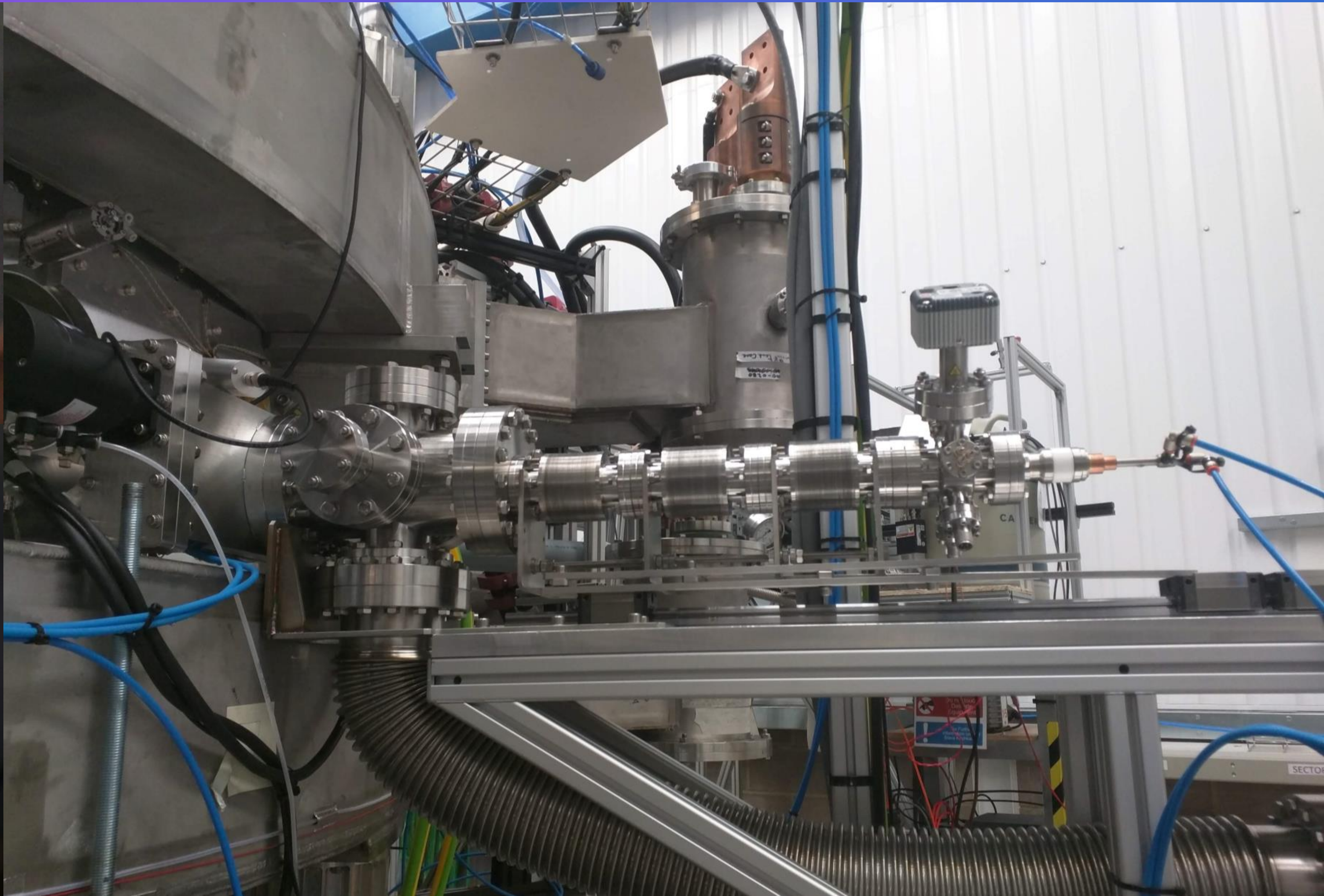
	Flowing liquid lithium divertor	Solid divertor with flowing liquid lithium pump	Lithium vapour box
Low recycling	✔	✔	✗
Heat flux (MW/m^2)	5-10	<15	15+
Low long term erosion	✔	✗	✔
Low Z impurities	✔	?	✔



ST40 lithium conditioning







Overview

- Introduction to Tokamak Energy
- The high field ST approach to fusion
- ST40: Overview and research programme
- HTS magnet development: Progress and future plans

HTS magnet development

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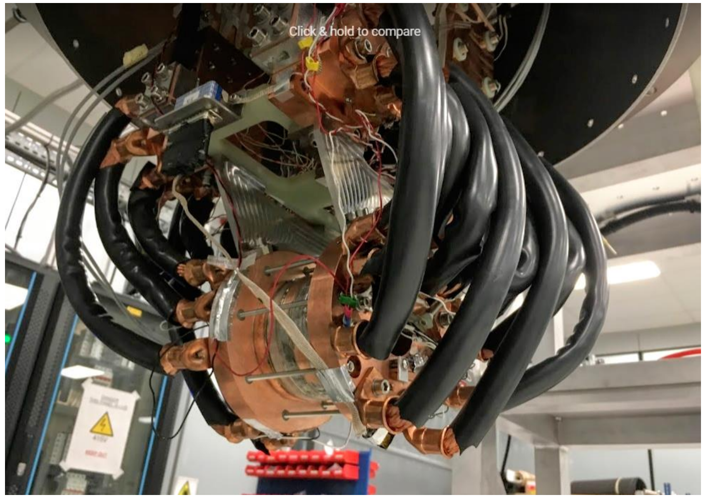
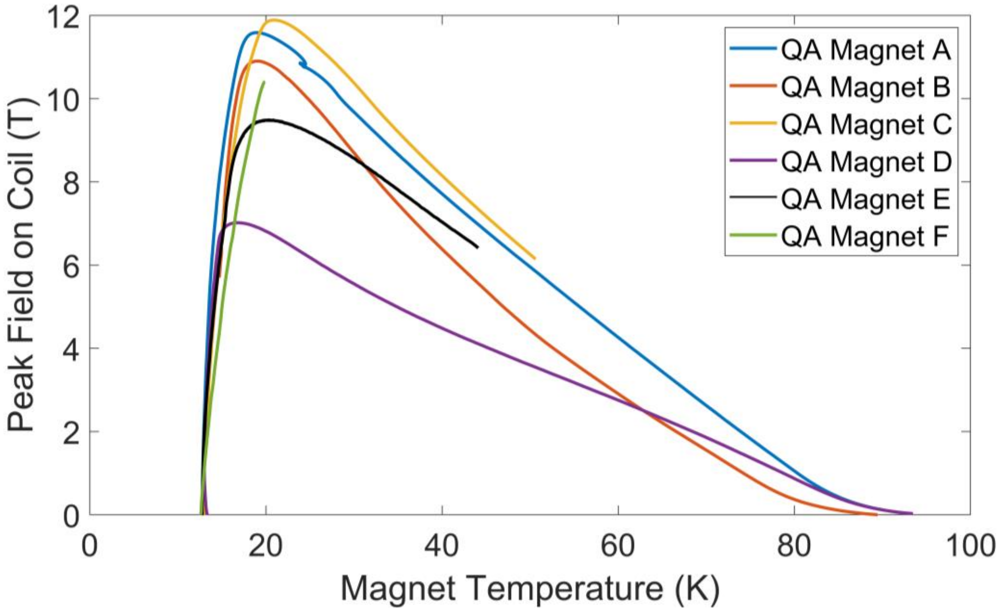
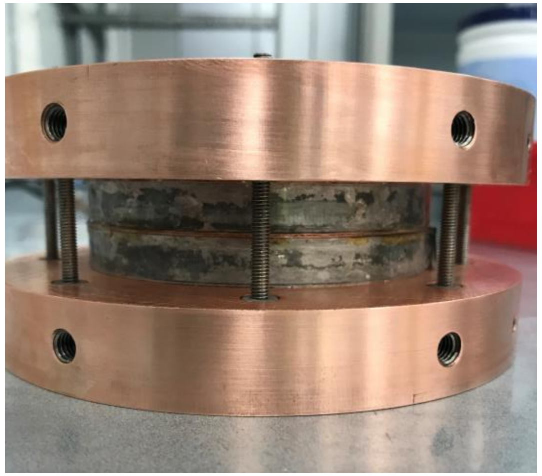


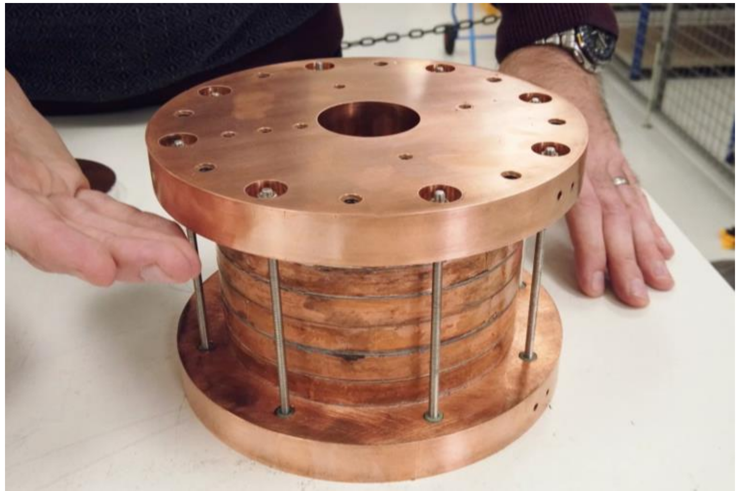
Characterisation and technology development

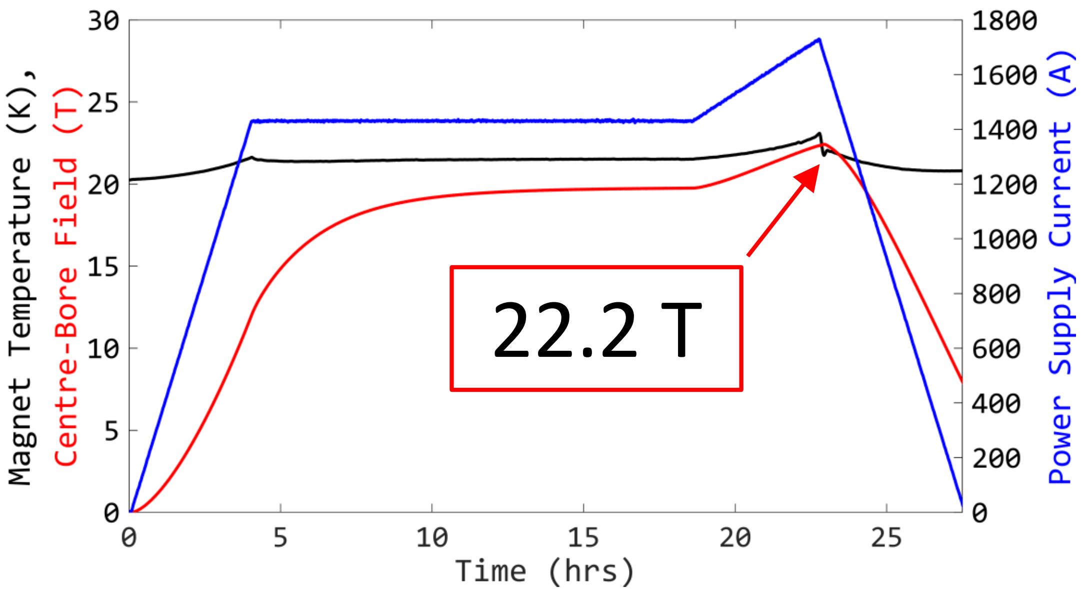
- Novel HTS magnet design
  - Soldered, non-insulated
  - Electro-Thermal Interface (ETI) plates for current injection
- "QA" magnets
  - Compared tape $I_C(B,T,\theta)$ from six different HTS suppliers
  - Characterised tape performance in a magnet as opposed to short sample
- Results used to verify magnet models





24.4T at 21K in all-REBCO Solenoid





- All-REBCO magnet, conduction cooled to 21K
- Six pancake stack
  - ID-50mm, OD-140mm
  - 735m of 12mm HTS tape
- **24.4T** peak field on coil
- Operated at >20T for 10s hours
- ~700 A/mm^2 current density

High field HTS magnet demonstrator

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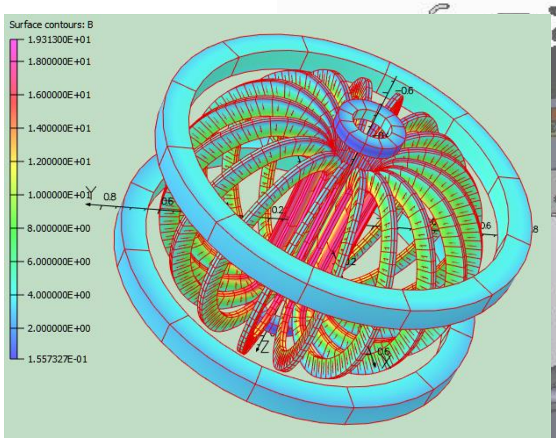
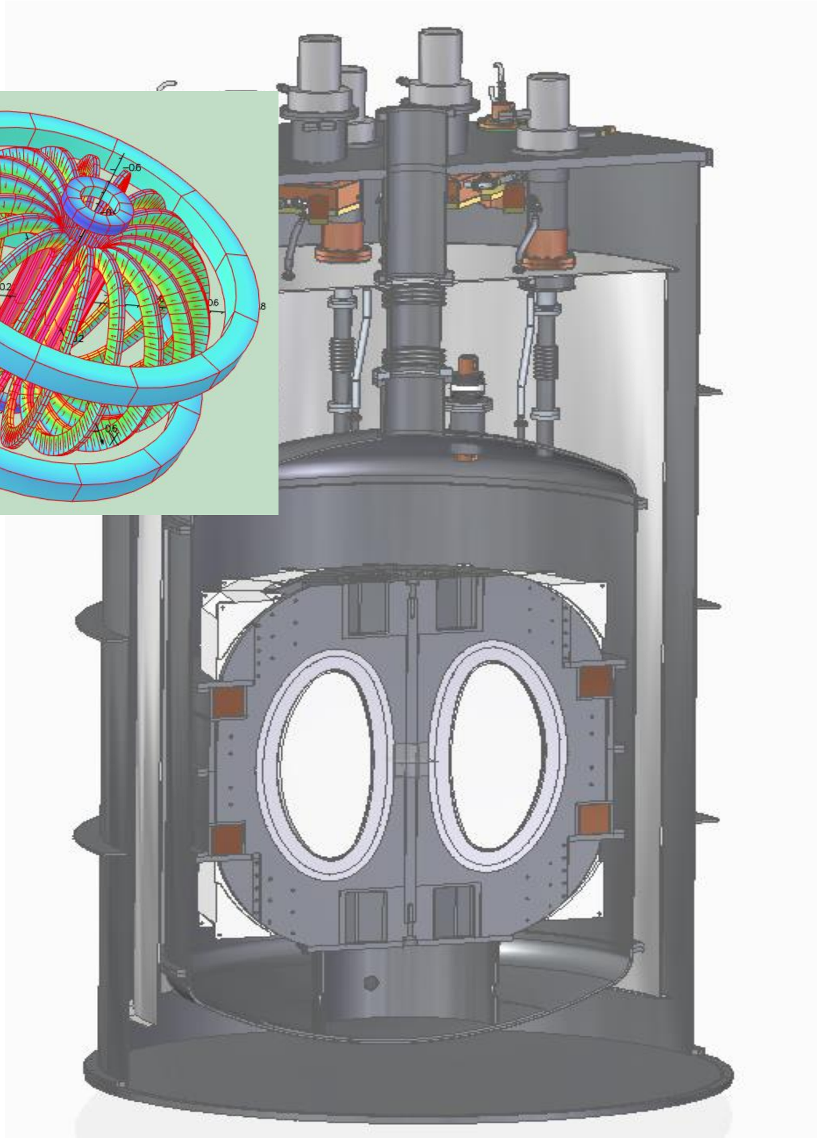
- **Demo4** – a mid-scale tokamak type magnet to develop and demonstrate HTS technology and manufacturing methods
- Approach conditions expected in a reactor:
  - Exceed 20T on HTS surface
  - Exceed 250MPa compressive stress is centre column
  - Simulate fusion heat loads
- Demonstrate scalable quench protection
- Test PF/TF interaction





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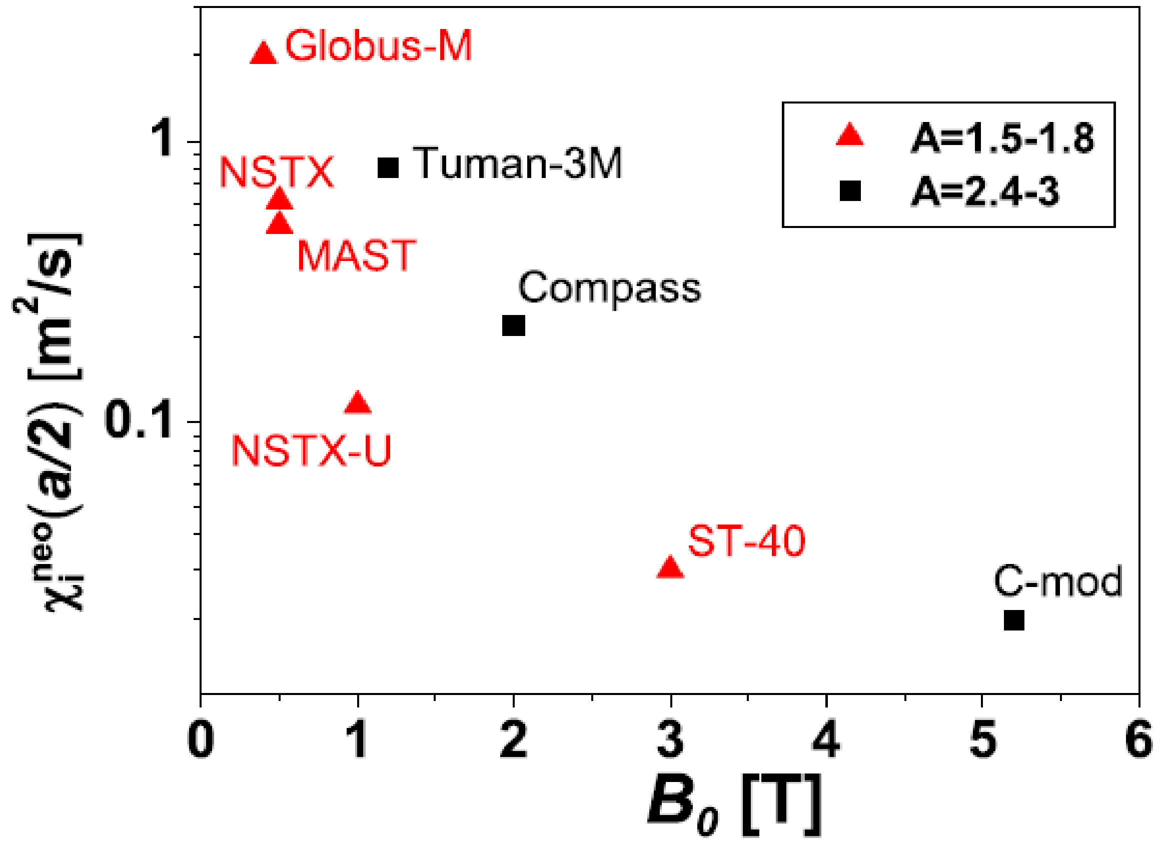
ST40: Performance Potential

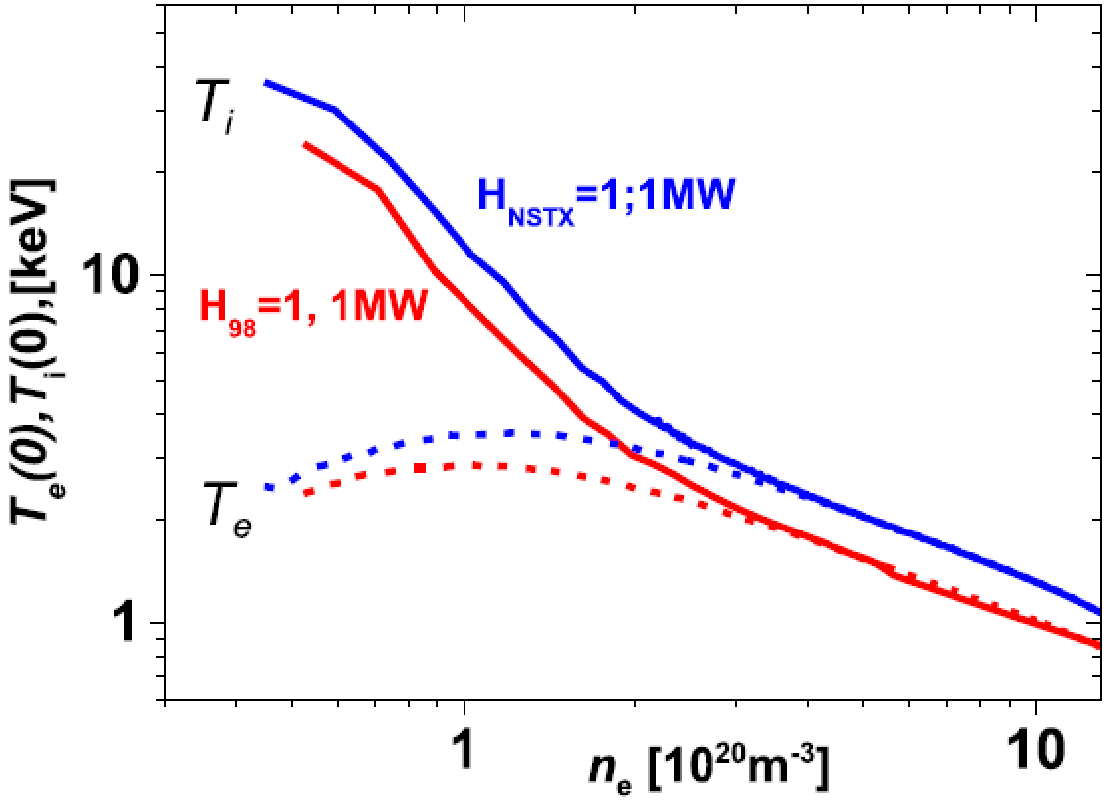
- ST40 has low neoclassical ion transport due to high field



Dnestrovskij, A. Y, J. W. Connor, & M. P. Gryaznevich. "On the confinement modeling of a high field spherical tokamak ST40." *PPCF* 61(5) (2019)

ST40: Performance Potential

- ST40 has low neoclassical ion transport due to high field
- ASTRA modelling indicates potential performance
  - Electron transport scaled to match global confinement time
- Hot ion mode access with as little as 1MW NB power
- ST40 will test ST scalings



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ST40: Performance Potential

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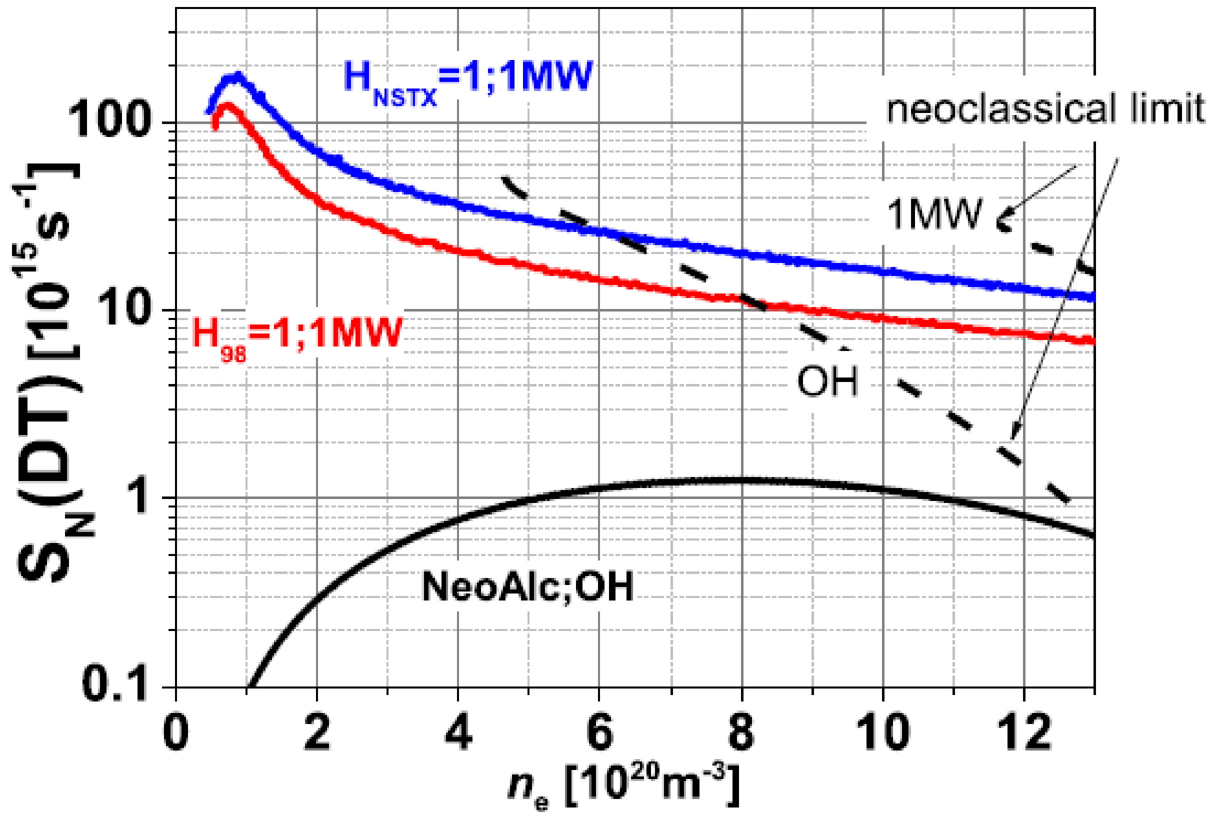
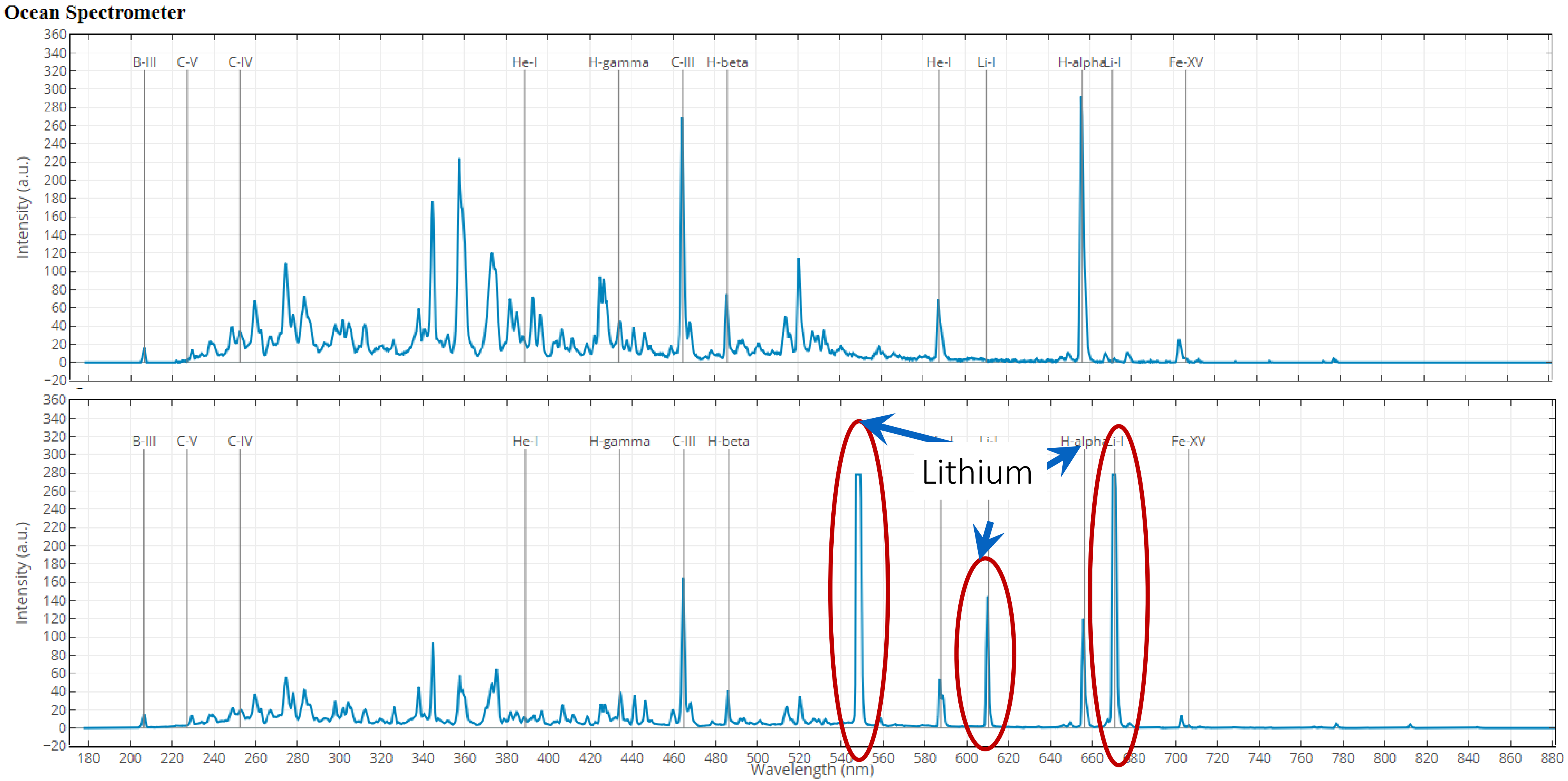
  - Electron transport scaled to match global confinement time
- Hot ion mode access with as little as 1MW NB power
- ST40 will test ST scalings
- Potential VNS?



Dnestrovskij, A. Y, J. W. Connor, & M. P. Gryaznevich. "On the confinement modeling of a high field spherical tokamak ST40." *PPCF* 61(5) (2019)

ST40 – first experience with lithium

- Significant reduction in impurities observed



Public fusion programmes

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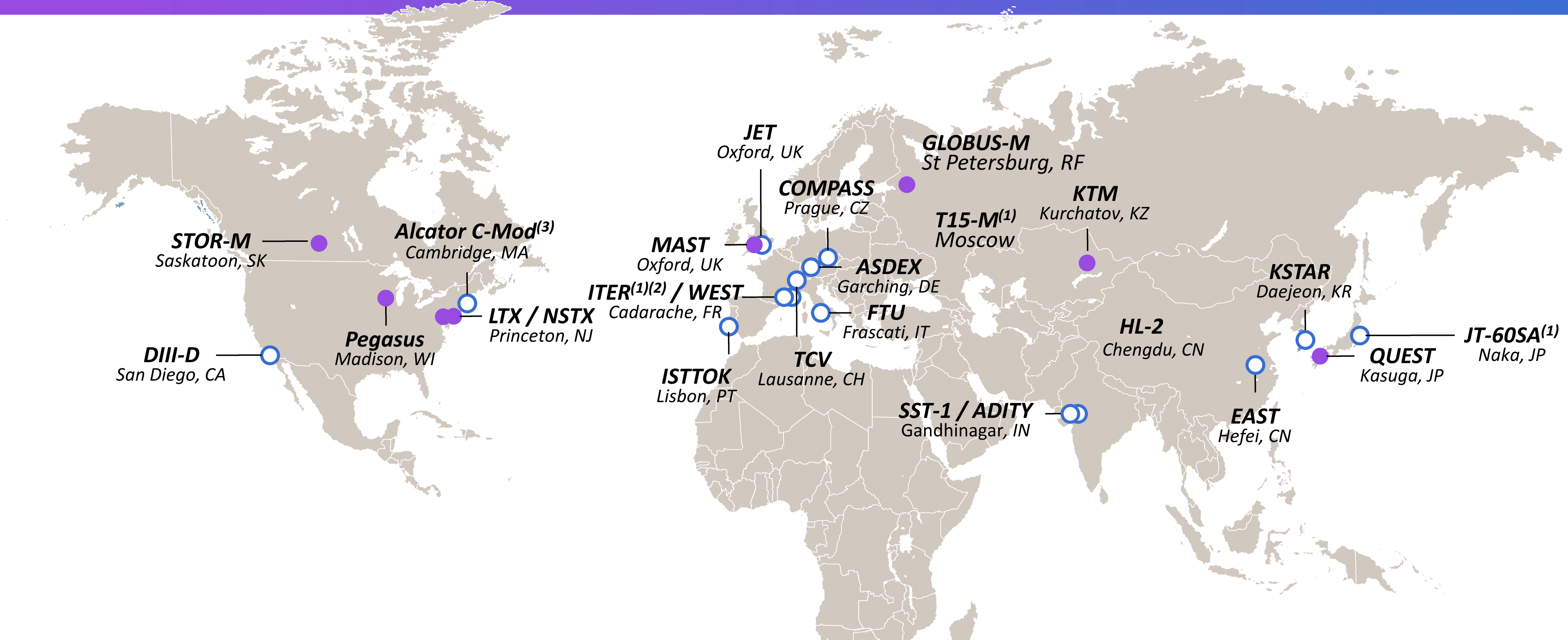

- Conventional Tokamak
- Spherical Tokamak

- Fusion research is advancing
- However, progress towards Fusion Power is constrained

Note: Tokamaks are operating unless indicated otherwise.
(1) Under construction.
(2) The International Thermonuclear Experimental Reactor ("ITER") megaproject is supported by China, the European Union, India, Japan, Korea, Russia and the United States.
(3) No longer in use.

Private fusion

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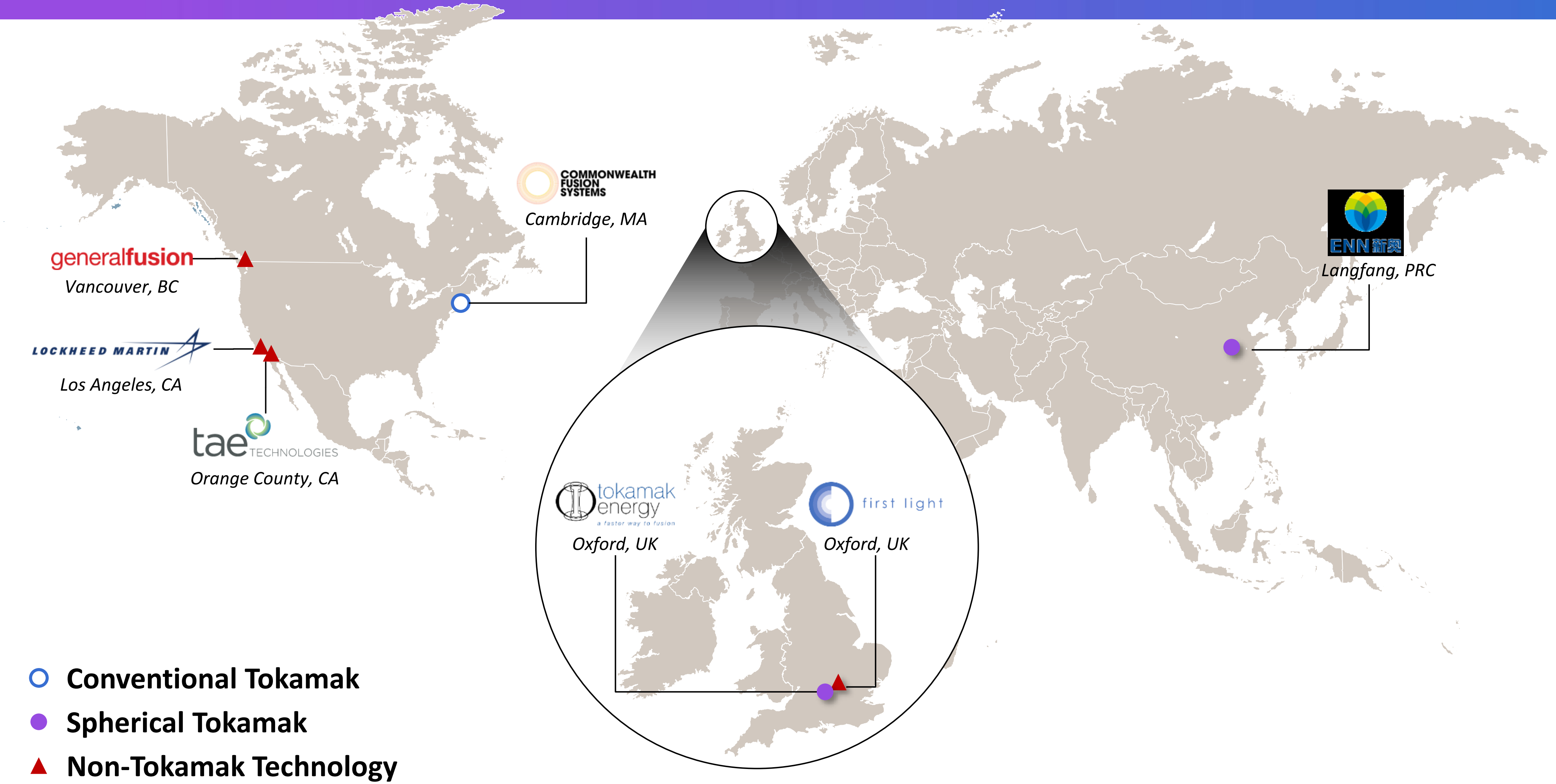

Expanding private sector

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