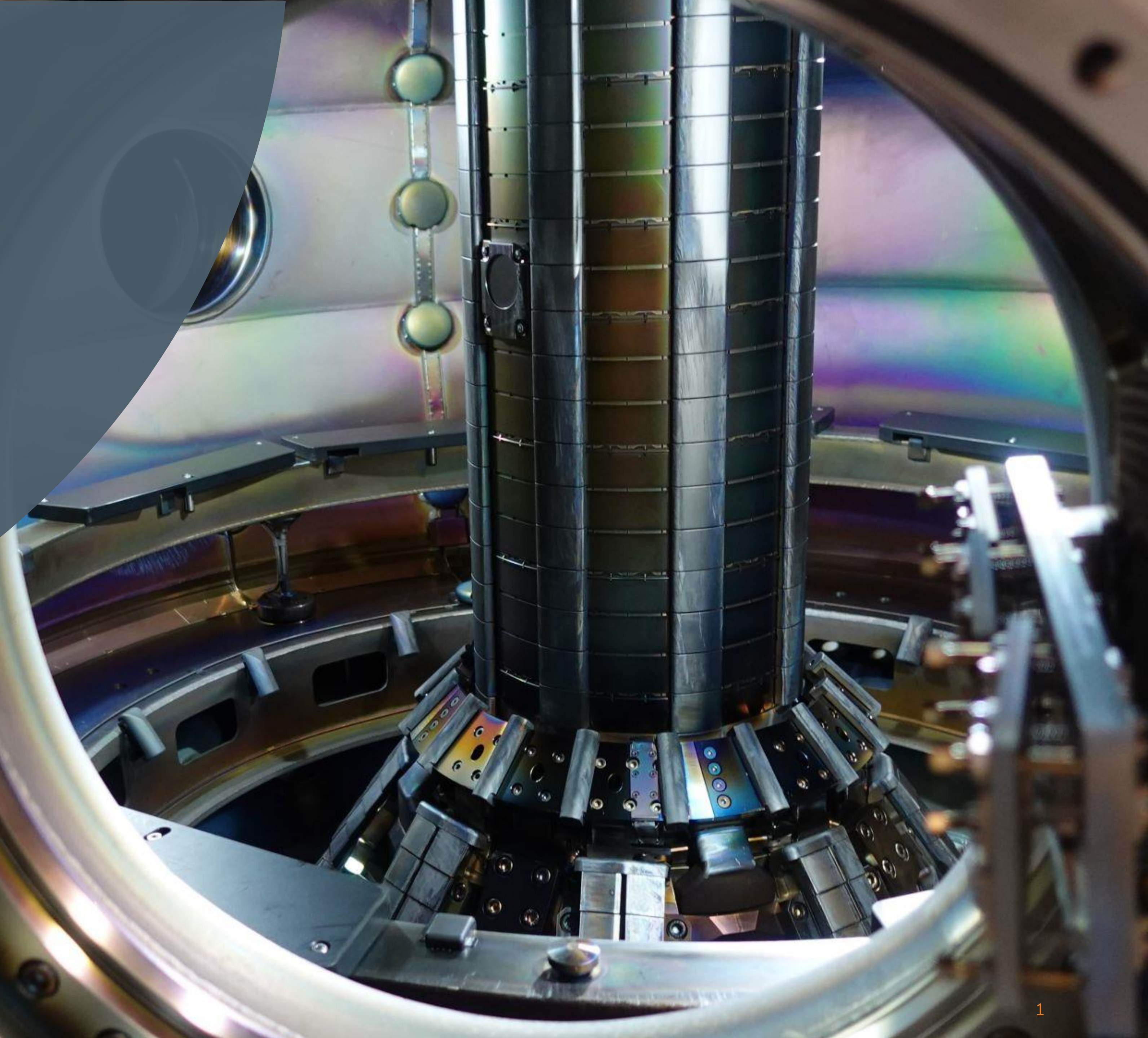
Tokamak Energy

OVERVIEW OF ST40 RESULTS AND FUTURE: EXPANDING THE PHYSICS BASIS OF HIGH-FIELD SPHERICAL TOKAMAKS



ST40 Team

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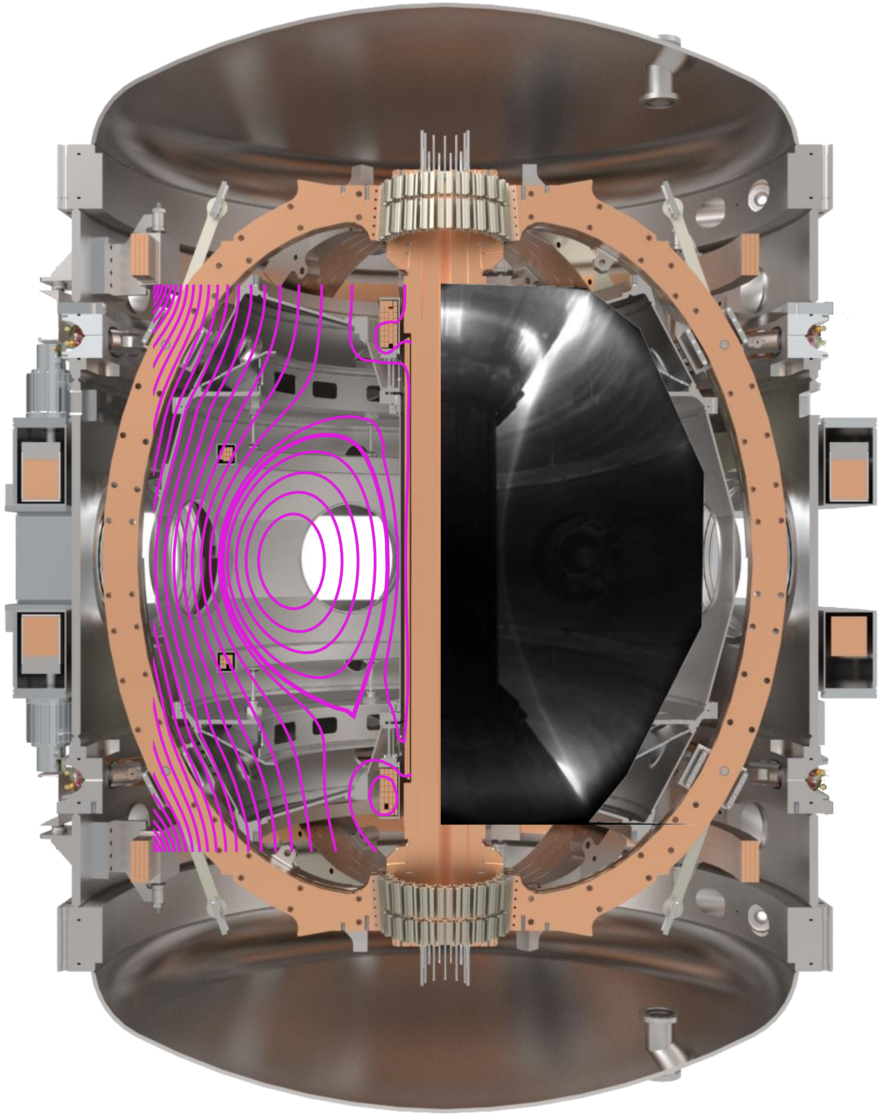
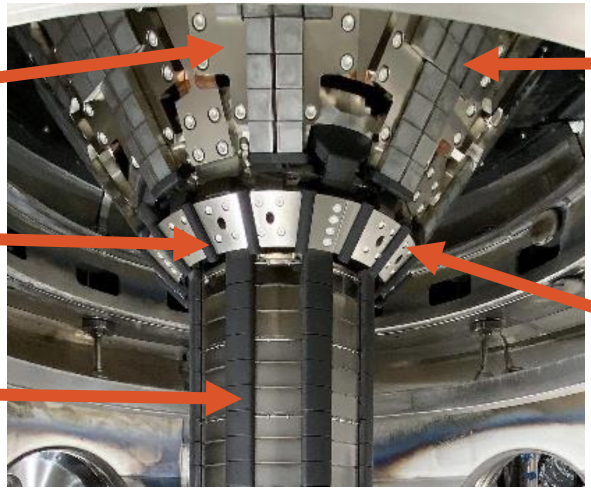
Contributions from collaborators at PPPL and ORNL were supported through U.S. DoE CRADAs NFE-19-07769 and NFE-24-10427

ST40 – Compact high-field spherical tokamak



Parameter	Range
B_t [T]	0.9 – **2.1**
I_p [MA]	0.15 – 0.85
R_{Geo} [cm]	40 – 55
A	1.6 – 1.9
P_{NB}, E_{NB} [MW, keV]	0.8, 24; 1.0, 55
κ	< 1.9
Flattop [ms]	<250
Start-up	Merging-compression



ST40 Programme

Goal: Explore physics of high-field spherical tokamaks (STs), validate empirical and theoretical models and, hence, build confidence in predictions required to support design of future generations of STs.

Main research areas of past 2 years:

(i) Transport and confinement – H-modes and Energy confinement in high-field STs.

(ii) Power exhaust – Scrape-off-layer width

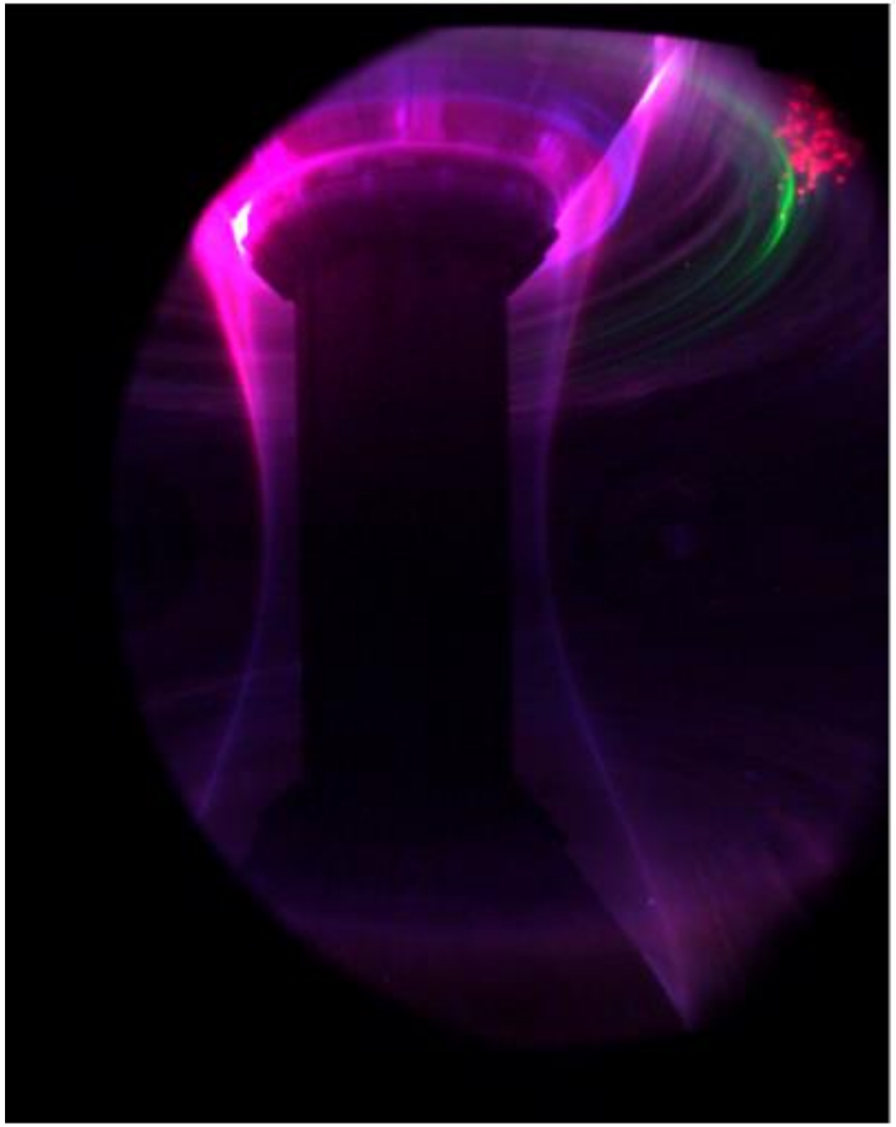
(iii) High-performance scenarios – Developing high I_p scenarios

Outline

i. ST40 capabilities and recent improvements

ii. Highlights of experimental results

iii. Exciting times ahead!



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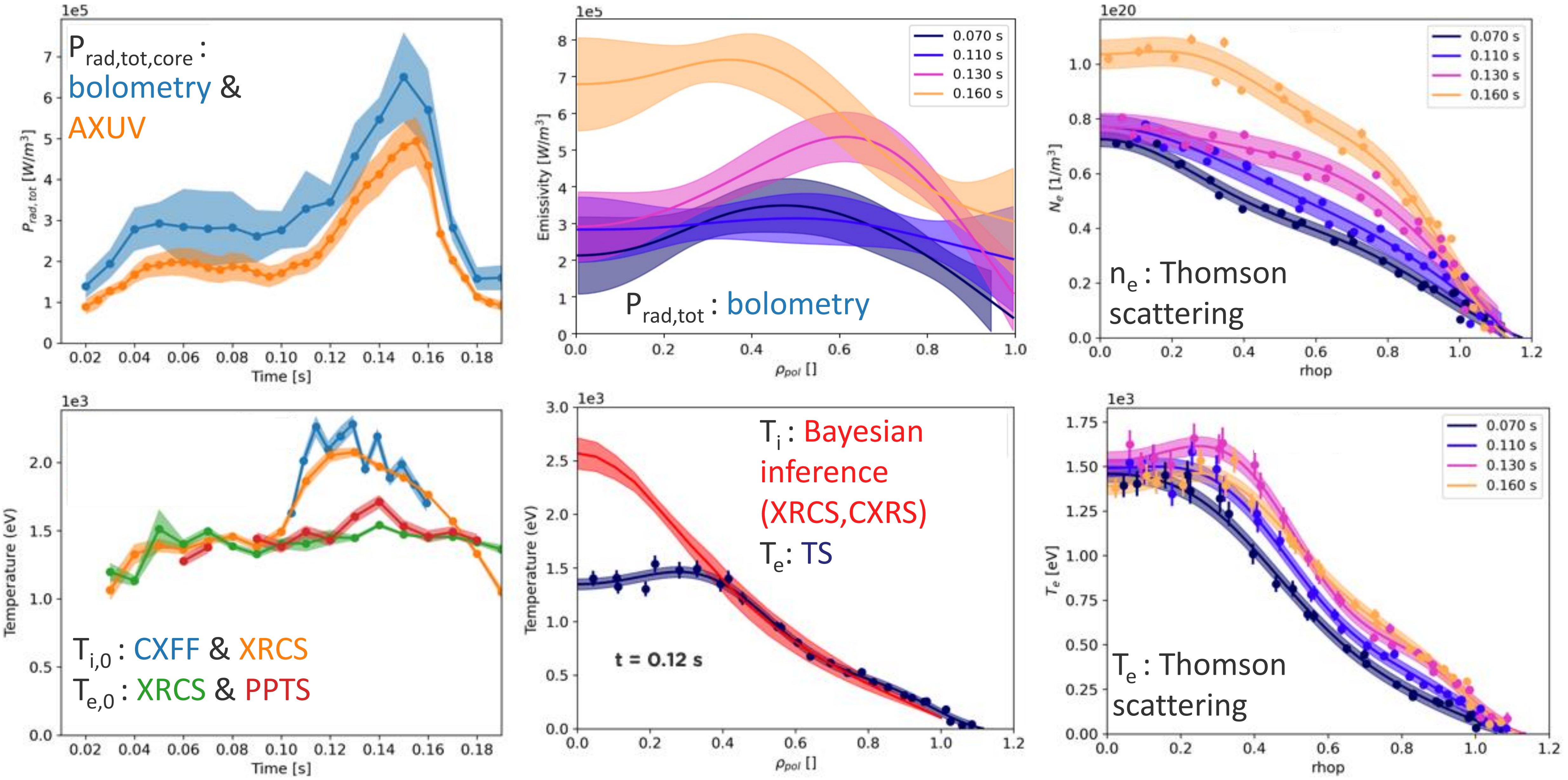
ST40 capabilities and recent improvements – hardware and software

Recent advancements in diagnostics, analysis and interpretation (#14419)

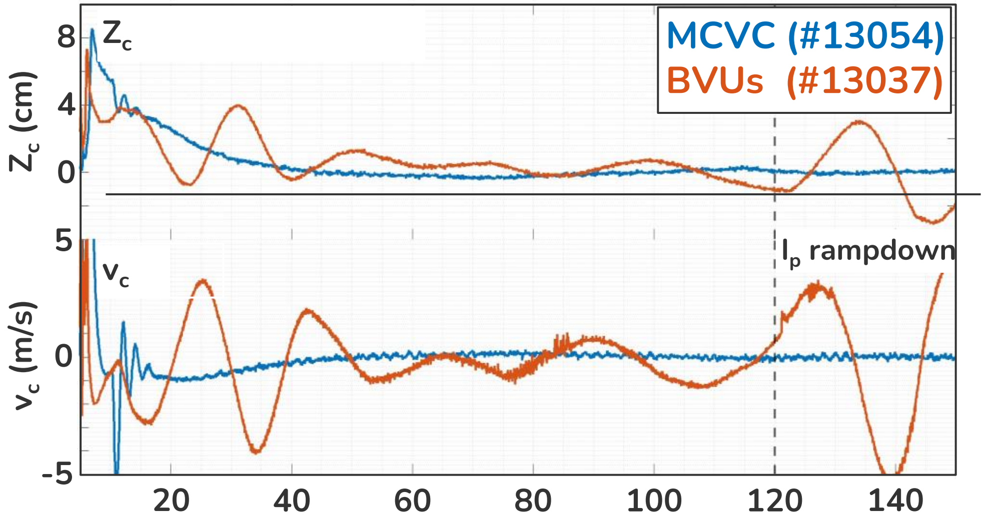


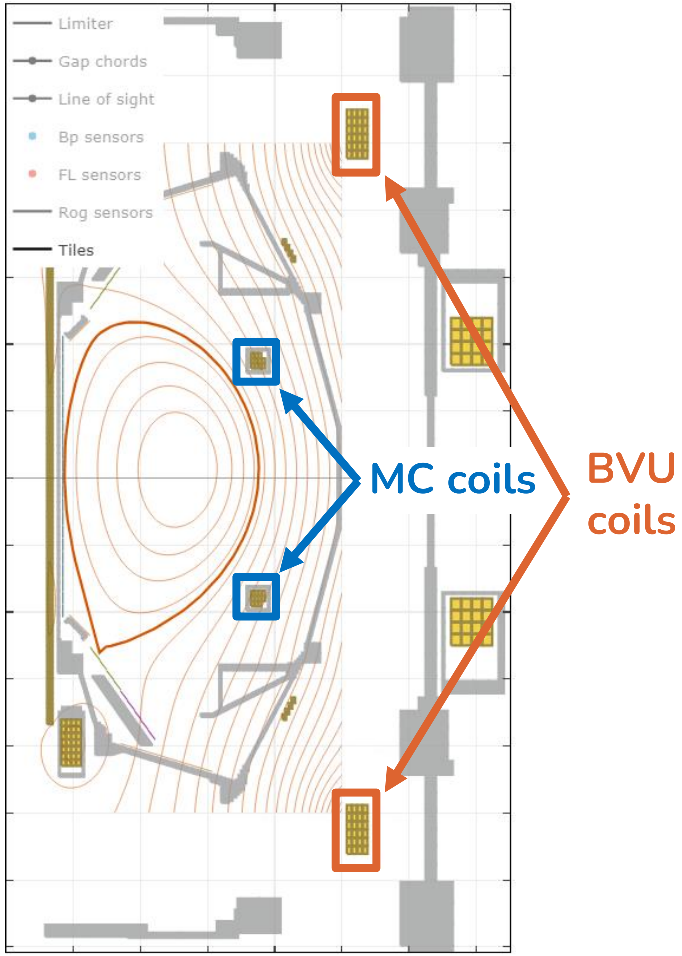
Vertical control using in-vessel MC coils

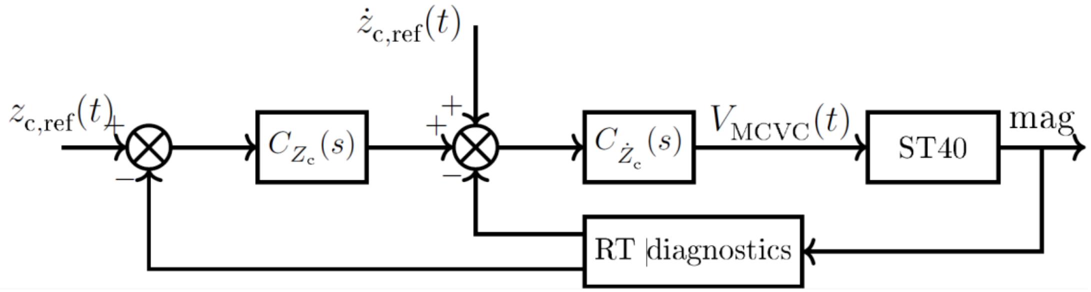
Benjamin Vincent, Tim Erskine, et al.

- **MC coils** in an ideal location for vertical control
- Real-time controllable LV PSU connected to them → MC coils used for start-up and vertical control
- Cascade controller in ST40 PCS to control Z_C and v_C

→ More accurate control + ability to stabilise more unstable plasmas



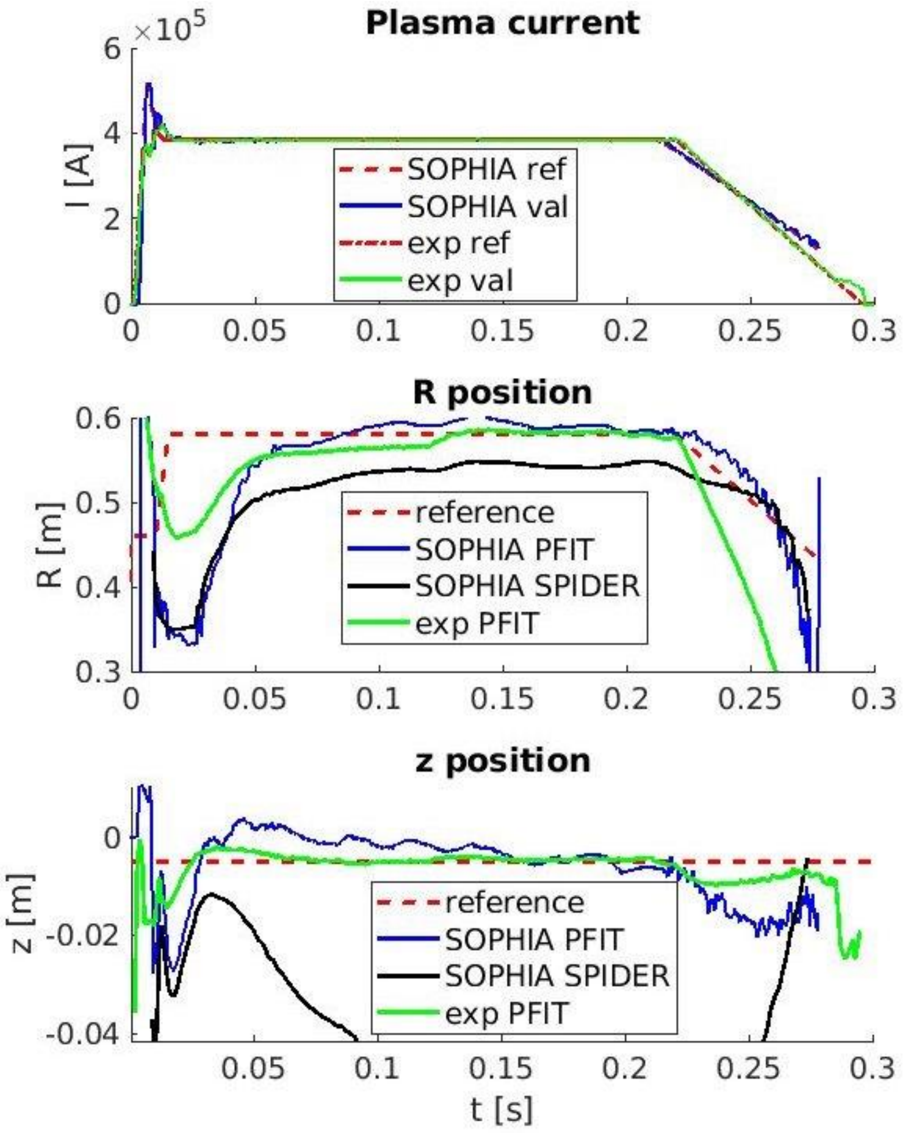




SOPHIA – Tokamak simulator

Filip Janky et al.

- **ST40 PCS + 1D transport code (ASTRA) + 2D free-boundary equilibrium solver (SPIDER) + diagnostic + actuators**
- Developed in MATLAB/Simulink
- Integrated to ST40 infrastructure: pulse preparation tools, data storage, plotting and analysis tools → Perfect tool for training
- Used for scenario development, controller and pulse validation, physics model cross-validation, etc.
- Can be adapted to any tokamak → used for scenario validation and controller design in TE's future device design efforts



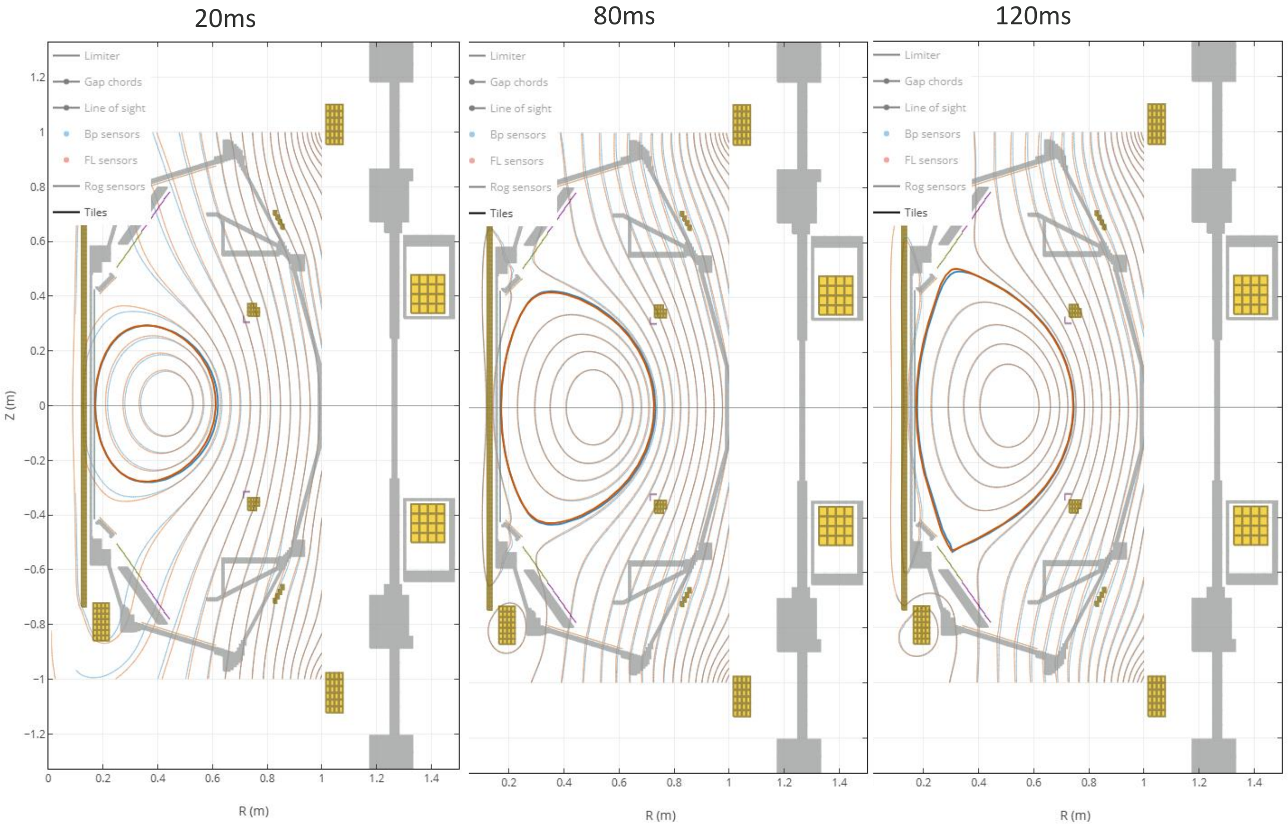
ST40 pulse #13349 compared w/ SOPHIA

GSFit/RT-GSFit

Peter Buxton, Alex Prokopyszyn, et al.

- **GSFit:** user-interface in Python, and compiled Rust for calculations.
- **RT-GSFit:** written in C for real time control. → Integration into ST40 PCS for shape control on-going.
- Both codes open source, and team open for collaborations
- Benchmarked against EFIT (magnetics only, incl. vessel currents): same inputs → nearly identical results

Pulse #12050: **EFIT**, **GSFit**



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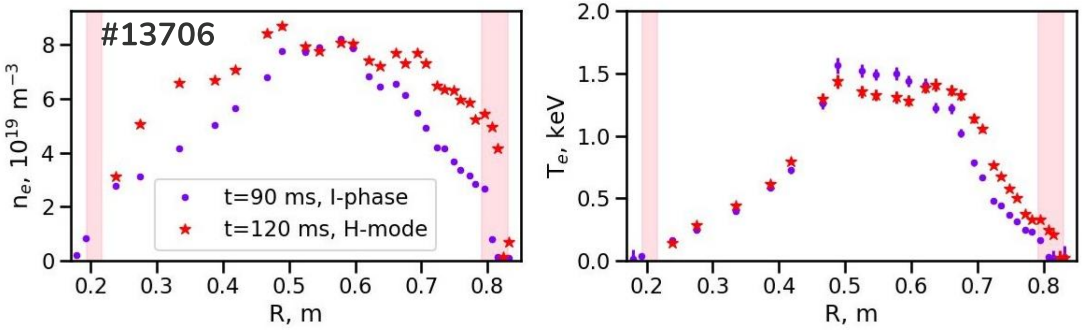
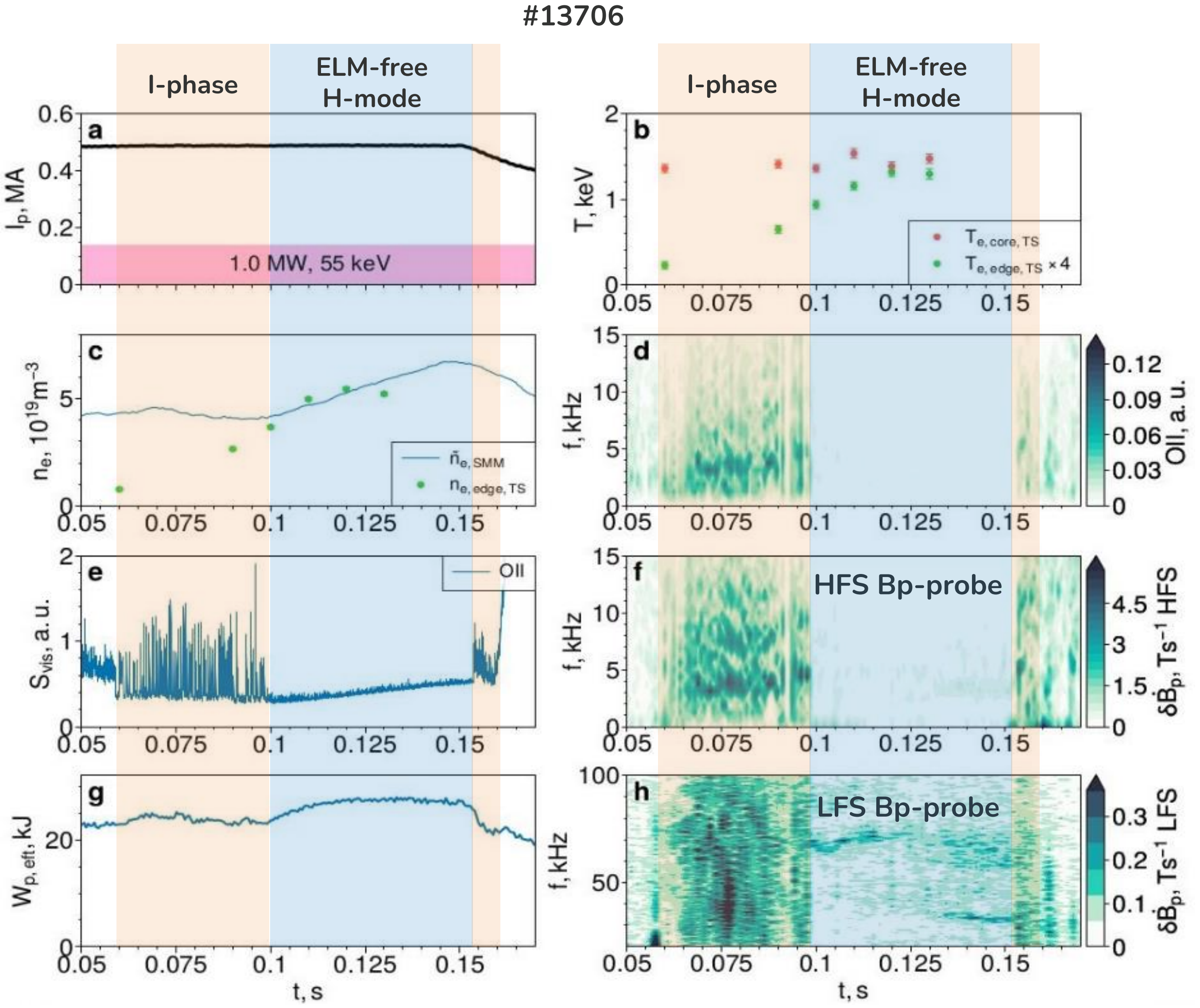
Highlights of experimental results

I-phase – Understanding the L-H transition

Alsu Sladkomedova

- ST40: L-H transition after entering diverted configuration
- Intermediate phase (I-phase, or Limit-cycle oscillations)
  - Seen in many pulses
  - Due to proximity to LH threshold
  - Characterized by kHz oscillations: 3kHz at start, increasing to 4.5kHz before entering H-mode
  - $n_{e,edge}$ (c) and $T_{e,edge}$ (b) increase throughout

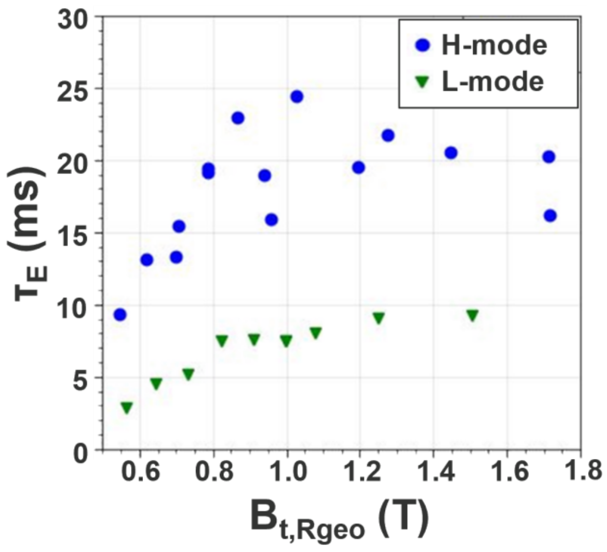




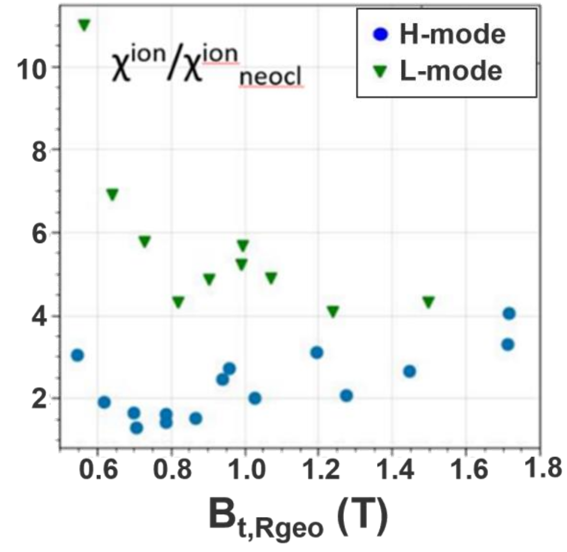
Confinement scalings: τ_E dependence on B_t saturates at $B_t > 1T$

Aleksei Dnestrovskii, Michele Romanelli, et al.

- In STs, in H-mode, at $\mathbf{B_t < 1T}$: $\boldsymbol{\tau_E \sim B_t^1}$ (MAST, NSTX, GLOBUS-M2)
- B_t scanned in ST40 diverted H-mode/L-mode scenarios: I_p = 390kA, P_{NBI} =1MW. n_e ~ constant.
- Interpretative analysis w/ ASTRA+SPIDER
  - @$B_t \leq$0.9T: in H-mode, strong dependence $\boldsymbol{\tau_E \sim B_t^{1.66}}$
  - τ_E saturates at B_t>1 for both H- and L-mode
  - B_t for saturation expected to depend on I_p
- H-mode χ^{ion} close to χ^{ion}_{neocl} at B_t ~ 0.8T → χ^{ion} increases w/ B_t up to ~4 χ^{ion}_{neocl}.
- L-mode χ^{ion} > 4 χ^{ion}_{neocl} throughout B_t scan.



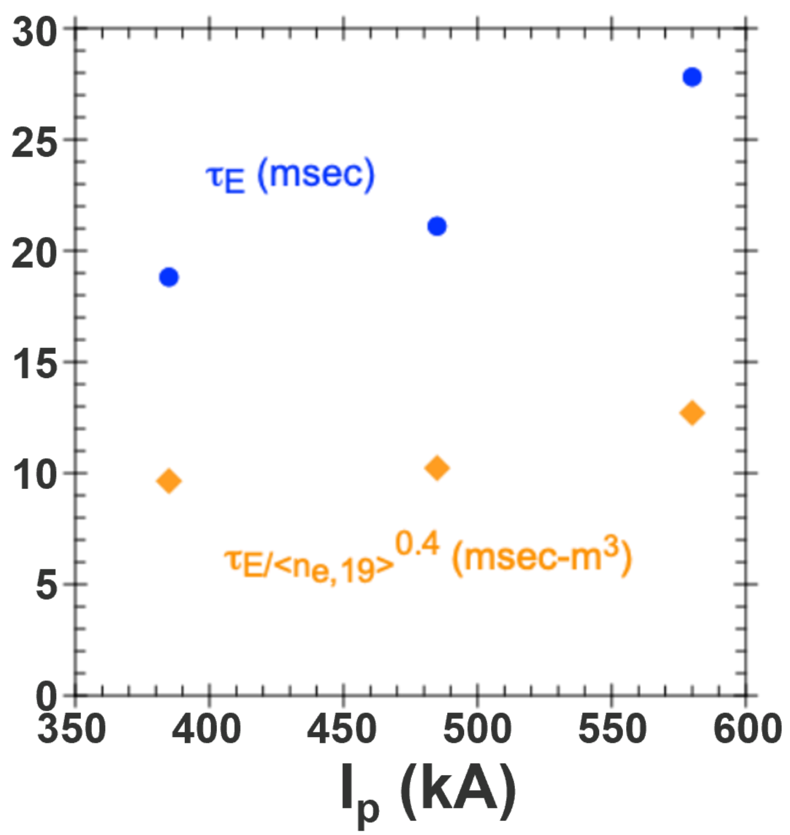
For modelling, see: M. Romanelli, poster #3351, IAEA FEC 2025



Confinement scalings: τ_E dependence on I_p follows other STs

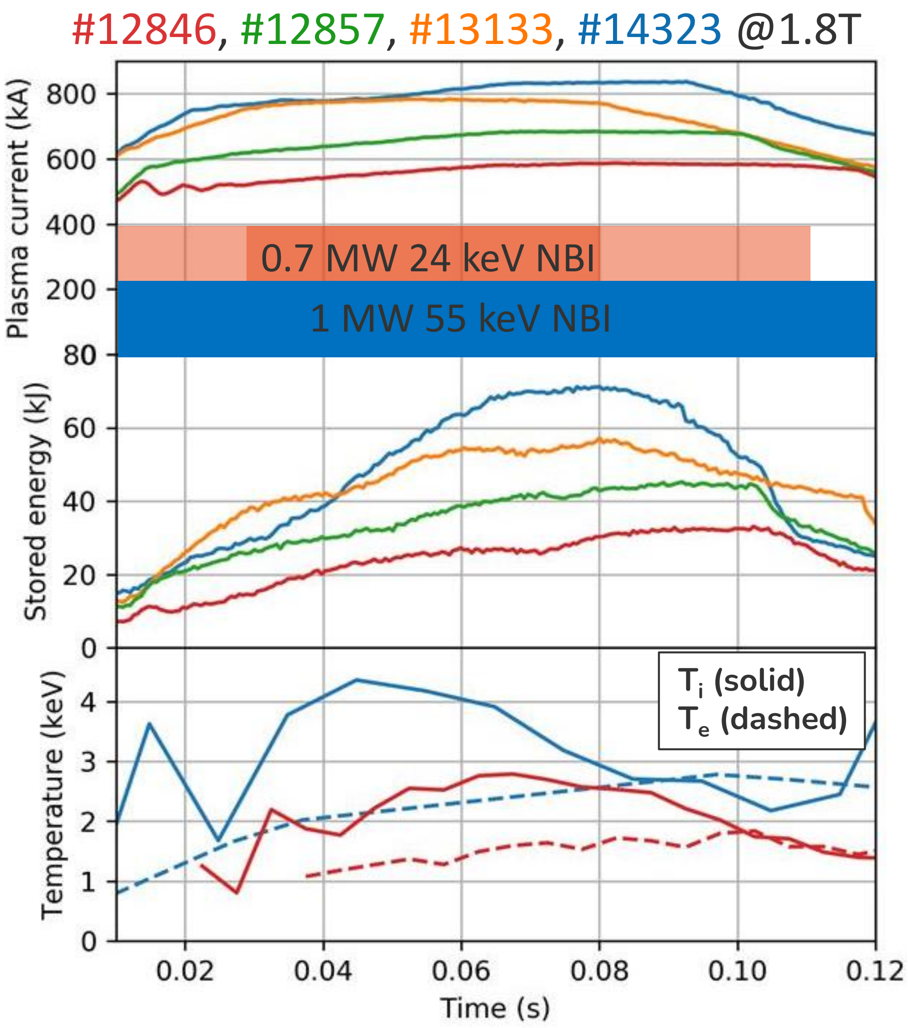
Stan Kaye, Michele Romanelli, et al.

- I_p scanned in ST40 diverted H-mode: B_t = 1.8T, P_{NBI} =1MW
- Interpretative analysis w/ TRANSP
- 30% variation in n_e between pulses
- $\tau_E \sim I_p^{0.93}$, but normalising out n_e dependence (based on ITER98y,2) → $\tau_E \sim I_p^{0.65}$ consistent w/ ST scalings.



High-performance scenarios: I_p=850kA

Jari Varje

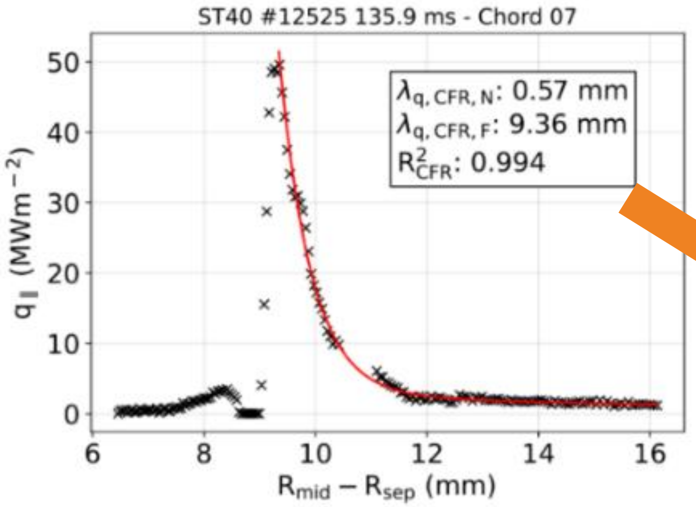


- Scenarios w/ I_p up to 850 kA achieved w/ optimised current ramp-up and LH transition.
- Tried various levels of I_p, ramp-ups, beam timings, …
- I_p~500kA from MC startup → rapid ramp-up, maintaining small limited plasma → rapid elongation into diverted once at Ip flattop → H-mode → ramp I_p to maximum of 850kA.
- Initial hot-ion scenario w\ Ti ≈ 2 T_e sustained into H-mode → n_e increases from 5e19m^{-3} approaching 1.e20m^{-3} → T_i & T_e equilibrate.
- Features: Steep density pedestal, modest temperature pedestal

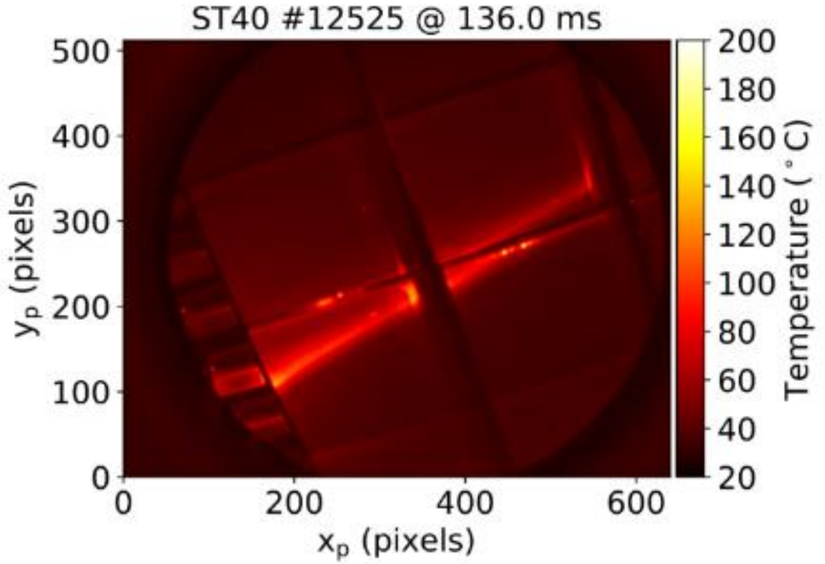
Narrow H-mode scrape-off-layer power fall-off widths, λ_q

Laura Zhang, Chris Marsden, Matteo Moscheni, et al.

Thermographic inversion

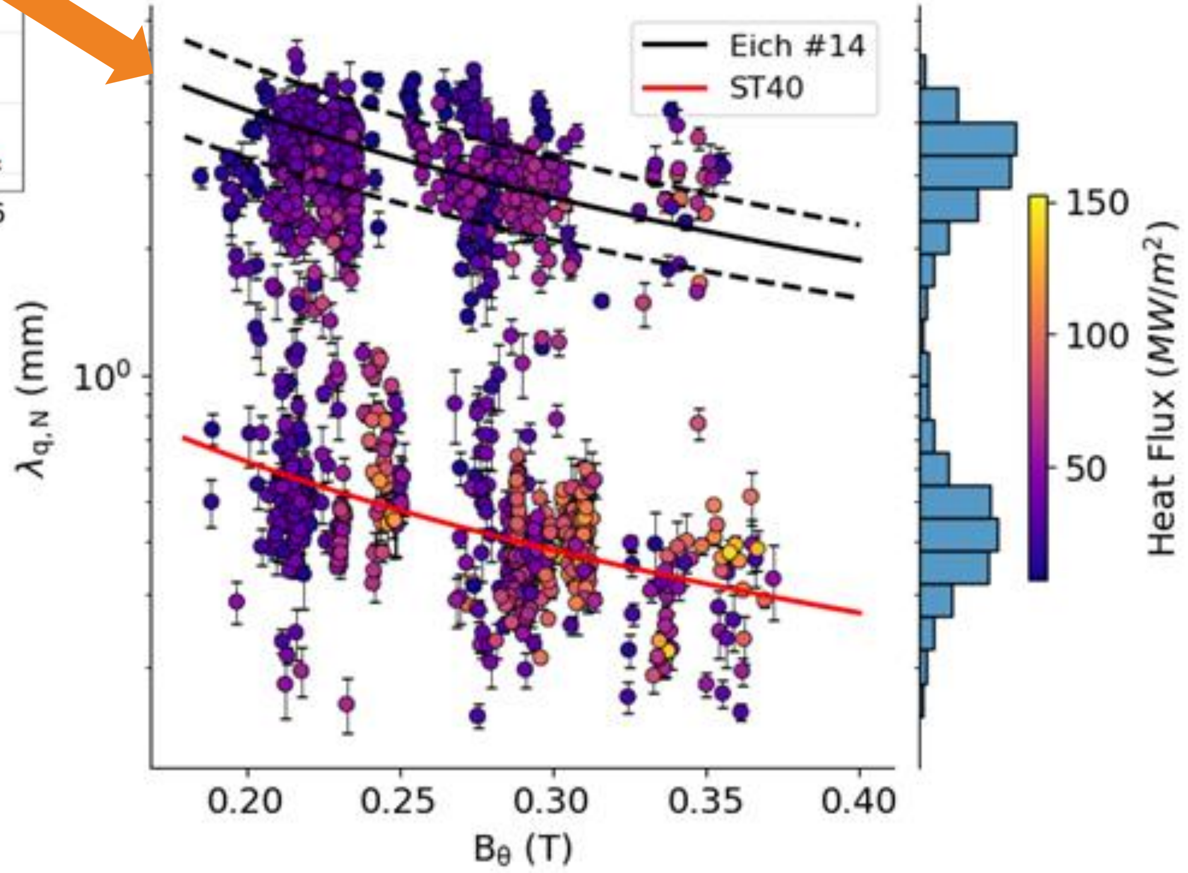


IR camera image



Double exponential fit to $q_{||}$ mapped from divertor to outer midplane

ST40 L-modes follow conventional H-mode scaling (black), H-modes are ~10 times narrower (red). Similar to COMPASS.



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Exciting times ahead for ST40!

Lithium Evaporations to Advance PFCs in ST40 (LEAPS)

- Major device upgrade and programme to **study low(er) recycling regimes in ST40 by evaporatively coating PFCs w/ Li**.
- Research topics include impact of Li on scrape-off-layer, pedestal, core confinement, H&CD, and fuelling.
- Funded by a cross-governmental public-private partnership between Tokamak Energy, U.S. DOE, and UK DESNZ, to be delivered in collaboration w/ PPPL and ORNL.
- Beyond LEAPS: Develop non-inductive start-up and scenarios.

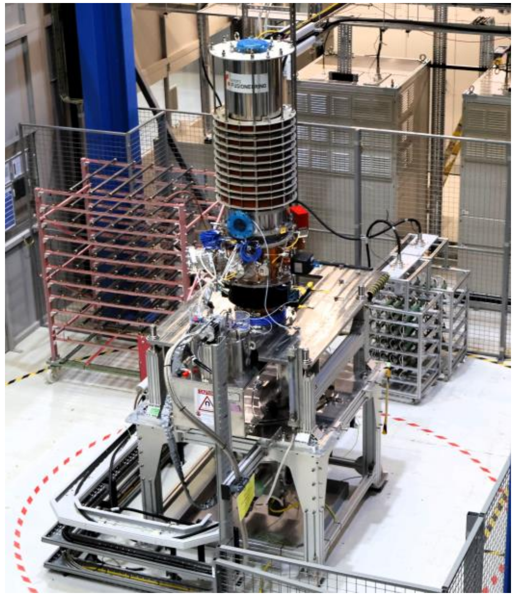
U.S. DEPARTMENT of ENERGY

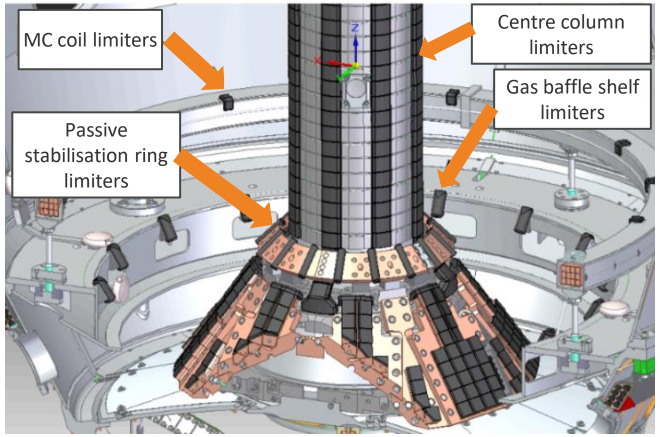
Department for Energy Security & Net Zero

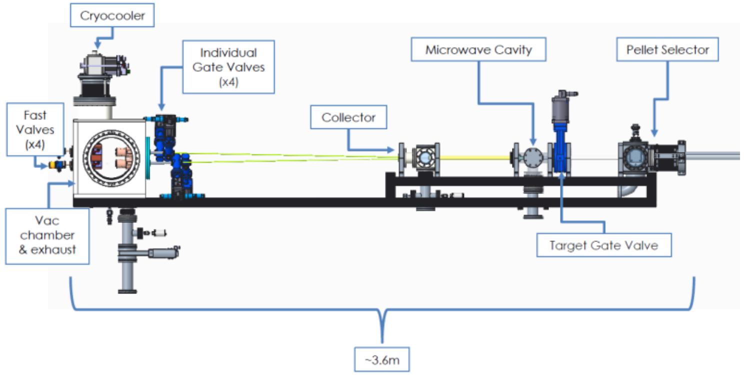
PPPL PRINCETON PLASMA PHYSICS LABORATORY

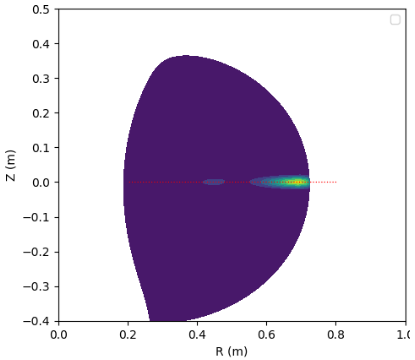
OAK RIDGE National Laboratory

Upgrades increasing relevance of ST40 for future STs









i. Install Li evaporators → Li-coated PFCs and low wall recycling

ii. Remove graphite → Metal (Mo) PFCs throughout

iii. 1MW dual-frequency (104/137 GHz) gyrotron → RF start-up and H&CD. Towards electron heated, non-inductive, low rotation scenarios.

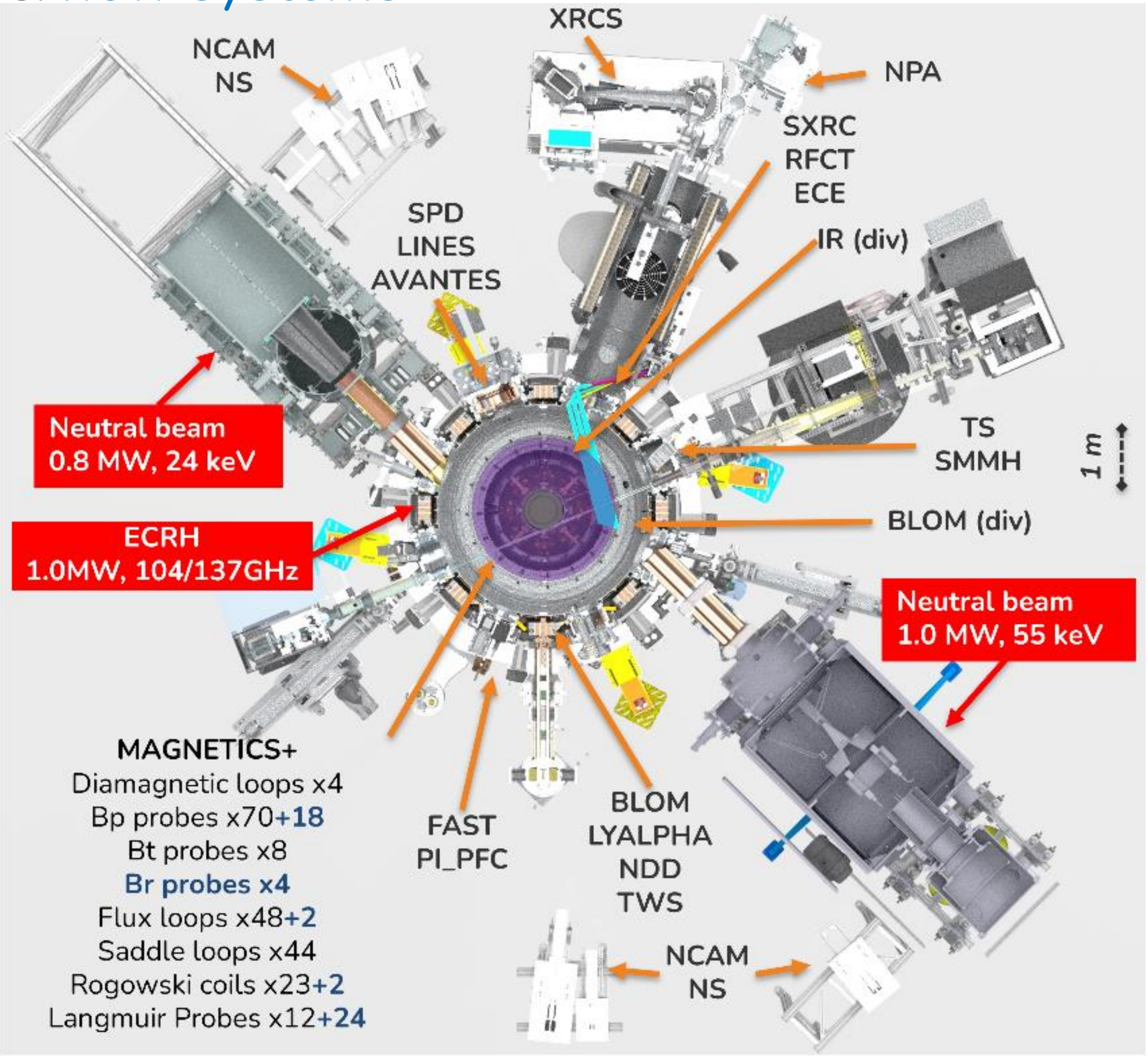
iv. 4-barrel D pellet injector → Core fuelling

v. Replace centre stack → Robustness + higher TF (2.4T @R=0.4m)

vi. Overhaul diagnostics suite → Support programme objectives

ST40 Diagnostics – upgrades & new systems

Electron temperature & density	**Thomson scattering (TS)**
	Sub-mm interferometer (SMMH)
	Near-infrared interferometer (NIR)
	Density Reflectometer (RFCT)
	ECE radiometer (ECE)
Ion temperature & rotation	**Charge exchange recombination (TWS)**
	X-ray Crystal Spectrometer (XRCS)
Spectroscopy	Vis-UV overview (AVANTES)
	Vis-UV filtered diodes (LINES)
	Vis-UV Spectroscopy (PI_PFC)
Probes	**Langmuir probes (LP)**
Cameras	**IR camera (IR_DIV)**
	Fast visible camera (FAST)
Pinhole cameras	**Foil bolometers (BLOM)**
	AXUV cameras (SXRC)
	Lyman-α (LYALPHA)
	SXR filtered diodes (SPD)
Particles, Neutrons	Hard X-ray diagnostic (HRX)
	Neutral particle analyser (NPA)
	Neutron detectors (NCAM/NS/NDD)
	Fission chamber (FC)
	Absolute neutron calibration (NCAL)

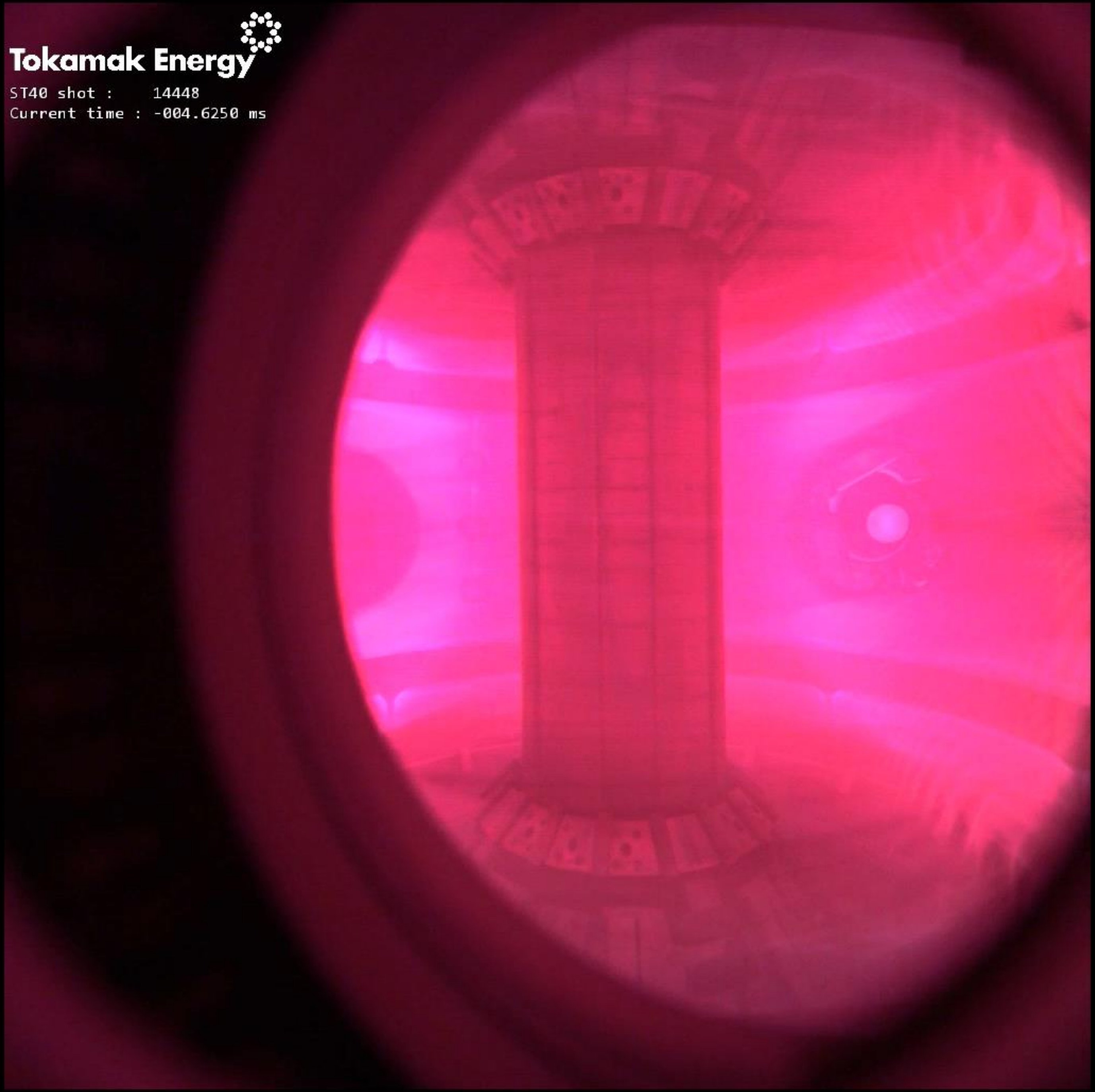


Summary

- ST40: Tokamak Energy's compact high-field spherical tokamak
- Recent experimental highlights:
  - Saturation of B_t dependence of τ_E at B_t >1T
  - Ultra-narrow SOL power-fall-off widths in H-mode plasmas
  - I_p=850kA scenarios
- Exciting times ahead: **L**ithium **E**vaporations to **A**dvance **P**FCs in **S**T40 **(LEAPS)** + 1MW of RF + pellets ++

See manuscript for more details and references

Thank you!


Tokamak Energy
ST40 shot :   14448
Current time : -004.6250 ms

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Thank you!

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