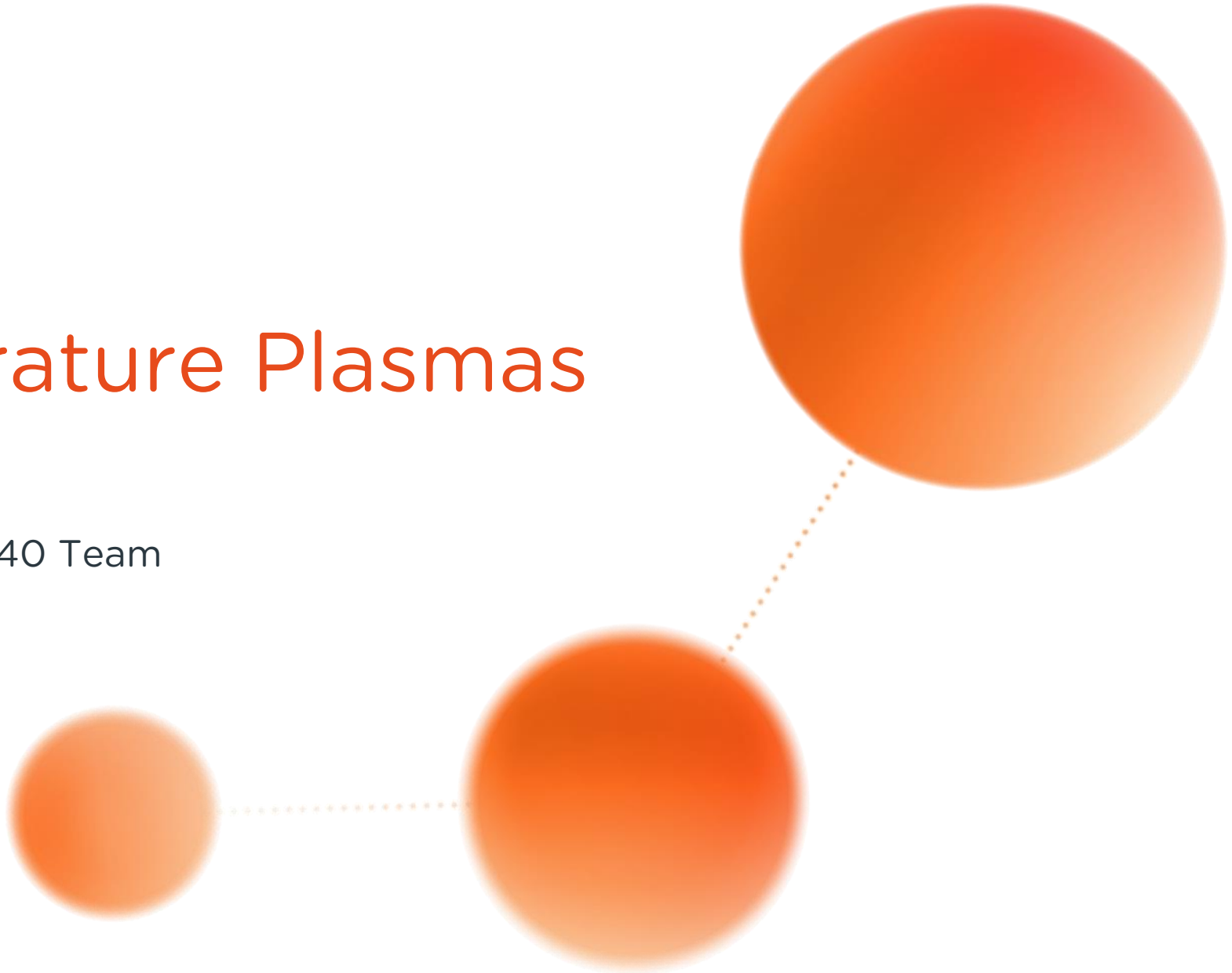
Tokamak Energy

High Temperature Plasmas in ST40

Otto Asunta on behalf of ST40 Team



Authors and contributors

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The Diagnostic Advisory Board, the TE management team and TE's investors.
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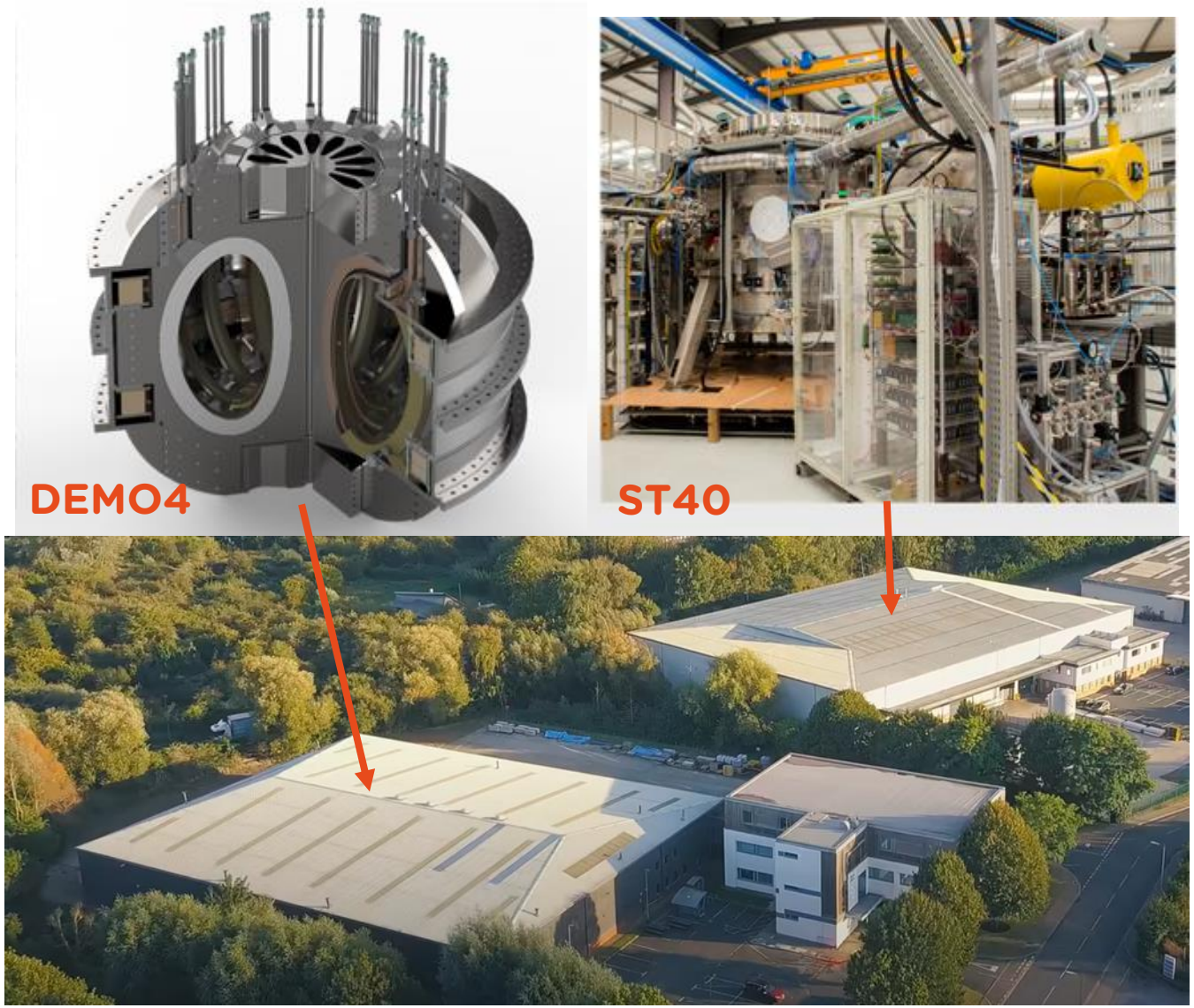
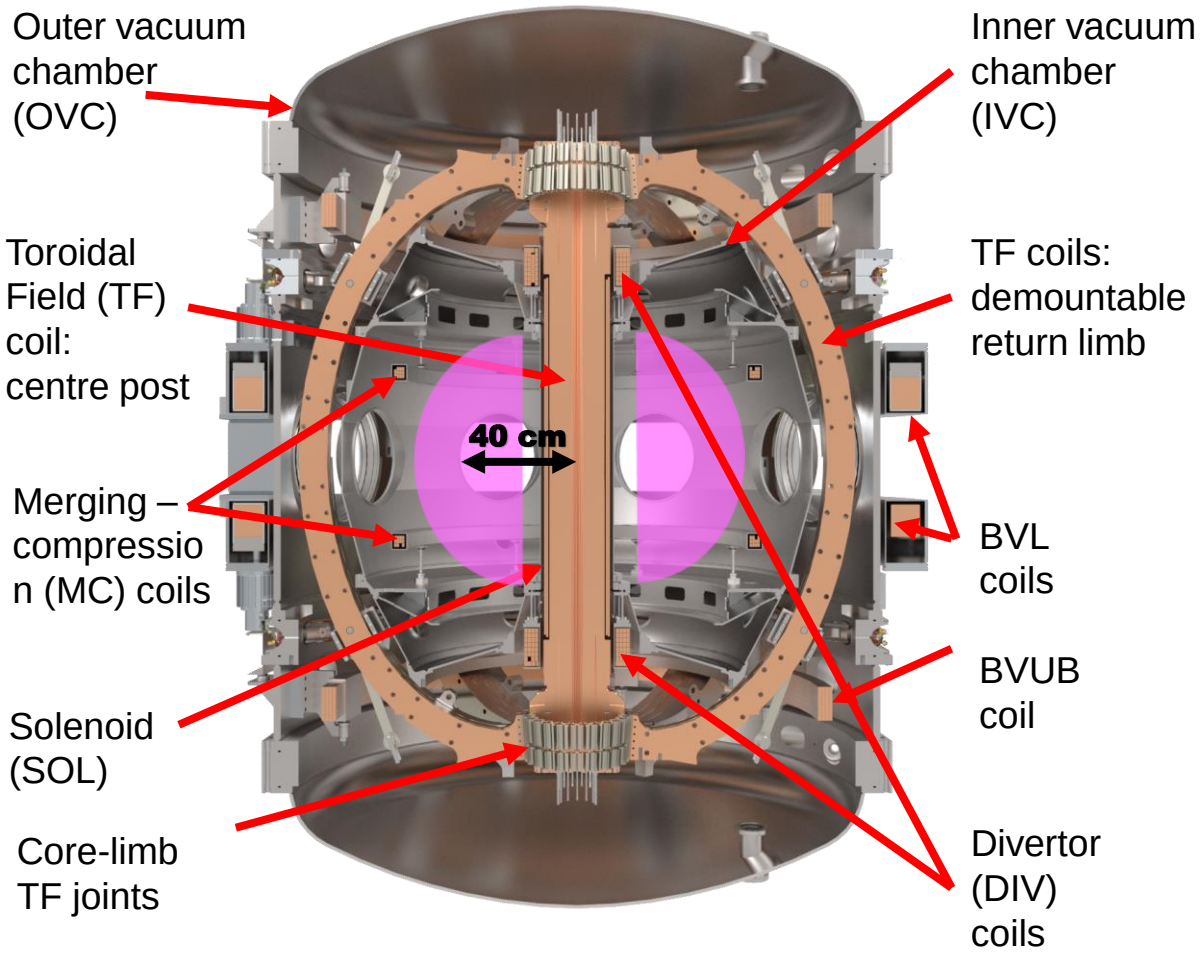
Tokamak Energy Ltd.

- Established in 2009 with a mission to develop a faster route to fusion energy
- Engineering centre in Milton Park, Oxfordshire, UK. US subsidiary expanding
- Over $200M investment with $50M from UK and US governments
- Team of over 220 and growing fast!
- Operating the ST40 compact high field spherical tokamak
- World leading high temperature superconducting magnet facility



ST40: High-field spherical tokamak w/ Cu magnets



Parameter	Range
Bt [T]	1.5 – 2.2
Ip [MA]	0.4 – 0.8
R_{Geo} [cm]	40 – 50
A	1.6 – 1.8
P_{NB}, E_{NB} [MW, keV]	0.8, 24; 1.0, 55
Pulse duration [ms]	~150
Start-up	Merging-compression
Fuel	Hydrogen/Deuterium

ST40 divertor

ST40: Advancing the high field ST physics basis

Confinement & stability at high field

Strong scaling of confinement observed on other STs with increasing toroidal field

Solenoid-free start-up schemes

Merging compression and RF driven start-up (EBW + ECRH)

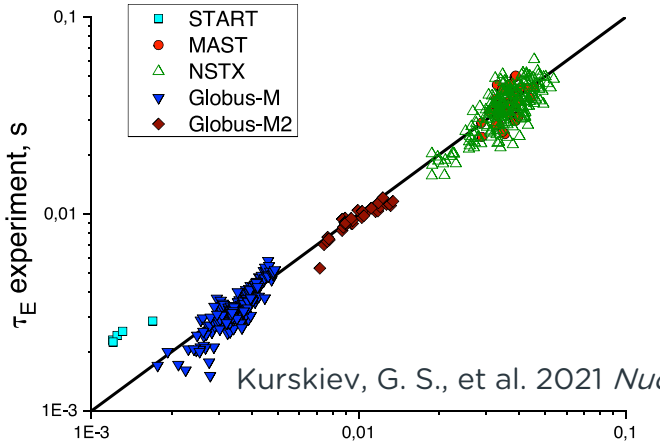
High performance reactor relevant operating scenarios

High bootstrap, high performance regimes with dominant RF H&CD

Characterise divertor performance

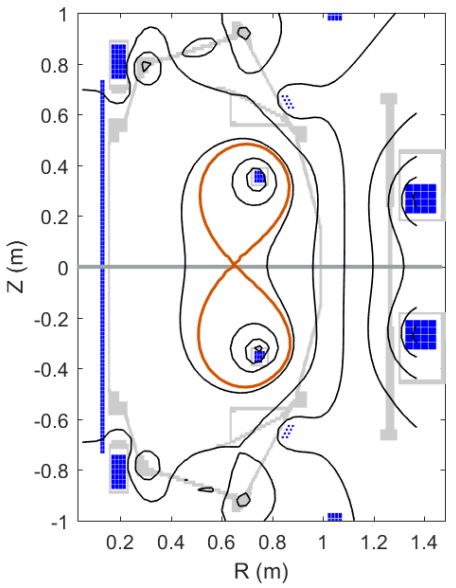
Scrape-off layer width scalings at high poloidal and toroidal fields

Talk by M. Romanelli on Tuesday: "ST40: Advancing the Physics Basis of Spherical Tokamak Reactors"



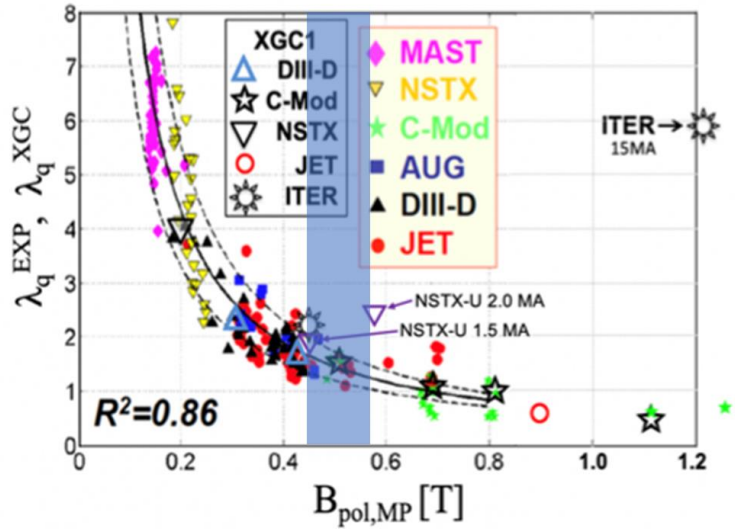
Kurskiev, G. S., et al. 2021 *Nucl. Fus* .**62**.

$$\tau_E(ST) \sim I_p^{0.5} \boldsymbol{B_T^{1.0}}$$



ST40
1MA

Chang, C. S., et al. 2021 *PoP* **28**



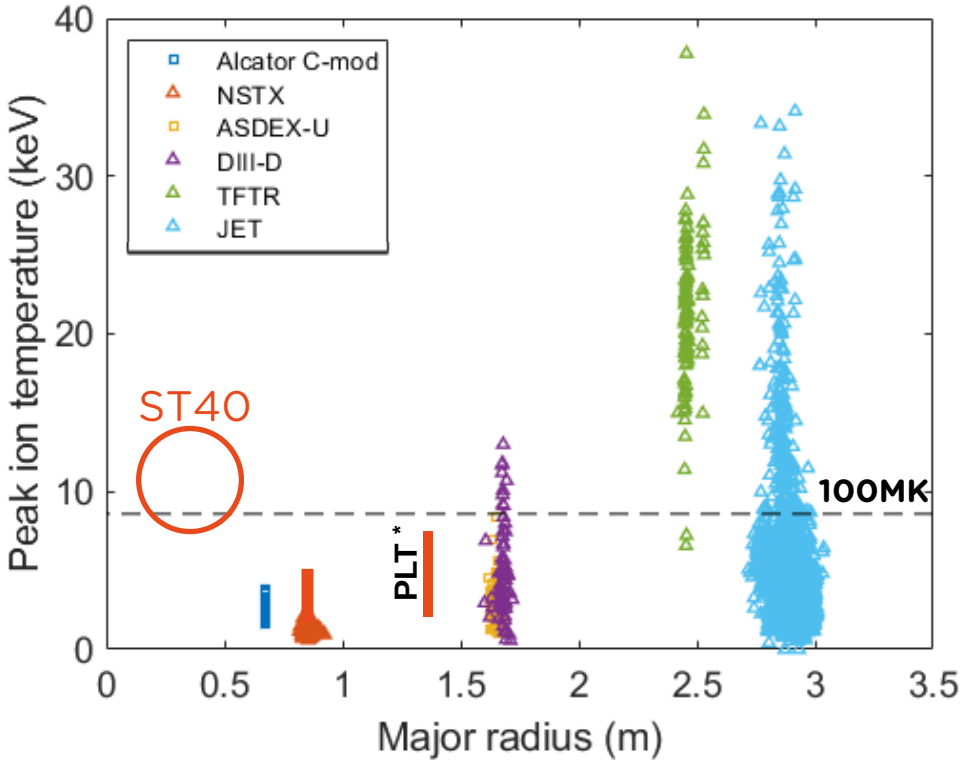
Fusion relevant ion temperatures in ST40

Business milestone: reach fusion relevant ion temperatures of 100MK (8.6keV) in ST40

Can we establish the necessary operating scenario?

Can we robustly measure the ion temperature?

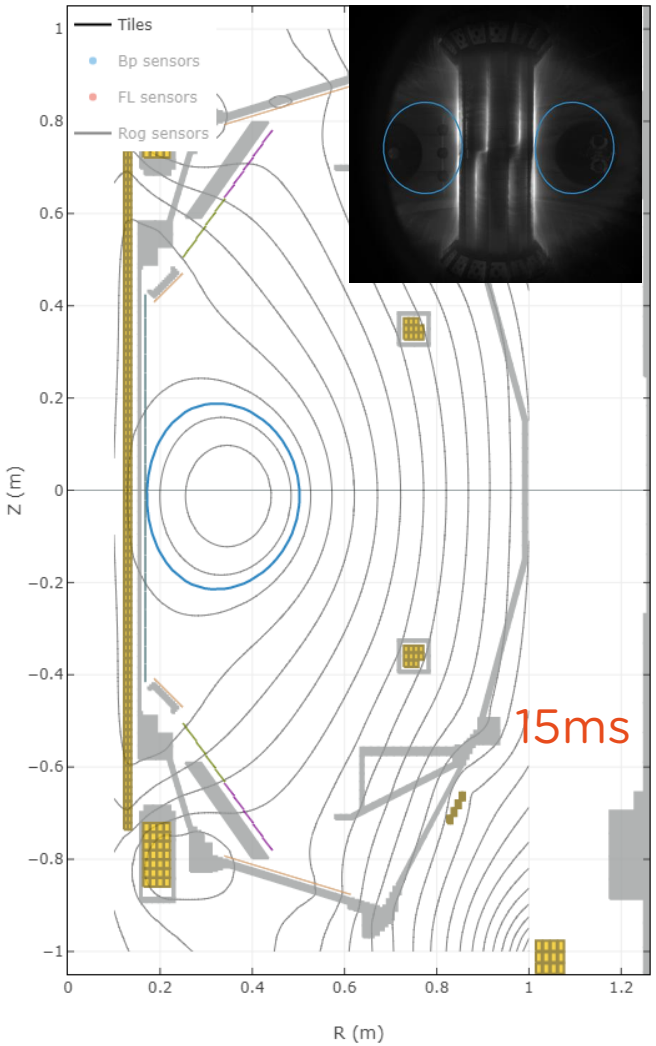
Do we understand what is going on and can we model it?

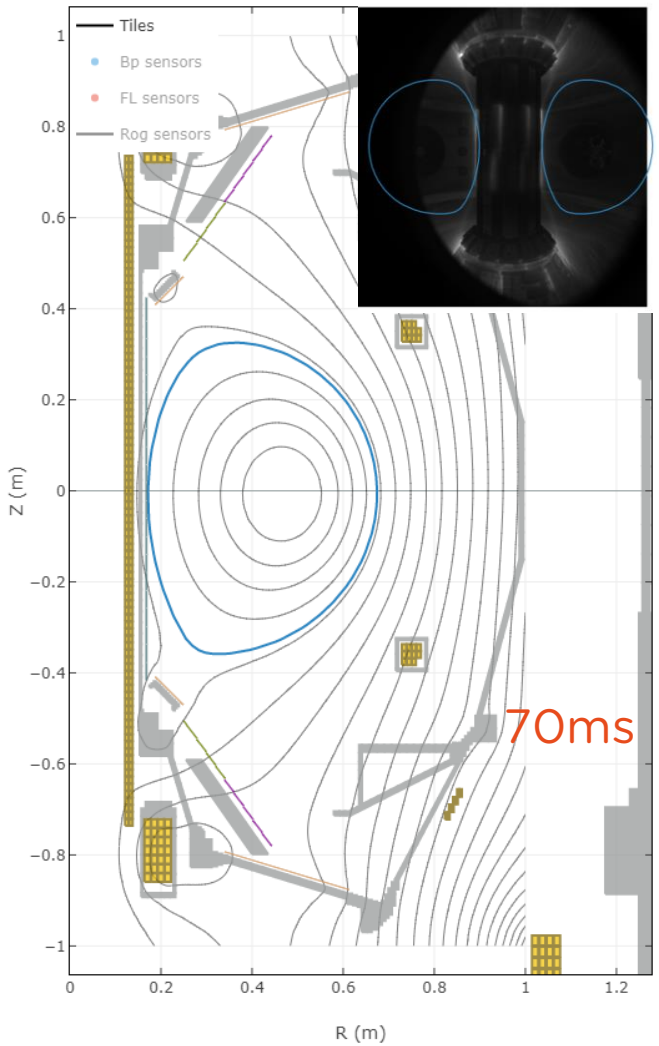


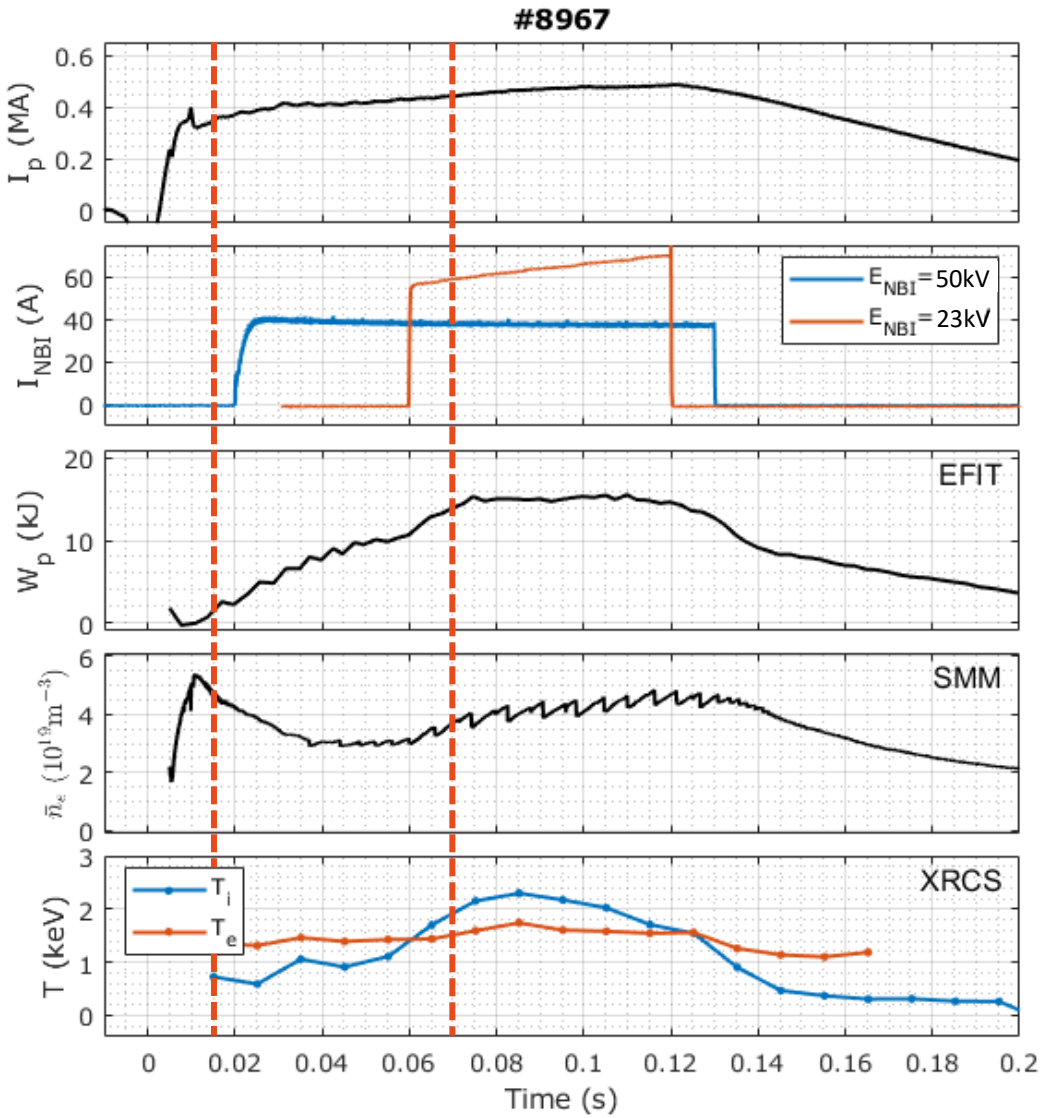
A Yu Dnestrovskij et al 2019 Plasma Phys. Control. Fusion 61 055009

Data from ITPA DB5V2.3 ITER confinement database
*W Stodiek et al., IAEA-CN-38/A-1 1980 no ripple

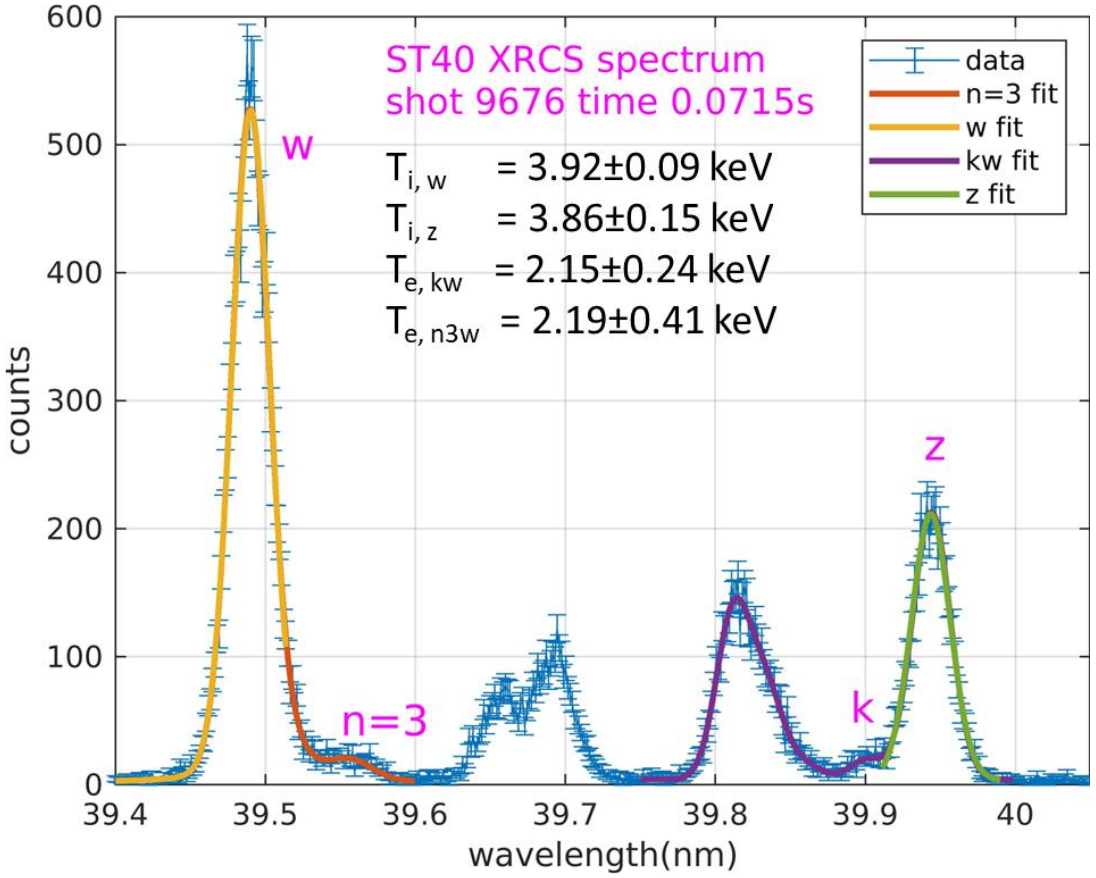
Early full power $H^0 \Rightarrow H^+$ pulse (09/21) – first hot-ion plasmas, $W_{p,max}$~15kJ

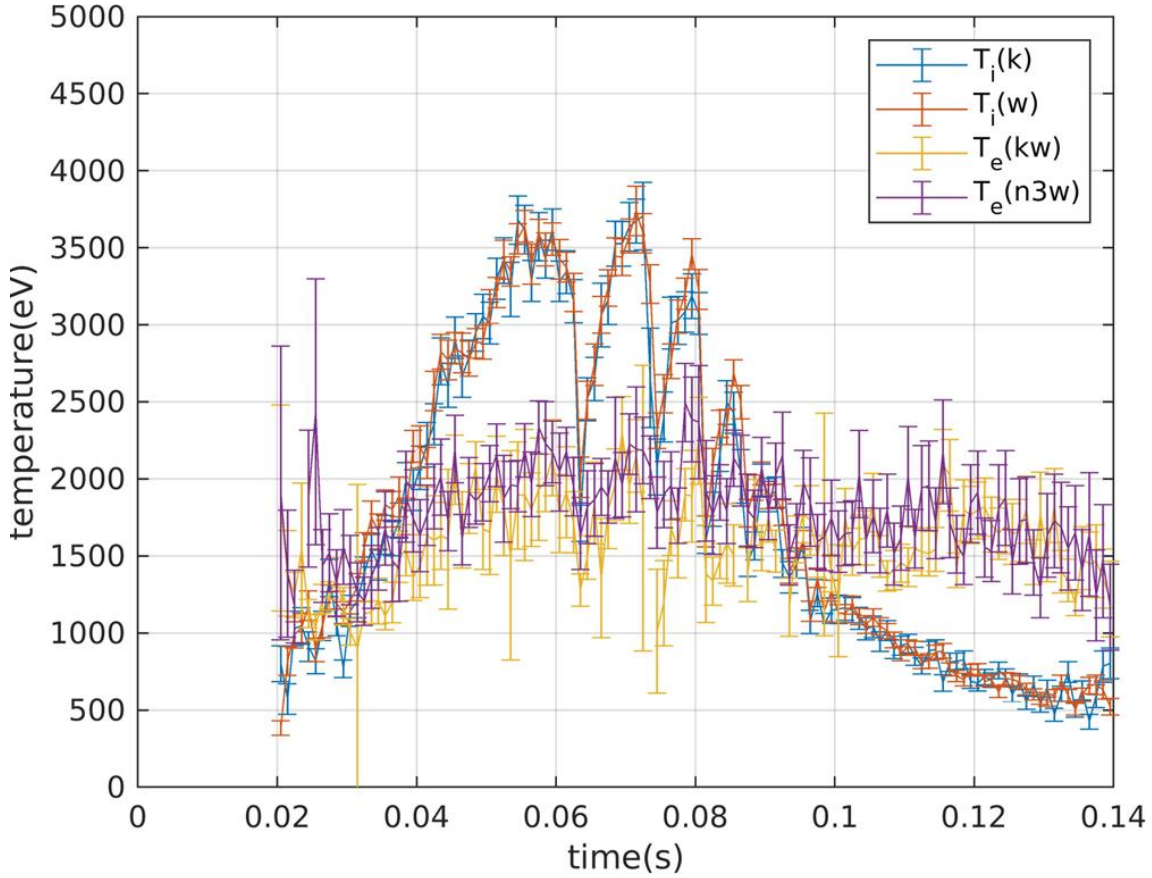






X-ray Crystal temperatures from He-like argon (pulse #9676)

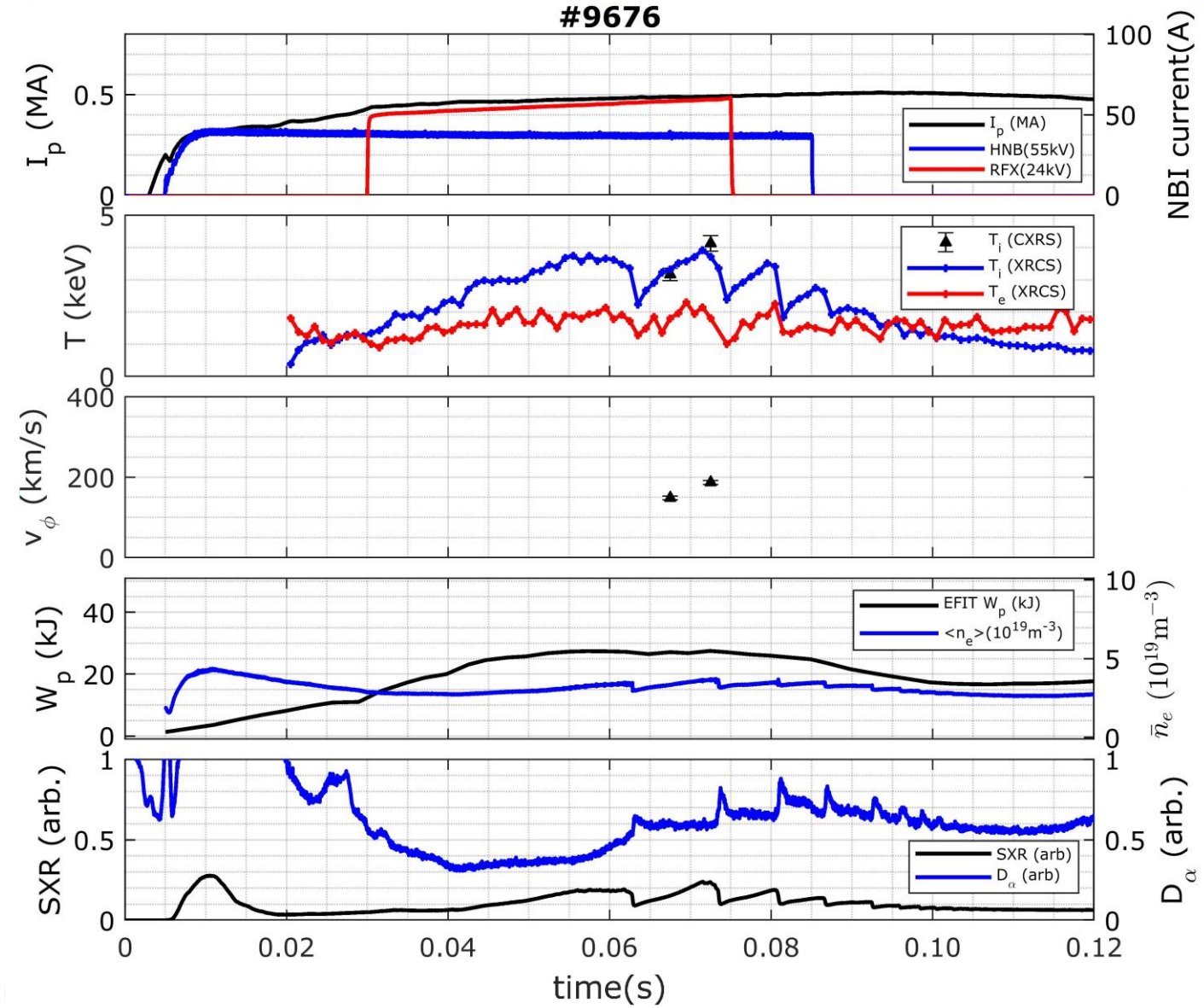




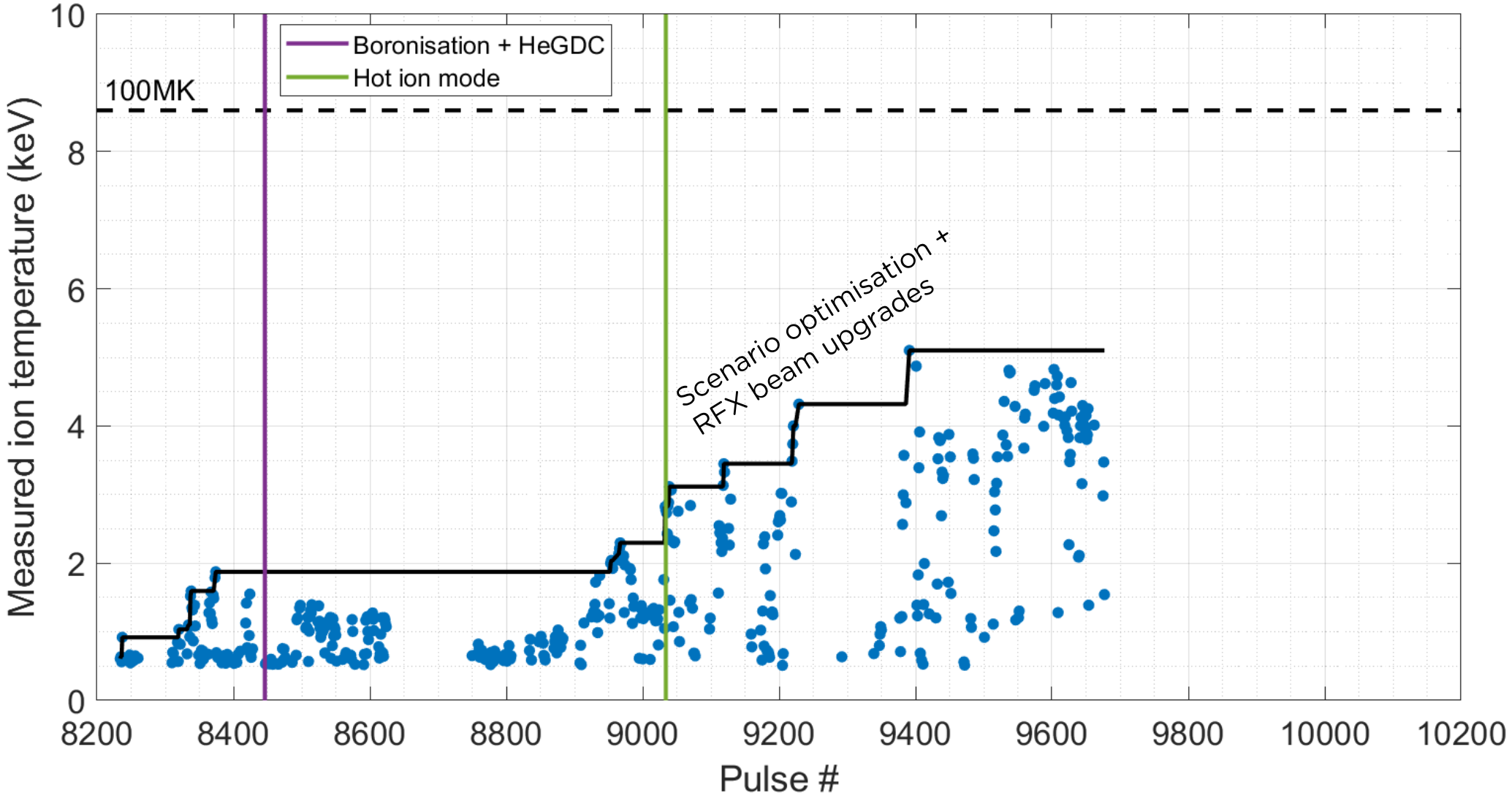
- Experiments were performed to test effect argon (and neon) injection on the plasma.
- Particle confinement improvement as observed on many other tokamaks

$H^0 \Rightarrow H^+$: 12/21 Getting hotter!

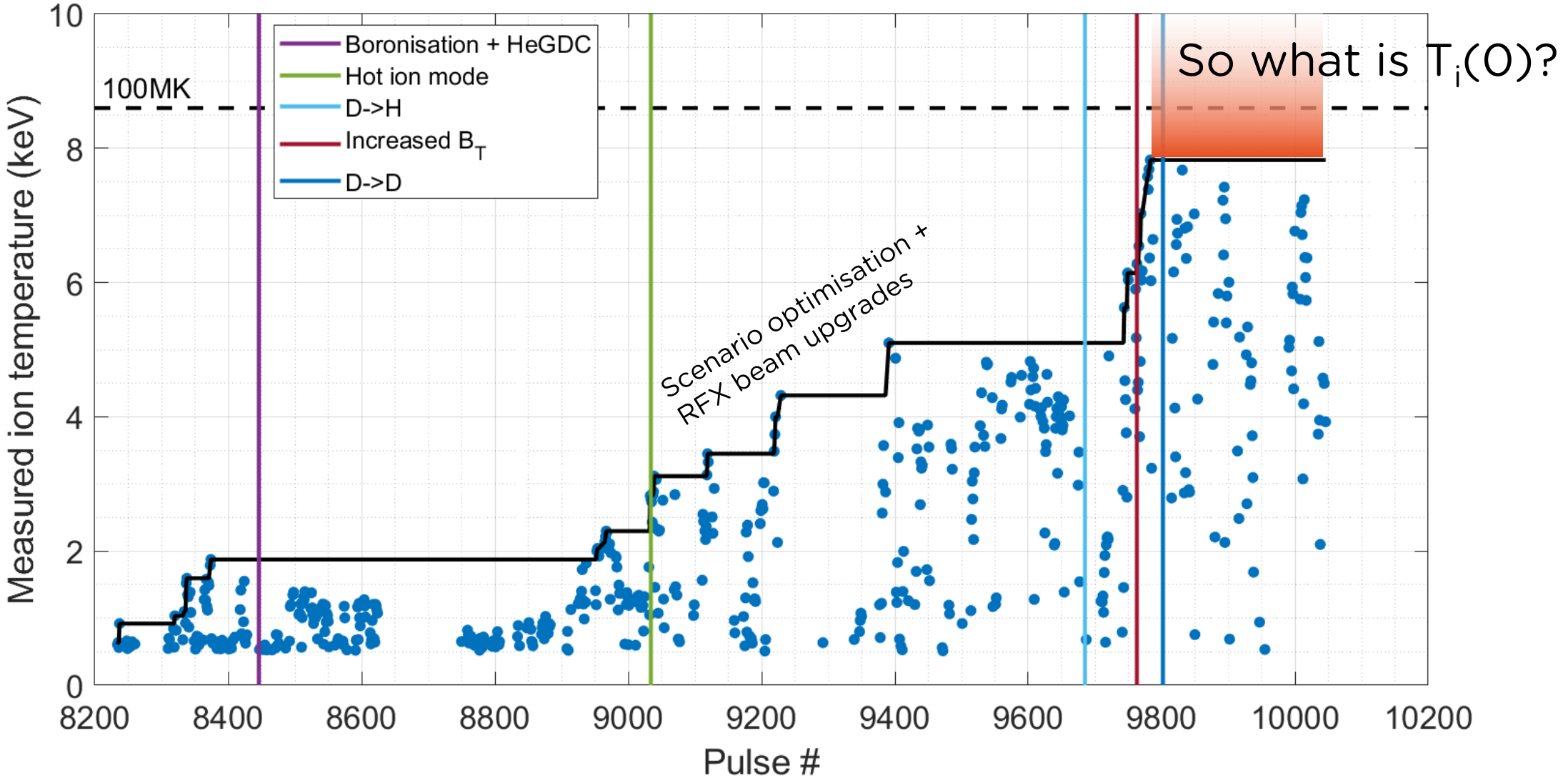
- Best T_i's slightly more than 4keV.
- Maximum T_e's hovering around 2keV.
- CXRS just coming online at the end of the hydrogen phase.
- Good agreement between XRCS and CXRS.
- **Maximum W_p in shot #9676 was 27kJ.**
- Sawtooth period during NBI ~10ms.



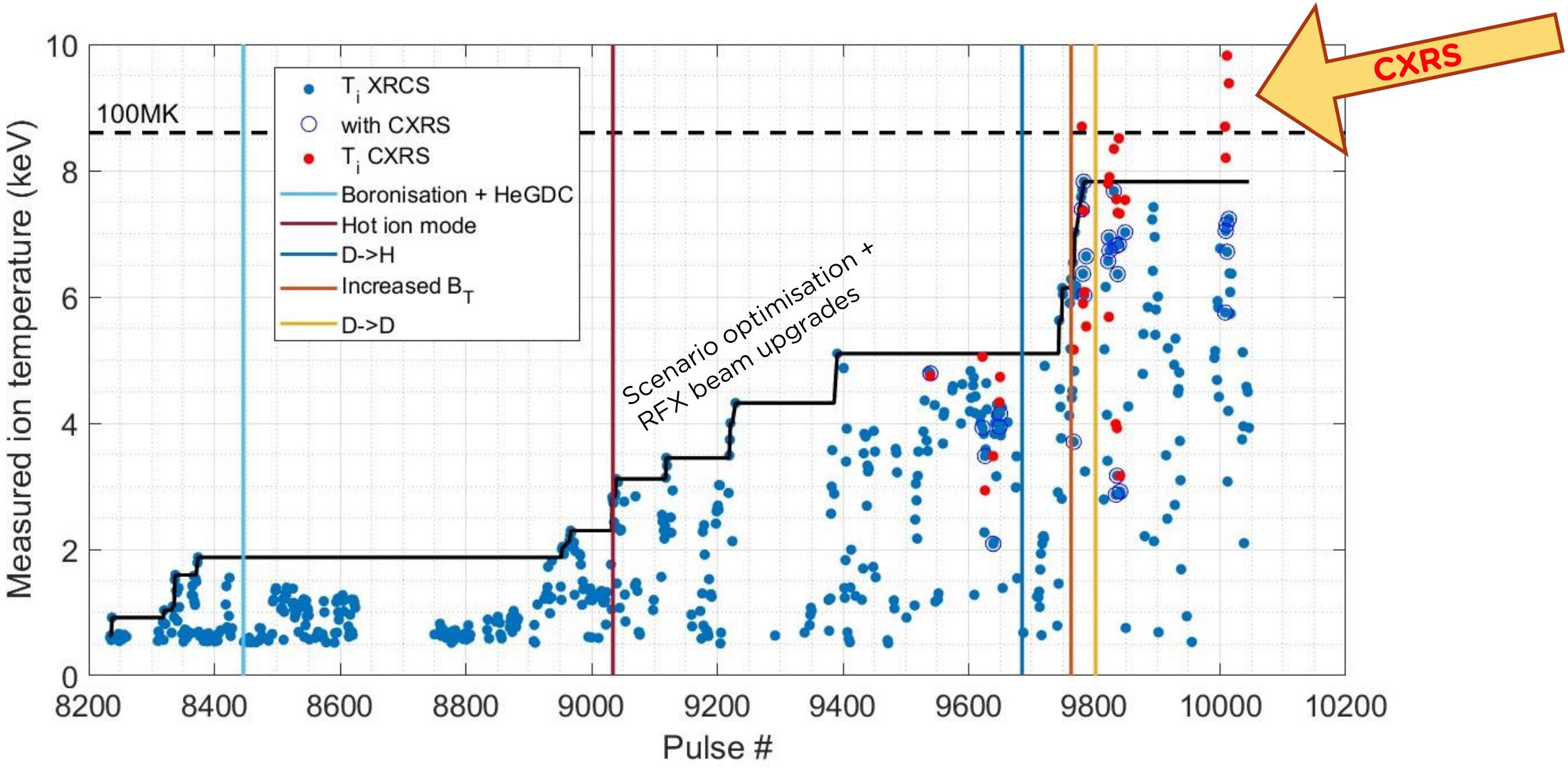
Progress to end 12/21 - $H^0 \Rightarrow H^+$ phase, measured Ti~5keV



Switch to $D^0 \Rightarrow D^+$ and increasing B_T got us very close to 100MK target

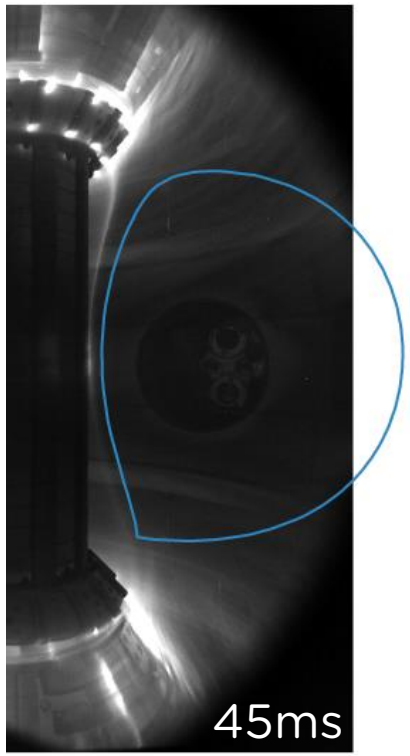


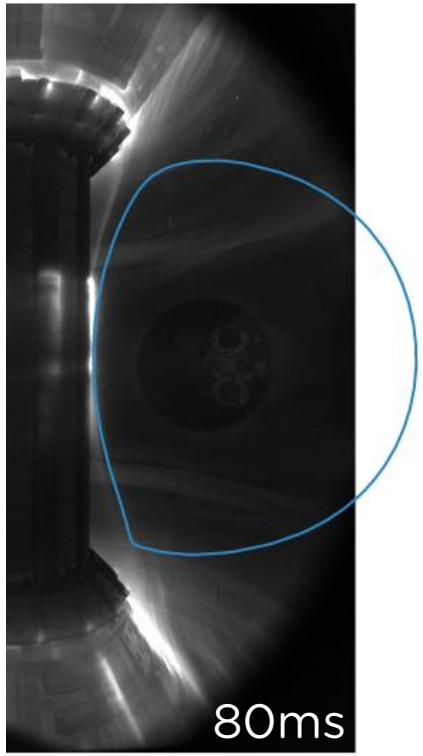
CXRS diagnostic confirmed achievement of $T_i(0)$ > 100MK

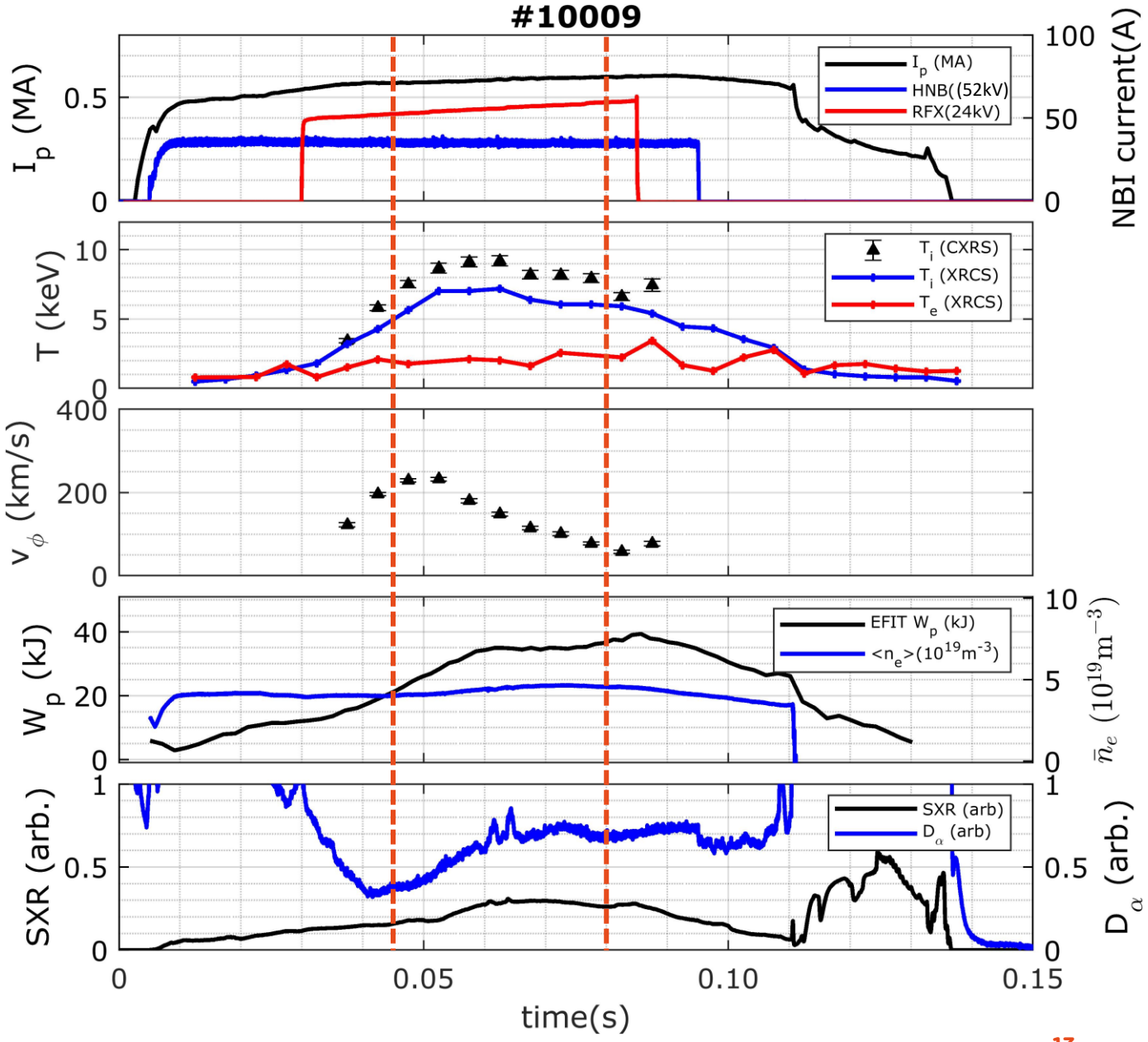


$D^0 \Rightarrow D^+$: High T_i and T_e

- Maximum W_p during high T_i phase of **35kJ**.
- Diverted up to ~48ms

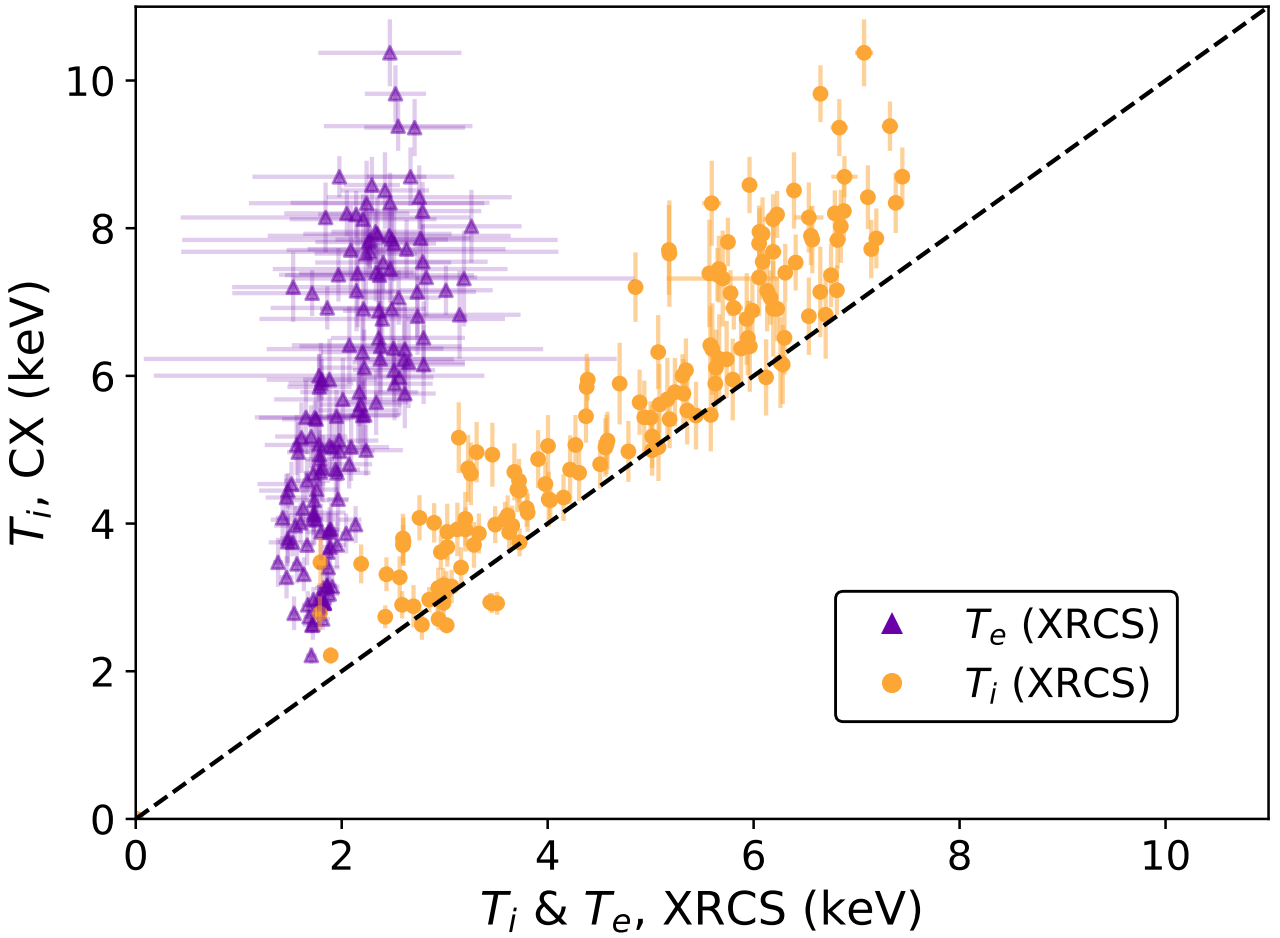






Xray Crystal and charge exchange spectroscopy

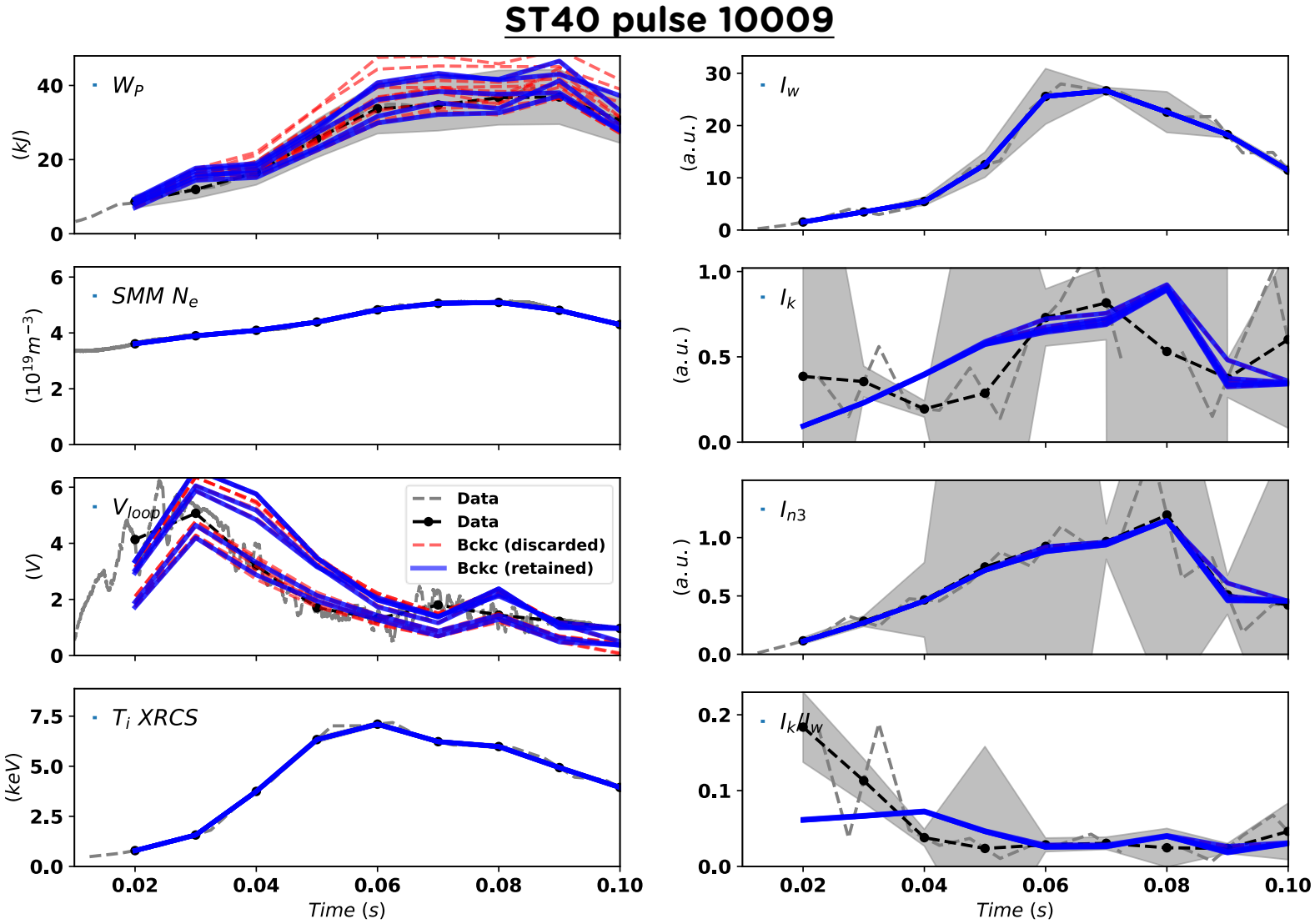
- The correlation between XRCS and CXRS is very good.
- In general, $T_{i,CXRS} > T_{i,XRCS}$ because the measurement is more core localised.
- As $T_e(0)$ increases beyond ~2keV, helium-like argon Xray emission falls off and the measured temperatures are increasingly biased away from the axis.
- CXRS has been confirmed to be localised using forward model that consists of FIDASIM and ADAS data.



$D^0 \Rightarrow D^+$: Inference of kinetic profiles

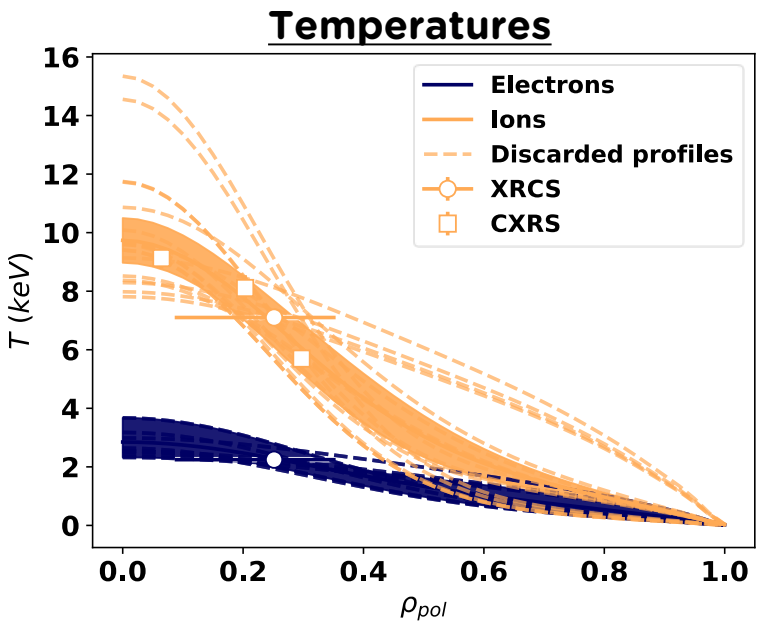
Kinetic profiles inferred launching parallel optimization workflows with different profile trial function combinations and optimizing for:

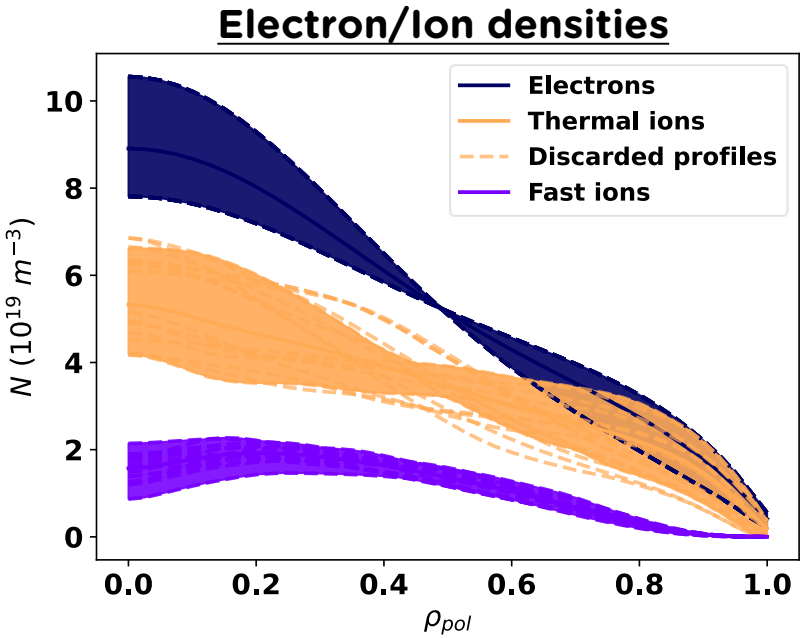
1. **Electron density**: interferometer electron density line integral
2. **Electron temperature**: XRCS line ratios (n3/w)
3. **Ion temperature**:$T_i$from XRCS w line & CXRS NeX and CVI lines
4. **Fast particle pressure**: using transport models (NUBEAM)
5. **Stored energy**: calculated from the total (thermal & fast) pressure and compared to EFIT W_P (*assuming a conservative 20% uncertainty*)



$D^0 \Rightarrow D^+$: Inference of kinetic profiles (pulse #10009 @ 60 ms)

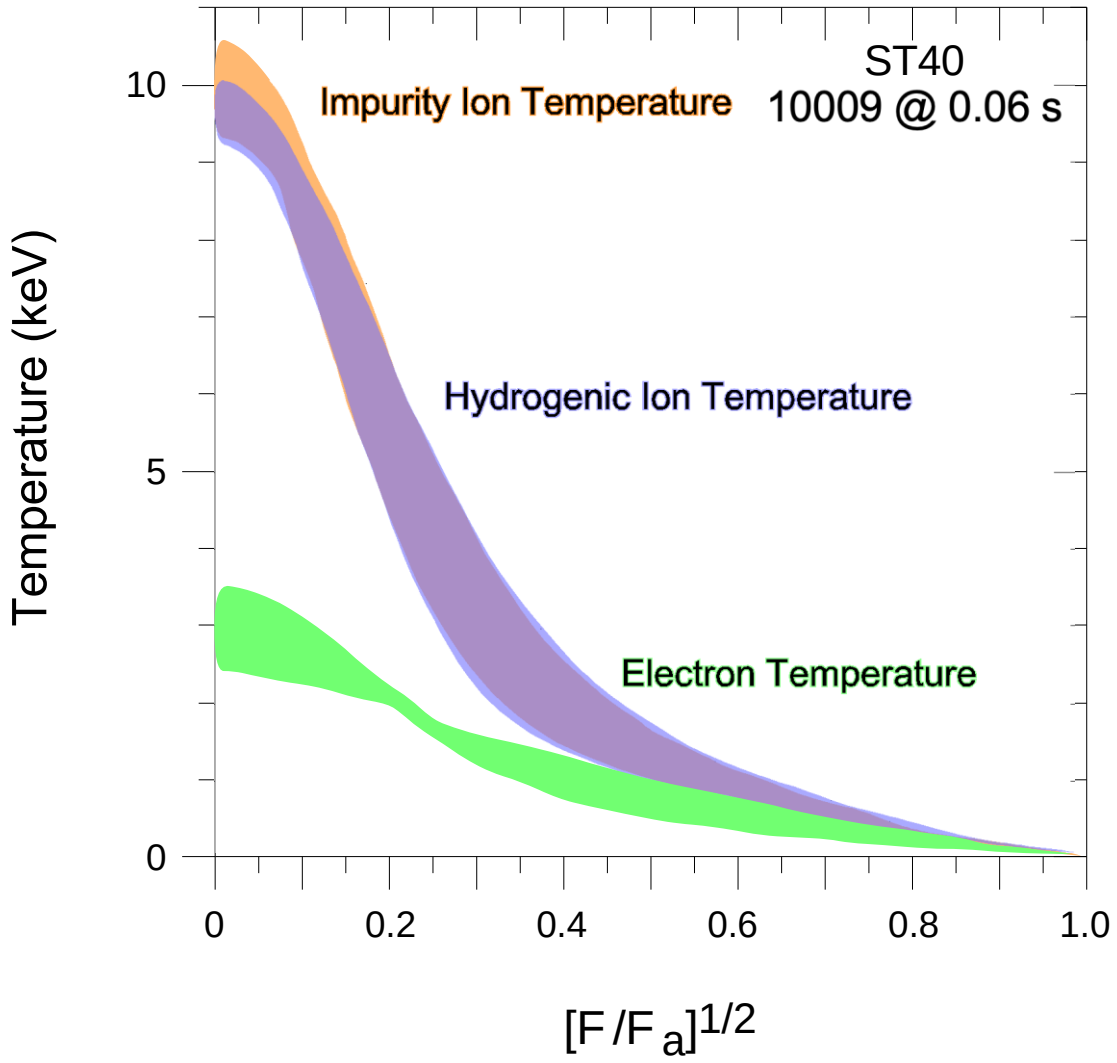
- Only profile combinations that satisfy desired constraints are retained, providing uncertainty bands
- Impurity density is assumed to be peaked to give conservative estimates for Ti and Te
- Consistent with preliminary results from new Bayesian optimisation framework
- Consistent with results obtained including transport in the ionization balance calculation
- Main ion temperatures (TRANSP) show T_i(D)~T_i(impurity) similar to measured values





Hydrogenic ion temperatures

- X-ray Crystal spectrometer measures Argon temperature
- Charge exchange measures Carbon or Neon temperature
- TRANSP analysis shows that deuterium temperature is only slightly below impurity temperatures. This confirms that ion temperatures of 100MK have been achieved.

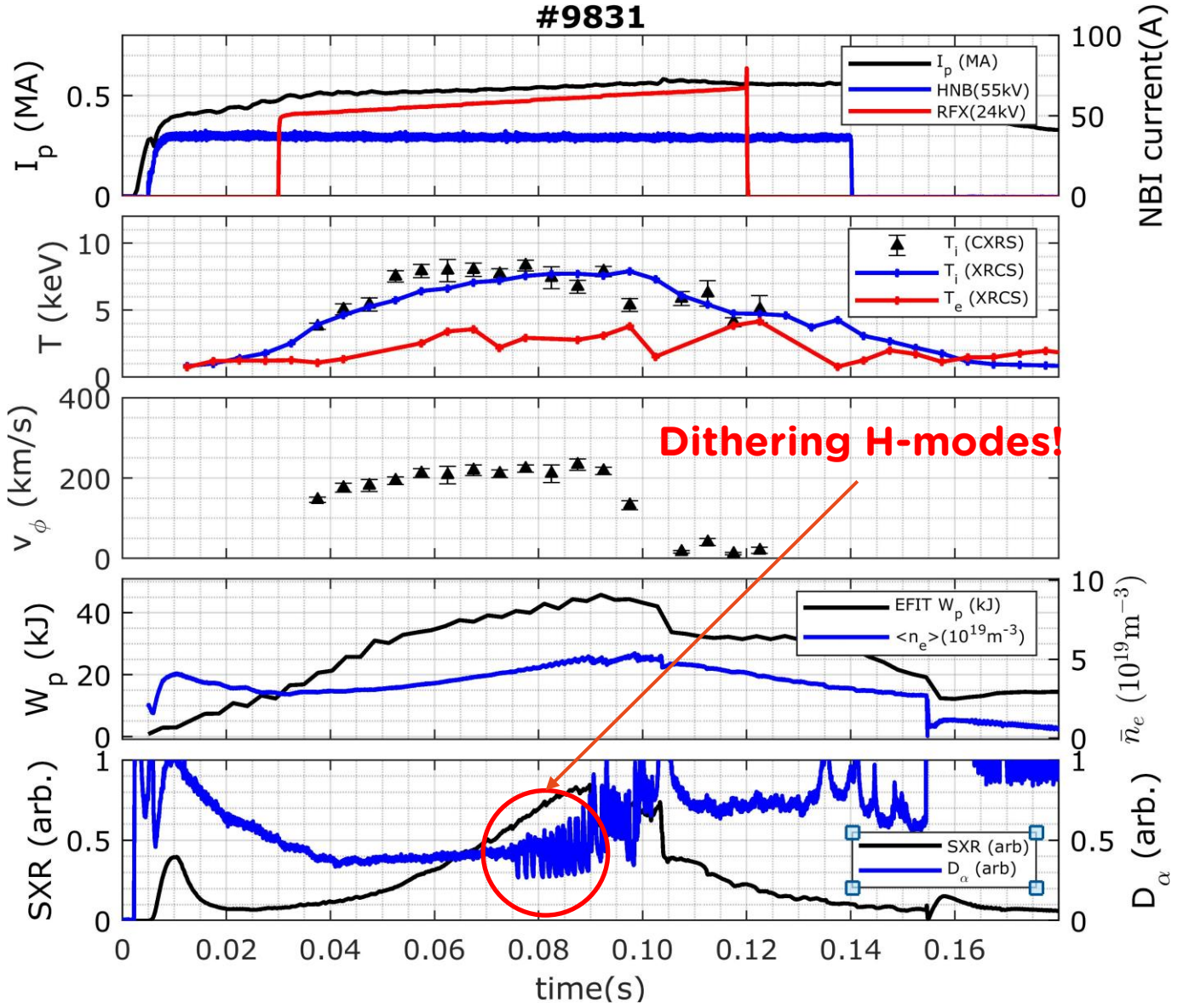


Poster by Stan Kaye on Wednesday: "Transport Analysis of ST40 High Performance Discharges"

$D^0 \Rightarrow D^+$: Dithering H-modes

- At slightly higher plasma density, dithering H-modes are observed.
- T_i sustained at ~8keV until 90ms and max stored energy was **45kJ**.
- Density is slightly above the minimum value for H-mode from multi-machine database[1] :

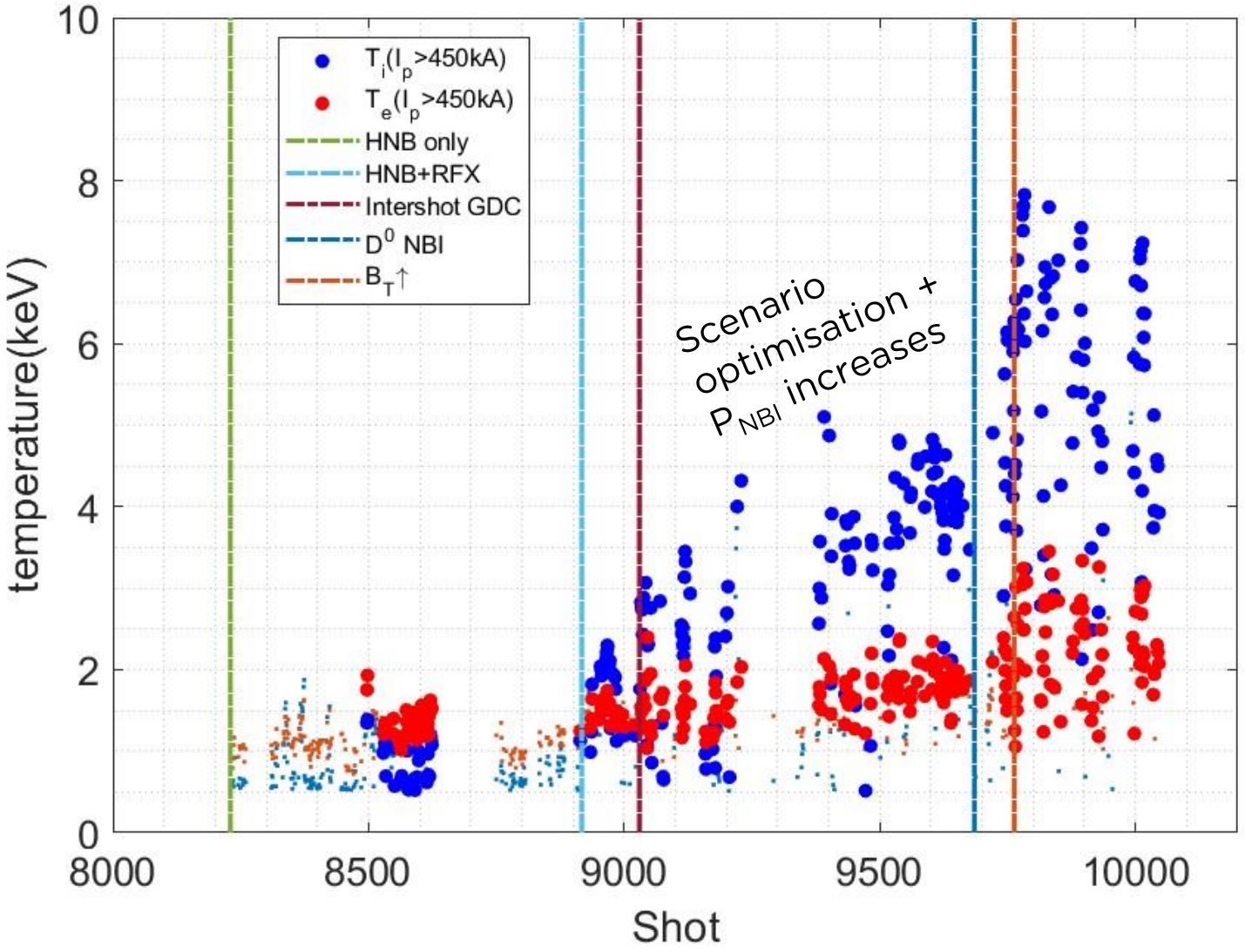
$$n_{e,min}^{scal} \approx 0.7 I_p^{0.34} B_T^{0.62} a^{-0.95} (R/a)^{0.4}$$



Talk by Michele Romanelli on Tuesday: "ST40: Advancing the Physics Basis of Spherical Tokamak Reactors"

[1] *F. Ryter et al., 2014 Nucl. Fusion **54** 083003*

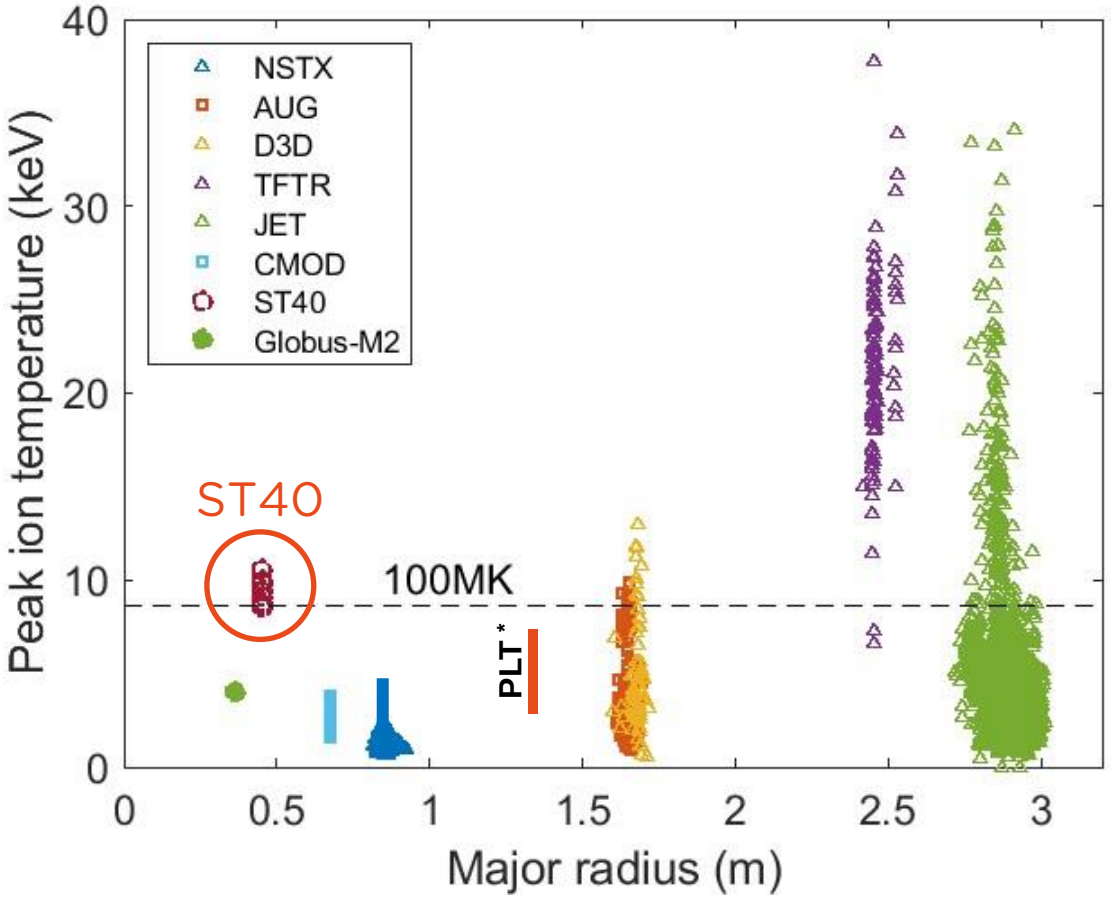
Higher B_t and operating in D increase T_i and T_e



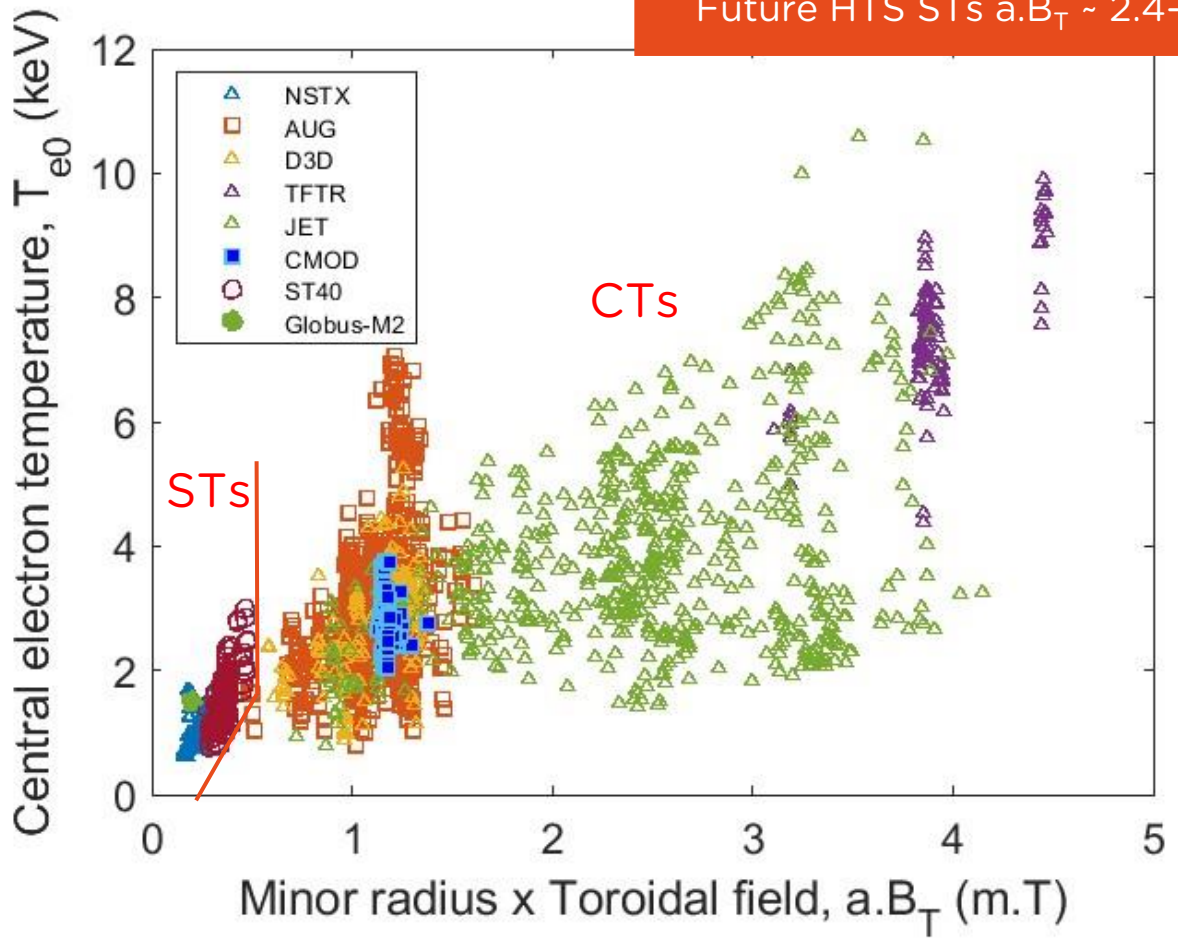
- Pick shots with I_p > 450kA, i.e. the high T_i attempts
- Maximum T_e barely changes through optimisation in H phase while T_i increases markedly.
- Switch to higher B_t and deuterium → T_e jumps from ~2keV to ~3keV
- TRANSP analysis: increase in T_e and T_i due to improved confinement

Poster by Stan Kaye on Wednesday: "Transport Analysis of ST40 High Performance Discharges"

High B_T with HTS will permit access to high temperatures in an ST



Future HTS STs a.B_T ~ 2.4-8



Future of ST40 – Next Programme

- Programme organised in three campaigns with maintenance and installation breaks between.
- New and improved diagnostics – most notably Thomson Scattering
- Passive plate resistance increased to ease access to diverted configuration
- Later, pellet Injector

Objective 1: T_e and n_e profiles using Thomson Scattering and P2.2 analysis/modelling verified.

Objective 2: Controlled divertor configuration established and divertor heat flux measured.

Objective 3: Determine toroidal field and plasma current dependence of confinement time

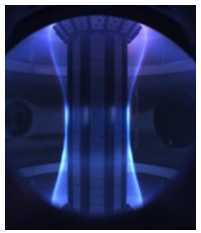
Objective 4: Scrape-off layer (SOL) width determined for a range of parameters.

Objective 5: Scenario with >50% non-inductive current and I_P>200kA for 100ms

Objective 6: Achieve highest fusion triple product, $n_i.T_i.\tau_E$, on ST40 to date.

Our path to commercial fusion: STs + HTS magnets

ST40

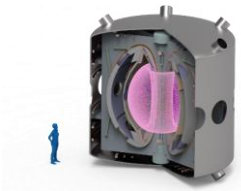


Further validation of ST benefits

DEMO4

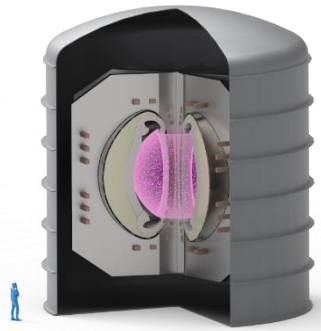
HTS magnet scale up and demonstration of full ST magnet configuration

ST80-HTS



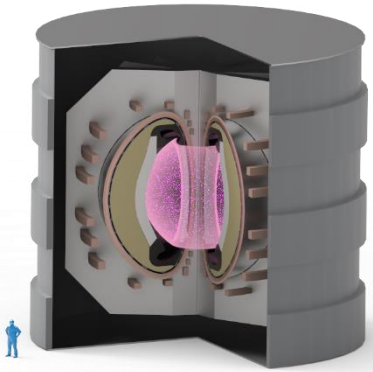
High performance ST with HTS magnets

Commercial Pilot Plant



Demonstrates technical & commercial capability

Commercial Deployment



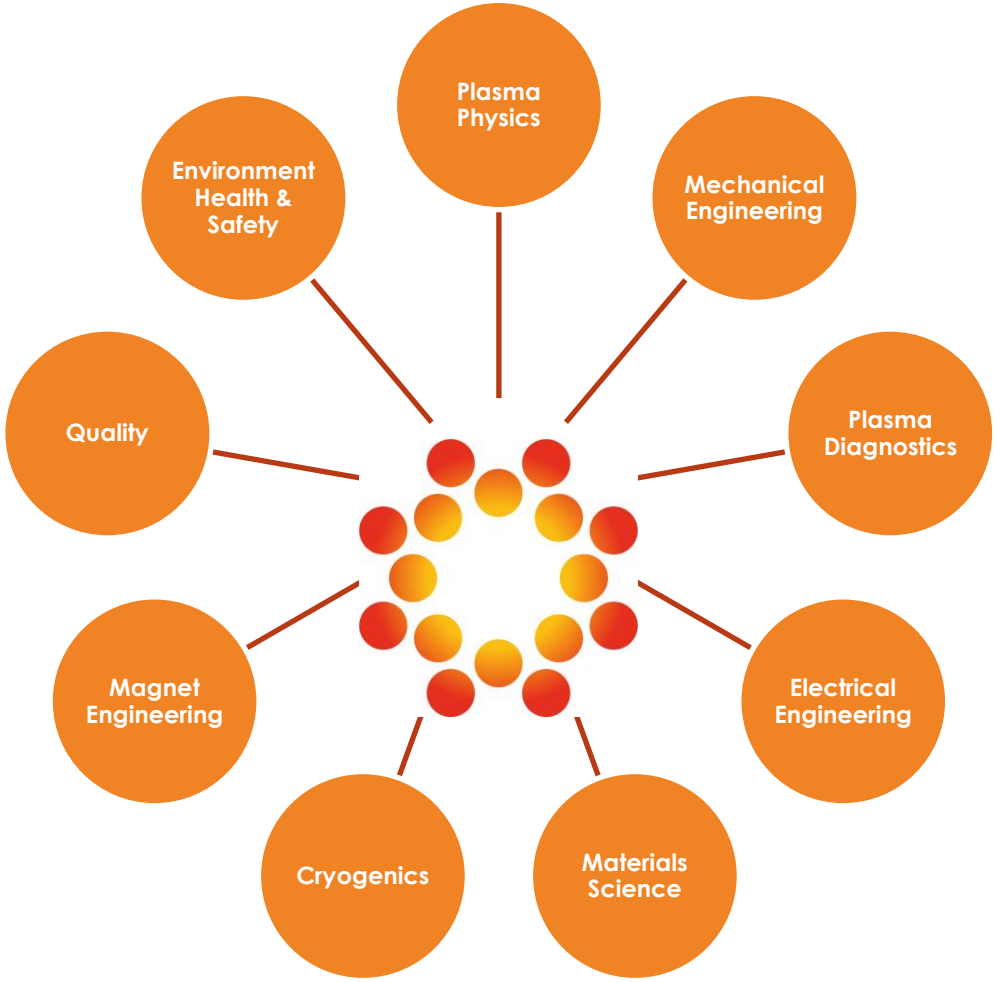
Designed for a rapid, global rollout

Mid 2020s → **Early 2030s** → **Mid 2030s**

Supporting Technology Development

An extraordinary mission requires extraordinary people – We are hiring!

Tokamak Energy Team celebrating reaching 100MK milestone



https://www.tokamakenergy.co.uk/careers/jobs/

Thank you for your attention

ST40 presentations at this meeting:

- Michele Romanelli – “ST40: Advancing the Physics Basis of Spherical Tokamak Reactors” (talk, on Tuesday)
- Stan Kaye – “Transport Analysis of ST40 High Performance Discharges” (poster, on Wednesday)
- Yang Ren – “Linear Instabilities in a ST40 Hot Ion Plasma” (poster, on Wednesday)
- Erasmus du Toit – “Overview of ECRH and EBW modelling on ST40” (talk, on Thursday)

Other Tokamak Energy contributions:

- Mikhail Gryaznevich – “ST Reactor – new considerations” (talk, on Tuesday)

Questions?