Overview of high temperature plasmas in the ST40 high-field spherical tokamak

29th IAEA Fusion Energy Conference, FEC 2023

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Tokamak Energy: developing spherical tokamak fusion pilot plants with HTS magnets for deployment in the 2030s

Approach

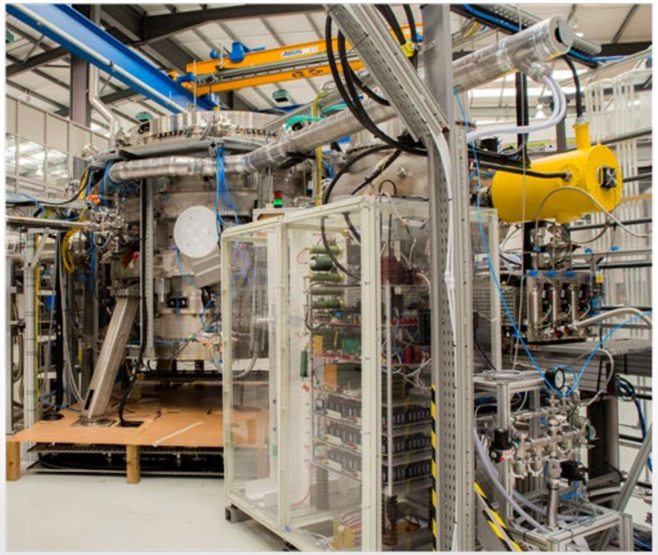
High-field spherical tokamak (ST) using magnet made from high temperature superconductor (HTS)

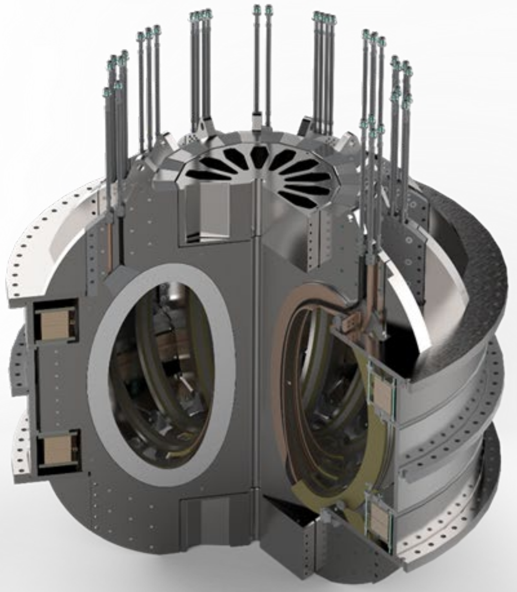
Team of 250+

World-class scientists, engineers and commercial specialists

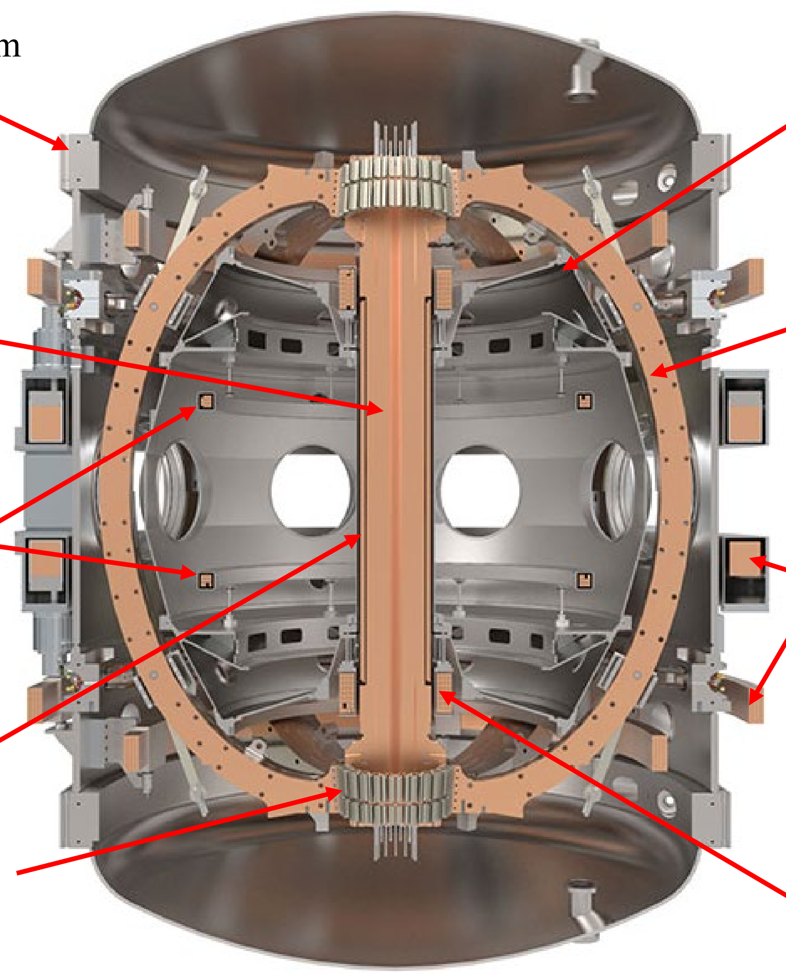
$250M raised to date

Financial backing from private capital and government grants



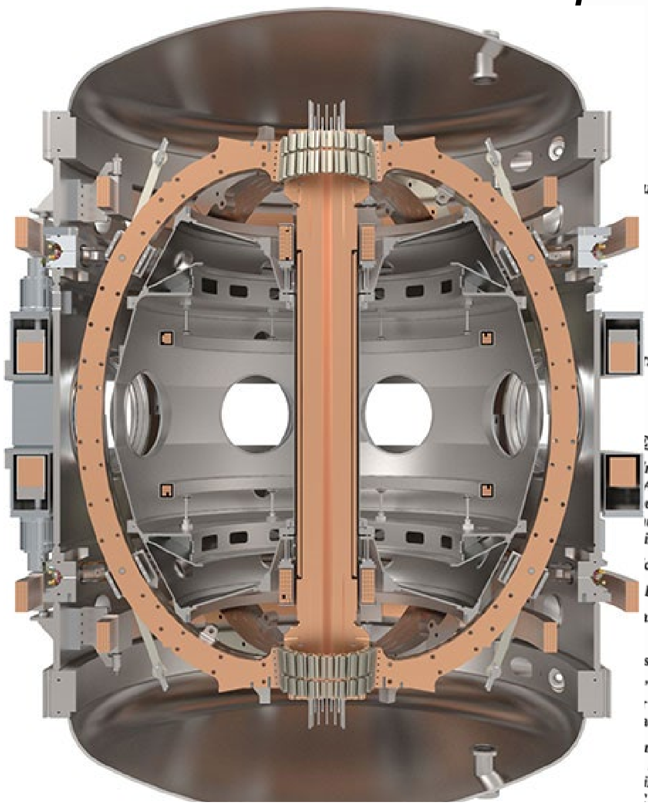


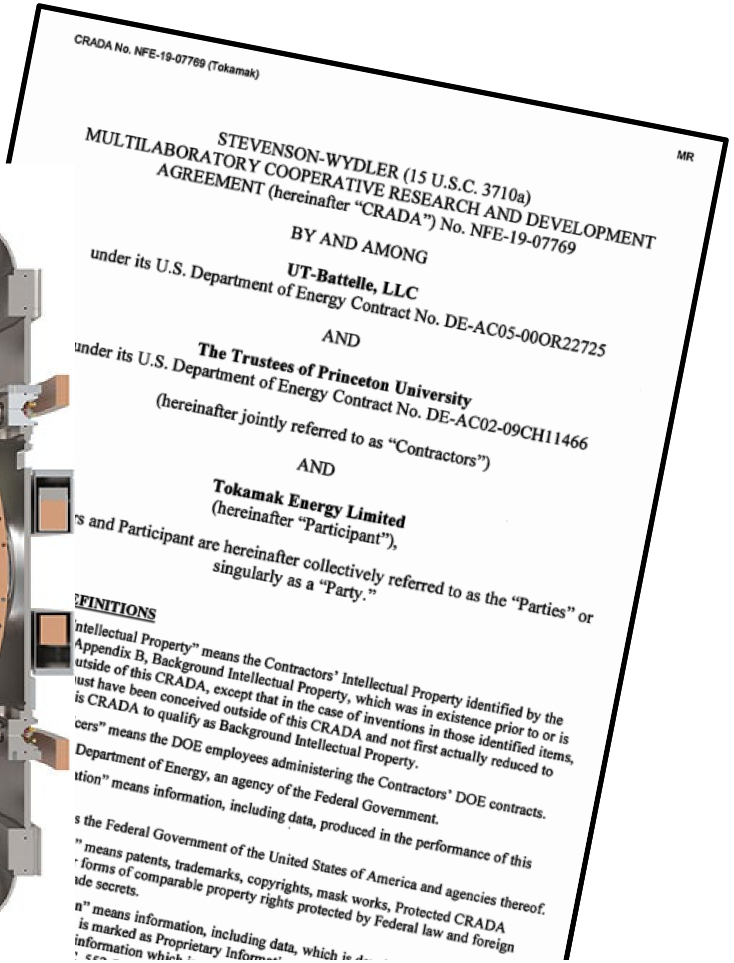
The ST40 high-field spherical tokamak



Parameter	Range
B_T [T]	0.9 – 2.1
I_P [MA]	0.3 – 0.8
R_{Geo} [m]	0.4 – 0.5
A / κ	1.6 – 1.9 / ≤ 2
P_{NB}/ E_{NB} [MW/kV]	0.8/24, 1.0/55
Start-up	Merging-compression
ψ_{sol} [mWb]	200
New diagnostics	TS, divertor-IR, Langmuir probe arrays

A first -of-a-kind public-private collaboration





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.

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...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 foreign ... ade secrets.

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In 2019 ORNL, PPPL, and Tokamak Energy signed a CRADA covering a ~3 year collaborative research program. This has since been extended to Aug-2024.

U.S Department of Energy Fusion Energy Sciences (DOE FES) program awarded a total of \$3.9M to ORNL and PPPL to carry out open public research on ST40.

The collaborative research covers:

- ST energy confinement scalings w.r.t. high B_T & I_p
- Thomson Scattering real-time data acquisition and hardware
- Modelling of RF driven scenarios
- Operations and measurement support
- Energetic particle studies
- And more !

OAK RIDGE National Laboratory

PRINCETON UNIVERSITY

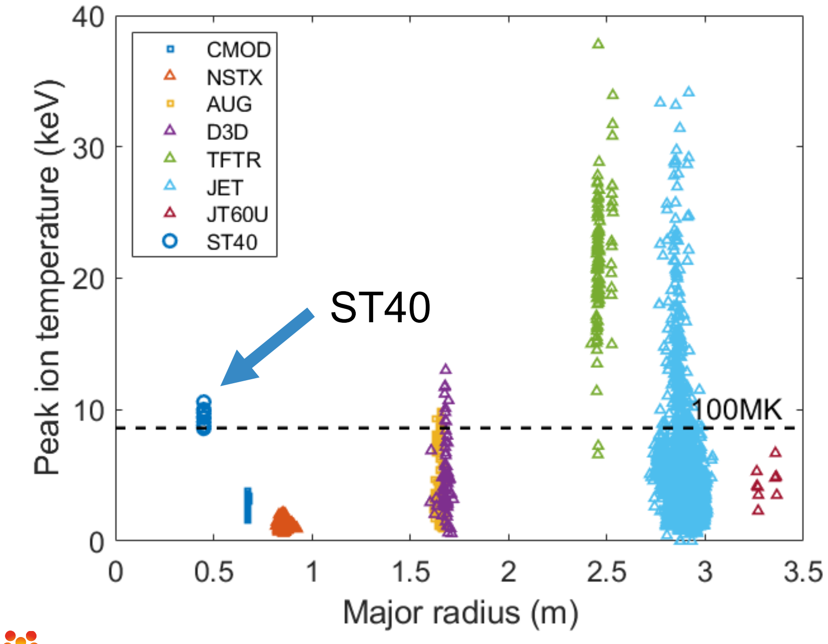
Tokamak Energy

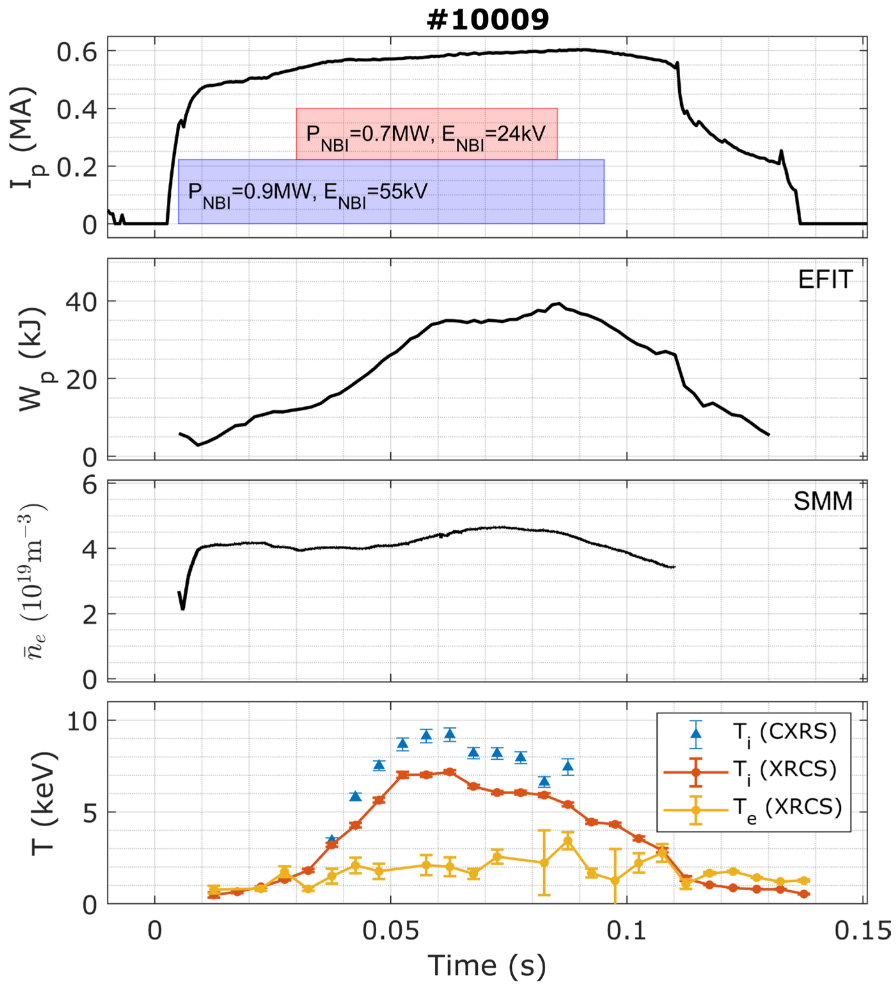
ST40: Expanding the high-field spherical tokamak physics basis for fusion energy development

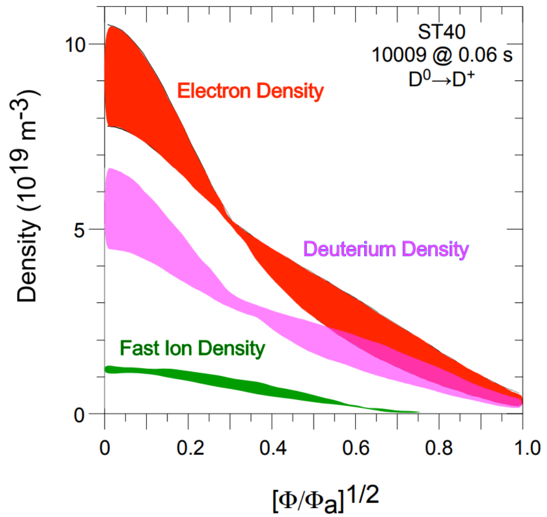
- High ion temperature plasmas
- Core confinement & stability
- Plasma exhaust
- Solenoid free start-up and ramp-up
- Recent scenario development and future plans

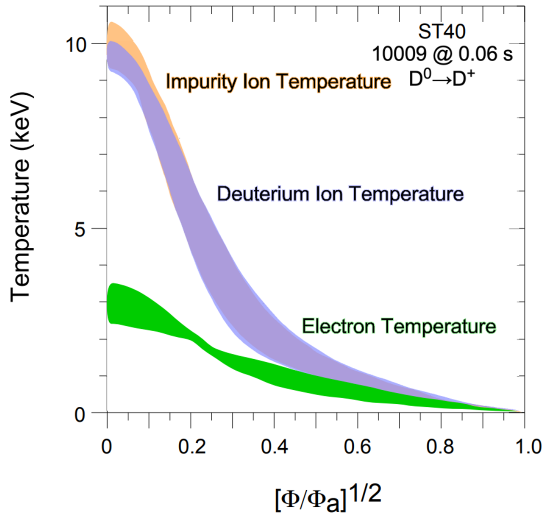
Record ion temperatures achieved in compact high-field ST

- Central ion temperatures of 9.6 ± 0.4 keV achieved in hot-ion mode ($T_i \gg T_e$) with R_{Geo}=0.45m, A=1.65, B_T=1.9T, I_p=0.6MA, and P_{NB}=1.6MW
- Corresponding triple product $n_{i0} T_{i0} \tau_E \approx 6 \pm 2 \times 10^{18} m^{-3}$keVs at 9.6keV









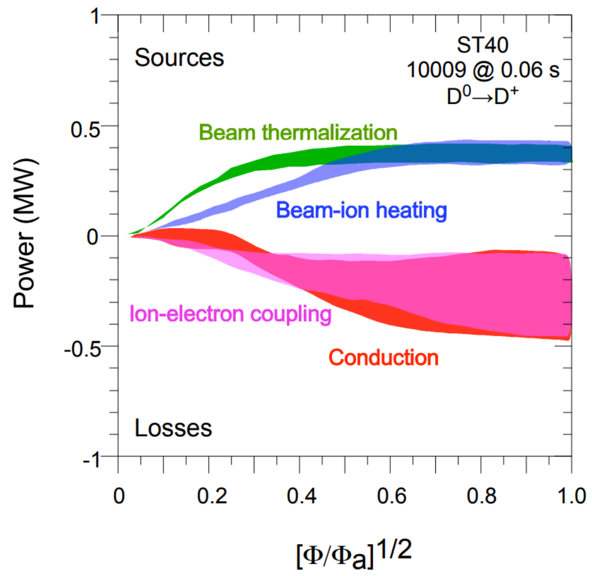
S. McNamara et al., NF 2023

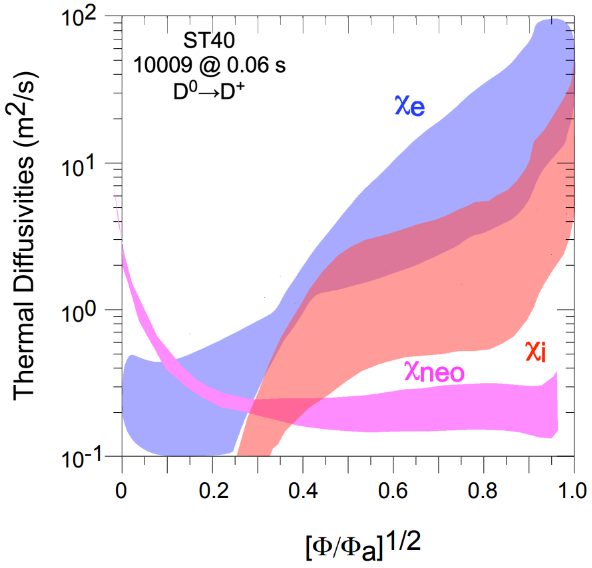
S. Kaye et al., PPCF 2023

Transport and micro -turbulence properties of high ion temperature plasmas

Transport properties

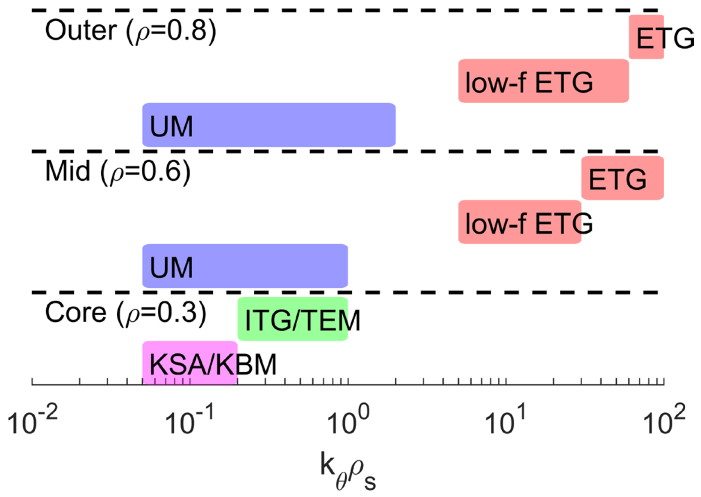
- Electrons are dominant loss channel, $\chi_e > \chi_i$, with ion power losses due to ion-electron coupling and transport comparable.
- Reduced core ion thermal diffusivity, χ_i, played important role in high T_{i0}.

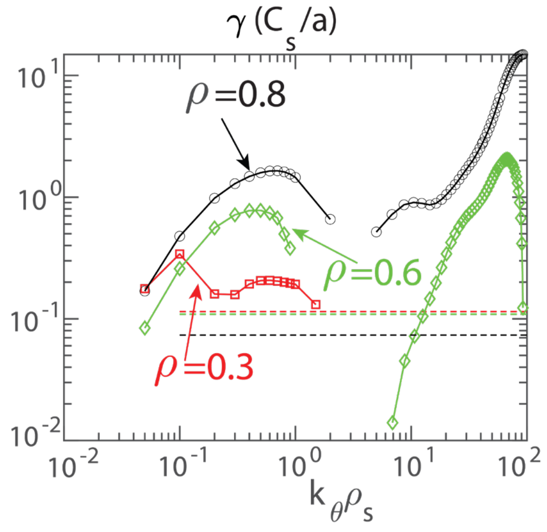




Micro -turbulence properties

- Instability growth rates of ion and electron scales decrease from edge to core, with no unstable electron-scale modes in core.
- Ion scale – KSA/ KBM, ITG/ TEM and UM
- Electron scale – ETG





→ poster by S. Kaye – Friday 14:00

Y. Ren et al., PPCF 2023

S. Kaye et al., PPCF 2023

ST40: Expanding the high -field spherical tokamak physics basis for fusion energy development

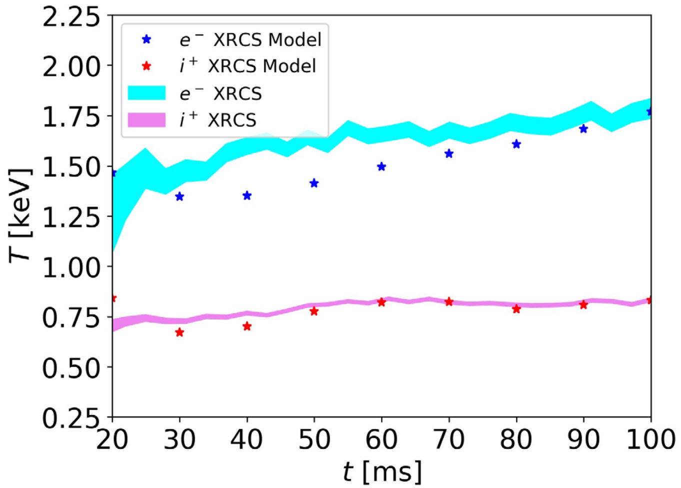
- High ion temperature plasmas
- Core confinement & stability
    - STs have unique transport and confinement properties that scale favourably to pilot plant regimes
    - ST40 is exploring confinement & stability at high toroidal fields
- Plasma exhaust
- Solenoid free start -up and ramp -up
- Recent scenario development and future plans

Applicability of reduced and analytic transport models investigated

Recalibration of trapped particle model in quasi -linear gyro -fluid transport model TGLF improves agreement

- Predictive modelling in good agreement with both Ohmic and hot -ion mode pulses

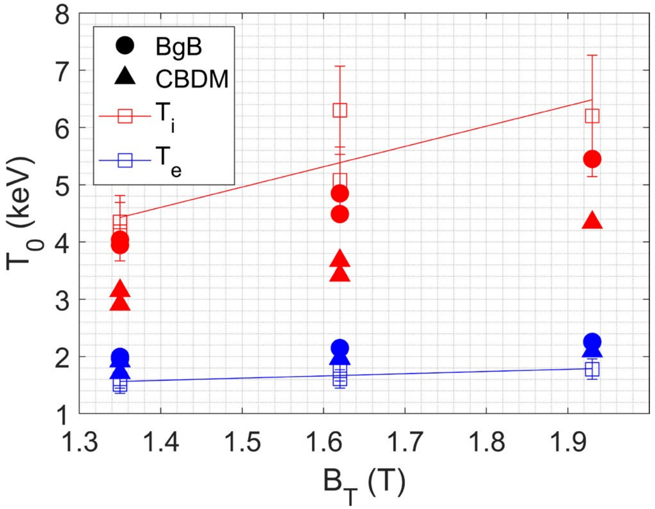
→ poster by M.S. Anastopoulos Tzanis – Thursday 14:00

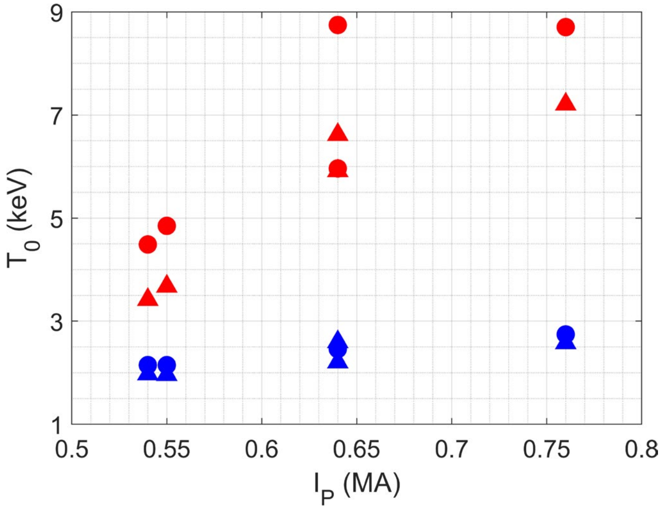


Analytical BgB and CBDM models tuned against database of ~100 pulses

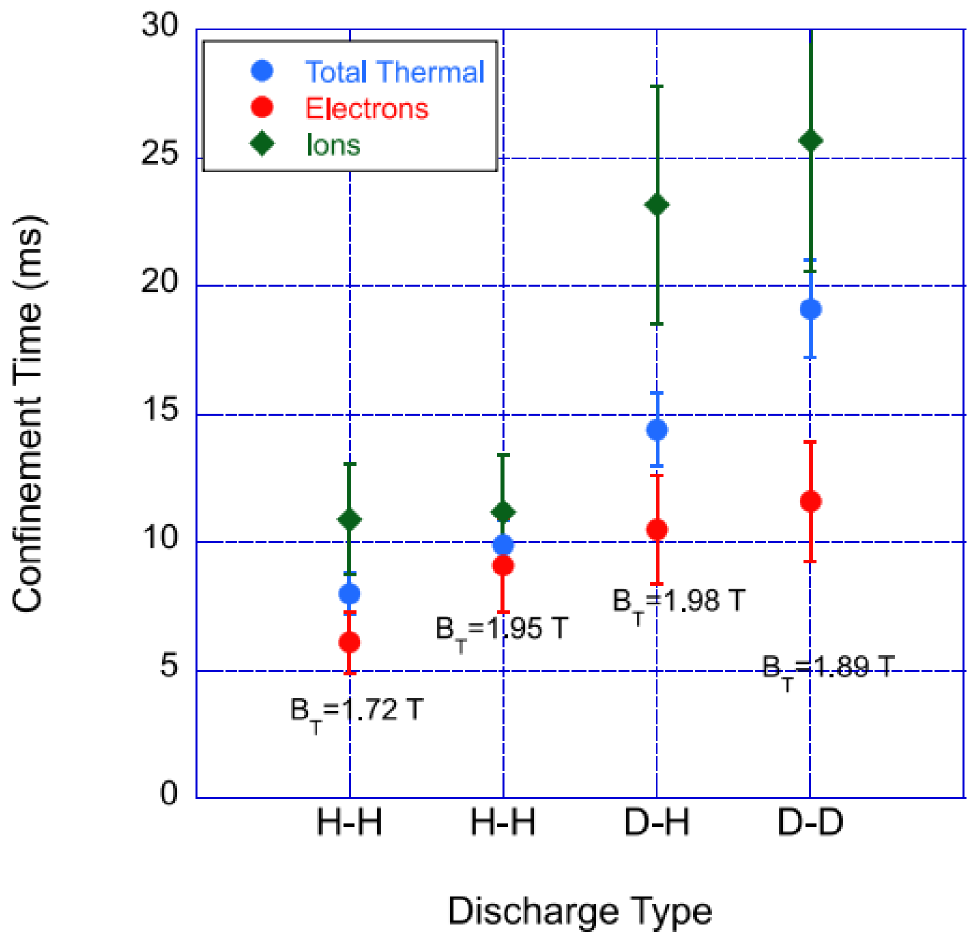
- Both models capture T_e and T_i trend with B_T
- Further experiments needed to test I_P dependence

→ poster by A. Dnestrovskii – Thursday 14:00





First look at confinement time mass dependence in spherical tokamaks



- Operations with different fuel species, $H^0 \rightarrow H^+$, $D^0 \rightarrow H^+$ and $D^0 \rightarrow D^+$, enabled first study of confinement time mass dependence in spherical tokamak
- Approximate doubling of core ion temperature from ~5 to ~10 keV with increasing ion mass

Strong near linear dependence of total confinement time on M_{eff} in hot -ion mode plasmas

→ poster by S. Kaye – Friday 14:00

S. Kaye et al., PPCF 2023

Improved particle confinement with argon impurity seeding

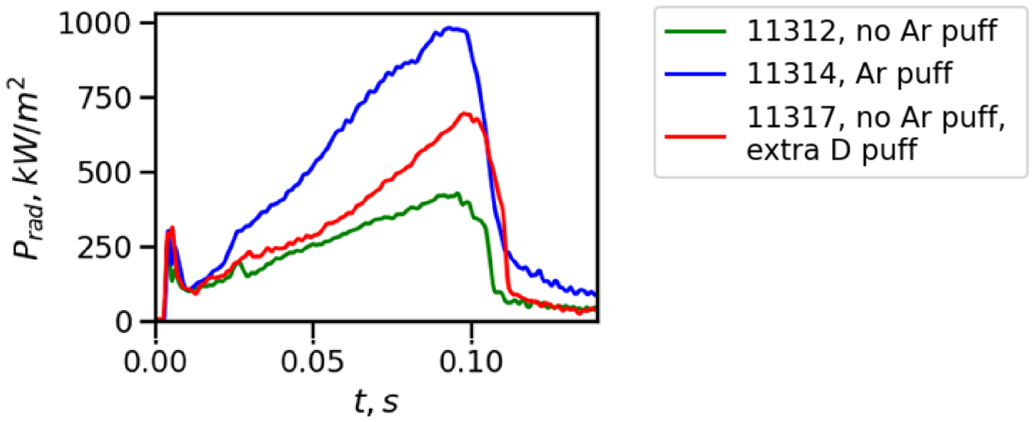
No degradation in performance observed with argon impurity seeding

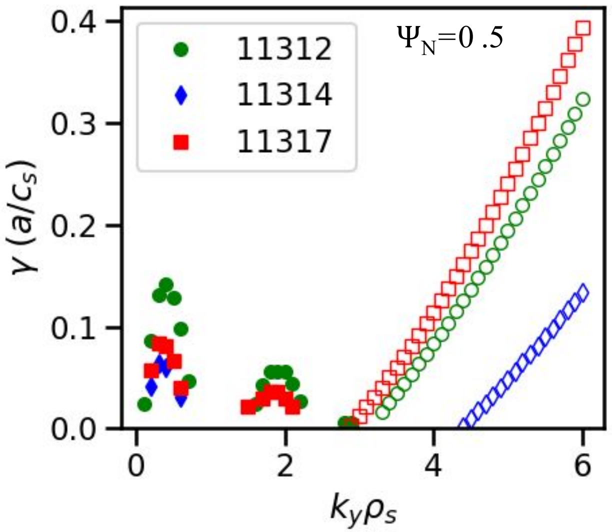
- Increased f_{rad} from 5% → 15% with no deterioration of T_i or T_e
- Additional electron source from argon alone cannot explain increase in n_e

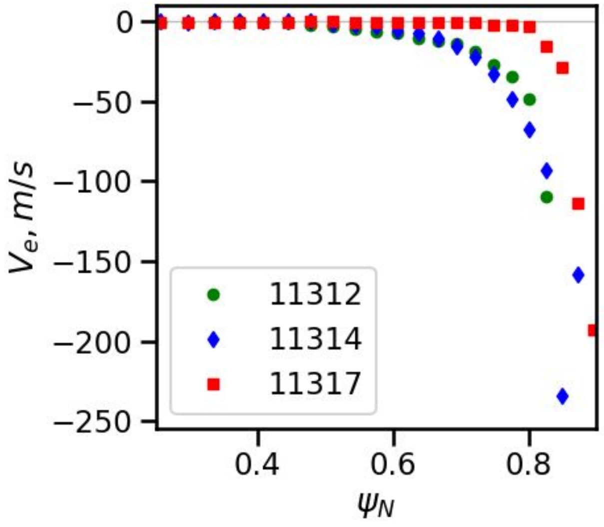
Experimental observations supported by linear and quasilinear transport analysis

- Stabilisation of ion- and electron-scale modes
- Reduced particle flux due to reduced diffusion and increased inward pinch

→ poster by A. Sladkomedova – Wednesday 14:00







Alfvénic instabilities transition from fixed to chirping frequency with reduced microturbulence scattering

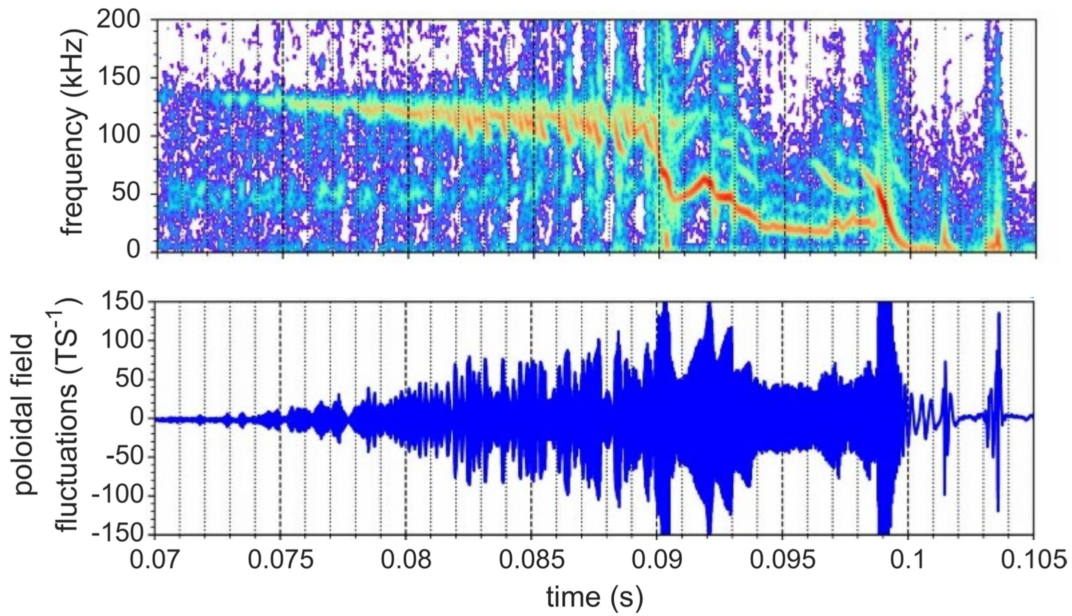
Nonlinear characteristics of Alfvénic instabilities are important for determining fast ion losses

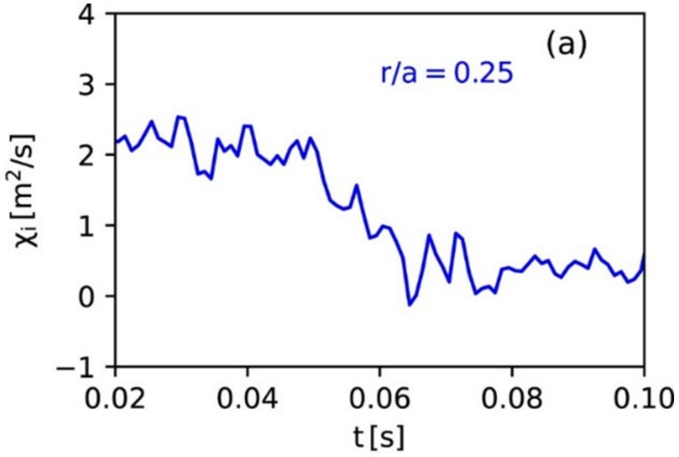
- STs – chirping/avalanching
- CTs – fixed -frequency

Transition from fixed to chirping response as χ_i decreases

- Modes identified as n=1 beta-induced Alfvén acoustic eigenmodes – BAAEs
- Criteria for chirping likelihood successful identifies response

→ poster by V. Duarte – Friday 14:00





V. Duarte et al., NF 2023

J. Bland et al., NF 2022

ST40: Expanding the high-field spherical tokamak physics basis for fusion energy development

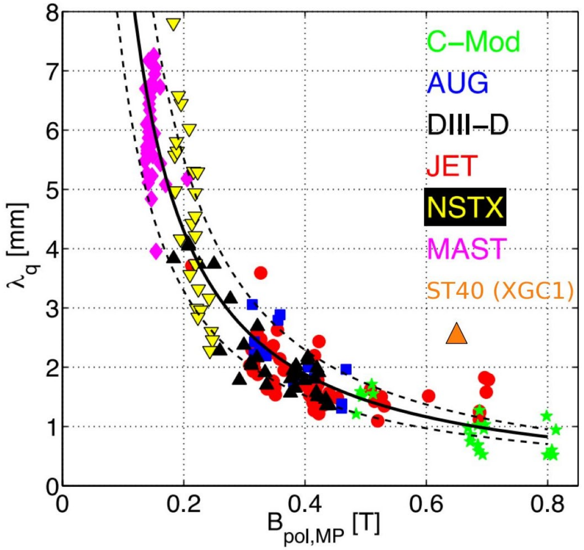
- High ion temperature plasmas
- Core confinement & stability
- Plasma exhaust
  - Compact devices are expected to have high heat loads to walls, and mitigation strategies are necessary
  - ST40 is studying scrape-off-layer width and heat exhaust properties in compact high-field ST
- Solenoid free start-up and ramp-up
- Recent scenario development and future plans

Potential for scrape -off layer width broadening in ST40 plasmas

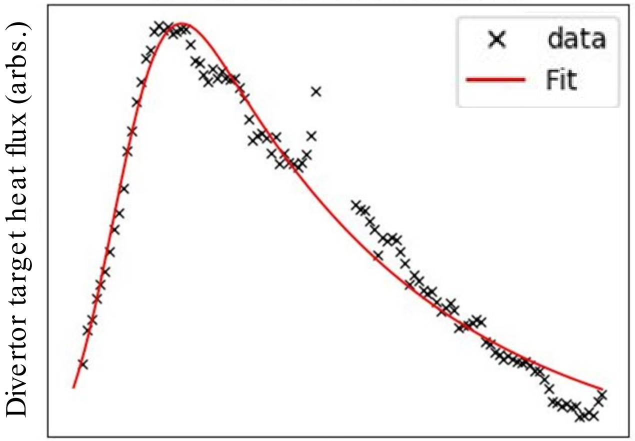
- Predictive scenarios developed using flight simulator coupled to plasma control system.
- XGC1 simulations (PPPL) show factor of 2-3 broadening above Eich scaling at I_p = 1MA.
- First heat flux measurements with divertor IR camera and Langmuir probes taken. Work ongoing to account for geometric effects.

→ poster by S. Janhunen – Thursday 8:30

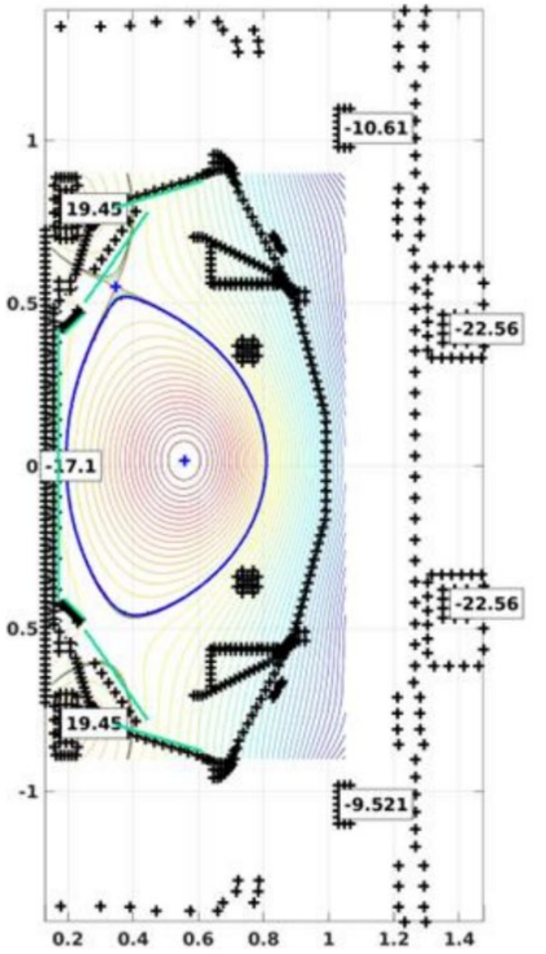
T. Eich et al., NF 2013



IR camera divertor heat flux profile



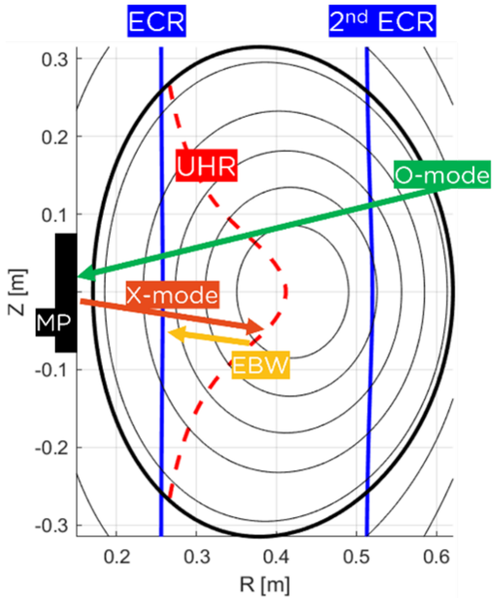
Distance from strike point (arbs.)

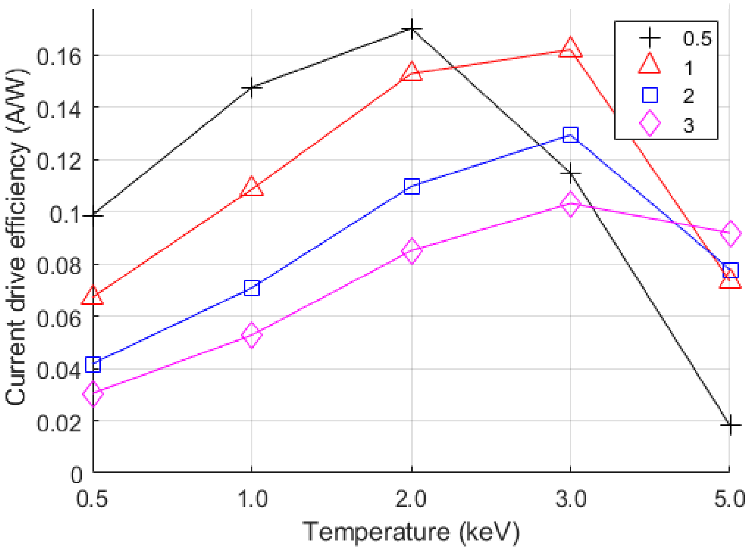


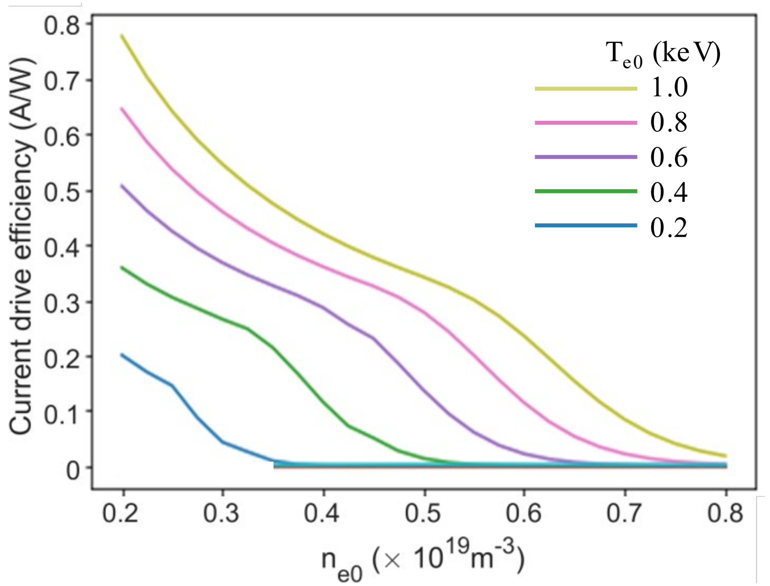
ST40: Expanding the high-field spherical tokamak physics basis for fusion energy development

- High ion temperature plasmas
- Core confinement & stability
- Plasma exhaust
- Solenoid free start-up and ramp-up
  - Several ST pilot plant concepts rely on RF H&CD for start-up and current sustainment
  - Being high field, ST40 can access more representative operating conditions and demonstrate these schemes
- Recent scenario development and future plans

EBW and ECR start-up modelling shows potential for high current drive efficiencies







1 MW (104 / 137 GHz) gyrotron on order ready for operations in 2025

- Steerable midplane LFS launchers with beam power splitter, and centre column O-X mirror polariser
- Enable development of non-inductive start-up techniques and EC H&CD

Electron Bernstein Wave (EBW) – ideal for start-up due to strong absorption, even at low n_e and T_e

- EBW excited via O-X-B scheme using centre column mirror polariser
- Peak current drive efficiencies of 0.15A/W expected

Fundamental LFS X-mode can generate significant current at low densities

- At low n_e and high T_e, X1 absorption can occur at Doppler shifted frequencies before reaching the cut-off if resonance condition is satisfied $(\omega - \omega_{ce})/(k_{\parallel} v_{th}) \leq 3$
- Generating significant current drive with high efficiencies of 0.8A/W

E. du Toit et al., PPCF 2022

M. Ono et al., NF 2022

KYOTO FUSIONEERING

ST40: Expanding the high-field spherical tokamak physics basis for fusion energy development

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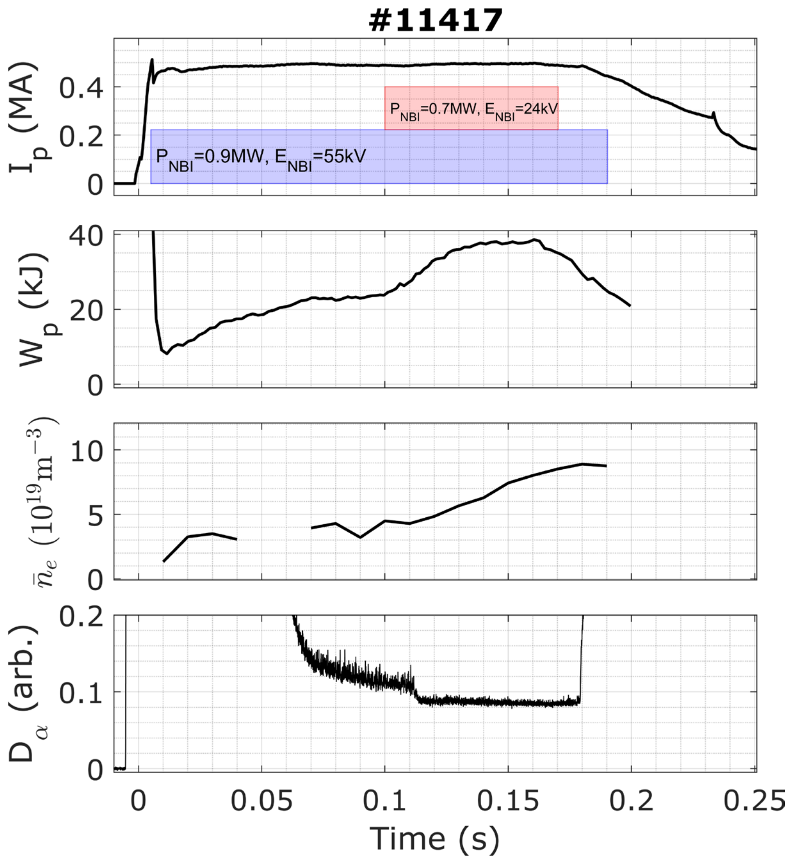
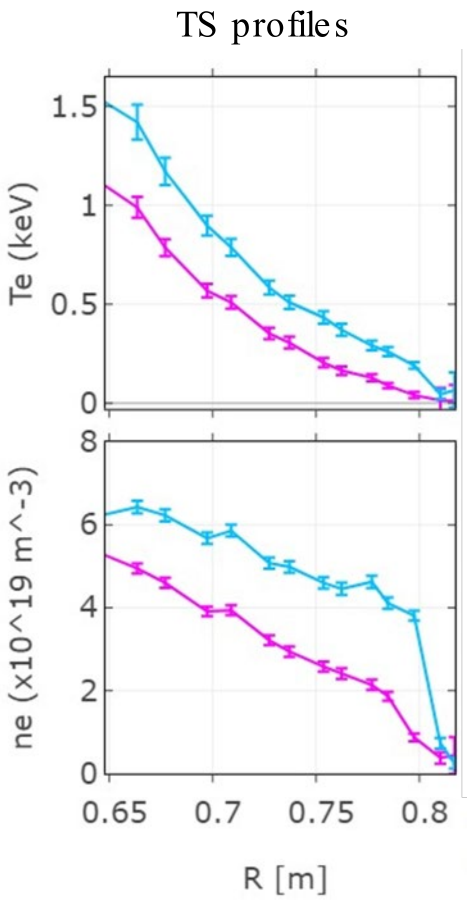
Diverted H -mode and non-inductive scenarios recently developed





Diverted H -mode scenarios

- DND, upper and lower SN
- Wide range of B_T=0.9 -2.1 T and I_P=300 -750 kA
- Sustained ELM free period
- First pedestal measurements with TS

Non -inductive scenarios

- Limited and diverted scenarios with I_p=300kA
- Ohmic solenoid swing is halted or reversed
- V_{loop} ~0, β_p~1.5, β_N~4, q_{95}~10

ST40 future upgrades and operations

2023	2024				2025	
Q4	Q1	Q2	Q3	Q4	Q1	...

Vent	Campaign 2	Vent	Campaign 3
Divertor bolometry and spectroscopy ◆ SXR (vertical R,Z) ◆ Bolometry (midplane R,Z) ◆ Multi-species impurity dropper ◆	• Confinement dependencies B_T, I_p, ν_*, M_{eff} • SOL width λ_q • Non-inductive scenarios • Maximise performance	EC 1MW ◆ Centre post O-X polariser ◆ NIRDI ◆	• EBW and EC start-up • EC H&CD • RF dominated scenarios

Summary

ST40 is expanding the high-field spherical tokamak physics basis for fusion energy development

Record ion temperatures of ~10keV demonstrated for first time the in compact device

ST40 is exploring confinement & stability at high toroidal fields

- Predictive capability developed with reduced and analytic transport models
- First look at confinement time dependence on ion mass showing strong scaling in hot-ion mode
- Argon seeding improved particle and energy confinement
- Turbulent suppression of chirping modes observed and chirping likelihood criteria validated

Potential for scrape-off-layer width broadening in ST40

- New divertor diagnostics enable first measurements of divertor heat flux

Operations with 1 MW gyrotron will develop non-inductive start-up and current drive techniques

- Predictions for EBW and LFS-X1 start-up show high current drive efficiencies can be achieved

ST40 and Tokamak Energy IAEA-FEC contributions

Wednesday 18th 14:00 poster session

EX-C-2145: A. Sladkomedova *et al.,* Impact of impurity injection on core confinement in ST40

Thursday 19th 8:30 poster session

TH-D-2412: S. Janhunen *et al.,* Assessment of the scrape off layer width and target heat loads in ST40

Thursday 19th 14:00 poster session

TH-C-2293: M.S. Anastopoulos Tzanis *et al.,* Validation of the TGLF model on ST40 ohmic and hot ion plasmas

TH-C-2251: A. Dnestrovskii *et al.,* Predictive modelling of hot-ion mode plasmas in ST40

TH-C-2268: A. Gibby *et al.,* GSFit: an open source, python based, equilibrium reconstruction algorithm

Friday 20th 14:00 poster session

TH-W-2328: V. Duarte *et al.,* Turbulent suppression of bursty fast-ion-driven instabilities in high-field ST40 experiments

EX-C-1900: S.M. Kaye *et al.,* Transport and microinstability properties of high performance ST40 plasmas