Tokamak Energy

Confinement studies in the ST40 High-Field Spherical Tokamak

Michele Romanelli

EFTC, 5 October 2023, Padova, Italy

Co-authors and contributors

M. Anastopoulos Tzanis, M. Barnes[2] , J. Bland, P. Buxton, A. Dnestrovskii, M. Gryaznevich,
M. Hardman, S. Janhunen, S. Kaye[3] , C. Marsden, S. McNamara, S. Medvedev, M. Moscheni,
Y. Ren[3], M. Sertoli, A. Sladkomedova, J. Varje, E. Vekshina, H. Weisen, X. Zhang, Y. Zhang[2]
and the ST40 Team

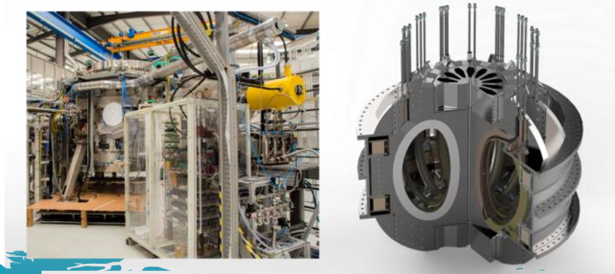
Tokamak Energy Ltd., 173 Brook Drive, Milton Park, Oxfordshire, OX14 4SD, United Kingdom

[2]Rudolf Peierls Centre for Theoretical Physics, University of Oxford, Oxford OX1 3NP, United Kingdom

[3]Princeton Plasma Physics Laboratory, Princeton, NJ, USA

Acknowledgements: the whole ST40 team. Contributions from US collaborators were funded by a public-private CRADA between Tokamak Energy Ltd, ORNL and PPPL.

About Tokamak Energy



250 people

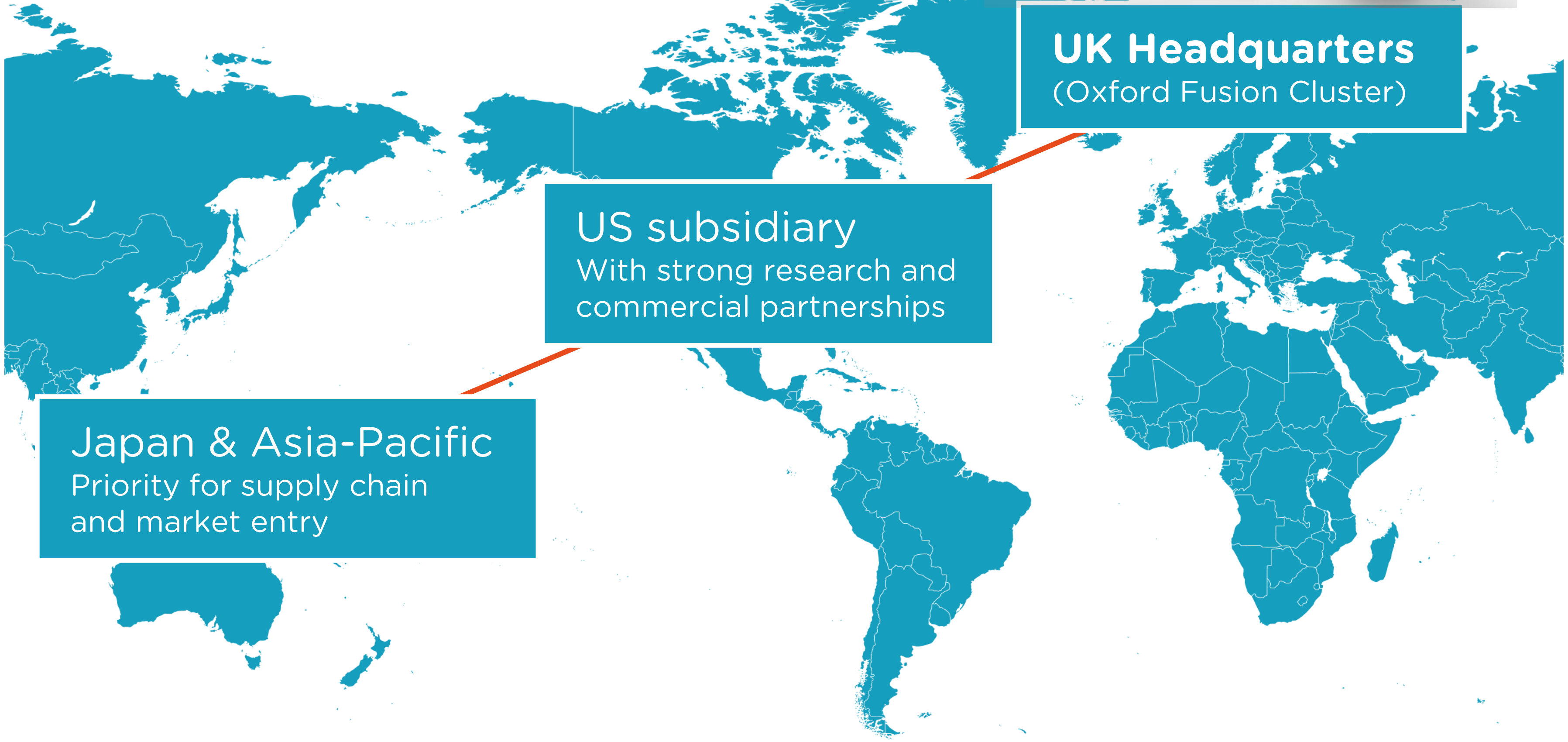
- World-class scientists, engineers and commercial specialists
- 60 PhD, 75 MSc

$250M raised to date

- Financial backing from private capital and government grants

Collaboration

- Governments
- National laboratories
- Strategic partners



UK Headquarters
(Oxford Fusion Cluster)

US subsidiary
With strong research and commercial partnerships

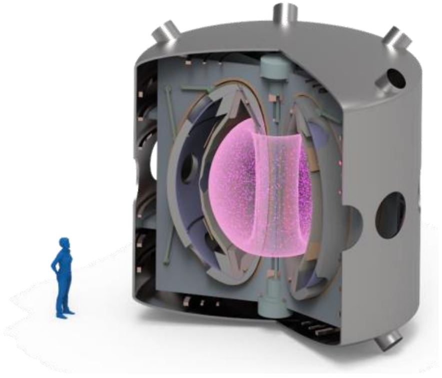
Japan & Asia-Pacific
Priority for supply chain and market entry

Strategic partnerships worldwide

Los Alamos NATIONAL LABORATORY · PPPL PRINCETON PLASMA PHYSICS LABORATORY · OAK RIDGE National Laboratory · SRNL SAVANNAH RIVER NATIONAL LABORATORY · GENERAL ATOMICS · ATI · UK Atomic Energy Authority · UNIVERSITÀ DEGLI STUDI DELLA TUSCIA · MITSUBISHI CHEMICAL · 東京大学 THE UNIVERSITY OF TOKYO · FURUKAWA ELECTRIC GROUP · Fujikura · KYOTO FUSIONEERING

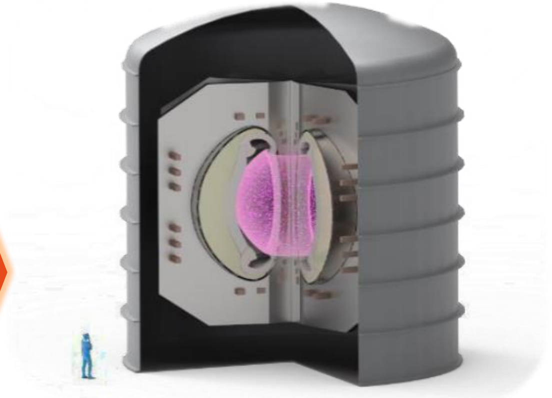
Our path to commercial fusion

Prototype



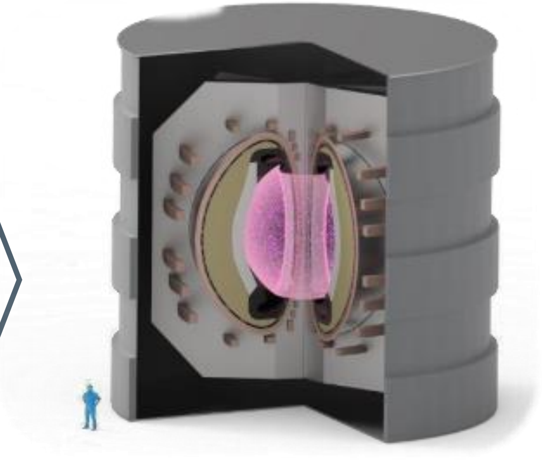
Our next advanced prototype, ST-HTS, will demonstrate long pulse, high performance D operation required for commercial fusion energy

Pilot Plant



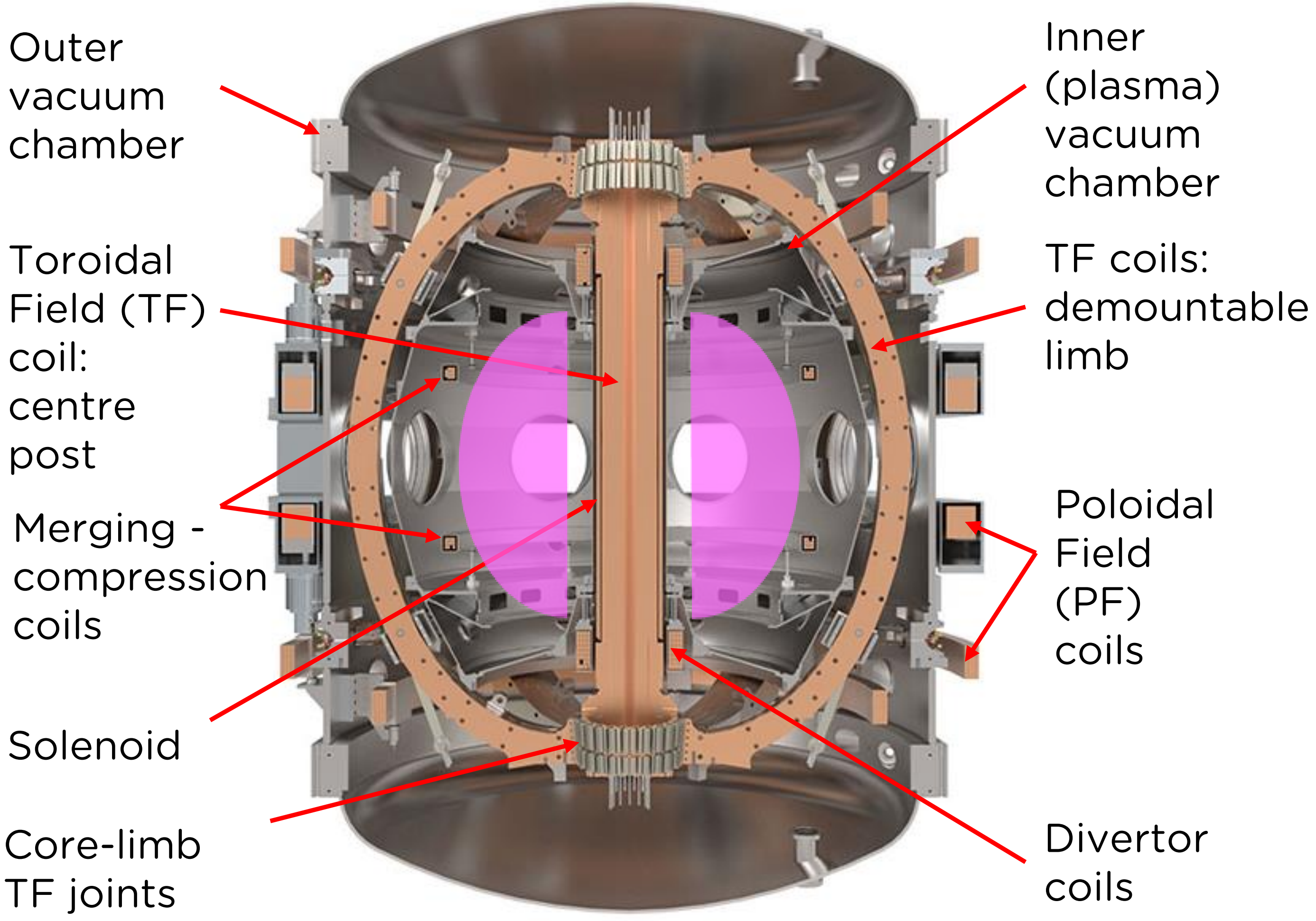
The pilot plant will demonstrate long pulse DT operation and net power gain required for commercial fusion energy

1st Generation



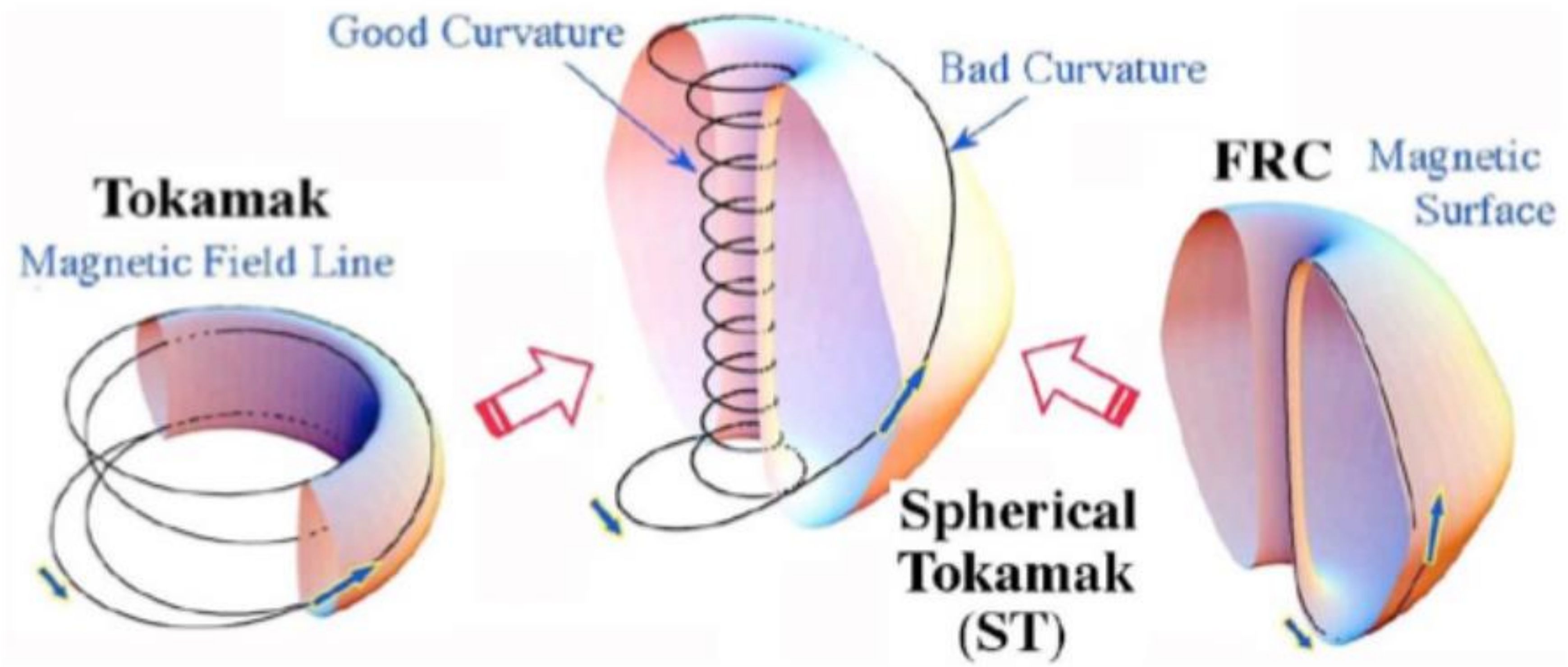
First of a Kind (FOAK) will be a commercial fusion power plant generating 500 MWe

ST40: Expanding the high field ST physics basis



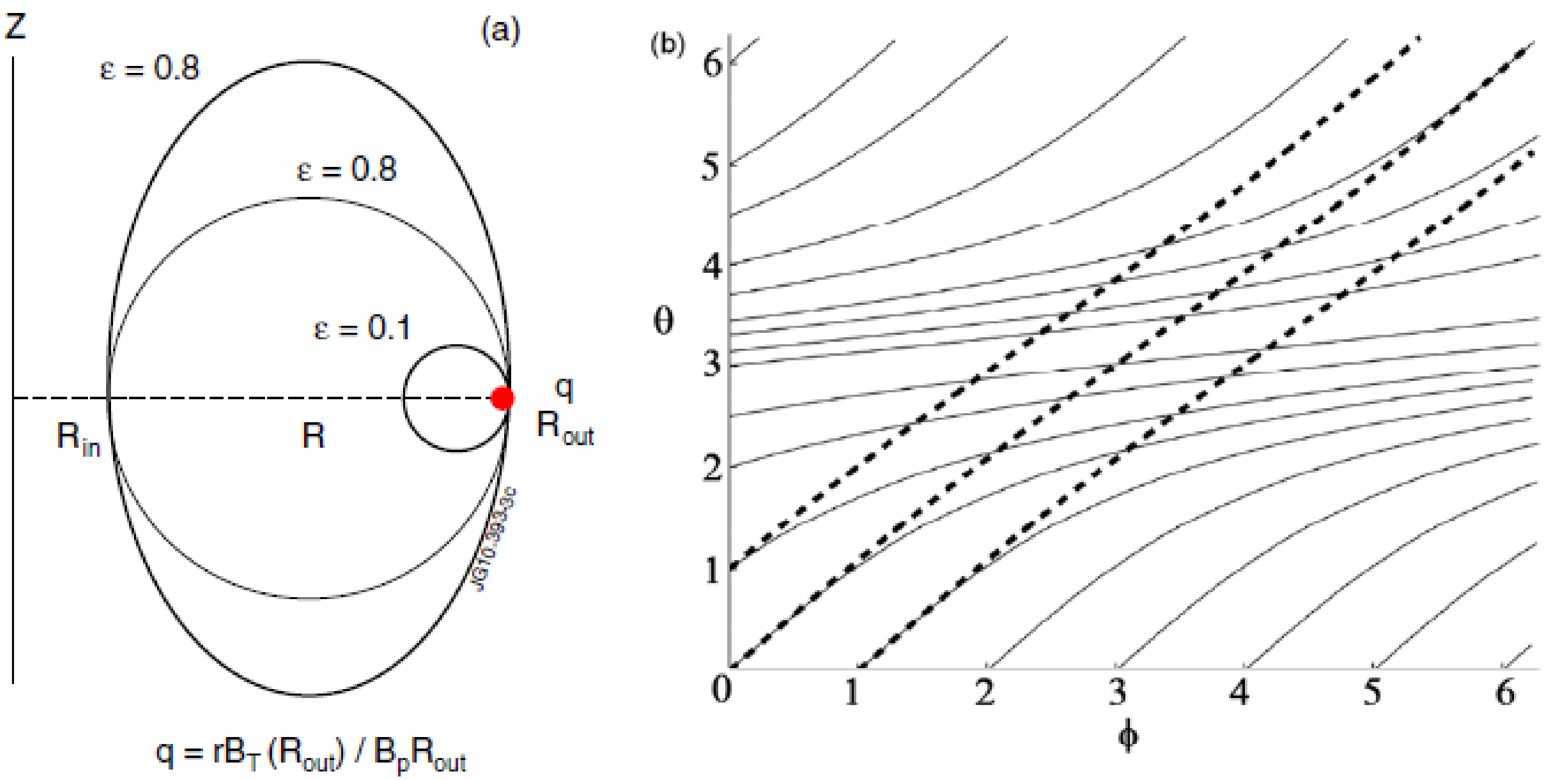
Parameter	Range
Bt [T]	1.5 – 2.2
Ip [MA]	0.4 – 0.8
R_{Geo} [cm]	40 – 50
A	1.6 – 1.8
P_{NB}/E_{NB} [MW/kV]	0.8/24, 1.0/55
ψ_{sol} [mWb]	200
Start-up	Merging-compression
Fuel	Hydrogen/Deuterium

Magnetic field lines in a Spherical Tokamak



Megnetic field lines in a Spherical Tokamak

Plasma Phys. Control. Fusion **53** (2011) 054017 M Romanelli *et al*

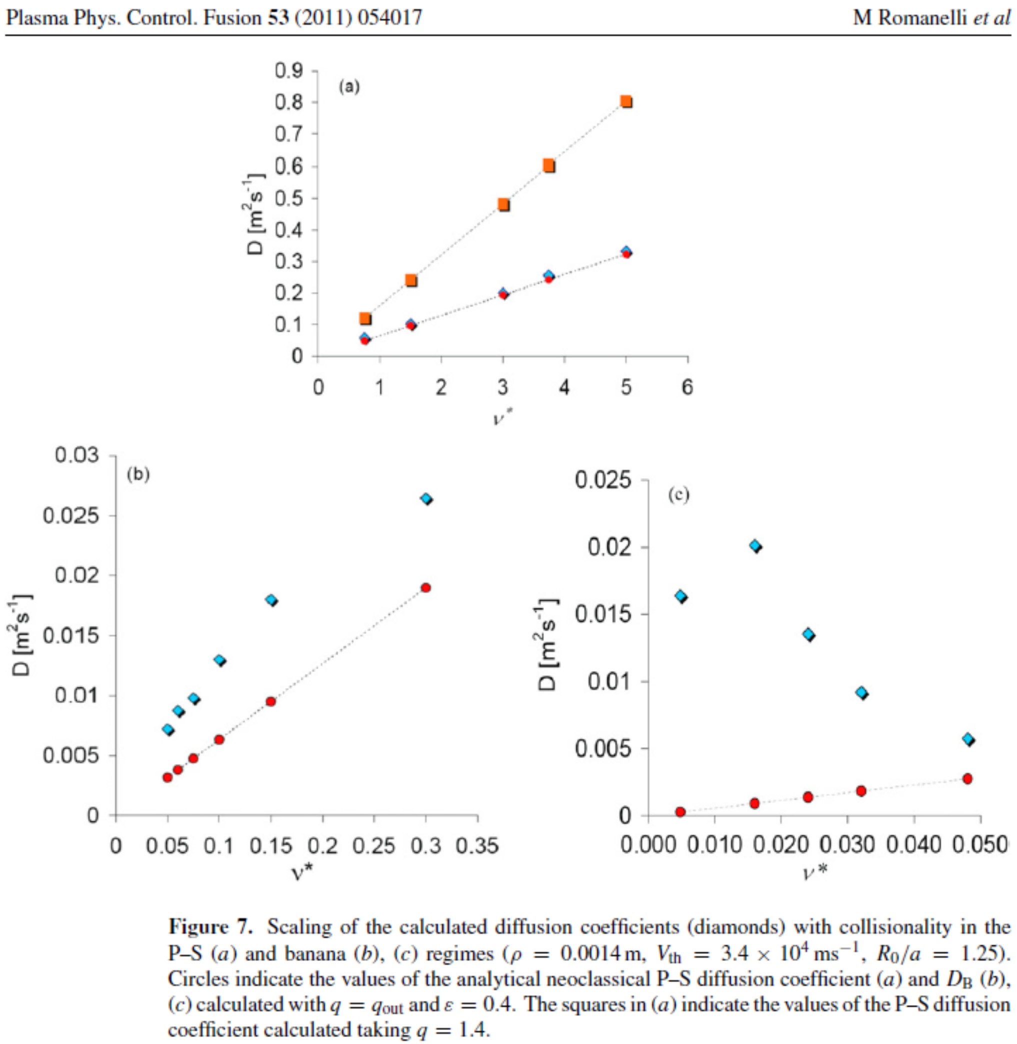


$q = rB_T(R_{out}) / B_pR_{out}$

Figure 5. (*a*) Cross sections of three flux surfaces having the same value of q_{out} but different aspect ratios or elongation. (*b*) Magnetic field lines on the magnetic surfaces in (*a*) for $\varepsilon = 0.1$ dotted line) and $\varepsilon = 0.8$ plotted in geometric angles. The field structure is chosen to coincide around $\theta = 0$ and $\theta = 2\pi$.

The safety factor *q* varies on the magnetic surface

Diffusivities and Fluxes in STs

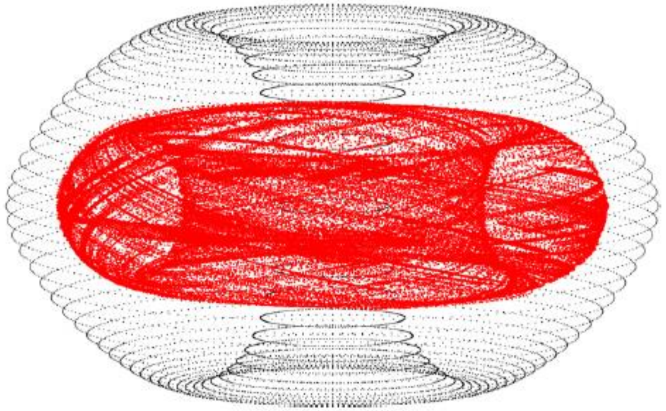


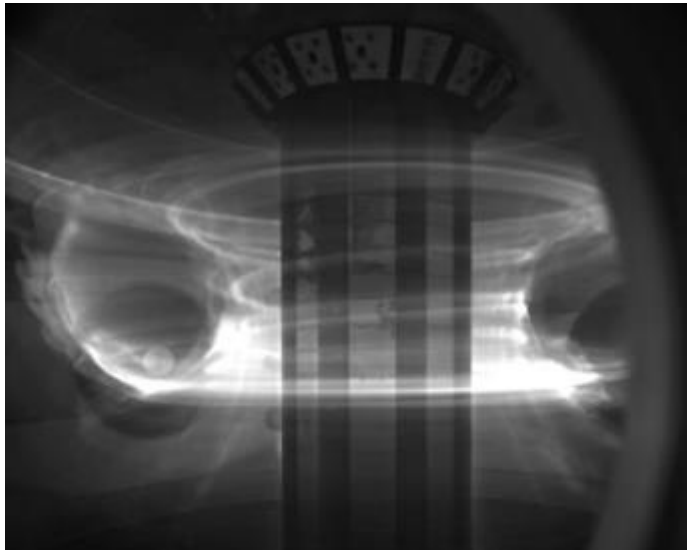
Plasma Phys. Control. Fusion **53** (2011) 054017 M Romanelli *et al*

Figure 7. Scaling of the calculated diffusion coefficients (diamonds) with collisionality in the P–S (*a*) and banana (*b*), (*c*) regimes ($\rho = 0.0014\,\mathrm{m}$, $V_{\mathrm{th}} = 3.4 \times 10^4\,\mathrm{ms}^{-1}$, $R_0/a = 1.25$). Circles indicate the values of the analytical neoclassical P–S diffusion coefficient (*a*) and D_{B} (*b*), (*c*) calculated with $q = q_{\mathrm{out}}$ and $\varepsilon = 0.4$. The squares in (*a*) indicate the values of the P–S diffusion coefficient calculated taking $q = 1.4$.

$$\Gamma_i = \langle n_i v_{i_\psi} \rangle = \left\langle \frac{B_\varphi}{eB^2}\left(\frac{1}{\psi}\frac{\partial p_i}{\partial \theta} - n_i e E_\theta\right)\right\rangle - \left\langle \frac{F_{ei\perp\varphi}}{eB_\theta} \right\rangle + \left\langle \frac{n_i E_\varphi^A B_\theta}{B^2} \right\rangle = \Gamma_i^{PS} + \Gamma_i^{cl} + \Gamma_i^{E^A\times B}$$

Due to the strong variation of the field in the toroidal direction of an ST the fluxes can be expected to be different





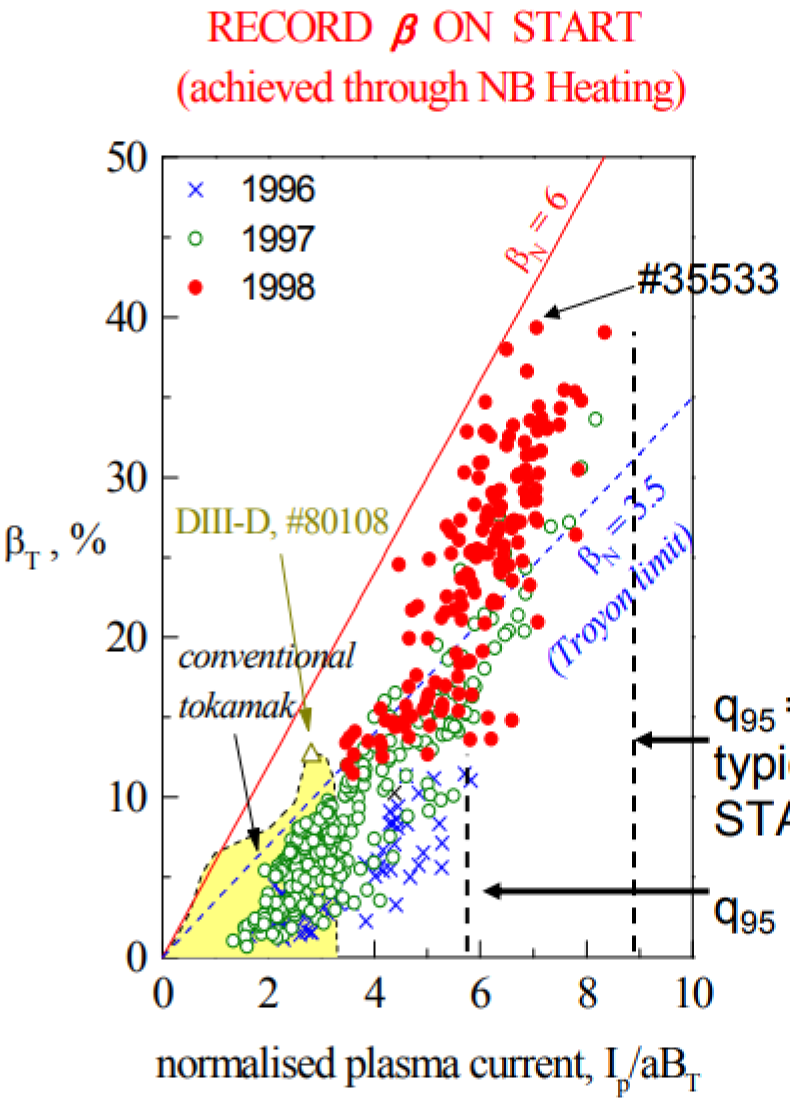
ST40 Visible Camera

STs can sustain higher beta operation

STs require much lower toroidal magnetic field on axis to achieve the same q_{edge} of CTs

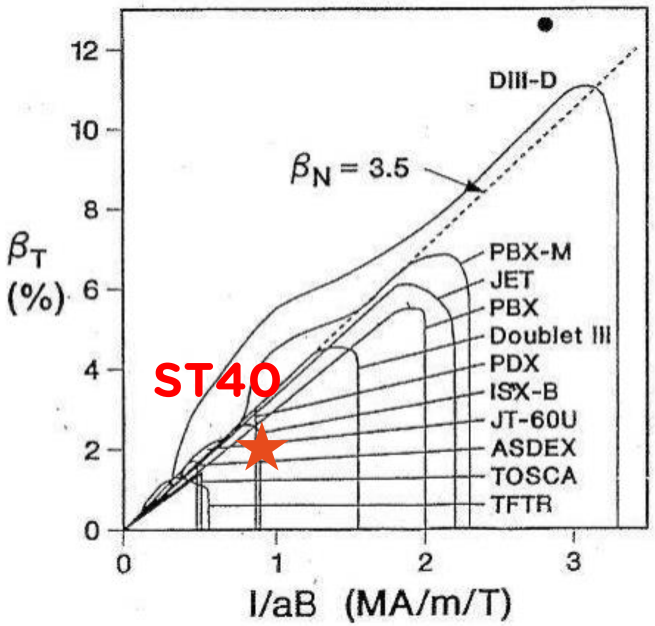
This means that for a given B_0 the plasma current can be much larger (β is proportional to I_p)

β values in STs are due to: small aspect ratio, high elongation, increased magnetic shear and higher plasma current accessible at the same B_0



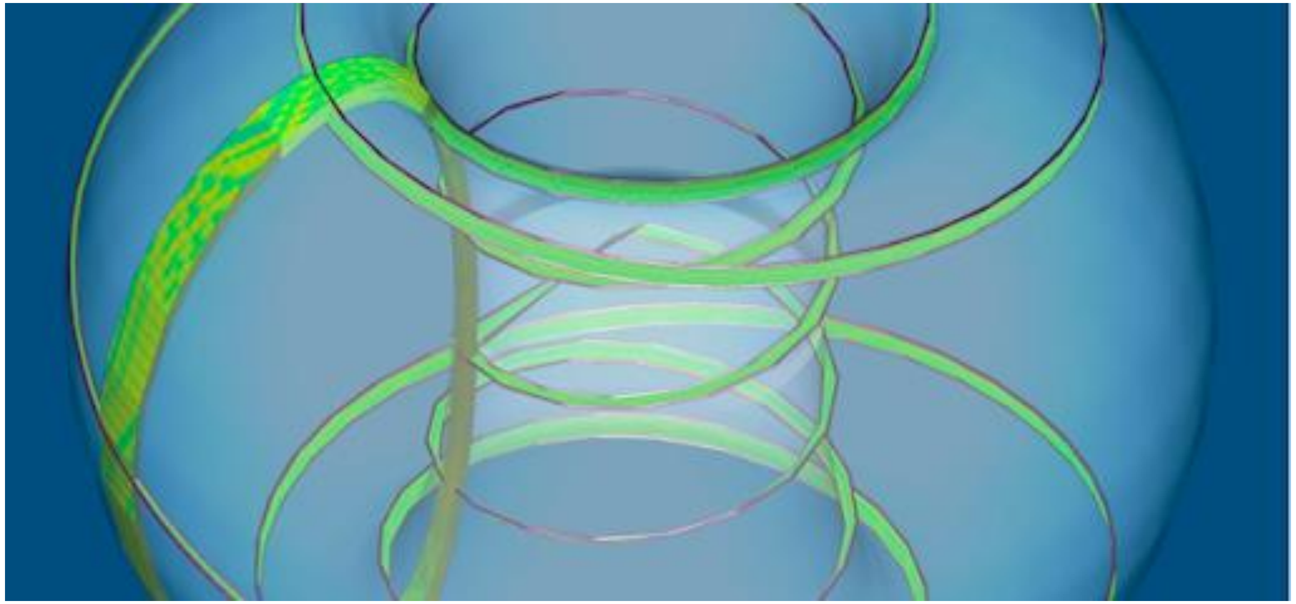
q_{95} = 2 for typical high-β START plasma

q_{95} = 3

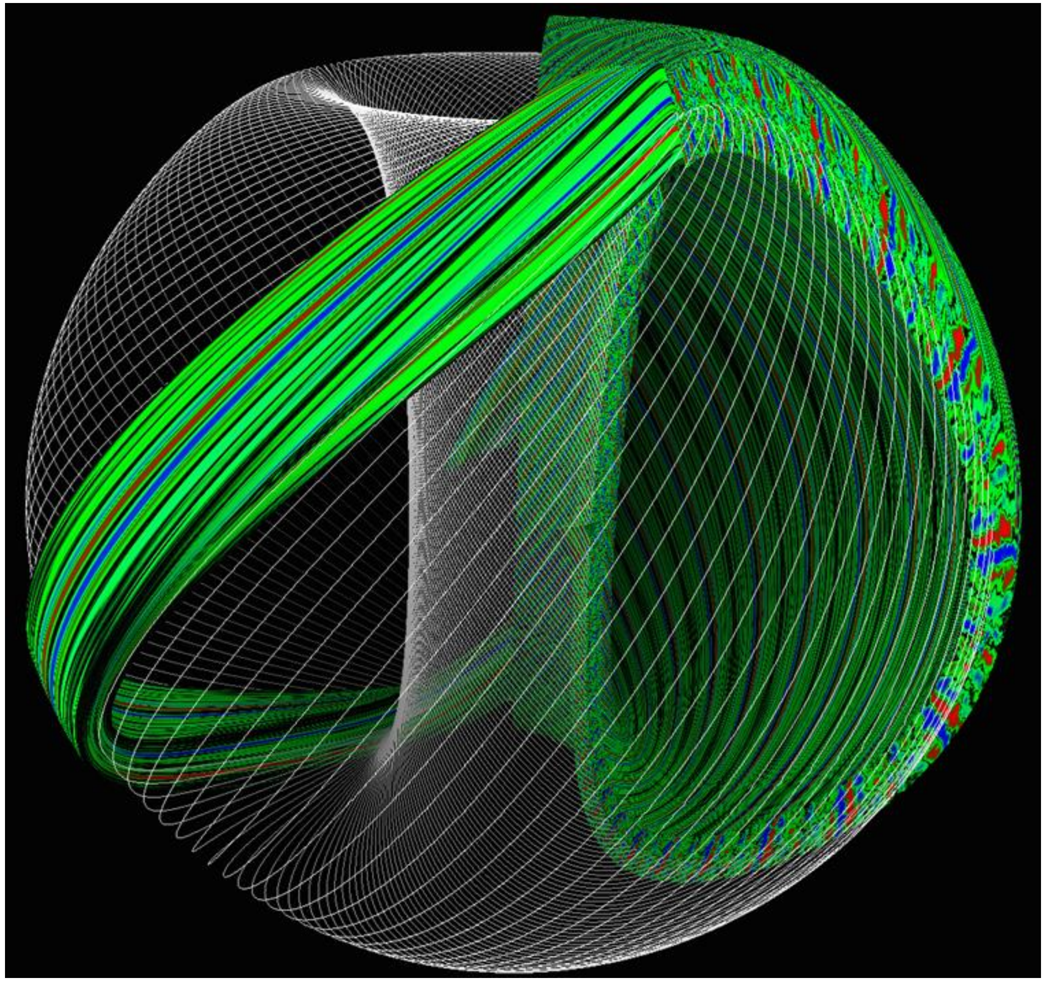


High B STs have I/aB in the range of that of CT

Turbulent Transport

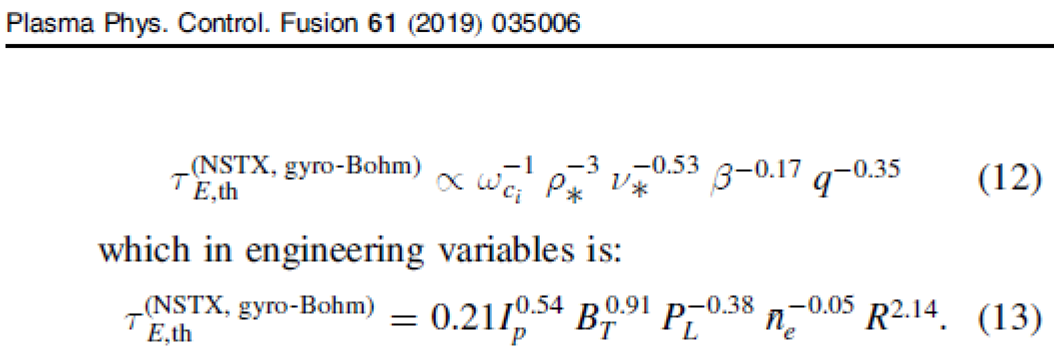


- Strong variation of the magnetic field / Larmor radius along the field lines (need higher resolution in the parallel direction)
- Electromagnetic turbulence
- Turbulent transport is different in STs



M. Barnes, TRINITY simulation of MAST

Global Confinement

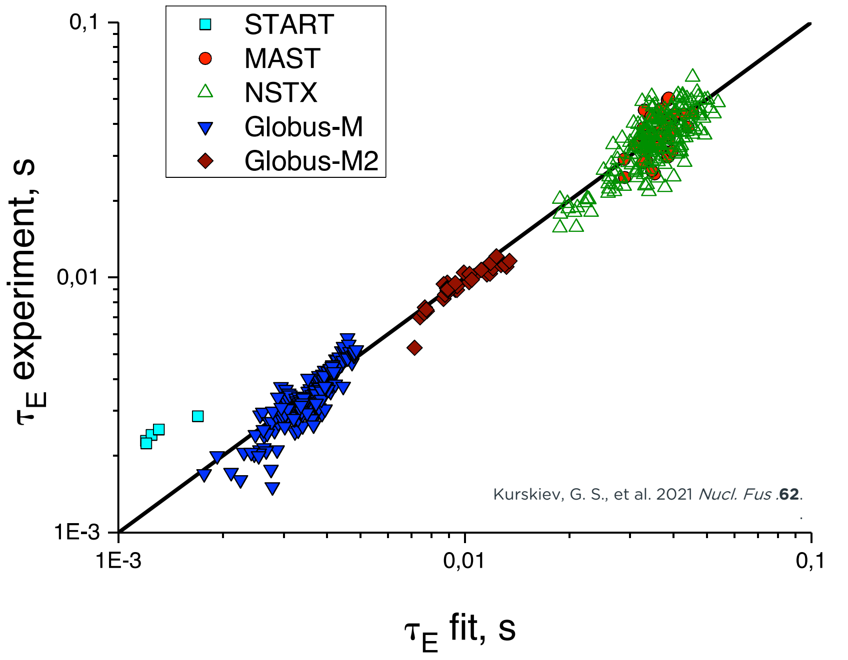


Plasma Phys. Control. Fusion **61** (2019) 035006 P F Buxton *et al*

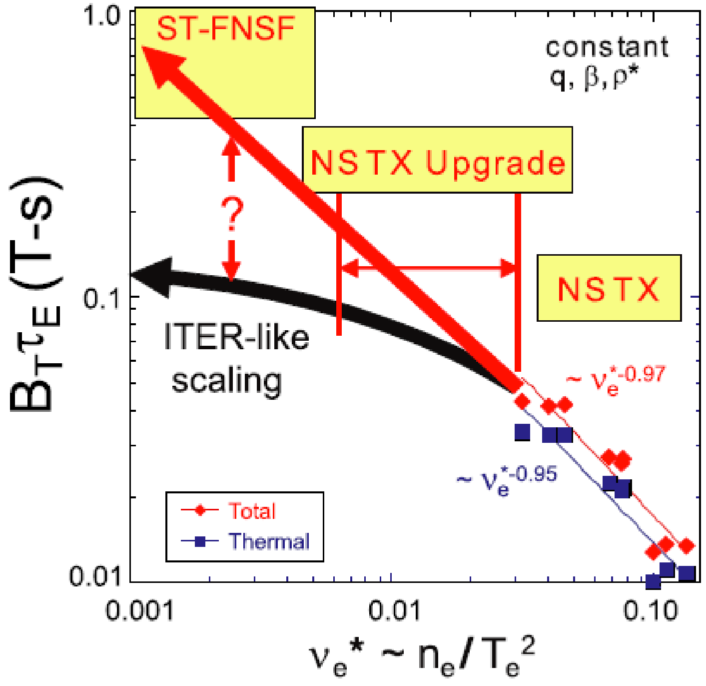
$$\tau_{E,\mathrm{th}}^{(\mathrm{NSTX,\ gyro\text{-}Bohm})} \propto \omega_{c_i}^{-1}\,\rho_*^{-3}\,\nu_*^{-0.53}\,\beta^{-0.17}\,q^{-0.35} \qquad (12)$$

which in engineering variables is:

$$\tau_{E,\mathrm{th}}^{(\mathrm{NSTX,\ gyro\text{-}Bohm})} = 0.21 I_p^{0.54}\,B_T^{0.91}\,P_L^{-0.38}\,\bar{n}_e^{-0.05}\,R^{2.14}. \qquad (13)$$



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



J.E. Menard *et al* 2012 *Nucl. Fusion* **52** 083015

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

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

Dimensionally correct scaling laws in physics variables

P. Buxton 2019, PPFC, **61**

Michele Romanelli and Francesco Paolo Orsitto 2021 PPCF **63**

- We assume that the thermal energy confinement time depends on plasma physics, and can be expressed as a power law using the following parameters:

$$\tau_{\mathrm{E,th,[s]}} \propto \omega_{c_i,[\mathrm{s}^{-1}]}^{x_\omega} \rho_*^{x_{\rho_*}} \nu_*^{x_{\nu_*}} \beta^{x_\beta} A^{x_A} q^{x_q} \epsilon^{x_\epsilon} \kappa^{x_\kappa}$$

- Note: the following variables are dimensionless: ρ_*, ν_*, β, M, q, ϵ, and κ. And only the cyclotron frequency, ω_{c_i}, has dimensions of inverse seconds.
- Therefore, for the equation to be dimensionally correct we require $x_\omega = -1$.
- So, we only need to experimentally find 7 exponents not 8!

Variable	Definition
Cyclotron frequency	$\omega_{c_i} \propto B_T A^{-1}$
Normalised ion Larmor radius	$\rho_* \propto A^{0.5} T^{0.5} \epsilon^{-1} R^{-1} B_T^{-1}$
Normalised collisionality	$\nu_* \propto \overline{n}_e R T^{-2} q \epsilon^{-1.5}$
Plasma beta	$\beta \propto \overline{n}_e T B_T^{-2}$
Safety factor	$\mathrm{q} \propto B_T R I_p^{-1} \epsilon^2 \kappa_a$
Inverse aspect ratio	$\epsilon = a R^{-1}$
Effective elongation	$\kappa_a = V_p/(2\pi^2 R a^2)$

Dimensionally correct scaling laws in engineering variables

- Using the definitions, we can re-write the scaling law into engineering variables

$$\tau_{\mathrm{E,th,[s]}} \propto \omega_{c_i,[\mathrm{s}^{-1}]}^{x_\omega} \rho_*^{x_{\rho_*}} \nu_*^{x_{\nu_*}} \beta^{x_\beta} A^{x_A} q^{x_q} \epsilon^{x_\epsilon} \kappa^{x_\kappa}$$

$$\tau_{\mathrm{E,th,[s]}} \propto I_p^{\alpha_I} B_T^{\alpha_T} P_L^{\alpha_P} \overline{n}^{\alpha_n} A^{\alpha_M} R^{\alpha_R} \epsilon^{\alpha_\epsilon} \kappa_a^{\alpha_\kappa}$$

Variable	Definition
Cyclotron frequency	$\omega_{c_i} \propto B_T A^{-1}$
Normalised ion Larmor radius	$\rho_* \propto A^{0.5} T^{0.5} \epsilon^{-1} R^{-1} B_T^{-1}$
Normalised collisionality	$\nu_* \propto \overline{n}_e R T^{-2} q \epsilon^{-1.5}$
Plasma beta	$\beta \propto \overline{n}_e T B_T^{-2}$
Safety factor	q $\propto B_T R I_p^{-1} \epsilon^2 \kappa_a$
Inverse aspect ratio	$\epsilon = aR^{-1}$
Effective elongation	$\kappa_a = V_p/(2\pi^2 R a^2)$

- But we still require $x_\omega = -1$, (we only need to experimentally find 7 exponents not 8). This requirement can be written as:

$$\alpha_R = \frac{5}{4}\alpha_B + \frac{1}{4}\alpha_I + 2\alpha_n + \frac{3}{4}\alpha_p + \frac{5}{4}$$

- So, we can deduce a size scaling from a single machine!
  (providing other exponents are well known)

Experimental practicalities

- Unfortunately, on NSTX the power and electron density were co-linear, meaning that we don't know both α_P and α_n, instead we know combined value.
- To resolve this, we followed a similar procedure, and choose to assume that the energy confinement time has a gyro-Bohm scaling, i.e.

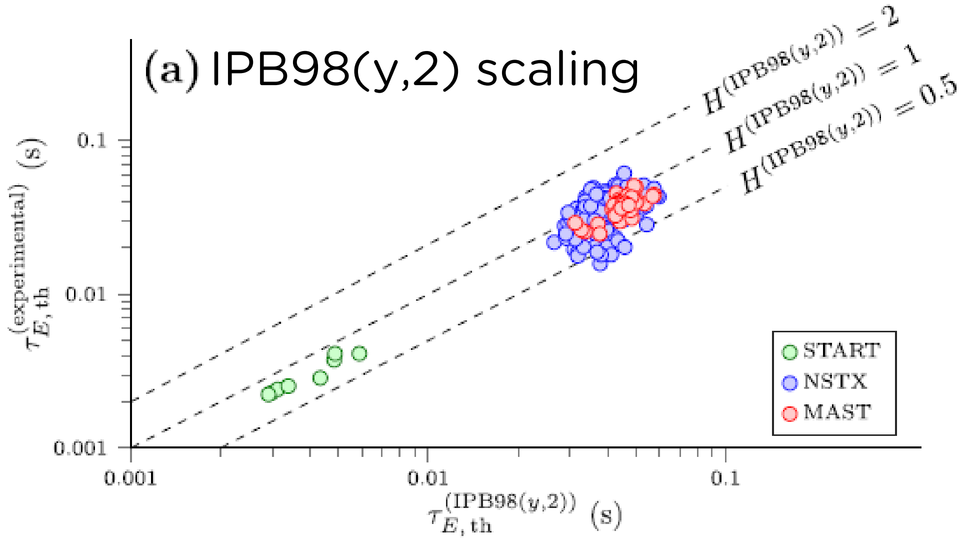
$$\tau_{\mathrm{E,th},[\mathrm{s}]} \propto \omega_{c_i,[\mathrm{s}^{-1}]}^{-1}\rho_*^{-3}\nu_*^{x_{\nu_*}}\beta^{x_\beta}A^{x_A}q^{x_q}\epsilon^{x_\epsilon}\kappa^{x_\kappa}$$

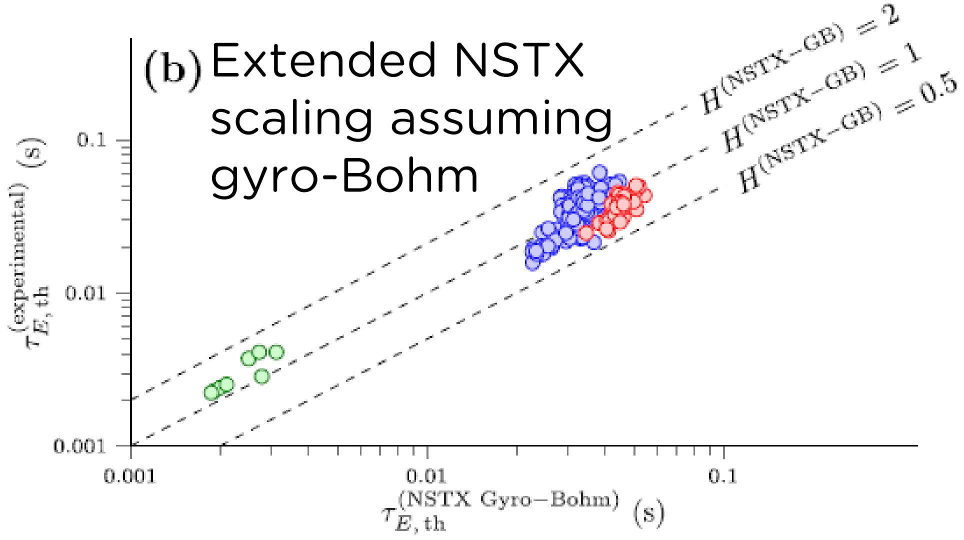
- We now have enough information to extend the NSTX confinement scaling to include a size dependence.

$$\tau_{E,\mathrm{th}}^{(\mathrm{NSTX,\ gyro\text{-}Bohm})} \propto \omega_{c_i}^{-1}\ \rho_*^{-3}\ \nu_*^{-0.53}\ \beta^{-0.17}\ q^{-0.35} \qquad (12)$$

which in engineering variables is:

$$\tau_{E,\mathrm{th}}^{(\mathrm{NSTX,\ gyro\text{-}Bohm})} = 0.21 I_p^{0.54}\ B_T^{0.91}\ P_L^{-0.38}\ \bar{n}_e^{-0.05}\ R^{2.14}. \qquad (13)$$

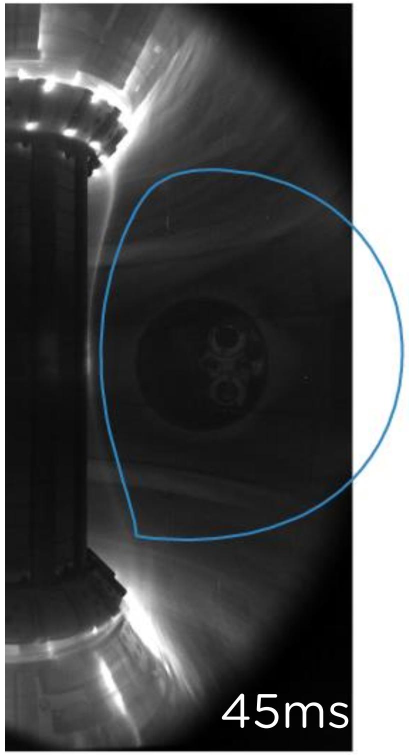

(a) IPB98(y,2) scaling

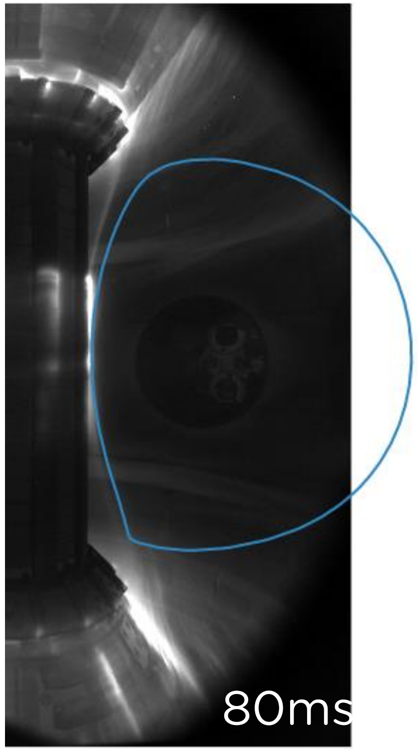

(b) Extended NSTX scaling assuming gyro-Bohm

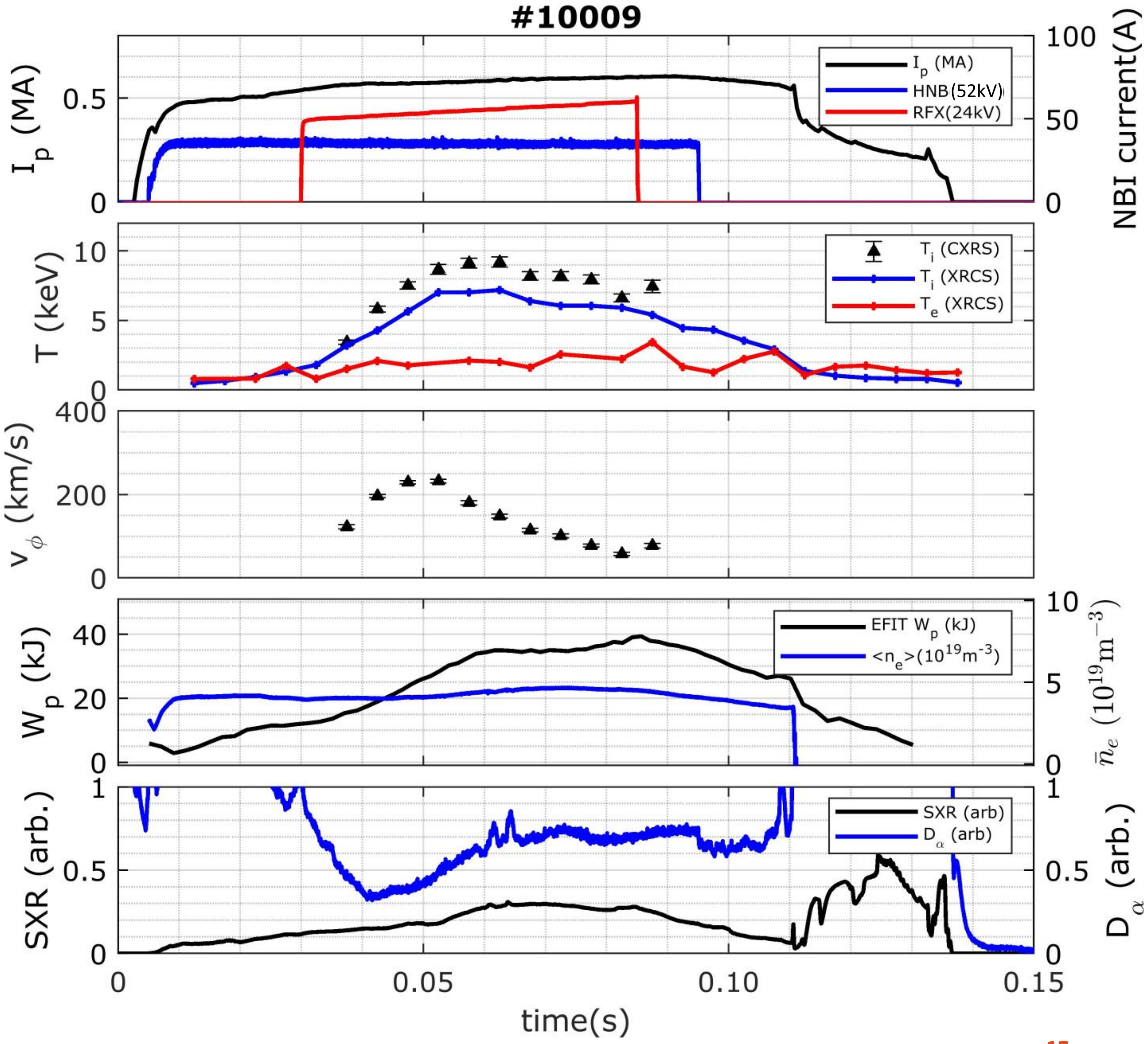
ST40 hot Ion mode scenario

S.A.M. McNamara *et al* 2023 *Nucl. Fusion* **63** 054002

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



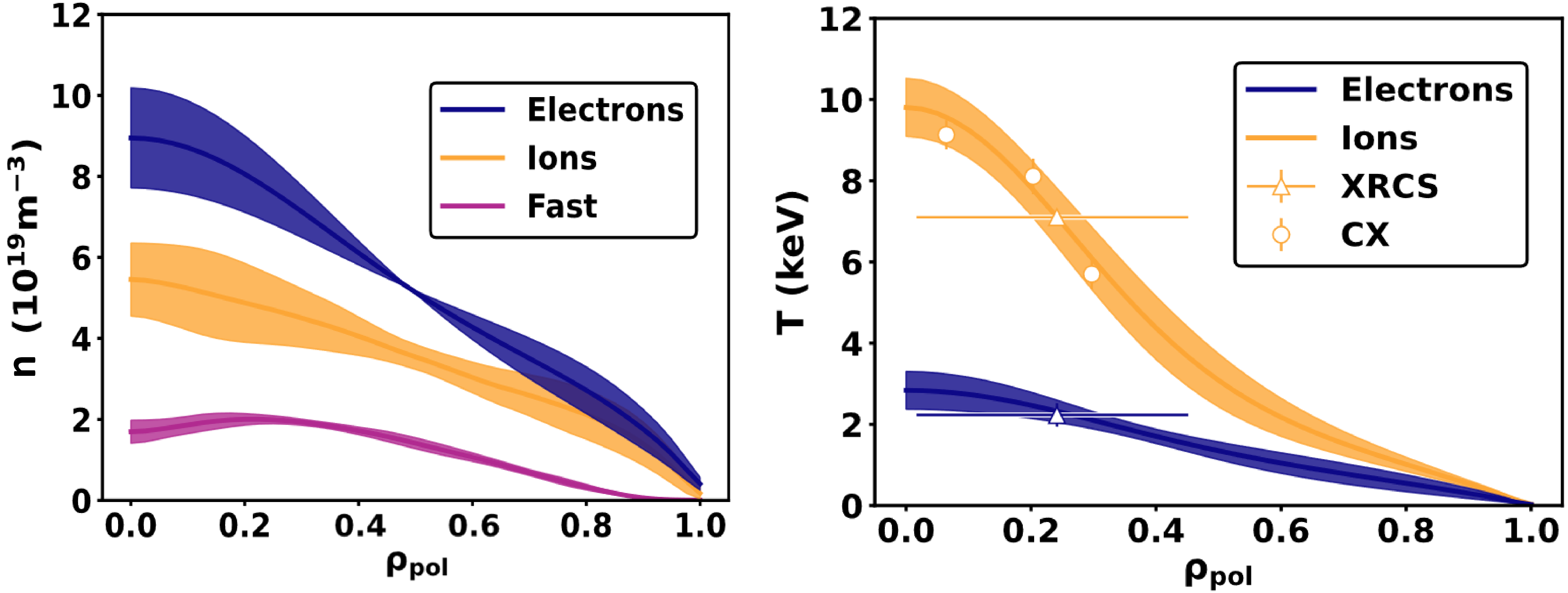




Record hot ion mode temperature - Profiles

S.A.M. McNamara *et al* 2023 *Nucl. Fusion* **63** 054002

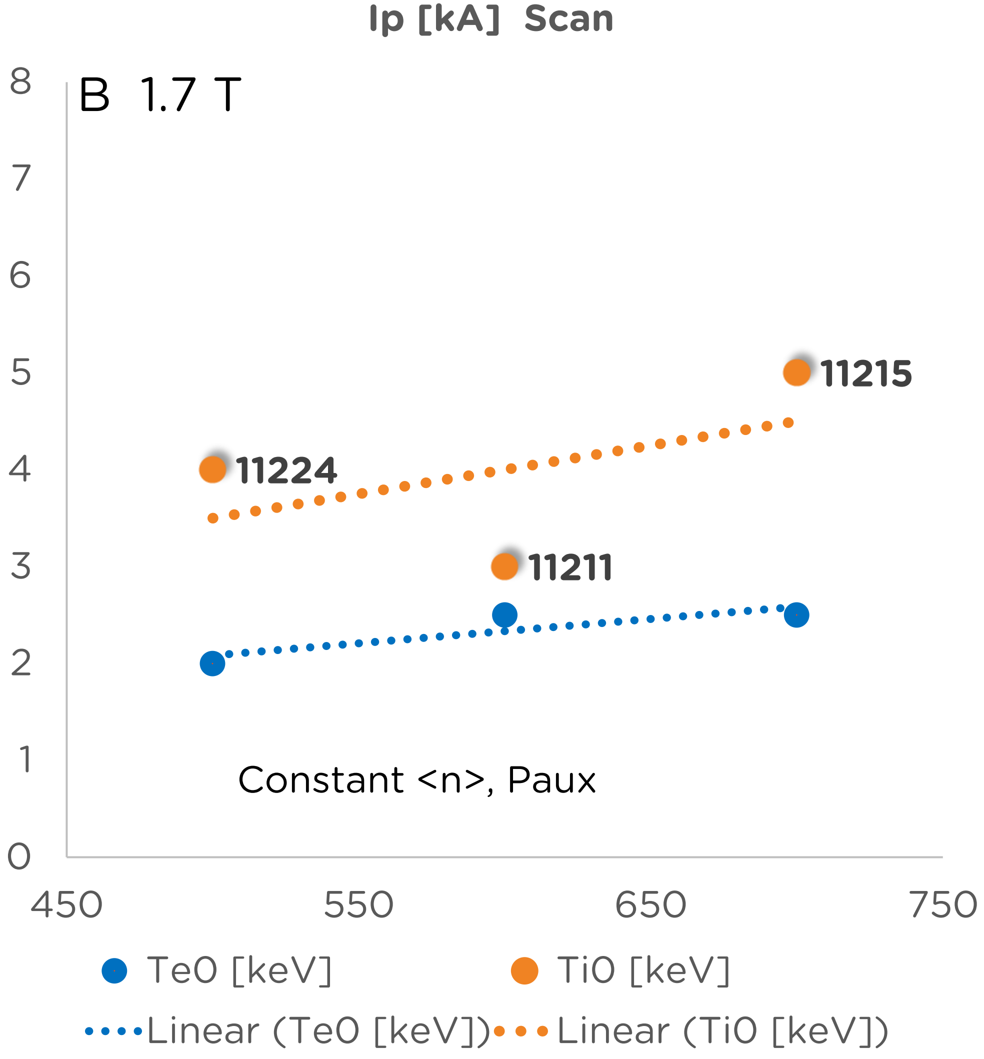
Shot 10009 at 57.5ms

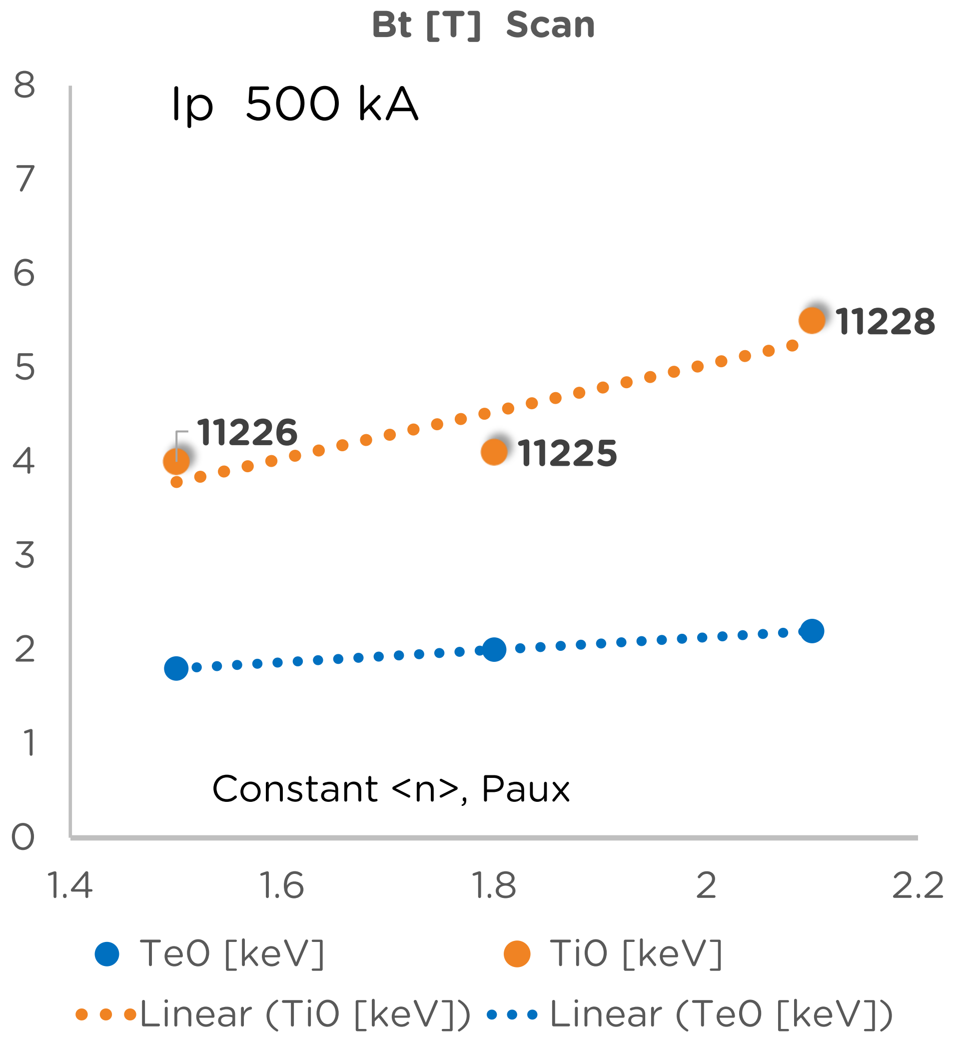


profiles inferred for pulse 10009, and shapes validated using TS in the 2023 campaign.

Magnetic Field and Current Scans (preliminary results)

$\langle n \rangle = 4.5 \times 10^{19}\ \mathrm{m^{-3}}$ Paux = 1.75 MW

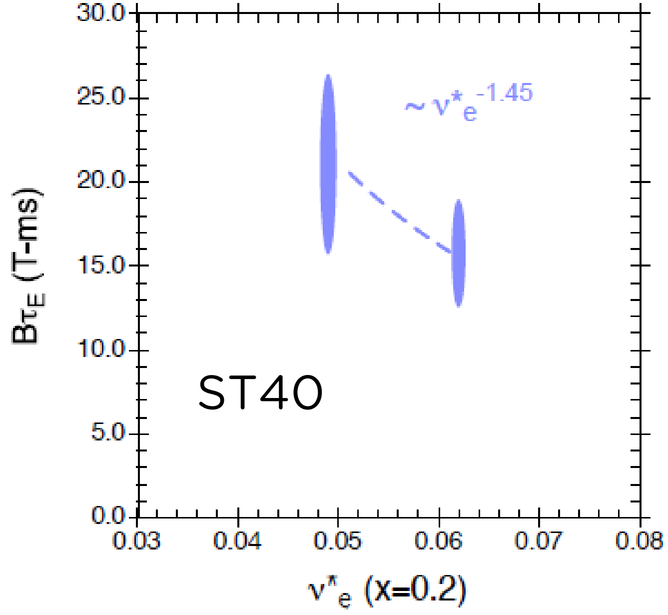


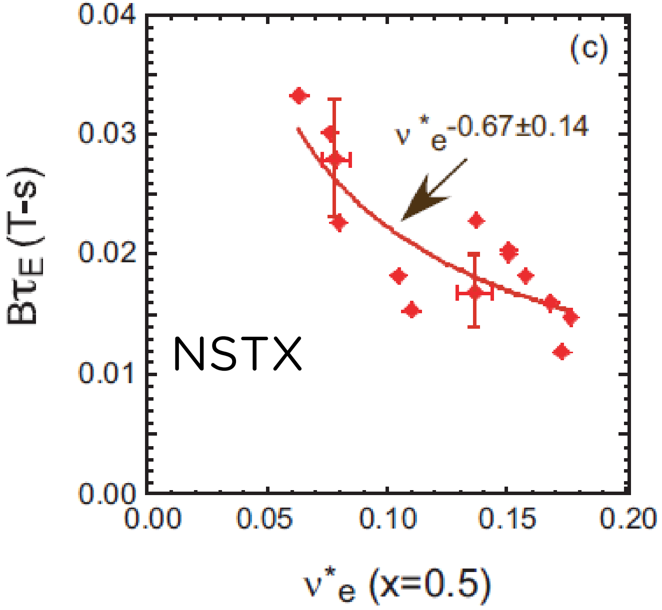


S. Kaye et al, IAEA FEC, 2023

Collisionality scan

S.M. Kaye et al 2013 Nucl. Fusion 53 063005





- A scan with same plasma conditions of NSTX (diverted, H-mode) is needed to confirm the ST trend of confinement strong dependency with collisionality

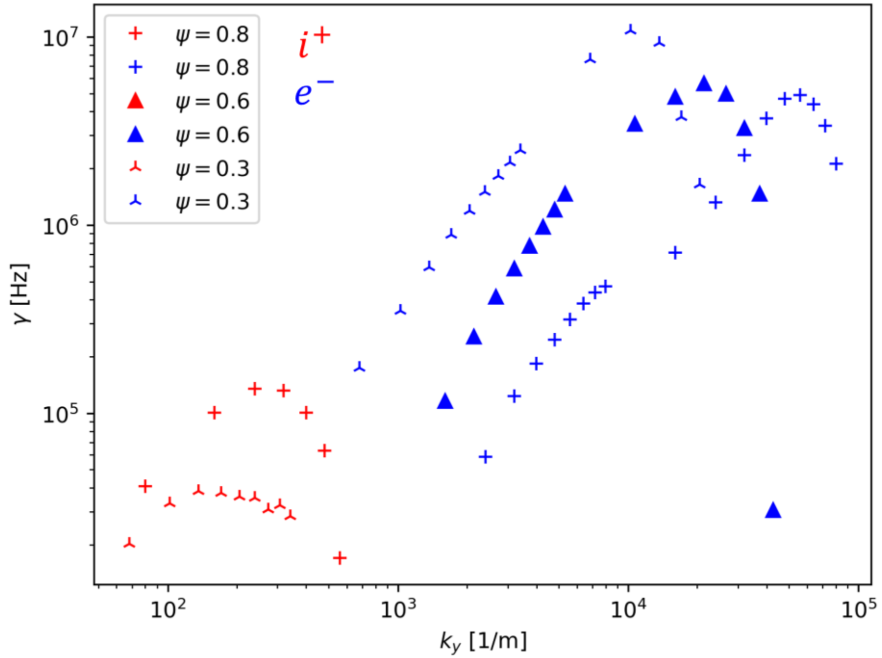
- Operation at lower density / higher temperatures in ST40 will allow to extend the scaling to even lower collisionalities (next ST40 campaign)

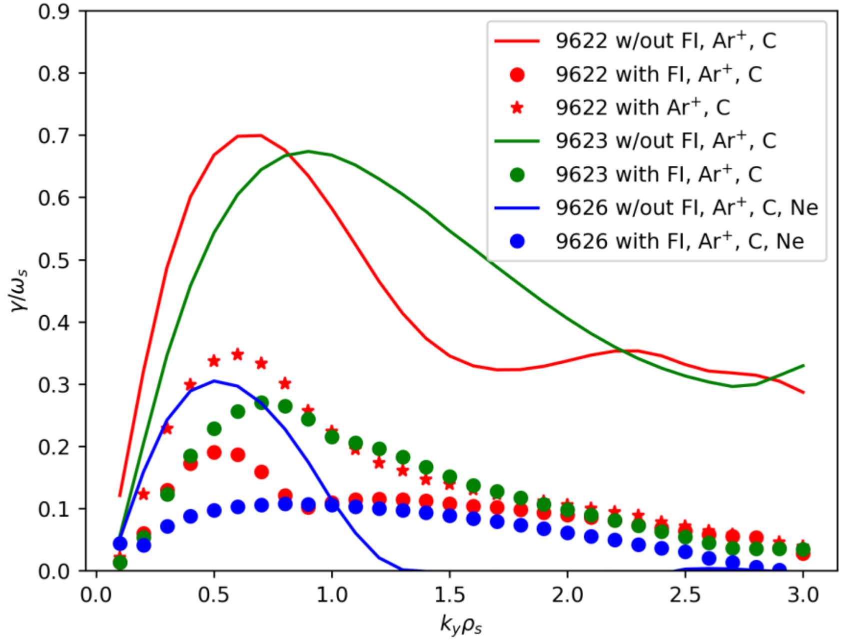
S. Kaye et al, IAEA FEC, 2023

GK analysis

Gyrokinetic analysis of ST40 high performance plasmas indicate a rich unstable turbulence spectrum (with unstable UMs at low-k_y, ETGs at high-k_y and intermediate-k_y electron modes), while fast ions and impurities provide substantial stabilisation of the linear turbulent modes.

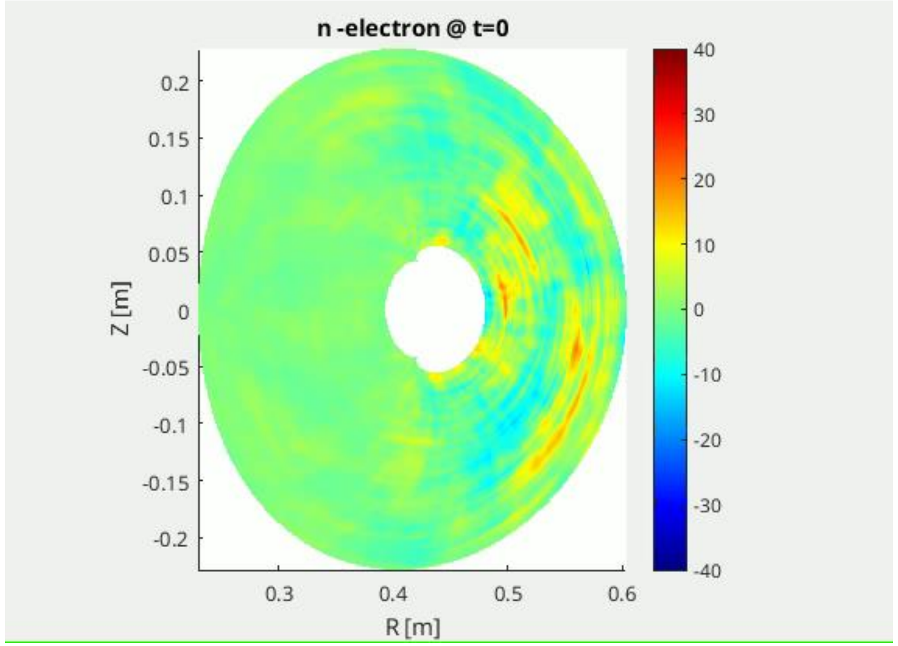
The plots show the linear growth rates of pulse 10014 (maximum T_i) flat top case and impurity/fast-ion stabilisation.



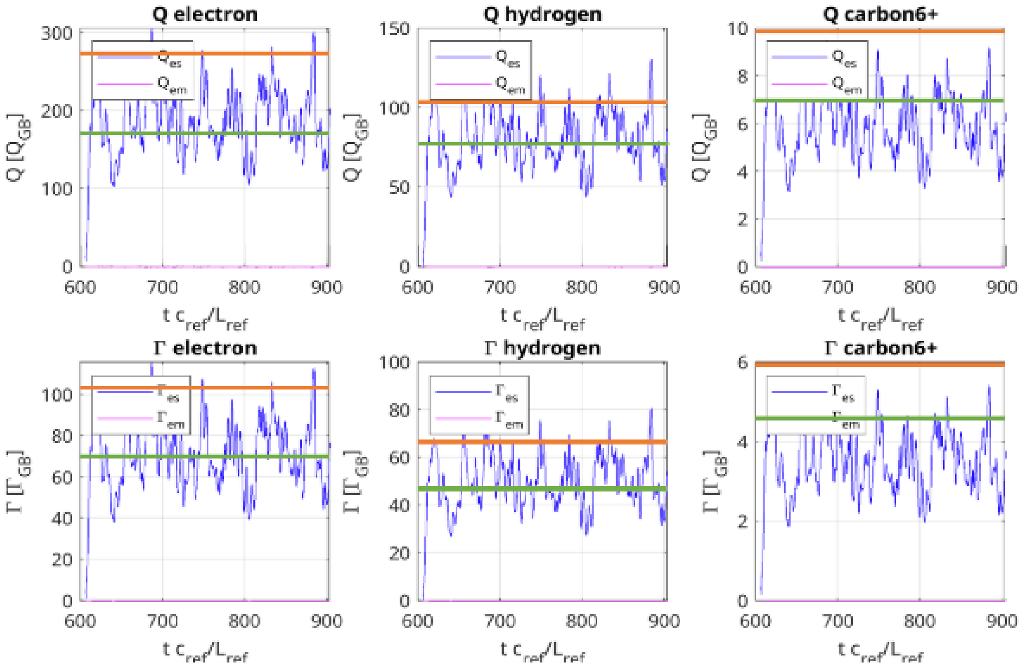


M. Anastopoulos, IAEA FEC, 2023
Y. Ren et al, PPCF, 2023

GENE’s non-linear simulation of ST40 ohmic plasmas



GENE’s nonlinear simulations (electron density fluctuations) for ohmic plasmas produce ion and electron heat fluxes in the range of those found with ASTRA-TGLF.

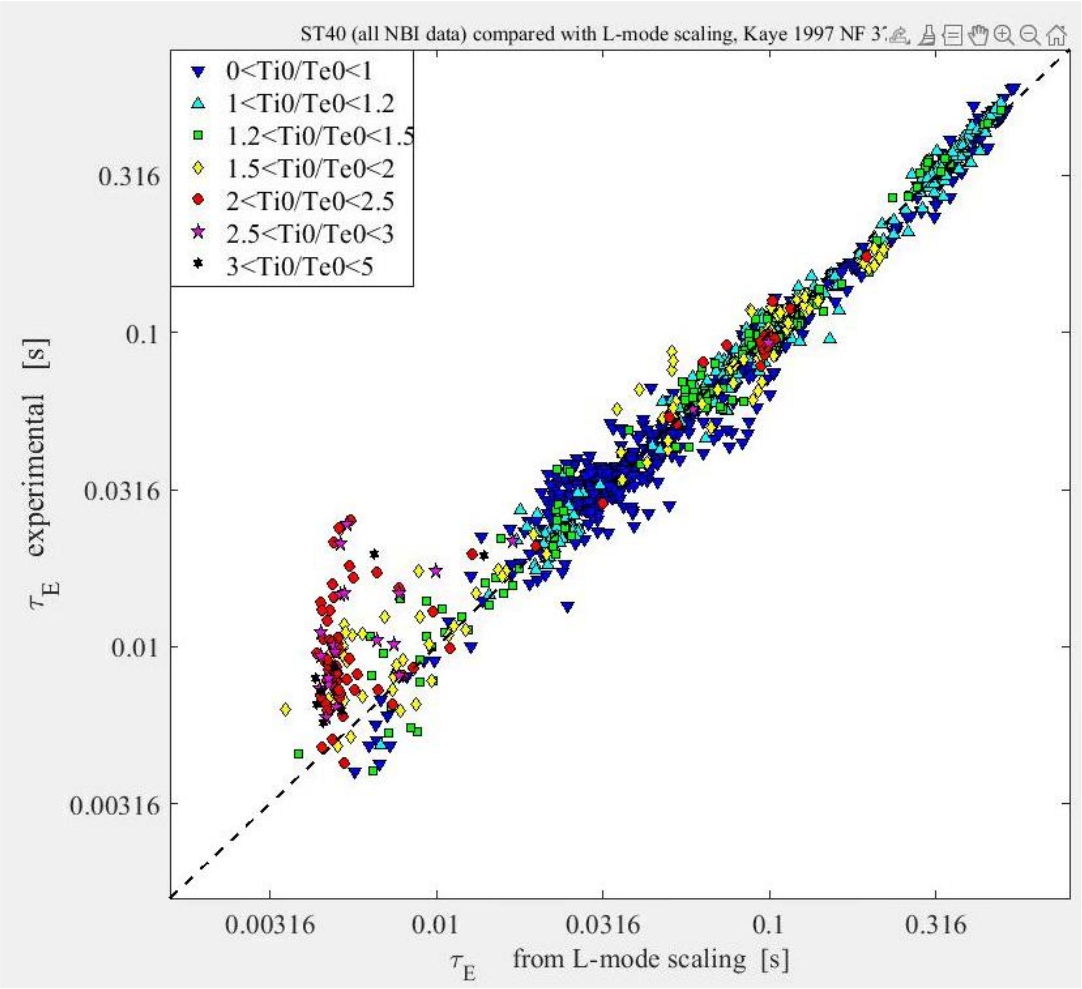


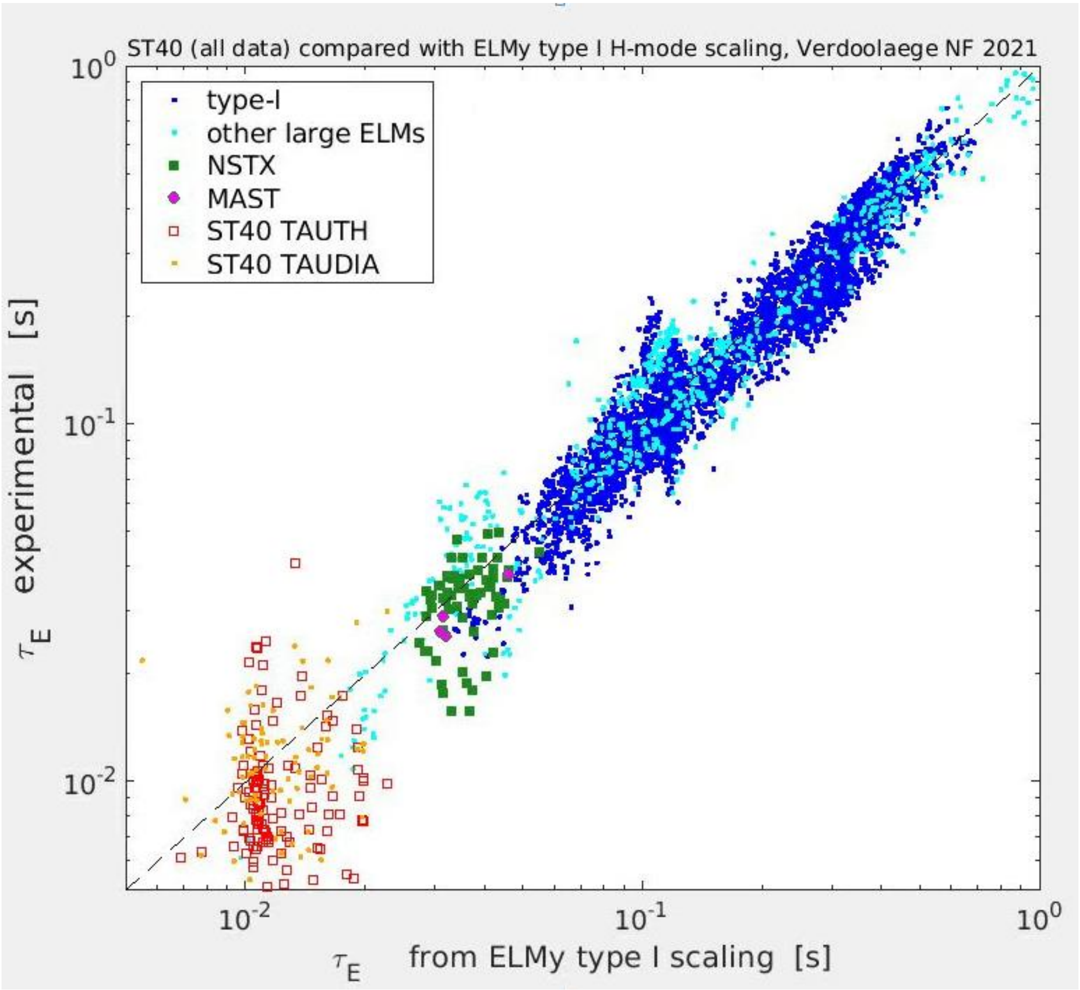
This confirms that ST40 plasmas are dominated by electrostatic turbulence

This is consistent with the relative low beta of the above plasmas

S. Janhunen
M. Anastopoulos, IAEA FEC, 2023

Global Confinement in ST40 Hot ion mode plasmas





H. Weisen

Conclusions

❑ ST40 is the only spherical tokamak operating at B > 2T (towards reactor conditions)

❑ ST40 scenarios have the potential to extend the range of dimensionless parameters of present day STs towards those of a ST reactor (high beta, low collisionality)

❑ Experiments / modelling / theory development are ongoing at Tokamak Energy to confirm the expectation of strong dependence of confinement from B and ν^* in ST power plant grade plasmas.