ST Path to Fusion – new challenges for the theory

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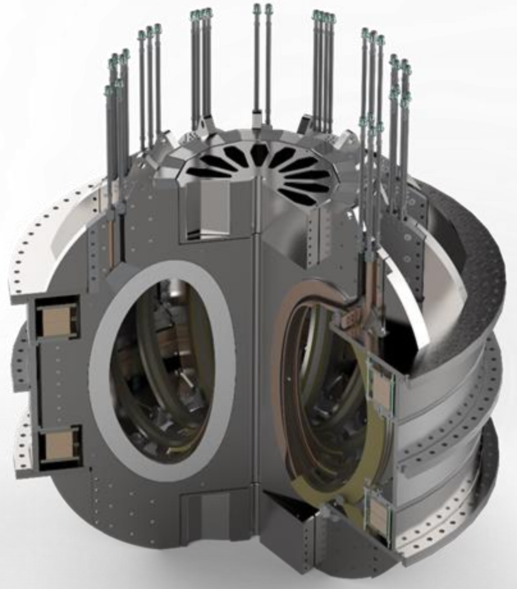
Tokamak Energy Limited

- 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 $250M investment with $50M from UK and US governments
- Team of over 250 and growing fast!
- Operating the ST40 compact high field spherical tokamak
- World leading high temperature superconducting magnet facility

ST-40

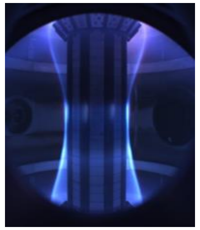


DEMO-4

Roadmap to commercial fusion energy

Prototype devices de-risk and accelerate

ST40



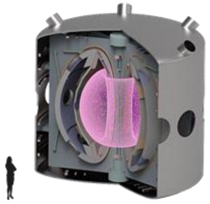
Further validation of ST benefits

HTS

HTS magnet scale up and demonstration of full ST magnet configuration

Advanced Prototype Device

LATE 2020s



- Long pulse plasma
- Proves new technology
- Builds IP

Fusion Pilot Plant

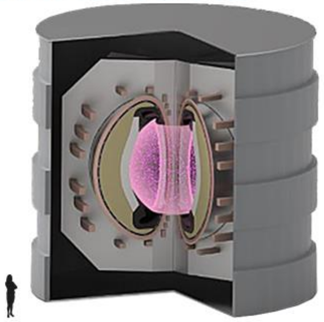
MID 2030s

- Long pulse DT operation required for commercial fusion energy

1st Gen Commercial Plant

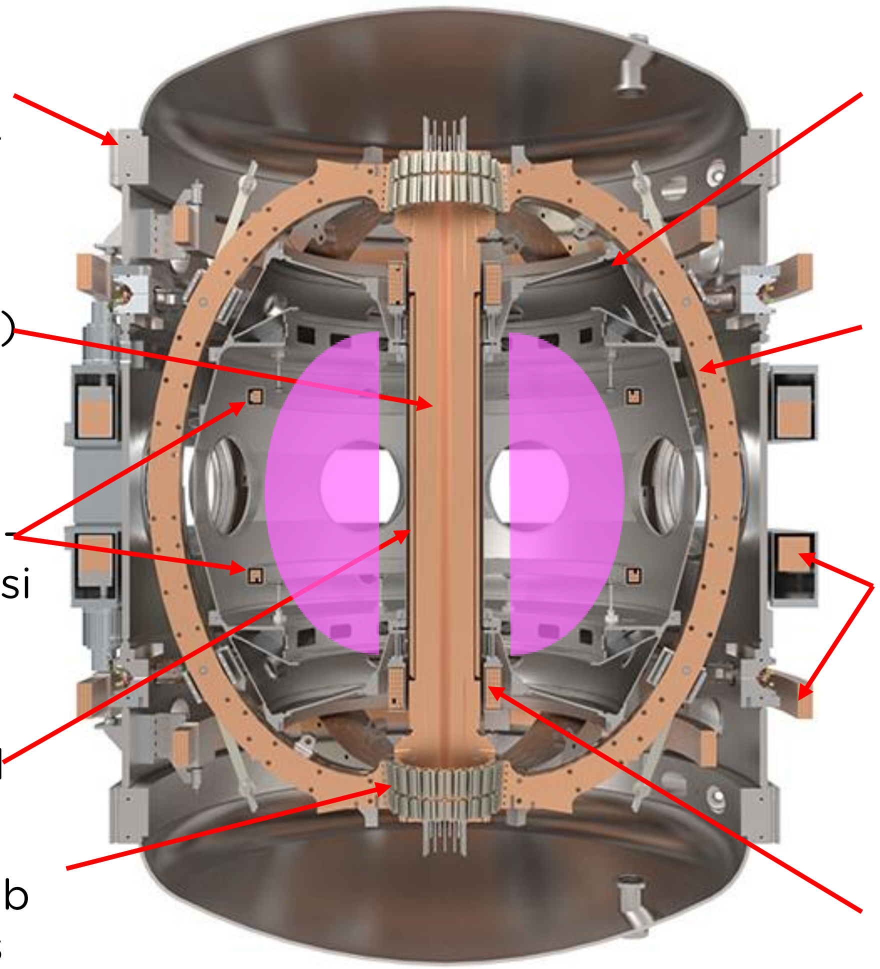
LATE 2030s

COMMERCIAL



- Commercial fusion power plant generating 500 MWe

ST40: Expanding the high field ST physics basis



Outer vacuum chamber

Toroidal Field (TF) coil: centre post

Merging -compression coils

Solenoid

Core-limb TF joints

Inner (plasma) vacuum chamber

TF coils: demountable limb

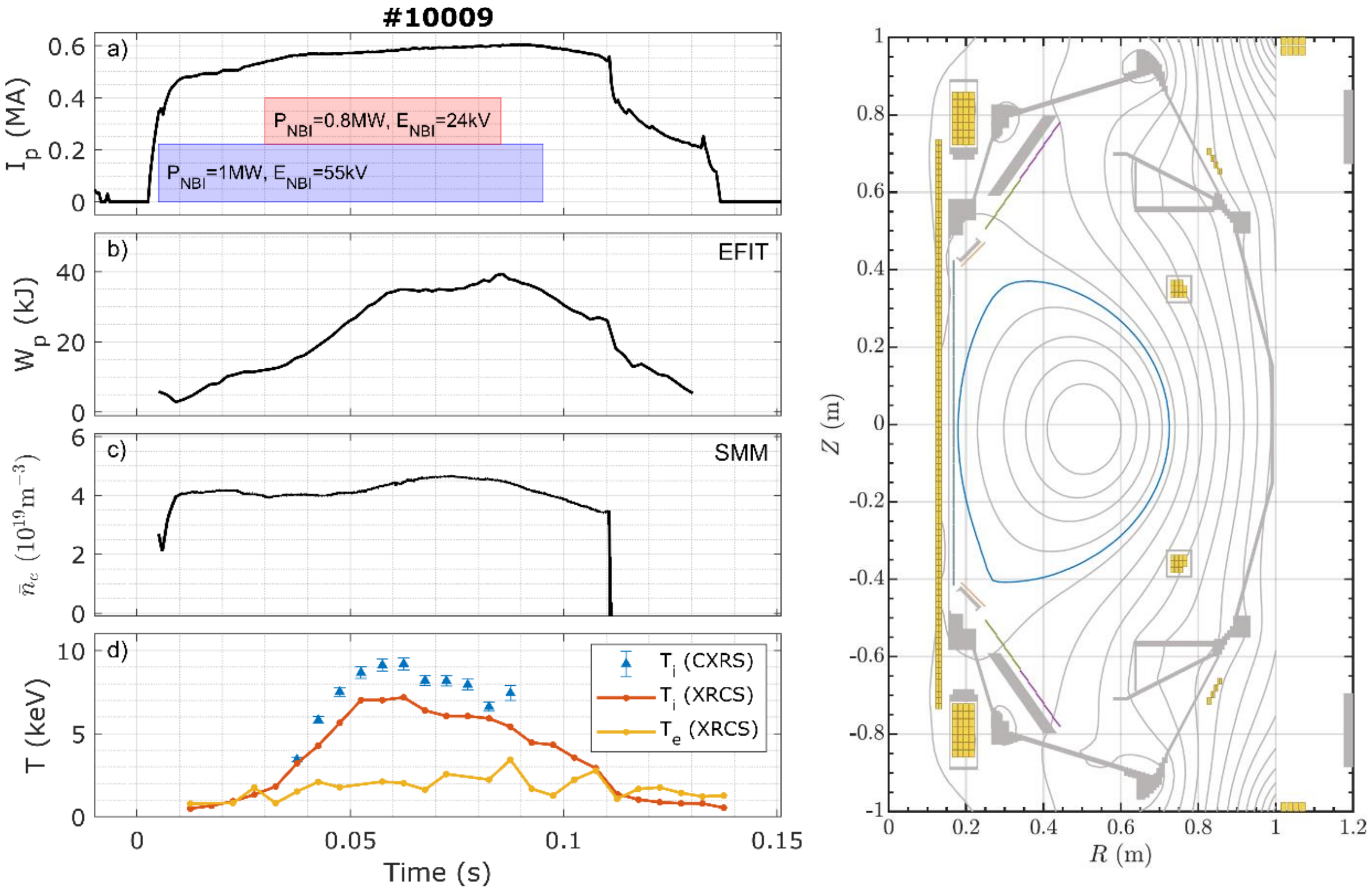
Poloidal Field (PF) coils

Divertor coils

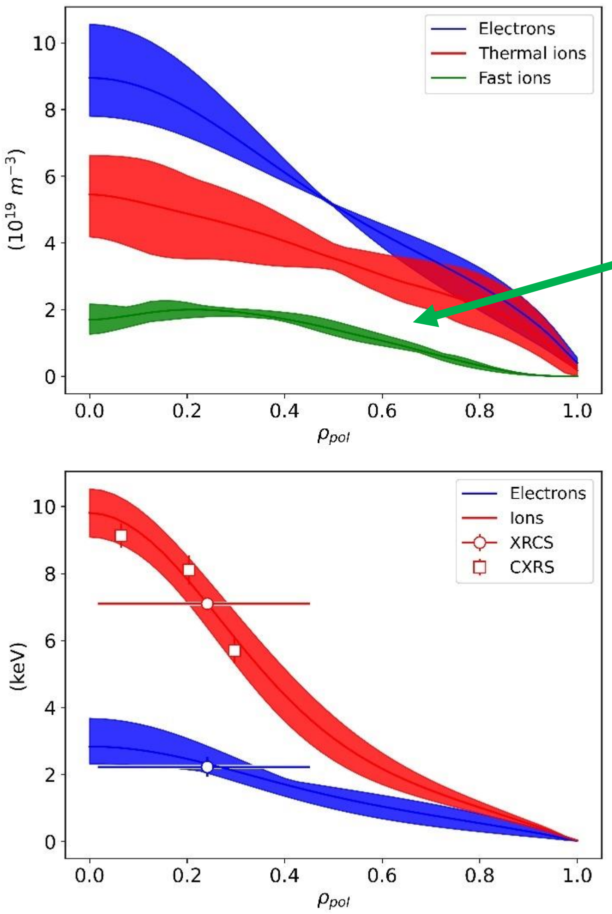
Parameter	Range
Bt [T]	1.5 – 2.2 (3)
Ip [MA]	0.4 – 0.8 (2)
R_{Geo} [cm]	40 – 50
A	1.6 – 1.8
P_{NB}/E_{NB} [MW/kV]	0.8/24, 1.0/55
ψ_{sol} [mWb]	200
Start-up	Merging-compression
Fuel	Hydrogen/Deuterium

- 2 gyrotrons and ICRH considered
- PI for fuelling

Achievement of ion temperatures in 10 keV range, hot ion mode

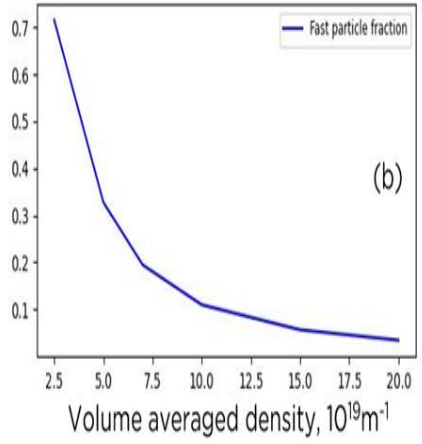


Typical waveforms and EFIT reconstruction for #10009, DD *McNamara et al, NF 2023*



NB!

(top) electron density, ion and fast particle densities, (bot) ion and electron temperature determined using the integrated analysis approach for pulse #10009 at time of maximum ion temperature



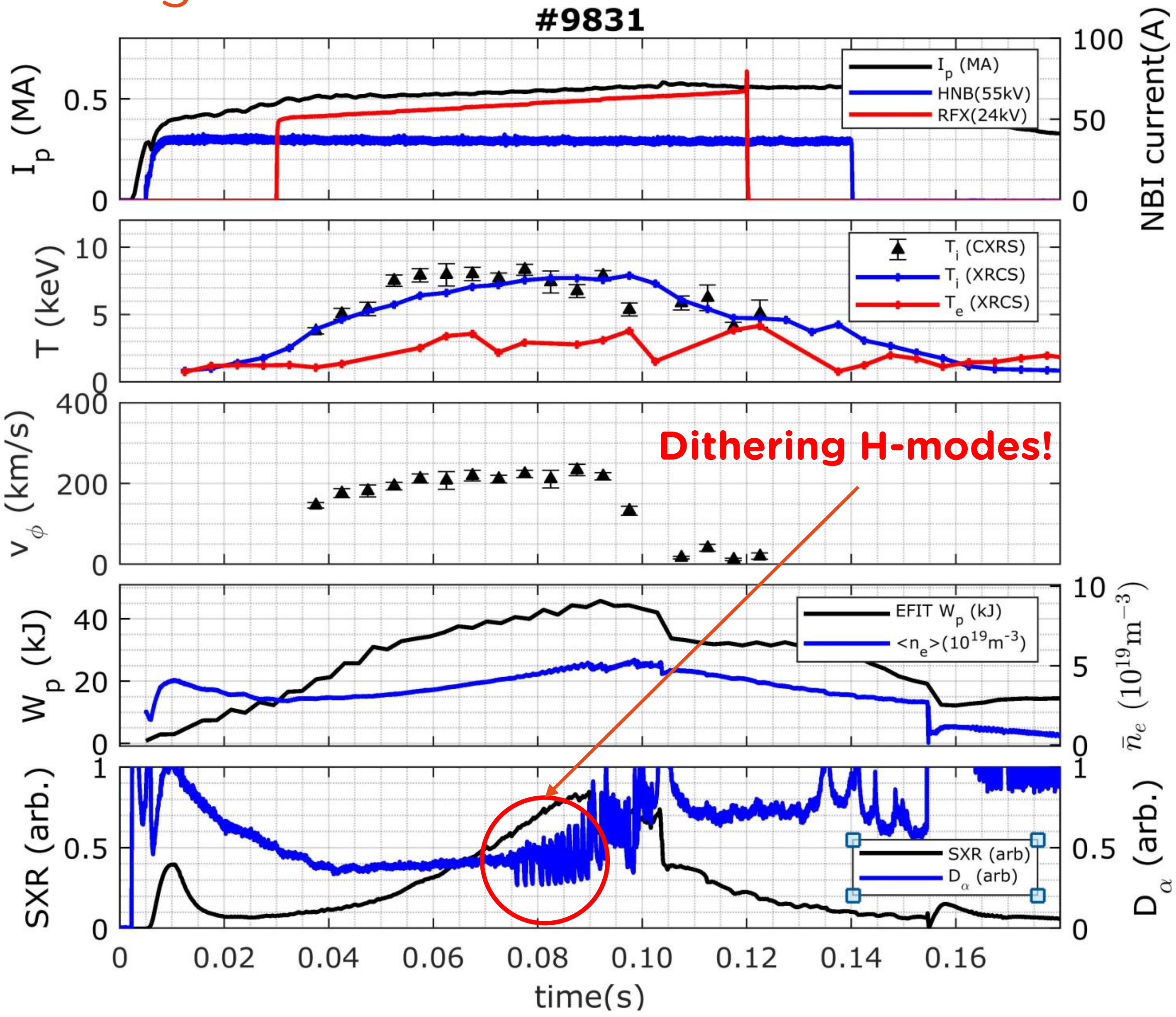
Typical fast particle energy fraction prediction for ST40

$D^0 \Rightarrow D^+$: High temperatures and dithering H-modes

- If target density raised slightly, dithering H-modes observed.
- T_i sustained at ~8keV until 90ms and does not decrease in H-mode
- Density is slightly above the minimum value for H-mode[1] from multi-machine database[2] :

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

- More in M Romanelli, this conference



Dithering H-modes!

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[1] *Y. Andrews et al., Phil. Trans. A, DOI:10.1098/rsta.2021.0225.R2*

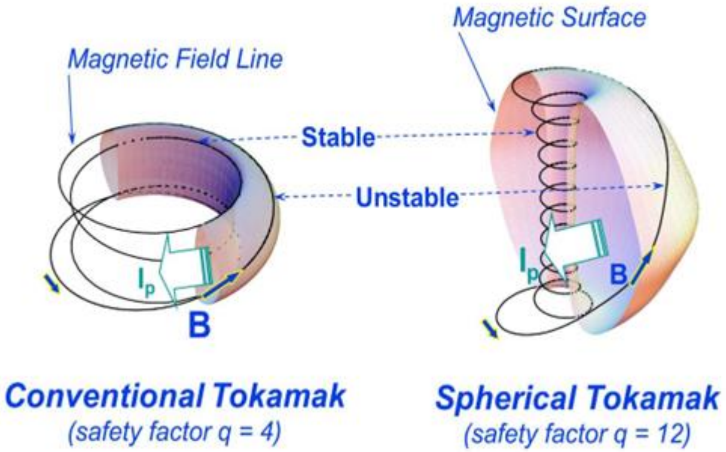
[2] *F. Ryter et al., Nucl. Fus.,**54** 083003*

New challenges for the theory

- Until recently, theoretical studies mostly focused on research in support of **ITER** and on the analysis of plasmas in **existing tokamaks and stellarators** which are typically far from ignition conditions.
- Recent appearance of privately funded Fusion research has advanced **alternative concepts**, in our case the development of high-beta spherical configuration with high magnetic field.
- Simultaneously with the development of technological and experimental research, the privately funded fusion industry is requesting and significantly contributing to the advancement of **theoretical fusion physics in areas specific to proposed concepts**.

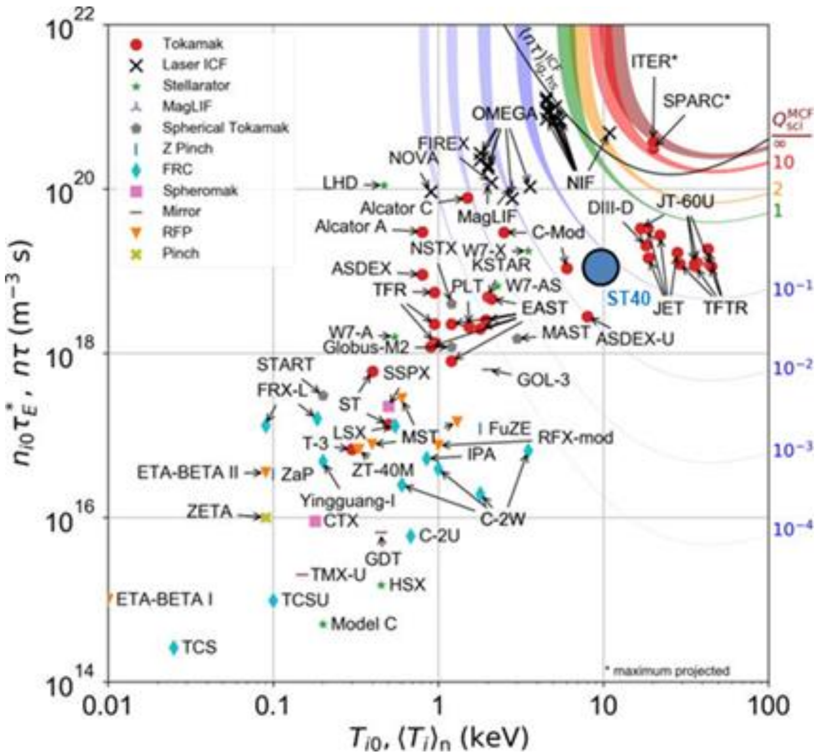
New challenges for the theory

- Although in many aspects physics of **STs** has the same basis/grounds as those in conventional aspect ratio tokamaks, there are certain **specifics** e.g. in areas of macro and micro instabilities, operational limits and disruptions, plasma confinement, neoclassical and turbulent plasma transport, divertor and the edge physics.

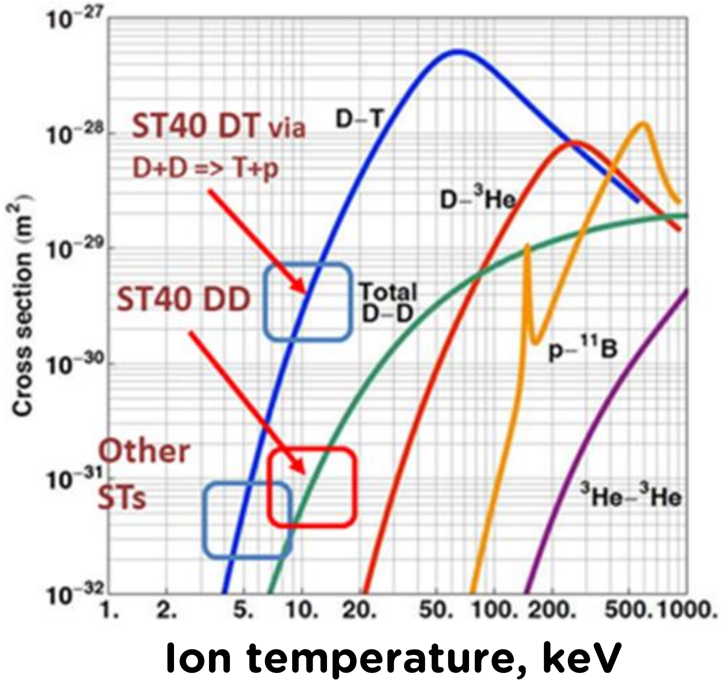


- Another important specifics of our studies is due to ST40 operating with plasma parameters well above previously achieved on STs, like very **low collisionality** and high **ion temperatures close to that required for burning conditions** (~ 10 keV).
- Also, hot ion mode, similar to ITB, has **high** temperature and density **gradients** which may be, or may be not good for micro stability

New challenges for the theory: close to burning plasma conditions



Triple product vs plasma temperature for the number of tokamaks, stellarators, other magnetic fusion devices and inertial fusion.



- All previous STs operated at $T_i < 5$ keV, with DT and DD cross-sections 1 – 2 orders lower than at 10 keV.
- Although ST40 operates without tritium fuelling, high T_i boosts the **secondary D-D reaction** that produces T, and at ~ 10 keV the cross-section of D-T reaction is high enough to contribute to the Fusion production, upper blue box.

New challenges for the theory: close to burning plasma conditions

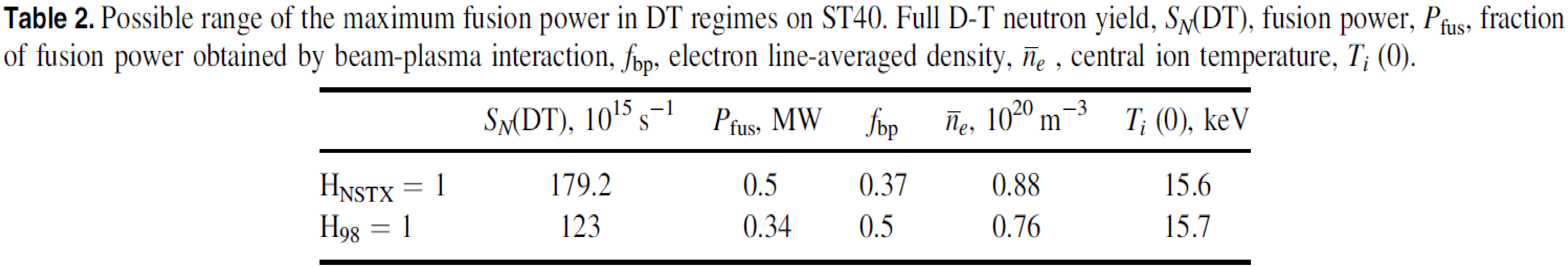


Table 2. Possible range of the maximum fusion power in DT regimes on ST40. Full D-T neutron yield, S_N(DT), fusion power, P_{fus}, fraction of fusion power obtained by beam-plasma interaction, f_{bp}, electron line-averaged density, $\bar{n}_e$, central ion temperature, T_i (0).

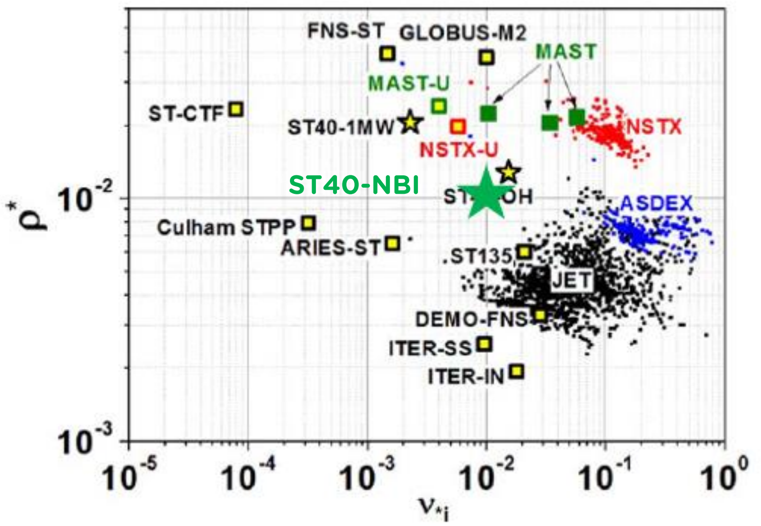
	S_N(DT), 10^{15} s^{-1}	P_{fus}, MW	f_{bp}	$\bar{n}_e$, 10^{20} m^{-3}	T_i (0), keV
$H_{\text{NSTX}} = 1$	179.2	0.5	0.37	0.88	15.6
$H_{98} = 1$	123	0.34	0.5	0.76	15.7

- The maximum fusion power may reach the level of 0.5MW for the NSTX scaling law with 1 MW of D NBI power at the line-averaged electron density $n_e = 0.88\text{x}10^{20}$ m^{-3}, for 3T/2MA ST40 regime, ASTRA-NUBEAM simulations. Similar P_{fus} for ITER IPB (y,2) scaling. *A Yu Dnestrovskij et al 2019 Plasma Phys. Control. Fusion 61 055009*

- $n\ T\ \tau_E \sim 10^{19}$ m^{-3} keVs has been already achieved on ST40 in DD

New challenges for the theory: low collisionality and gyro effects

- An important specifics of our studies is due to **ST40 operating at very low collisionality.** Gyro kinetic simulations show possibility of different, and sometimes non-monotonic behaviour of micro instabilities at decreased collisionality.



- Increase in TF may affect **gyro stabilisation** of some modes.
- Also, hot ion mode has high temperature and density gradients. The first plays destabilising effect (ITG, ETG modes), the second may may be good for **micro and macro stability**.

- All these should affect plasma confinement, neoclassical and turbulent plasma transport, but we don’t see significant performance degradation due to core micro instabilities in the hot ion mode.

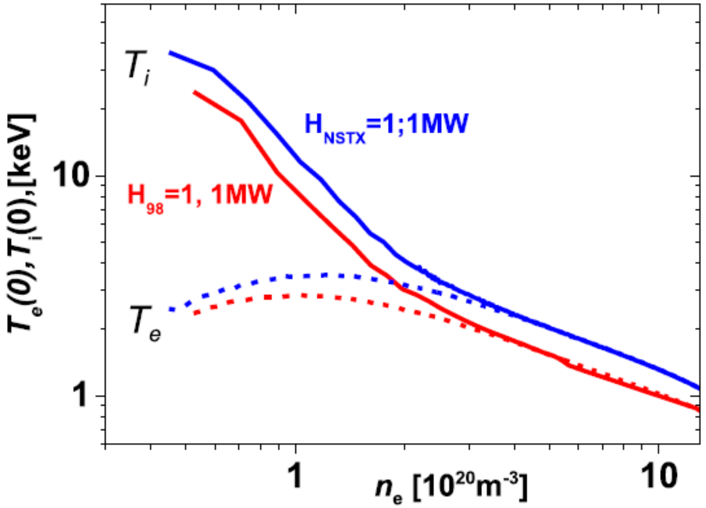
New challenges for the theory: hot ion mode

- Hot ion mode not only is characterised by high gradients in the core, but by flattening of temperature profiles in outer regions. Gradient driven modes may be more stable here and interplay of spatially separated modes may play role.
- Although ST40 may be operating in a low recycling regime, where electron temperature pedestal may raise adding to stabilisation of ETG mode at the periphery, more detailed studies are needed to justify this mechanism.

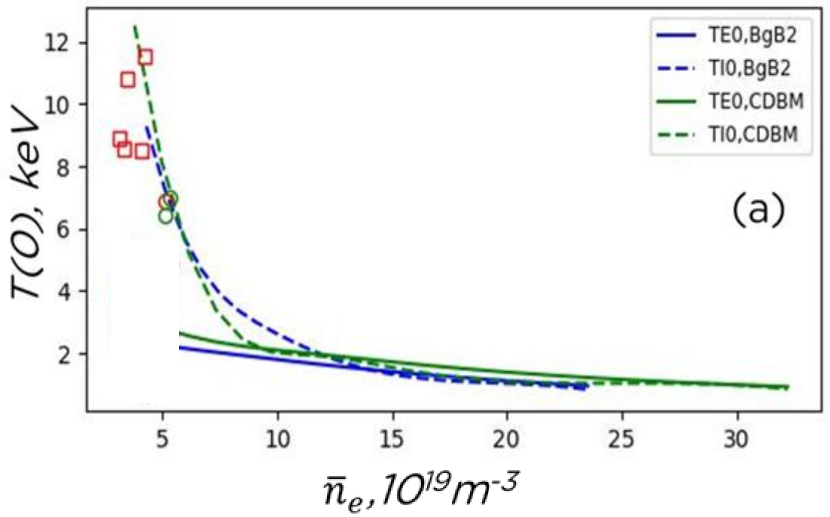
- An important feature of NBI heated ST plasmas is high content of fast ions which helps to sustain hot ion mode (similar to FIRE mode in KSTAR).
- Another effect to consider is possible turbulent driven inward particle pinch that contributes to peaking of the plasma density.

New challenges for the theory: hot ion mode

- Achievement of hot ion mode at low density is not very sensitive to transport models
- The ion temperature can rise significantly above the electron one if the plasma density is not so high as to allow decoupling ions and electrons, and if the ion heat losses are assumed to follow the neoclassical formula.



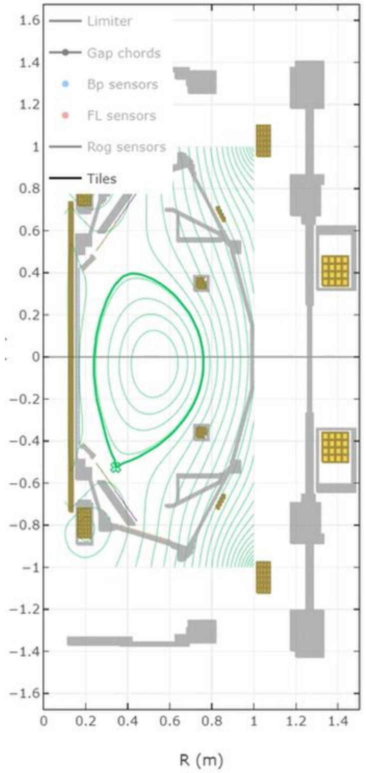
The maximum T_i reaches the level of 13 keV for the NSTX scaling law with **1MW** of D NBI power at the line-averaged electron density $n_e = 0.88\ 10^{20}\ m^{-3}$, for 3T/2MA ST40 regime, ASTRA. Similar T_i for ITER IPB (y,2) scaling.

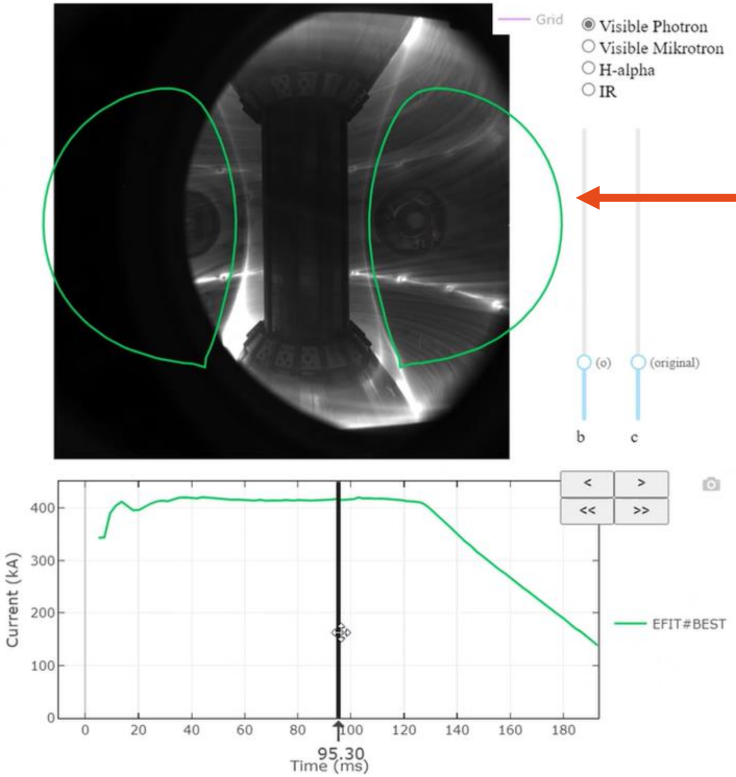


Predictive calculation with BgB (blue), CPTM (green) and CDBM (red) models normalized to the experimental results achieved on ST40.

New challenges for the theory: edge and divertor physics in STs

- In a low recycling hot ion mode edge profiles are different to an H-mode
- Some STs show different scrape of layers to a conventionally observed (Globus-M) and edge studies have priority in the ST40 experimental programme.

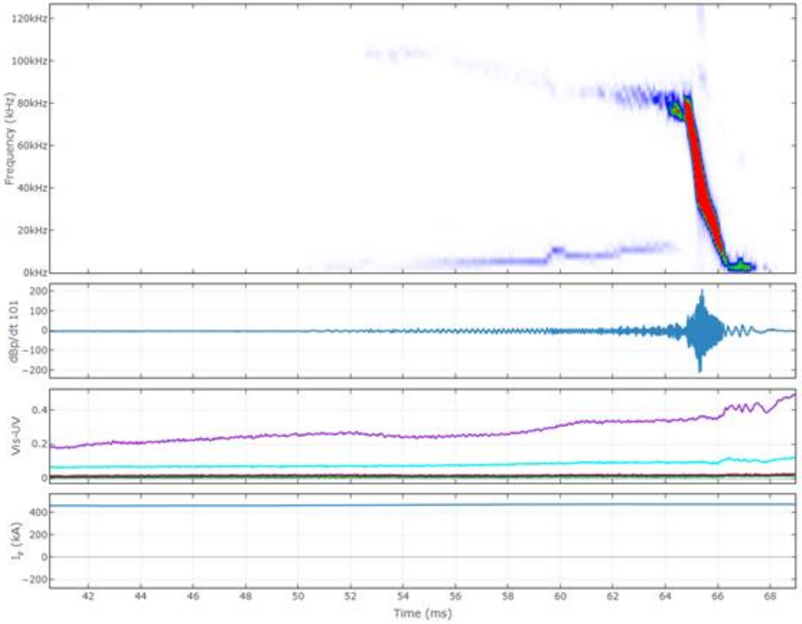




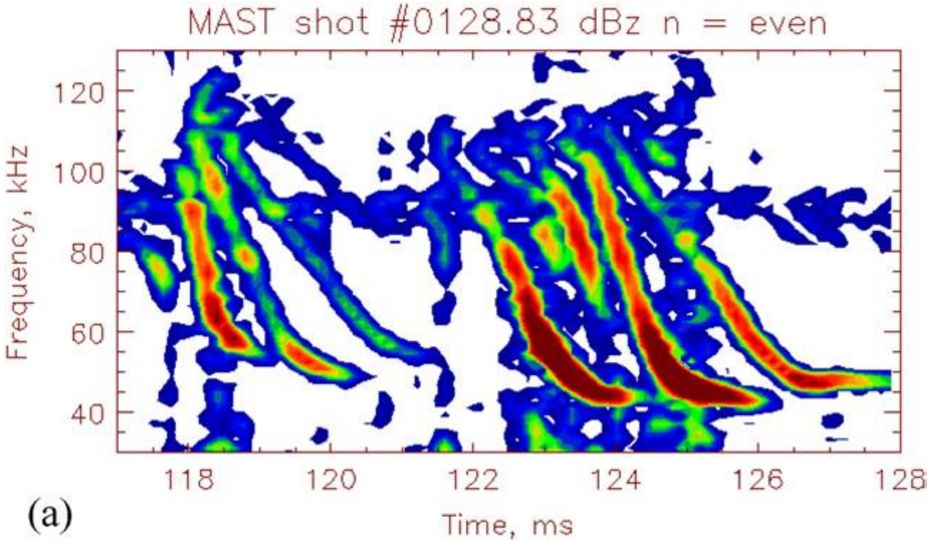
- Due to vertical drifts, disconnected DND configuration may give advantages for more equal divertor loads (as demonstrated on Globus-M
- What are specifics of these in STs?

New challenges for the theory: MHD, fast particles

- Close to no-wall limit, beta collapse events, but no NTMs ?
- Long chirping modes go down to very low frequency



2/1 chirping mode, starting f ~ 80 kHz, electron direction (anticlockwise), preceded by TAE f ~ 105 kHz

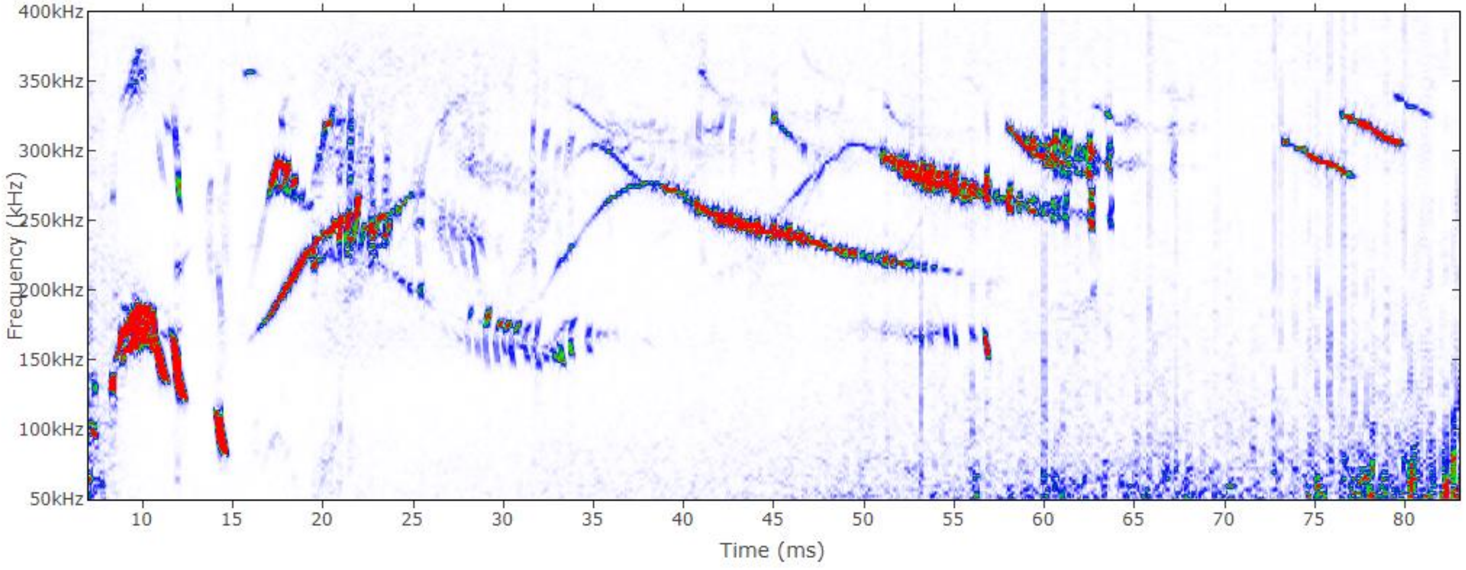


On MAST such modes never locked

New challenges for the theory: MHD, fast particles

- ST40 uses merging-compression plasma formation when two plasma rings formed around in-vessel coils merge and final plasma heats due to reconnection heating
- ACs after m/c – evidence of reversed shear?
- New type of ACs evolving into TAEs?

#11523



“Zoo of AEs” Also, multiple ACs of different types

ST40: Expanding the high field ST physics basis. Recent publications

Bland, James; et al. *Interplay between beam-driven chirping modes and plasma confinement transitions in spherical tokamak ST40*. Nuclear Fusion NF-105643.R2 2022

Y Andrew et al. *H-Mode Dithering Phase Studies*. Phil Trans Article 2022

M Gryaznevich et al. *First observations of AEs in a high field ST*. IAEA TM on EPs, November 2022

V. N. Duarte, et al. *Perturbative analysis of low-frequency instabilities in high-field ST40 experiments*. NF 2022

A Nicolai, M. Gryaznevich. *Modelling of the Neutral Gas and Plasma Transport in the scrape- off layer and divertor of ST40-Tokamak*. EPS 2022

Buxton, P. F., et al, *On the energy confinement time in spherical tokamaks: implications for the design of pilot plants and fusion reactors.* Plasma Physics and Controlled Fusion, 61(3), 035006. 2019

M Gryaznevich, et al. *Theoretical and experimental studies of confinement in high field ST*. Presentation at 18th European Fusion Theory Conference, October 7—10, 2019 Ghent, Belgium. O-07

A Nicolai, M. Gryaznevich. *Modelling of Merging-Compression Formation of High Temperature Tokamak Plasmas*. The 46th European Physical Society Conference on Plasma Physics, July 8-12 2019, Milano.

A Yu Dnestrovskij, J M Connor, M P Gryaznevich. *On the confinement modelling of a high field spherical tokamak ST40*. Plasma Phys. Control. Fusion 61 (2019) 055009

A Nicolai1, M. Gryaznevich. α *- Particle and NBI - Ion Deposition in a Compact Spherical Tokamak due to Slowing Down.* The 45th EPS Conference on Plasma Physics, July 2nd-6th 2018, Prague. P1.1001

A Salmi, M Gryaznevich, P.Buxton, M Nightingale, T Tala. *Neutral beam alignment optimisation for the spherical tokamak ST40*. Fusion Engineering and Design 117 (2017) 14–19

P Buxton, M Gryaznevich, Tokamak Energy Ltd. Team. *Merging compression start-up predictions for ST40.* Fusion Engineering and Design 123 (2017) 551

TE.Ltd is very interested in and opened for collaborations

In EU we have collaboration with

RFX Padova (Neutral beam on loan)

University of Tuscia (1 PhD student funded by TE)

University of Aalto (1 Master student)
Technical University of Munich (1 Master student)
DTU – NORTH tokamak and RF studies
University of Eindhoven, Holland
University of Seville

In UK

University of Oxford (1 PhD student funded by TE)
University of Cambridge (2 PhD students and 1 post doc funded by TE)
University of York (1 PhD student working on TE problems)
Imperial College of London (1 PhD student funded by TE)

Extensive collaborations with PPPL, ORNL, GA etc

Collaboration with University of Tokyo, with QUEST and other institutions

Collaboration with Khalifa University of Science and Technology, UAE

Collaboration with University of Seoul

CONCLUSIONS

- To support advances in the privately funded Fusion research, theoretical fusion physics studies should be carried on in areas specific to proposed concepts.
- TE.Ltd develops ST path to Fusion. Important specifics of our present studies is due to ST40 operating with plasma parameters well above previously achieved on STs, like very low collisionality and high ion temperatures close to that required for burning conditions.
- Benchmarking of the theory in necessary to predict performance of the next step devices on our path to Fusion.