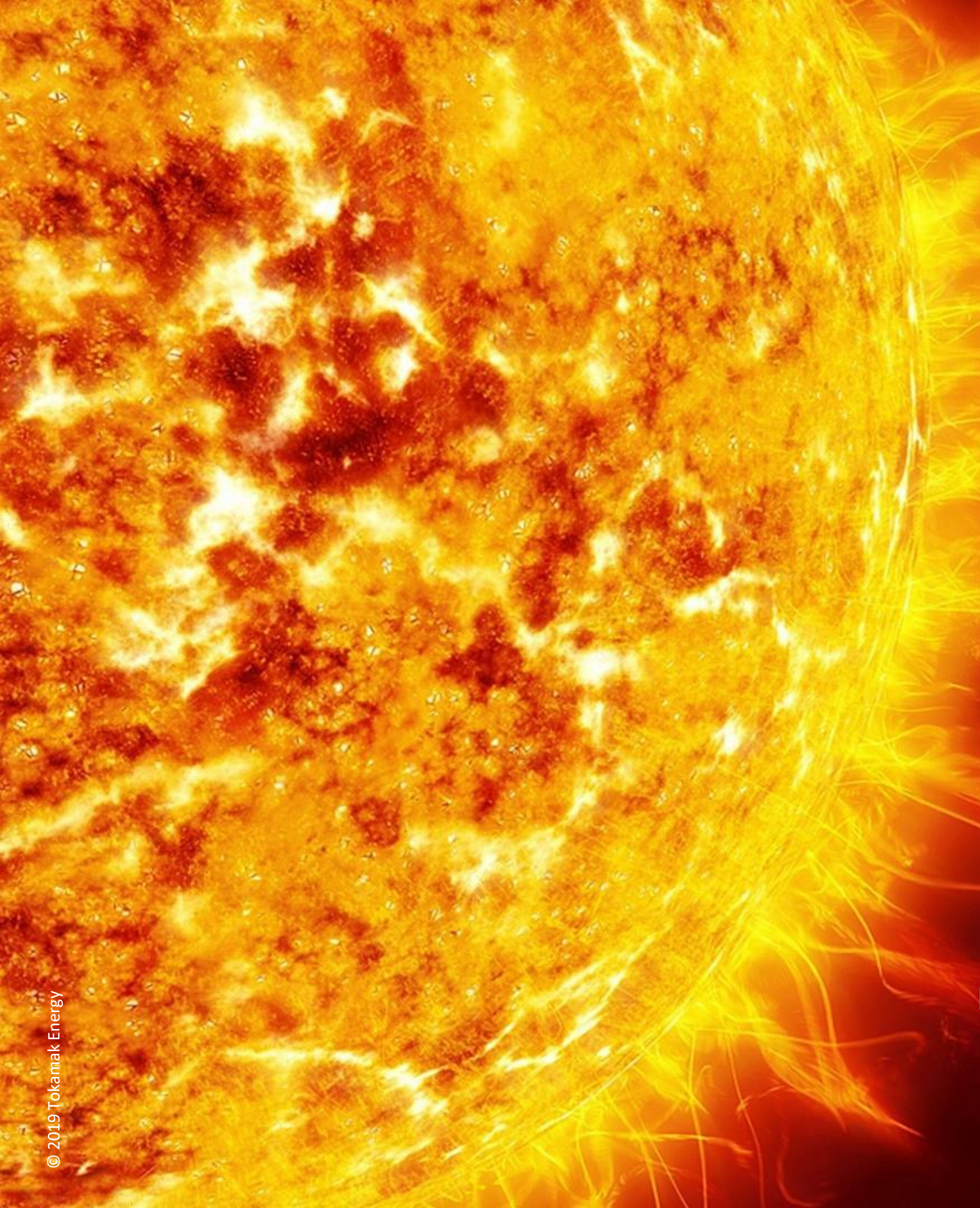

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Faster Fusion: ST40, engineering, commissioning, first results

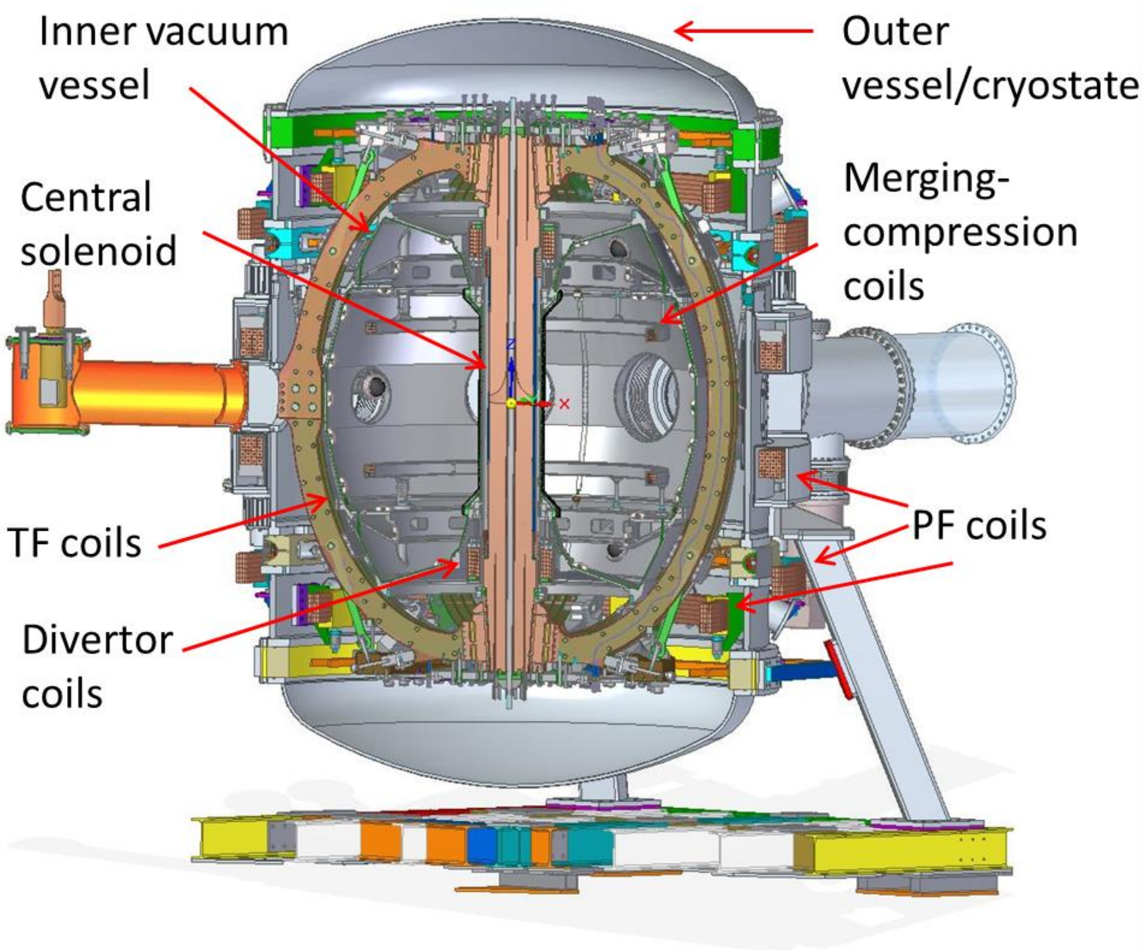
M Gryaznevich and Tokamak Energy Ltd. Physics Team

P Thomas, S McNamara, PF Buxton, O Asunta, V Shevchenko, JM Wood, J Komppula, V Nemytov, A Rengle, J Connor, VA Chuyanov, J Olsen, A Nicolai, A Salmi, H Tanabe, Y Ono, A Dnestrovskij

Presentation at 20th ISTW-2019, 29 Oct 2019, ENEA Frascati

ST40 – High field ST

- B_t =3T (1.5T achieved), I_p =2MA (>0.4 MA achieved),
- R_0 =0.4-0.6m, R/a=1.6-1.8 κ=2.5 (k<1.5 at present)
- Solenoid-free or solenoid-assisted start-up using merging-compression
- >4MW of auxiliary heating (NBI / ECRH)
- Pulse flattop length 1 – 2 s, 1s at full TF (pulse duration ~200 ms now)



Diagnostics available in Phase0, 2018

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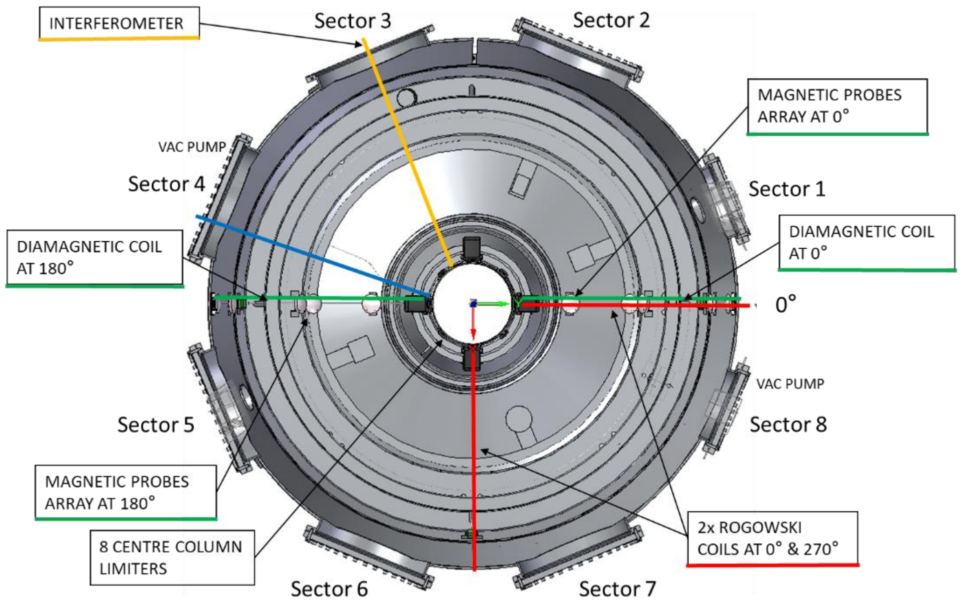

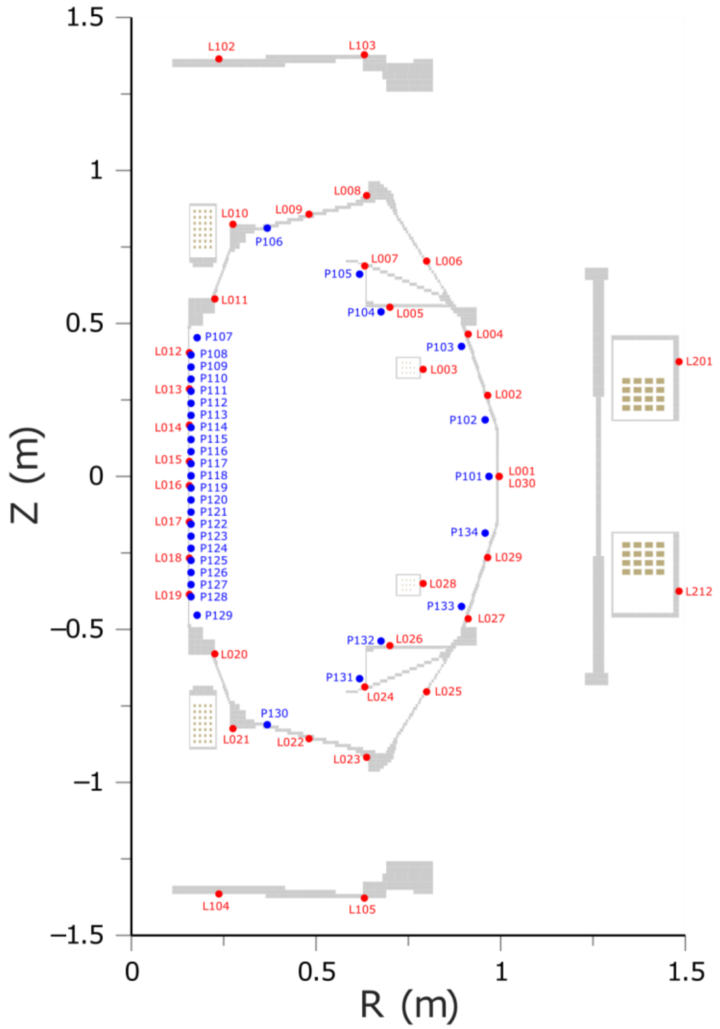

- Fast monochrome camera
- Spectrometer (200-700nm), line diodes
- Magnetics: Bp-probes, flux loops, Rogowski coils, diamagnetic loops
- NIR interferometer, ECE radiometer

ST40 Summer 2019

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Diagnostic Neutral Beam Injector (DNBI)
0.15 MW 50 keV, 1 s

NIR Retro-reflector

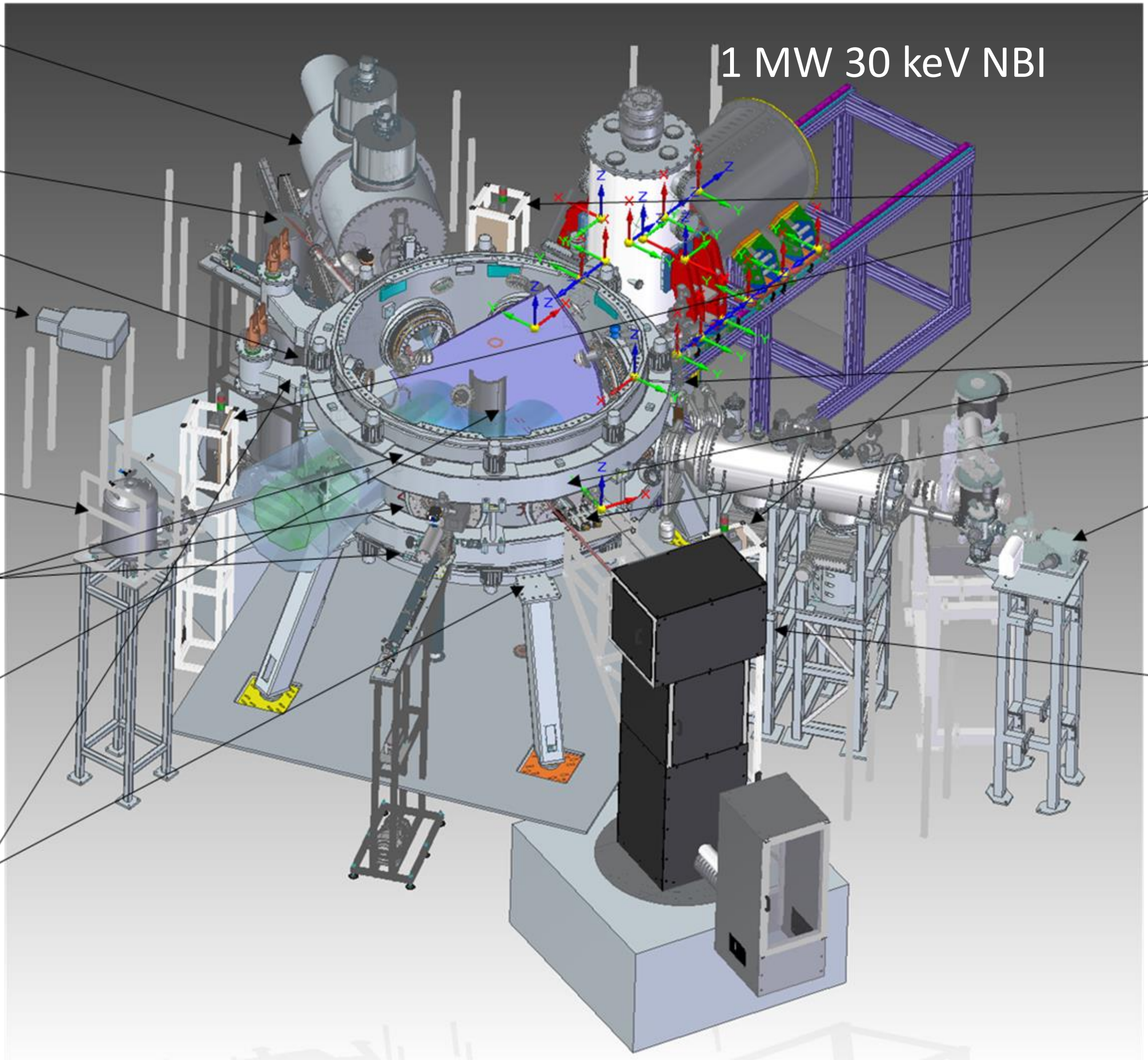
UV/Visible Doppler (Avantes) (Princeton) Spectrometers

Soft X-ray (Canberra) Spectrometer

Foil Filtered Soft X-ray Linear Arrays/Cameras

Panoramic (Ocean) Spectrometer

Line Emission Monitors



Hard X-ray & Gamma Detectors

Fast Visible & H-alpha Cameras

Infrared Camera

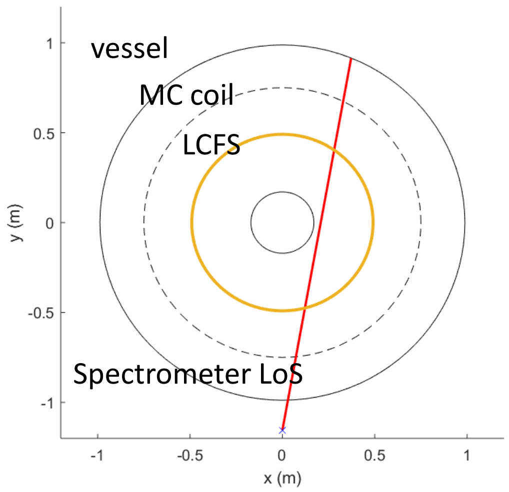
Neutral Particle Analyser (NPA)

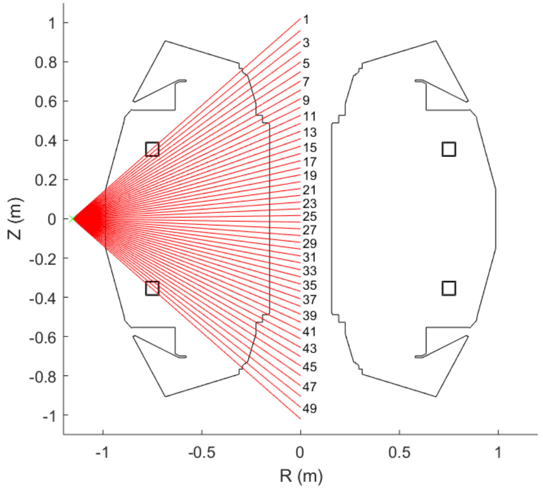
Vibration Isolated Diagnostic Tower provides support for:

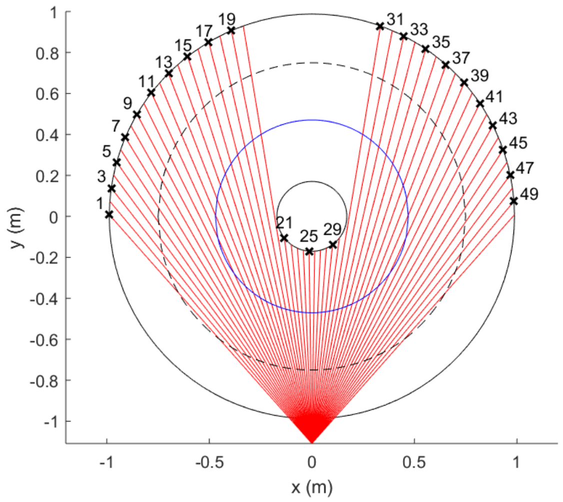
- SMM Interferometer
- NIR Interferometer
- ECE Radiometer

Ion temperature measurements

- Ion Doppler broadening: visible/near-UV spectrometer
- 50 chords: vertical/horizontal and radial/tangential alignments to rule out effect of rotation
- Experiments w/ various lines: CIII (464.74nm), CV (227.09nm), BIV (282.16nm). Mostly CV used in 2018. CVI (529.05nm), used in 2019
- DNBI 50kV 150 kW 1 sec installed, under commissioning
- Cristal spectrometer installed







X-ray diagnostics, 2019

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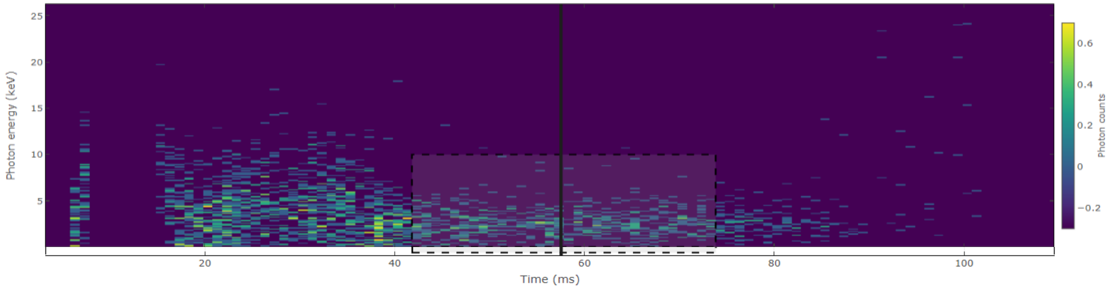
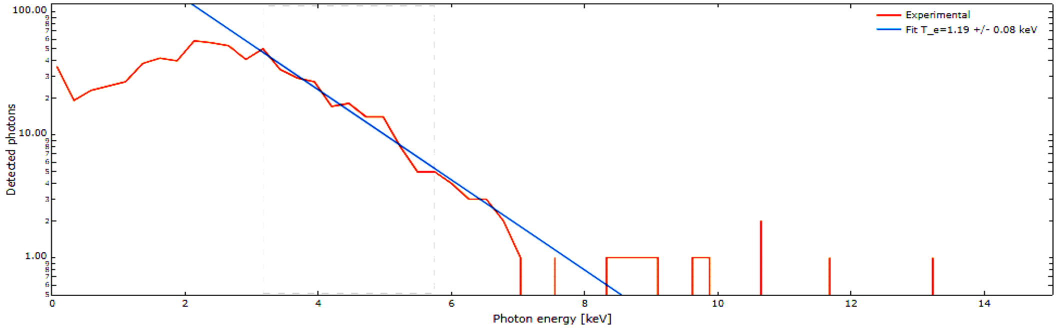
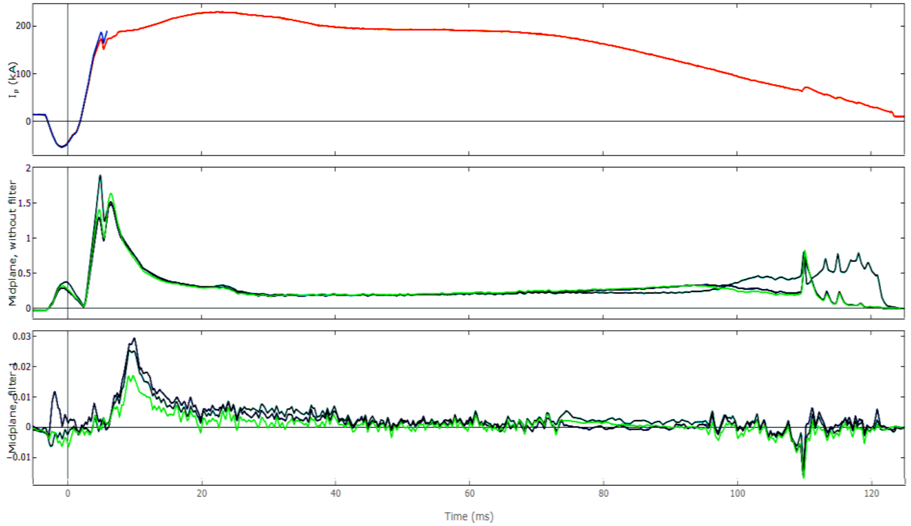
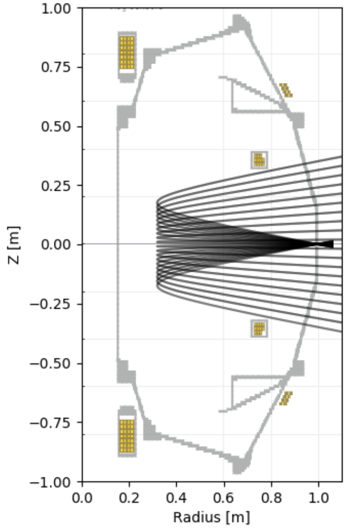
- Temporal X-ray spectroscopy
  - Si(Li) detector
  - Up to 200k photons per second





- SXR diode arrays
  - 3 heads
    - 4 filters for different X-ray energies
    - 20 channels per photo diode

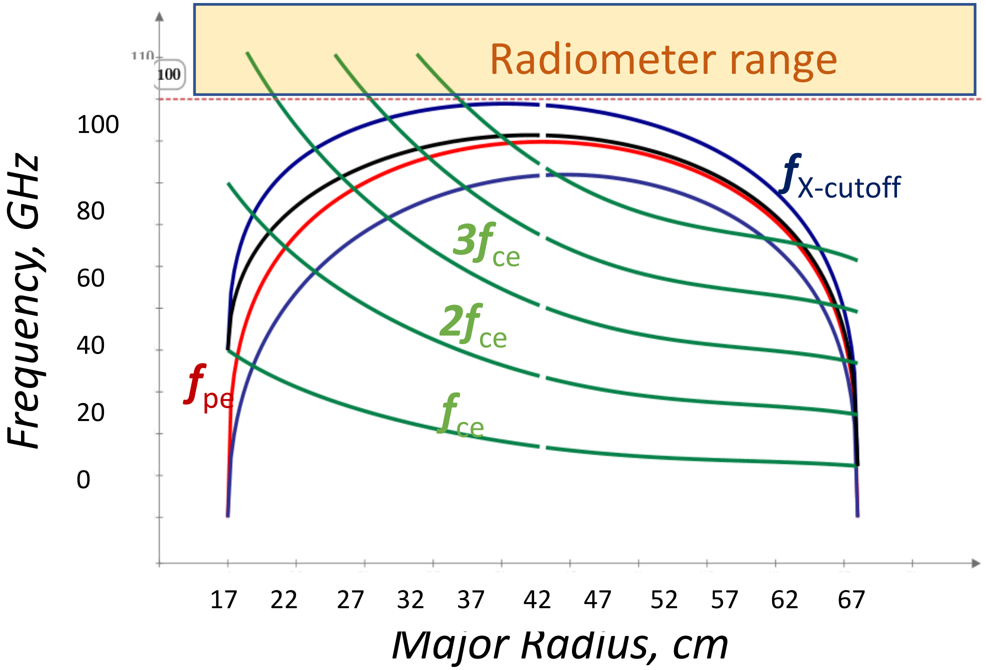




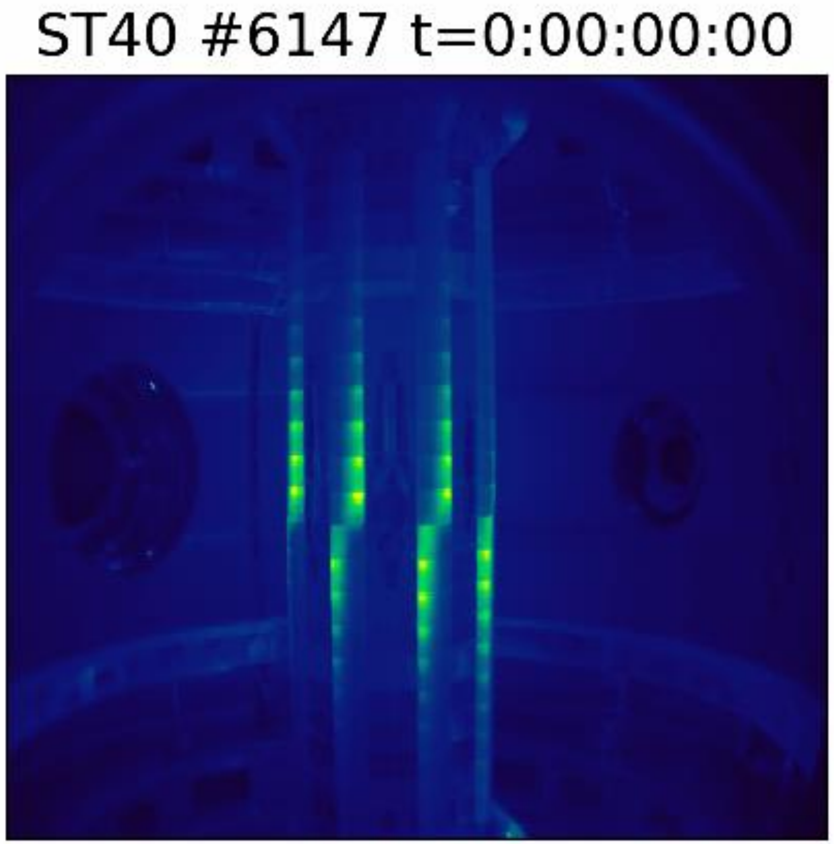
Density measurements

- NIR interferometer: line averaged densities 10^{20} m^{-3}
- 325 GHz interferometer
- ECE radiometer: n_e regularly above 10^{20} m^{-3} because 3rd harmonic signal (100GHz) is cut off

Midplane cross-section of plasma cut-offs and resonances for majority of ST40 first operations: $n_e = 10^{20}$ m^{-3}, I_{TF} = 50 kA ($B_{t,0}$=0.6 T)



Infra red camera



- Infra red camera shows load on the central post

Phase0, 2018

Goals of Phase0:

1. Scenario development, to find best target for solenoid and beam heating scenarios
2. Check/confirm m/c scaling (can we get 100M from m/c?)
3. Check/confirm performance improvement with TF
4. Check/confirm performance improvement with Li

Main findings:

- It was possible, qualitively, to confirm both reconnection and confinement scalings.

  - Flat-top ion temperature increases with TF.

  - Reconnection ion temperature does not depend on TF but strongly depends on MC current and plasma current (e.g. on reconnection field).

- No apparent increase of T_i with Li conditioning, however up to 30% increase in plasma current was observed.

Main results from Phase0, 2018

Main achievements of Phase0:

- Maximum plasma current on ST40 is 400kA, shot 5347. This is higher than ever achieved on MAST w/o use of solenoid, due to **higher TF and reconnection field**.
- Maximum ion temperature from merging-compression is **2114 ±340eV**, measured using BIV line, shot 5178 (50kA in TF, 0.34 T). Overall there are 13 "trusted", e.g. no MHD etc, shots with temperature over 1keV, where we had full set of data. Highest T_i on MAST was 1.2keV.
- Highest TF >1T (and the record for STs) at R_{geo} was achieved in several pulses.

Test of confinement scalings

List of most interesting pulses, TF scan

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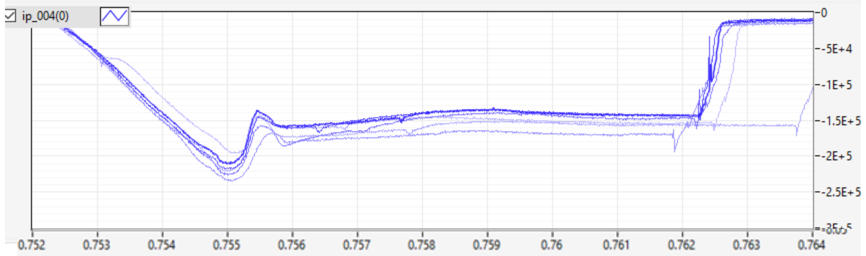
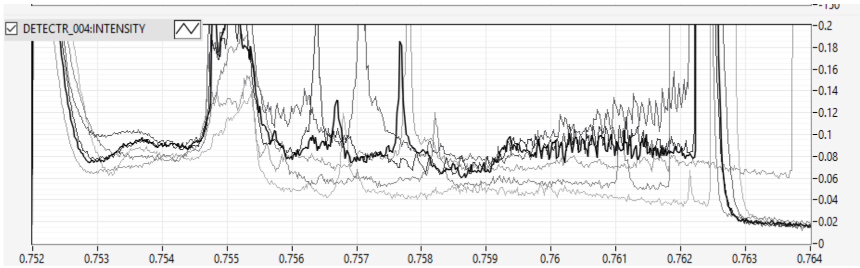
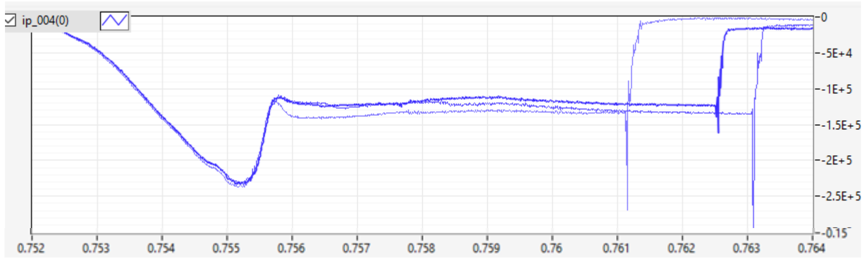
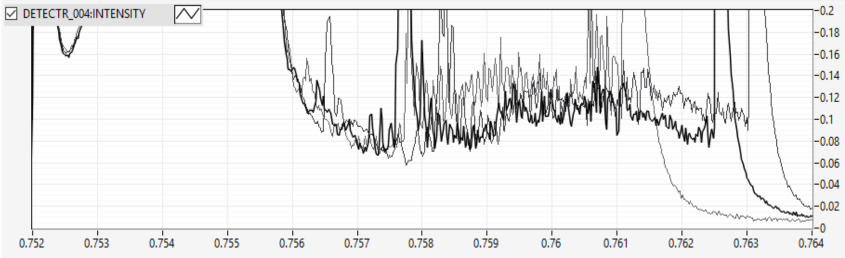
P3 7 kV: gas 6.8ms, BVL 8kV, 4669, 4764. gas 12.8ms, BVL 8kV, **5041, 5103**. gas 16.8ms, BVL 8kV, 4678, 5093



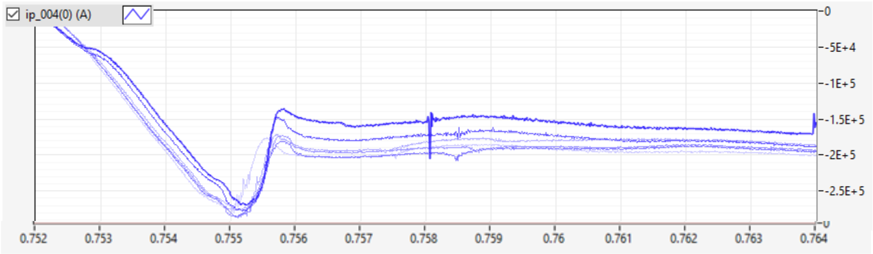


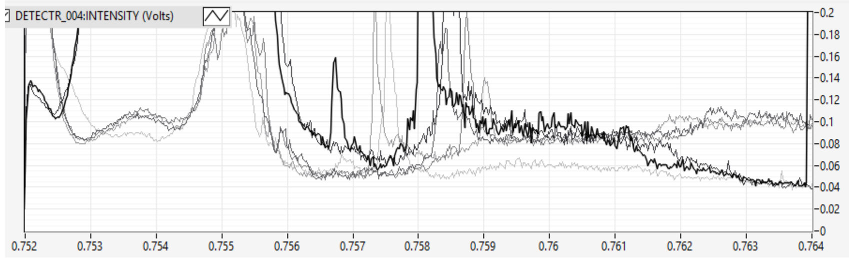
P3 8 kV: gas 12.8ms, BVL 7kV, **5260, 5257, 5254**. gas 15.6ms, BVL 8kV, **5161, 5162** (MC 8.5kV)





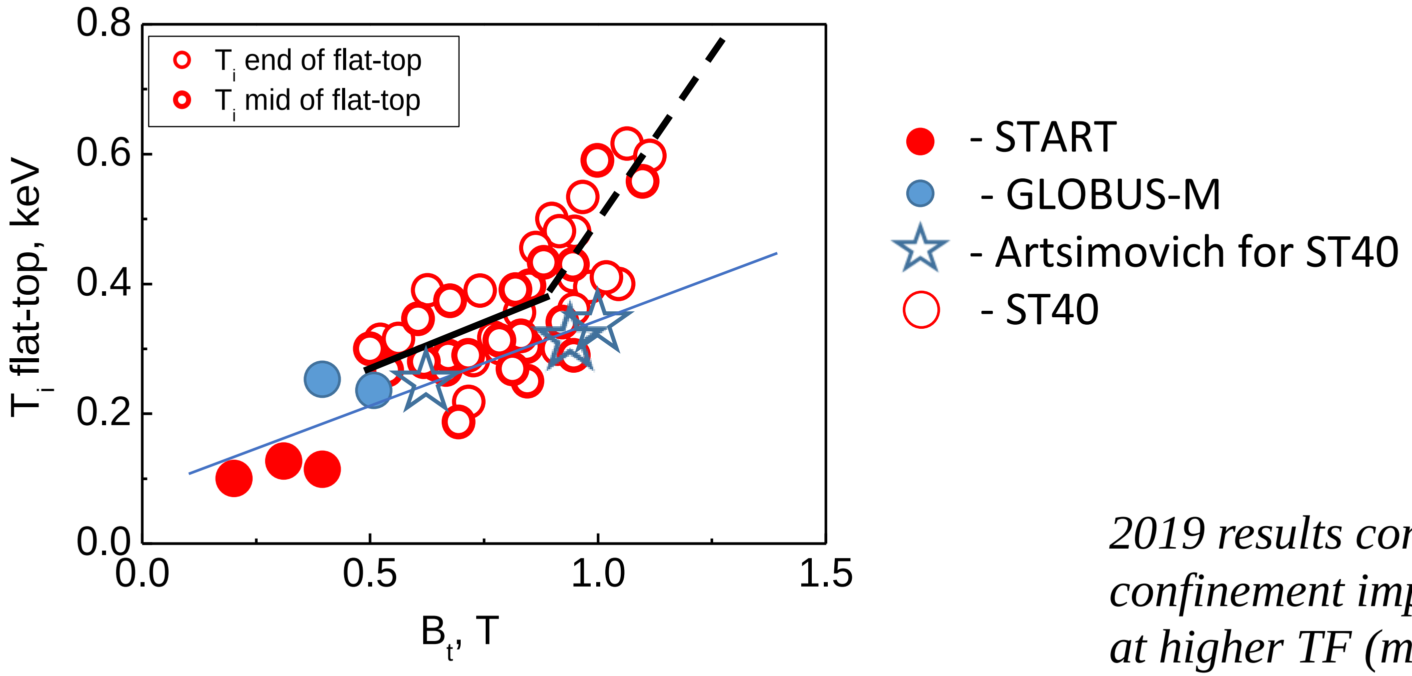
P3 9 kV: gas 8ms, BVL 8kV, 5351, 5356. gas 16.8-20.8ms, BVL 8kV, 5152, 5154, 5156, 5159, 5160, 5162

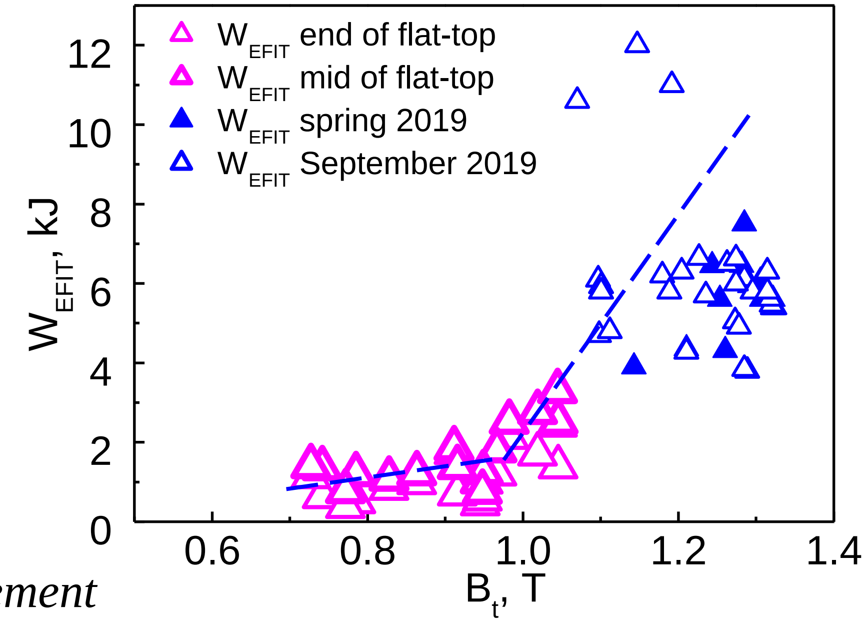




Confinement studies, Phase0 experiment

- At the flat-top, measured T_i and W_{therm} increase with B_t, in agreement with START and Globus-M data and also with Artsimovich formula.
- However, at B_t ~ 1T we observe sharp increase in T_i and W_{therm} which may suggest transition to better confinement at higher toroidal field.

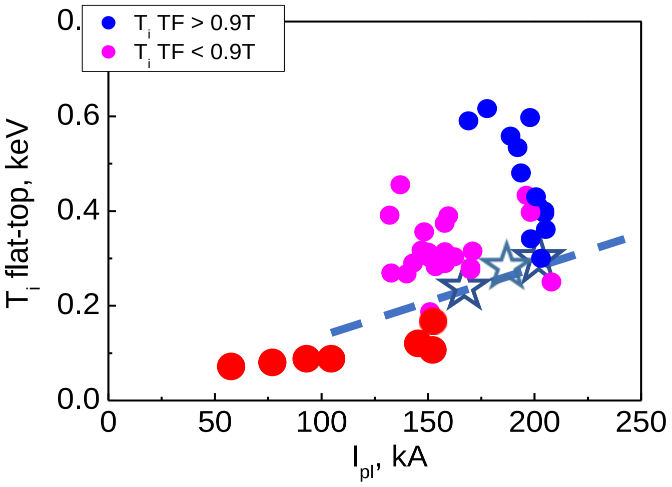




2019 results confirm confinement improvement at higher TF (more later)

Comparison of W_{dia} and W_{EFIT} with T_i

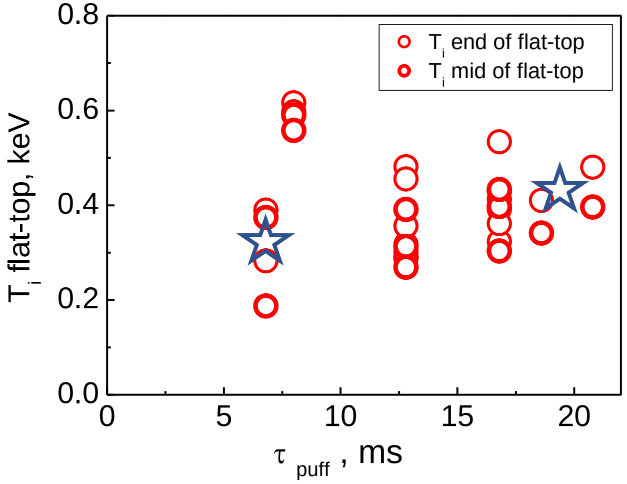
- Some dependence on plasma current and gas (density)

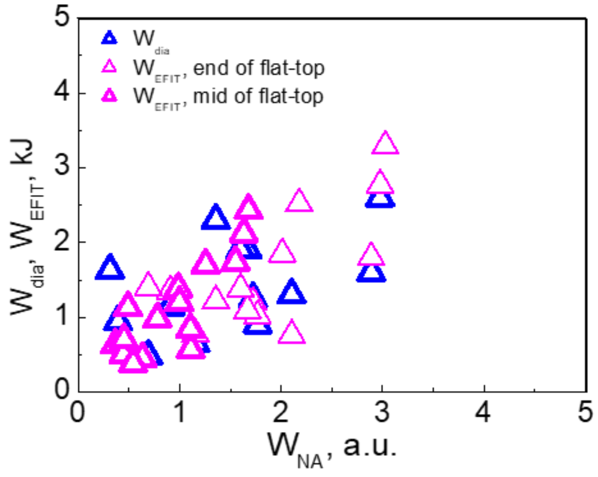


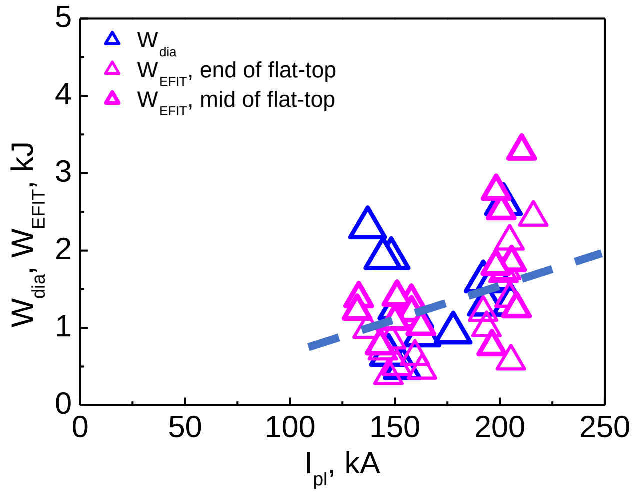
- START

- - GLOBUS-M

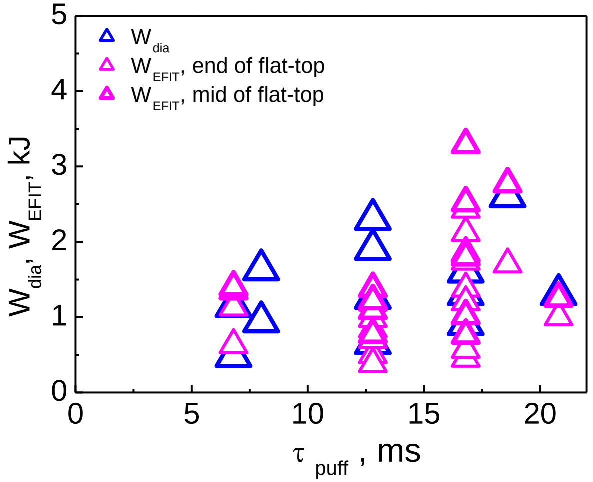
☆ - Artsimovich for ST40







GLOBUS-M



Comparison of W_{EFIT} and W_{dia} with neoAlcator scaling (more later)

$\tau_E^{NA}=0.07 \times \kappa^{0.5} n_e a R^2 q_{95}$

$W_{NA} \sim a\, R^2\, n_e\, q_{95}$

Confinement studies, comparison with scalings

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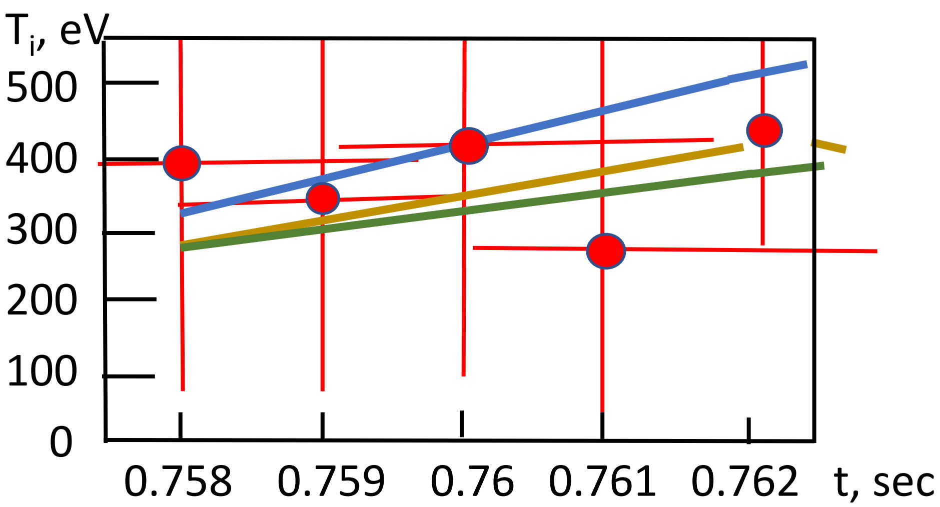
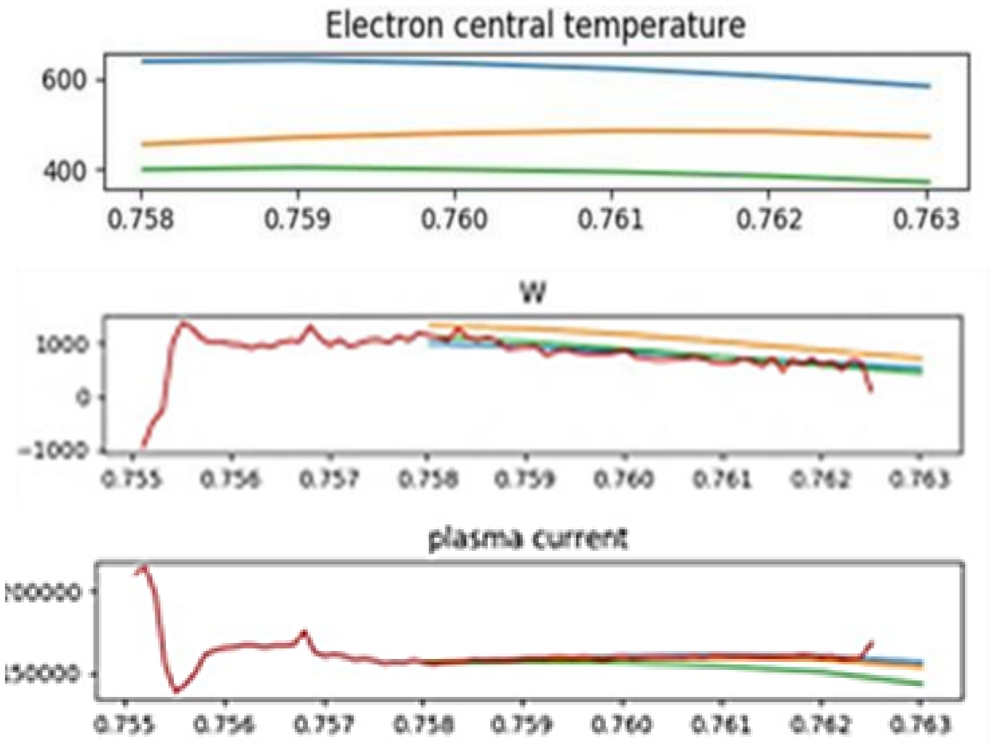
- ASTRA modelling, #4669: Ions neoclassical, electrons fit to get different Hoh=TauE/TauE_NeoAlcator
- blue – n_e = 4 x 10^{19} Hoh=3; yellow – n_e = 7 x 10^{19} Hoh=2; green – n_e = 7 x 10^{19} Hoh=1.4. red line – EFIT, red crosses – T_i from Doppler;



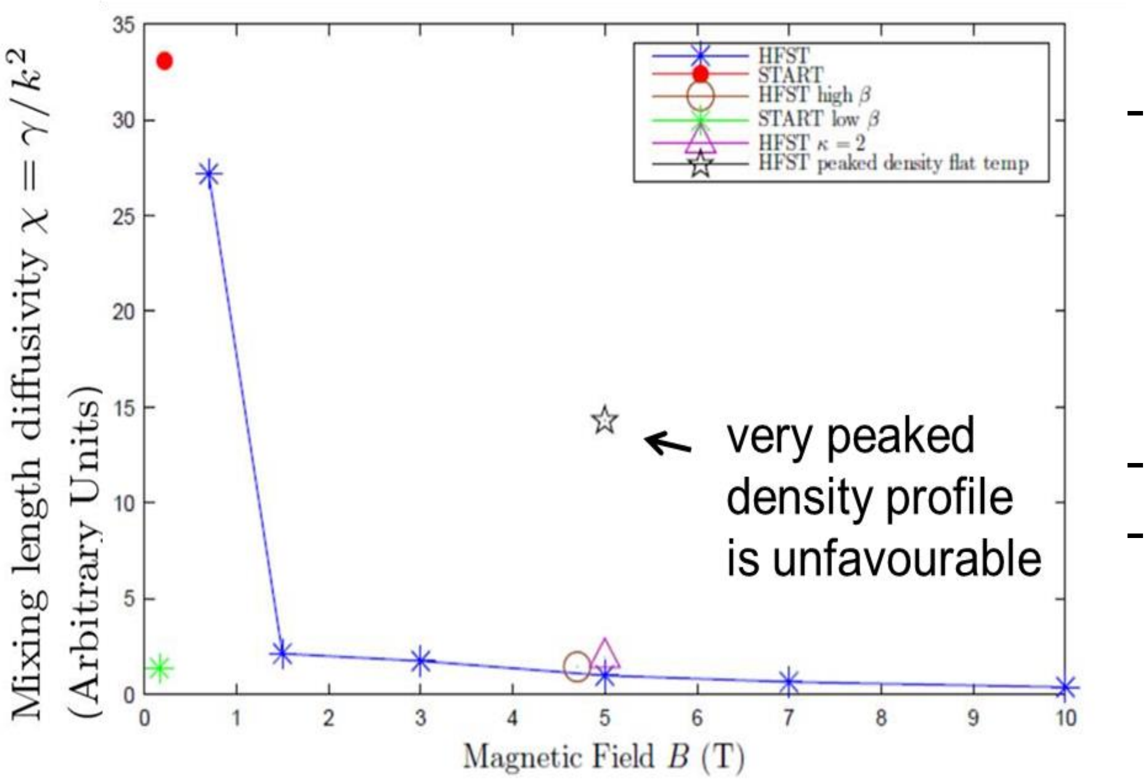


- Closest fit: yellow, n_e = 7 x 10^{19};
- Confinement above NeoAlcator ohmic scaling?

- In latest 200kA 200ms shots confinement was estimated up to ~ 60ms, which is about 7-10 times higher than NeoAlcator scaling prediction

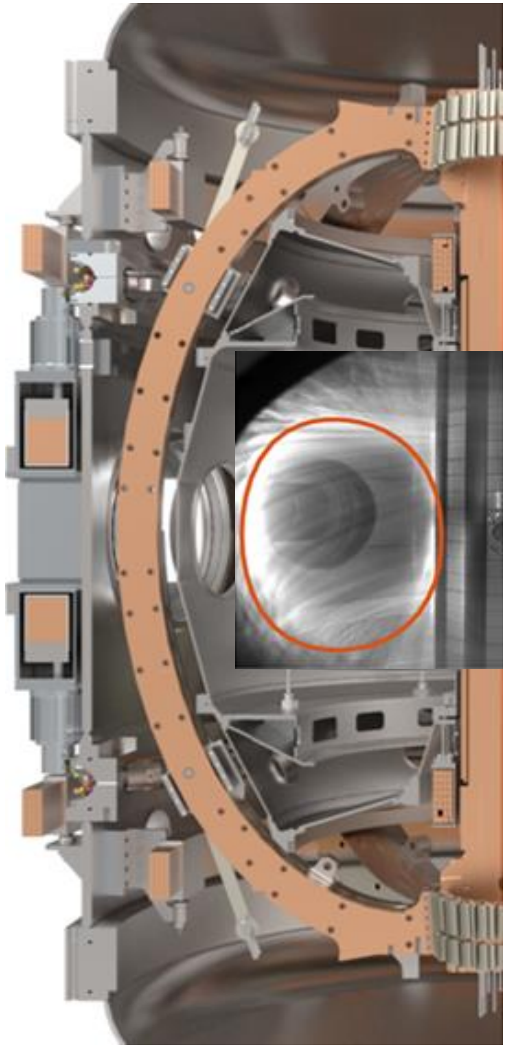
Improvement in confinement at higher Toroidal Field

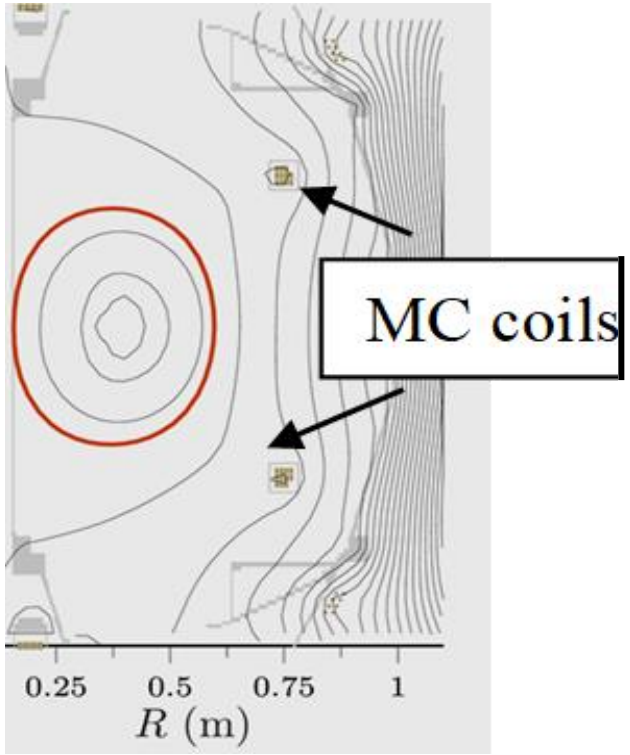
- Observed sharp increase in T_i and W_{therm} at B_t ~ 1T may be connected with the predicted (in GS2 simulations) reduction in transport at higher toroidal field in an ST:

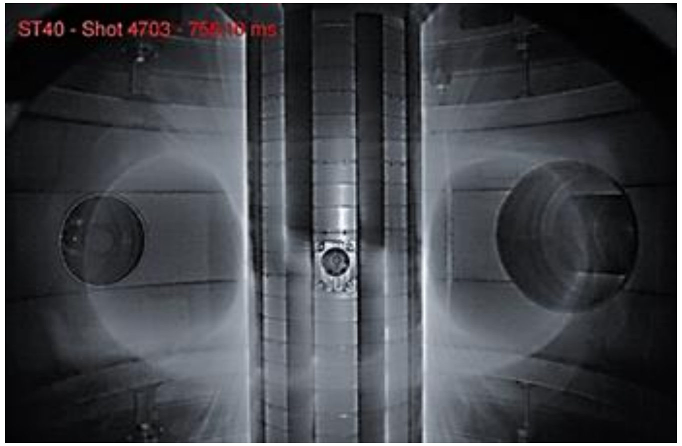


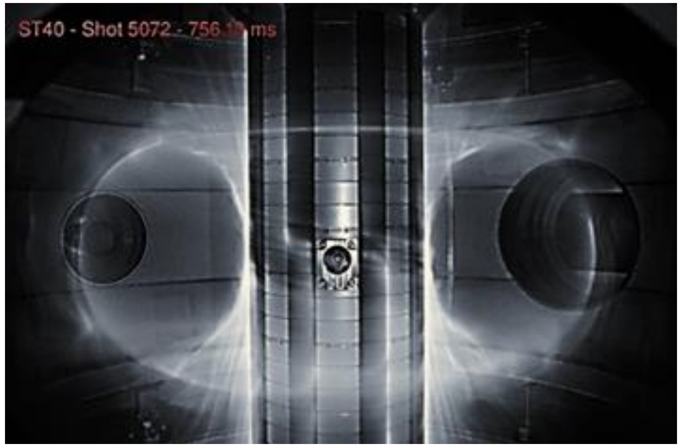
- At **low** magnetic field the mixing length diffusivity is dominated by **electromagnetic** tearing modes; these are **stabilised at higher B_t,** diffusivity then being dominated by **electrostatic** twisting modes.
- no beta or shape dependence at high field
- Threshold toroidal field is quite low, close to one **observed in ST40, ~1-1.5 T**

Ohmic H-mode?

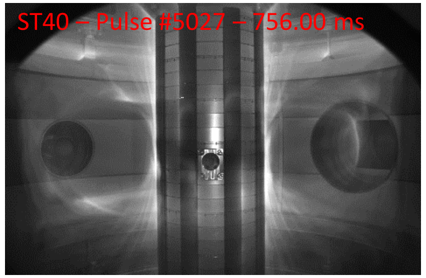


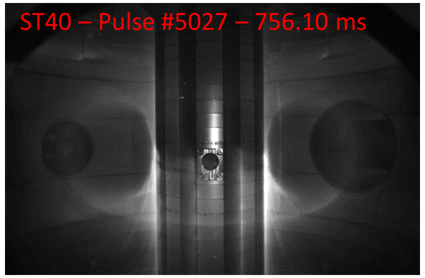


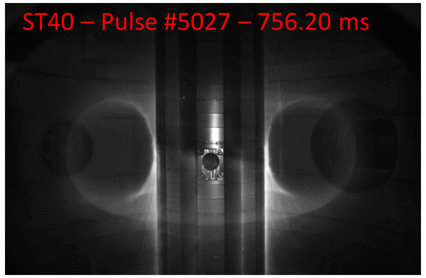


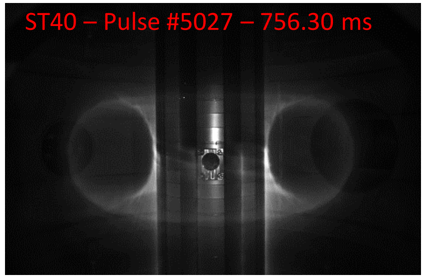


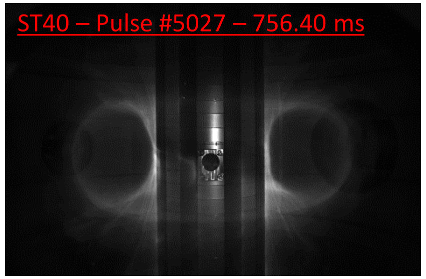
Well-defined plasma edge

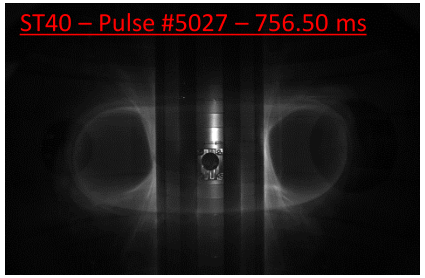


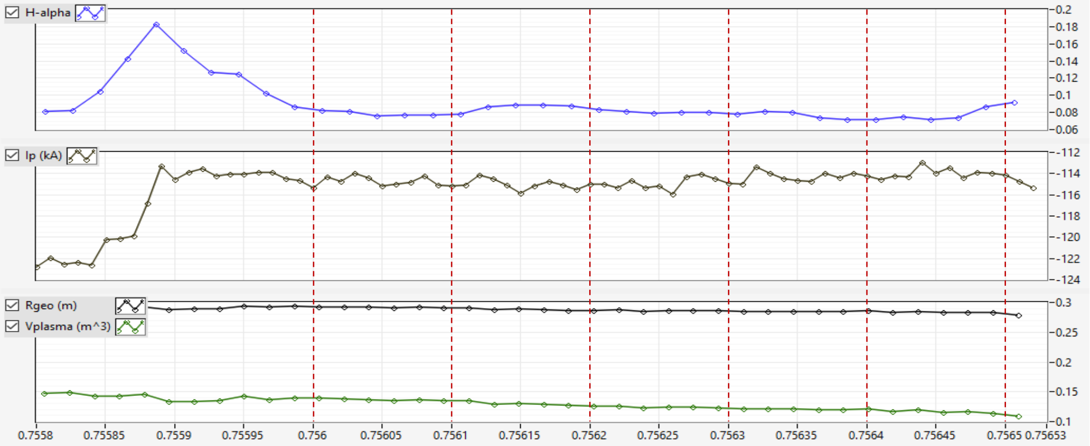












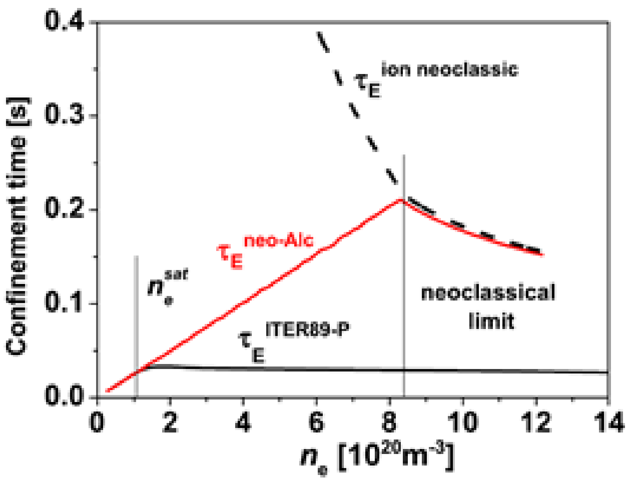
- Spontaneous transition to sharp edge plasma
- Reduction in H_α
- W_{MHD} increase up to x2

Confinement studies, modelling

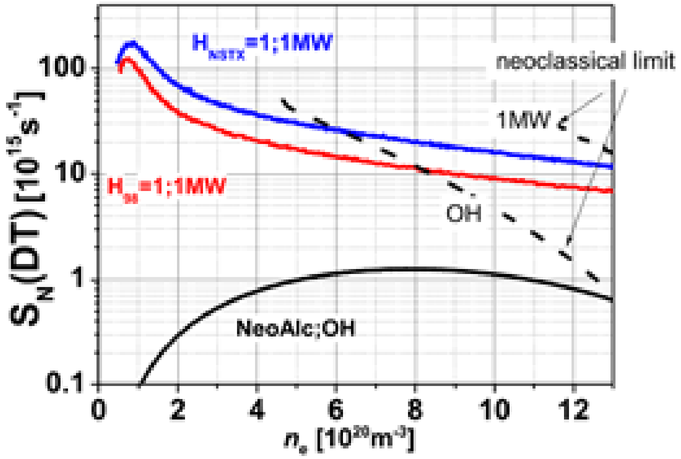
- Transport simulations with ASTRA, NUBEAM and TSC codes have been performed to model ST40 parameters and to support the physics basis of the compact high field ST path to Fusion.
- We show that high confinement regimes with **neoclassical** transport can be expected even when plasma is only ohmically heated.
- In an auxiliary heating regime, we find a **hot ion mode** with T_i in the 10keV range to be achievable with as low as 1MW of absorbed power.
- **Limitations** of applicability **of confinement scalings** for prediction of performance of ST40 and beyond.
- However, we show that if the performance achieved on other spherical tokamaks can be extended to ST40 conditions, up to **1 MW of Fusion power** can be expected in **DT operations**.

Confinement studies, ASTRA - NUBEAM simulations

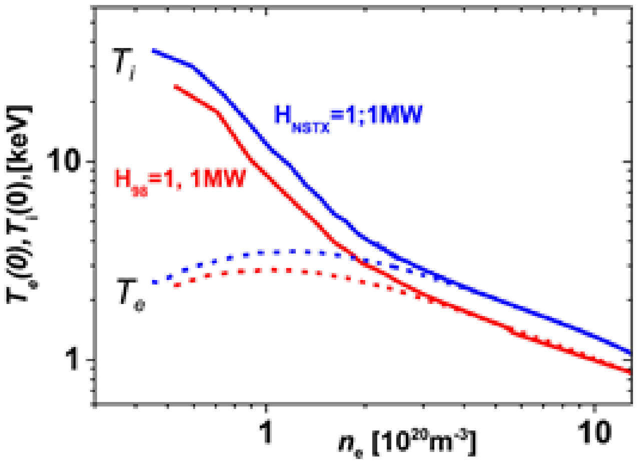
- ST40 can check **applicability of neoclassical theory** in a high field ST
- Can **Q_{fus} ~ 1** be achieved in a high field compact ST?
- Can hot ion mode be achieved in a high field ST?



τ_E vs line averaged density in OH regime



DT neutron yield vs line averaged density with 1MW absorbed power

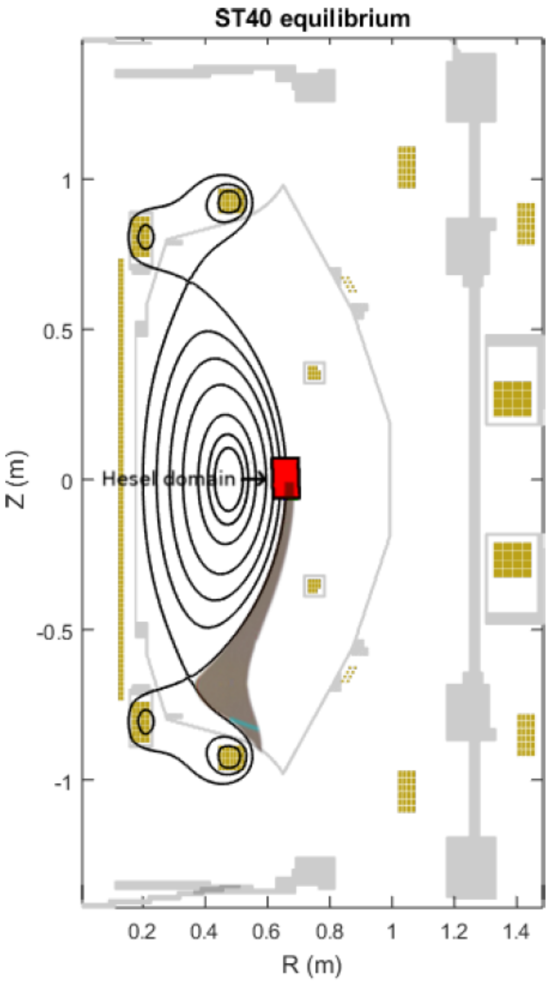


Central T_i, T_e vs line averaged density with 1MW absorbed power

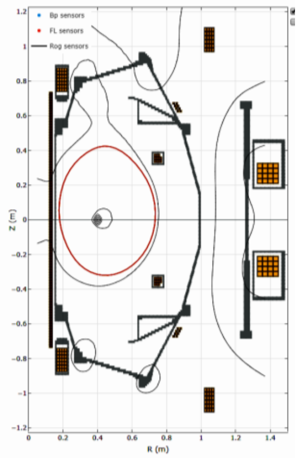
Edge simulations

Edge simulations

Map to divertor with EFIT



- Evaluate parallel heat flux in ST40 using HESEL[1]
- Determine λ_q from turbulence simulations
- $\lambda_{q,HESEL} = 1.9$ mm for $P_{SOL} = 2.2$ MW
- $\lambda_{q,Eich} = 1.7$ mm for similar conditions
- Range of parameters scanned, $\lambda_{q,HESEL} \in [1.8; 2.7]$ mm



Transient SND

Globus-M experiments:

$$\boxed{\lambda_{q\ \mathrm{MP}} \sim I_p^{-1.4} B_T^{0.6}}$$

Eich 2011, Scaling for Conventional tokamaks:

$$\lambda_q \sim I_p^{-1.1} B_T^{0.42}$$

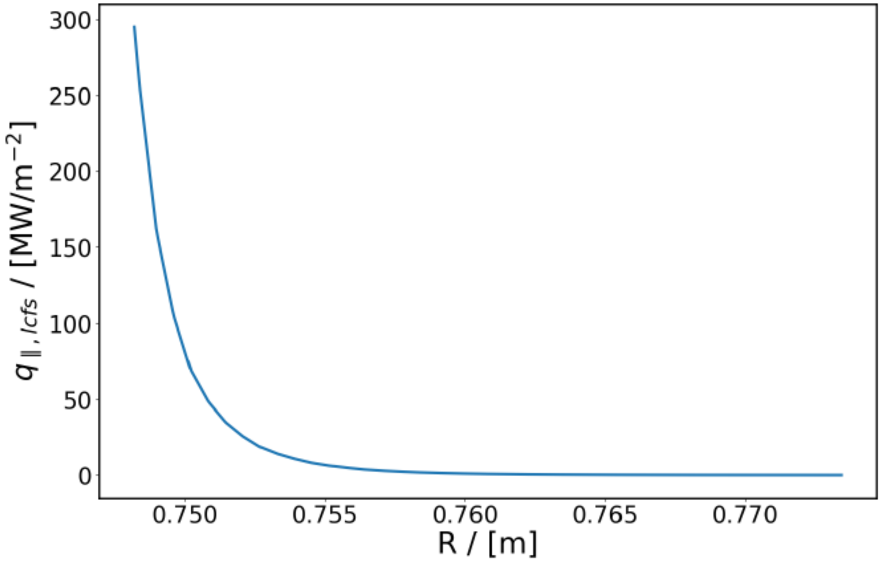
Eich 2013, Scaling for Spherical tokamaks:

$$\lambda_q \sim I_p^{-1}$$

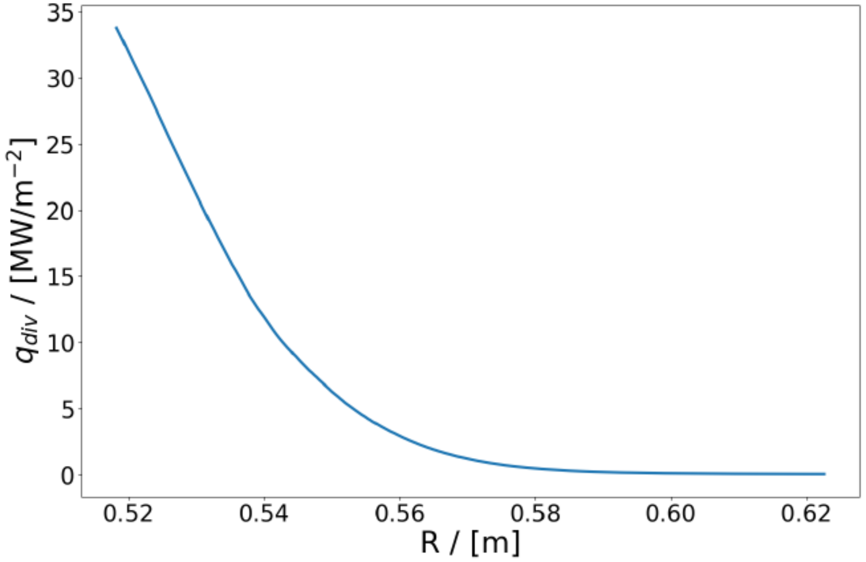
[1] [A. H. Nielsen et. al. PPCF 59 (2017) 025012]

Edge simulations, Power Profiles

Parallel heat flux at LCFS



Parallel heat flux at divertor



$$q_{div} = \frac{R_{LCFS} q_{\parallel,LCFS}}{R_{div} f_x}, \qquad f_x = f_{x,\perp} / \sin(\beta)$$

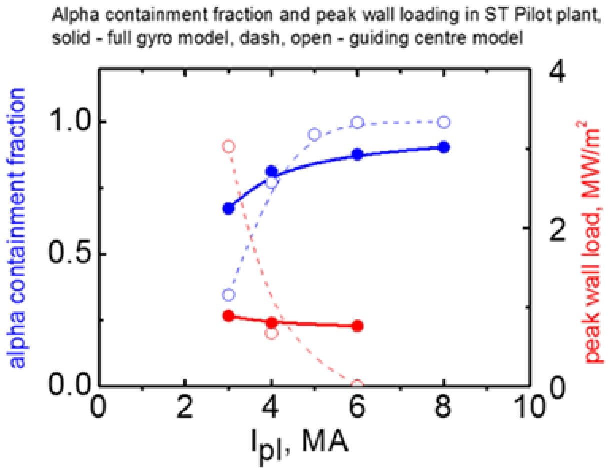
- Large $f_x \rightarrow$ tolerable heat loads at divertor

Fast particles studies

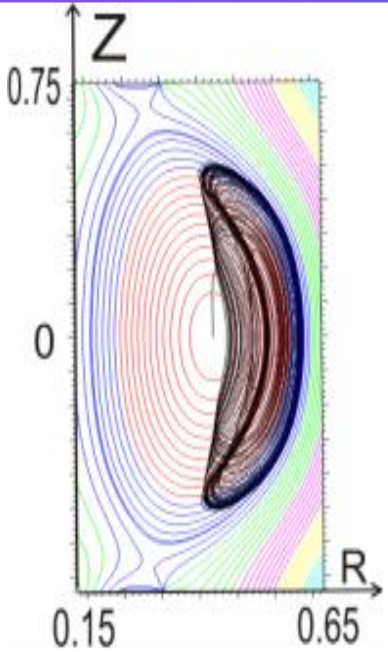
Fast particles studies

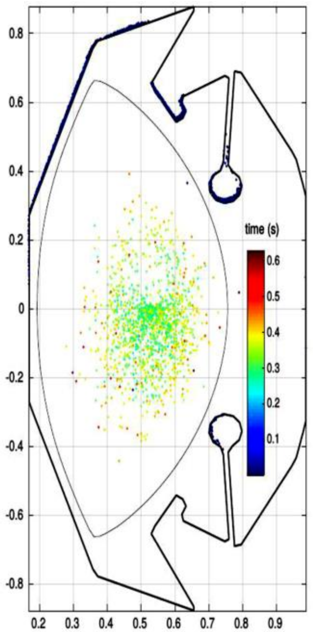
- Studies of **fast ions and alpha particle** transport, heating and current drive, **torque** deposition and **momentum** transport have been performed using ASCOT, NUBEAM, Monte Carlo code NFREYA and the Fokker - Planck code NFIFPC.
- Different NBI energies and launch geometries have been studied and optimized.
- The **confinement of thermal alphas** in ST40 3T/2MA scenario is studied with full orbit following (which is necessary because of the large alpha particle gyro radius).
- The **first orbit losses** are seen to be almost **60%** even in the high-performance scenario illustrating that the alpha confinement in a small device is very difficult even at the highest available fields. However, experiments on ST40 will provide useful information for **verification** of such simulations.

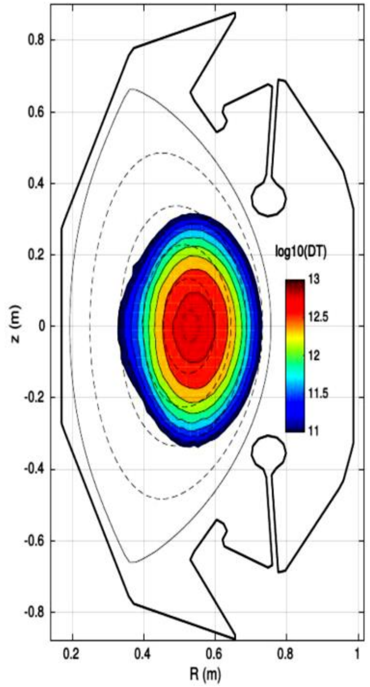
Fast particles studies, α-particles



- *Importance of full-orbit simulations for ST reactor*







*α-particle slowing down by banana orbits. The co–legs of the bananas try to move toward the right stagnation point and the counter-legs move away from the left stagnation point. Monte Carlo (M-C) code **NFREYA**.*

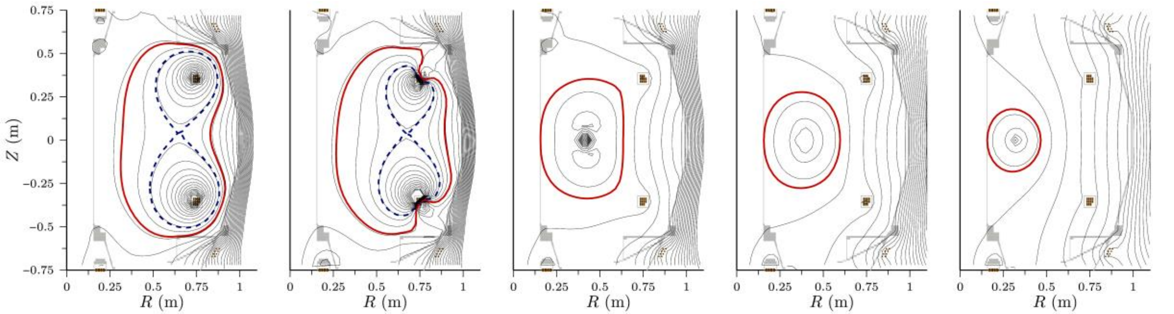
*Tritium thermalisation and wall losses in ST40. Marker colour indicates the time it took to reach the final position (wall hit or thermalisation). Roughly 50% of the Tritons are **first orbit losses. ASCOT**.*

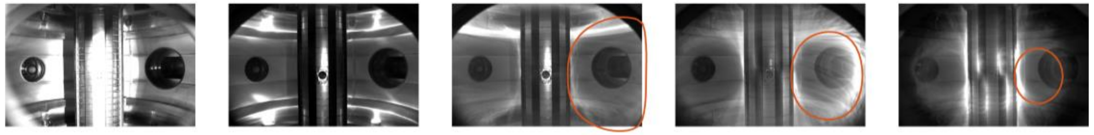
*Fast-thermal TD reaction rate from a DT reaction between 1.01 MeV Tritium slowing down against thermal Deuterium for 1.2T/2MA, $1.1\times10^{19}m^{-3}$,1MW NBI. This is the main channel producing 14 MeV neutrons. **ASCOT**.*

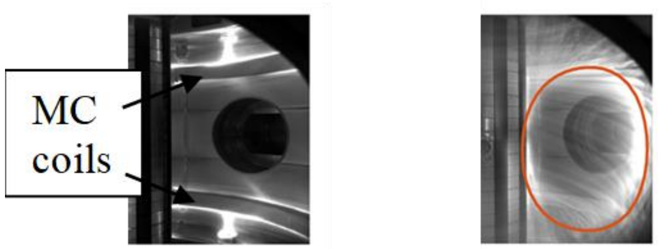
Test of reconnection scaling

Better use of Magnetic Field: reconnection heating

- Magnetic confinement is based on containment of hot plasma and insolation of it from the wall of the vacuum vessel, by the externally applied magnetic field.
- It is possible to transfer **magnetic energy** directly into the plasma **thermal energy** with a very high efficiency (up to 90%), thus using magnetic field **not only for the containment**, but also **for** the plasma **heating**.
- This can be achieved using magnetic reconnections during merging-compression formation of the tokamak plasma, as used on START and MAST



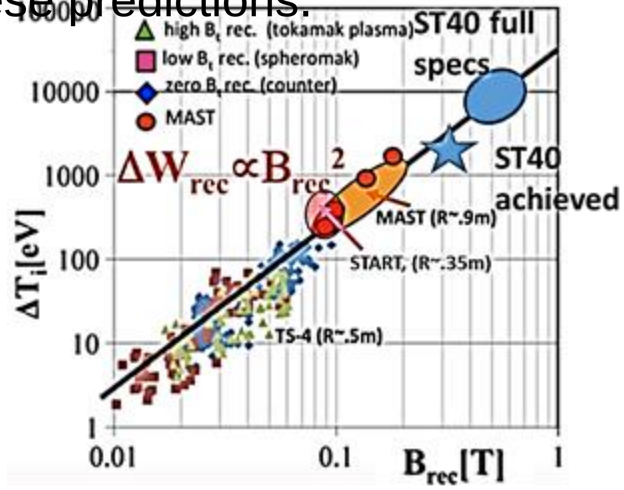




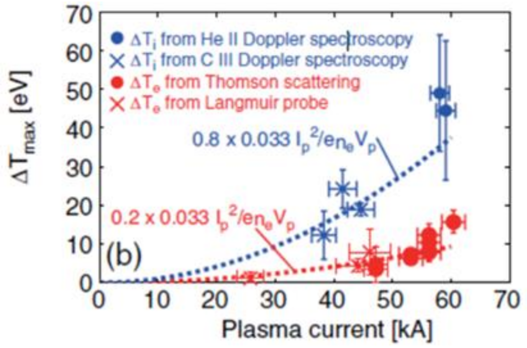
Better use of Magnetic Field: reconnection heating

tokamak energy
a faster way to fusion

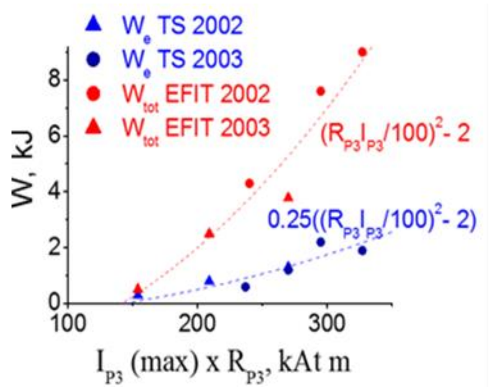
- Reconnection theory has been developed in astrophysics in 60-70th
- According to theory that predicts heating due to reconnection ~ B^2, and experimental data from START, MAST and Japanese devices, plasma in ST40 should show ignition parameters ($nT\tau$) with temperatures ~10 keV
- First results from ST40 already confirm these predictions.



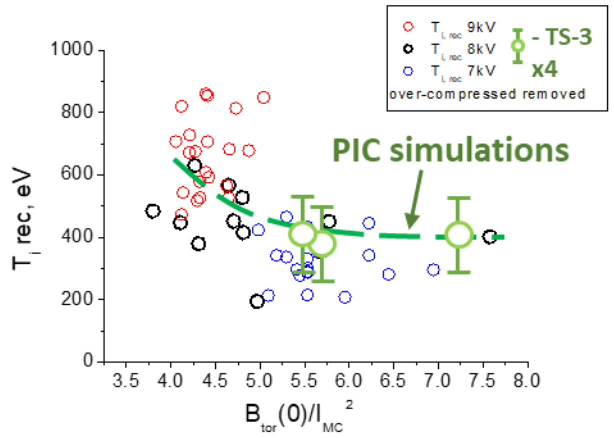
Predictions

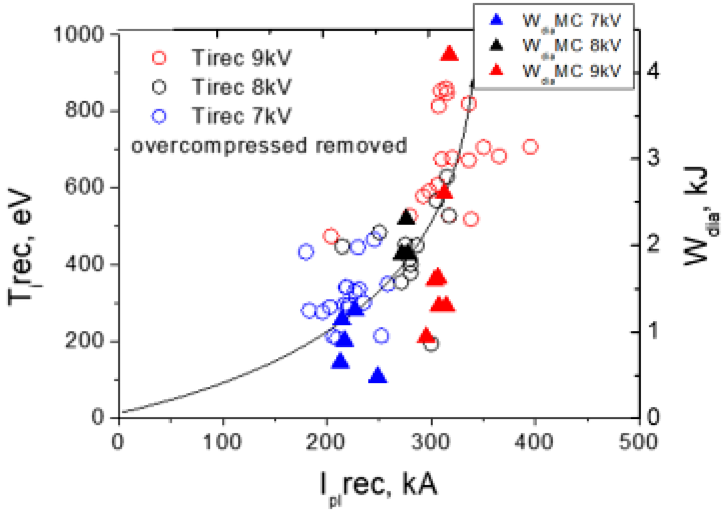


UTST



MAST



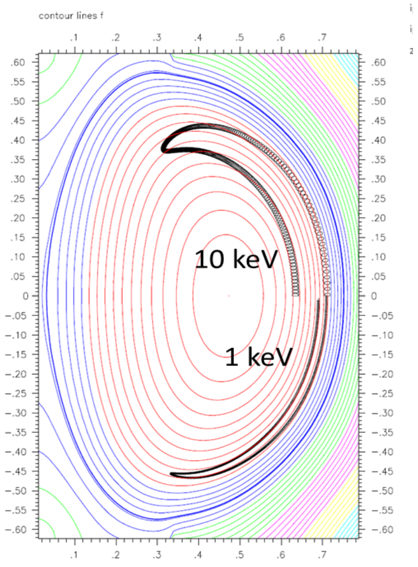


Previous results

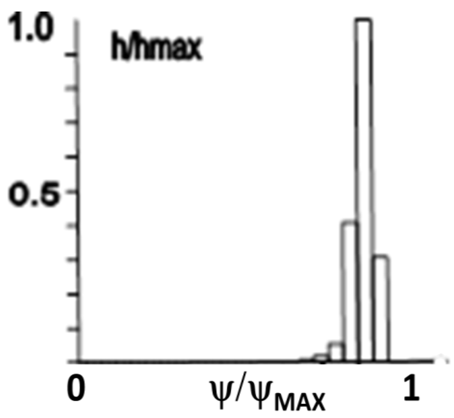
First results from ST40: scaling confirmed!

Reconnection heating – injection of fast ions

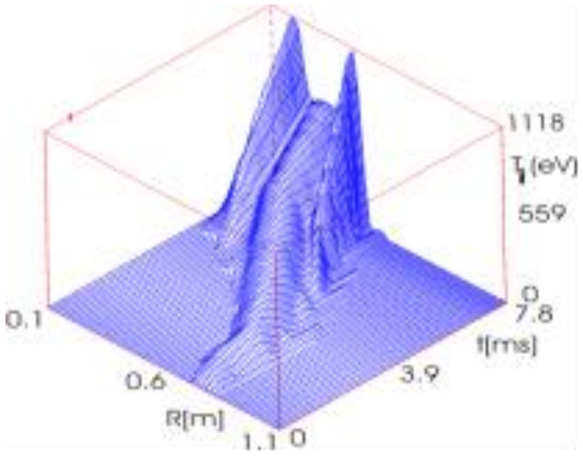
- To model merging-compression process codes NFREYA, TSC and Torus II have been used.
- NFREYA – Monte Carlo simulations are based on the assumption that the ions formed during the reconnection reach the poloidal Alfven energy and are mainly running in co-direction
- Assuming reconnection heating power of 20 MW with the deposition D(r) and a heating time of 3 ms, temperature of T_i ~1 keV is obtained in rough agreement with MAST & ST40 results



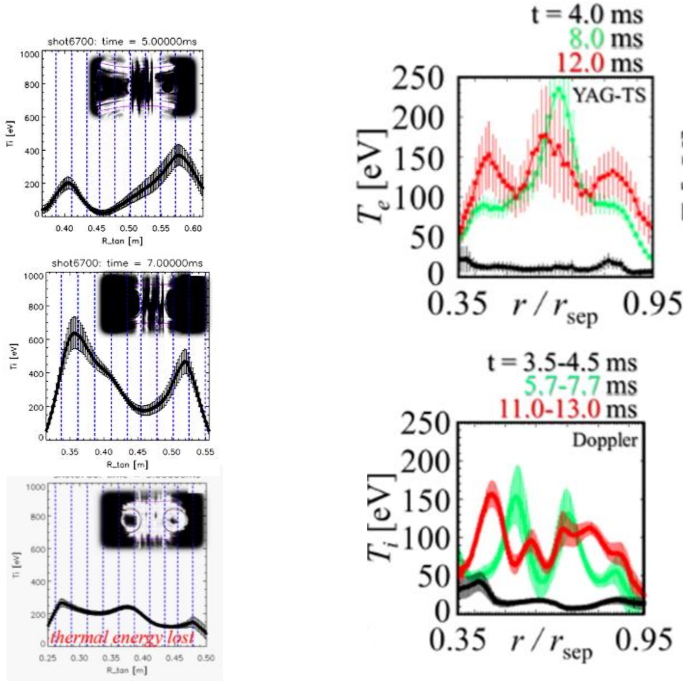
Orbits of the ions produced by reconnection



Deposition profile of reconnected ions D(r)



Time evolution of T_i due to reconnection heating, TSC



Time evolution of $T_{e,i}$ on MAST and of T_i on ST40

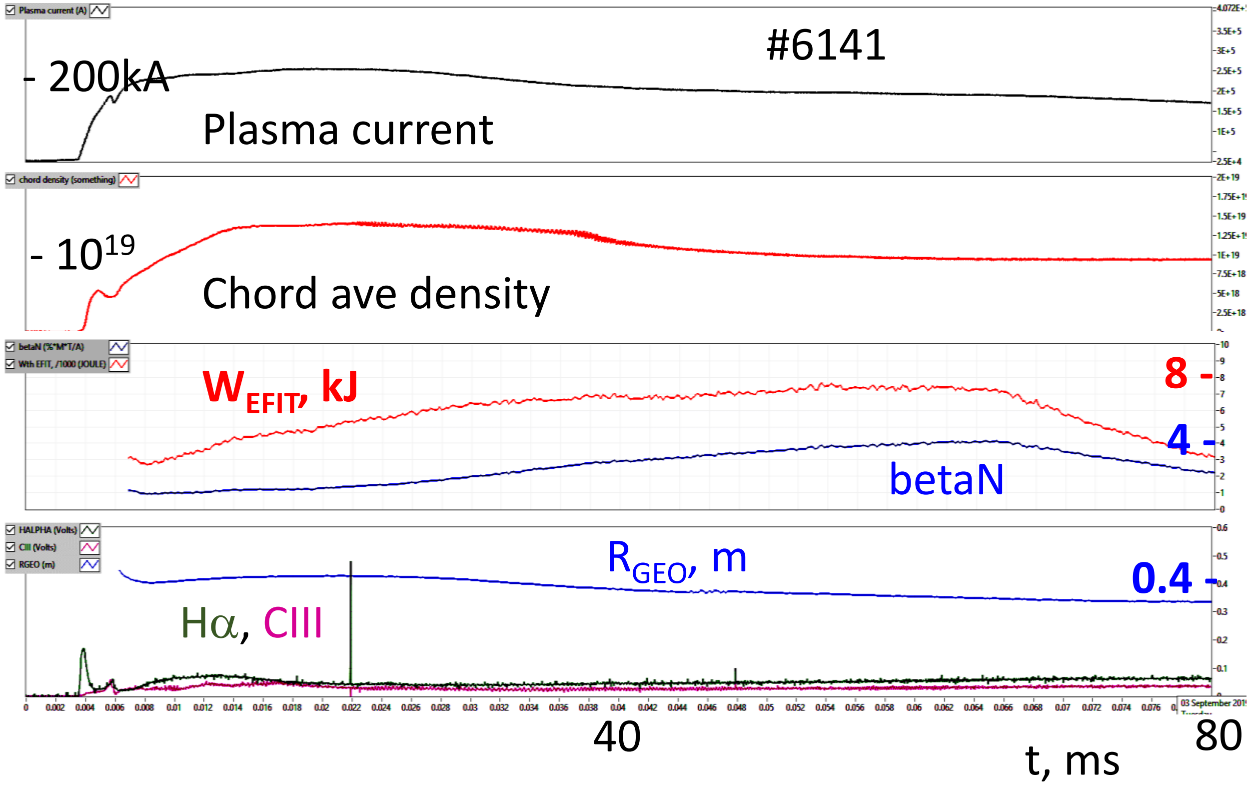
2019, first results

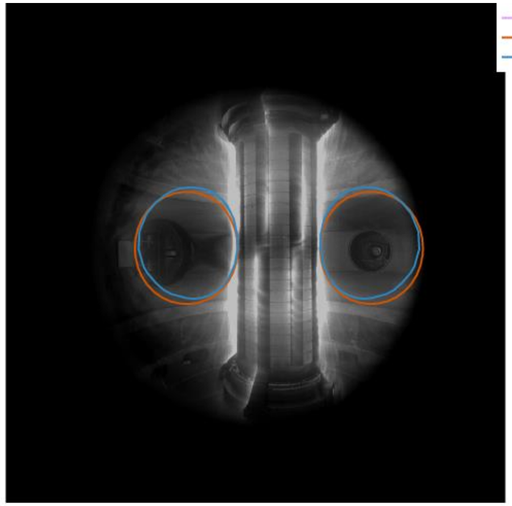
2019, first results

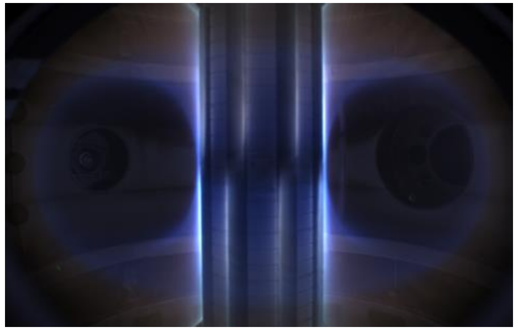
Highlights:

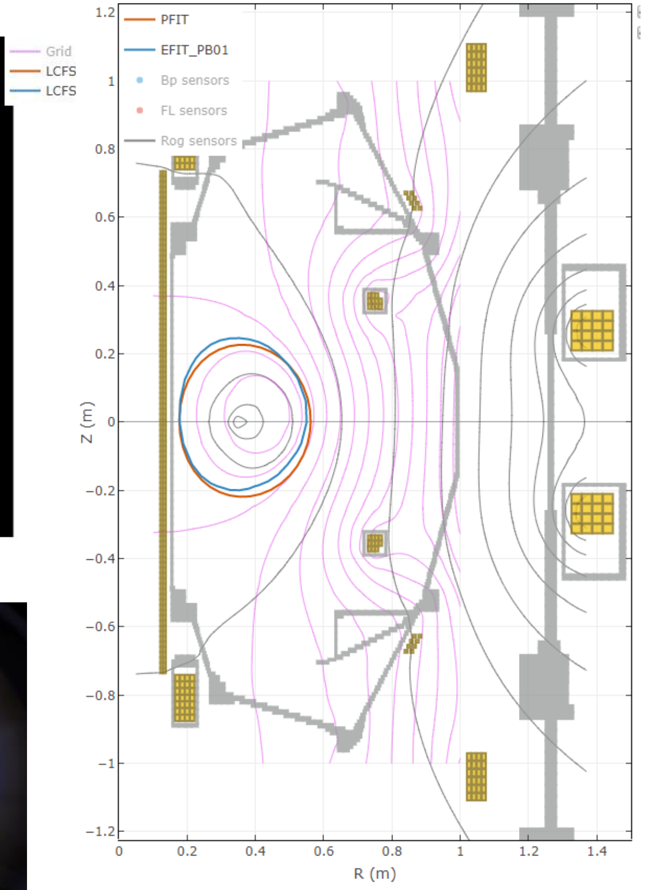
- Solenoid (0.3 Vsec) fully operational. Pulse duration increased from tens of ms to **200 ms** with plasma current at flat-top > **200kA**.
- **TF up to 1.5T** is now routine
- Good confinement, up to 5x Neo-Alcator (at lower densities, ~ $2 \times 10^{19} m^{-3}$)
- Highest β_N (EFIT) above 4, and this is in OH! W_{EFIT} doubled, now 4 – 12 kJ.
- First measurements of T_e (SXR spectrometer), keV-range
- EFIT operational, PFIT for position control.
- NPA operational.
- DNBI installed, RFX NBI (30kV, 1MW, 120 ms) under commissioning

2019, first results





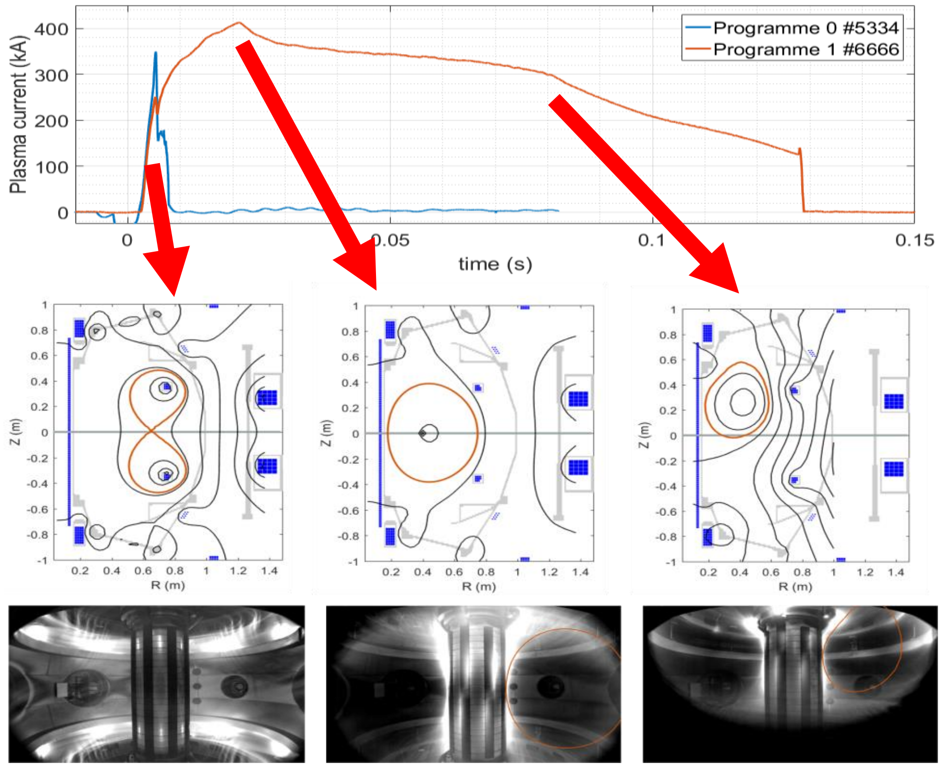


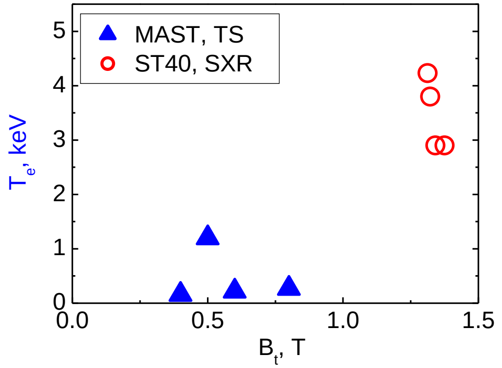


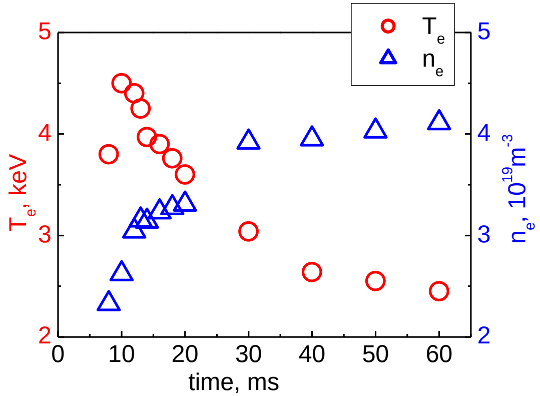
- 200ms+ shots with solenoid
- All ops in H
- Data extended to over-Tesla TF
- Highest β_N (EFIT) above 4, W_{EFIT} ~ 7.5 kJ – confirmed by diamagnetic loop data

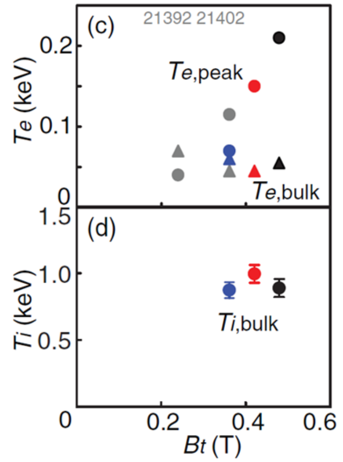
2019, first results

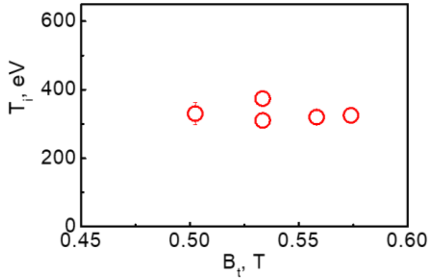
- Typical Ohmic discharge initiated using merging-compression
- Pulse duration extended using pre-programmed control
- Vertically unstable operating region entered. Closed loop plasma control system to be implemented in Programme 2





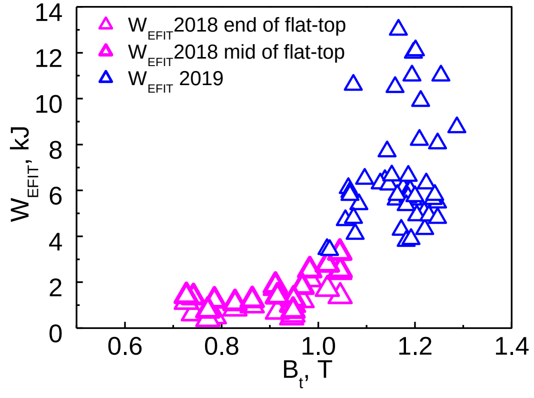


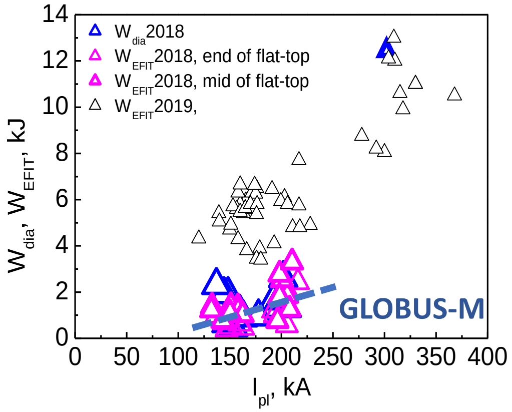


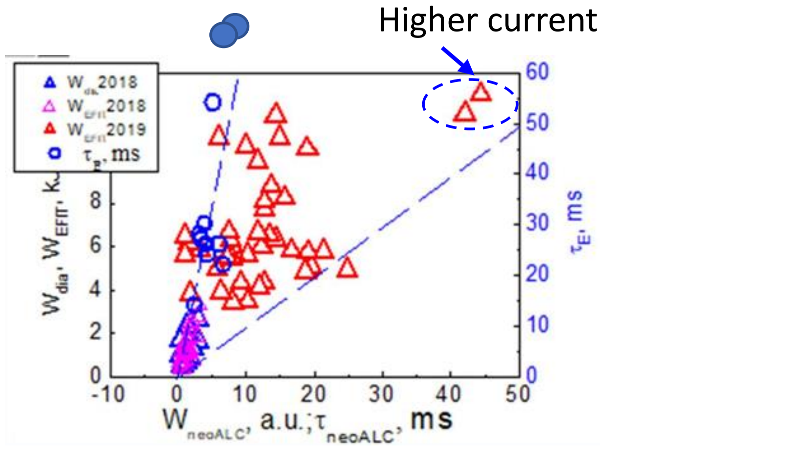


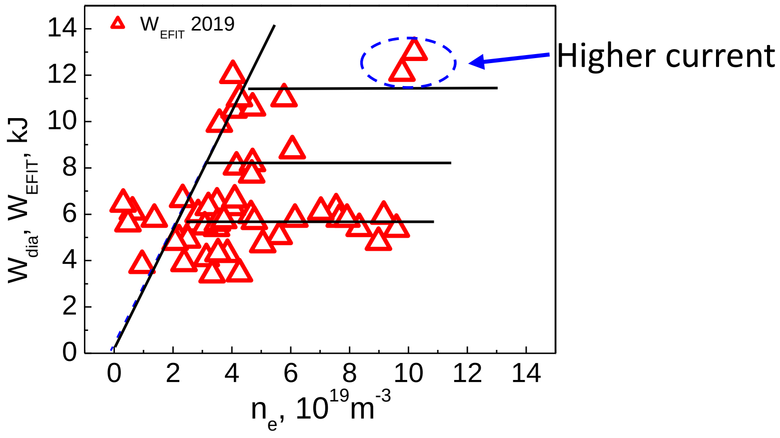
- T_e in hot spot after reconnection increases with TF, Ti does not depend on TF (as on MAST)
- Two possible explanations of T_e evolution:
  - slowing down of electrons accelerated during reconnection
  - equipartition with ions heated during reconnection

2019, test of Confinement Scalings:



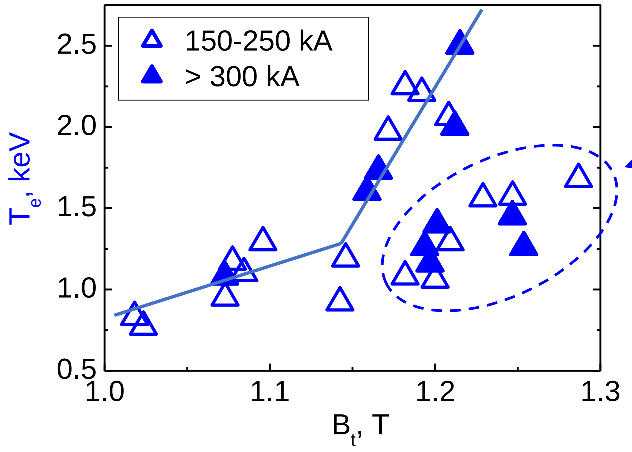






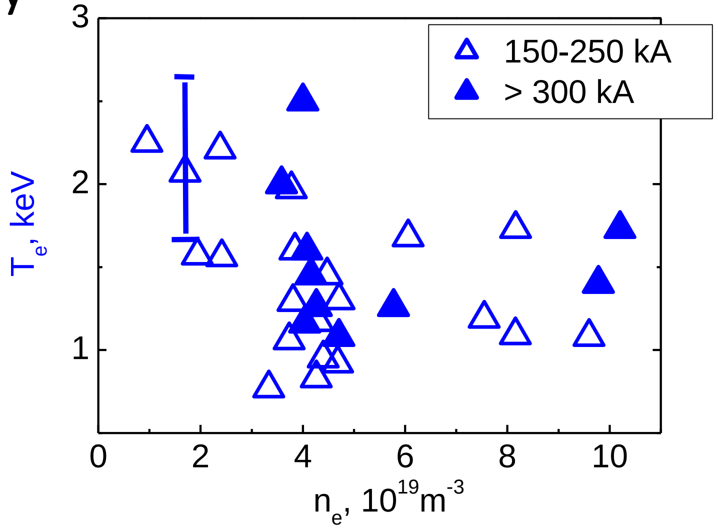
- Data extended to over-Tesla TF, trend of improved performance at higher TF confirmed
- Strong dependence on I_{pl} as on Globus-M
- Some qualitive agreement with neo-Alcator, but higher values of τ_E.
- Possible SOC?

First T_e measurements

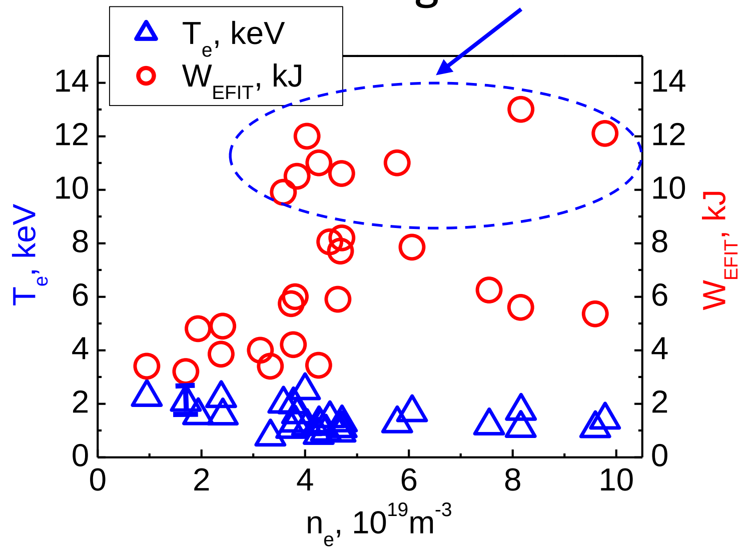


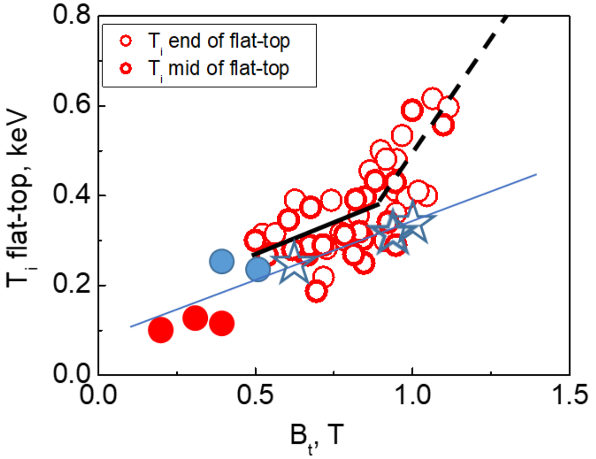
Higher density

- Similar increase in T_e with TF but at higher TF threshold than for ions



Higher current





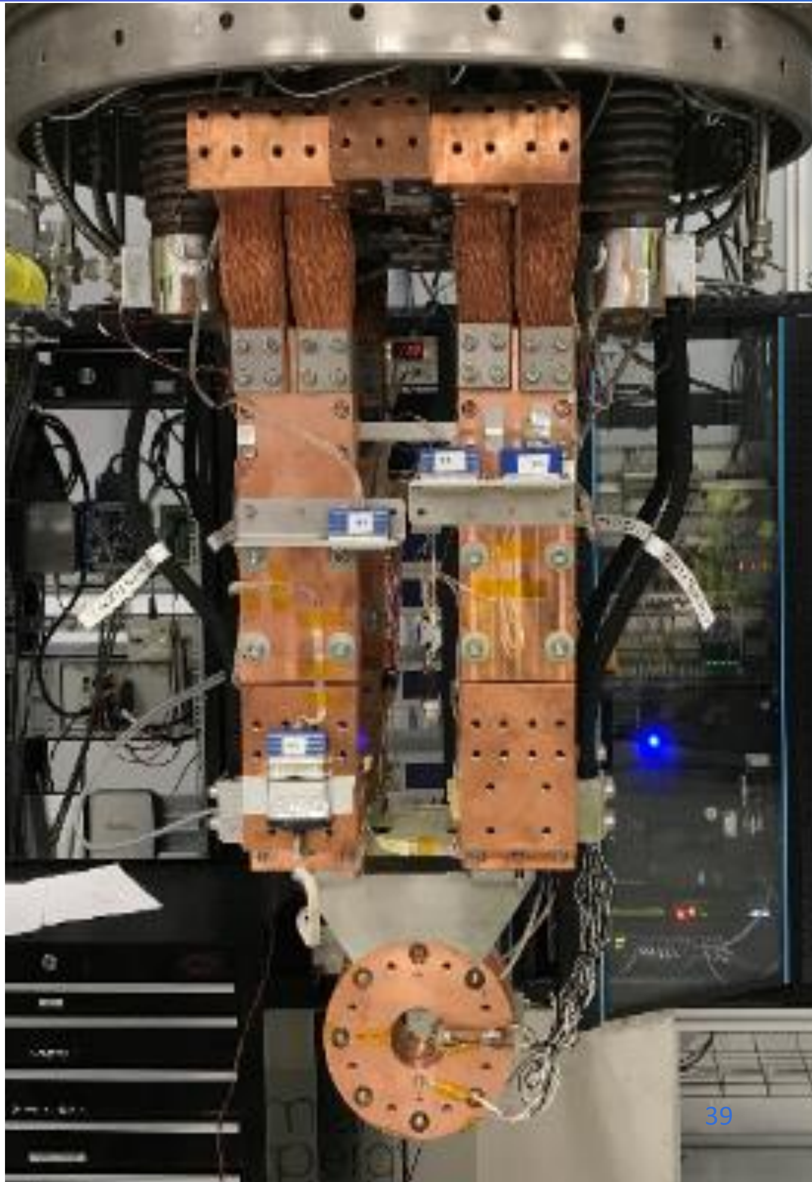
- T_e vs n_e in rough agreements with ASTRA predictions
- Reduction in W_{EFIT} with density above $5x10^{19}m^{-3}$ (none at I_{pl} > 300kA)

HTS

Arguments:

- Only solution for >20T on conductor
- Reduction in cryo power – needed for compact reactors
- Can tolerate some heating (while LTS will quench!)
- Good mechanical properties
- Good performance under neutrons
- Supply chain improving all the time (i.e. SuperOx)

David Hawksworth Magnet Laboratory



- Coil winding & assembly
- 77 K test facilities
- Instrumentation & magnet integration capability
- 4 kA, 12-50 K conduction-cooled cryogenic test rig
- One QA coil made and tested **per week**

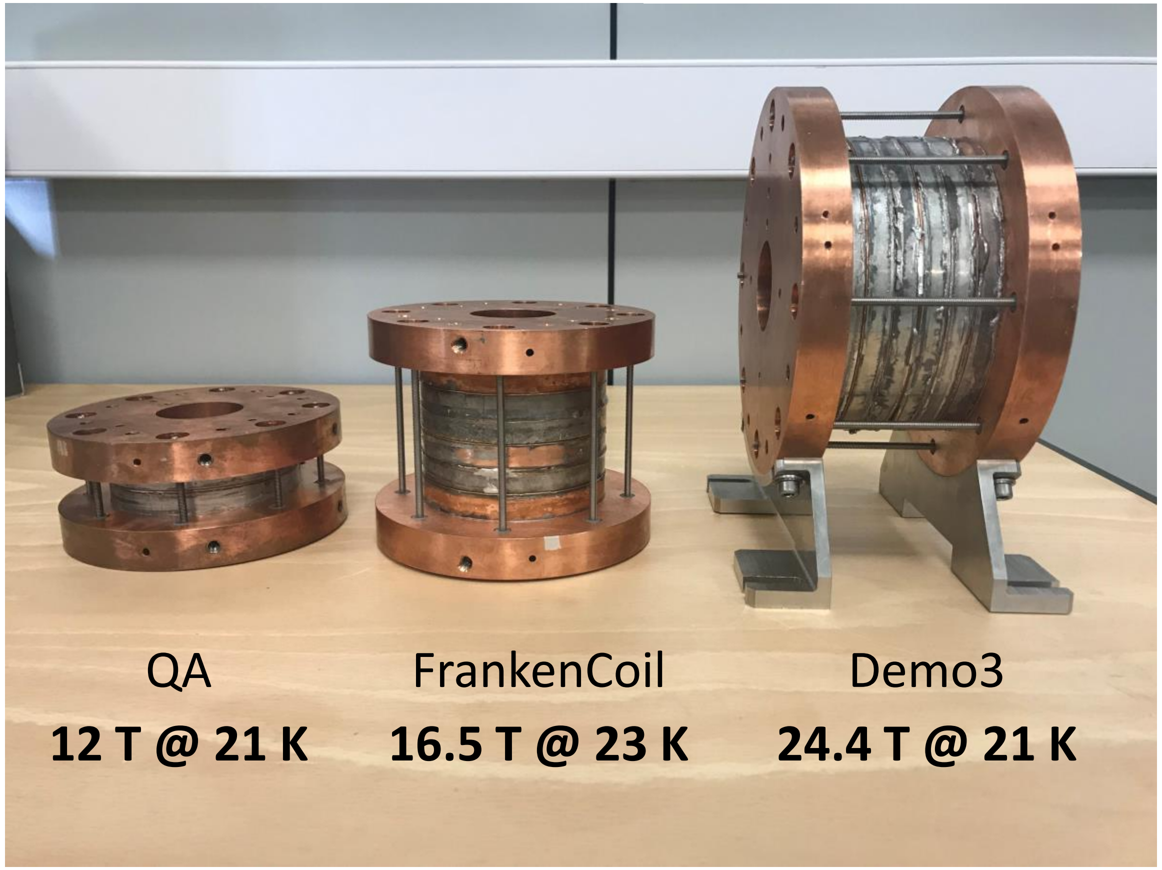
HTS development at TE Ltd

R Slade
3 Sept 2019
2-LO-FH-02S
Dochart room, 16:45

EUCAS 2019 GLASGOW

- Modular, robust & scalable high field HTS magnets
- Simple assembly and disassembly (no soldering)
- **24.4 T achieved conduction cooled at 21 K**
- Survives repeated fast (LTS-like) quenches
- High voltage insulation is not required
- Defect and damage tolerant
- No need for long tape lengths (~20 m is OK)
- Saturated mode: no screening error fields or drift ?

Our QA coil technology is ready for your and also for non-fusion application !



Scale up plan for fusion:

- Retain benefits of NI quench protection with fast ramp capability using novel partial insulation
- No twisting / transposition (enables > 300 A/mm^2)
- Ex-situ cooling & structural support – simple large coil manufacture
- Neutron-resistant HV insulation not required

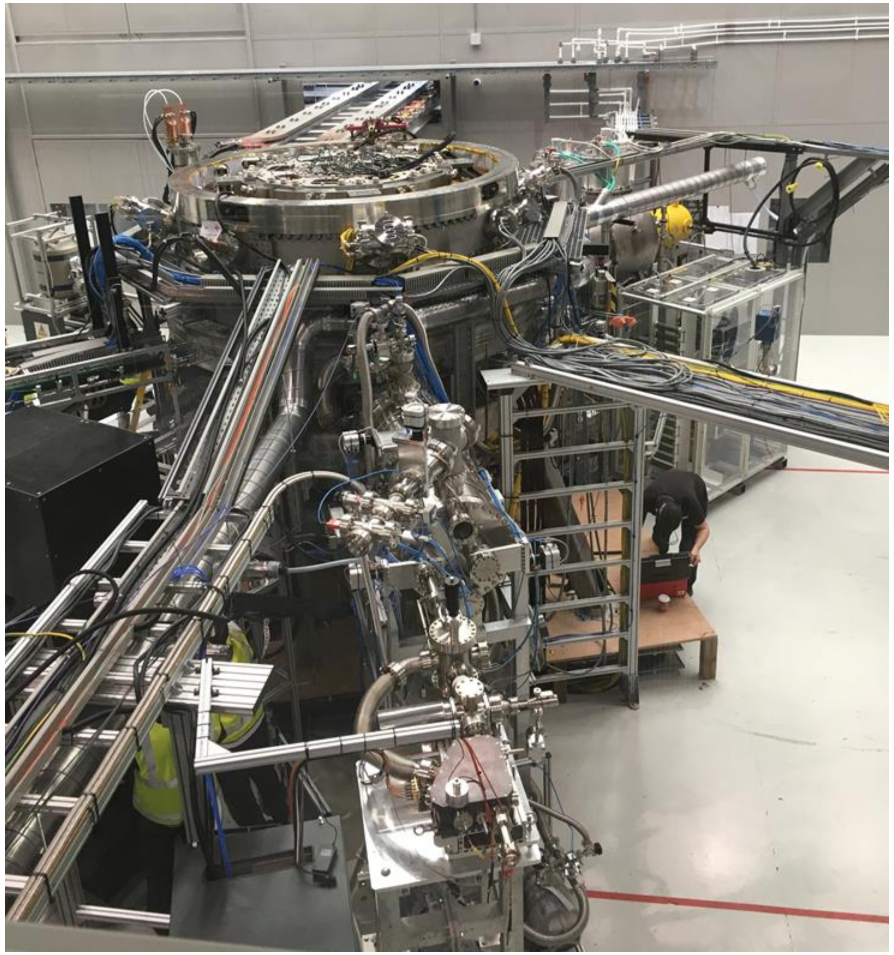
CONCLUSIONS

tokamak energy
a faster way to fusion

- **Demonstration of burning plasma in a compact high-field ST is the current challenge for Fusion**

- **The ST path to commercial application of Fusion can start from Compact ST with R as low as 0.4 m**

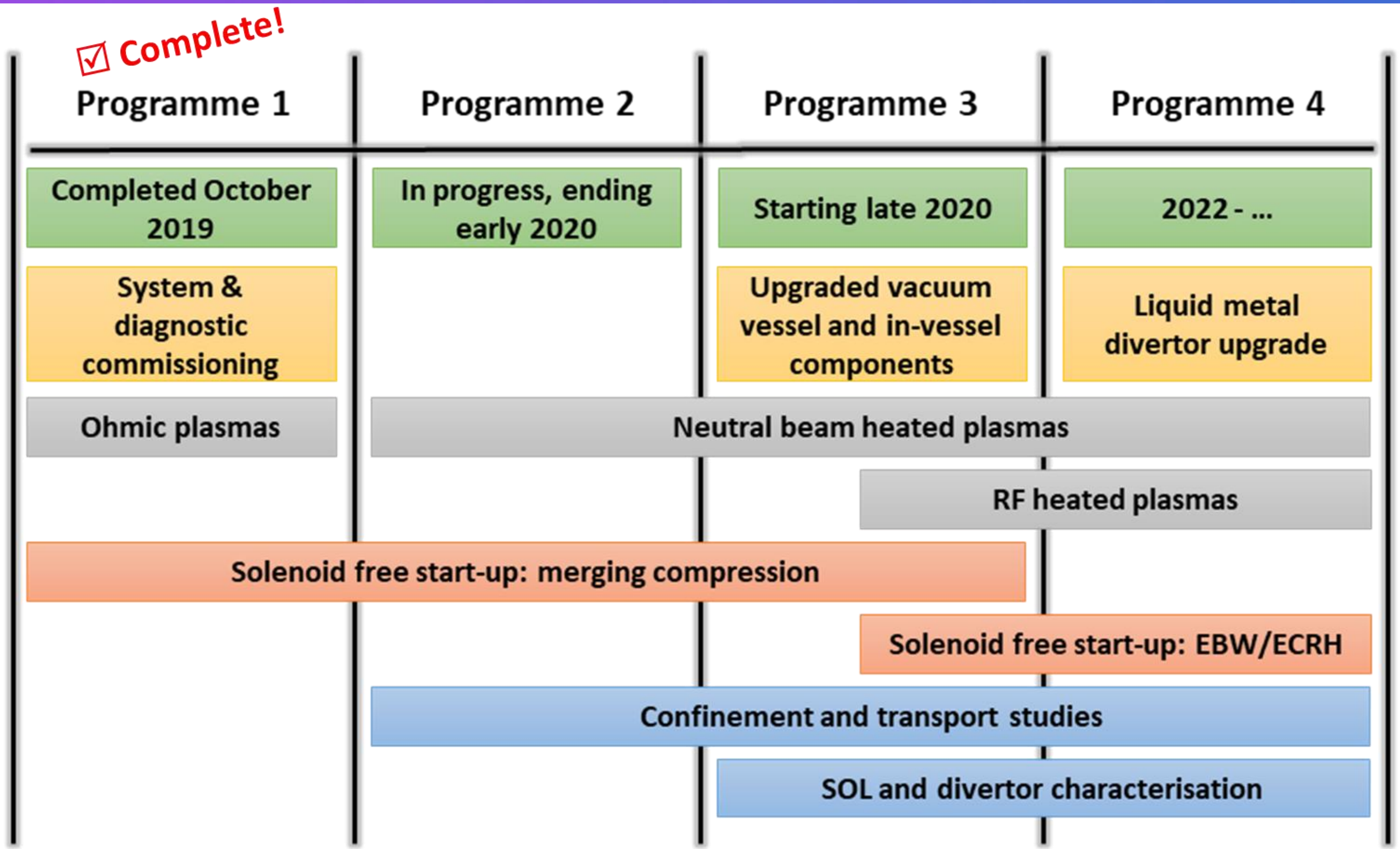
- **Innovations can make Fusion sooner and cheaper**



- ST40 is the first high field Spherical Tokamak

Future Plans

tokamak energy
a faster way to fusion



Together we can make Fusion Faster!

tokamak energy
a faster way to fusion

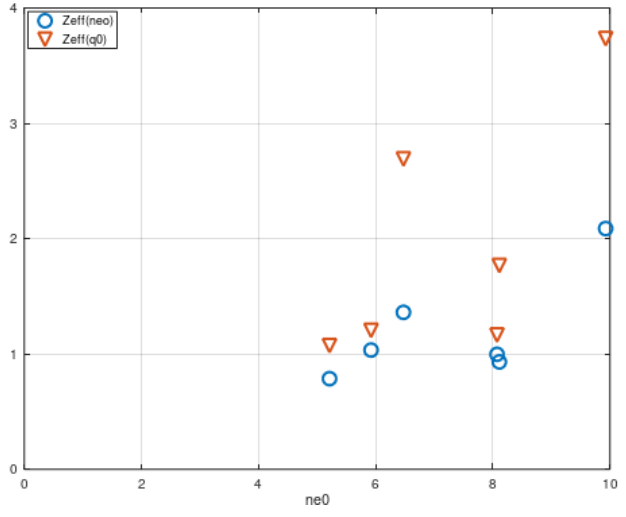
Our principles:

- **Collaboration** in development of Fusion Science and Technologies
- Use of **multiple compact devices** and demonstrators to validate modelling and progress at a **faster pace** and **lower financial risk**

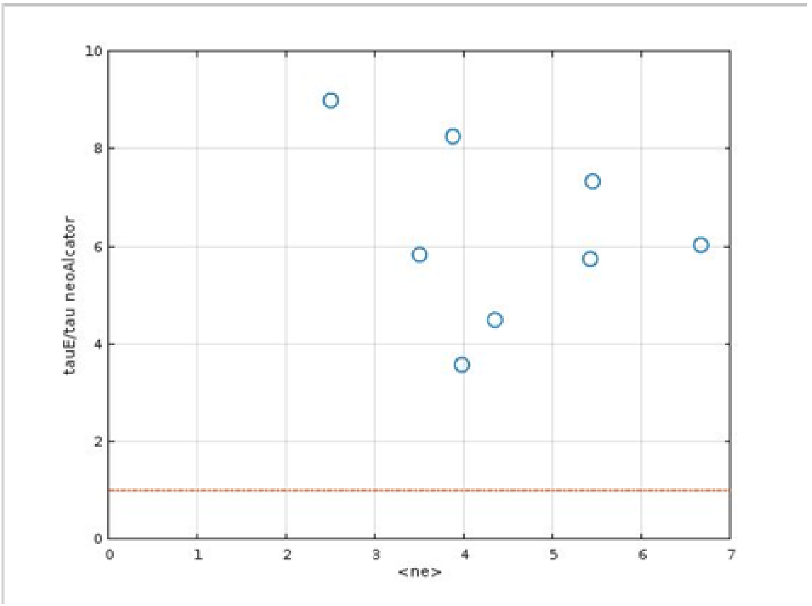
- Strong focus on **industrial 'deliverability'** and **cost** of the commercial device
- Our approach has **common ground with** mainstream Tokamak Fusion (e.g. **ITER**, DEMO, STEP).

We rely on the **same physics** behind the magnetic fusion concept … but we have a faster way to get to a commercially viable device.

Back-up slides



Estimate of Zeff



Comparison with NeoAlcator scaling