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a faster way to fusion

Theoretical and experimental studies of confinement in high field ST

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Tokamak Energy Technology Roadmap to Faster Fusion

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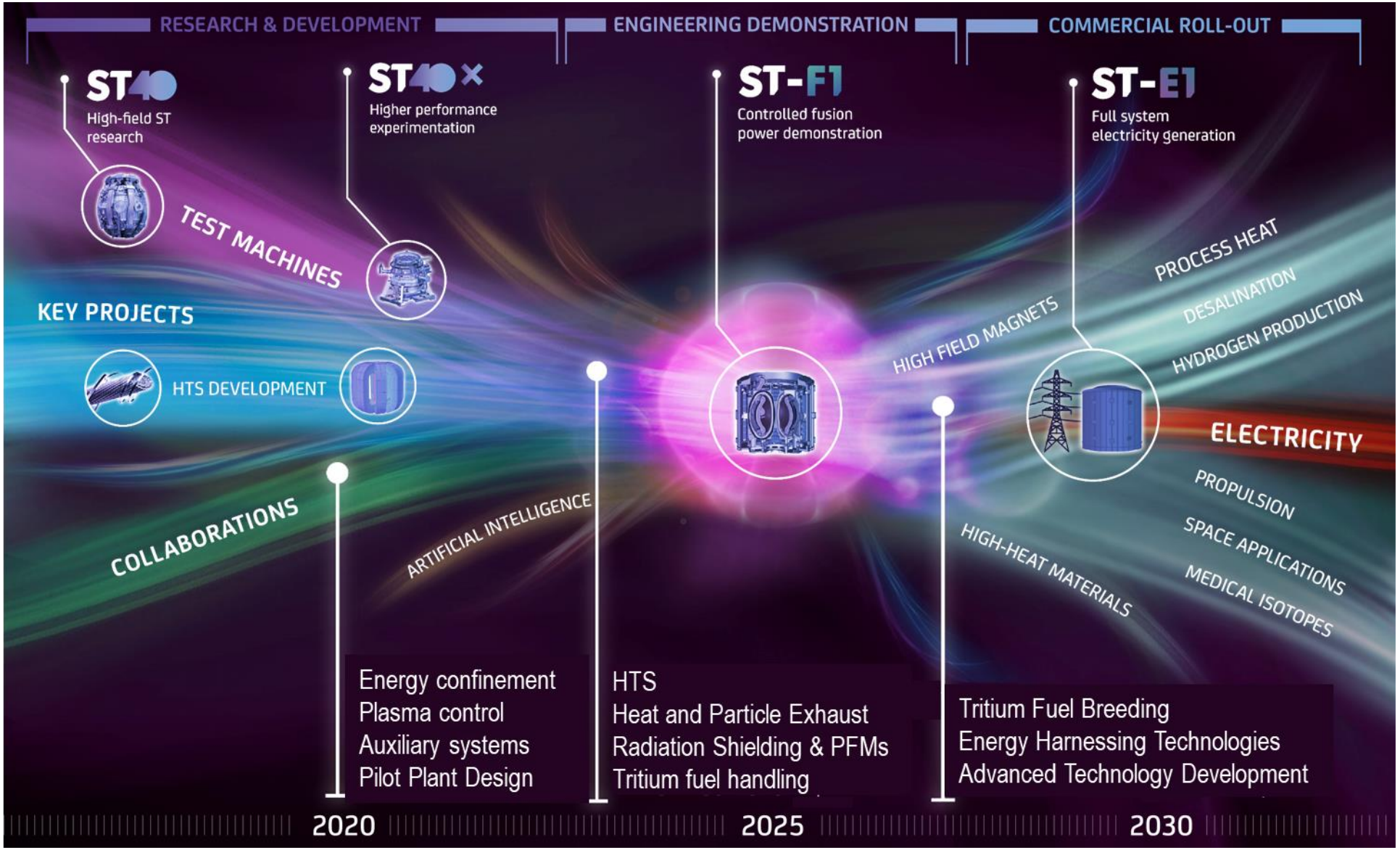

Together we can make Fusion Faster! Our principles:

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- **Collaboration** in development of Fusion Science and Technologies
- Use of **multiple compact devices and test beds** to advance technologies, 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), with some specifics of an ST.
  - So, we rely on the **same physics** behind the magnetic fusion concept … but we have a **faster way** to get to a commercially viable device due to use of innovations (i.e. HTS) and the modular approach for power plant based on compact high-field ST low-power modules.

Achievements & Progress to date

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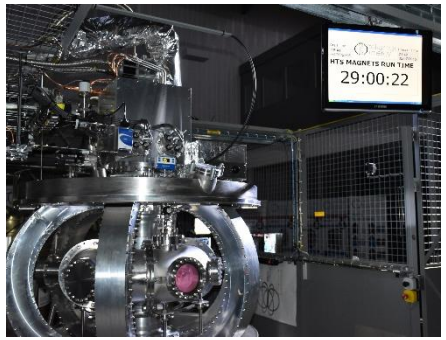
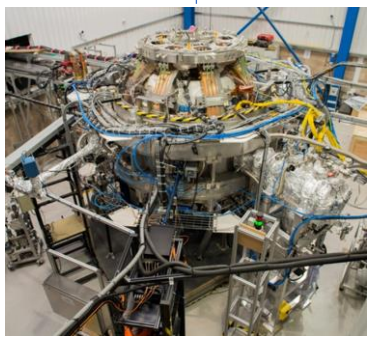
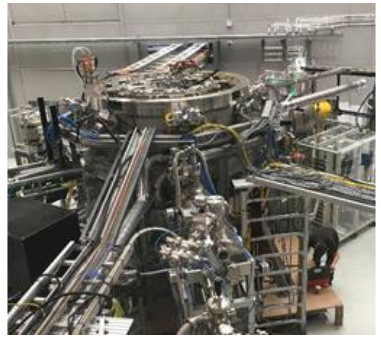
2012 | 2013 | 2014 | 2015 | 2016-18 | **2019**



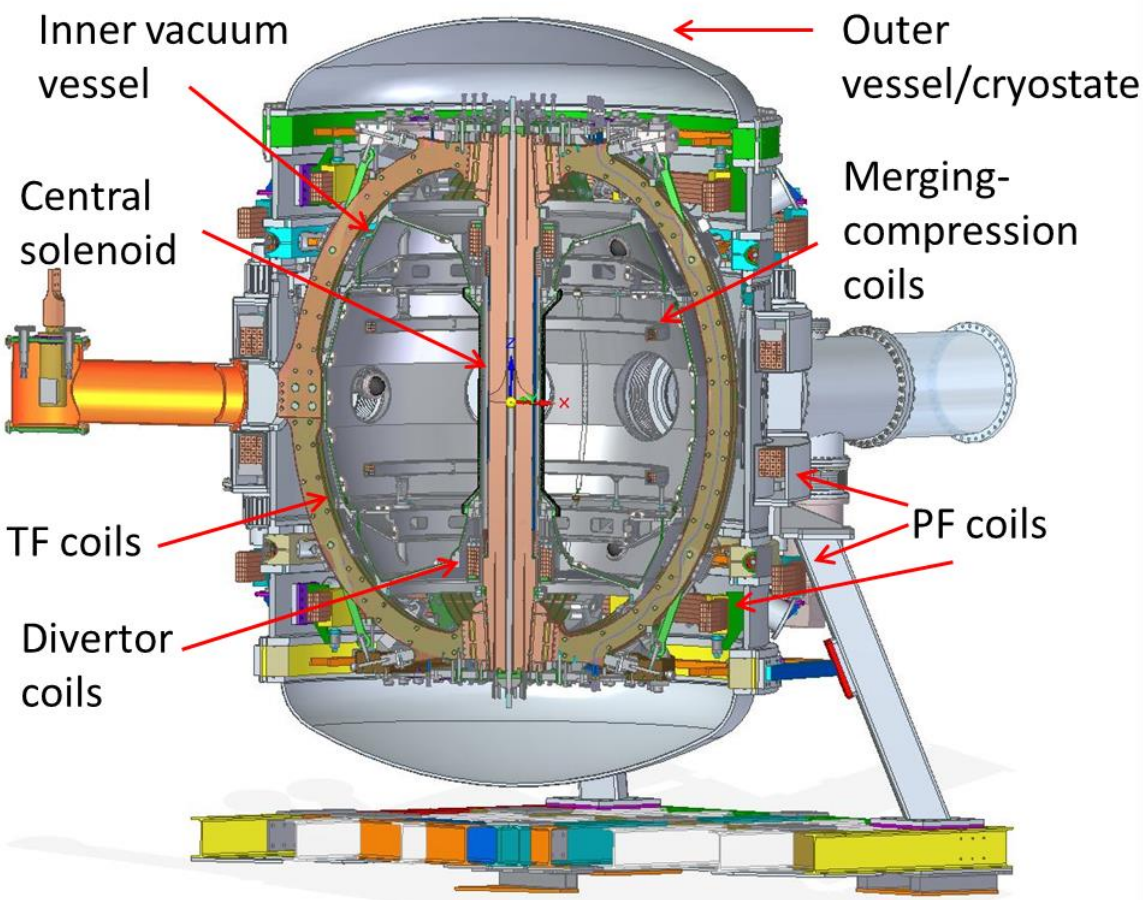




ST25 1.0	ST25 1.1	ST25 1.2	ST40 1.0	ST40 1.1
Field: Low Poloidal Field: Copper Toroidal Field: Copper	Field: Low Poloidal Field: **HTS** Toroidal Field: Copper	Field: Low Poloidal Field: **HTS** Toroidal Field: **HTS**	Toroidal Field: 1 T Poloidal Field: Copper Toroidal Field: Copper	Toroidal Field: **1.5 T** Poloidal Field: Copper Toroidal Field: Copper
Plasma pulse of a few milliseconds (extended to > **20s** with micro-wave current drive)	Industrial HTS PF coils, Stable operations	**World First** Tokamak with **all HTS magnets** Plasma pulse of >100s in 2014 **29-hour plasma** in 2015	Construction of **ST40** (the world's **highest field Spherical Tokamak**) completed, 1st operation campaign completed, sub-keV ion temperatures achieved, 400 kA plasma current from **m/c formation**	ST40 is operating with significant upgrades of PSUs, coils, diagnostics. **First plasmas: 200 ms, 400 kA, $2x10^{20}m^{-3}$, keV-range electron and ion temperatures**
We can build a small spherical tokamak quickly	We can use HTS in tokamak magnets	Long pulses feasible with HTS and RF (or micro-wave) current drive	A high magnetic field in a small tokamak is the key to compact fusion energy	Results from first experiments indicate improvement in performance with increased TF
First patent application filed on fusion power from compact spherical tokamak with HTS magnets	Patent filed on fusion power from low power spherical tokamak	Papers published showing tokamaks do not have to be huge to achieve Fusion. First patent grant, four new patent applications on HTS magnets	Papers on physics, engineering and financial viability of Compact Fusion and 1st results of ST40 published Three further patent applications on HTS magnets	Results are published and presented at main Fusion conferences. Progress in HTS magnets development

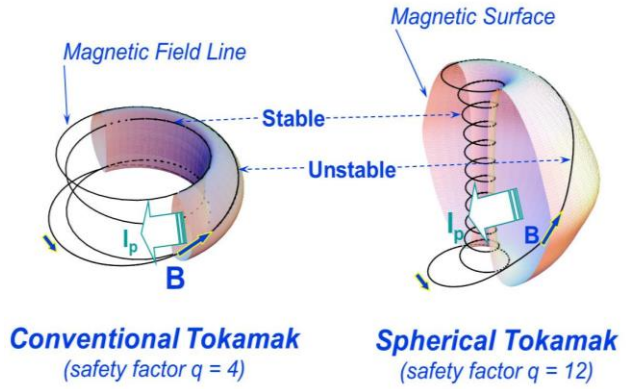
ST40 – High field ST

- 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
- Solenoid-free start-up using merging-compression
- >4MW of auxiliary heating (NBI / ECRH)
- Pulse flattop length 1s at full power (200 ms now)
- Well equipped with diagnostics

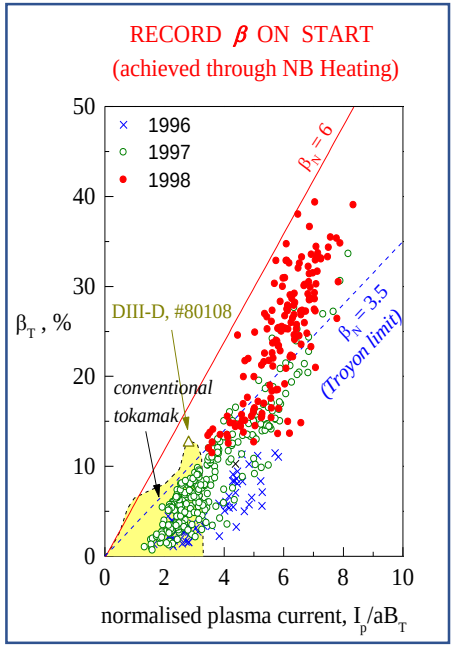


Spherical Tokamaks, why?

High safety factor, better stability

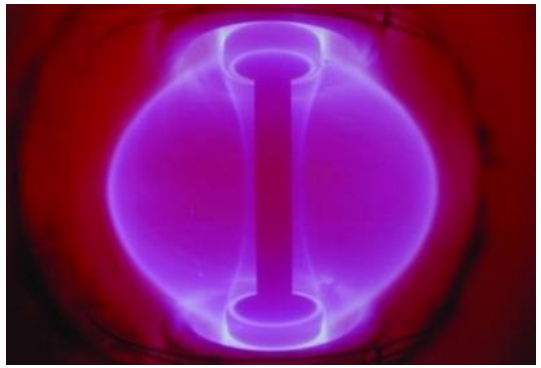


High beta (β), $P_{FUS} \sim \beta^2 B_t^4 V$, so volume (reactor size) can be reduced!



"Apparently the high beta potential of the ST is so great that the physics of this device will not determine its size".

Ron Stambaugh, "THE SPHERICAL TOKAMAK PATH TO FUSION POWER", FUSION TECHNOLOGY VOL. 33 JAN. 1998



Plasma in START, Culham, 1996
H-mode, improved confinement

- Improvements in performance with increased field already demonstrated in first experiments **on ST40**
- Field already increased to 1.5T, and will be 3T next year

Main areas of theoretical studies

- Confinement studies, validation of scalings for STs
- Edge and divertor studies
- Fast particles, heating, CD, alpha confinement
- Reconnection studies (merging-compression formation)

Not covered in this talk:

- HTS studies - engineering
- Materials studies with Imperial College
- Li divertor studies with Oxford University and University of Illinois

Confinement studies

Confinement studies

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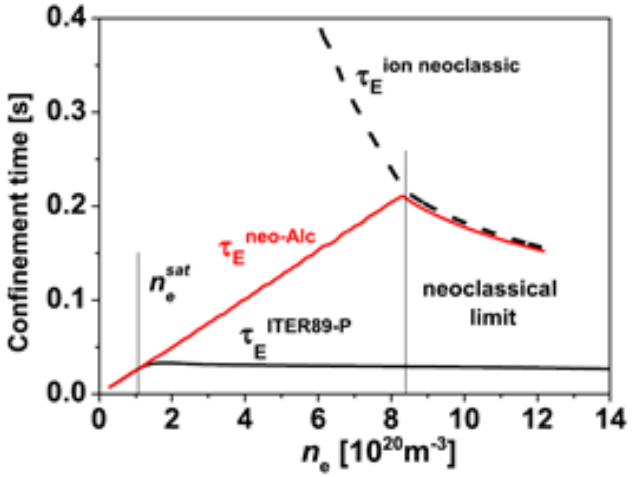
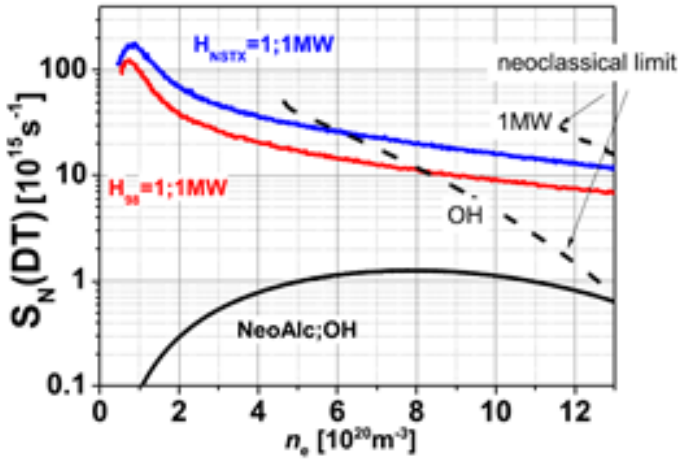
- Transport simulations with ASTRA, NUBEAM and TSC codes have been performed to model ST40 parameters and to support the physics basis of the compact high field ST path to Fusion.
- We show that high confinement regimes with **neoclassical** transport can be expected even when plasma is only ohmically 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

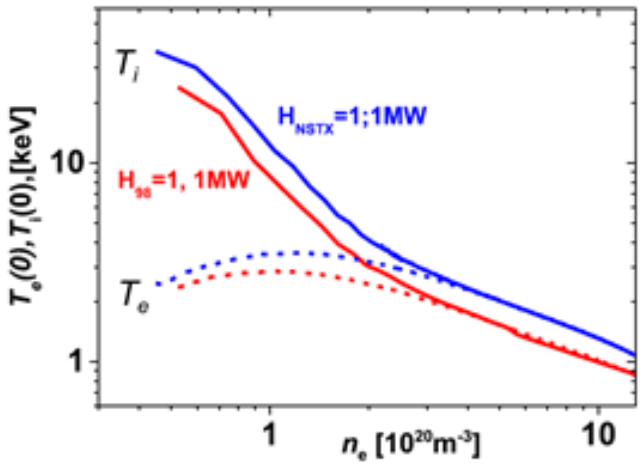
- ST40 can check **applicability of neoclassical theory** in a high field ST
- Can **Q_{fus} ~ 1** be achieved in a high field compact ST?
- Can hot ion mode be achieved in a high field ST?



τ_E vs line averaged density in OH regime



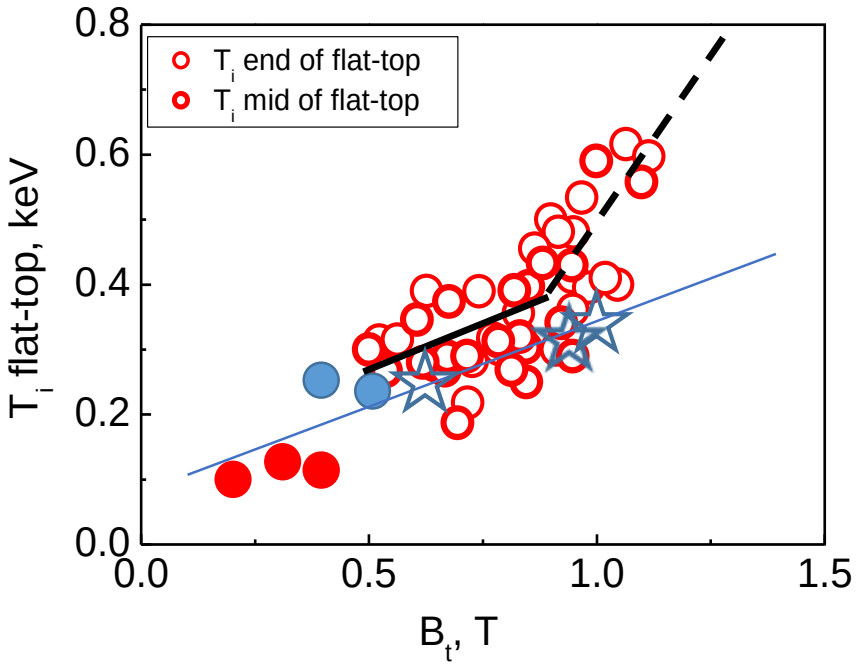
DT neutron yield vs line averaged density with 1MW absorbed power



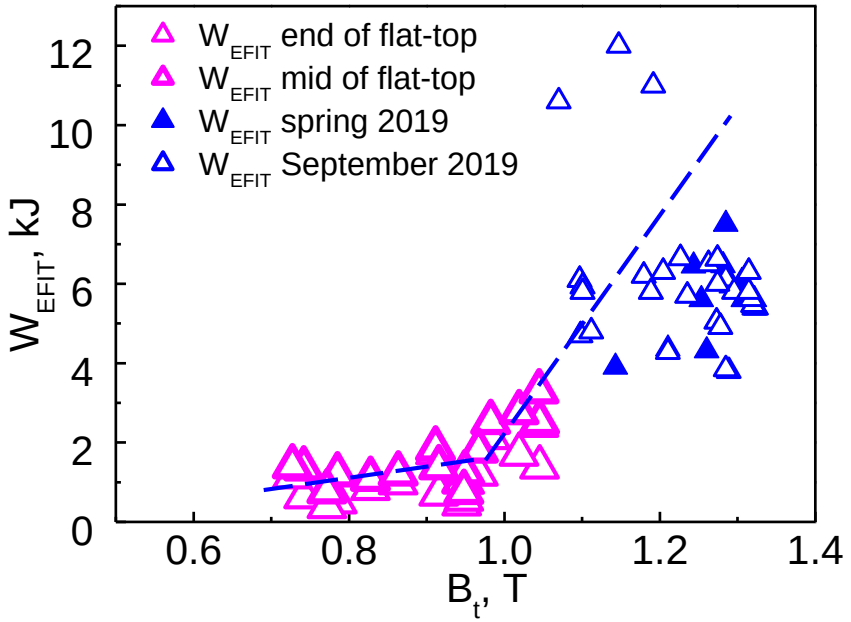
Central T_i, T_e vs line averaged density with 1MW absorbed power

Confinement studies, 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.



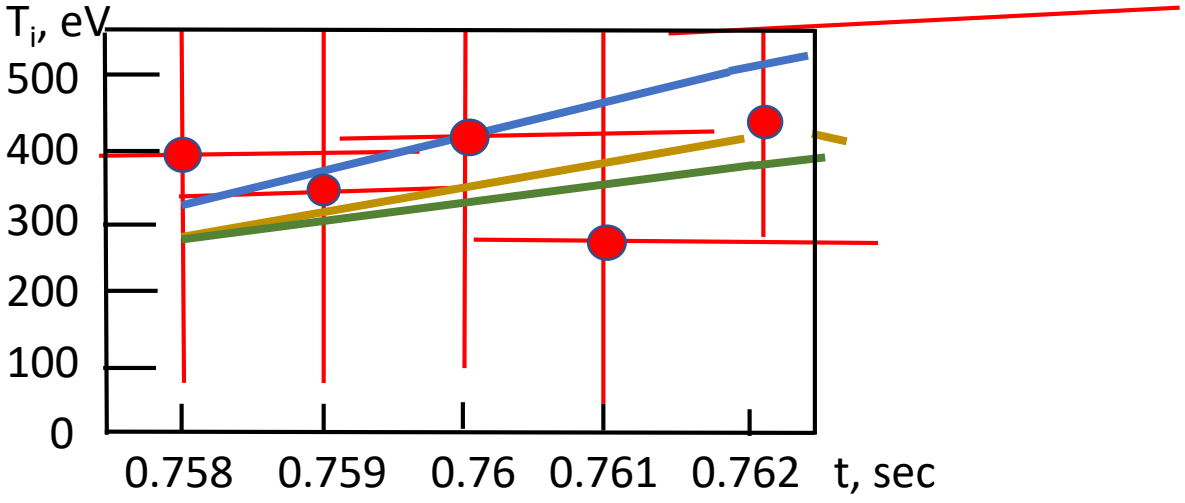
- START
- GLOBUS-M
- Artsimovich for ST40
- ST40

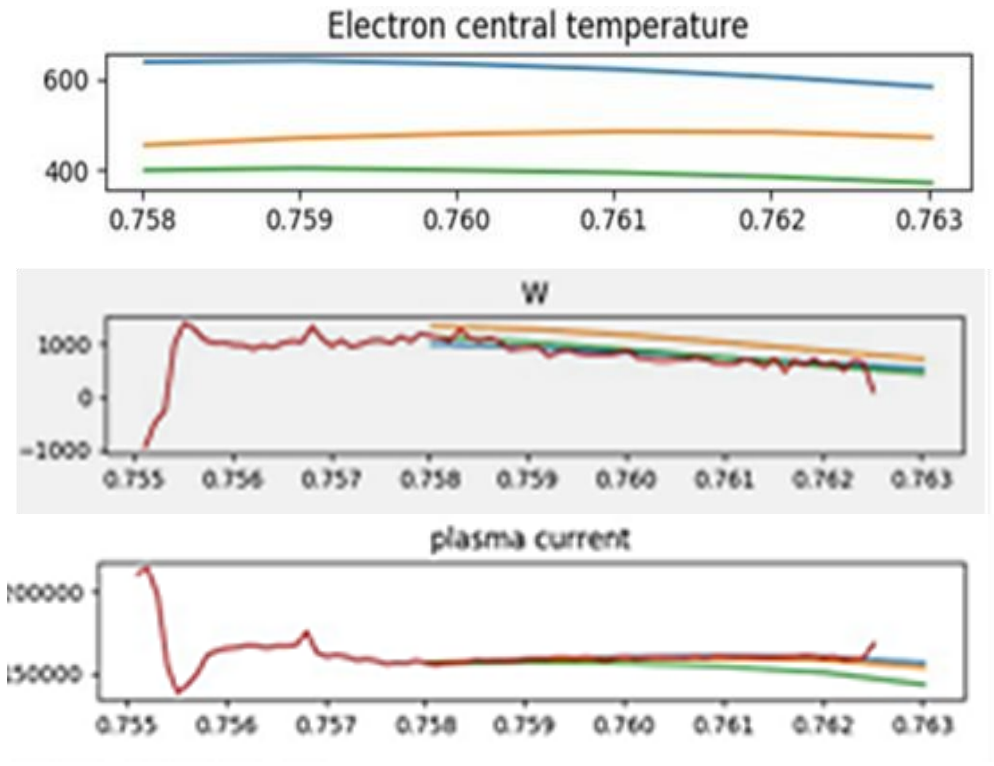


Most recent results confirm confinement improvement at higher TF

Confinement studies, comparison with scalings

- 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;

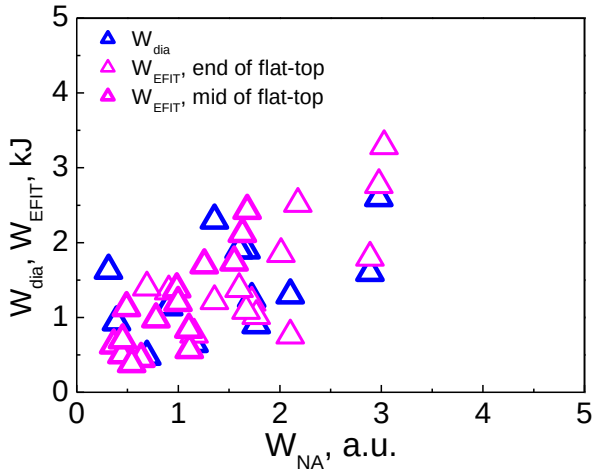




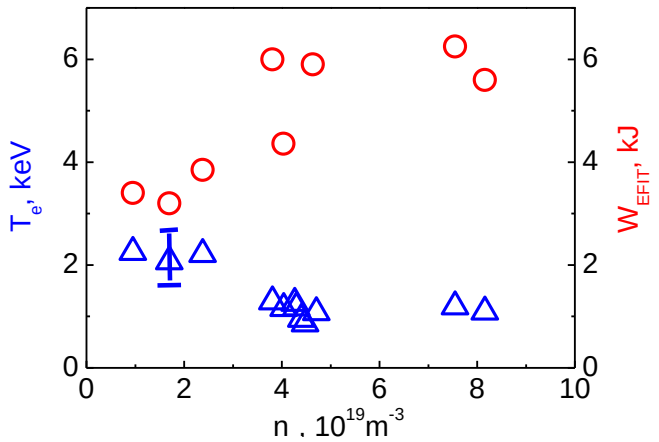
- Closest fit: yellow, n_e = 7 x 10^{19};
- Confinement above NeoAlcator ohmic scaling?
- In latest 200kA 200ms shots confinement was estimated ~ 45-50ms, which is about 7-10 times higher than NeoAlcator scaling prediction

Confinement studies, comparison with scalings

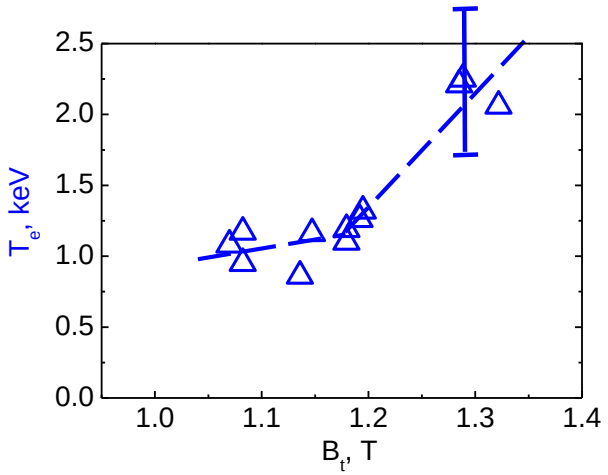
- Experiment shows similar trends as in NeoAlcator scaling, but much better confinement at higher TF
- T_e increases at lower density, in agreement with ASTRA predictions
- Similar increase in T_e with TF but at higher threshold TF than for ions



Comparison of W_{EFIT} and W_{dia} with neoAlcator scaling



T_e and W_{EFIT} vs line averaged density in OH regime

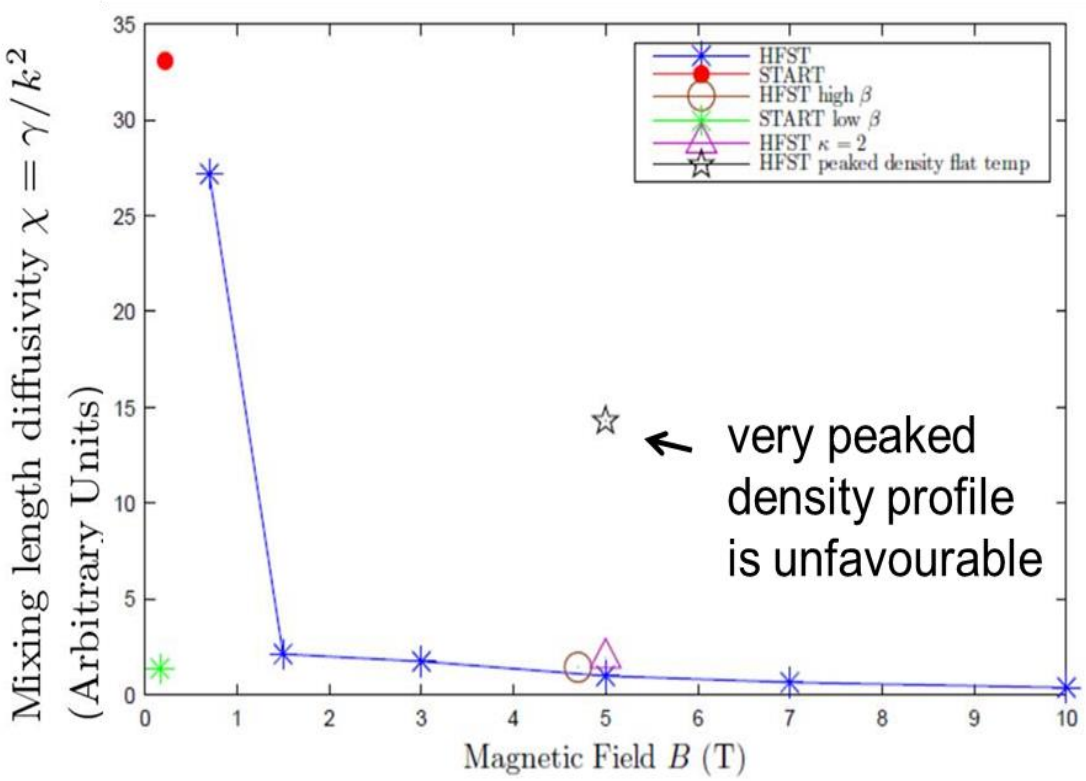


T_e measured with SXR spectrometer vs TF

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

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 GT2 simulations reduction in transport at higher toroidal field in an ST:

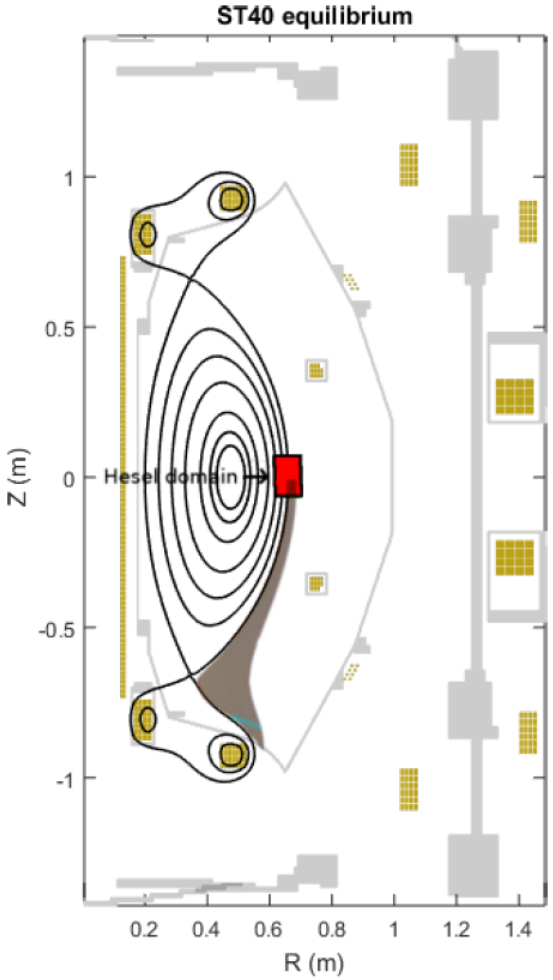


- At **low** magnetic field the mixing length diffusivity is dominated by **electromagnetic** tearing modes; these are **stabilised at higher B_t,** diffusivity then being dominated by **electrostatic** twisting modes.
- no beta or shape dependence at high field
- Threshold toroidal field is quite low,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

Edge simulations

Edge simulations

Map to divertor with EFIT

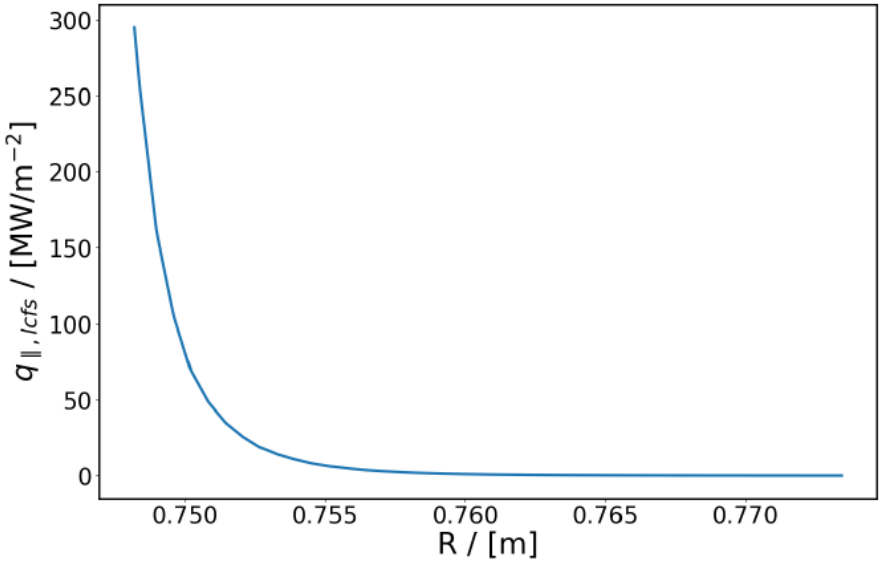


- Evaluate parallel heat flux in ST40 using HESEL[1]
- Determine λ_q from turbulence simulations
- $\lambda_{q,HESEL} = 1.9$ mm for $P_{SOL} = 2.2$ MW
- $\lambda_{q,Eich} = 1.7$ mm for similar conditions
- Range of parameters scanned, $\lambda_{q,HESEL} \in [1.8; 2.7]$ mm

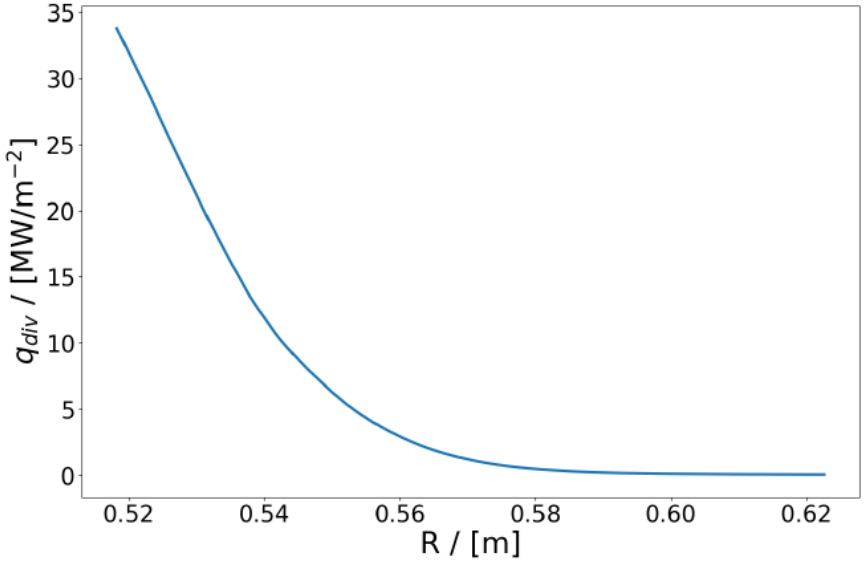
[1] [A. H. Nielsen et. al. PPCF 59 (2017) 025012]

Edge simulations, Power Profiles

Parallel heat flux at LCFS



Parallel heat flux at divertor



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

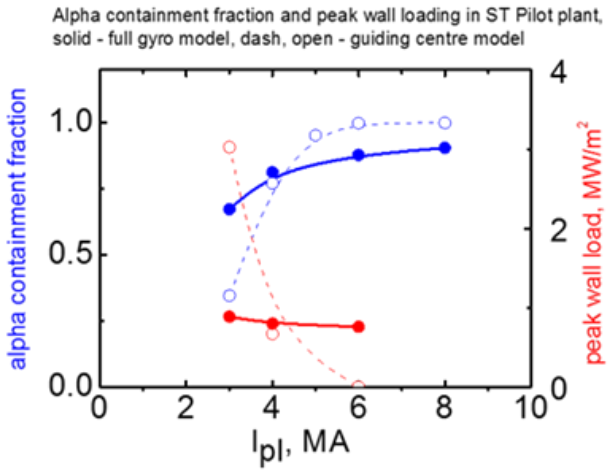
- Large $f_x \rightarrow$ tolerable heat loads at divertor

Fast particles studies

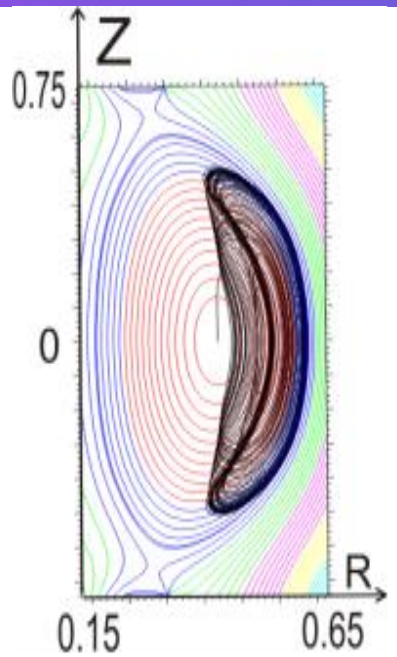
Fast particles studies

- 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.

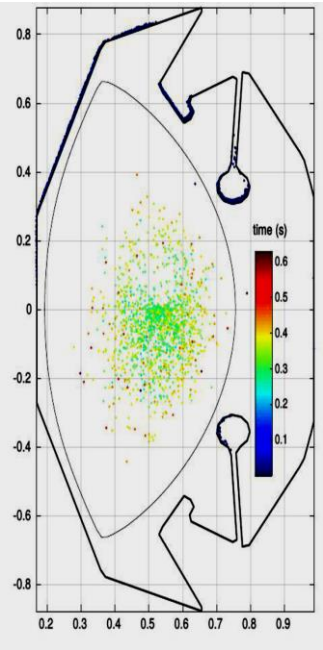
Fast particles studies, *α-particles*



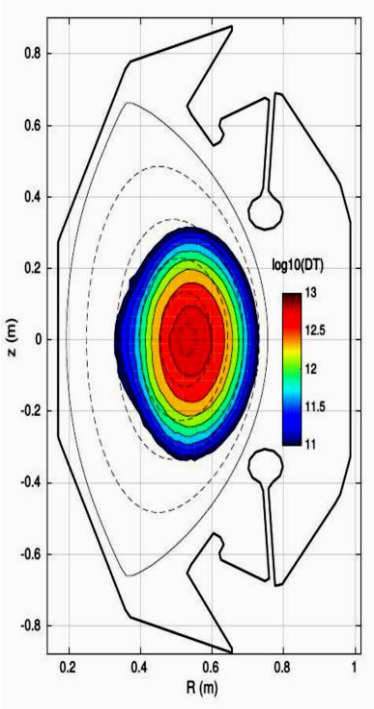
- *Importance of full-orbit simulations for ST reactor*



*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**.*



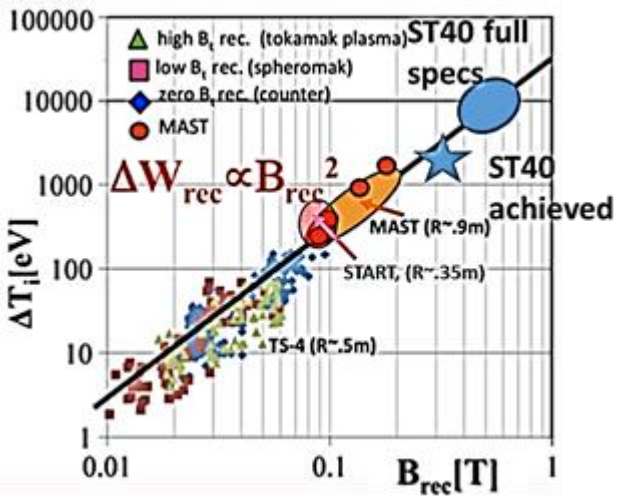
*Fast-thermal TD reaction rate from a DT reaction between 1.01 MeV Tritium slowing down against thermal Deuterium for 1.2T/2MA, $1.1 \times 10^{19} m^{-3}$,1MW NBI. This is the main channel producing 14 MeV neutrons. **ASCOT**.*

Reconnection studies

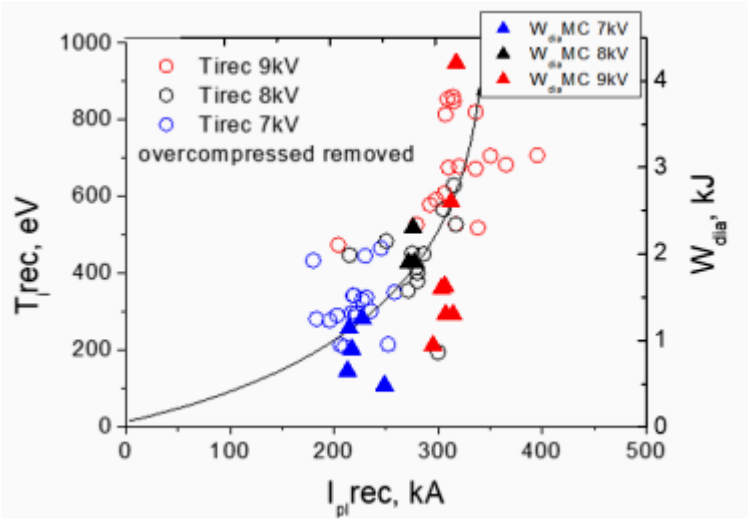
Better use of Magnetic Field: reconnection heating

- 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

- 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 and show temperatures >2keV.



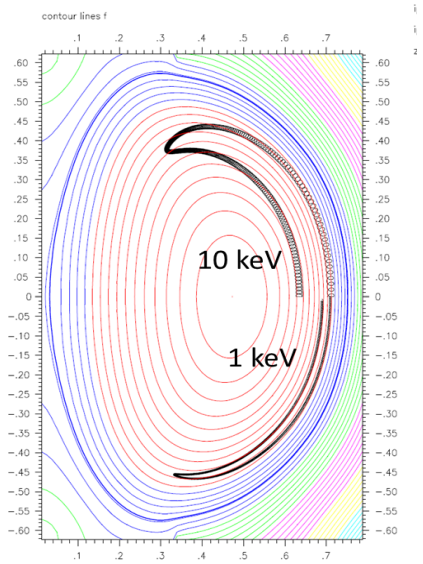
Predictions



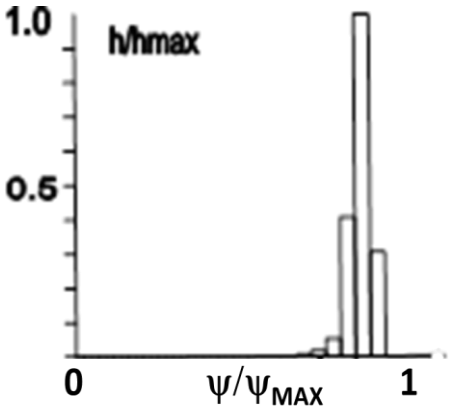
First results: scaling confirmed!

Reconnection heating – injection of fast ions

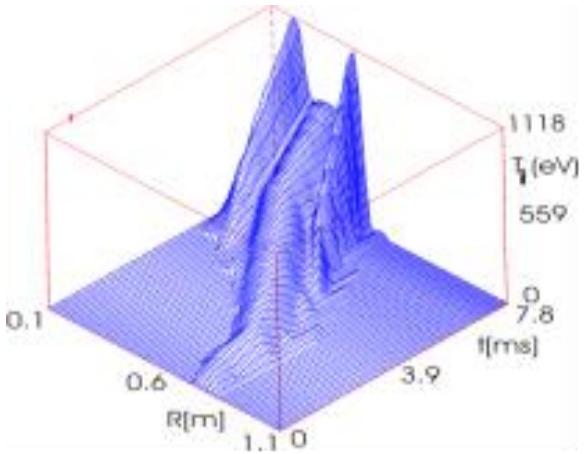
- To model merging-compression process codes NFREYA, TSC and Torus II have been used.
- NFREYA – Monte Carlo simulations are based on the assumption that the ions formed during the reconnection reach the poloidal Alfven energy and are mainly running in co-direction
- Assuming reconnection heating power 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



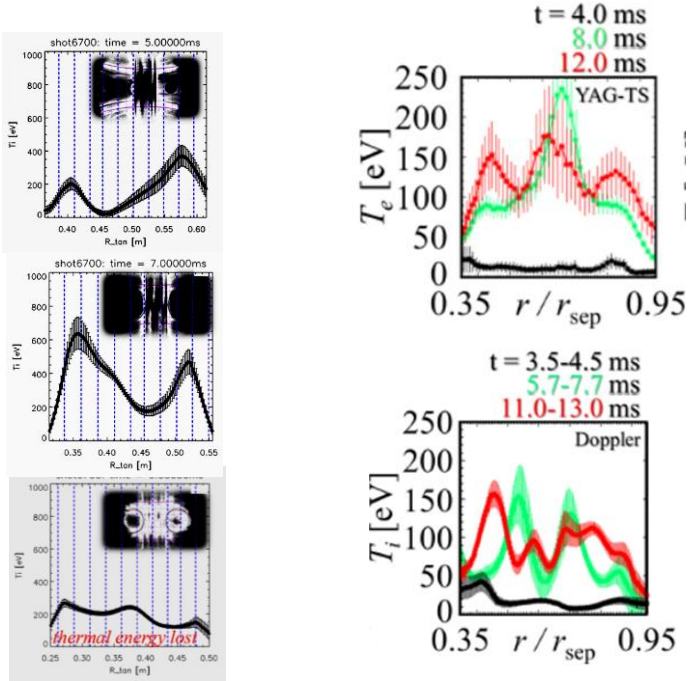
Orbits of the ions produced by reconnection



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

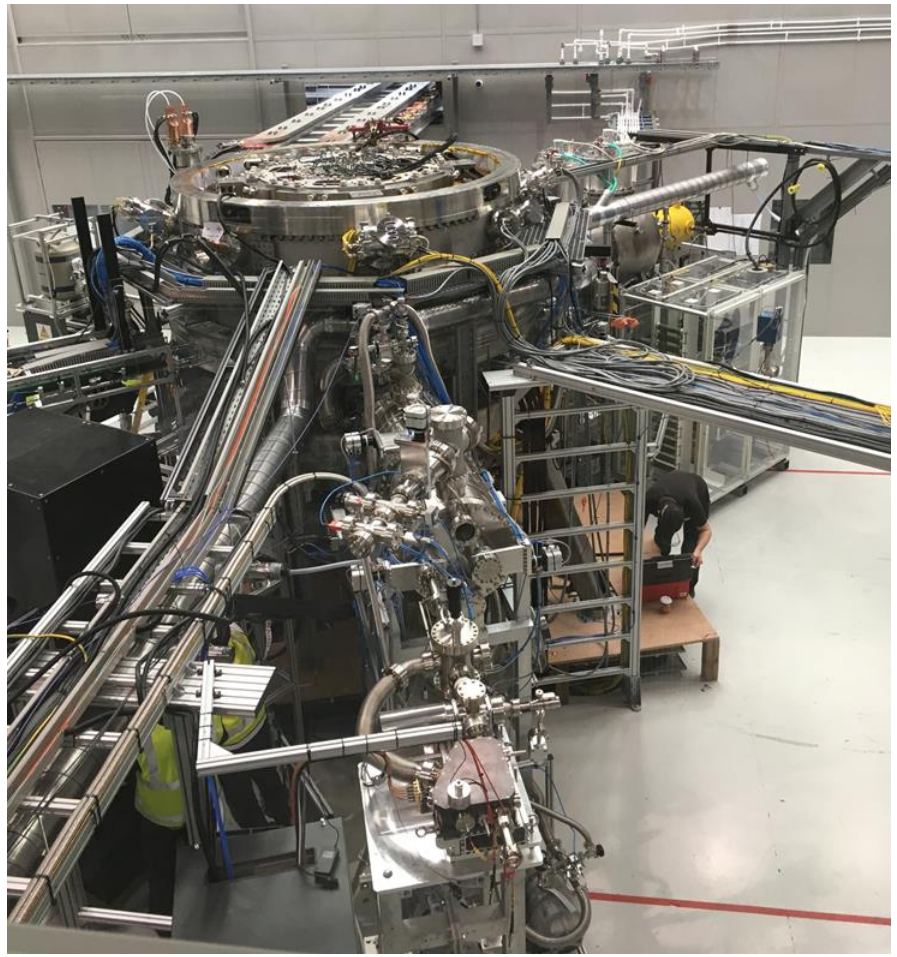
CONCLUSIONS

- **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**

- **More theoretical and experimental studies are needed to support the ST path to Fusion**



- ST40 is the first high field Spherical Tokamak