Merging/compression plasma formation in Spherical Tokamaks

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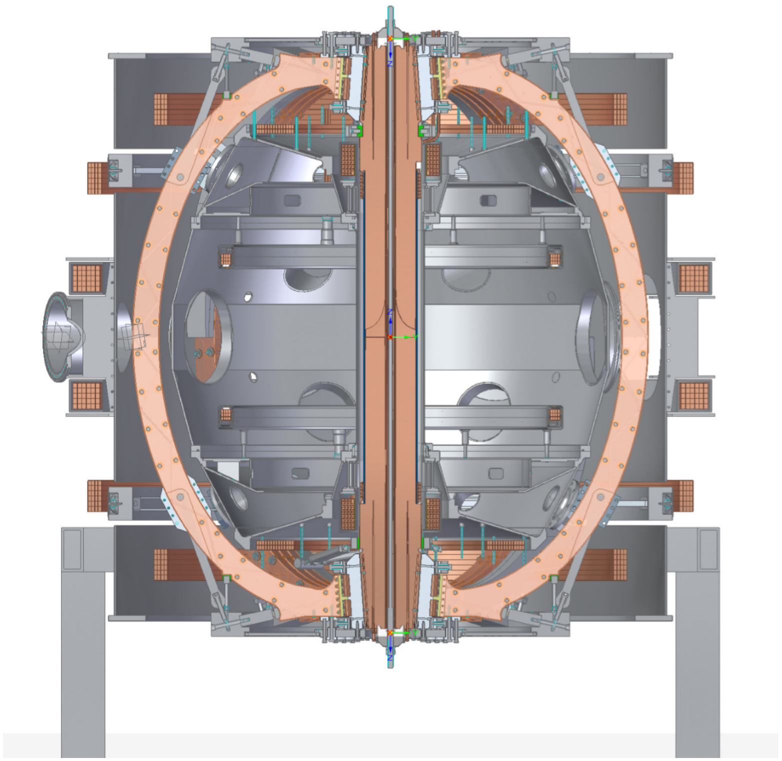
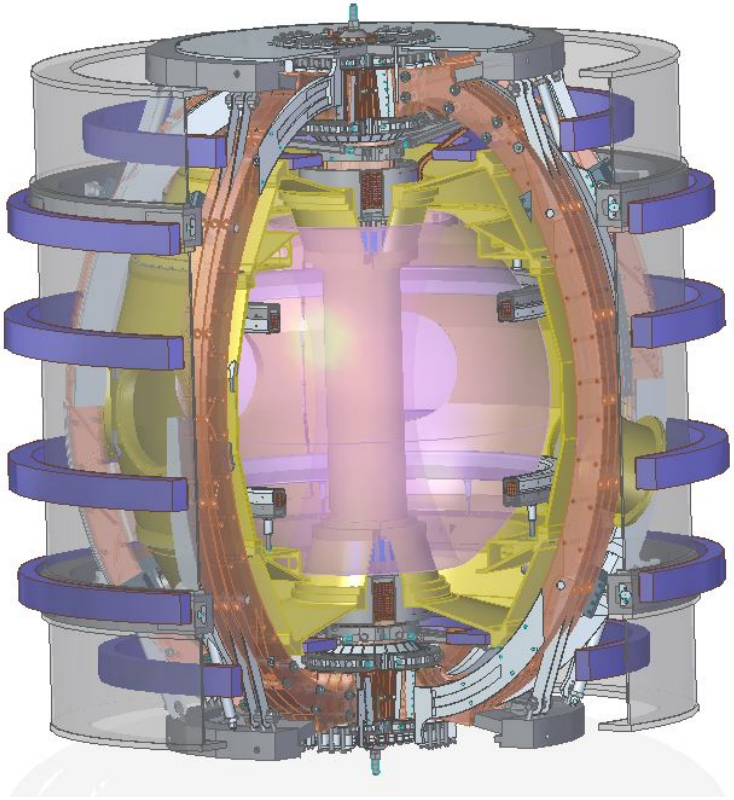
18th International Spherical Torus Workshop (ISTW 2015)
3 – 6 November 2015, Princeton US

Plasma formation in ST40

ST40: 3T/2MA, water or LN2 cooled copper magnet; R_0=0.4 - 0.6m, R/a = 1.6-1.8, k~2.5, DND, NBI and EBW/ECRH/RF heating at Phase II





- ST40 has, like START&MAST, in-vessel merging-compression coils and only small solenoid

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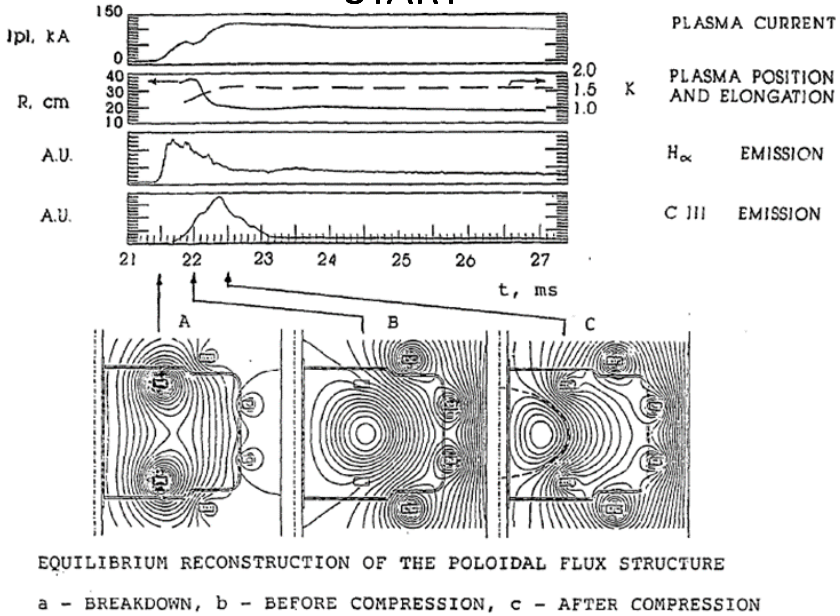
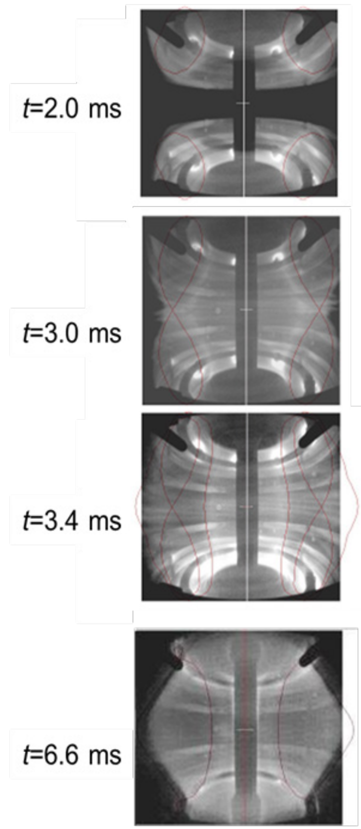
Merging-compression plasma formation

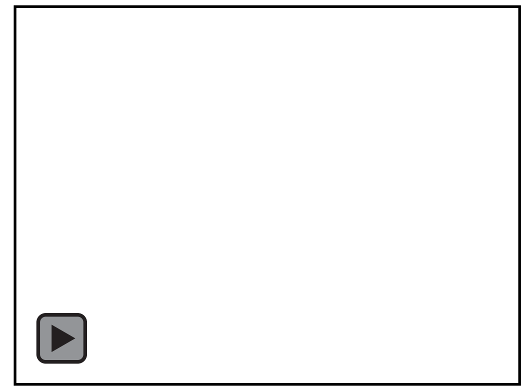
- First used on START, at Culham, in 1991. Successfully applied on MAST to achieve first plasma in 1998. Recently studied in detail on MAST, UTST etc.

START



- 3 stages:
  - *- plasma around coils*
  - *- merging (reconnection)*
  - *- compression*





MAST

- Plasma currents 200-500kA without CS assistance

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Merging-compression in ST40

- First stage – merging and compression

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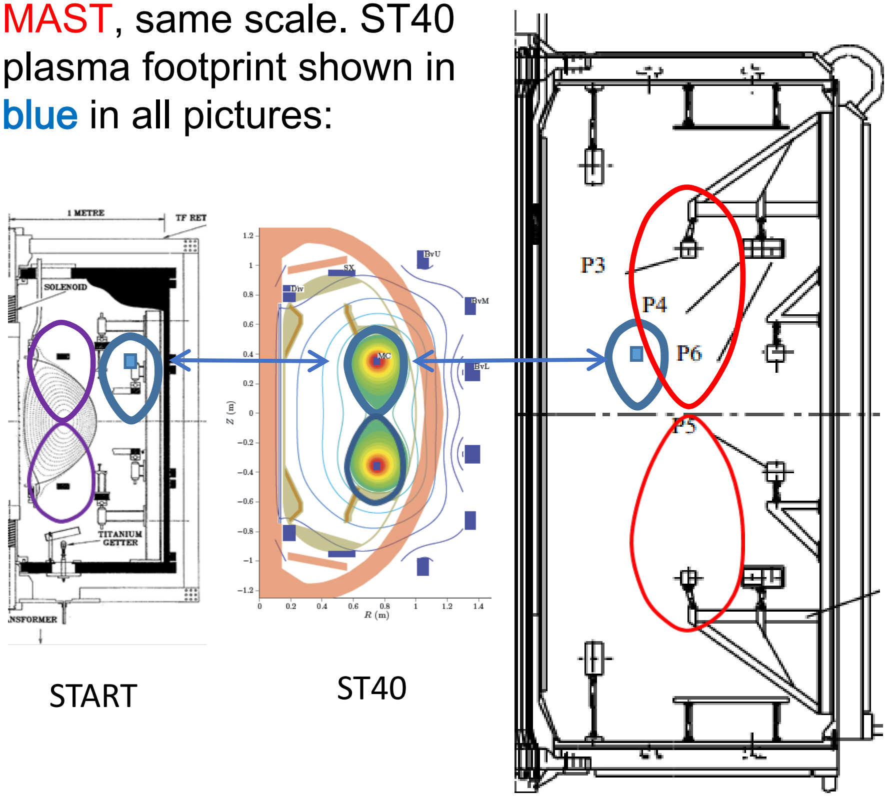
Merging-compression in ST40

- Second stage – DND formation

Merging-compression plasma formation

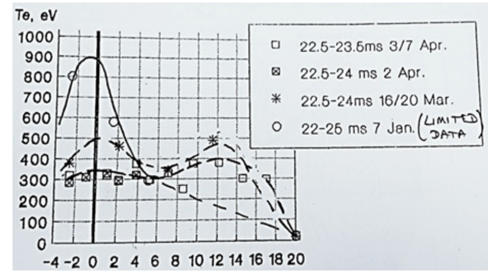
M/c on START, ST40 and MAST, same scale. ST40 plasma footprint shown in blue in all pictures:



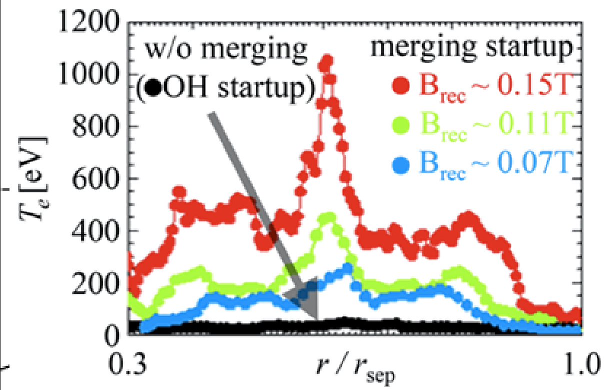
START

ST40

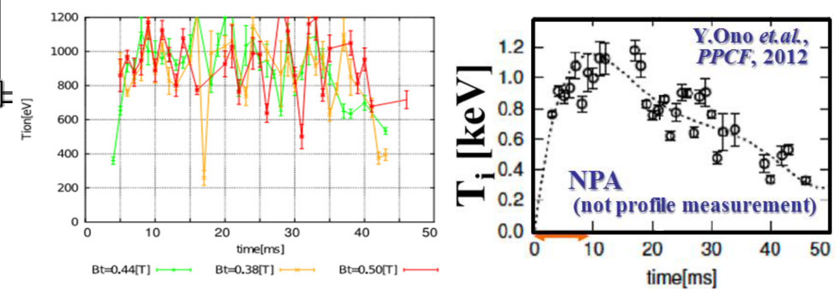
MAST



START, SiLi data



MAST, TS data



MAST, NPA data

- START and ST40 are similar in geometry
- ST40 has more compression

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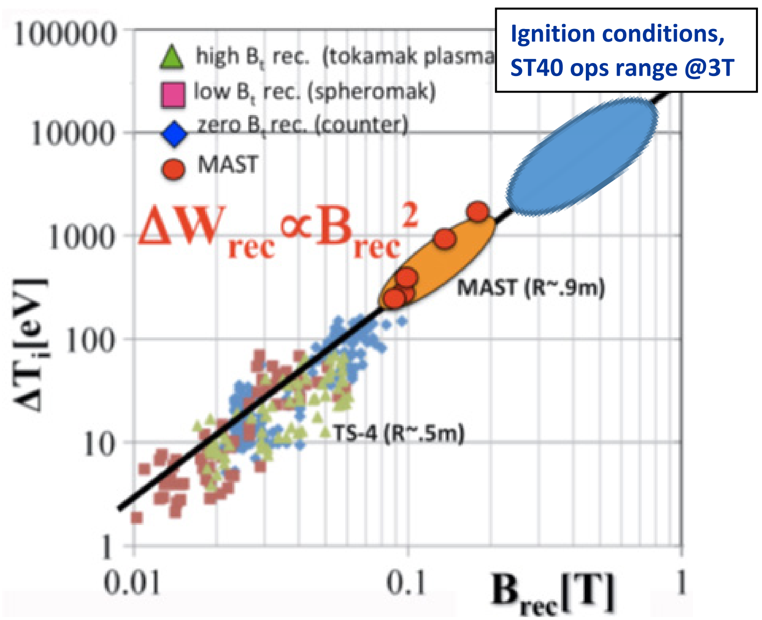
- START and MAST demonstrated 1keV temperatures

Merging-compression plasma formation

- ST40 Phase 1 (2016) objective:
  - Demonstration of merging/compression plasma formation and achievement of high performance already during formation phase
- Why this may be exciting:



- 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

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- Reconnection scaling predicts 10keV in ST40

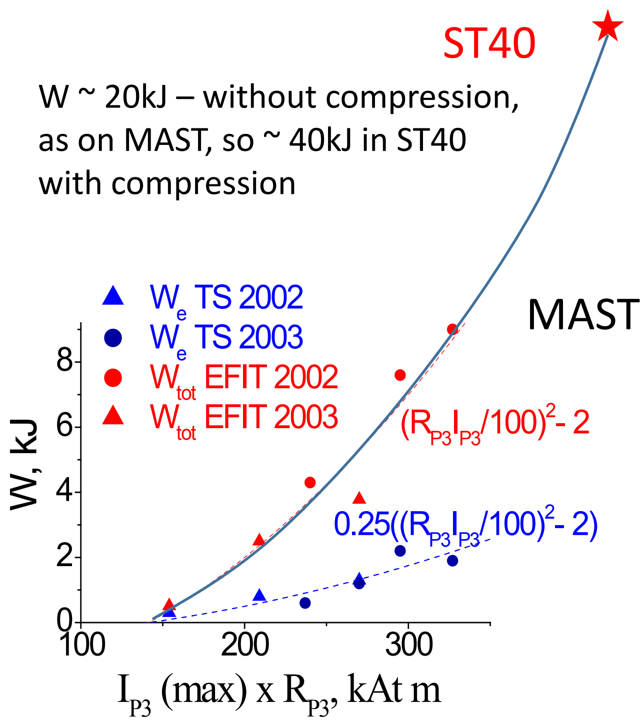
Predictions based on START and MAST data

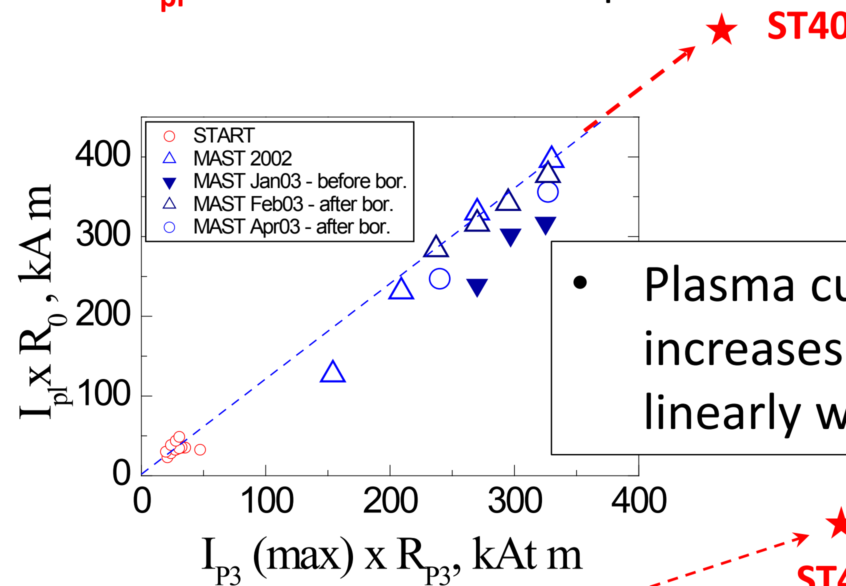
- **M/C performance:**

Plasma energy increases ~ $(R_{P3}\, I_{P3})^2$

ST40: R_{P3}=0.75m, I_{P3}=600kAt,
I_{pl} **~ 750 kA** before compression

W ~ 20kJ – without compression, as on MAST, so ~ 40kJ in ST40 with compression

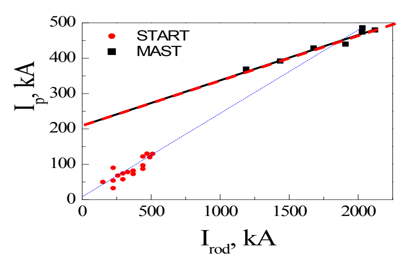




- Plasma current increases linearly with I_{P3}

ST40

I_{pl}**~ 1MA before compression**



M Gryaznevich, *Formation in STs*, IAEA TM on ST, St Petersburg 3-6 Oct 2005

Difference in W_e and W_{tot} could be partly attributed to ion heating

- Plasma current increases with TF

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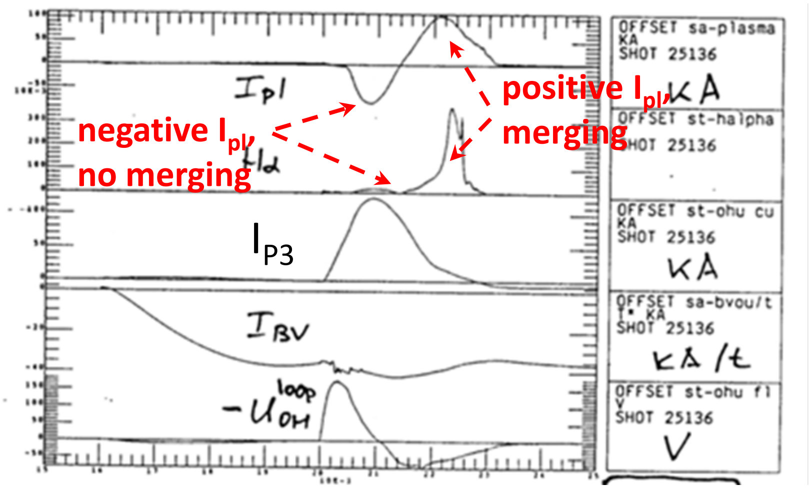
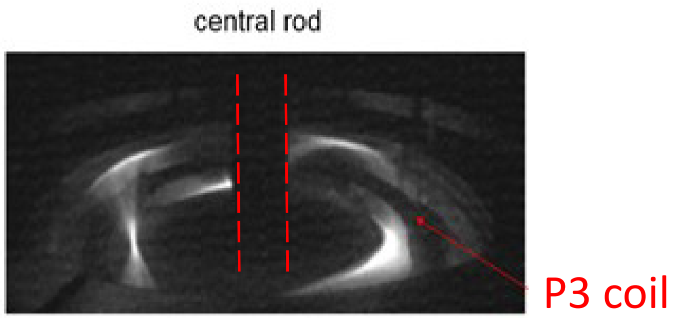
- Results from START and MAST are encouraging

Stage One: plasma rings around P3 coils

- Two plasma rings are formed around in-vessel (P3) coils when current in these coils rapidly changes. Duration of this stage – from few to tens of ms.
- Plasma rings merge when current in P3 coils decreases.
- Plasma in these rings is more like "levetron" plasma, equilibrium is supported by combination of TF and P3 current. Applied vertical field plays little role!



START: applied BV does not affect plasma current in rings



Indeed, plasma around coils has clear 3D structure (MAST)

- Magnetic energy of two rings converts into kinetic during reconnection, so high initial current is needed

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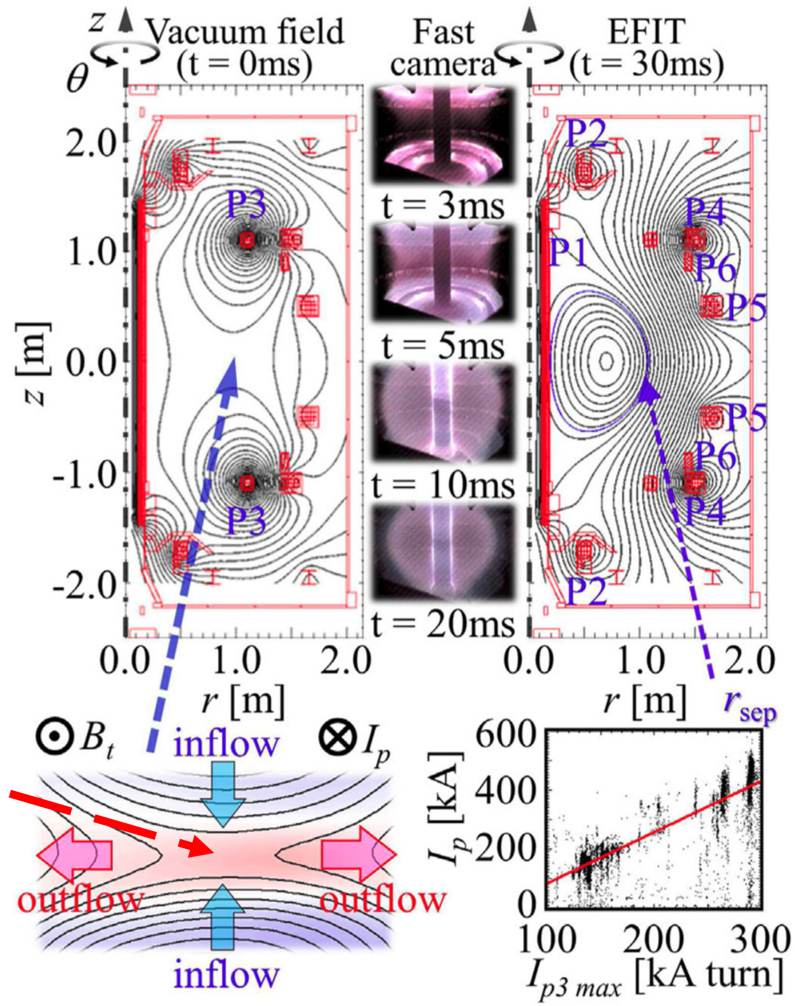
Stage Two: merging

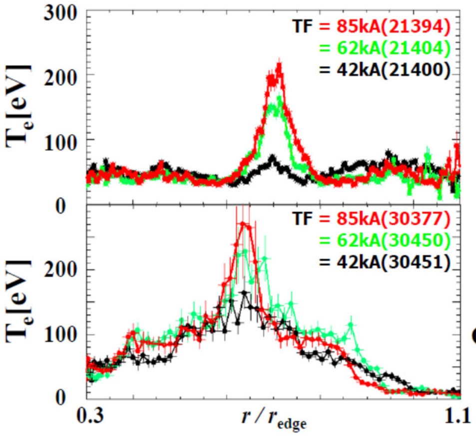
- Magnetic energy of two plasma rings is converted via magnetic reconnection, when plasma rings merge, into kinetic energy of the final single torus plasma.
- Theory predicts that up to 90% of the poloidal magnetic energy can be converted into kinetic energy, mainly going into ions.
- Magnetic energy released by reconnection (8-15MW estimated on MAST) may both heat the plasma and drive plasma flows – the latter may also dissipate to provide further heating (slow shock model).
- Current sheet formed at X-point provides anomalously high electron heating. 2D detailed TS measurements on MAST confirm formation of the current sheet.



Tanabe et al, PRL November 2015

- Efficient heating of ions and electrons

Stage Two: heating due to merging

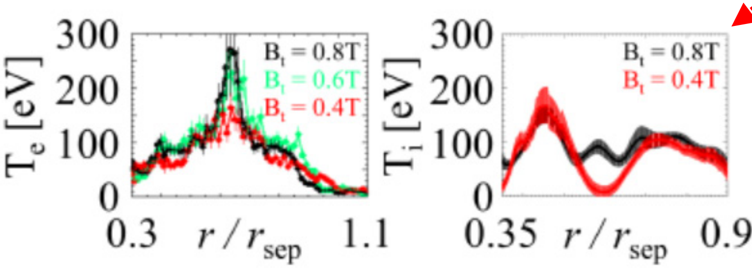


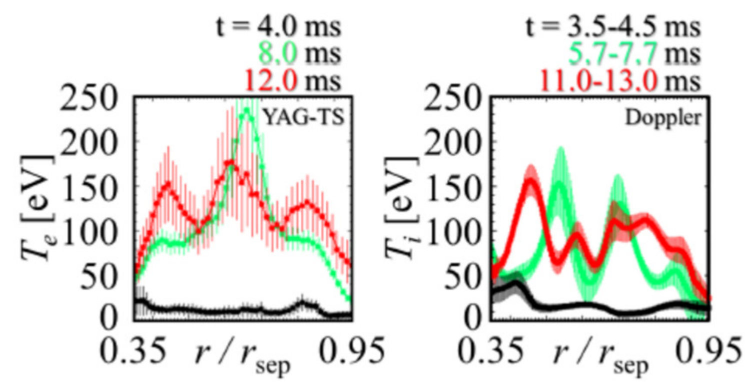
Without centre solenoid

With solenoid

Reconnection + Ohmic induction hybrid startup

- Electron heating inside current sheet hot spot is enhanced with TF on MAST
- Adding loop voltage from central solenoid helps to form “shoulders” outside hot spot
- However, ions heating from reconnection does not depend on TF (as predicted)





- Evolution after merging is set by exchange between ions and electrons. This explains “triple-peak” profiles formation. τ^E_{ei} ~ 4 – 10 ms

- Temperature evolution is very complicated

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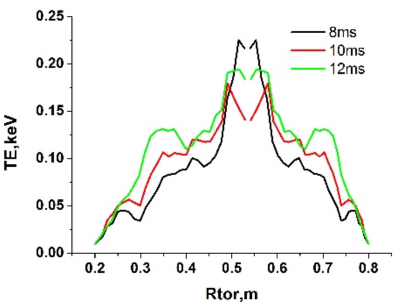
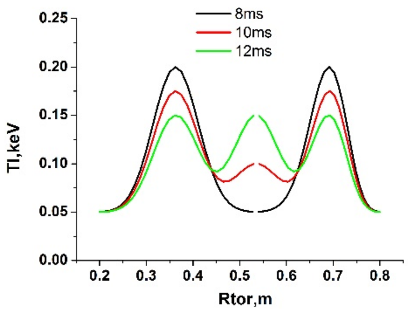
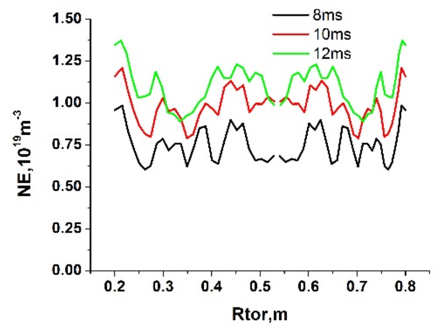
Understanding of post-merging phase

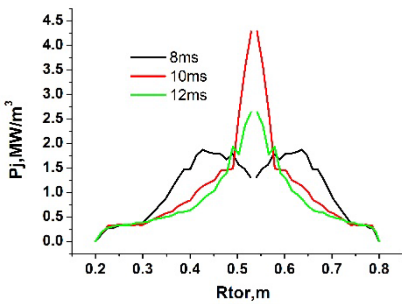
- ASTRA modelling of post-merging phase has been performed using experimental data from MAST ##21374-21380 & ##30367-30380

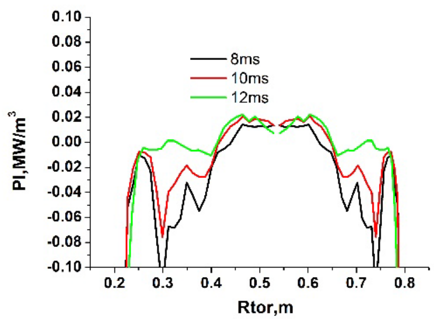


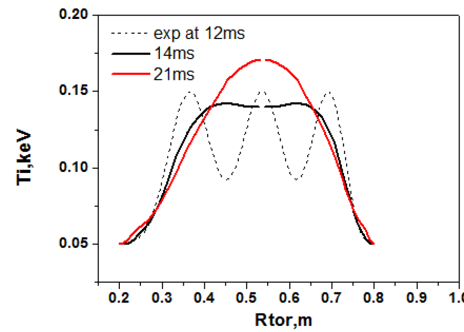




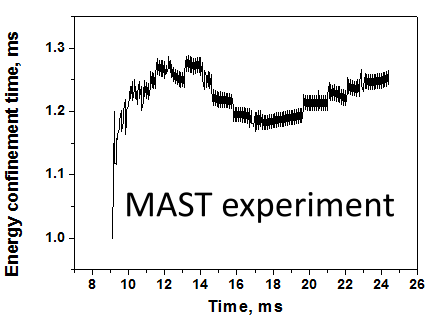
MAST experiment: transport model adjusted to fit experimental profiles

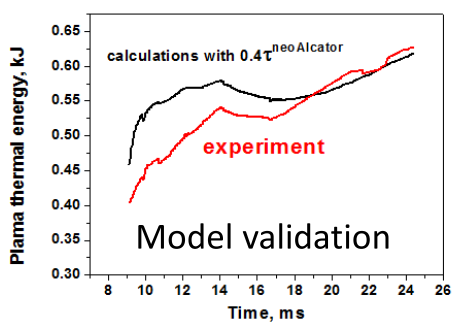






ASTRA modelling: electron heating, ion heating, T_i evolution





- Confinement did not degraded during post-merging evolution (experiment)
- Neo-Alcator scaling is in good agreement with experiment, so can be used for predictions of ST40 m/c

- 3-peak profiles naturally evolve to "normal plasma"

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Stage Three: compression

- Adiabatic compression along major radius has been investigated in detail on ATC, TUMAN-3, TFTR, T-13.
- Confinement time, calculated using ASTRA validated on well-diagnosed m/c plasmas on MAST, exceeds 10ms, so compression may be not too fast.
- Detailed studies of compression on START show doubling of the plasma current when major radius changes from 40cm to 20cm, confirming I_{pl}~1/R rule.
- Vertical position control may be an issue during compression (as observed on ATC). However as compression is relatively slow, feedback system should provide an efficient position control.

- **ST40 is aiming at several keV temperatures and MA-level plasma currents to be achieved using merging-compression**

- Adiabatic compression may double plasma current

CONCLUSIONS

- "two merging STs with B=1-3T, n=10^{20}m^{-3} will be transformed into an ST with T»20keV within reconnection time." Y. Ono, et al,*"Direct Access to **Burning Spherical Tokamak** Experiment by Pulsed High-Power Heating of Magnetic Reconnection"*, 20th IAEA Fusion Energy Conference 2004.
- "We, Japan-UK merging team are now planning to produce two merging STs with B_{rec} > 0.4 T to heat ions over 5keV (**alpha-heating region**) without using *any* additional heating." Y. Ono et al, PoP 2015.

- First plasma in ST40 is expected in 2016

Back-up slides

- First plasma in ST40 is expected in 2016

Who are we?

- Tokamak Energy Ltd is a private company funded by private investors, it is based at Culham, UK

Who are we?

- Two small tokamaks are operating at TE Ltd Milton Park site: Cu ST25 and full-HTS ST

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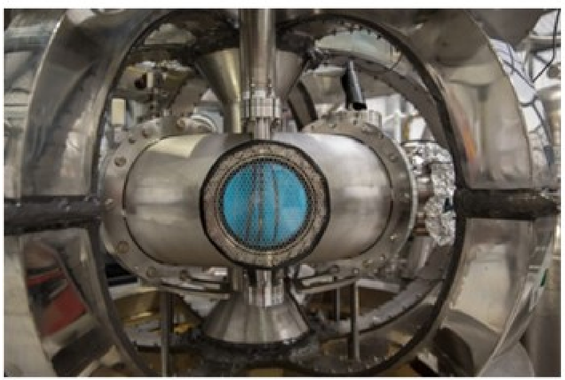
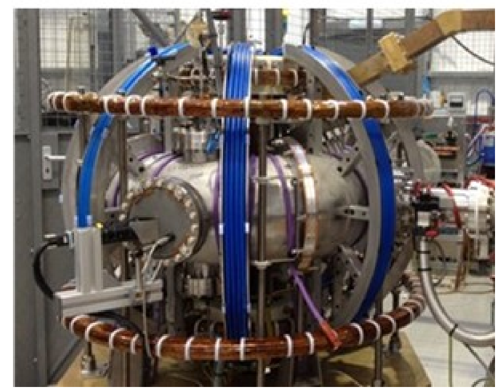
Tokamak Energy Tokamak Engineering Centre





- Two small tokamaks are operating at TE Milton Park site, third tokamak under construction, 3T/2MA ST40

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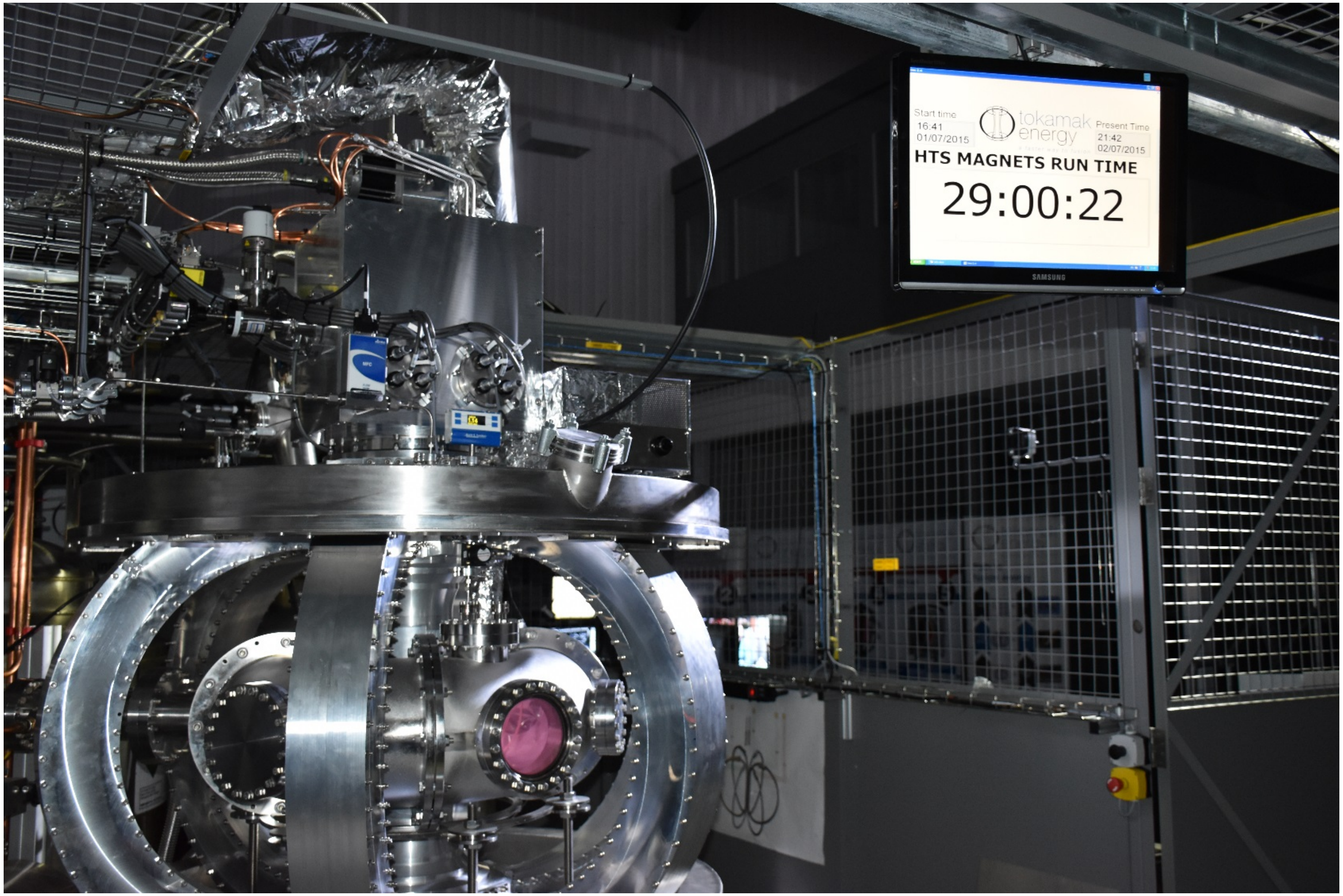
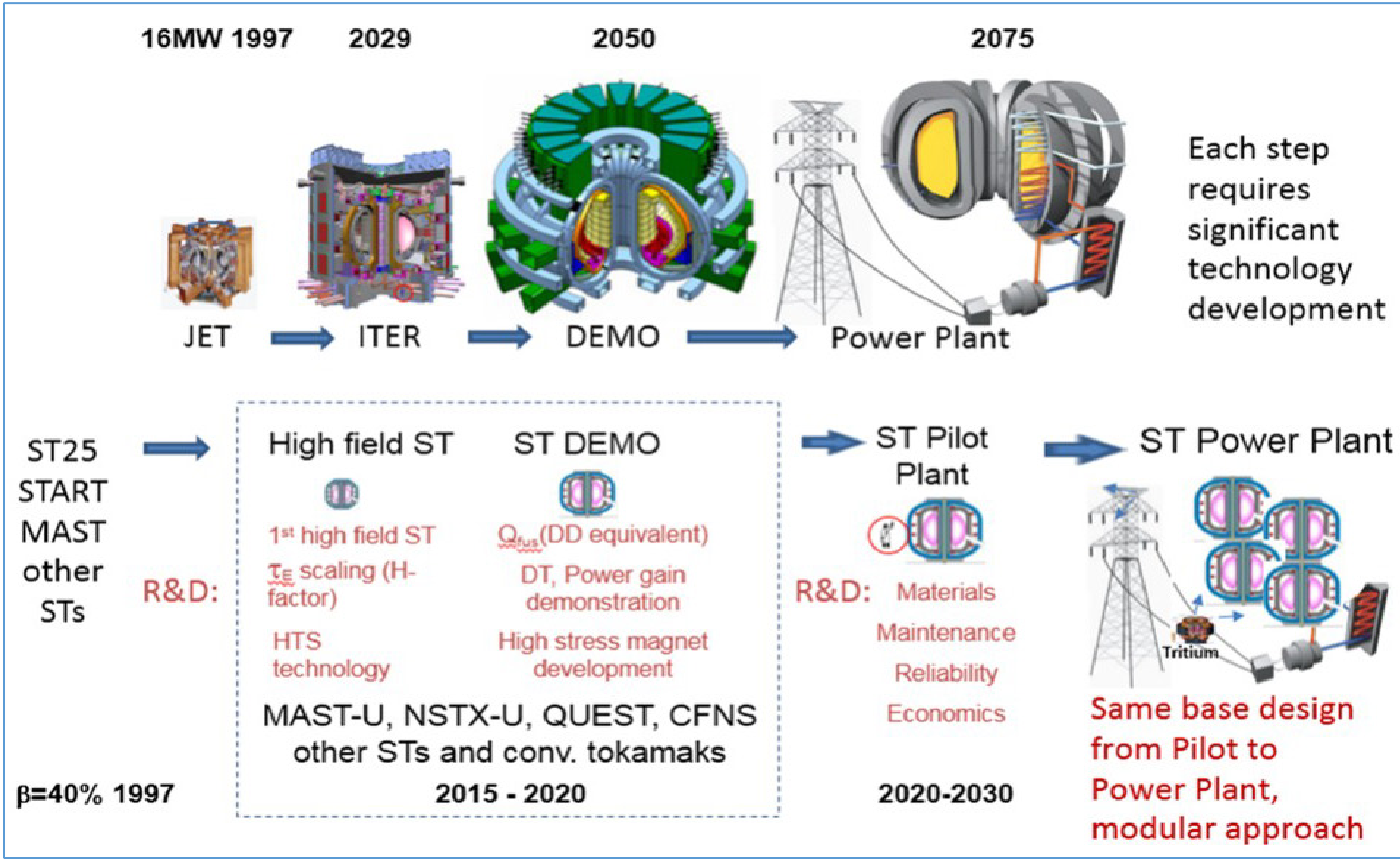
ST25(HTS): world's first all-HTS tokamak



- Summer 2015, 29h RF discharge, now with cool head.

What is our goal? TE Path to Fusion



- Our goal is demonstration of electricity production in a fusion reactor based on high field ST

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TE Path to Fusion, why compact high field ST?

*"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

See also A Costley et al, " On the power and size of tokamak pilot plants and reactors", Nuclear Fusion 55 (2015) 033001

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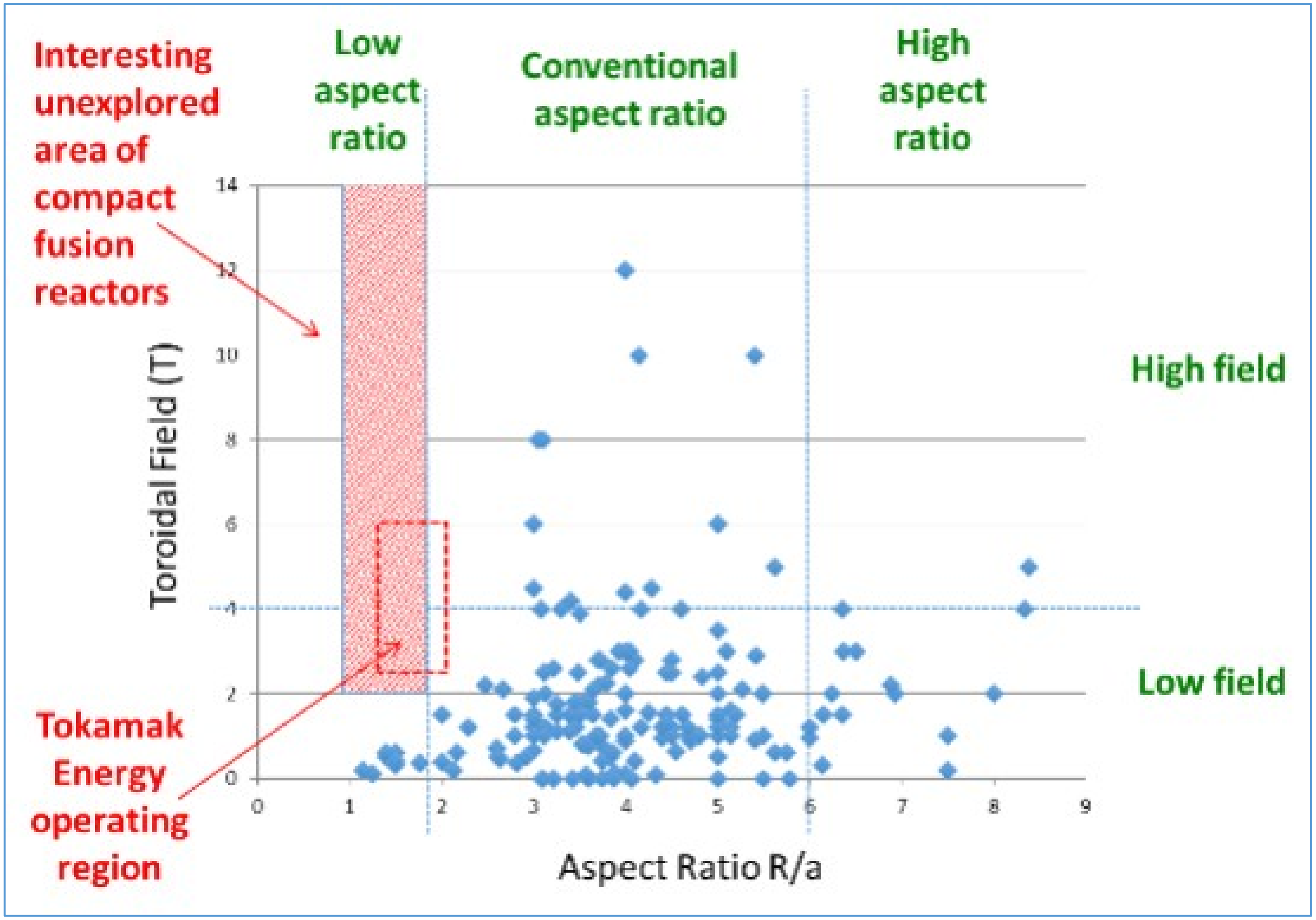
- High field ST reactor path has been proposed in 90th

Why we are building ST40?



- High field in ST is a real challenge! That is why we need to build it.

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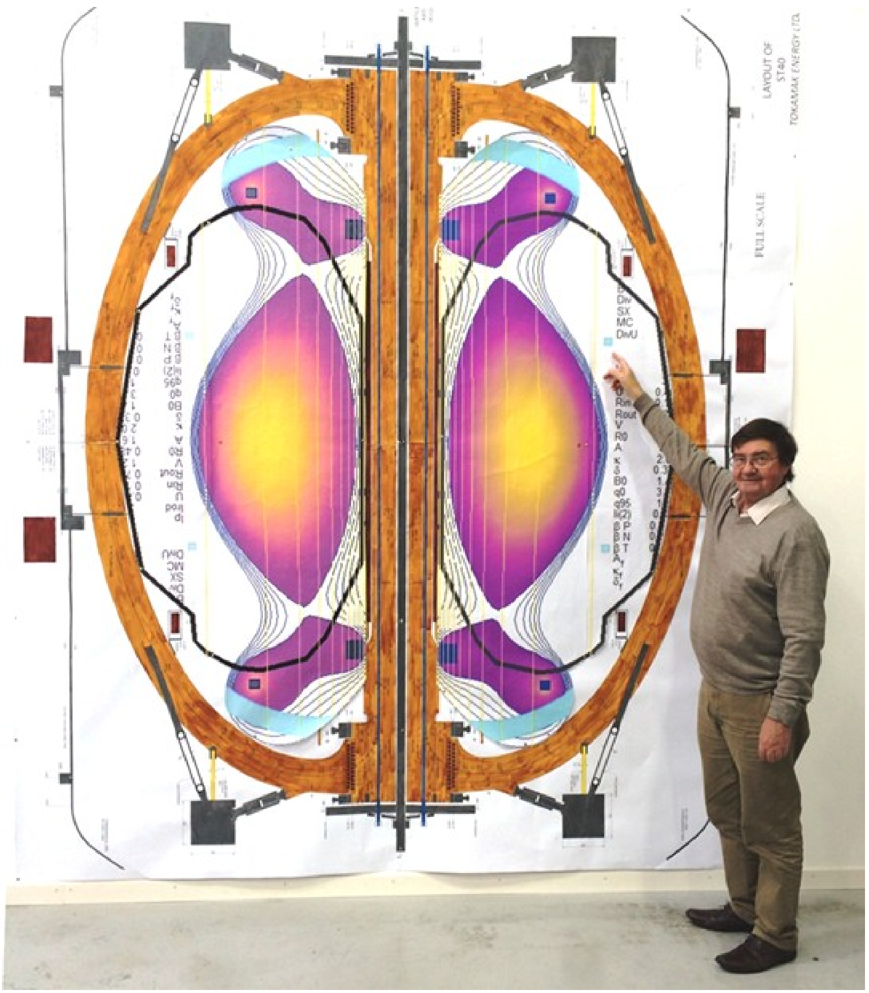
ST40 project



Main features:

- High toroidal field up to 3T, water or LN2 cooled copper magnet
- Plasma major radius 0.4 - 0.6m, R/a = 1.6-1.8
- Moderate elongation (κ~2.5) and triangularity (δ~0.3), DND
- Plasma current up to 2MA, merging/compression plasma formation
- NBI and EBW/ECRH heating
- Possibility of DT ops

- To be constructed in 2016 at Milton Park TE Ltd site

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