

Merging/compression plasma formation in Spherical Tokamaks

Mikhail Gryaznevich

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Plasma formation in ST40

ST40: 3T/2MA, water or LN2 cooled copper magnet; R₀=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 mergingcompression coils and only small solenoid

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.





Plasma currents 200-500kA without CS assistance

Merging-compression in ST40





• First stage – merging and compression

Merging-compression in ST40





• Second stage – DND formation

Merging-compression plasma formation



ST40 has more compression

MAST, NPA data



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 ~ B², and experimental data from START, MAST and Japanese devices, plasma in ST40 should show ignition parameters (nTτ) with temperatures ~10 keV



Reconnection scaling predicts 10keV in ST40

Predictions based on START and MAST data



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!





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

START: applied BV does not affect plasma current in

rings



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

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



- Evolution after merging is set by exchange between ions and electrons. This explains "triple-peak" profiles formation. $\tau^{E}_{ei} \simeq 4 - 10$ ms
- - Temperature evolution is very complicated

- 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)





Understanding of post-merging phase

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



a faster way to fusion

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"

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



CONCLUSIONS

- "two merging STs with B=1-3T, n=10²⁰m⁻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.



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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

Tokamak Energy Tokamak Engineering Centre





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

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

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



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

Why we are building ST40?







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