東京大学
THE UNIVERSITY OF TOKYO

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Will the MHD model coupled with plasma diagnostics be able to reconstruct out of reach core plasma parameters?

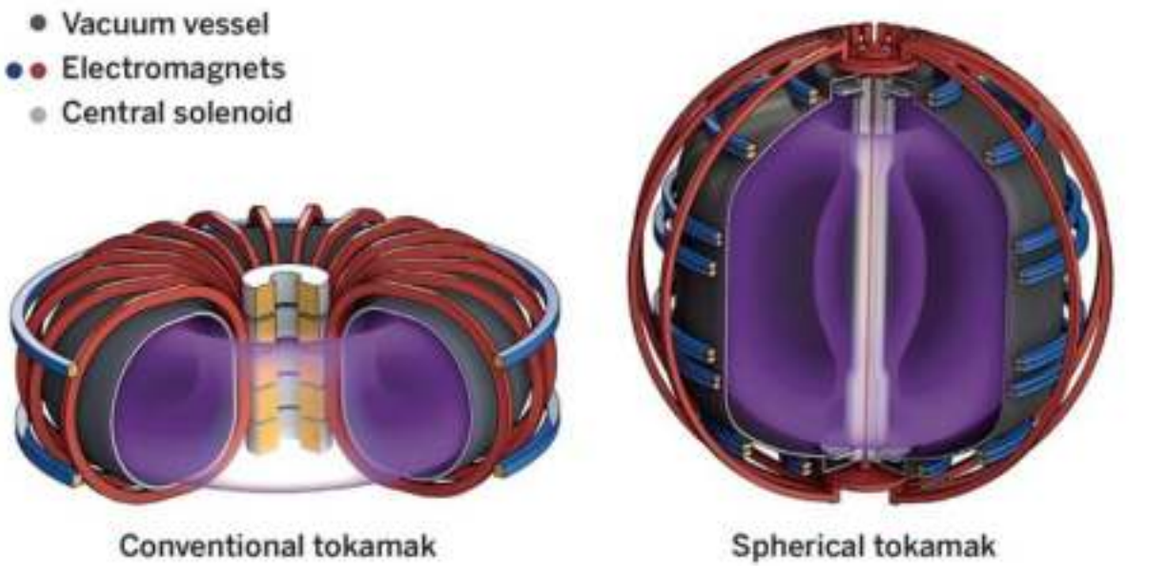
Tara Ahmadi (University of Tokyo)
Yasushi Ono, Hiroshi Tanabe, Yunhan Cai, and TS-6 team

Special thanks to ST-40 team

Nov. 4th 2022

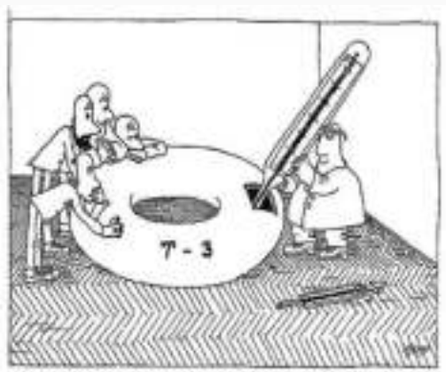
Tokamak and Spherical Tokamak

The **magnetic topology of the spherical Tokamak is same as that of the Tokamak**, with a toroidal field generated mainly by toroidal field coils and a poloidal field mainly by plasma current.



Changing the shape of a fusion reactor from the traditional doughnut to an apple improves plasma stability (higher safety factor) and heat retention (higher plasma β) but requires the magnets that **hold the plasma in place**.

The issues related to the magnetic configuration inside the fusion devices are crucial.



Magnetic Diagnostic Systems

The magnetic diagnostics are the essential part of both the operation and the physics experiments in any magnetic confinement devices.

For the **measurement of local magnetic field**:

- axis-symmetric poloidal flux loops,
- diamagnetic-flux loops,
- magnetic probes,

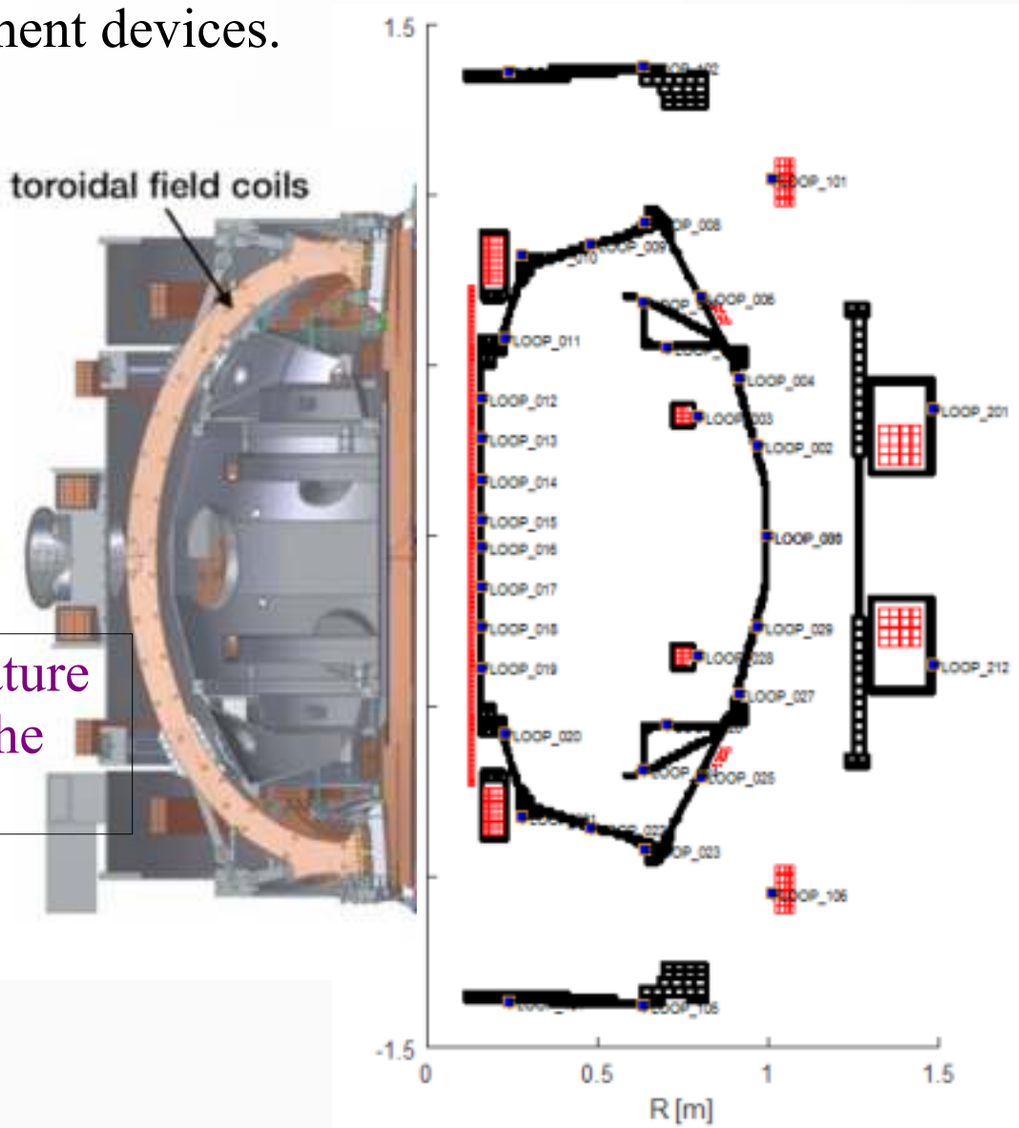
saddle loops.

For the measurement of **coil and plasma current**:

- Rogowski loops.

In high β experiments, due to the high plasma temperature inside the vacuum vessel, it is impossible to install the magnetic diagnostic systems.

Only external magnetic field is measured!

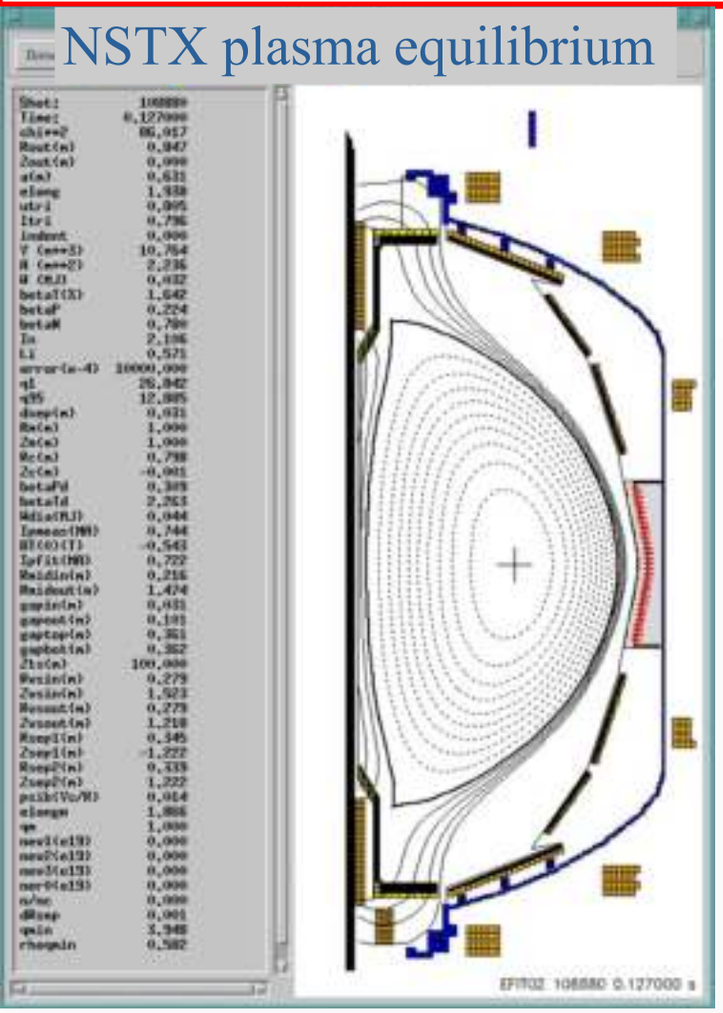


Internal from External?

Unfortunately, the plasma will not just sit there.
There are gas and electromagnetic pressures forcing the plasma to grow in radius.

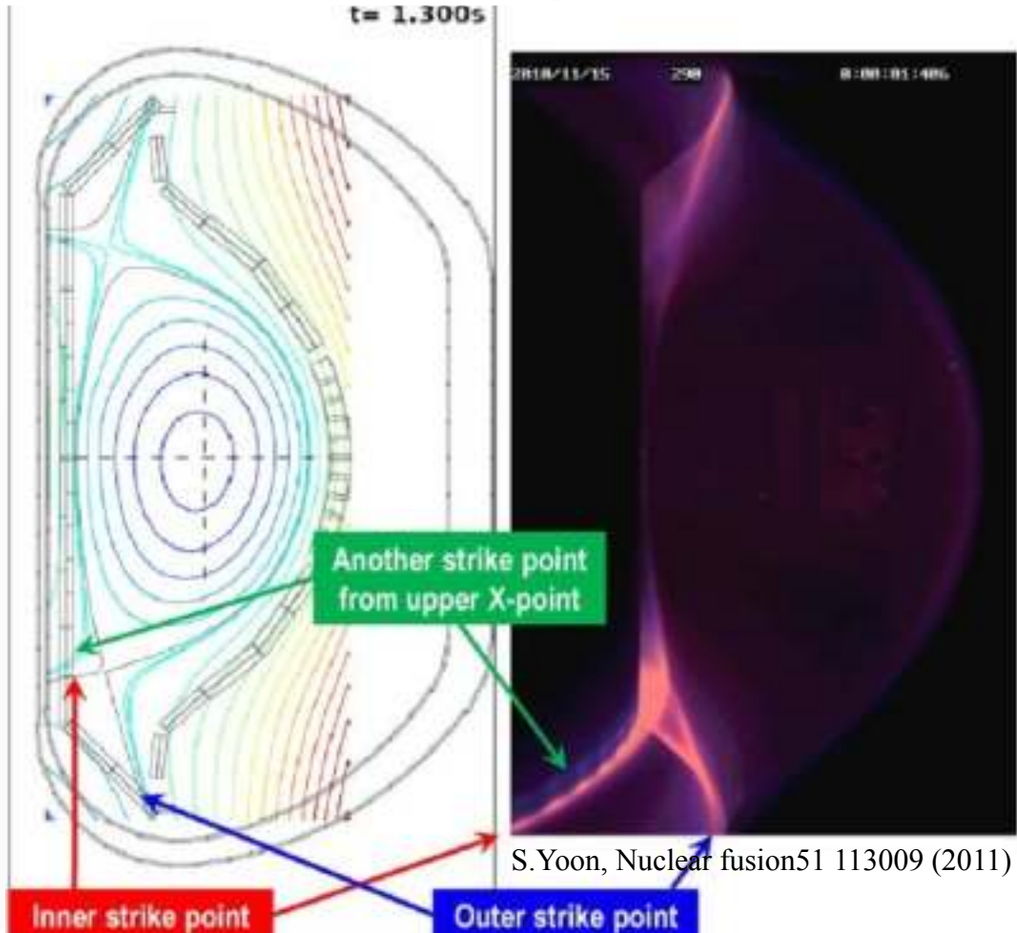
The Tokamak equilibrium reconstruction code EFIT has served as the de-facto standard technique to infer equilibrium from experimental diagnostics

NSTX plasma equilibrium



Good physical models of the configuration are essential, particularly for future power stations which cannot accommodate complex diagnostics programs.

EFIT reconstructed plasma shape with the CCD view



S.Yoon, Nuclear fusion51 113009 (2011)

MHD-FIT~Old but New

Instead of solving only GS-equation, let's solve the MHD system of equations.

The macroscopic equations of magneto hydrodynamics (MHD) provide the basic starting point for an understanding of plasma physics in Tokamak devices.

The dimensionless Hall-MHD equations used for the simulations in BOUT++ framework are as follows:

$$\partial_t(n\mathbf{v}_i) + \nabla\cdot(n\mathbf{v}_i\mathbf{v}_i + pI + \pi_i) = \mathbf{j}\times\mathbf{B}$$

$$\mathbf{E} = -\mathbf{v}_e\times\mathbf{B} - \frac{d_i}{n}\nabla p_e + \eta\mathbf{j} - \eta_H\nabla^2\mathbf{j}$$

$$\partial_t\mathbf{B} = -\nabla\times\mathbf{E}$$

$$(\gamma-1)^{-1}\left[\partial_t p + \mathbf{v}_i\cdot\nabla p + \gamma p\nabla\cdot\mathbf{v}_i\right] = \eta j^2 + \eta_H(\nabla\mathbf{j})^2 - \pi_i:\nabla\mathbf{v}_i - \nabla\cdot\mathbf{q}$$

What we need as the initial conditions:

1. Magnetic field components/flux measured externally
2. Plasma current measured by Rogowski loops
3. Some information regarding the plasma current start-up
4. The initial plasma parameters, such as density, temperature, and etc

As the magnetic diagnostic systems consist of a series of point probes, it is possible to implement the externally measured data on the simulation domain as a series of zero-size per-defined Helmholtz coils

Outline: Reconstruction of the magnetic field configuration

U-Tokyo Merging device: TS-6

Tokamak Energy high field experiment: ST-40

1 Introduction

2 Reconstruction model, a.k.a. 'MHD-Fit'

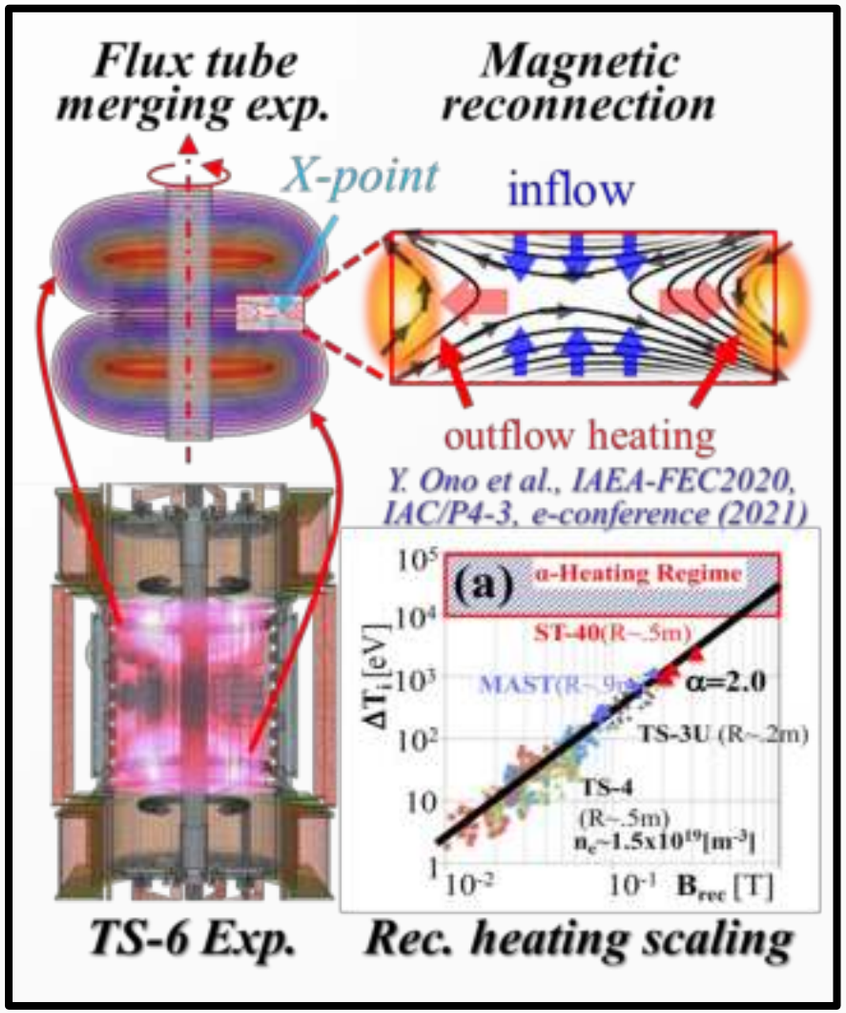
3 TS-3U (TS-6) spherical Tokamak

Internally measured versus reconstructed config. in TS-6

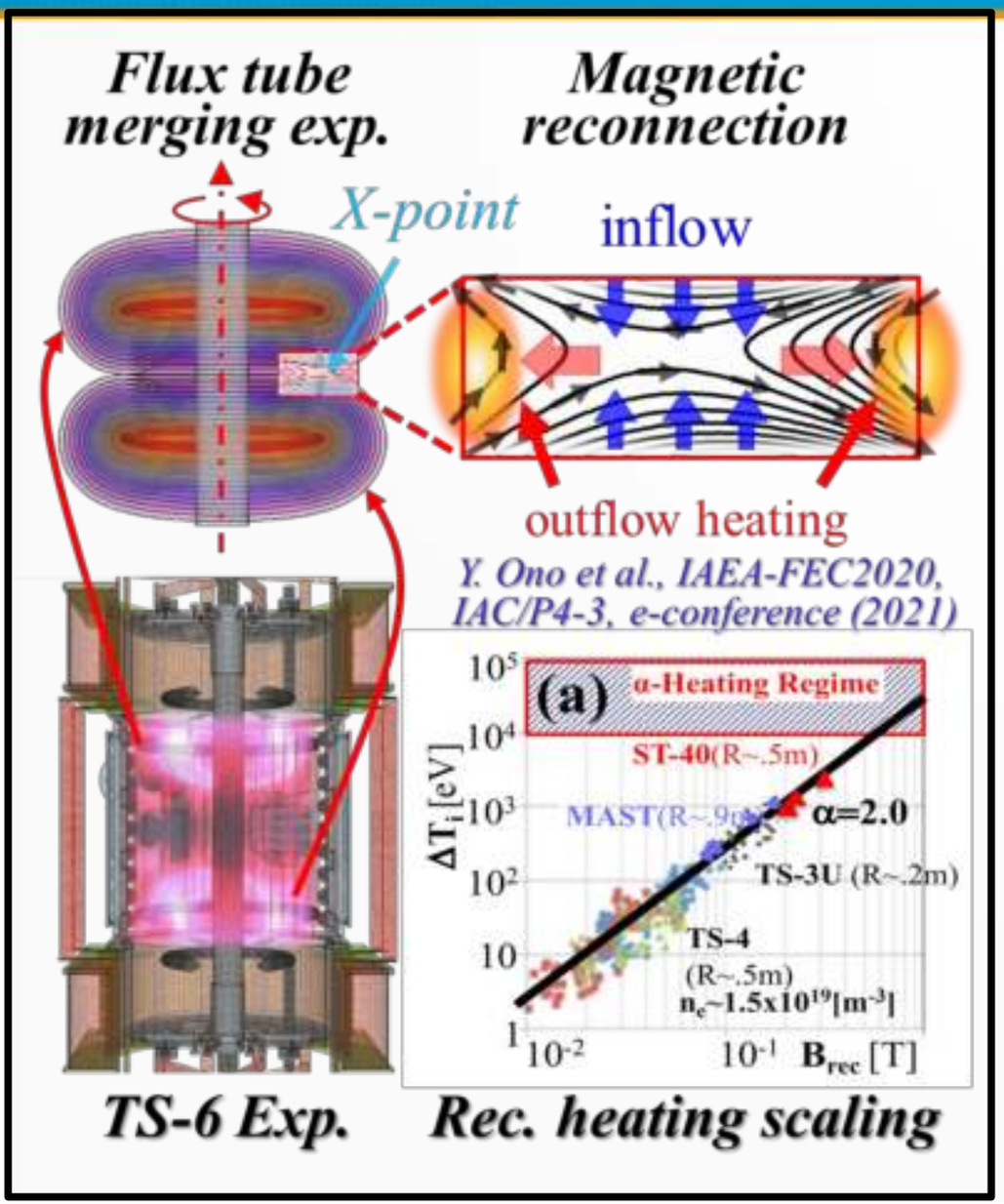
Related talk:
Yasushi Ono – "High-Power Reconnection Heating for Formation of High-Beta Spherical Tokamak with Absolute Minimum-B in TS-3,4,6 ST merging experiments"

Fast speed camera versus reconstructed config. in ST-40

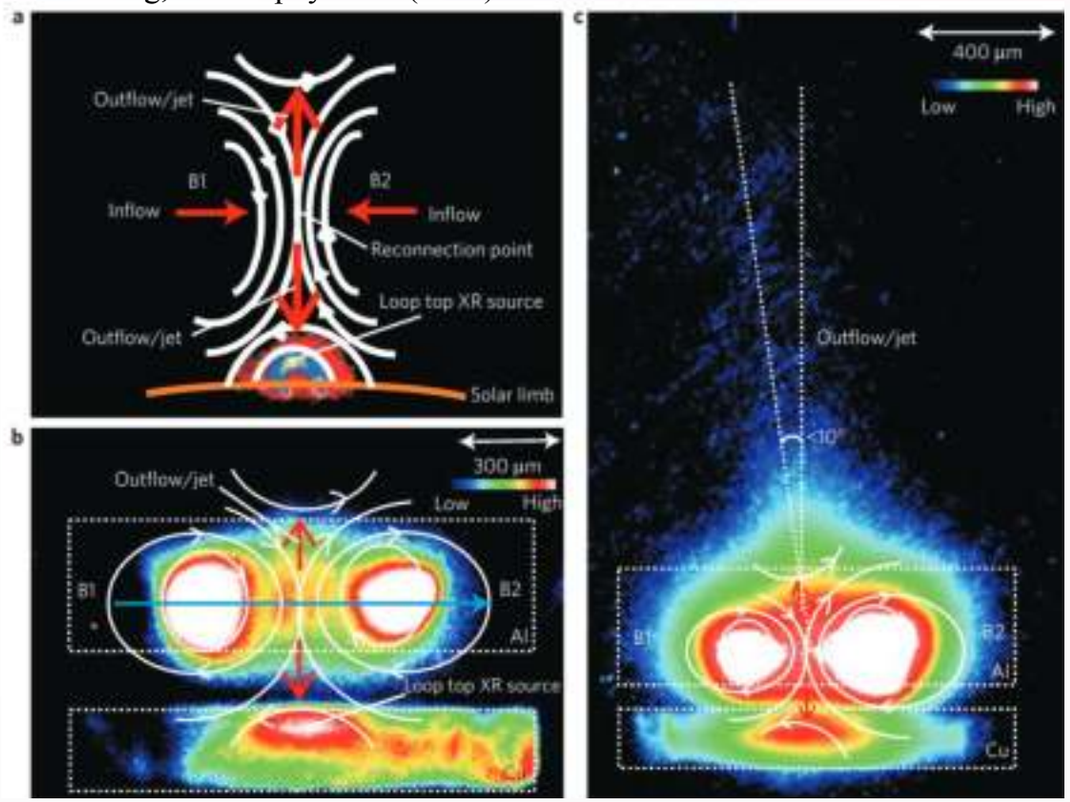
5 Conclusion



Magnetic Reconnection in Solar flares and Merging exp.



J. Zhong, Nature physics 6 (2010)



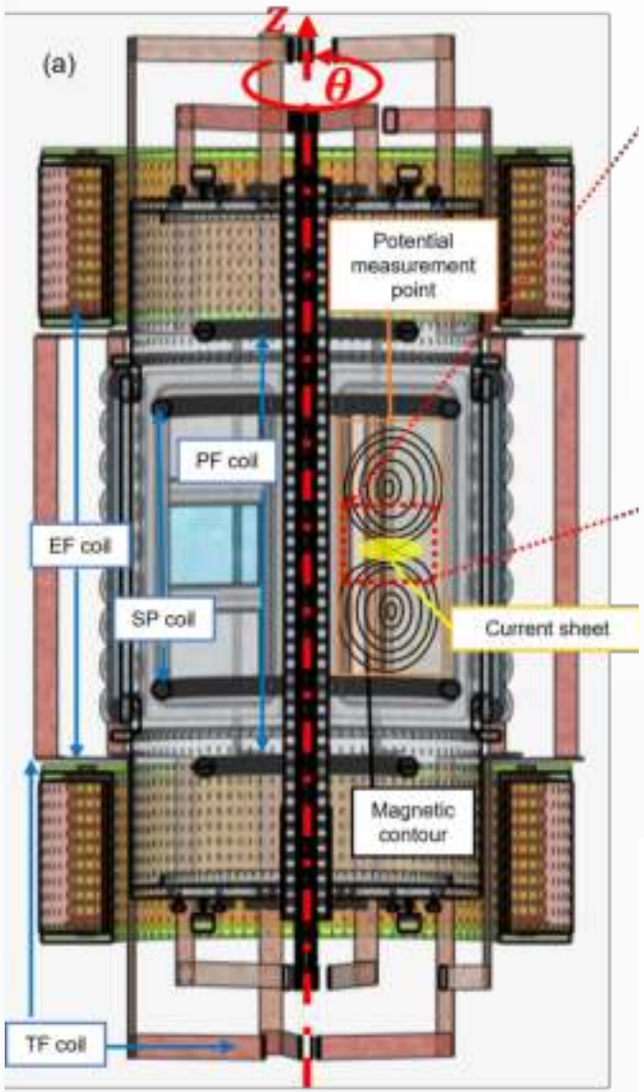
TS-6 Has a simple chamber, operates in low T, multiple diagnostics

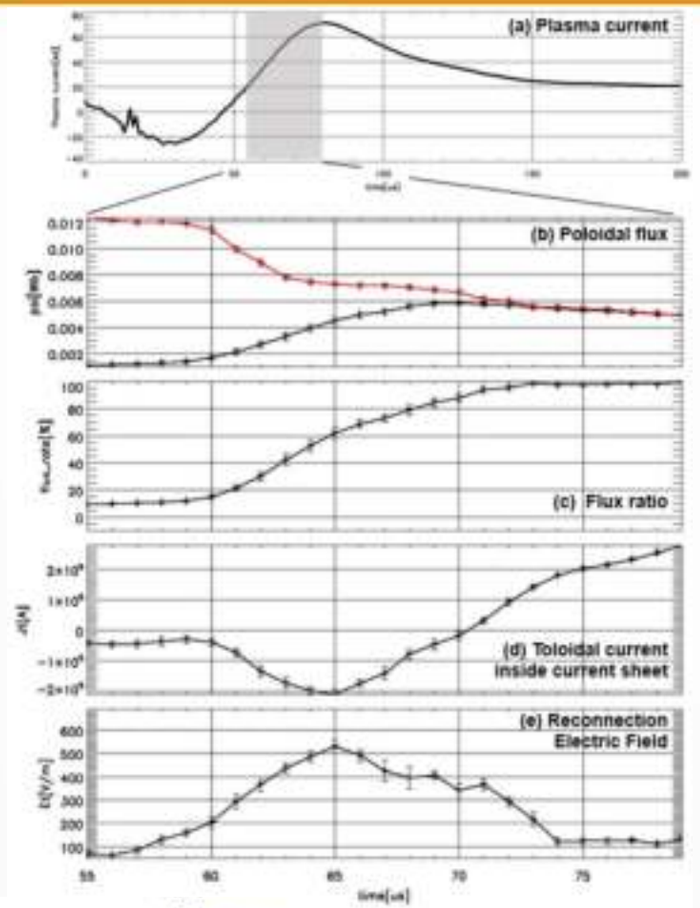
What happens during magnetic reconnection?

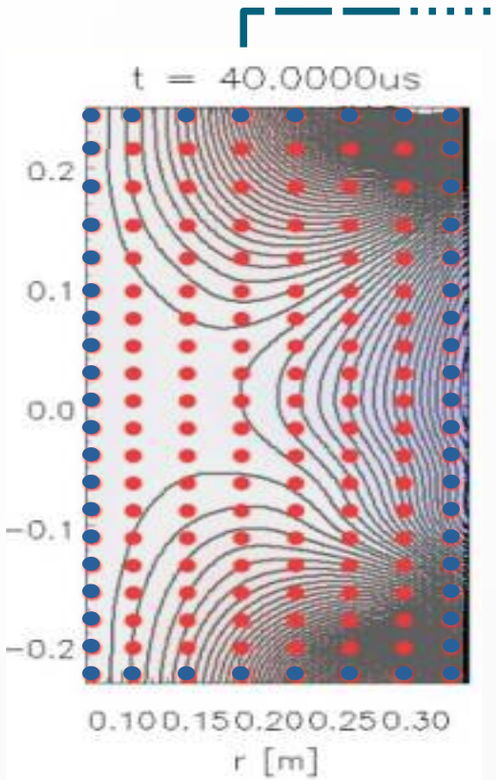
- Magnetic topology is changed
- Magnetic energy is converted to plasma thermal and kinetic energies

TS-3U (TS-6 flux tube merging)

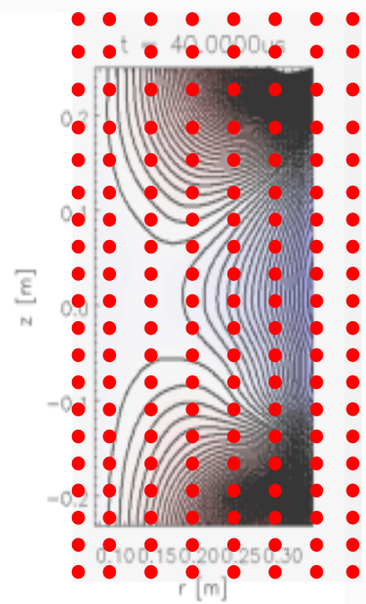
Two plasma rings moving toward each other at the mid-plane where their flux lines break and reconnect again.

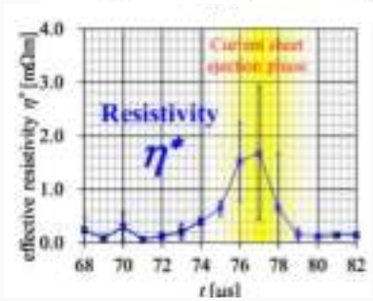






Probes outside separatrix
Probes inside separatrix





PAPER

2D Hall-MHD investigation of the magnetic pressure balance during merging start-up in spherical tokamaks

T. Ahmadi[1,] and Y. Ono[2]

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Nuclear Fusion, Volume 61, Number 12

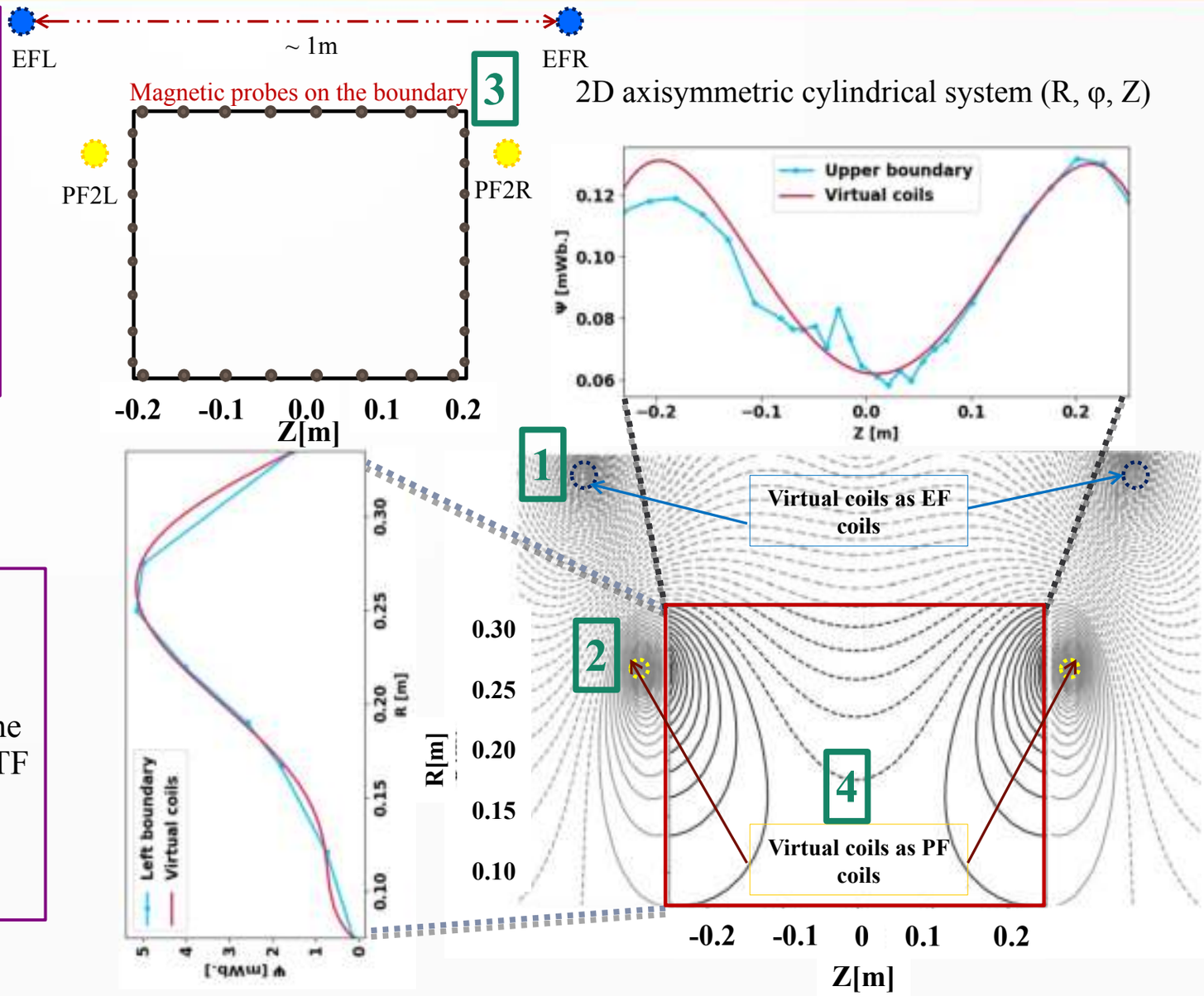
Citation T. Ahmadi and Y. Ono 2021 Nucl. Fusion 61 126007

Poloidal flux contours and out of plane current density

Reconstruction for Simple TS-6 Setup

What we have:
1. Magnetic probe arrays outside and inside the separatrix
2. Plasma current measured by Rogowski loops
3. ST plasmas are formed inductively around PF coils
4. The initial plasma parameters, such as density (1e20 1/m³), temperature (10 eV), and etc.

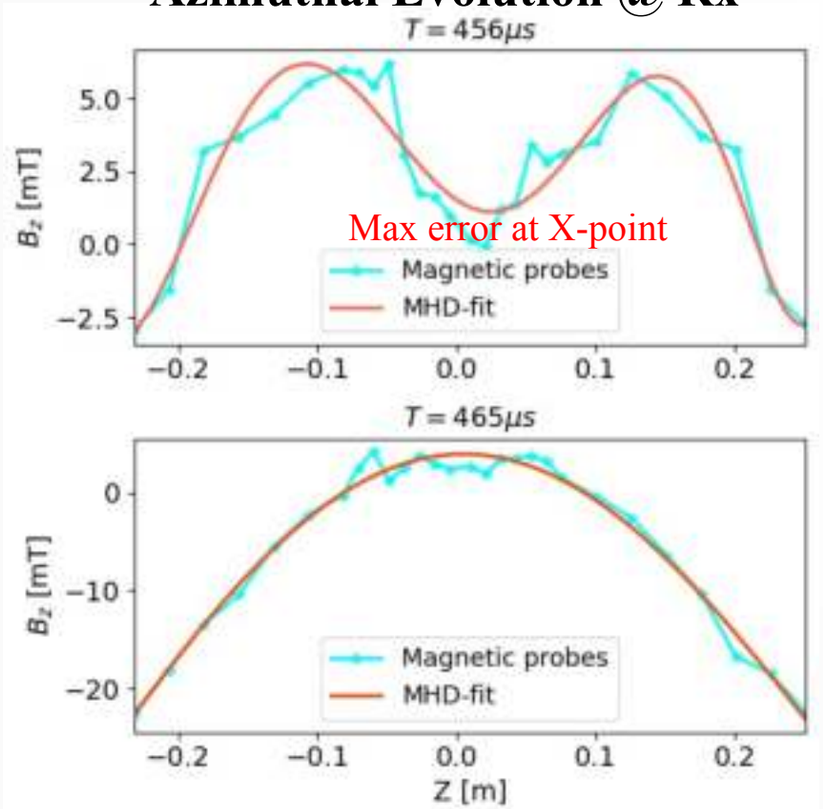
What we did:
1. A pair of EF coils are producing the external field
2. A pair of PF coils are forming plasma inductively
3. Only the probes outside the separatrix (72 probes on the measurement boundary) are considered to adjust PF/EF/TF coils current
4. The resistivity is manually adjusted to match with the measured plasma current



Magnetic Configuration during Merging

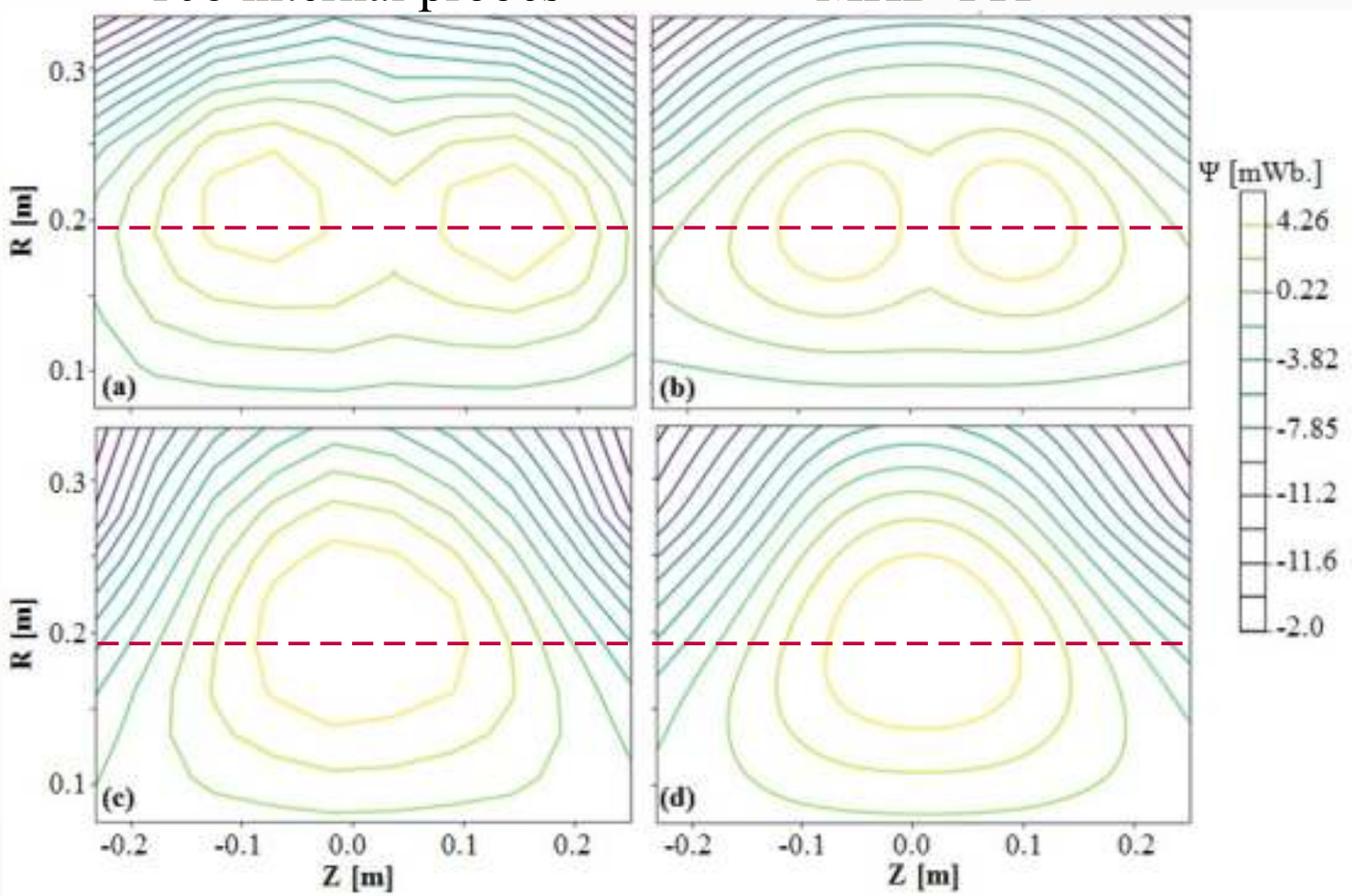
There are 168 magnetic probe arrays located inside the separatrix, so we can compare reconstruction and original.

Azimuthal Evolution @ Rx



168 internal probes

MHD-FIT

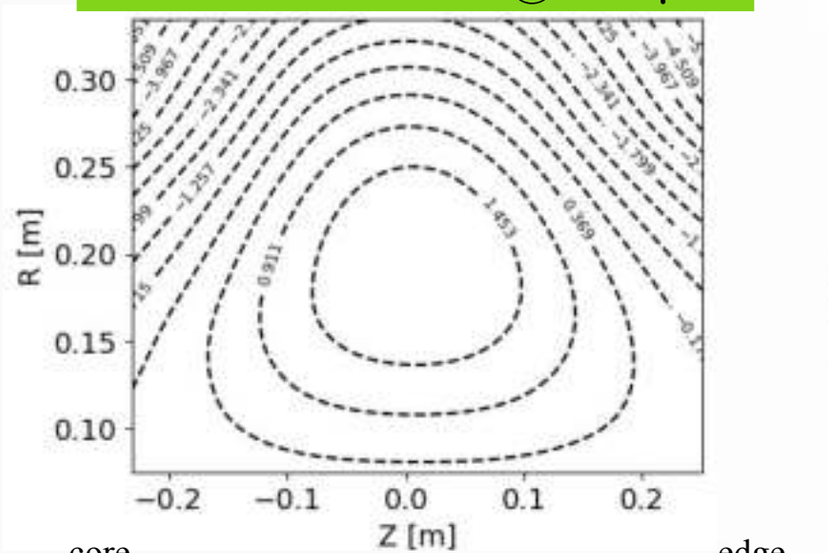


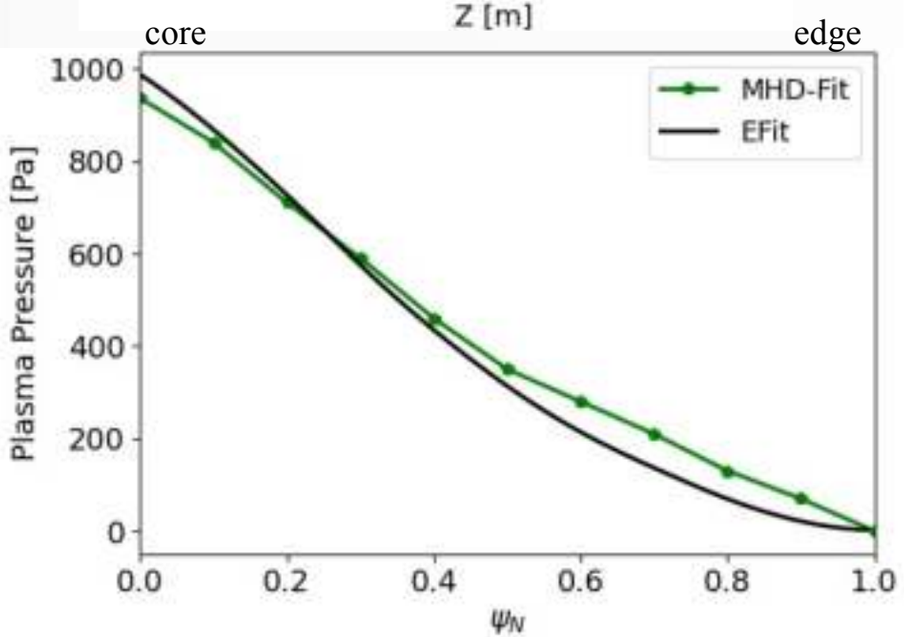
Poloidal flux contours during the merging and equilibrium calculated from experimental and reconstruction model data

Some Important Parameters

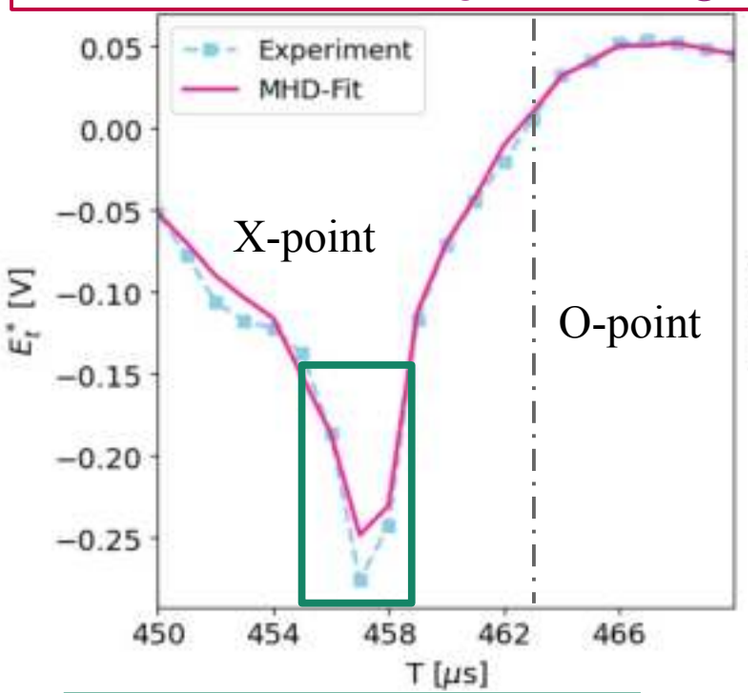
The reconnecting electric field characterizes the **speed of changes** in the poloidal flux **topology** during the merging process.

EFIT reconstruction @ 465 μs

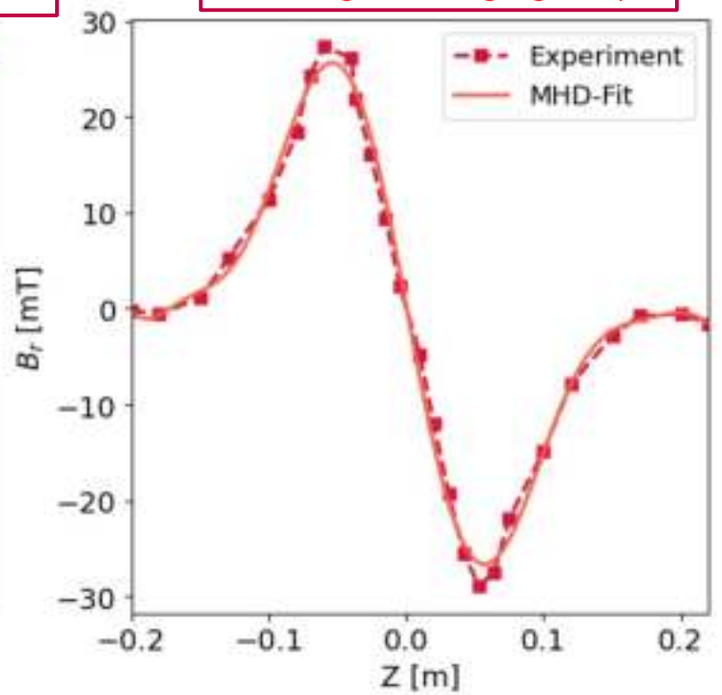




Evolution of the reconnecting electric field @ X



Br during the merging 457μs



Magnetic reconnection of flux ropes

MHD-FIT is able to reconstruct both internal and global plasma parameters related to the reconnection topology, speed and heating.

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Internally measured versus reconstructed config. in TS-6

4 ST-40 spherical Tokamak

Fast speed camera versus reconstructed config. in ST-40

5

Related talks:

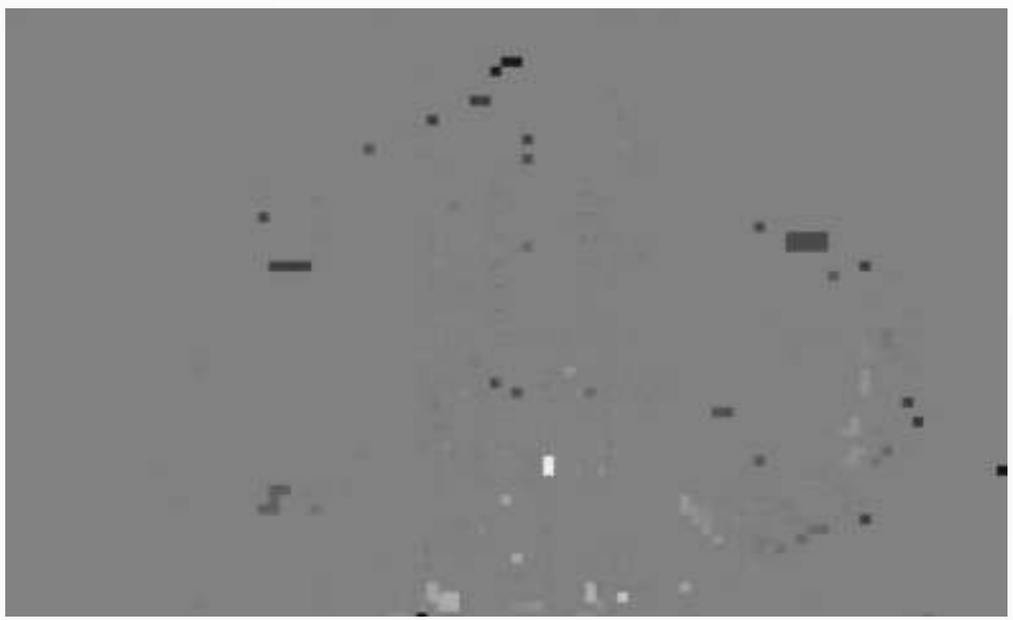
Otto Asunta – "High temperature plasmas in ST40"

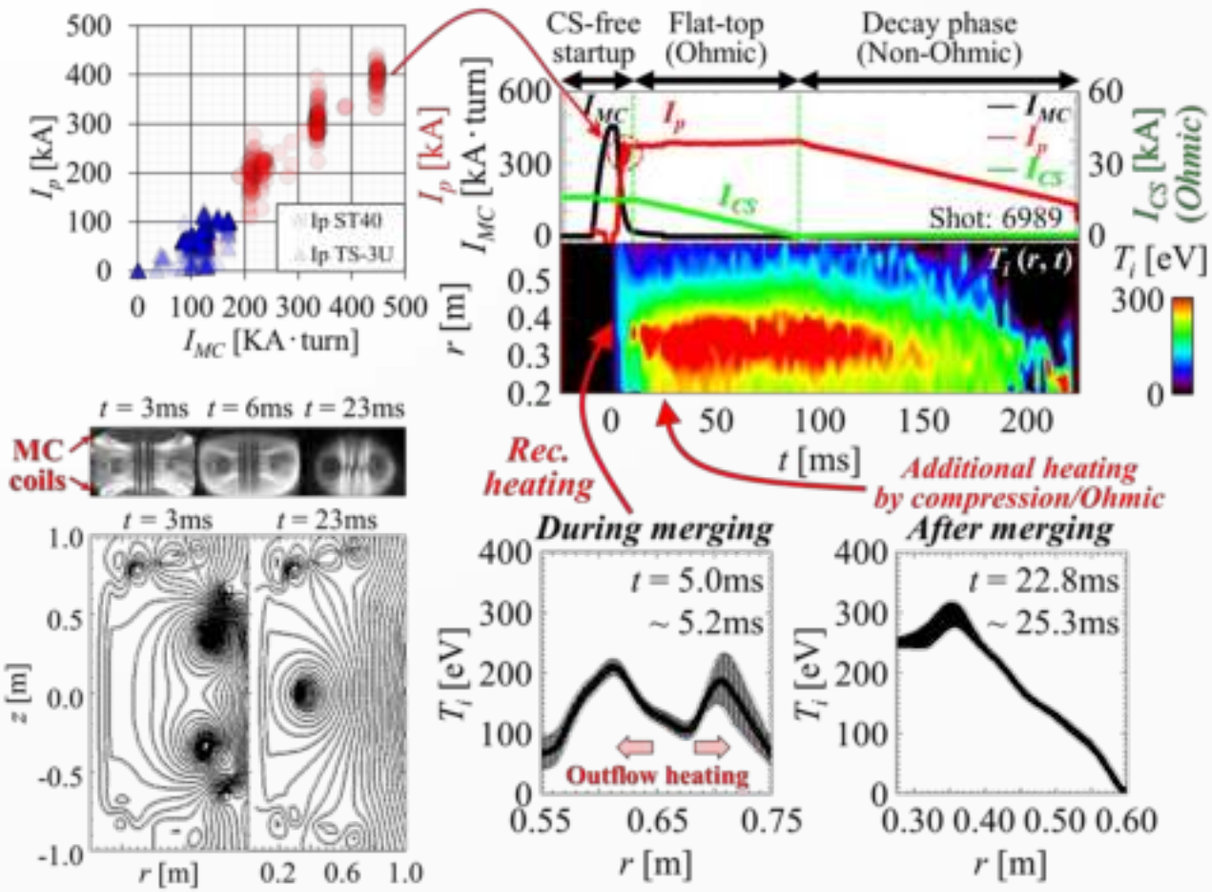
Michele Romanelli – "ST40: Advancing the Physics Basis of Spherical Tokamak Reactors"

Mikhail Gryaznevich – "ST Reactor – new considerations"

High Field ST-40 Merging/compression Exp.

A UK private company *Tokamak Energy* starts high field application of reconnection heating

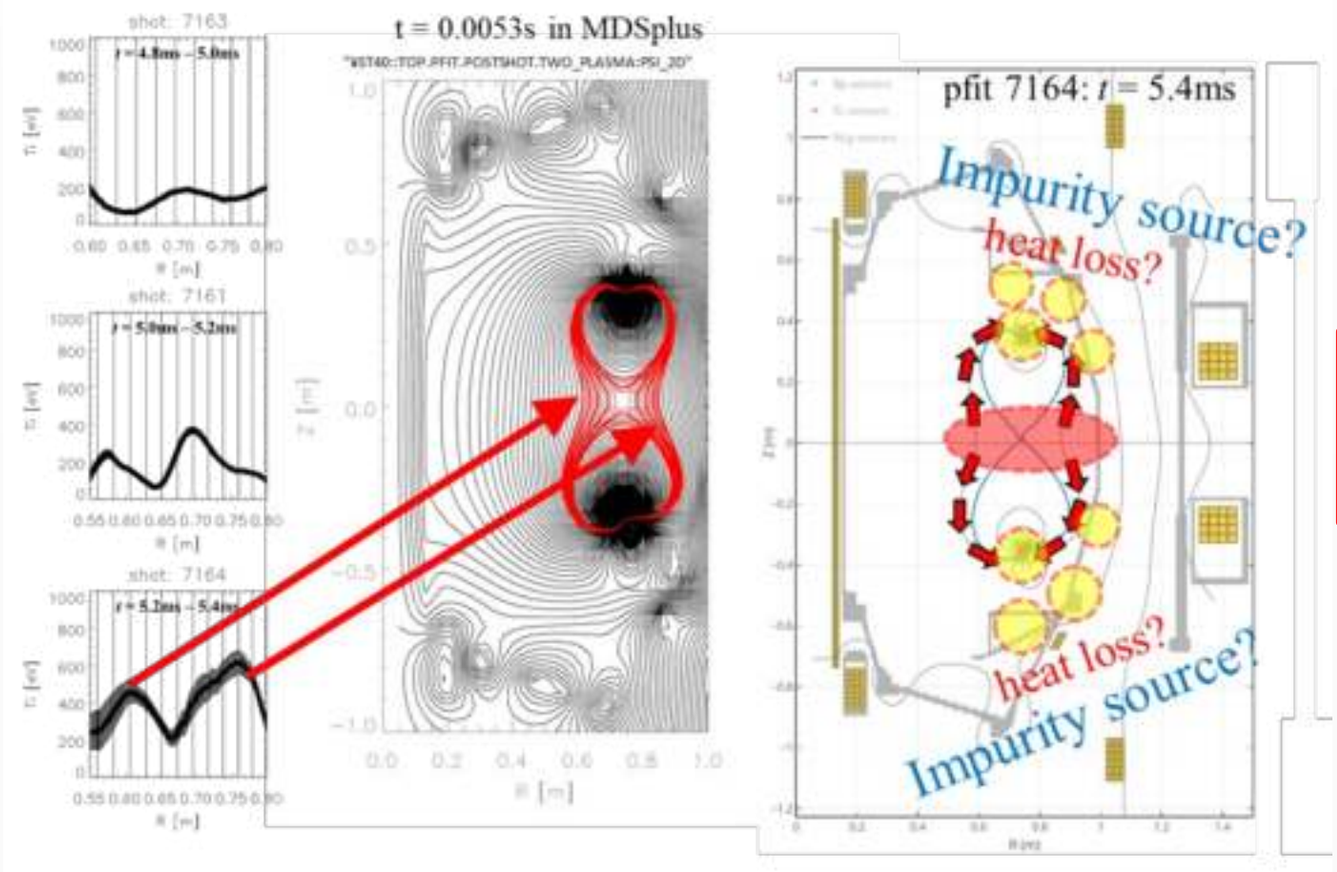




Current Issues~ detachment

Profile measurement revealed that there is active heat loss when Rec. driving coils are not well "detached"

Onset of fast reconnection must be delayed to drive it after the achievement of better detachment from M/C coils

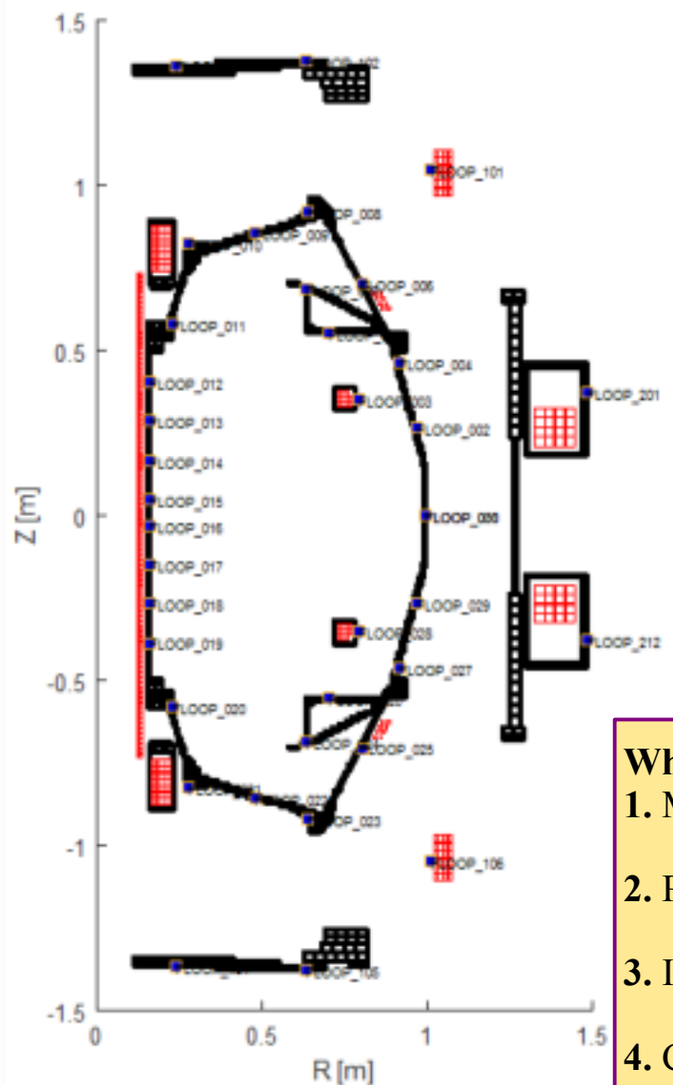


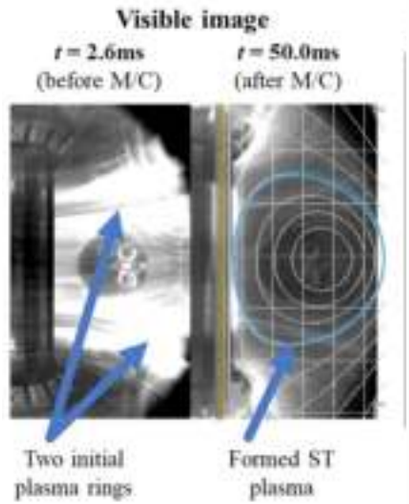
EFIT reconstruction?
It is not reliable?

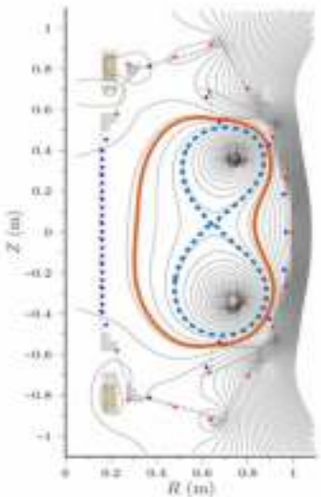
Tanabe et.al, US-Japan Workshop on Magnetic Reconnection (2022)

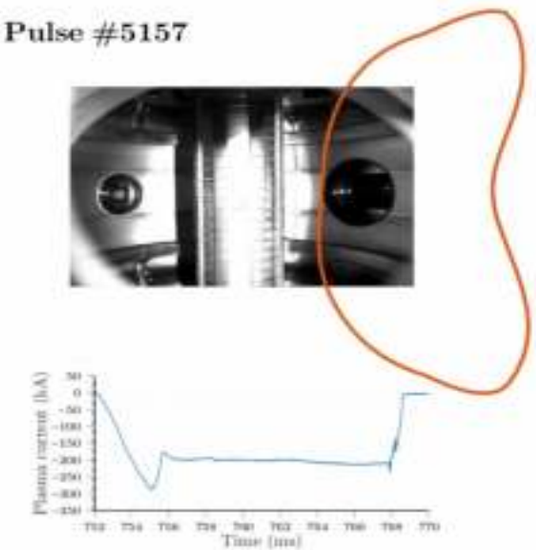
Magnetic Diagnostics

Grad-Shafranov solvers are used to reconstruct the magnetic configuration in ST-40 device









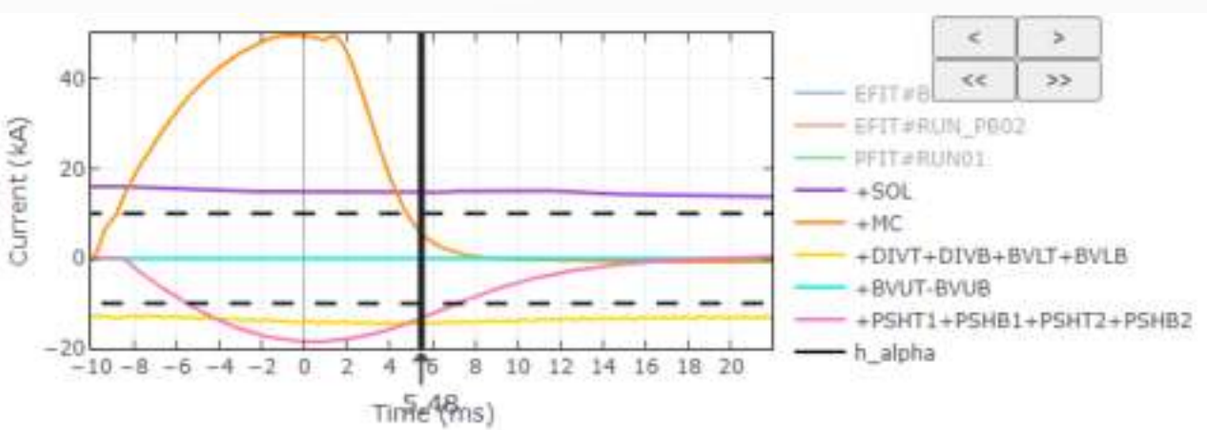
What we have:

1. Magnetic field probe arrays/flux

2. Plasma current

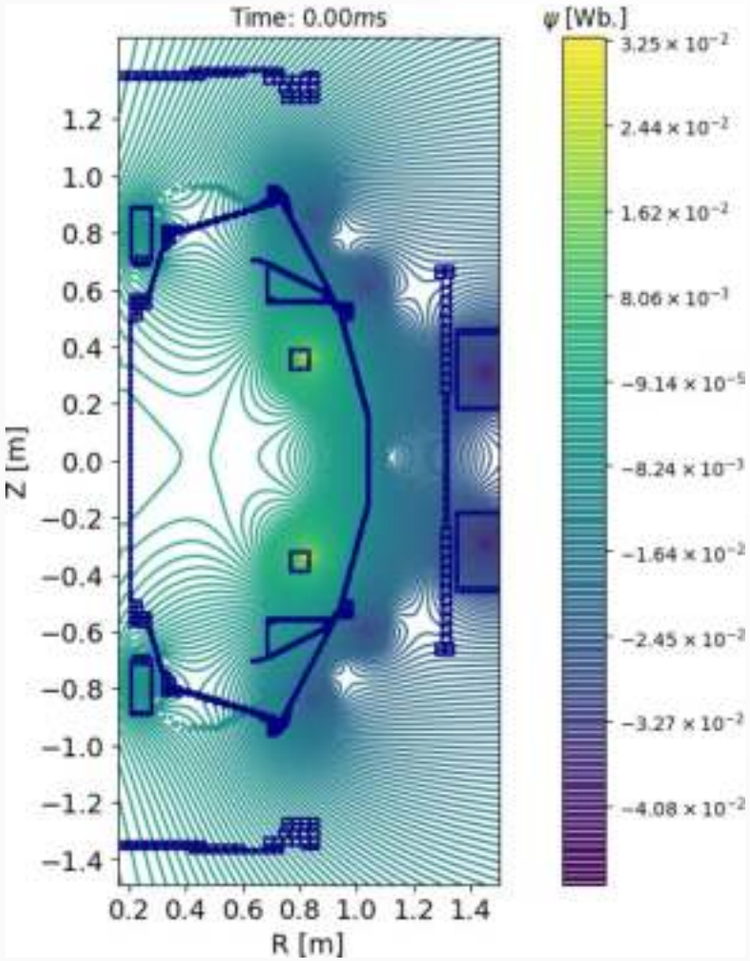
3. Inductive plasma formation

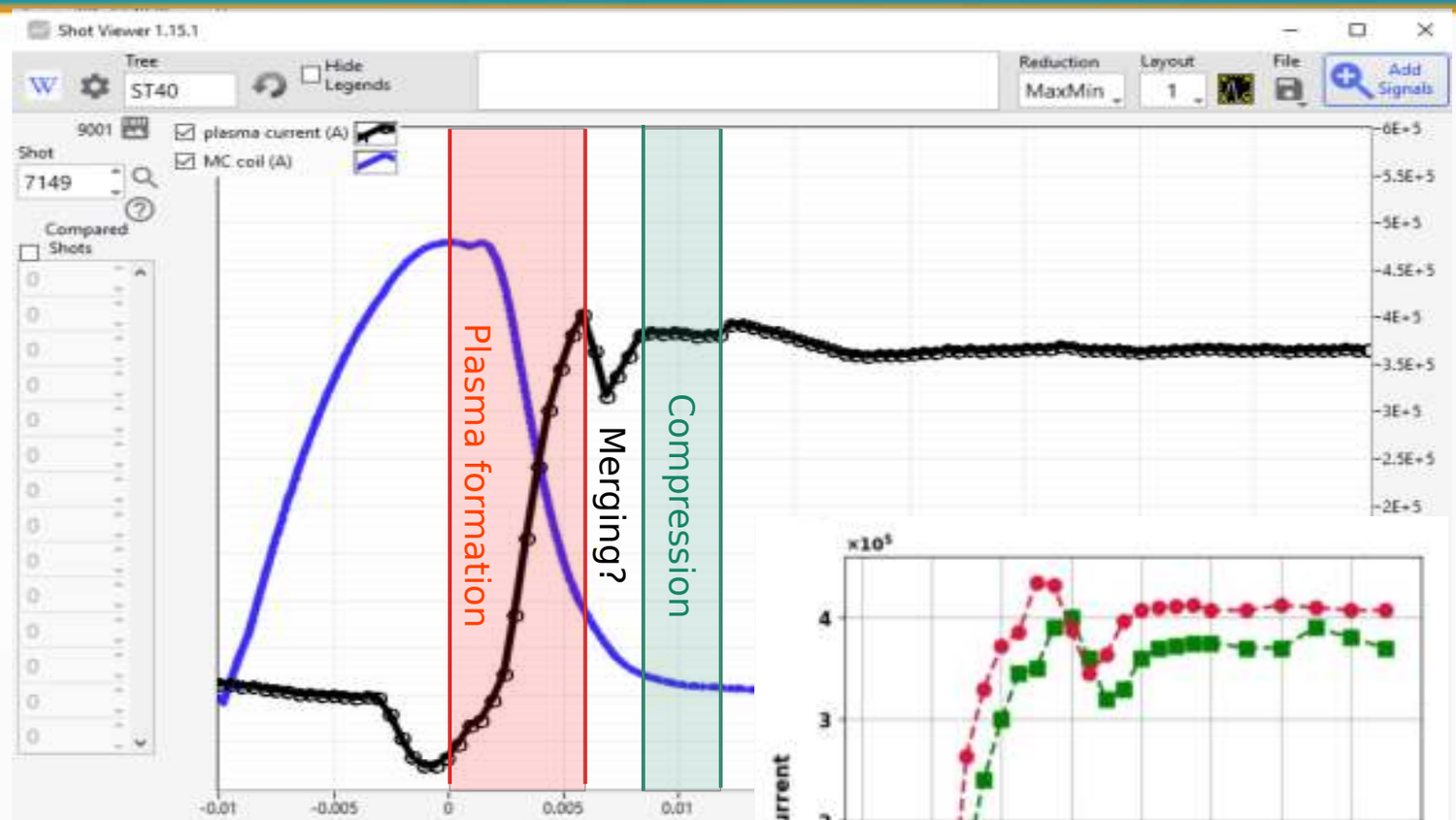
4. Coils current waveform



MHD-FIT

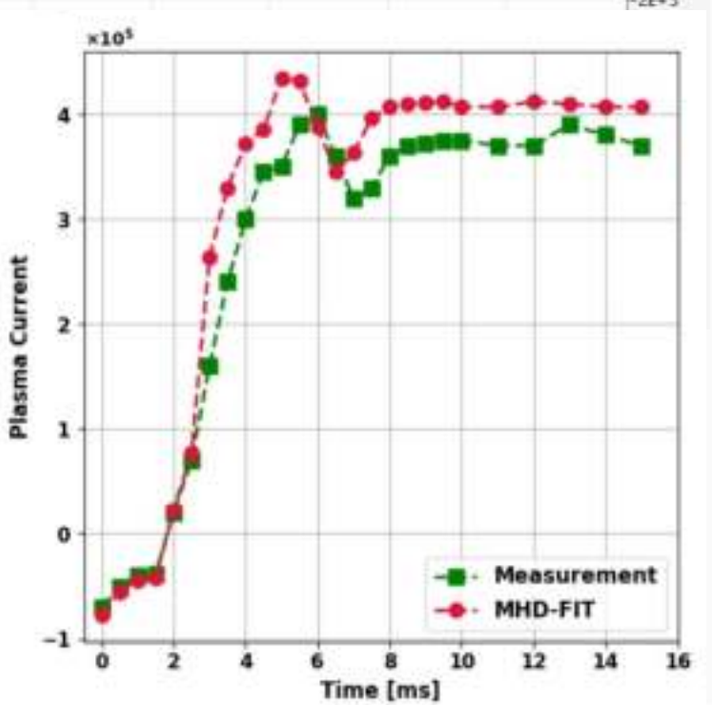
No internal plasma diagnostics!
How can we compare the reconstruction with actual?





Coils currents are applied directly and adjusted by the flux loops signals received from the vacuum vessel

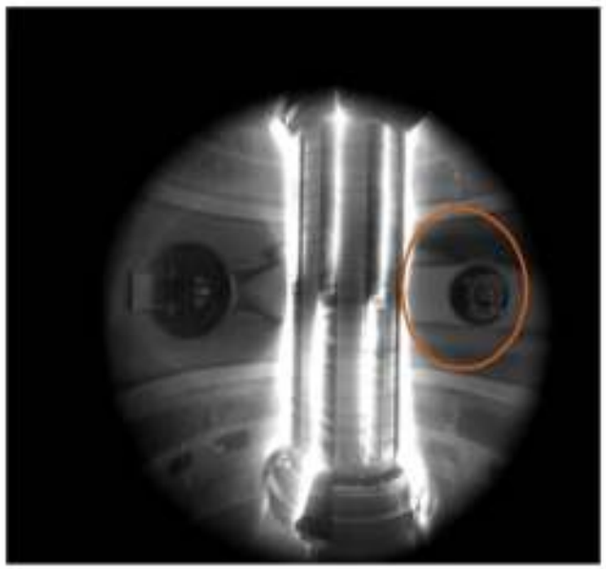
Yes. Merging happened when the plasma toroids are still connected to the M/C.

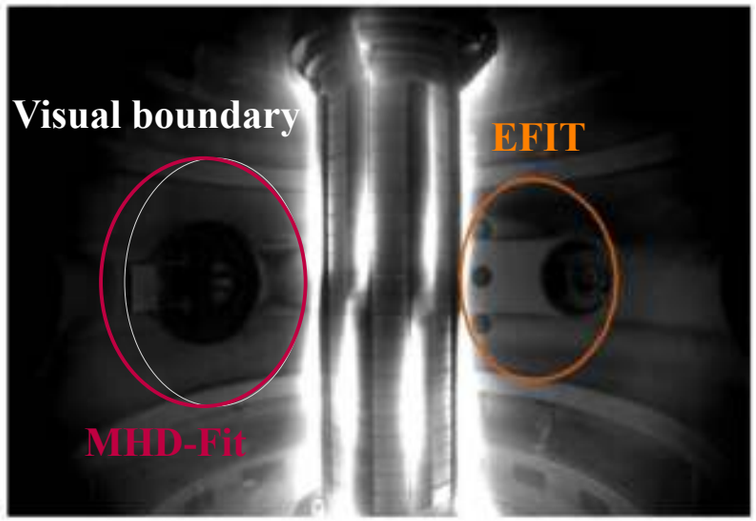


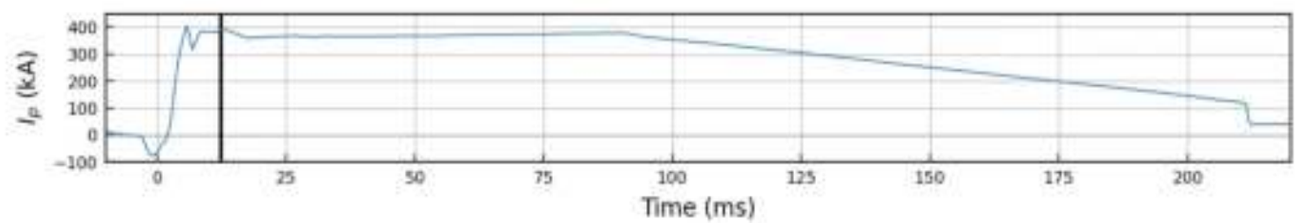
Fast Speed Camera Images and MHD-FIT

MHD-FIT core plasma is larger than the actual plasma.

ST40 #7149



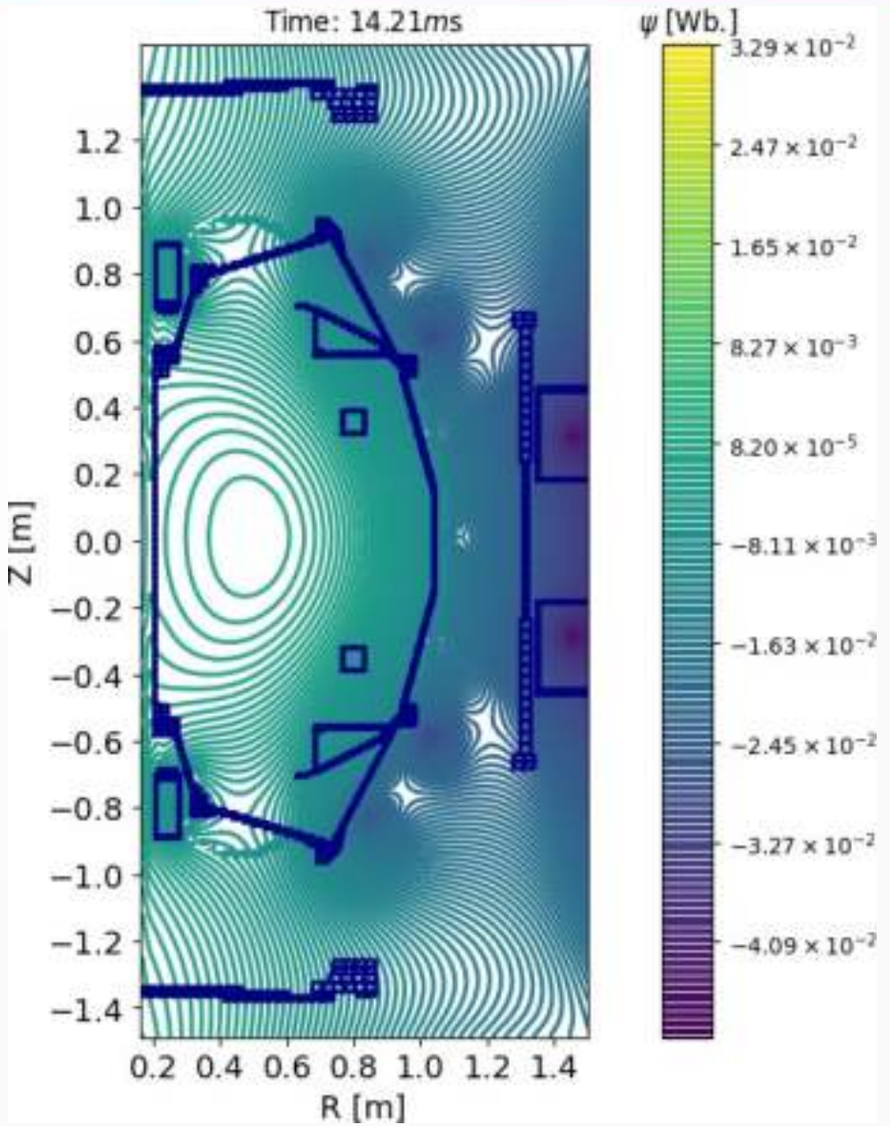




The MHD-Fit is closer to the visual boundary observed in CCD camera in comparison to the EFIT.

EFIT error~ 17%

MHD-FIT error~ 9%



Fast Speed Camera Images and MHD-FIT

PFIT core plasma is smaller than the actual plasma.

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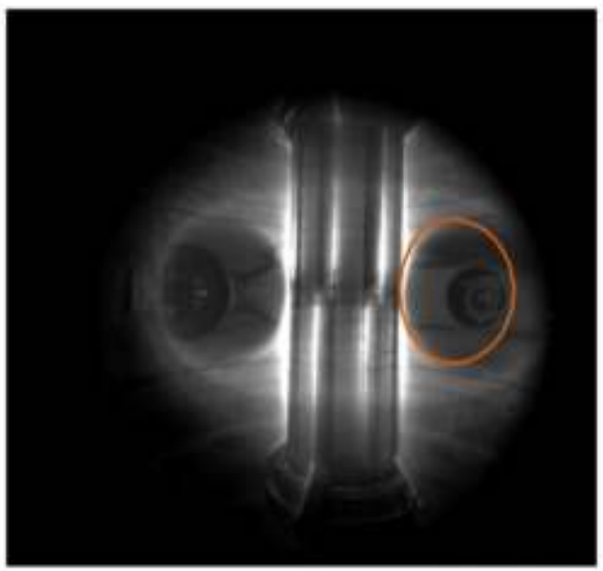
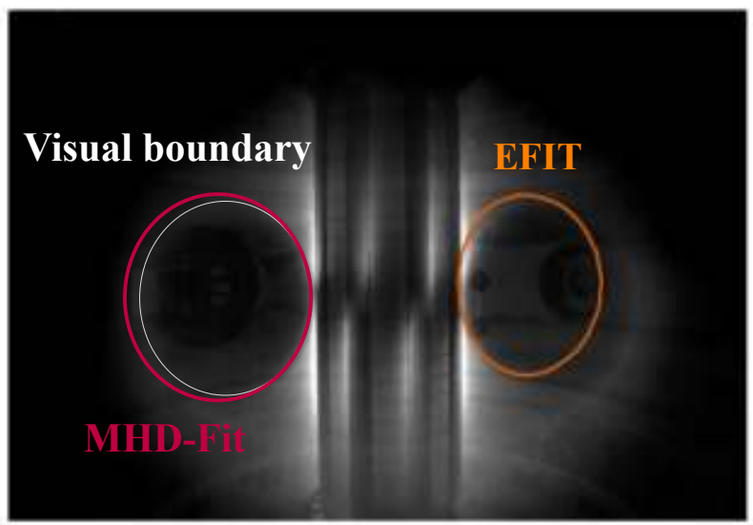
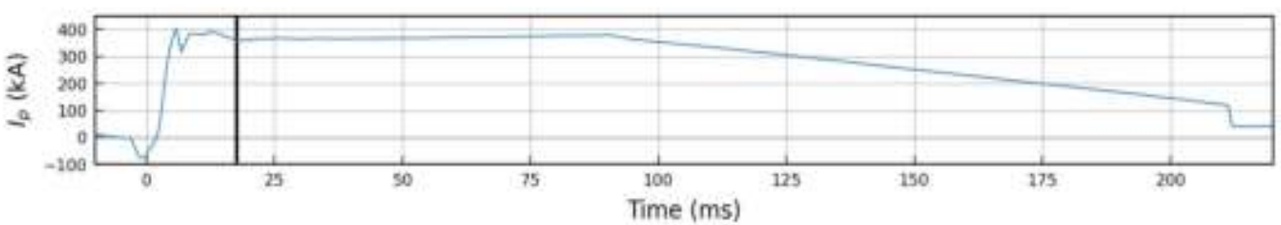


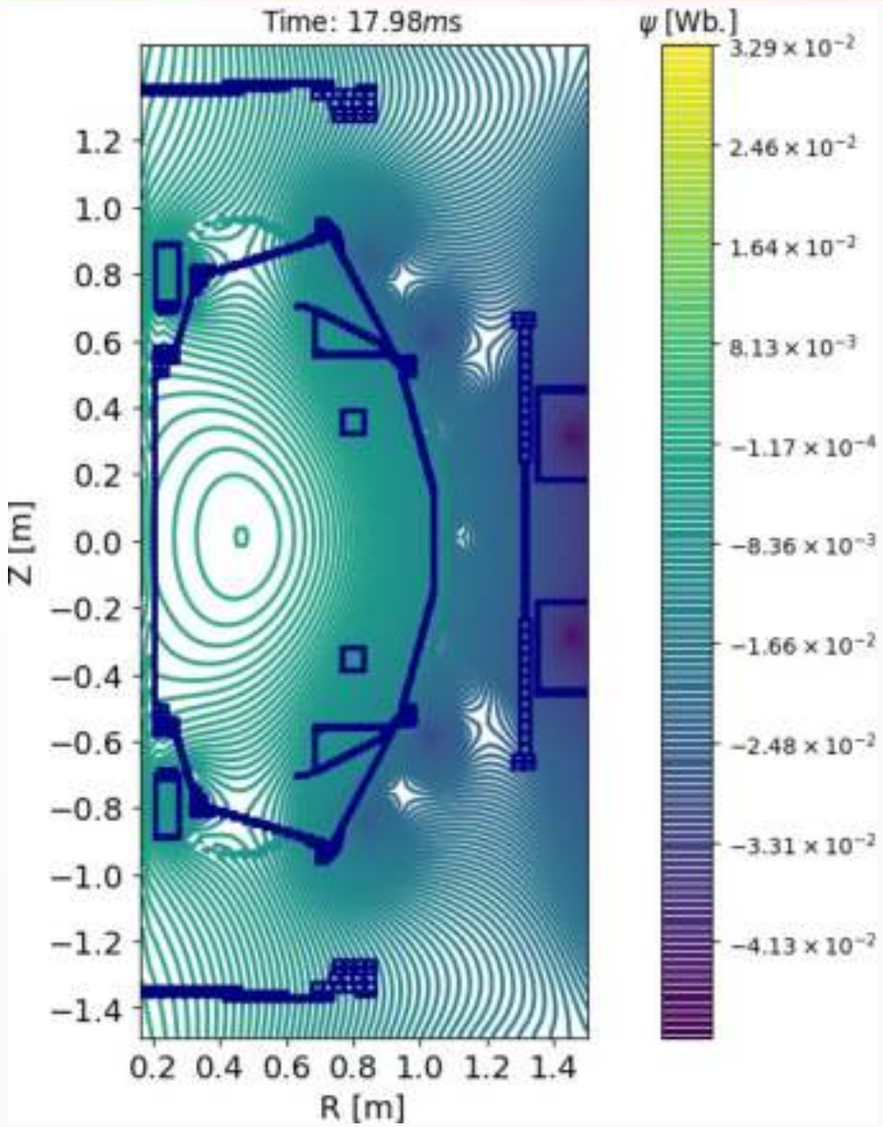




The MHD-Fit is closer to the visual boundary observed in CCD camera in comparison to the EFIT.

EFIT error~ 19%

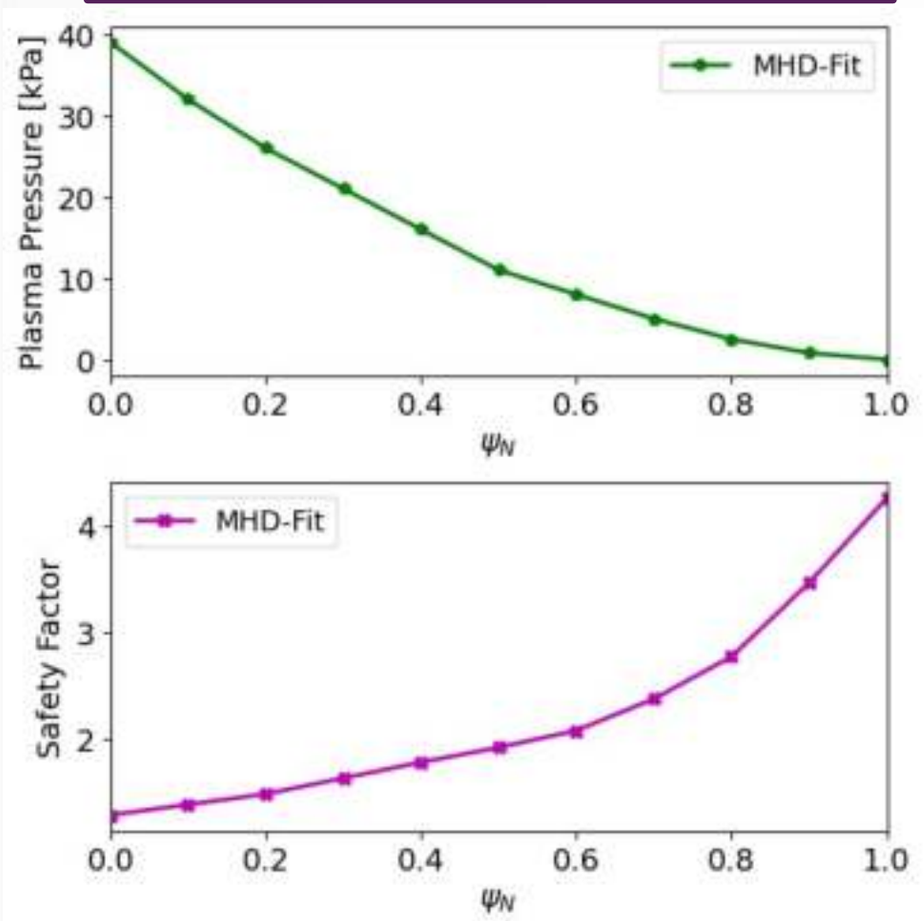
MHD-FIT error~ 7%



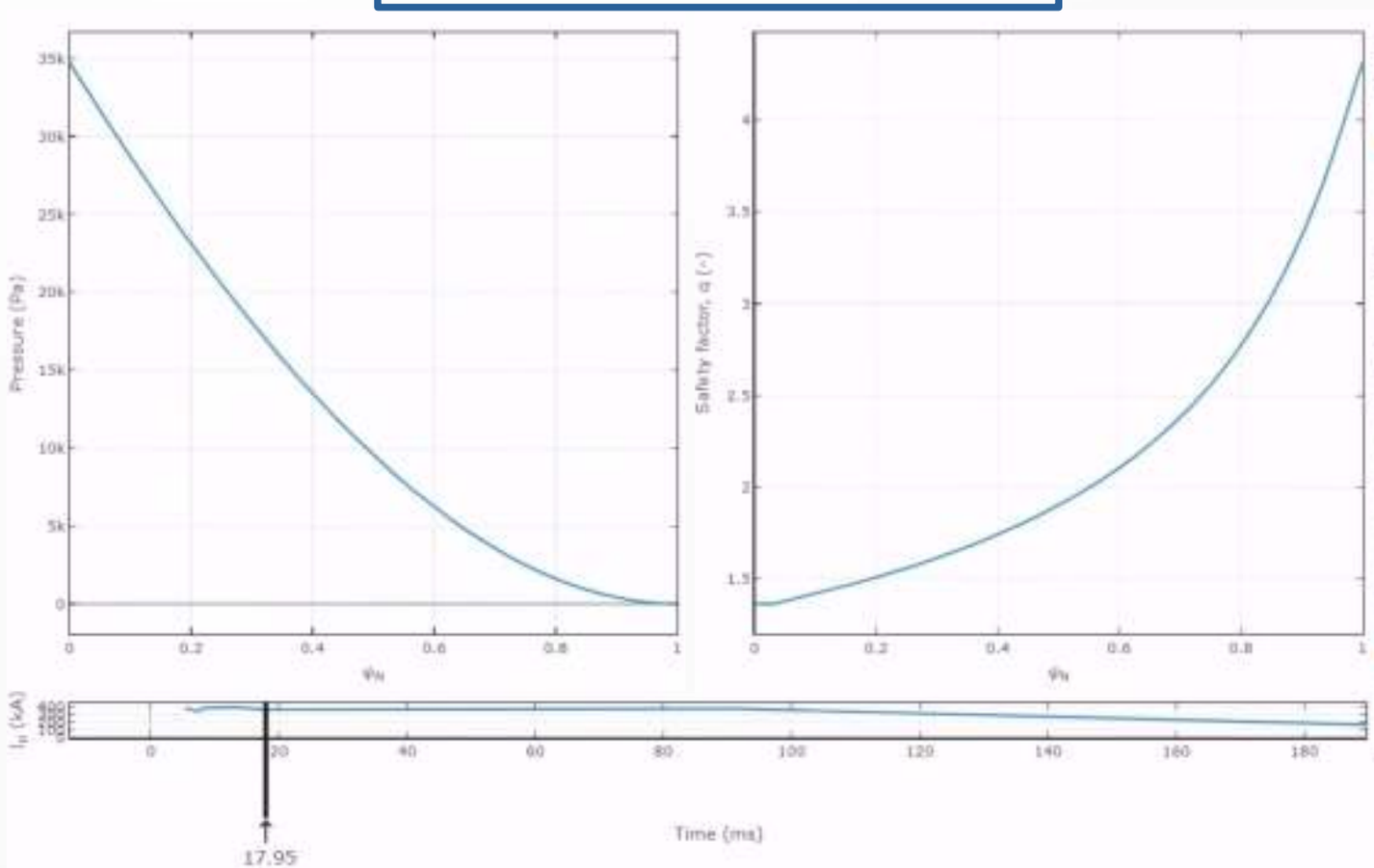
Equilibrium Internal Plasma parameters

There is no available internal measurements (in progress), so it is not easy to validate EFIT or MHD-FIT.
The reconstructed pressure profile is relatively 15% larger than the EFIT values.
Safety factor value is higher in EFIT reconstruction (~5%.)

MHD-FIT Reconstruction Profiles



EFIT Reconstruction Profiles



Summary and Conclusion

- The plasma shape, position and size are crucial parameters to control the hot magnetized plasma in Tokamak and spherical Tokamak device.
- Current methodology of solving Grad-Shafranov equation is not able to reconstruct the basic parameters of the core plasma, at least in the tested spherical Tokamaks.
- In spite of its simplicity, the MHD-FIT shows the better results in comparison to the common PFIT/EFIT solver.
- The current 2D MHD-FIT is unable to catch the 3D and kinetic effects; thus, it is important to provide a base to develop 3D version and PiC-FIT (in progress)
- Magnetic reconnection starts from the micro-scale diffusion regions affecting the global image. MHD-FIT enables the reconstruction of global characteristics with low error.