Magnetics in KSTAR (for 1st campaign)

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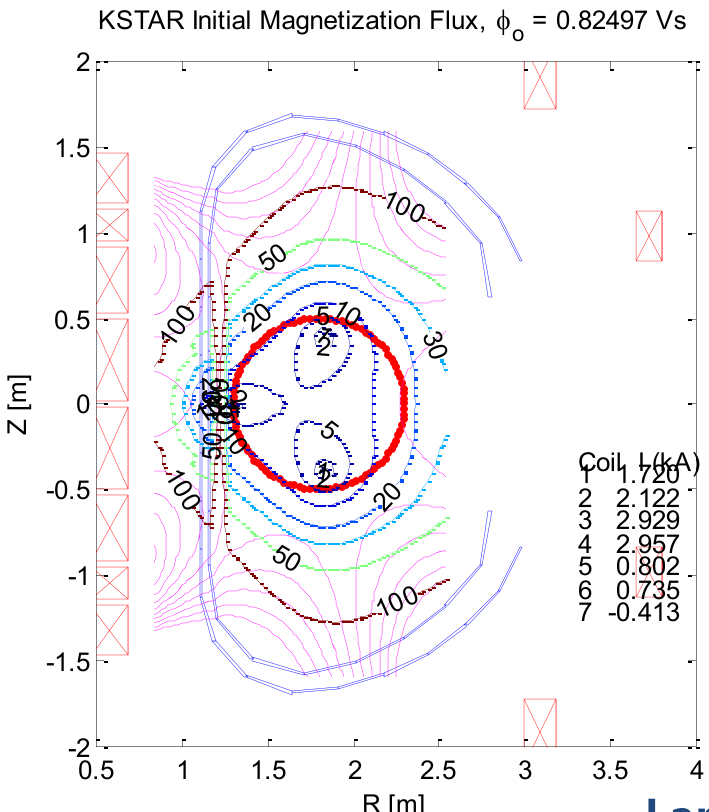
Startup Scenario

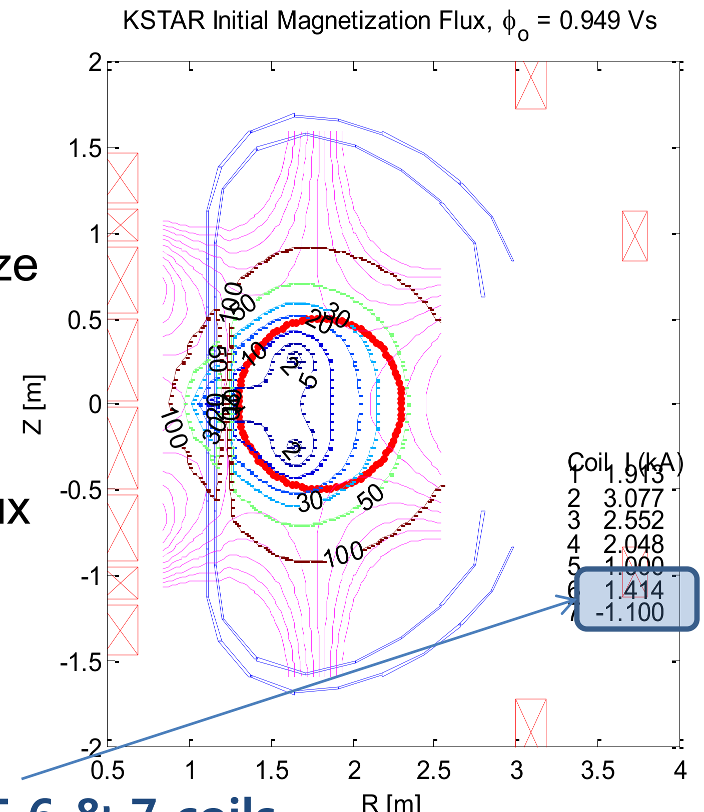
Initial Magnetic Configurations: "Conventional" and "Dipole" Modes

Conventional mode is favorable for initial breakdown but dipole configurationprovides hi gher flux for current ramp-up and improved feedback control

Conventional mode
#858 (Ip=107 kA during 247 ms)



Dipole mode
#977 (Ip=130 kA during 250 ms)



Field null size

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Magnetic flux
V_{loop}, B_z

<

Large I_{PF} for PF 6 & 7 coils

KSTAR

NFRI

Comparison between "conventional" and "dipole" modes

- **Conventional PF scenario**

✓ Field-null formation mainly by CS -low IPF for outer coils
✓ Loop voltage mainly by swing of CS coils
✓ Vertical field by increasing current of outer PF coils
✓ Suitable for normal conductor tokamaks
  Fast plasma current ramp-up is difficult due to large L/R of superconducting coil

- **(outer) Dipole scenario**

✓ Field-null formation by CS and outer coils (dipole configuration of PF6&7)
✓ More like solenoid-free configuration
✓ Loop voltage by swing of both CS and the outer coils
✓ Vertical field by preset I_{PF} at outer coils (fast ramp-up of I_p ~1MA/s)
✓ Suitable for superconducting tokamaks
  Lower EM load on CS coils
  Faster plasma current ramp-up is possible

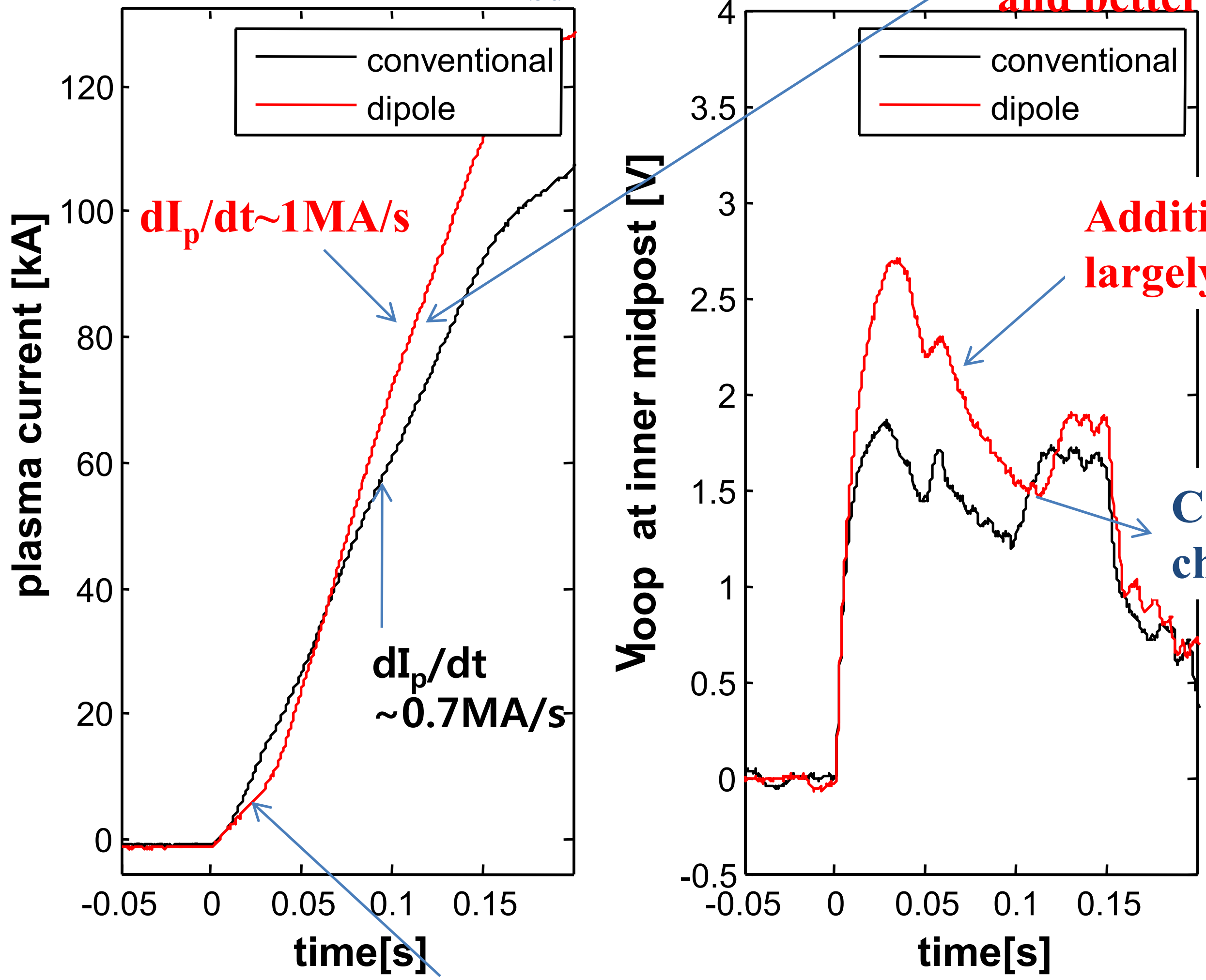
V_{loop} higher than 4V is not achievable with conventional scheme at KSTAR
→Dipole mode will be the reference scenario for KSTAR 1st plasma

Dipole configuration has more capability for Ip

Startup uses the identical constraints as ITER

2^{nd} Har ECH assist and E_{bd}=0.3V/m

Higher Ip ramp due to higher V_{loop} and better Bz control



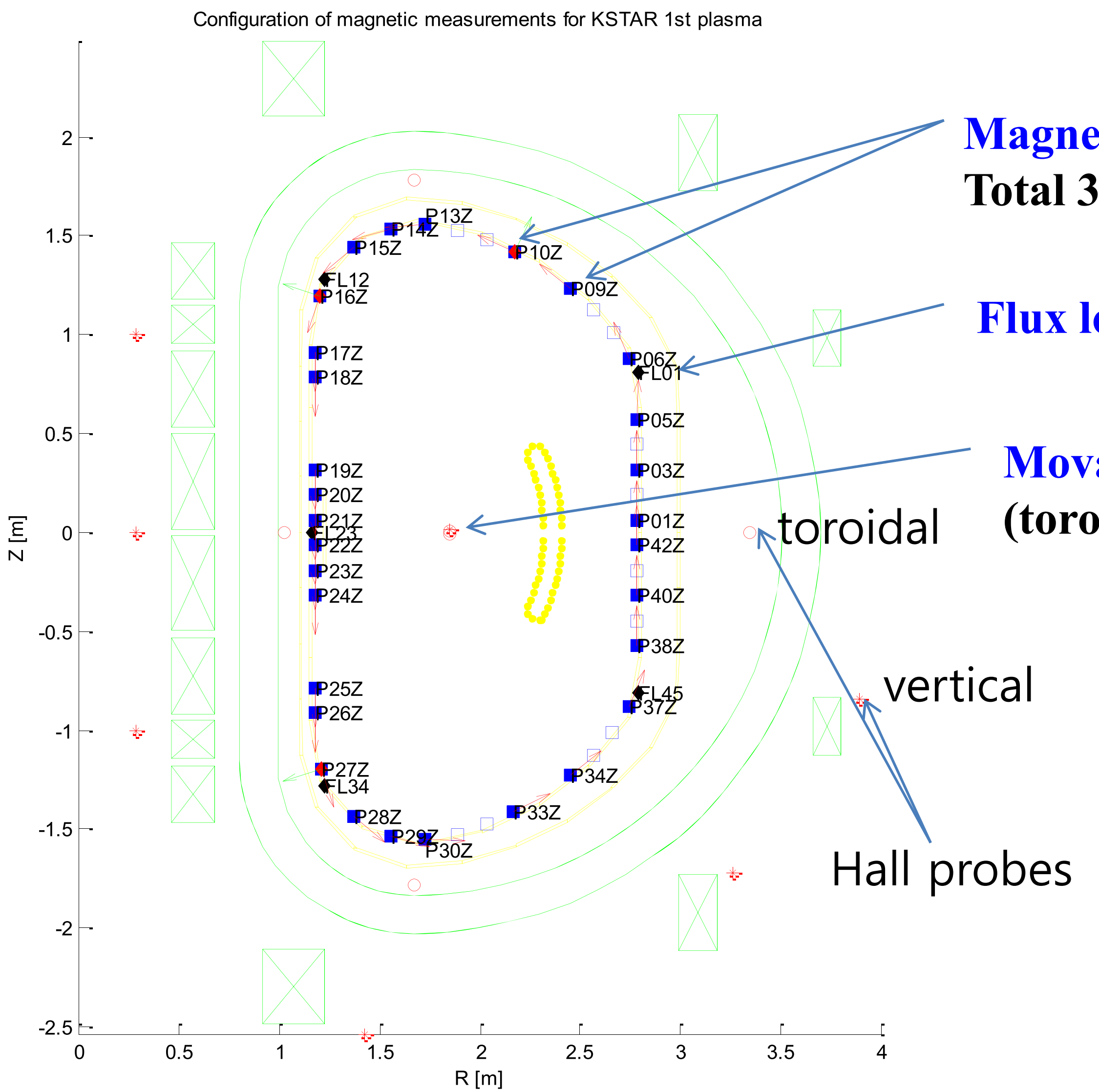
Additional V_{loop} largely from outer PF6 blip

Change in V_{loop} due to Rp change after ECH off

Slow Ip ramp due to larger parallel loss (Poorer initial field-null for dipole)

Measurement capabilities

Magnetic measurements systems for 1st plasma



Magnetic probes
Total 32 with integrators

Flux loops : total 5

Movable hall sensors
(toroidal, vertical)

Magnetic Diagnostics

Issues for the magnetic measurements

Magnetic probes

- -large integrator drift and linear correction is not perfect
- -remnant field from magnetic materials
- -a simple calibration is impossible due to the presence of magnetic materials

Hall sensors

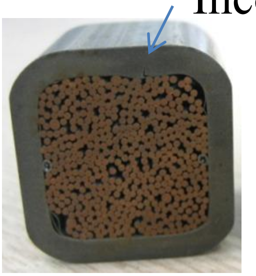
- -limited sets are installed (mainly for machine-check purpose)
- -invalid dynamic field measurements due to perturbation from the cabling

Understanding magnetics

-Issues

Issues for KSTAR magnetics

▪**KSTAR has an inherent source of magnetization inside the PF & TF coils**
- Incoloy 908 is the jacket material for superconducting strand
- Weakly ferromagnetic with max μ_r~10 (saturation B~1T)
- Toroidally symmetric but problematic for field-null quality



▪**Experimental findings :**
- Downward shift of plasma
- Lower measured loop voltage than the calculated by the circuit equations
- PF coil currents decay faster than the calculated by the circuit equations

=> **Need additional up-down asymmetric sources of current and field**

▪**Cryostat is a potential source of up-down asymmetry**
- Large current at the lower cryostat will drive plasma downward
- Other discrepancy might be due to cryostat current also

Understanding magnetics

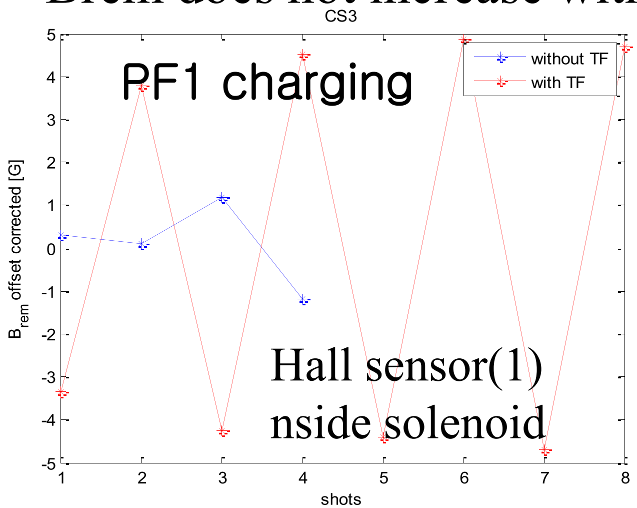
-The effect of Incoloy 908

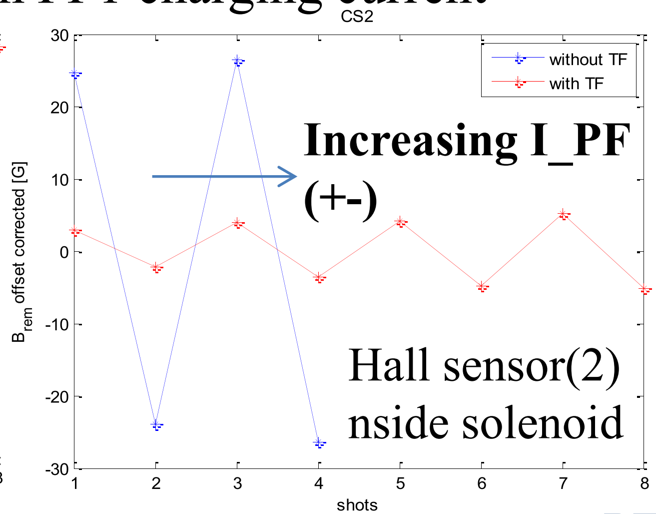
Dependence of Brem on TF charging (Hall sensor)

At near machine center (R=1.85[m], Z~0[M])

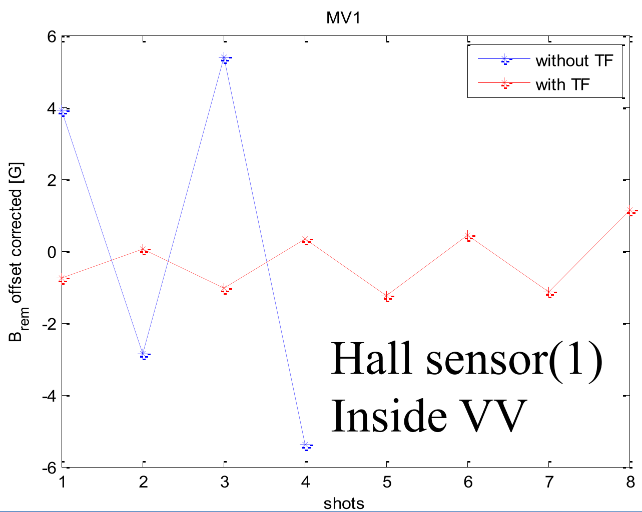
Max of Brem ~ 2G (**negligible**) near field-null center

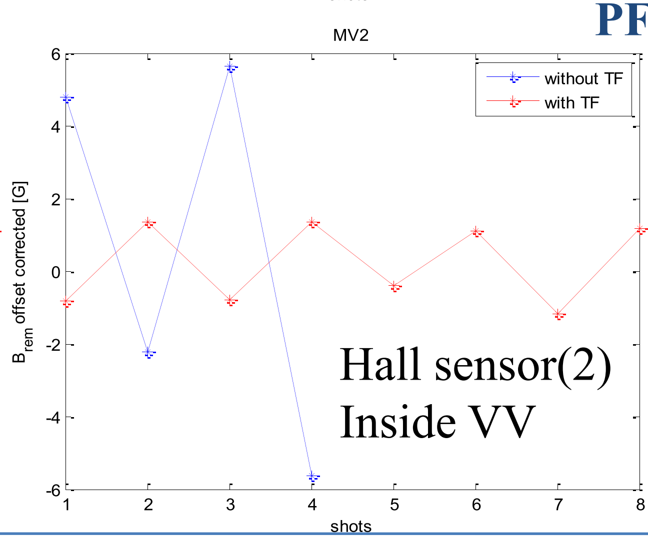
Brem does not increase with PF1 charging current





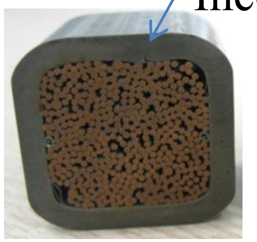
Brem increased with TF on
The trend is the same
for upper one (CS1)





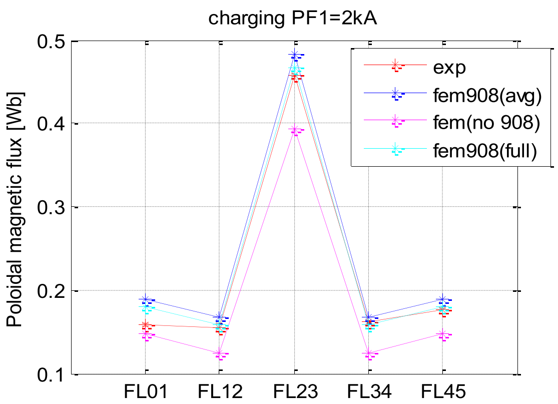
PF1 charging upto +-4kA

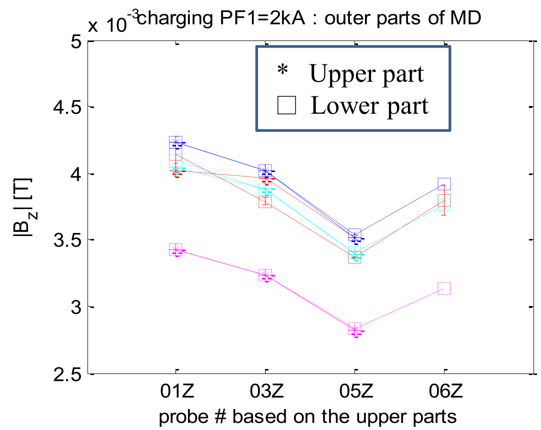
Incoloy 908



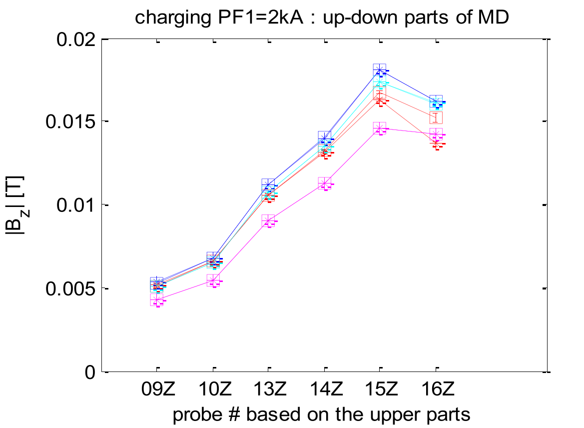
The effect of Incoloy 908 on magnetics

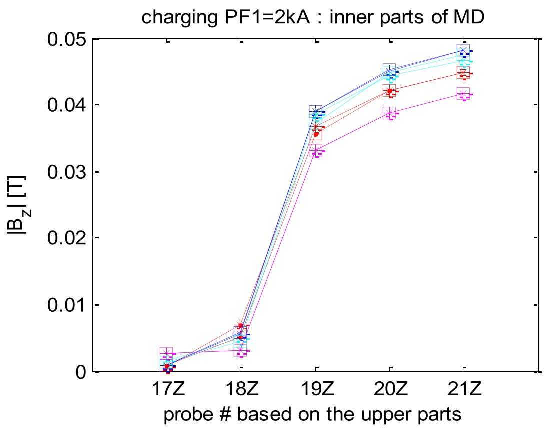
Comparison between measurements and model calculations





Incoloy 908





<u>Non-linear FEM models</u>

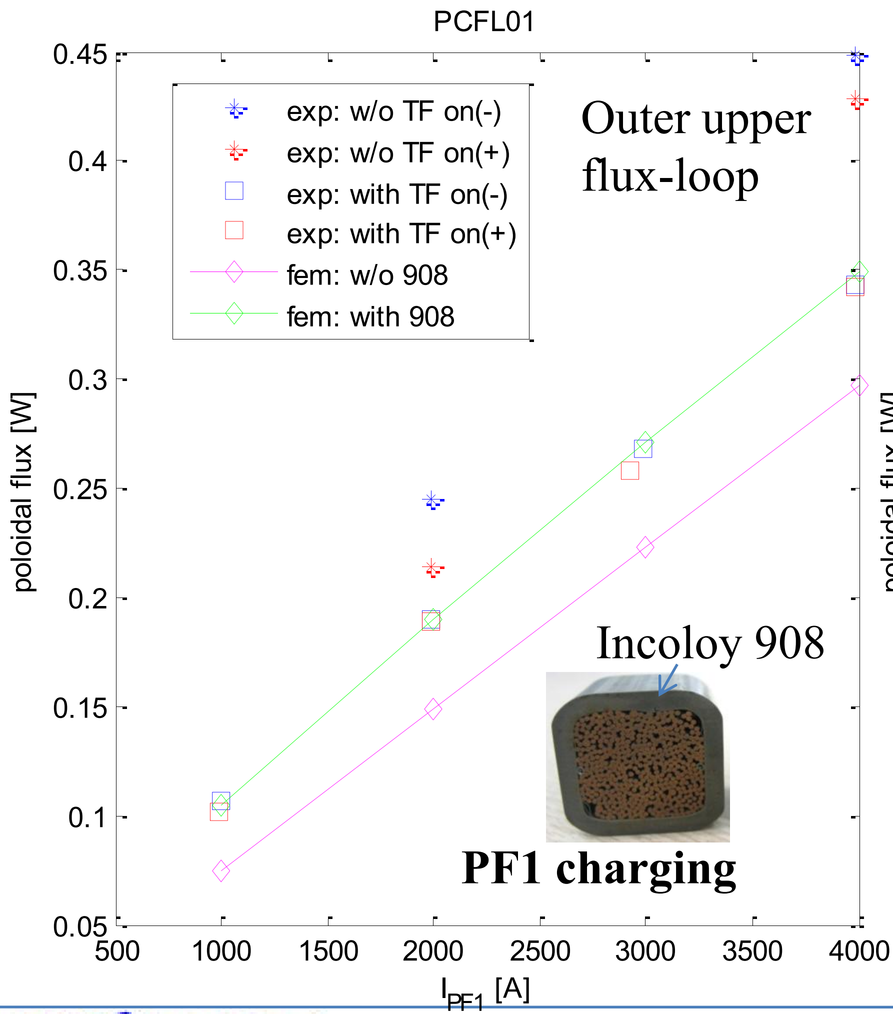
•avg : average model of cicc
•full : each cicc structure considered
•No 908: without incoloy908

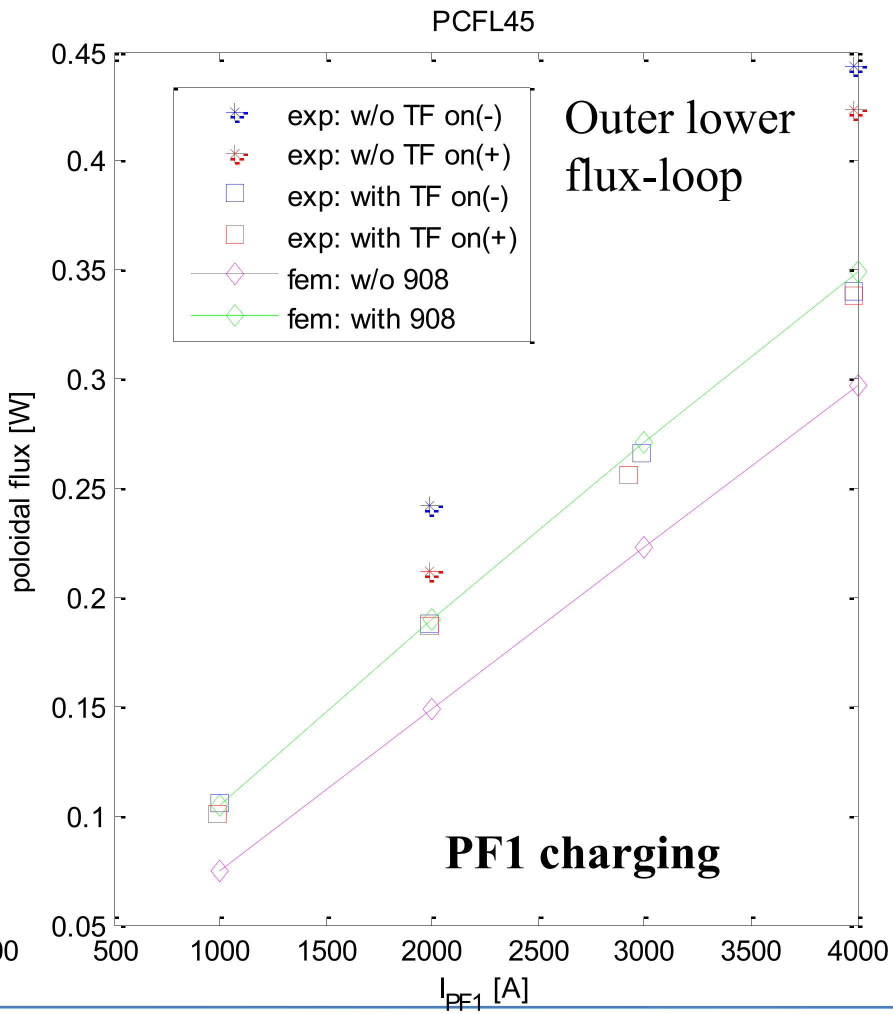
This generates additional ~20G for initial field-null state

•Jacket of winding in TF & PF coils is magnetic materials (μ_r~10 at low B)
•Non-linear FEM model match better but there is still some deviation
•Need further analysis for reliable reconstruction

Effect of Incoloy 908 on Flux-loop measurements

The measured flux is higher by 15% - Incoloy effect is not negligible!
FEM calculations match well with all the flux-loop measurements

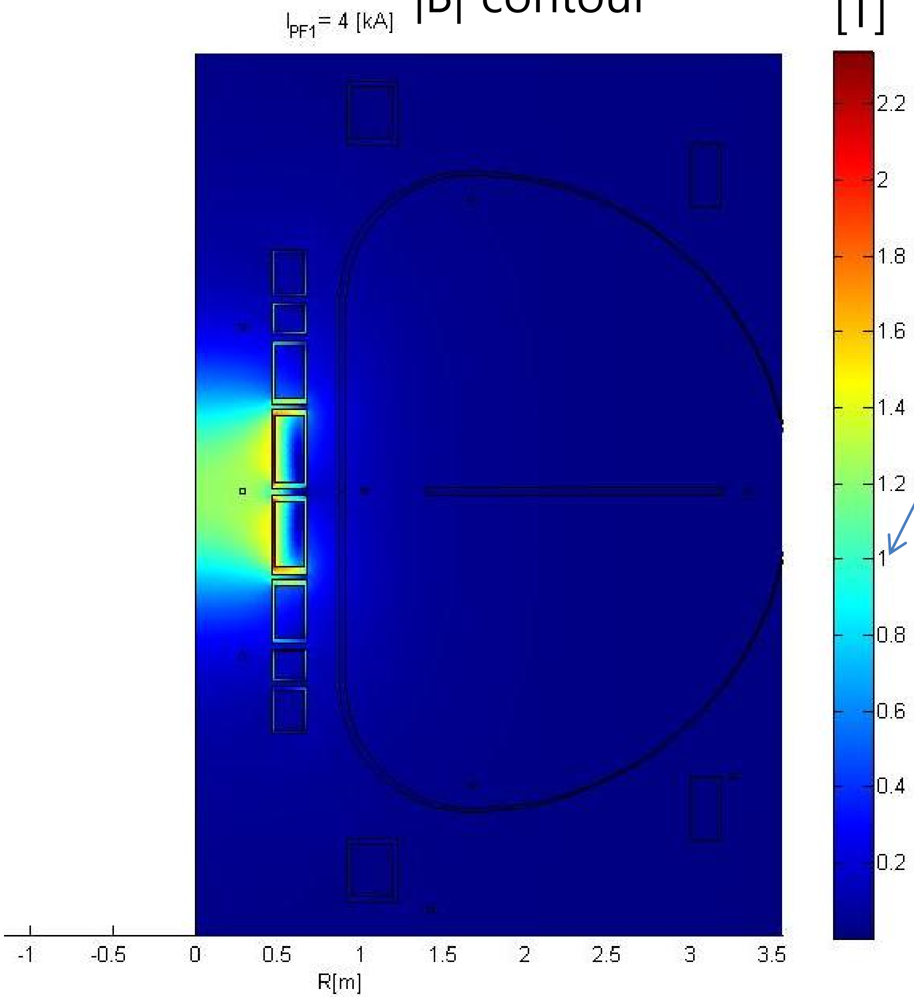




KSTAR NFRI

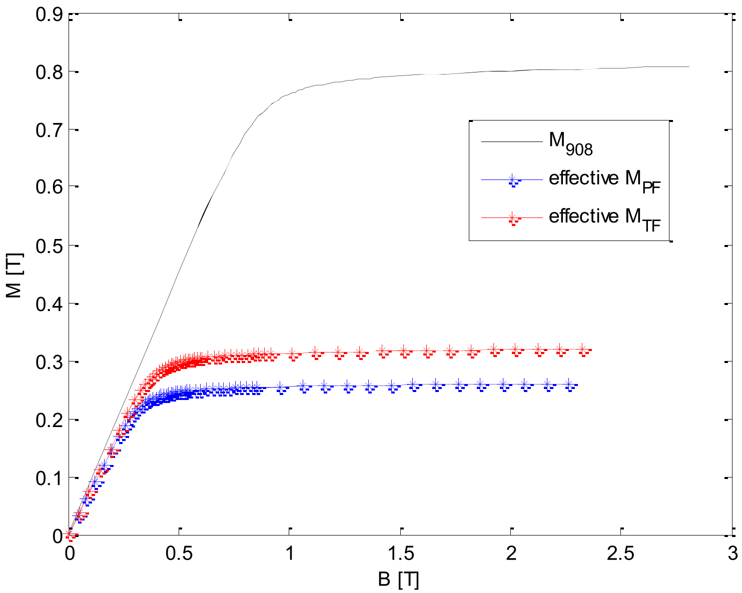
Even at 4 kA of PF1 charging, some part of PF coils are not fully saturated (nonlinear model required)

|B| contour



Saturation B
for Incoloy 908

B-M curve for Incoloy 908



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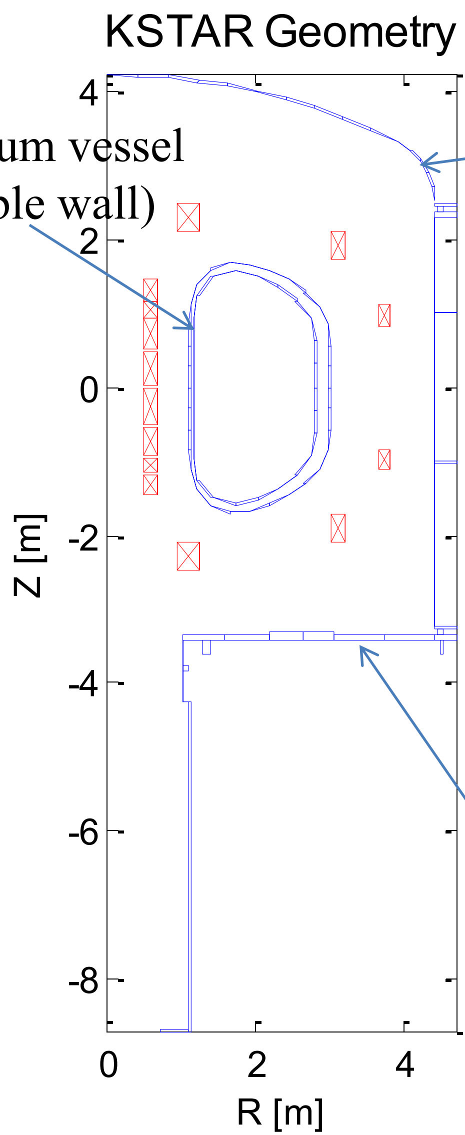
Understanding magnetics

-The effect of eddy current in cryostat

Cryostat might be a source for up-down asymmetry



Vacuum vessel (double wall)

Rough approximation of cryostat roof

Using the same resisitivity for vacuum vessel and cryostat (stainless steel-316LN)

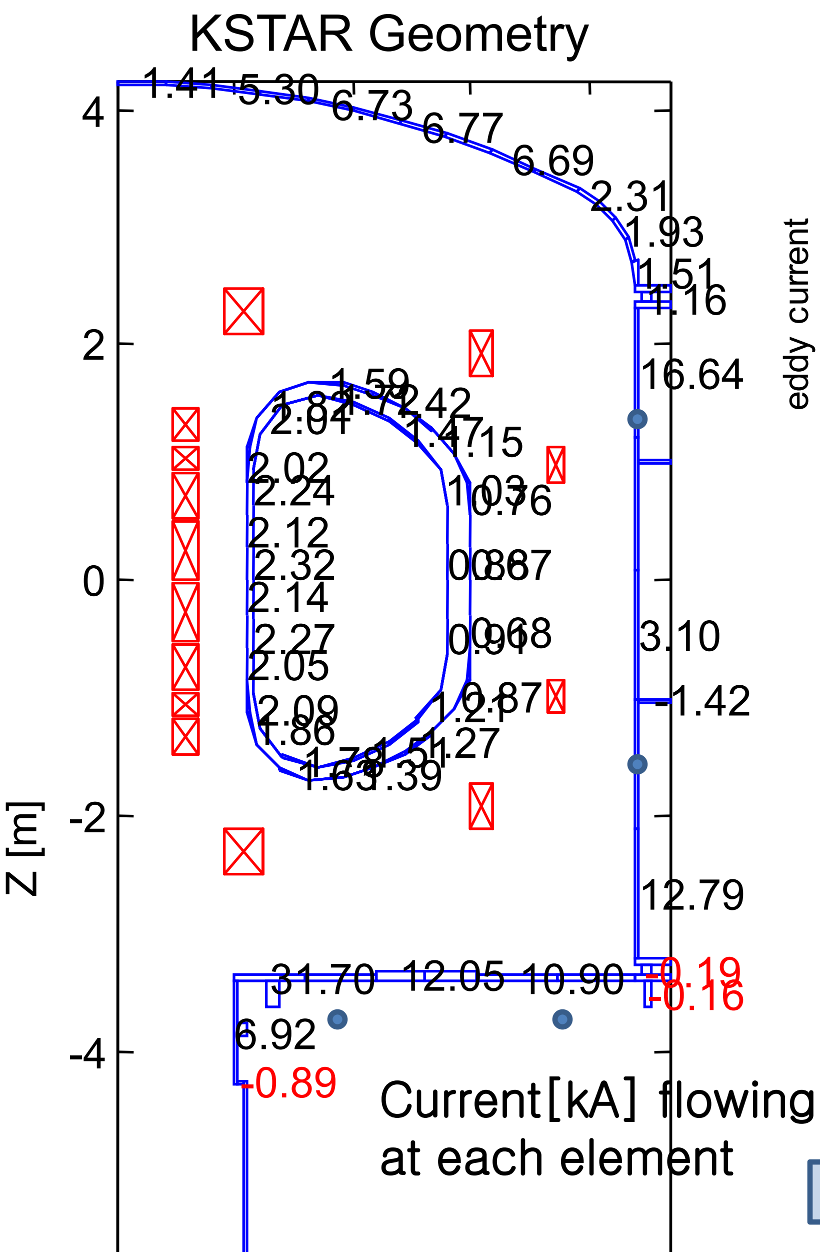
Circuit equations with a system of linear differential equations for active current elements

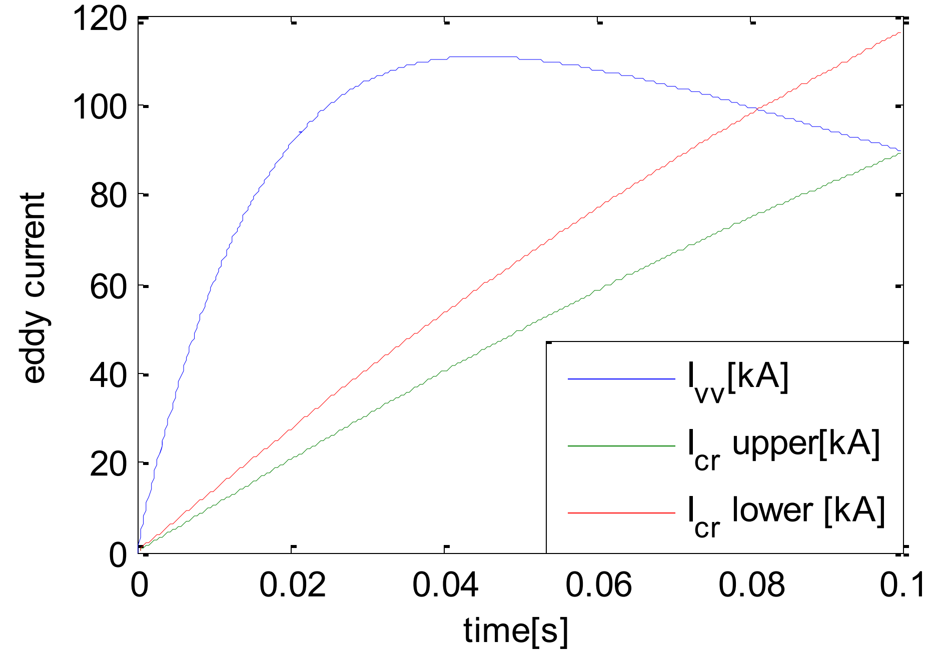
$$\sum_j M_{ij} \frac{dI_j}{dt} + R_i I_i - V_i = 0$$

$j = 1, \ldots j_{PF}, j_{plasma}, \ldots\ldots, j_{wall\_seg}, j_{cryo\_seg}$

Thick(5cm) bottum plate

Eddy current distribution in the cryostat





– Current in the cryostat will attract the plasma downward

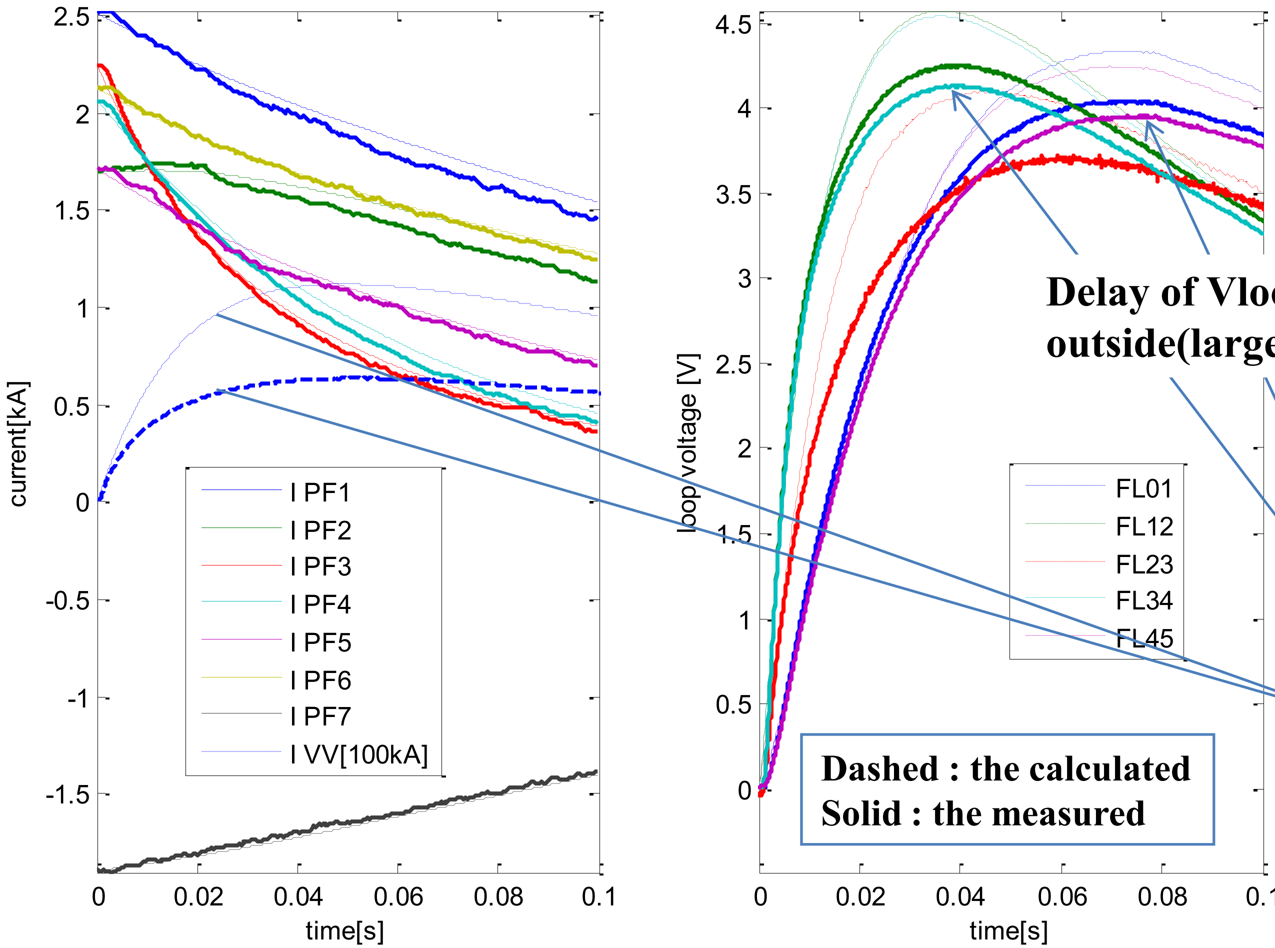
– However, Current in the cryostat does not reduce vessel current much

● Possible positions of magnetic probes

Comparison between the measured and the calculated

(for vacuum shot : 614 – including cryostat conducting structure)

- Model : circuit equation with filaments vessel current with the measured V_MPS
- Larger deviation at the I_PF1, I_PF2 and FL23
- **Need time dependent FE model to include the effect of Incoloy!**
- Up-down asymmetry can be partially explained with current in the cryostat



Wall model : ‘full VV+ Cryostat’

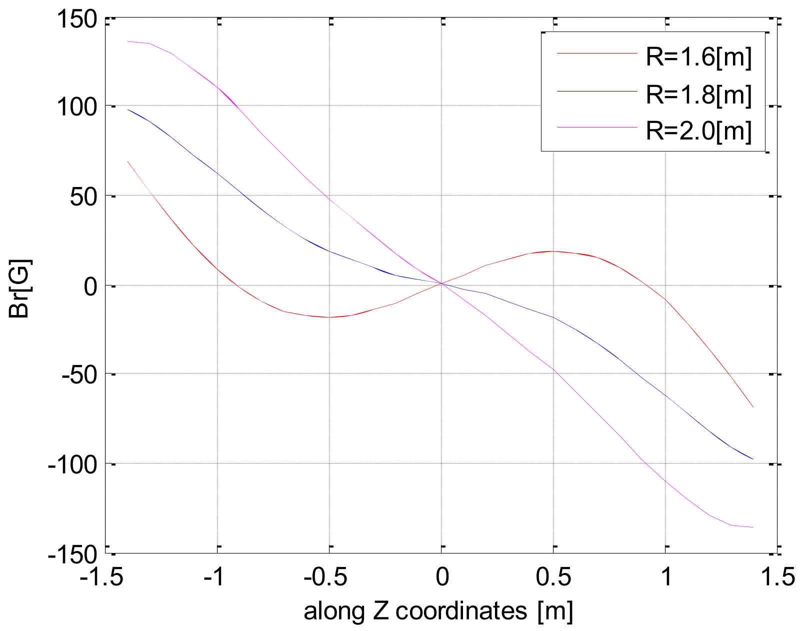
Delay of Vloop is increasing to outside(larger current at the outside)

Up-down asymmetry reproduced!

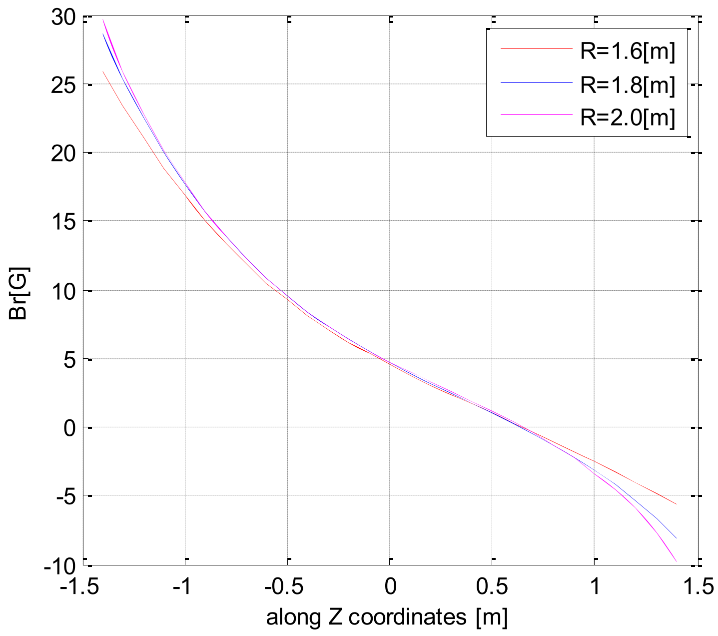
Still large discrepancy for vessel current

Vacuum field at 100ms with the cryostat current

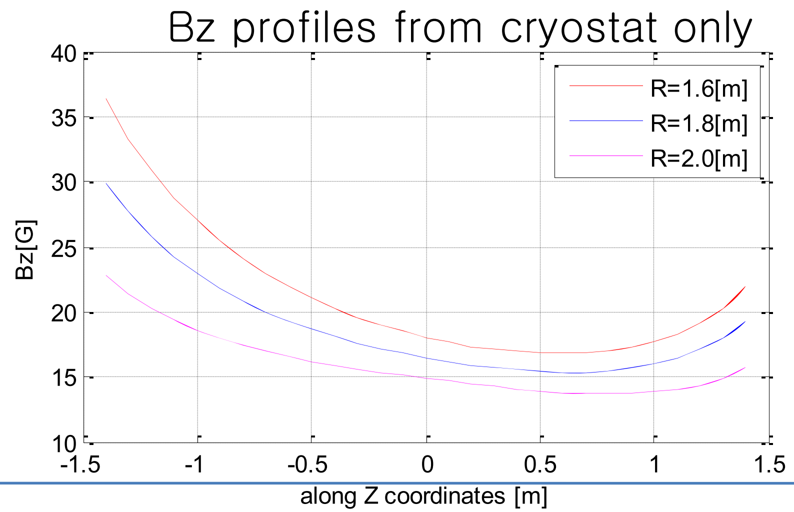
Br profiles for up-down symmetric case



Br profiles from cryostat only



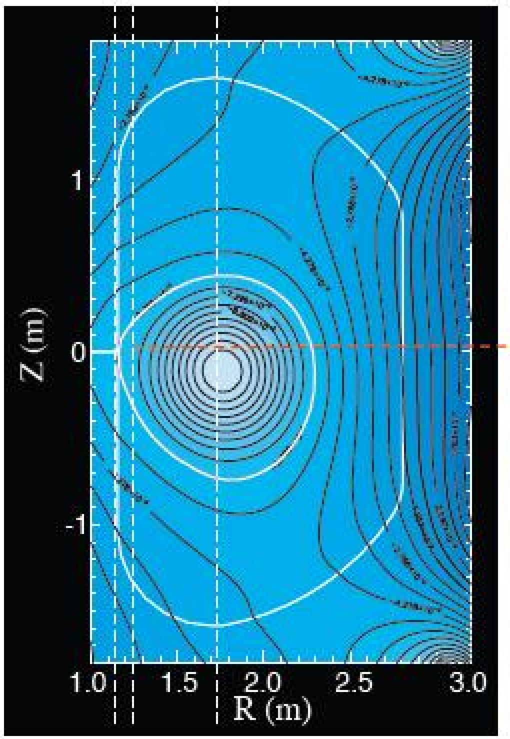
-The current in the cryostat will attract the plasma column downward (positive Br at the mid-plane)

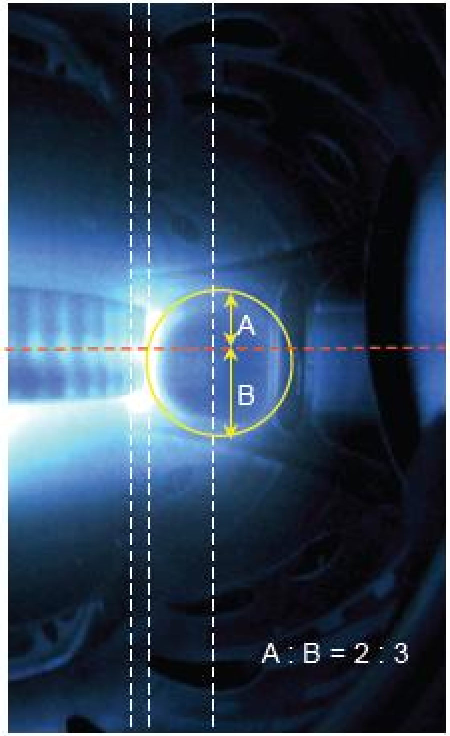


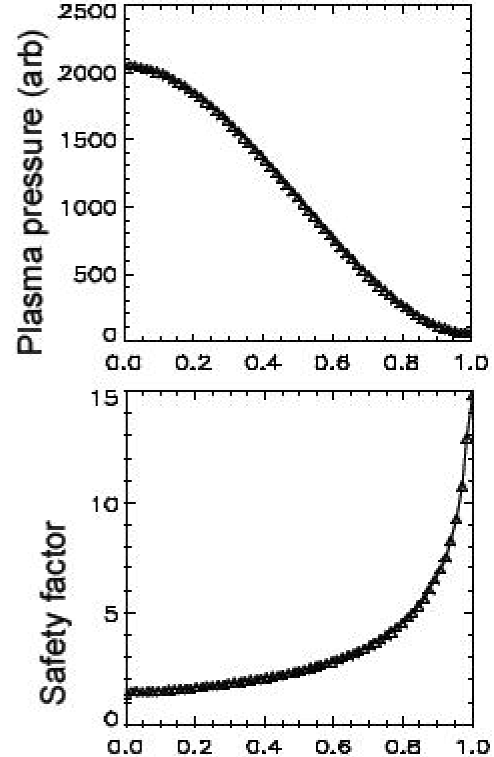
Reconstruction tools

EFIT reconstructions match well with CCD image

Shot 1127







t=0.545s case (frame#133, 543.1 ms)

a: R=1.16m (vessel wall);
b: R=1.26m (inboard limiter);
c: R=1.7m (ECH pre-ionization resonance layer).

- The plasma center shifted about 10 cm below the midplane
- Significant wall current is on the order of plasma current
  - reconstructed $I_{p\text{-}wall}$ = 70 kA
  - reconstructed $I_{p\text{-}comp}$ = 93kA
  - measured $I_{p\text{-}meas}$ = 95 kA

By O. Hopkins

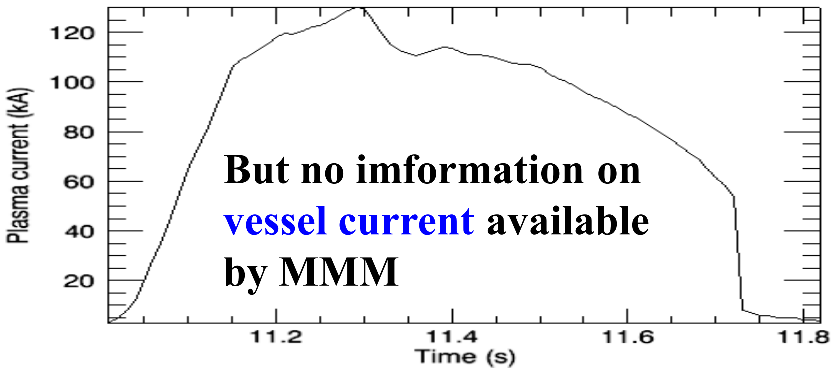
- The effect of Incoloy is not included

KSTAR NFRI

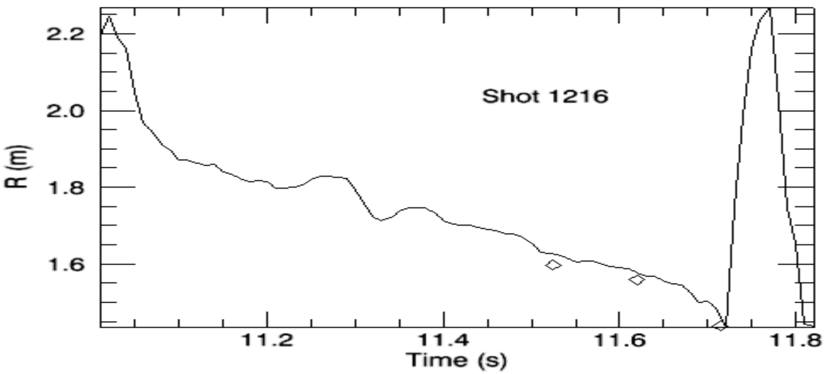
Rp & Zp from Multi-pole Moment Method(MMM)

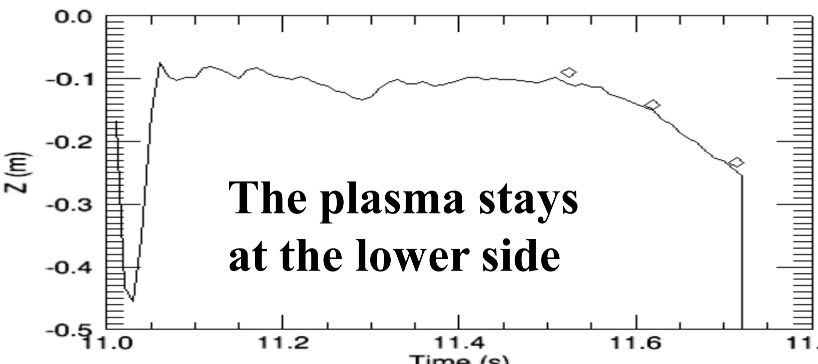
Incoloy effect is bypassed by MMM

(1.597,−0.0896)@0.5243
(1.559,−0.142)@0.6195
(1.439,−0.233)@0.7148

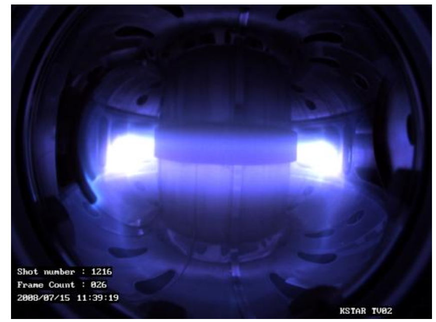


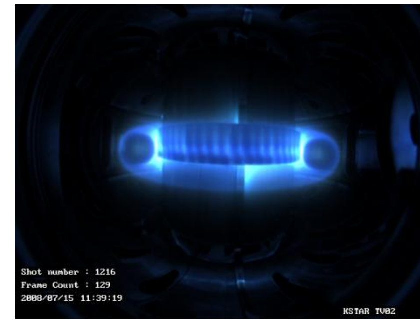
But no imformation on vessel current available by MMM





The plasma stays at the lower side



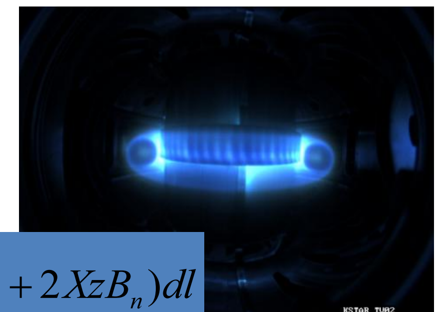


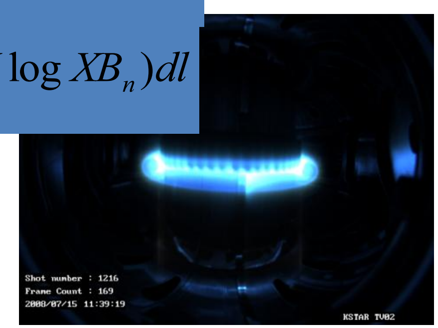
@0.0338

$$I_P = \int j_\phi dS_\phi = \frac{1}{\mu_0}\oint_l B_\tau dl$$

$$I_P \overline{X}_P^2 = \int j_\phi X^2 dS_\phi = \frac{1}{\mu_0}\oint_l (X^2 B_\tau + 2XzB_n) dl$$

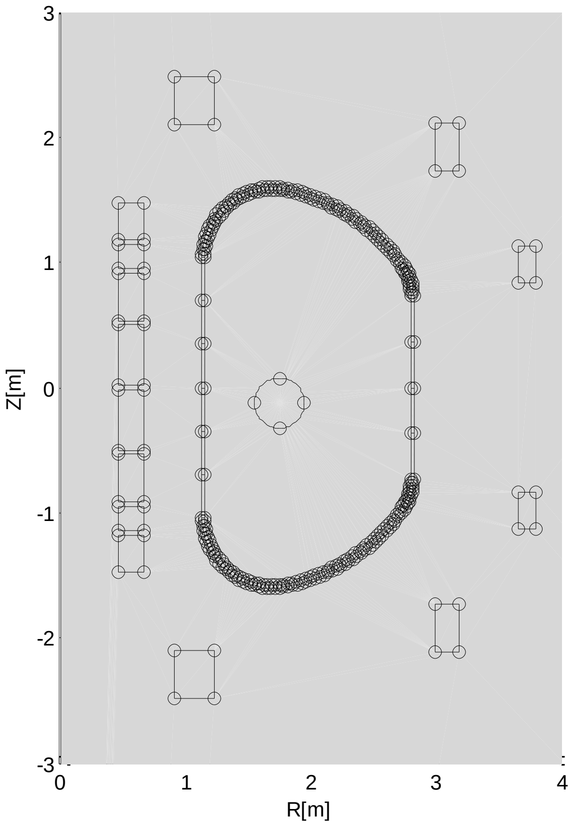
$$I_P \bar{z}_p = \int j_\phi z dS_\phi = \frac{1}{\mu_0}\oint_l (zB_\tau - X\log XB_n) dl$$





KSTAR NFRI

Reconstruction of plasma position & current using a Nonlinear Finite Element Method



-Nonlinear Least Square Minimization of vessel and plasma current with R&Z position

-Plasma as a single current filament
(Will be upgraded with Grad-Shafranov equation)

-Max 37 measured data with integrator hooked

-Single shell of vacuum vessel (~24 segments)

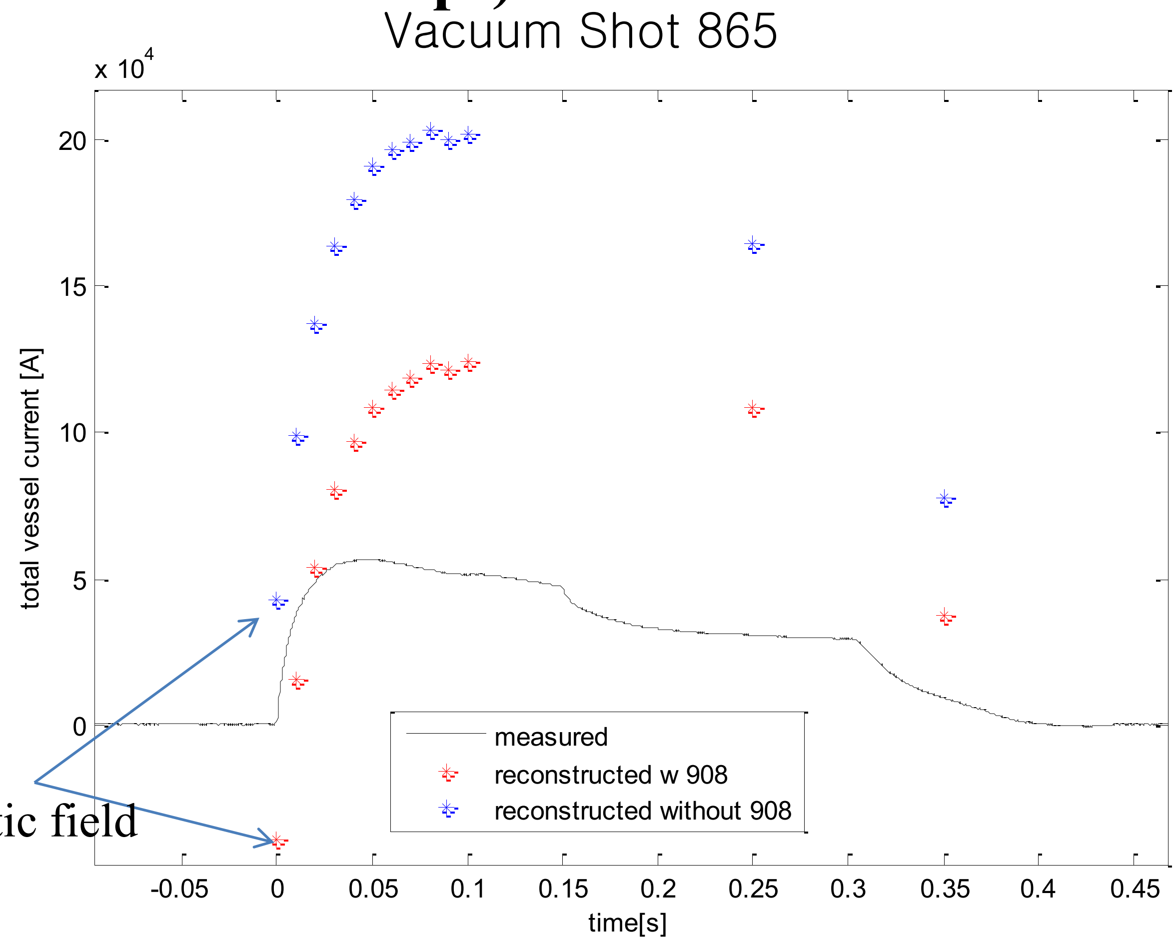
-Using nonlinear FEM solver with the measured BH curve

-with real shape of vessel elements

-Weighting is optimized with extensive parameter scans

Reconstructed vessel current by nonlinear FEM
(Using magnetic probes and flux-loops)

Using 24 segments of
Vacuum vessel



Erroneous current due to
poor understanding of the static field

Reconstruction also suggesting the measured vessel current is inconsistent with probe measurements!!

Issues for reconstruction

1. We don't understand the static field good enough

- Though it's better when Incoloy is included, the match is still in poor condition (without incoloy, vessel current(Jvv) reconstruction will be a nightmare!)

- Erroneous vessel current is due to the mismatch between the measured & calculated for Jvv=0 case : Jvv~-38 kA (shot 865 IM case)

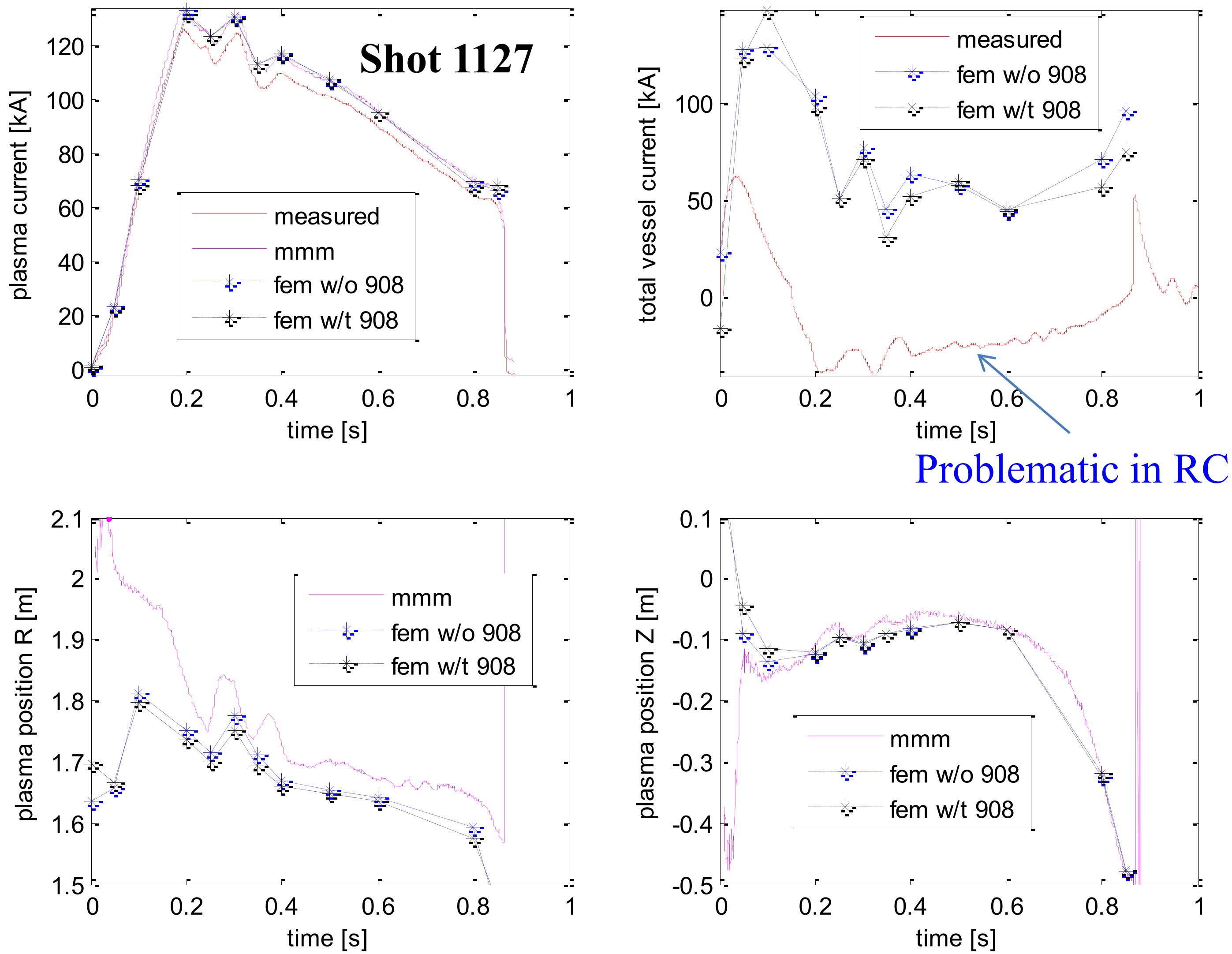
- And this erroneous Jvv is changing during blip time (Hard to determine!!)

2. Nonlinearity

- Simple Green function method will be out of the question (no linear relation between Jvv & Bprobe)

- **Nonlinear optimization technique is required based on the proper calculations of the effect of Incoloy on the magnetic probe measurements**

Results of FEM reconstruction



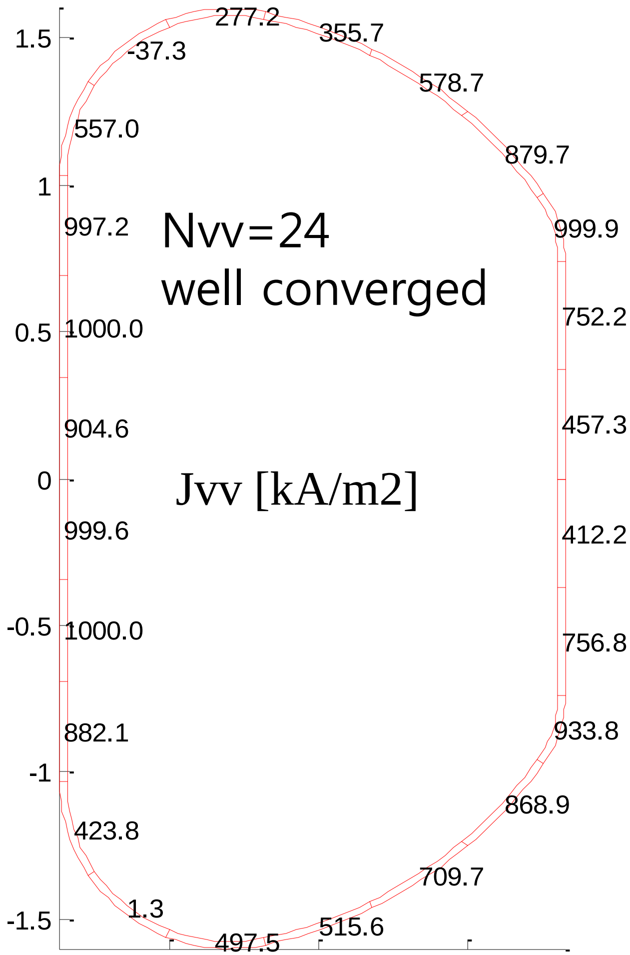
N_{vv}=24

Problematic in RC measurements

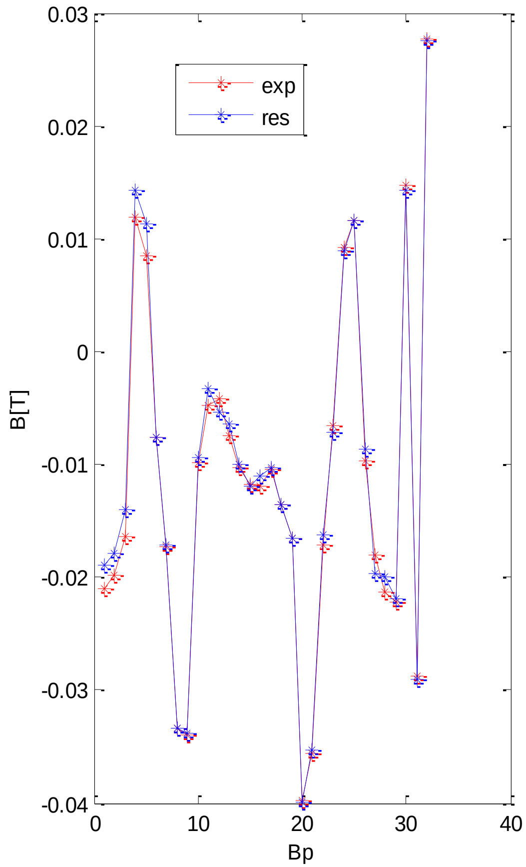
- Incoloy does not affect the global parameters much
- Incoloy affects R_p rather than Z_p

FEM reconstruction shows reasonable distribution of the eddy current along the vessel

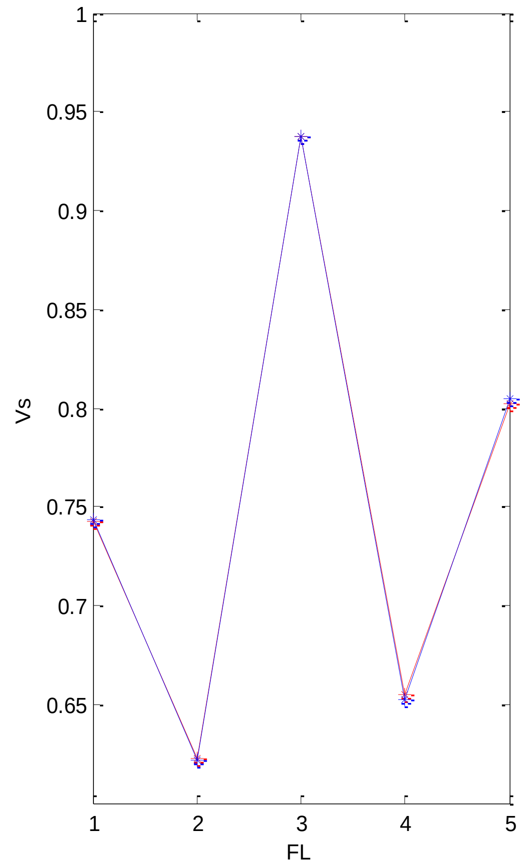
Reconstructed vessel current density



Comparison between Measured and Reconstructed



Magnetic probes



Flux loops

Major Upgrade for magnetic Measurements for 2009' campaign

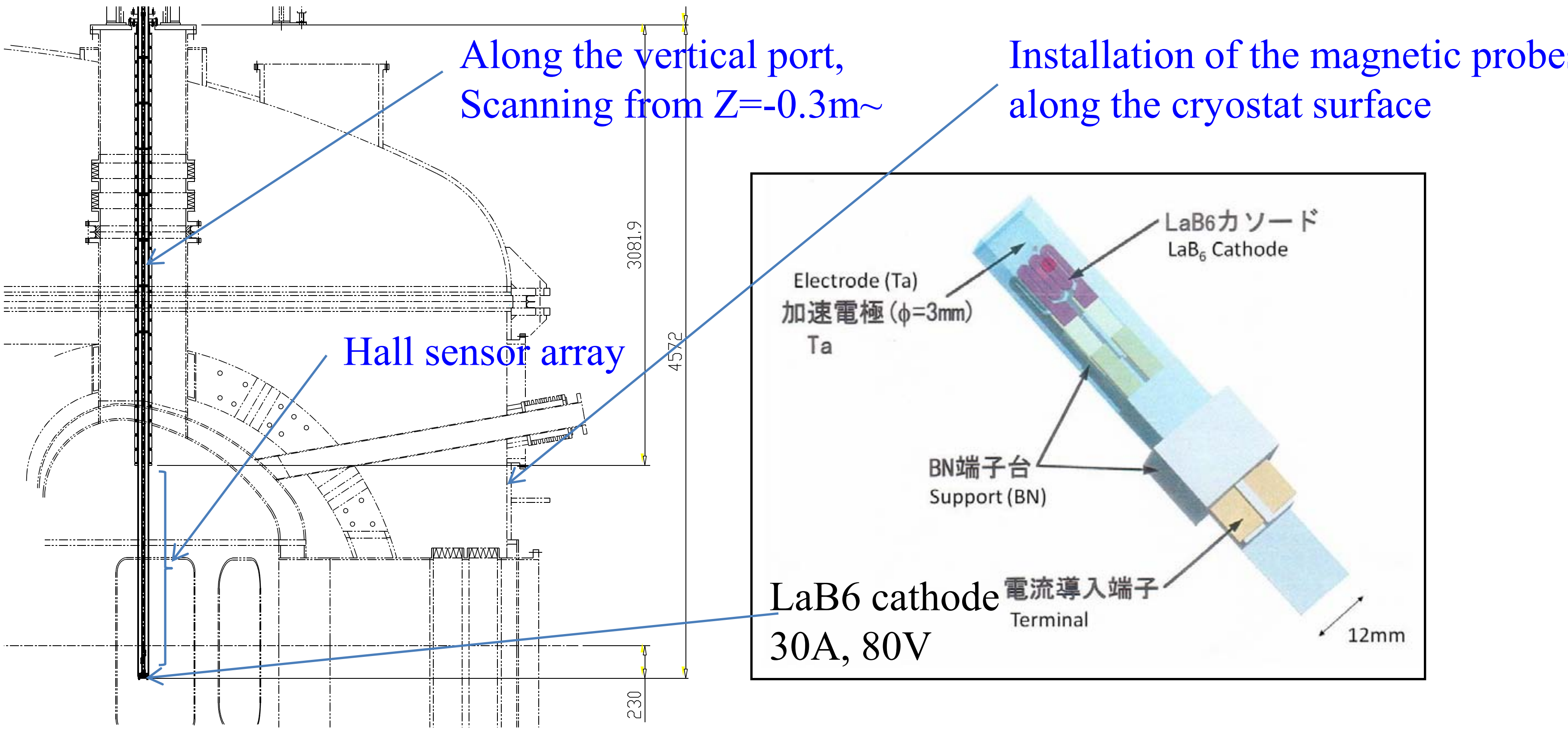
1. Upgrade of magnetic probes and loops
   - New calibration factors
   - New sets of probes and loops at another toroidal section with improvement
   - New probes(5) along the cryostat (to measure eddy current in the cryostat)

2. Error field measurements by electron beam
   - Capable of 2m Vertical stroke (-0.3m from the midplane to above)
   - Beam line will be visible by Ar gas-puff and a Phosphor screen

3. Upgrade of Hall sensors
   - Along the E-beam port, 10 sensors will be installed (Br+Bz)
   - Extensive coverage around the field-null
   - Radiallly movable Hall sensors (2 sensors)

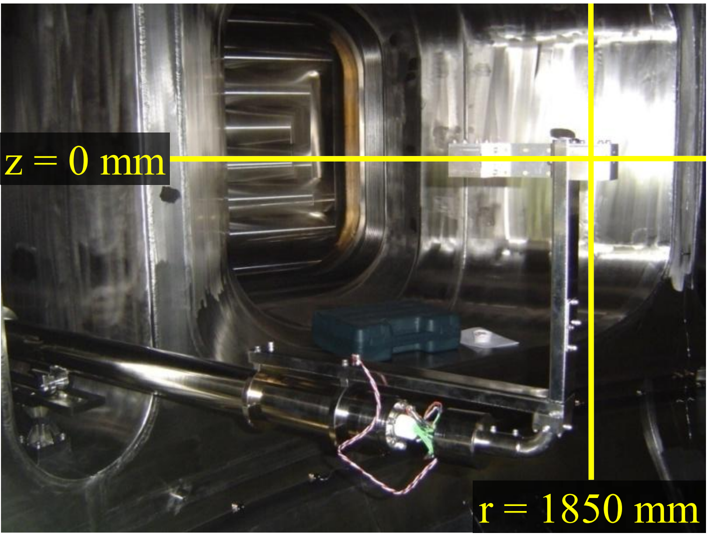
Vertical electron beam system for in-vessel B measurements

- To clarify up-down symmetry issue, field-null quality, and connection length measurements (also for calibrating magnetic probes)
- Together with Hall sensors installed for double-check
- Additional magnetic probes for eddy current in the cryostat

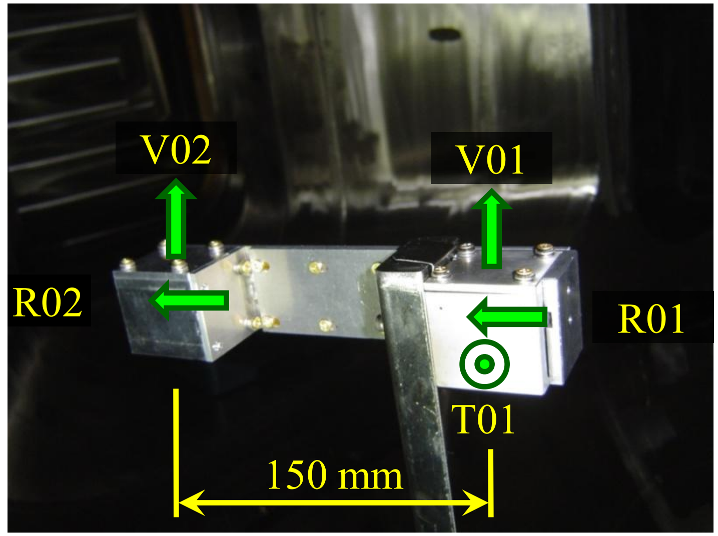


B measurement system with radially scanning Hall sensors

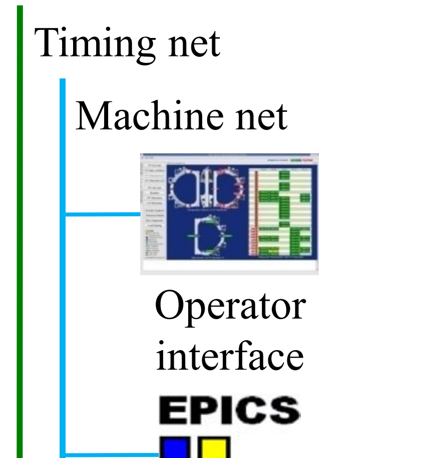
Field-null measurements of Br, Bz along the mid-plane from R=1.85m~

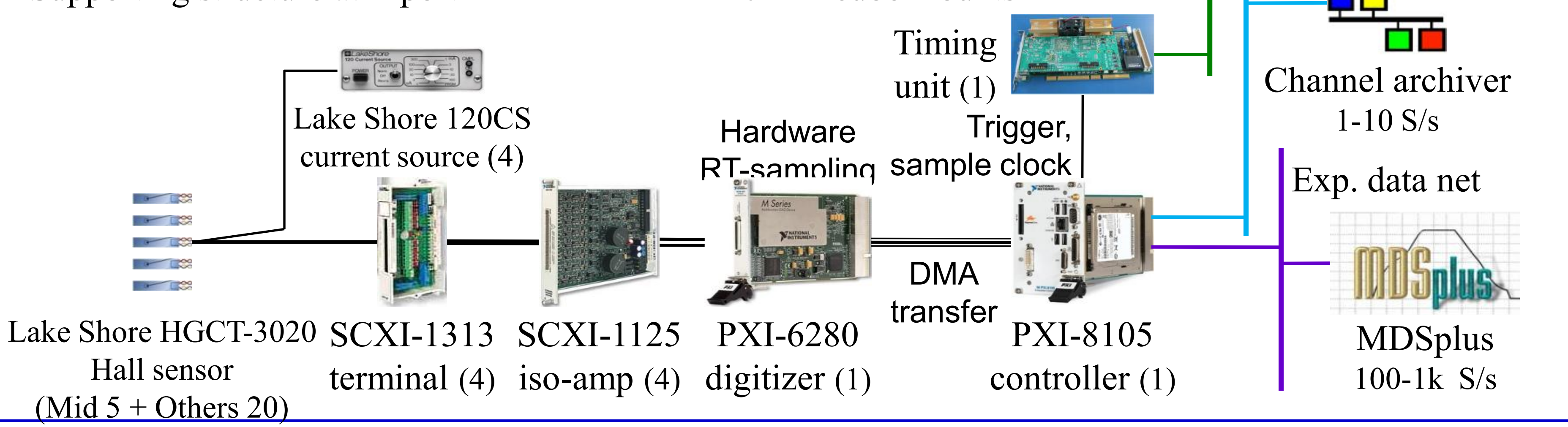


Supporting structure at E port



40 mm cube mounts





Summary

- A genuine startup scenario, i.e., "Dipole mode" is developed and implemented successfully for KSTAR 1st plasma in accord with ITER requirements

- A genuine reconstruction code is developed to cope with nonlinear magnetization from Incoloy 908 and partially validated with the measurements, however,
  - -still require better understanding of the probe measurements and its validation
  - -still large discrepancy between the measured and the calculated vessel current
  - -developed analysis tools are directly applicable to ITER TBM analysis

- The cryostat is a potential source of up-down asymmetry
  - -according to the calculations, rather large current flows in the cryostat(~200kA)
  - -better agreement with loop voltage measurements with the cryostat circuit
  - -potentially problematic in ITER also

- By upgrading and through validation of the magnetic diagnostics next campaign, these issues will be examined in more quantitative way