Equilibrium reconstruction using EFIT

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2009. 4. 15
US-KSTAR workshop, GA

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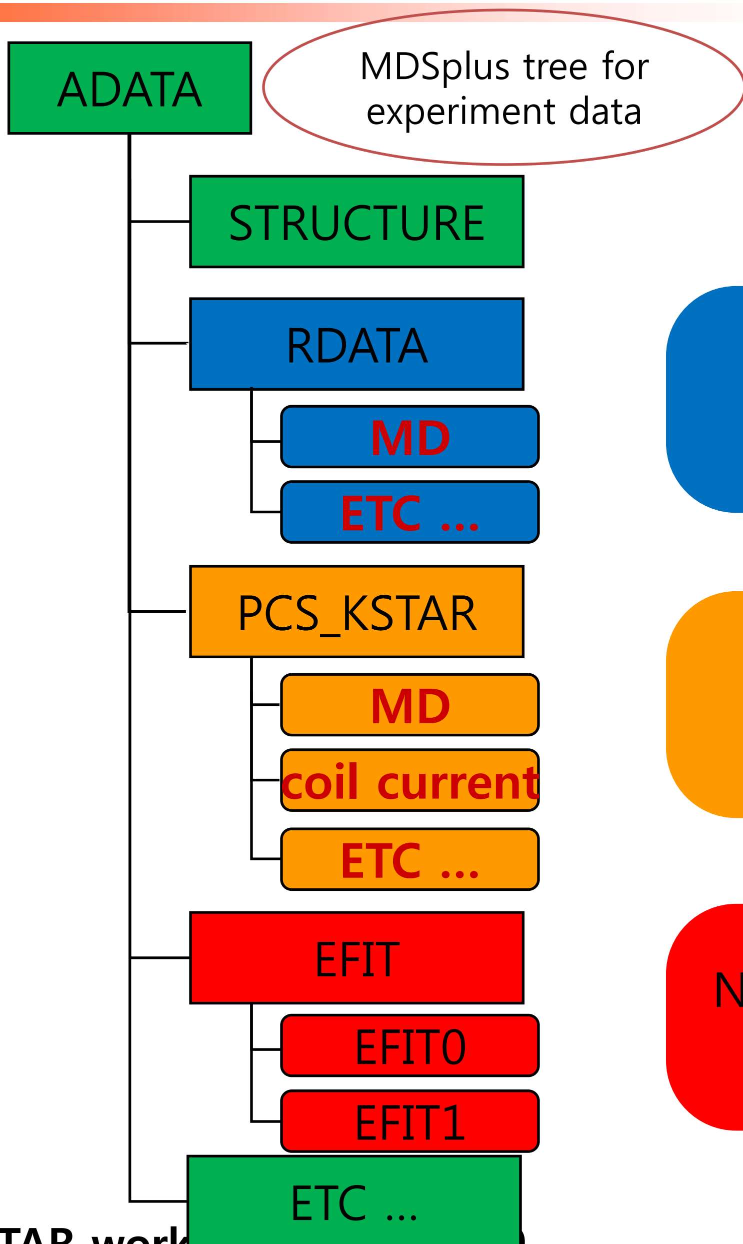
EFIT is chosen as standard equilibrium reconstruction code

- Needs reconstruction of plasma equilibrium from experimental data.
  - To understand the plasma equilibrium property such as plasma current profile, plasma pressure profile, magnetic field quantity, *etc.*
  - To be used for plasma shape control and for supporting plasma operation and data analysis.
  - To be used for calculation of plasma stability and particle transport.
- For KSTAR, we installed EFIT code as standard equilibrium reconstruction code.
  - EFIT solves Grad-Shafranov equation in (R, Z) coordinates.
  - Advantages using (R, Z) coordinates :
    - new experimental data can be easily included.
    - no singular point in solving Grad-Shafranov equation.

MDSplus : KSTAR Data Acquisition System (1)



Linked to an independent tree for diagnostic data storage

Linked to an independent tree of diagnostic data for plasma control system

Node for recording EFIT results (EFIT results are also treated as same as diagnostic data)

MDSplus : KSTAR Data Acquisition System (2)

- SCS (Supervisory Control System) automatically run the EFIT, which should be pre-compiled appropriately, using a script file after each shot (between-shot analysis).
- For the between-shot analysis, EFIT uses the diagnostic data in the PCS_KSTAR tree, which sampling rate is lower than RDATA and stored quickly, and the results are stored in the EFIT0 node.
- Requirements for automatic analysis
  - Shot number
  - Snap file
  - Number of frames and interval between each frame
- For more precise analysis, every researcher can run the EFIT using the diagnostic data in the diagnostic tree (RDATA tree).

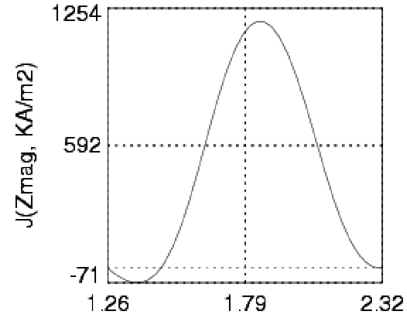
Adapting EFIT to KSTAR system

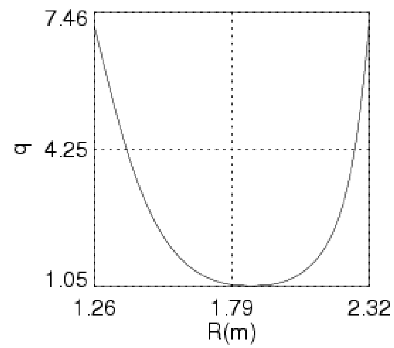
- Data needed for equilibrium reconstruction is imported directly from MDSplus data acquisition system.
- Data being varied with each shot such as 'goodness' of each magnetic probe (*fitting weight* in EFIT code) also be imported from MDSplus system directly.
- Data being varied in long time such as structure information also be read from MDSplus system, even though these are not varied with every shot.
- The ***eqdsk*** files will be temporarily stored in hard disk. ***eqdsk*** files can be used as input file of another calculation, for example, GATO.
- Several supplement codes are made
  - As an example, **d2mds.f** is a fortran code writing ***eqdsk*** data to MDSplus system

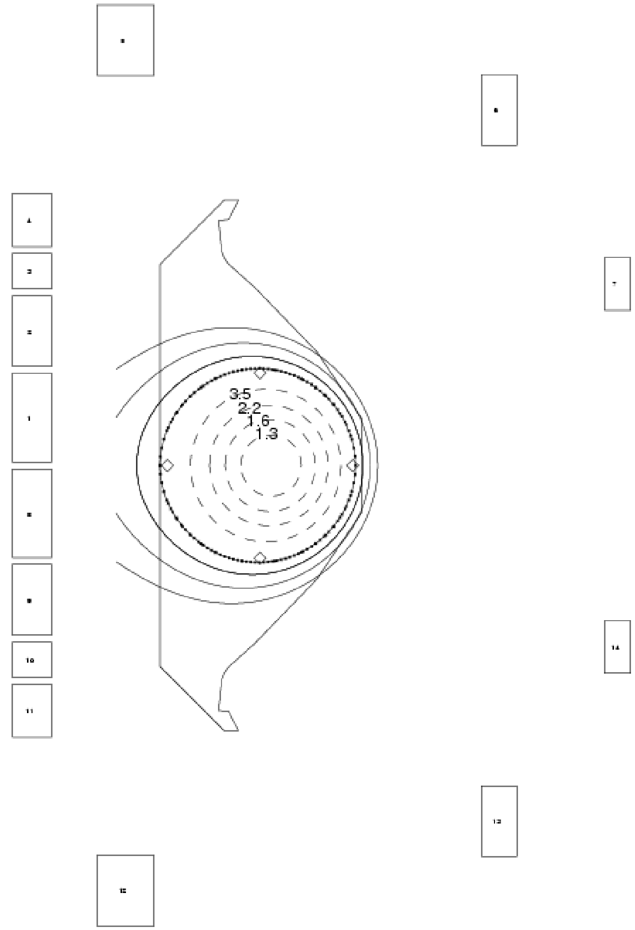
An artificial circular plasma (I_p = 200 kA) made by EFIT equilibrium calculation mode as a test

h EFITD 65x65d 09/01/2008h
date ran =
shot # = 10004
t(ms,us) = 1100 0
chi2(mag)= 2.353E-29
rout(cm) = 178.77
zout(cm) = 0.000
a(cm) = 52.77
elong = 0.992
utri,ltri= -0.02 -0.02
indent = 0.000
V,A(m3,2)= 9.71 0.863
energy(j)= 2.701E+04
betat(%) = 0.20
betap(3) = 0.80
betan,In = 0.81 0.25
li(3),li = 1.83 1.83
error, # = 8.248E-06 56
delstar = 4.5E-05 4.5E-05
ux,lx(cm)= -89.00 -89.00
J0n,J1n = 5.13 0.00
q1,q95 = 7.15 5.86
dsep(cm) = 3.497
rm,rc(cm)= 186.3 187.5
zm,zc(cm)= 0.00 0.00
betapd,w = 1.06 0.00
betatd,w = 0.27 0.00
wdia(J) = 3.582E+04
wtor(J) = 0.000E+00
data used:
ip(ka) = 200.0
bt0(t) = 1.500
0 flux loops
0 magnetic probes
1 rogow 0 fc 0 ec
scrapof(mm) 40.0 80.0120.0160.0200.0

r010004.001100







icp, ivs= 0 0
kf, kp, E= 3 3 0
fpd, p, E= 1.0 1.0 0.0
fwbp, fwq= 0.0 1.0
Ze(cm) = 0.000
kcf, kcp= 0 2

Reconstruction result of previous test equilibrium with calculated MP and FL data for testing self-consistency of EFIT installed

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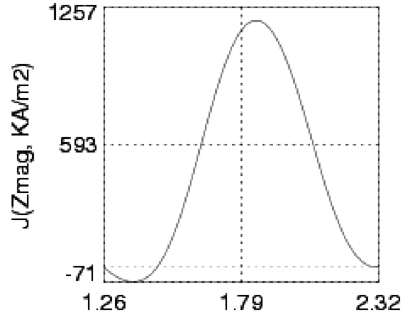
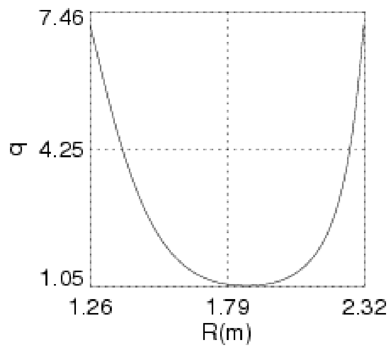
- Using same representation of plasma current
- Gives same betap (0.80), li (1.83), plasma shape,

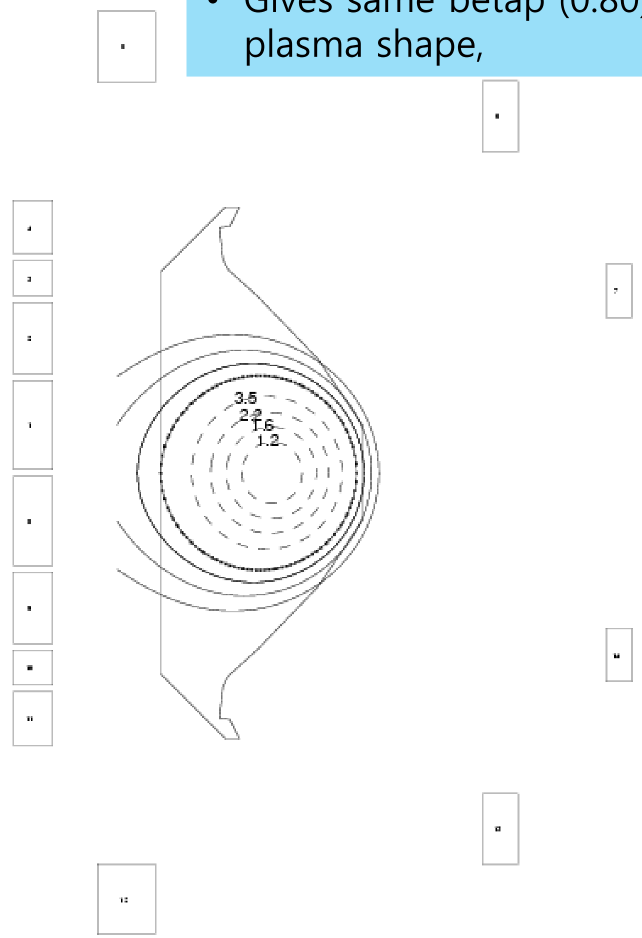
h EFITD 65x65d 09/01/2008h
date ran =
shot # = 10004
t(ms,us) = 1101 0
chi2(mag)= 6.139E-12
rout(cm) = 178.77
zout(cm) = 0.000
a(cm) = 52.77
elong = 0.992
utri,ltri= -0.02 -0.02
indent = 0.000
V,A(m3,2)= 9.71 0.863
energy(j)= 2.692E+04
betat(%) = 0.20
betap(3) = 0.80
betan,In = 0.81 0.25
li(3),li = 1.83 1.83
error, # = 5.068E-03 9
delstar = 9.2E-02 9.2E-02
ux,lx(cm)= -89.00 -89.00
J0n,J1n = 5.14 0.00
q1,q95 = 7.15 5.86
dsep(cm) = 3.497
rm,rc(cm)= 186.3 187.5
zm,zc(cm)= 0.00 0.00
betapd,w = 1.06 0.00
betatd,w = 0.27 0.00
wdia(J) = 3.582E+04
wtor(J) = 0.000E+00
data used:
ip(ka) = 200.0
bt0(t) = 1.500
5 flux loops
33 magnetic probes
1 rogow 0 fc 0 ec
scrapof(mm) 40.0 80.0120.0160.0200.0

m010004.001101





icp, ivs= 0 0
kf, kp, E= 3 3 0
fpd, p, E= 1.0 1.0 0.0
fwbp, fwq= 0.0 0.0
Ze(cm) = 0.000
kcf, kcp= 0 2



Attempts to reconstruct equilibrium for a shot #1127 @ 545 ms (for this time, Steve already reconstructed the equilibrium)

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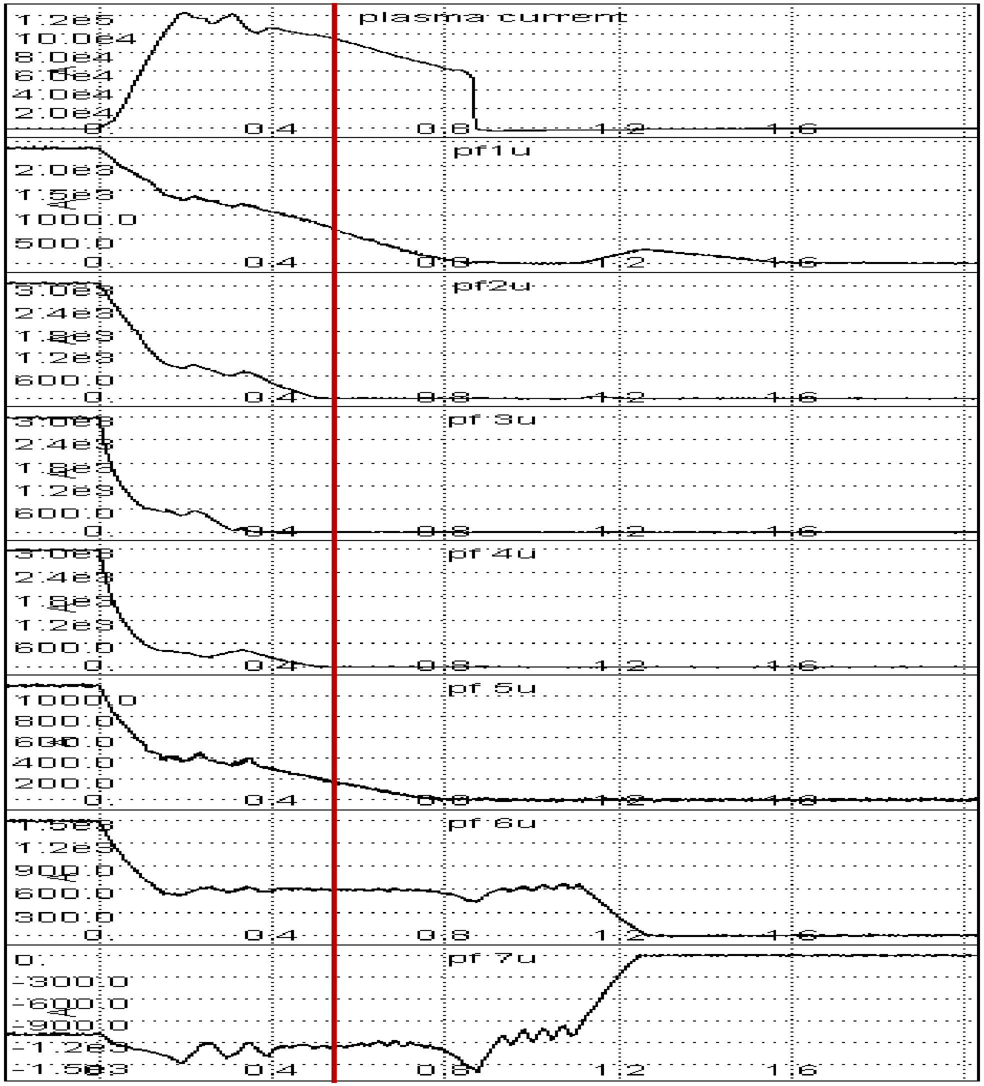
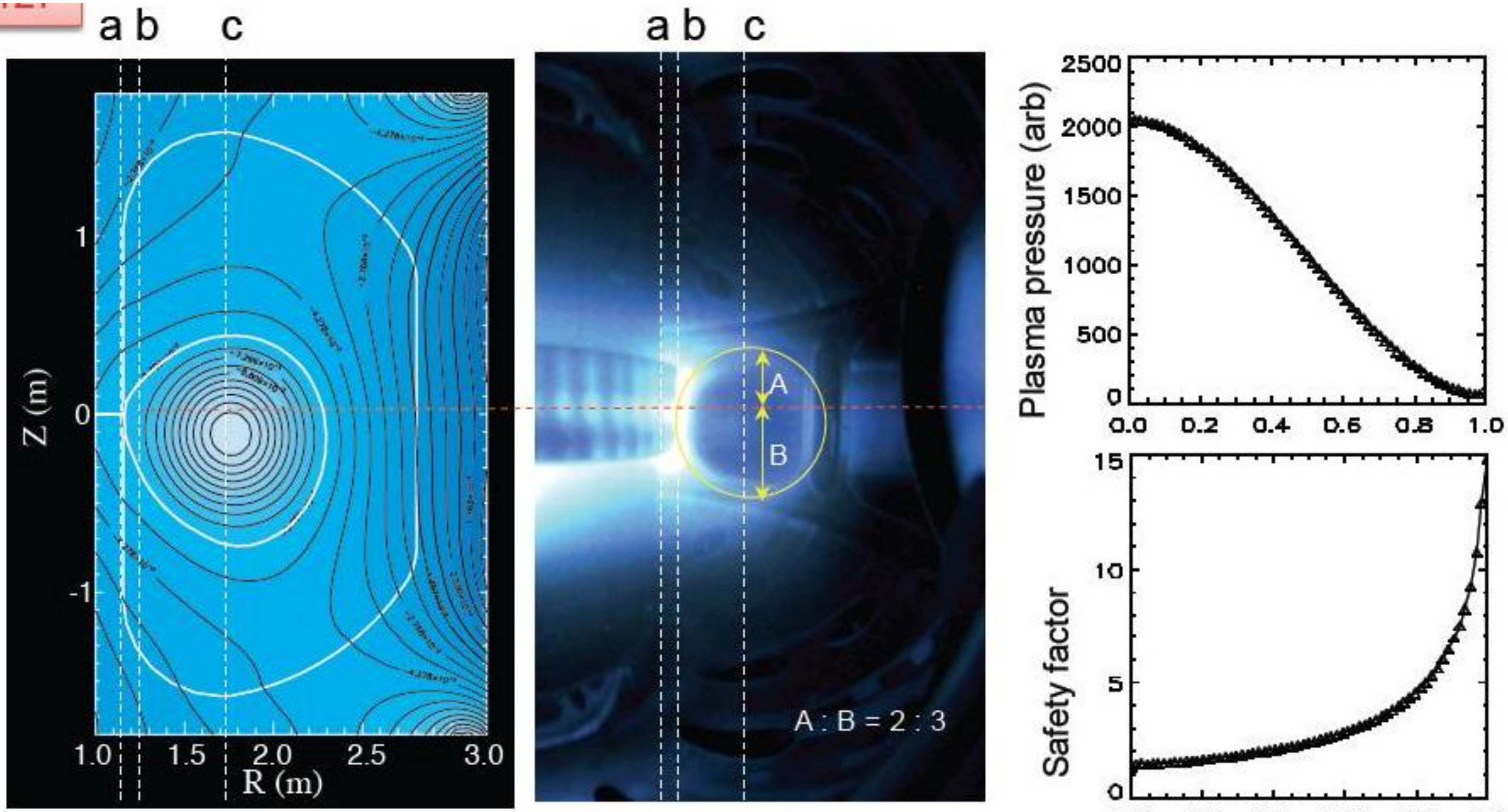


Ip = 97.1 kA

coil	Current (A/turn)
PF1	693.9
PF2	9.535
PF3	2.689
PF4	-0.0781
PF5	172.9
PF6	594.5
PF7	-1258.1

- For this case, PF1, 5, 6, and 7 coils are important

Steve's reconstruction results (presented @ 08' APS)

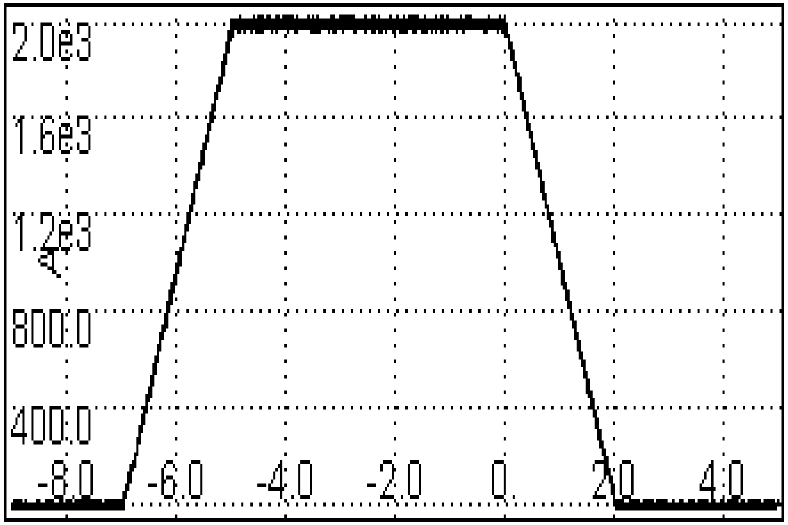


t=0.545s case (frame#133, 543.1 ms)

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

We analyze 7 vacuum test shots, in which only 1 upper and lower PF coils are charged



- This shows PF1 current form of #899
- No eddy current @ -2 sec
- No currents in all other coils
- EFIT and MD data should agree each other

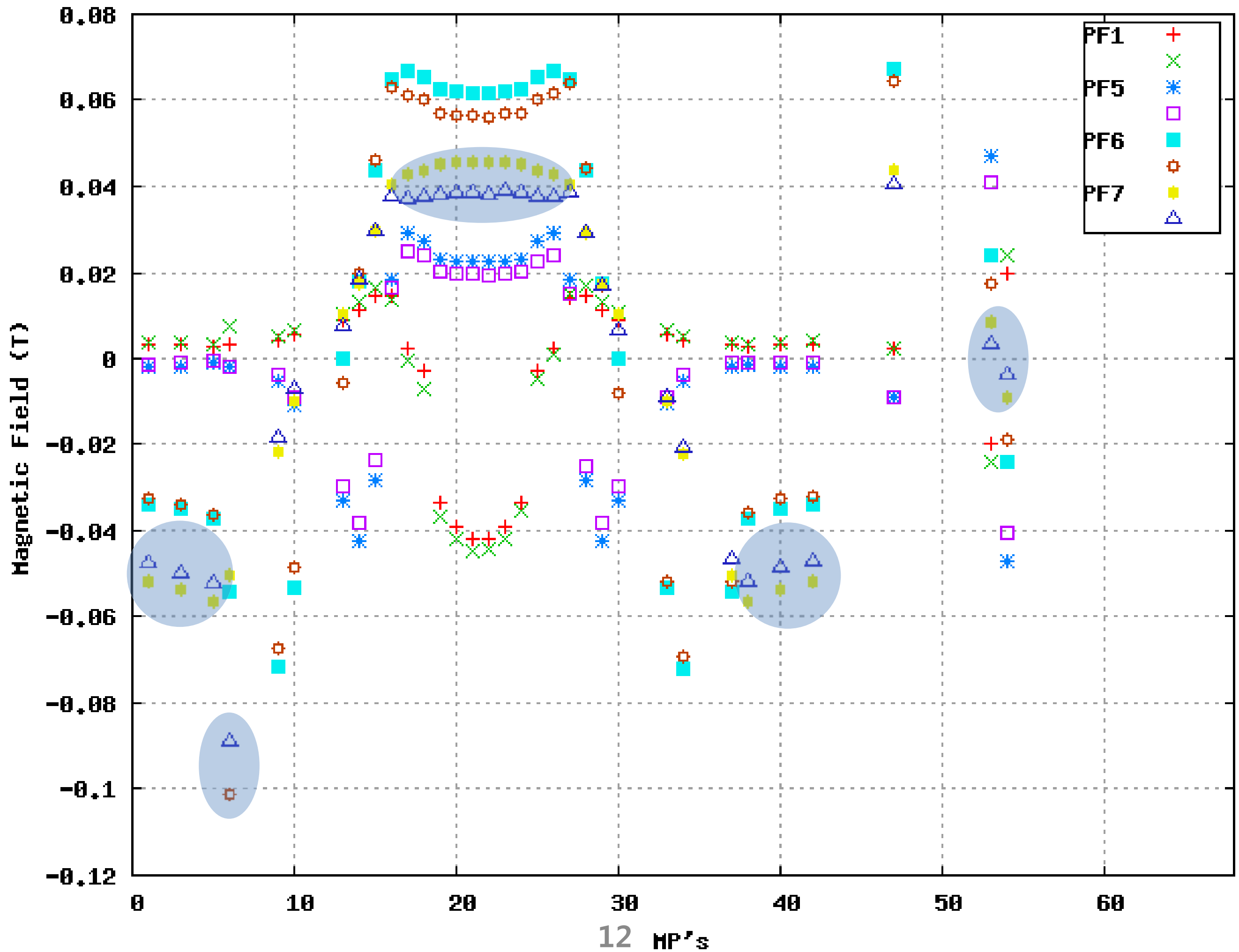
✓ EFIT and MD data agree in signal direction and order

✓ However, there are several MD signals significantly different from EFIT prediction

Analysis results of 4 important vacuum shots (1)

KSTAR

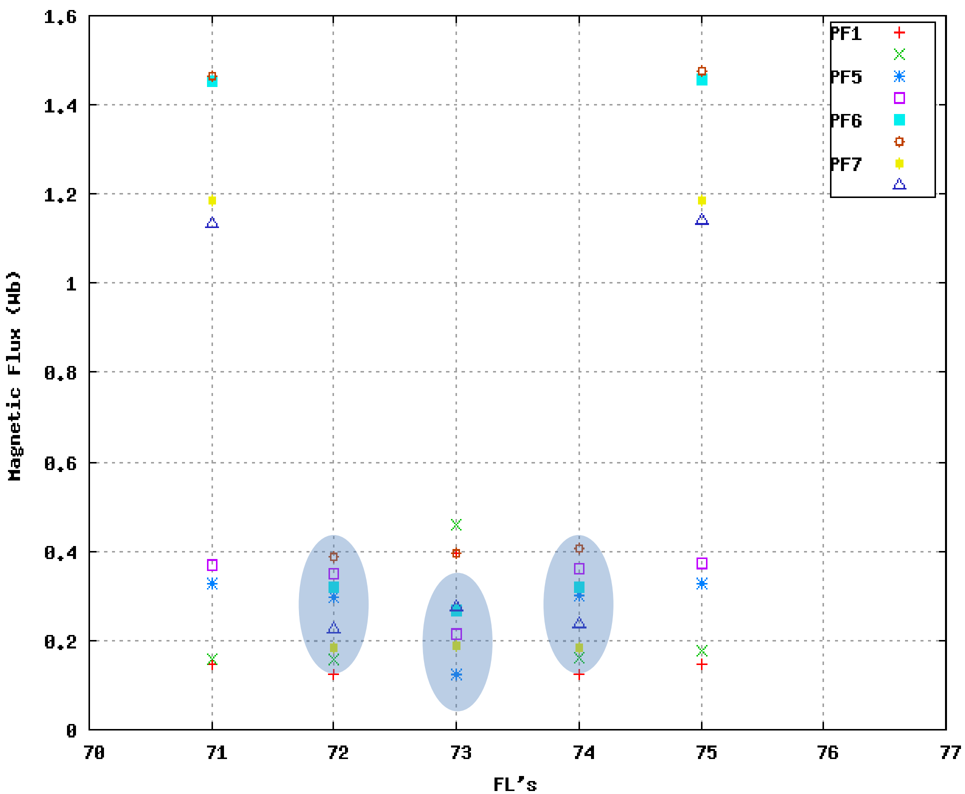
: MP's data showing big difference from EFIT for 4 important vacuum shots



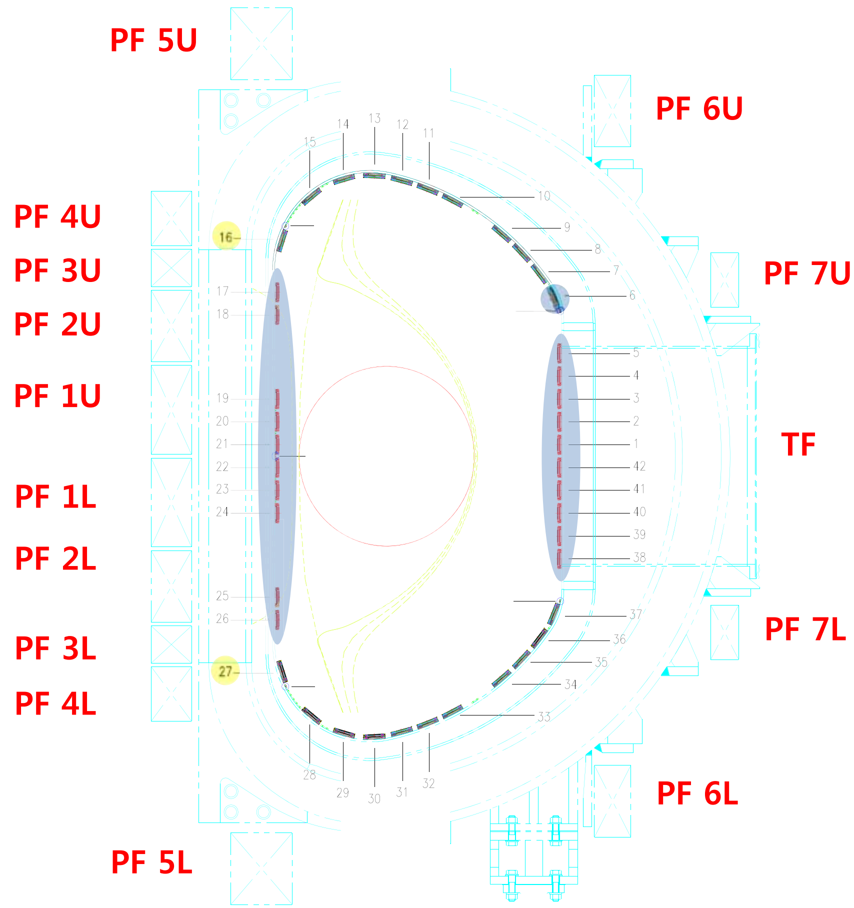
Analysis results of 4 important vacuum shot (2)

KSTAR

: FL's data showing big difference from EFIT for 4 important vacuum shots



✓Position of MP's and FL's showing big difference from EFIT prediction



EFIT results w/o vacuum vessel when all bad MD signals are ignored (only 14 MP's are used) : converged but looks like fail to get real equilibrium

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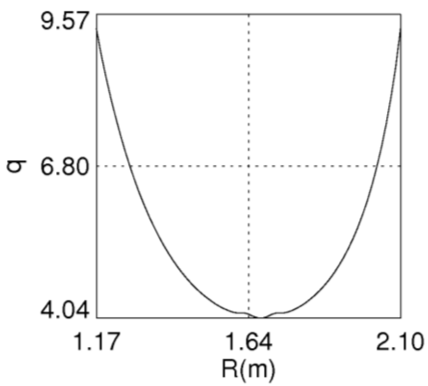
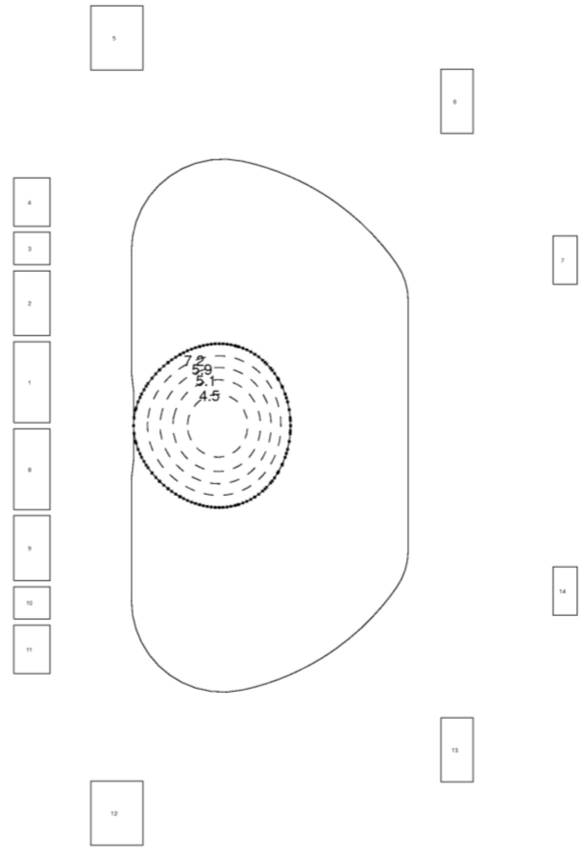
h EFITD 65x65d 09/01/2008h
date ran =
shot # = 1127
t(ms,us) = 545 0
chi2(mag)= 2.967E+01
rout(cm) = 163.77
zout(cm) = 0.000
a(cm) = 46.52
rm,rc(cm)= 167.4 164.9
zm,zc(cm)= 0.00 0.00

data used:
ip(ka) = 97.1
bt0(t) = 1.394
0 flux loops
14 magnetic probes
1 rogow 7 fc 0 ec



kf, kp, E= 2 1 0
fpd, p, E= 0.0 1.0 0.0
fwbp, fwq= 0.0 0.0
Ze(cm) = 0.000
kcf, kcp= 1 0



- $I_{pl,rec}$ = 121.8 kA (big difference of 25%)
- Zout, Zm = 0 cm (< 0 ?)
- Very high q_{95} = 8.63
- Not so bad chi2. Number itself is not so important because the ***serror*** is arbitrarily put as 0.1. However, lower chi2 is better

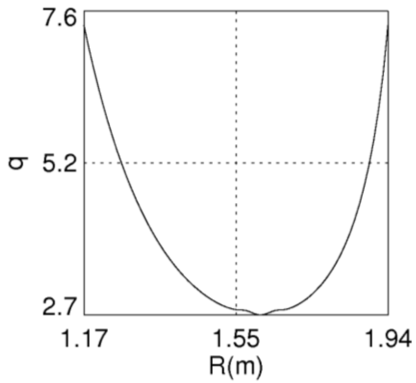
- Good condition number (8.697 e4)
- NO FL's used : converged to worse solution when used

Using all MP's and FL's (small ***fitting weight*** given to bad signals) : better condition no. & worse chi2

KSTAR

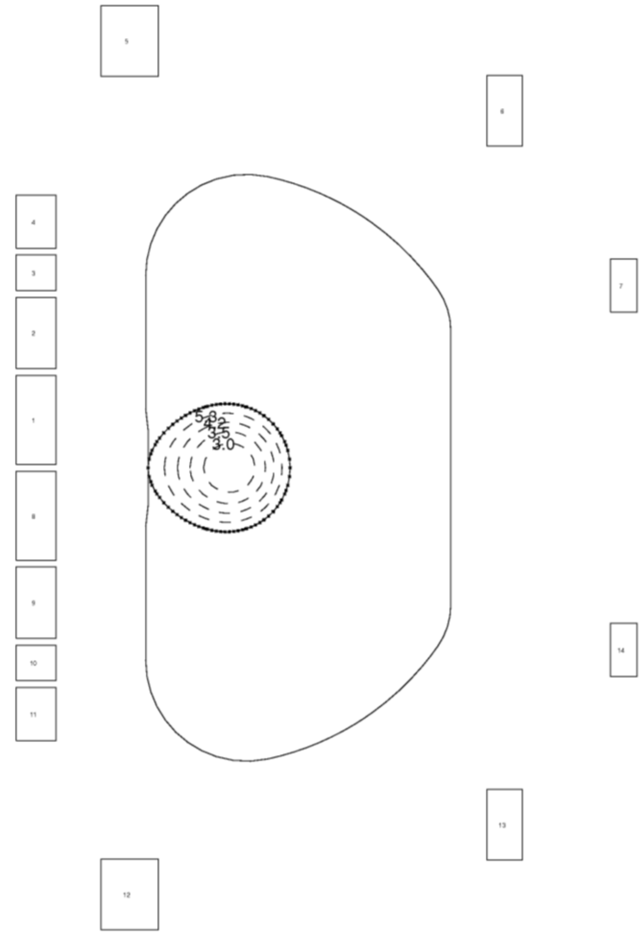
h EFITD 65x65d 09/01/2008h
date ran =
shot # = 1127
t(ms,us) = 545 0
chi2(mag)= 2.648E+02
rout(cm) = 155.43
zout(cm) = 0.000
a(cm) = 38.18

rm,rc(cm)= 161.6 159.9
zm,zc(cm)= 0.00 0.00



data used:
ip(ka) = 97.1
bt0(t) = 1.394
5 flux loops
32 magnetic probes
1 rogow 7 fc 0 ec

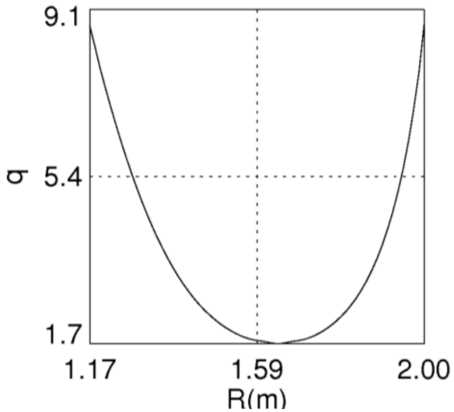
kf, kp, E= 2 1 0
fpd, p, E= 0.0 1.0 0.0
fwbp, fwq= 0.0 0.0
Ze(cm) = 0.000
kcf, kcp= 1 0



- $I_{pl,rec}$ = 101.8 kA (good)
- Zout, Zm = 0 cm (still bad)
- High q_{95} = 6.67
- Worse chi2
- Better condition no. (1.732 e4)

EFIT result considering vacuum vessel using all MP's and FL's w/ optimized ***fitting weight***

h EFITD 65x65d 03/03/2009h
date ran =
shot # = 1127
t(ms,us) = 545 0
chi2(mag)= 6.376E+00
rout(cm) = 158.64
zout(cm) = -6.995
a(cm) = 41.39
rm,rc(cm)= 163.9 163.0
zm,zc(cm)= -6.87 -6.84

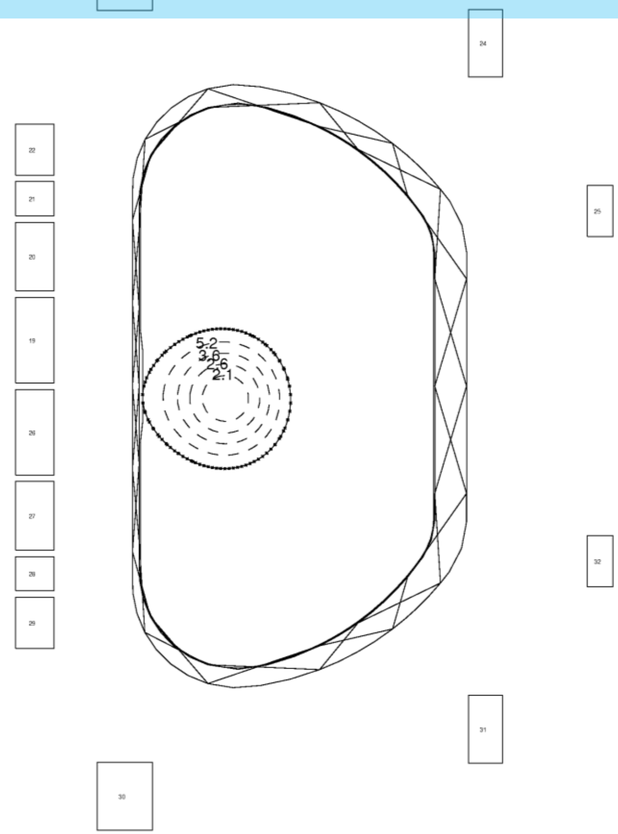


data used:
ip(ka) = 97.1
bt0(t) = 1.394
5 flux loops
31 magnetic probes
1 rogow 7 fc 0 ec
scrapof(mm) 0.0

kf, kp, E= 3 2 0
fpd, p, E= 0.0 0.0 0.0
fwbp, fwq= 0.0 0.0
Ze(cm) = 0.000
kcf, kcp= 1 2

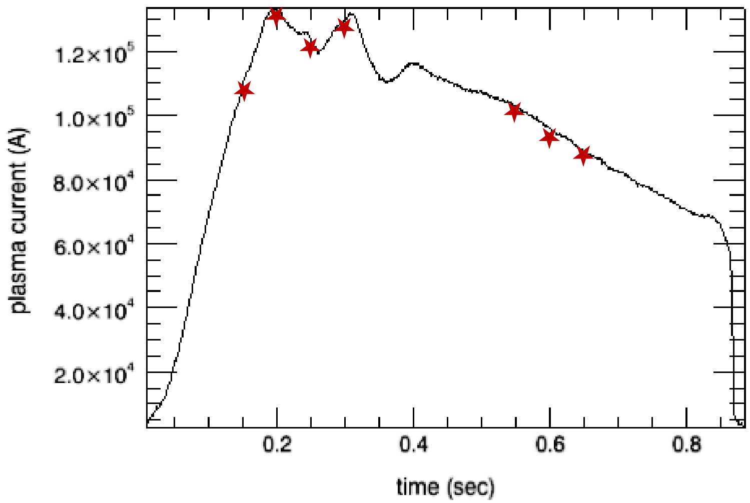
- $I_{pl,rec}$=102.0 kA, I_{vv} = 55.8 kA
- Zout = -6.995 cm
- High q_{95} = 7.53
- Good chi2
- Good condition no. (6.16 e3)

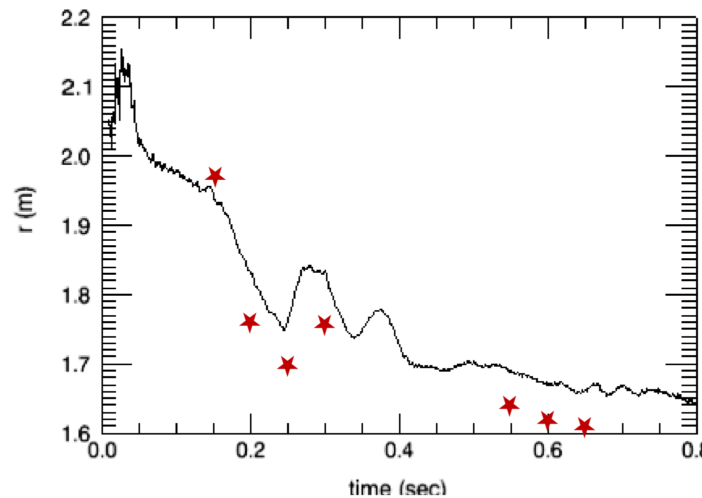
- Vacuum vessel is modeled as 18 current segments composed of many filaments. And the total filaments are more than 1000.

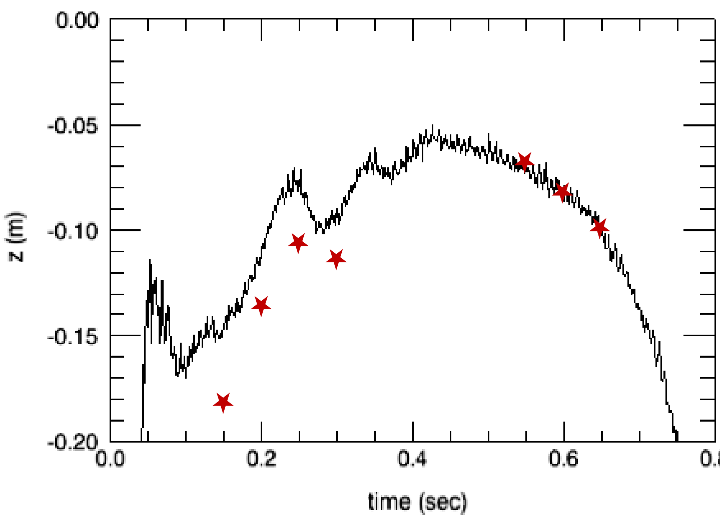


Comparison with Multipole Moments Method results

- Ip agrees very well with MMM results
- R of magnetic axis follows only tendency
- Z of magnetic axis agree very well in ramp down phase

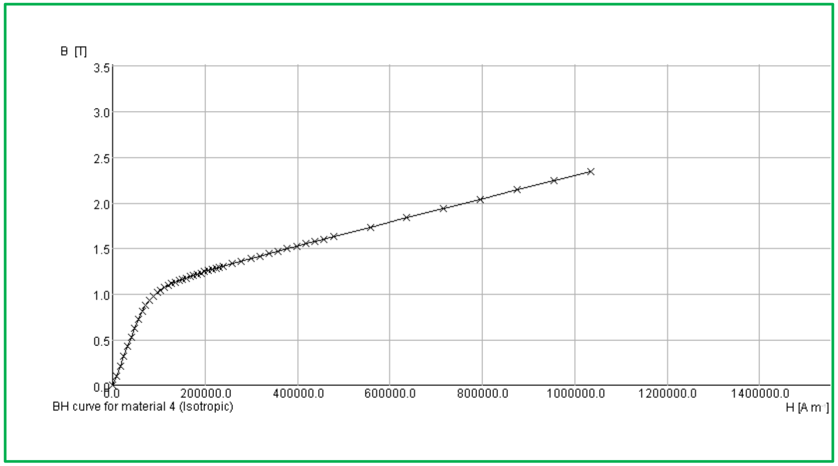






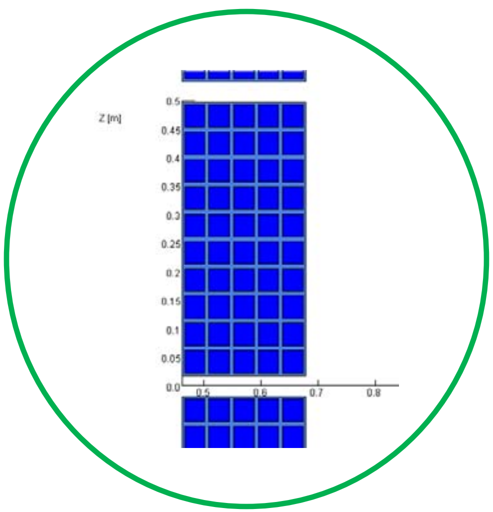
Ref : S. H. Seo,
Phys. of Plasmas 16 032501 (2009)

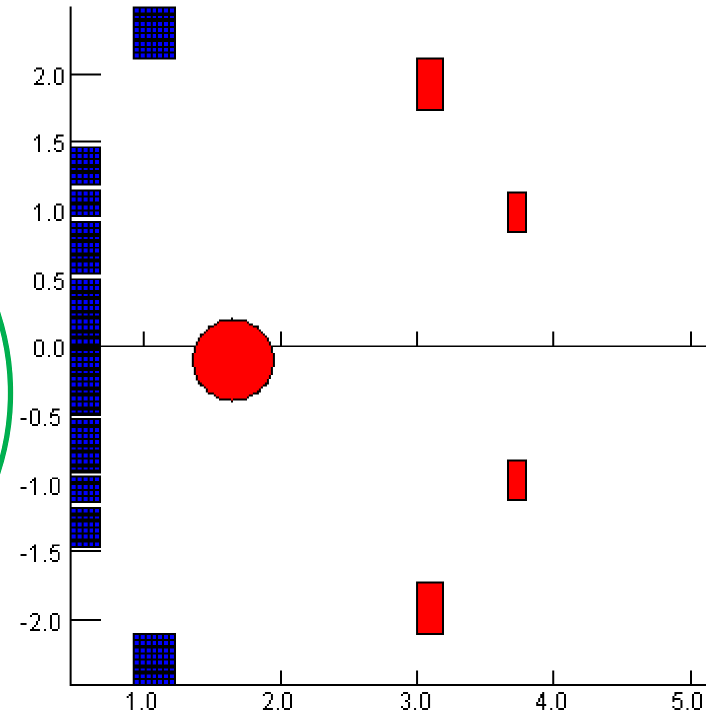
Paramagnetic material Incoloy908 is used as jacket of CICC (Current In Conduit Conductor) of PF1~5 and TF coils of KSTAR



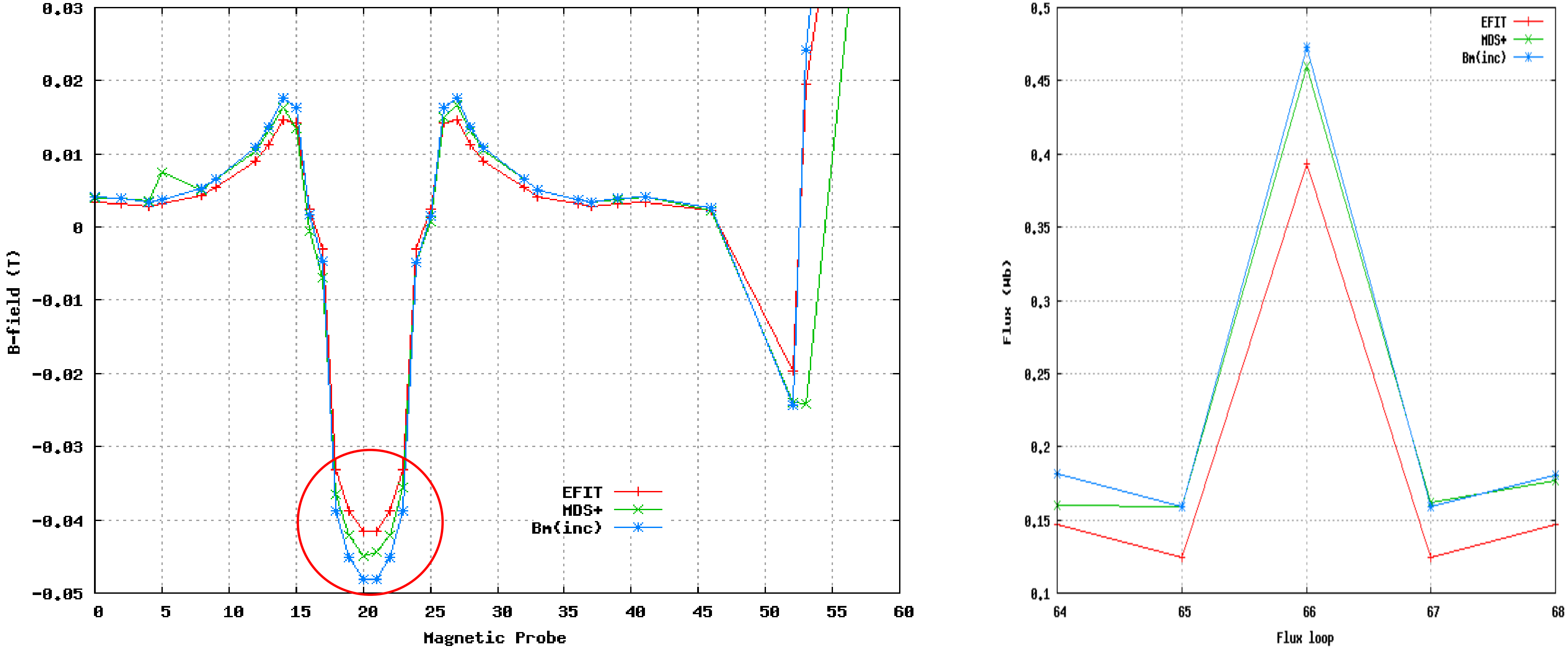
- BH curve of Incoloy908
- Magnetization is saturated at around 1 T of external field

✓ We developed a model for OPERA/TOSCA module (details of PF1U model is shown in circle)





For vacuum test shot (# 899 @-2 s), Incoloy908 effects reduce the differences between MD signal and EFIT prediction



- ✓ These figures show the EFIT result (red), MD signal (green), and OPERA/TOSCA results (blue) considering Incoloy908
- ✓ When we consider Incoloy908 effects, the differences become smaller (especially in flux loop signals), except MP signals presented in circle.

Norm square calculation shows that disagreement between calculation and MD signal can be reduced when the Incoloy908 effects is considered

KSTAR

Exp no.	EFIT	Bm(air)	Bm(inc)
899 (PF 1)	1.01738E-02	1.03026E-02	3.07682E-03
922 (PF 2)	1.11187E-02	1.12312E-02	2.98956E-03
944 (PF 3)	5.54401E-03	5.58857E-03	1.32241E-03
945 (PF 4)	4.61810E-03	4.68534E-03	7.92198E-04
946 (PF 5)	2.73852E-02	2.83623E-02	1.26519E-02
963 (PF 6)	3.50005E-02	3.95085E-02	1.31540E-02
900 (PF 7)	1.86324E-02	1.74380E-02	1.20323E-02

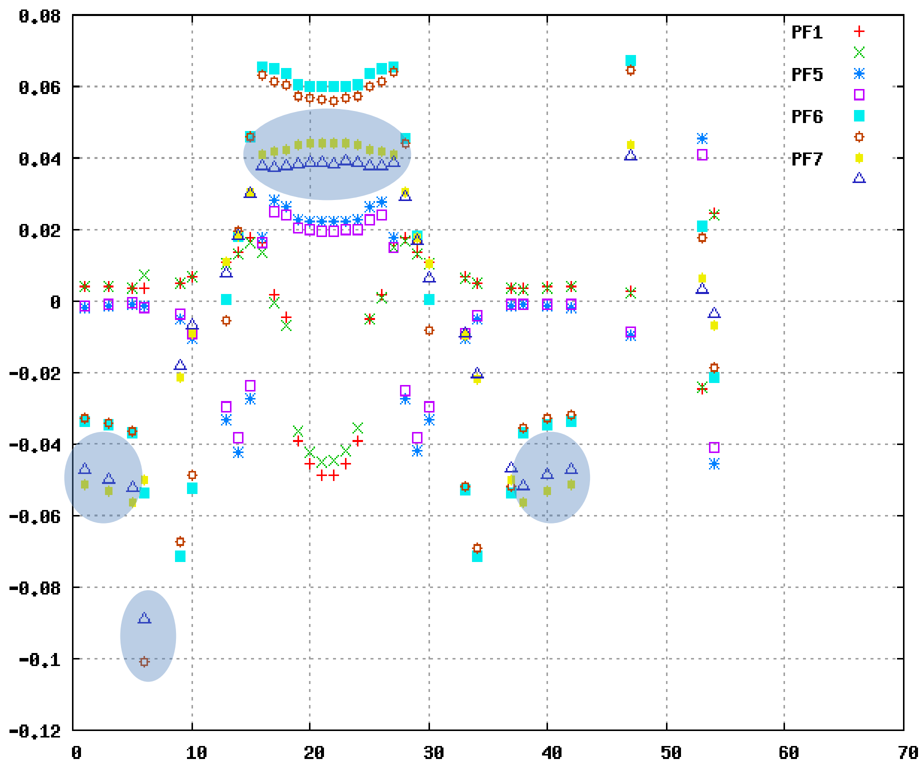
- ✓ For quantitative comparison, we calculate 'norm square'
- ✓ norm square≡∑((cal. value - exp. value)^2) : sum along MP's and FL's
  - norm square = 0, when perfectly same
- ✓ Considering Incoloy908, norm square are smallest

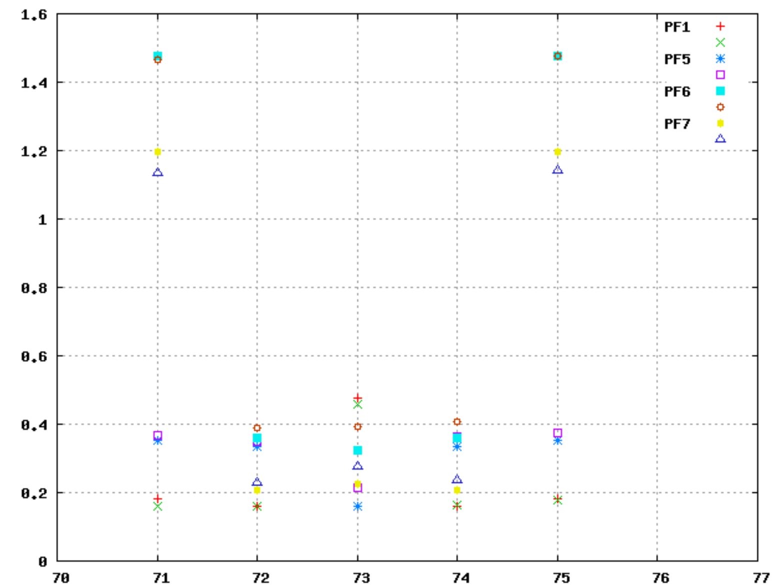
How to count the Incoloy908 effects in equilibrium reconstruction

- ✓ Step 1 : reconstruction equilibrium w/o considering Incoloy908 using EFIT
- ✓ Step 2 : simulation the MD signal for 2 cases, including and not including Incoloy908, using OPERA/TOSCA module
- ✓ Step 3 : calculation difference between above 2 simulation results
- ✓ Step 4 : reduction this difference from original MD signal
- ✓ Step 5 : re-reconstruction equilibrium using above compensated MD signal
- ✓ Step 6 : iteration (step 2 ~ 5) till convergence; we hope that only 1 iteration is enough, because the difference calculated in step 3 is very small to original MD signal.

We compare again the MP and FL signal and OPERA results considering Incoloy908 for ***fitting weight***

: big difference between OPERA and MP data





Re-reconstructed results (1^{st} iteration) using compensated MP's FL's signals with appropriate ***fitting weight***

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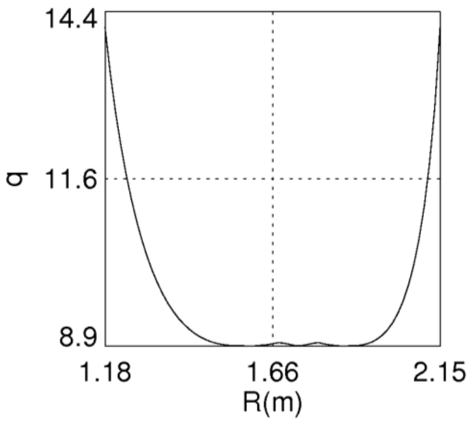
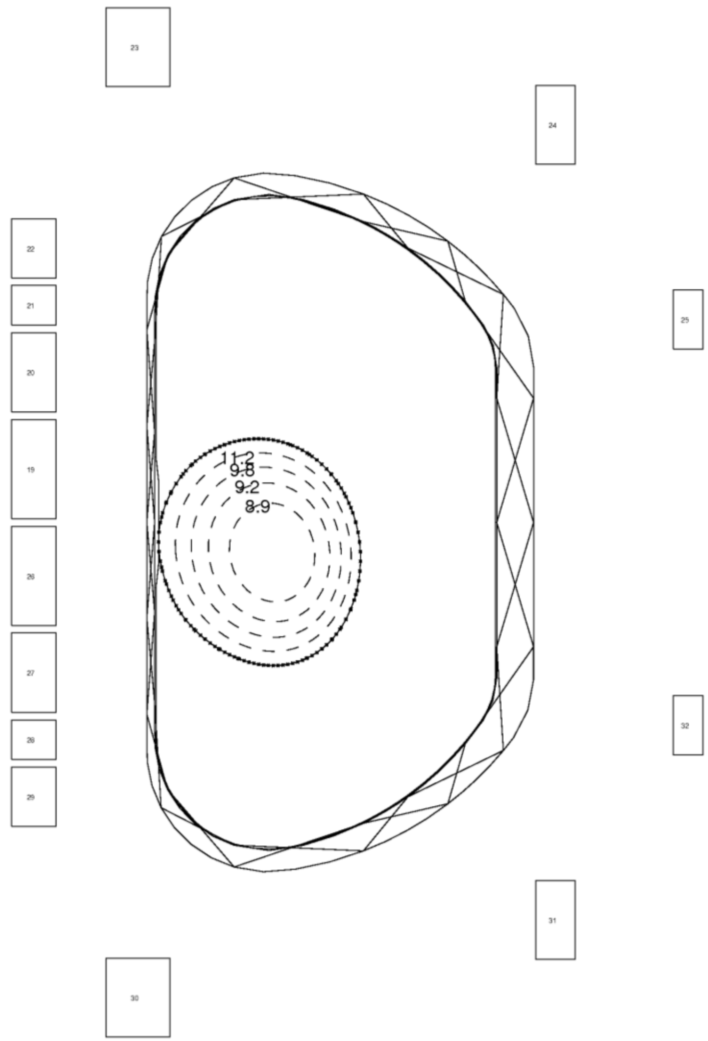
h EFITD 65x65d 03/03/20
date ran =
shot # = 1127
t(ms,us) = 545 0
chi2(mag)= 2.165E+01
rout(cm) = 166.03
zout(cm) = -14.351
a(cm) = 48.78
rm,rc(cm)= 173.8 170.3
zm,zc(cm)= -14.62 -14.07

data used:
ip(ka) = 97.1
bt0(t) = 1.394
5 flux loops
31 magnetic probes
1 rogow 7 fc 0 ec
scrapof(mm) 0.0



kf, kp, E= 3 2 0
fpd, p, E= 0.0 0.0 0.0
fwbp, fwq= 0.0 0.0
Ze(cm) = 0.000
kcf, kcp= 1 2



- $I_{pl,rec}$=98.2 kA, I_{vv} = 41.5 kA
- Zout = -14.4 cm : become worse
- High q_{95} = 13.1
- Chi2 is 21.7
- Condition no. is 2.9 e5

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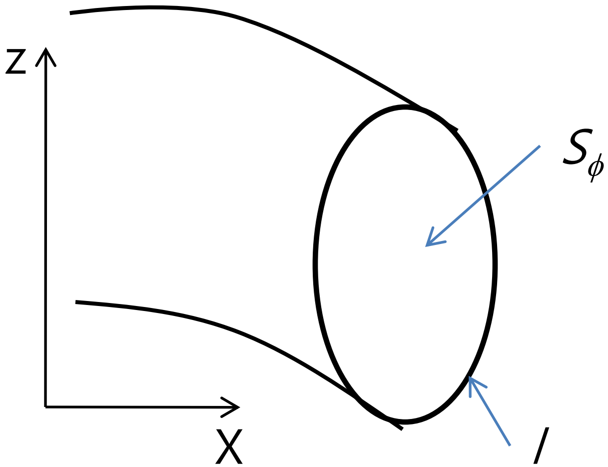
Future works

- The re-reconstructed equilibrium very differ from other's results including fast CCD camera. The re-reconstructed equilibrium does not reflect Incoloy908 effect. Thus this is not correct equilibrium. How to add up the flux/field from Incoloy908? *Or, is there another strategy to count Incoloy908 effect?*
- Remained works when Incoloy908 does not be considered are :
  - Serror estimation : should be calculated…
  - Equilibrium reconstruction in time series
  - Storing the results into MDS+ system
  - Improving vessel model using Fourier series representation

전류 모멘트[1)]

KSTAR



축대칭성이 있는 토로스 구조에서 경로 l에 접선 방향 자기장 B_τ 와 수직 방향 자기장 B_n 은 경로 l 이 둘러싼 면적 S_ϕ 에 흐르는 전류 밀도 j_ϕ 와 다음 적분식이 성립한다.

$$\int j_\phi f dS_\phi = \frac{1}{\mu_0}\oint_l (fB_\tau + XgB_n)dl$$

여기서 f 와 g 는 다음 식을 만족하는 임의의 함수이다.

$$\frac{\partial^2 f}{\partial X^2} - \frac{1}{X}\frac{\partial f}{\partial X} + \frac{\partial^2 f}{\partial z^2} = 0$$

$$\frac{\partial g}{\partial z} = \frac{1}{X}\frac{\partial f}{\partial X}, \quad \frac{\partial g}{\partial X} = -\frac{1}{X}\frac{\partial f}{\partial z}$$

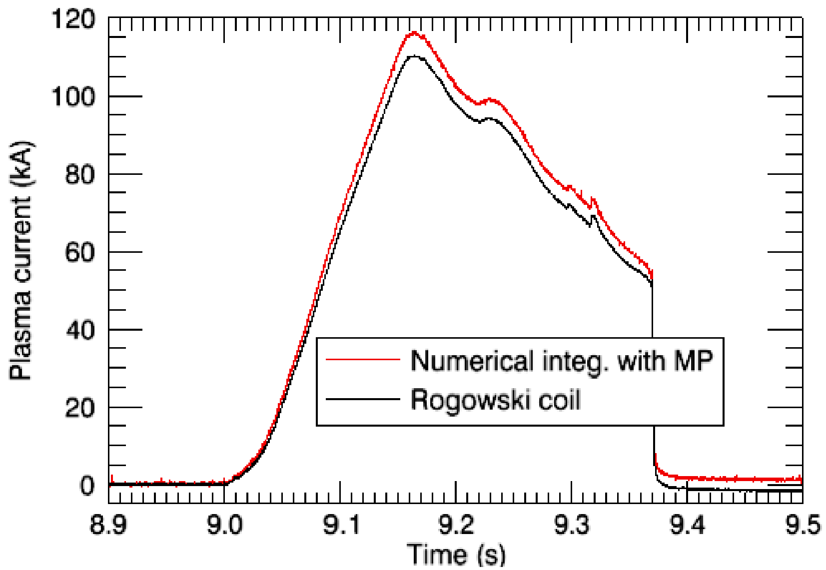
1) Hiroshi Aikawa *et al.*, Japan. J. Appl. Phys, **15**, 2031 (1979)

0차 전류 모멘트

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

B_τ 를 균일하게 선적분하면 플라즈마 전류 I_P 가 구해진다.

선적분을 하드웨어적으로 구현한 것이 로고프스키 코일 (RC01-03)이다. 이것은 자장 탐침 (BZ01-42) 측정값을 수치적으로 선적분한 것과 같은 결과를 준다.



두 방법은 약 5%의 차이내에서 서로 잘 일치하는 것을 볼 수 있다. 이 차이는 적분기가 없는 자장 탐침 측정값에 비선형적인 잔류 편차가 존재하기 때문이다. 잔류 편차는 그라운드 루프에 의해 PF 코일의 전류나 전압이 디지타이저에 영향을 주는 것으로 추정된다.

1차 전류 모멘트

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

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

플라즈마 전류의 위치 (X_P, Z_P)의 평균값을 구할 수 있다.

KSTAR 에는 Bn 탐침은 진공 용기의 위와 아래쪽에만 (BR6-16, 27-37) 설치되어 있다. 따라서, 1차 전류 모멘트의 오른쪽 선적분을 구하기 위해서는 안쪽과 바깥쪽에서 Bn 을 유추할 수 있는 알고리즘이 필요하다.