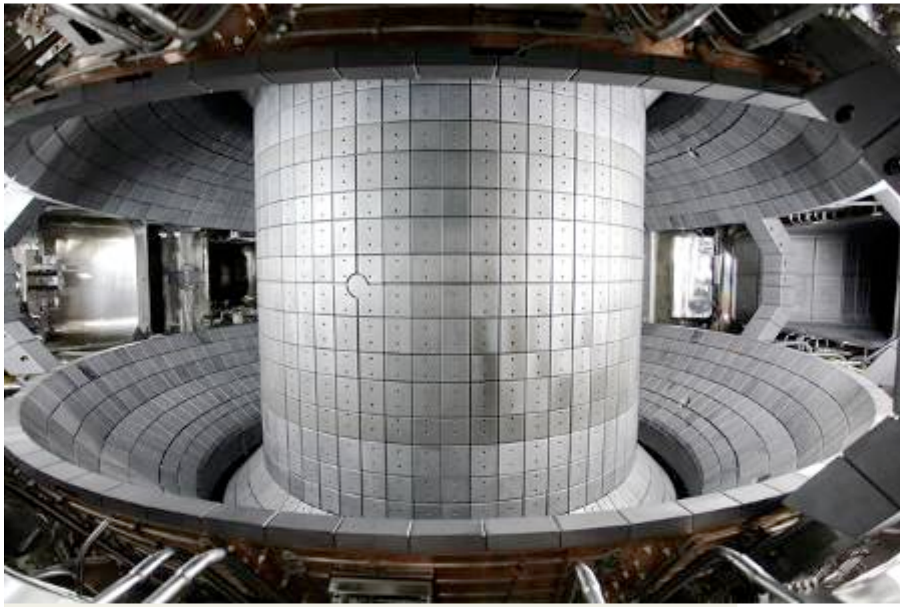

SOFE, June, 2011

Key Features in the Operation of the KSTAR

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KSTAR Research Center
National Fusion Research Institute

NFRI 국가핵융합연구소 National Fusion Research Institute

KSTAR

Brief history of the past 4 years

- **1st campaign (2008)**
  - 2007. 9 Device construction
  - 2008. 4 SC magnet cool-down (4.5 K)
  - 2008. 5 TF operation up to 15 kA (1.5 T)
  - 2008. 6 ~ 7 First plasma up to 107 kA (ECH preionization)
- **2nd campaign (2009)**
  - 2009. 10 Plasma current up to 320 kA (ECH 110 GHz, 2 T)
  - 2009. 11 TF magnet operation up to 35 kA (3.5 T @ R=1.8 m)
- **3rd campaign (2010)**
  - 2010. 7 Baking of PFC & vacuum vessel
  - 2010. 9 ~ 10 IVC coil operation, NBI beam injection
  - 2010. 10 ~11 Plasma startup, shaping, and H-mode
- **4th campaign (2011)**
  - 2011. 5 Baking of PFC & vacuum vessel up to 300C
  - 2011. 6 PF coil test up to 15 kA and startup, shaping

Contents

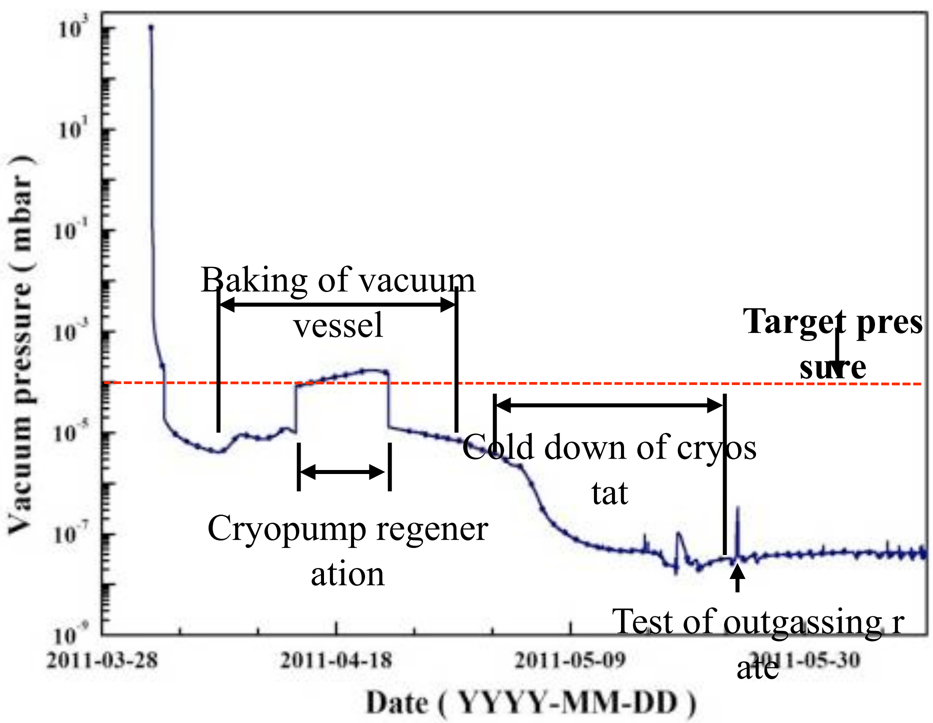
◆ **Machine operation**
- Vacuum in main vessel and cryostat
- Superconducting Magnet
- Machine control and DAQ system

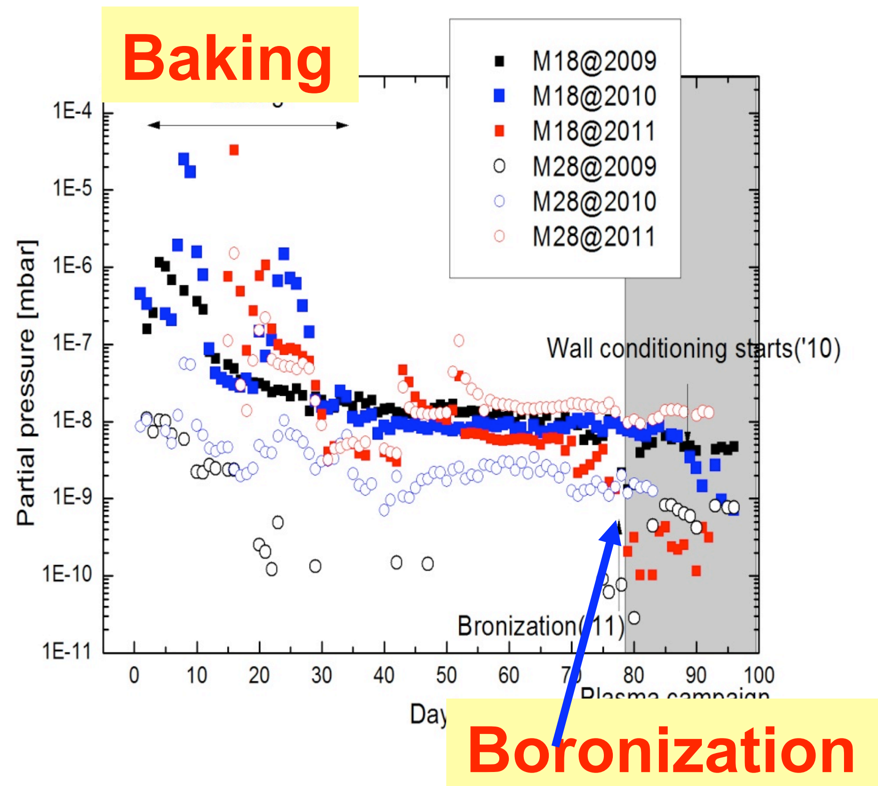
◆ **Plasma operation**
- Start-up
- Plasma control

◆ **Key system**
- IVCC
- Heating

◆ **H-mode in 2010**

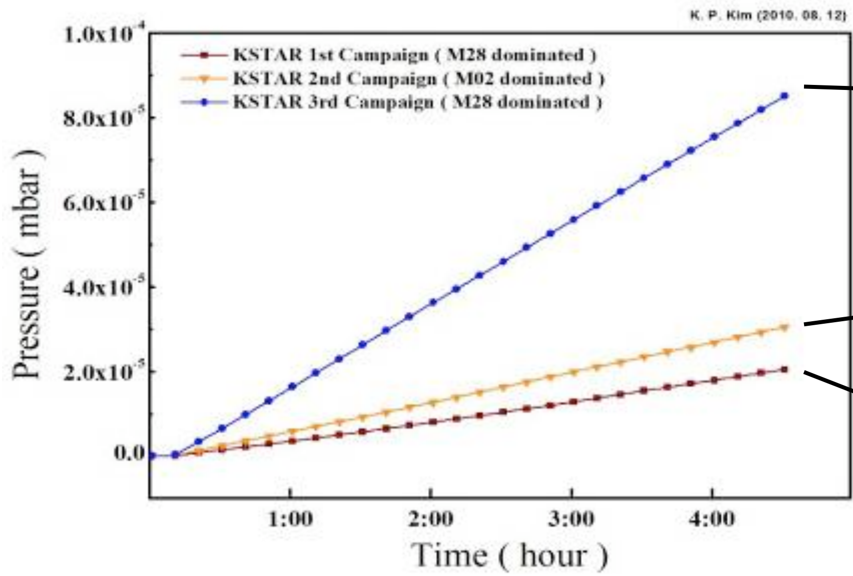
Vacuum Pressure during Campaign

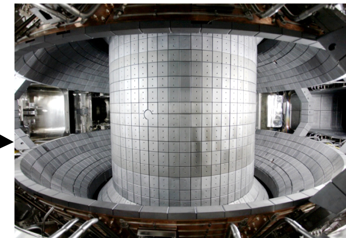




- Baking on vessel wall(130 °C), pumping duct(120 °C) and PFC(300 °C)
- Routine(dailly) GDC (Gaseous Discharge Cleaning) and boronization
- Base pressure was less than 8x10^{-8} mbar
- Water level drops after baking and boronization
- Pumping period for plasma experiment: 2 months at commissioning phase

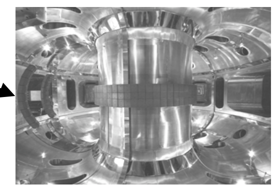
Outgassing Rate of Vacuum Vessel





3rd Campaign

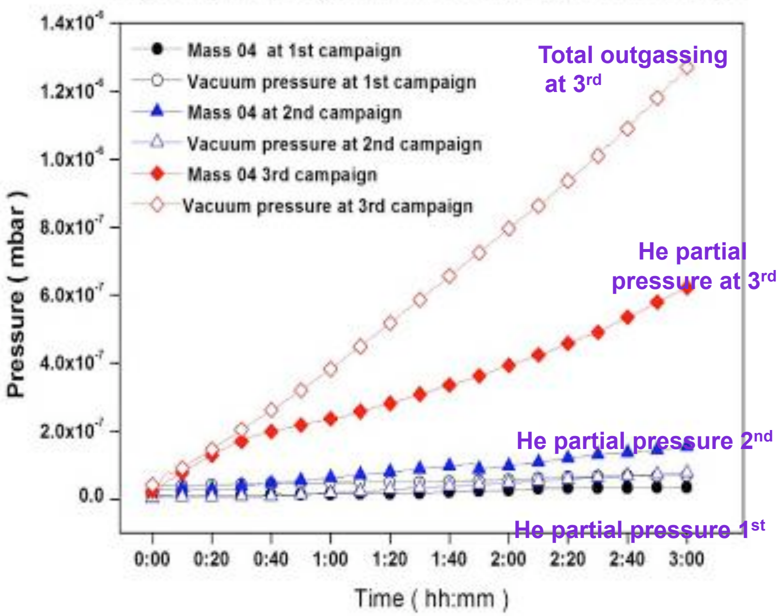
2nd Campaign



1st Campaign

Campaign	PFC area (unit : ㎡)	Outgassing rate (unit : m·bar·ℓ·s^{-1})	Per unit area (unit : m·bar·ℓ·s^{-1}m^{-2})	Baking system
1st (2008)	1.54	1.43 ×10^{-4} (M 28 dominated)	**9.31× 10^{-5}**	• Vessel wall (100 °C)
2nd (2009)	11	1.93 ×10^{-4} (M 02 dominated)	**1.75 ×10^{-5}**	• Vessel wall and pumping duct (130 °C)
3rd (2010)	**54**	6.49 ×10^{-4} (M 28 dominated)	**1.20 ×10^{-5}**	• Vessel wall and pumping duct (130 °C) • Hot **N2 gas on PFC (225℃)**
4th (2011)	**54**	4.21 × 10^{-4} (M 28 dominated)	**7.80 × 10^{-6}**	• Vessel wall and pumping duct 130 °C) • Hot **N2 gas on PFC (300 ℃)**

Outgassing Rate of Cryostat

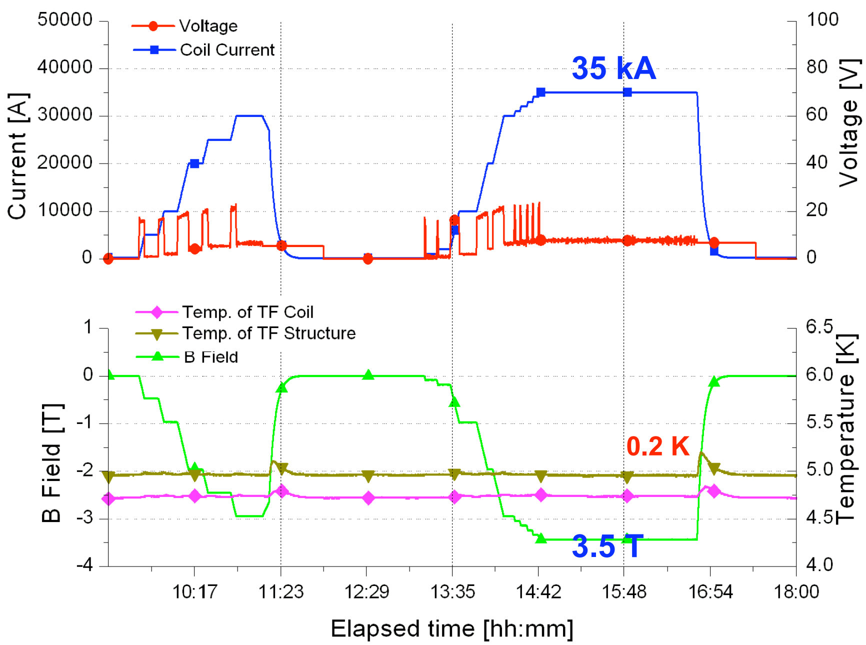


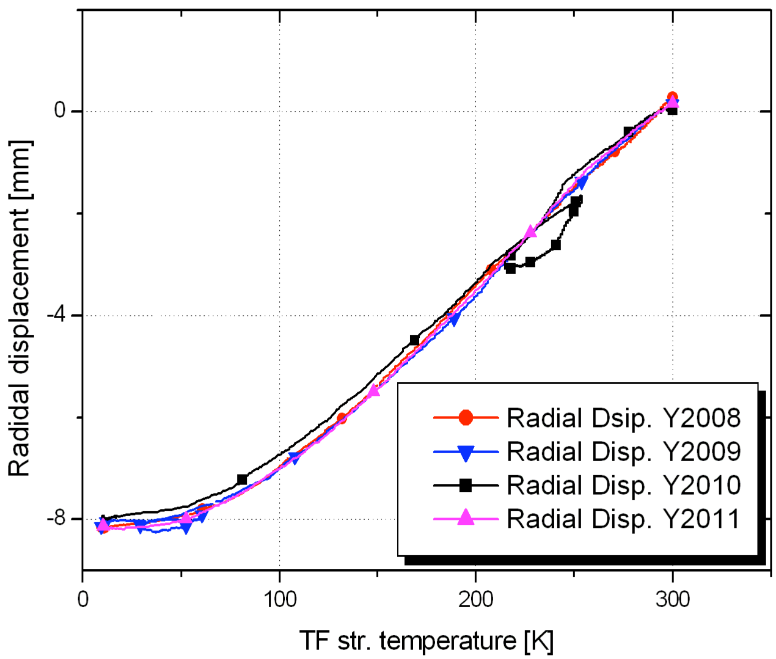
- He outgassing rate in the cryostat is the key parameter in the operation of SC magnet in terms of a good thermal barrier and Paschen discharge
- The outgassing rate increased year by year, however it was saturated around in the range of 10^{-5} mbar·ℓ/s.
- At 4th campaign, the vacuum pressure in the cryostat is **5 ×10^{-8} mbar**.
  (Note : Max. allowable pressure is **1.0 x 10^{-5} mbar**)
- PF coil/structure circuit was suspected to be the dominant source of the cold leak.

	Total outgassing rate	Helium leak rate	unit
1st campaign	1.12E-07	8.92E-08	mbar·ℓ/s
2nd campaign	3.08E-06	2.45E-06	mbar·ℓ/s
3rd campaign	3.33E-05	1.47E-05	mbar·ℓ/s

TF Magnet Operation

- The TF magnet system was charged up to **35 kA**, which produced 3.5 T at the center of the vacuum vessel.
  - The coil temperature increase was below **0.2 K**
  - Maximum mechanical stress of the TF structure was 152 MPa, which is lower than the operational criteria of 500 MPa
  - Maximum radial displacement of toroidal ring is less than 0.4 mm.

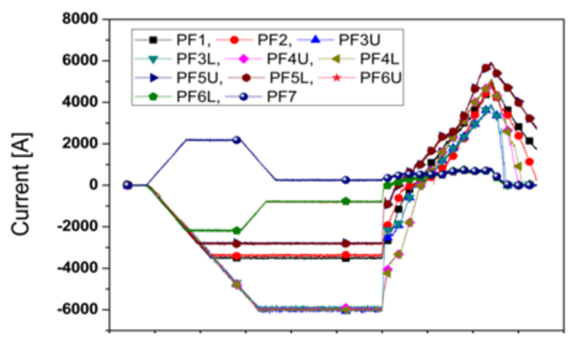


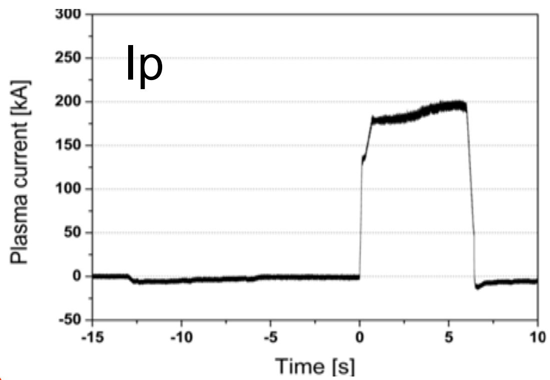


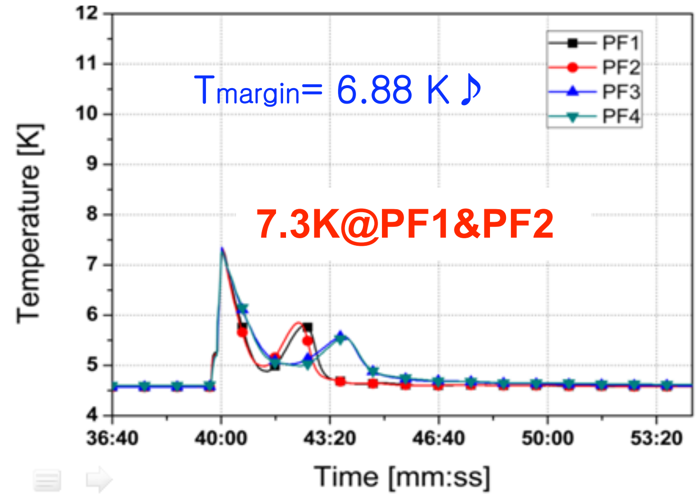
PF Magnet Operation

◆ Normal plasma operation(#3267)

- Current ramp rate was usually less than 3 kA/s.
- PF 1&2 temperature rise was just up to **7.3K**.

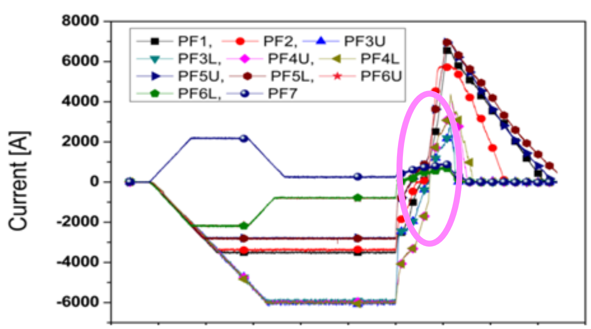


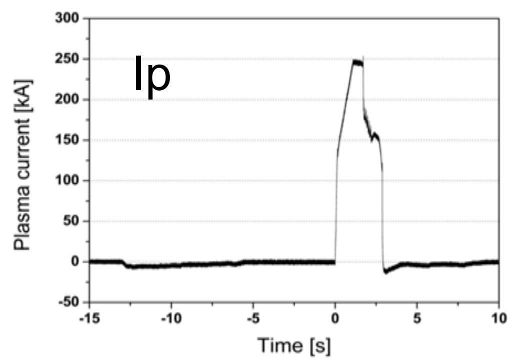


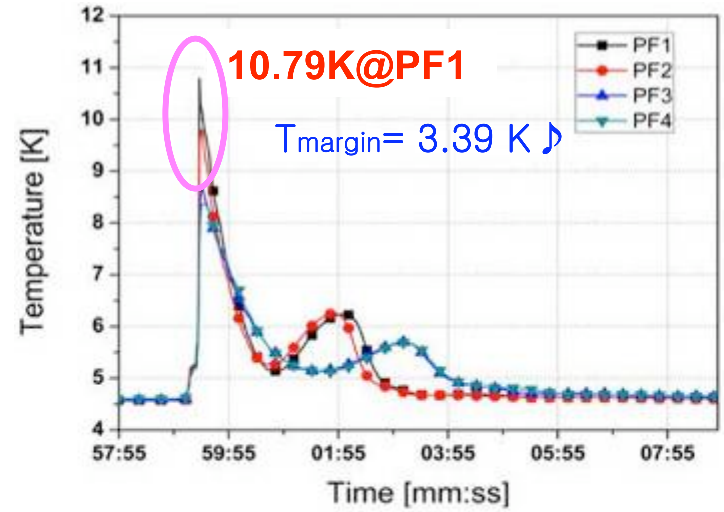


◆ Abnormal operation (#3305)

- PF currents rise rapidly to recover Ip (20 kA/s)
- PF1 temperature rise was **10.79K**.







◆ Blip operation(100 ms) doesn't have large affect on the temperature rise.

◆ The temperature rise is influenced by Lhe coolant pass as well as dI/dt(dB/dt) and duration time.

- R&D activities of TH analysis using Gandalf, VINCENTA and 4C code.

Machine Control with EPICS

◆ Machine Control System

- **Reliability and stability of CW superconducting machine**
- Integration of heterogeneous controllers:
  - VME, VXI, cPCI, PXI, PCI, PLC, and cFP
  - 32 control systems with 110 subsystems participated in 3rd campaign
- **Real time control based on the distributed network with EPICS**
  - No. of handling signals : ~ 50,000 I/O
  - Total operational data : 614 GB(dailly increasing of data : about 5~6 GB)
  - Data storage : EPICS Channel Archiver

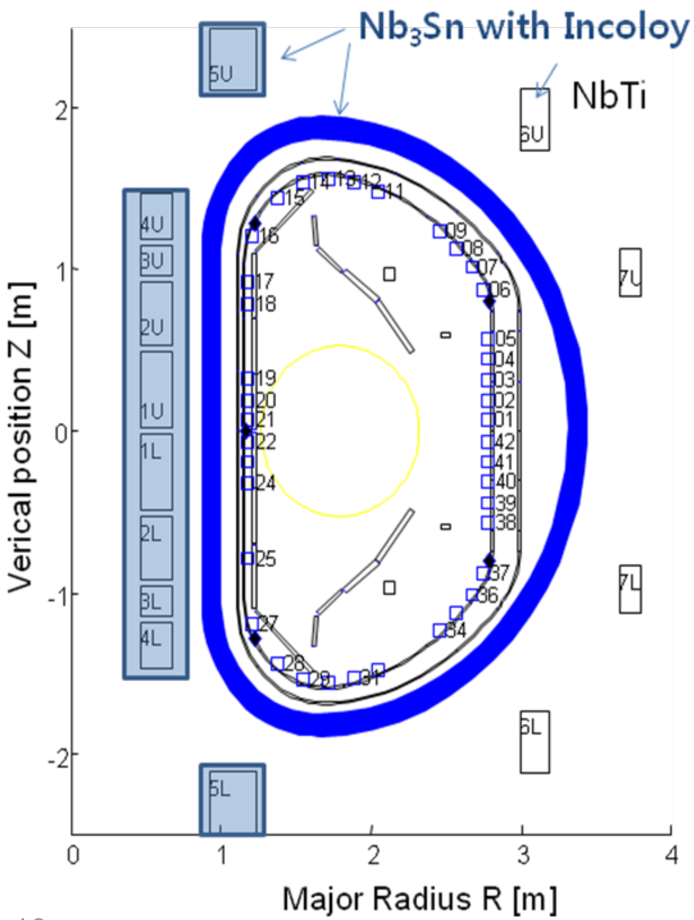
◆ DAQ System for Plasma Diagnostics

- **25 diagnostics systems synchronized with Local Timing Unit(LTU)**
  - No. of I/O : ~ 11,600 tags
  - Data stored to the MDSplus server/Central storage
  - Archived data at 2010 : 1794 GB/2,126 shots(daily increasing of data : about 40 GB)
- **a distributed clustered storage system for 2-D image advanced diagnostics**

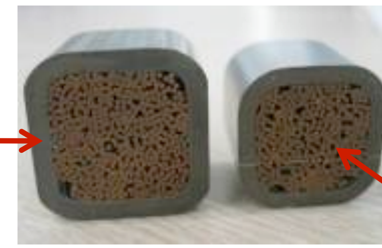
Incoloy 908 in SC Magnet Coil Jacket

- Incoloy 908 in SC coil jacket as it has low thermal expansion coefficient compatible to Nb_3Sn.
- On the other hand, ferromagnetic incoloy 908 (μ~10) nonlinearly deforms magnetic field structure

.



Incoloy 908



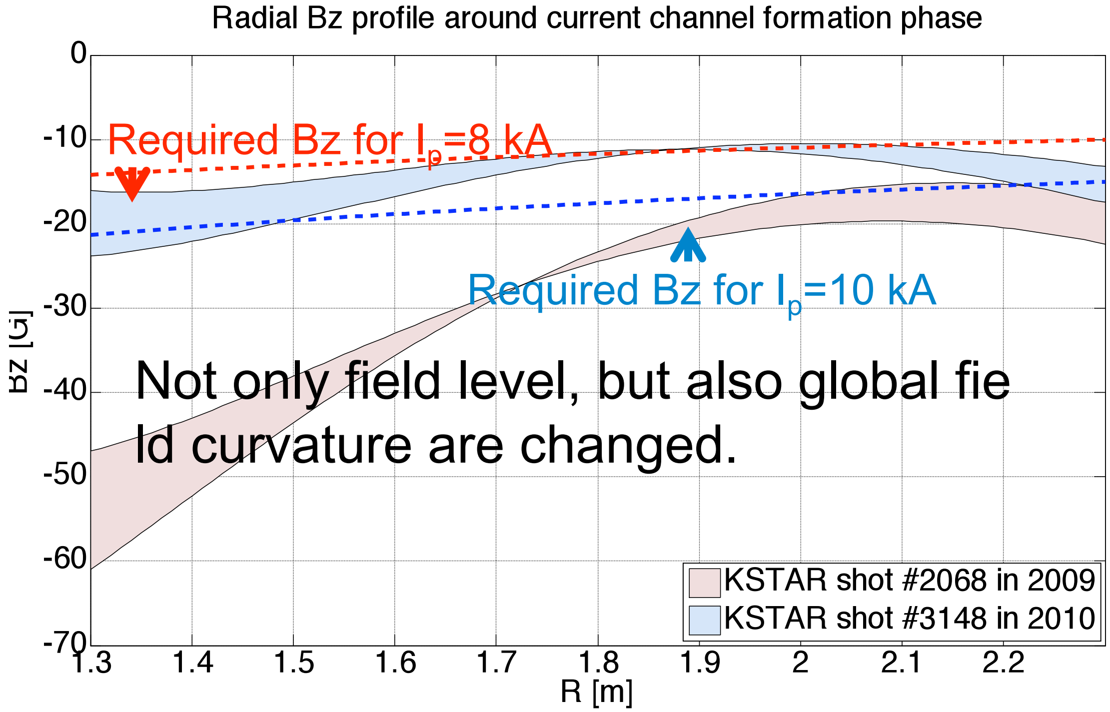
Nb_3Sn

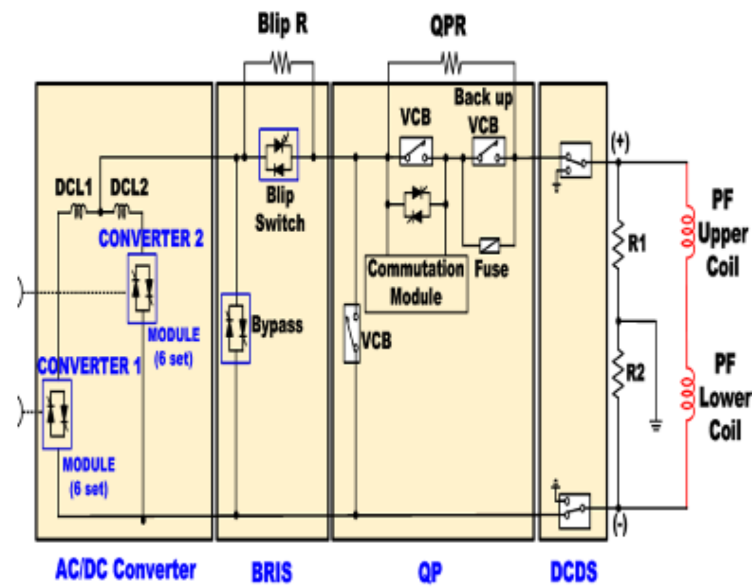
Design value of KSTAR:

R_0= 1.8 m
a=0.5 m
I_P=2 MA
κ= 2.0
δ= 0.8
B_0= 3.5 T
t_{pulse}= 300 s

KSTAR superconducting coils		
Coil name	material	Amount
TF coil	Nb3Sn	16
PF1 Coil	Nb3Sn	2
PF2 Coil	Nb3Sn	2
PF3 Coil	Nb3Sn	2
PF4 Coil	Nb3Sn	2
PF5 Coil	Nb3Sn	2
PF6 Coil	NbTi	2
PF7 Coil	NbTI	2

Radial Bz Profile during Start-up



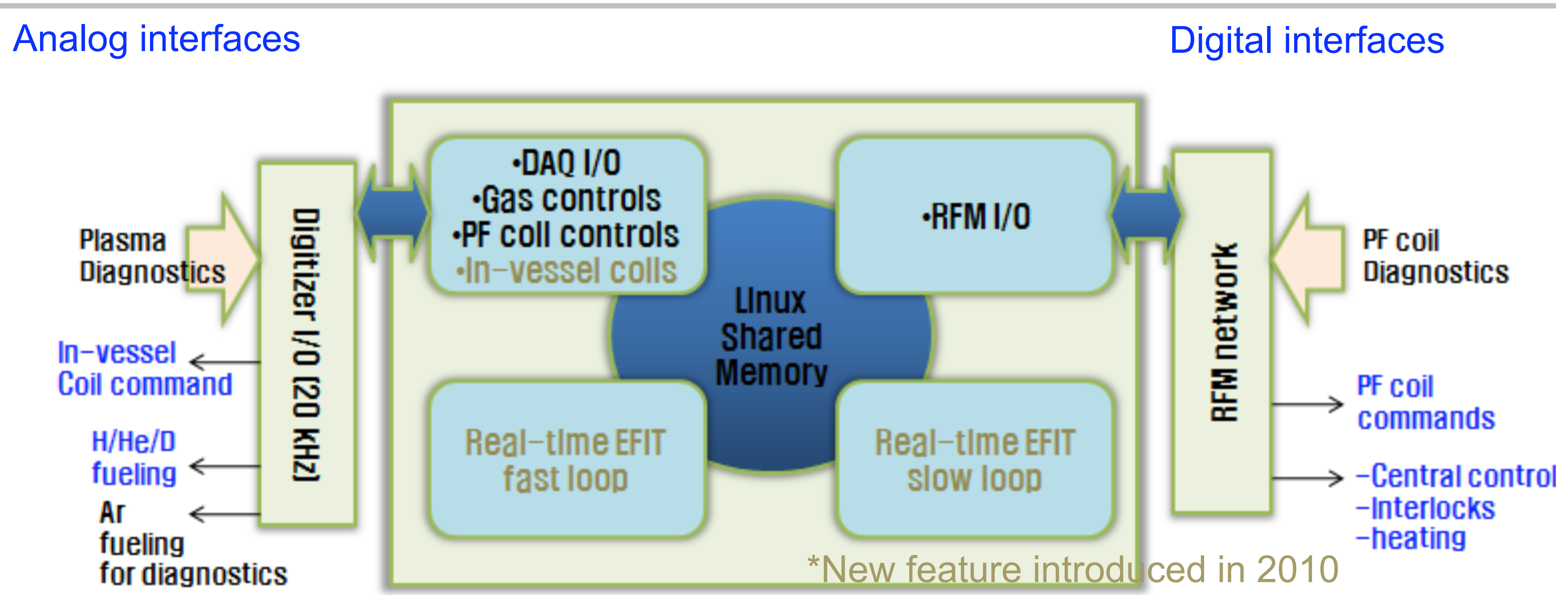


PF circuit with blip resistor

- The magnetic field structure near in-board side is affected by Incoloy
  - Without compensation, the deviation could increase up to 60 G
  - The deviation should be less than 20 G for successful startup
- Success shot rate increased up to **74.3 %** in 2010 (**21.5 %** in 2009)
  - Pure ohmic start-up was achieved with ~3V of the loop voltage in 2010
  - Start-up w/o blip resistor was achieved for switching Ip direction.

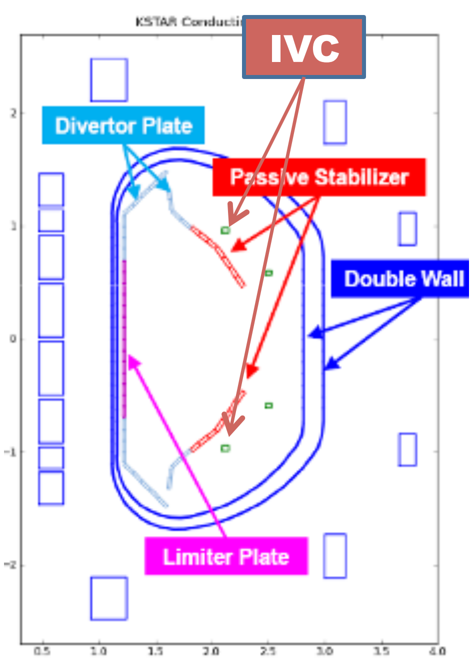
Plasma Control System (PCS)

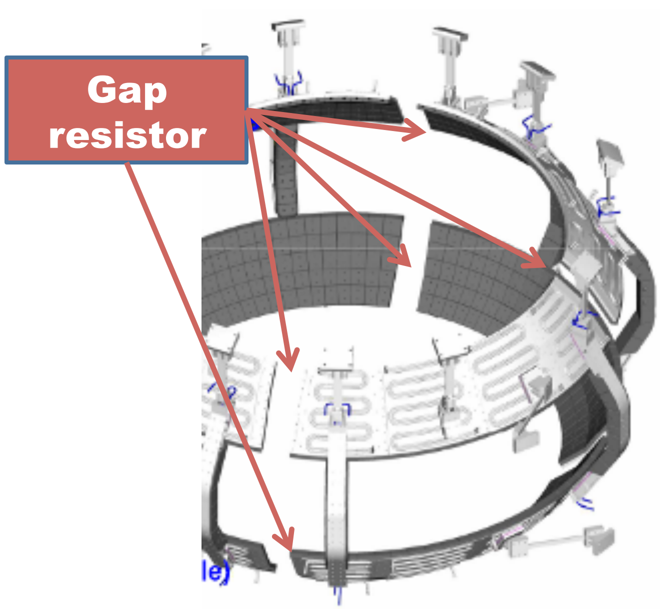
- **A fast, flexible control system in operation since 2008**
  - **Based on the Linux cluster tech, embedding 8 processes in a box**
    - Adapted from DIII-D PCS, with ~20 kHz control cycles
  - **Extended digital interfaces on reflective memory (RFM)**
  - **Integrated control capability for tokamak actuators**
    - Magnets, fueling, heating and IVCC etc.
    - Capable of getting ~200 plasma diag. through the built-in digitizers

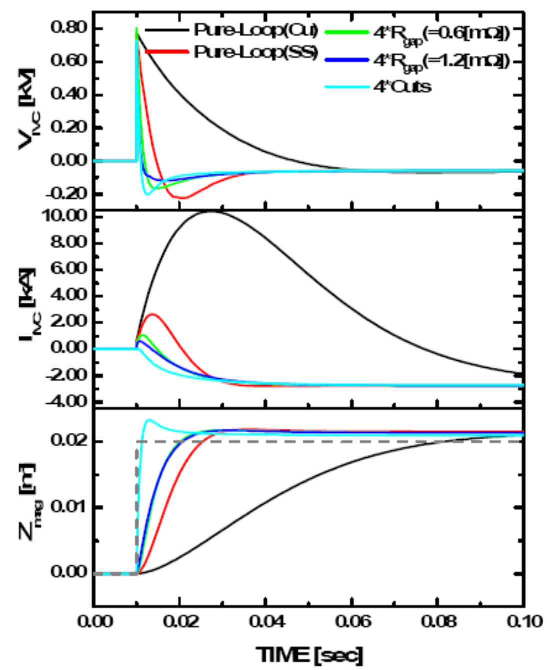


Vertical Control and Shaping

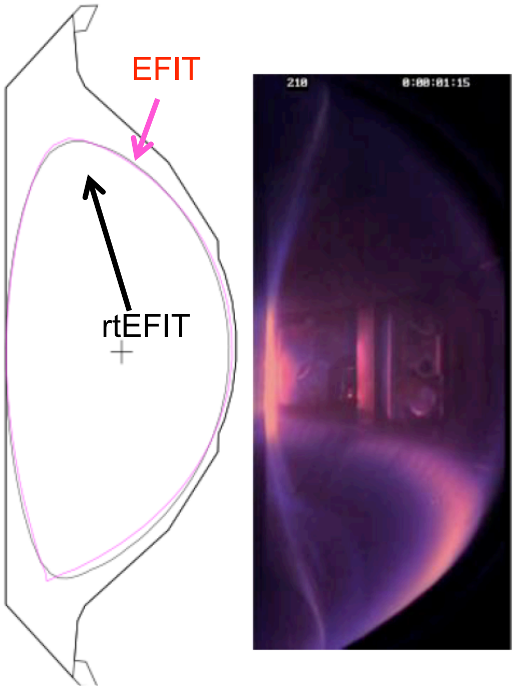
- **Vertical stabilization is done with passive Cu plates and IVCC**
  - **In-vessel vertical coil [IVC] installed behind the passive plates**
    - PS spec. : +-10 kA/turn, 960 V, PWM
  - **Design changes of the passive plates enhances control speed by 5 times**
    - Each up/down Cu plate is cut into 4 pieces
    - Gap resistance(2.1 mohm) per toroidal turn is attached

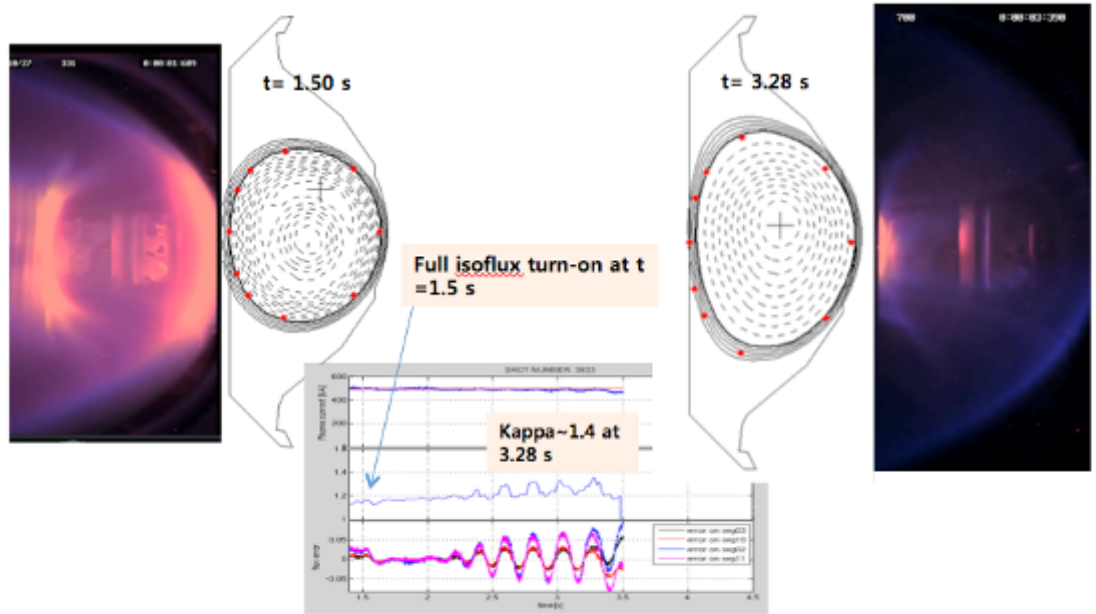






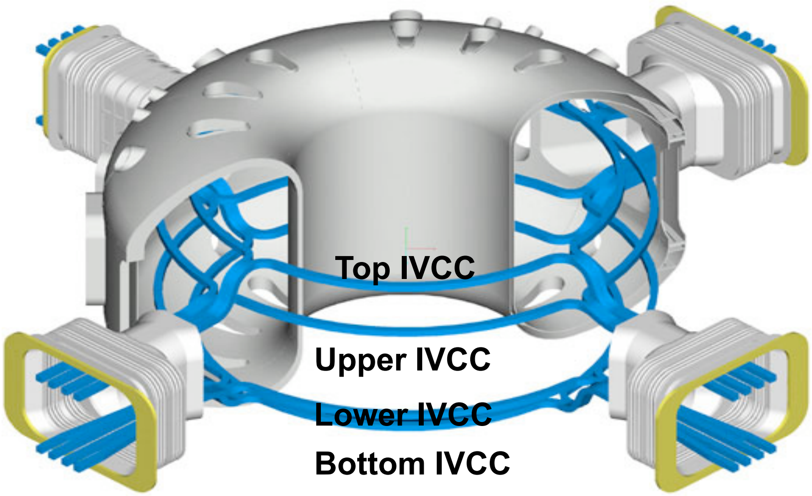
Magnetic shape control with real-time EFIT & isoflux algorithm

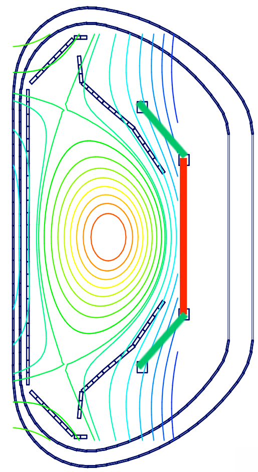


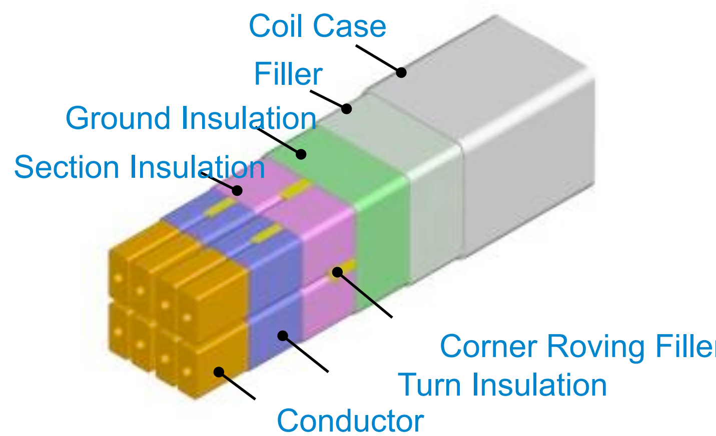


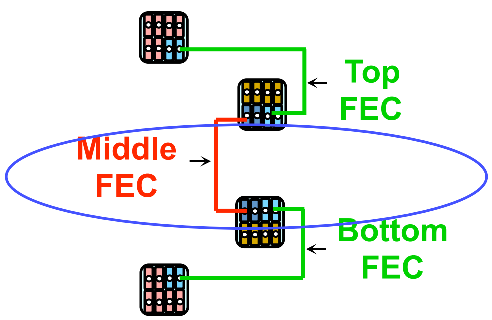
- **The real-time EFIT set as a shape verification tool for L-mode d ischarges as in 2010**
  - Based on the 12-element vessel model EFIT
- **Real-time shape control using iso-flux was verified in low-kapp a realm in 2010**
  - Extending to the well-balanced DND in 2011

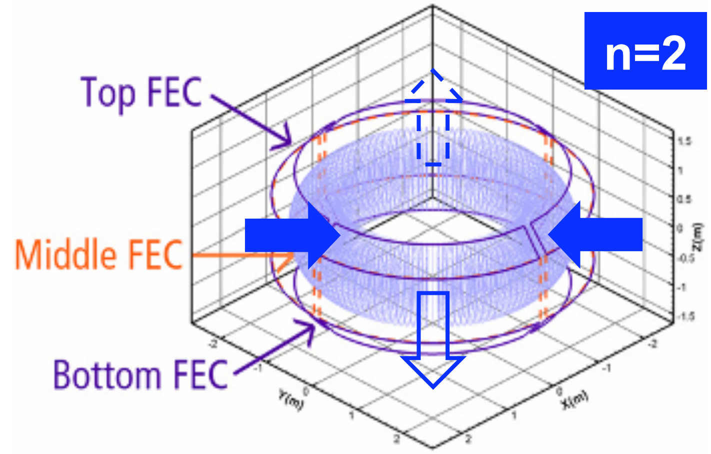
In-vessel Control Coils





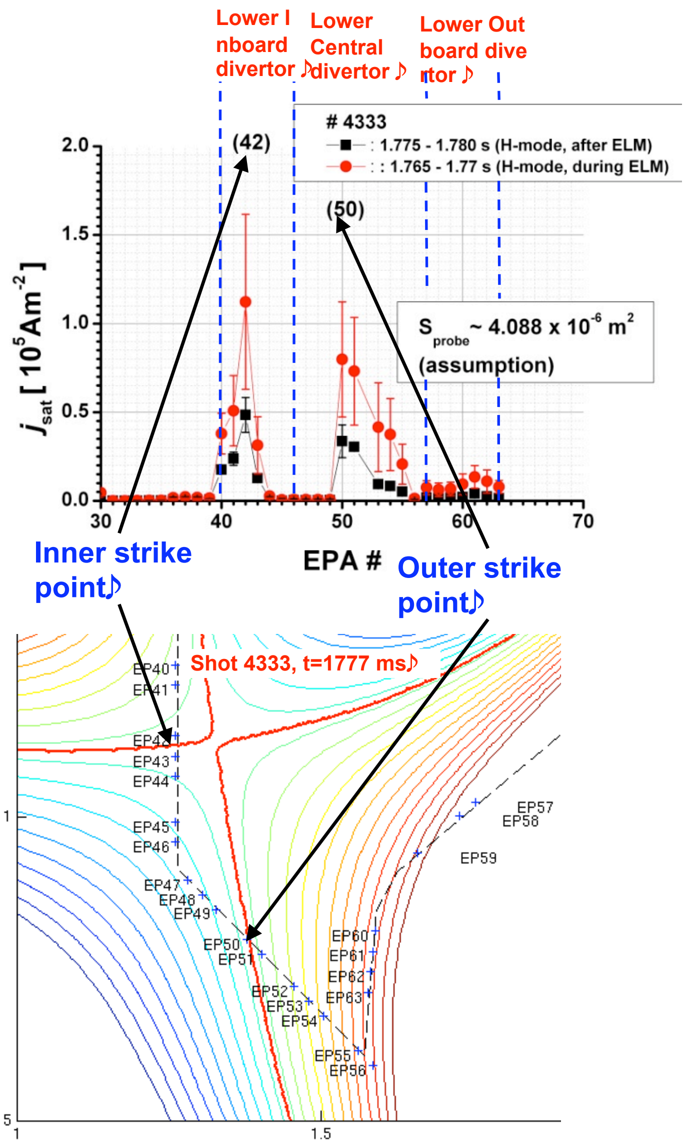


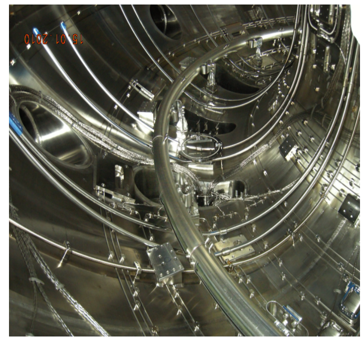


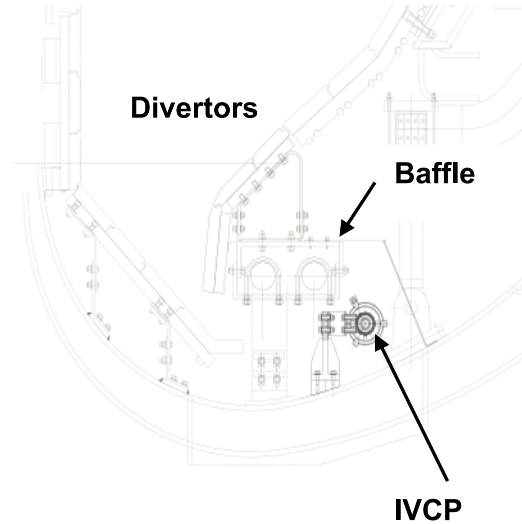


- **16 segmented modules**
  (4 circular coils for position Control and 12 FEC coils)
- **n=1 and 2 capabilities, poloidally three coils(parity change)**
- **Wide physics experiment and flexibilities of control(IRC, FEC, RWM)**

Diverter Operation



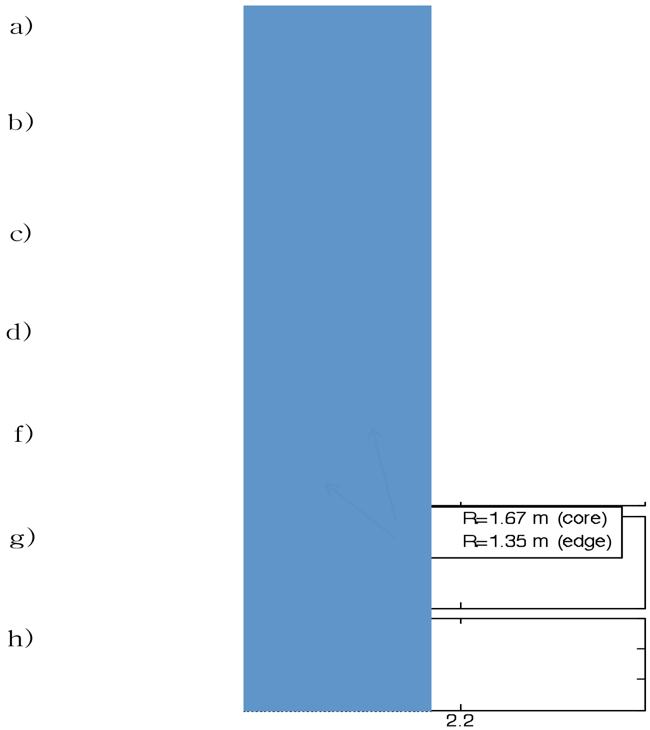


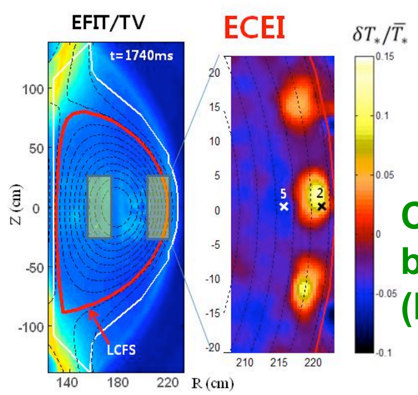


- **Double null operation**
  - Two striking points are god agreement between EFIT & measurements by Langmuir probes (within ~ 2 cm)
  - IR camera is available in 2011

- **In-vessel cryo-pump (IVCP)**
  - Installation of IVCP was finished
  - Tentative use LHe supply system for 1-2 years
  - Open loop of LHe (from 1,000 liter dewar)
  - **4 working hours per day/ lower diverter region**

H-mode in 2010



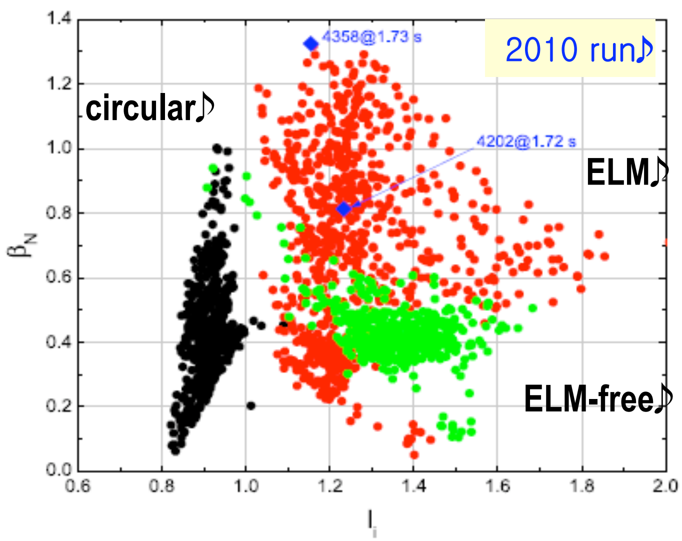


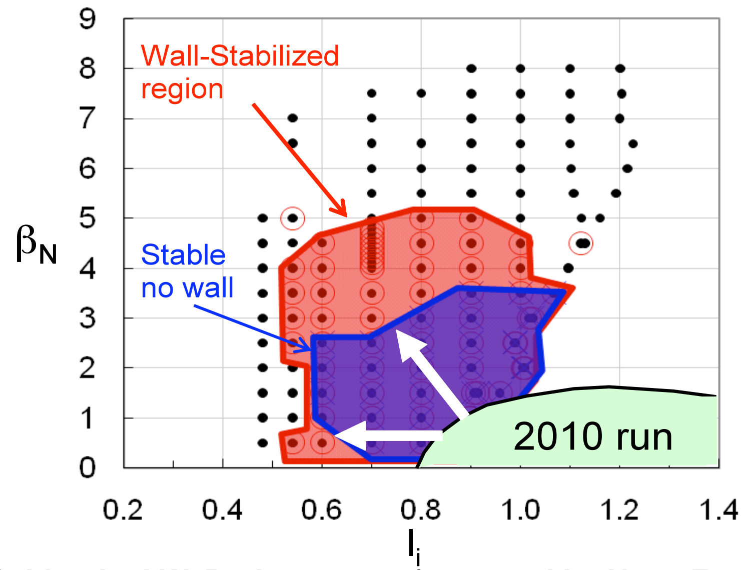
Courtesy by G.S. Yun (Postech)♪

- **Access to H-mode around B_T~2 T**
- **Ip=600kA, R~1.8 m, a~0.5 m,**
  n_e > 1.4x10^{19} m^{-3}, κ~1.8
- **Clear indication of L-H transition from**
  D_α, W_{MHD}, XICS, ECE, CES, etc
- **Low threshold power, P_{LH} < 1.5 MW**
- **Relative low density regime**
- **Marginal powers for L/H transition**
  - Slow L/H transitions and dithering
  - Often synchronized with sawtooth crashes
- **ELM filament dynamics revealed b**
  y 2-D ECEI measurement

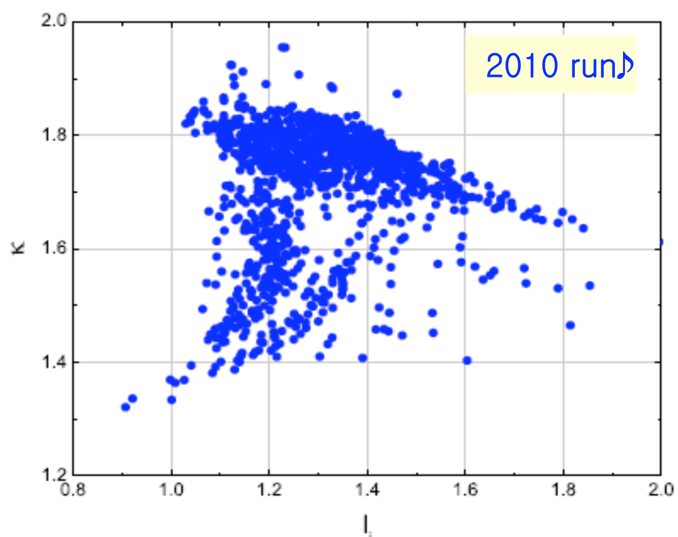
KSTAR

Widely extended operation regime in KSTAR 2010





* Y.S. Park, S.A. Sabbagh, J.W. Berkery, et al. (accepted by Nucl. Fusion) (2011)



- In 2010, KSTAR operation regime was widely extended
  - β_N up to 1.3, Elongation up to 1.9
  - Triangularity up to 1.0
  - l_i covered: 0.8 to 1.9, but only circular has l_i<1.0
- For n=1 RWM and vertical stabilities,
  - li should be decreased more

KSTAR

KSTAR joined the H-mode club in 2010

KSTAR Mission

- To achieve the superconducting tokamak construction and operation experiences, and
- To develop high performance steady-state operation physics and technologies that are essential for ITER and fusion reactor development

- Based on achieving H-mode in 2010
- In 2011 experimental campaign,

  - H-mode will be fully commissioned within given machine capability
  - ITER relevant/urgent, KSTAR specific research issues will be pursued
  - 1.5MW NB, 1MW ECH, and 1 MW ICRF are available in 2011
  - 15 MW auxiliary heating system will be available in 5 years.

- So that we will prepare the second stage of KSTAR mission.

Summary

◆ **Machine commissioning**

- Vacuum of the vacuum vessel and the cryostat
- TF and PF coils are operated within the safety margin of SC magnet.
- Control systems based on distributed network and EPICS

◆ **Plasma operation**

- PCS for plasma shaping and Iso-flux control with real time EFIT
- Startup scenario compensating Incoloy
- H-mode in 2010

◆ **Key system**

- Picture framed in vessel coils(IVC, IRC, RMP, RWM, FEC)
- 1.5MW NB, 1MW ECH, and 1 MW ICRF is available
- 15 MW auxiliary heating system will be available in 5 years.

◆ **ELM mitigation with RMP is the top priority in 2011**

KSTAR Papers to SOFE 2011

SPL2-1 (invited) "Recent Experimental Results of KSTAR" M. Kwon
SO4C-2 (invited) "The Construction of ITER, Viewed from Lessons Learned from KSTAR Project" H. Y. Yang

- SP1-15 Design Feature & Operation Results of Kstar PFC GN2 Baking System S. T. Kim
- SP1-29 Investigation of the Radioactivity Inside the Kstar Vacuum Vessel after Shutdown by Using Gamma-Ray Spectrometry Y.S. Lee
- SP1-32 Temporal and Spatial PFC Temperature Profiles in KSTAR 2010 Campaign E. N. Bang
- SP2-24 Influence of Plasma Operation on the PF circulator of the KSTAR HRS System During 2010 Campaign H. J. Lee
- SP3-37 Conceptual Disign of the Kstar Motor Generator C. H. Kim
- SP3-39 Current Control Method of Thyristor Converter for PF superconducting Coil in KSTAR, H. S. Ahn
- SP3-40 Development of in-Vessel Vertical Coil Power Supply J. K. Jin