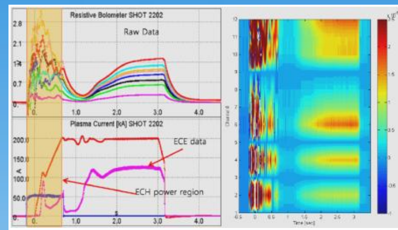
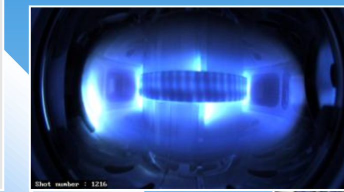




Operational Results and Experience of KSTAR Integrated Control System

Mikyung Park

KSTAR Research Center

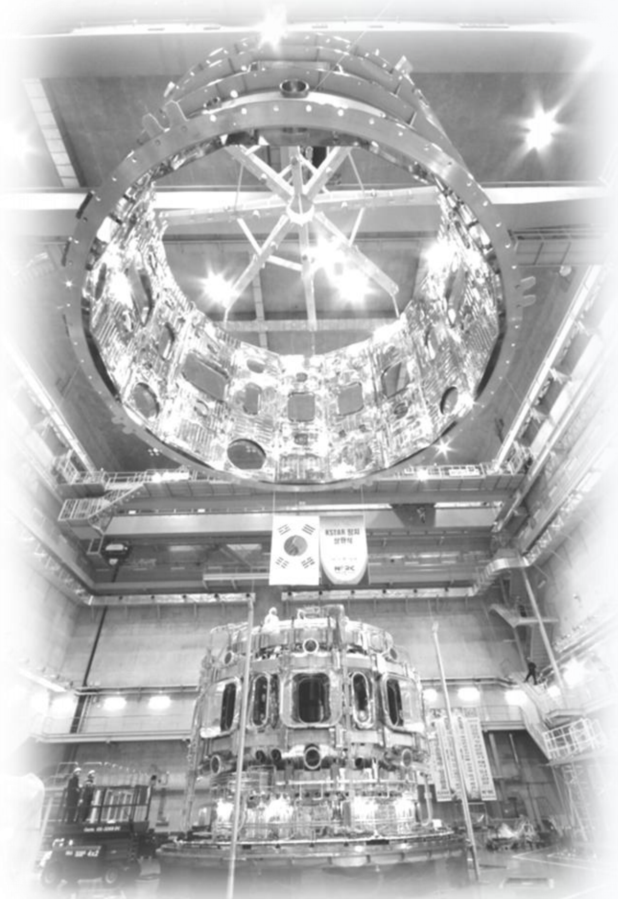
NFRI 국가핵융합연구소 National Fusion Research Institute

Outlines

KSTAR

- Introduction of KSTAR Project
- Implementation of KSTAR Control System
- Operational Result and Issues
- Summary

KSTAR Project



KSTAR Project ?

- **KSTAR - <u>K</u>orea <u>S</u>uperconducting <u>T</u>okamak <u>A</u>dvanced <u>R</u>esearch**
- **Missions -**

  Development of a steady-state-capable advanced superconducting tokamak to establish the scientific and technological base for an attractive fusion reactor as a future energy source.

- **History-**

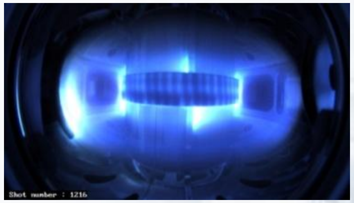
  1995 : Project launched

  1998 : Construction started

  2007 : Completion of Assembly

  2008 : Achievement of the 1st plasma

Major radius, R_0 / Minor radius, a	**1.8 m , 0.5 m**
Elongation, κ / Triangularity, δ	**2.0 / 0.8**
Plasma volume	**17.8 m^3**
Plasma surface area / cross section	**56 m^2 / 1.6 m^2**
Plasma shape	**DN, SN**
Plasma current, I_P	**2.0 MA**
Toroidal field, B_0	**3.5 T**
Pulse length	**300 s**
β_N	**~5.0**
Plasma fuel	**H, D-D**
Superconductor	**Nb_3Sn, NbTi**
Auxiliary heating /CD	**~ 28 MW**
Cryogenic	**9 kW @4.5K**



Fusion ?

KSTAR

- **Fusion has the potential of providing an essentially inexhaustible source of energy for the future.**
- **Via nuclear fusion, the low atomic number elements react to convert mass to energy.**

Principal Fusion Reaction

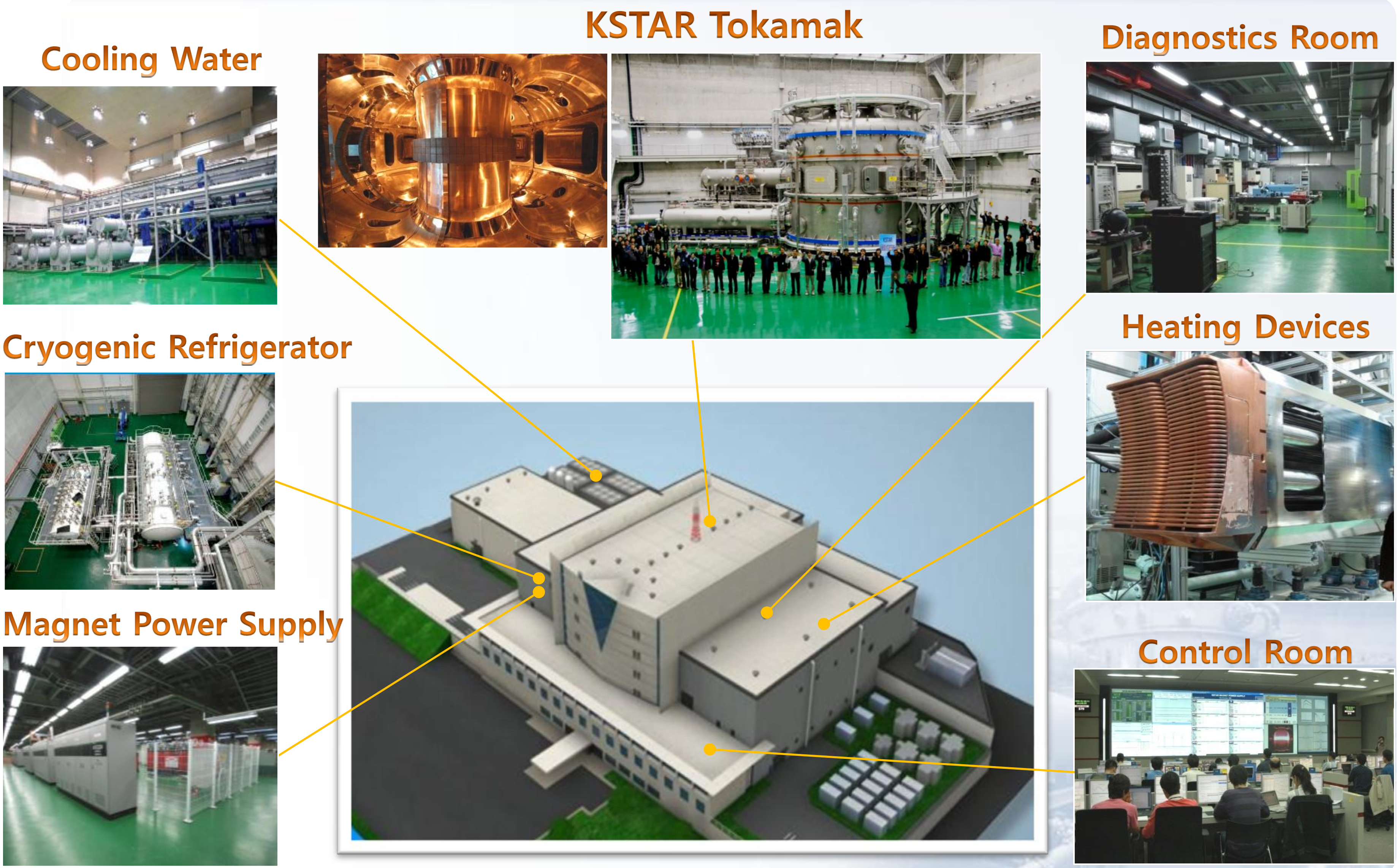
1) $D + D = {}^3He + n + 3.2MeV$
2) $D + D = T + p + 4MeV$
3) $D + T = {}^4He + n + 17.6MeV$
4) $D + {}^3He = {}^4He + p + 18.3MeV$

- *D can be obtained from sea-water and T from ^7Li and ^6Li (quite abundant in nature).*
- *^3He can be found on the moon.*
- *D, Li and ^4He are stable nuclei.*

"The fusion of 1g of T(together with 2/3g of D) produces $1.6x10^5$kW-hr of thermal energy."

Tokamak & Ancillary Systems

KSTAR



Long-term Plan of KSTAR

Last update : 2009.12.3

Operation Phase I 2008 ~ 2012	Operation Phase II 2013 ~ 2017	Operation Phase III 2018 ~ 2022	Phase IV 2023 ~
SC Tokamak operation	Long-pulse operation	High performance operation	DEMO test bed
• Superconducting tokamak operation • First plasma & inductive current ramp (2 MA) • Plasma shaping & heating (DN & SN, H-mode)	• Steady-state operation & ITER pilot device roles (300 s+) • Plasma heating & non-inductive current drive • Instability control in H-mode and AT-mode	• Advanced scenario for DEMO beyond ITER • High-beta and high bootstrap current scenario • Extreme operation of the superconducting tokamak	• DEMO Engineering • DEMO simulator • Reactor material test

- First Plasma ('08)
- Current & Position control ('09)
- Divertor plasma ('10)
- H-mode operation ('11)
- Fast stabilization ('12)

KSTAR Control System

KSTAR

Features

KSTAR

- **Missions**
  - Integrating all **Plant System I&Cs** for Tokamak Operation
  - Establishing the environment for **Real-time F/B Control** on plasma
  - Implementing **Machine Interlock & Protection**
  - Achievement of **Synchronized** Operation
  - Development of Schema for Sequential operation

- **Communication standard and software framework**
  EPICS (Experimental Physics and Industrial Control System)

- **Using every possible Open-source Tools for development**

- **Integration of Heterogeneous controllers**
  : VME, VXI, cPCI, PXI, PCI, PLC, and cFP

- **About 15,000 I/Os and 45,000 PVs (integrated in EPICS)**
- **About 800 experimental signal channels (managed by MDSplus)**

- **Using Five Different Optical Networks**

- **Adopting Two Databases : EPICS Channel Archiver, MDSplus**
- **Additional Databases for web_portal, signal DB and RDB (MSsql, Mysql)**

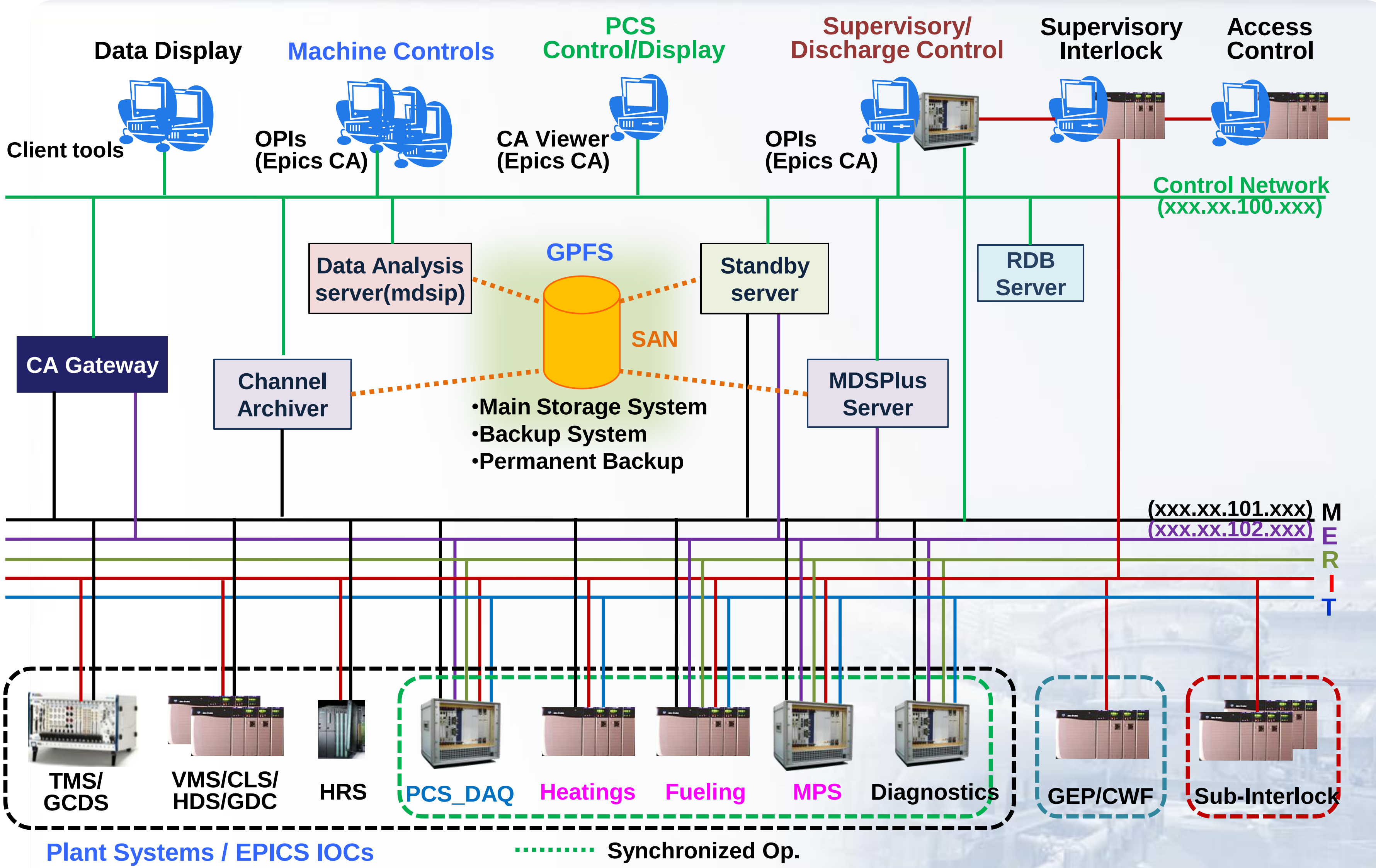
The our control system is still growing and evolving !!

Features

KSTAR

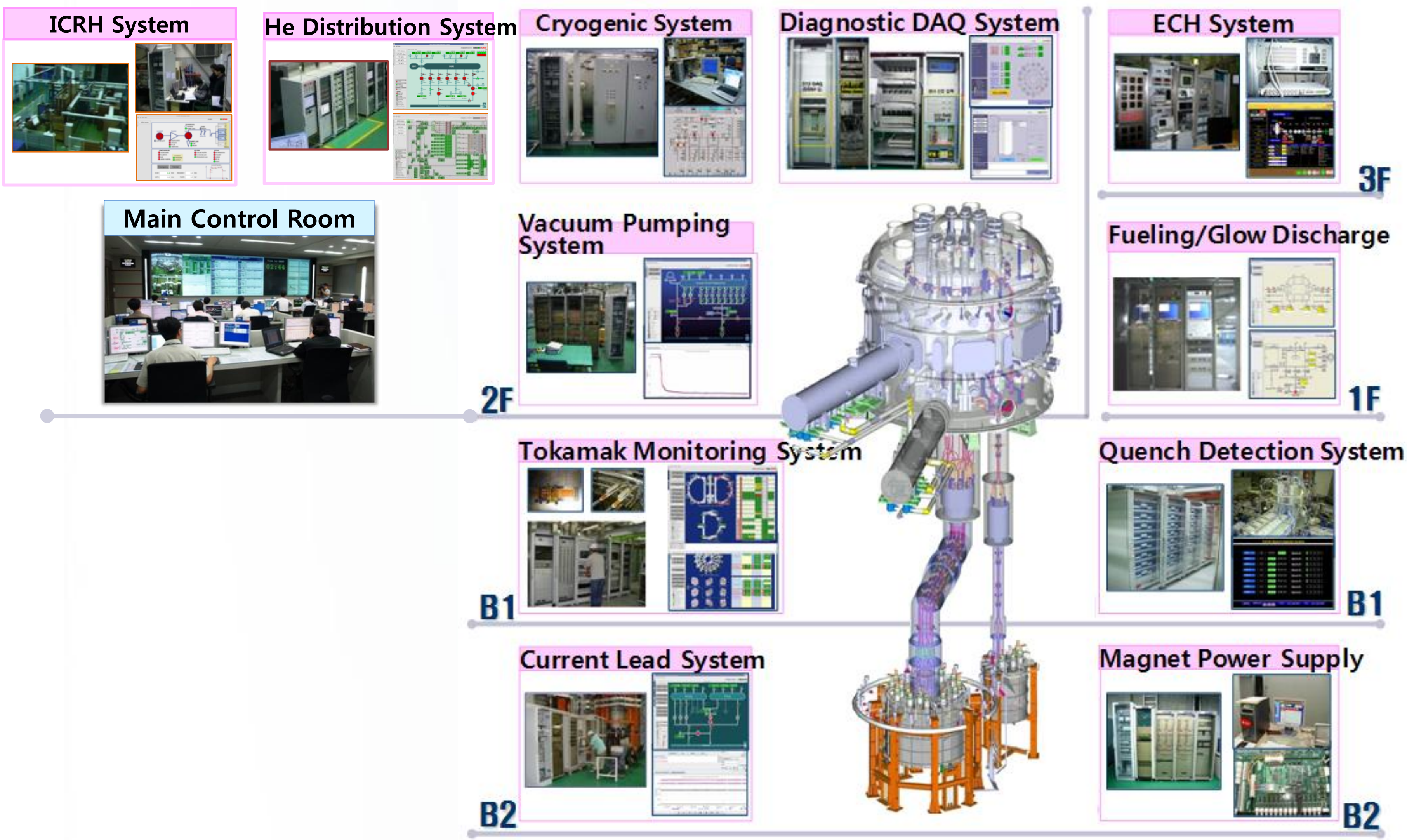
Structure	2 Tier		•Control --- Interlock+Safety
	2 Layer		•Central --- Local
Middleware	EPICS		
Operating system	Linux		•Plant monitoring & control
	VxWorks		•Feedback control
H/W Platform	Slow control		•PLC, cFP
	Fast control		•VME, PXI, cPCI, PCI, VXI, (ATCA)
Interface (Networks)	Machine	EPICS CA	•Plant monitoring & control •Operational data transfer
	Experimental Data	MDSip	•Shot-based data storing
	Real-time	Shared-memory	•Real-time feedback control
	Interlock	(ControlNet)	•Machine interlock & protection
	Timing	Home-made protocol	•Timing & synchronized operation
OPI	Qt (open source)		•Home made
Data Managements	EPICS Channel Archiver		•Low rate continuous operational data
	MDSplus		•High rate shot-based experimental data

Control System Architecture



Plant Control System

KSTAR



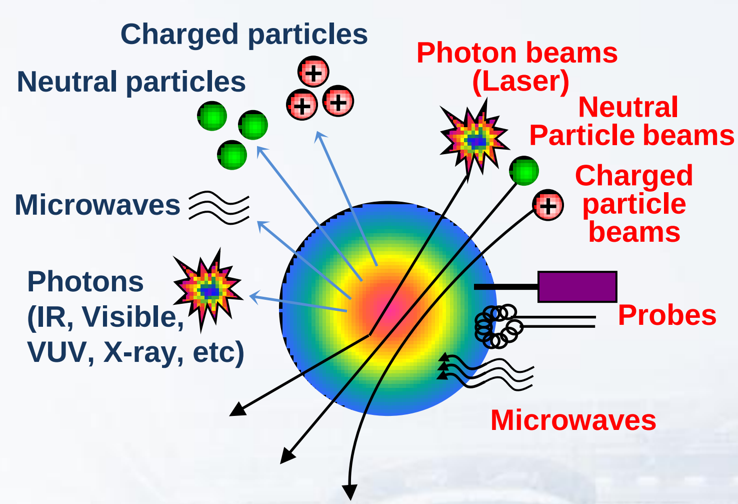
Plasma Diagnostic DAQ System

KSTAR

- 50 types of Diagnostics / 21 diagnostics installed until 2009 (channels are increasing)
- MDSip / Experimental network : data stored to the MDSplus server/Central storage
- EPICS CA / Machine network : configuration, system status reporting, receiving of operation information
- Operated in synchronized manner using LTU (Local Timing Unit)

System	Channels(Final)	DAQ
Rogowski Coil	3	cPCI, max 200KHz
Flux/Voltage Loop	45	cPCI, max 200KHz
Magnetic Field Probe	244 (512)	cPCI, max 200KHz
Diamagnetic Loop	9	cPCI, max 200KHz
Saddle Loop	40	cPCI, max 200KHz
Vessel Current Monitor	3	cPCI, max 200KHz
Halo Current Monitor	15 (273)	cPCI, max 200KHz
Mirnov Coil	8 (72)	VXI, 1 ~ 10MHz
Fast Reciprocating Probe	5 (25)	cPCI, max 200KHz
Fixed Edge probe	6 (120)	cPCI, max 200KHz
MMW Interferometer	8	VME, max 200KHz
ECE Radiometer	40	VME, max 200KHz
Edge Reflectometer	4	PXI, max 200MHz
Resistive Bolometer	12	PXI, max 500KHz
X-ray Crystal Spectrometer	1	PCI, max 10KHz, Window
Visible Survey Spectrometer		PCI, max 100KHz, Window
Visible Filterscope		PCI, max 100KHz, Window
H_alpha Monitor	30	VME, max 200KHz
Soft X-ray Array	2	PXI, max 250KHz
Hard X-ray Array	80 (240)	PCI, 10MHz, Window
Visible/H_alpha TV	3	PCI, Window

Passive diagnostics **Active diagnostics**



Physics Parameters

- Plasma current
- Loop voltage
- Plasma shape & position
- Temperature, density
- Stored energy, impurities
- Stability
- confinement
- Real-time measuring for feedback control

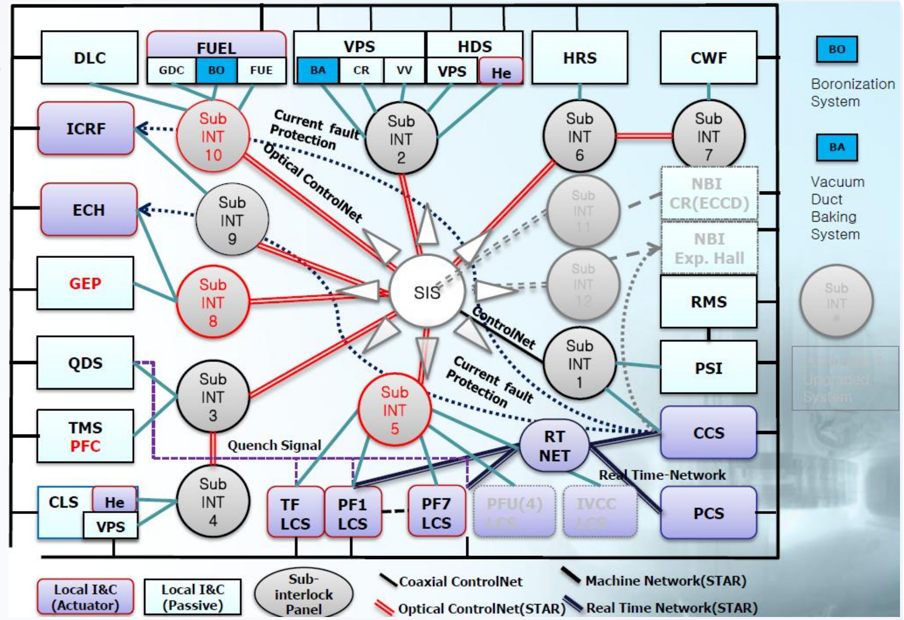
Machine Interlock

KSTAR

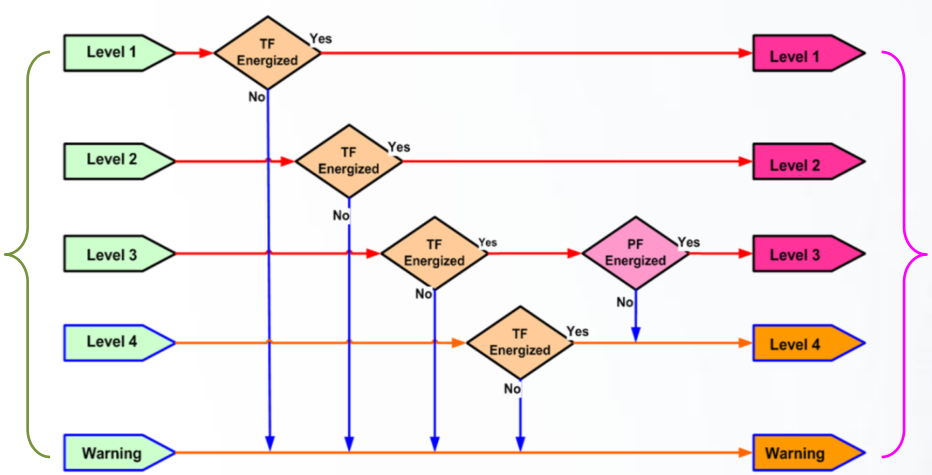
- **Structure**
  - 1 Supervisory Interlock (Fully redundant system)
  - 10 sub-interlock systems for 28 Local controllers
  - About 300 I/O points (in the initial stage)

- **Communication (ControlNet/duplicate)**
  - Media: Optical Fiber/ coaxial
  - Method: star + daisy chain

- **Assistant or Redundant Interlock**
  - Plasma Current Fault protection
  - Direct Quench signal for Magnet Power Supply
  - SMS (Short Message Service)



Local Interlock Level

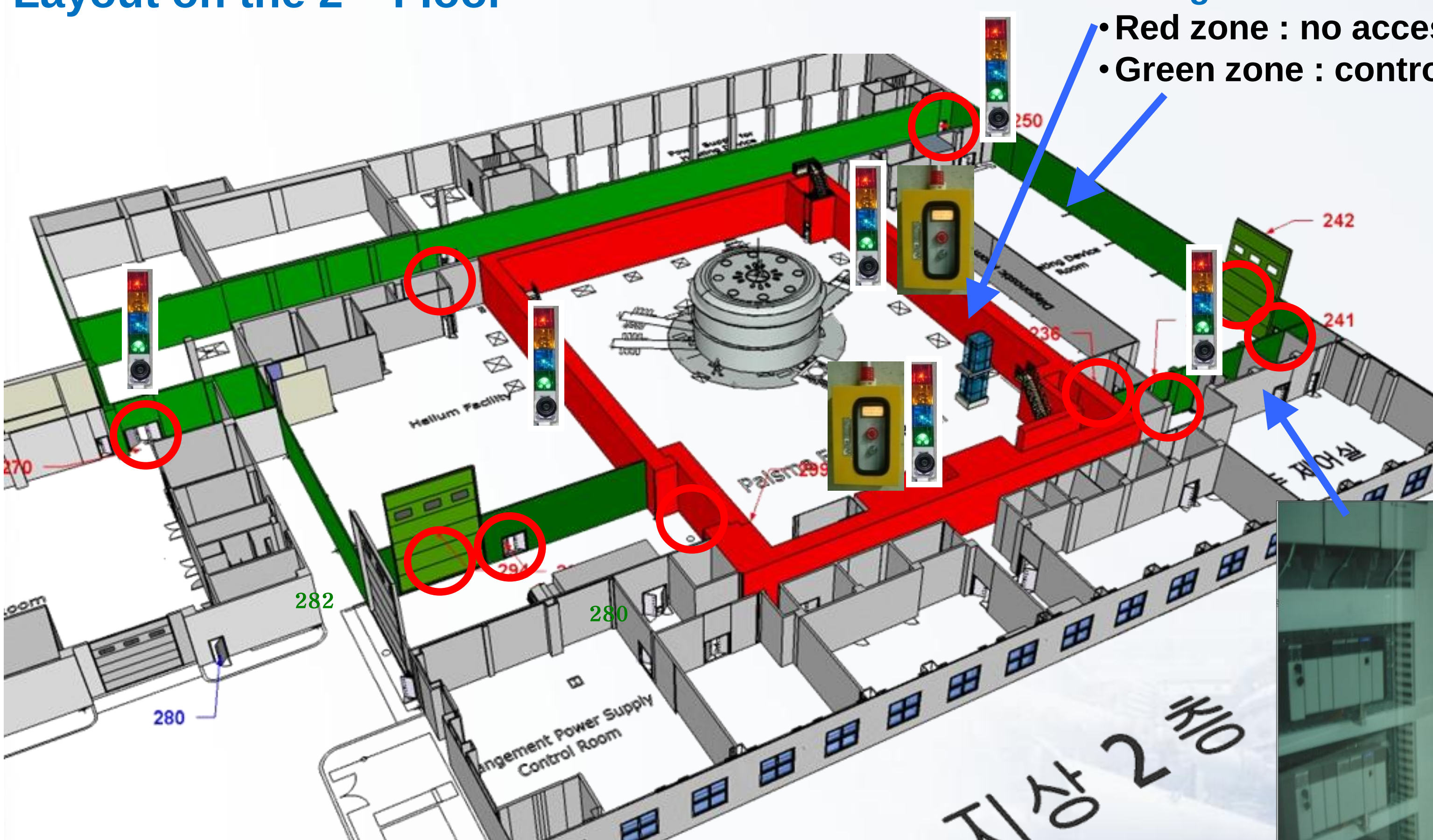


- **Four Interlock levels**
  - **Level 1 : Fast discharge of TF current**
  - **Level 2 : Slow discharge of TF current**
  - **Level 3 : Experiment stop**
    fast discharge of PF current
  - **Level 4 : Next shot inhibit**
  - **Warning**

Access Control System

KSTAR

- **Layout on the 2nd Floor**



- **During Plasma Shot**
  - Red zone : no access
  - Green zone : controlled access

In the Main Control Room

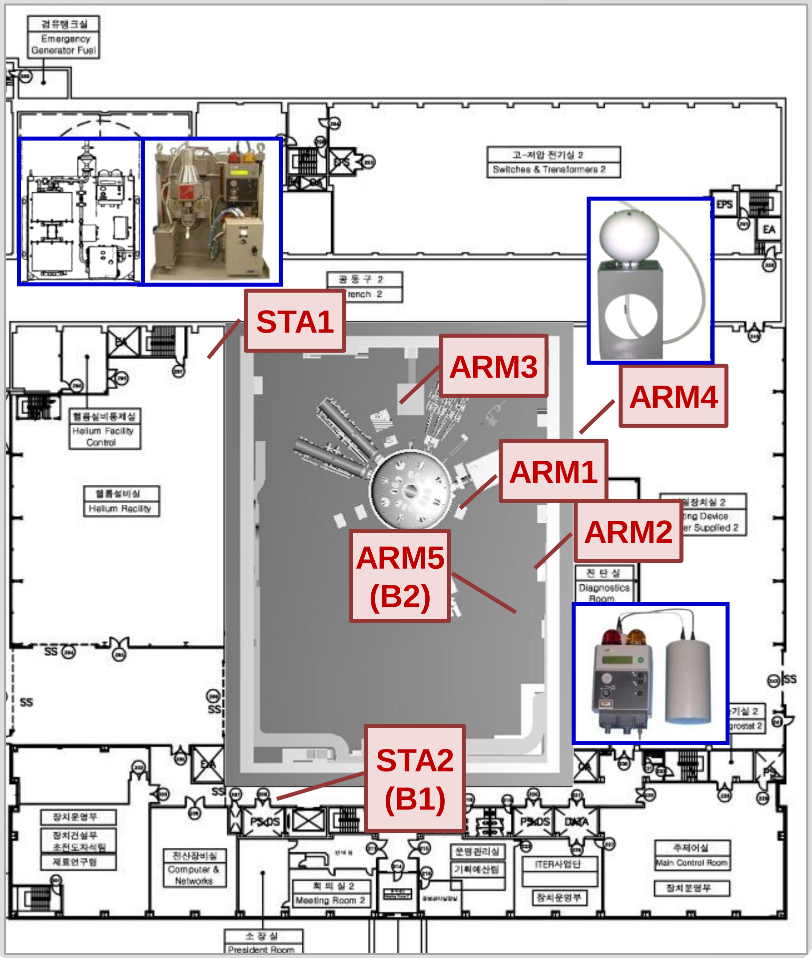
Controlled Door

Emergency Exit

: Warning Lights & Siren

Radiation Monitoring System

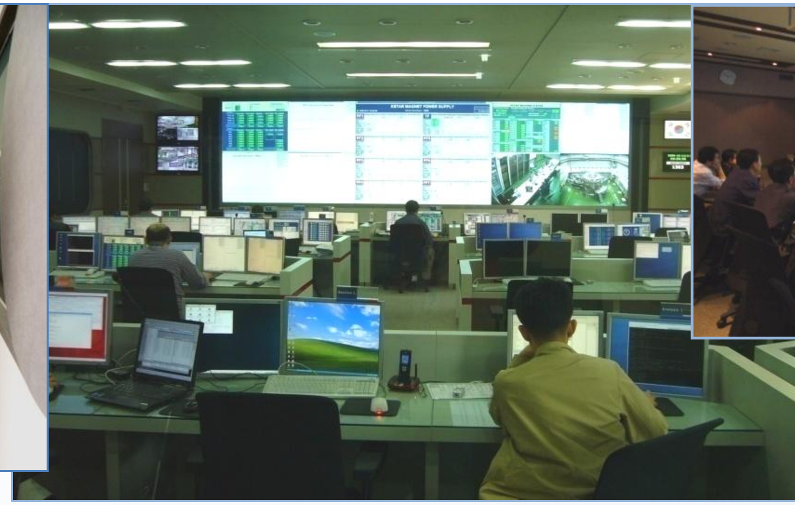
KSTAR



Groups	Measurements	Detectors
Room		
ARM2	Gamma	Ionization Chamber
	neutron	He-3
ARM1	Gamma	Ionization Chamber
ARM3	Gamma	Ionization Chamber
ARM4	Gamma	Silicon
	neutron	He-3
ARM5	Gamma	Silicon
	neutron	He-3
STA1 (exhaust)	Particle(α,β)	Ionization Chamber
	Gas(α,β)	Double Silicon
STA2 (exhaust)	Particle(α,β)	Ionization Chamber
	Gas(α,β)	Double Silicon
Environmental		
ERM1 (200m)	Gamma	Silicon
	neutron	He-3
ERM2 (100m)	Gamma	Silicon
	neutron	He-3
ERM3 (300m)	Gamma	Silicon
	neutron	He-3

Infrastructure






● Main Control Room

- **Operator's area** : 24 operator's seats, Display wall containing 12 DLP cubes, 5 aux. displays
  E-stop buttons, access key-box, portable H.323, web-cam for web service, audio, ..
- **Equipment room** : mainframes of OPI servers, CCS, Central timing, SIS, PSI, RMS, a node of PCS, ..
- **Meeting room** : H.323, audio, project, etc.…
- **Plan** : enlargement of MCR, construction of remote OP room for KSTAR and ITER

● **Storage system**
- Main storage : IBM DS 8100, 14TB
- Disc Backup Storage : EMC, 6.5TB, temporary backup
- Tape Backup Library : IBM TS3500, 110TB, permanent backup

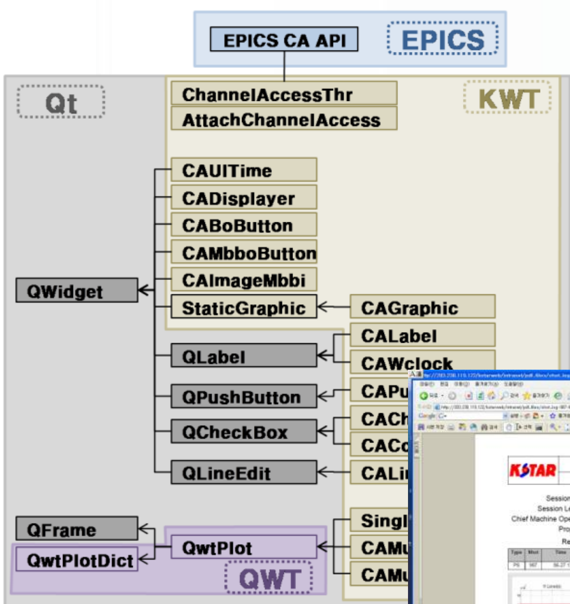
● **Shared file system : GPFS v.3.2.1 (IBM)**

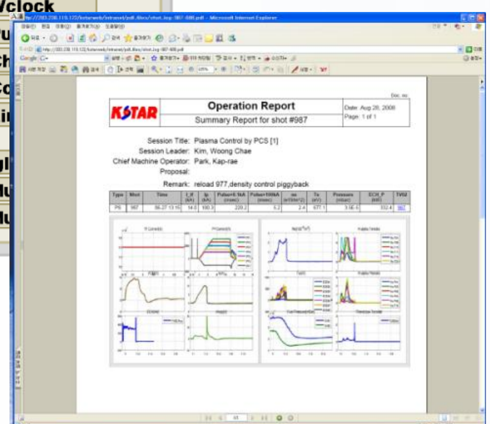
● **Network :** 2 backbones, 11 workgroup SW, multi-mode fiber-optic, star-topology

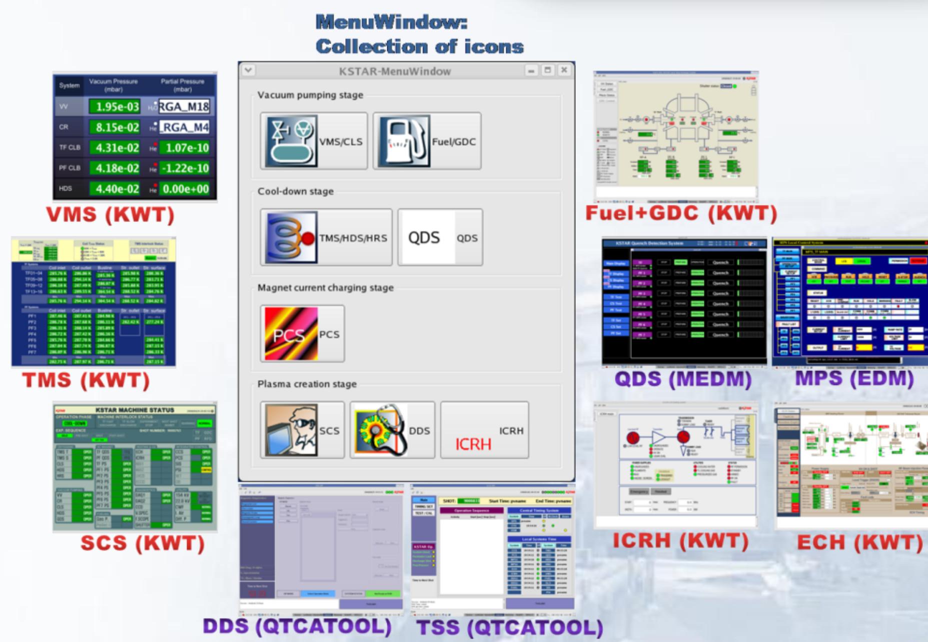
● **Servers** : Gateway, Data archiving, Data analysis, Computing, Relational DB, Web_portal, Standby, etc

Data Visualization

- Operator Interface
  - Developed panels : 154 first the 1st campaign
  - Development tool : Qt 4.3.1 Open source tool
- Data Visualization
  - Run-time Data Display : SinglePlot, MultiPlot
  - Experimental data display : jScope, Rtscope, Reviewplot, IDL/Matlab applications

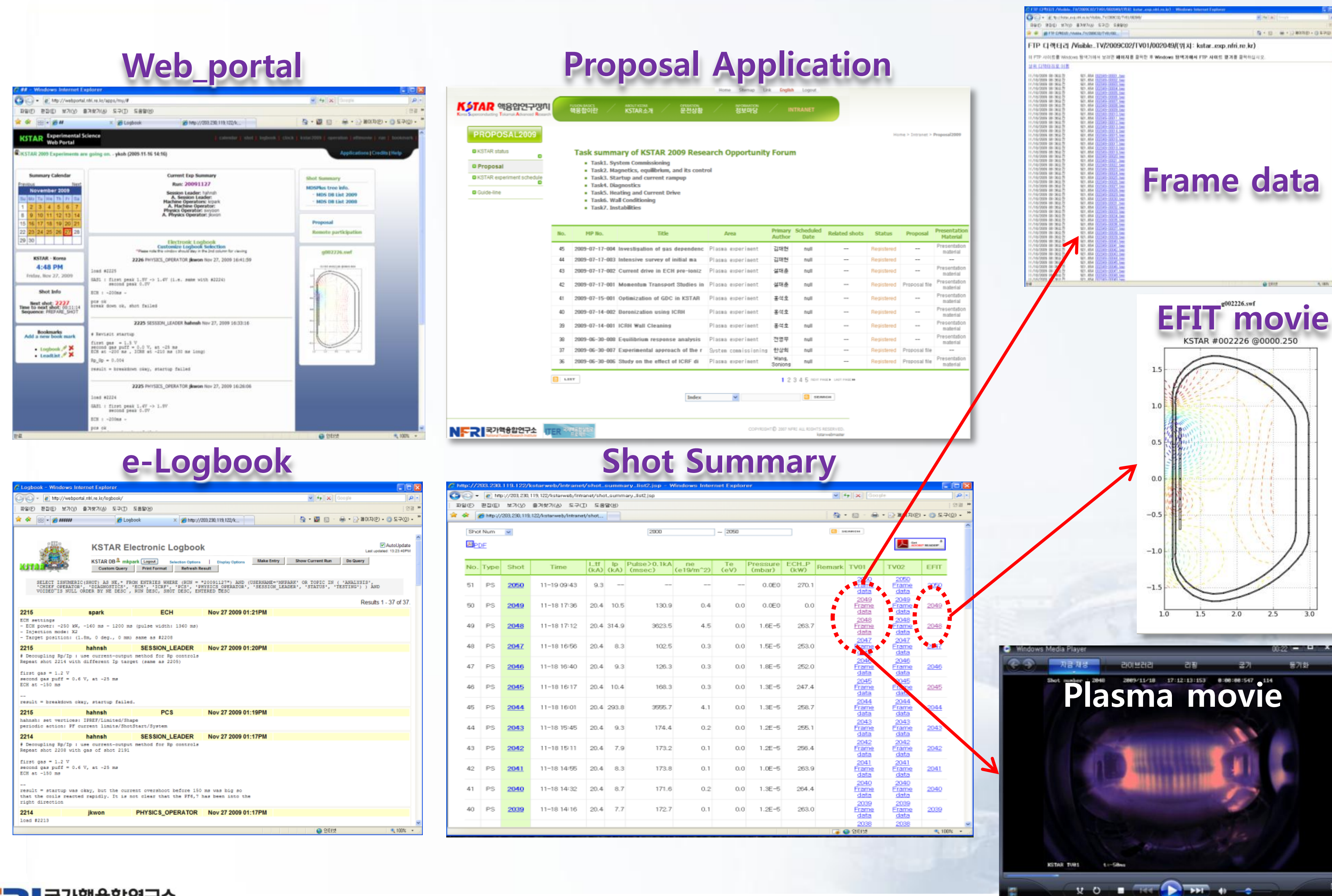






Experiments Information Services

KSTAR

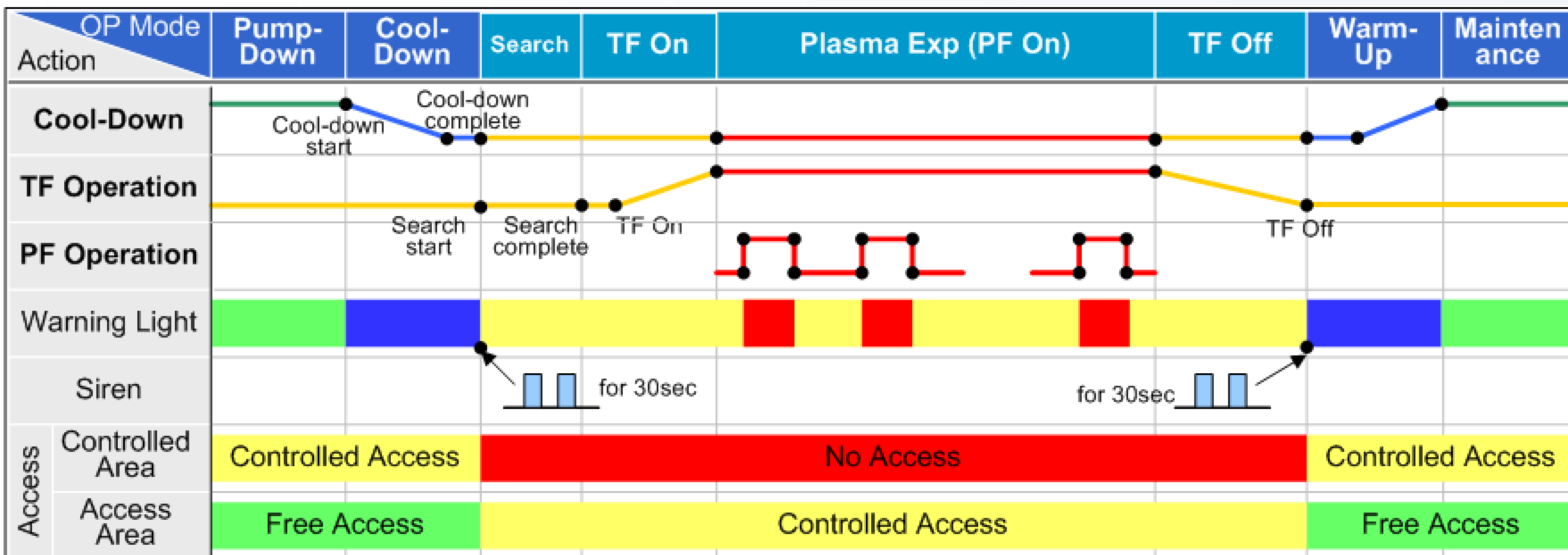


Operational Results and Issues

Operation Mode and Access Control

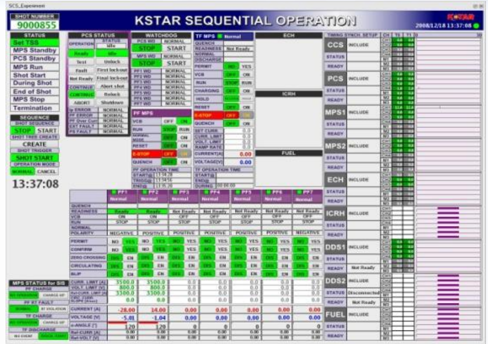
KSTAR

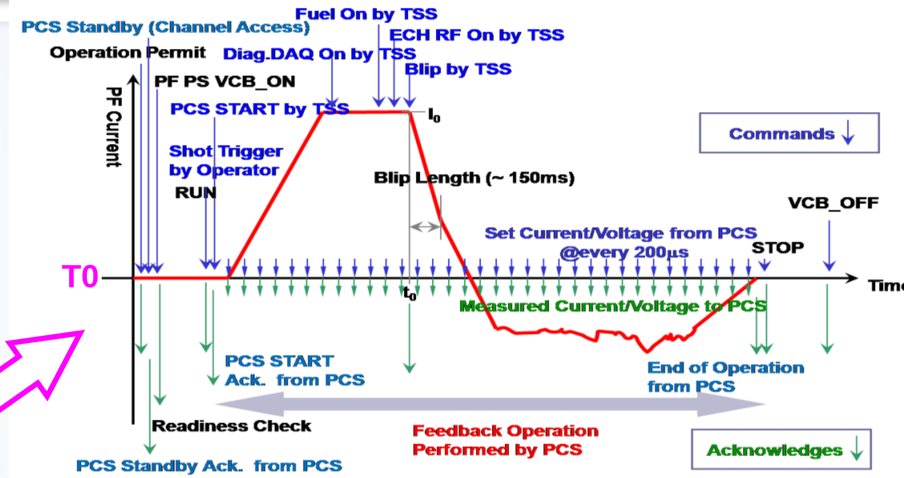
- **6 Long-term Operation Stages**
  Vacuum pumping – Cool down – Magnet test – Plasma Experiment – Warm up – Maintenance
- **Daily Operation**
  Search – Readiness check – TF on – Reference shot – Plasma shot – TF Off



Experiment(Shot) Sequence

KSTAR





Prepare for Next Shot

Create Next Shot #

Readiness check?

Timing & parameter set

Parameter set DONE?

@T0 – 2min.

Lock

Create MDStree

Sequential Operation

Controlled by PCS

PF On — Plasma — PF Off

Timing generation

PFPS current=0?

Start of shot @T0

End of shot

- Lockout
- PF PS Standby -> Run
- PCS Standby

Start of sequence

End of sequence

@T0 – 1min.

Data transfer

Calculation

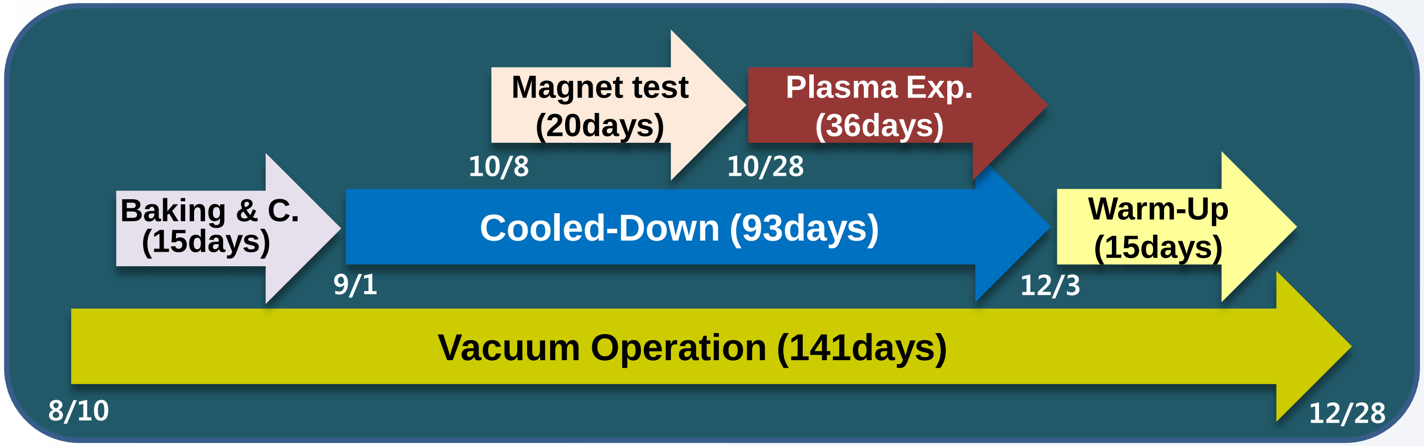
Post activity

- Data auto-display
- Shot-result upload
- Shot summary create ..

Operation of the 2nd Campaign in 2009

KSTAR

- **Operation Period : 08/10 2009 ~ 12/28 2009 [~ 5 months]**



- **Plant Control and Diagnostic DAQ systems**
  - 2008 : 27 systems with 17911 Processing Variables (PVs)
  - 2009 : 37 systems with 45375 PVs
- **Total Experimental Shots including vacuum shot and plasma shot**
  - 2008 : 1 - 1283 shot (1283 shots)
  - 2009 : 1284 - 2342 shot (1059 shots)
- **Plasma Experimental Data (MDSplus data)**
  - 2008 : 211.904GB
  - 2009 : 479GB (due to the expansion of diagnostic channels)
- **Plant Operational Data (EPICS data)**
  - 2008 : 1143GB /8365 PVs (13 Archive engines)
  - 2009 : 389GB /4886 PVs (11 Archive engines)(optimization in # of signals & archiving rate)

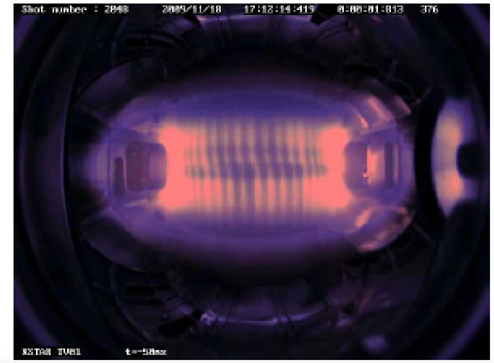
Experimental Results

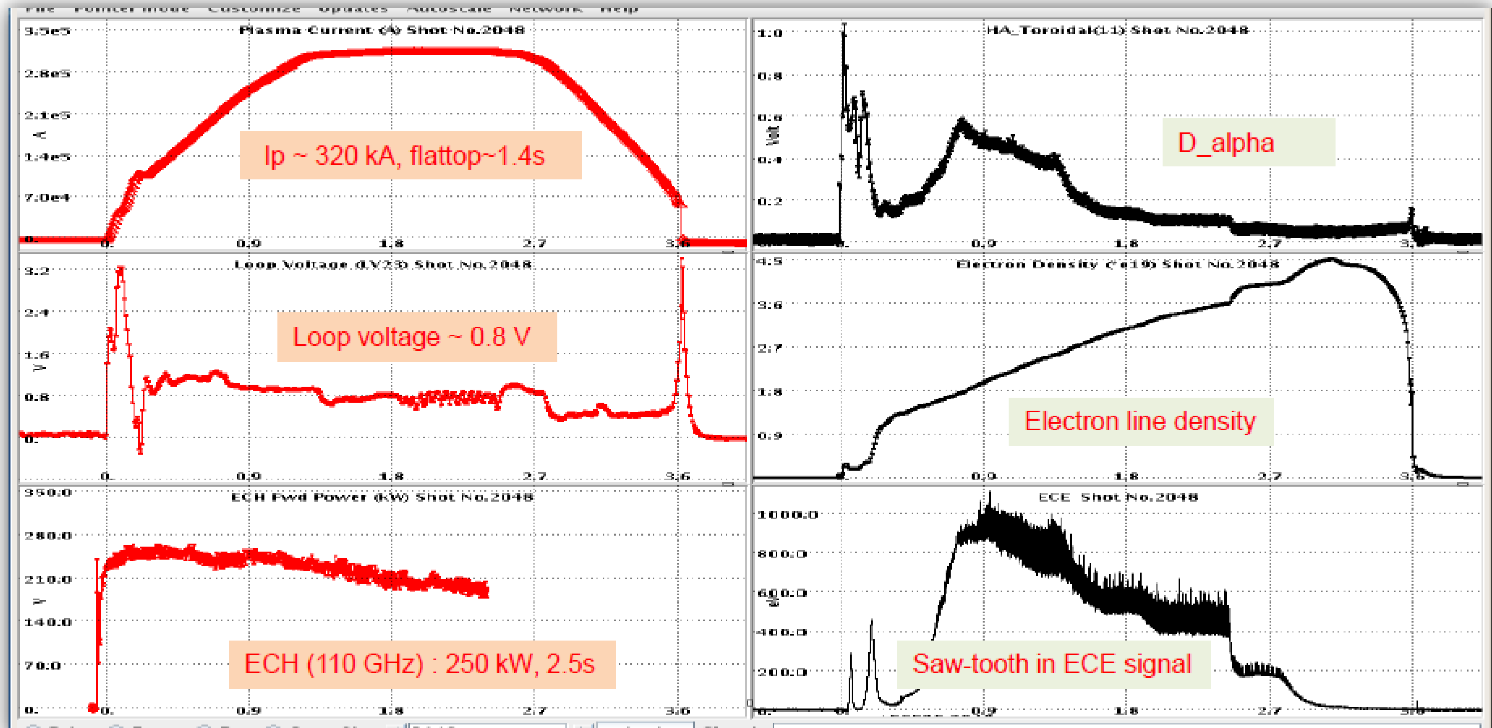
KSTAR

2009 KSTAR Target Plasma Achievement (2009. 11. 18)

Achieved parameters (target value)

- Plasma current : 320 kA (>300 kA)
- Flattop : 1.4 s (> 1s)
- Pulse length : 3.6 s (> 2s)
- Shot # 2048
- Date : 2009. 11. 18
- ECH : 110 GHz, 250 kW, 2.5s





Operational Results in 2009

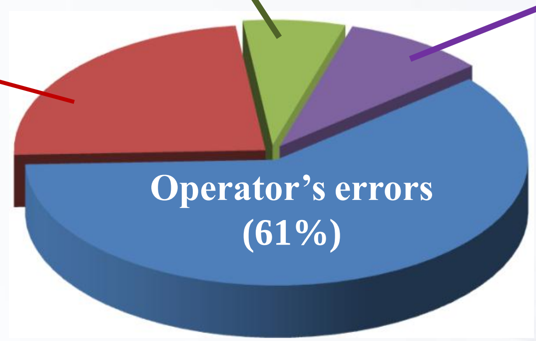
KSTAR

◆ Analysis of Faults

Causes	Occurrence	Consequences
Operator’s errors	46	Stop the plasma shots
Plant Control Faults	18	Fain in operation monitoring Fail in synchronized operation
Servers Faults	7	Fail in data monitoring & archiving
Diagnostic DAQ Faults	5	Fail in Data acquisition

Diagnostic DAQ Fault (7%)

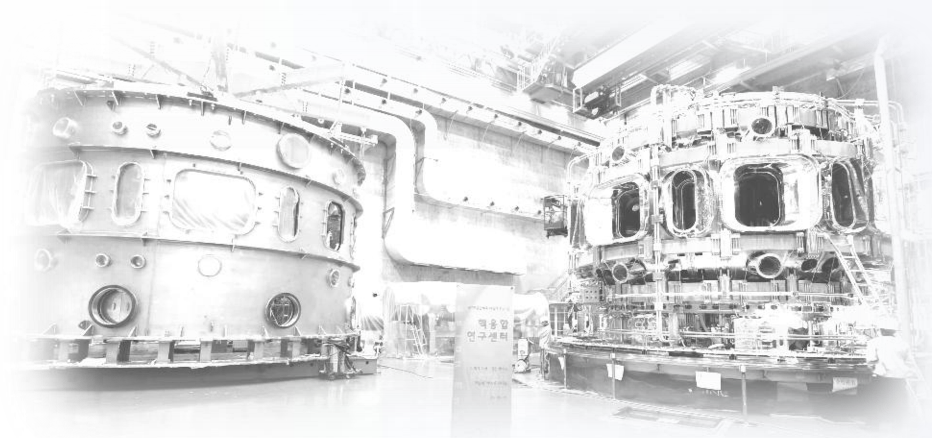
Plant Control Fault (24%)
- CCS RT violation fault
- CLS_HCS communication error
- TMS IOC down
- Fuel_DAQ fault
- ECH sequence error
- ECH synchronization fail



Servers Fault (9%)
- CA gateway down
- MDSplus server down
- Archiver server down

● Results
1. Upgrades and modifications conducted to enhance the performance and stabilities by solving the problems occurred during the 1st operation
2. NOT serious faults to effect on the plasma experiments
3. Major faults caused by operator’s errors in violating the operational sequences and making mistakes in system configurations

Summary



Summary

KSTAR

- KSTAR is the first tokamak to adopt EPICS fully for the control system.
- KSTAR integrated control system has performed its missions successfully during the last two campaigns.
- Therefore, KSTAR control system is becoming a new standard in tokamak control because ITER decided to use EPICS after verifying its performance in KSTAR.

- Next consideration in the operation is to increase the availability of machine.
  - Human error became the major source of machine interrupt.
  - Besides the training of operators or practical documentation, the robustness & automation must be achieved in the control systems.

Near-term Plan to Support Operation

KSTAR

- Expanding the control system to cope with newly installed plant & diagnostic systems

- Enhancing stability and availability of control system
  : Non-interrupt Operation of KSTAR
  - Redundancy : Hardware, EPICS IOC, Applications
  - Self-Protection logics implemented into each control system against unintended actions such as sequence violation, operator's errors, etc
  - Document the procedures for operation practically and intimately

- Improving the management of control systems
  - Update the guideline for control system development
  - Improve the environment for run-time monitoring & configuration of control system

- Establishing the environment for remote participating in KSTAR experiments and operations outside KSTAR
  - Enhance the security of access to KSTAR
  - Development a tool for remote operation

- Setting to R&D work for longer pulse operation in the future

On the date of the first plasma target achievement (Jun. 13, 2008)