



# Current status of the KSTAR diagnostics

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Presented for  
1st ENEA-KFE Remote Meeting on Bilateral Collaboration Activities

Korea Institute of Fusion Energy, Daejeon, Korea  
Thu 28 Nov 2024

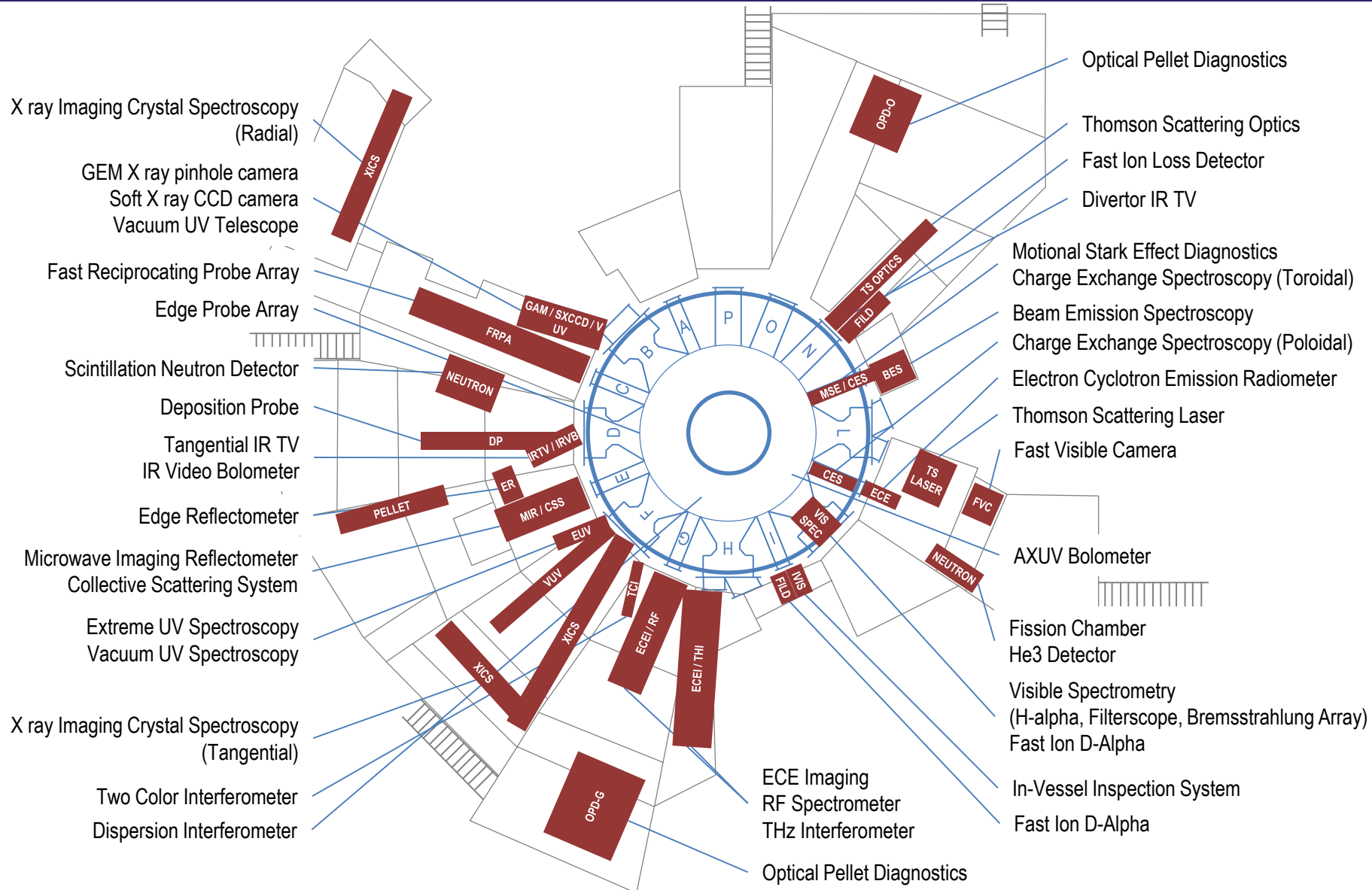
**Overall layouts and features**  
**Role-based groupings with brief introduction**  
**Future plans**

**Overall layouts and features**

**Role-based groupings with brief introduction**

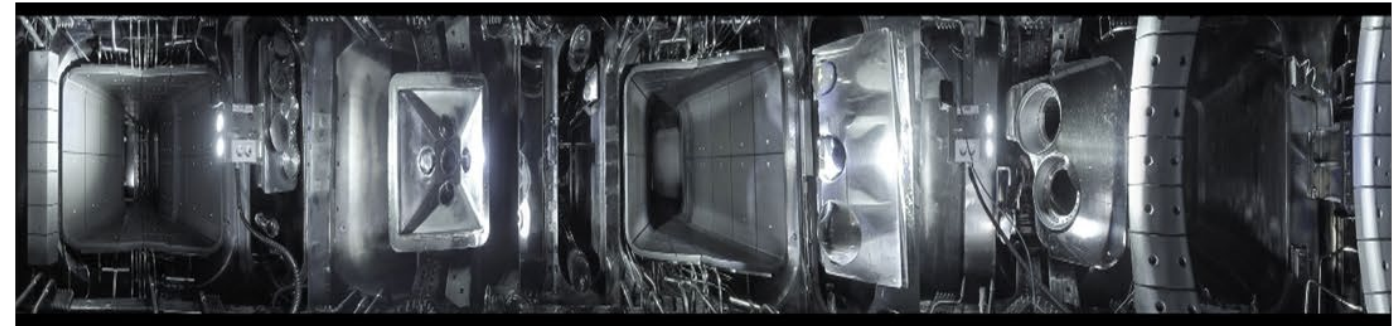
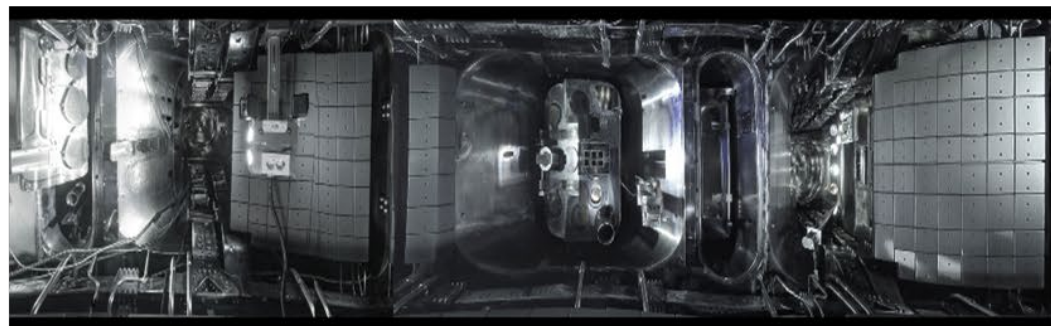
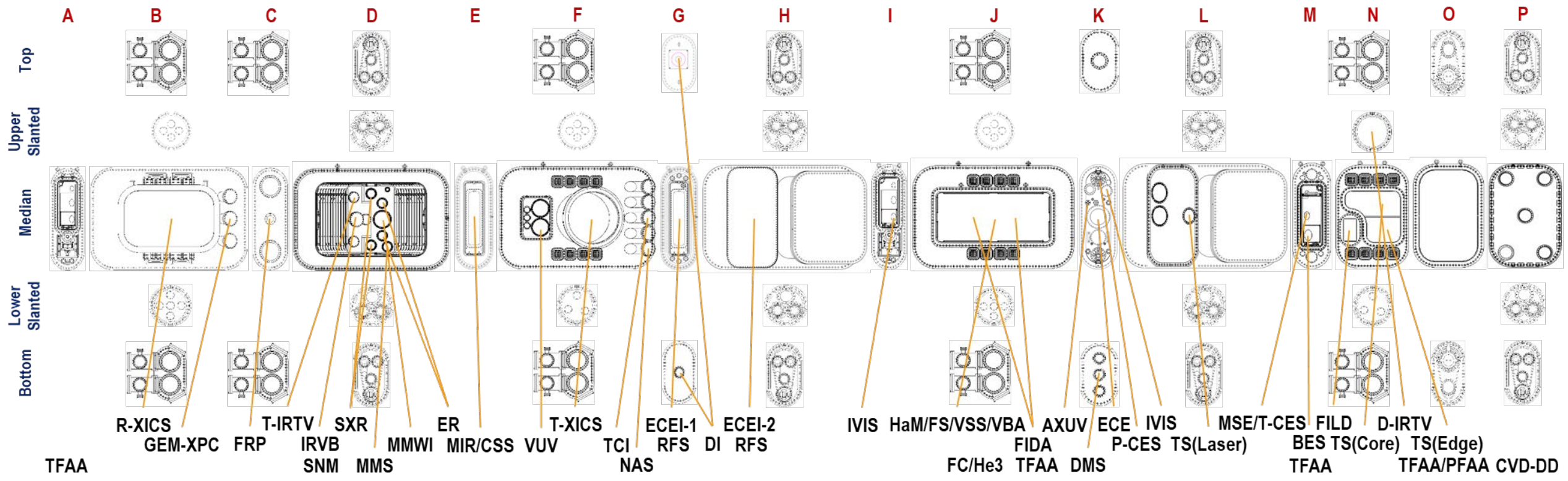
**Future plans**

# KSTAR Diagnostics Layout

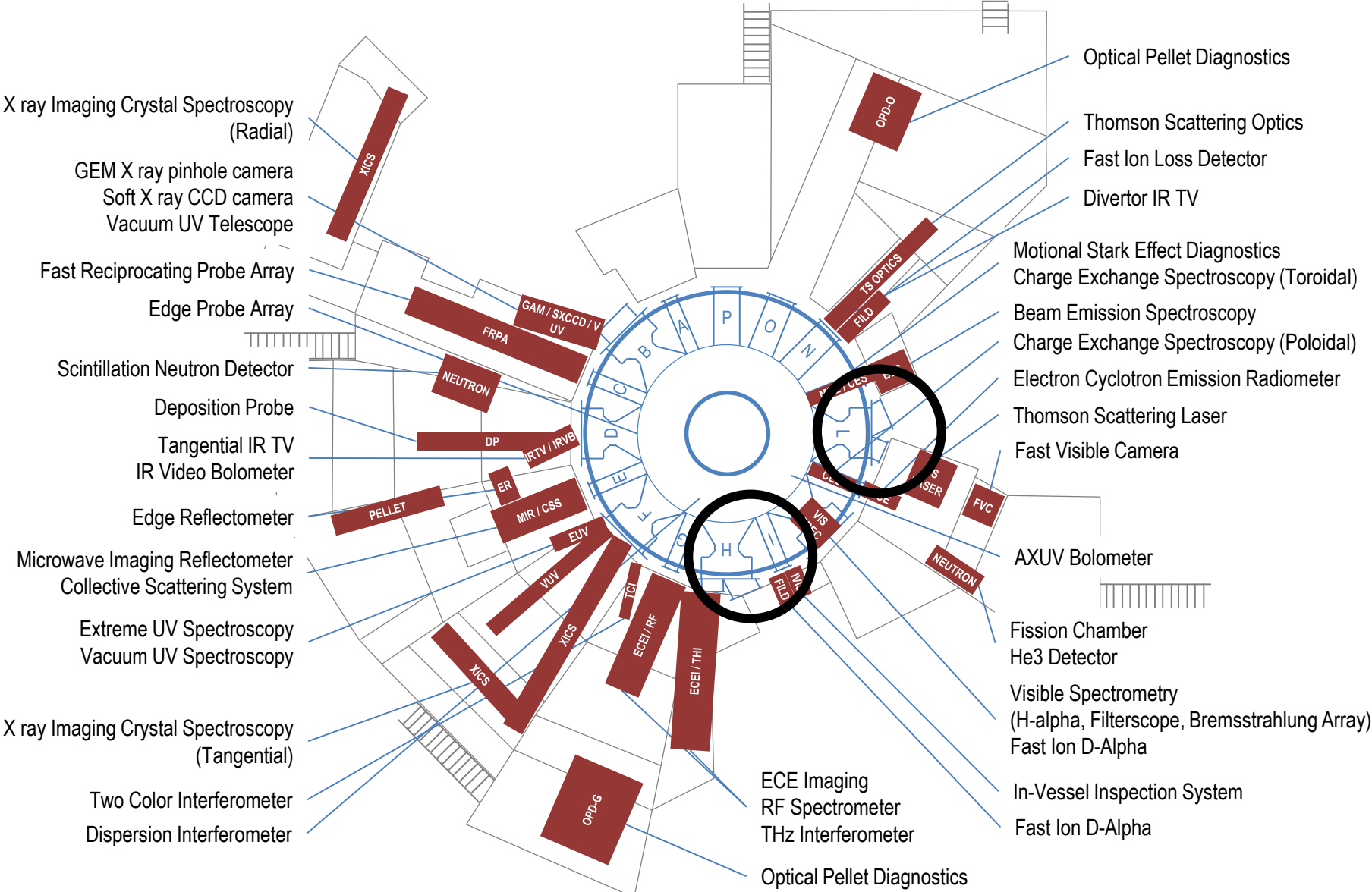




# Diagnostics Port Allocation



# Cassette structures to accommodate some 'tangential' views



- X ray Imaging Crystal Spectroscopy (Radial)
- GEM X ray pinhole camera
- Soft X ray CCD camera
- Vacuum UV Telescope
- Fast Reciprocating Probe Array
- Edge Probe Array
- Scintillation Neutron Detector
- Deposition Probe
- Tangential IR TV
- IR Video Bolometer
- Edge Reflectometer
- Microwave Imaging Reflectometer
- Collective Scattering System
- Extreme UV Spectroscopy
- Vacuum UV Spectroscopy
- X ray Imaging Crystal Spectroscopy (Tangential)
- Two Color Interferometer
- Dispersion Interferometer

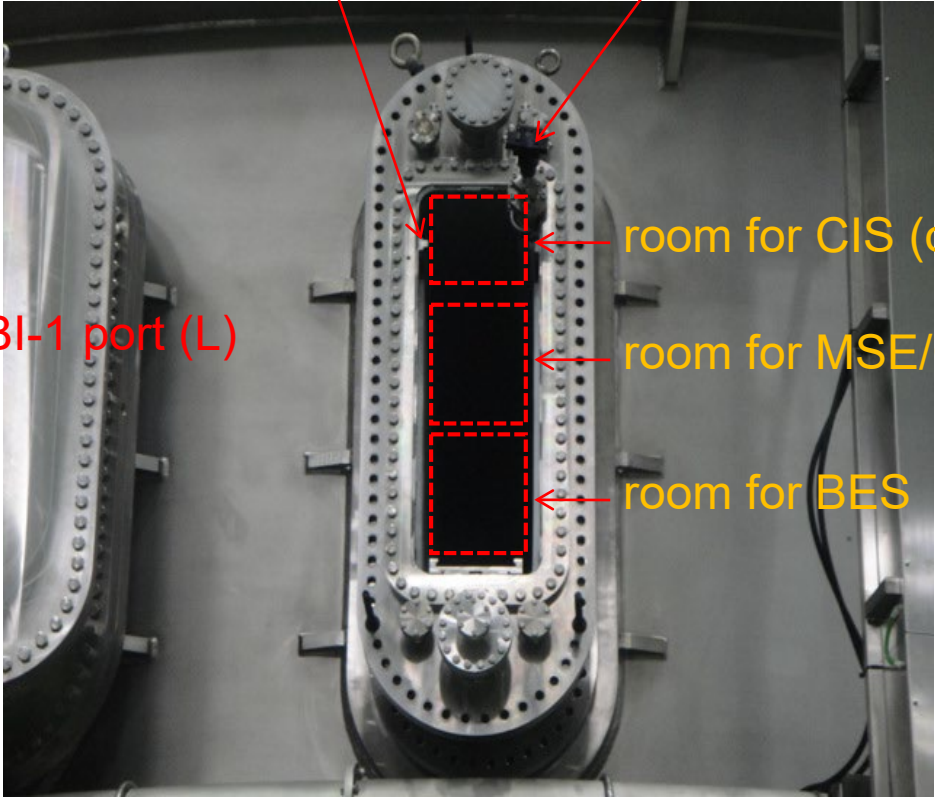
- Optical Pellet Diagnostics
- Thomson Scattering Optics
- Fast Ion Loss Detector
- Divertor IR TV
- Motional Stark Effect Diagnostics
- Charge Exchange Spectroscopy (Toroidal)
- Beam Emission Spectroscopy
- Charge Exchange Spectroscopy (Poloidal)
- Electron Cyclotron Emission Radiometer
- Thomson Scattering Laser
- Fast Visible Camera
- AXUV Bolometer
- Fission Chamber
- He3 Detector
- Visible Spectrometry (H-alpha, Filterscope, Bremsstrahlung Array)
- Fast Ion D-Alpha
- In-Vessel Inspection System
- Fast Ion D-Alpha



# Cassette structures to accommodate some 'tangential' views

mounting rail

Shutter control actuator



NBI-1 port (L)

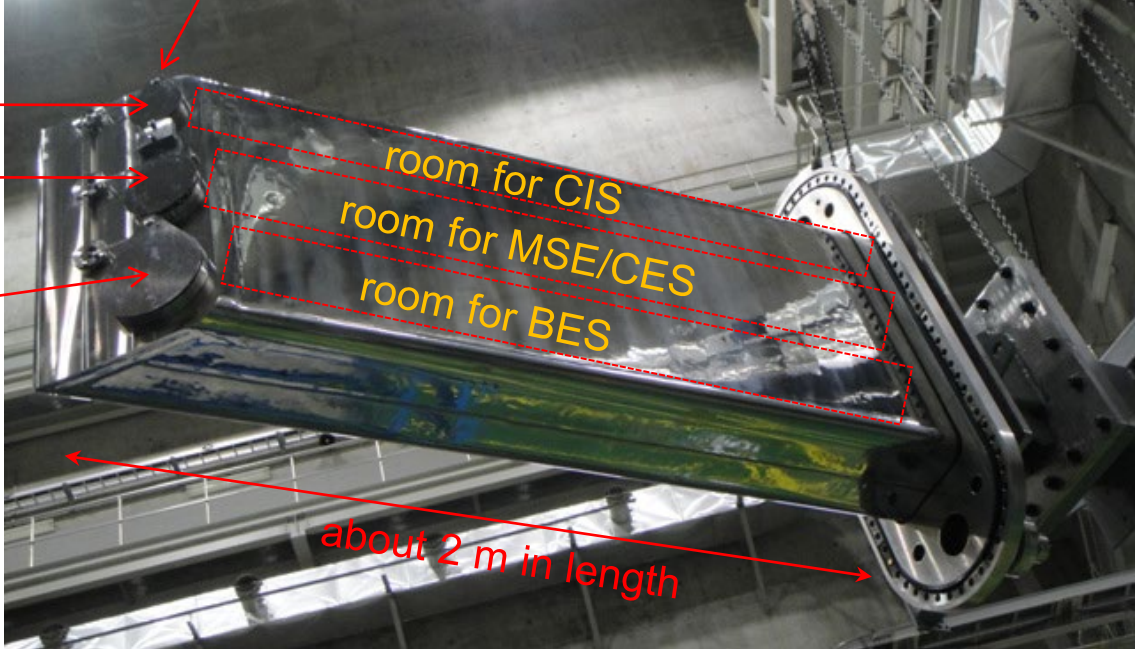
room for CIS (obsolete)

room for MSE/CES

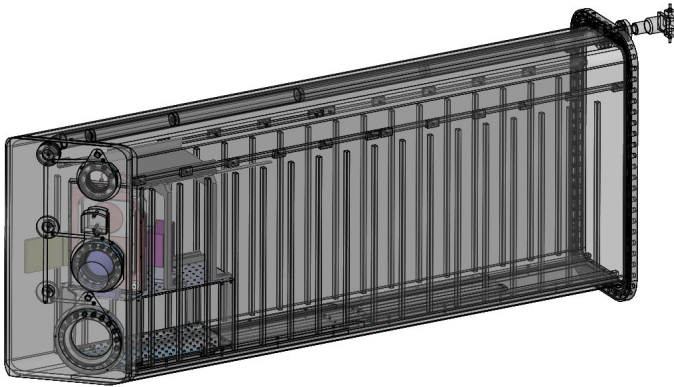
room for BES

Shutters and windows

CIS  
MSE  
CES  
BES

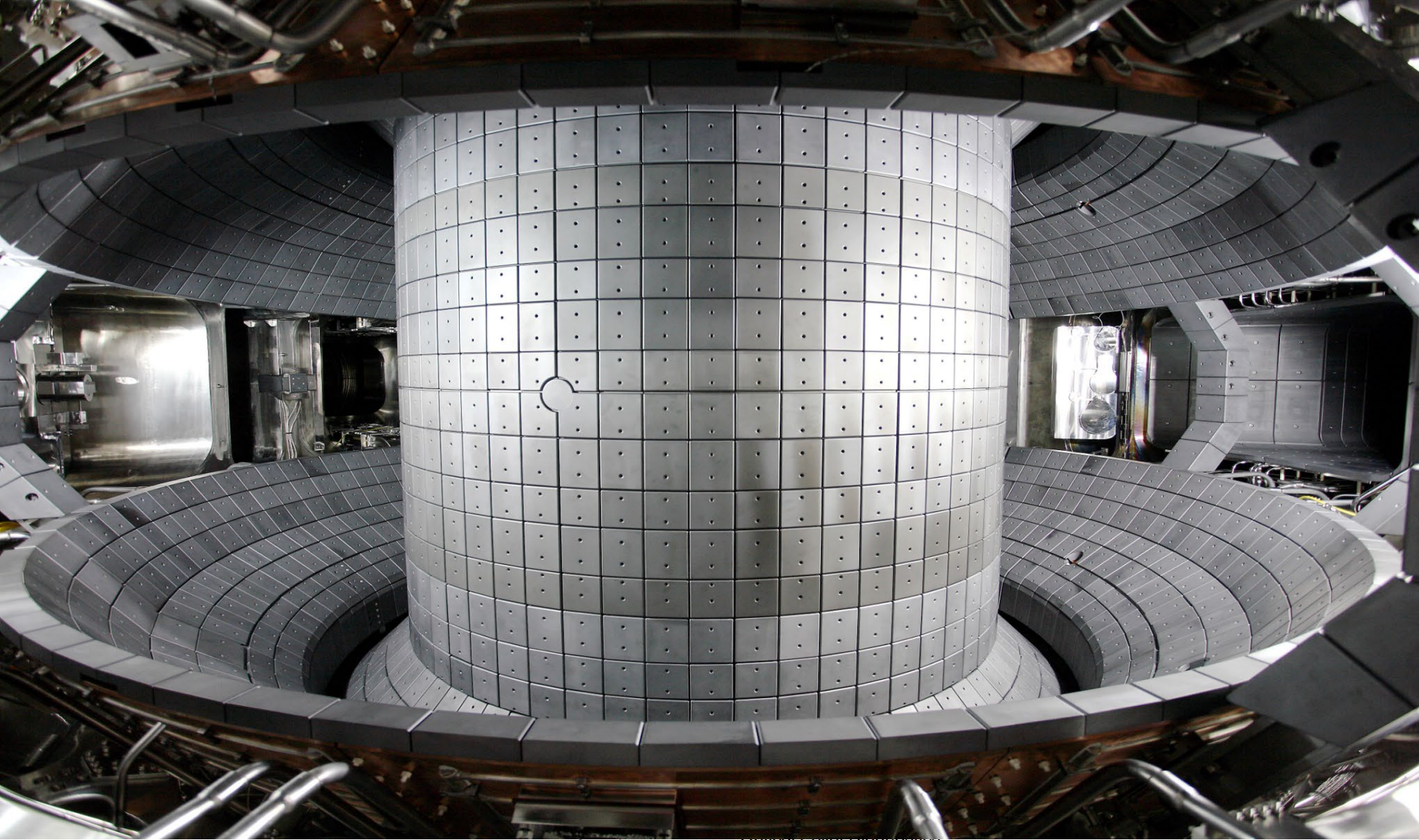


about 2 m in length





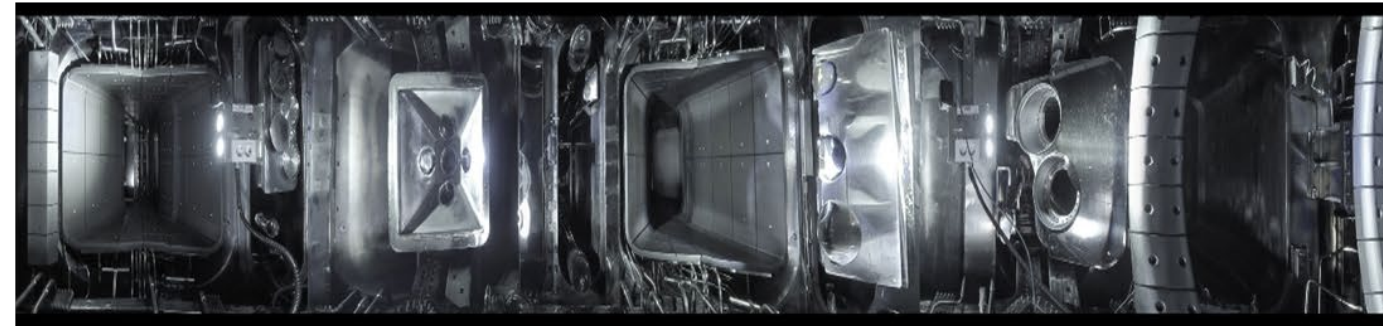
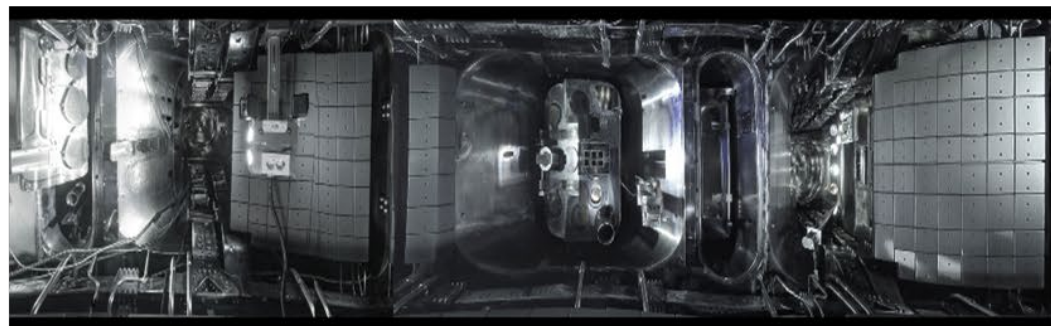
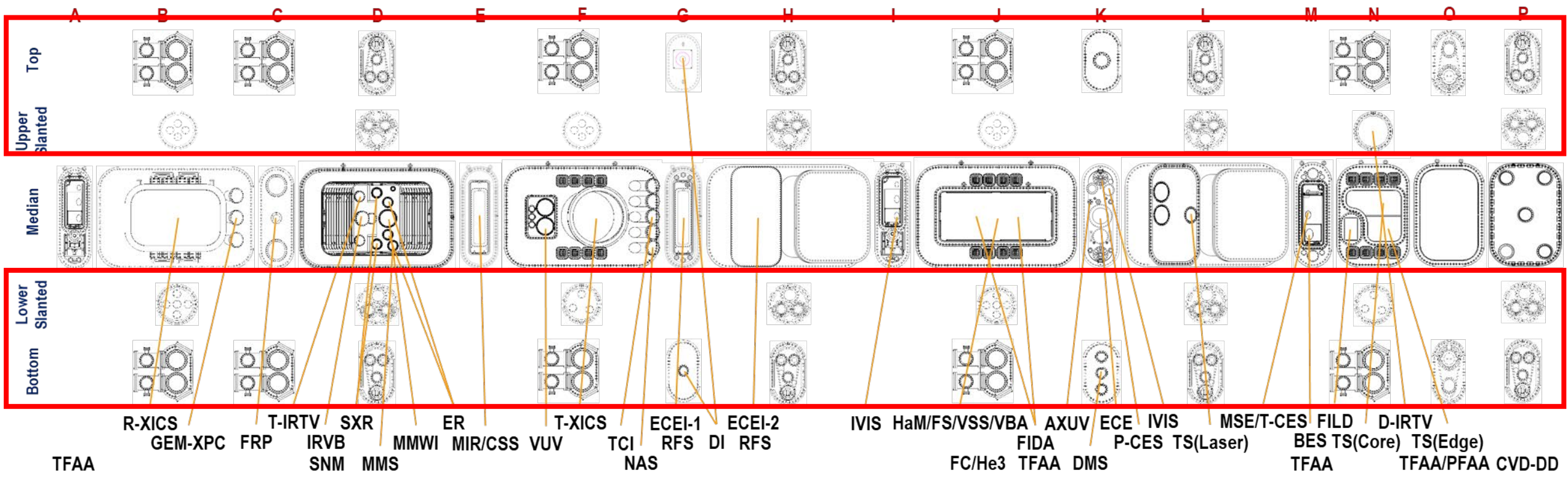
# Passive stabilizer and in-vessel control coils



Optical Fiber Diagnostics



# Trade-offs against top/bottom vertical and slanted ports



**Overall layouts and features**

**Role-based groupings with brief introduction**

**Future plans**

# Roles of KSTAR Diagnostics

## Control Diagnostics

**Provide optimum sensor data to control plasma in real-time**

*magnetics(position & shape), current, density, profile, event(MHD, disruption)  
stable & reliable measurements, fast on-line data processing*

**MD, Interferometer, ECE (+ECEI, MSE, CES, TS)**

## Profile Diagnostics

**Routine operation with sufficient resolution & accuracy**

*$n_e$ ,  $T_e$ ,  $T_i$ ,  $V_t$ ,  $I_p$ , impurities,  $Z_{eff}$ ,  $R_{tot}$ , etc  
INTEGRITY, support kinetic reconstruction*

**TS, Reflectometer, ECE, MSE, CES, XICS, Spectroscopy (+TCI, BES)**

## Fluctuation Diagnostics

**Investigate underlying physics through comprehensive analysis**

*$n_e$  &  $T_e$  / core to edge / turbulence structure & transport  
2D measurements, spatial & temporal coverage, correlation analysis*

**ECEI, MIR, CSS, BES, RF Spectrometer, (+Doppler Reflectometer)**

## Radiation & EP Diagnostics

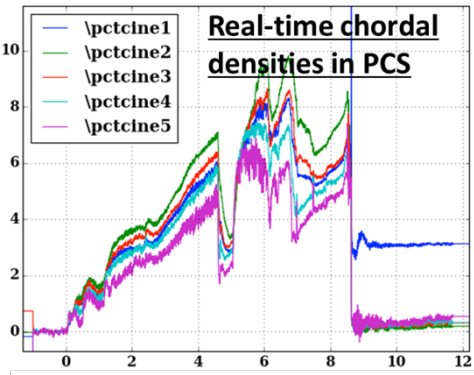
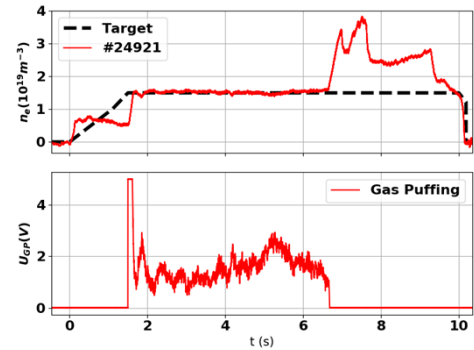
**Research on transient event & specific physics phenomena**

*radiation & SPI IRVB, SXR, AXUV, FVC, OPD  
energetic particle FILD, FIDA, neutron diagnostics  
divertor LP, TS, VS, VUV, IR, neutral diagnostics*



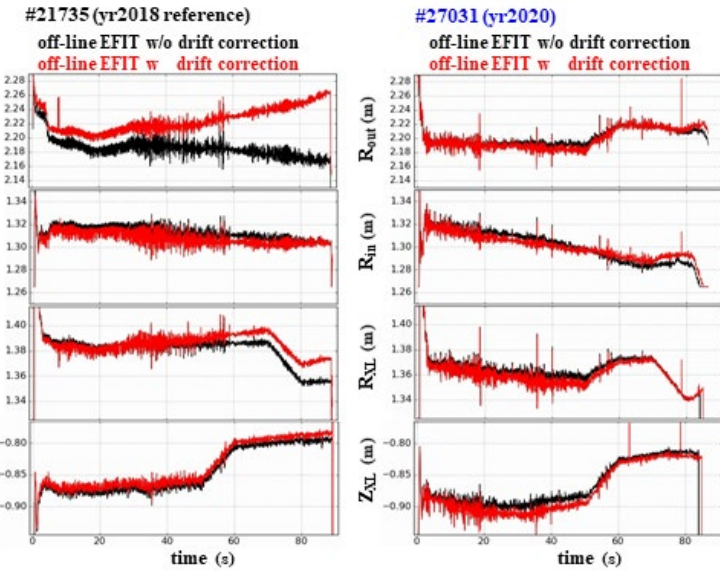
# Control Diagnostics

SISO density control example




Real-time MDs are ready for stable long pulse operation

Tangential TCI provides stable density control in long pulse H-mode

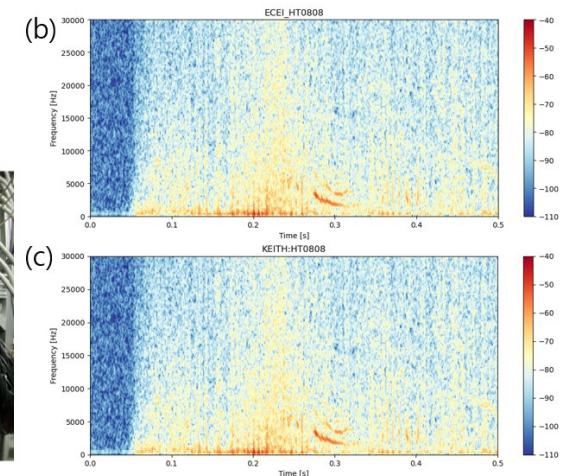
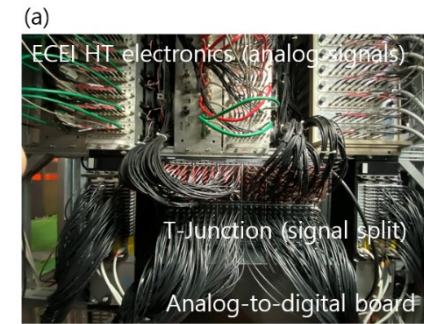


Several profile diagnostics will equip real-time capability

Parameter	Diagnostics	Status
Te profile	ECE Radiometer	real-time signal measured
Current profile	MSE	system will be delivered in 2025 
Ti & V <sub>φ</sub>	CES	real-time & ultrafast system was tested
Te & ne profile	TS	neural network algorithm was tested

Real-time detection of Disruption & MHD event is on-going

Real-time ECEI DAQ (a) and off-line (b) & real-time (c) data



# Profile Diagnostics – List

Parameter	Diagnostics	Channel	Time Res	Status
<b>Electron Density</b>	Thomson Scattering	31	20Hz	<i>routine operation</i>
	Reflectometer		50Hz	<i>reconstructed profile refining</i>
	BES	4(P)X16(R)	2MHz	<i>profile estimation study</i>
	Two-color Interferometer	5	100kHz	<i>require additional channel</i>
<b>Electron Temperature</b>	Thomson Scattering	31	20Hz	<i>routine operation</i>
	ECE Radiometer	76	500kHz	<i>routine operation (calibrated by TS)</i>
<b>Ion Temperature</b>	CES	32	100Hz	<i>routine operation</i>
	XICS		100Hz	<i>require Ar injection</i>
<b>Plasma Current</b>	MSE	25	100Hz	<i>routine operation</i>
<b>H alpha</b>	H alpha monitor	20(H) / 10(P)	20kHz	<i>routine operation</i>
<b>Zeff</b>	Visible Bremsstrahlung	10(H) / 10(P)	20kHz	<i>preliminary result calculated</i>
<b>Fast Ion D alpha</b>	FIDA Spectroscopy	16	100Hz	<i>on-demand operation</i>



**Routine operation of profile diagnostics will supply data for kinetic reconstruction**

# Example of 'routine' Te

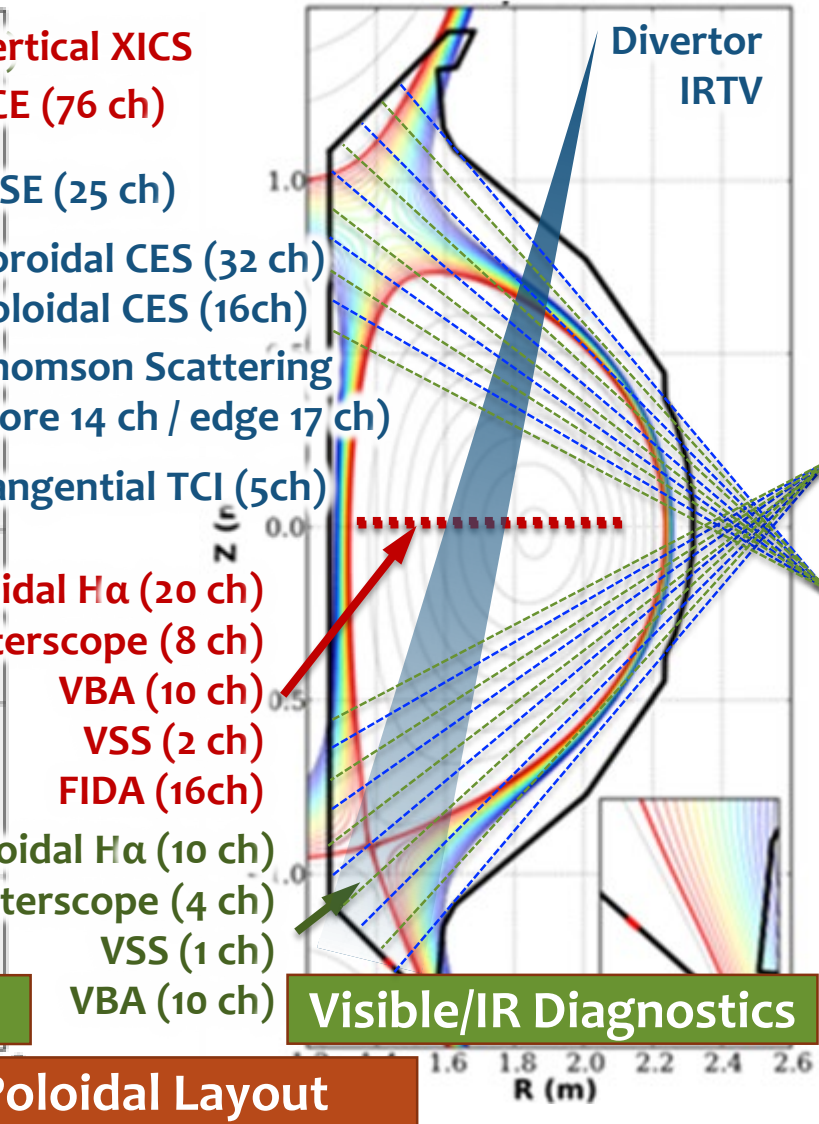
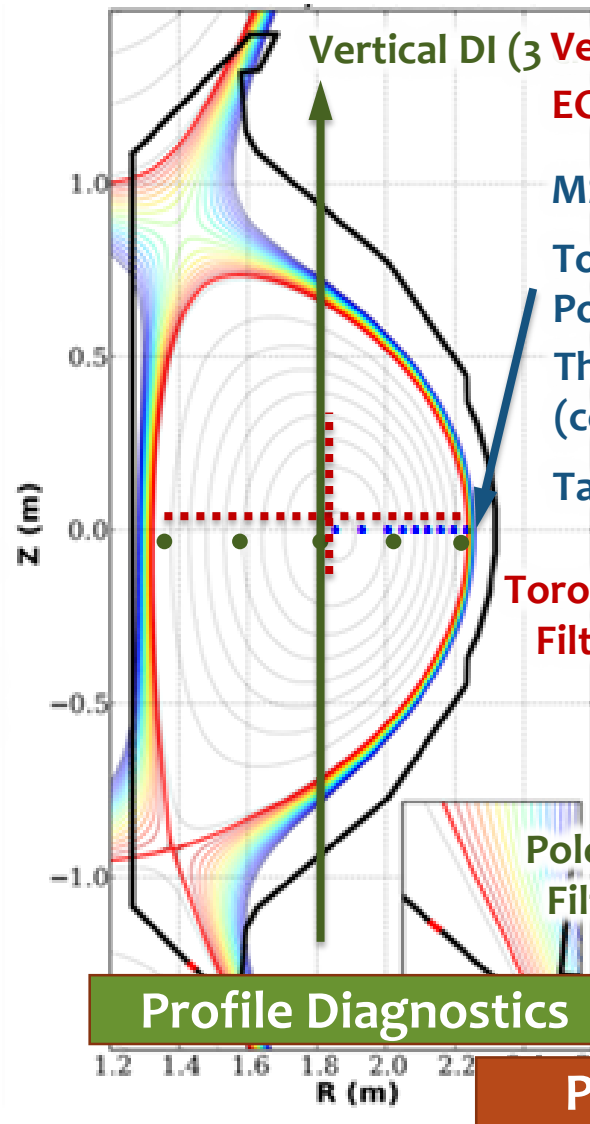
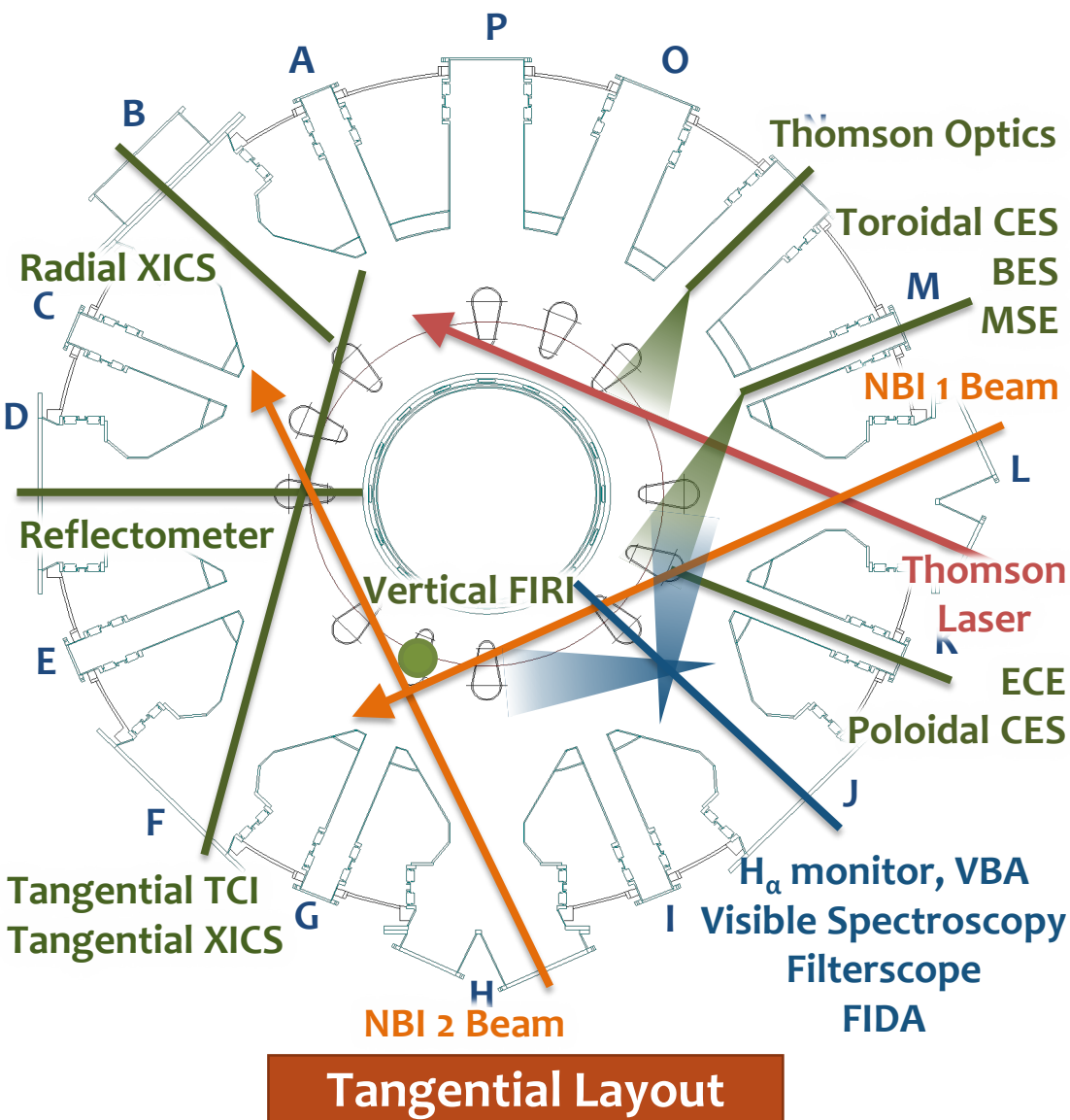
Parameter	Diagnostics
Electron Density	Thomson Scattering Reflectometer BES Two-color Interferometer
Electron Temperature	Thomson Scattering ECE Radiometer
Ion Temperature Ion Velocity	CES XICS
Plasma Current	MSE
H alpha	H alpha monitor
Zeff	Visible Bremsstrahlung
Fast Ion D alpha	FIDA Spectroscopy



Routine operation of profile dia



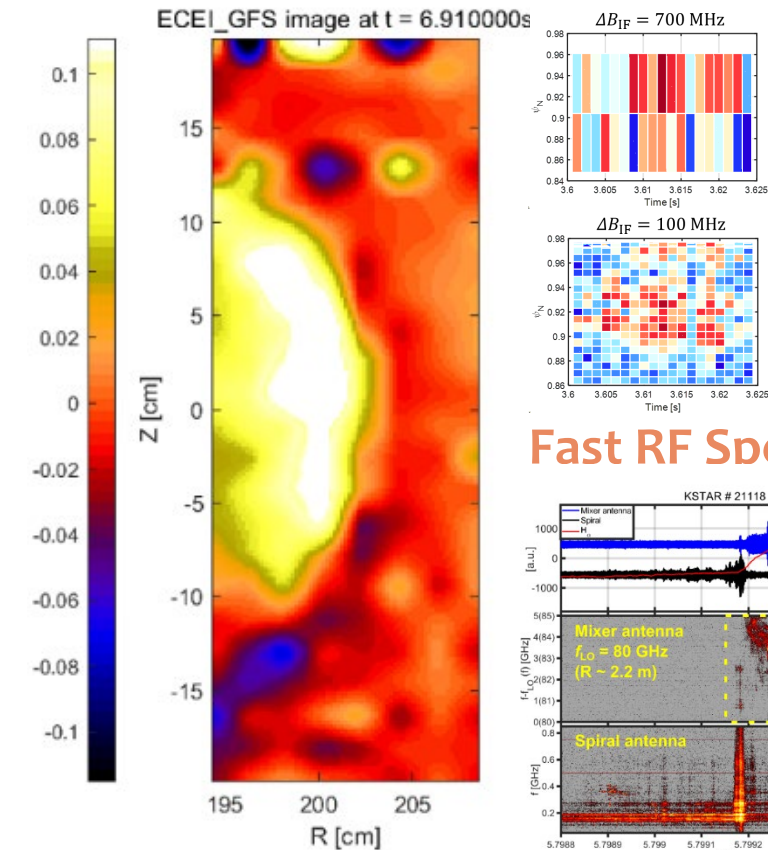
# Profile Diagnostics – Layouts



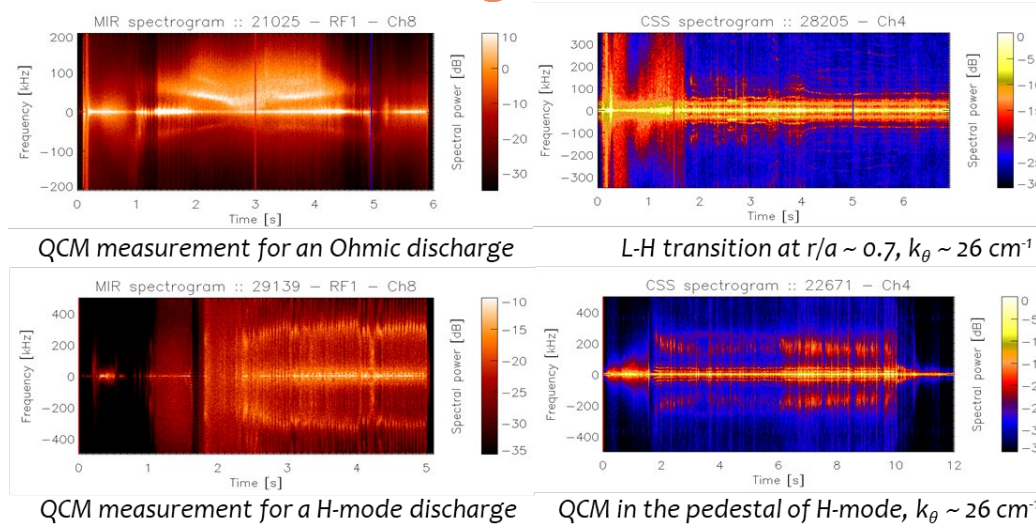


# Fluctuation Diagnostics

**ECEI : Te fluctuation & turbulence structure**  
 Total 3 modules cover wide radial range & 3D analysis  
 Spatial resolution was improved by optical & electrical upgrade



**MIR : small-scale ne turbulence**  
**CSS : high-k ne turbulence**



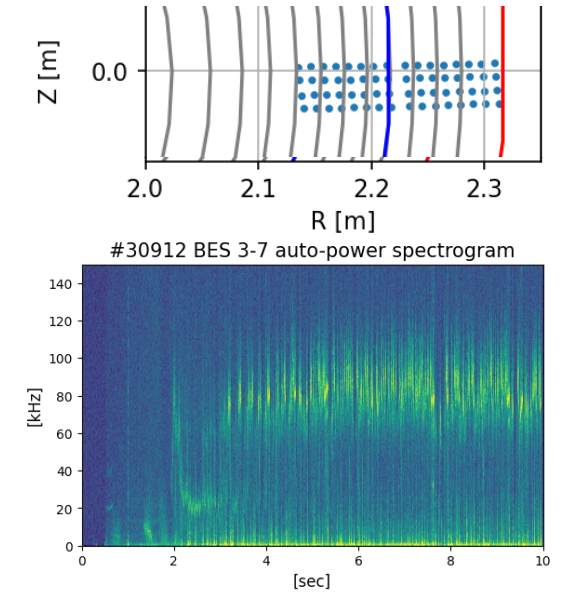
QCM measurement for an Ohmic discharge

L-H transition at  $r/a \sim 0.7$ ,  $k_\theta \sim 26 \text{ cm}^{-1}$

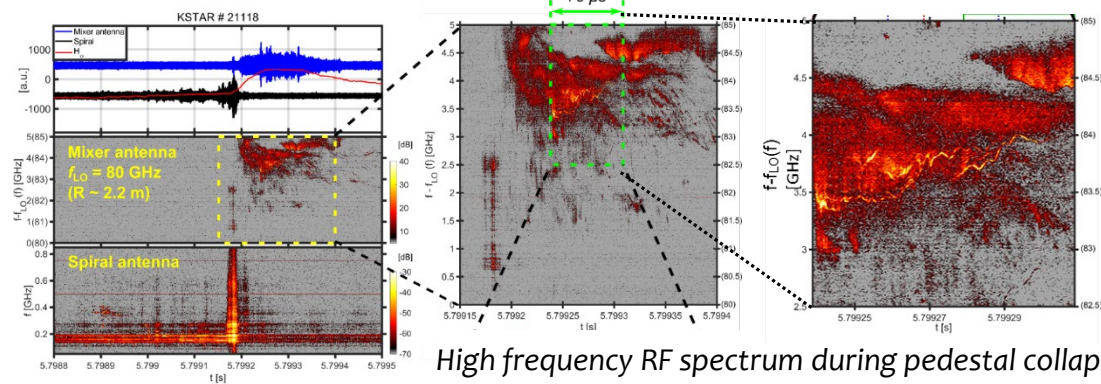
QCM measurement for a H-mode discharge

QCM in the pedestal of H-mode,  $k_\theta \sim 26 \text{ cm}^{-1}$

**BES : 2D ne fluctuation**



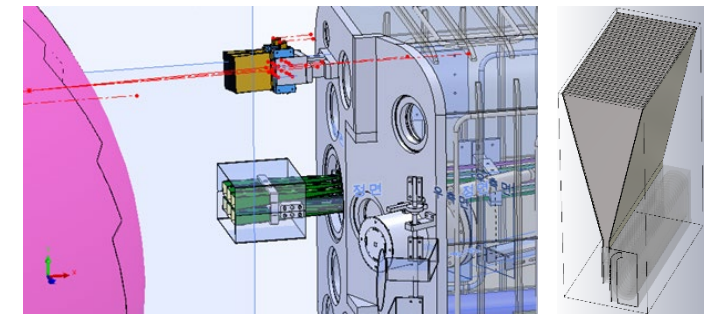
**Fast RF Spectrometer : GHz RF radiation**



High frequency RF spectrum during pedestal collapse

**Doppler Reflectometer (plan)**

New phase array antenna is manufacturing



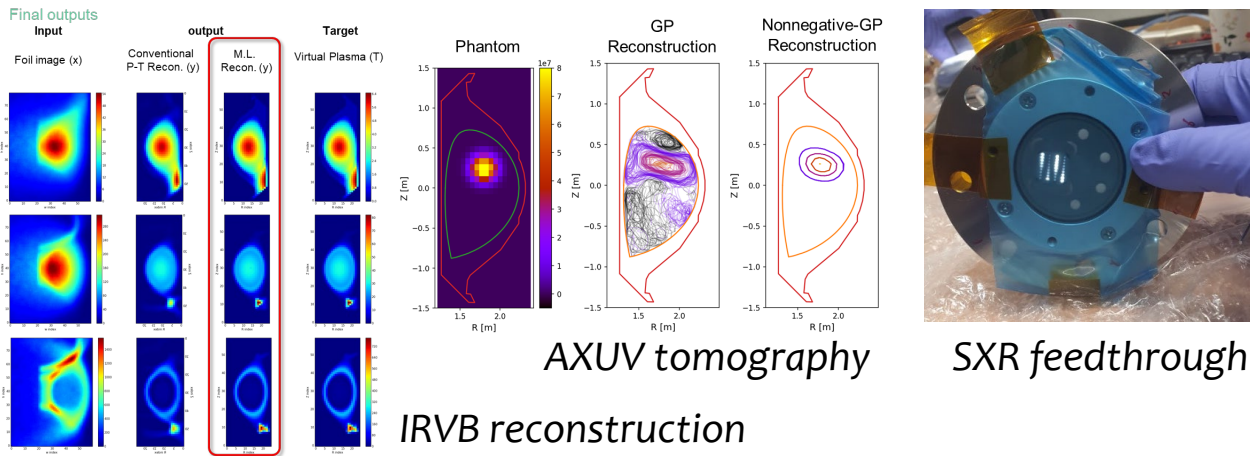
# Radiation Diagnostics: Fast & Imaging, Absolute Prad

## Radiation Diagnostics : IRVB, AXUV, SXR

IRVB reconstructs radiation image by ML based algorithm

AXUV with filters provides tomographic image on 3 energy ranges

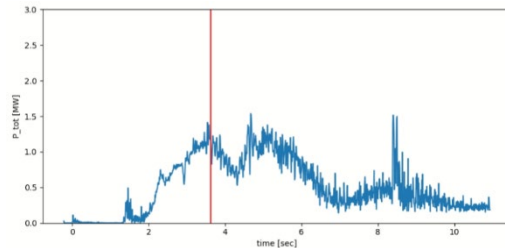
Scintillator-based SXR installed with fiber optic feedthrough



## Total radiation power calculation

$P_{tot}$  is calculated from the ring volume integration of every pixel of the 2D profile on IRVB

Plan for resistive-type bolometer is under consideration



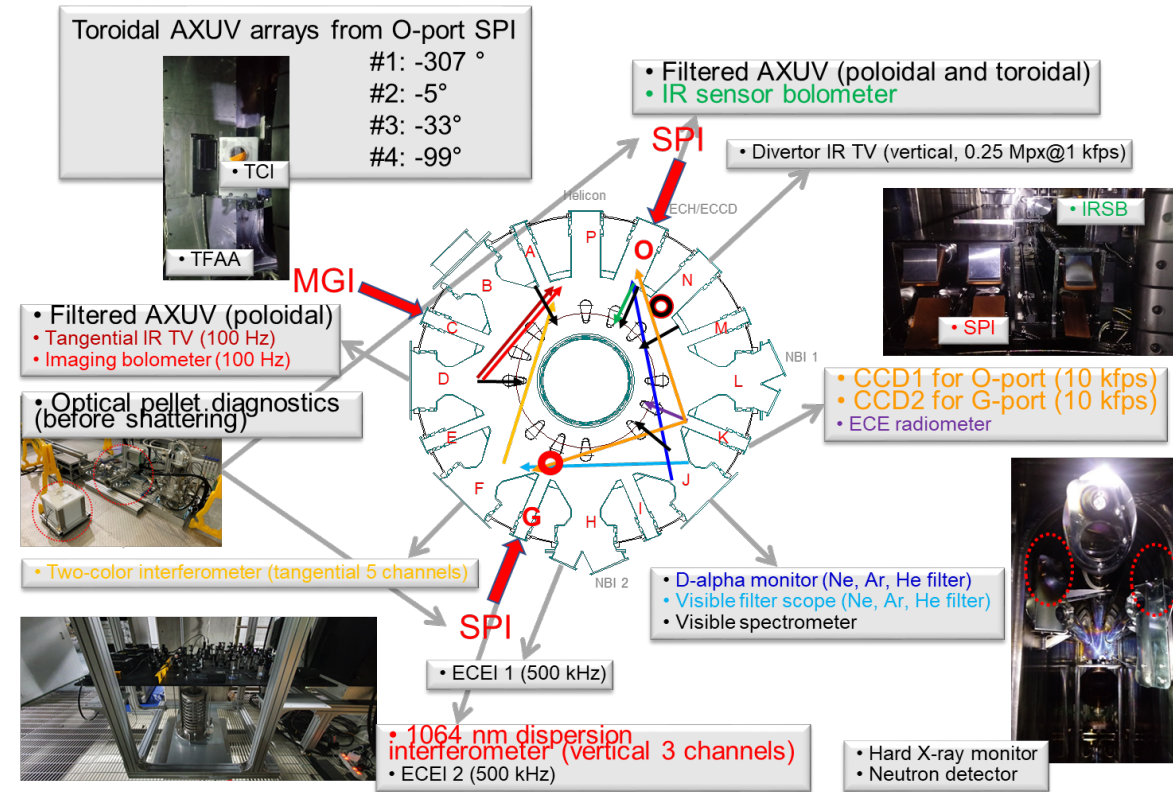
calculated total radiation power

## Diagnostics for Shattered Pellet Injection

Dispersion Intef., AXUV, Fast Camera, Optical Pellet Diag.

Fast diagnostics for transient event (disruption)

Radiation asymmetry meas. with toroidal coverage



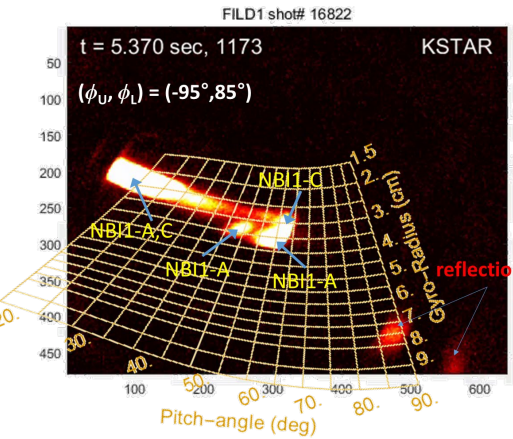


# EP Diagnostics

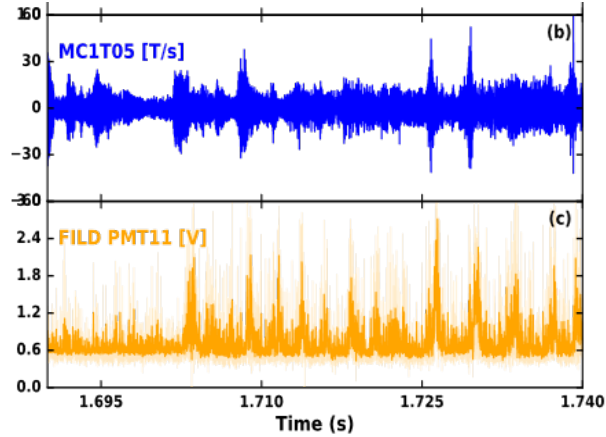
## Fast Ion Loss Detector

FILD CCD camera (200 fps): *Phase-space* of lost fast-ions

FILD PMT (2 MS/s): *Fast measurement* of transient fast-ion loss



CCD

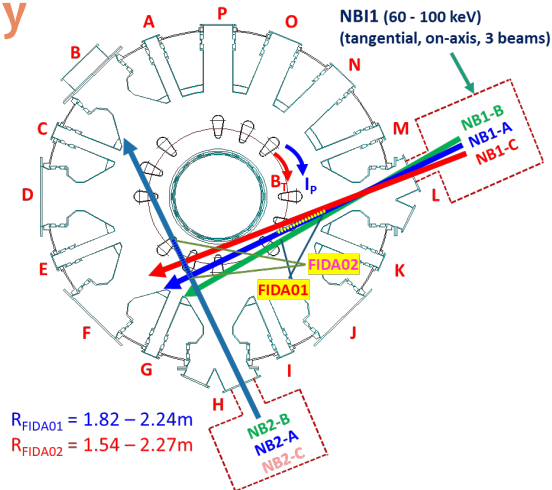
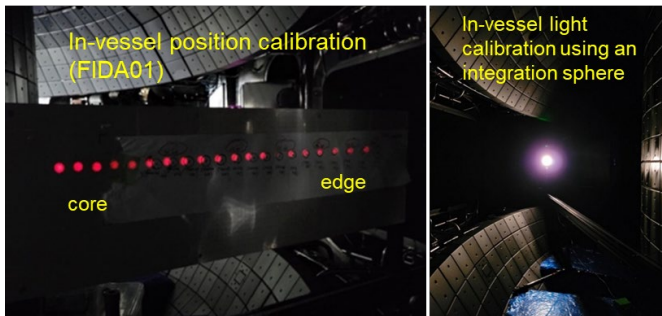


PMT

## FIDA (Fast Ion D $\alpha$ ) Spectroscopy

FIDA01 (blue-shifted 16ch)

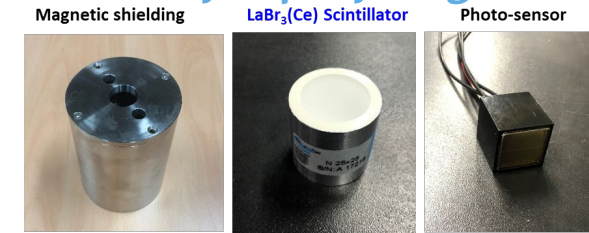
FIDA02 (red-shifted 10ch)



## Fission-chamber / He3 counter



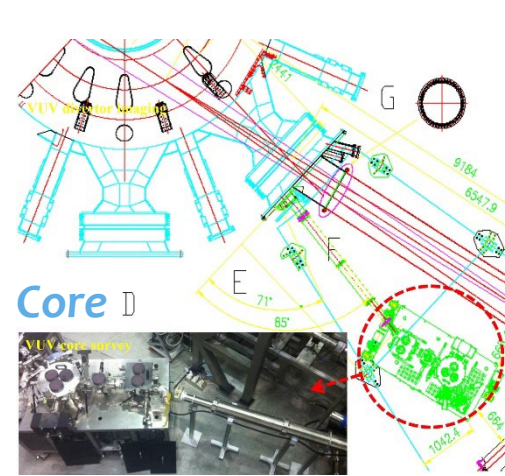
## Hard x-ray & $\gamma$ -ray diagnostics



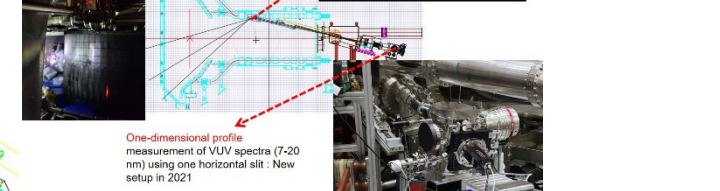
## Scintillator-based detector



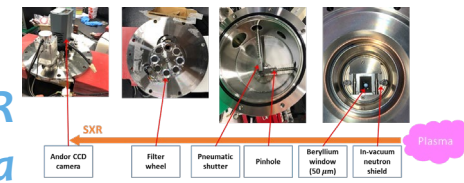
## Scintillating fiber (Sci-Fi) detector



## Divertor



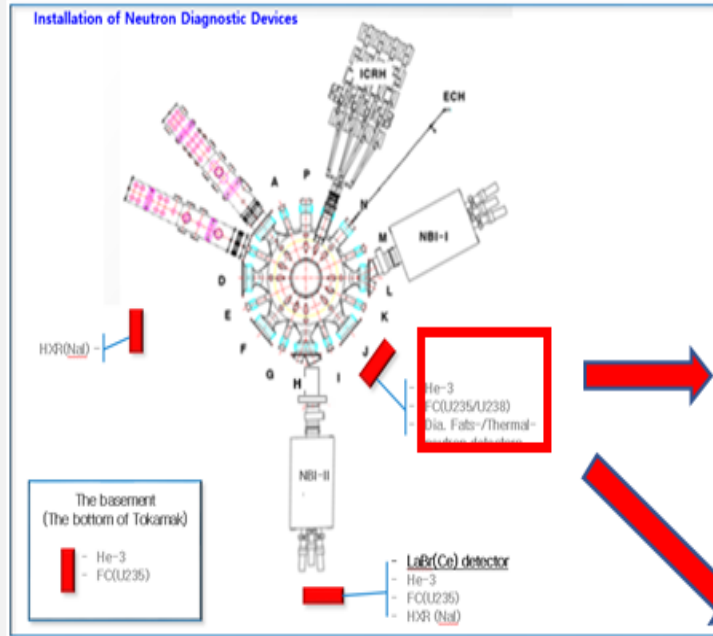
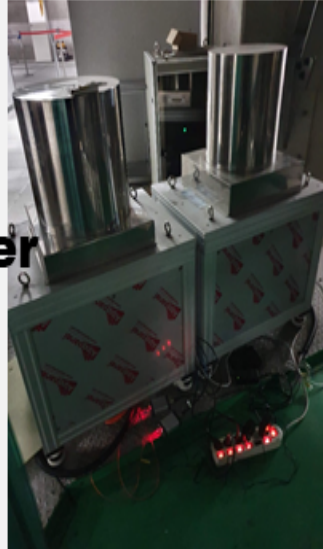
## VUV/SXR camera





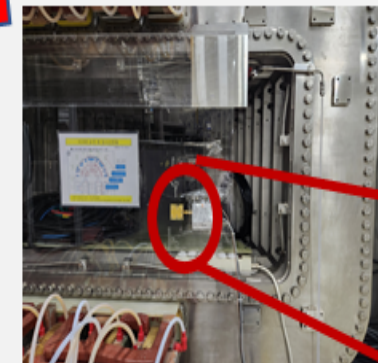
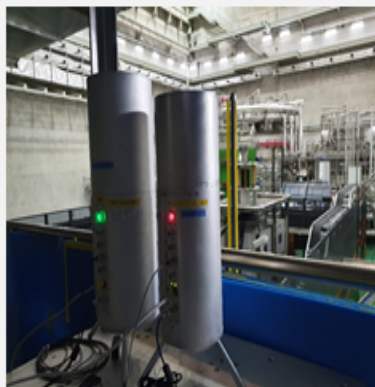
# Neutrons Diagnostics - Layouts

**He-3 Counter  
Fission Chamber**

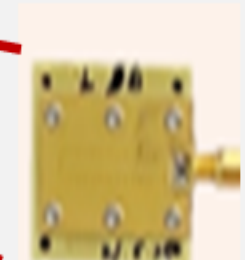


**He-3 Counter  
Fission Chamber**

**He-3 Counter  
Fission Chamber**



**Diamond-based  
fast neutron  
detector**



**Neutron Diagnostic Devices Installed in the KSTAR tokamak**

**Overall layouts and features**

**Role-based groupings with brief introduction**

**Future plans**

# Future Plans - General

## Control Diagnostics

Expanding real-time capability for various control  
Research on robust sensor sets for burning plasma condition

## Profile Diagnostics

Provide qualified data sets for reconstruction & simulation  
Integrated data analysis aided by synthetic diagnostics – V-KSTAR  
Remote & automatic calibrations

## Fluctuation Diagnostics

Expanding turbulence measurements coverage  
2D/3D multi-field fluctuation diagnostics developments

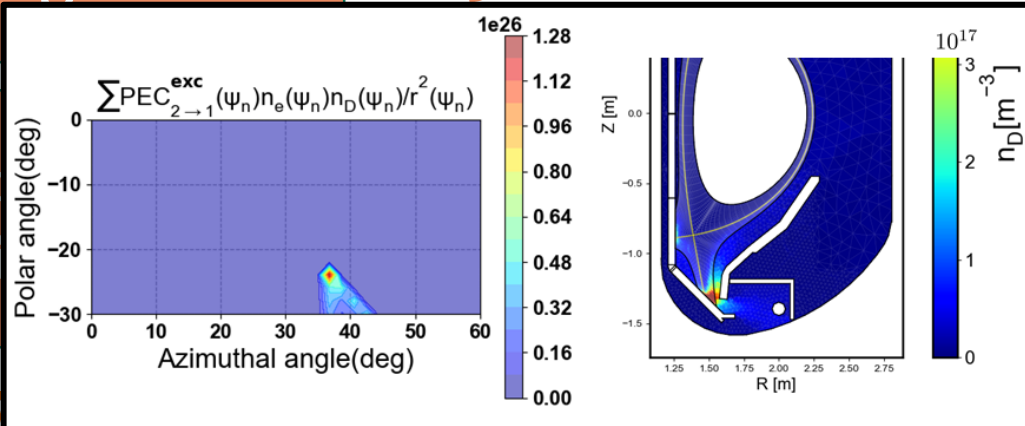
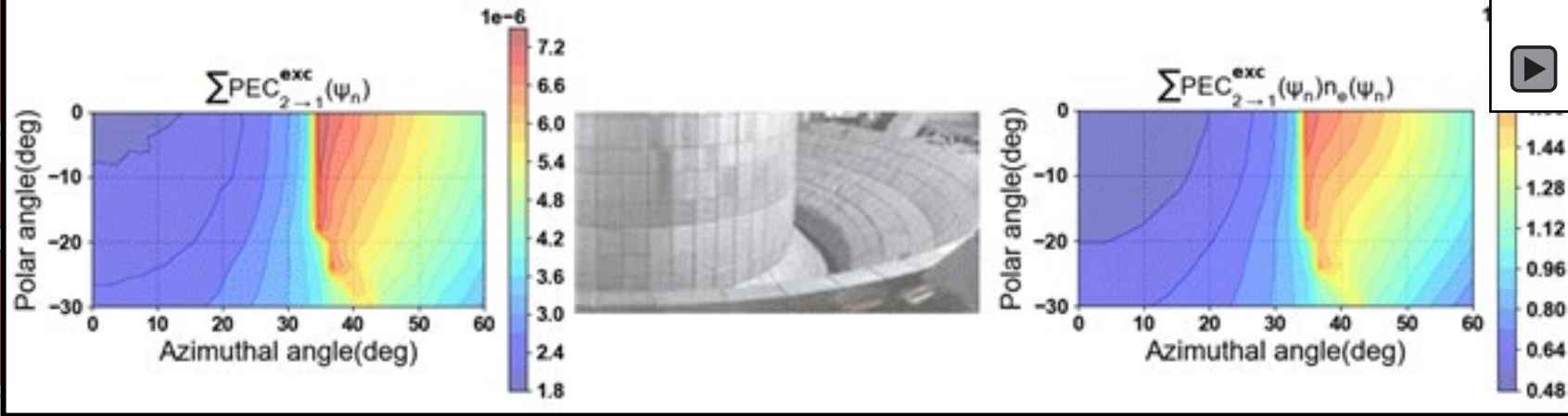
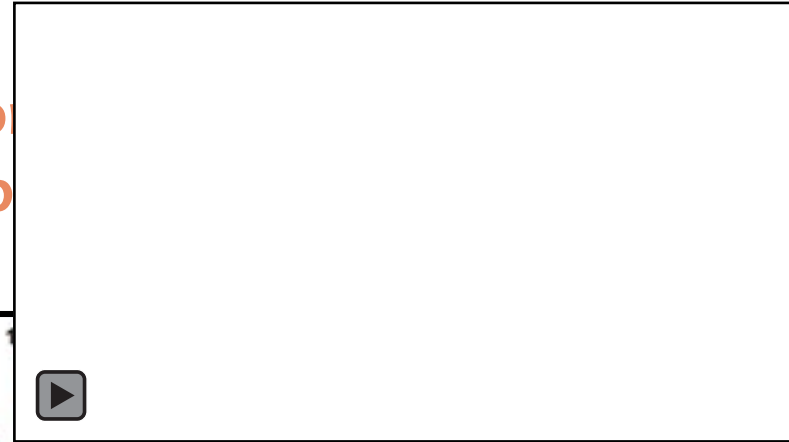
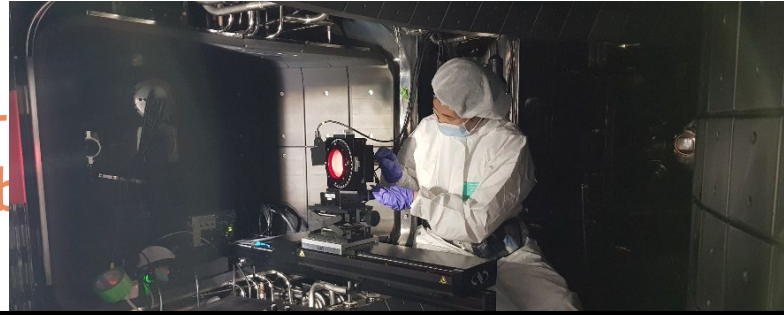
## Radiation & EP Diagnostics

Advanced diagnostics for energetic particles study  
Combined analysis on edge-SOL-divertor region  
Diagnostics for new W divertor conditions - Divertor LP, IR TV, Neutral

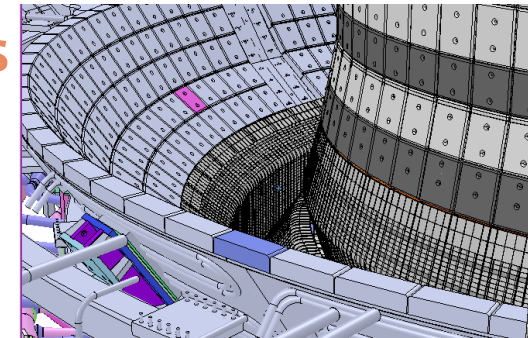
# Future Plans - General

Control  
Diagnostics

Expanding real-  
Research on rob



for energetic particles study  
edge-SOL-divertor region  
divertor conditions - Divertor LP, IR TV, Neutral



# Future Plans – ITER-specific

## Synthetic diagnostics and data integration

- Development of synthetic diagnostics for virtual KSTAR and ITER Integrated Modeling Analysis Suite (IMAS) and Cherab
- Data integration with high reliability compatible with Integrated Data Analysis (IDA)

## Spectroscopy with W-PFC environment & boronization\*

- Passive spectroscopy – Identification of which lines best for W influx/erosion
- Charge exchange spectroscopy (CES/CXRS) with W & B
  - Nuisance W lines in CES/CXRS measurements (ITPA Joint Experiment)
  - Usefulness of BV lines for CES/CXRS
- KSTAR test-bed for ITER spectral motional Stark effect diagnostic

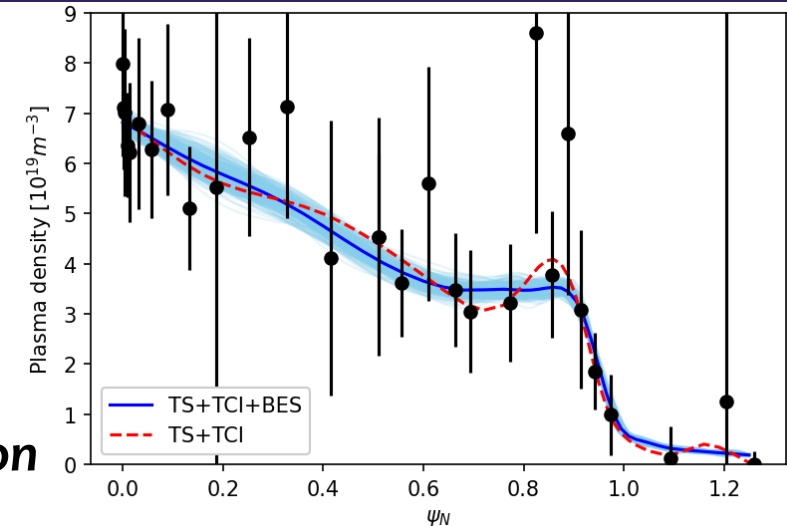
## First mirror\*

- Limited test of the single crystal mirror without active cleaning under boronization

## Neutrals diagnostics (KSTAR exclusive)

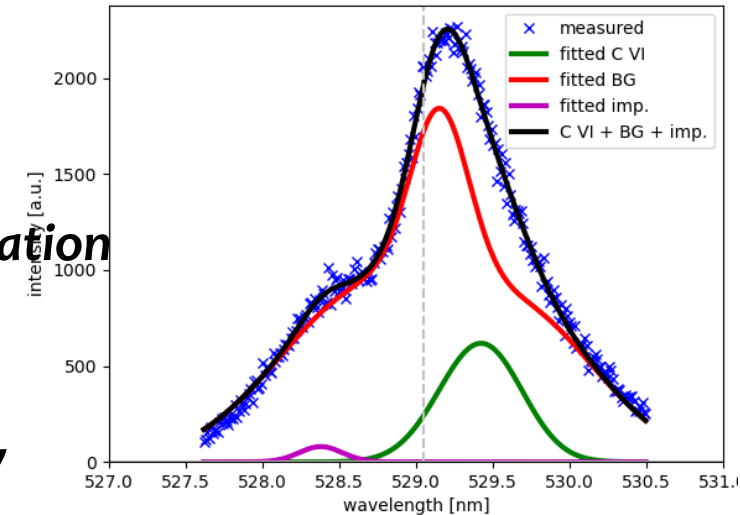
- Validation of unique model for H-mode mechanism
- Two-photon Absorption Laser Induced Fluorescence (TALIF), Lyman- $\alpha$  spectroscopy

\*Highest-priority items in ITER new baseline R&D needs



[ne reconstruction by Bayesian data integration]

#34142 at t=3.802s, R=1.794m



[Multi-Gaussian fit for CES data with W divertor]



# Collaborators

## DIAGNOSTICS

Millimeter-Wave Interferometer (+THz)  
 Infrared Interferometer (+TCI)  
 Dispersion Interferometer  
 Thomson Scattering  
 Electron Cyclotron Emission  
 Charge Exchange Spectroscopy  
 Ultrafast CES  
 X-ray Imaging Crystal Spectroscopy  
 Motional Stark Effect  
 Coherence Imaging  
 Electron Cyclotron Emission Imaging  
 Microwave Imaging Reflectometer  
 Collective Scattering System  
 Beam Emission Spectroscopy  
 Doppler Reflectometer  
 Radio-Frequency Spectrometer

## COLLABORATORS

SNU, UC Davis  
 SNU, KAIST  
 KAIST, ITER, GA  
 NIFS, QST  
 KAERI, Kyushu-U, NIFS  
 NIFS  
 SNU  
 PPPL, ASIPP  
 MIT, CFS, Columbia-U  
 Nova Photonics  
 ANU  
 POSTECH, UNIST, KNU  
 UNIST, KNU  
 UNIST, KNU  
 WIGNER RCP  
 NIFS  
 POSTECH

## DIAGNOSTICS

Filter Scope  
 VUV / EUV Spectroscopy  
 Soft X-Ray Array  
 GEM Camera  
 Soft X-ray Camera  
 VUV Camera  
 IR Imaging Video Bolometer  
 Resistive Bolometer  
 Filtered AXUV  
 Fast Camera / Optical Pellet Diagnostics  
 Fast Ion Loss Detector  
 Fission Chamber  
 Diamond Neutron Detector  
 Neutron Activation System  
 Scintillating Detector  
 Neutral Diag. (ASDEX / Penning gauge)  
 Neutral Diag. (ERD, Liman- $\alpha$ , TALIF)  
 Multi-channel Probe  
 Real-Time Diagnostics for DECAF  
 SMBI

## COLLABORATORS

ORNL  
 ITER Korea, KAIST, Ajou-U  
 KAIST  
 KAIST  
 NIFS  
 NIFS  
 NIFS, KAIST  
 NIFS, POSTECH  
 ITER  
 ITER  
 NIFS  
 TRINITY  
 JINR  
 ITER Korea  
 NIFS, Toyama-U  
 KAIST, SNU  
 PPPL, UNIST, SNU  
 HYU  
 Columbia-U, PPPL  
 SWIP



Thank you

Thank you



# Back-ups

# Control Diagnostics : Magnetics & Density

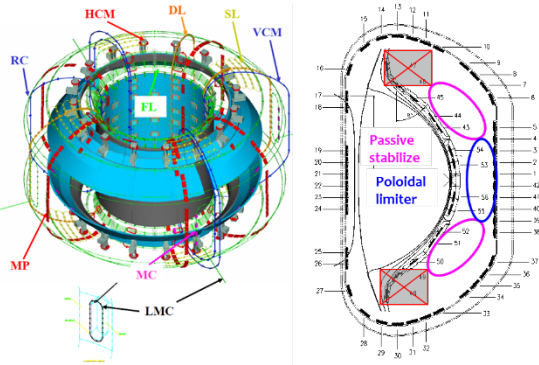
## Real-time MDs are ready for stable long pulse operation

Stable **plasma position & shape control** with real-time MP arrays

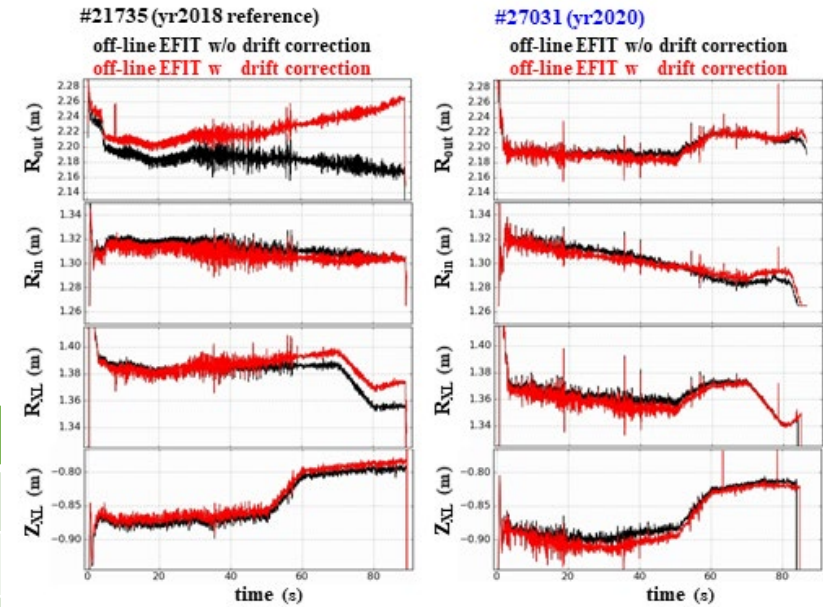
**Drift in MP** is minimized through **temperature effect** control

**Additional integrator** will be set up for stable long pulse operation

Real-time **3D & MHD** control are planned



Category	Status	Ch
Axisymmetric MD	RC, VCM, FL, MP, DL, LV, IVC	166
3D MD	MPZ, locked mode, Mirnov	28
MHD	Mirnov coil (plan)	14



MP drift effect on the shape control

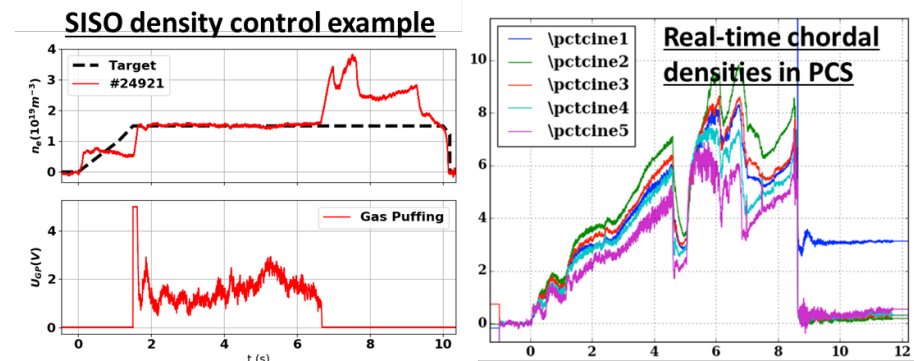
## Tangential TCI provides stable density control in long pulse H-mode

FPGA based real-time **two-color interferometer** (CO<sub>2</sub> / DPSS laser)

All **5 tangential line** densities are transferred to the PCS

**Profile control** with **actuators** (Pellet, SMBI and GPs) are planned

Discussion on **2nd TCI** for the **profile reconstruction** is on-going.



# Control Diagnostics : Profile & Event

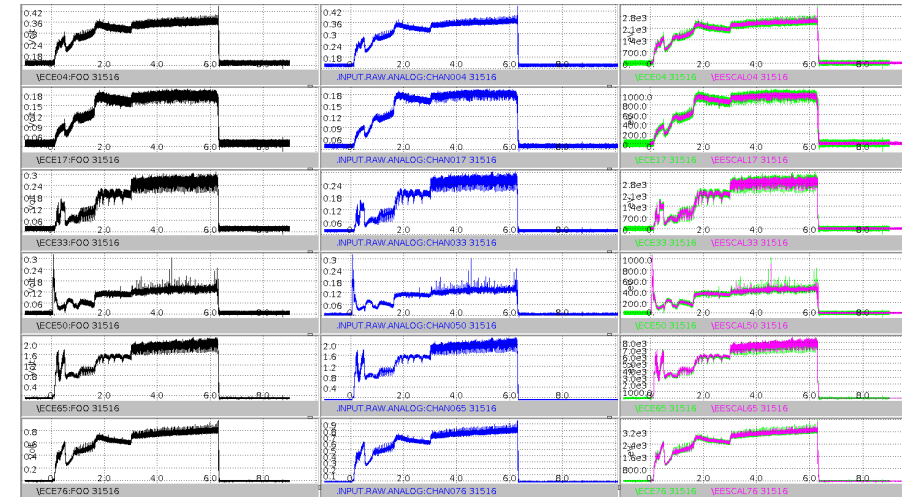
Several profile diagnostics will equip real-time capability

*RT DAQ & fast processing algorithm* are under development

Profile control can be tested with *actuator (off-axis heating, etc)*

*RT monitoring & event detection* are possible with RT diagnostics

Parameter	Diagnostics	Status
Te profile	ECE Radiometer	real-time signal measured
Current profile	MSE	system will be delivered in 2023
Ti & $V_{\phi}$	CES	real-time & ultrafast system was tested
Te & ne profile	TS	neural network algorithm was tested



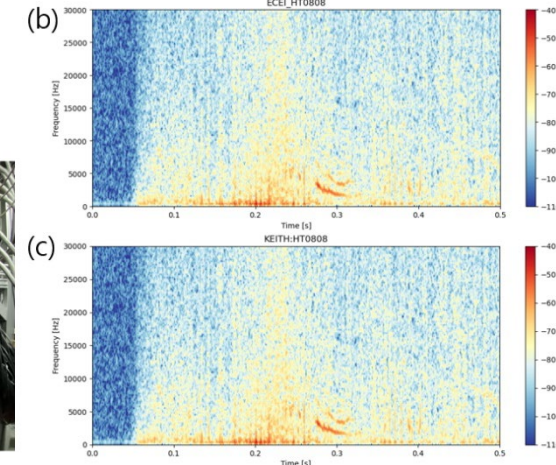
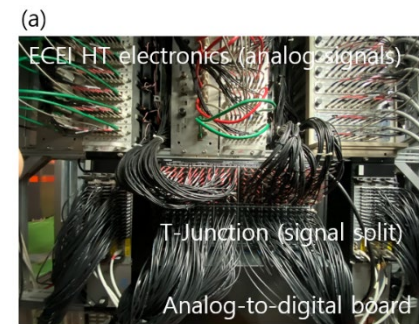
Comparison between Off-line & Real-time ECE Data

Real-time detection of Disruption & MHD event is on-going

*Disruption prediction* system based on real-time MD, ECE, ECEI

*NTM control* through mode amplitude monitoring

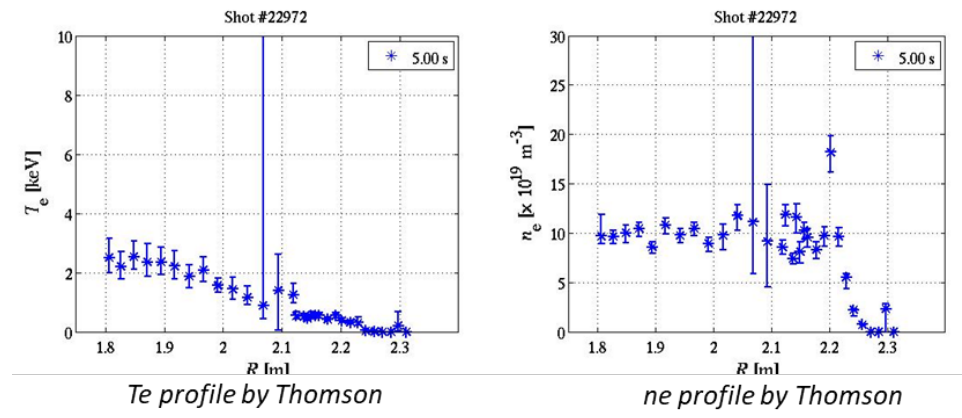
Real-time ECEI DAQ (a) and off-line (b) & real-time (c) data



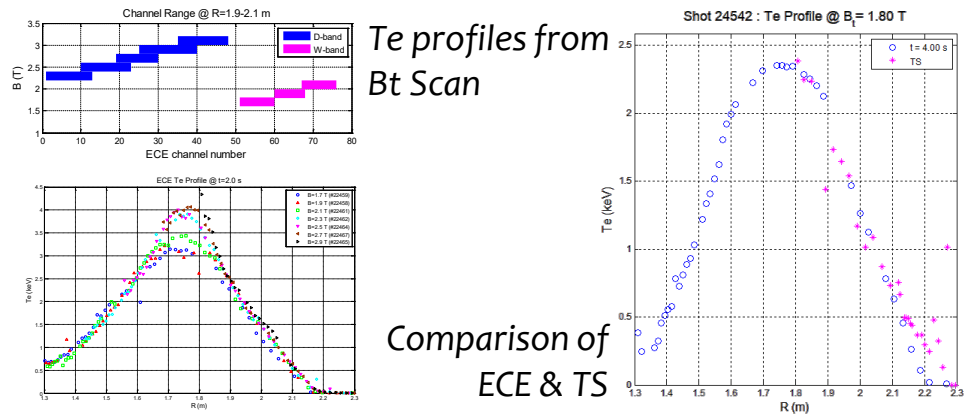
# TS profile data supported by other diagnostics

Electron Temperature

**TS : stray light compensation**  
 precise pulse fitting from **5GS/s digitizing** system  
 can minimize the effect of **stray light**

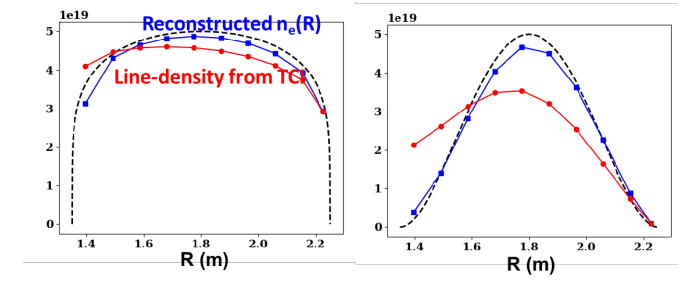
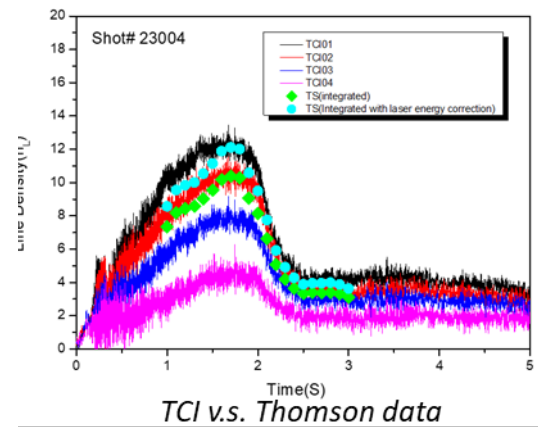


**ECE : calibration with Bt scan & TS data**  
 ECE provide fast (500kHz) Te profile data

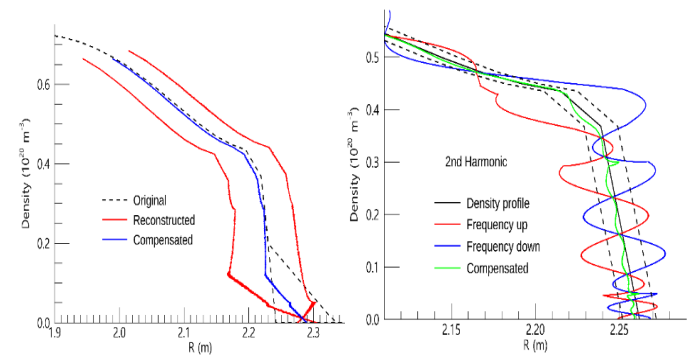


## Electron Density

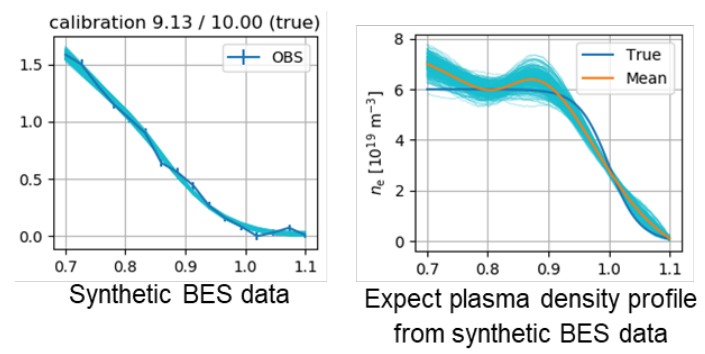
**TCI : line ne comparison**  
 profile inversion from multi-channel TCI  
 is considering with **2nd TCI (+5 ch)**



**Reflectometer : edge profile fluctuation induced distortion**  
 can be compensated by new **sweeping condition**



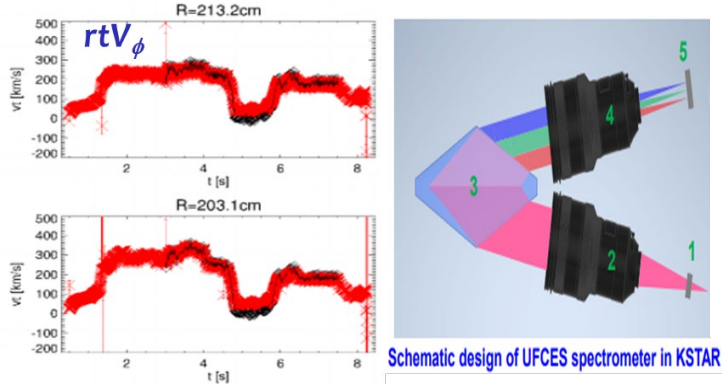
**BES : profile estimation density profile**  
 can estimated from BES intensity using **synthetic analysis**



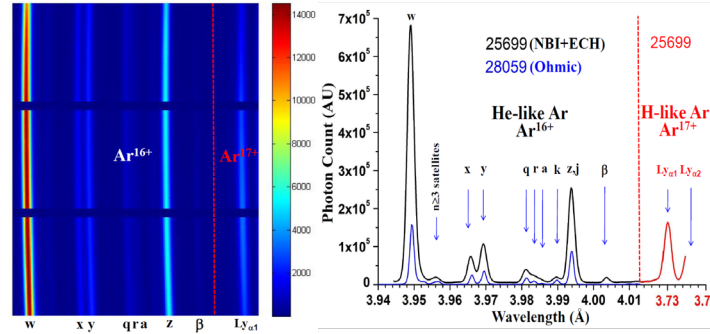


# Fast ion & Zeff added to profile diagnostics

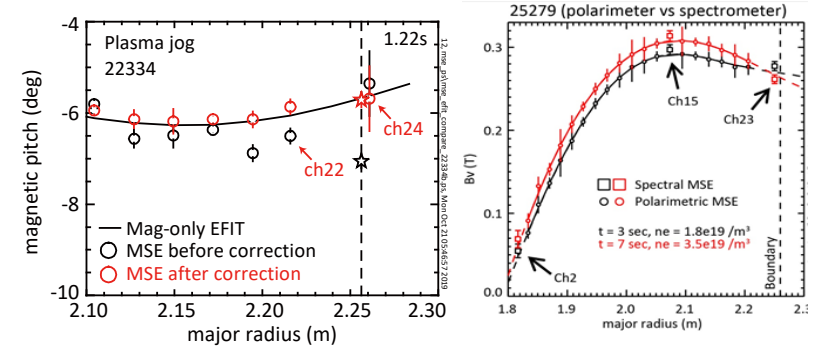
**CES** : real-time & ultrafast system  
installation & test is on-going



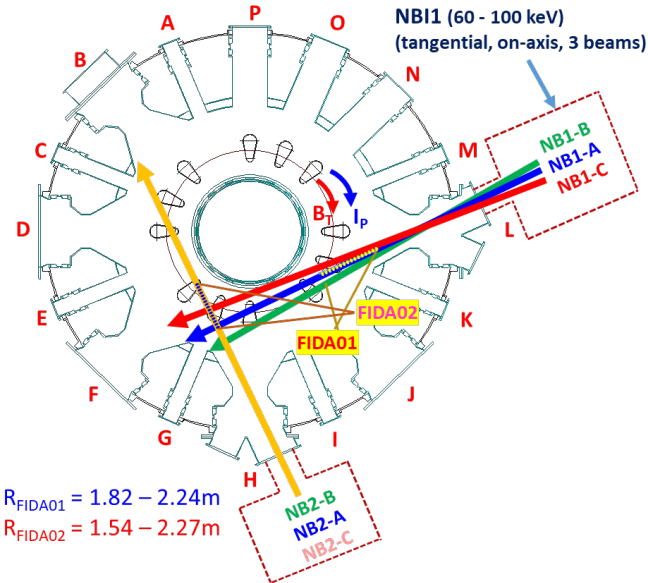
**XICS** : dual crystal assembly  
*additional crystal* expands  
*spectral coverage*



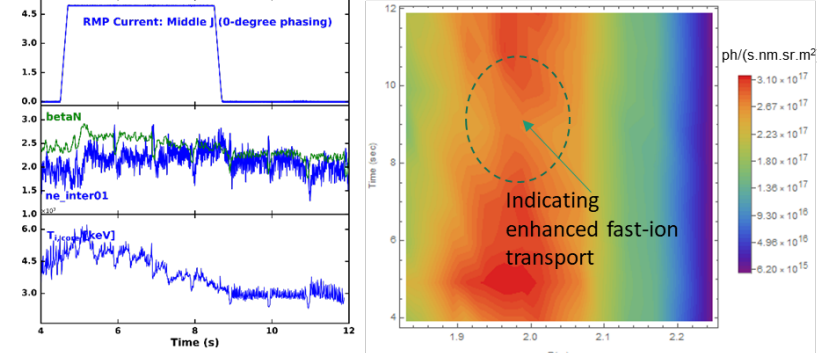
**MSE** : optimized calibration & spectral  
*calibration scheme* is more optimized  
*spectral MSE* extended to *main-ion CX*



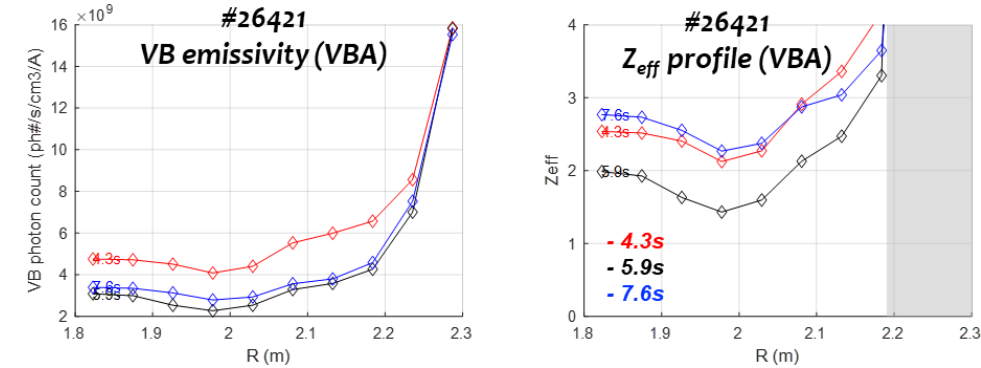
**FIDA** : fast ion distribution  
new diagnostics for *energetic particle study*



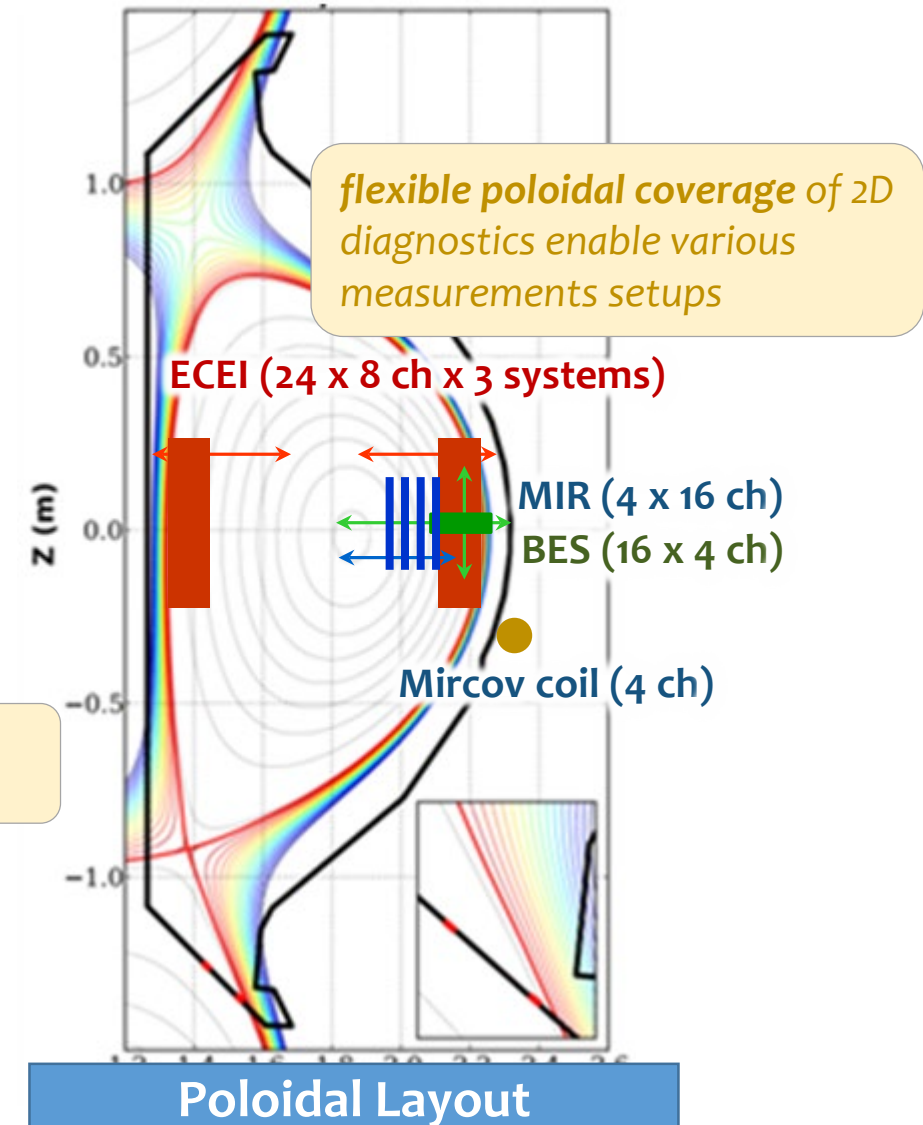
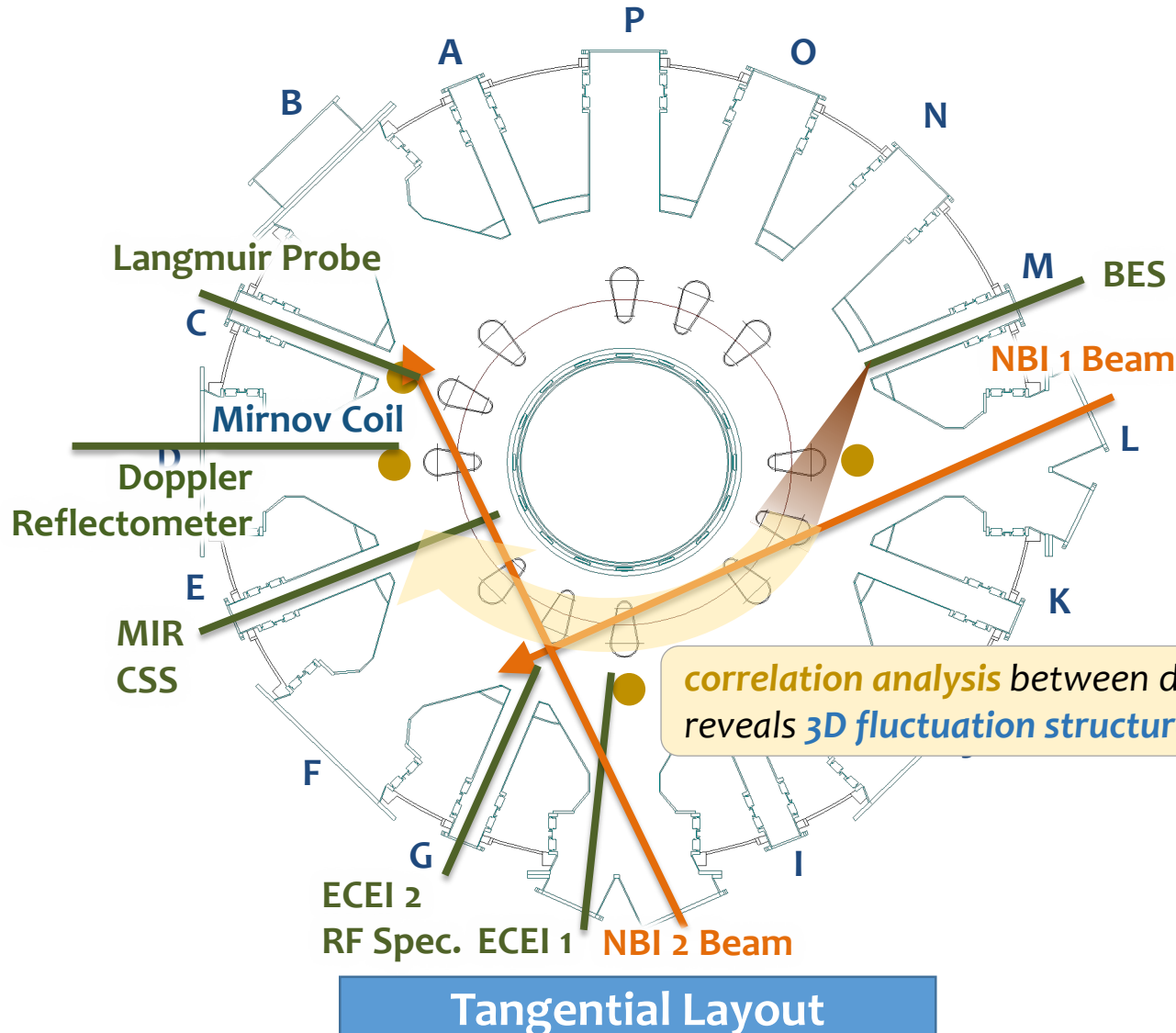
e.g. Single energy FIDA intensity profiles



**Zeff** : visible Bremsstrahlung Array  
*preliminary results* was calculated from VBA



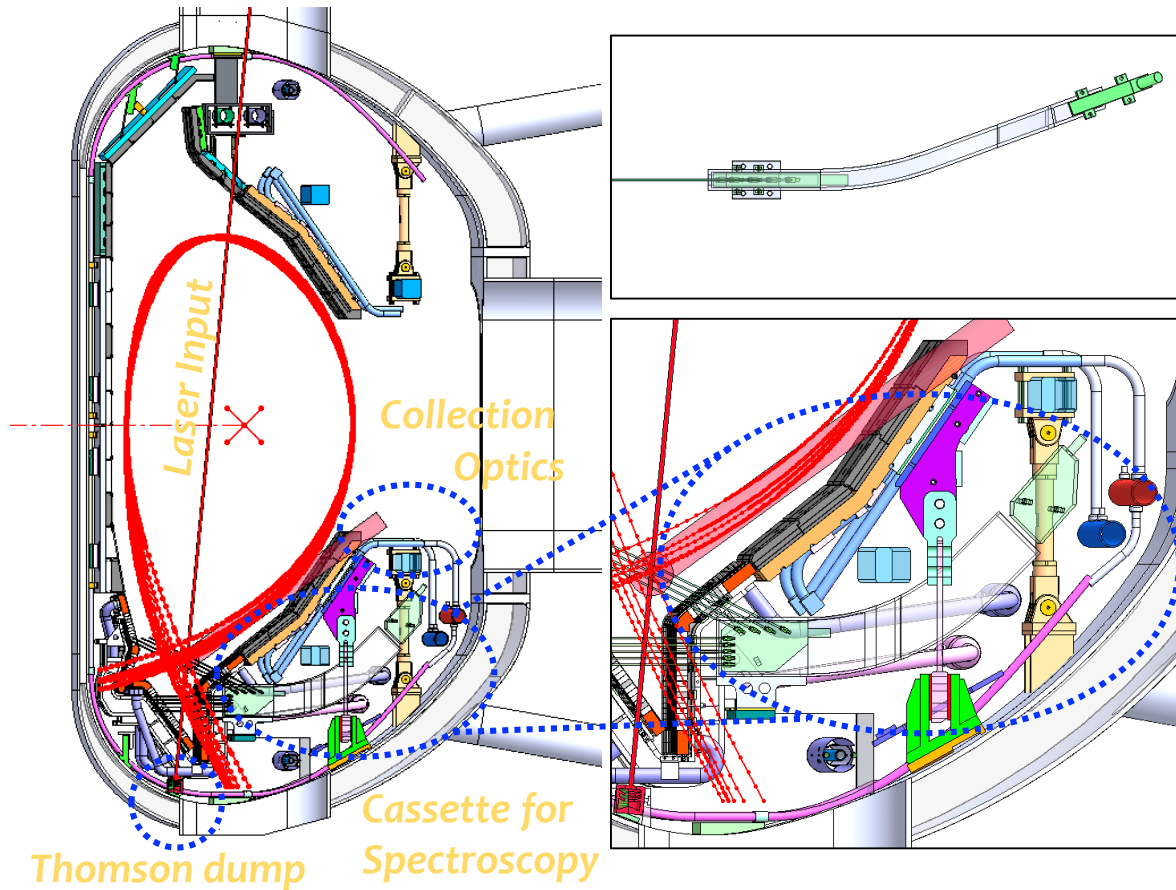
# 2D fluctuation diagnostics cover wide toroidal & poloidal range



# Diagnosics for New W Divertor will be developed stage by stage

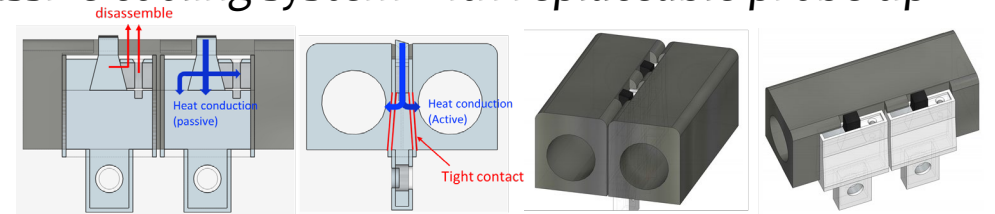
## Divertor TS / Spectroscopy

Securing **diagnostics space** in limited geometry  
**Indispensable parts** will be installed with W divertor



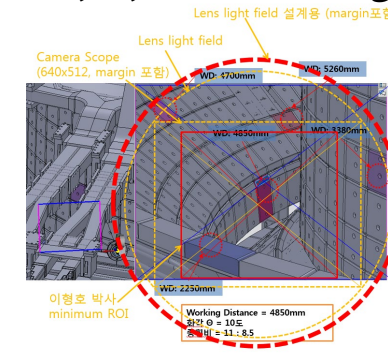
## Divertor Langmuir Probe

Active/Passive cooling system with replaceable probe tip



## Divertor IR TV

Two tangential IR TV covers  
 half of in-vessel region



## Neutral Diagnostics

ASDEX-gauge with LaB6  
 High field penning gauge



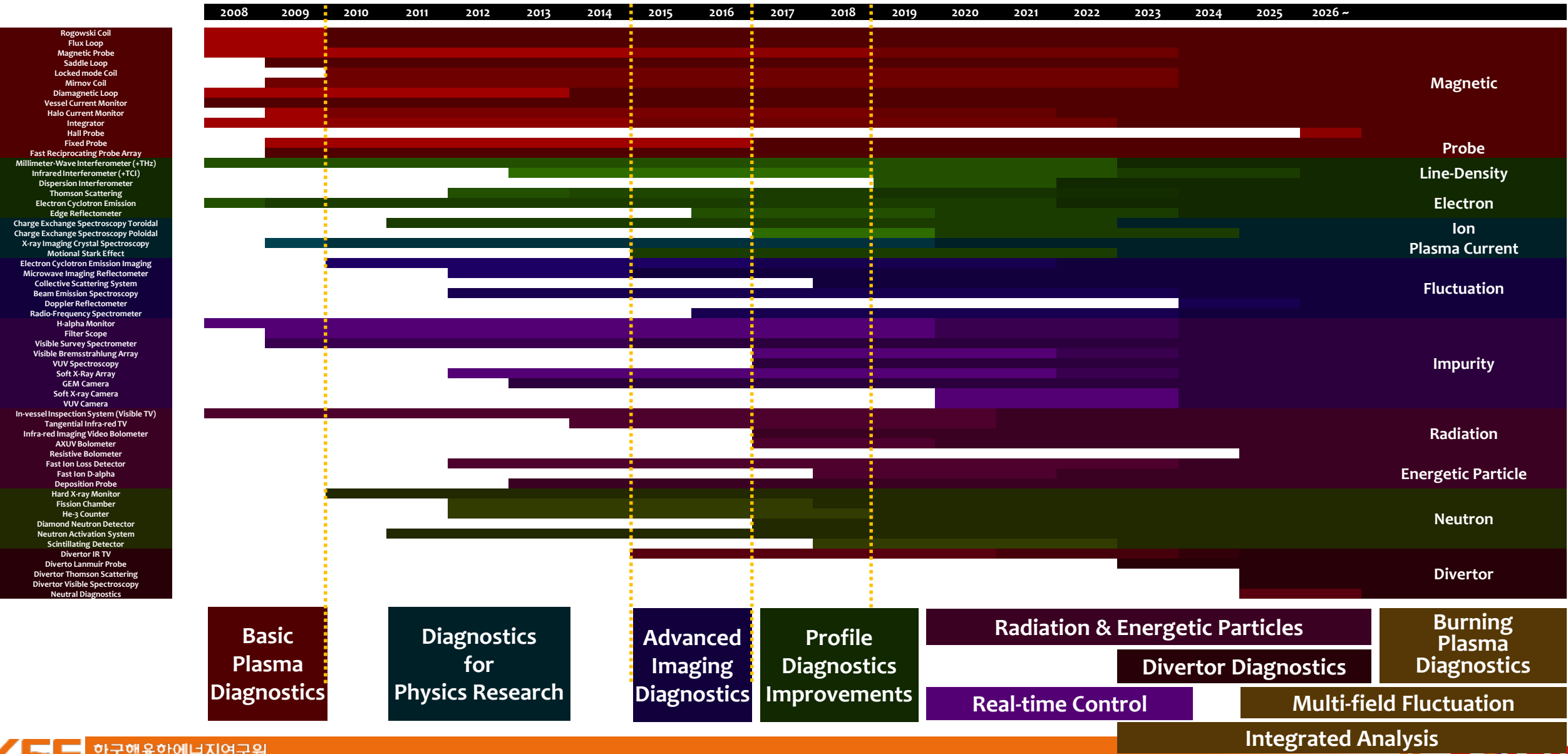
## TALIF, Edge Rotation Diag.

Assessing installation feasibility

Year	Plan
~ 2023	LP & support structures installation
~ 2025	Div. Spectroscopy development, expanding IR TV coverage
2025 ~	Div. TS development, preparation for full W environment



# KSTAR Diagnostics Development Roadmap



# KSTAR Diagnostics Development Timeline

	2024	2025	2026	2027 ~
MDs	additional integrator	additional RT (3D/MHD control)	low drift for 300s operation	
Hall Probe				feasibility study & test for K-DEMO
THz Interferometer	<b>installation</b>		high precision & fluctuation meas.	
Two-Color Interf.	2nd unit design	<b>2nd unit installation</b>	10 ch. density profile recon.	core/edge density control
Thomson Scattering Reflectometer	RT TS using 5GS/s DAQ	improve polychromator temp. control freq. sweeping upgrade	RT TS accuracy improvement edge density reconstruction	
CES	RT CES	ultra fast (100kHz) CES	poloidal CES improvement	
MSE	RT MSE	spectral MSE for main-ion CX		2nd MSE for Er
Integrated Analysis	provide data for reconstruction	improve resolution & accuracy	<b>integrated data analysis aided by synthetic diagnostics</b>	
ECE Imaging	RT ECEI improvement		fluctuation radial profile meas.	
MIR / CSS	optics upgrade	small scale & high-k turbulence study		<b>2D/3D multi-field fluctuation diagnostics developments</b>
BES	edge density profile estimation	2D channel upgrade (8x16)		
Doppler Reflect.	antenna & mw parts test	<b>installation</b>	fluctuation & poloidal velocity meas.	
RF Spectrometer	physics study with simulation			<b>Robust MW diag. for burning plasma</b>
Visible Bremss.	refining Zeff profile reconstruction			
H- $\alpha$ / FS / Survey		poloidal optics upgrade		
VUV Spectroscopy	camera upgrade	optimization for W meas.		<b>multi species (including neutral) &amp; full range simulation</b>
Neutral Diagnostics	feasibility study & selection	conceptual design	<b>installation (alpha ver.)</b>	
Soft X-Ray Array	channel & electronics upgrade	tomographic system	extension to the 3D MHD diagnostics	real-time application study
SXR / VUV Camera	lab test & infrastructures	<b>installation</b>		
Visible TV	increase coverage / dual illumination / remote insert filter			
Tangential IR TV	optics upgrade study	upgrade for physics study		
Bolometer	resistive-type bolometer study	conceptual design	<b>installation &amp; <math>R_{tot}</math> meas.</b>	
FILD	FILD-head modification	optimization & electronics upgrade		fast-ion phase-space engineering for burning plasma research
FIDA	<b>installation (oblique-view)</b>	spectrometer upgrade, fast-ion velocity-space tomography		rapid measurement of neutron yield
Neutron Diagnostics	Sci-Fi detector upgrade	absolute calibration	MCNP simulation study	
Div. Lanmuir Probe	<b>installation</b>			
Div. TS / Spec.	structure installation & optics design	development & lab test	<b>installation</b>	consideration for full W environment
Div. IR TV	additional TVs design	<b>installation (for divertor study)</b>	<b>installation (for full toroidal monitoring)</b>	