Preliminary results of commissioning of EAST full W upper divertor and deuterium retention & permeation of W irradiated by heavy ions

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2RCM of W-CRP, Seoul National University, Korea, Sept. 8-11, 2015

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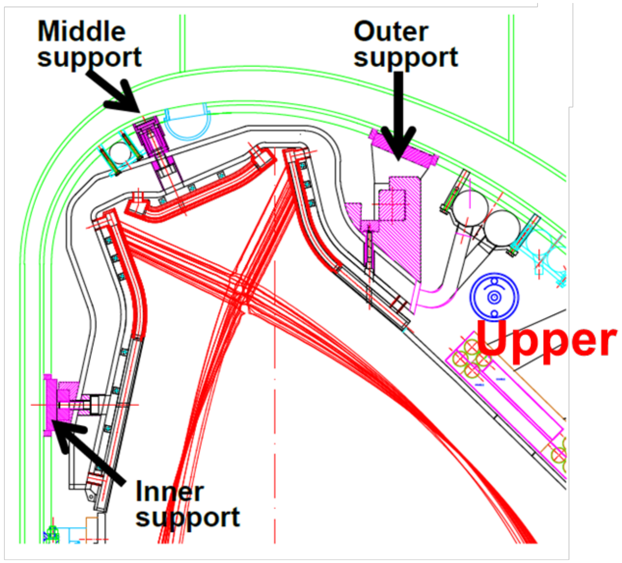
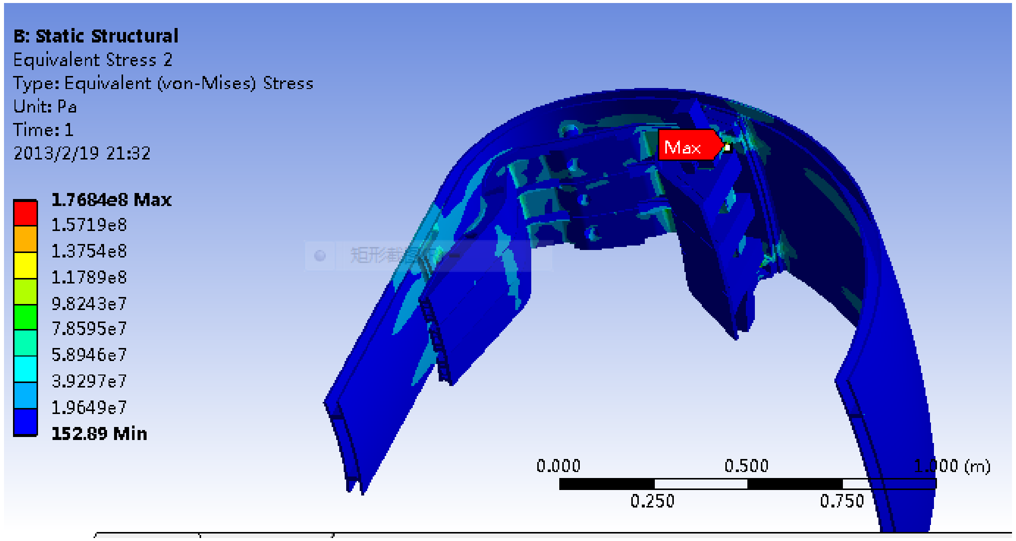
W/Cu divertor on EAST

- Engineering

Structure Design and Evaluation

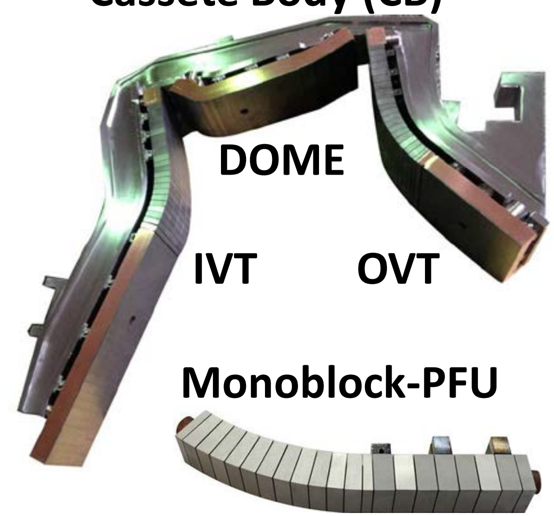
ASIPP



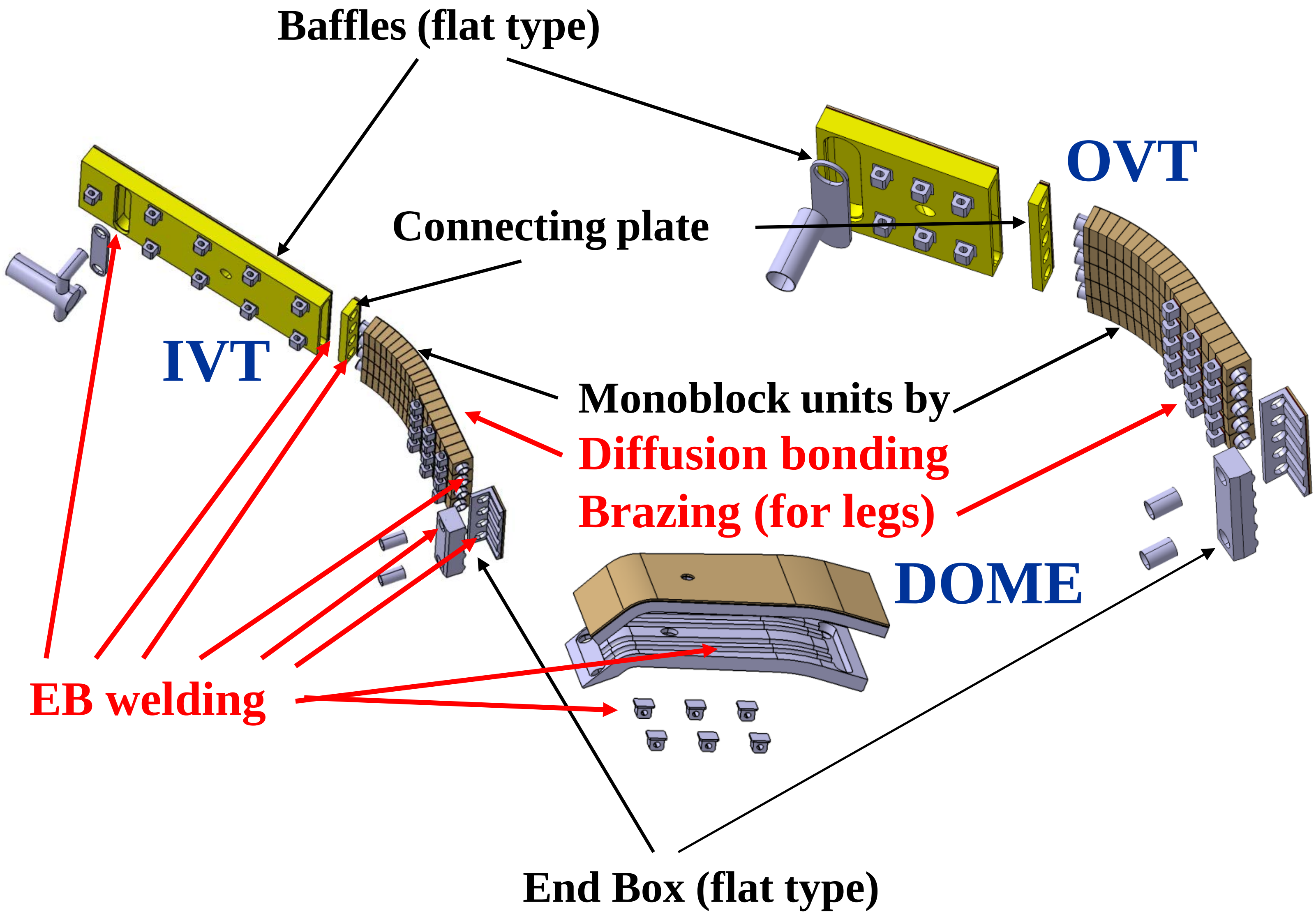


Module = CB + IVT + DOME + OVT

EAST upper tungsten divertor has modular structure with 80 modules in total. Each module supported by inner/outer rail and middle support.



PFCs Configuration and Connections



ITER-like Monoblock W/Cu PFUs

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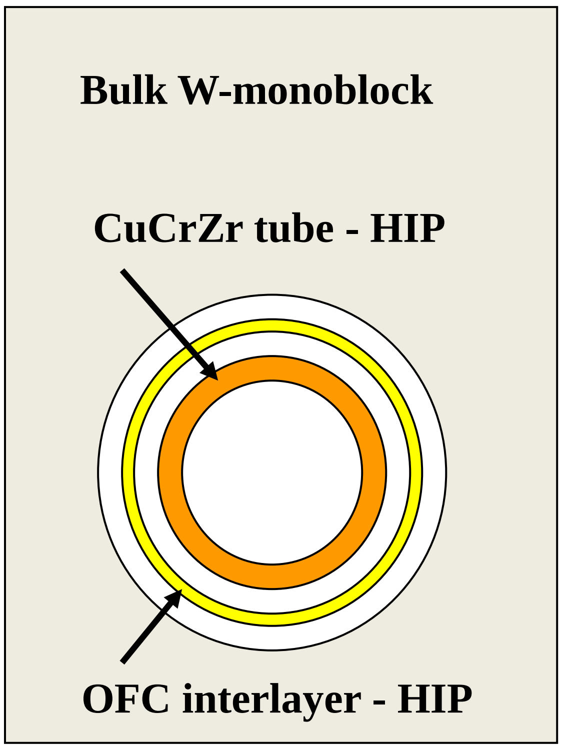
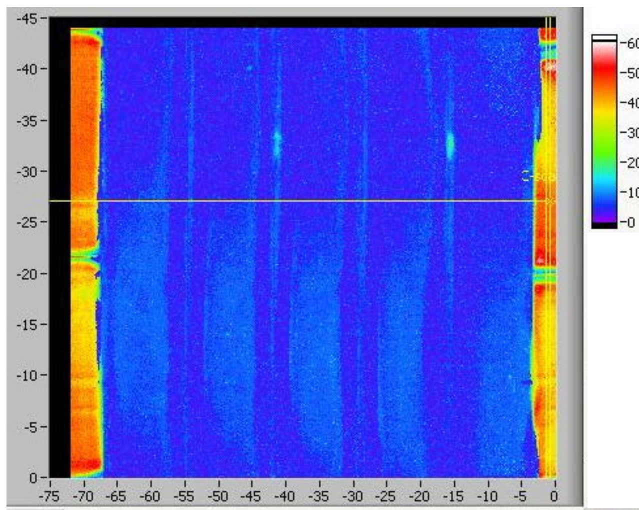
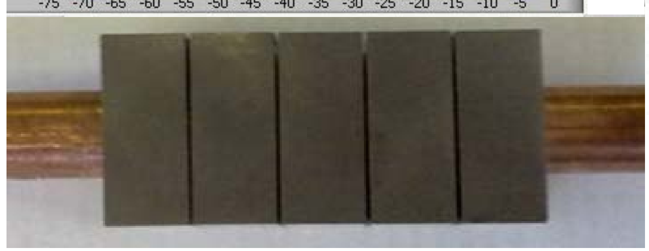
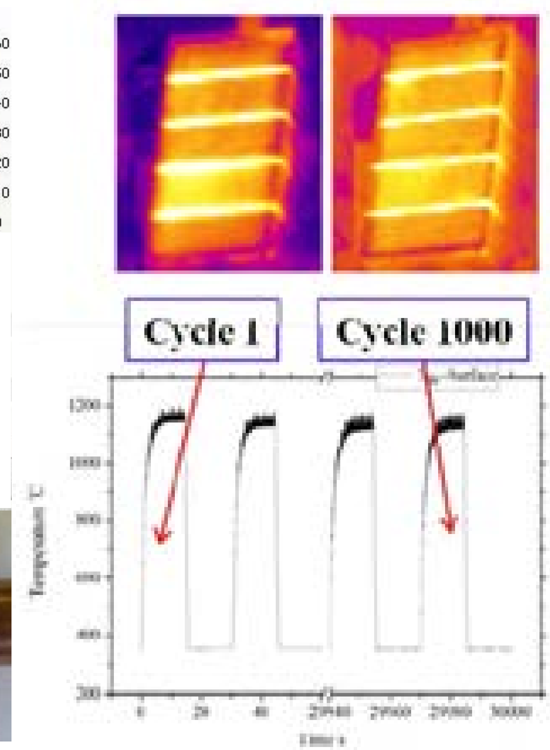
- **HIP+HIP:** W/Cu mockups were manufactured successfully by a double Hot Isostatic Pressing (HIP) technology
- **NDT results**: Passed NDT check for dual bondings between W/OFC/CuCrZr tube; **HHF testing**: 10MW/m^2-1000cycles









Flat-type W/Cu PFUs

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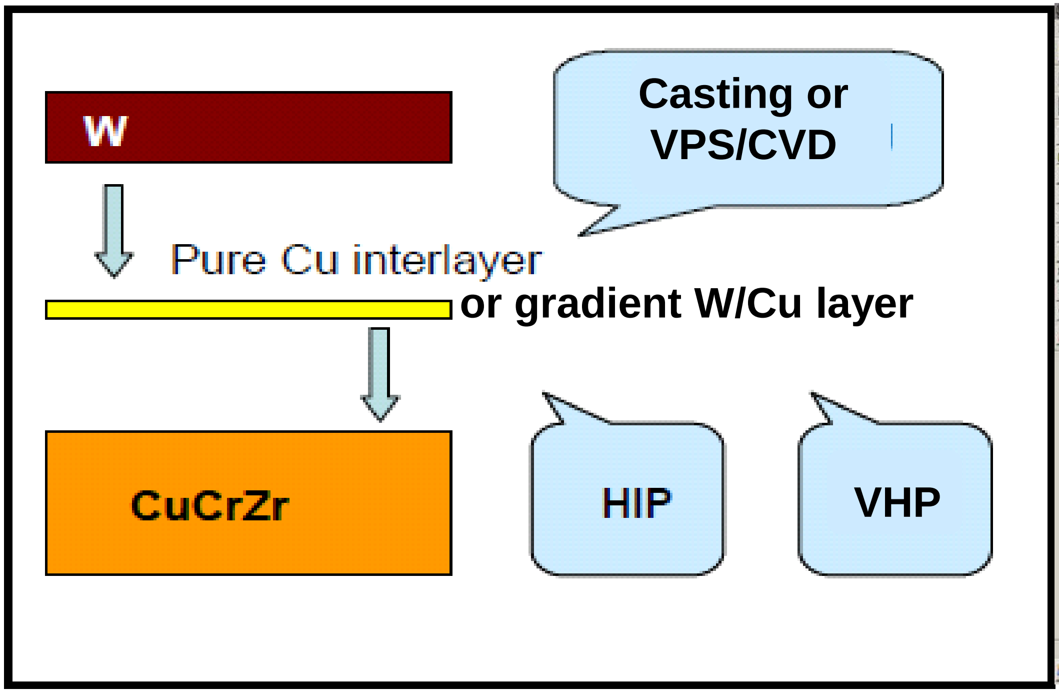
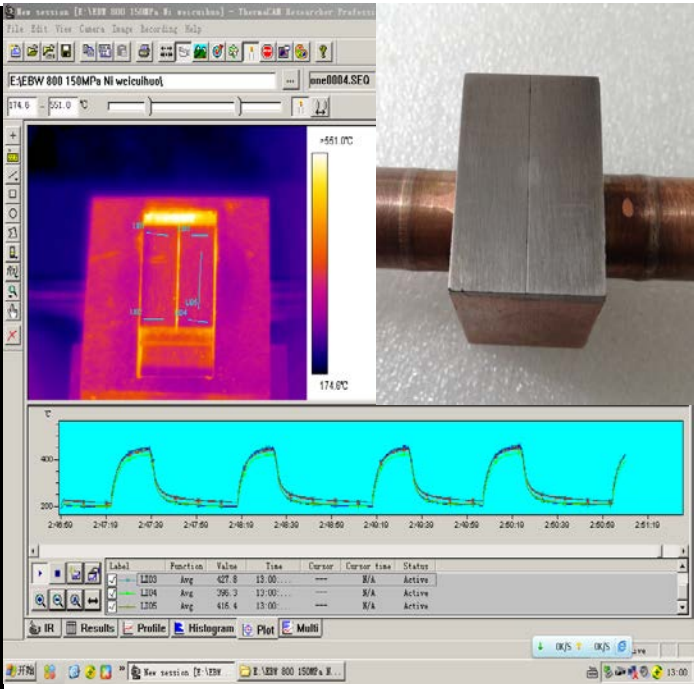
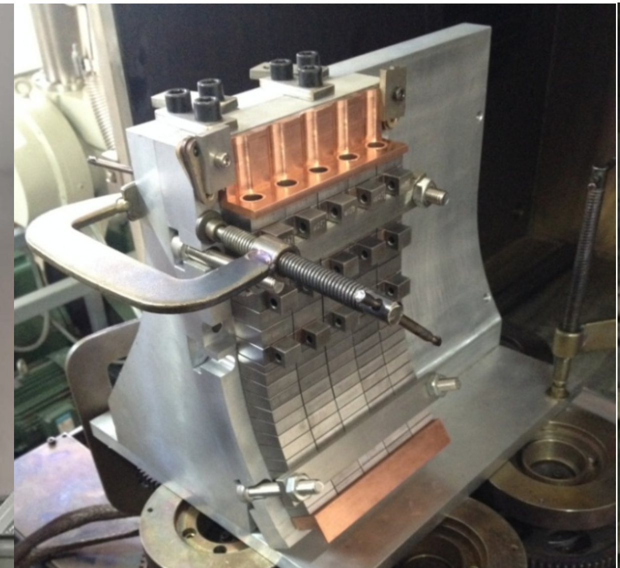
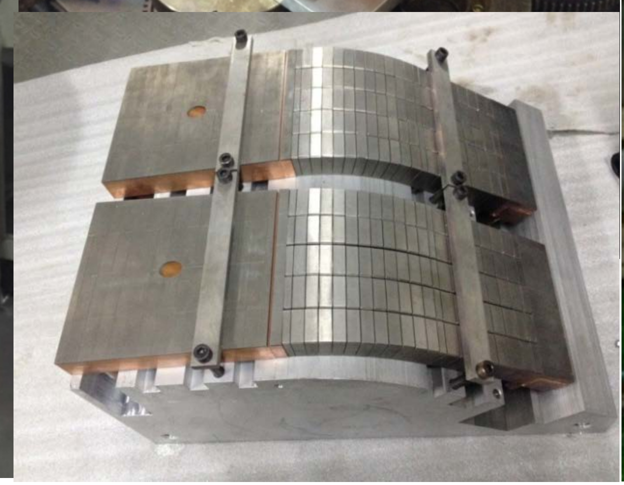
- **Casting + HIP**: **The interface of W/Cu were joined by casting, and then the interface of Cu/CuCrZr was bonded by HIP at lower temperature of 500~600℃.**
- **NDT results**: **Passed NDT check for dual bondings between W/OFC/CuCrZr plate; HHF testing: 5MW/m^2-1000cycles**





E-beam welding of PFCs





OVT/IVT/DOME-PFCs

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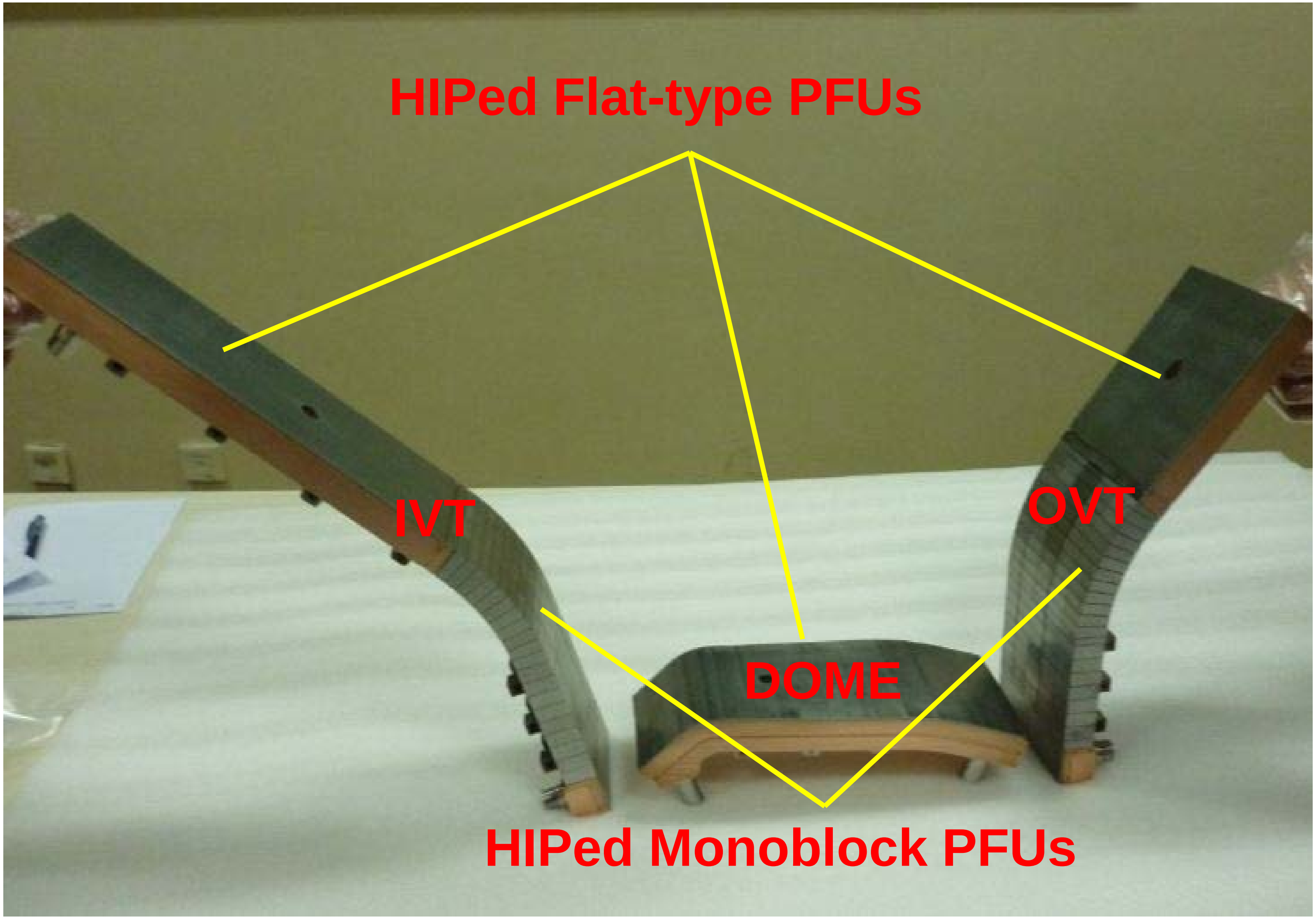
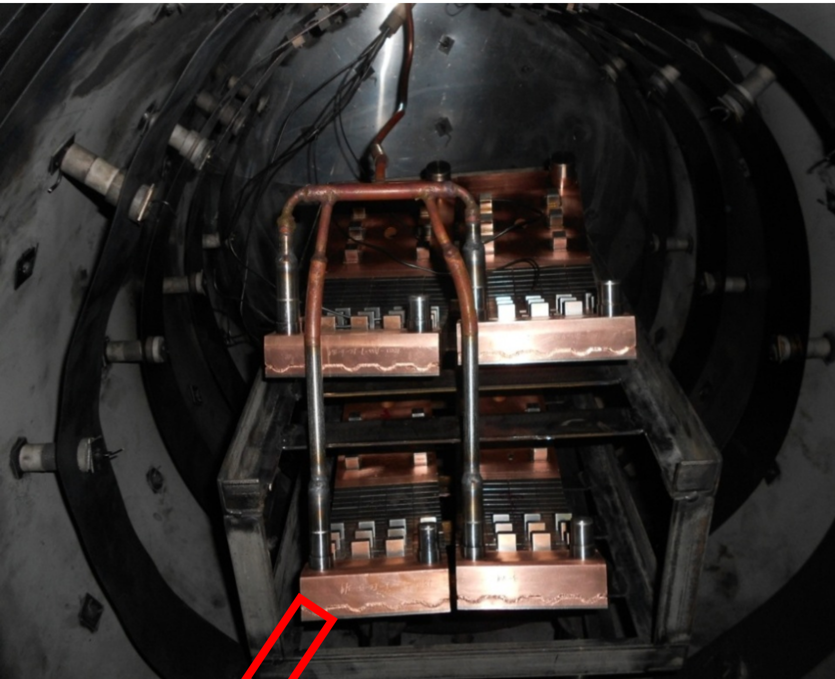
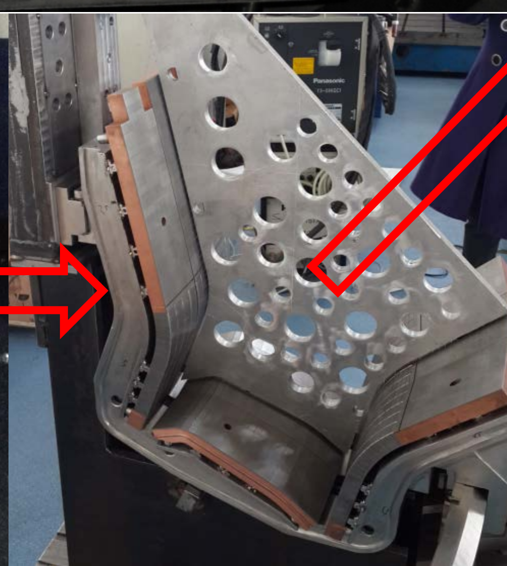
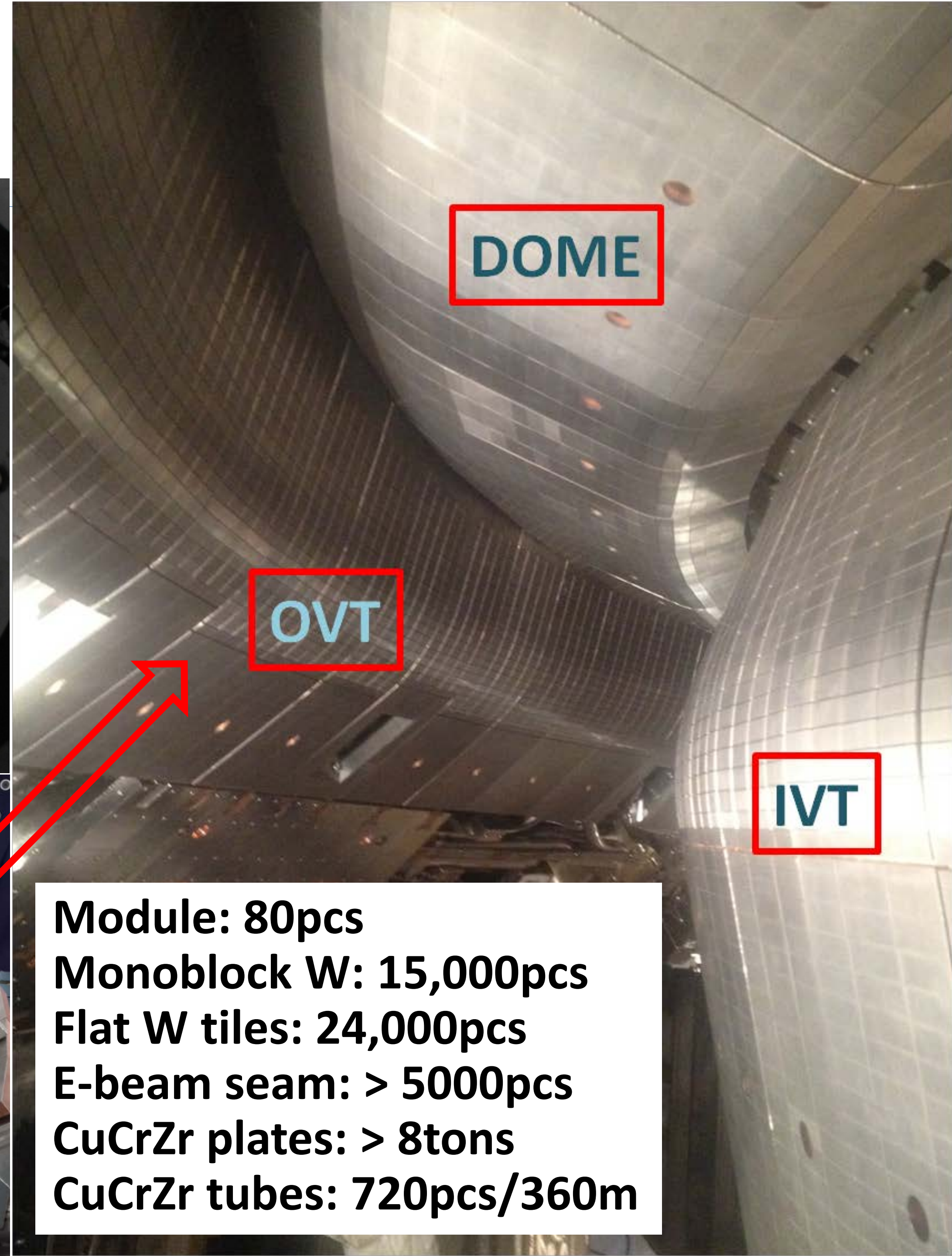


Assembly

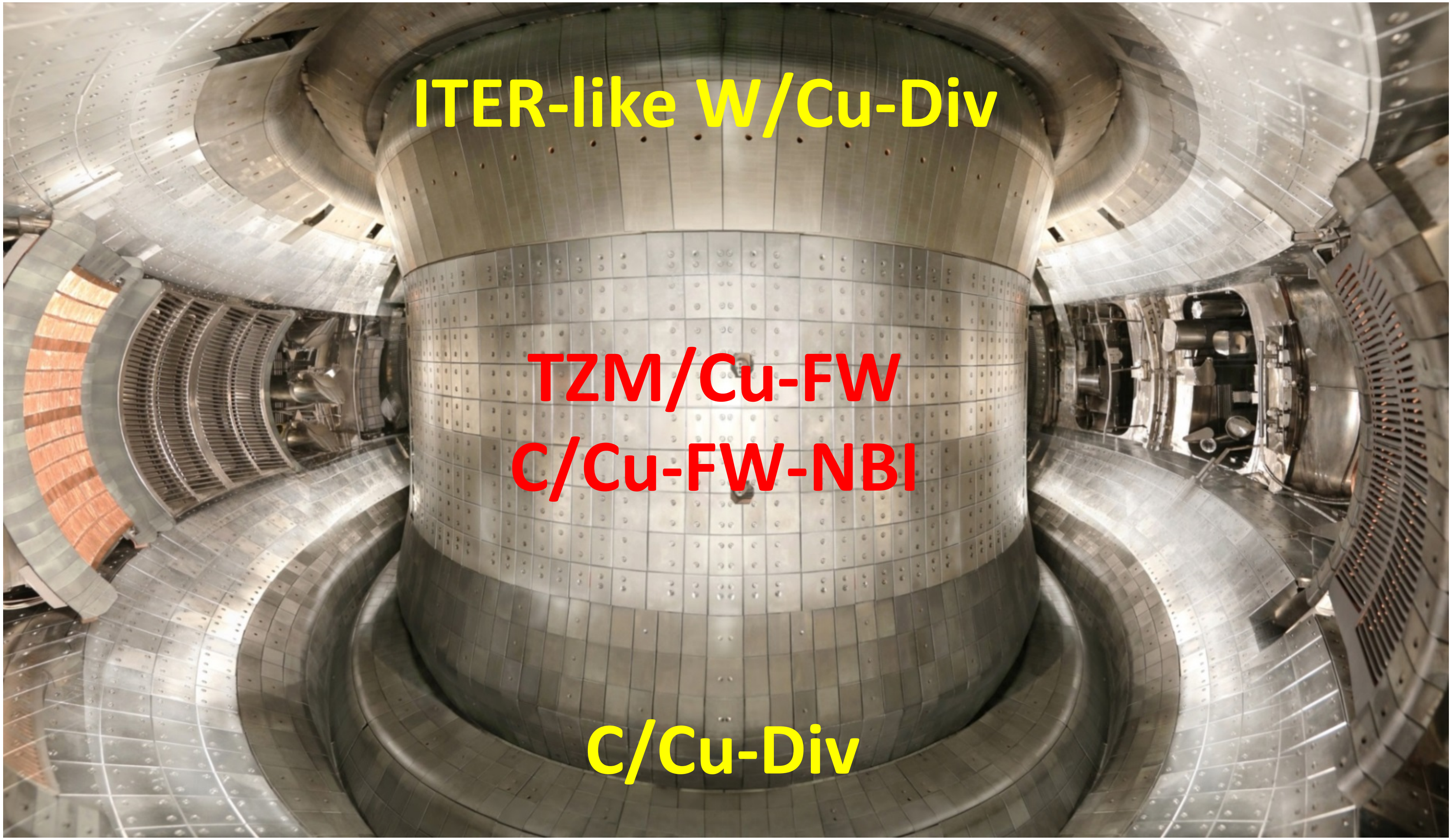






Module: 80pcs
Monoblock W: 15,000pcs
Flat W tiles: 24,000pcs
E-beam seam: > 5000pcs
CuCrZr plates: > 8tons
CuCrZr tubes: 720pcs/360m

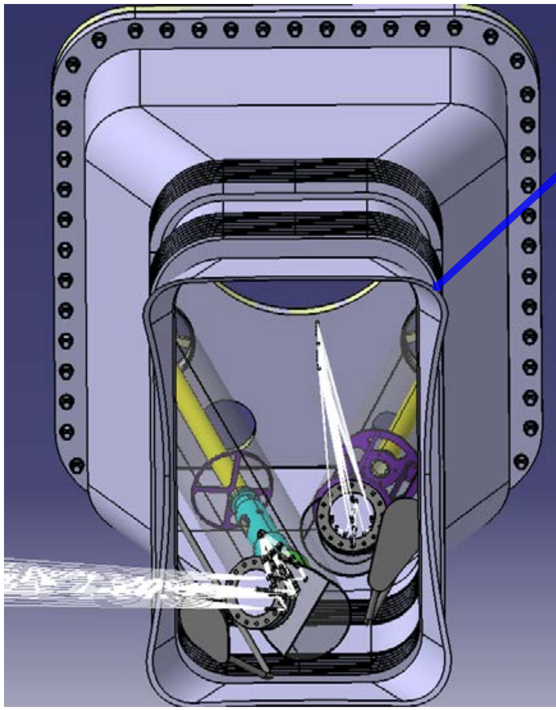
Grandview of the whole PFMC

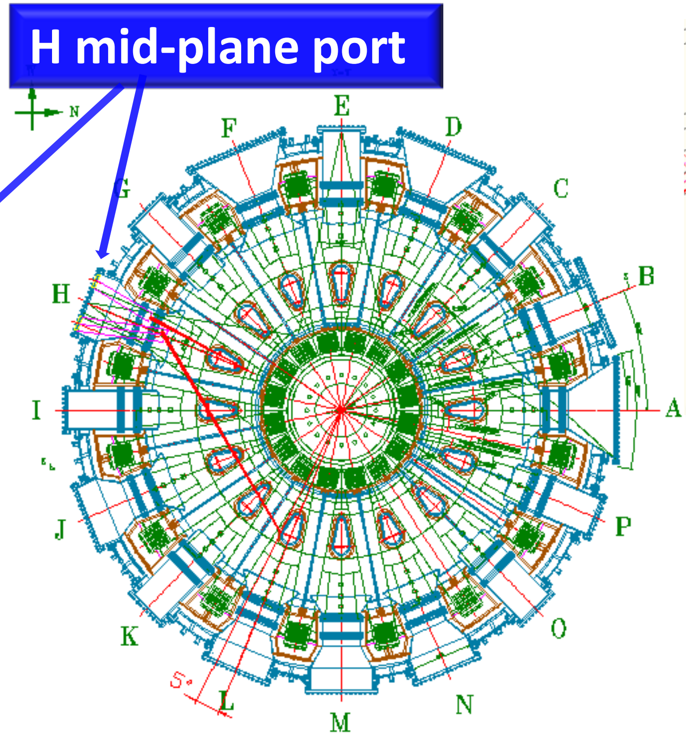


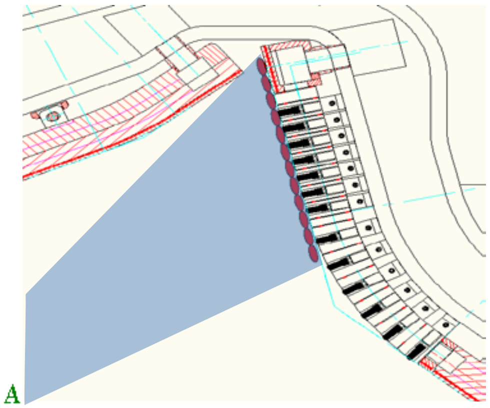
W/Cu divertor on EAST

- Commissioning in 2014

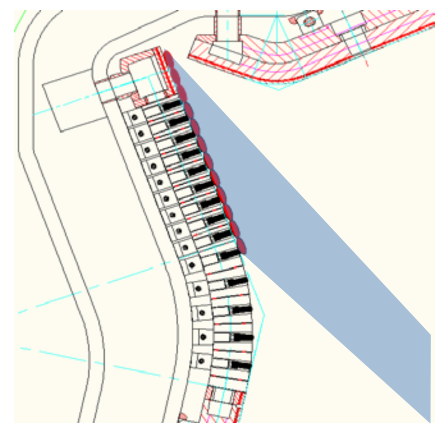
Monitoring W source on EAST







Outer target plane (H section)



Inner target plane (L section)

Spectroscopy system: Spectrometer & Filter + PMT

- 350nm - 800nm
- 300 / 600 /1200 /1800 /3600 l/mm gratings
- Spatial resolution: 13 mm (poloidal)
- Time resolution: 200 Hz (12 channels, EMCCD)
  Max. 20 kHz (PMT)

W source during NBI heating

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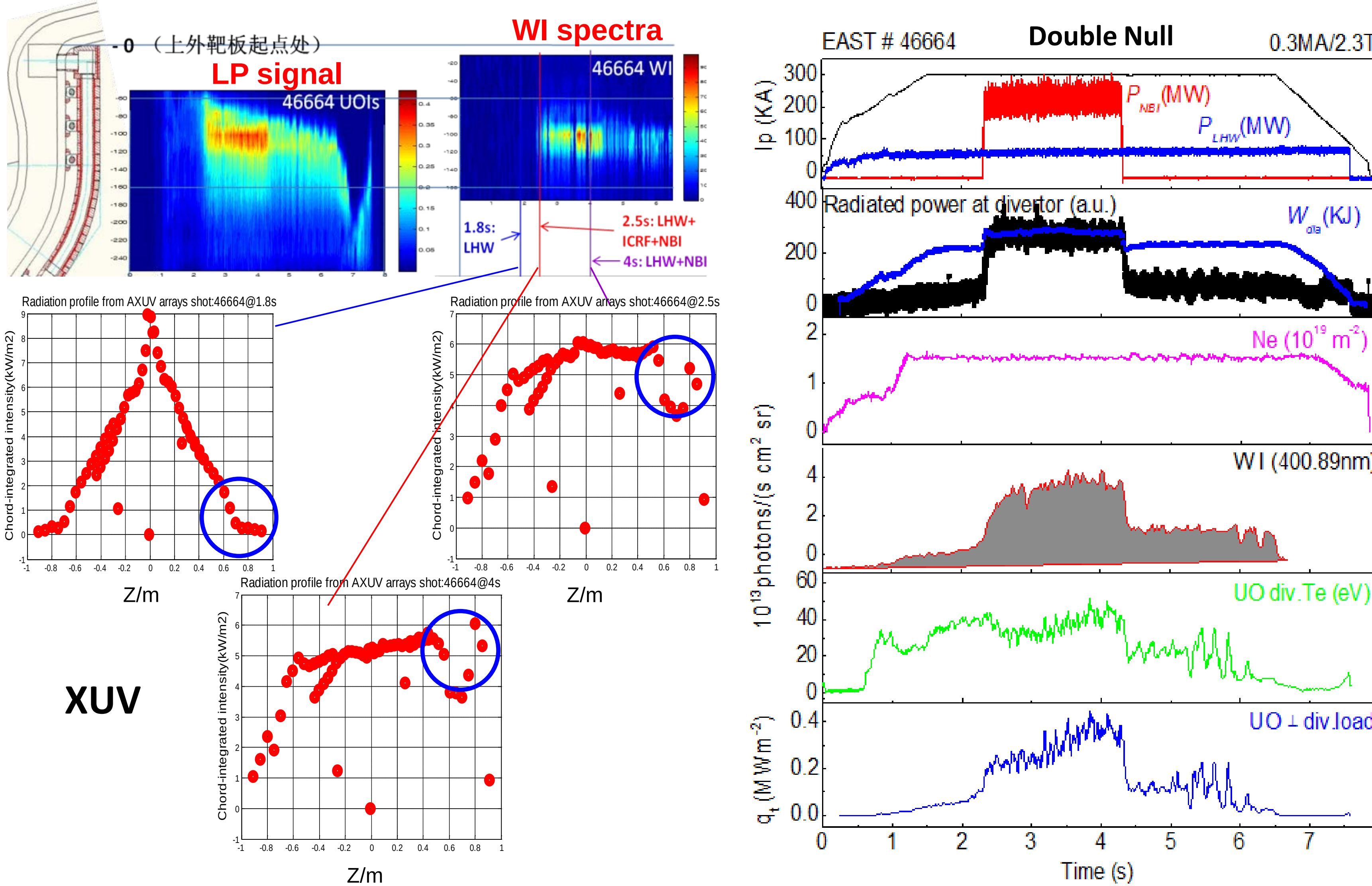
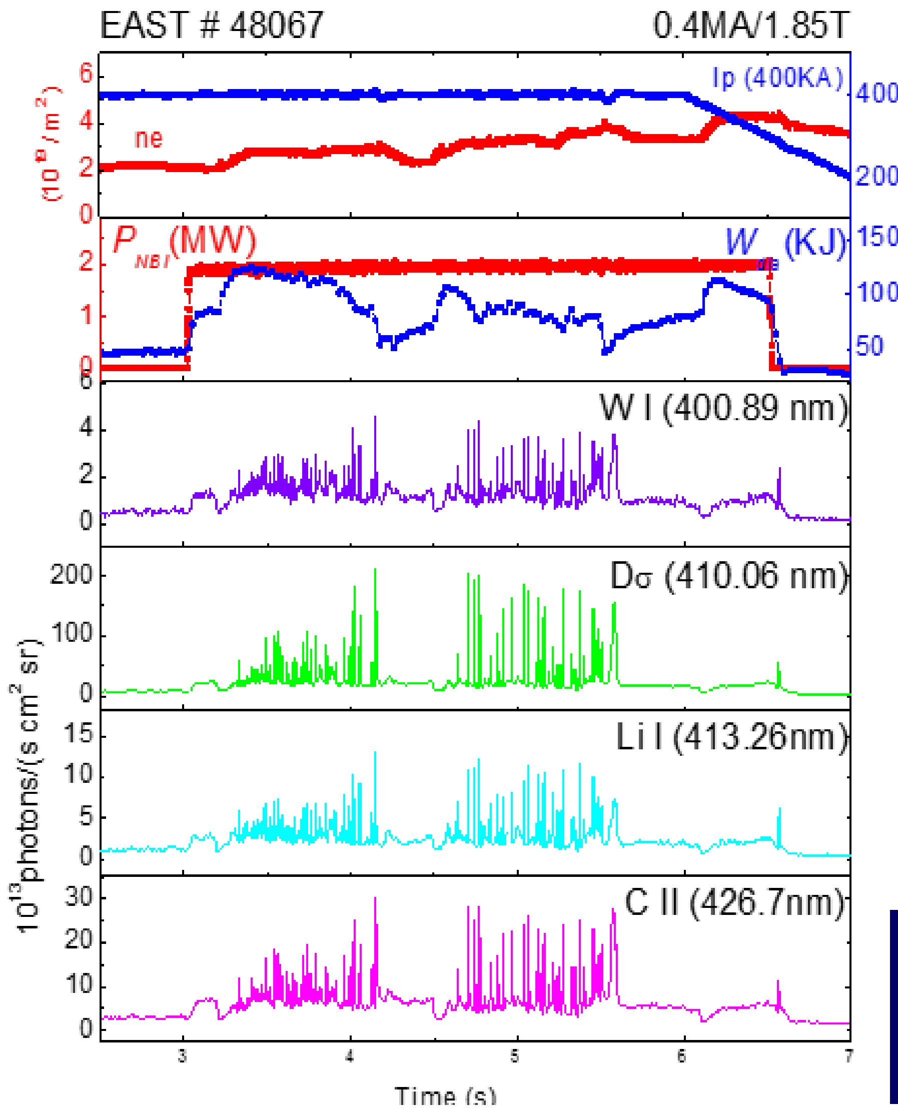
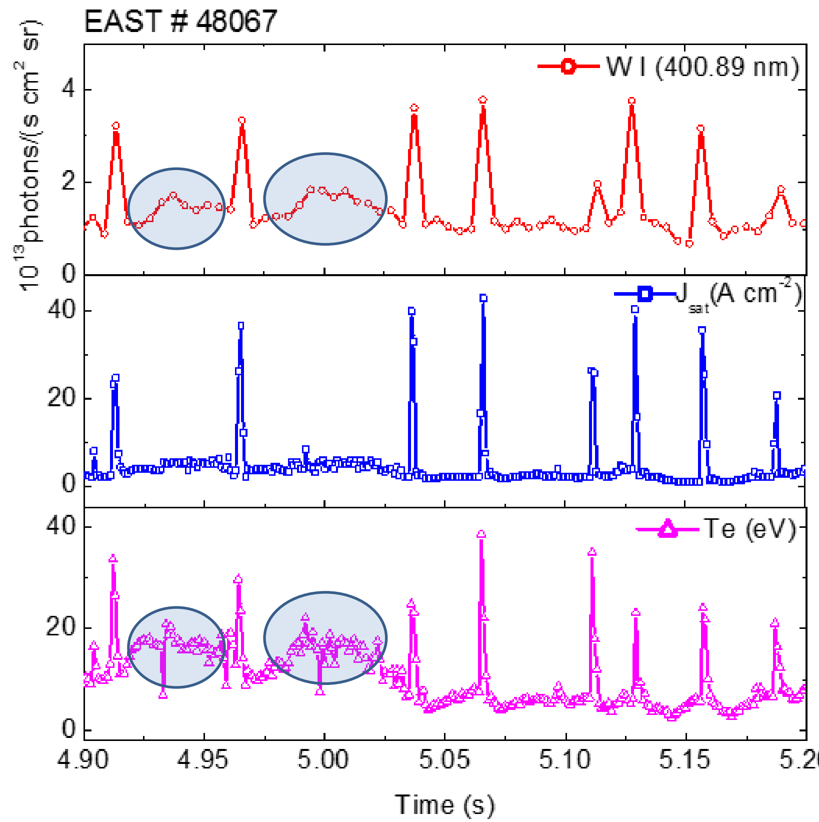


W source in type I ELMy H mode plasma

ASIPP





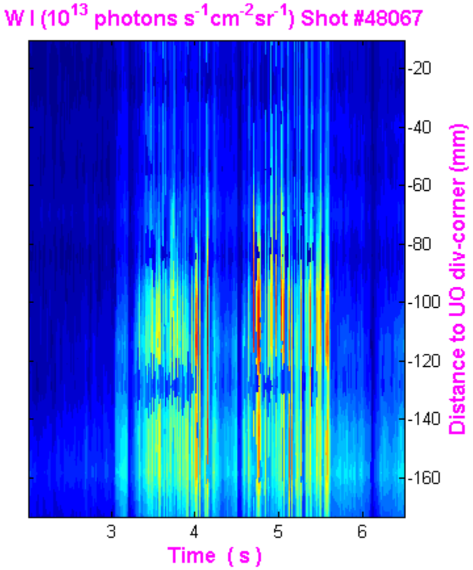
400KA, LSN, NBI L+R 3MW

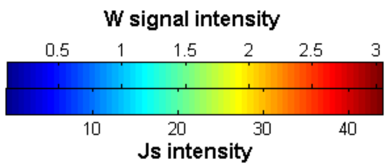
A strong W source appears during type I ELMs, together with other impurities including C, Li, etc., and inter-ELM vs Te

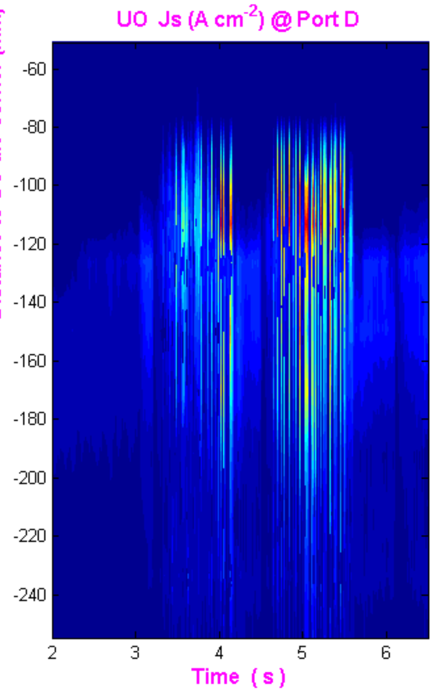
W source in type I ELMy H mode plasma

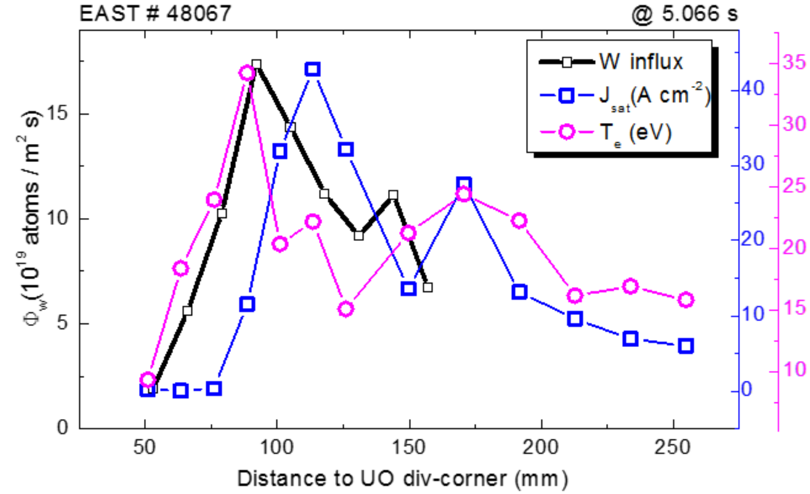
ASIPP

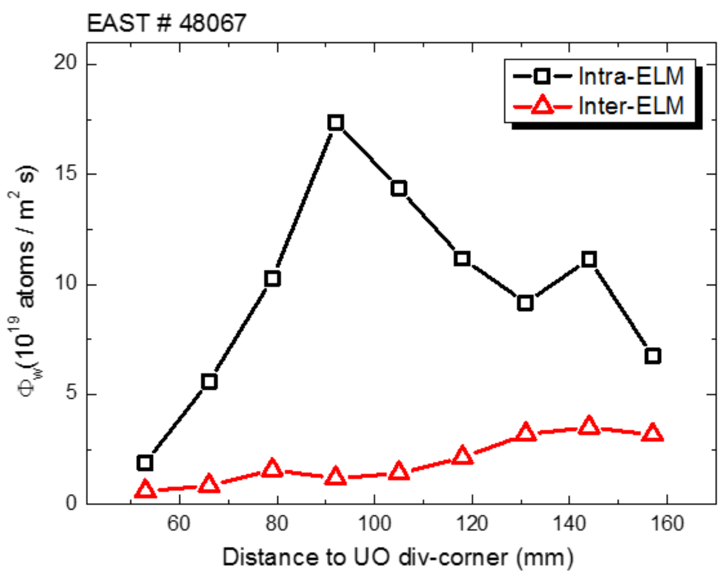
EAST # Shot :48067











Poloidal distribution of intra-ELM W influx presents a significant increase at strike point region, corresponding to T_e distribution at divertor.

Problems in 2014 campaign

- **Twice leak events during baking at 170℃, and first repaired and second evacuated (given-up).**
- **Baking at the end of campaign at 270℃ to test PFCs and find put weak points (possible leaks).**
- **After campaign, 13 leaks in total were found, all related to e-beam welding (improper joint/connection design and insufficient non-destructive testing).**
- **Some W tile damages observed due to assembly issue.**

Repair/Optimization in 2014/5

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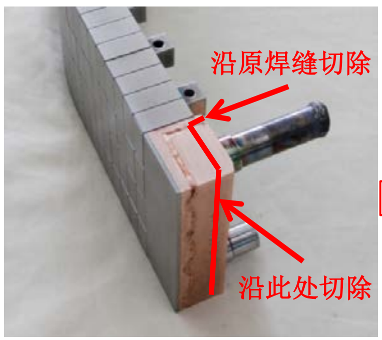
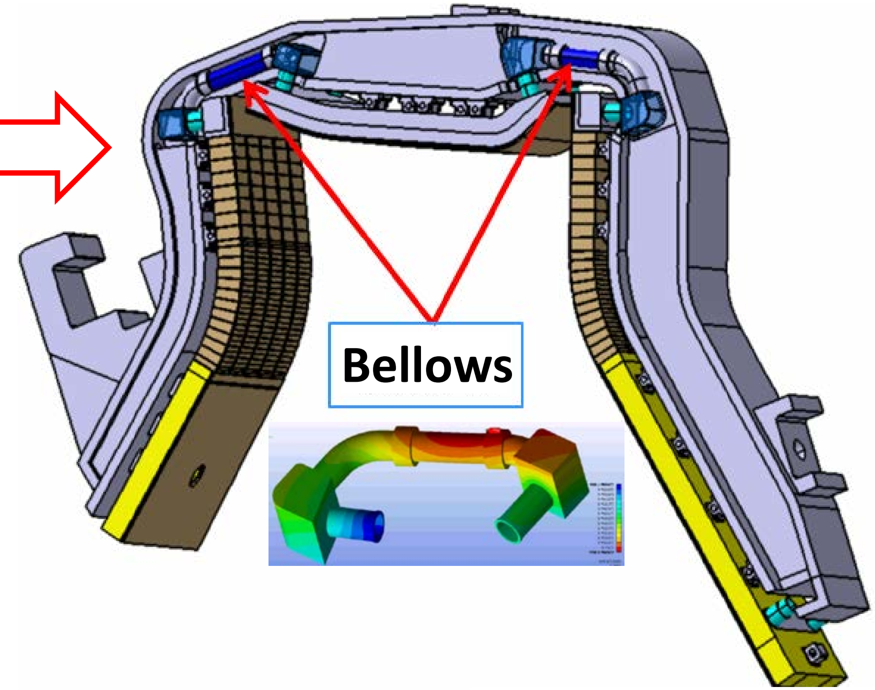
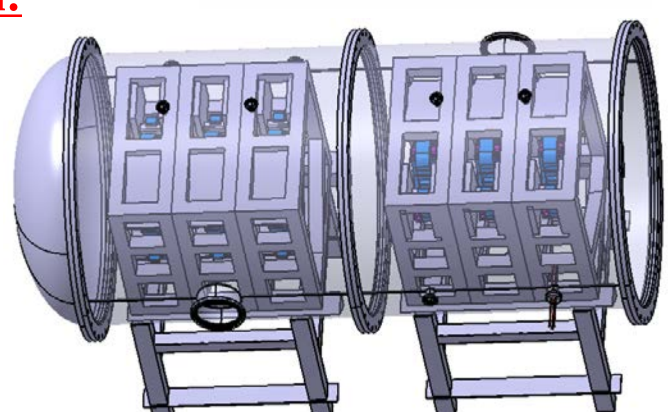
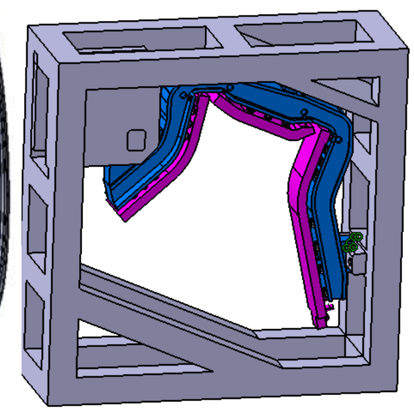




<u>Three measures for leak problem:</u>

- **Cooling tube connection: TIG welding -> soft bellows**
- **QA&QC for EBW btw tube and heat sink enhanced**
- **PFCs+CB baking at 250℃ prior to assembly in VV**

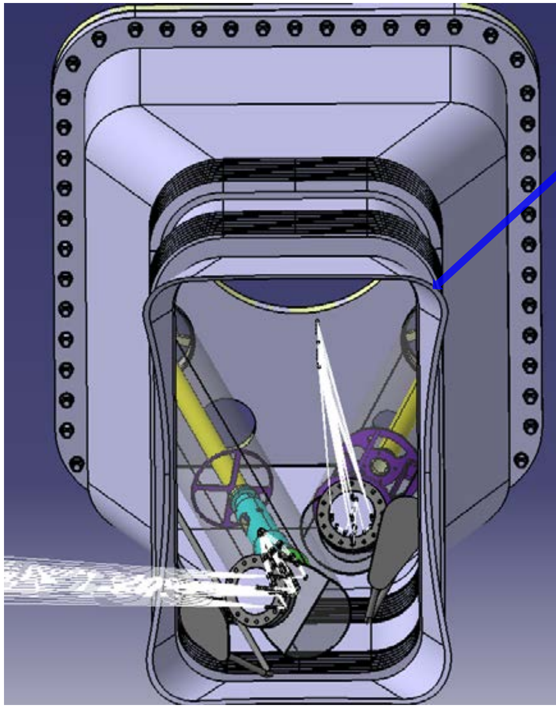


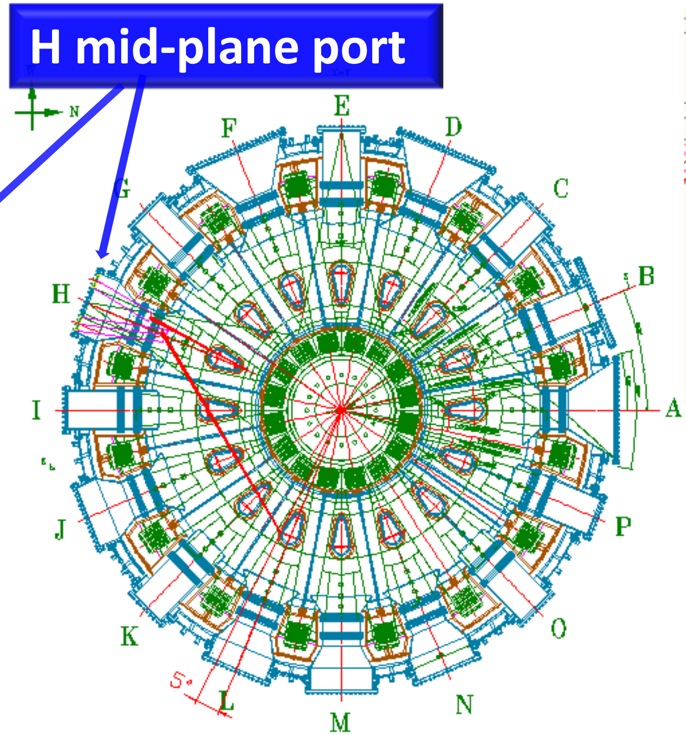


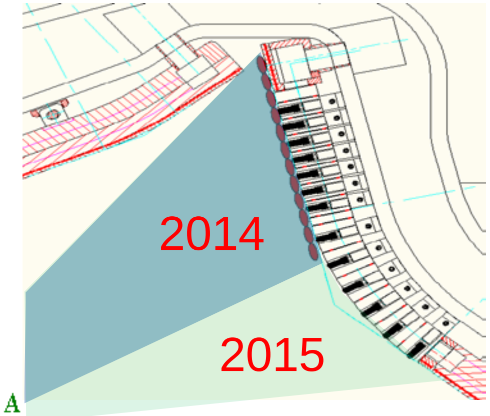
W/Cu divertor on EAST

- Commissioning in 2015

Monitoring W source on EAST







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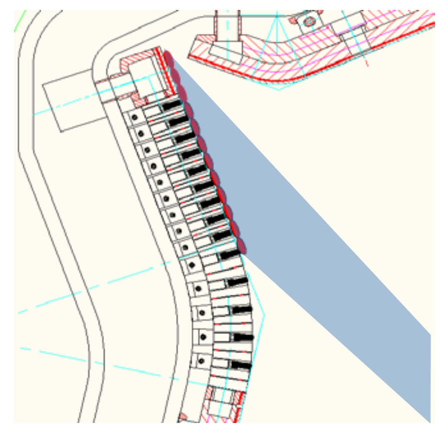

Inner target plane (L section)

Spectroscopy system: Spectrometer & Filter + PMT

- 350nm - 800nm
- 300 / 600 /1200 /1800 /3600 l/mm gratings
- Spatial resolution: 13 mm (poloidal)
- Time resolution: 200 Hz (12 channels, EMCCD)
  Max. 20 kHz (PMT)

Shot 57499 (34s, H-mode/10s)

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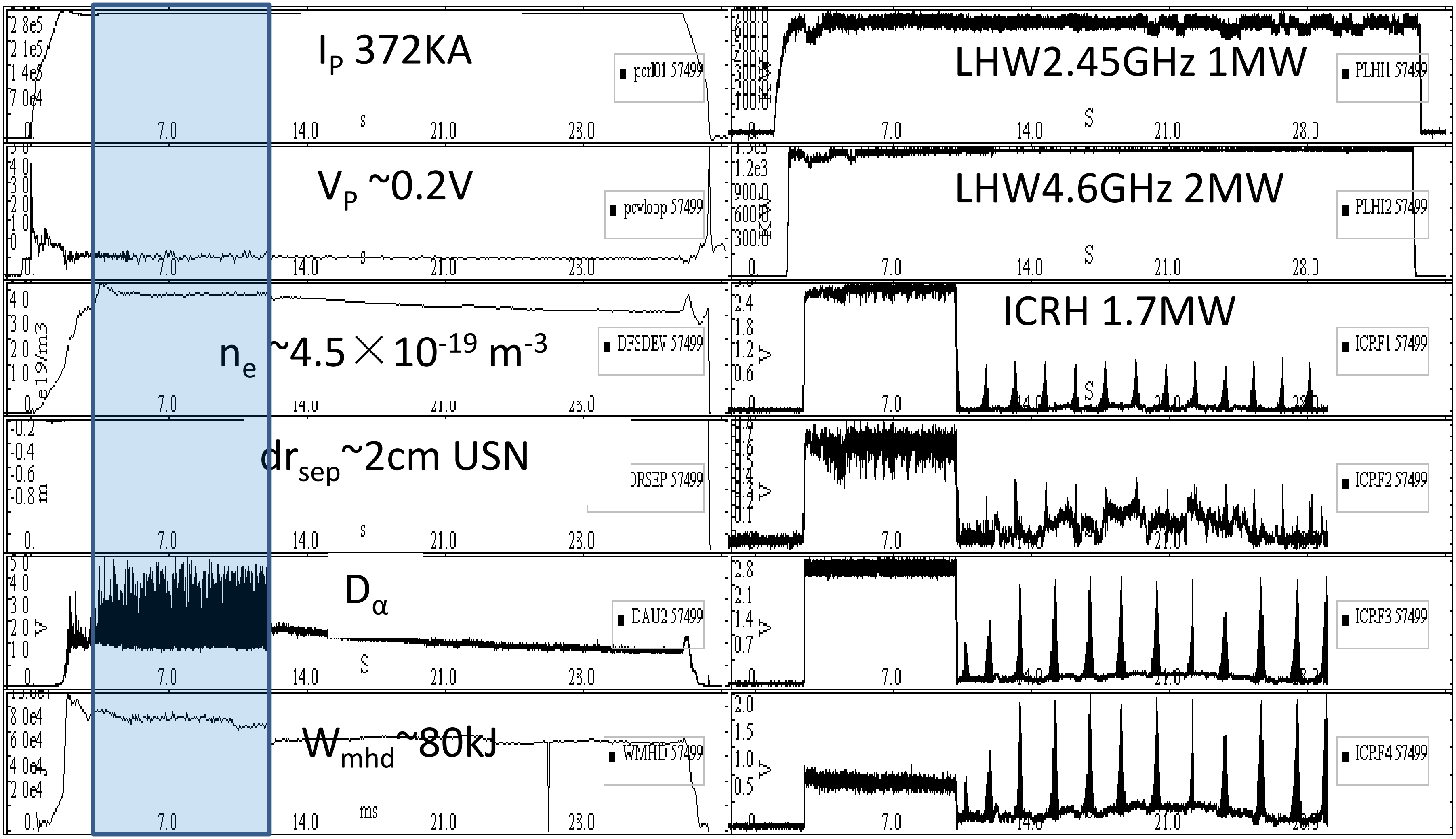
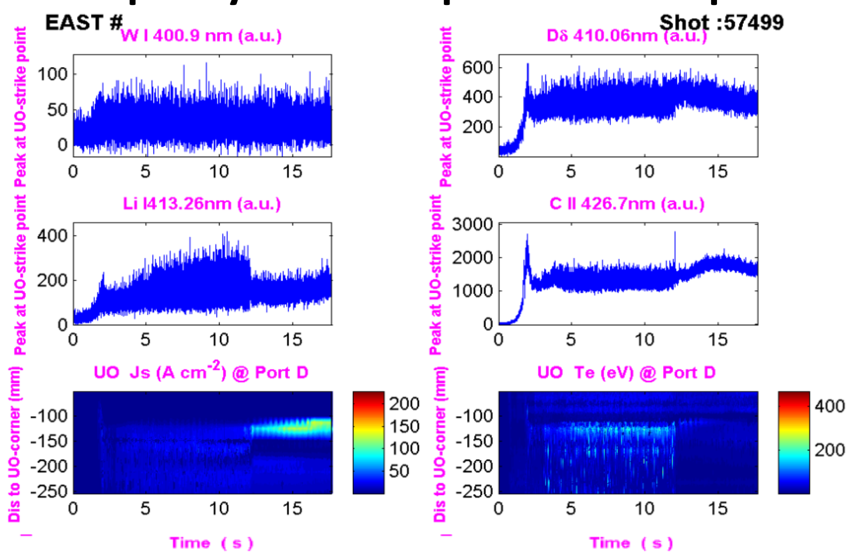
Type III ELM

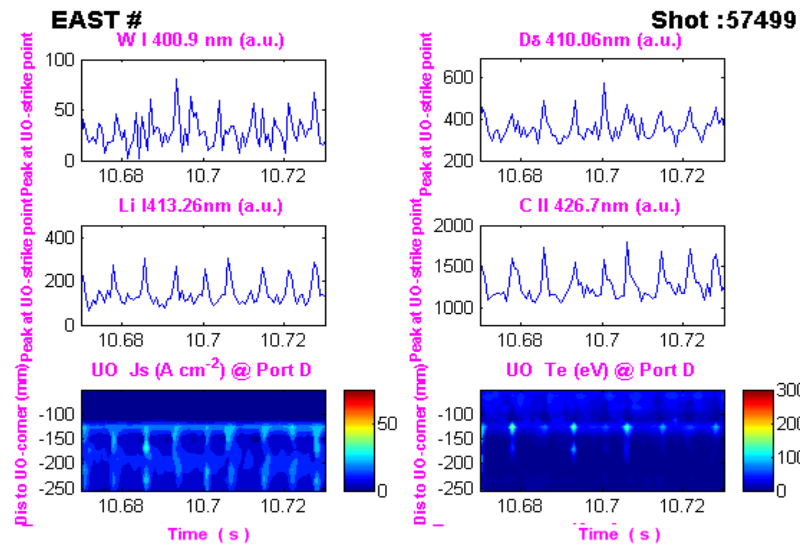


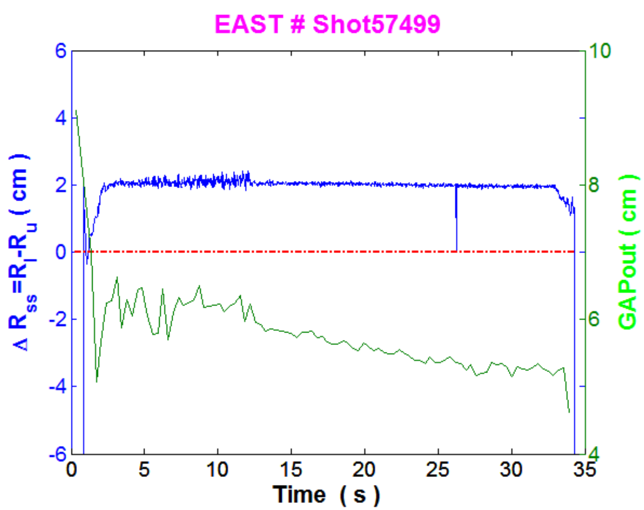
Shot 57499 (34s, H-mode/10s)

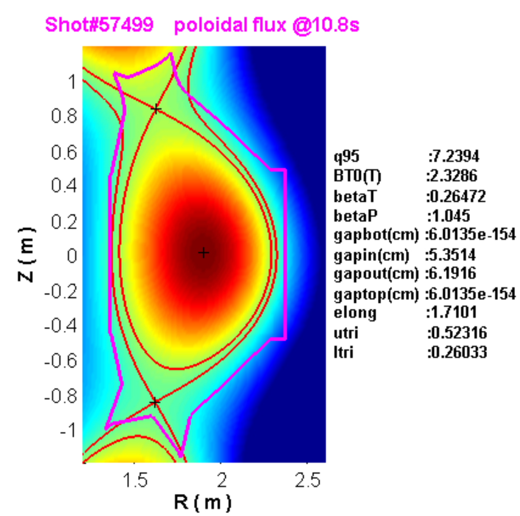
ASIPP

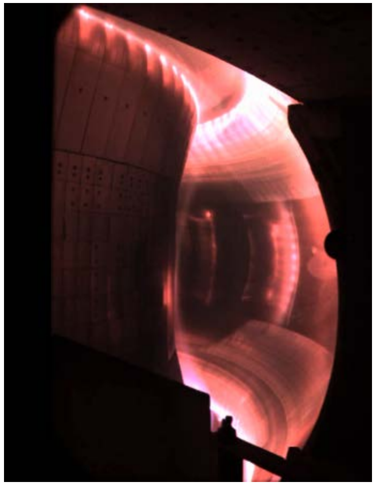
Impurity data comparison btw spectroscopy and LP @ SP/OVT during H mode）







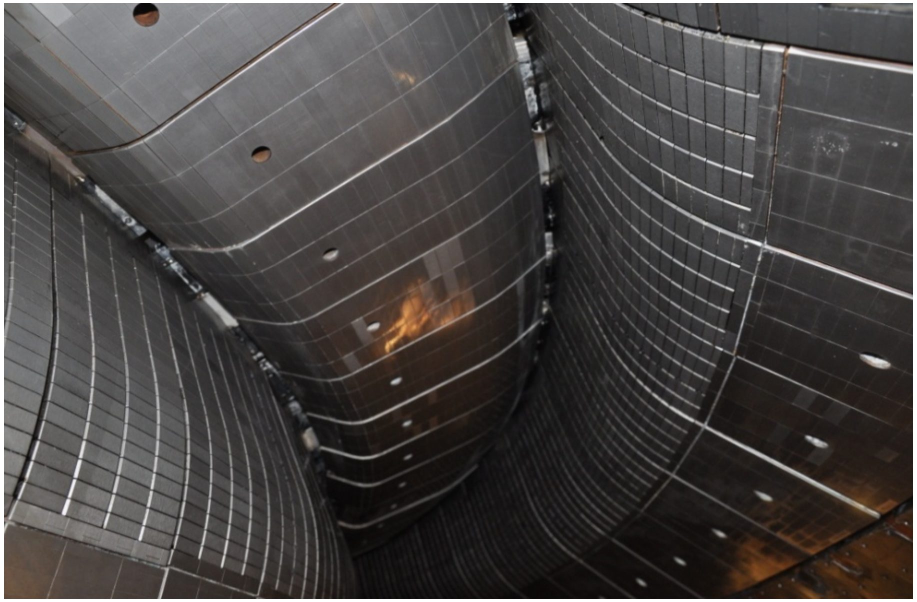




Engineering performance

- No leak till the end of the Spring campaign
- Survival from 200ºC baking and discharges
- Thick Li coating existing !

- Careful cleaning of Li
- No significant damages found on PFMC !



D retention & permeation

- W irradiated by heavy ions

Objectives & approaches

Objectives

- To clarify the D retention mechanism in bulk damaged W
- To investigate the D permeation behavior through bulk damaged W

✓ **W foils (1373 K,2 h)**

Φ20*0.11 mm, Φ20*0.05 mm

✓ **HIRFL**

122 MeV $^{20}Ne^{+7}$, 3.0×10^{2} ions/m^{2}, ~713 K

✓ **Defects characterization**

PALS, DBS

✓ **Deuterium retention**

Gas exposure, TDS

✓ **Deuterium permeation**

Gas-Driven Permeation

Irradiation chamber with an energy degrader and cooling/heating stages at HIRFL-SFC.

High energy heavy ions irradiation

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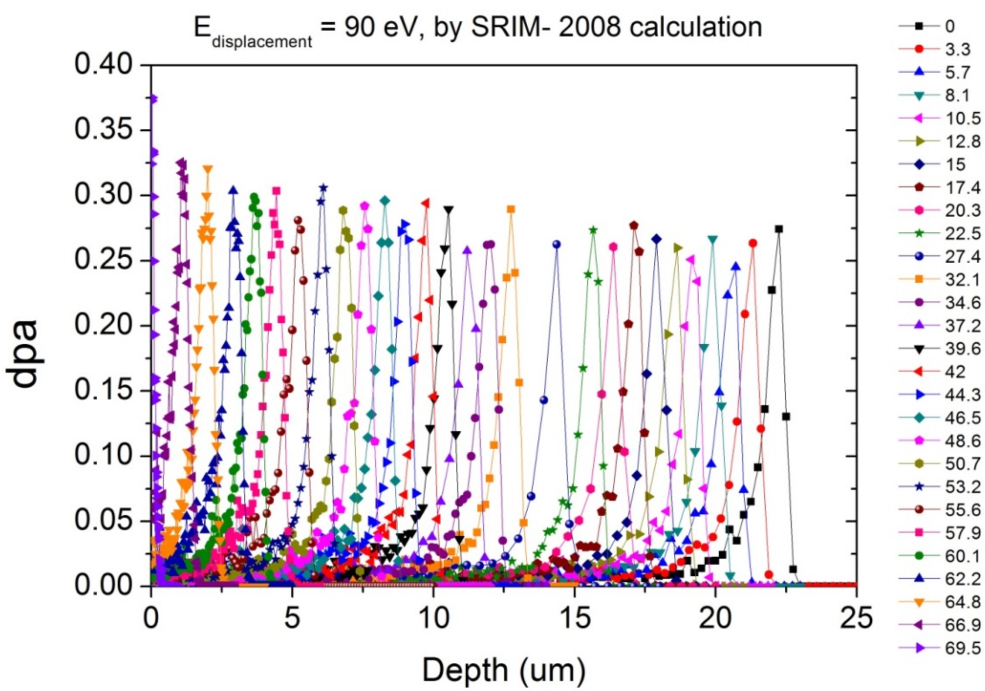
➢ Uniform distribution of irradiation defects in W

- High energy $^{20}Ne^{+7}$ ions (122 MeV), incident range is ~22.0 μm in W;
- An **energy degrader wheel** made of 30 pieces of Al-foils revolving in front of the sample;
- A sample-double-side-irradiation mode.



Estimated depth profile of displacement damage at one side of W. The right column shows the thickness (μm) of Al-foils used in the energy degrader.

A quasi-homogeneous distribution of atomic displacement damage to 0.3 dpa within a depth of 50 μm in W.

Positron annihilation lifetime spectroscopy (PALS)

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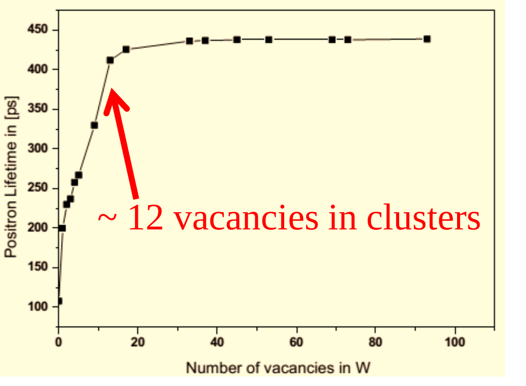
- The measured PALS were analyzed based on a two-state trapping model by assuming:
  - τ_1 - free positrons and positrons trapped at the mono-vacancies/dislocations,
  - τ_2 - positrons trapped at the vacancy clusters or voids.

Dislocations **Large vacancy clusters !**

	Thickness of W (μm)	Lifetimes 1 (ps)	Intensities (%)	Lifetimes 2 (ps)	Intensities (%)
Annealed (1373 K)	50	139.6±1.7	100	---	---
	110	139.5±2.6	100	---	---
Irradiated	50	118.6±3.4	59.5±1.0	406.8±5.2	40.5±1.0
	110	118.9±3.6	62.7±1.3	366.4±6.1	37.3±1.3

Reference*:
a. positron lifetime in defect-free W : τ_f = 105 ps
b. Correlation: positron lifetime *vs.*. the number of vacancies clusters in W (right figure)
c. The lifetimes of positrons trapped at dislocation: slightly shorter than τ_{1V}



n-irradiated W/Mo: τ_2=350~470 ps

* H.E.Schaefer, phys. stat. sol. (a) 102, 47 (1987);
T. Troev, E. Popov, N. Nankov, et al., J. Phys.: Conf. Ser. 207 (2010) 012033
M. Eldrup, X. Meimei-Li, L.L. Snead, et al., Nucl. Instr. Meth. B 266 (2008) 3602–3606

Doppler broadening spectroscopy (DBS)

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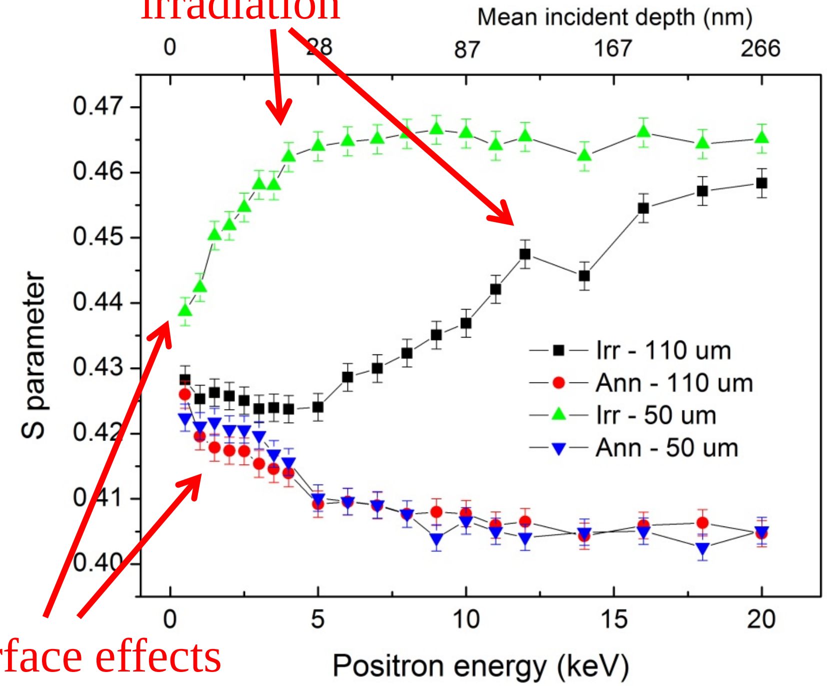
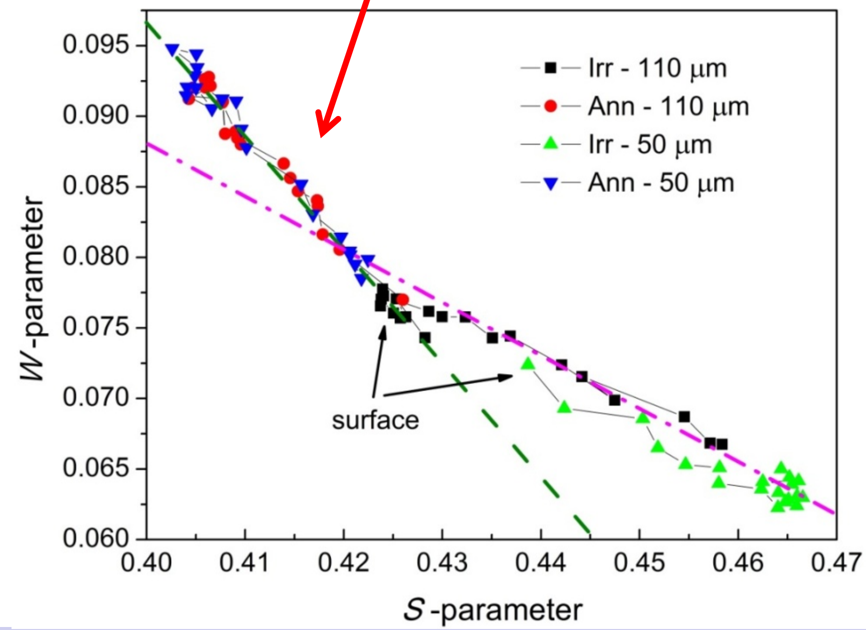
- ➢ Slow positrons: 0.18 -20 keV, $R_{max} \approx 0.5\ um$ → near surface information

Increase of S parameter after irradiation

Change in slops





Surface effects

- ✓ Larger S parameter in S(E) plot & larger slope value in S-W plot for two irradiated tungsten: <u>strong evidence of vacancy-type clusters formation</u> under Ne-ion irradiation;
- ✓ Defects <u>quasi- homogenously distributed</u> at the near surface.

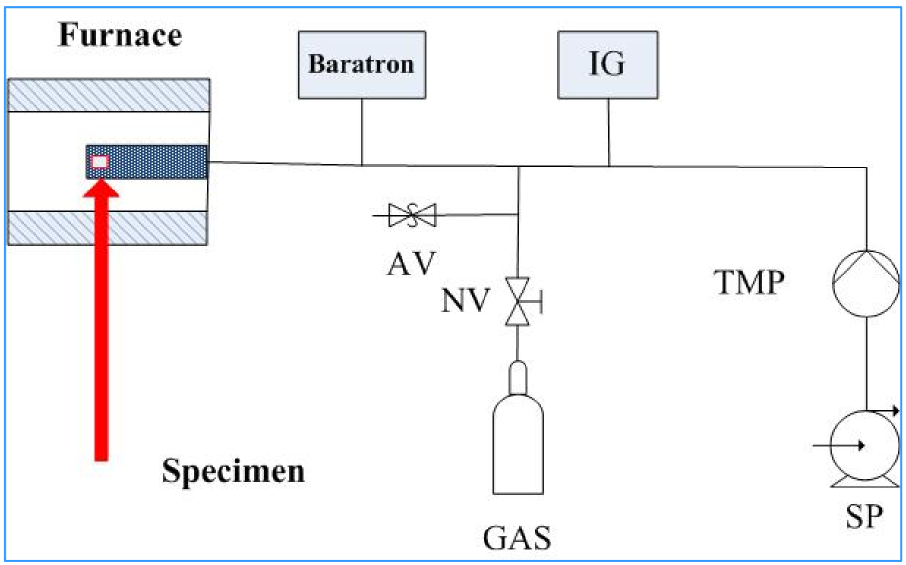
Deuterium bulk retention (D_2 gas loading)

ASIPP

- D_2 gas loading to introduce an uniform distribution of D in the damaged W

  (instead of plasma exposure: to avoid further modification of near surface structure under plasma irradiation & larger D retention in the plasma irradiated side of the damaged W)

- Focus on high temperature D bulk retention behavior



Sketch of the D_2 gas loading facility

Loading conditions:

773 K /1.3 bar;

Holding time: 2 h
(long enough to ensure the diffusion length of D > sample thickness)

Samples quick cooled by liquid N_2

Deuterium bulk retention (TDS analysis)

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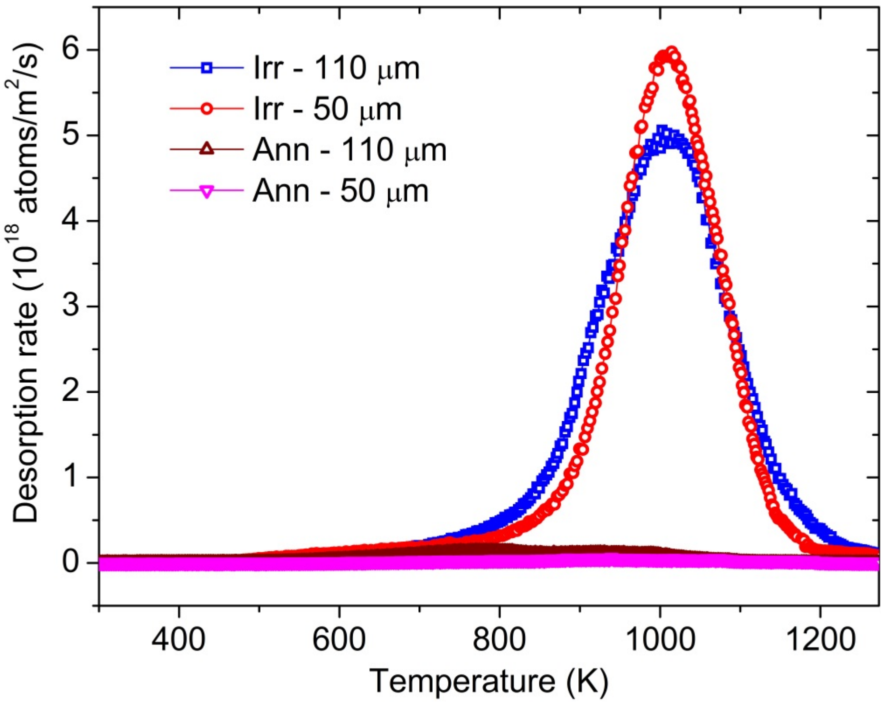
TDS: 1 K/s to 1173 K (infrared heating)



TDS spectra of D for annealed and Ne-ion irradiated W after D_2 gas exposure at 773 K for 2 h.

- ✓ **A high desorption peak at about 1010 K only for two irradiated W**

  ~1050 K for n-irradiated W [Hatano,et al]

- ✓ **Broad D desorption spectra from 730 K to 1173 K for the Ne-ion irradiated W**

  i. 730->1173 K for the n-irradiated W
  ii. 930-1050 K for the single energy W-ions irradiated W [Hatano,et al]

- ✓ **Trapping energy: ~1.8 eV** ; nano-voids/large vacancy clusters formed by cascade collisions or the clustering of mono-vacancies during Ne-ion irrdiation

High-energy Ne-ion irradiation together with an energy degrader for tailoring the damage distribution may be an effective way to simulate defects production in bulk W under neutron irradiation.

Deuterium permeation through irradiated W

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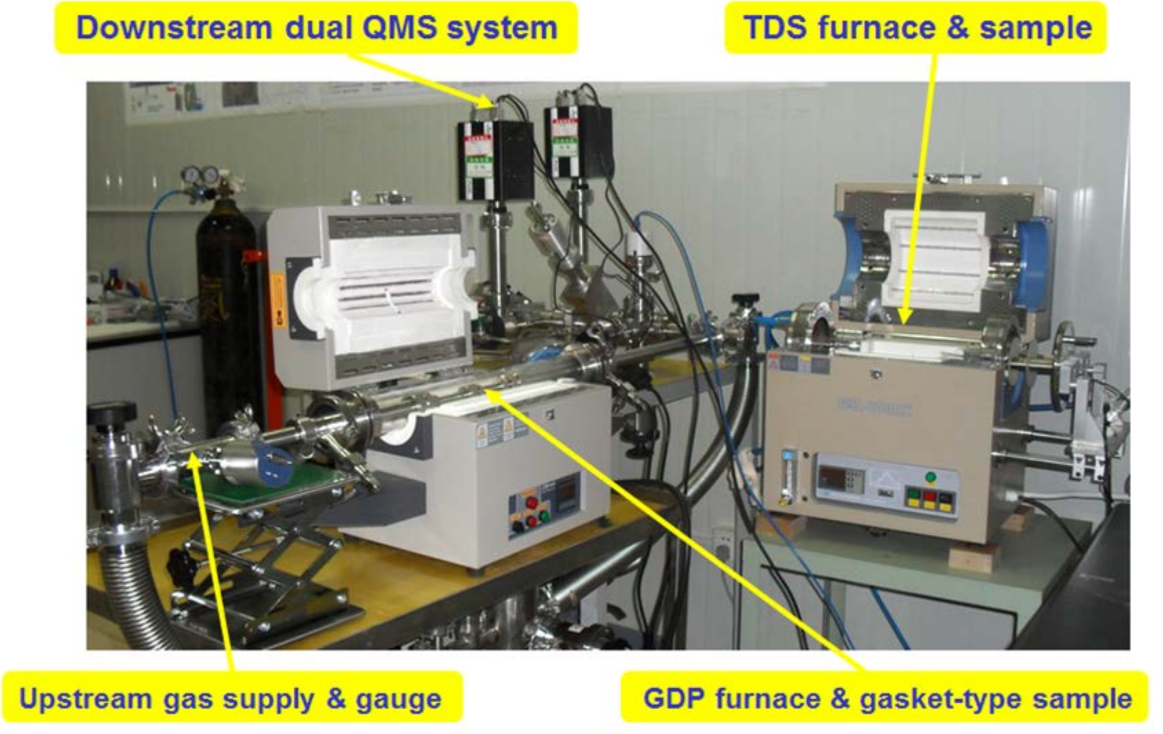
➤ Building a GDP & TDS device at ASIPP



Parameters for GDP device

- **Background pressure: 10^{-5} Pa**
- **Driven D_2 pressure: 10^3-10^5 Pa**
- **Sample temperature: RT-1000 K**
- **Sample sealed by VCR couplings**
- **Signal monitored using QMS**

We tried to study the D permeation behavior through irradiated W with the GDP device. Unfortunately, the irradiated W was very brittle and irradiated samples were limited, we failed to seal the samples.

Effects of non-irradiated defects on D permeation

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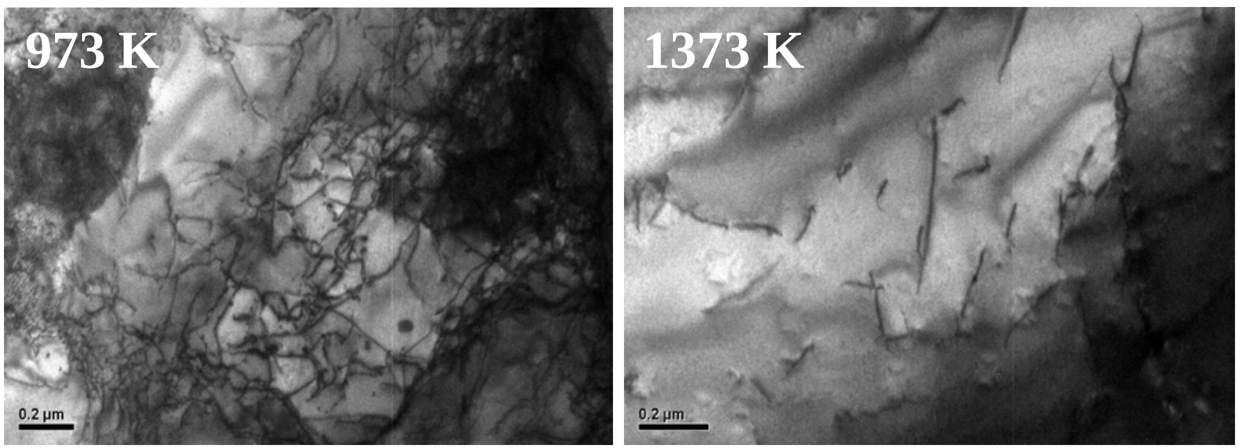
Irradiated W samples failed at sealing, then we focused on the GDP of non-irradiated W specimens which possess different defect types and densities through thermal treatment.

Materials:
- Rolled W : 973 K/2 h
- Annealed W: 1373 K/2 h
- Recrystallized W:1673 K/2 h



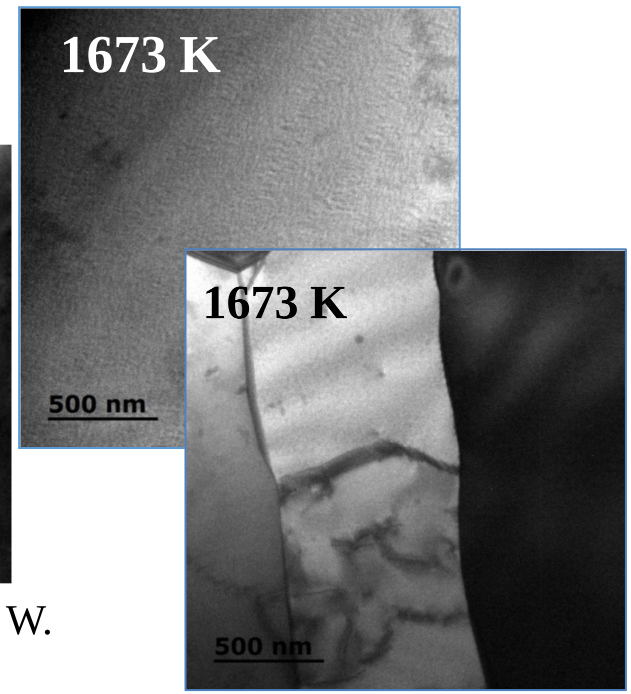
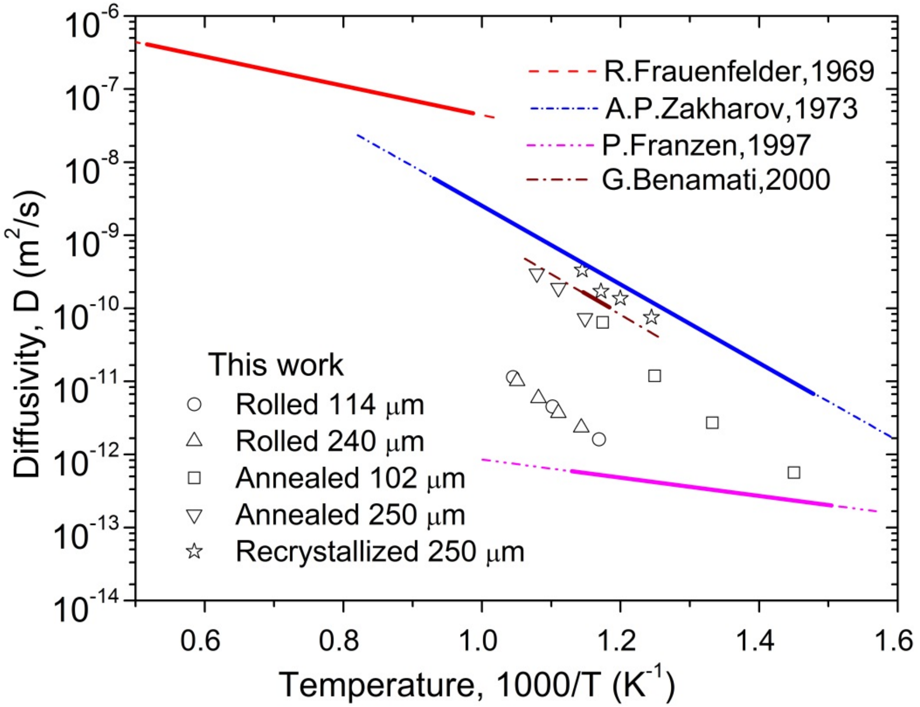


Fig. Bright field TEM observation of rolled/annealed/recrystallized W.

- Rolled W: a dense network of dislocations;
- Annealed W: dislocations fragmented into shorter individual lines or disappeared;
- Recrystallized W : large areas free of dislocations.

Diffusion coefficient of D in various W foils

ASIPP



Diffusivity of D in rolled/annealed/recrystallized W compared with data from literatures

$$J = -D_L \frac{dc_L}{dx} \quad \text{(lattice diffusion)}$$

$$J = -D_{eff} \frac{dc}{dx}, \quad (c = c_L + c_t)$$

(diffusion with trapping sites)

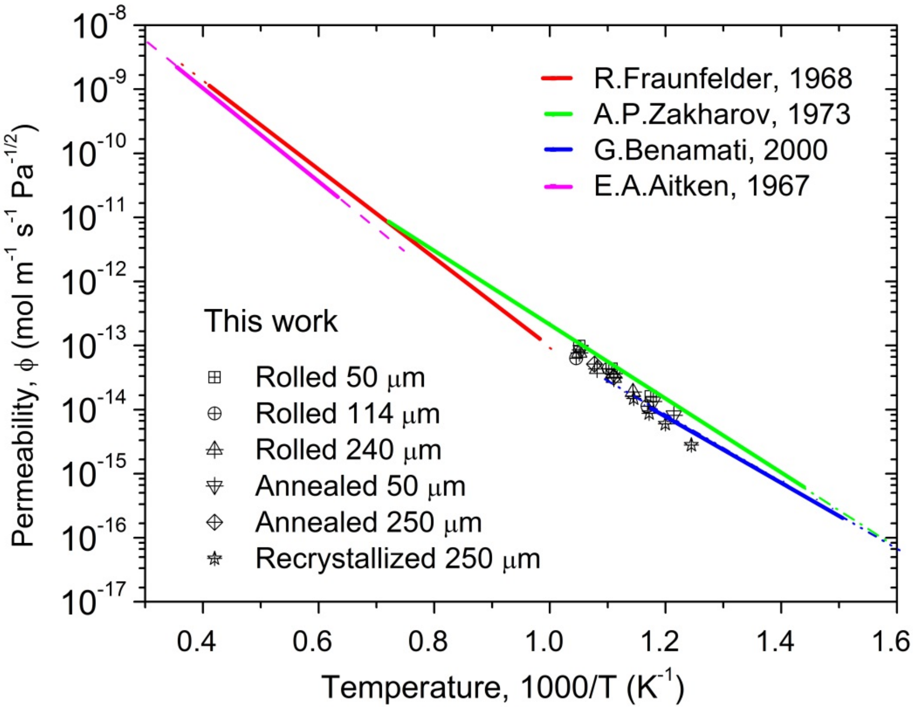
$$D_{eff} = \frac{D_L}{1 + \frac{n_T}{n_L} \exp(\frac{E_t}{RT})}$$

[Oriani' work,1970]

- ✓ The higher the density of defects (n_T) , the lower the effective diffusivity (D_{eff}). Thus the measured diffusivity of D in rolled W, annealed W, recrystallized W increases one by one.
- ✓ If there are trapping sites, $D_{eff} < D_L$; only when the experimental temperature is high enough, the trapping effects can be neglected, then $D_{eff} \approx D_L$.

Permeation coefficient of D in various W foils

ASIPP



Permeability of D in rolled/annealed/recrystallized W compared with data from literatures.

- ✓ Invariable with the dislocation density;
- ✓ Comparable to the literature data which were measured by hydrogen gas-driven permeation method .

The defects in non-irradiated W does not significantly affect the cross section of D diffusion fluxes, hence the permeability of D is almost not affected by the defects in W.

Summary and outlook

Summary & Outlook

- **EAST upgraded its upper divertor into full W/Cu-PFCs, employing HIP technology and e-beam welding in 2014.**
- **Commissioning in 2014 found leaks and damages, and after repairing and optimization, commissioning in 2015 was successful to the end of the Spring campaign.**
- **Plasma-tungsten interactions (PWI) have been studied in 2014-5 campaigns via monitoring the upper divertor by means of spectrocopies and Langmuir probes.**
- **A quasi-homogeneous atomic damage (mainly large vacancy clusters) achieved to 50 μm deep in W by heavy ion irradiation.**
- **High D desorption peak and broad D desorption spectra, similar to that from n-irradiated W, have been observed.**

Thanks for your attention!
Welcome to collaborations!