EAST
/HT-7

ASIPP

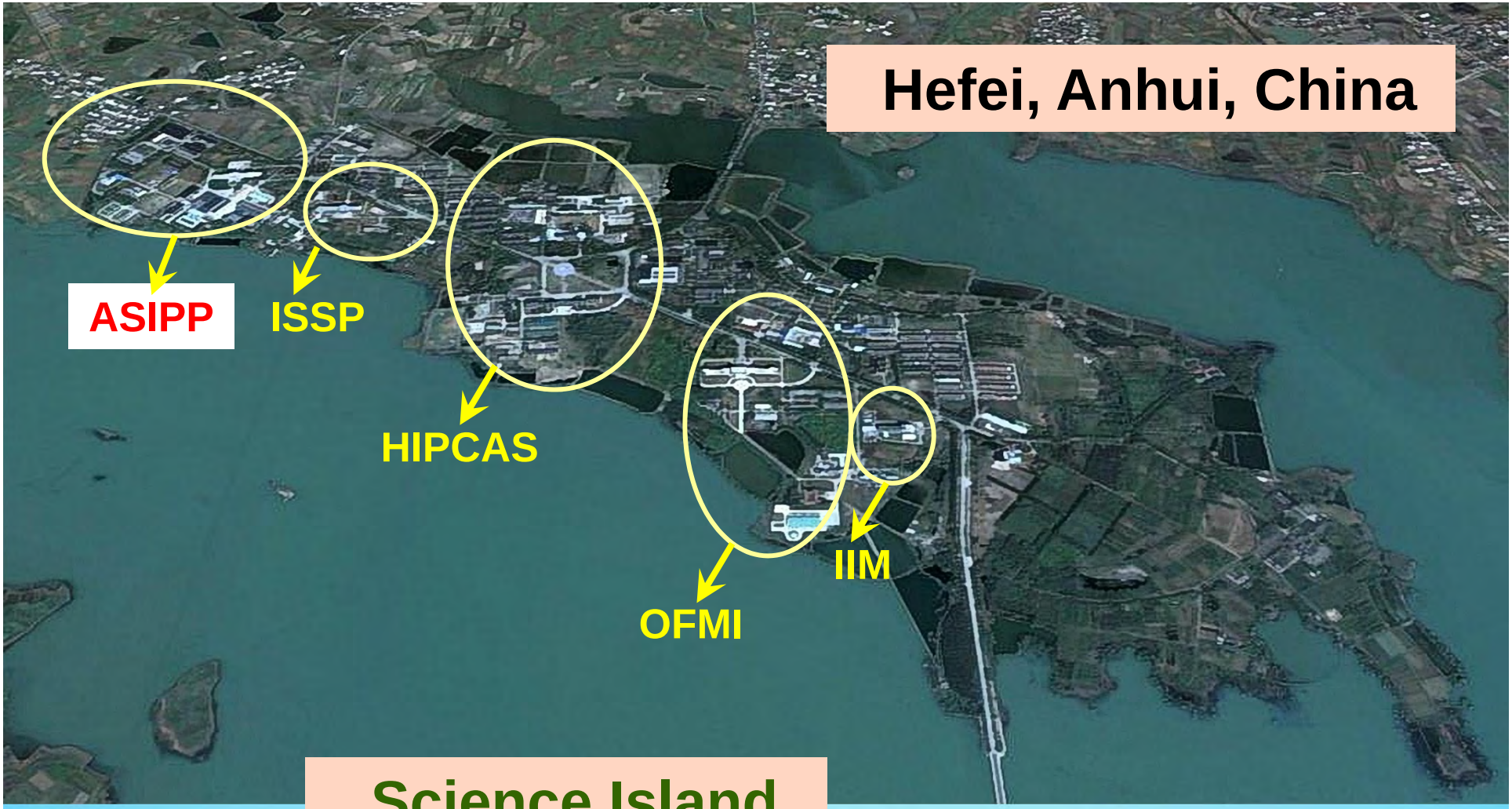
PFM Group and Activities

Guang-Nan Luo

Institute of Plasma Physics, CAS

ORNL Talk, Oak Ridge, October 25, 2011

Institute of Physics Plasma, Chinese Academy of Sciences (ASIPP)


Hefei, Anhui, China
ASIPP
ISSP
HIPCAS
OFMI
IIM

Science Island

Activities at ASIPP

Main research activities

- Magnetic confinement fusion and high temperature plasma physics
- Fusion engineering and technologies
- Low temperature plasma
- and application
- Superconductor and cryogenic engineering
- High magnetic field
- R&D of solar cell

Manpower and team

• Permanent staff	460
• Contract	140
• Average age	42
• Senior researchers	46
• Associate professors	80
• Graduate students	436
• Post-doctors	16
• Divisions	14
• Centers	2
• R&D Companies	6

Plasma-Facing Materials Gr.

ASIPP

Missions

- Maintenance of EAST PFMC (engineering)
- PFMC for future use on EAST & DEMO (R & D)
- PWI Studies (experiments and simulations)

Staff (>20)

- 1 professor, 1 associate professor, 5 assistants
- 6 PhD candidates, 8 postgraduates

Funding (>￥5million/year)

- Ministry of Science and Technology (MOST-ITER)
- Natural Science Foundation of China (NSFC)

EAST - Experimental Advanced Superconducting Tokamak

National Mega-Science Project

EAST: Mega-science Project

ASIPP

Steady-state high-performance plasma: physics and technologies

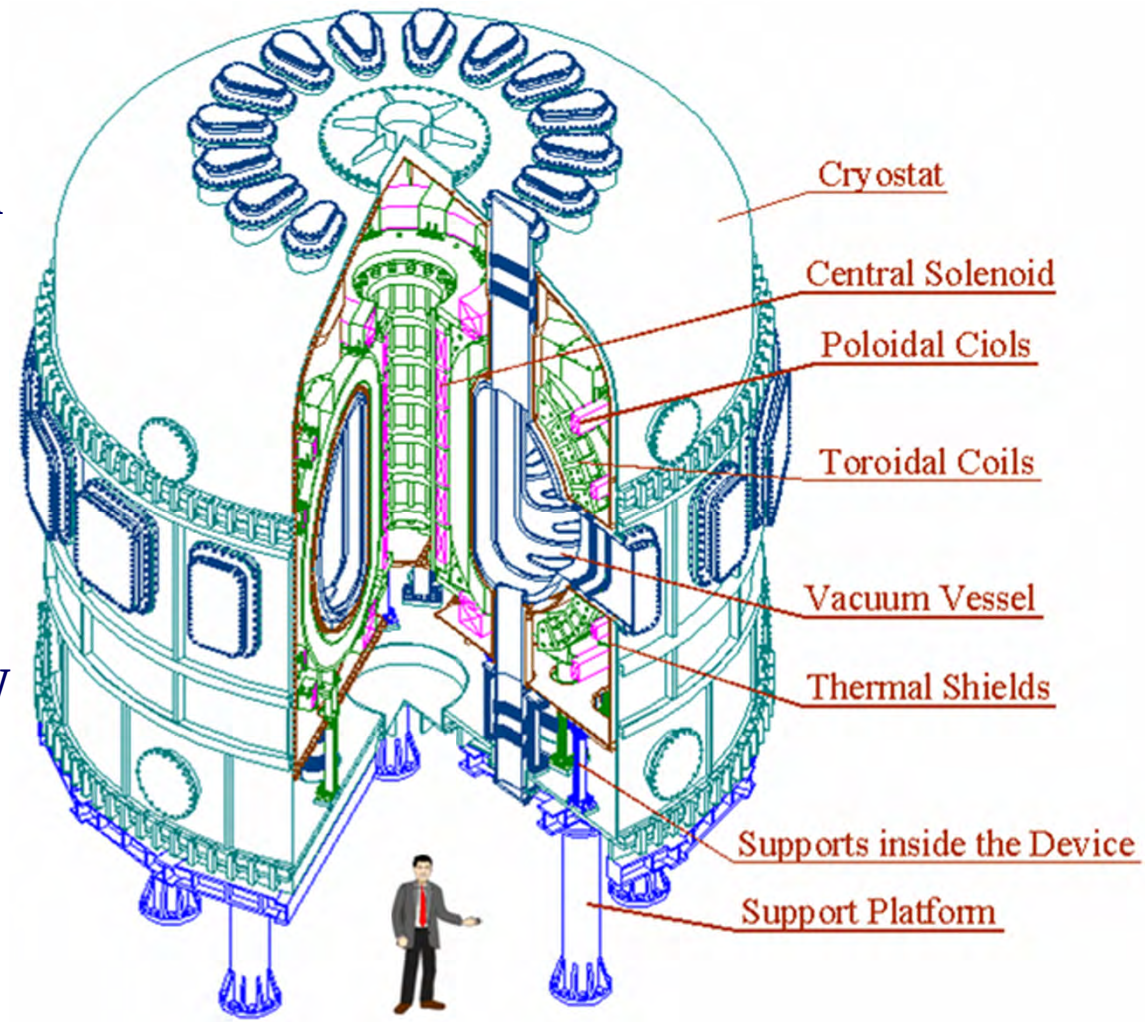
Main Parameters

Toroidal Field, B_o	3.5(4) T
Plasma Current, I_P	1(1.5) MA
Major Radius, R_o	1.7-1.9 m
Minor Radius, a	0.4-0.5 m
Aspect Ratio, R/a	4.25
Elongation, κ_x	≤ 2
Triangularity, δ_x	≤ 0.6

Heating andCurrent Driving:

ICRH	6 (9) MW
LHCD	4 (10) MW
NBI	0 (4) MW
ECRH	0 (6) MW

Pulse length	1000 s
Configuration: DN,	SN



2006 Spring/Completion, September/first plasma

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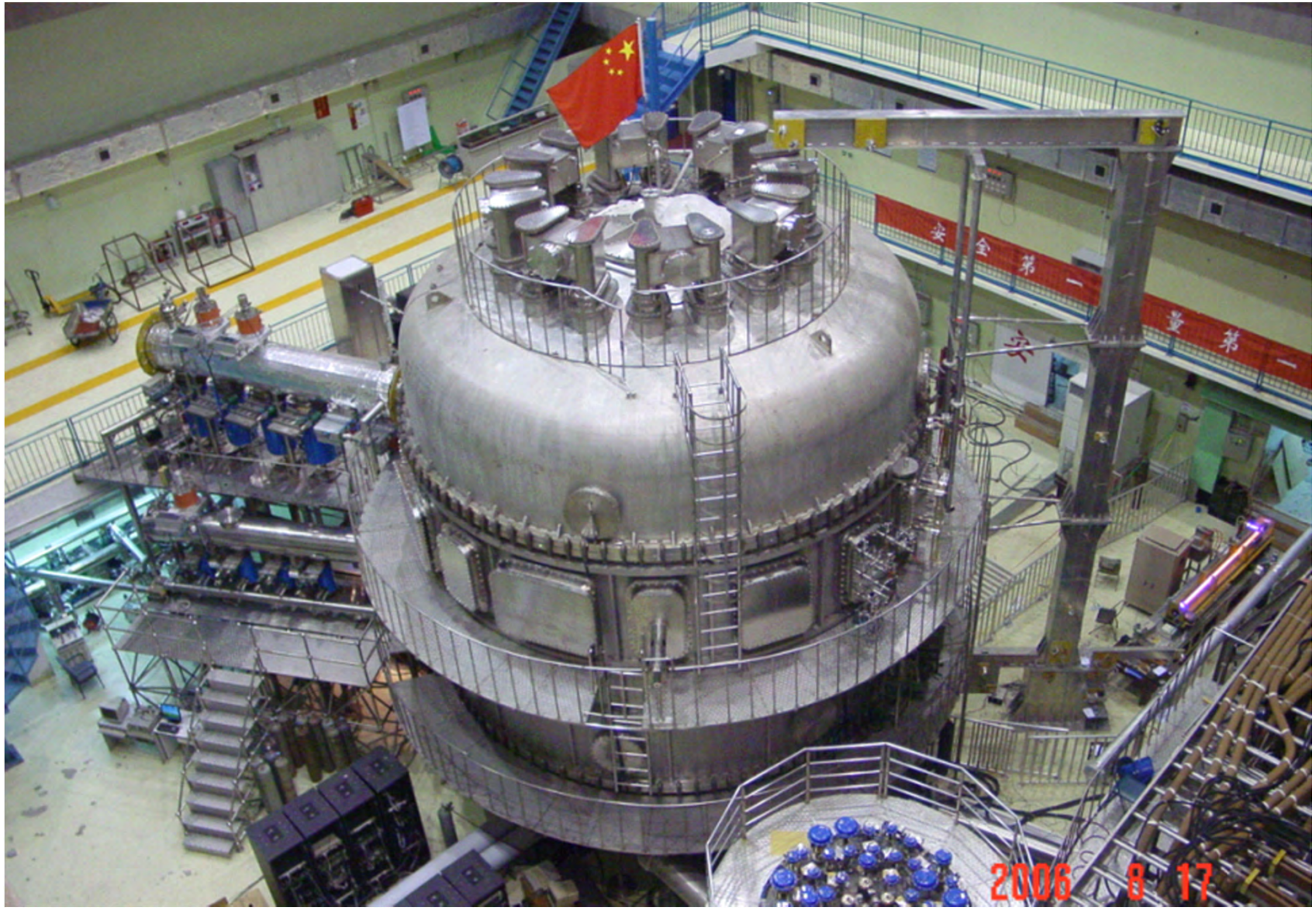

Recent progress → 0.6MA/6.4s H-mode

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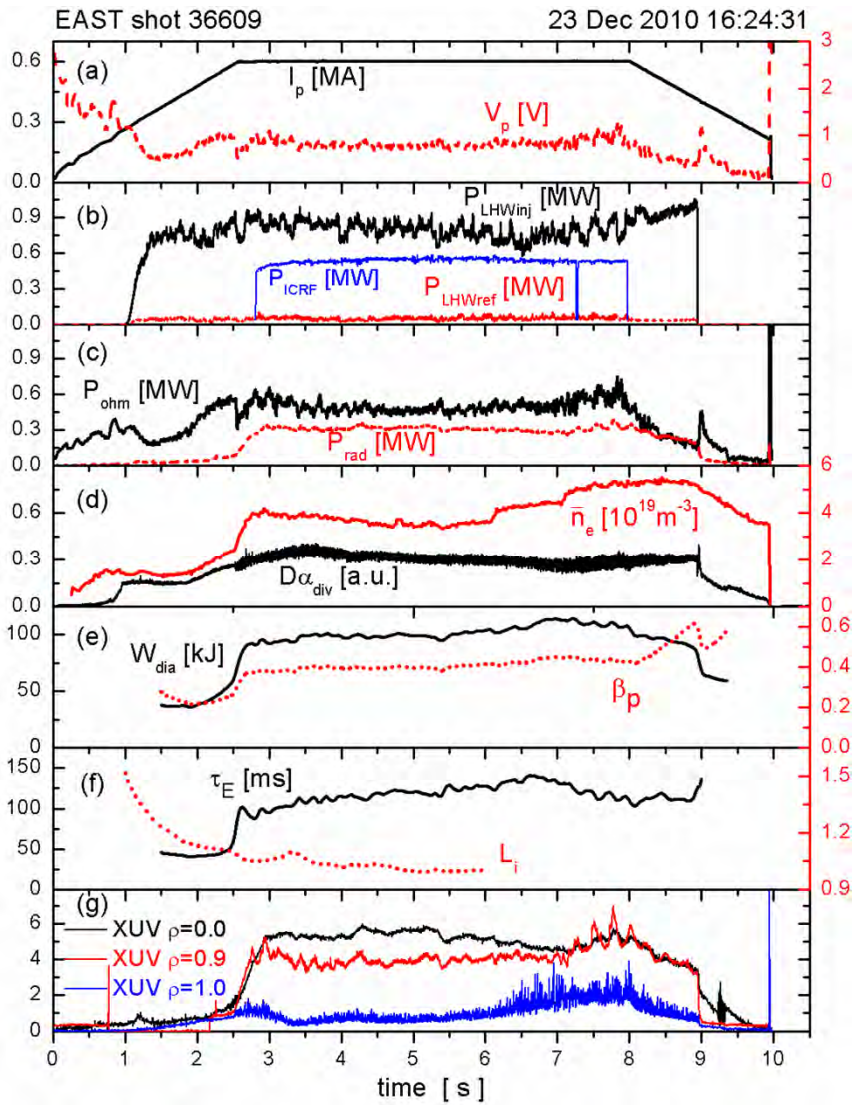

Power: LHCD 2.45GHz, 1.3MW, ~14% transmission line loss; ICRF 20-70MHz, 1MW, effective coupling < 0.5 MW

PFC: Doped graphite tiles with a ~100 μm SiC coating bolted to Cu heat sink

Wall conditioning: Lithium evaporation and lithium powder injection

Pumping: In-vessel cryopump, pumping speed ~75.6 m^3/s for D_2

5 -Year Plan of EAST experiments

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	2011	2012	2013	2014	2015
Ip(MA)	1.0	1.0	1.0	1.5	1.5
LHCD(MW,CW)					
2.45GHz	4.0	4.0	4.0	4.0	4.0
4.6GHz			6.0	6.0	6.0
ICRF(MW,CW)					
20-75MHz	4.5	4.5	4.5	4.5	4.5
30-100MHz	1.5	4.5	4.5	4.5	4.5
NBI(MW,80keV,10s)			4.0	4.0	4.0
ECRH(MW,140GHz,CW)		2.0	4.0	6.0	6.0
Diagnostics	40	45	50	50	50
Duration(s)	100	200	300	400	400
t-Hmode(s)	10	20	30	60	100

With over 20MW CW power and 50 diagnostics, EAST could play a key role for long pulse advanced high performance plasmas for ITER within next 5 years!

Tungsten Plasma-facing Materials

PFMs for ITER

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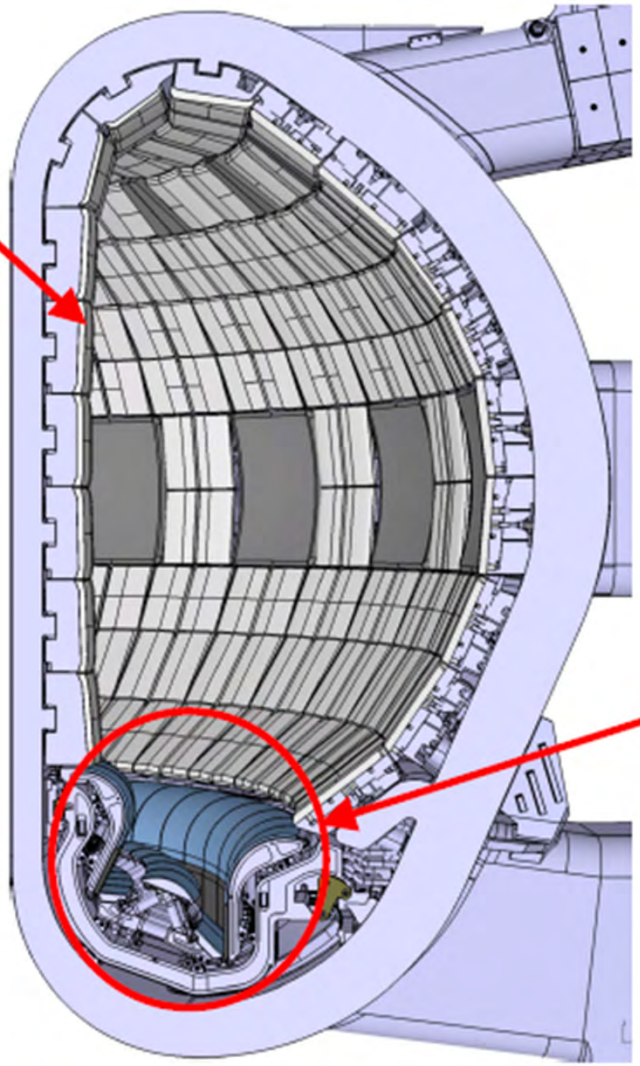
First wall
~700 m^2
Beryllium
replaceable → high Z (W) after first DT phase?



Divertor
~160 m^2
CFC/W, non active phase
All-W, for nuclear phases

PFCs for ITER Divertor

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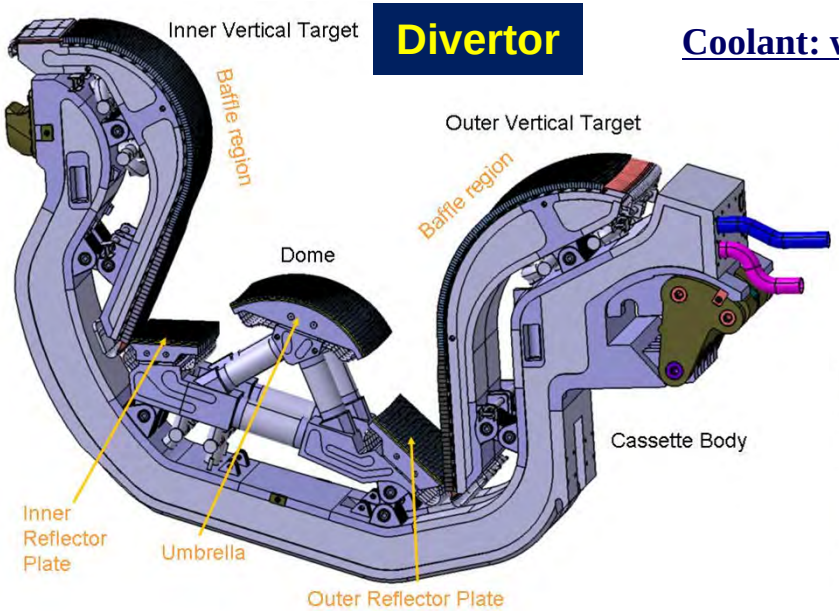
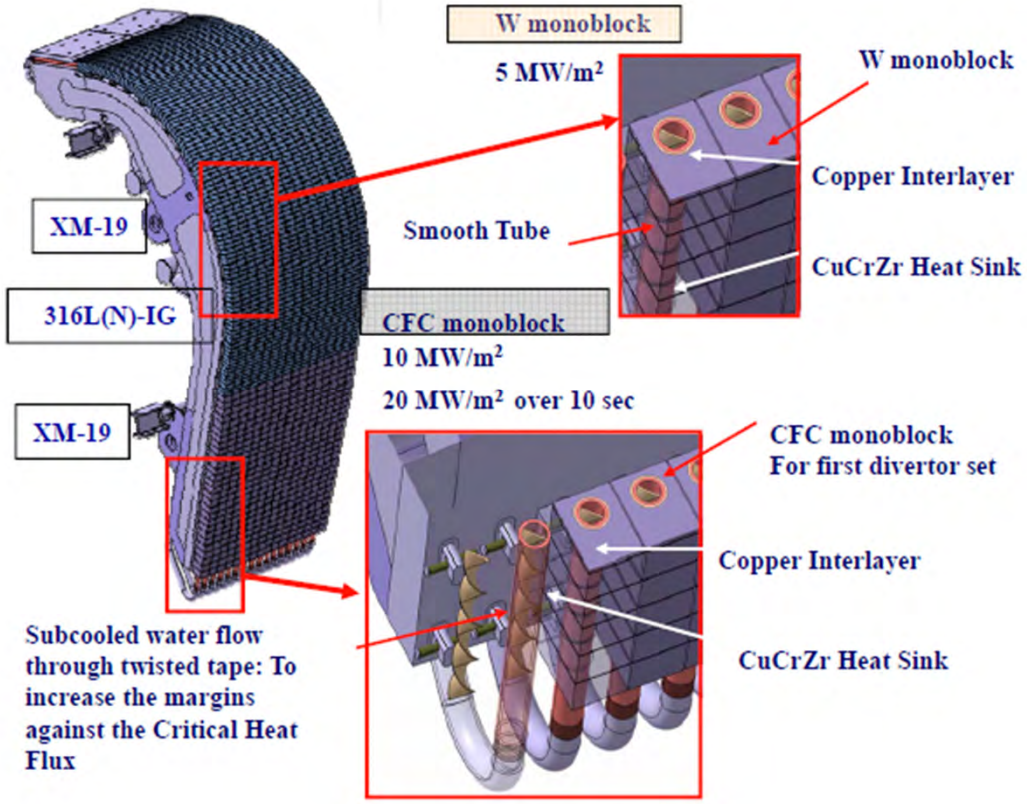
Divertor

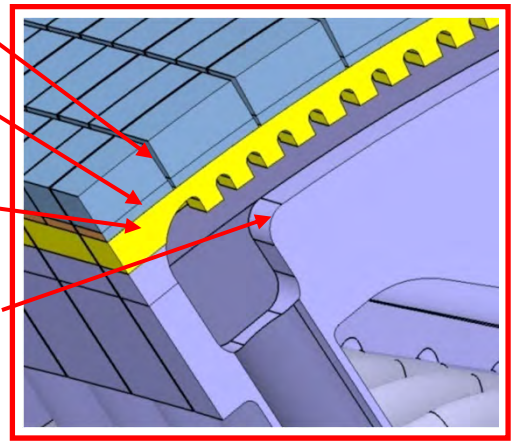
Coolant: water@100℃/4.2MPa



Vertical targets



W Flat Tiles on Dome **5 MW / m²**



54 divertor assemblies (~8.7 tonnes each)
4320 actively cooled heat flux elements
Bakeable to 350° C
First divertor (nonactive operation):
CFC at strike points, W on the baffles
All-W for nuclear phase

Divertor Qualification Prototypes

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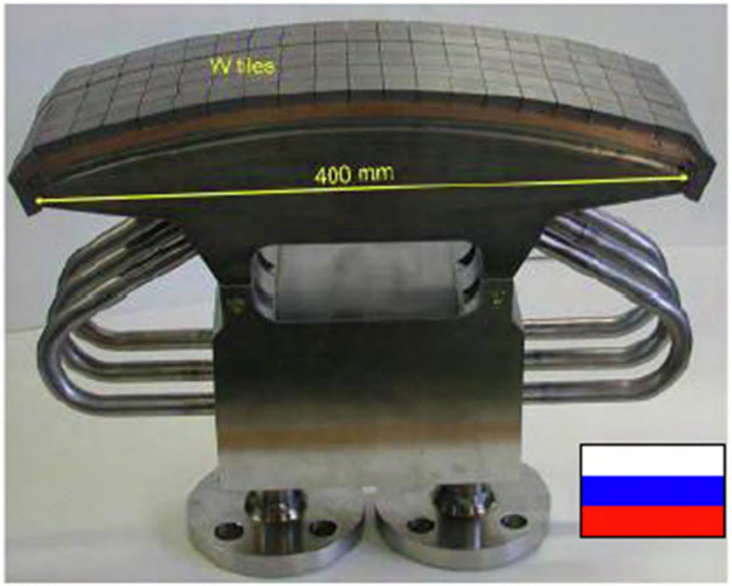
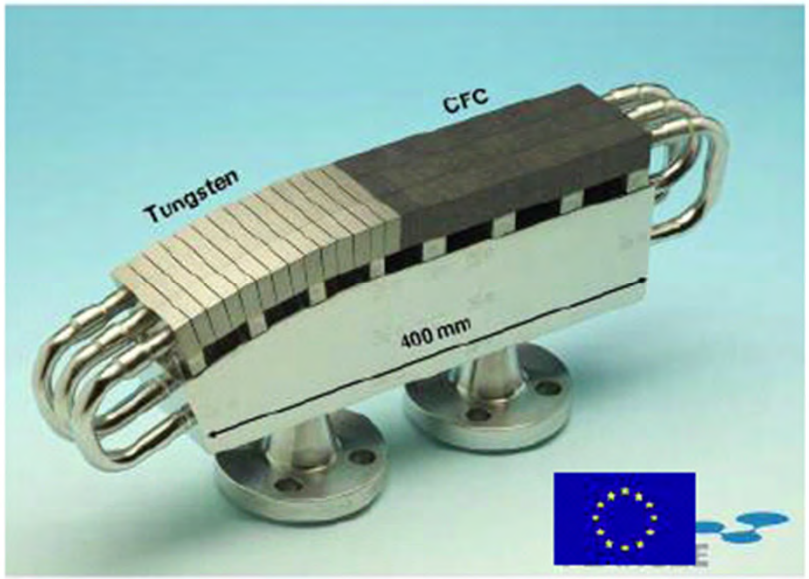
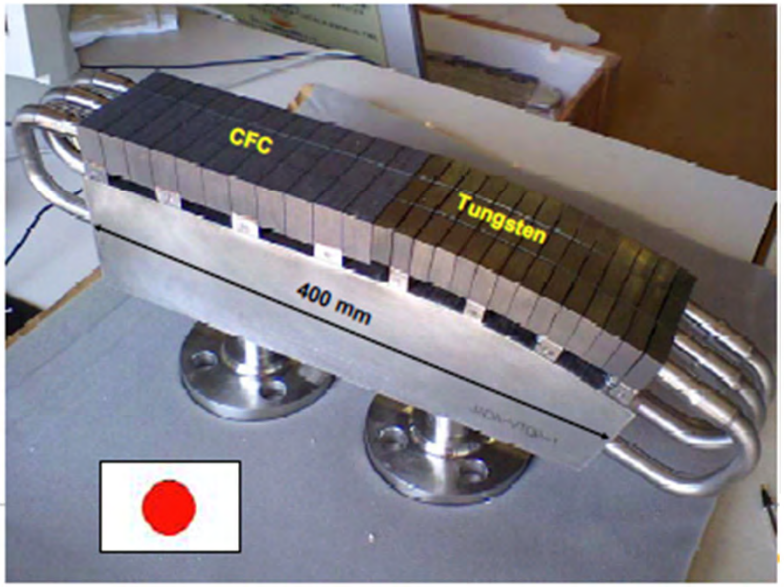
A qualification is "*…needed for the critical procurement packages shared by multi-Parties…*", including the divertor

All the 3 Domestic Agencies have qualified

Procurement started in June 2009







JET ITER-like Wall (ILW) Project

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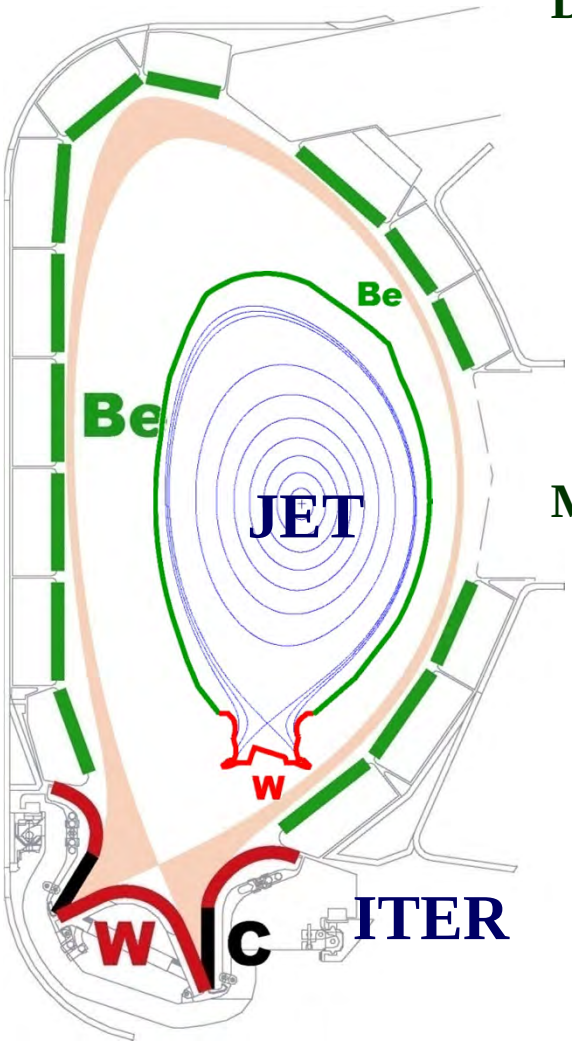
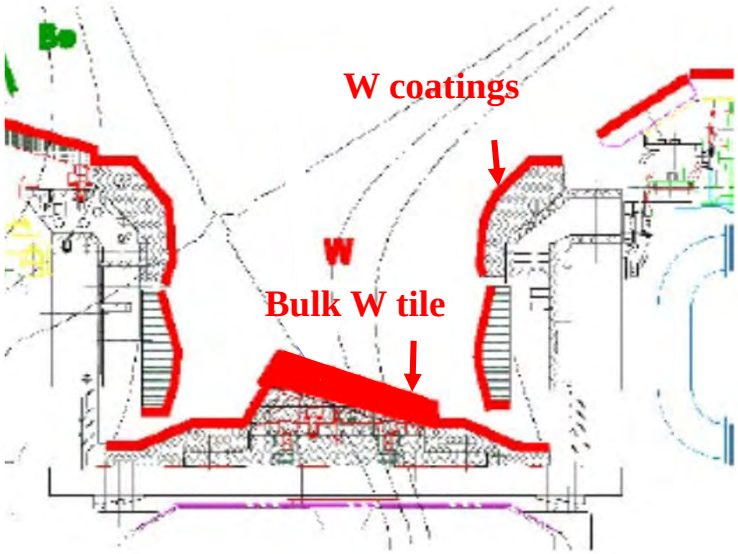


Divertor

- **Outer divertor**
  - **W coating and bulk W tile**
  - **Marginal erosion lifetime of thin (10 µm) W coatings at the strike point**
- **Inner divertor**
  - **W coating**
  - **Strong deposition zone**

Main chamber

- **Large amount of bulk Be tiles and Be coating on Inconel tiles**



Lamellae design as bulk W component

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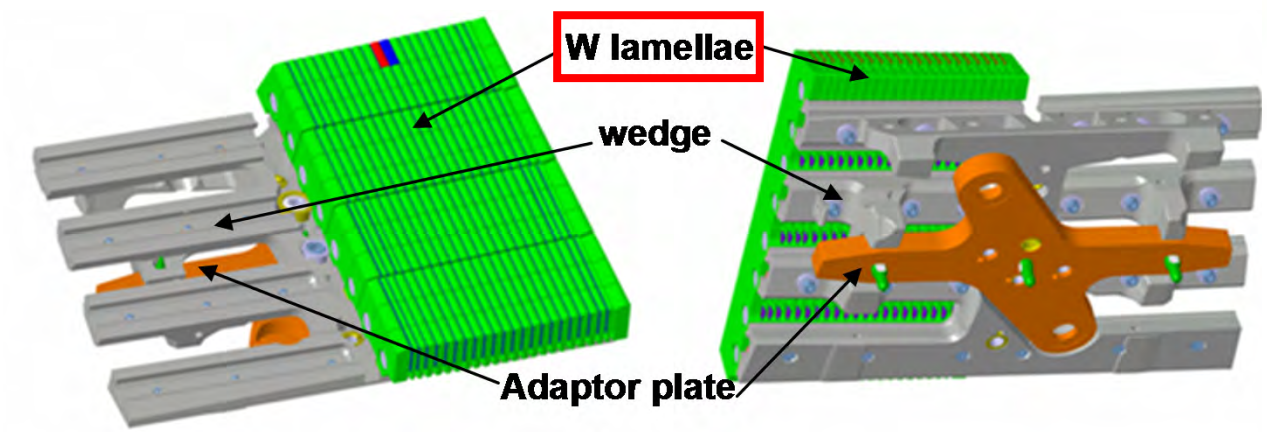
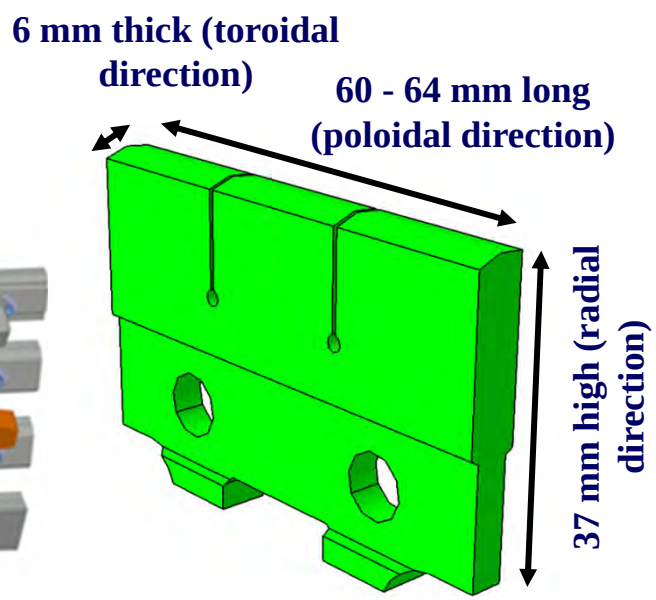
- **Bulk W component: thermal load ≤ 7 MW/m^2 for 10 s, goal for development of 10 MW/m^2 for 10 s without direct active cooling**
- **W lamellae parts**
  - **Keep heat capacity, but keep dimension and weight-limit.**
  - **Reduce EM loads**
- **Support structure (wedge, adaptor plate)**

Procurement
~10,000 tiles



View from top

View from bottom



Standard lamellae

First Plasma – a huge success

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- At 18:29, 24 August 2011, eye witnesses following the first plasma after the 22-month shutdown 2009-2011, the scientists at JET saw an extraordinary plasma on the first attempt
- The plasma was created and controlled for 15 seconds, reaching a maximum current of 1.1 MA
- The plasma appeared on the screen as a "pink, poached salmon plasma" with the first impression from spectroscopy that the plasma was very clean

Plasma-facing Materials for EAST

PFMC for EAST

ASIPP

Missions of EAST

- steady-state high-performance plasma
- physics research and technology development

PFMC corresponding to different phases

- Initial phase (2006-2007), PFM was SS plate bolted to the support w/o active cooling
- First phase (2008-2010) with limited heating (max. heat flux onto divertor ~ 2MW/m^2), PFM is mainly SiC-coated doped graphite tiles bolted to Cu heat sink
- Transition phase (2011-2013) TZM on FW, still C on Div
- Second phase (2014-) with more heating (>10MW), PFCs will be changed into actively-cooled W/Cu-PFC gradually (max. heat removal onto divertor ~10MW/m^2)

PFMC plan for EAST

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- **To accommodate to Li wall conditioning and to reduce wall recycling, the whole first wall of EAST has been being replaced using TZM in 2011, while keeping C for divertor**
- **To withstand rapid increase in particle and power impact onto divertor, EAST has launched a project to achieve a divertor with ITER-like PFC configuration (completion before 2015)**
- **The project could not only help EAST experiments, but also realize ITER PFC technology validation and bring answers in a timely manner for ITER full W divertor for the nuclear phase**
- **Three kinds of actively-cooled W/Cu-PFCs are under development currently, i.e., thick VPS coatings, monoblock type, and flat type**

Three phases for EAST

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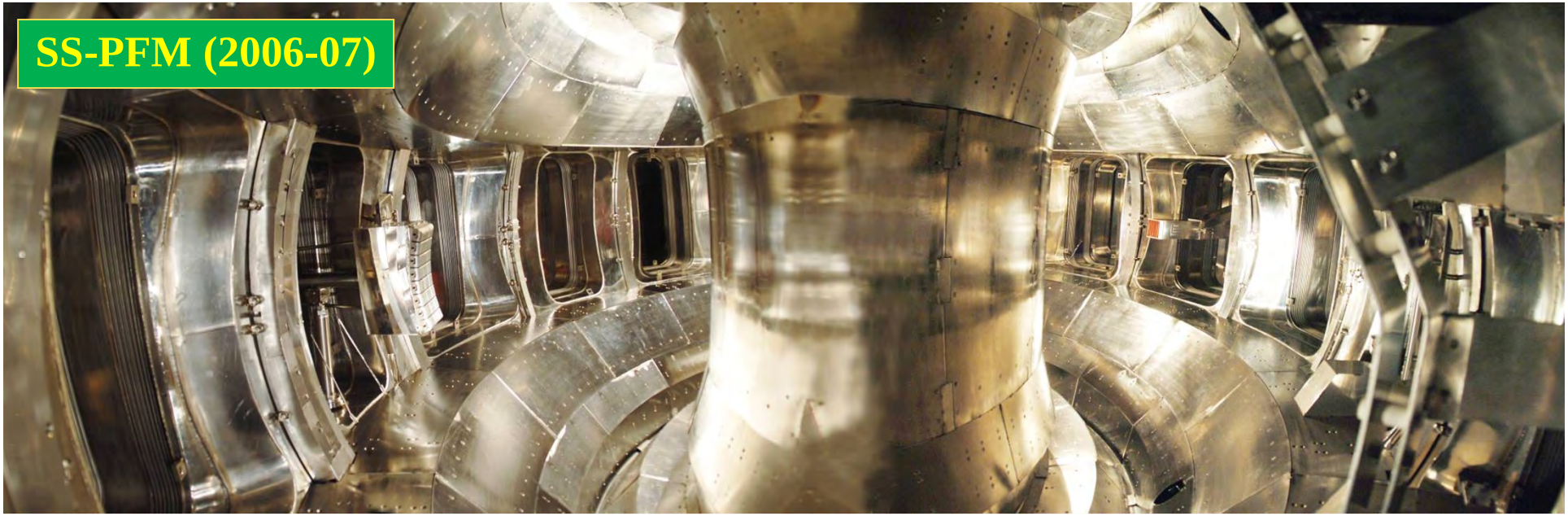

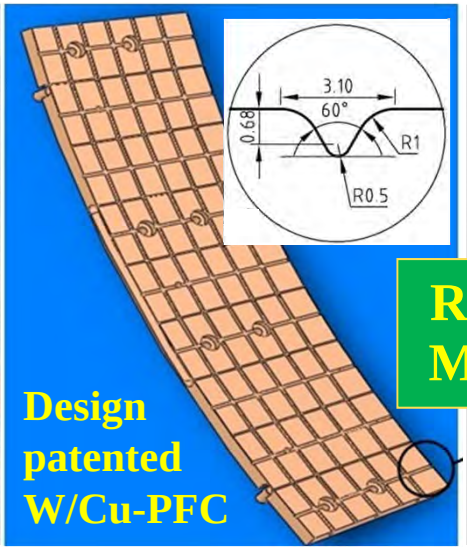

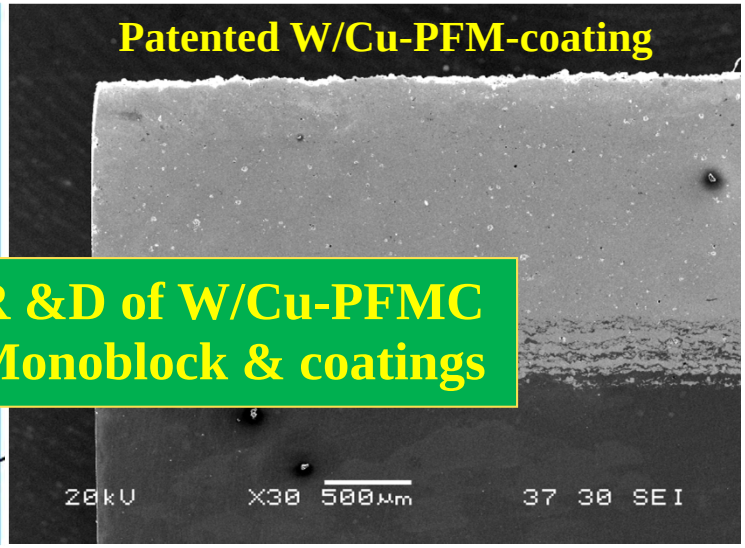

Transition phase – TZM as PFM

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Divertor: SiC/C

Targets

Dome

First wall: TZM

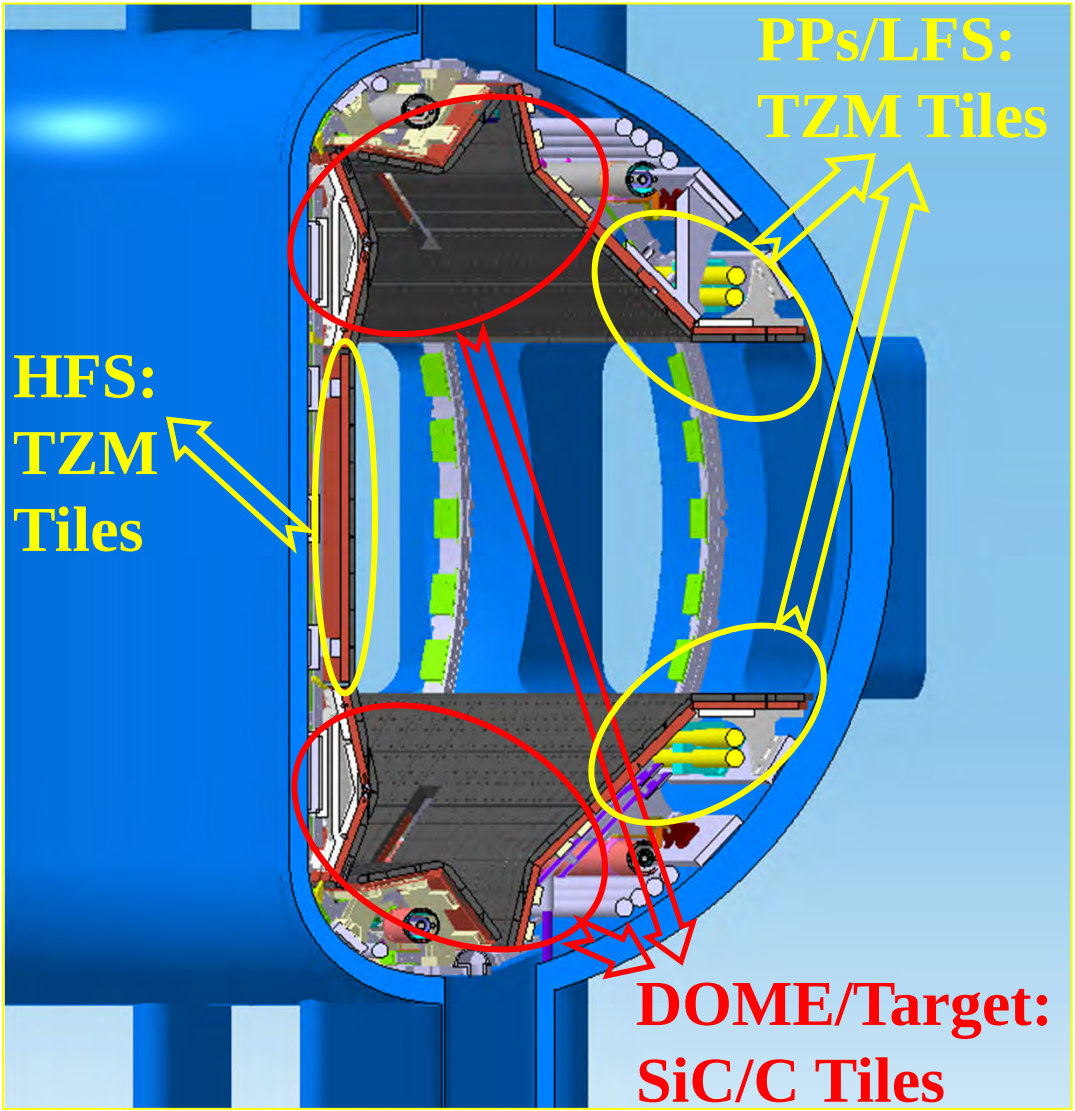
HFS/LFS

Passive plates

Connection

Bolting/C-sheet

1-2MW/m^2



TZM for EAST

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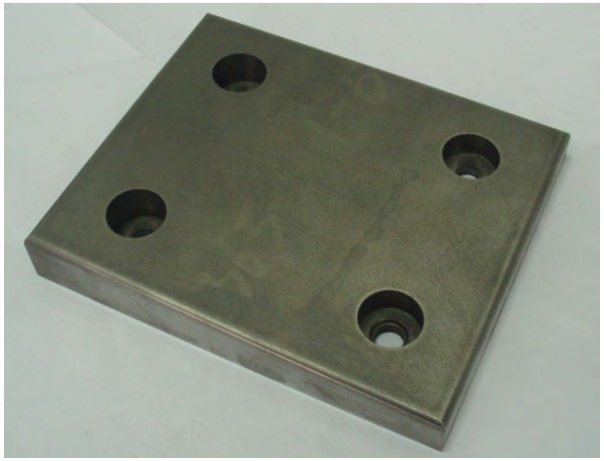
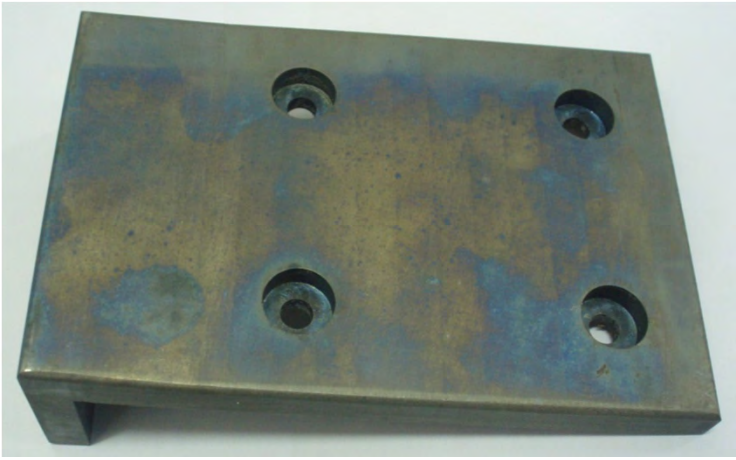
- **Procurement: 24 types, 3261 pieces, 3200 kg, 180 days**
- **Quality: chemical composition: Mo-0.5Ti-0.1Zr (ASTM B387 type 364, Powder Metallurgy, equivalent to GB/T3876-2007); upset forging working, both x & y directions: $\sigma_b \geq 600$MPa, $\delta_5 \geq 3\%$, and $\sigma_b \geq 500$MPa for z direction (judged by metallographic uniformity)**
- **Same quality as those for C-Mod use from H.C.Stark**





Details of the W/Cu project

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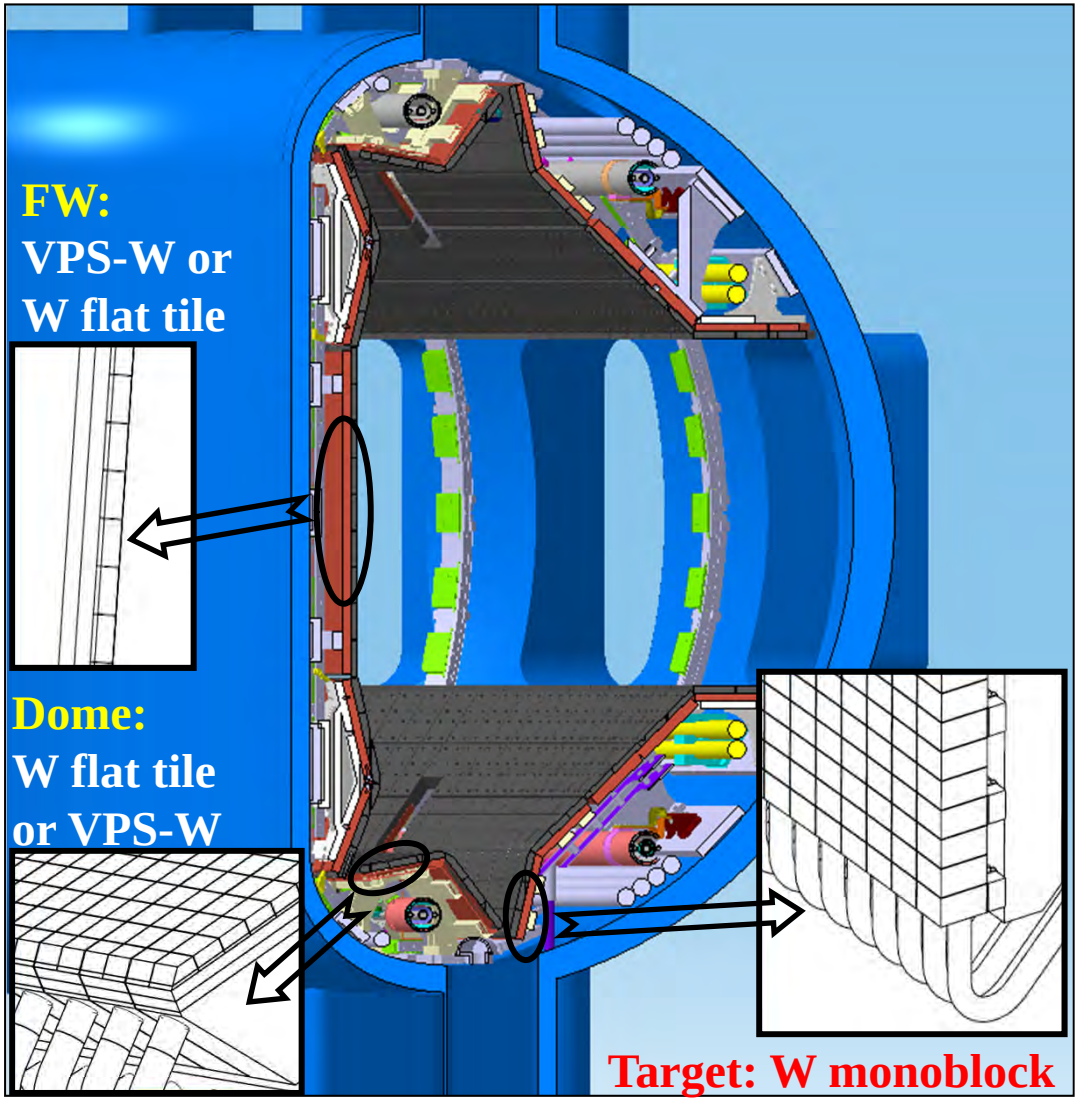
Divertor

- ITER-like configuration and structure, i.e., Monoblock targets and flat type dome
- Max. heat flux capability of divertor targets ~10MW/m^2

First wall

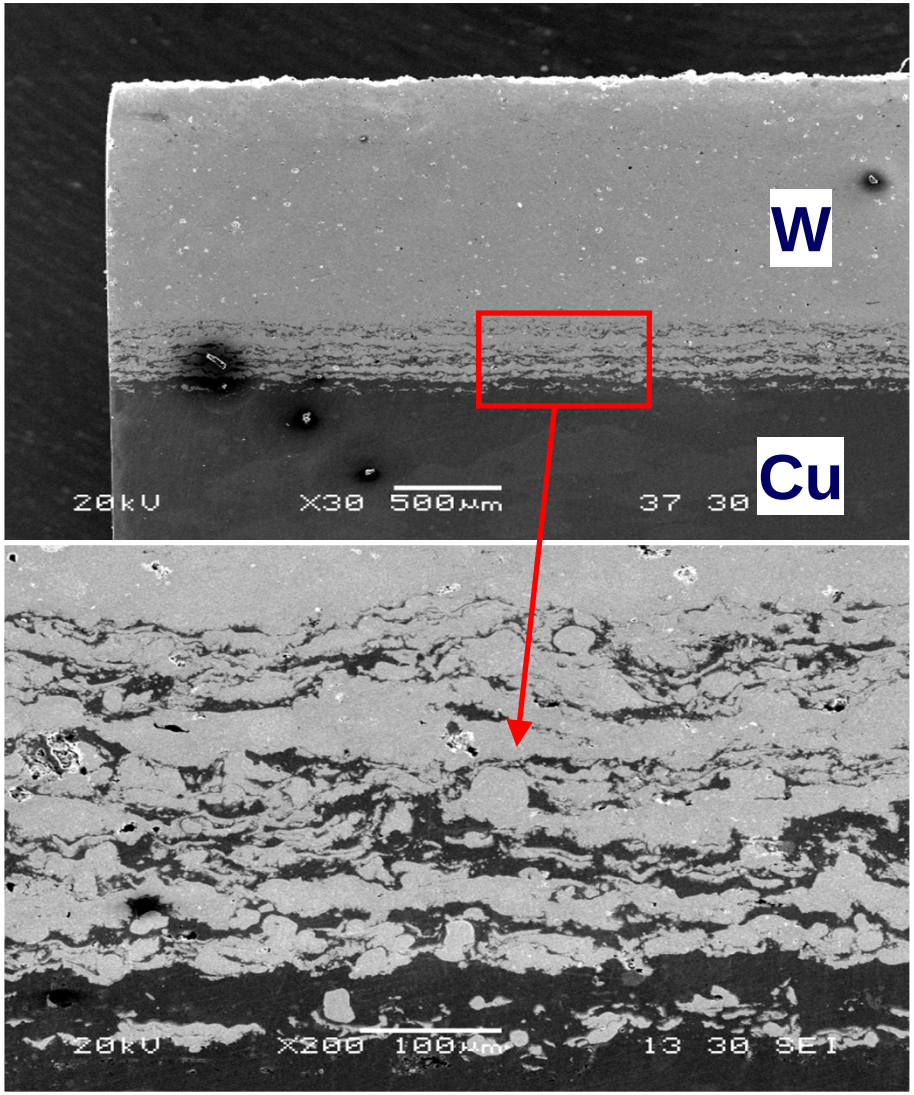
- VPS-W coatings on actively cooled Cu heat sink or the flat type PFC
- Max. heat flux capability ~2MW/m^2



R & D of W/Cu-PFMC for EAST

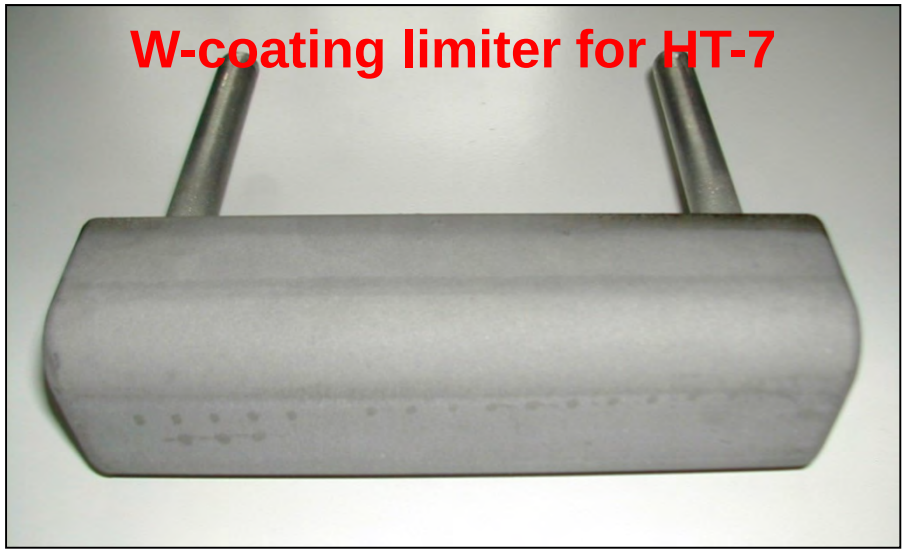
VPS-W coatings (properties)

ASIPP



Properties of VPS-W coatings

Thickness (mm)	1~1.5
Bonding strength (MPa)	40
Porosity (%)	~2.8
Thermal conductivity (W/m/K)	122
Oxygen content（wt%）	0.1



R & D of VPS-W/Cu PFC

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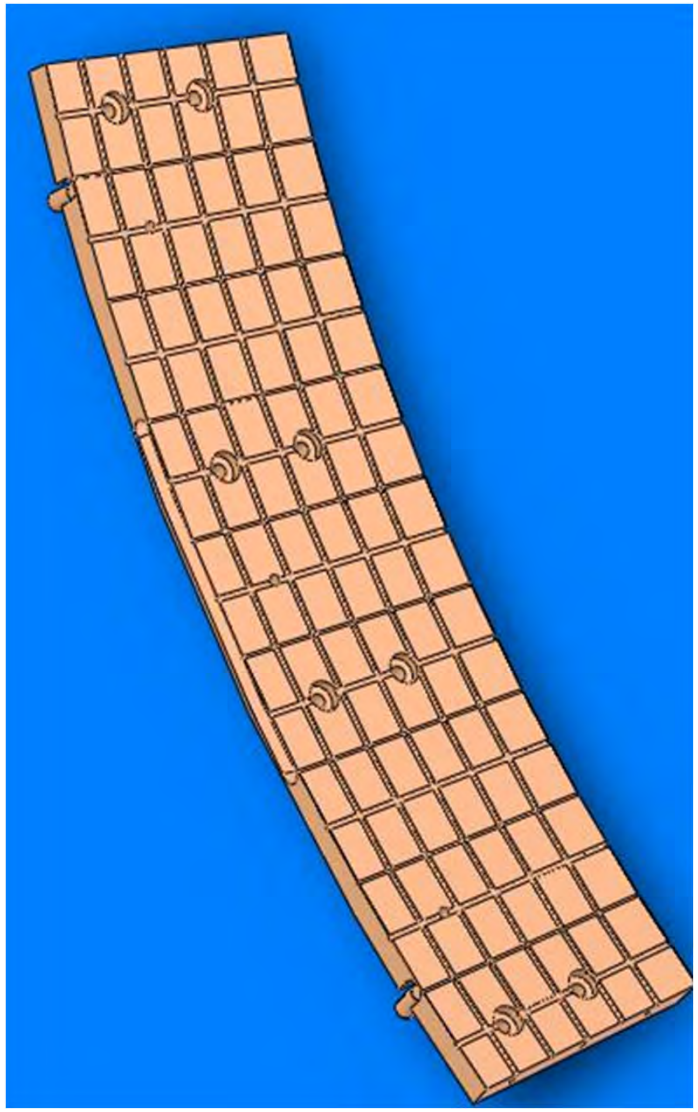

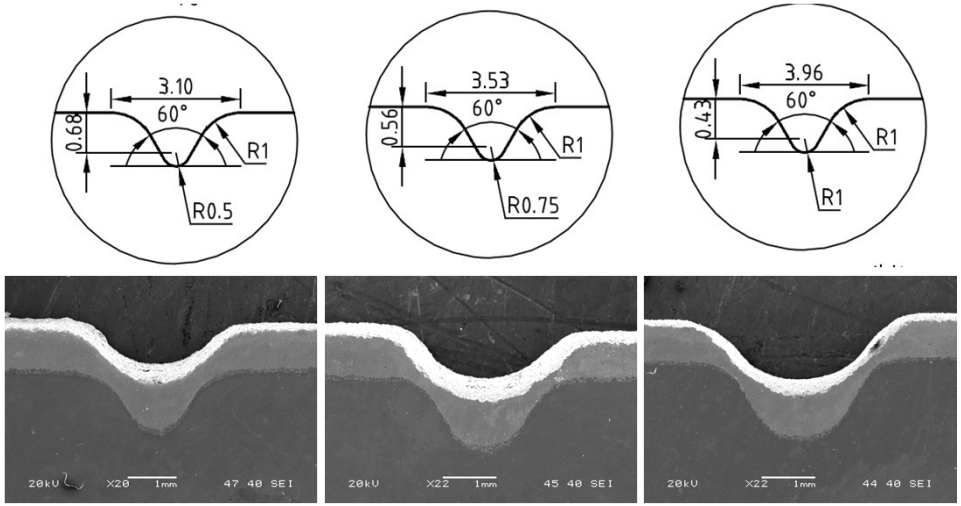

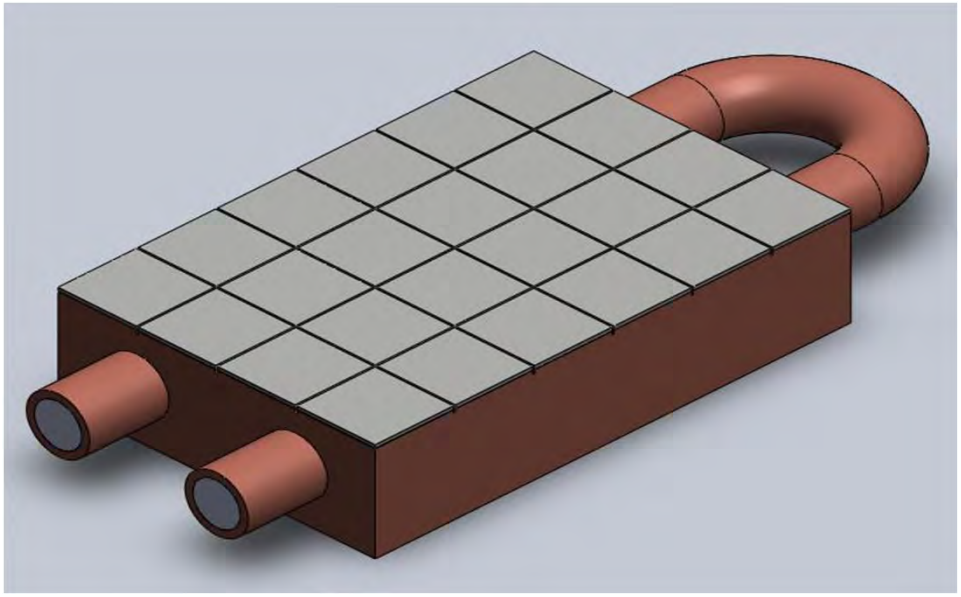

ITER-like W/Cu monoblocks

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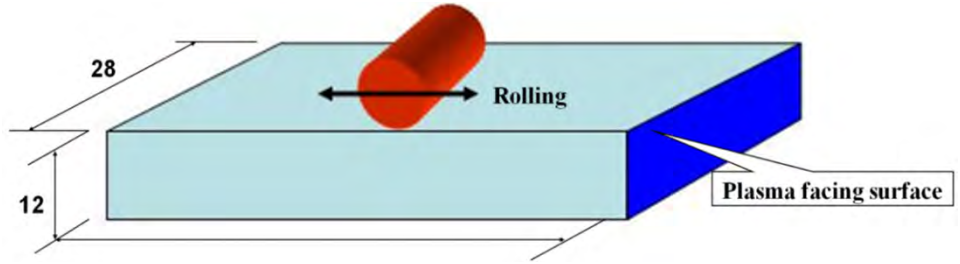
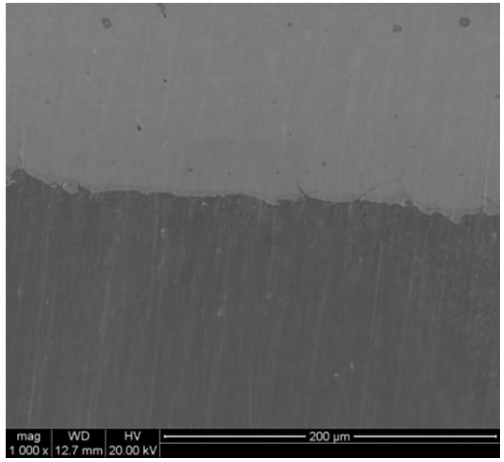
- **ITER grade W has been manufactured recently and efforts to achieve ITER-like monoblock W/Cu PFC were also made in collaboration with domestic institutions**
- **W/Cu monoblocks have been successfully prepared by means of HIP technology with W/Cu bonding strength ~150MPa**

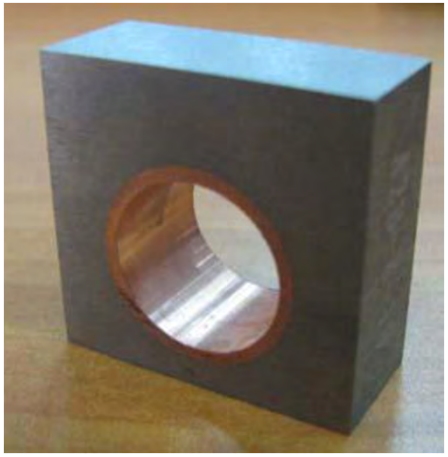


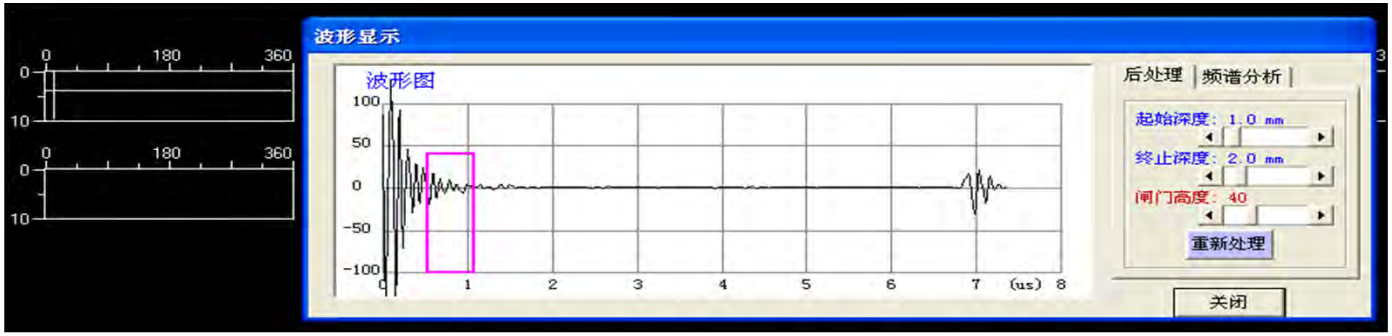


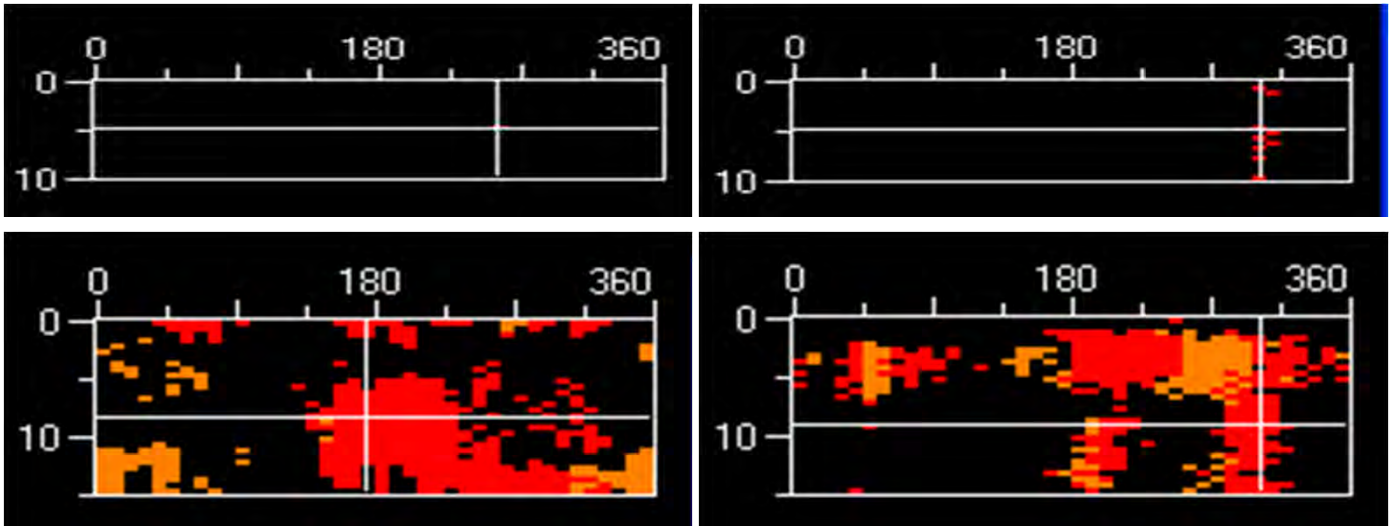
NDT of W/Cu monoblocks

ASIPP

- **HIP connection of OFC and W**
- **Spiral+translation Ultrasonic and more NDTs**
- **Batch production capability**







ITER-like Monoblock W/Cu PFMC

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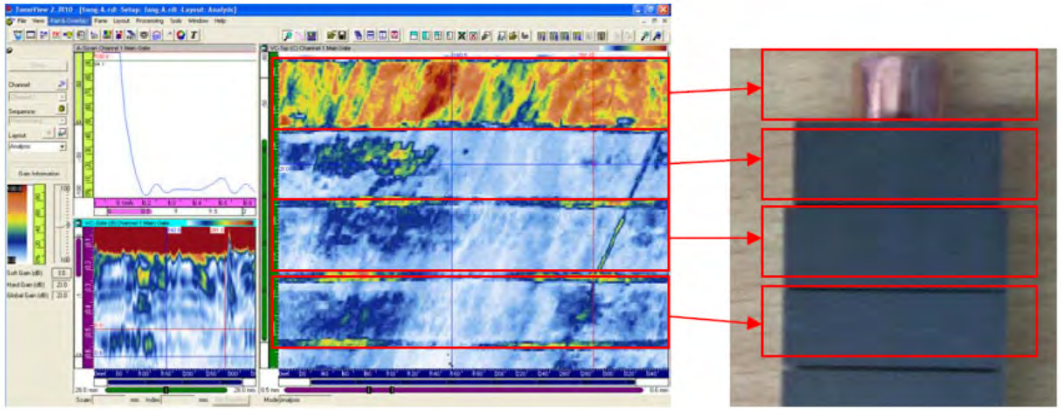
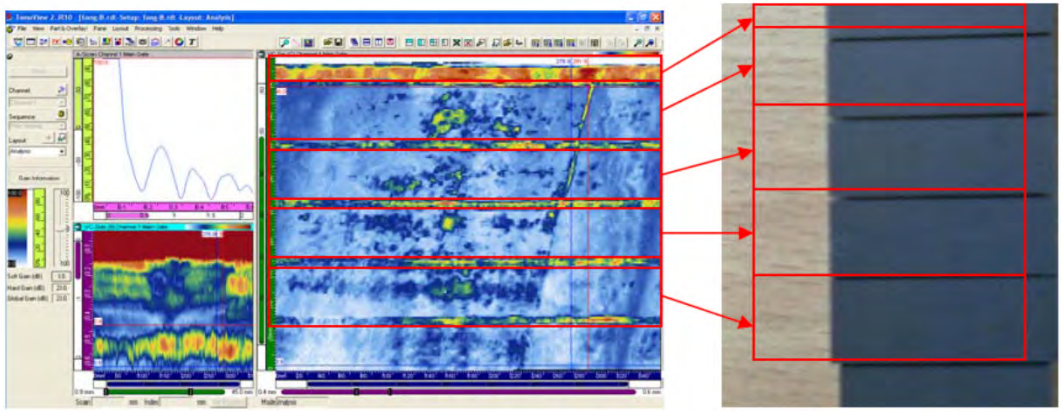
Brazing welding of the monoblocks to the CuCrZr cooling tube and NDT testing have been done, and the HHF testing is underway.





ITER-like Monoblock W/Cu PFMC

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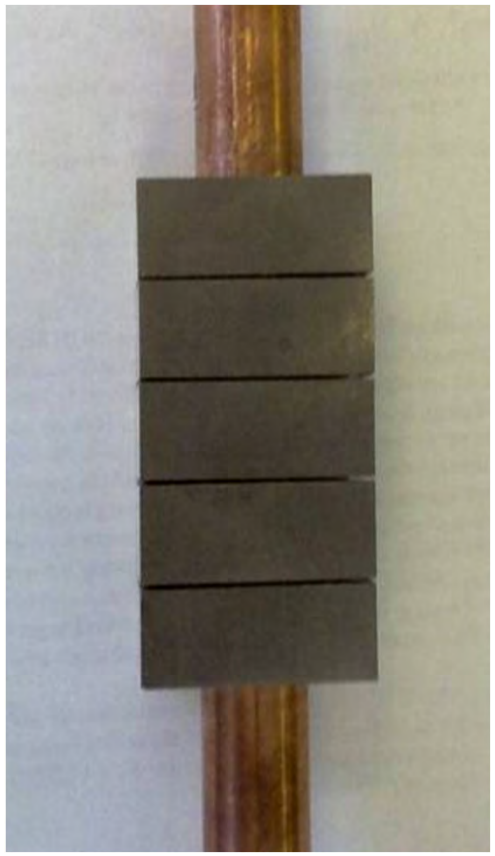
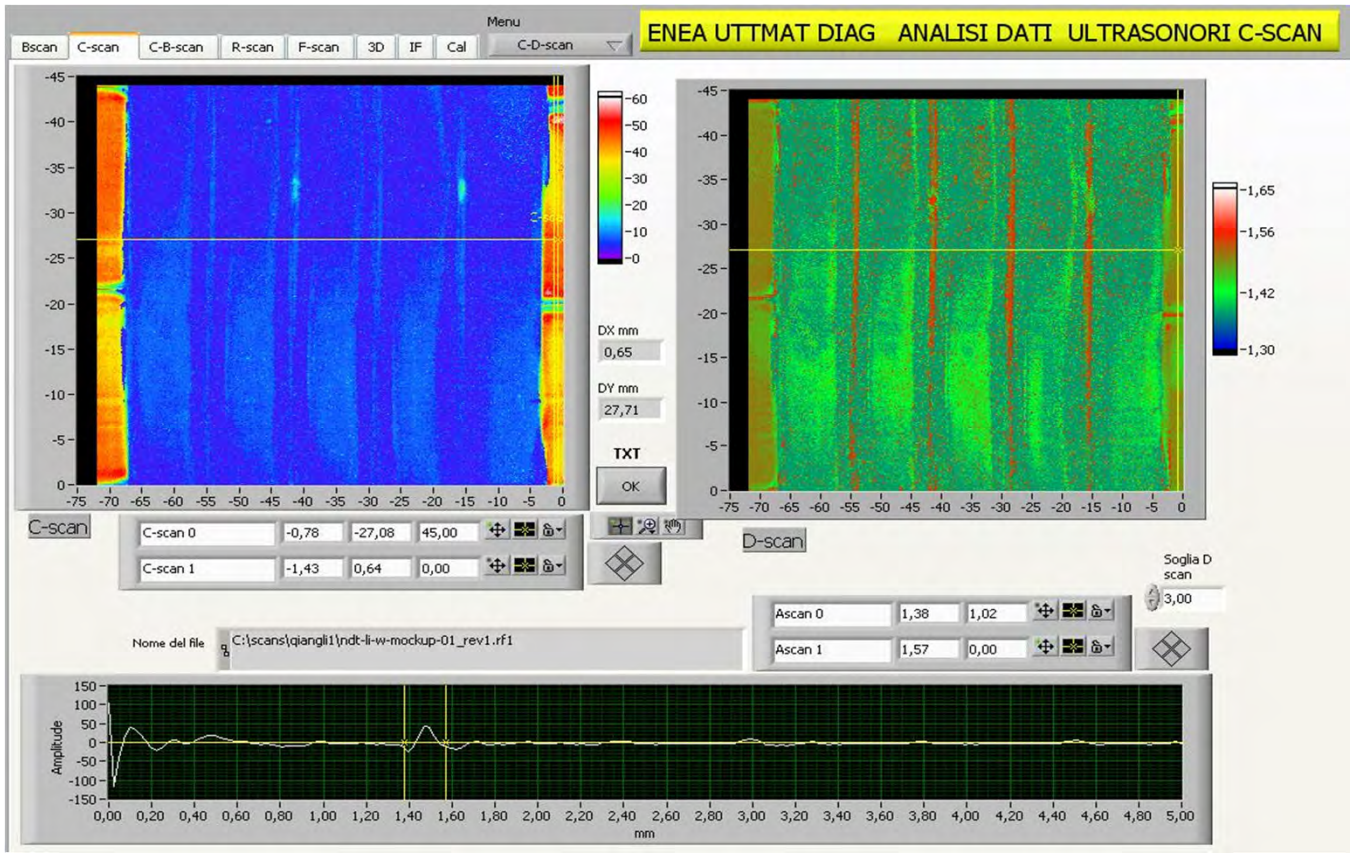
- **W/Cu mockup with five W tiles was manufactured by Hot Radial Pressing at ~600ºC, ~60MPa, ~100min**
- **Ultrasonic NDT shows that the bonding of tube and copper was excellent**





Flat-type W/Cu PFMC

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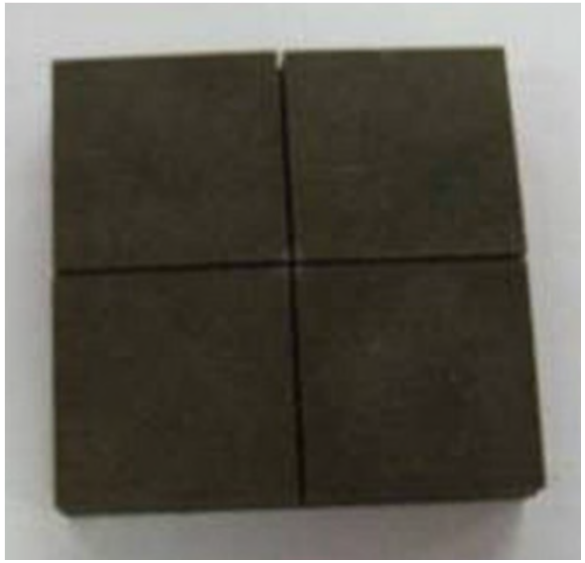
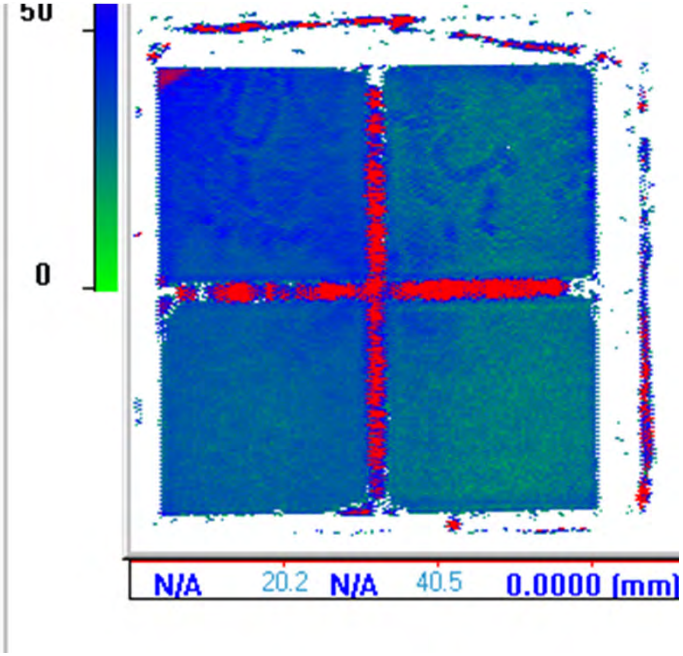
- **Flat-type W/Cu PFC has also been being explored by means of brazing or HIP technologies**
- **Ultrasonic inspection NDT showed good quality of the W/Cu interface also obtained**





QA：HHF, IR/UT/EC-NDTs at ASIPP

ASIPP

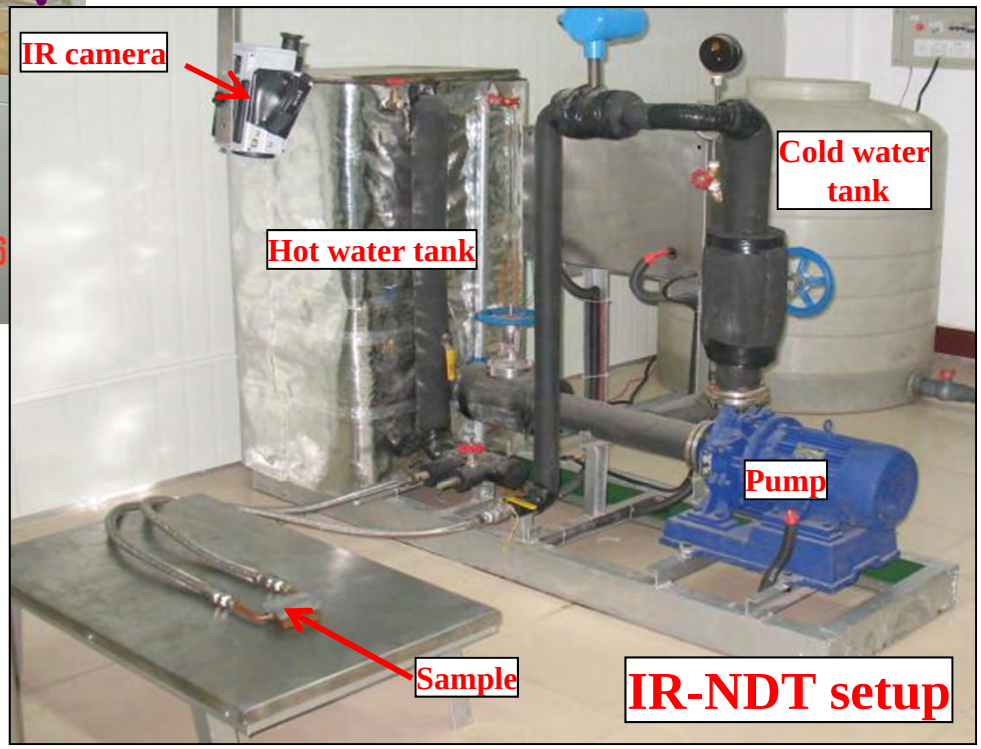
HHF testing

Evaluation of PFC integrity and lifetime; NDT calibration

Max. power: 10 kW/10 kV;

Cooling water: 0.4 MPa, 2 m^3/h;

Max. scanning area: > 30×30 mm.



Non-destructive Testings (NDT)

Establish acceptance standards

Quality control at batch reception

Ultrasonic and IR thermography inspection methods (hard/softwares) are being developed for EAST PFCs

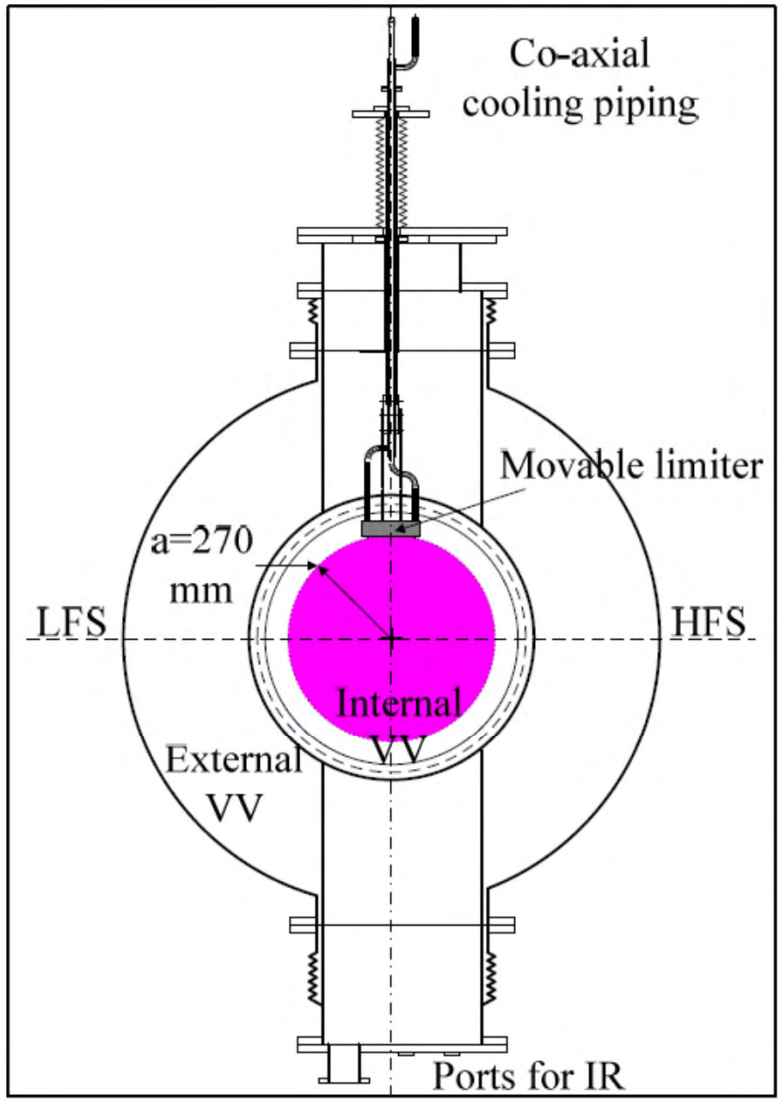
Outline

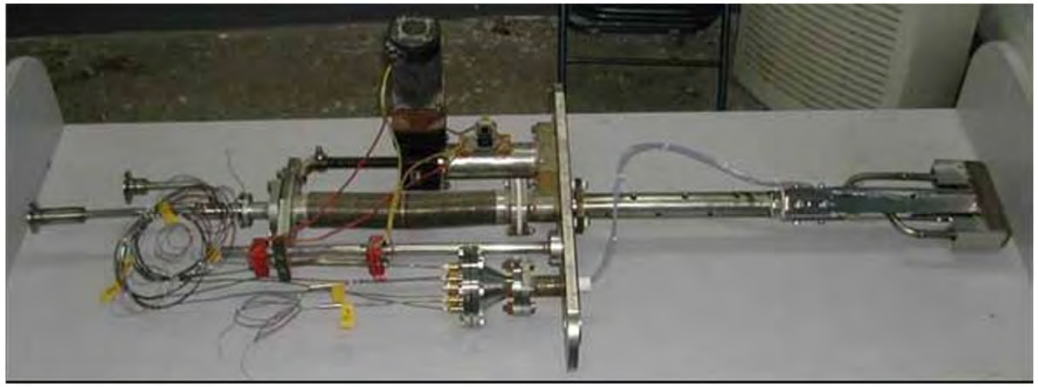
ASIPP

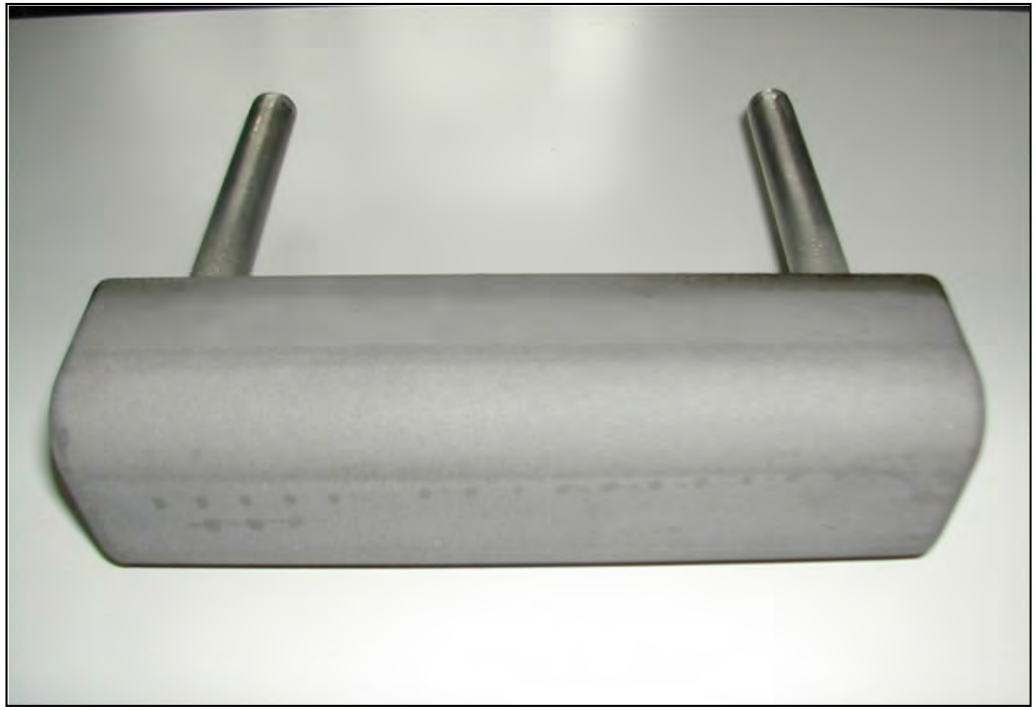
Plasma Exposure of W Materials

W coating PFC as limiter on HT-7

ASIPP





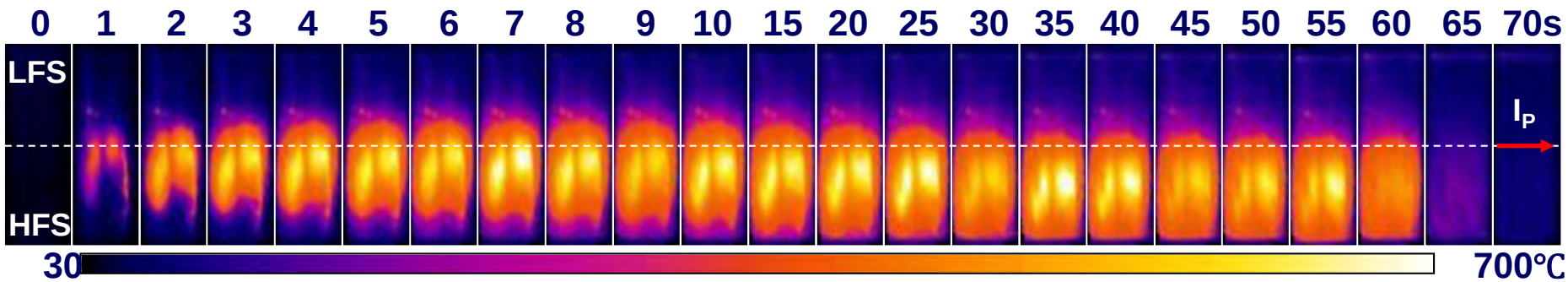


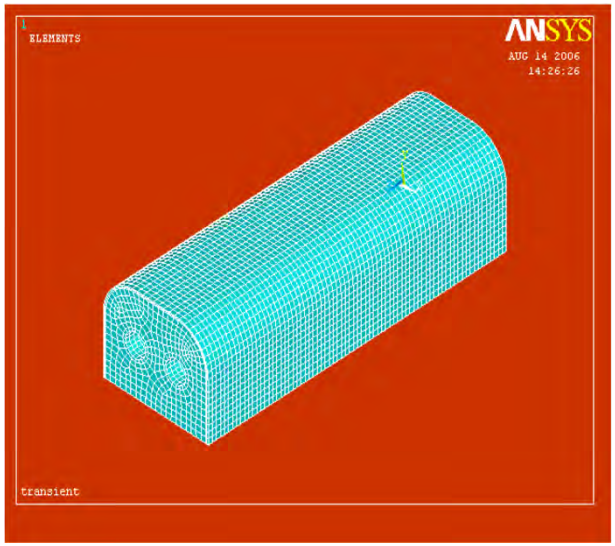
W coating PFC exposed to plasma

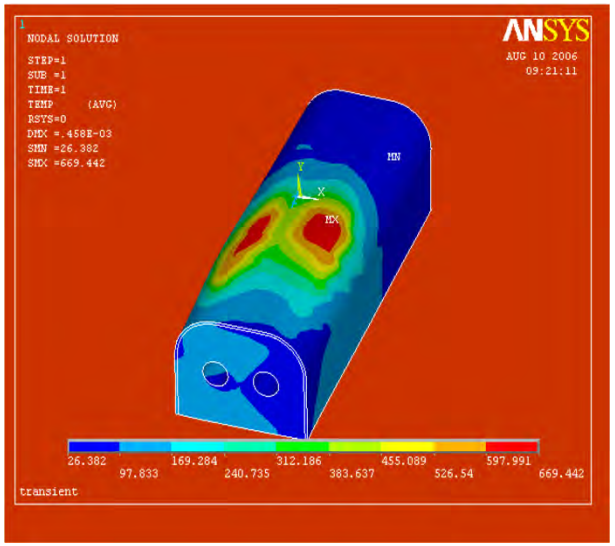
EAST /HT-7

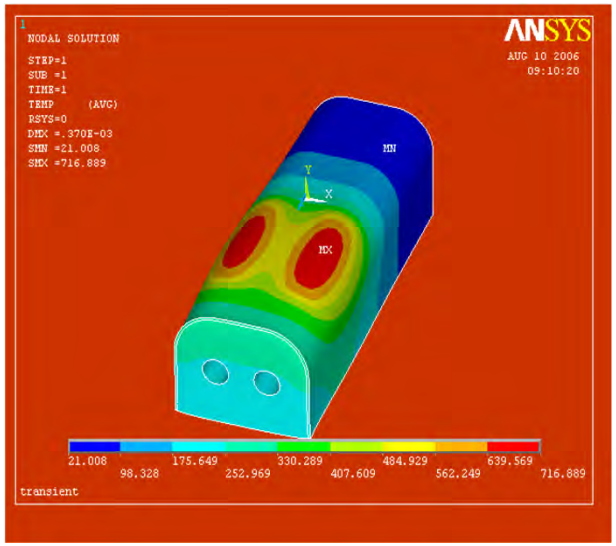
ASIPP

Long pulse discharge (HT-7 #89050, LHCD heating Ip~ 50kA, ne~ 0.5, t = 61s, r = 265mm, a = 270mm)







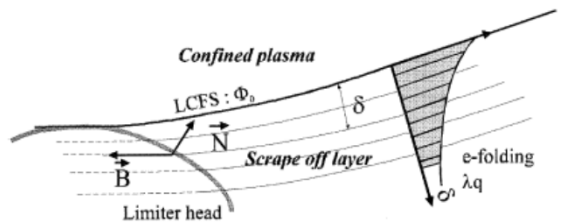


Modeling of heat deposition on the ML

ASIPP

- **The so-called cosine model**

$$\phi = \phi_0 \exp\left(-\frac{\delta}{\lambda_q}\right) \cdot |\boldsymbol{b} \cdot \boldsymbol{n}|$$

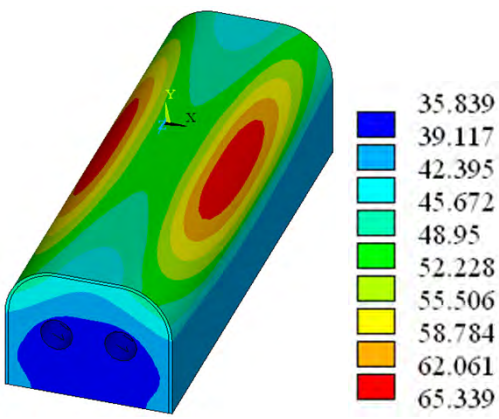


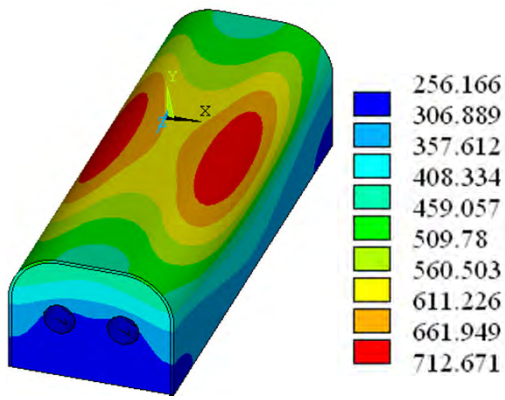
$$q_{//} = \gamma \Gamma_{//} k T_e \approx \frac{1}{2} \gamma n_0 c_s k T_e$$

$$q_{0//T} / q_{0//P} = f_q$$

$$\phi = \phi_{0\square\phi} \exp\left(-\frac{\delta}{\lambda}\right)|\mathbf{b} \bullet \mathbf{n}| + \phi_{0\square\theta} \exp\left(-\frac{\delta}{\lambda}\right)|\mathbf{b} \bullet \mathbf{n}| + \phi_{0\perp} \exp\left(-\frac{\delta}{\lambda}\right)|\mathbf{r} \bullet \mathbf{n}|$$

$$\frac{\phi_\perp}{\phi_\square} = \left(\frac{L_f}{L}\right)^{\frac{1}{2}}$$



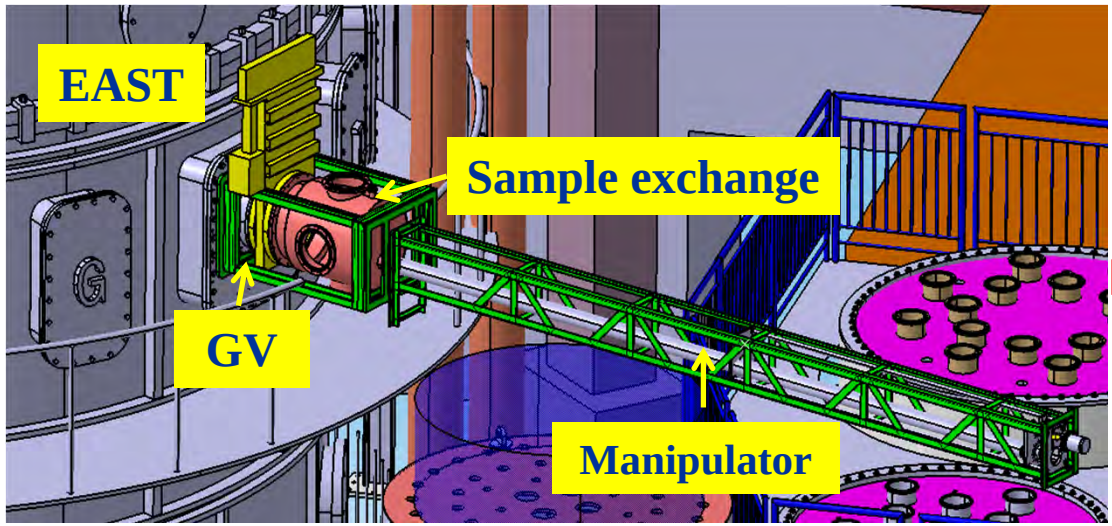


OHCD: ϕ_0=2.3MW/m^2
$\phi_\perp / \phi_{||}$ =1/10 $\phi_{0||\phi} / \phi_{0||\theta}$=4
λ=5.5mm

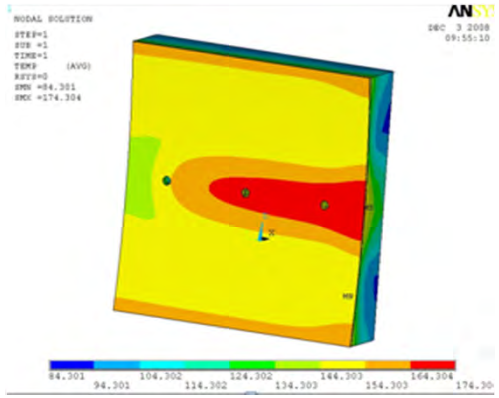
LHCD: ϕ_0=18MW/m^2
$\phi_\perp / \phi_{||}$ =2/10 $\phi_{0||\phi} / \phi_{0||\theta}$=4
λ=1cm

- **OHCD: the max. temperature ~65℃, a peak heat flux ~ 0.8MW/m^2, consistent with the IR measurements**
- **LHCD: ~700℃ and 7MW/m^2. The calculated heat flux is too low to reproduce the IR data, and a much higher parallel heat flux is required, which probably arises from fast particles driven by LHCD**

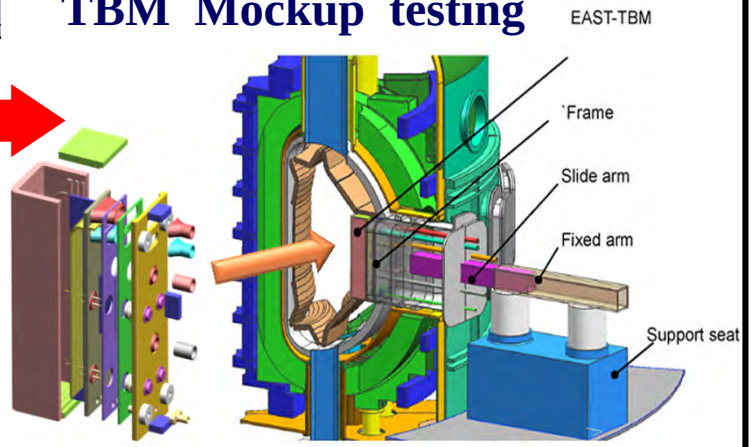
Materials and Plasma Evaluation System (MAPES)



Sample exposure



TBM Mockup testing

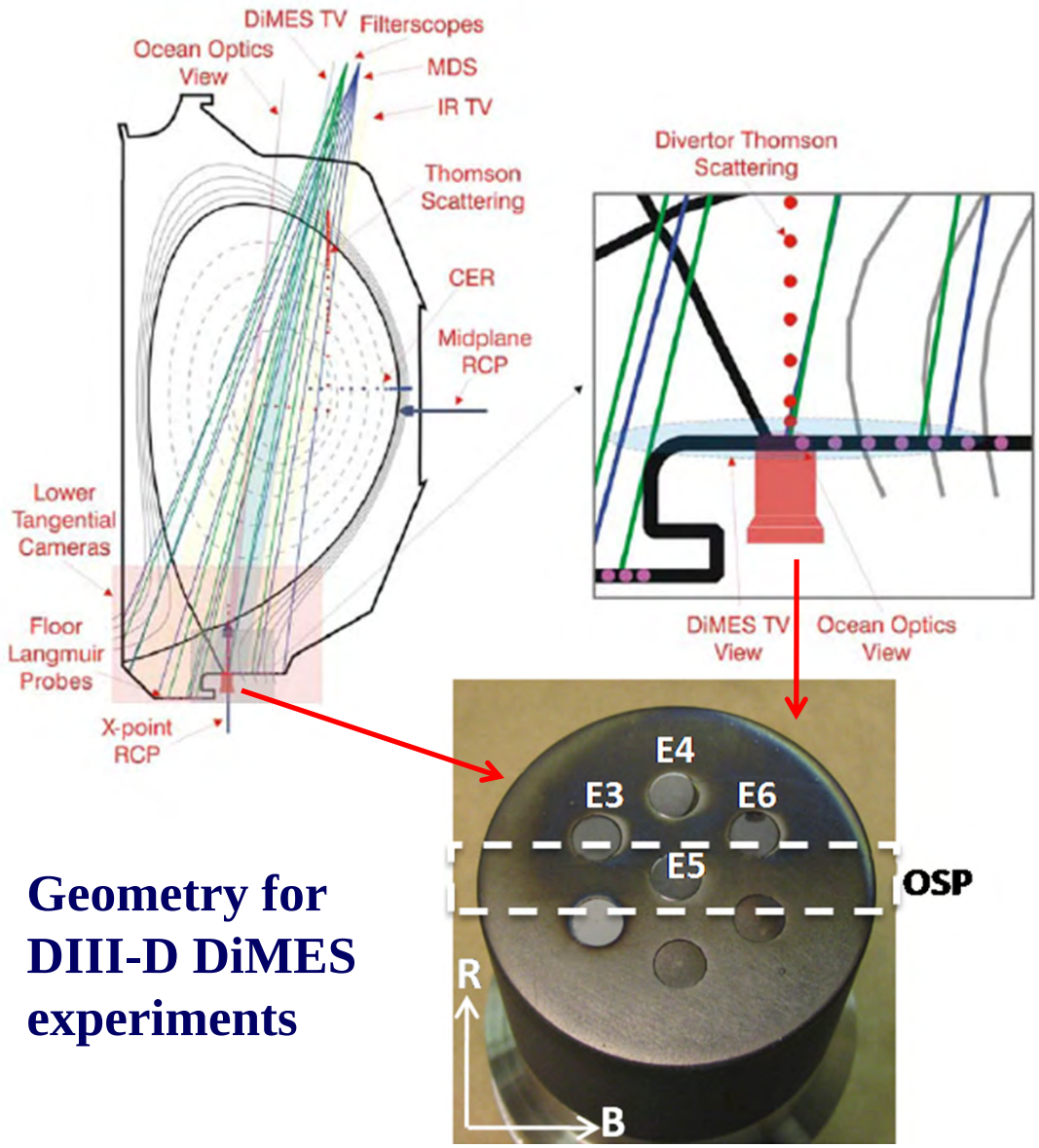


Laser Induced Breakdown Spectroscopy (LIBS)

W coating exposed to DIII-D plasmas

EAST /HT-7

ASIPP



Geometry for DIII-D DiMES experiments

E3, E5, D pre-damaged/PISCES

Exposed to DIII-D ELMing He plasmas with the OSP adjusted on the DiMES system.

The DiMES holder were lowered during wall conditioning

Shots Exposed (42)

- **138705-138711**
- **138721-138739**
- **138755-138770**

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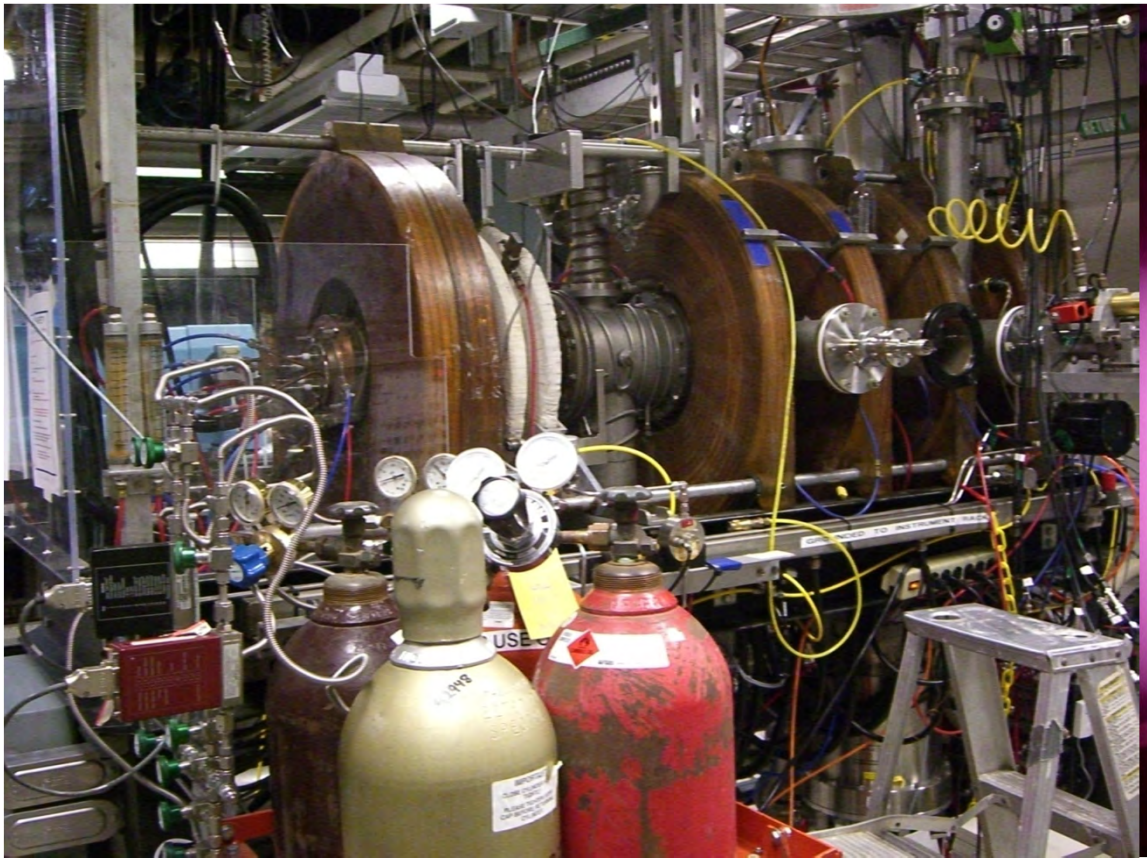
(1) H. S. Zhou, et al., (2) G. Tynan, et al., (3) C.P.C. Clement, *5th US-PRC MFCW*, Wuhan, May 5-7, 2010

W coating exposed to PISCES plasmas

EAST /HT-7

ASIPP



Irradiation parameters

- Energy: 100 eV
- Flux: 2e22 D/m^2/s
- Fluence: 1e26 D/m^2
- Temperature: RT, 473K, 773K

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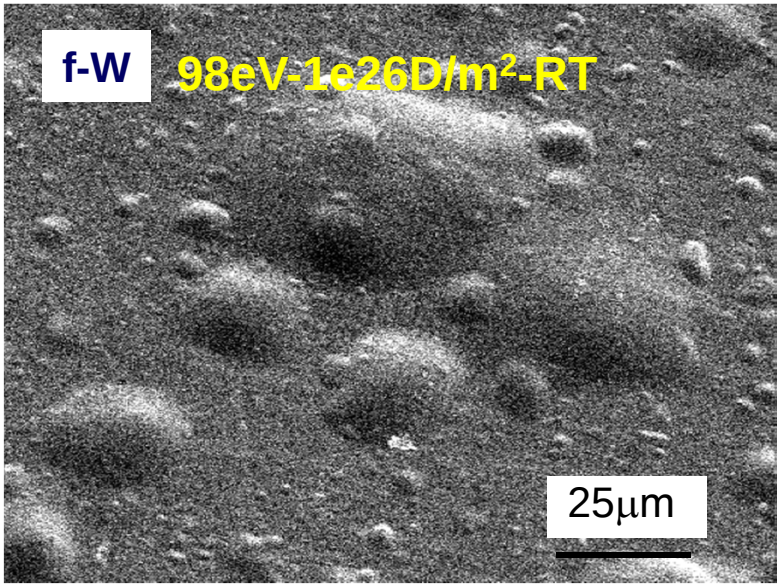
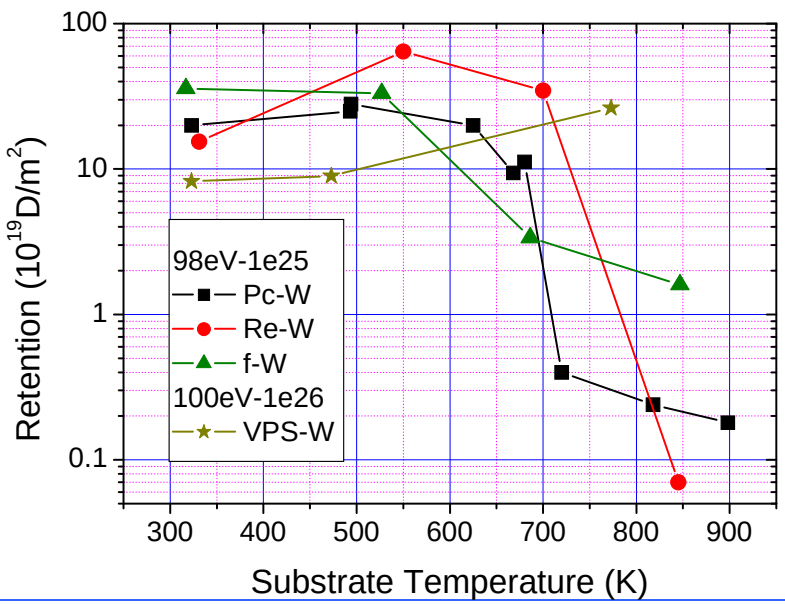
G. -N. Luo, et al., *NIMB*, 267 (2009) 3041

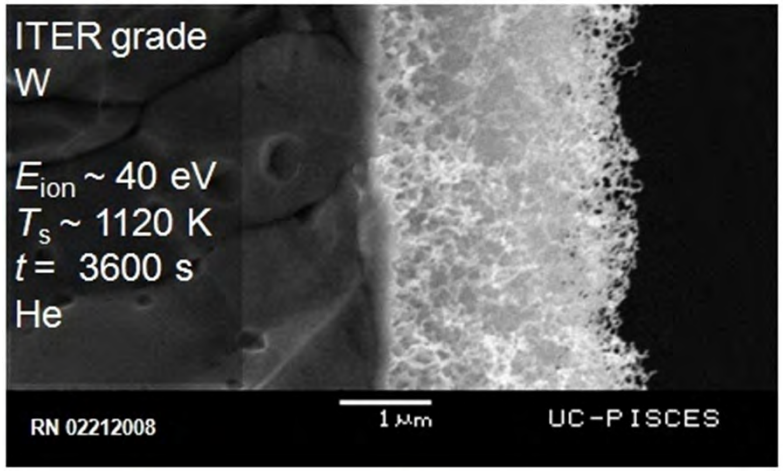
Steady state particle & heat flux

EAST /HT-7

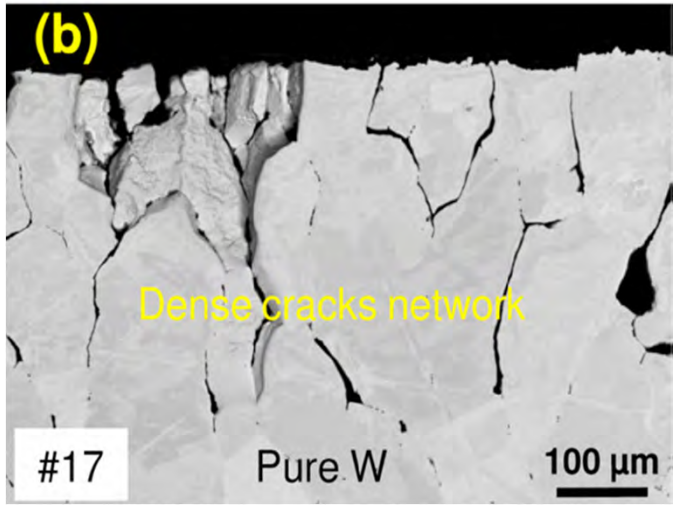
ASIPP







Nanostructure on all types of tungsten exposed to He plasma above 900K



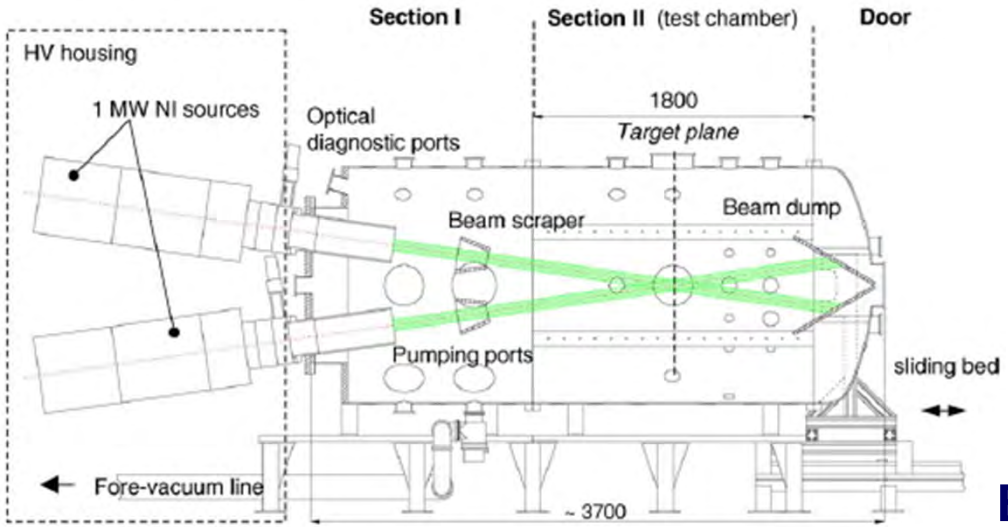
G. Ritz. Fusion Engineering and Design. 2009, 84: 1623–1627, 10MW/m^2, He

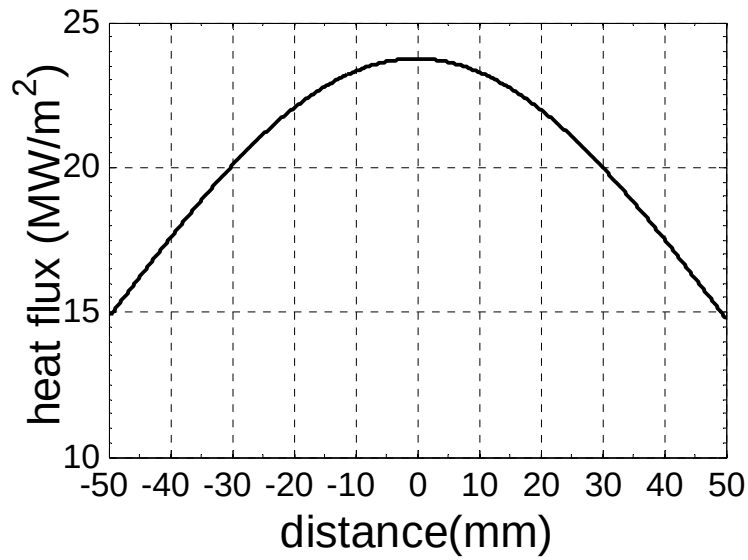
HHF Behavior of Hot-rolled W

Experimental

ASIPP

GLADIS @ IPP-Garching





Beam profile w/ max of 23MW/m^2

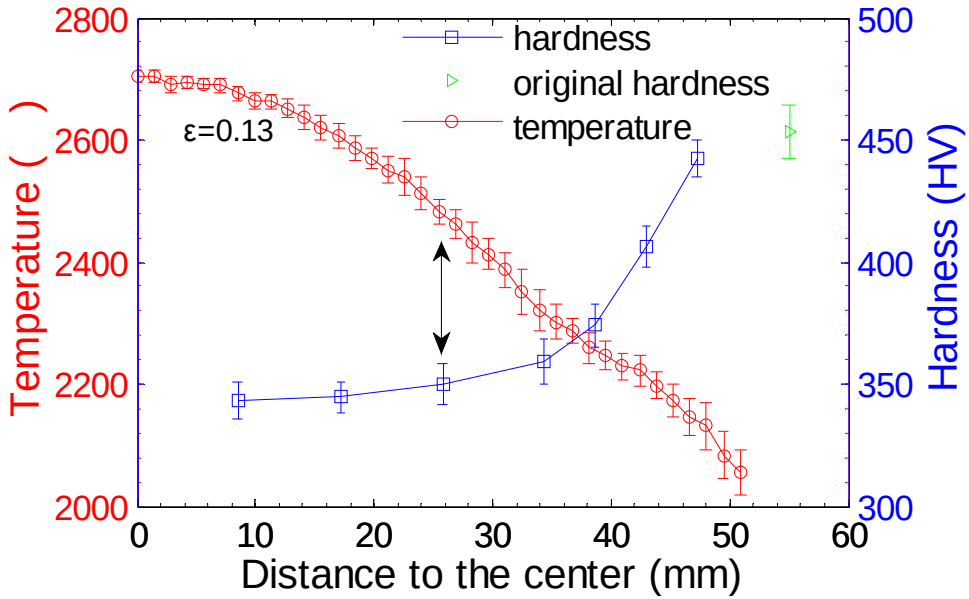
Experimental parameters

Beam species:
H (He soon)
Power flux:
23MW/m^2 (with one 1.1 MW NB)
Pulse length:
0.5, 1.0, 1.5, 1.8s, cycle rate 45-100/h

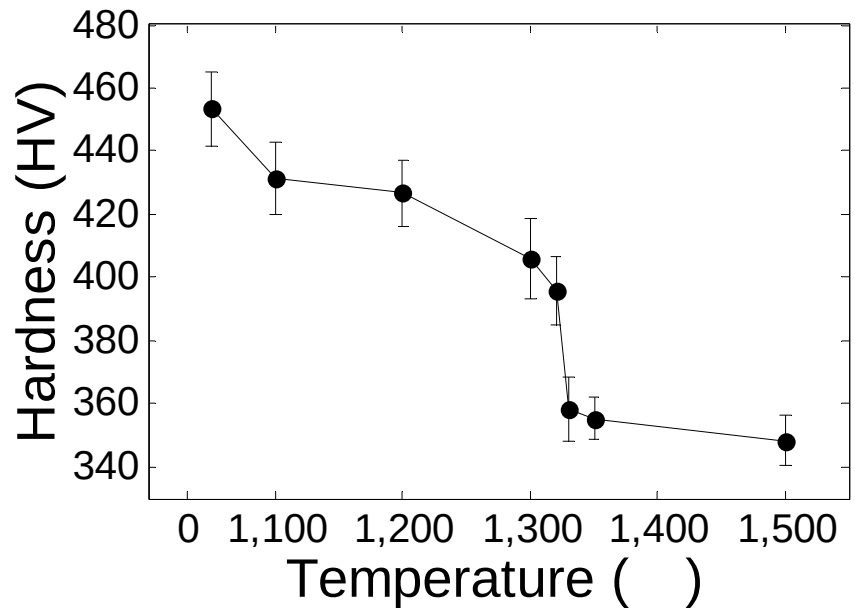
Event	Repetition	Duration [ms]	Energy dump [MJ/m^2]	Power flux [GW/m^2]
Disruption	Low	1-10	10-10^2	10^2
A giant ELM	>1 Hz	0.1-0.5	1-3	1-10
VDE	Low	10^2-10^4	20-60	0.01-0.1

Recrystallization under HHF

ASIPP



HHF, 23MW/m^2, 1.0s (GLADIS)



Annealing, 1100-1500℃/ 1h

Treatment	T-start	T-finish
HHF	**~2120 ℃**	**~2480 ℃**
Annealing	**~1200 ℃**	**~1330 ℃**

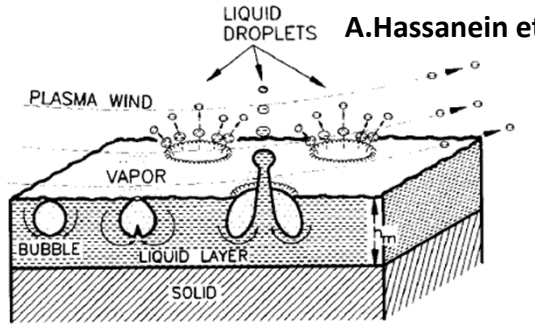
Melt layer – bubbles and dusts

EAST /HT-7

ASIPP

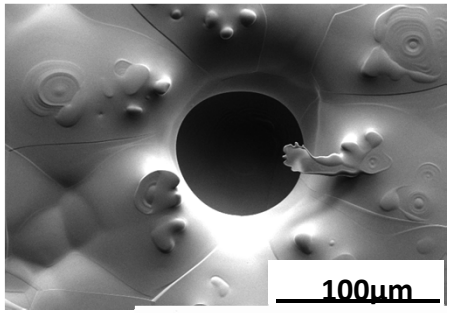
70mm

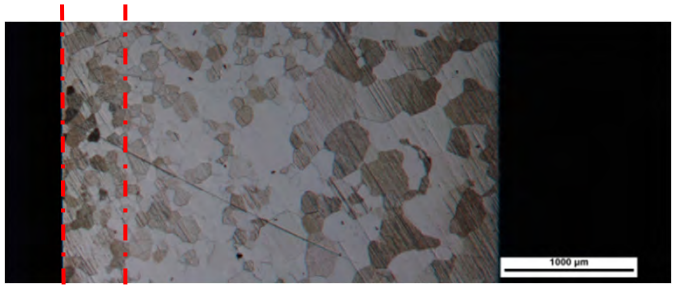
23MW/m^2-1.8s



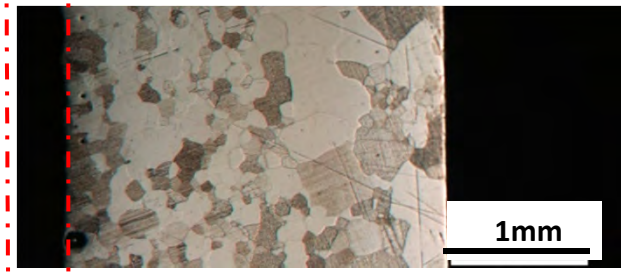
A.Hassanein et al. J. Nucl. Mater. 241-243(1997)288-293

Fig. 4. Bubble growth, vaporization and loss by incident plasma wind.



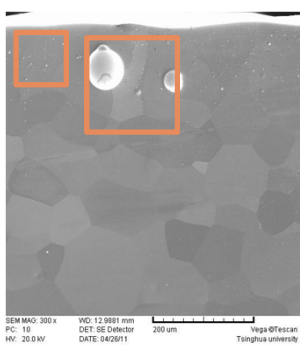


1.5s

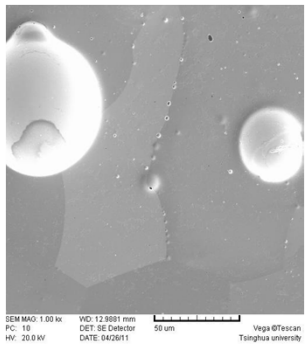


1.8s

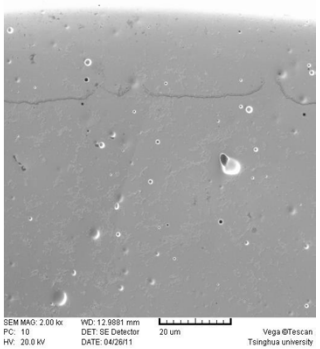
thickness loss ~400μm



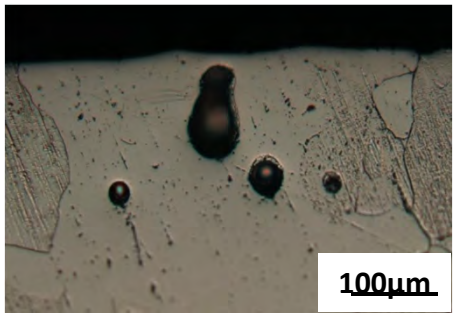
200μm

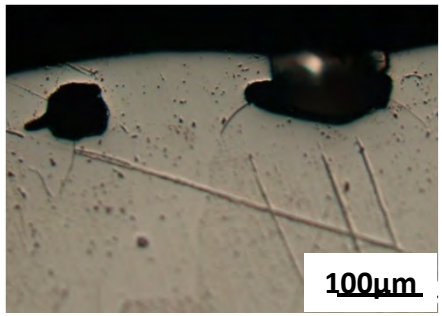


50μm



20μm

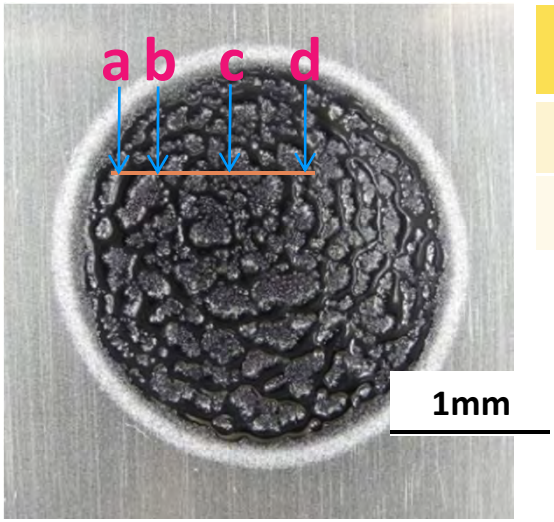




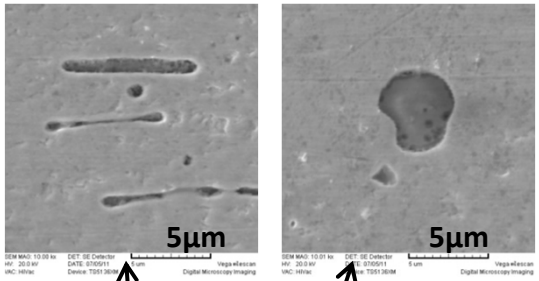
LM-images of cross-section

Melt layer of W-1wt.% La_2O_3

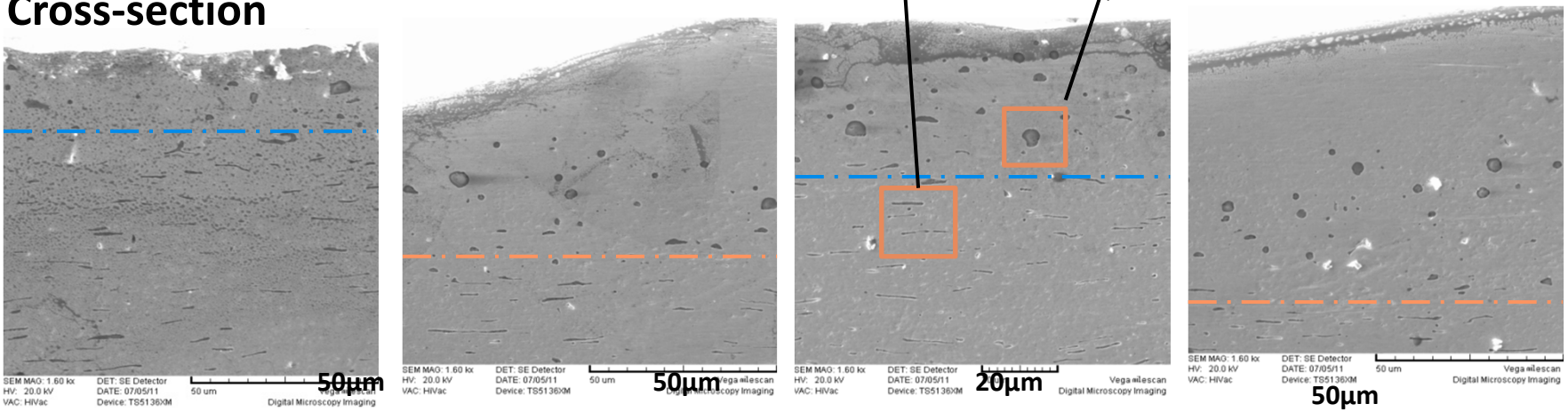
ASIPP



	Melting (℃)	Boiling(℃)
W	3422	5555
La_2O_3	2315	4200



Cross-section



a b c d

Summary

ASIPP

- **EAST has passed its initial and first phases of PFMC, i.e., SS and SiC/C tiles, and is now at the beginning of the transition phase, employing TZM as the first wall PFM**
- **EAST will pursue ITER-like design and technology for its tungsten divertor project, plus VPS-W coatings as backup or for the first wall application in the near future**
- **PFM group at ASIPP has long been involved in plasma-tungsten interactions via tokamak and laboratory experiments. The MAPES on EAST will contribute significantly to the society**

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- **New tungsten grades and gas-cooled divertor concept/ components will be developed.**
- **Neutron effects, especially transmutation and damage will be studied experimentally and by simulation**

Thank you for your attention!