International Collaborations and Device Exploitation

R. Doerner, M. Jaworski, R. Maingi, J. Rapp

Fusion Materials PI meeting

25-29 July 2016

U.S. DEPARTMENT OF ENERGY | Office of Science
OAK RIDGE National Laboratory
UCSD
PPPL

International devices have capabilities that complement US capabilities

- **Purpose of talk:** introduce international devices and capabilities, for assessment if they can be used for; no judgment made amongst the facilities
- **Time-scale**: Snap shot of current capabilities and near term upgrades over the next year, and collaboration prospects over ~ five year time frame
- **Goal**: provide input to panel discussions, to see if/how international facilities can be used to answer questions in the PSI community, e.g. as in the PMI workshop report
- **Organization:** by facility, grouped by toroidal devices, linear devices, test stands, etc. *Facilities with carbon walls not discussed, due to reactor relevance*

Outline

- **Plasma devices with metallic PFCs**
  - ASDEX-Upgrade: all W divertor and wall
  - JET: W divertor and Be wall
  - EAST: W upper divertor, Mo wall, C lower divertor, flowing liquid lithium limiter
  - WEST: all W PFCs, long pulse; FTU & TJ-II
- **Linear Devices and Test Stands**
  - MAGNUM-PSI: long pulse linear plasma test stand
  - JUDITH, GLADIS, NAGDIS, others
- **Other toroidal devices with carbon PFCs**

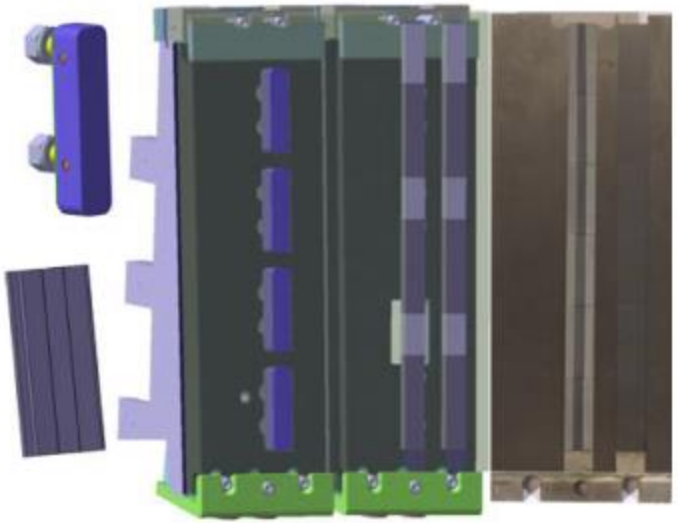
ASDEX Upgrade – main parameters

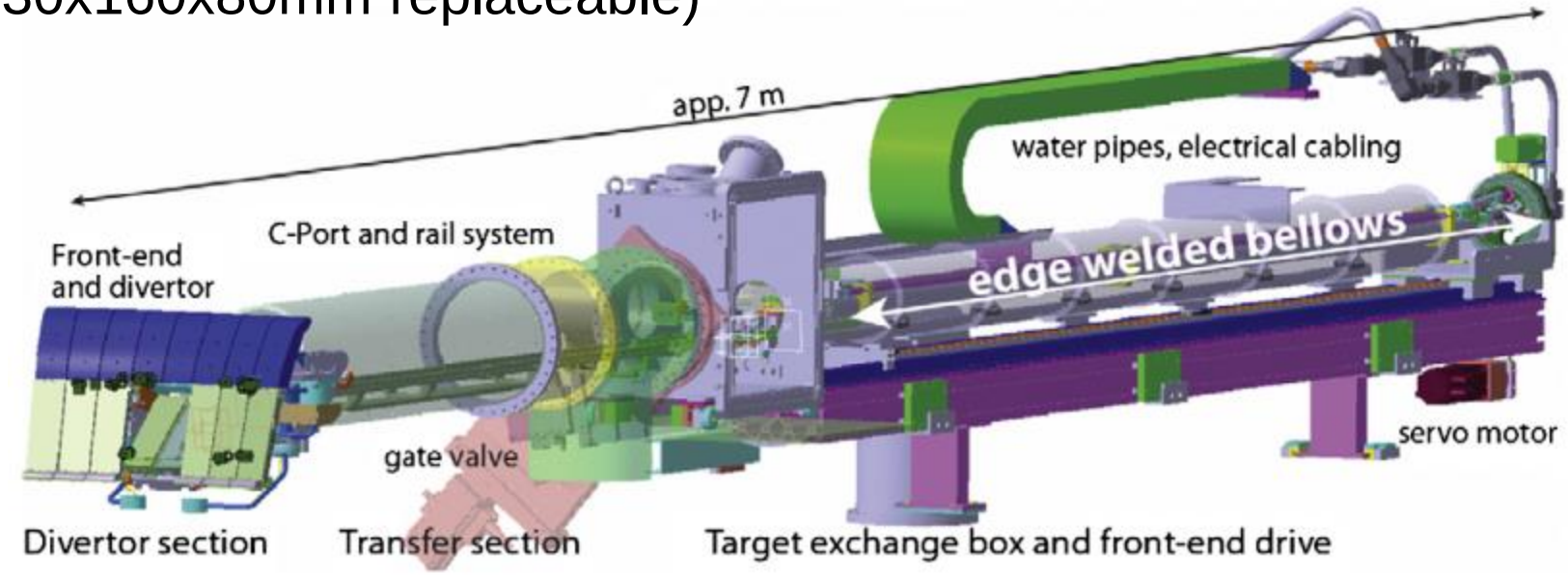
Parameter	typical	Maximum
R/m	1,65	
b/a /m	0,8/0,5	
I_{plasma}/MA	1,0	1,6
B_{tor}/T	< 3	3,9
P_{NBI}/MW	10	20
P_{ECRH}/MW	< 4	4
P_{ICRH}/MW	< 6	8
P_{Heat}/R / MW/m		18
t_{dis}/s	< 6	10
$\Delta t_{intershot}$ /min	20	
Gas	D	H, D, He

- Pulsed operation
- Adiabatically loaded components
- Water cooled

ASDEX-U Divertor manipulator (DIM-II)

- Interchangeable material and diagnostic studies in AUG divertor
- Water-cooled (T_{cool} <230C)
- Seamless integration of macroscale component (230x160x80mm replaceable)





A. Herrmann, 2015 FED

JET

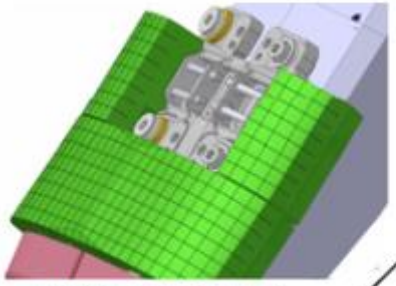
- Only DT capable device
- R = 3 m, a = 1 m
- 5 MA / 4 T max (translates in low ρ^* and low ν^*)
- NBI: up to 35 MW (slightly higher in T, slightly lower in D)
- ICRH: up to 10 MW (includes ITER-like antenna)
- LHCD: mothballed
- ELM size can be as high as $\Delta W \sim 1$ MJ (demonstrated in carbon JET)
- ITER-like wall (Be and W)
- Pulse length with full power: 5 – 10 s depending on density and configuration

Plasma-facing components installed in the JET ITER-Like Wall

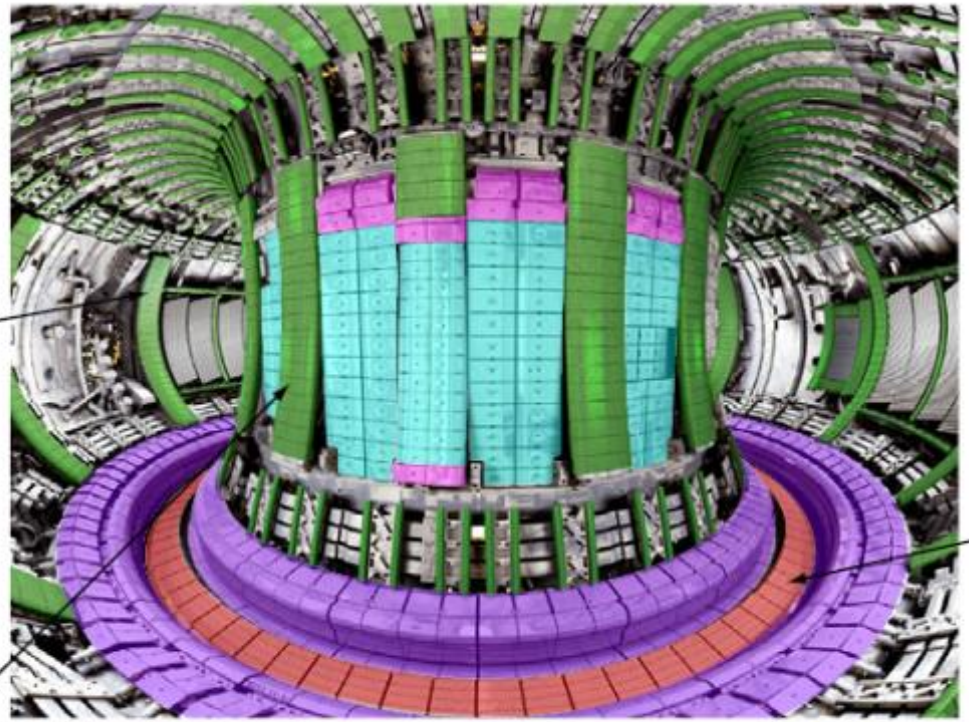
Limiter components

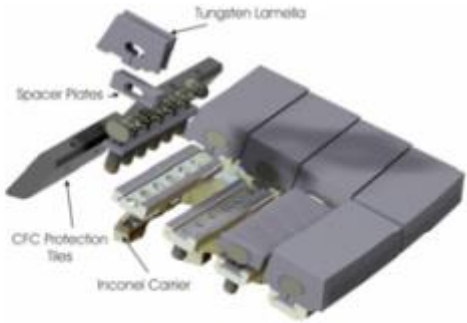
Divertor components

WOPL tile assembly



IWGL tile assembly





Divertor horizontal outer target tile assembly

G.F. Matthews et al. PS2011
A. Widdowson et al.

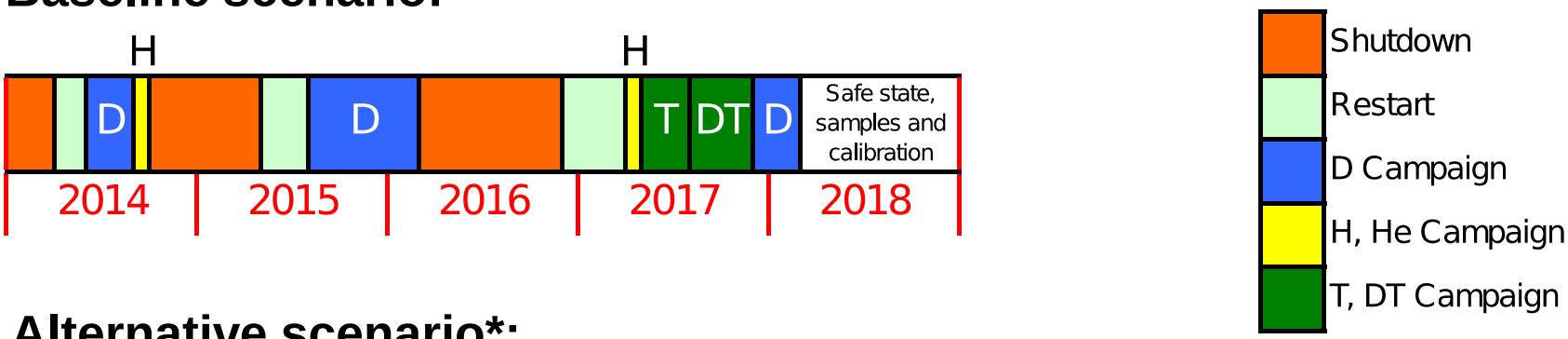
- All PFCs are only inertially cooled which is different to actively cooled PFCs in ITER
- PFCs are shaped to ensure good power handling [I. Nunes et al.]
- PFCs are castellated to minimise material stress [V. Riccardo et al. Phys Scr. 2008]

JET

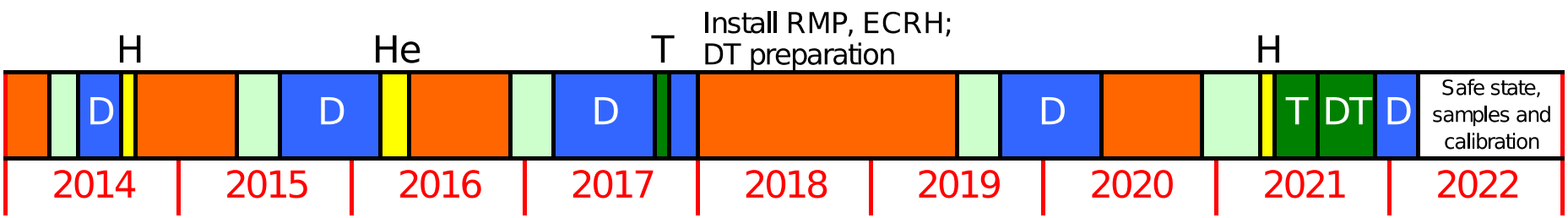
Future Program Options for JET

There are two possible scenarios for the future use of JET:

Baseline scenario:



Alternative scenario*:

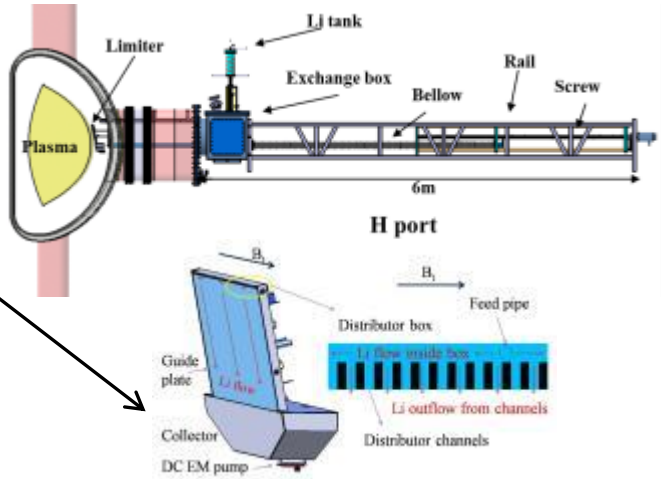


*Details of the Alternative Scenario are not yet agreed (see F. Romanelli et al. IAEA 2014)

- Substantial ITER scenario development since DTE1 (1997)
- Aim for sustained high fusion performance in new JET scenarios at high plasma beta (β_N=2.5-3) with their control requirements in DT (ITER operational regimes)

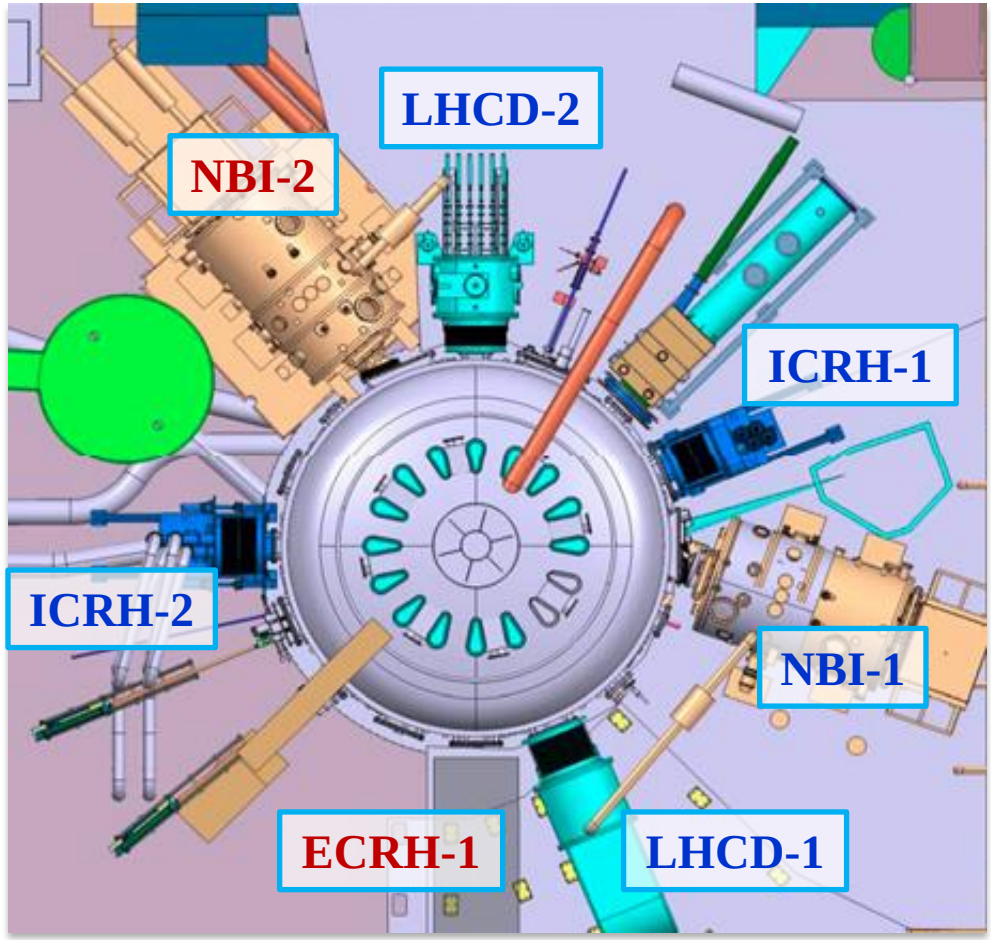
EAST: long pulse super-conducting tokamak, focus on testing ITER technologies

- Aim for 100 s long H-mode, 400-s long L-modes
- Substantial heating power, and hence substantial power extraction needs
- PSI is a focus, but challenging in mixed-material environment
- Midplane sample manipulators for sample and limiter testing, e.g. flowing liquid lithium limiter
- Two collab. recently funded, one focused solely on PMI



Heating & Current Drive on EAST

ASIPP



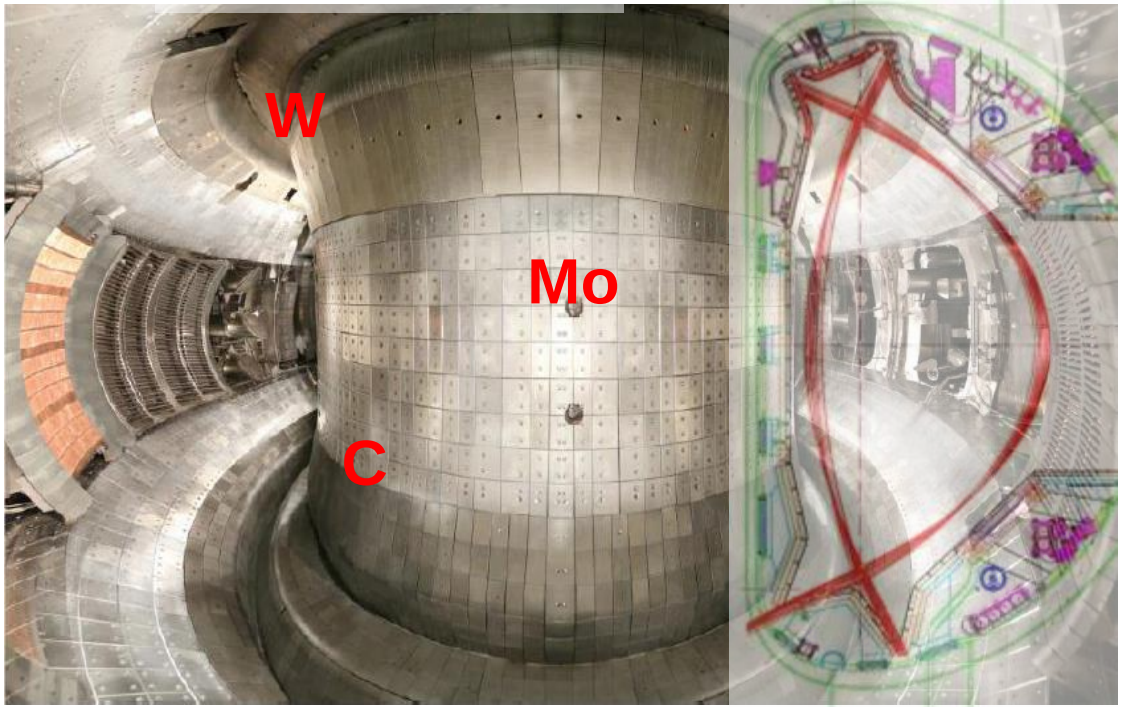
- **LHCD 4+6 MW(2.45/4.6GHz)**
  - Fast Electron Source
  - Edge Current Drive /Profile
- **ICRH 6+6 MW (25-75MHz)**
  - Ion and Electron Heating
  - Central Current Drive
- **NBI 4+4 MW (co/counter, 80kV)**
  - Sufficient power to probe β limit
  - Variable rotation/ rot-shear
- **ECRH 2(4) MW (140GHz)**
  - Dominant electron heating
  - Steering mirror, j_ϕ tailoring

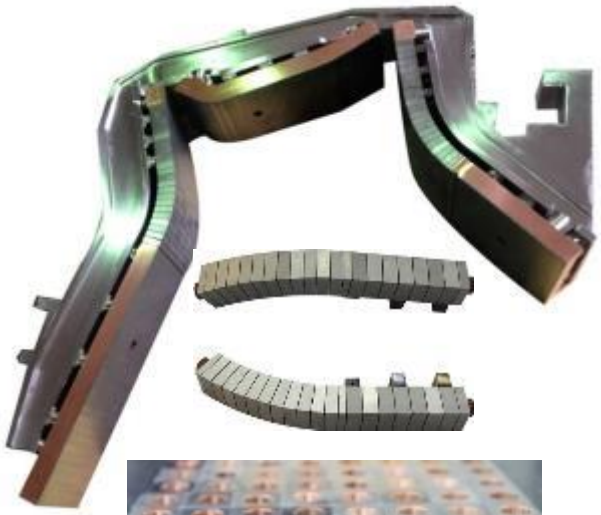
- **ITER-like RF-dominant H&CD, capable of high performance SS operations**
- **Each individual power is sufficient to access H-mode plasmas**

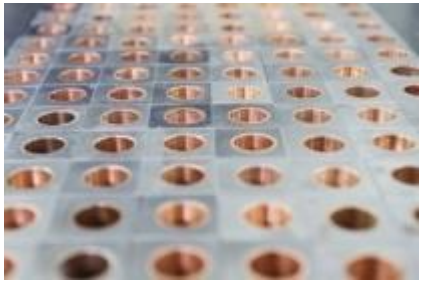
PFC Upgrade Facilitates for High Power Long-pulse Operations on EAST

ASIPP

2014: W + Mo + C

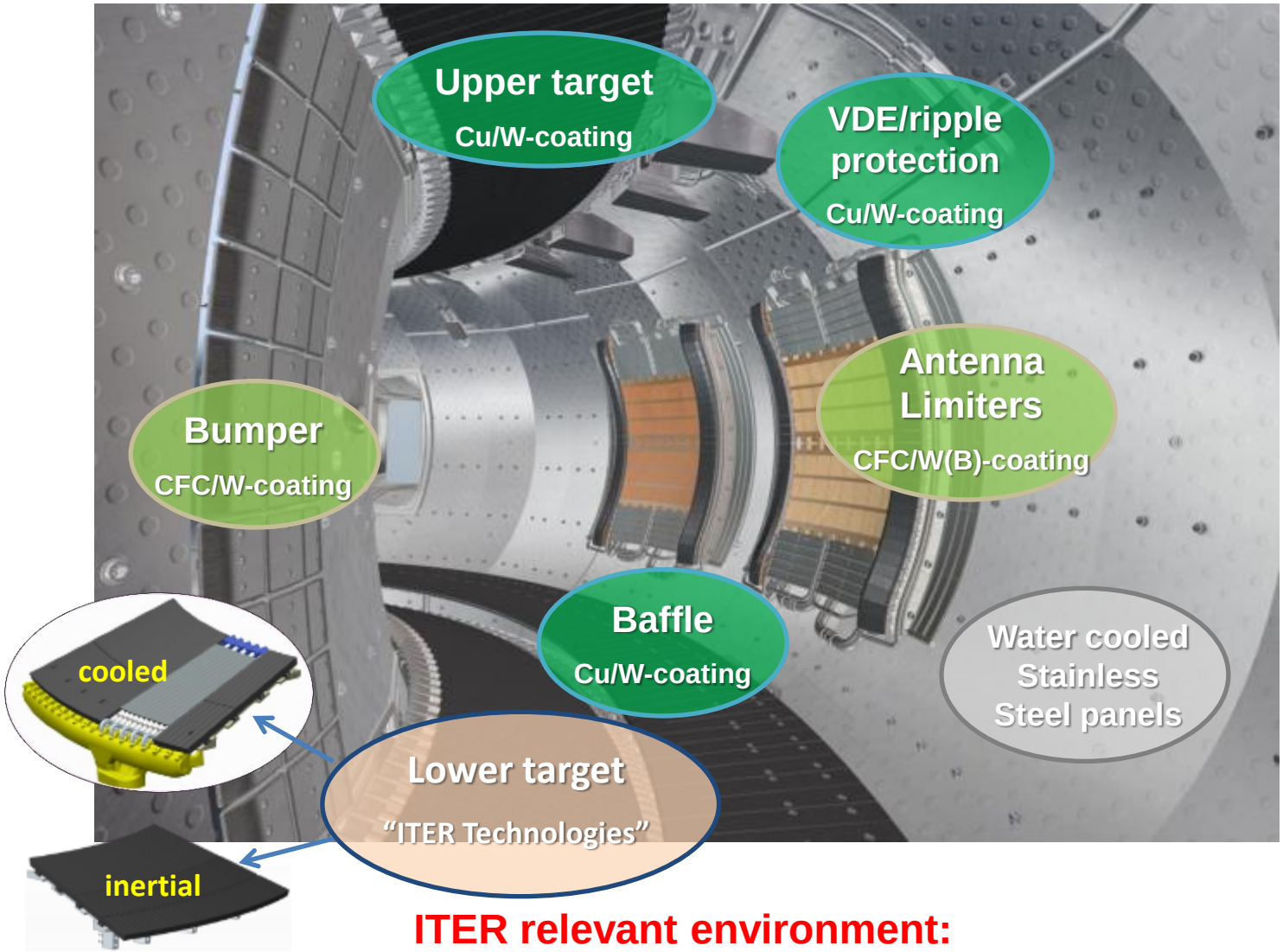






- **ITER-like cassette body structure with actively water cooling**
- **ITER-like W mono-blocks:**
- **Divertor targets (10 MW/m^2)**
- **Flat type W/Cu PFCs:**
- **Divertor dome and baffles (5 MW/m^2)**

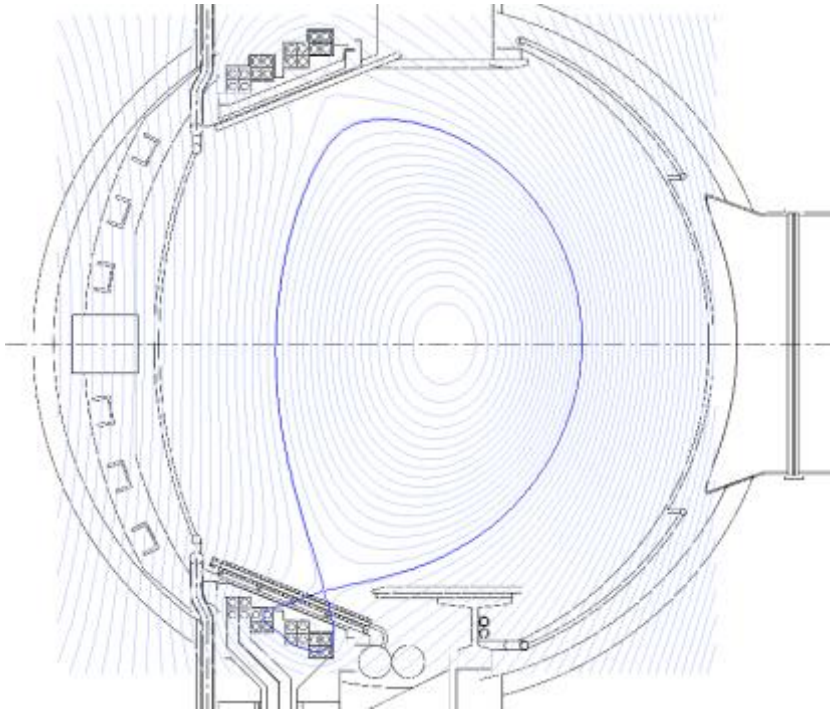
WEST : a full W actively cooled environment



ITER relevant environment:

Actively cooled bulk tungsten components, steady sate surface temperature

First WEST plasma scheduled by the end of 2016



- Superconducting MA class facility
- Full tungsten actively cooled environment
- CW RF heating (9 MW), current drive (7 MW)
  - ➔ Long pulse capability (1000 s)
- Flexible magnetic configuration (LSN, USN, DN)
- Large aspect ratio, no angular momentum

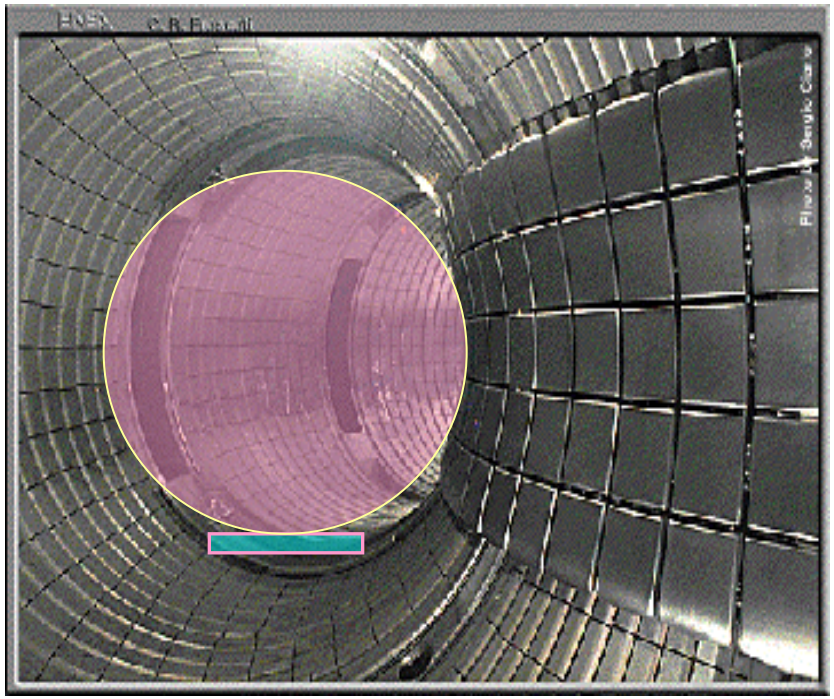
WEST PFC program mission

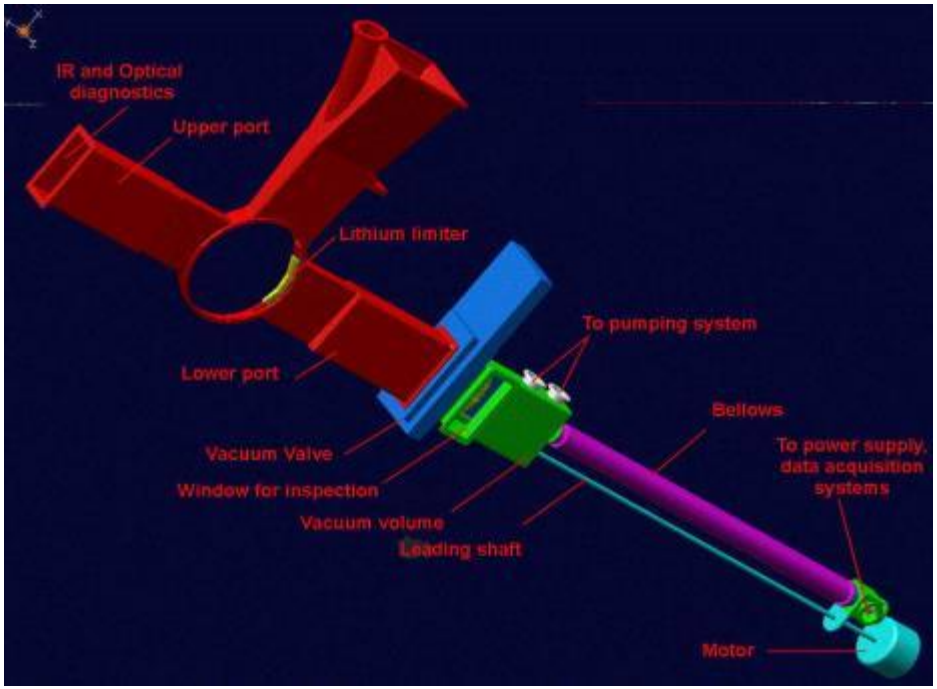
- Optimization of industrial scale production / qualification processes ahead of ITER divertor procurement
- Test monoblock shaping : urgent ITER design issue (10 MW/m^2)
- PFC evolution under large number of thermal cycles : sub damage threshold ELMs
- Test of pre-damaged, below specs, misaligned W components
- Validated scheme for protection of actively cooled metallic PFCs

WEST also has long pulse H mode program mission

FTU tokamak operating with liquid Li and liquid Sn limiters

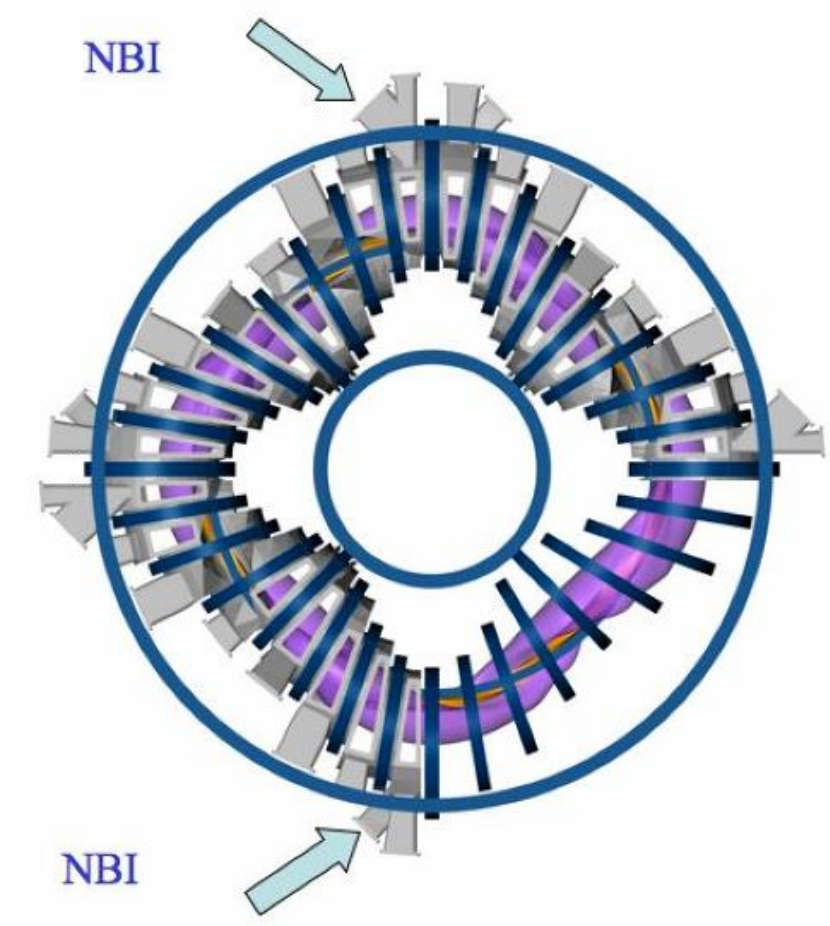
- Circular, limited tokamak: R=0.93m, a=0.33, B<8T, 4-5s pulse lengths with reduced fields (~4T)
- Molybdenum PFCs (TZM) with S.S. vacuum walls
- Testing liquid metal limiters
  - Water-cooled Li “CPS” by Red Star
  - Cooled Sn limiter tests to be conducted Autumn 2016





TJ-II and CIEMAT Laboratory Experiments

- TJ-II Heliac stellarator
  - R=1.5m, a=15-25cm, B=1T
  - ~1.4MW heating from ECH+NBI
  - Testing boronization and Li evaporations (2x CPS limiters by Red Star)
- Laboratory experiments also exploring Li and Sn-Li PMI
  - Focus on fuel retention
  - Recent results on SEE in plasmas
  - Collaboration with IPFN (Portugal)



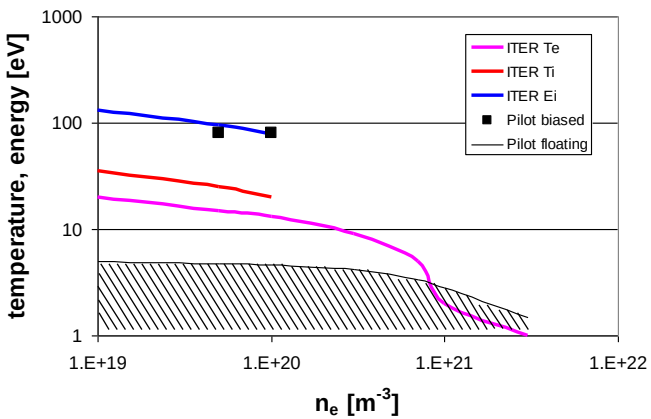
Tabares, 2015 ISLA

Outline

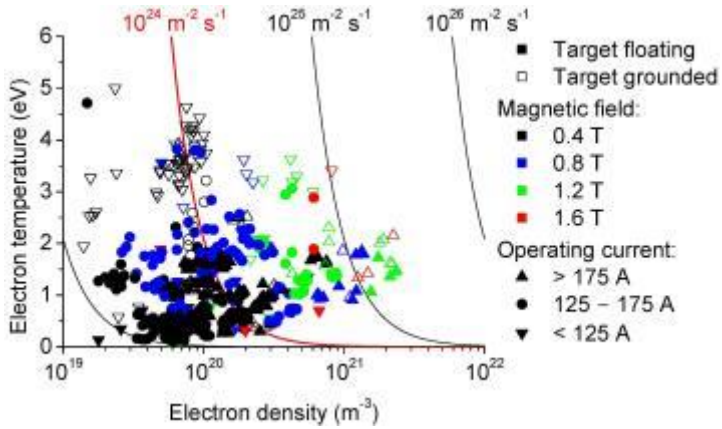
- **Plasma devices with metallic PFCs**
  - ASDEX-Upgrade: all W divertor and wall
  - JET: W divertor and Be wall
  - EAST: W upper divertor, Mo wall, C lower divertor, flowing liquid lithium limiter
  - WEST: all W PFCs, long pulse; FTU & TJ-II
- **Linear Devices and Test Stands**
  - MAGNUM-PSI: long pulse linear plasma test stand
  - JUDITH, GLADYS, NAGDIS, others
- **Other toroidal devices with carbon PFCs**

Magnum-PSI/Pilot-PSI

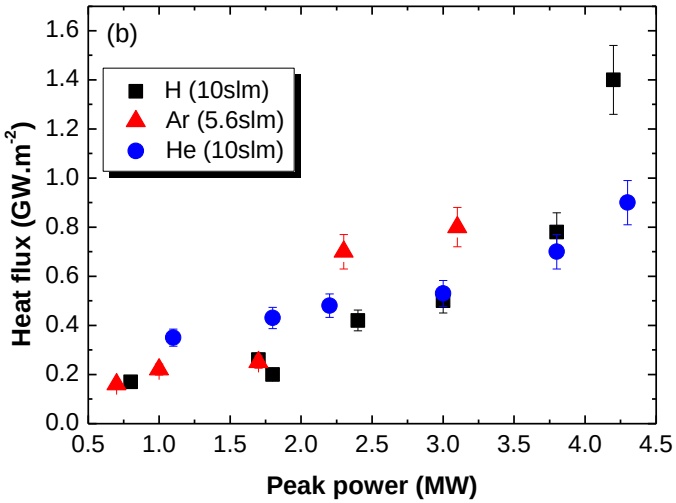
	Magnum design values	Achieved in Pilot or Magnum
Power [kW]	270	135
Pressure target [Pa]	< 3	1-10
T_i target [eV]	0.1-10	0.1-5
T_e target [eV]	0.1-10	0.1-5
n_i target [m^{-3}]	10^{20}-10^{21}	10^{21}
Ion flux target [m^{-2} s^{-1}]	10^{24}-10^{25}	2 x 10^{25}
Power flux target [MW m^{-2}]	10	30 (80)
B [T]	3	1.6
Beam diameter [cm]	10	1.5
Pulse length [s]	steady state	4
Extra heating [kW]	50	0
Target size [cm]	60 x 12	30 x 12



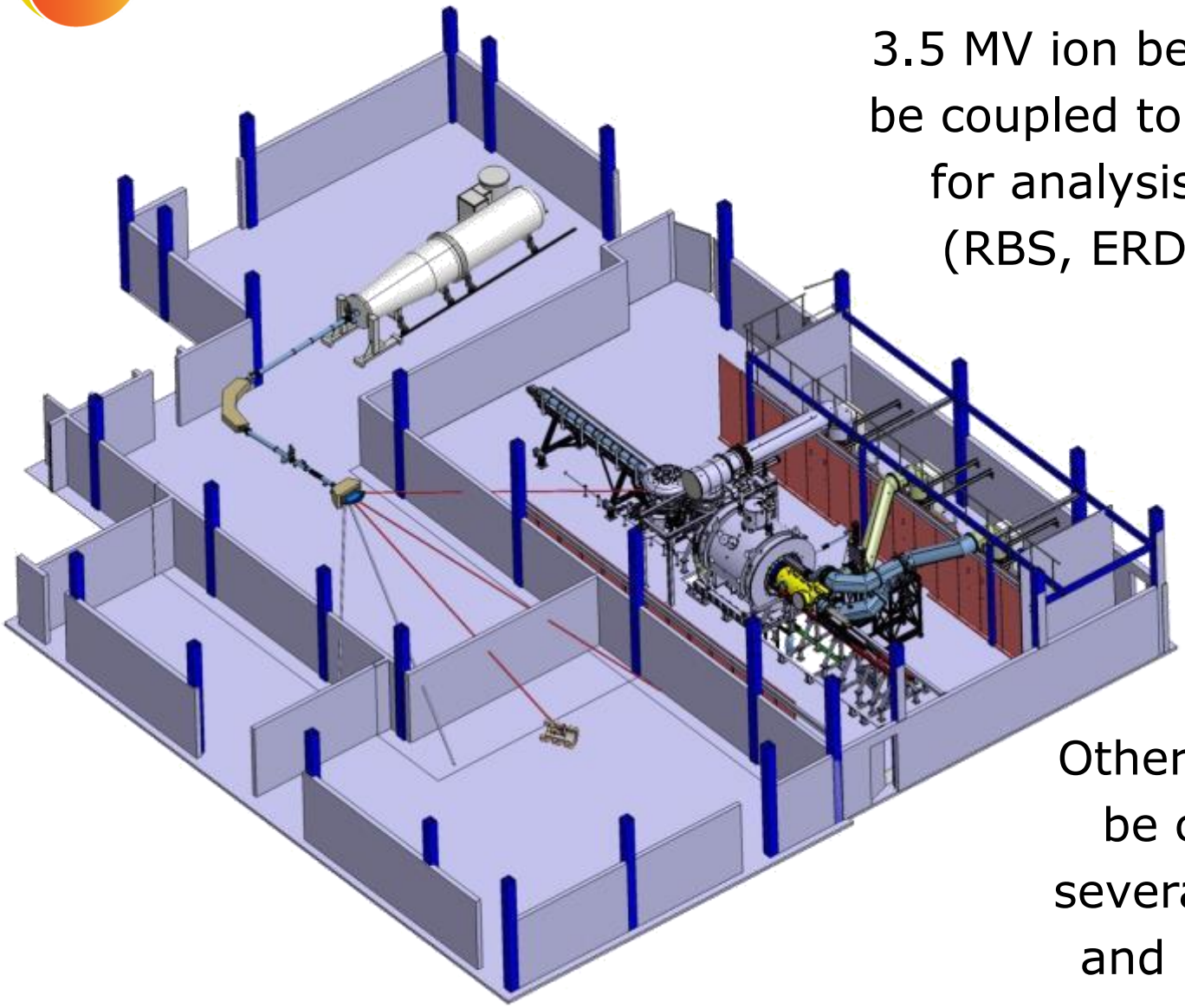
Pilot, quasi steady-state values



Pilot, ELM simulation



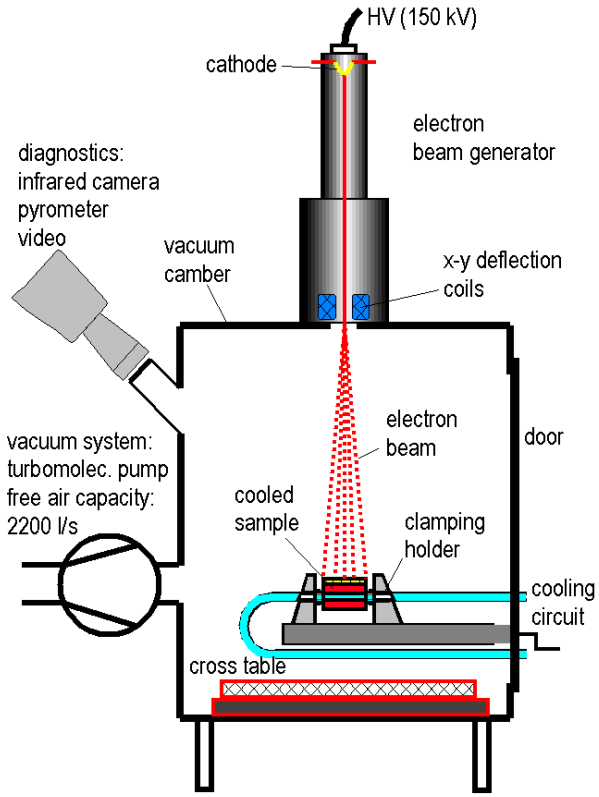
DIFFER PSI-lab

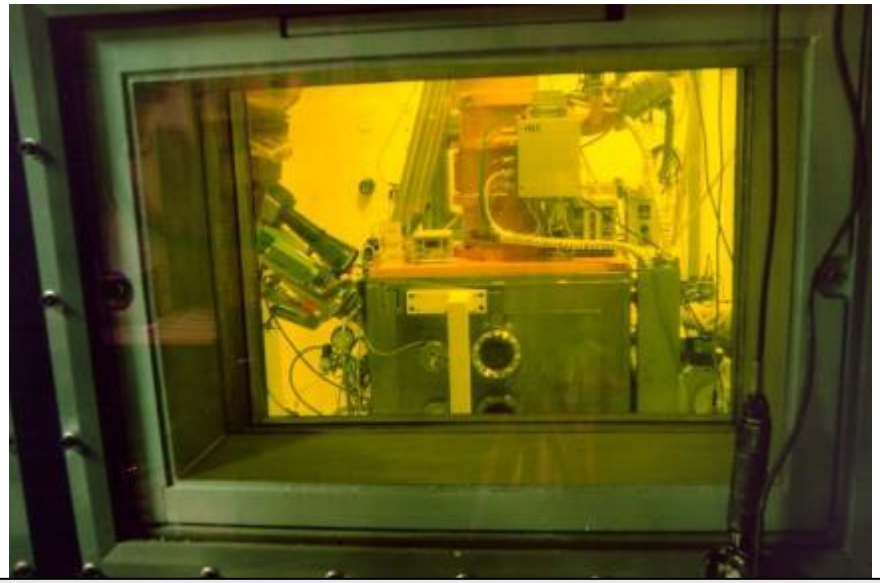


3.5 MV ion beam source to be coupled to Magnum-PSI for analysis of targets (RBS, ERD, NRA etc.)

Other beam lines to be connected to several experiments and Pilot-Upgrade

Juelich Divertor Test Facility Hot Cells (JUDITH)





total power:	60 kW
acceleration voltage:	≤ 150 kV
power density:	≤ 15 GWm^{-2}
loaded area:	4 mm^2 … 100 cm^2
pulse duration:	1 ms to continuous

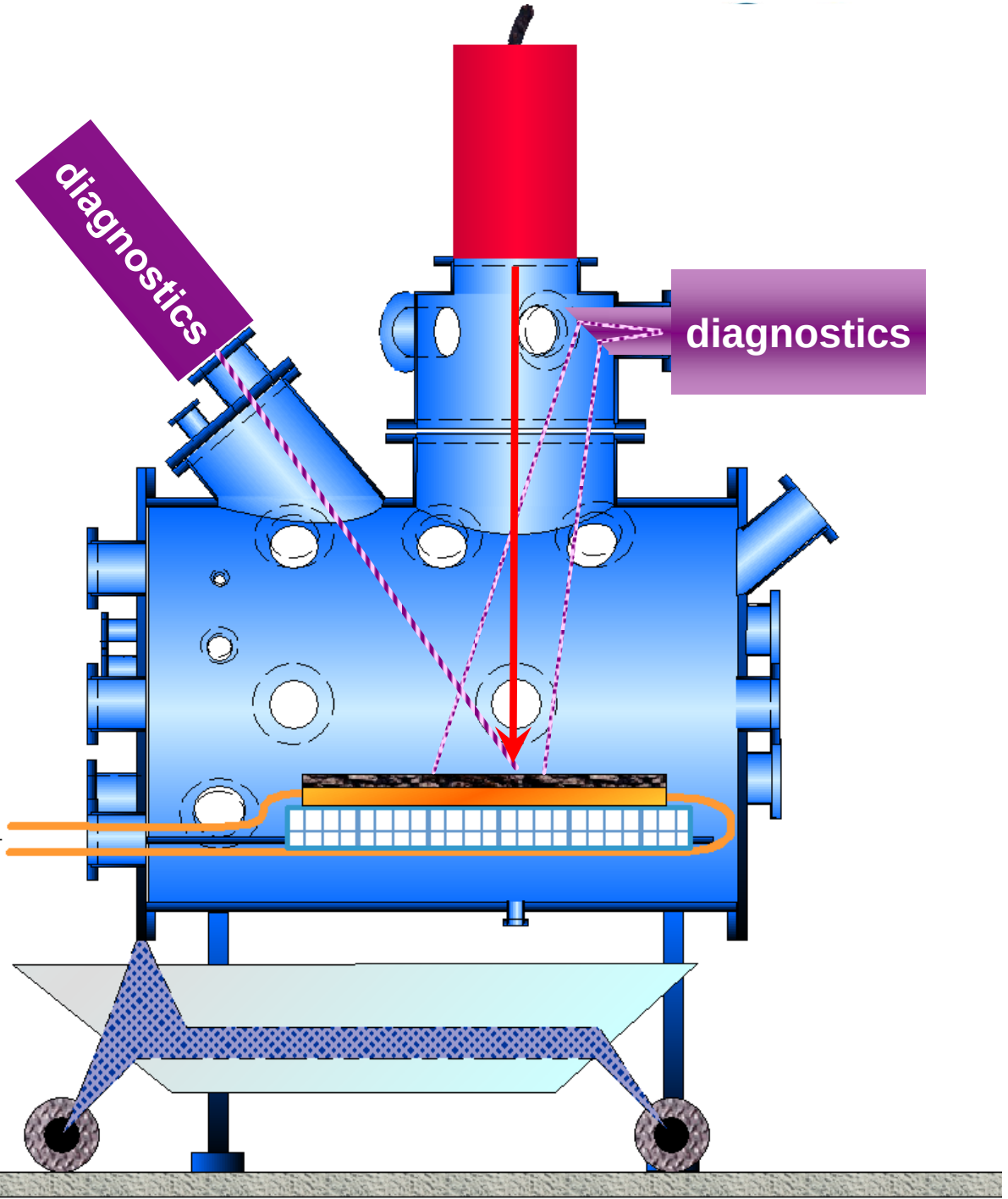
- EMS-60 (60 kW, 0.15 x 0.15 m) and EBS-400 (400 kW, 0.5 x 0.8 m) electron beam facilities exist at SWIP, China
- ITER Divertor Test Facility (800 kW, 2.5 x 1.5 m) exists for acceptance testing of ITER components at Efremov Institute, Russia

JUDITH 2

schematic view into the vacuum chamber

Diagnostics:

- IR-camera
- Optical camera
- Pyrometers
- Spectroscopy
- Thermocouples
- Photo diodes
- Acoustic emission



2. GLADIS (Garching LArge DIvertor Sample test facility)

Neutral beams offer a homogeneous heating of metallic and non-metallic surfaces
Designed to test actively cooled mock-ups, small material samples as well as full size components
Two completely independent ion sources allow superposition of different thermal and particle loading
➔Unique capability for operation with H, He or mixed H/He neutral beams and thermal loads

Technical characteristics:

Power	2 x 1 MW ion sources
Acceleration voltage	15 - 50 kV
Heat flux	2 - 45 (90) MW/m²
Neutral beam	∅ 70 mm (80% central q')
Pulse duration	1 ms - 45 s
Cycle rate	80 - 100 /h
Target dim.	up to 2 m (0.6 m using vacuum lock)

Target cooling

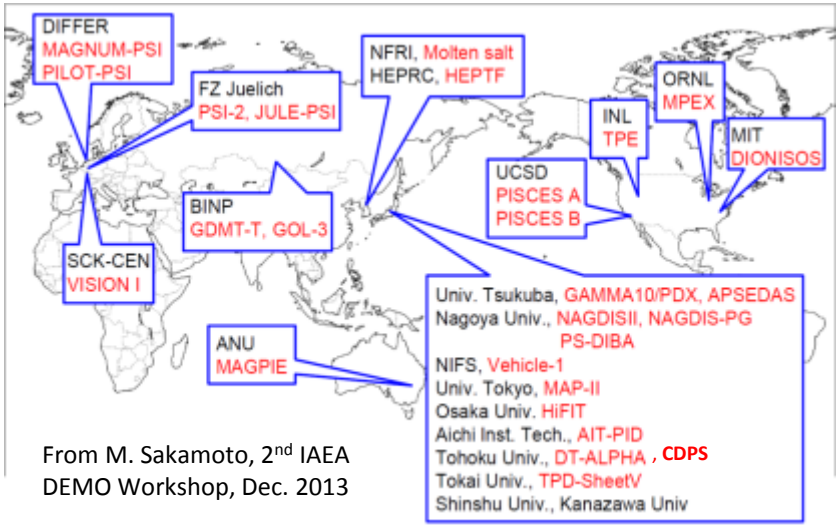
Water, RT up to 8.5 l/s, 25 bar
2015 upgraded to meet ITER and DEMO:
≤230 °C, 1.5 l/s, 40 bar

H. Greuner et al. / Journal of Nuclear Materials 367–370 (2007) 1444–1448

ELM simulation in different test devices

	e-beam	QSPA	laser-beam
energy density / ≤ 0.5 MJm^{-2}	+	+	+
pulse duration/ 200 – 500 µs	+	+	+
repetition rate / ≥ 1 Hz	+	--	+
incident particles:	electrons	ions	photons
loaded spot size:	small	large	very small

magnetic field	--	+	+
plasma pressure	--	+	--
preheated targets	+	+	+
neutron irradiated test samples	+	--	+



From M. Sakamoto, 2nd IAEA DEMO Workshop, Dec. 2013

Linear Plasma Devices exist throughout the world, many have unique, niche capabilities.

- NAGDIS-PG : NAGDIS-type LPD coupled to a plasma gun for disruption simulations of plasma loaded surfaces
- PS-DIBA : Plasma source coupled to dedicated ion beam analysis facility
- CDPS : Compact plasma source for neutron irradiated sample exposures
- PSI-2 : Prototype linear device for JULE-PSI development
- JULE-PSI : Plasma source to be located in hot cell lab, tritium containing samples, plasma exposure of activated samples
- MAGPIE : High-power Helicon source physics development
- Additional LPDs have been built in China since 2013 (ASIPP, Beihang U., SWIP)

Other international toroidal devices carbon PFCs for near-term, but may offer unique PSI capabilities in future

- **KSTAR:** long pulse superconducting device
- **W7-X:** long pulse stellarator in Germany, most capable stellarator in the world
- **MAST:** spherical tokamak in UK, focused on divertor concepts but not PSI; similar capabilities to NSTX-U
- **TCV:** small tokamak with flexible shaping for testing of divertor concepts
- **GAMMA-10 tandem mirror:** plasma physics focus

International facilities have substantial capabilities that can be used to fulfill PSI R&D needs

What are the best ways to exploit these facilities?

Thank you for your attention