START OF THE WEST FACILITY

BUCAOSSI Jérôme and the WEST team

21 MARCH 2017
OUTLINE

WEST mission
Physics and engineering design
Manufacturing and load assembly
Commissioning status
Summary
Divertor: a crucial component for power exhaust

ITER divertor heat loads specs:
- Steady state: 10 MW/m²
- Slow transients: 20 MW/m²
- ELMs - disruptions

**Keys figures for ITER divertor risk analysis**
- Cost > 100 M€
- Manufacturing: ~ 6 to 8 years
- Installation and commissioning in nuclear environment: ~1 year

**WEST: testing ITER technology in tokamak environment to minimize risks for ITER divertor**

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WEST HIGH LEVEL DELIVERABLES FOR ITER

D1-D2: optimization of industrial scale production / procurement organization
D3: power handling, shaping and tolerances
D4: PFC lifetime under high fluence
D5-D6-D7-D8: divertor protection / learning curve / long pulse H-mode / advanced scenarios

* need dates as defined by IO

ITER
Preparation phase
Production phase

PFUs
Preparation phase
Production phase

WEST
PFC manufacturing:
Feedback on large scale industrial production

PFUs

Ops
Operation phase I
Short pulse at 10 MW/m²
First validation in tokamak

Operation phase II
Long pulse at 10-20 MW/m²
PFC degradation, High fluence PWI
Long pulse H mode
WEST ADDRESSES PLASMA EXHAUST GAPS IN THE EU STRATEGY

Unprecedented particle fluence in next step devices

- Orders of magnitude step from today devices to ITER → Impact on materials?
- Wide range of issues to address
  - Material erosion and surface modification → PFC lifetime
  - Dust production
  - Fuel retention in vessel walls

Large aspect ratio physics

- SOL width / ELM energy density
- Test for scaling / models (good diagnostic coverage)

Double null and compact divertor physics

- Divertor detachment control over wall equilibrium time

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WEST BUILDS ON TORE SUPRA MAIN ASSET: DESIGNED FOR LONG PULSE OPERATION

From Tore Supra
- Superconducting toroidal field coils
- Cryogenic plant
- Vacuum vessel and cryostat
- Poloidal field system
- Pressurized cooling water loop (40 bars, 200°C, 6 MW CW)
- 12 MW LHCD system (generators)
- 12 MW ICRH system (generators)
- Fueling systems
- Diagnostics

To WEST
- Divertor coils and power supplies
- W actively cooled PFC
- Upgraded cooling syst. (12 MW CW)
- ICRH ELM-resilient antennas (x3)
- New diagnostics
- New CODAC and PCS
WEST MAIN PARAMETERS
WIDE RANGE OF DIVERTOR EQUILIBRIA

IR Wide Angle camera
Vis. Camera Fast
Vis. Camera Q4
Vis. Camera Q6A & Q6B
Reflectometry cluster
Bolometer Narrow Angle
Massive Gas Injection
Vis. Spectro inner bumper
He thermal BES Horizontal

Thomson laser dump
Thomson Scattering
UV spectro SURVIE
Vis. Spectro upper div
AIA (SXR)
Vis. Cameras
Doppler reflectometry

Reciprocating Lang. Probe
Reciprocating Lang. Probe

Bolometer
XICS
Zeff tangential
ECE 2D
Pellet injection

Metallic impurity inj.
Vis. Cam. outer bumper
Zeff poloidal
UV spectro SIR
HXR
SMBI

Interferopolarimetry
Reflectometry
Pecker probes

IR Camera
IR Camera HR

I_p (q95≈2.5)
B_T
R
a
A
κ
δ
V_p
n_GW (1MA)
P_ICRH
P_LHCD
T_{flat tricky} (0.8 MA)
1 MA
3.7 T
2.5 m
0.5 m
5-6
1.3-1.8
0.5-0.6
15 m³
1.5 \times 10^{20} \text{ m}^{-3}
9 MW
7 MW
1000 s

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WEST TARGET IS REPRESENTATIVE OF ITER VERTICAL TARGET

<table>
<thead>
<tr>
<th>Parameter</th>
<th>WEST vs ITER IVT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plasma Facing Unit</td>
<td>Identical to high heat flux flat part</td>
</tr>
<tr>
<td>Assembling technology</td>
<td>Identical</td>
</tr>
<tr>
<td>Monoblock geometry and shape</td>
<td>Identical</td>
</tr>
<tr>
<td>Thermal hydraulic conditions</td>
<td>Identical</td>
</tr>
<tr>
<td>Area / nb of monoblocks</td>
<td>~14 % ITER</td>
</tr>
<tr>
<td>Length of PFU</td>
<td>Scale 1/3</td>
</tr>
<tr>
<td>Number of PFU</td>
<td>~ 1/2 ITER</td>
</tr>
</tbody>
</table>
WEST PROVIDES ITER RELEVANT STEADY-STATE HEAT LOADS

Close X-point
(P_{SOL} \sim 10 \text{ MW}, \lambda_q = 5 \text{ mm})

Far X-point
(P_{SOL} \sim 3 \text{ MW}, \lambda_q = 5 \text{ mm})

Outer strike point (LFS)
~10 \text{ MW/m}^2

Inner strike point (HFS)
~5 \text{ MW/m}^2

... as well as ITER relevant fluence (~10^{27} \text{ D/m}^2) within a few days of operation (phase 2)

[courtesy R. Pitts]
## WEST Plasma Scenarios

### Scenario (B\(_T\) = 3.6T)

0.5D simulations, H98 = 1.0

<table>
<thead>
<tr>
<th></th>
<th>High Confinement</th>
<th>High Heat Flux</th>
<th>High Fluence</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>I(_p)</strong> (MA)</td>
<td>0.8</td>
<td>0.6</td>
<td>0.6</td>
</tr>
<tr>
<td><strong>n(_e)</strong> (10(^{19})m(^{-3}))</td>
<td>8</td>
<td>7</td>
<td>6.7</td>
</tr>
<tr>
<td>(f_{GW})</td>
<td>64%</td>
<td>75%</td>
<td>72%</td>
</tr>
<tr>
<td>LHCD (MW)</td>
<td>6</td>
<td>6</td>
<td>6.3</td>
</tr>
<tr>
<td>ICRH (MW)</td>
<td>9</td>
<td>6</td>
<td>3</td>
</tr>
<tr>
<td><strong>T(_{ped})</strong> (keV)</td>
<td>0.6</td>
<td>0.4</td>
<td>0.3</td>
</tr>
<tr>
<td><strong>n(_{ped})</strong> (10(^{19})m(^{-3}))</td>
<td>5.3</td>
<td>4.8</td>
<td>5.0</td>
</tr>
<tr>
<td>Bootstrap fraction (%)</td>
<td>19</td>
<td>30</td>
<td>29</td>
</tr>
<tr>
<td>LHCD fraction (%)</td>
<td>53</td>
<td>63</td>
<td>73</td>
</tr>
<tr>
<td>LHCD eff. (A.W(^{-1})10(^{20})m(^{-2}))</td>
<td>0.14</td>
<td>0.11</td>
<td>0.12</td>
</tr>
<tr>
<td>Loop voltage (V)</td>
<td>0.078</td>
<td>0.023</td>
<td>0.006</td>
</tr>
<tr>
<td><strong>Pulse length (s):</strong> 14 Wb or ICRH generator limit</td>
<td>30s</td>
<td>60s</td>
<td>1000s</td>
</tr>
<tr>
<td><strong>Target for PFC testing</strong></td>
<td><strong>ELMs</strong></td>
<td><strong>20 MW/m(^2)</strong></td>
<td><strong>10(^{27}) D/m(^2)</strong></td>
</tr>
</tbody>
</table>
LHCD capability is compatible with long pulse operation at high pedestal density
Flexibility in ICRH power deposition, in ion/electron heating

Scenario (B_T = 3.6T)
0.5D simulations, H98 = 1.0

- 15 MW, 0.8 MA, 30 s
- 12 MW, 0.6 MA, 60 s
- 9.3 MW, 0.6 MA, 1000 s
WEST H-mode-like configuration: high density case with $N_2$ seeding ($f_{\text{rad}} \approx 85\%$)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{\text{SOL}}$</td>
<td>8 MW</td>
</tr>
<tr>
<td>$n_{\text{sep}}$</td>
<td>$3.6 \cdot 10^{19} , m^{-3}$</td>
</tr>
<tr>
<td>Gas Puff</td>
<td>$1 \cdot 10^{21} , \text{part} , s^{-1}$</td>
</tr>
<tr>
<td>Total radiated power</td>
<td>6.9 MW</td>
</tr>
</tbody>
</table>

Transport coefficient derived from ASDEX Upgrade experiments

- Heat flux (MW/m$^2$)
- Plasma density
- Plasma temperatures (eV)

![Graphs showing heat flux, plasma density, and plasma temperatures]
WEST ENGINEERING: INTEGRATION IN AN ACTIVELY COOLED ENVIRONMENT
WEST ENGINEERING: INTEGRATION IN AN ACTIVELY COOLED ENVIRONMENT

Torus Hall (building 500)
DIVERTOR INTEGRATION
VERY TIGHT SPACE FOR COILS AND PFC

- Independent 30° sectors (38 PFU), toroidal gap between PFU ~0.6 mm, vertical misalignment <0.3 mm

- Coil conductor: 32x30 mm with a bore of φ 20mm (16 turns in total)
DIVERTOR STRUCTURE AND COILS MANUFACTURED AND INSTALLED

- Contract signed June 2013
- Structures delivered Oct 2014
- Structures installation completed April 2015
- Coil casings and conductors delivered May 2015
- Casings installation completed Jan 2016
- Winding construction completed July 2016

The 6 sectors of the lower divertor coil casing assembled on CNIM machine tool

Divertor supporting structure elements

Machining of a 60° casing sector
Tight tolerances on large components to be assembled in situ, 150 brazing joints, joggles and feedthroughs.
Coils impregnation (@ 50°C) and curing (@ 170°C, 3 stages) performed after vacuum vessel evacuation with the main cooling loop (2 mocks up necessary to optimize the process)
First ITER like prototypes manufactured by JA-DA and ASIPP
- Reception: HHF testing (100 cycles at 10 MW/m² for ASIPP / 10 for JADA PFUs)
- Pre-characterization: hardness test, IR thermography (SATIR), confocal microscopy, erosion markers, etc.
WEST WILL START WITH A MIXED CONFIGURATION OF THE MAIN DIVERTOR

**Phase 1:** mix of ITER like and inertially cooled PFU (2016-2018)

- Modular divertor design for PFC testing (12 sectors, 38 PFU/sector)
- W coated graphite PFU: energy limitation (few s) but more imbedded diagnostics (Langmuir probes, thermocouples, Fiber Bragg Grating, etc.)
- Start up test sector for WEST phase 1

**Phase 2:** full ITER like divertor (from 2019 on)

- ITER monoblock
- CuCrZr tube
- Cu interlayer

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TEST SECTOR WITH ITER-LIKE PFU AND W-COATED GRAPHITE PFU (15 µm)
INERTIALLY COOLED SECTOR SHOWING PFU SHAPING AND LANGMUIR PROBES
“Close” X-point configuration for $P_{\text{div}} = 1$ MW and $\lambda_q = 5$ mm ($s = 1$ mm)
2000 Tungsten coated PFC manufactured, qualified and pre-assembled

30° upper divertor sector (Cu / W coating)

30° baffle sector (Cu / W coating)
PVD COATING PROCESS ON CUCRZR SUBSTRATE VALIDATED

- HHF tests at GLADIS
  - 10 MW/m² on the upper divertor
  - 3.5 MW/m² on the baffle

- Many campaigns from the R&D samples to the full size prototype shown no limitation at the required thermal load

Temperature map during HHF test on a upper divertor PFC

Temperature map during HHF test on a baffle PFC
LOAD ASSEMBLY COMPLETED
3 PHASES FROM OCT. 2014 TO NOV. 2016

- **Phase 1** (Oct. 14-April 15): magnetic meas. (part 1), outer vessel panels, upper & lower casks, divertor supports
- **Phase 2** (May 15-July 16): in situ construction of the divertor coils
- **Phase 3** (July 16-Nov. 16): inner vessel protection panels, PFC, in-vessel diagnostics
- **Commissioning** (Nov. 16-April 17): leak detection, coils impregnation, vessel baking, GDC, first plasma, LH antenna installation, divertor coils commissioning, PCS
Introduction: manual translation
+ rotation on the tray with ball bearing (yaw)
+ inclination for entering the port

Positioning: electric lift
+ inclination to avoid the rail
+ alignment on divertor centering pin
LOAD ASSEMBLY: INSTALLATION OF THE LAST UPPER DIVERTOR PFC SECTOR
LOAD ASSEMBLY – MOUNTING AND BRAZING OF THE LOWER STABILIZING PLATE

First brazing ongoing

First plate after brazing
LOAD ASSEMBLY – MOUNTING OF THE LAST SECTORS OF THE LOWER DIVERTOR

Test sector mounted

Mounting of the last divertor sector

Mounting of the last baffle sector
Upper divertor target
W-coating, actively cooled. 8MW/m²

Lower divertor target
W-coating, inertially cooled
+ 6 ITER-like PFUs (20 MW/m²)

Inner bumper
W-coating, actively cooled

VDE protections
W-coating, actively cooled

Vessel protection panels
stainless steel, actively cooled

Divertor baffle
W-coating, actively cooled
Plasma ops: water inlet temperature 70°C (PFC) and 50°C (divertor coils), pressure at pump inlet 2.4 MPa
Baking: 200°C, 2 MPa
FIRST PLASMA BREAKDOWN ACHIEVED IN DECEMBER 2016

- About 15 plasma breakdowns obtained in Dec. (1st = 50037) without divertor coils
- New magnetic measurement commissioned
- Optimization of the magnetic field map is still underway (comparison with magnetics)
Each simulation is performed by taking input data from the experimental database:
- Initial condition: PF coils currents + loop voltage for passive currents
- Time evolution: PF voltages

Cam: 794ms
Sim: 20

Cam: 798ms
Sim: 22

Cam: 802ms
Sim: 24

Cam: 806ms
Sim: 26

Cam: 810ms
Sim: 28ms
SHORT SHUTDOWN FROM JANUARY TO MARCH 2017 TO INSTALL THE LH LAUNCHERS
2 Power Supplies 300V $+13\text{kA}-1000\text{s}/3600\text{s}$
or $+20\text{kA} - 10\text{s}/1200\text{s}$ (39t)
Delivered in July 2016 at Cadarache
First qualification with divertor coils in January with Chinese colleagues from SWIP and NERCC (supplier)

Commissioning will be completed in the coming weeks with plasma operation
COMMISSIONING ONGOING IN MARCH
NEW PLASMA CONTROL SYSTEM DEBUGGING

New Pulse Editor

- Xedit from W7X
- Workflow to prepare plasma discharge tested
- Evolutions ongoing with IPP Greifswald

New Controllers

- PCS based on ASDEX
- Upgrade DCS
- Control of plasma position (R, Z) and shaping (gaps, dx) implemented
- Emission/Reception of time event is being validated
- Communication with RT network → reliability improvement ongoing
Workflow includes 0D models for flux consumption and density evolution
- $I_p$ ramp-up: 200 → 600kA in 2s
- 2 modes of control used successively: position control (R, Z) → pos. + shape control
- Plasma position and shape are well controlled, X-point is formed at ~0.8s

Expected in the coming weeks
<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td><strong>PFC</strong></td>
<td>Mix of actively + inertially cooled startup divertor elements</td>
<td>Full actively cooled divertor</td>
</tr>
<tr>
<td><strong>Pulse length</strong></td>
<td>~ 5-10 s &gt; ITER like PFU time constant</td>
<td>Up to 1000 s</td>
</tr>
<tr>
<td><strong>Main focus for PFC testing</strong></td>
<td>Power handling</td>
<td>High particle fluence / long pulse operation</td>
</tr>
</tbody>
</table>

**Phase 1**
- ITER like PFU prototypes testing @10 MW/m² / low fluence
- PFU misalignment
- Operation with damaged PFU
- Urgent design issues for ITER

**Phase 2**
- Large scale ITER like PFU testing @ 10-20 MW/m² / high fluence
- Long pulse H mode with metallic walls
- Test of innovative PFCs
- Divertor operation for ITER / Innovative PFC testing (DEMO)
WEST PHASE I EXPERIMENTAL SCHEDULE
PREPARING WEST PHASE II

April 2017
C1 – Heat loads / L-H transition
- Steady state heat load pattern
- Tolerance to PFU misalignment
- L-H transition

P_{LHCD} = 5 MW
P_{ICRF} = 0 MW
+ ICRF antenna commissioning (end of C1)

Oct 2017
C2 – PFC testing / H mode characterization
- H mode characterization (ELMs)
- PFC testing @ 10 MW/m² (few prototypes)

P_{LHCD} = 5 MW
P_{ICRF} = 5 MW

2018
C3 – Preparation for long pulse
- Preparation for long pulse operation (USN)
- Melting experiments

P_{LHCD} = 6-7 MW
P_{ICRF} = 8-9 MW

C4 – He campaign
- ITER like PFU @ low He fluence
- He vs D confinement

P_{LHCD} = 6-7 MW
P_{ICRF} = 8-9 MW

Total Heating Power (MW)
- 5 MW
- 10 MW
- 15 MW

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WEST to support ITER divertor strategy
- Diverted tokamak with W environment and long pulse capability (1000 s)
- WEST divertor target representative of ITER divertor target
- Risk mitigation for ITER tungsten divertor procurement and operation

Commissioning ongoing
- Major components delivered and installed
- Load assembly completed
- Vessel evacuation early November 2016
- First plasma breakdown in December 2016

First experimental campaign to start soon
- Staged approach for WEST exploitation
- First phase with a mix of ITER-like and inertially cooled Plasma Facing Units (PFU)
- ITER-like PFU prototypes will be exposed during the first campaigns
- Series production to be launched in 2017 with WEST partners
Thank you for your attention
J. Bucalossi and the WEST team,
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3 new ICRH antennas: design with EU / CN labs → based on CEA 2007 prototype and JET-ILA
Manufacturing of antenna components by ASIPP (China)
First antenna parts delivered on site in July 2016

First antenna assembly is ongoing at Cadarache → installation expected in May 2017
Antenna 2 and 3 parts to be delivered at Cadarache in May 2017 → installation in September 2017

Main features

<table>
<thead>
<tr>
<th>Feature</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steady state operation (→ active cooling)</td>
<td>1MW / antenna</td>
</tr>
<tr>
<td>Maximum power operation (30s)</td>
<td>3MW / antenna</td>
</tr>
<tr>
<td>ELM resilient (H mode)</td>
<td>Conjugate T / internal matching (capacitors)</td>
</tr>
</tbody>
</table>