WEST and ASDEX-Upgrade capabilities for boronization studies in full-W tokamaks

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and the EUROfusion TE team

Joint WP TE and WP PWIE Technical Meeting on Plasma Wall Interactions in full W devices, Sep 17 – 19 2024, Aix-en-Pce

ASDEX Upgrade

MAX-PLANCK-INSTITUT
FÜR PLASMAPHYSIK

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Boronization of future magnetic fusion machines with full-W walls and long plasma pulses: do we have a plan?

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- heavy metal (W) walls to cope with extreme heat and particle exhaust
- long plasma pulses (100 s – 1000 s) to study steady state operations

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- transiently mitigated W erosion in low ion flux regions (unlike divertor)

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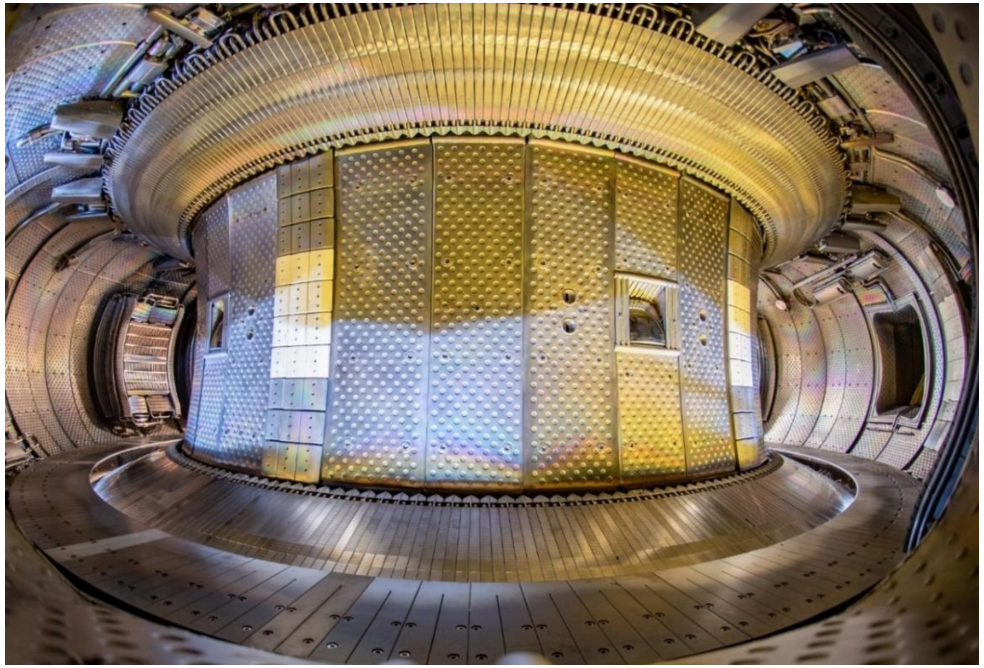
Issue Bigger constrains with respect to last or current generation devices :

- limited magnet duty cycle ==> glow discharge boronization not routine solution
- larger vacuum vessel surfaces ==> larger B mass for similar layers thickness
- long plasma pulses and high fluence ==> B layers quickly removed / remobilized
- few data on T retention in B layers and dusts ==> unknown impact on T inventory

WEST : long pulses, active cooling, ITER grade divertor

Tungsten (**W**) **E**nvironment **S**teady state **T**okamak :

- Superconducting toroidal field coils, 3.7 T
- Maximum plasma current = 1 MA
- Major radius = 2.5 m, minor radius = 0.5 m
- Total heating power (LH + IC) = 16 MW
- Maximum pulse duration 1000 s (**364 s**)



[J. Bucalossi, FED, 2014] [C. Bourdelle, NF, 2015]

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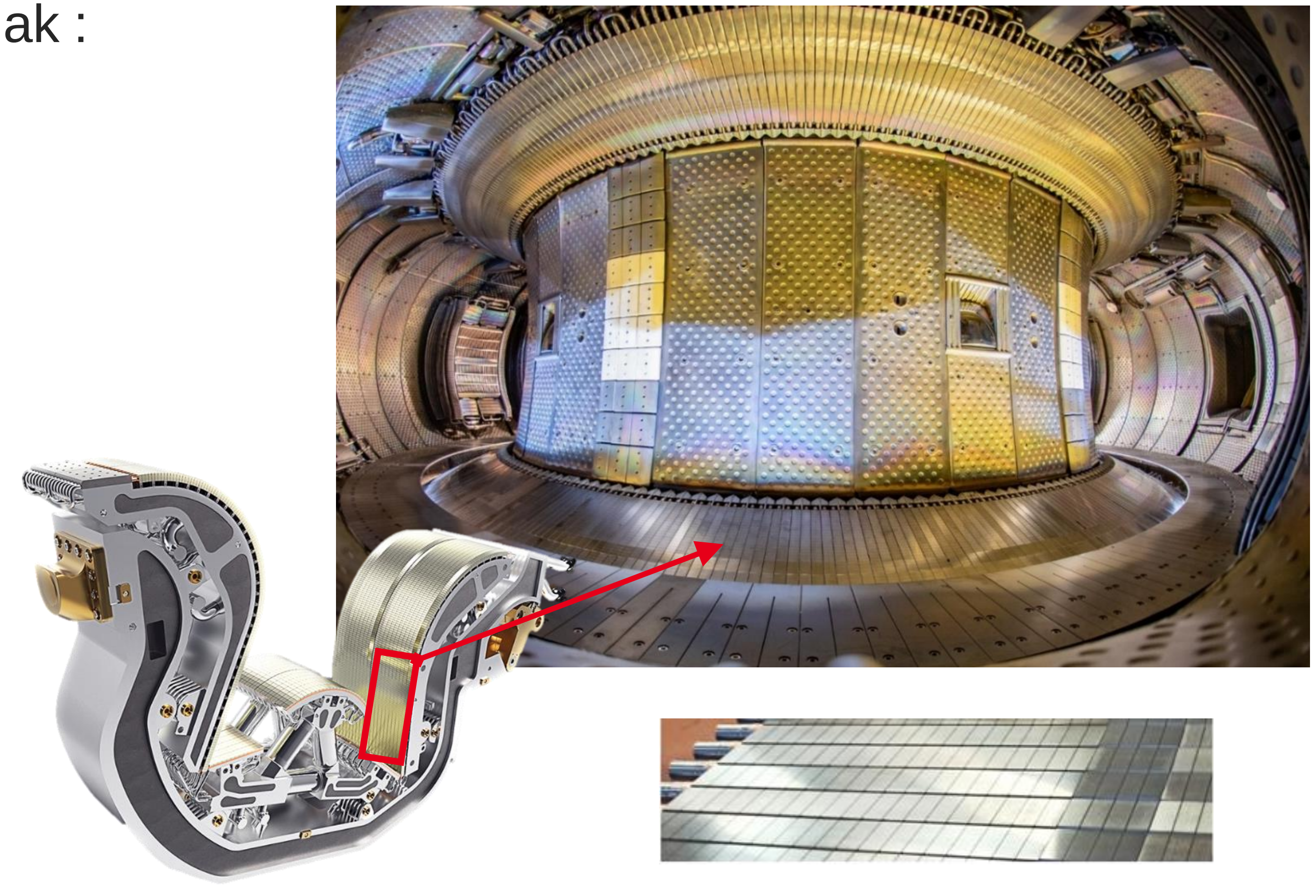

Goal Qualify actively cooled, ITER grade divertor technology under 10 MW m^{-2} heat flux density (**11 MW m^{-2} * 5 s**)

In 2022 : entirely new, actively cooled, ITER grade lower divertor

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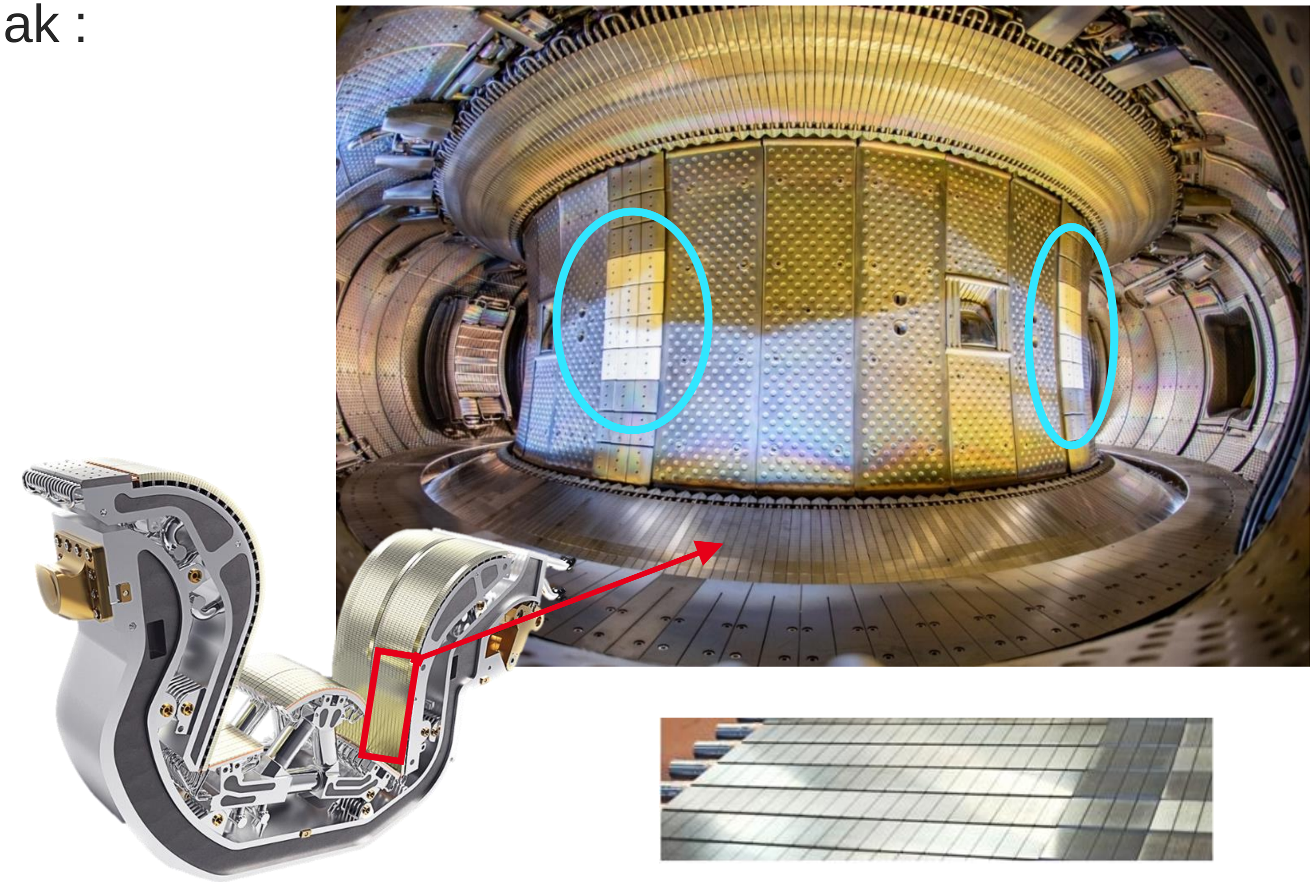

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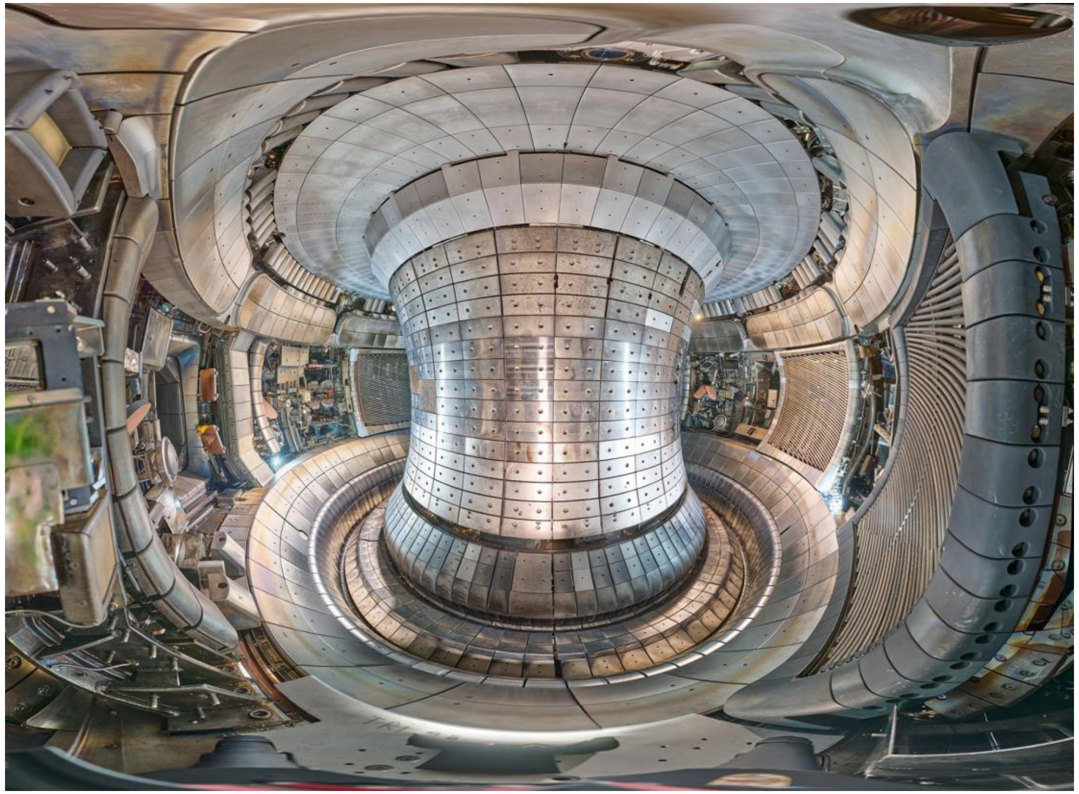
Fall 2024: back to full-W environment (no longer **BN limiter tiles**, replaced with bulk W)

[J. Bucalossi, FED, 2014] [C. Bourdelle, NF, 2015]

ASDEX-Upgrade : high P/R, high current, advanced scenarios

W coating on graphite wall, full-W divertor targets

All-new upper divertor for compact radiative scenario



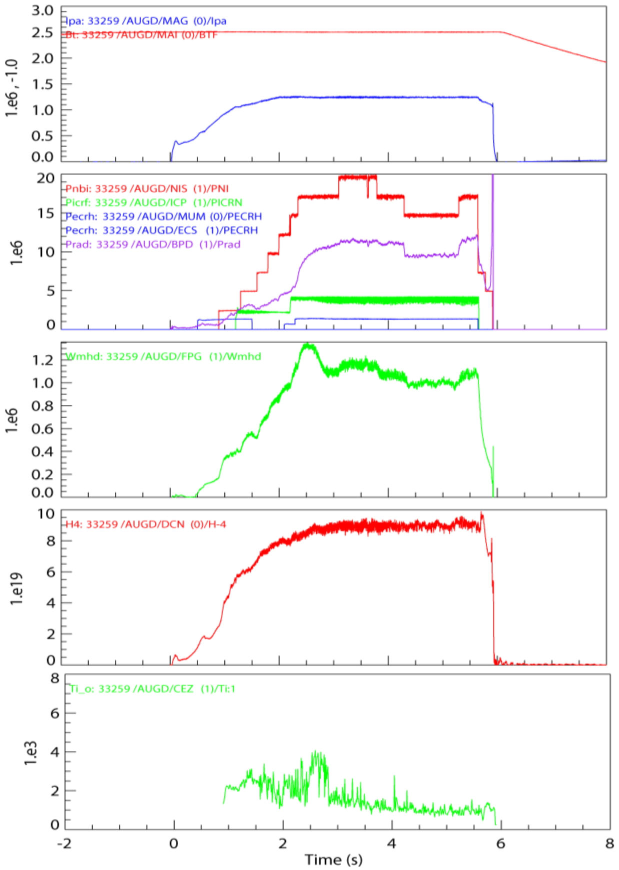
B	I_p	R	A	V_p	κ / δ	P_{aux}	Magnetic conf.
3.2 T	1.4 MA	1.65 m	3.1	13 m³	1.6 / 0.3	30 MW	LSN, USN, DN

High radiation scenario:

N_2 and Ar seeded
Magnetic field: 2.5 T
Plasma current: 1 MA

Heating:
- NBI up to 20 MW
- ICRH 5 MW
- ECRH 1 MW

Stored energy: 1.3 MJ
Electron dens: $9*10^{19}$ m^3
Ion temperature 4 KeV
Discharge time   6 s



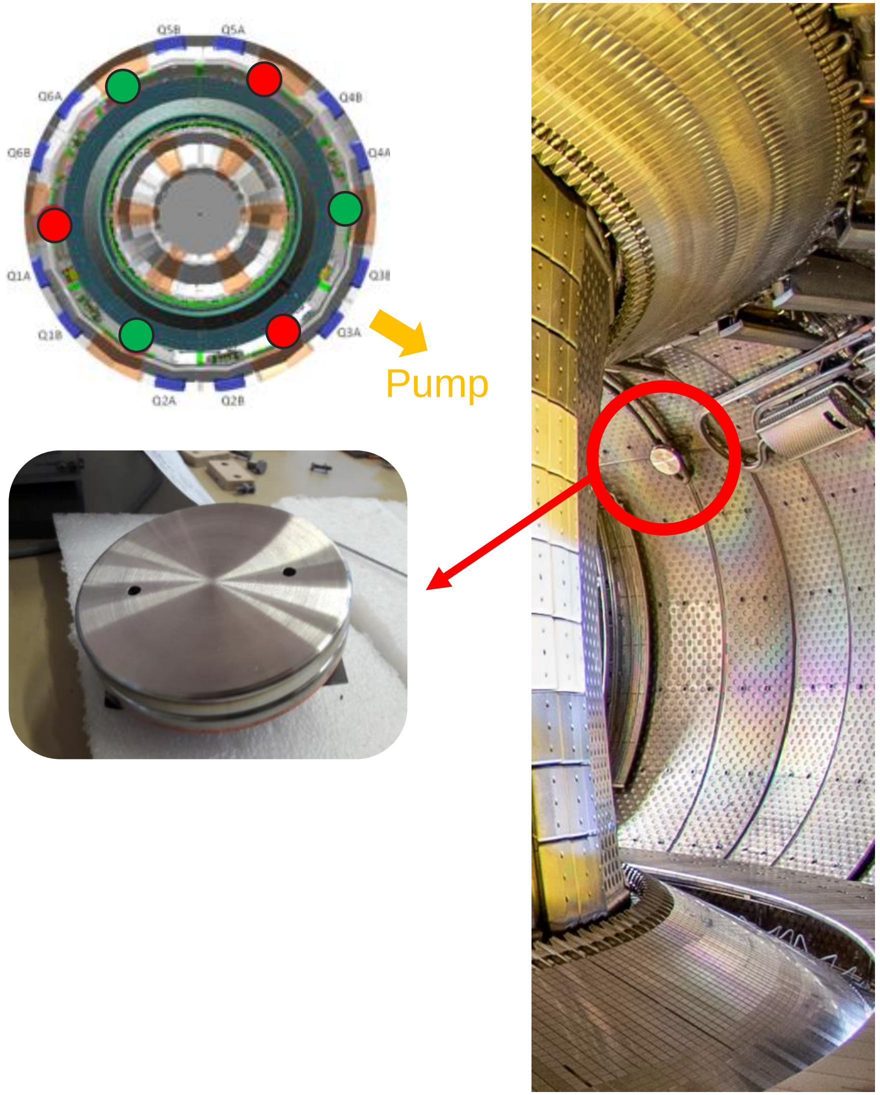
Even in impurity seeded high radiation scenarios only 50 % core radiation

WEST glow discharge boronization setup

6 glow anodes at the top of the vessel, equally spaced in ϕ

$V = 500$ V, $I_{tot} = 4 - 6$ A, $p = 0.3 - 0.6$ Pa

2 power supplies: - possibility to power only 1-3-5 or 2-4-6
- possibility to use electrodes to collect current instead (like Langmuir probes)



[A. Gallo, submitted to NME, 2024]

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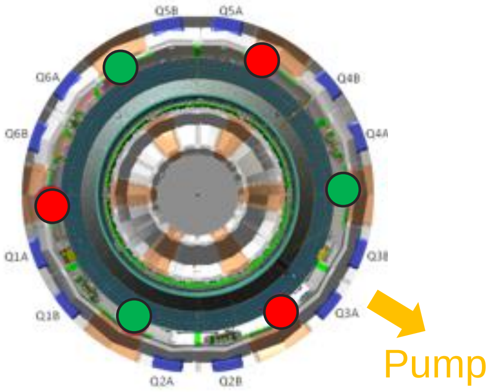
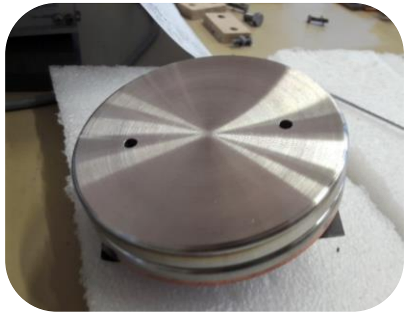
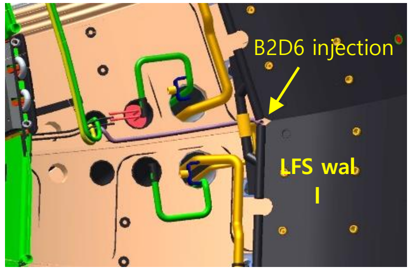
6 diborane injection points at the bottom of the vessel, (equally spaced in ϕ) behind baffle, near LFS wall

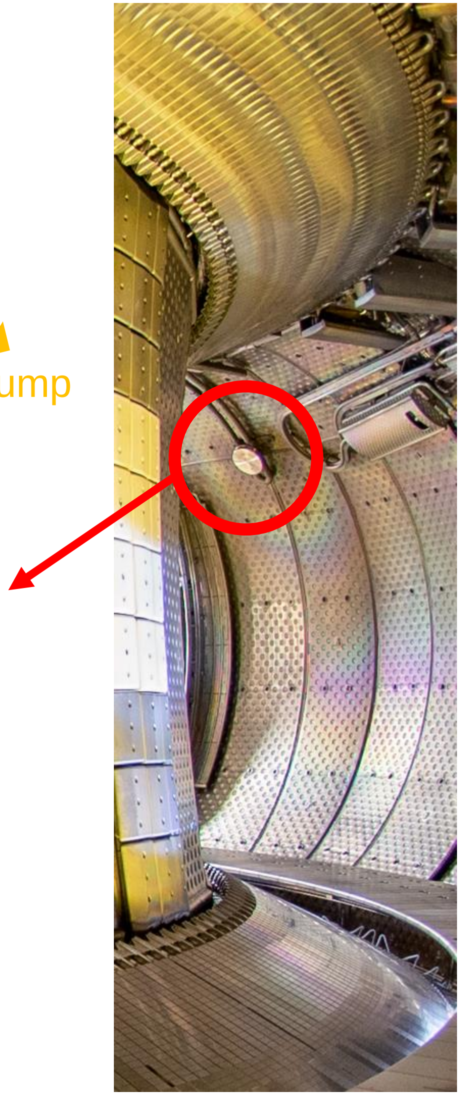
2 gas injection lines: possibility to inject only 1-2-3 or 4-5-6

Flexible system to study role of spatially non-uniform boronization on B layers during ITER early operations









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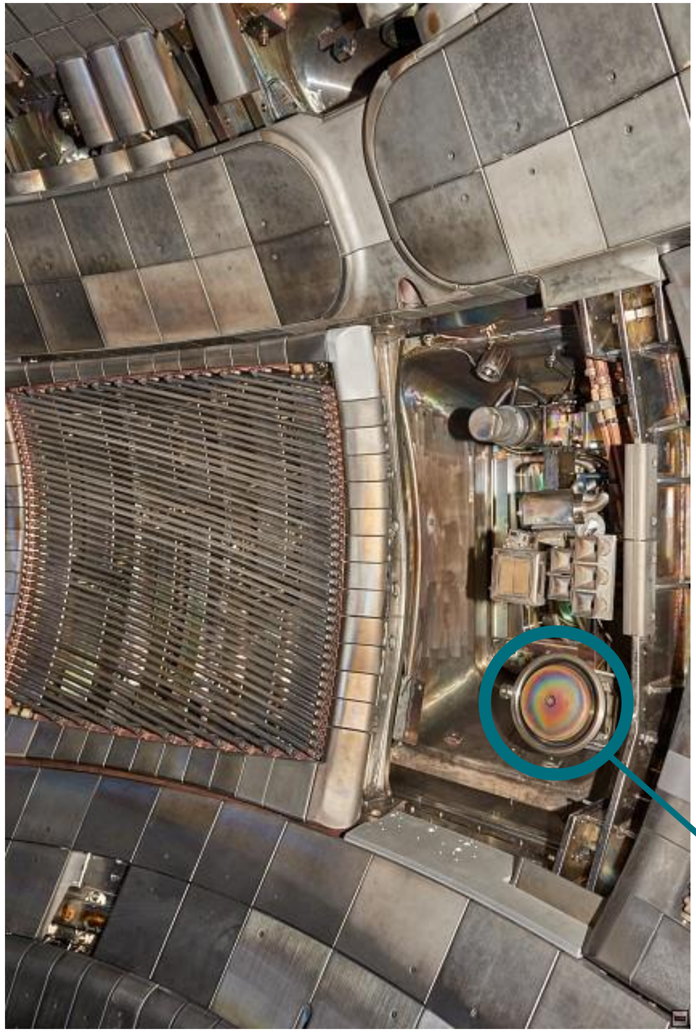
ASDEX-Upgrade glow discharge boronization setup



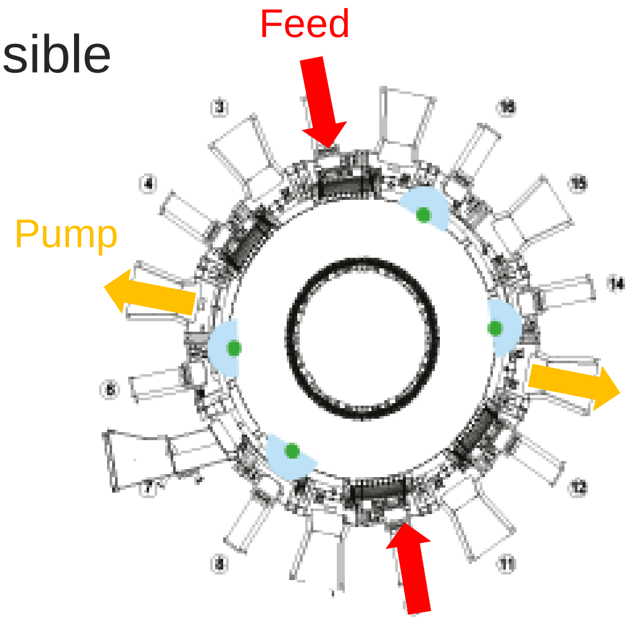
Anodes, inlet, pumping: as symmetric as possible

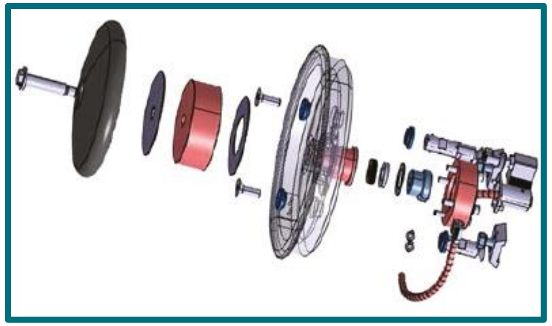
4 glow anodes located at midplane

4 individual power supplies (2 A / 2 kV)

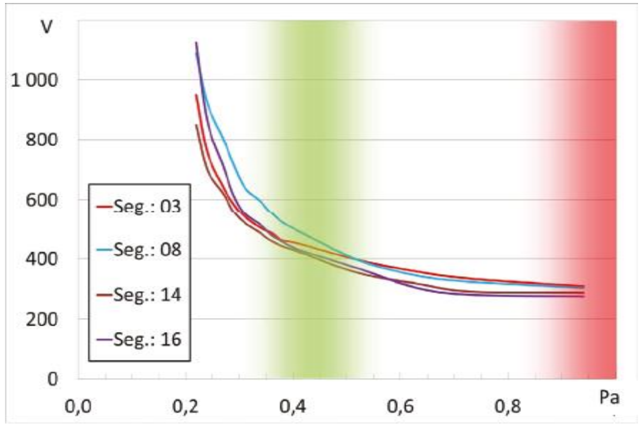
Working gas: D_2 , He or H_2 by MFCs

Used for initial wall cleaning, boronisation, wall cleaning in-between discharges





p = 0.5 Pa
room T
V = 550 V
V_{fl} = 355 V
I = 4*2 A

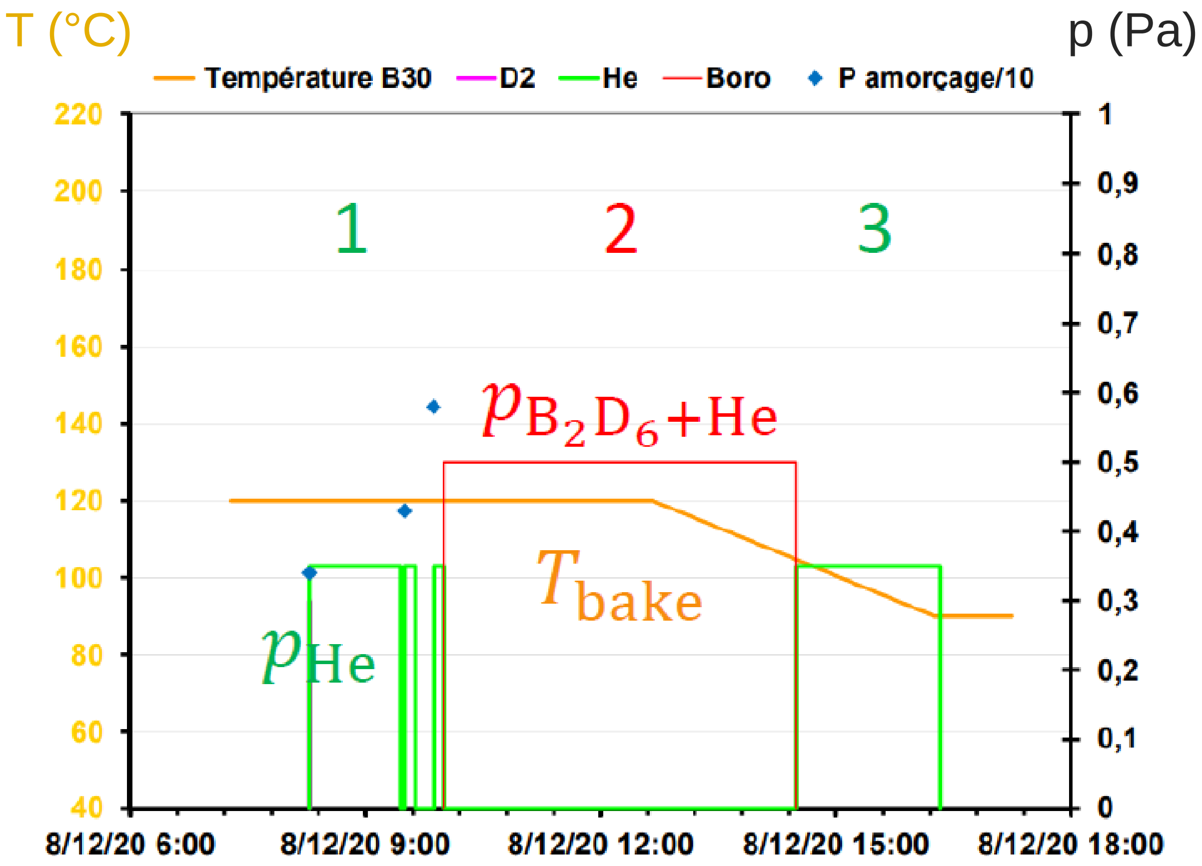


WEST glow discharge boronization procedure

Working gas: He >85 % - B_2D_6 <15%
Only supplier: Air Liquide (no D_2 carrier)

B mass = 10-12 g, total duration ~6 h

Layer thickness currently unknown
Spatial uniformity currently unknown



[Courtesy of WEST tokamak operators]

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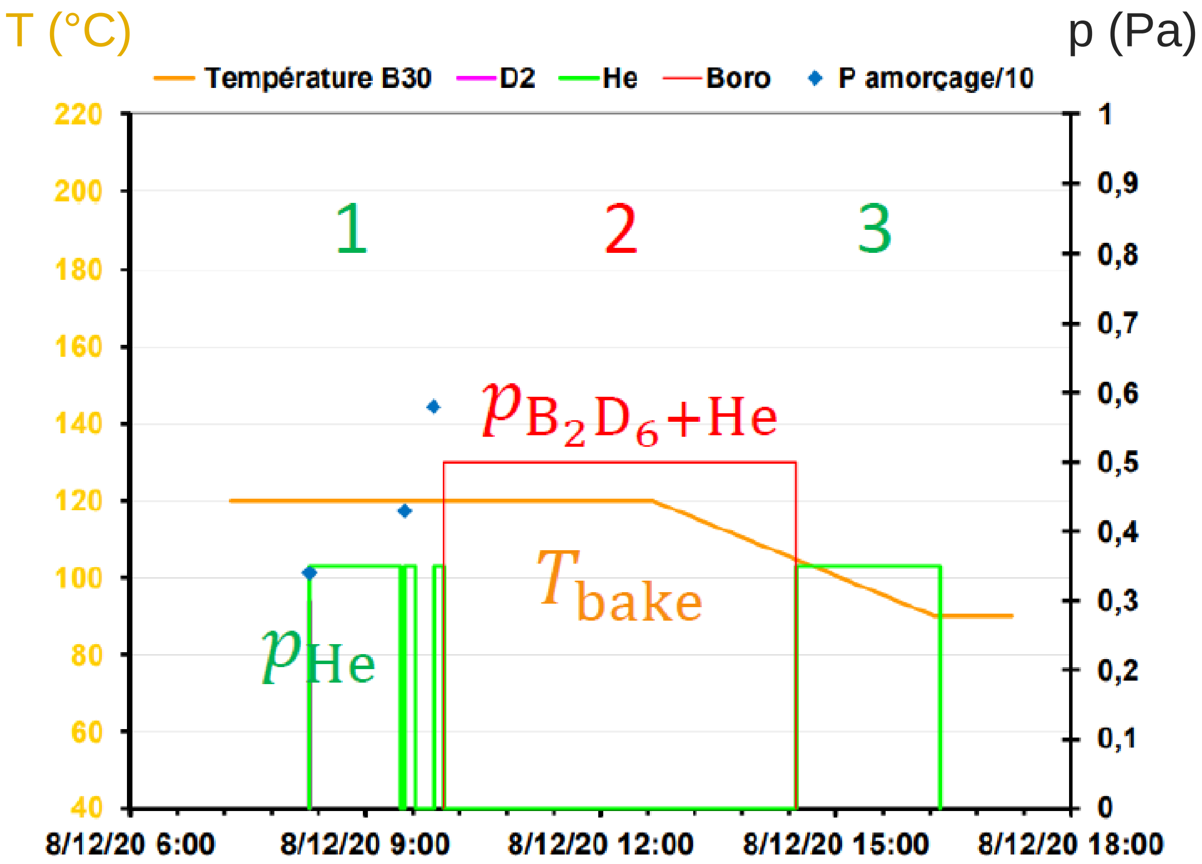
1) He glow to clean surfaces

2) He+B_2D_6 glow to deposit B-rich layers (some traps filled with D_2)

3) He glow to rinse B_2D_6 lines (20 min or longer to remove D_2 from traps)



Possible vessel temperature : 70 °C to 170 °C

[Courtesy of WEST tokamak operators]

ASDEX-Upgrade glow discharge boronization procedure

Working gas = 10 % B_2D_6 in He carrier:

==> No H_2 but He contamination

B mass = 8 g, duration ~ 4 h

==> Layer thickness = 30 nm

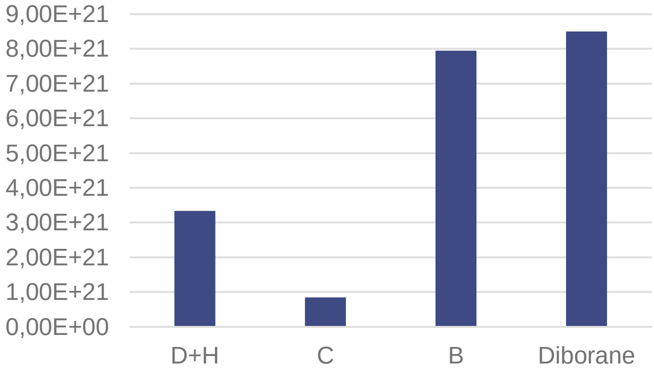
Midplane manipulator and RGA:

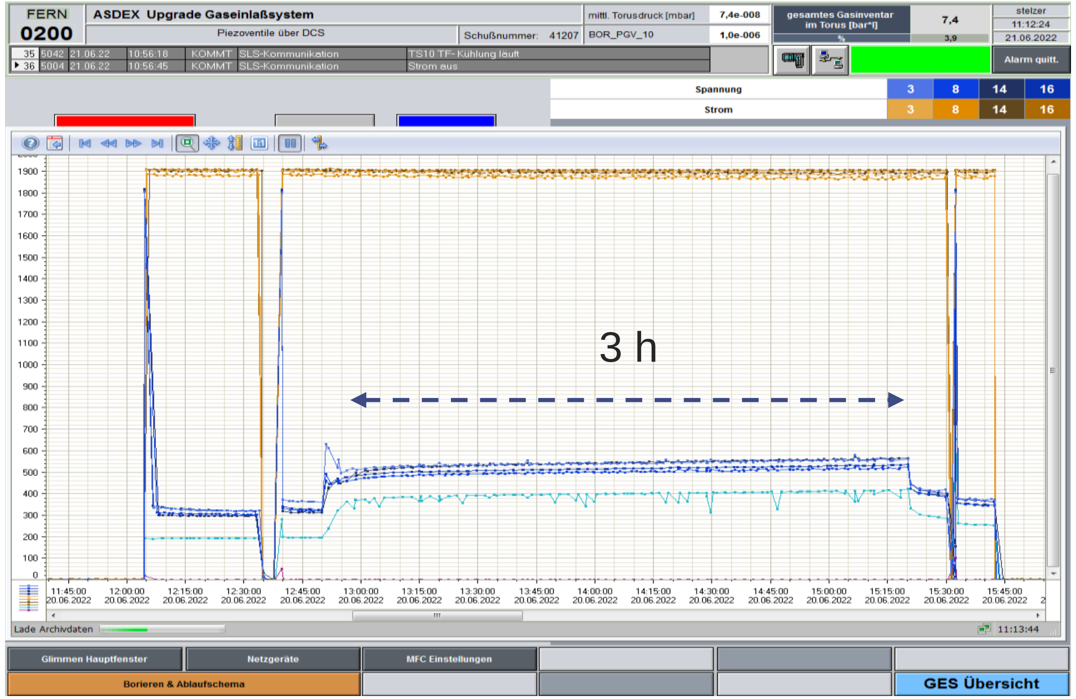
~ 94 % deposition, homogenous layer

Divertor manipulator:

Almost no coating in divertor slits

Layer analysis (2006)
30 % D+H
10 % C





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36 5004 21.06.22 10:56:45 KOMMT SLS-Kommunikation Strom aus
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HeGD GES
Wall cleaning

HeGD BOR
check

B_2D_6 BOR
coating

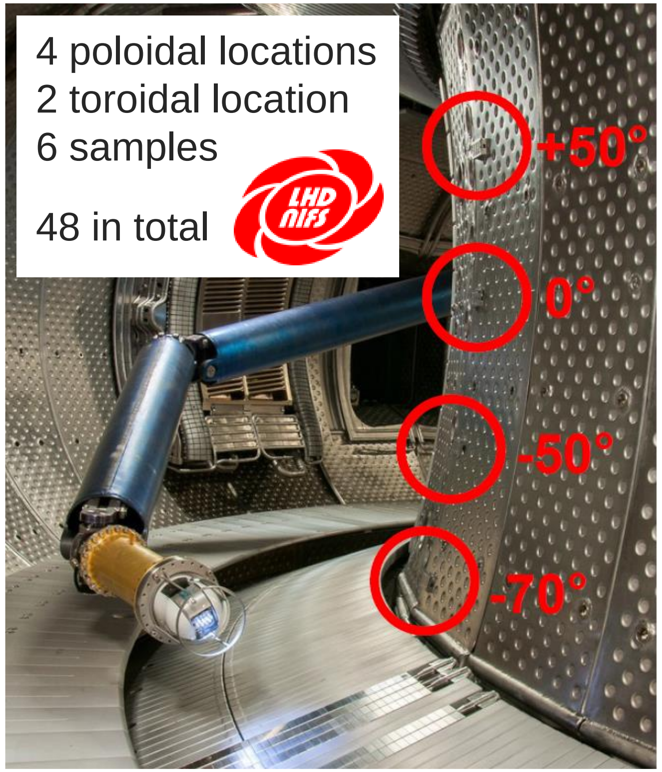
HeGD BOR
clean

HeGD GES
Diborane cleaning

WEST post mortem analysis diagnostics

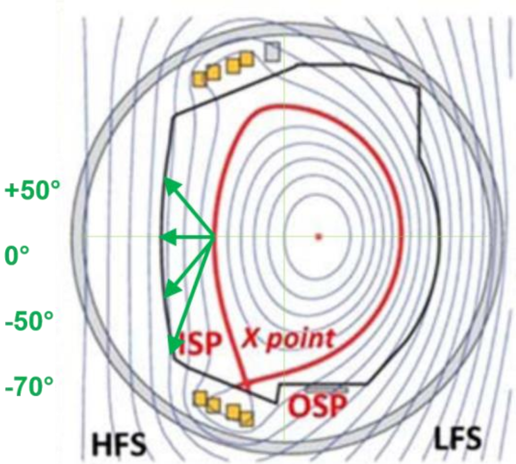
Limited set of boronization post mortem tools:

HFS wall coupons (campaign-integrated data), no ion flux in diverted pulses, only CX neutrals



4 poloidal locations
2 toroidal location
6 samples

48 in total



[Courtesy of R. Sakamoto, E. Bernard, M. Diez, B. Guillermin]

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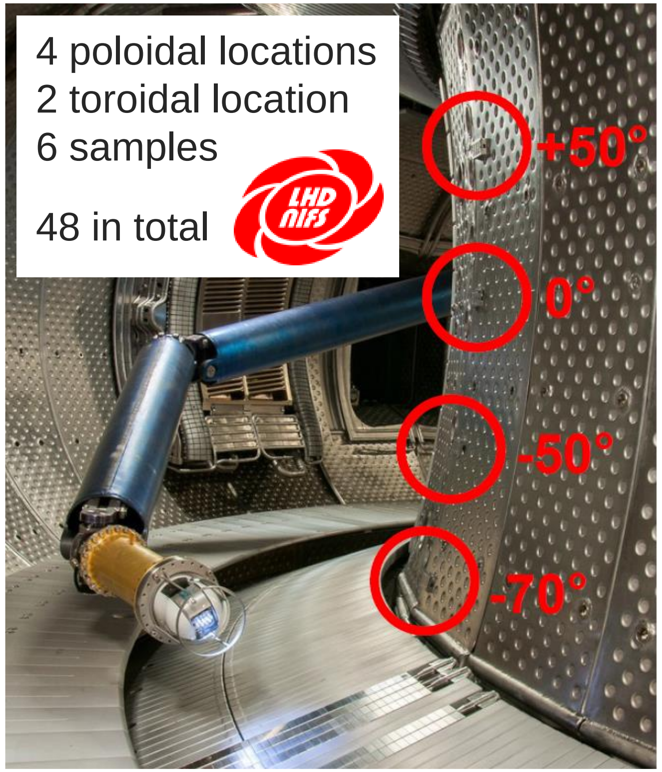

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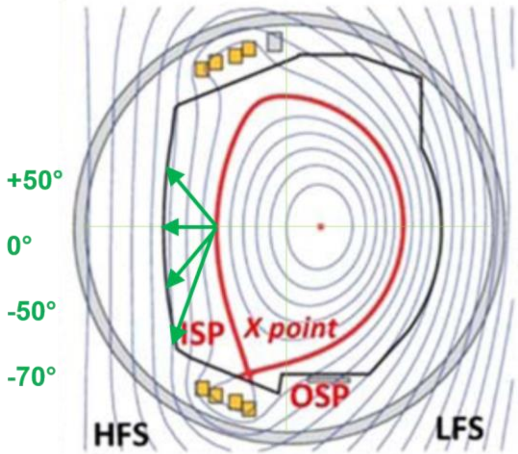
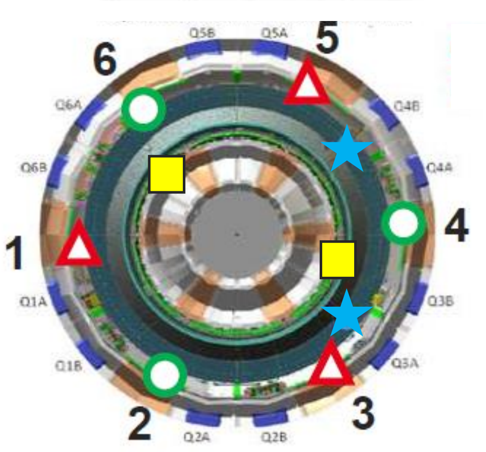
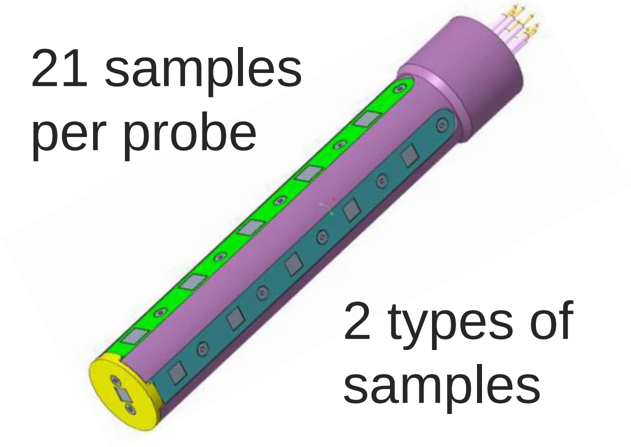


2025: boronization probe (TE enhancements)



△ ○ Glow electrodes
★ Reciprocating probes
🟨 Wall coupons



21 samples per probe

2 types of samples

A. Gallo, V. Rohde, T. Wauters et al., TE+PWIE meeting 2024, Aix-en-Pce

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ASDEX-Upgrade post mortem analysis diagnostics

Extensive array of diagnostics to characterize B layers both before and after plasma exposure

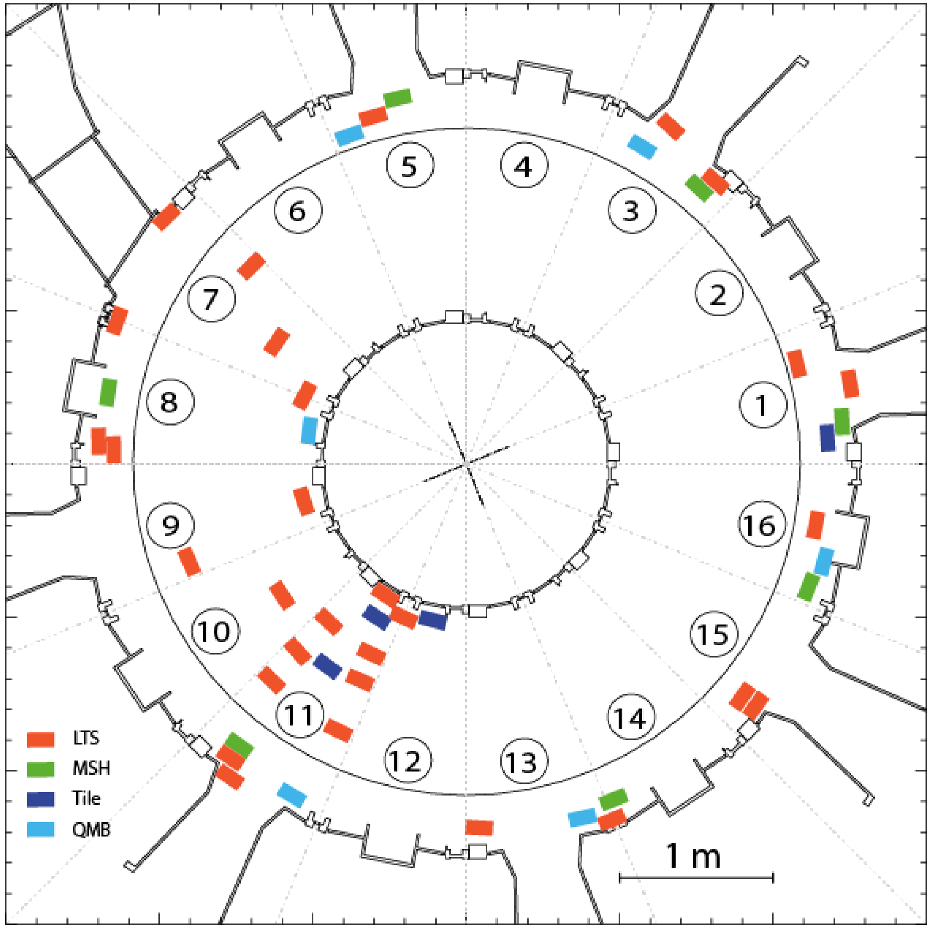
Pre-characterized tiles
at 4 locations

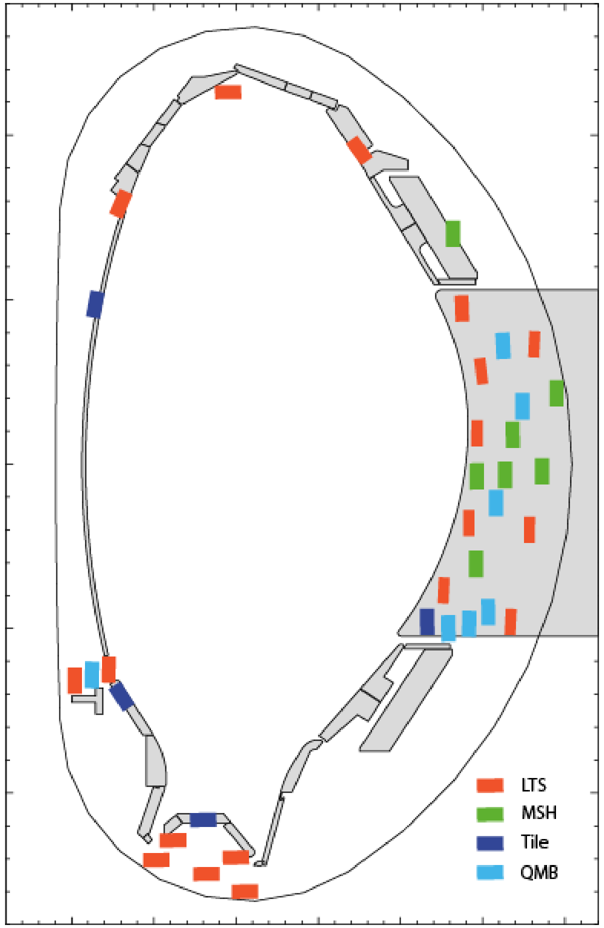
Magnetic SHutter probes (MSH)
at 7 toroidal locations

Quartz MicroBalances (QMB)
at 7 toroidal locations

Long Term Samples (LTS)
52 toroidal/poloidal loactions

4 manipulators (not shown) :
omp, low div, X-point, LBO





Open boronization issues specific to ITER

1) When and how often should ITER be boronized? Longer pulses but colder SOL

2) Optimal boronization parameters be for ITER? He or D_2 carrier, B_2D_6 concentration, glow discharge pressure, glow anodes/injections configuration, vessel temperature…

3) Little knowledge about properties of B coating layers (both from glow and dropper): erosion rate, H/D/T inventory, O gettering capabilities, depth range for fuel removal via isotopic exchange

4) Little knowledge about B accumulation, flaking, dust formation and effect on plasma operations. Same for layer reactivation capabilities (both from glow and dropper).

5) Can powder dropper be a good risk mitigation to ensure Q=10 if boronization fades too quickly?