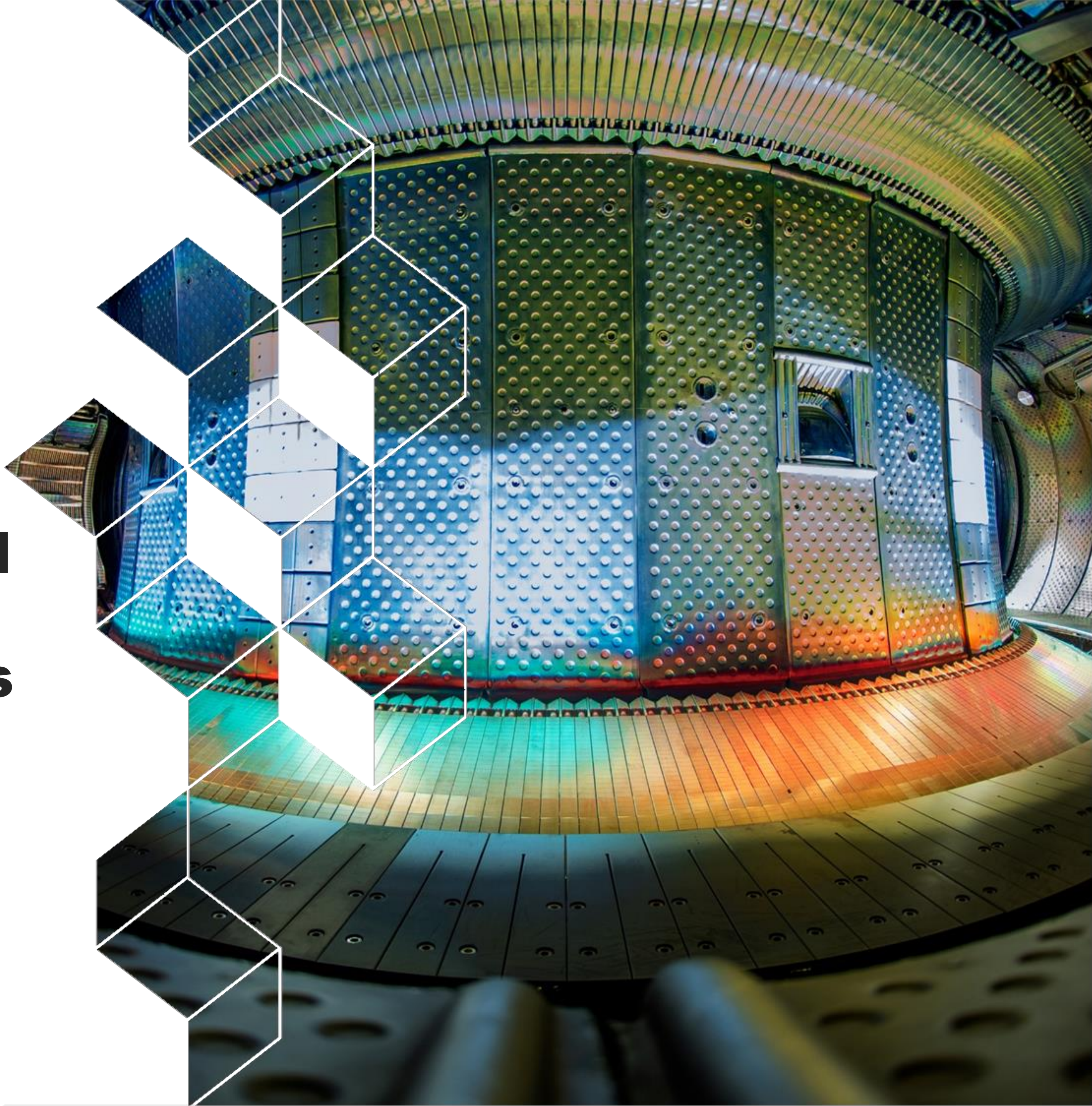
Seminar IFJ PAN
28th March 2024 Krakow, Poland

# Operating a tungsten-wall tokamak: the key role of Soft X-Ray measurements

Didier Mazon



# Harmonia NCN project

Study of the mutual dependence between Lower Hybrid (LH) current drive and heavy impurity transport in tokamak plasmas

Marek Scholz
(Project Leader)

Axel Jardin

Jakub Bielecki

Krzysztof Król

Dominik Dworak

Jędrzej Walkowiak
(PhD student)

Didier Mazon

Yves Peysson

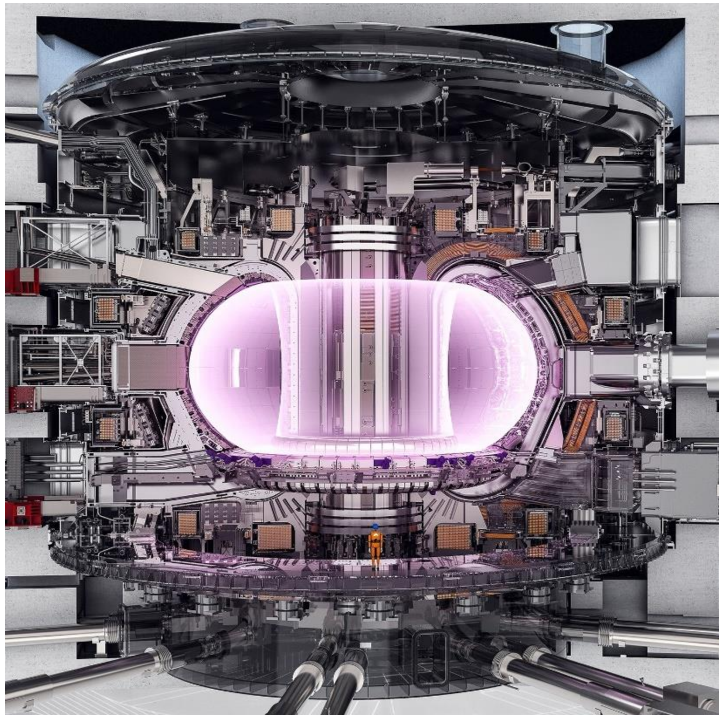
# Outline

1. Reminder about fusion and tokamak
2. WEST brief description
3. Operating plasma in a full tungsten tokamak
4. Soft X-Ray measurements and tomography
5. Reconstructing tungsten distribution
6. Summary and prospects

# Outline

1. Reminder about fusion and tokamak
2. WEST brief description
3. Operating plasma in a full tungsten tokamak
4. Soft X-Ray measurements and tomography
5. Reconstructing tungsten distribution
6. Summary and prospects

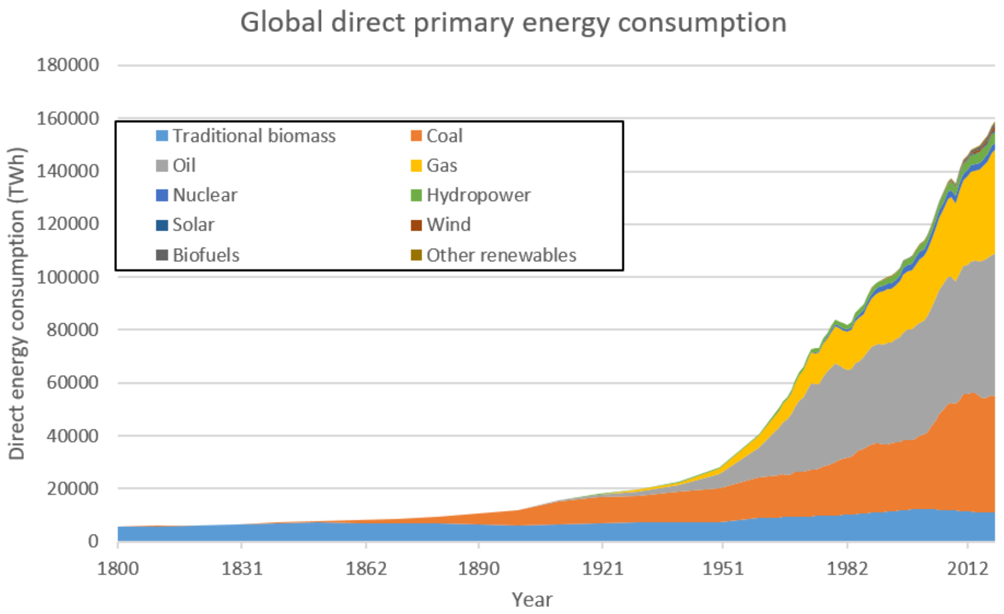
# CEA Cadarache: a site dedicated to nuclear research and also Fusion (IRFM)



WEST

ITER

# Actual energy production in the world



Increasing energy consumption

Limited amounts of available fossil fuels

Negative impact of fossil fuels on the environment

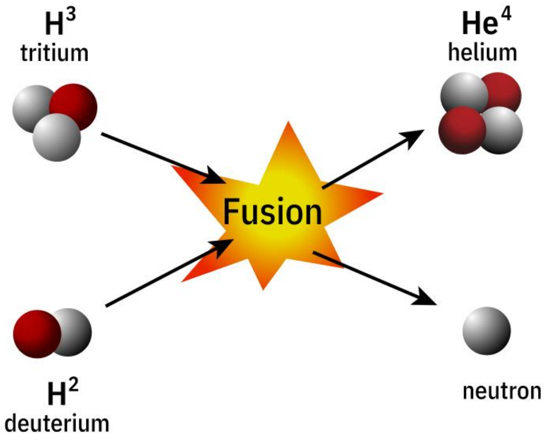
Nuclear fusion:

Nuclear reaction leading to the release of a high amount of energy

Occurs in a plasma at very high temperature (T~$10^8$ °C)

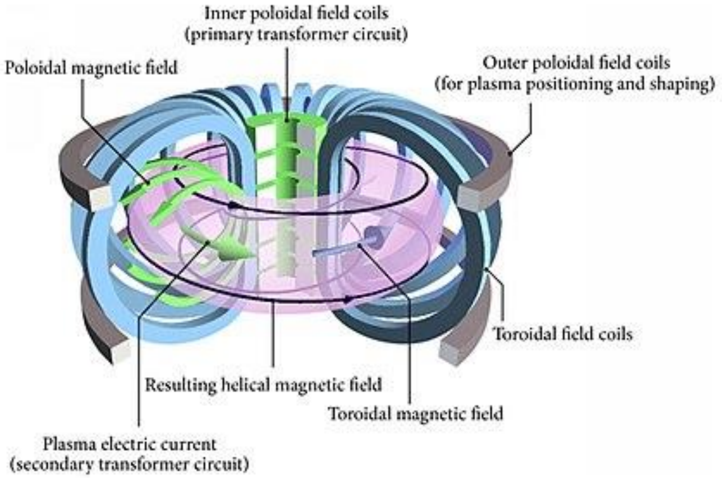
Virtually unlimited fuel reserves, very low environmental impact

## Fusion reaction:



# Principle of a Tokamak

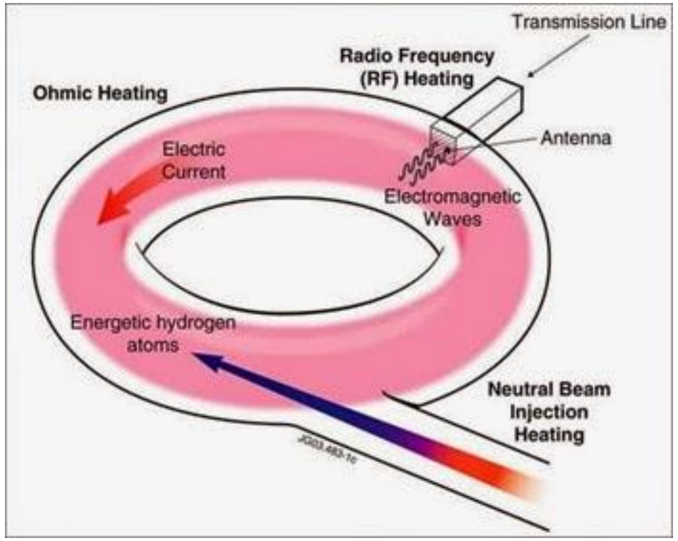
## Magnetic confinement of the plasma

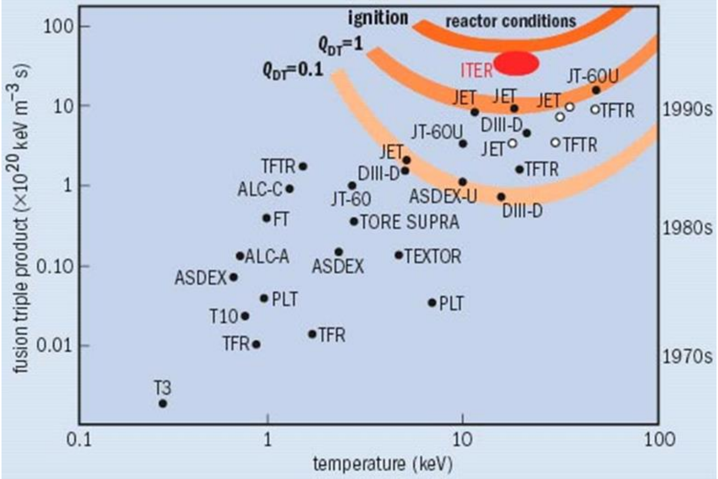


Ignition (Q→∞) criterion:

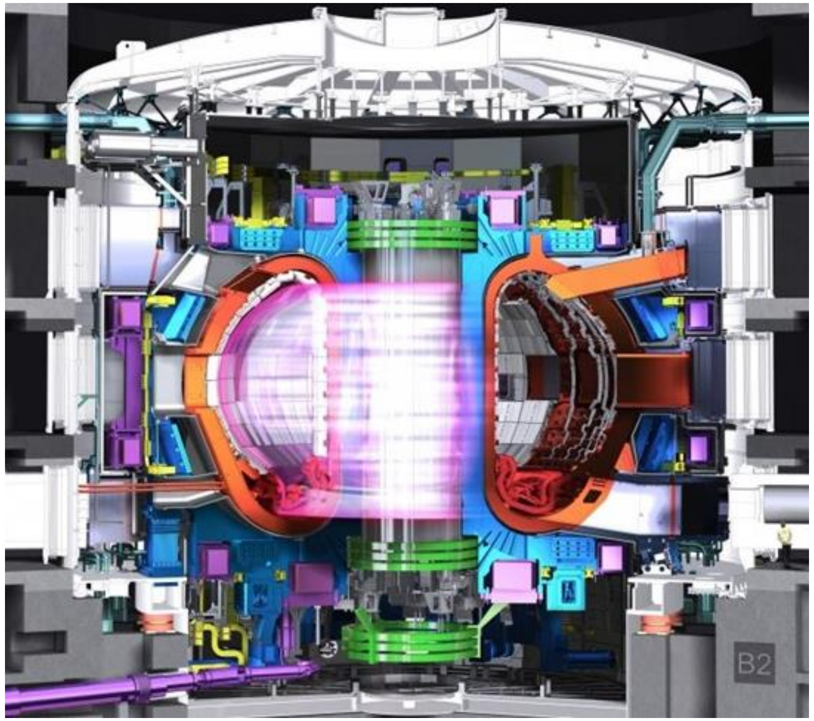
$$n\,\tau_E\,T > 3 \cdot 10^{21}\ m^{-3}\ keV\ s$$

## Heating systems





# The ITER TOKAMAK



| | |
|---|---|
| Major radius | $6{,}2\ m$ |
| Minor radius | $2{,}0\ m$ |
| Plasma volume | $837\ m^3$ |
| Core $T_e$ | Up to 40 keV |
| Plasma facing components | **W**, C, SS |

## ITER goals:

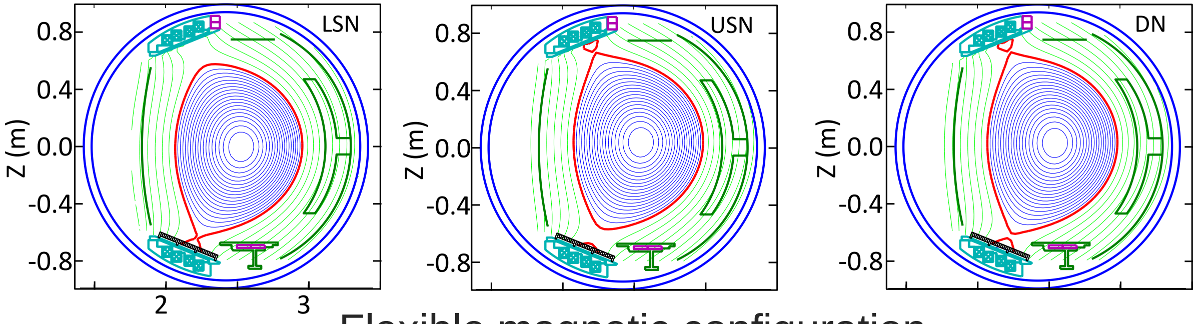
- Demonstrate the experimental feasibility of a nuclear fusion reactor
- $P_{fusion} = 500MW$, $P_{heating} = 50MW$ for 400 to 600 seconds
- Achieve ignition

# Outline

1. Reminder about fusion and tokamak
2. WEST brief description
3. Operating plasma in a full tungsten tokamak
4. Soft X-Ray measurements and tomography
5. Reconstructing tungsten distribution
6. Summary and prospects

# WEST : a superconducting MA class full W tokamak

| B | $I_p$ | R | A | $V_p$ | $\kappa / \delta$ | $P_{RF}$ | Magnetic conf. |
|---|---|---|---|---|---|---|---|
| 3.7 T | 1 MA | 2.5 m | 5-6 | 15 $m^3$ | 1.4 / 0.5 | 16 MW | LSN, USN, DN |



Flexible magnetic configuration

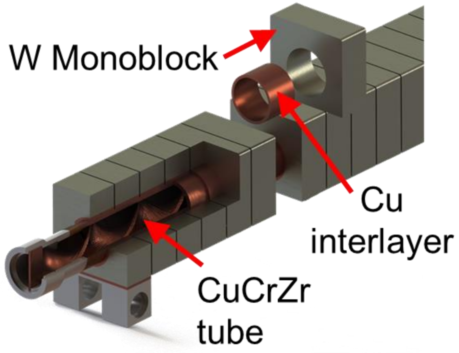
- ▶ Superconducting tokamak
- ▶ Actively cooled Plasma Facing Components
- ▶ Steady state heating / fueling / pumping / diags systems
- ▶ Large current drive capability (LHCD)

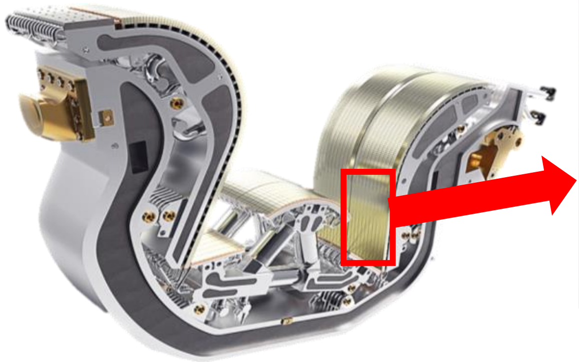
**Long pulse operation ➔ 1000 s**

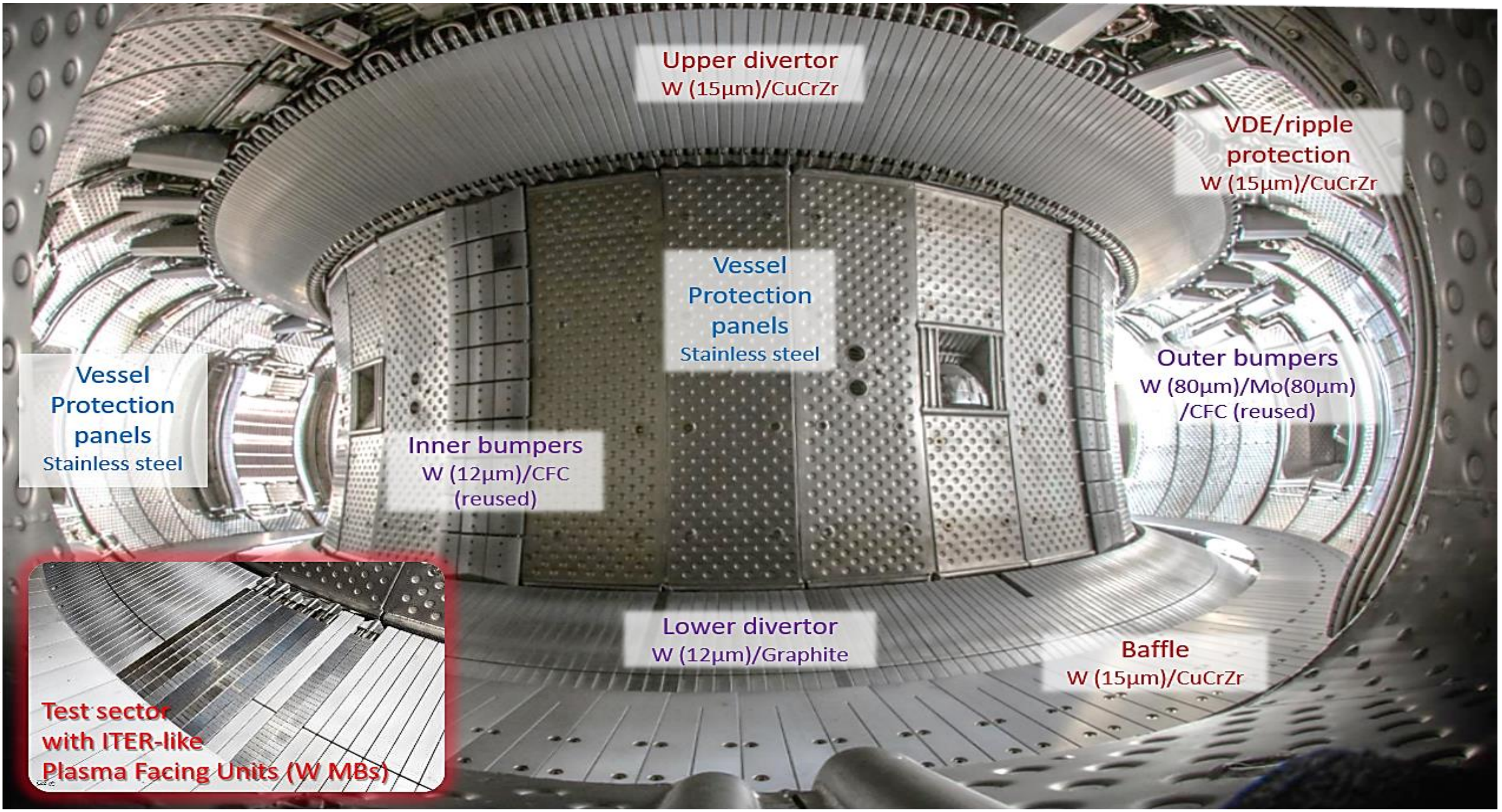
- ▶ Dominant e- heating, no external torque ➔ relevant for transport studies
- ▶ Compact divertor with good diagnostic access ➔ test bed for plasma edge modelling

# Inside WEST : a full W environment

**ITER divertor**

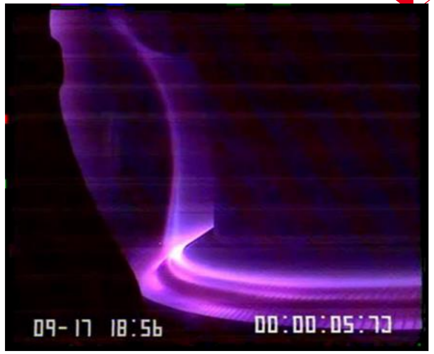






- ▶ Full W environment (W coatings on CuCrZr/CFC, W bulk)
- ▶ ITER grade divertor prototypes tested on the lower divertor (same monoblock geometry, same thermohydraulic conditions)

# WEST key mission is twofold



- Pave the way towards the ITER actively cooled tungsten divertor procurement and operation
- Master integrated plasma scenario over relevant plasma wall equilibrium time scale in a metallic environment

➔ **Supporting ITER and guiding DEMO design**

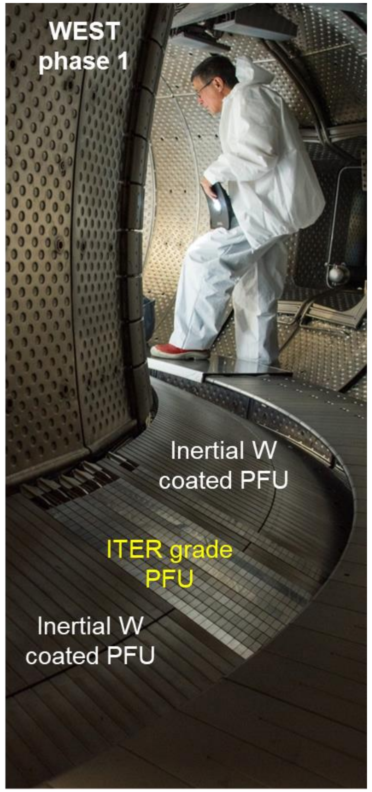
# WEST operation is phased

- **Phase 1 (2017-2021): set of ITER-grade prototypes complemented by tungsten coated PFC**
  - Test prototypes of ITER-grade Plasma Facing Unit (PFU) from ITER potential suppliers (F4E, JADA and ASIPP)
  - Start development of long pulse scenarios
  - 5 experimental campaigns performed (C1-C5)

**Now completed**

- **Phase 2 (2022-present) : complete ITER-grade lower divertor ➔ full long pulse capability**

**Starting**



**Today : lessons learnt from phase 1**

# Outline

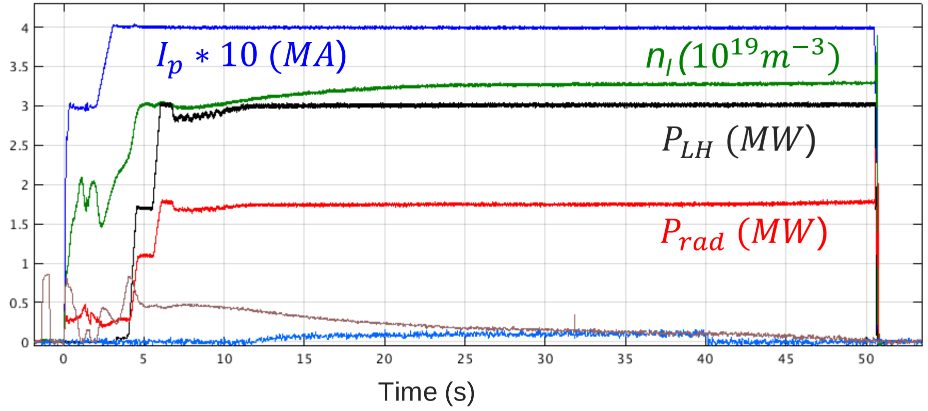
1. Reminder about fusion and tokamak
2. WEST brief description
3. Operating plasma in a full tungsten tokamak
4. Soft X-Ray measurements and tomography
5. Reconstructing tungsten distribution
6. Summary and prospects

# WEST phase 1 now successfully completed

For more details, see [J. Bucalossi and the WEST team, NF2022] and references therein

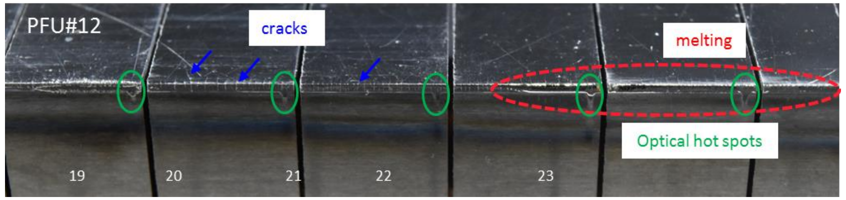
## Main achievements

- Up to ~9 MW of combined LH/ICRH
- First transitions to H mode
- Long pulse operation up to ~1 minute (upper divertor)
- Up to 6 MW/m$^2$ of divertor peak heat load
- First medium fluence Helium campaign
- ITER divertor prototypes : evolution under plasma exposure



## Challenges from operating in a full W environment

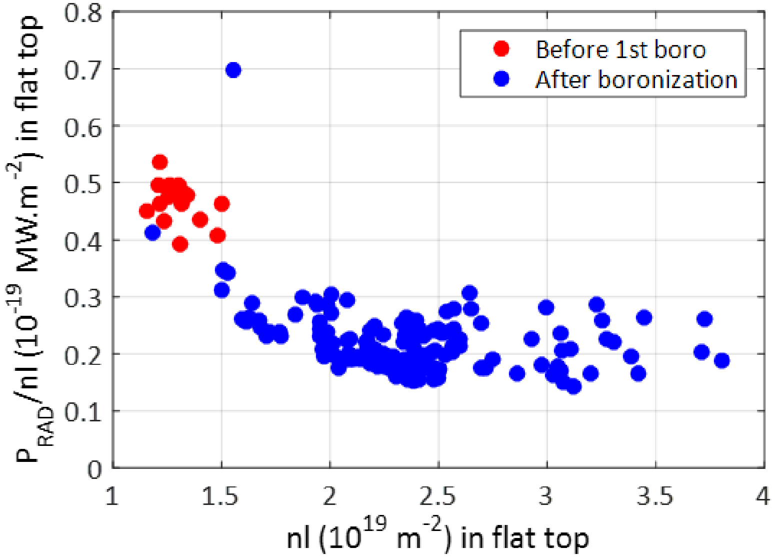
- Boronization needed to extend the operational domain
- Radiated power fraction (W mainly) generally 50-55%
  - Issue for H mode access and power loads for divertor testing
- Core W radiation leads to plasma regimes prone to MHD
  - Te central cooling : flat / hollow current profile ➔ MHD



## Successful completion of the ITER grade divertor of WEST

- 456 ITER grade Plasma Facing Units (~16 000 tungsten monoblocks)
- Feedback from large scale industrial production (optimization of PFU assembly process, rejection rate, manufacturing tolerances, …)

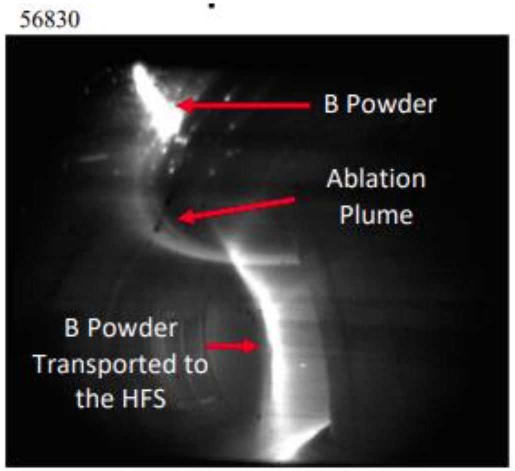
# Boronization needed to extend the operational domain



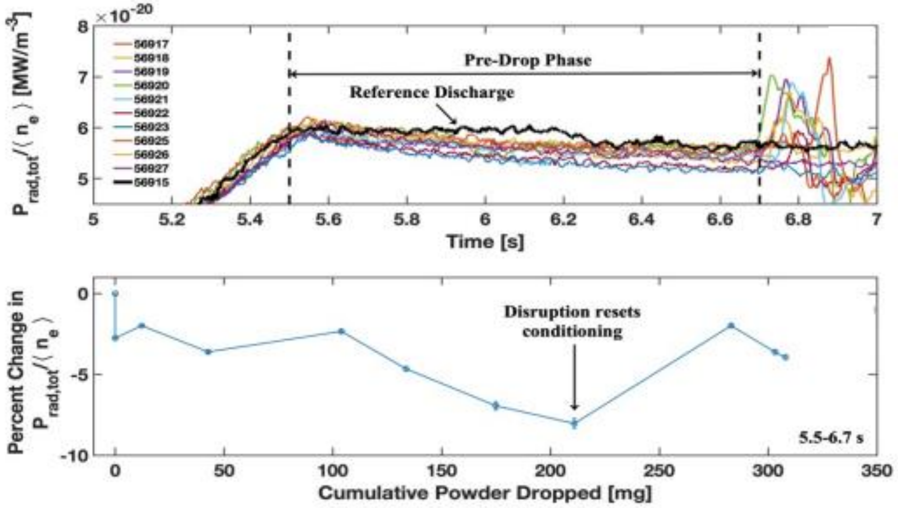
## First boronization performed during C3 campaign

- Initial Wall conditioning: 200°C baking and glow discharge cleaning
- First boronization :
  - Long lasting impact : strong reduction of light impurities (Oxygen) ➔ improved breakdown conditions and higher density achievable
  - Transient impact (~1-2 pulses) : strong reduction of total radiation (W)

## Real time conditioning with the Impurity Powder Dropper (IPD)



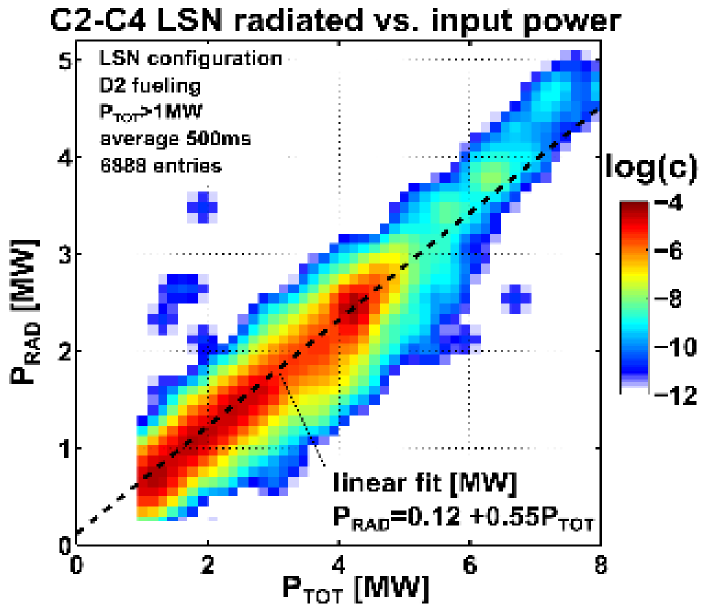
- Evidence of wall conditioning observed in total radiated power
- Improved core confinement with radiative boundary
- More experiments to come to fine tune injection rate etc …

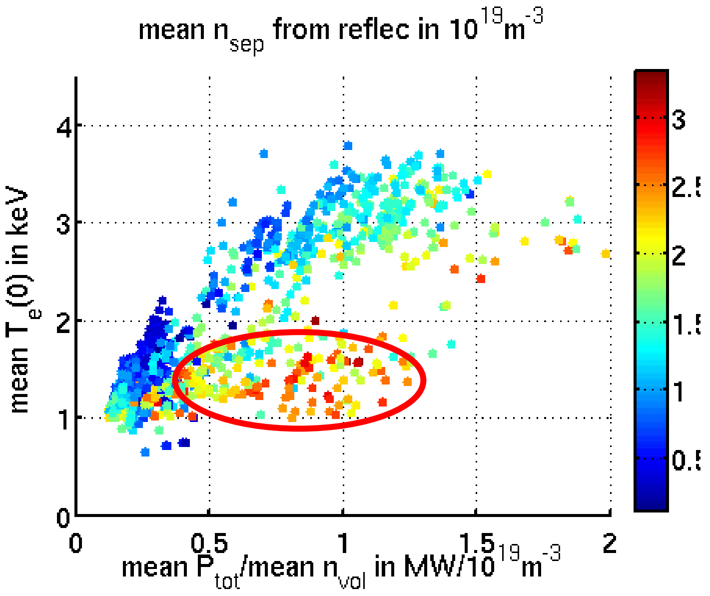


Bodner et al., 2022 Nucl. Fusion

# Controlling W content : a key for scenario development

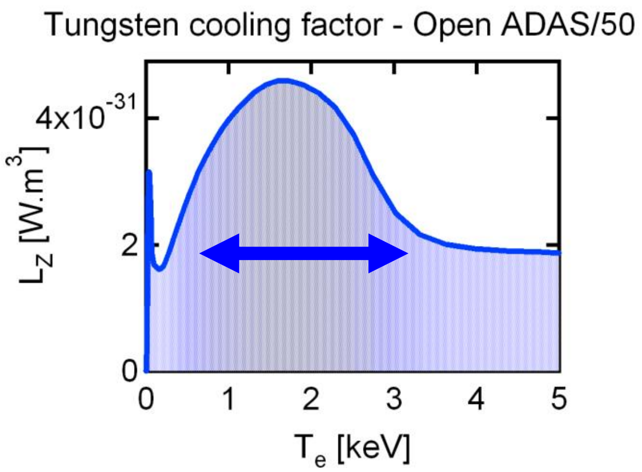
- W is the dominant impurity radiating in the core
  - Radiated fraction ~50-55 %, independent of heating system (LH vs ICRH)
  - Significant W core concentration $n_W/n_e \leq 3 \times 10^{-4}$, even if no accumulation in most cases for conditions explored so far (L mode)
- Strong impact on scenario development
  - Need to go through W radiation peak (~1.5 keV)
  - Plasma current ramp up : early nitrogen injection to avoid MHD, BN tiles on start up limiters
  - Flat top at full power : risk of radiative collapse





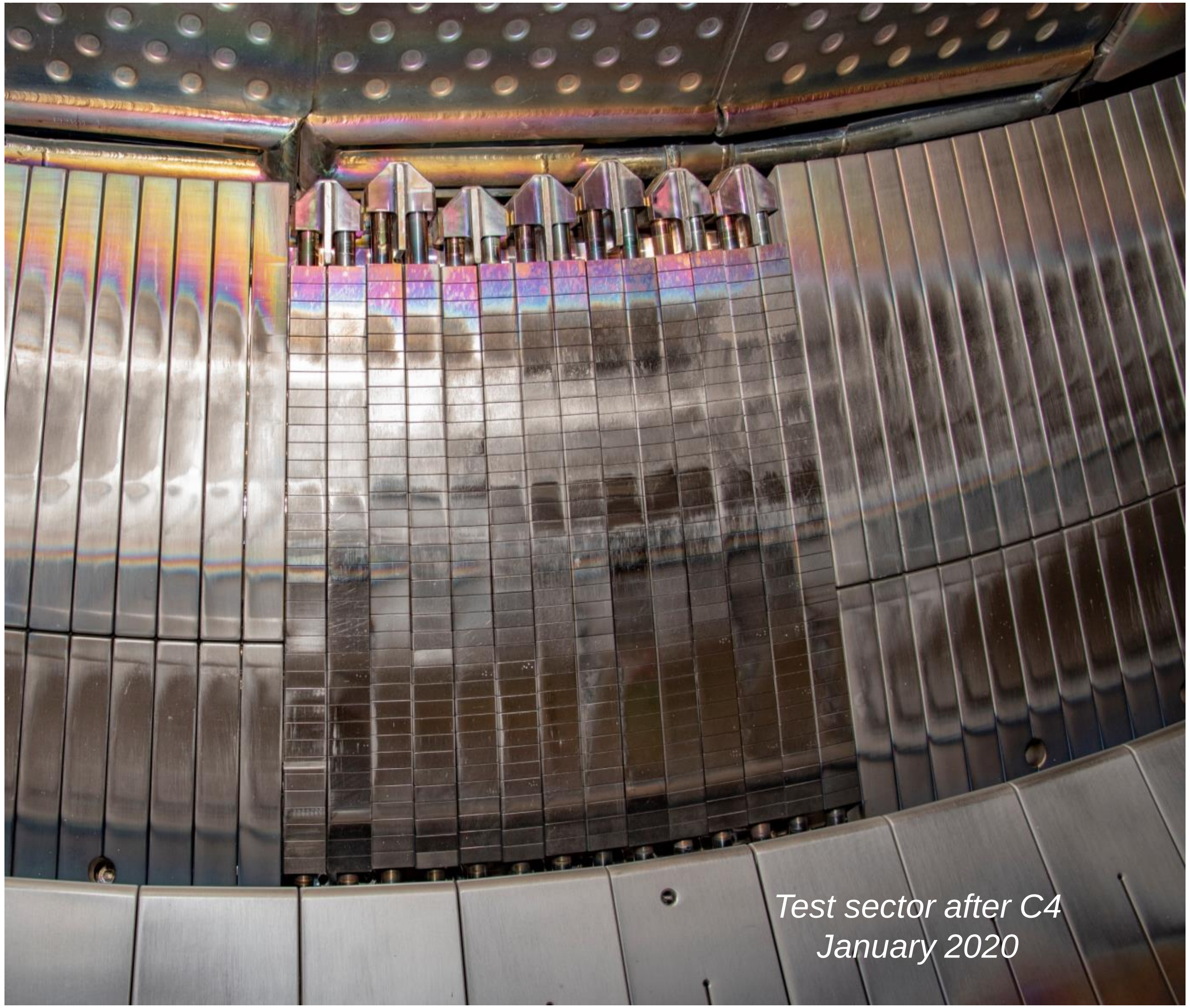
- Avoiding the "cold branch" …
  - $T_e \in [1.5, 2.5]$ keV potentially unstable
  - Fine tuning of gas puff / power ramp up required
  - Need to maximize central electronic heating

**Challenge for MHD-stable scenario in a full W environment**



*Ostuni, Nuc Fus 2022, Maget, IAEA 2021, Bourdelle APS 2022*

# Complex erosion / deposition pattern on WEST divertor

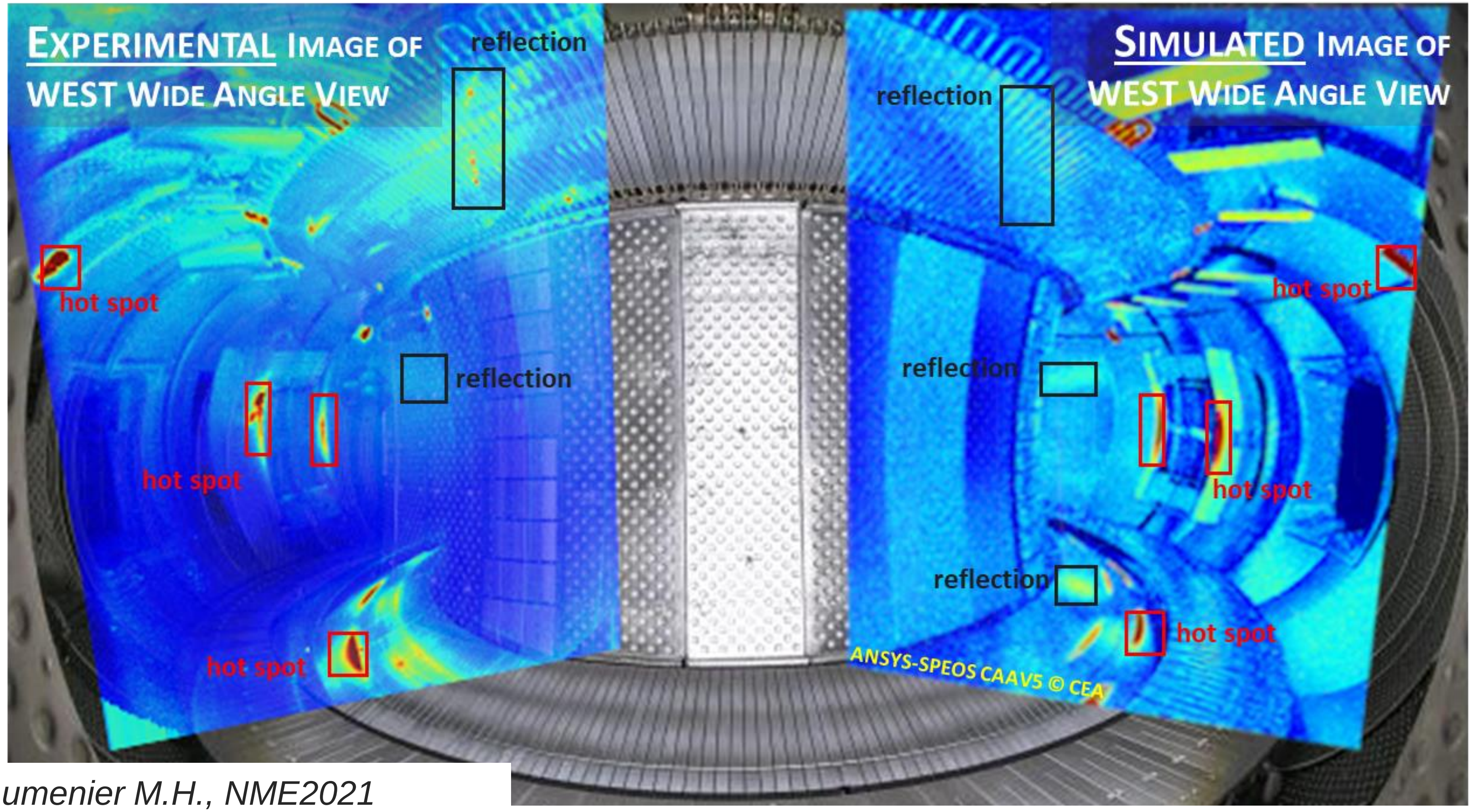


*Test sector after C4*
*January 2020*

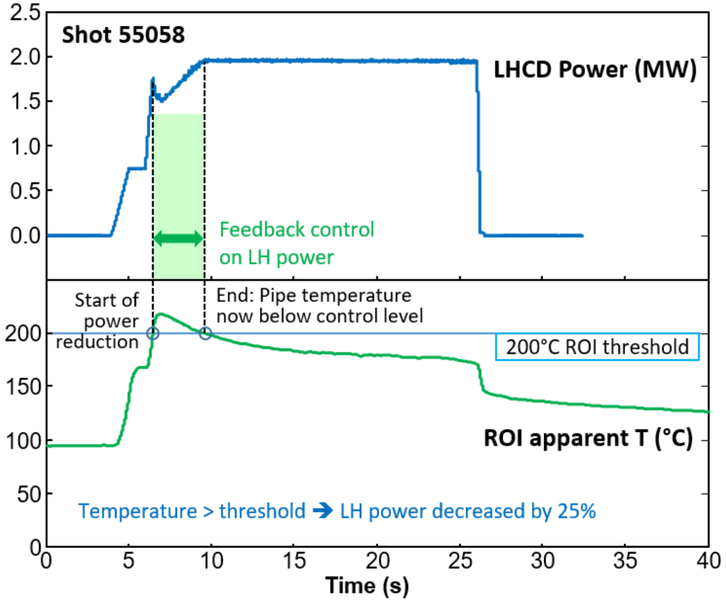
# Protecting the plasma facing components

- Wall Monitoring System routinely used in WEST to protect PFC, using the extensive IR system
- Real time image processing, thermal events detection (machine learning, scene simulation)
- Various real time feedback control strategies implemented (> 30 Region Of Interests)

*X. Courtois., IAEA 2021*



*Aumenier M.H., NME2021*



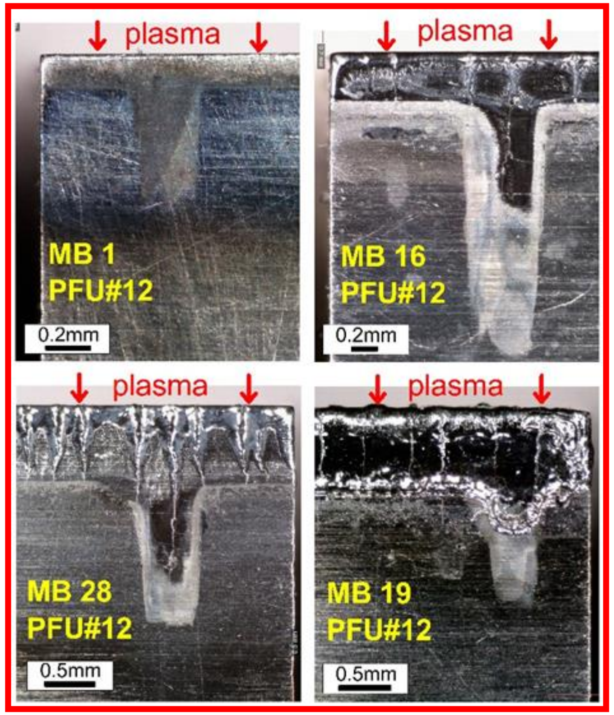
*Real-time control of LH power, to avoid PFC overheating*

- Interpreting IR in metallic environment is tricky : W emissivity, reflections, …
- Photonic modelling required

**Crucial for safe operation in ITER metallic environment**

# Optical Hot Spots evidenced in WEST

## Optical hot spots (OHS) observed after the C3 campaign



- Optical hot spots also impact PFU aligned within ITER specs

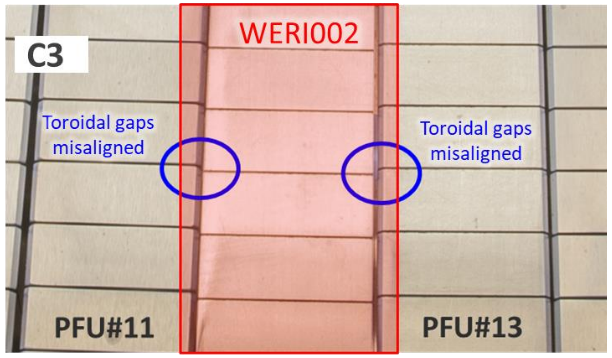
*J. Gunn, Nucl. Fus. 2017, NME 2021*
*M. Diez, Nucl. Fus. 2020*

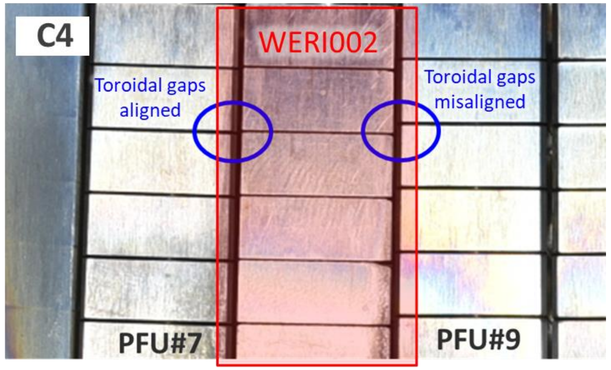
## OHS evolve consistently with toroidal gap alignment

- Away from OSP : new C4 OHS formed consistently with toroidal gap alignment, C3 OHS still visible
- In OSP area : C3 OHS not visible anymore
- Confocal microscopy : deposited layers in gaps during C4 hiding OHS ?

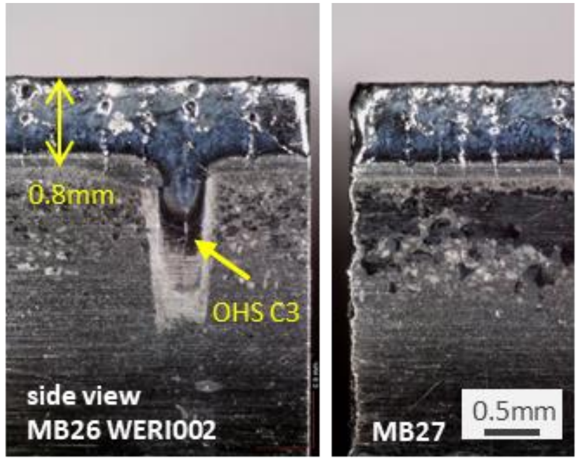
## Evolution after the C4 campaign

- Lower PFU vertical misalignment (0.8 ➔ 0.5 mm)
- Better toroidal gap alignment

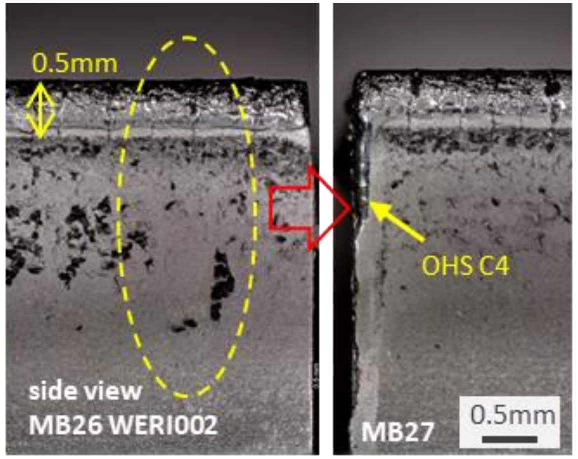




**Post C3 – OSP area**



**Post C4 – OSP area**



*M. Diez, Nucl. Fus. 2021*

# Outline

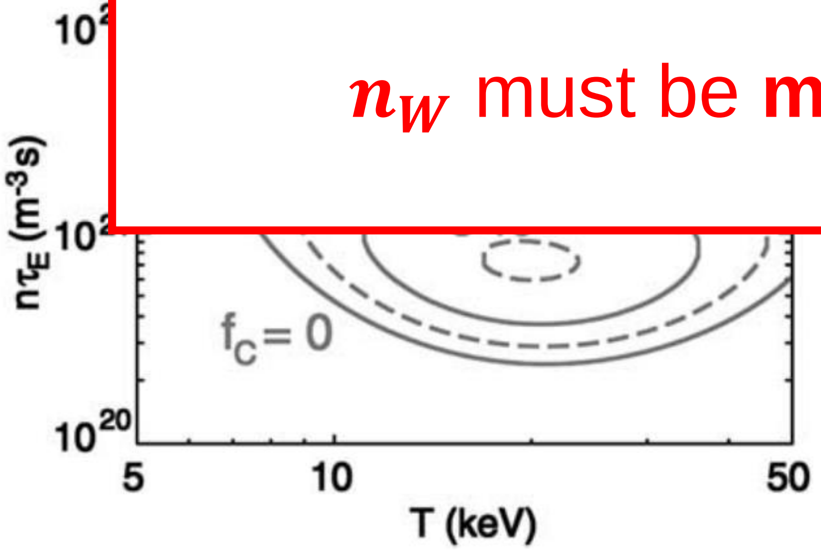
1. Reminder about fusion and tokamak
2. WEST brief description
3. Operating plasma in a full tungsten tokamak
4. Soft X-Ray measurements and tomography
5. Reconstructing tungsten distribution
6. Summary and prospects

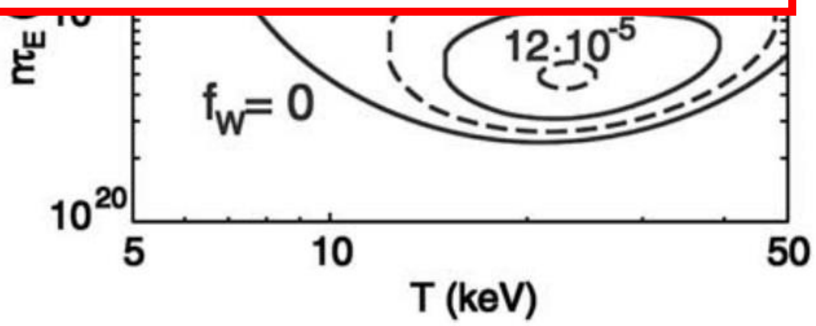
# Tungsten, good or bad?

Advantages of W over C:

- Higher heat flux resilience
-
-
-

Pl tions :





W is **mandatory** to handle the **heat fluxes** on ITER and to **limit tritium retention** but its **erosion** can lead to **high energy losses** and even **plasma radiative collapse**!

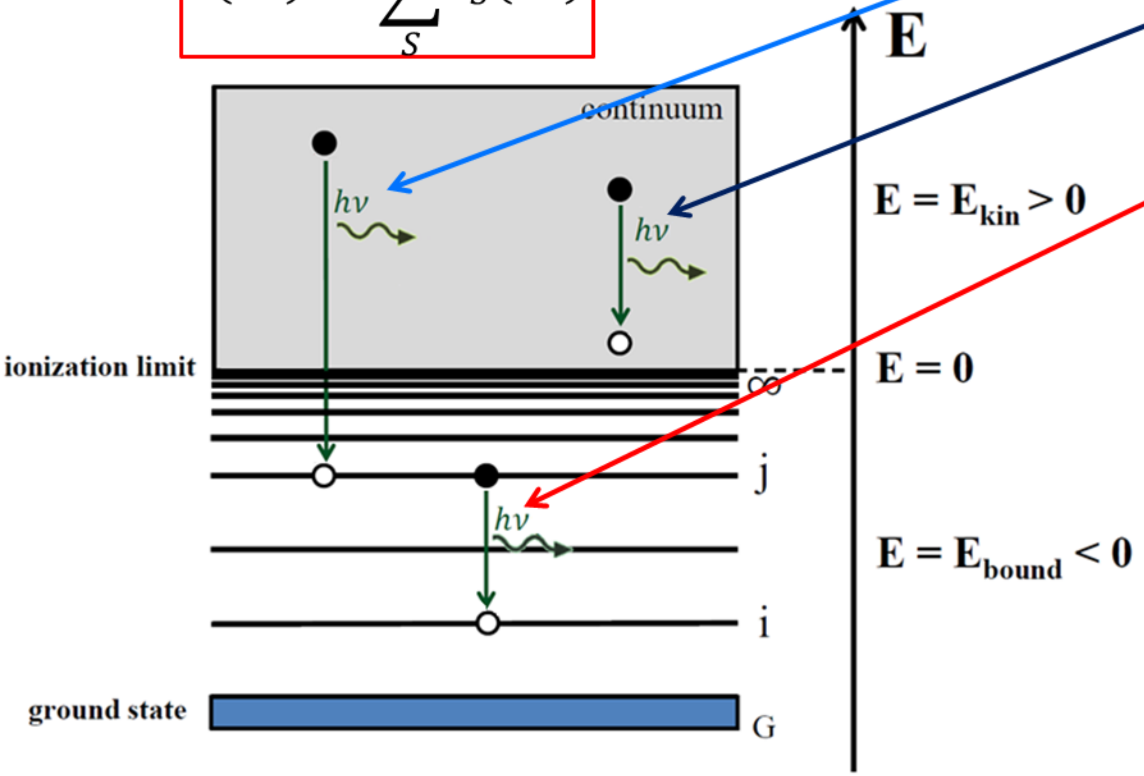
$\boldsymbol{n_W}$ must be **measured** and monitored

# X-ray emissions in tokamaks

X-ray emissivity due to interaction with the S species ( $W \cdot m^{-3} \cdot eV^{-1}$ ) :

$$\varepsilon_S(h\nu) = n_e \cdot n_S \cdot \sum_q f_{S,q}(T_e,\Gamma_{S,q}) \cdot \Big( \underbrace{k^{fb}_{S,q}(h\nu,T_e)}_{\text{Recombination}} + \underbrace{k^{ff}_{S,q}(h\nu,T_e)}_{\text{Bremsstrahlung}} + \underbrace{k^{fb}_{S,q}(h\nu,T_e)}_{\text{Line emission}} \Big)$$

$$\boxed{\varepsilon(h\nu) = \sum_S \varepsilon_S(h\nu)}$$



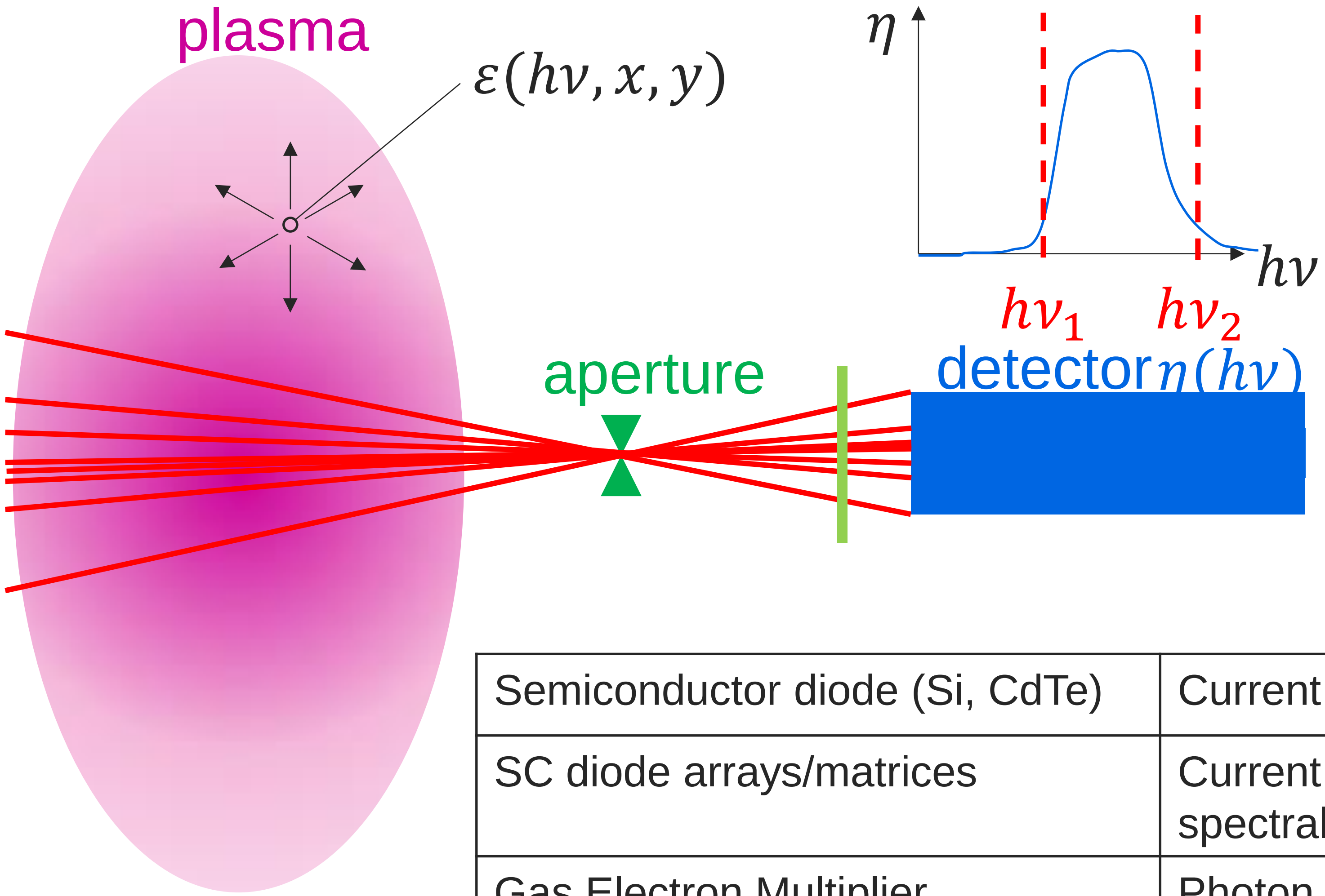
$n_e$ : electron density $[m^{-3}]$

$n_S$ : S ion density $[m^{-3}]$

$f_{S,q}$ : ratio of the $S^{q+}$ ion

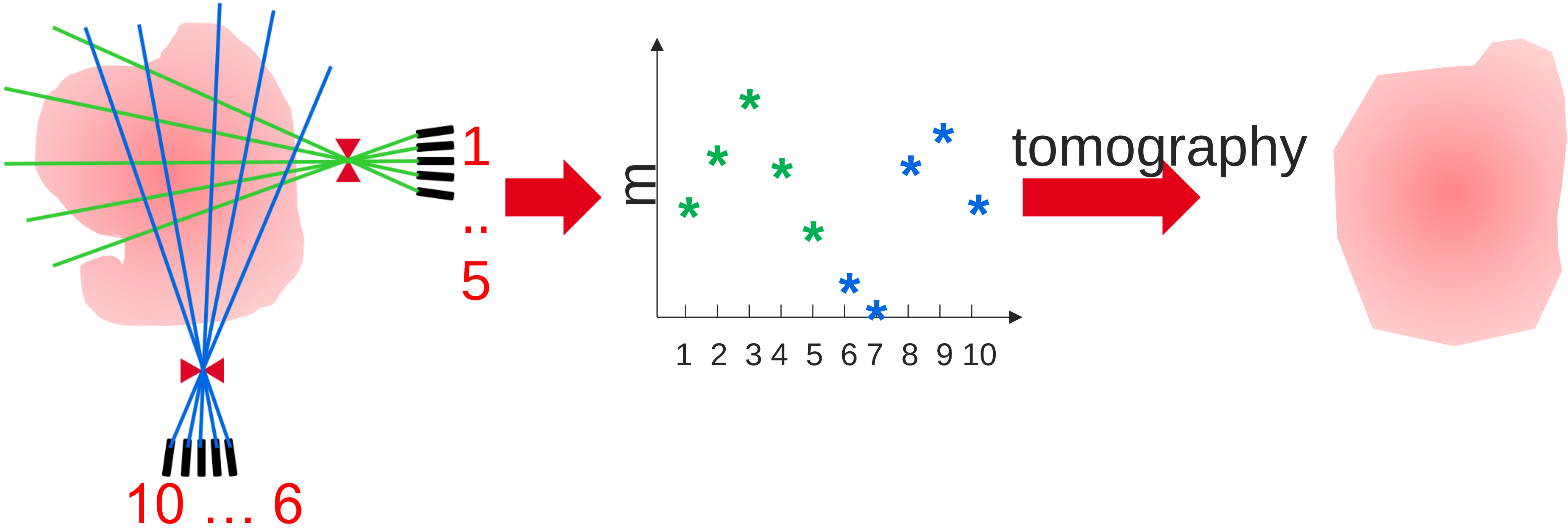
$k^{\eta,bb}_{S,q}$, $k^{\eta,fb}_{S,q}$ and $k^{\eta,ff}_{S,q}$ : Emissivity coefficients of the $S^{q+}$ ion $[W\ m^3\ eV^{-1}]$

# X-ray detection



| | |
|---|---|
| Semiconductor diode (Si, CdTe) | Current mode |
| SC diode arrays/matrices | Current mode with spectral information |
| Gas Electron Multiplier | Photon counting mode |
| Ionization chambers | Current mode |

# From line-integrated measurement to local emissivity: tomography



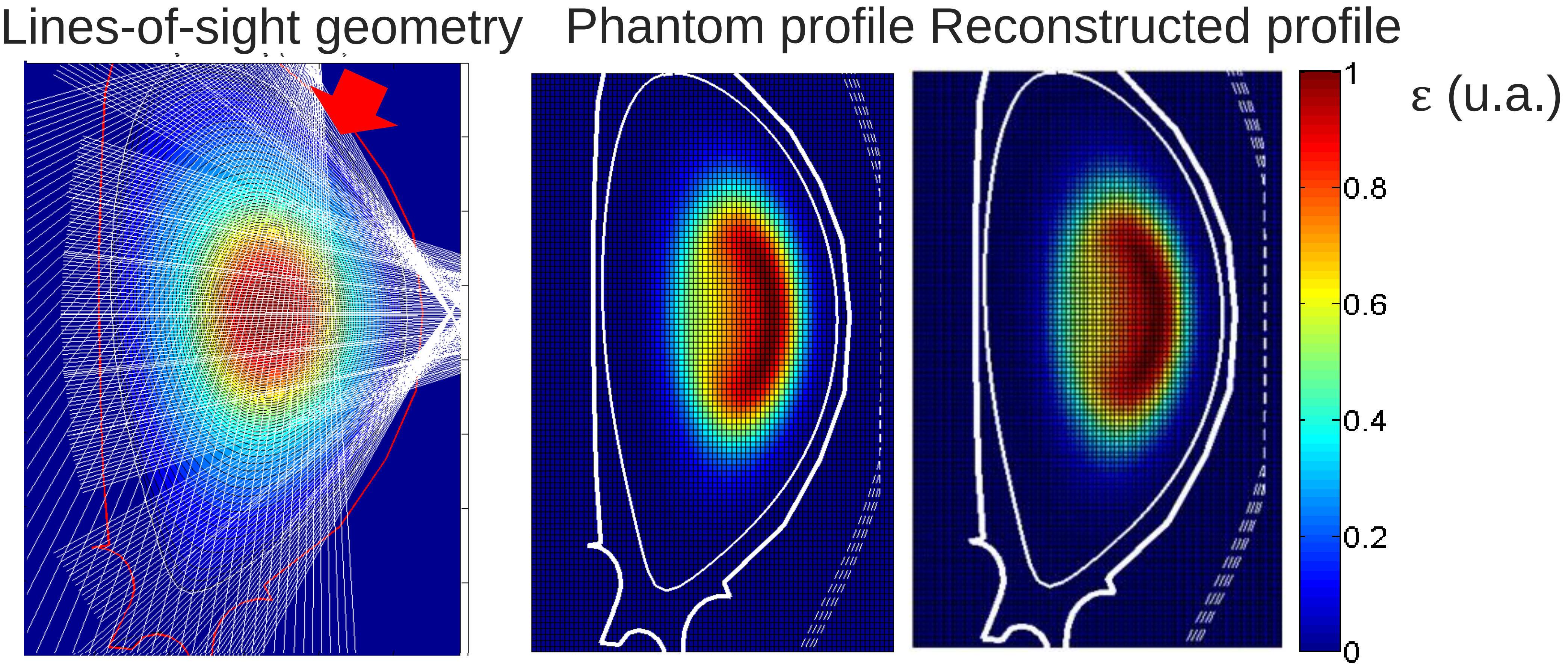
Tomographic algorithm:
Finds the solution which fits best the measurement while retaining some physical sense :

$$\varepsilon_{rec} = argmin(\,|m - f(\varepsilon)|^2 + \lambda R(\varepsilon)\,)$$

Regularization using the Minimum Fisher Information:
Minimizes

$$I_F = \int \frac{1}{\varepsilon(r)}\left(\frac{d\varepsilon(r)}{dr}\right)^2 dr$$

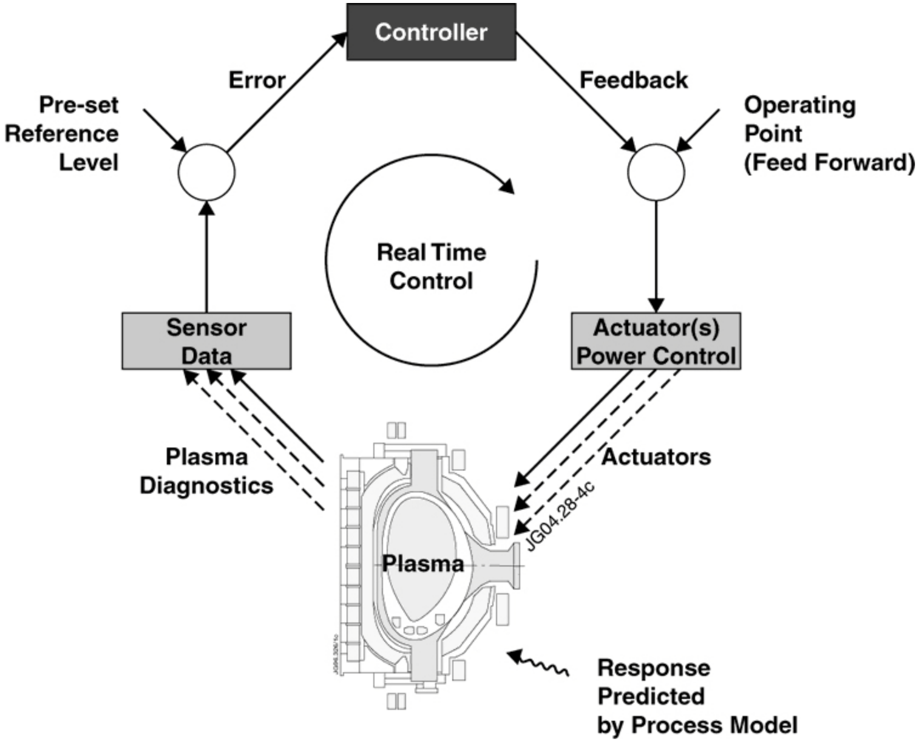
# An example of tomography (phantom)



# Prospect for real-time impurity control

☐ Control of W concentration?

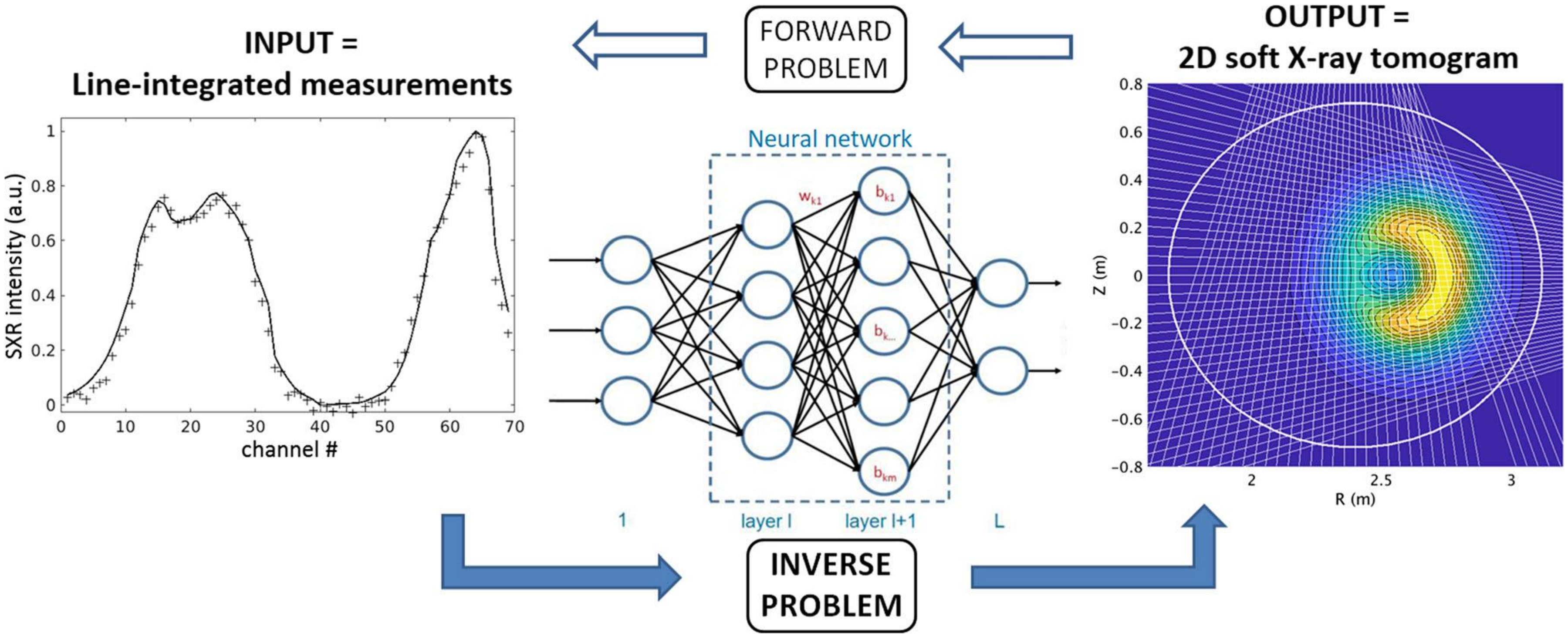
- Reduce W sources (erosion)
- Higher pumping rate
- Avoid strong W poloidal asymmetries
- Central ECRH (pump-out effect)
- Shape plasma profiles: peaked $T_e$ (temperature screening)
- Trigger mitigating/flushing MHD: sawteeth (core), ELMs (edge)…



→ **Possibility of real-time X-ray tomography?**

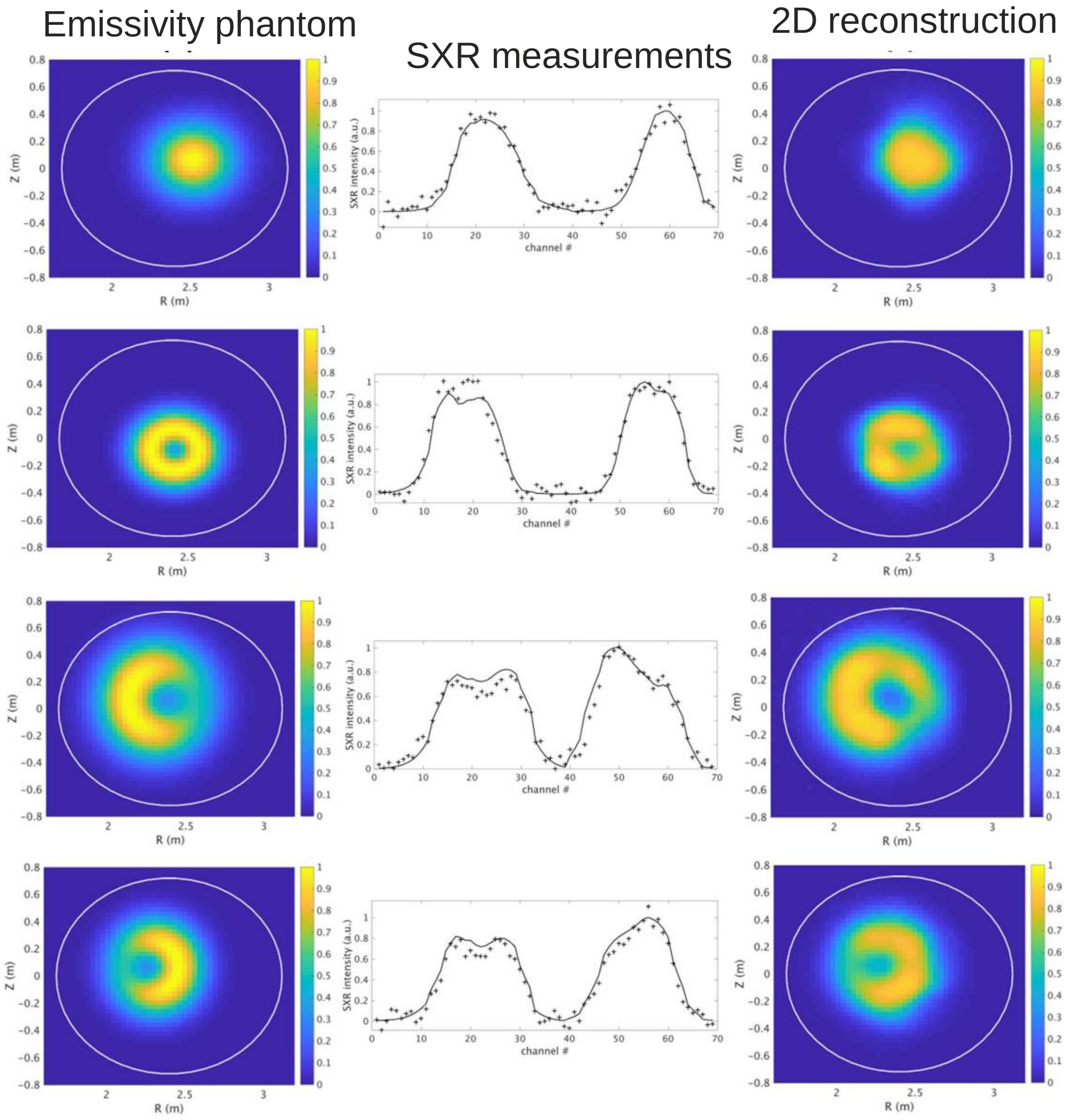
# Neural networks for SXR tomography

- Issue of traditional Tikhonov approach: computing time > 0.01 - 10 s
- Fast tomography for real-time control < 0.1 ms → **Neural networks**
  Neural Network: successive neuron layers connecting inputs and outputs.
  Neuron biases and weights are iteratively adjusted by training from a dataset.



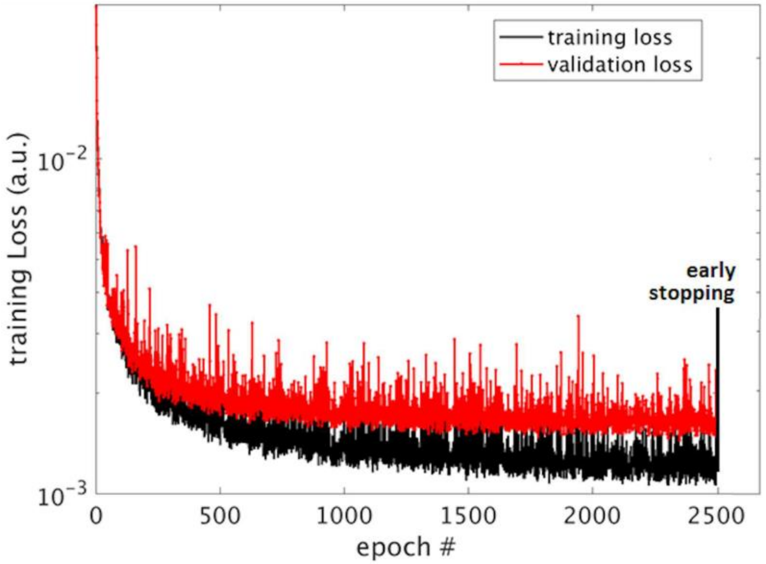
[A. Jardin (D. Mazon) et al., Neural networks: from image recognition to tokamak plasma tomography, 2019 *Laser and Particle Beams* 1–5]

# Neural networks tests with synthetic data



- ❑ Large training database to optimize the network parameters $(\vec{w}, b)$
- ❑ Minimization of a Cost Function (MSE) with stochastic gradient-descent method:

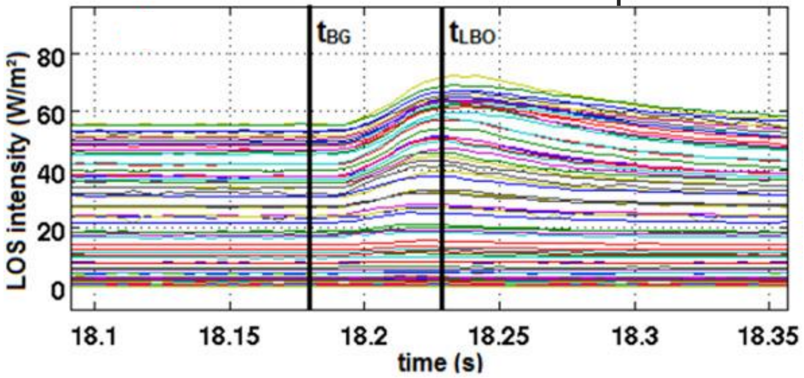
$$C(\vec{w},b) = \frac{1}{2n}\sum_x [\underbrace{y(x)}_{\text{desired output}} - \underbrace{a(x,\vec{w},b)}_{\text{output from the network}}]^2$$



# Neural networks tests with experimental data

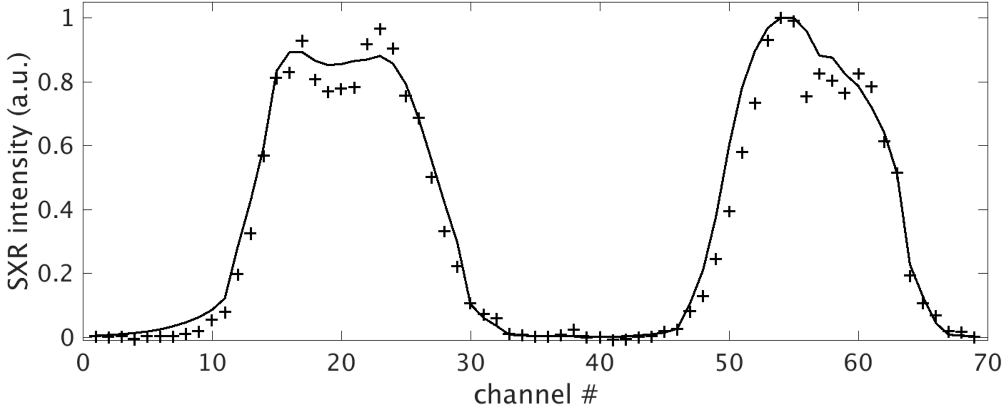
❑ Controlled injection of tunsgen impurities in Tore Supra:

SXR time traces – Tore Supra #46564

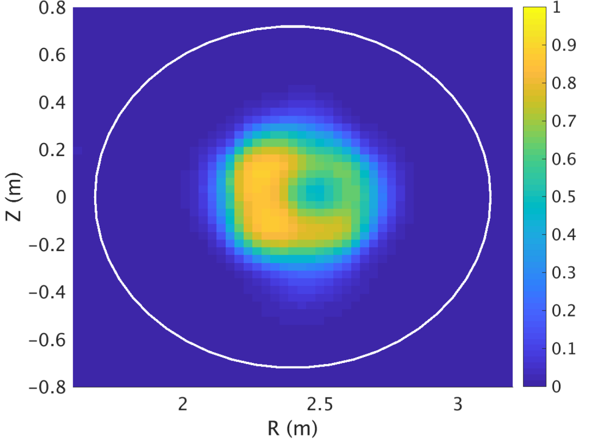


[A. Jardin (D. Mazon) et al, Acta Phys. Pol. A, 138 (2020) 626-631]

SXR line-integrated measurements at $t_{LBO}$ - $t_{BG}$



Tomography by neural network



→ Consistent with traditional Tikhonov method but fast enough for real-time control (< 0.1 ms)

# Outline

1. Reminder about fusion and tokamak
2. WEST brief description
3. Operating plasma in a full tungsten tokamak
4. Soft X-Ray measurements and tomography
5. Reconstructing tungsten distribution
6. Summary and prospects

# Measuring x-ray emissivity and impurity concentration

$$\varepsilon(h\nu) = \sum_S \varepsilon_S(h\nu) \xrightarrow{\text{measurement}} m = \int_r \int_{h\nu} \varepsilon^{\eta}(h\nu)\, dh\nu\, dr \xrightarrow{\text{tomography}} \varepsilon^{\eta}_{\mathrm{rec}}(\mathrm{x},\mathrm{y})$$

$$\boxed{\varepsilon^{\eta}(x,y) = n_e(x,y) \sum_S n_S(x,y) L_S^{\eta}(T_e(x,y), \Gamma_{S,q}(x,y))}$$

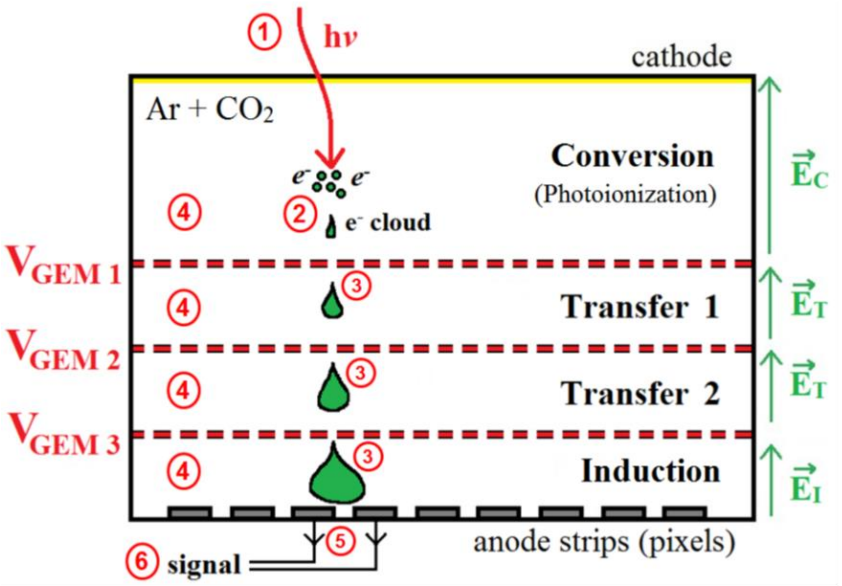
$L_S^{\eta}$ : radiating function of the S species filtered by the detector

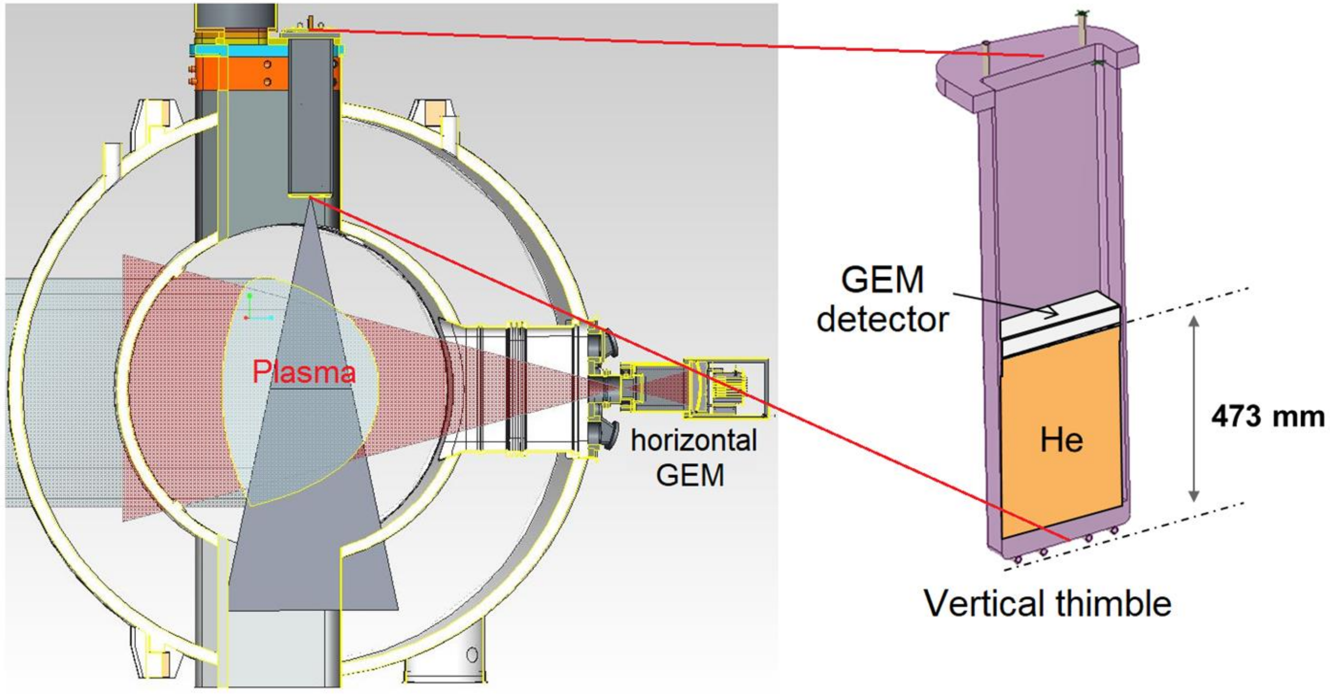
$\Gamma_{S,q}$: transport of the $S^{q+}$ ion

**Case of a plasma where $\varepsilon$ is dominated by W and H and $n_W \ll n_H$**

$$\varepsilon^{\eta}_{rec} = n_e^2\, L_H^{\eta}(T_e, \Gamma_H) + n_e\, n_W\, L_W^{\eta}(T_e, \Gamma_W) \longrightarrow \boxed{n_W = \frac{\varepsilon^{\eta}_{rec} - n_e^2\, L_H^{\eta}(T_e, \Gamma_H)}{n_e \cdot L_W^{\eta}(T_e, \Gamma_W)}}$$

# SXR: GEM measurement on WEST

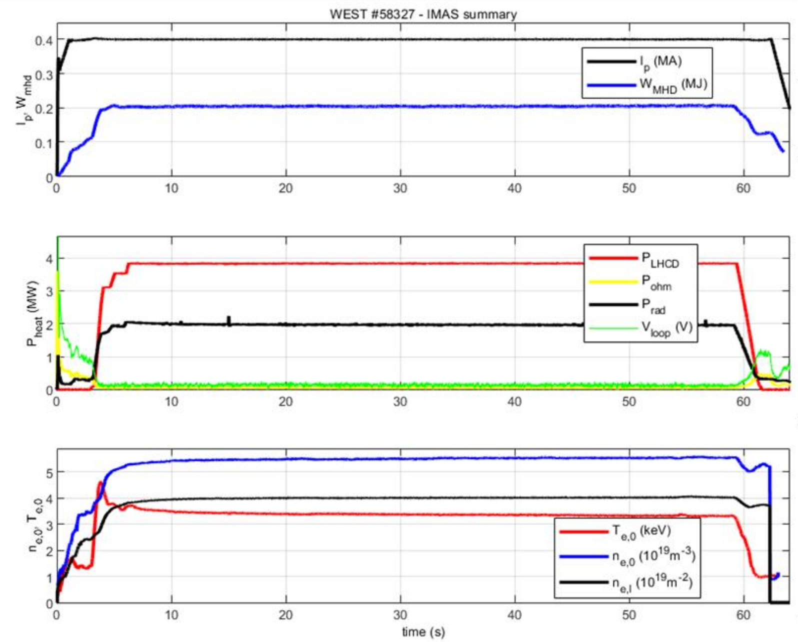


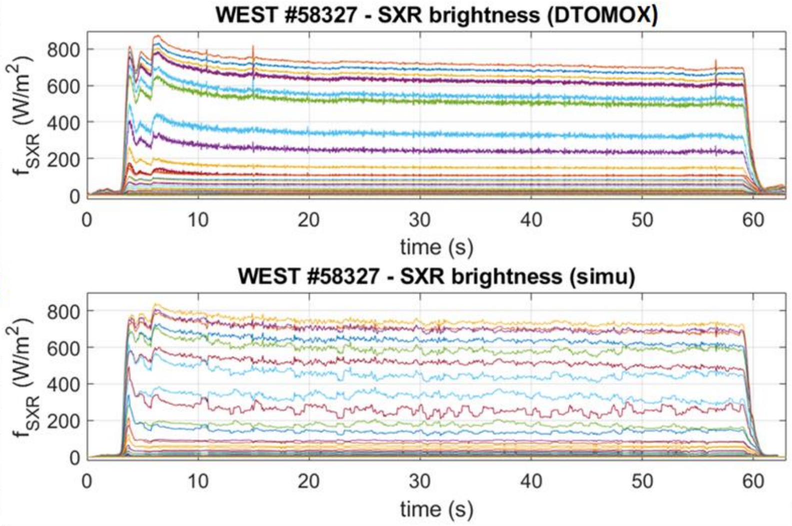


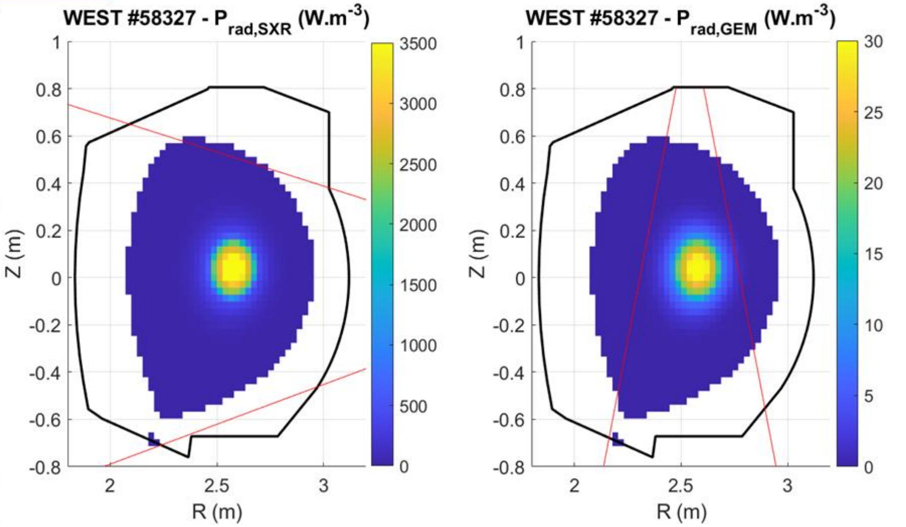
# Modelling SXR GEM; determining cW

$$\varepsilon_W^{\eta} = \int \eta(h\nu)\varepsilon_W(h\nu, T_e)dh\nu = n_e.n_W.L_W^{\eta}(T_e)$$

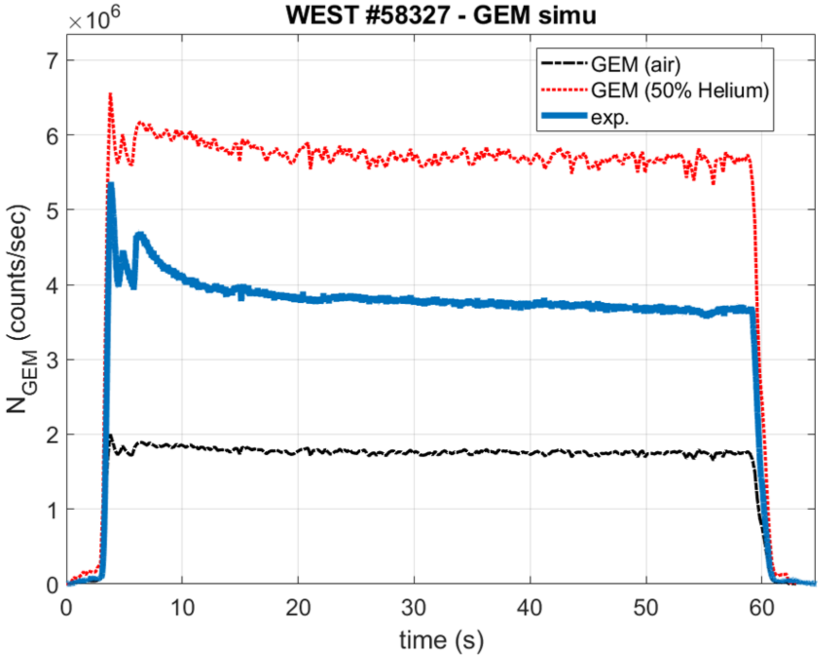
$$\boxed{c_W = 2 \times 10^{-4}}$$

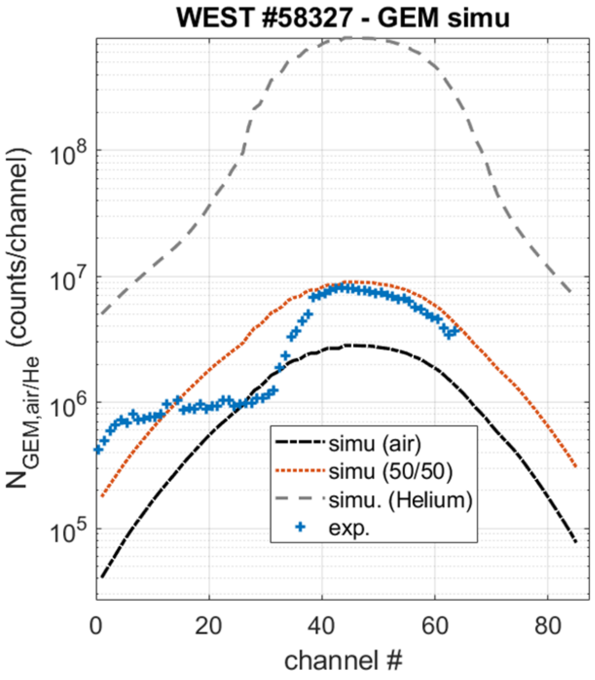


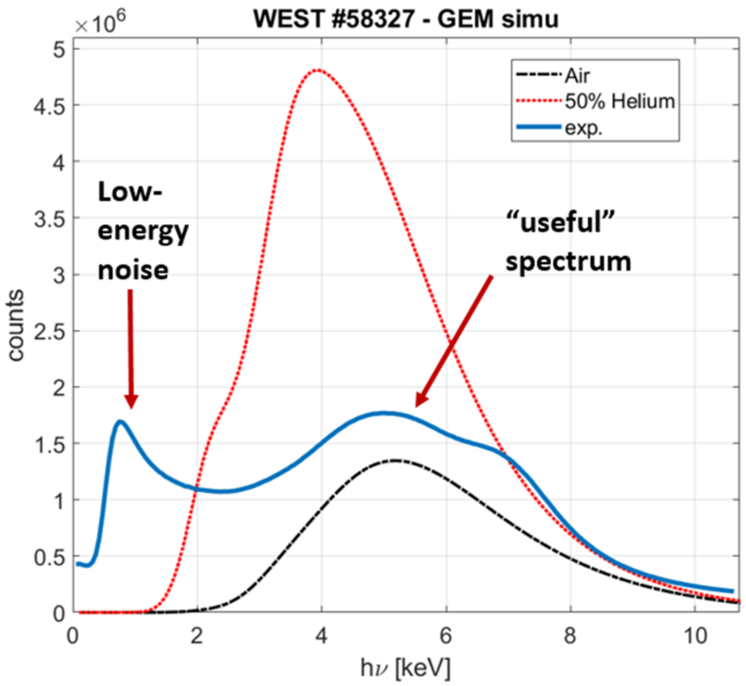




# Modelling SXR GEM; using the determined cW

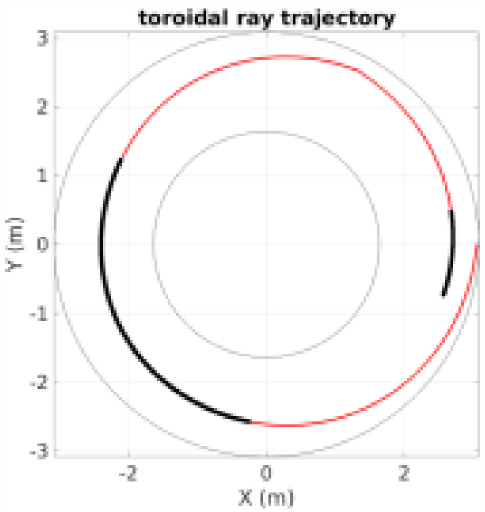


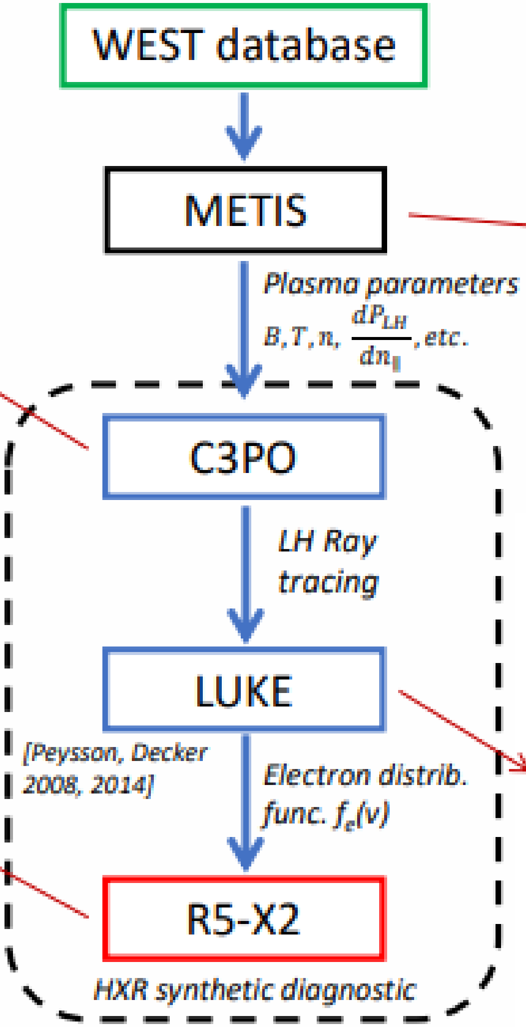




Good agreement when the Helium proportion is correct
Cross validation of information to get cW

# Another approach (see M. Scholz former seminar) developed in Harmonia using HXR measurements and modelling





WEST database

METIS

*Plasma parameters*

$B, T, n, \frac{dP_{LH}}{dn_\parallel}$, etc.

C3PO

*LH Ray tracing*

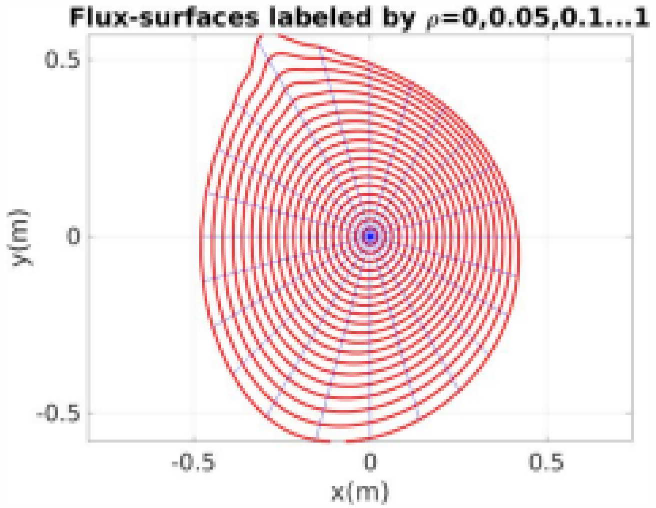
LUKE

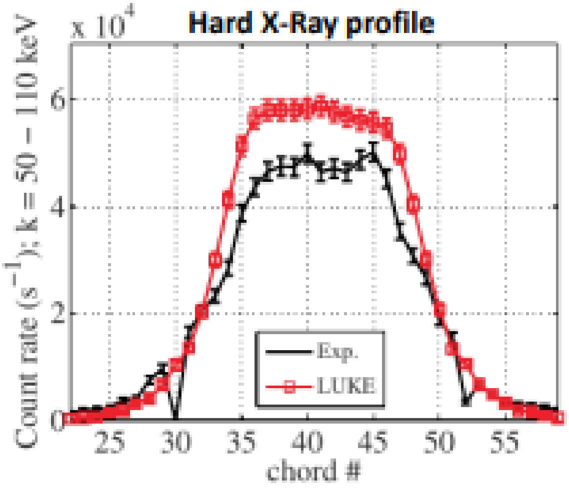
*[Peysson, Decker 2008, 2014]*

*Electron distrib. func. $f_e(v)$*

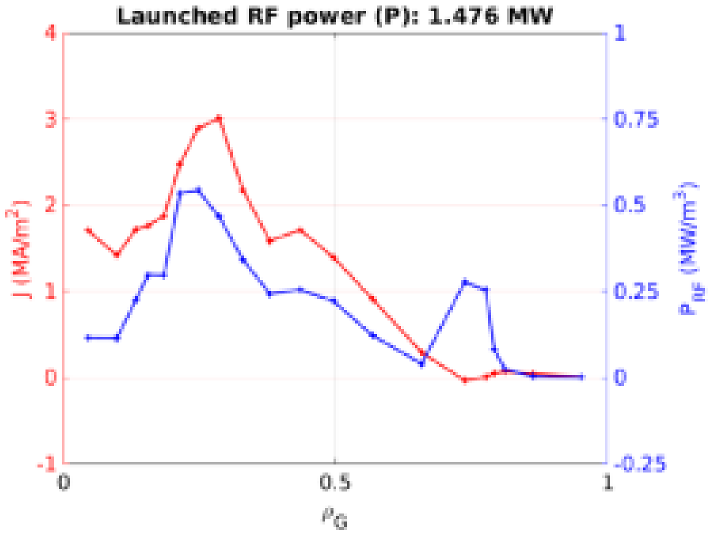
R5-X2

*HXR synthetic diagnostic*



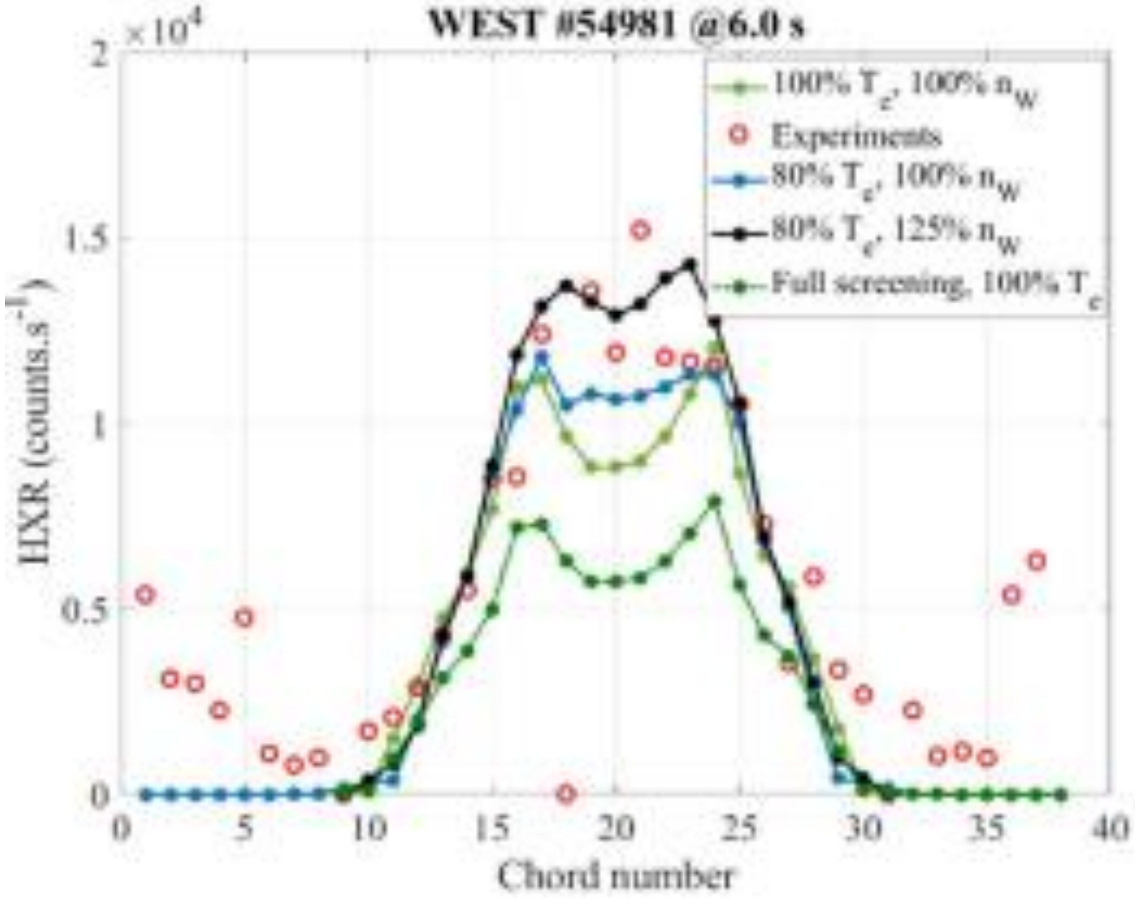


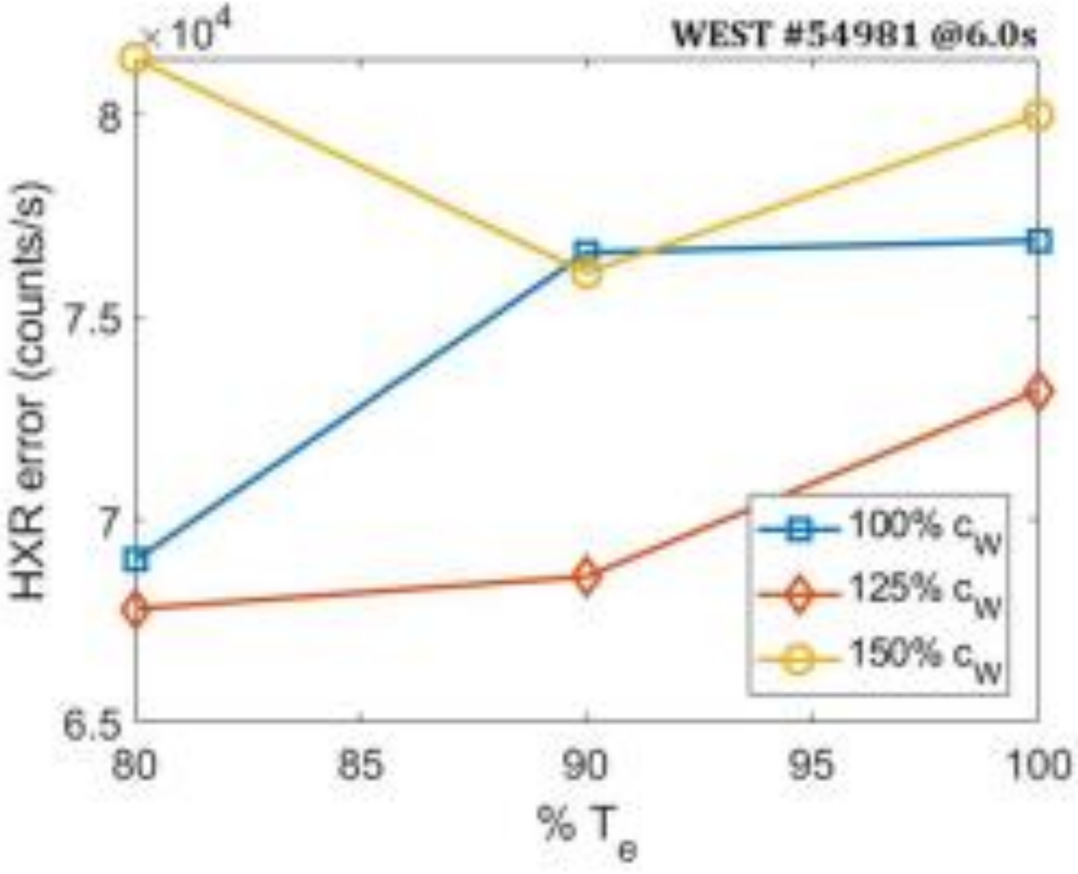
*[E. Nilsson et al. NF 2013]*



⇒ It was needed to upgrade these codes with the physics of W impurities

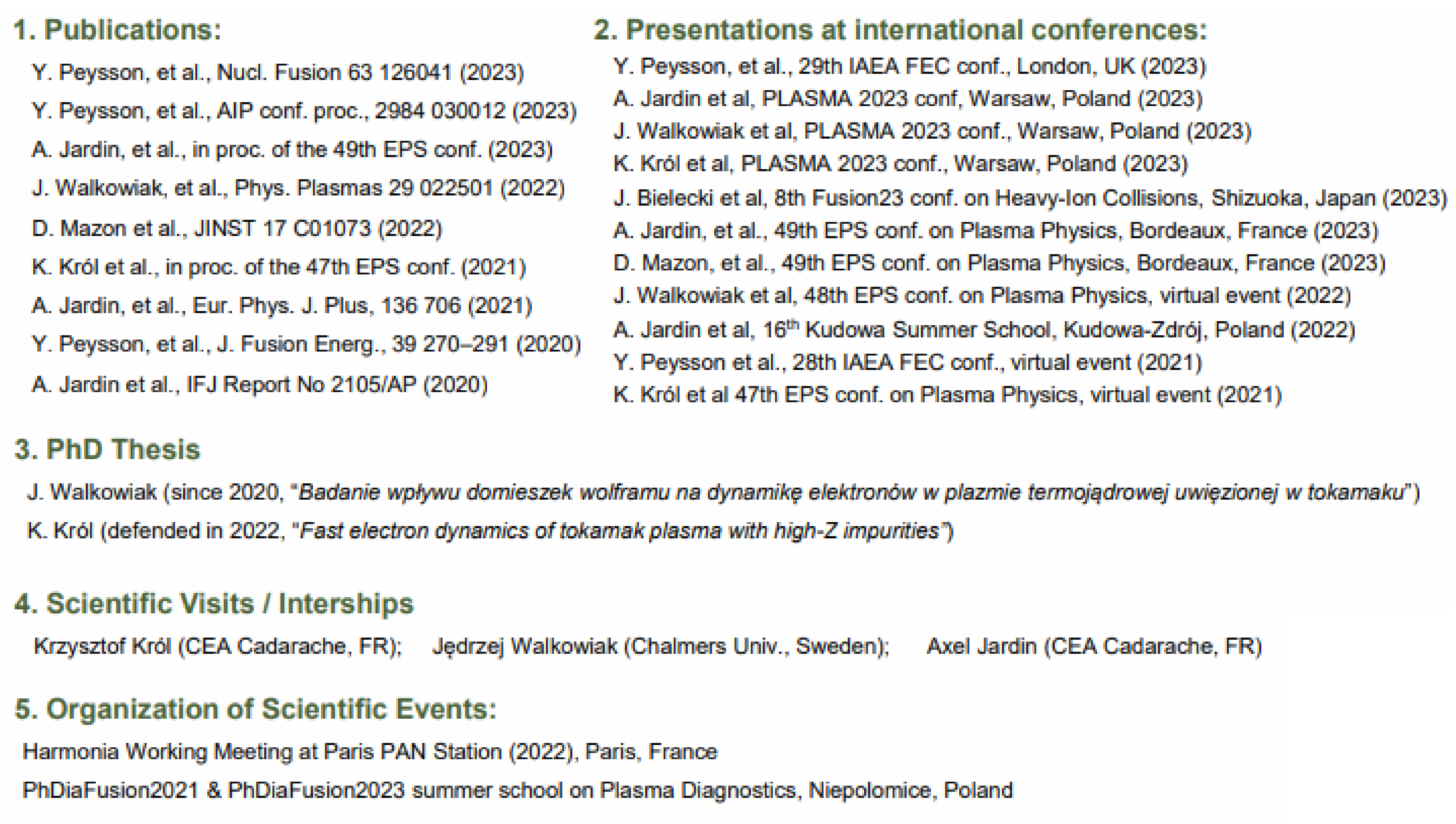
# Possibility to refine measurements and determine Cw





Determination of W concentration

# Many publications for those who are interrested (non exhaustive list)



## 1. Publications:

Y. Peysson, et al., Nucl. Fusion 63 126041 (2023)
Y. Peysson, et al., AIP conf. proc., 2984 030012 (2023)
A. Jardin, et al., in proc. of the 49th EPS conf. (2023)
J. Walkowiak, et al., Phys. Plasmas 29 022501 (2022)
D. Mazon et al., JINST 17 C01073 (2022)
K. Król et al., in proc. of the 47th EPS conf. (2021)
A. Jardin, et al., Eur. Phys. J. Plus, 136 706 (2021)
Y. Peysson, et al., J. Fusion Energ., 39 270–291 (2020)
A. Jardin et al., IFJ Report No 2105/AP (2020)

## 2. Presentations at international conferences:

Y. Peysson, et al., 29th IAEA FEC conf., London, UK (2023)
A. Jardin et al, PLASMA 2023 conf, Warsaw, Poland (2023)
J. Walkowiak et al, PLASMA 2023 conf., Warsaw, Poland (2023)
K. Król et al, PLASMA 2023 conf., Warsaw, Poland (2023)
J. Bielecki et al, 8th Fusion23 conf. on Heavy-Ion Collisions, Shizuoka, Japan (2023)
A. Jardin, et al., 49th EPS conf. on Plasma Physics, Bordeaux, France (2023)
D. Mazon, et al., 49th EPS conf. on Plasma Physics, Bordeaux, France (2023)
J. Walkowiak et al, 48th EPS conf. on Plasma Physics, virtual event (2022)
A. Jardin et al, 16th Kudowa Summer School, Kudowa-Zdrój, Poland (2022)
Y. Peysson et al., 28th IAEA FEC conf., virtual event (2021)
K. Król et al 47th EPS conf. on Plasma Physics, virtual event (2021)

## 3. PhD Thesis

J. Walkowiak (since 2020, "*Badanie wpływu domieszek wolframu na dynamikę elektronów w plazmie termojądrowej uwięzionej w tokamaku*")
K. Król (defended in 2022, "*Fast electron dynamics of tokamak plasma with high-Z impurities*")

## 4. Scientific Visits / Interships

Krzysztof Król (CEA Cadarache, FR); Jędrzej Walkowiak (Chalmers Univ., Sweden); Axel Jardin (CEA Cadarache, FR)

## 5. Organization of Scientific Events:

Harmonia Working Meeting at Paris PAN Station (2022), Paris, France
PhDiaFusion2021 & PhDiaFusion2023 summer school on Plasma Diagnostics, Niepolomice, Poland

# Outline

1. **Reminder about fusion and tokamak**
2. **WEST brief description**
3. **Operating plasma in a full tungsten tokamak**
4. **Soft X-Ray measurements and tomography**
5. **Reconstructing tungsten distribution**
6. **Summary and prospects**

# A very successful collaboration

Tomography

SXR measurements

Modelling

Synthetic diagnostics

Artificial intelligence

PHd and postdocs

Summer schools

And much more…

New framework of collaboration in preparation!

# Many thanks for your attention!

Looking forward to welcome you for a visit at Cadarache.