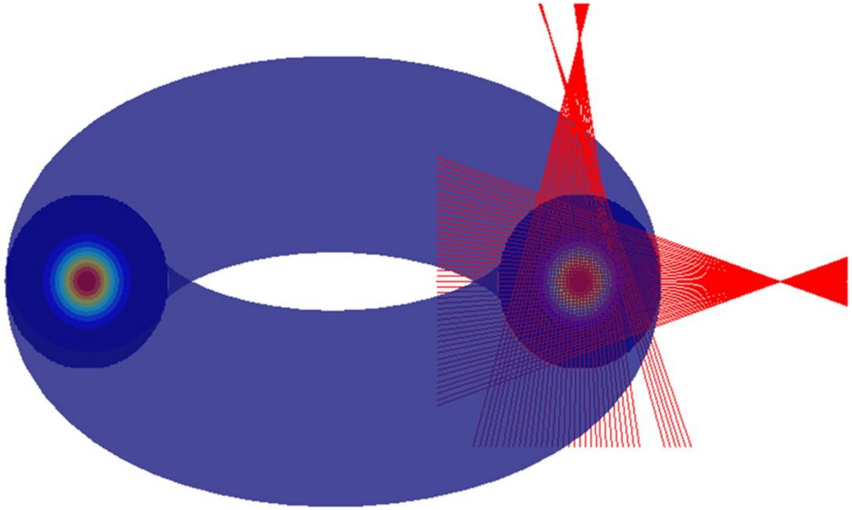
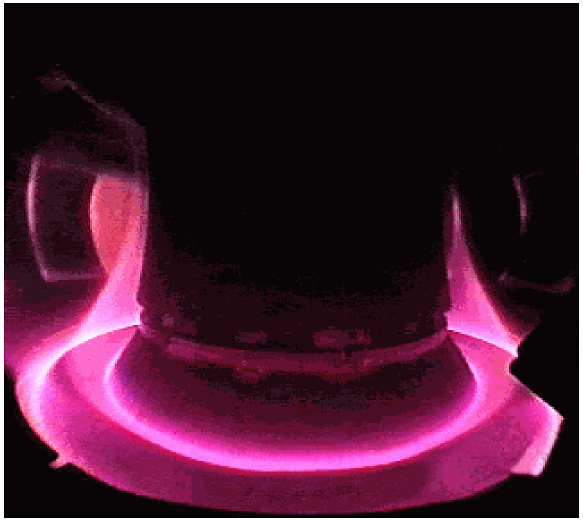
X-ray tomography for the control of high-Z impurities in tokamak plasmas





Axel Jardin | N06 – NZ61 | 17-03-2022

Department of Radiation Transport Physics (NZ61)
Institute of Nuclear Physics Polish Academy of Sciences (IFJ PAN), Krakow

Background

☐ **Zakład Fizyki Transportu Promieniowania** (N06/NZ61)

Research: neutron/X-ray radiation, nuclear fusion, plasma physics

✓ Plasma Focus PF-24,
✓ Neutron generator,
✓ Neutron transport MCNP calculations,
✓ ITER neutron spectro. (HRNS), IFMIF-DONES,
✓ Fusion plasma diagnostics and X-ray imaging,
✓ Collaborations: CEA (WEST), IPP Prague (COMPASS), etc…

The PF-24 device

☐ My post-doctoral researches in IFJ PAN since 2018:

✓ Tomography methods for X-ray/neutron diagnostics [POLONIUM 2018 - 19]
✓ Impurity transport studies in fusion devices (tokamaks) [EUROFusion 2018 - …]
✓ Fast electron collisions with high-Z ions, current drive [HARMONIA 2019 - 23]

[K. Król PhD 28.03.2022]
[J. Walkowiak PoP 2022]
[D. Mazon JINST 2022]
[Y. Peysson IAEA 2021]
[A. Jardin IFJ 2020]

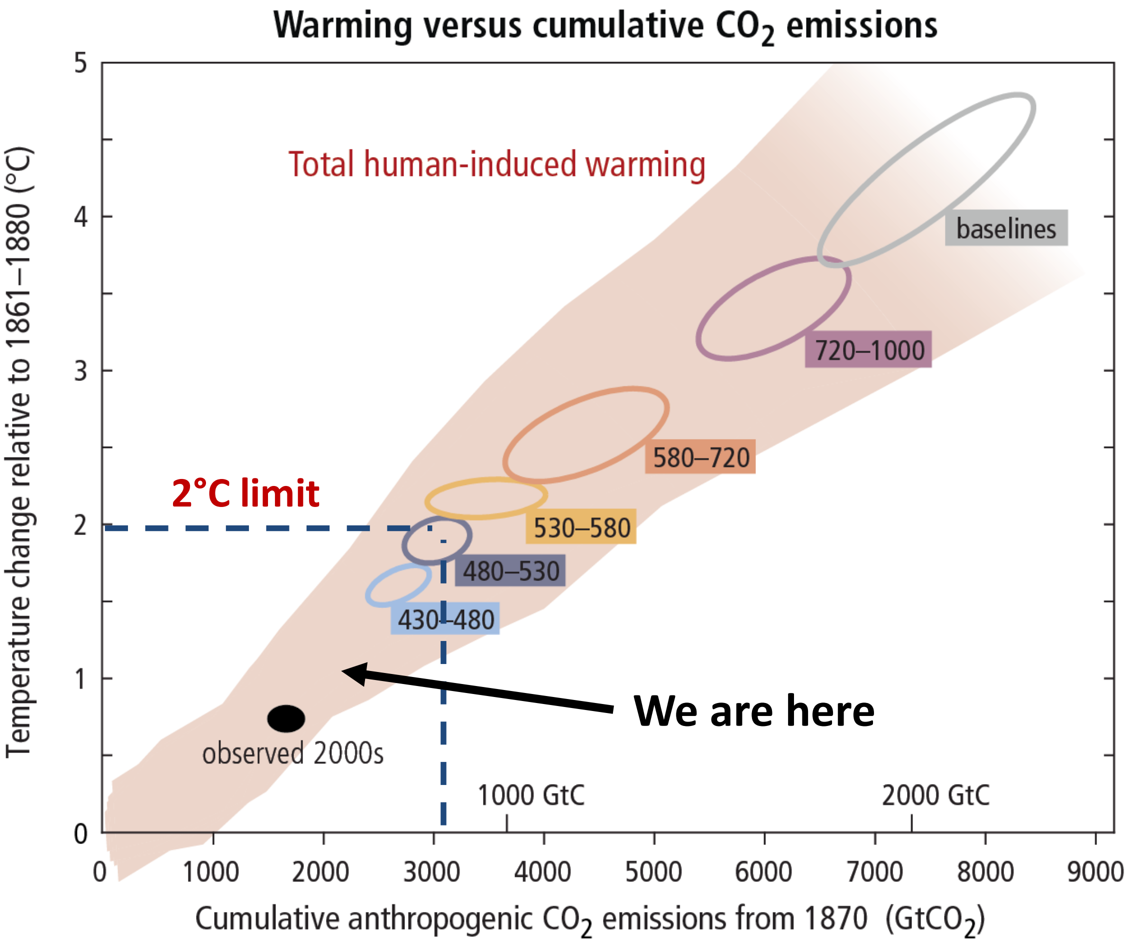
☐ Nagroda naukowa im. Henryka Niewodniczańskiego 2021:

„The development of soft X-ray tomography methods for experimental and theoretical investigations of high-Z impurities transport in tokamak plasmas"

- ☐ **Fusion Energy & recent results (NIF, JET)**
- ☐ **The tokamak concept**
- ☐ **Radiation of high-Z impurities**
- ☐ **X-ray tomography for monitoring impurity transport**
  - Soft X-ray tomography
  - Impact of heating systems on impurity distribution
  - Prospect for real-time control

CO_2 and Climate Change

- Environmental constraints → limit global warming < 2°C
  → limit CO_2 emissions < 3000 $GtCO_2$

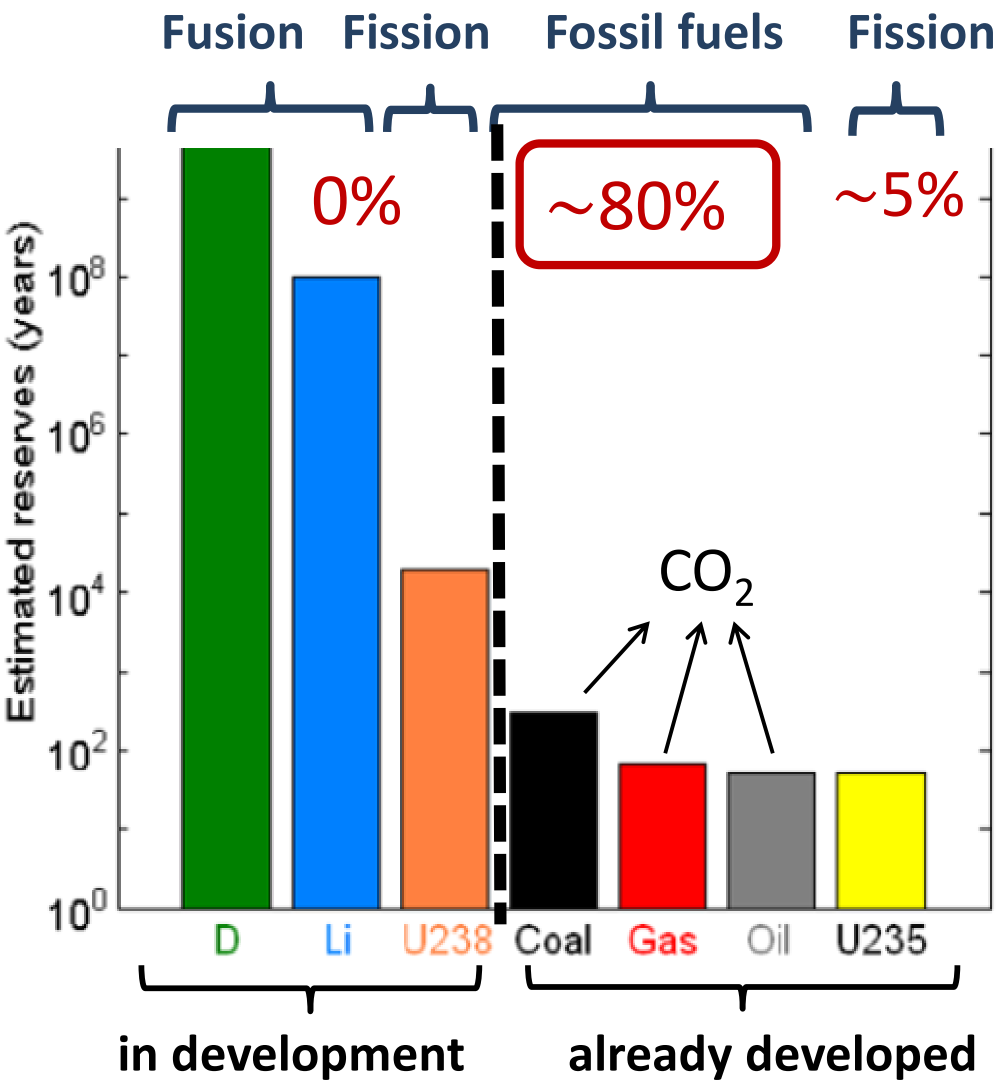


2°C limit

We are here

[IPCC 2014]

World energy reserves ~10^2 years



+ Renewable energies (∞)

(Wood, Hydroelectricity, Sun, Wind, …)

~5% ~ 5% ~ 5%

close to saturation **intermittent & sparse**

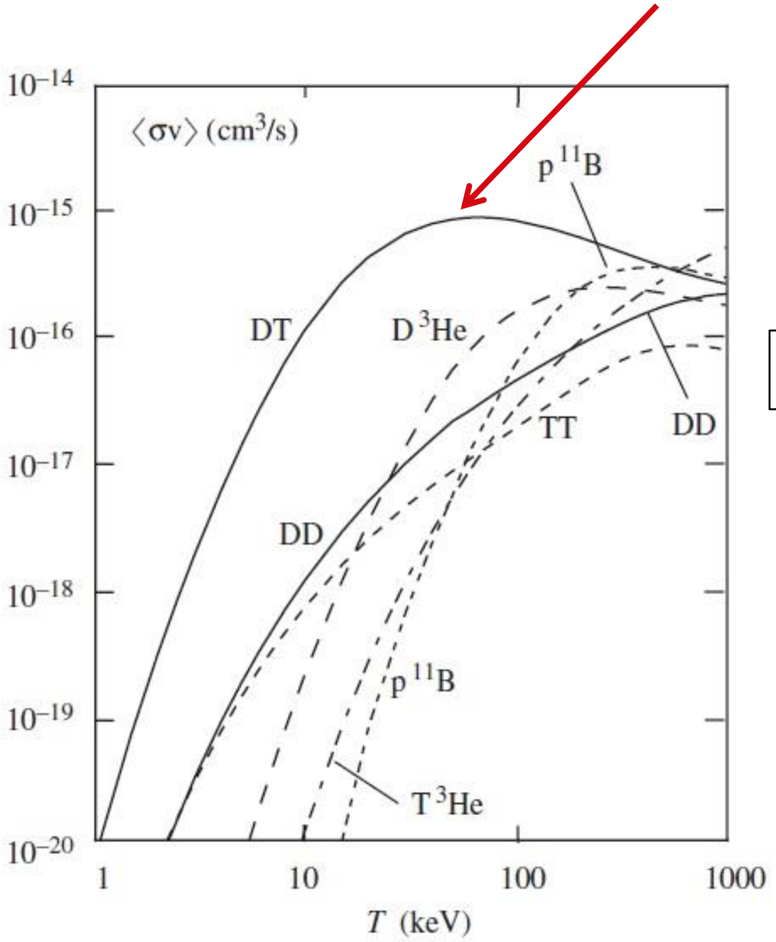
→ Need for abundant, stable and low-CO_2 energy sources.

[C. Guillemaut PhD 2013]

fusion reaction rate $\langle\sigma v\rangle$

- ☐ Fusion reaction rate for different reactants:

→ **D-T** easiest fusion reaction on Earth.



$\langle\sigma v\rangle$ = fusion reaction rate
σ = reaction cross-section
v = reactants relative velocity
$\langle\ldots\rangle$ = average over Maxwellian distribution

$$\boxed{{}^2_1D^+ + {}^3_1T^+ \rightarrow {}^4_2He^{2+}(3.5MeV) + {}^1_0n\ (14.1MeV)}$$

→ Requires plasma at T $\geq$ 10 keV

$(> 10^8\ K)$

→ How to obtain efficient plasma?

Efficiency of thermonuclear fusion

Plasma energy confinement τ_E

$$\tau_E = \frac{Q_p}{P_{loss}} = \frac{3nT}{P_{loss}}$$

Q_p – internal plasma energy per unit volume,

P_{loss} – power loss density,

n – plasma density, T – temperature,

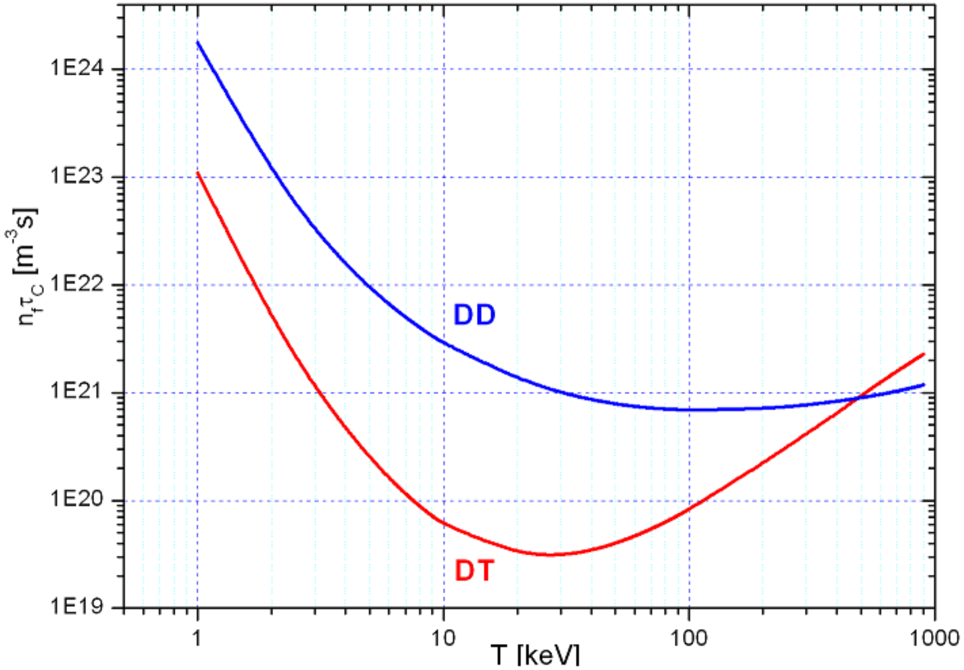
τ_E – Energy confinement time

a measure of the plasma cooling rate in the event of switching off the heating systems

$$P_f \geq \frac{Q_p}{\tau_E}$$

P_f – fusion power density,

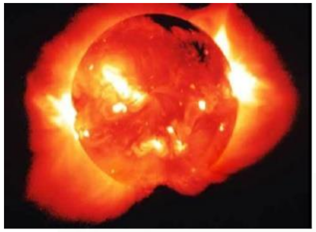
Condition for $P_f \geq P_{loss}$



$$\frac{1}{4} n^2 \langle \sigma v \rangle Q_{DT} \geq \frac{3nT}{\tau_E} \Longrightarrow n\tau_E \geq \frac{12T}{\langle \sigma v \rangle Q_{DT}}$$

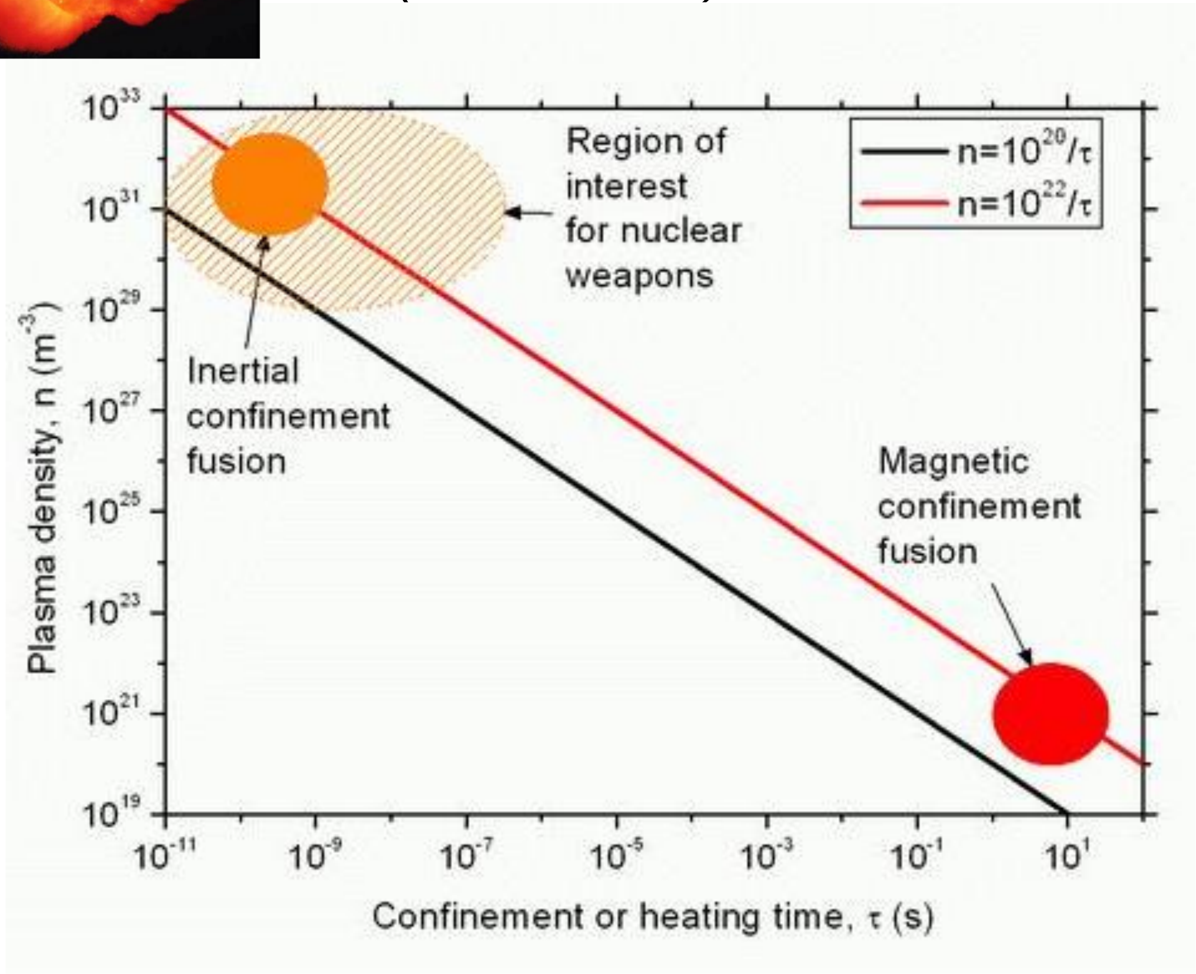
$n\tau_E$ - quantity characterizing the quality of energy maintenance in the plasma

Efficiency of thermonuclear fusion

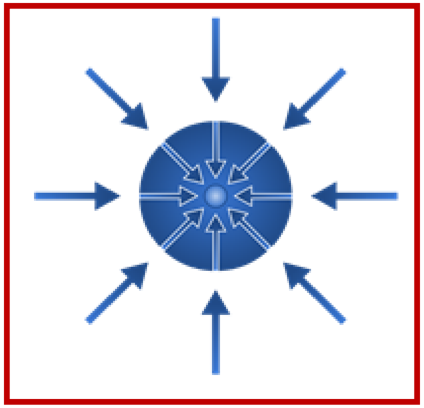


T ~ 24 keV; $(n\tau)_{min} > 10^{19}$ m^{-3}s (D,T)

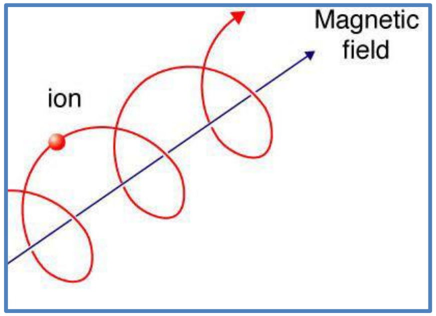
(1 keV ~ 10^{7} K)



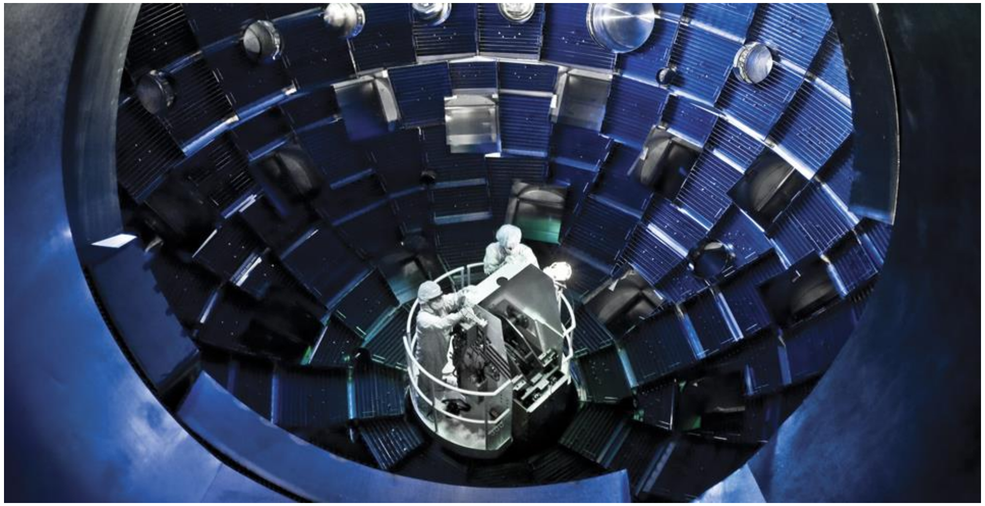
Inertial confinement

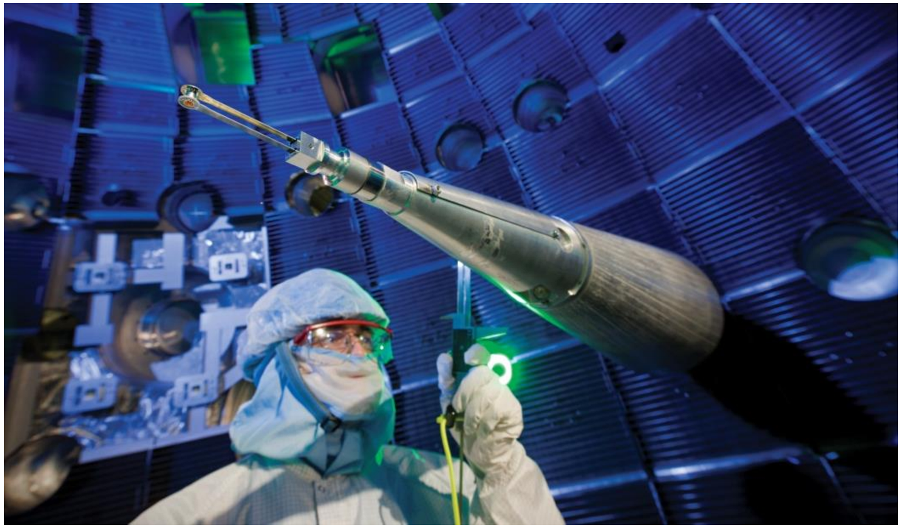


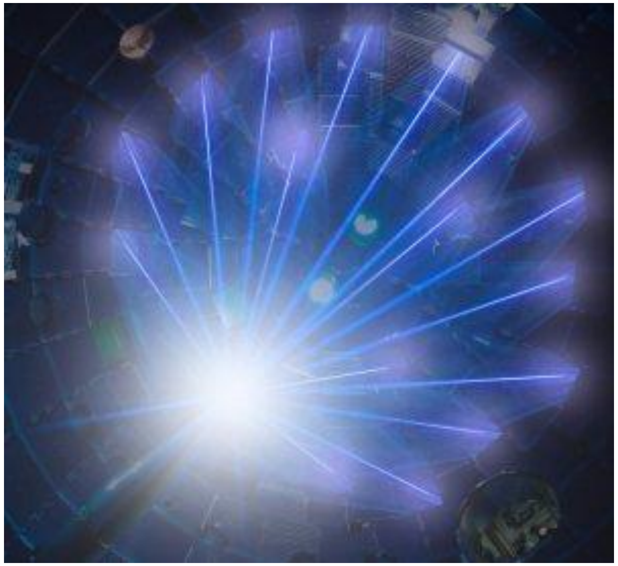
Magnetic confinement

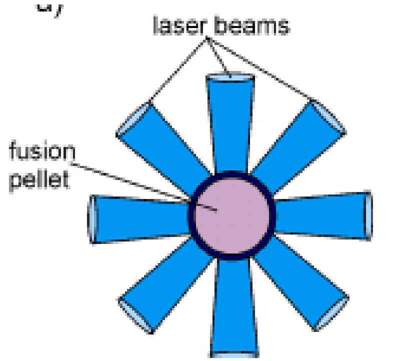


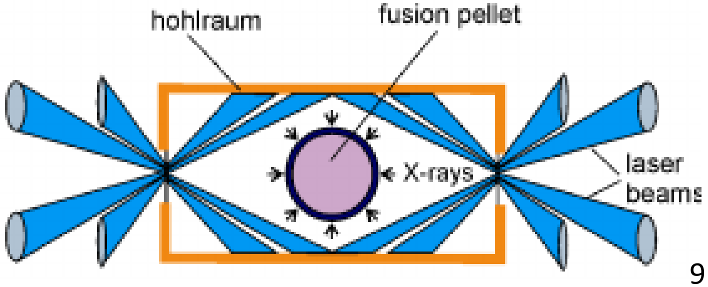
Inertial Fusion: Laser ignition devices







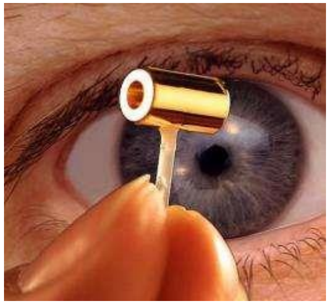


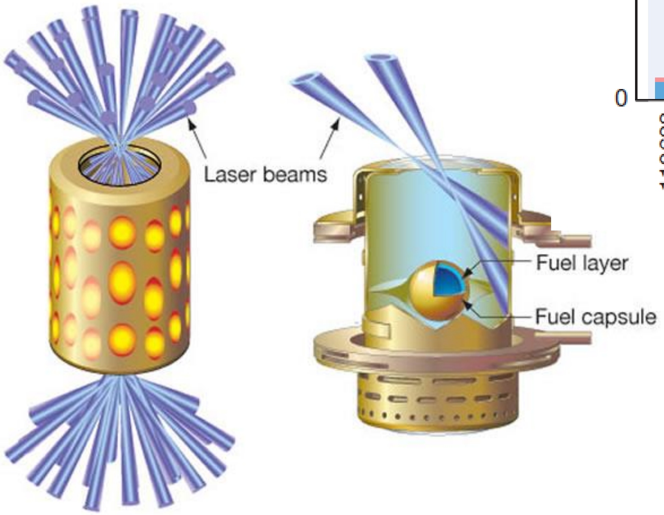


National Ignition Facility (NIF, USA)

[O. Hurricane (2014) Nature]

- **Method**: indirect drive





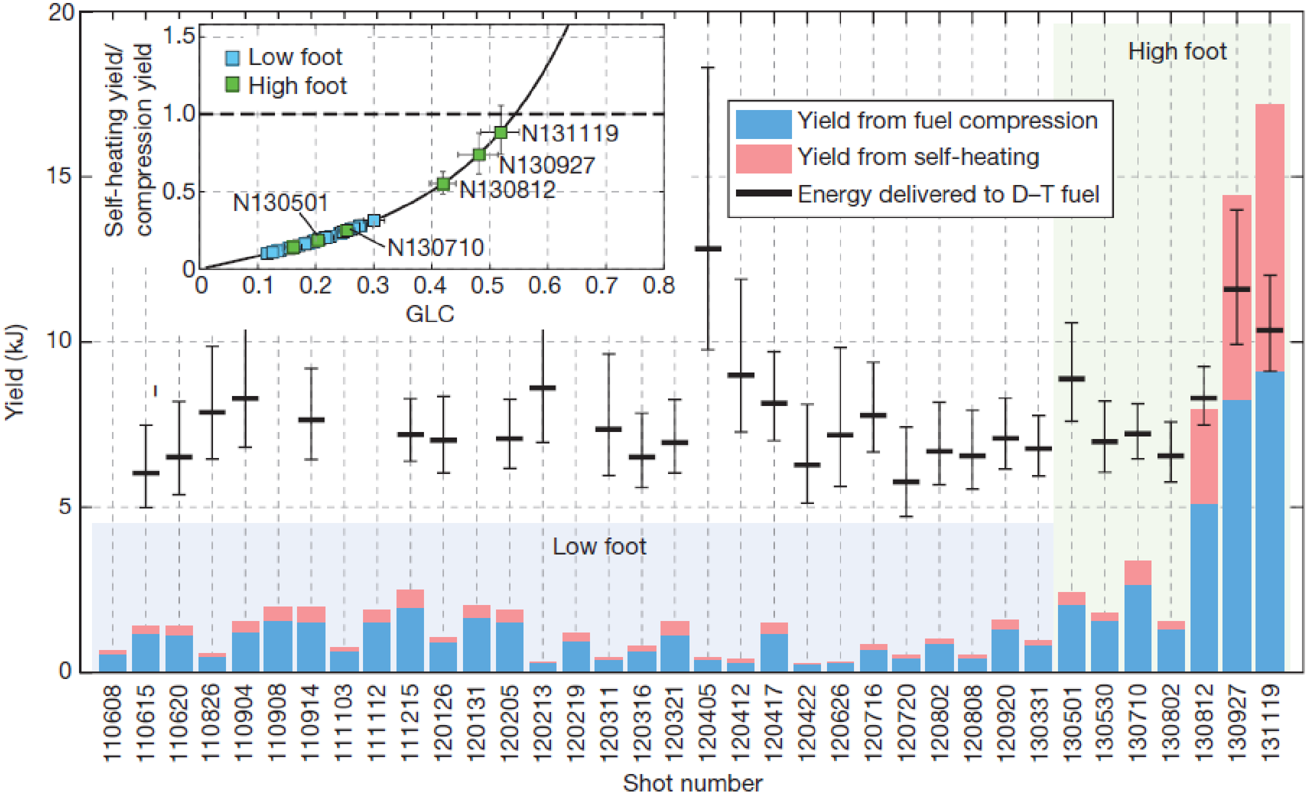
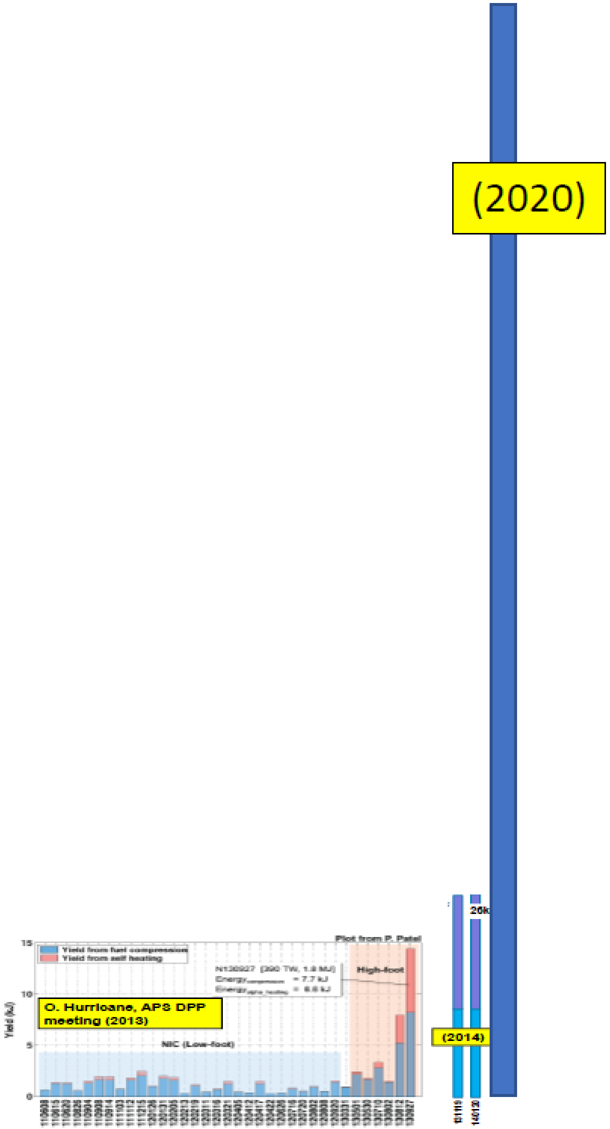


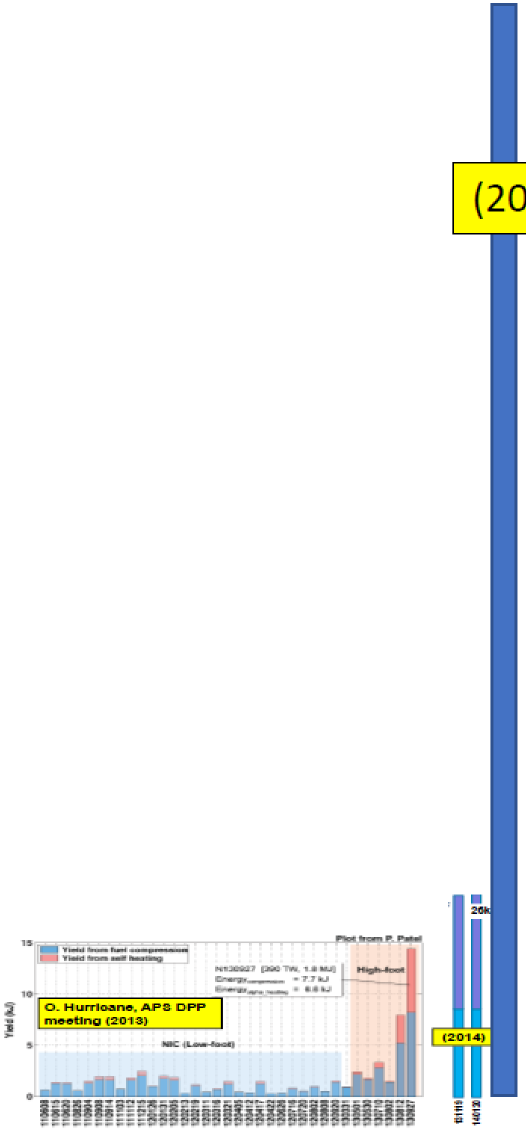
Figure 3 | Yield and energetics metrics for shots on the NIF. Total fusion yield is plotted versus shot number (that is, time). Shots 110608–130331 are low-foot shots. Shots 130501–131119 are high-foot shots. The bars showing total yield are broken into components of yield coming from α-particle self-heating and yield coming from compression. The black dashes denote the energy delivered to the D–T (fuel plus hotspot) with error bars (black vertical

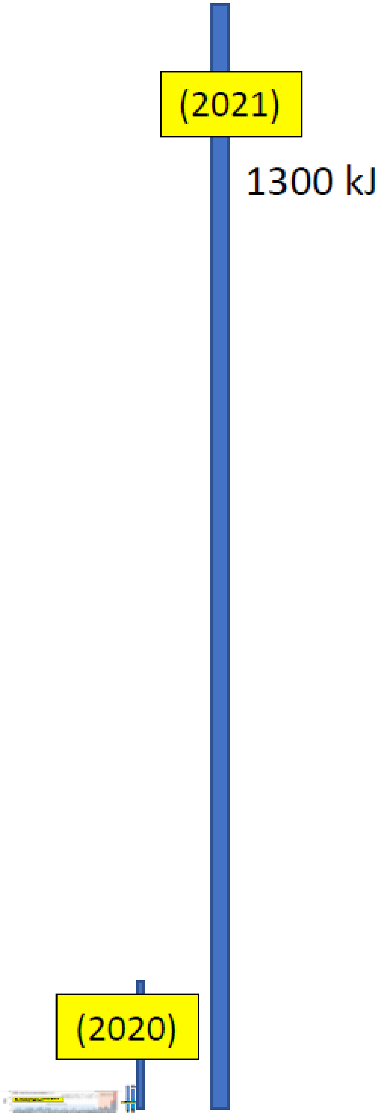
Recent results on NIF (2020)



[D. Batani, PhDiaFusion, 09-2021]

Recent results on NIF (2021)





[D. Batani, PhDiaFusion, 09-2021]

Recent results on NIF (2021)

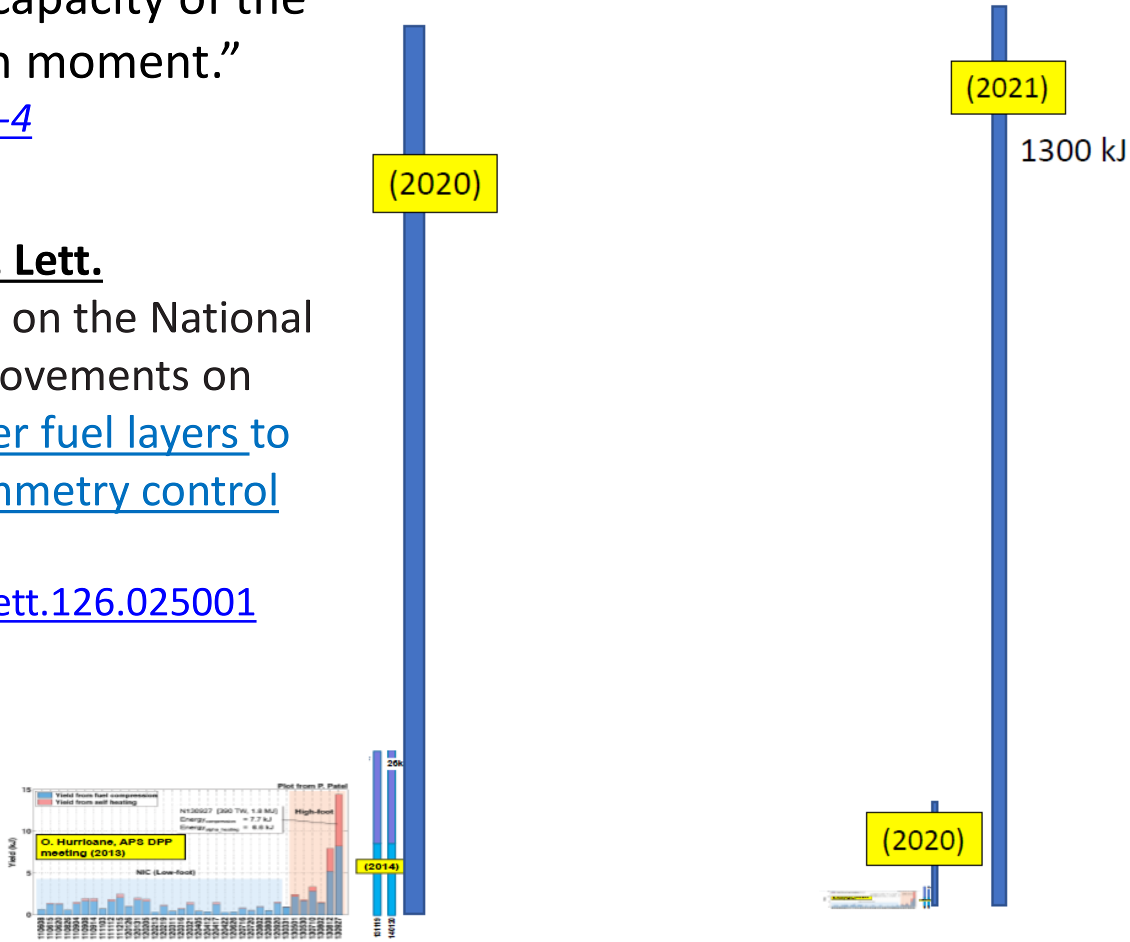
- ☐ **Nature article, 2021:**

„roughly 700 times the generating capacity of the entire US electrical grid at any given moment.”
https://doi.org/10.1038/d41586-021-02338-4

- ☐ **A. B. Zylstra et al. (2021) Phys. Rev. Lett.**

„We report new implosions conducted on the National Ignition Facility (NIF) with several improvements on recent work […]: larger capsules, thicker fuel layers to mitigate fuel-ablator mix, and new symmetry control via cross-beam energy transfer”
https://link.aps.org/doi/10.1103/PhysRevLett.126.025001

But concept still far from a fusion reactor…

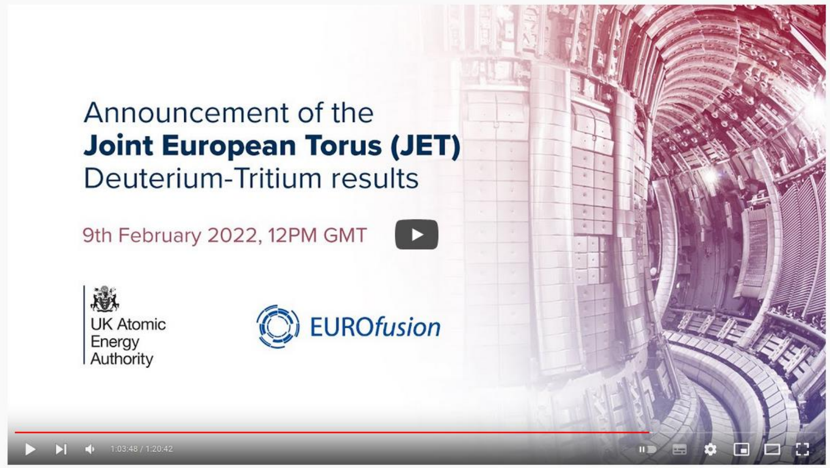


[D. Batani, PhDiaFusion, 09-2021]

Magnetic confinement fusion

❑ JET (Joint European Torus) Press conference (09.02.2022):

- ➢ Record of fusion energy in one tokamak plasma discharge (59 MJ)


Announcement of the
Joint European Torus (JET)
Deuterium-Tritium results

9th February 2022, 12PM GMT

[M. Scholz, „*Recent results of the DTE2 experiment at the JET ILW*”, PEGAN seminar 02.03.2022]

https://www.youtube.com/watch?v=H99hvPlC4is

JET recent results

Fusion power (MW) on JET tokamak (UK)

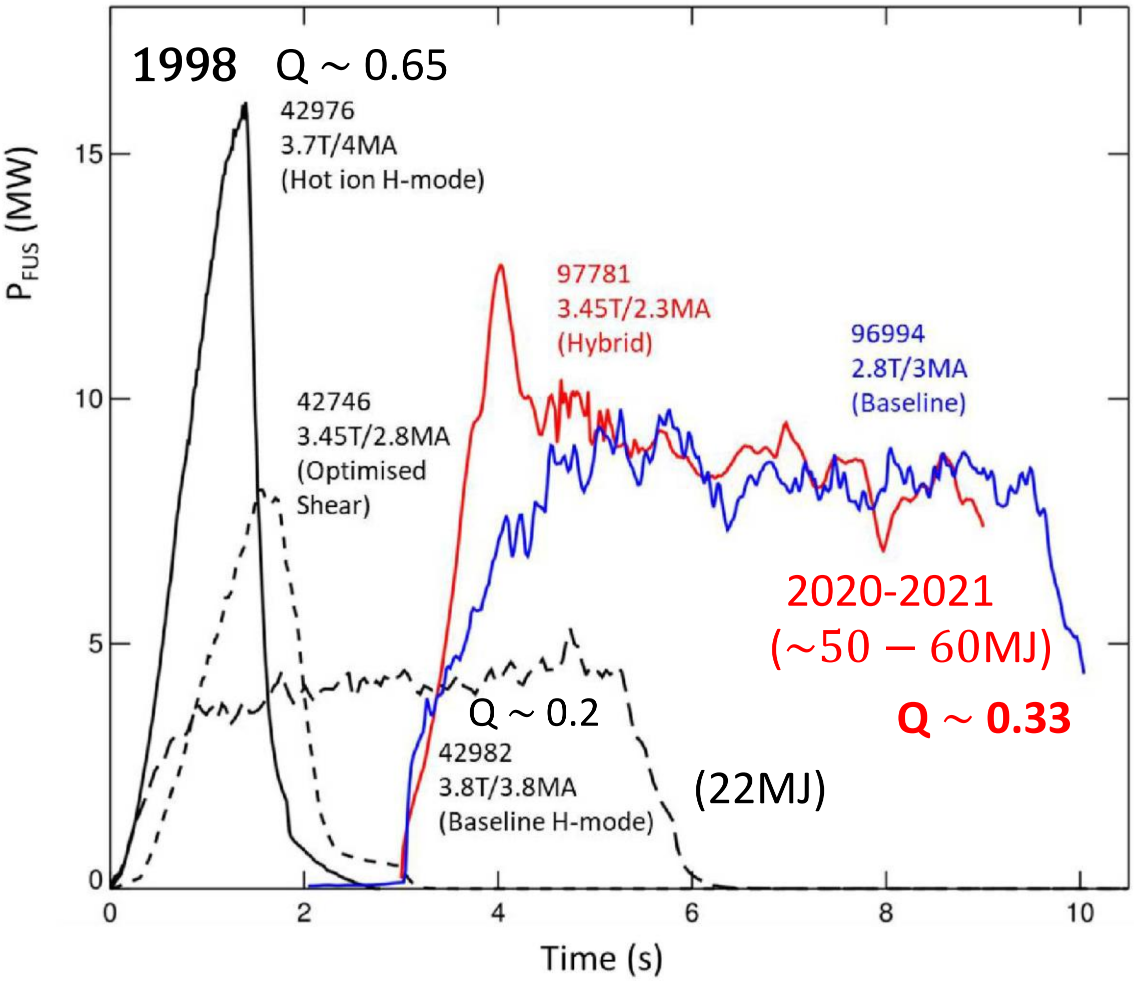


Figure 1 - P_{FUS} for DTE1 shots (black) with peak power and energy and $P_{EQ,DT}$ for JET-ILW best sustained performance for hybrid (red) and baseline (blue) plasmas. The start time is adjusted to facilitate comparison.

Fusion Energy gain:

$$Q = \frac{P_{fus}}{P_{heat}}$$

[J. Mailloux et al., *Overview of JET results for optimising ITER operation* (2022) *Nucl. Fusion]*

❑ Fusion Energy & recent results (NIF, JET)

❑ **The tokamak concept**

❑ Radiation of high-Z impurities

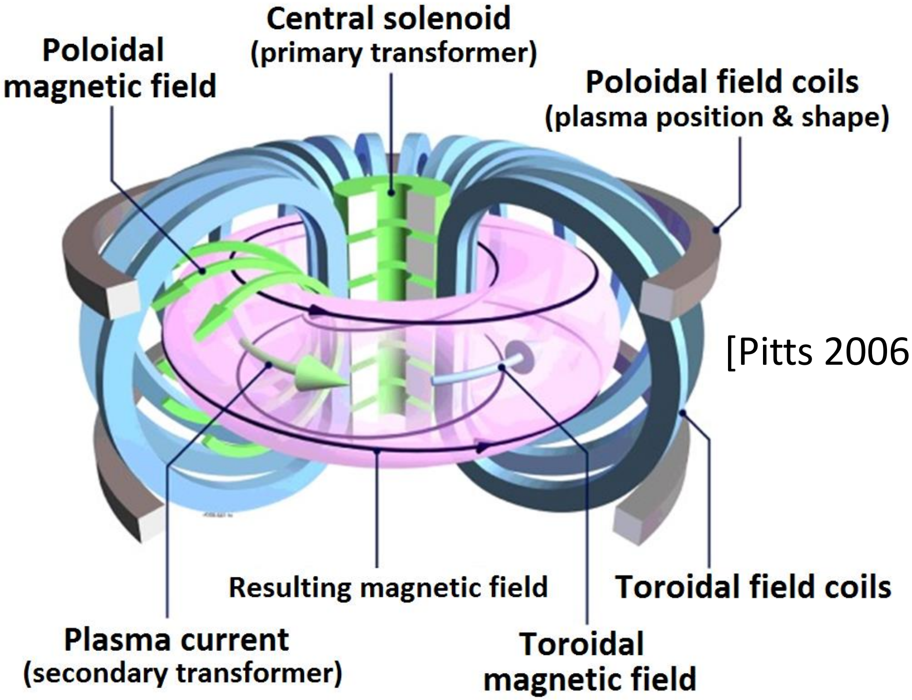
❑ X-ray tomography for monitoring impurity transport

- Soft X-ray tomography
- Impact of heating systems on impurity distribution
- Prospect for real-time control

Tokamak – magnetic confinement

- Tokamak is based on magnetic confinement:

✓ **Toroidal** magnetic field created by external coils
→ trapping of particles in a torus-shaped vacuum chamber



[Pitts 2006]

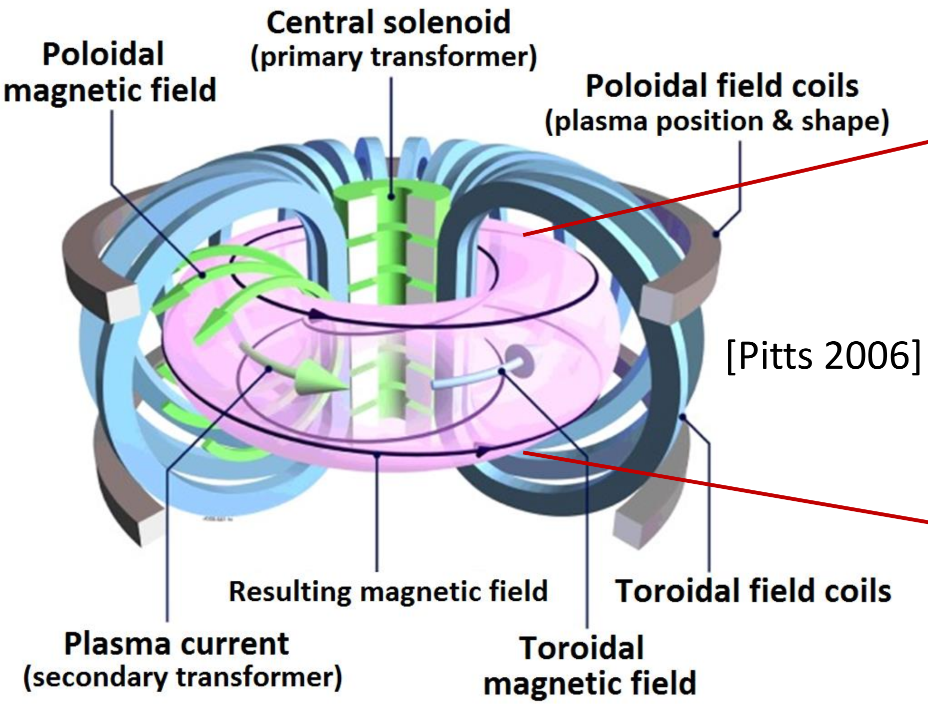
Tokamak – magnetic confinement

- Tokamak is based on magnetic confinement:

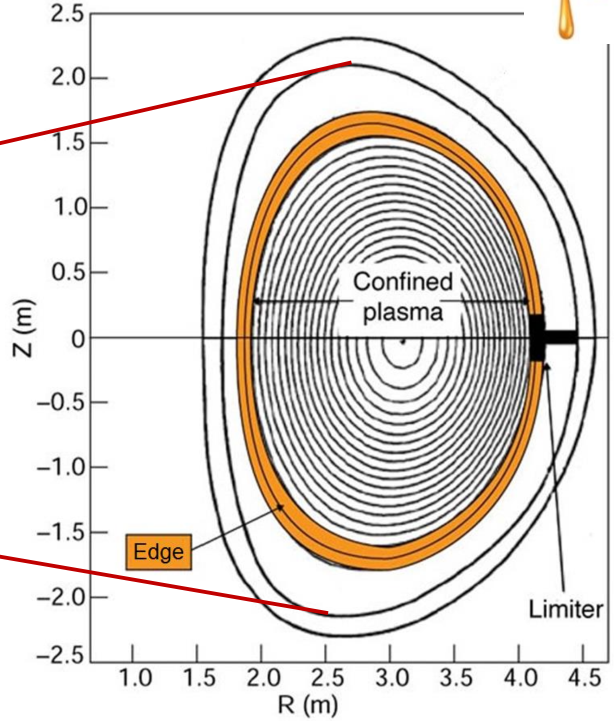
✓ **Toroidal** magnetic field created by external coils
→ trapping of particles in a torus-shaped vacuum chamber

✓ **Poloidal** field self-generated by plasma electric current
→ compensate for drifts and stabilize the plasma
→ control of the plasma current profile is crucial!

Nested magnetic flux surfaces

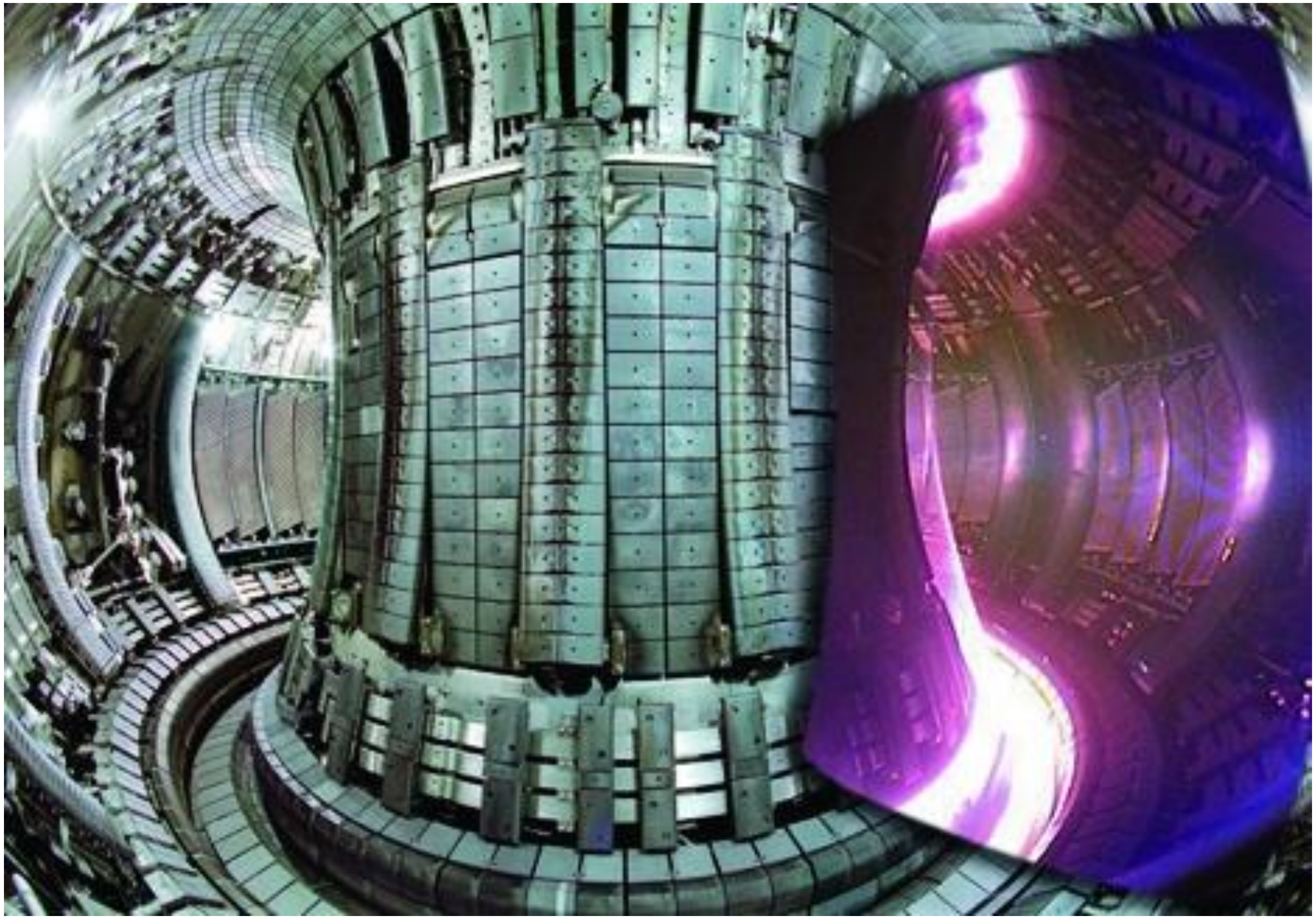


[Pitts 2006]



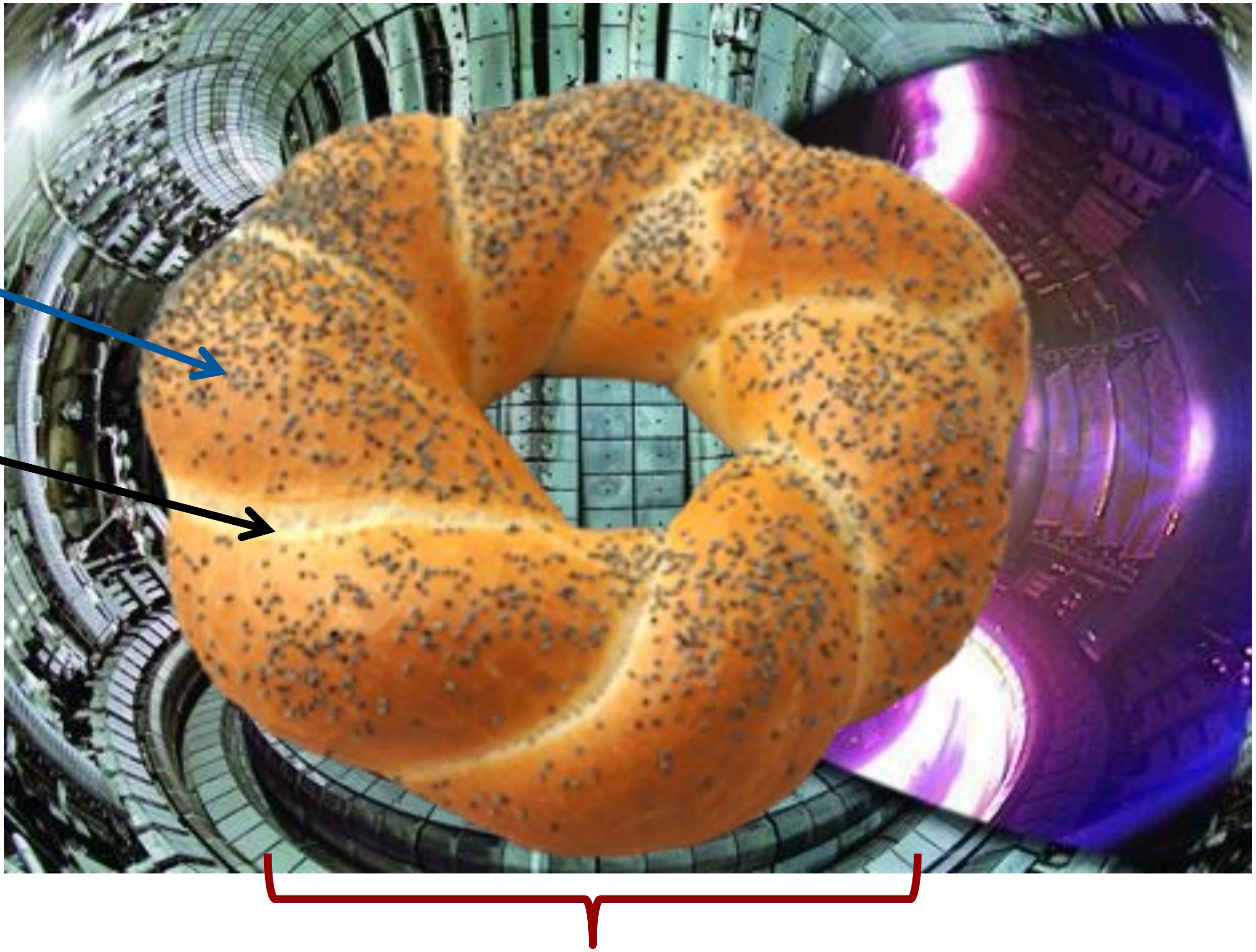
Tokamak

- The **Joint European Torus (JET)**, EUROfusion, Oxfordshire:



Tokamak = Obwarzanek z makiem

- The **Joint European Torus (JET)**, EUROfusion, Oxfordshire:



Confined plasma particles

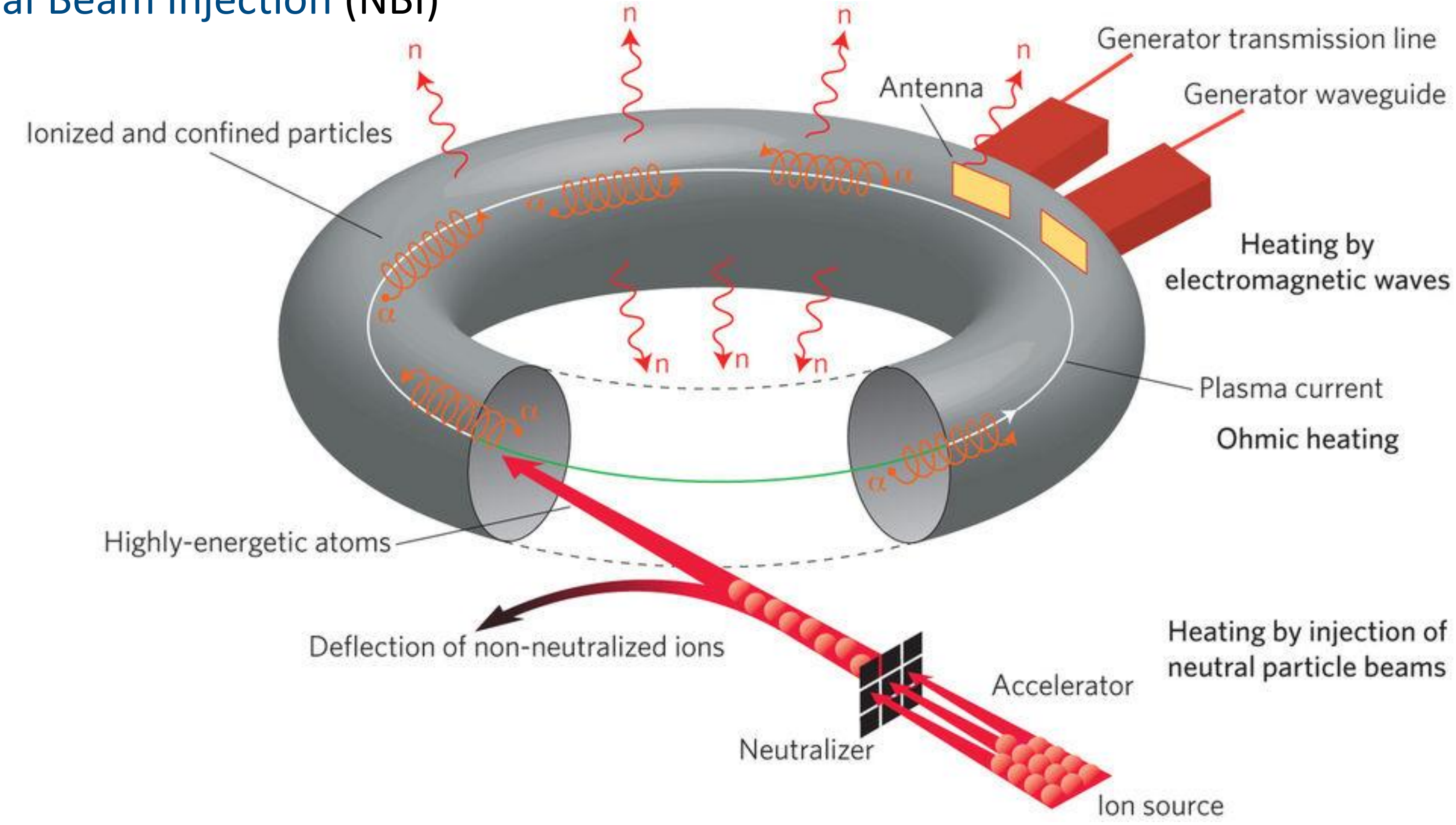
Helical magnetic field lines

Torus shape

Plasma heating methods in tokamaks

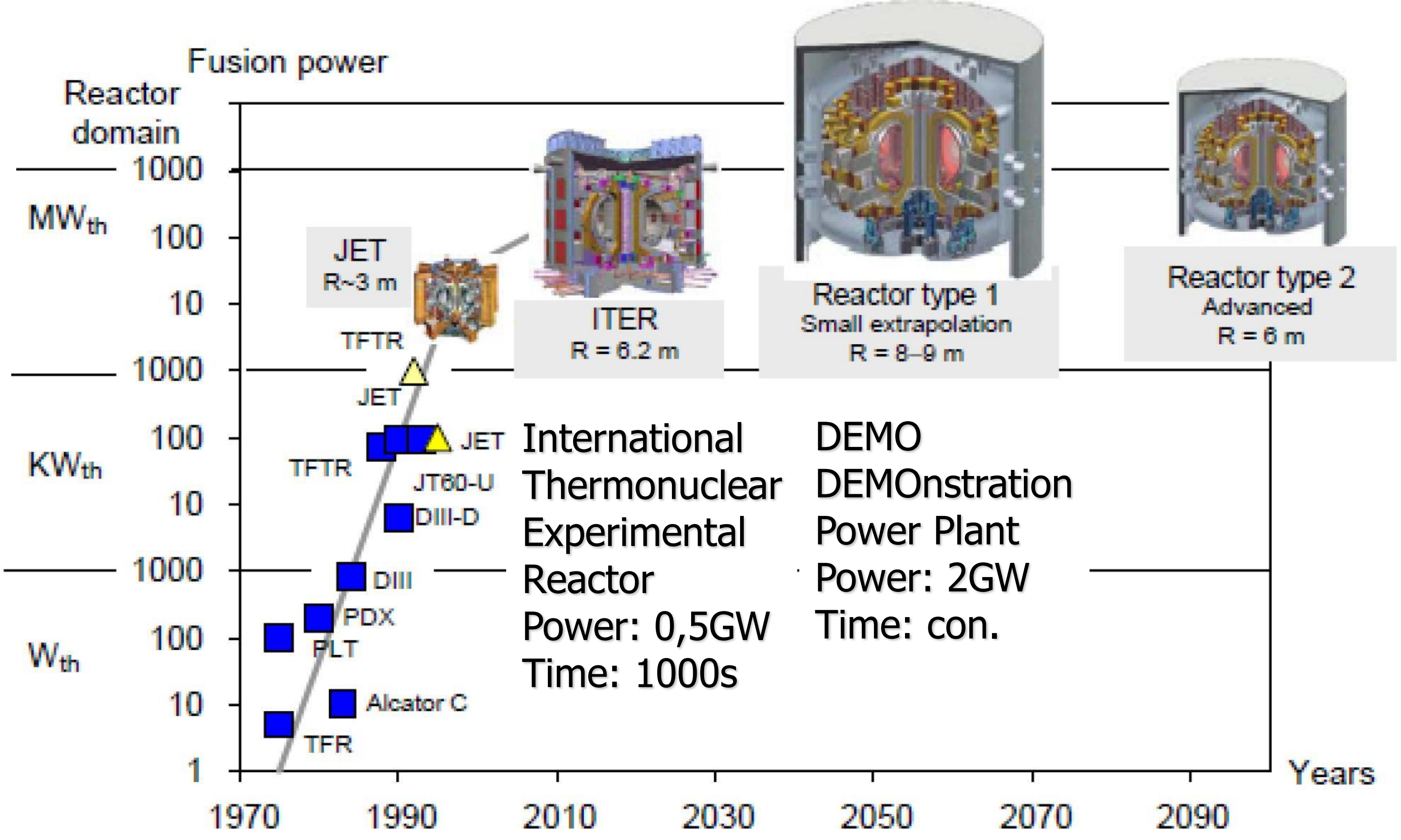
☐ Main heating methods in tokamak plasmas:

- ✓ Central solenoid: plasma heating by Joule effect, transient.
- ✓ Electromagnetic waves: Electron / Ion Cyclotron Resonance Frequency (ECRH, ICRH)
- ✓ Neutral Beam Injection (NBI)



[D. Mazon et al., Nature Physics 2016]

History of Fusion Reactors



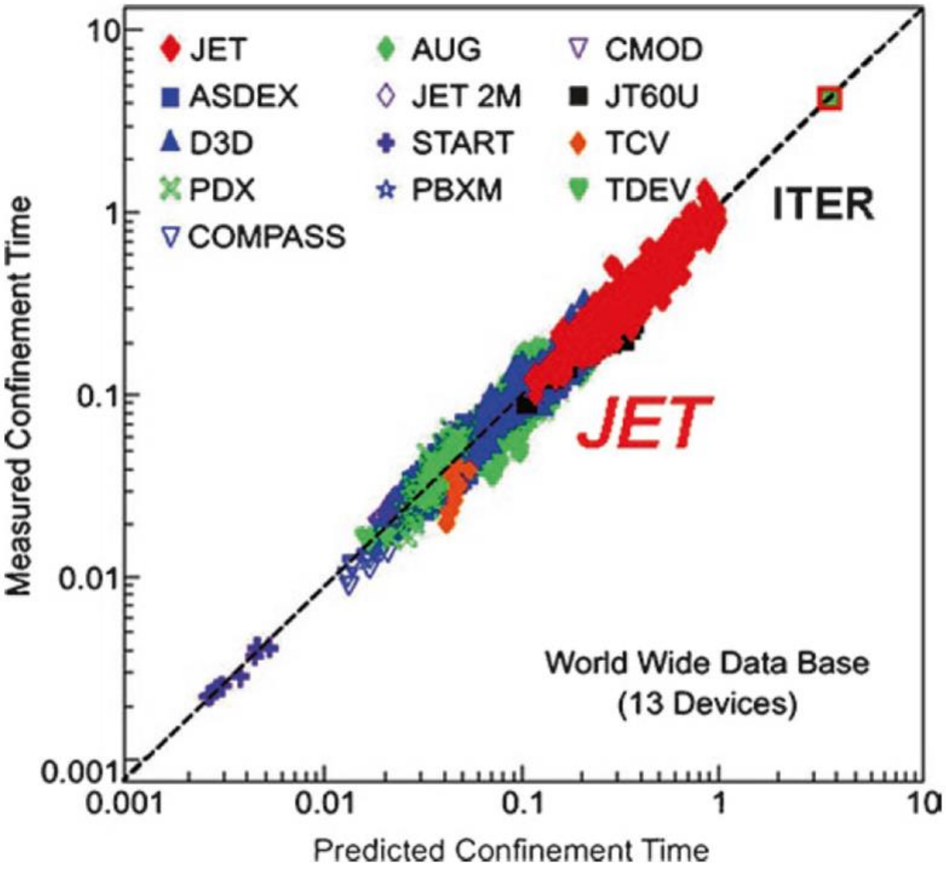
International Thermonuclear Experimental Reactor
Power: 0,5GW
Time: 1000s

DEMO
DEMOnstration Power Plant
Power: 2GW
Time: con.

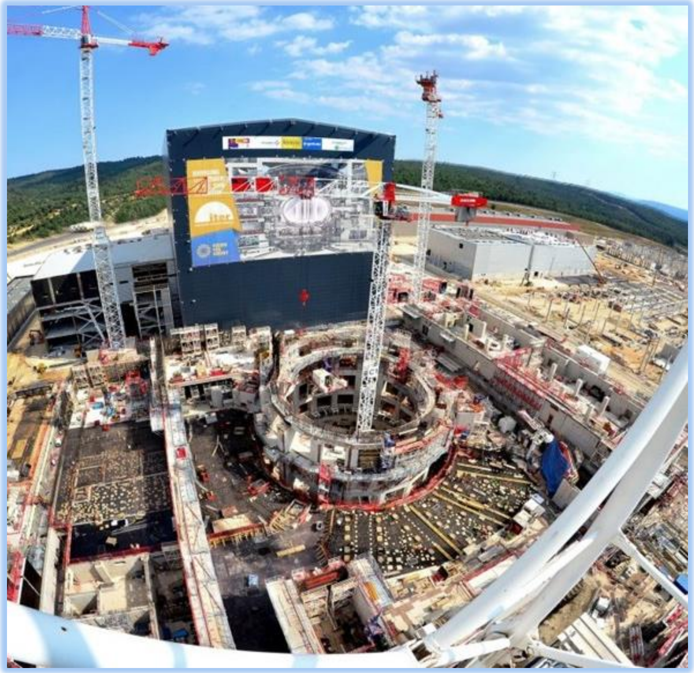
ITER → increase confinement time τ_E

- ☐ Optimize nτ_E in tokamaks: low density n, high confinement time τ_E
- ☐ Efficient Fusion reactor: bigger is better (for energy confinement time τ_E)

$$\tau_E \sim I_p^{0.93} B_T^{0.15} P^{-0.69} n_e^{0.41} M^{0.19} \boxed{R^{1.97}} \varepsilon^{0.58} \kappa^{0.78}$$



International Thermonuclear Experimental Reactor: ITER (under construction in France)



→ First device with τ_E > 1s in fusion relevant steady-state conditions.

Some ITER physics challenges

- ✓ **Disruptions**: loss of confinement, heat / mechanical loads
  → Prediction, Avoidance, Mitigation
- ✓ **Plasma wall interaction**: wall erosion, heat flux (active cooling)
- ✓ **High-Z (W) impurity radiation** → avoid central accumulation
- ✓ **Diagnostics**: hardness to neutrons/heat flux → which technologies?
- ✓ **Real-time control** of fusion power and plasma stability
- ✓ **Tritium** cycle and retention in walls
- ✓ Burning plasma: **neutron load, energy extraction, Helium ashes** exhaust
- ✓ etc…

- ☐ Fusion Energy & recent results (NIF, JET)

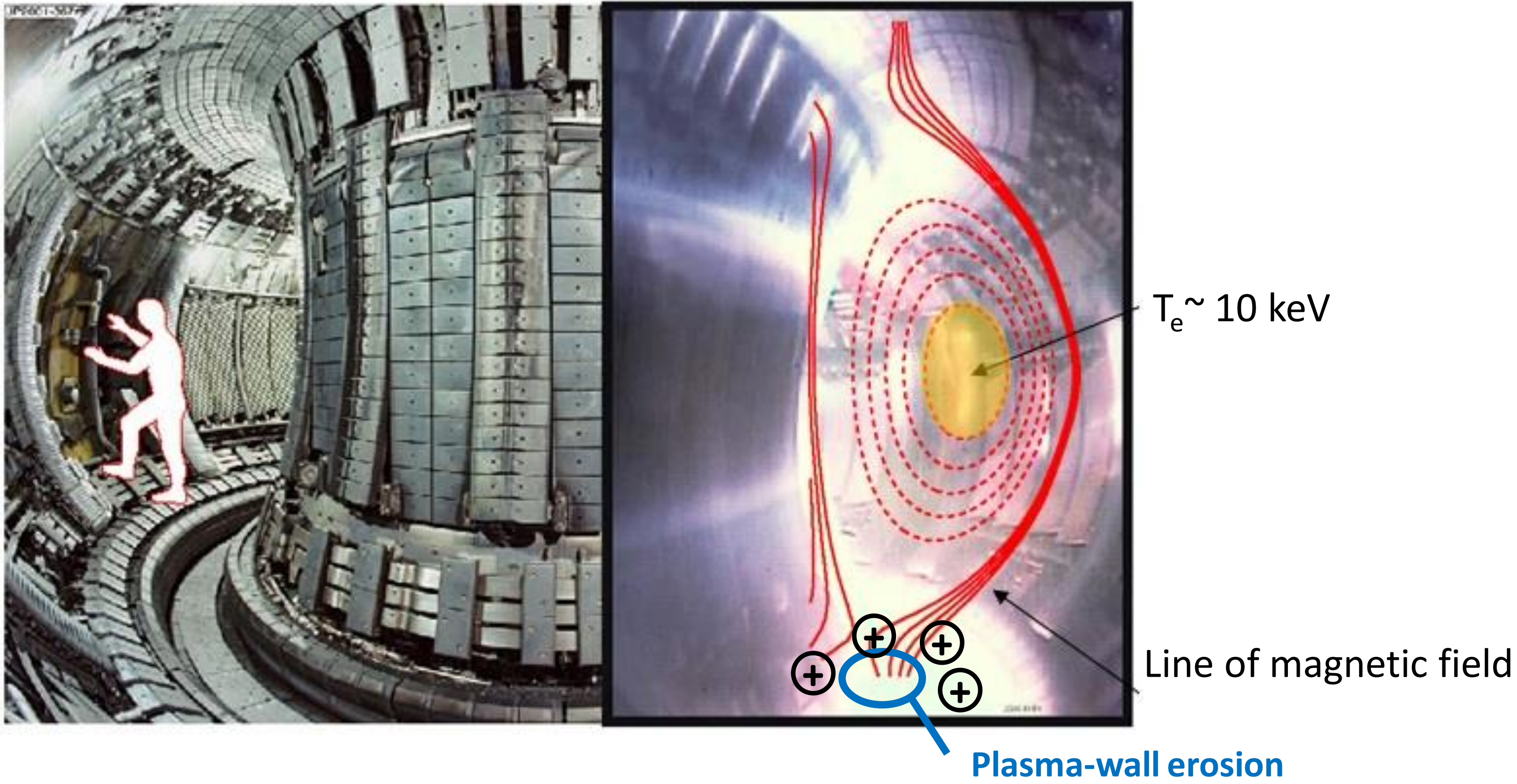
- ☐ The tokamak concept

- ☐ **Radiation of high-Z impurities**

- ☐ X-ray tomography for monitoring impurity transport
  - Soft X-ray tomography
  - Impact of heating systems on impurity distribution
  - Prospect for real-time control

Plasma-wall erosion and impurities

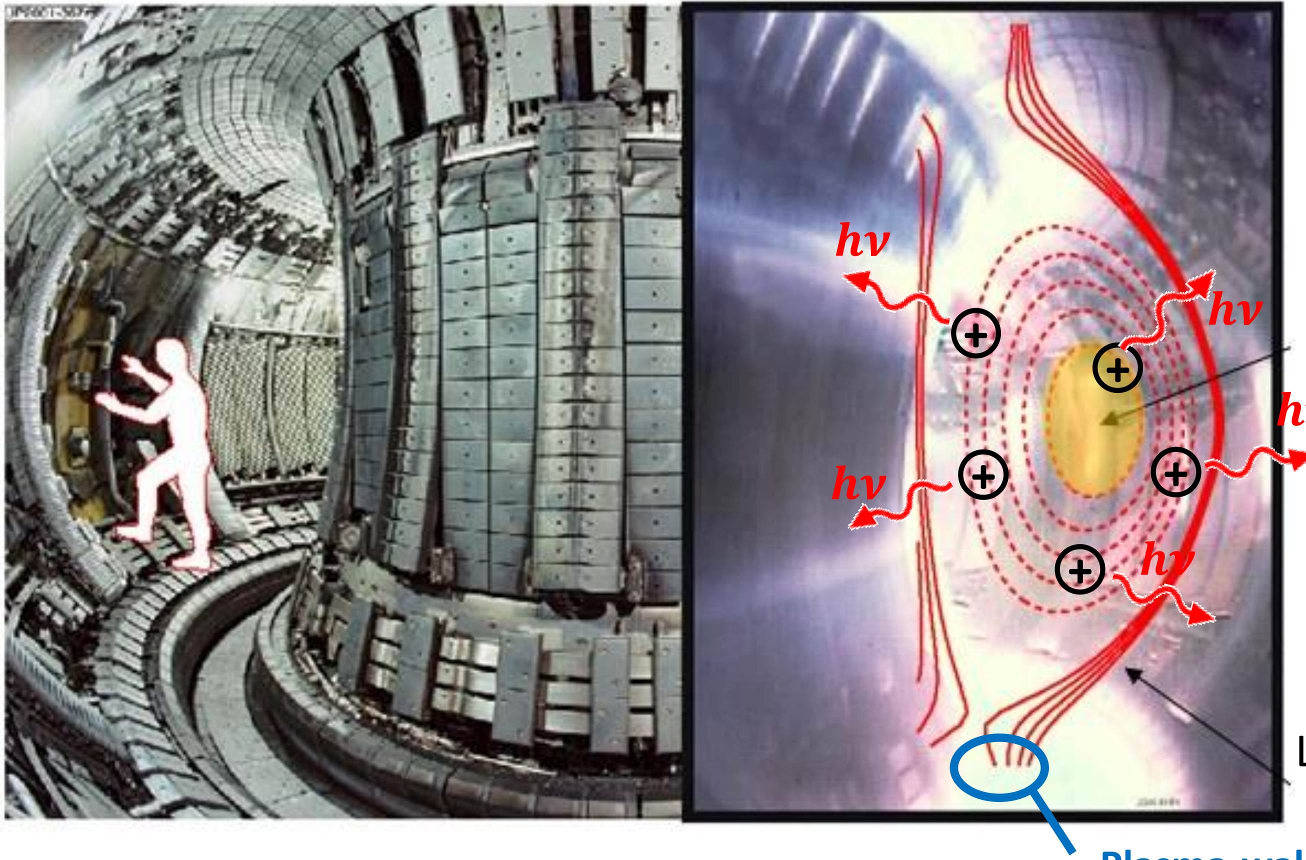
Joint European Torus (JET), Oxfordshire.



- Heat and particle fluxes from the confined region toward the wall
  → erosion of plasma-facing components of the tokamak.

Plasma-wall erosion and impurities

Joint European Torus (JET), Oxfordshire.



$T_e \sim 10$ keV

Line of magnetic field

Plasma-wall erosion

- ❑ Heat and particle fluxes from the confined region toward the wall
  → erosion of plasma-facing components of the tokamak.
- ❑ Migration of the sputtered impurities → **Radiation in the plasma core**
  → **Degradation of fusion performances**

High-Z impurity radiation in plasmas

- ☐ Radiated power of impurities: $P_{rad,Z} = n_e^2 \, c_Z \, L_Z(T_e)$

electron density (m^{-3})

Impurity concentration

Cooling factor of Z ($W.m^3$)

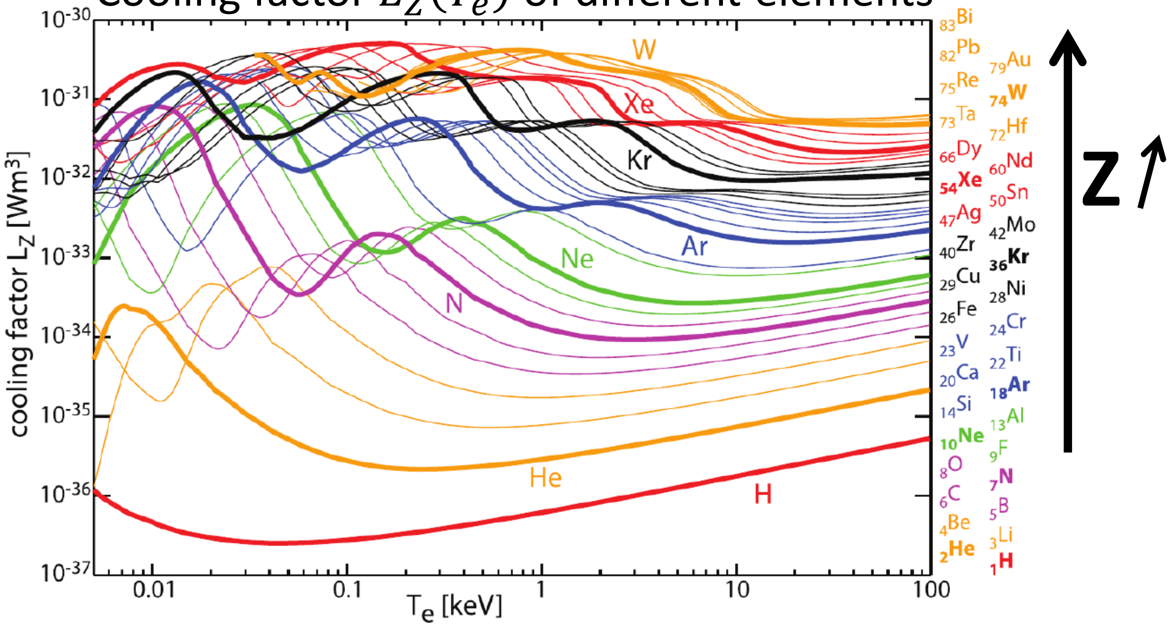
- ☐ Impurity radiation increases with atomic number Z (high-Z):

Dominant radiation processes:

- **Bremsstrahlung** (free-free)
- **Radiative recombination** (free-bound)
- **Line radiation** (bound-bound)

Soft X-ray range [0.1 keV – 20 keV]

Cooling factor $L_Z(T_e)$ of different elements

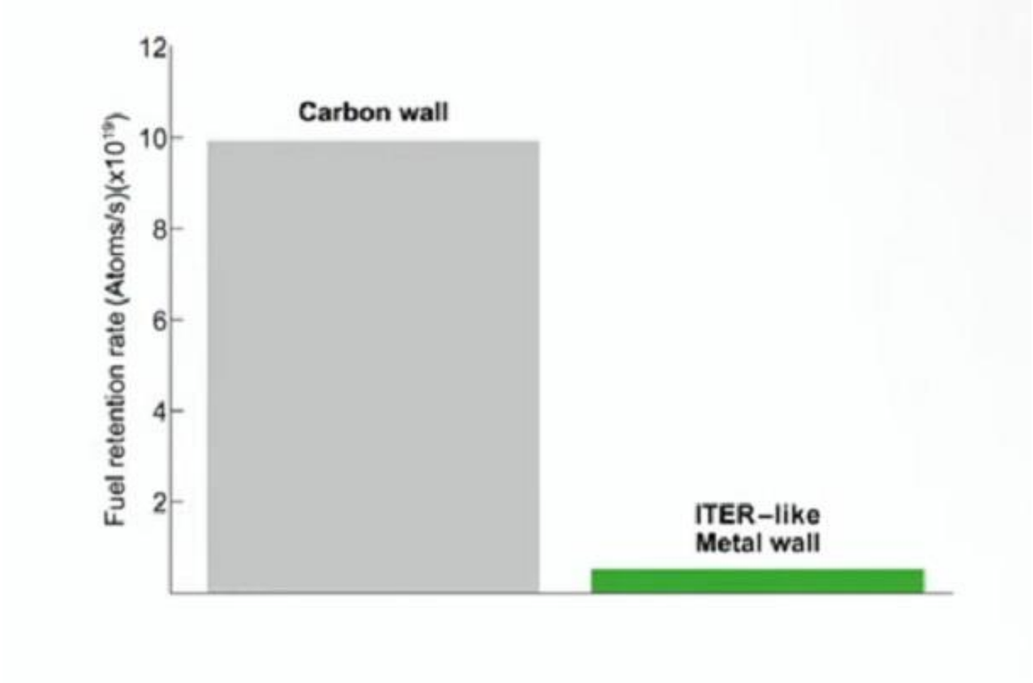


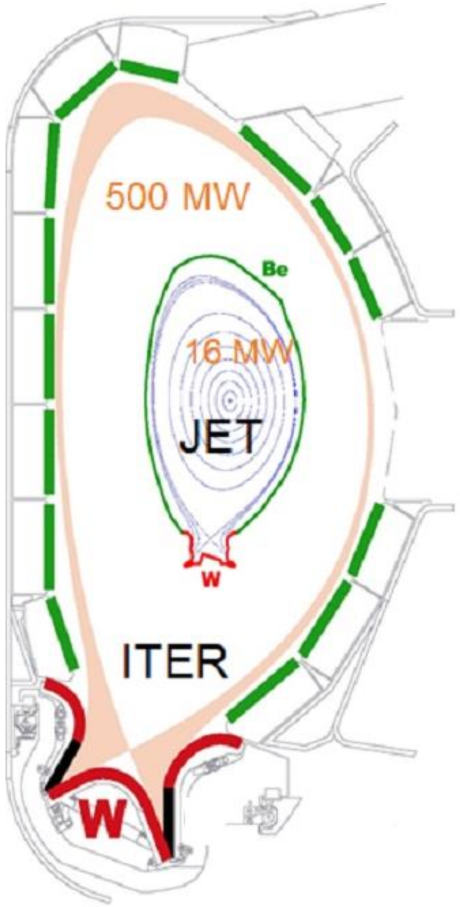
[Puetterich NF 2019]

JET - from carbon wall to metallic wall

Modern tokamaks:

~~carbon~~ (C) → metallic wall (Be, W) to avoid tritium retention

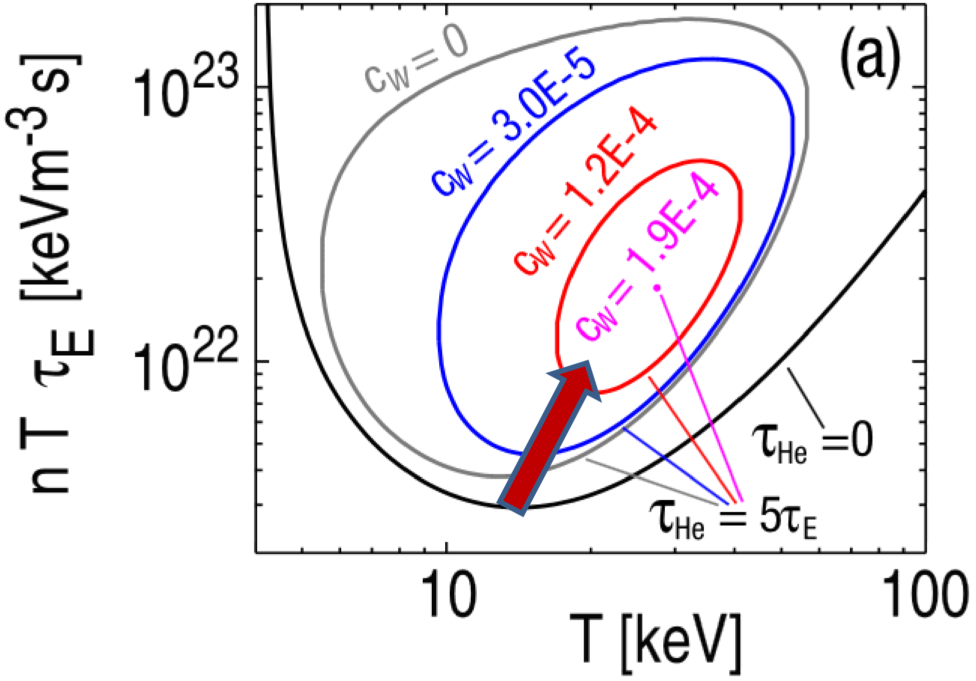




Reduction of fuel absorption in the walls by a factor >10

W impurities shrink the operational domain

ignition domain of fusion plasma



T **[keV]   – *plasma temperature***
n **[1/m^3] – *plasma density***
τ_E [s]   – energy confinement time

τ_{He} – Helium confinement time
c_W – impurity concentration (W)

[T. Putterich et al., Nuclear Fusion 50 (2), 025012 (2010)]

- ☐ A concentration $f_W < 0.01\%$ is a requirement for a fusion reactor

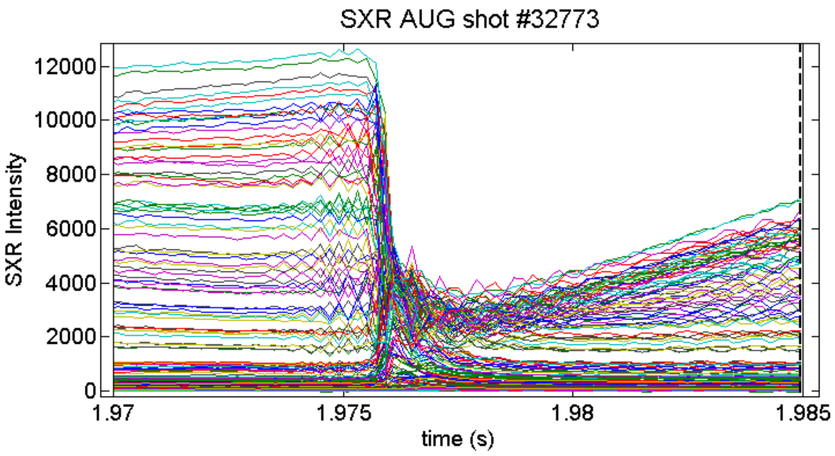
→ Diagnostic tools and actuators to control the tungsten core concentration are required!

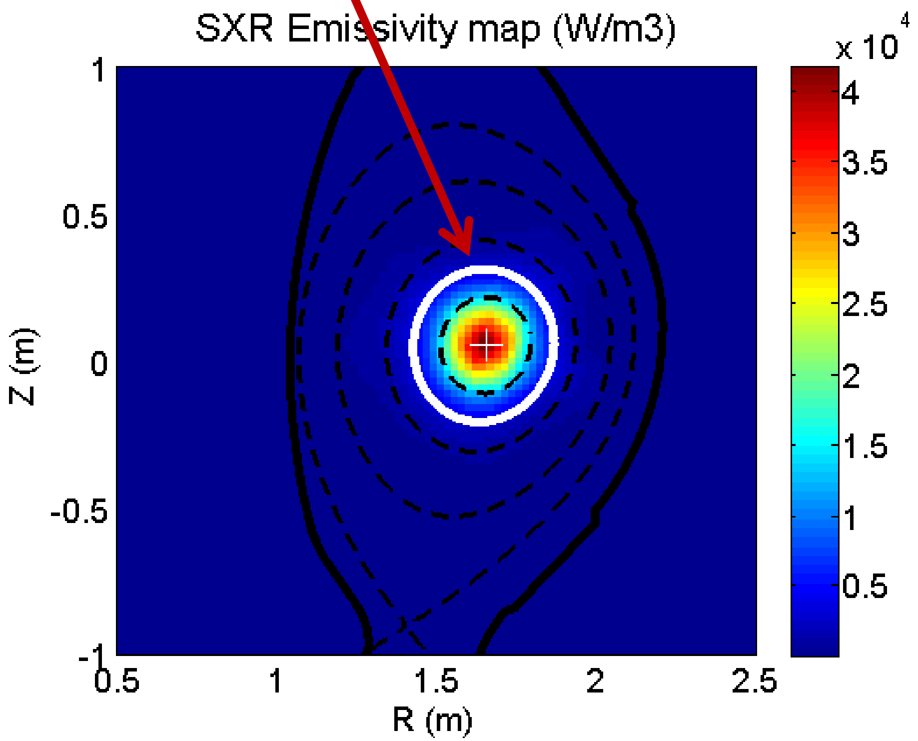
- ☐ Fusion Energy & recent results (NIF, JET)
- ☐ The tokamak concept
- ☐ Radiation of high-Z impurities
- ☐ **X-ray tomography for monitoring impurity transport**
  - **Soft X-ray tomography**
  - Impact of heating systems on impurity distribution
  - Prospect for real-time control

Soft X-ray plasma tomography

- ❑ Soft X-rays (SXR) in the energy range 0.1 keV – 20 keV can provide valuable information, through 2D tomography, on:
  - **<u>Impurity transport,</u>**
  - **Magnetohydrodynamic (MHD) activity,**
  - **Magnetic equilibrium.**
    (plasma positioning)

(e.g. sawtooth crash in ASDEX-U)





The SXR tomography problem

- ☐ Soft X-ray (SXR) tomography in tokamaks:

$$\mathbf{m} = \mathbf{T}.\boldsymbol{\varepsilon} + \tilde{\mathbf{m}}$$

measurement vector

Transfer matrix

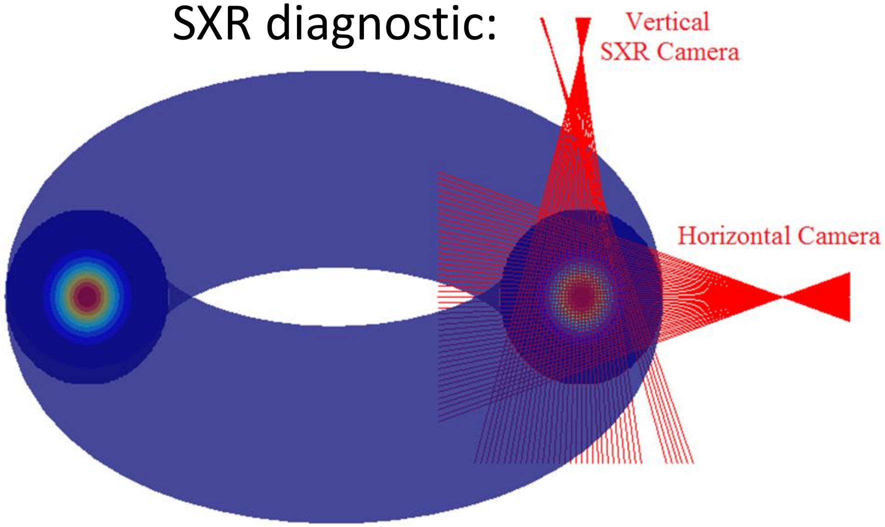
2D emissivity

noise

Recover 2D emissivity from line-integrated measurements, but:
→limited number of lines-of-sight + noise,
→ Mathematically ill-posed inversion problem:

$$\boldsymbol{\varepsilon} \xrightarrow{?} \cancel{\mathbf{T}}^{-1}.\mathbf{m}$$

Tore Supra
SXR diagnostic:



The SXR tomography problem

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→ Mathematically ill-posed inversion problem:

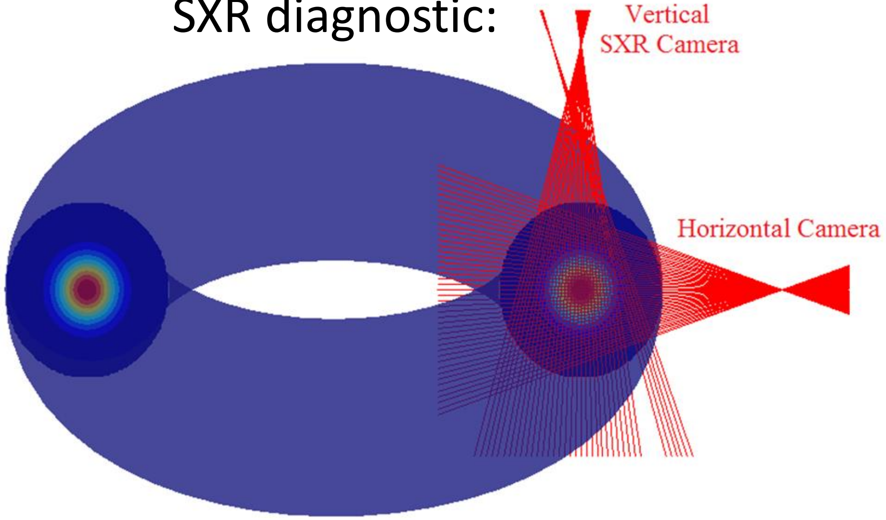
$$\boldsymbol{\varepsilon} \overset{?}{\rightarrow} \cancel{\mathbf{T}^{-1}}.\mathbf{m}$$

☐ *A priori* info required as additionnal constraint to regularize the inversion process:
→ Challenging task, benchmark needed to develop robust inversion algorithms

Tikhonov regularization: $\boxed{\boldsymbol{\varepsilon} = ({}^{\mathbf{t}}\mathbf{T}.\mathbf{T} + \boldsymbol{\lambda}\mathbf{H})^{-1}.{}^{\mathbf{t}}\mathbf{T}.\mathbf{m}}$

$\mathbf{H}$: regularization operator (impose smoothness)
$\boldsymbol{\lambda}$: regularization parameter

Tore Supra SXR diagnostic:

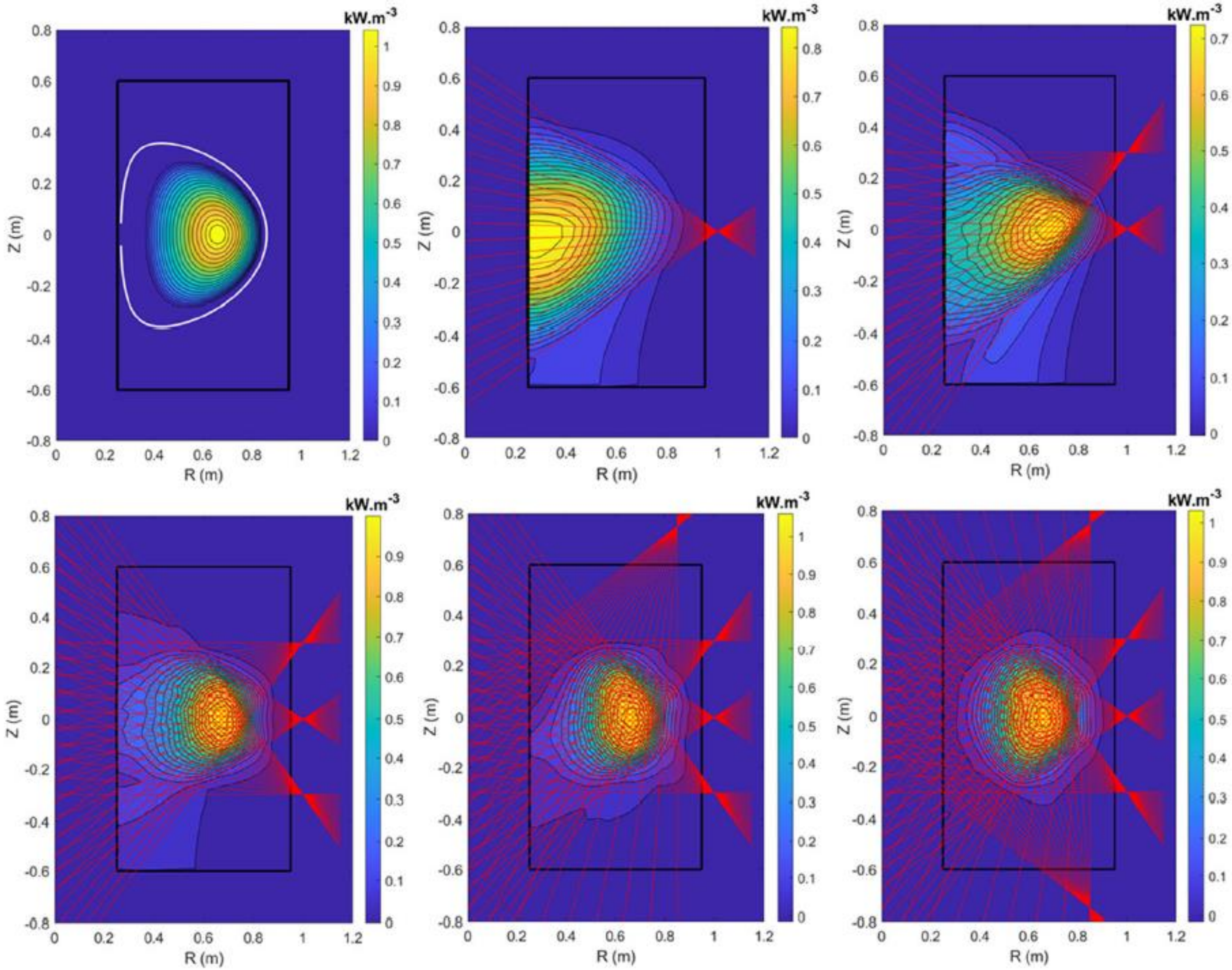


POLONIUM collaboration programme between Poland (IFJ PAN) & France (CEA)
<u>Project Leader</u>: Dr hab. J. Bielecki

[A. Jardin, D. Mazon and J. Bielecki, Phys. Scr. 91 (2016) 044007]

An example of reconstruction

- ☐ A generic example with an increasing number of cameras: [A. Jardin et al., EPJP 2021]



❑ Fusion Energy & recent results (NIF, JET)

❑ The tokamak concept

❑ Radiation of high-Z impurities

❑ X-ray tomography for monitoring impurity transport

  - Soft X-ray tomography
  - **Impact of heating systems on impurity distribution**
  - Prospect for real-time control

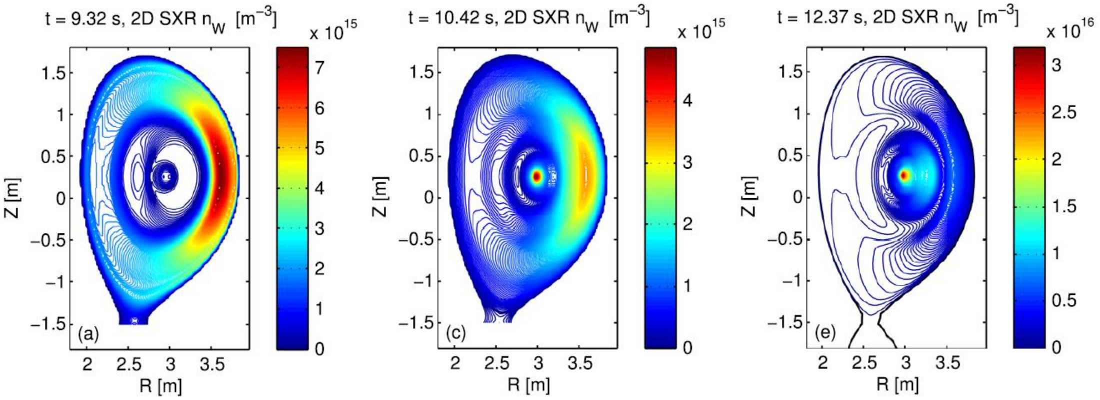
Impurity poloidal asymmetries

☐ Impurity force balance equation on a magnetic flux surface:

$$\underbrace{\frac{m_z n_z \omega^2}{2}\nabla_\| R^2}_{\text{inertia (centrifugal)}} + \underbrace{Z n_z e \nabla_\| \Phi}_{\text{electrostatic}} + \underbrace{T_z \nabla_\| n_z}_{\text{pressure}} = \underbrace{R_{z,\|}}_{\text{friction}}$$

[Reinke PPPL Seminar 2015]

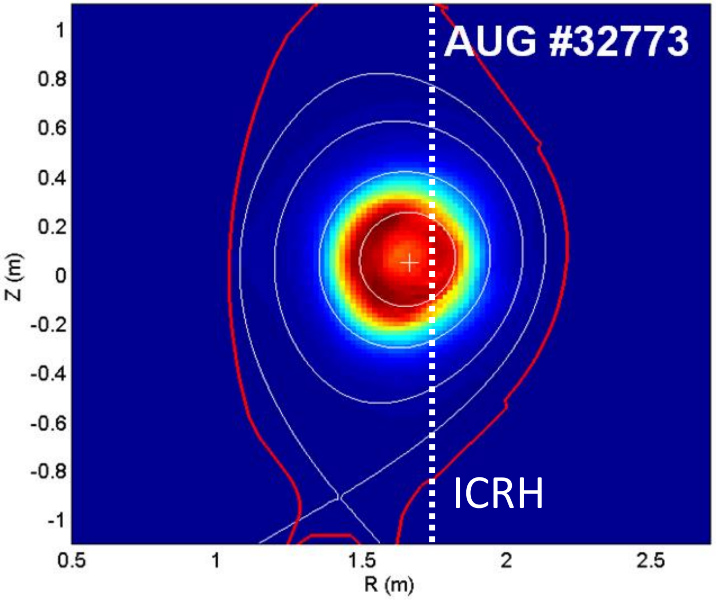
Neutral Beam Injection (NBI):



W 2D density distribution evolution with 17 MW of NBI (JET #83351)

[C. Angioni et al., PoP 2015]

Ion Cyclotron Resonance Heating (ICRH)



Tokamak experiments (EUROfusion)

Investigations of the impact of heating schemes and poloidal asymmetries on the heavy impurity transport in AUG and TCV

EUROfusion

Work Package Tokamak Exploitation (WP-TE, RT01)

- Analysis of impurity injection experiments on **ASDEX-U (AUG)** and **TCV tokamaks**, in different plasma heating schemes and plasma (D/He) composition [1].
- Impurity distribution reconstructed by **soft X-ray (SXR) tomography**. Prediction of power deposition and impurity asymmetry thanks to **TORIC-SSFPQL** [2] modeling.
- **AUG**: Higher W content and stronger SXR asymmetry in the helium discharge wrt. deuterium, confirmed by SXR and from the numerical model. ***Prospect:*** *estimate W transport coefficients and correlate them with the level of impurity asymmetry.*
- **TCV**: A transient up-down asymmetry was observed on TCV after impurity gas puff. Use of the code developed in [4] to study up-down impurity asymmetry due to friction forces on TCV is foreseen.

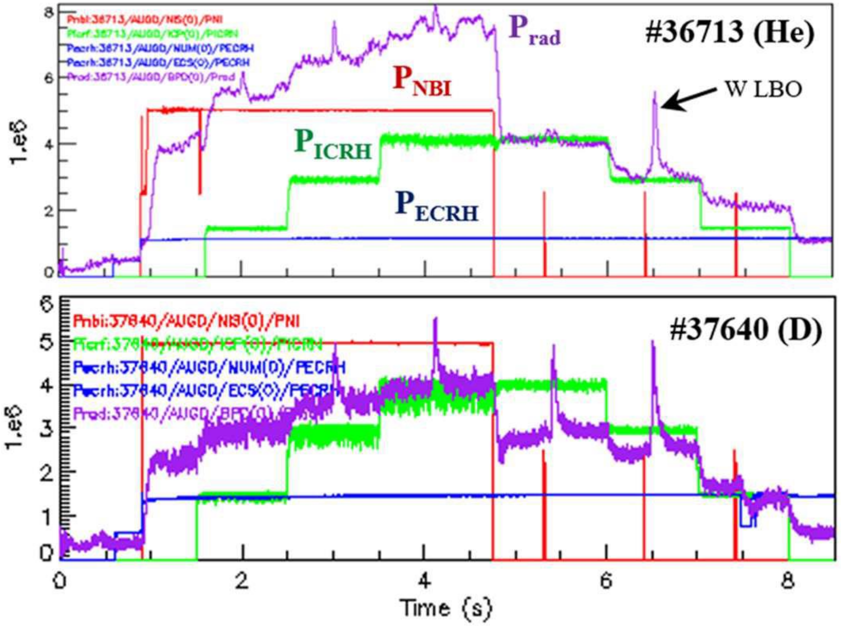


Figure. *W impurity transport experiments on AUG*

[1] WP-TE RT01, EUROFusion wiki. https://wiki.euro-fusion.org/wiki/RT01_2021_reports

[2] R. Bilato et al., Nucl. Fusion 51 (2011) 103034.

[3] A. Jardin et al., 47th EPS Conference on Plasma Physics (2021) P3.1065.

[4] P. Maget et al, Plasma Phys. Control. Fusion 62 (2019) 025001

THE HENRYK NIEWODNICZAŃSKI
INSTITUTE OF NUCLEAR PHYSICS
POLISH ACADEMY OF SCIENCES

IPP Max-Planck-Institut für Plasmaphysik

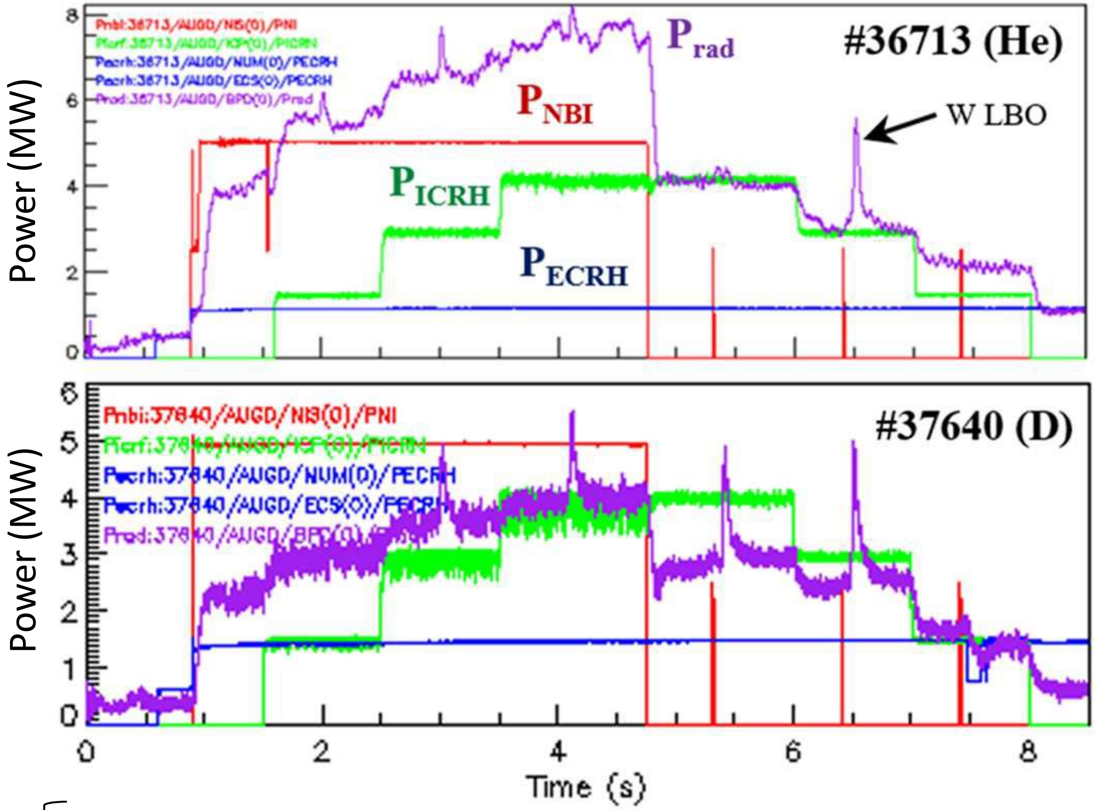
EPFL ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

SWISS PLASMA CENTER

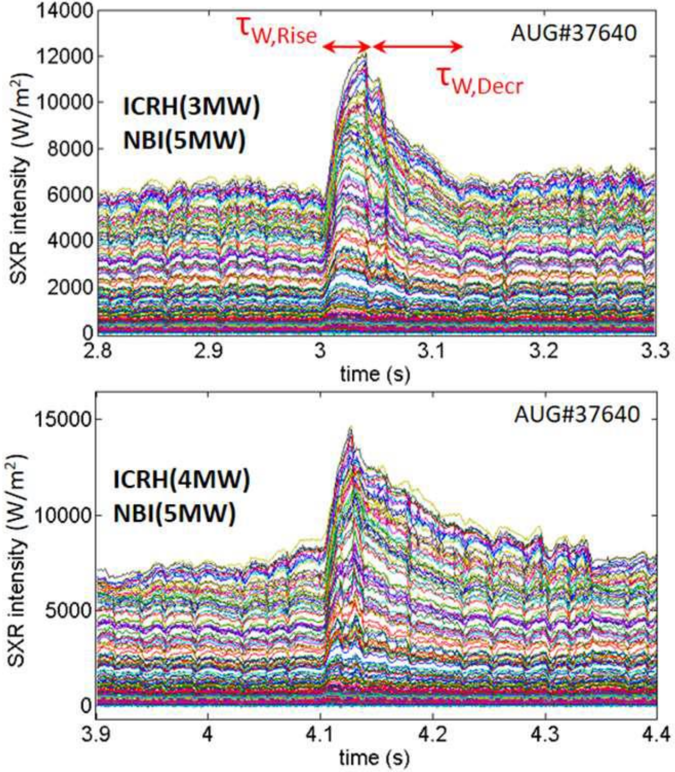
ASDEX-U experiments

- ☐ **ASDEX-U** plasma discharges in helium (He) and deuterium (D) plasmas:

Time traces of ECRH, ICRH, NBI and radiated powers (AUG)



SXR time traces, AUG #37640

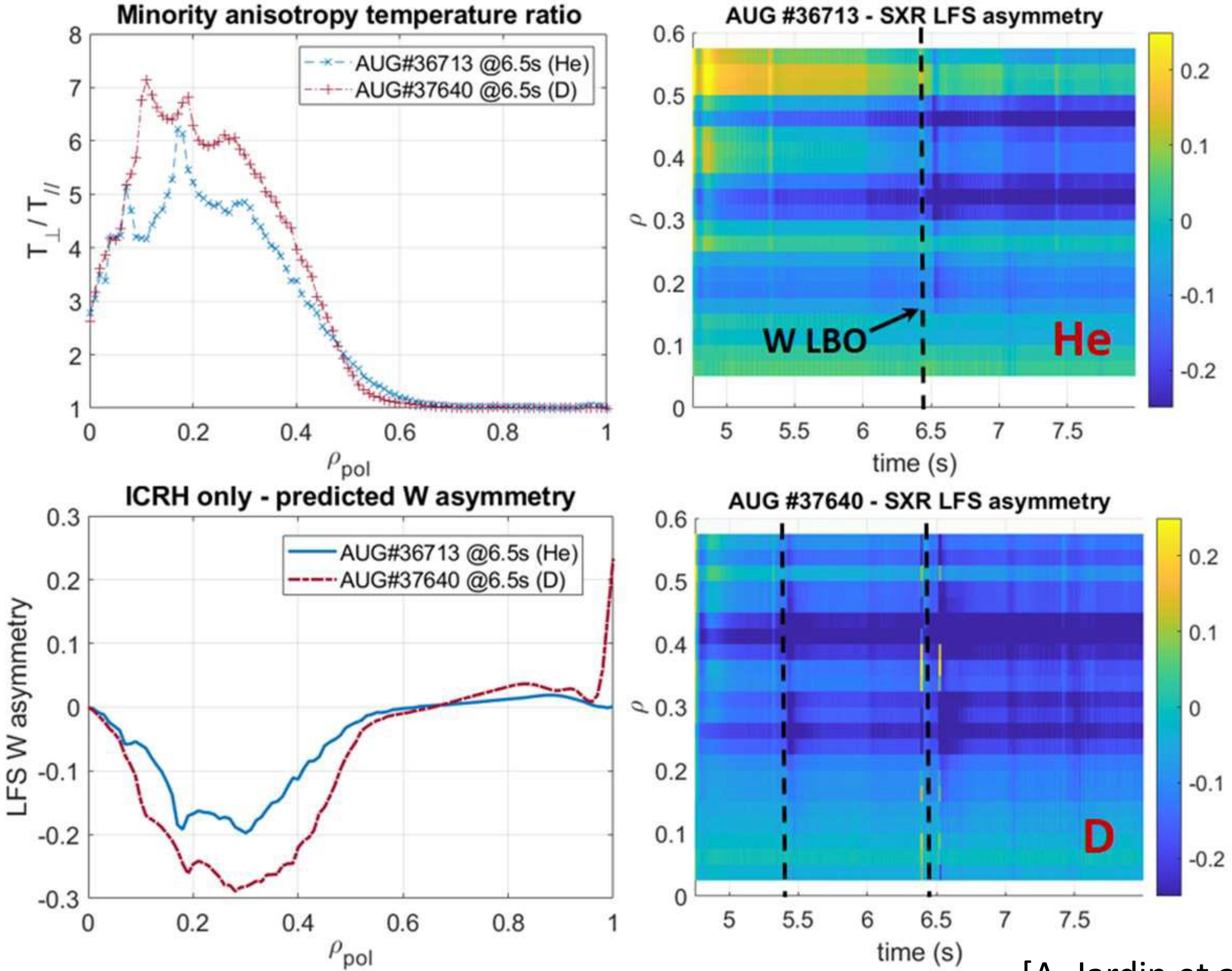


P_{rad} : Radiated power (MW)
ICRH : Ion Cyclotron Resonance heating (MW)
NBI : Neutral Beam Injection (MW)
ECRH: Electron Cyclotron Resonance Heating (MW)

[A. Jardin et al., EPS 2021]

ASDEX-U experiments

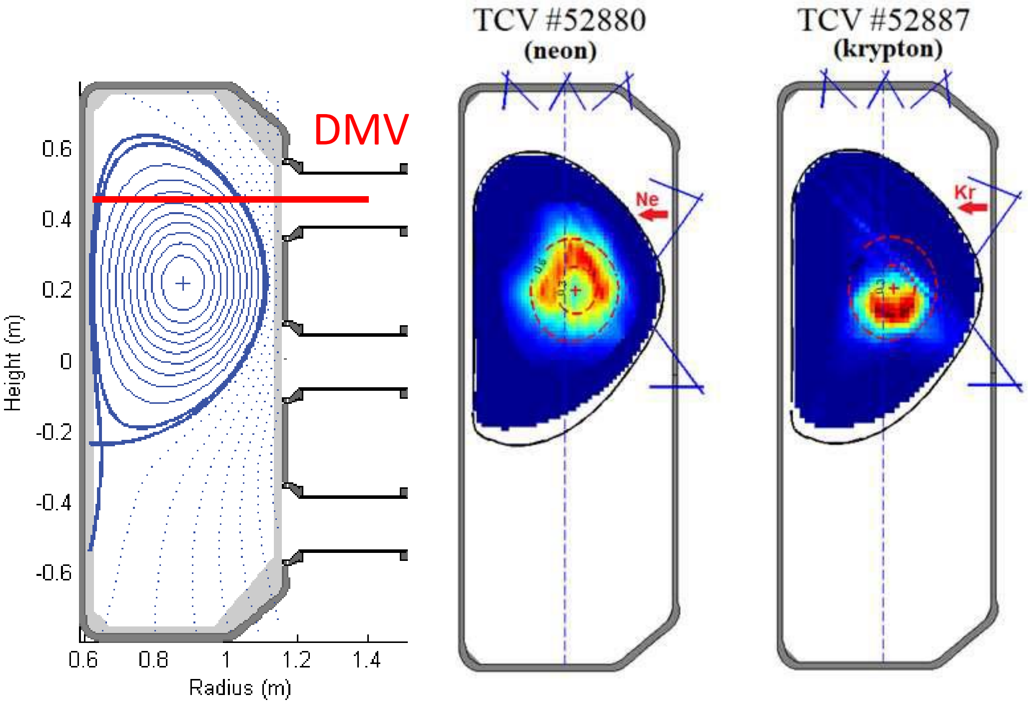
- ❑ ICRH-induced asymmetry in helium (He) and deuterium (D) plasmas:



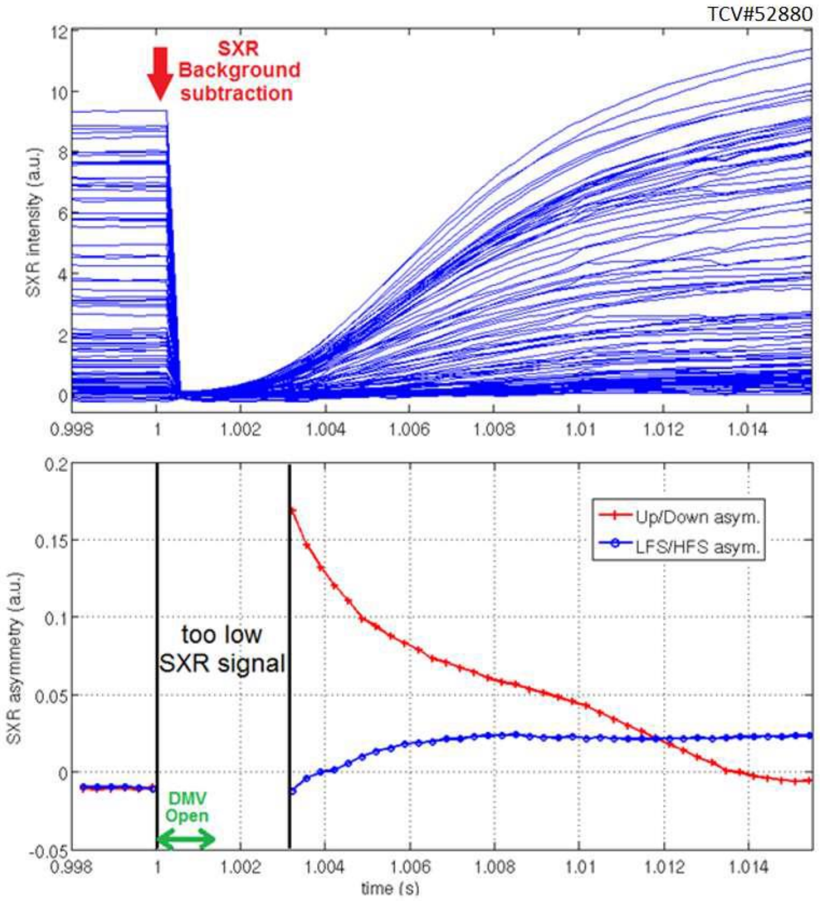
[A. Jardin et al., EPS 2021]

Tokamak a Configuration Variable (TCV)

- **TCV**: transient up-down SXR asymmetry observed on TCV after impurity gas puff using the disruption mitigation valve (DMV).



Time traces of SXR channels brightness



→ Potential impact of asymmetries on the radial influx of impurities?

→ Studies foreseen to investigate the effect of friction forces.

[P. Maget et al, Plasma Phys. Control. Fusion 62 (2019) 025001]

☐ Fusion Energy & recent results (NIF, JET)

☐ The tokamak concept

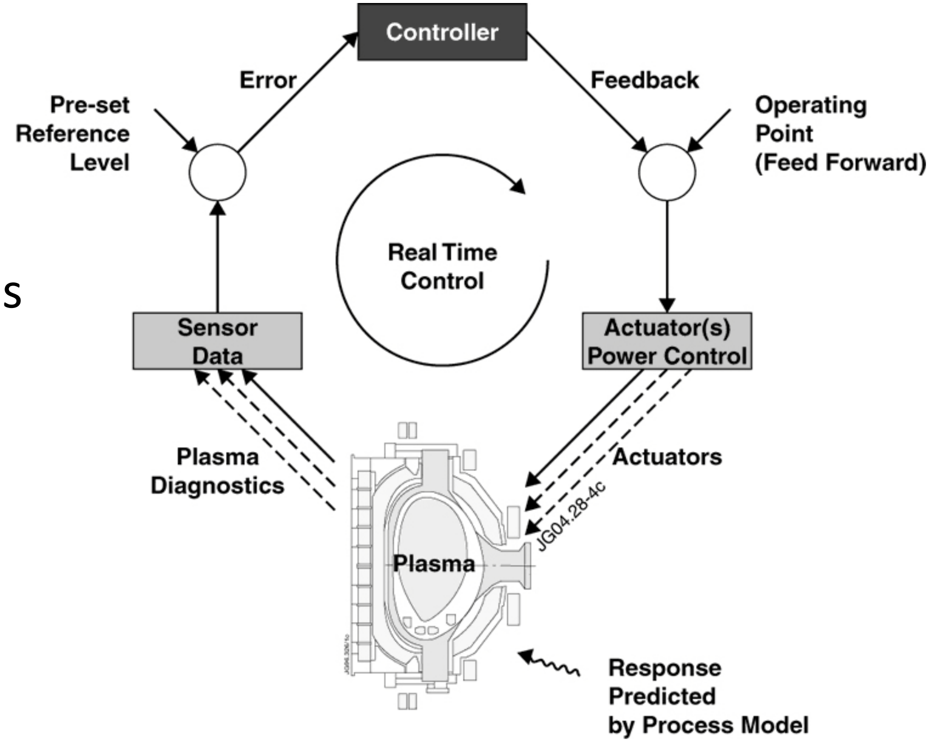
☐ Radiation of high-Z impurities

☐ X-ray tomography for monitoring impurity transport
  - Soft X-ray tomography
  - Impact of heating systems on impurity distribution
  - **Prospect for real-time control**

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)…

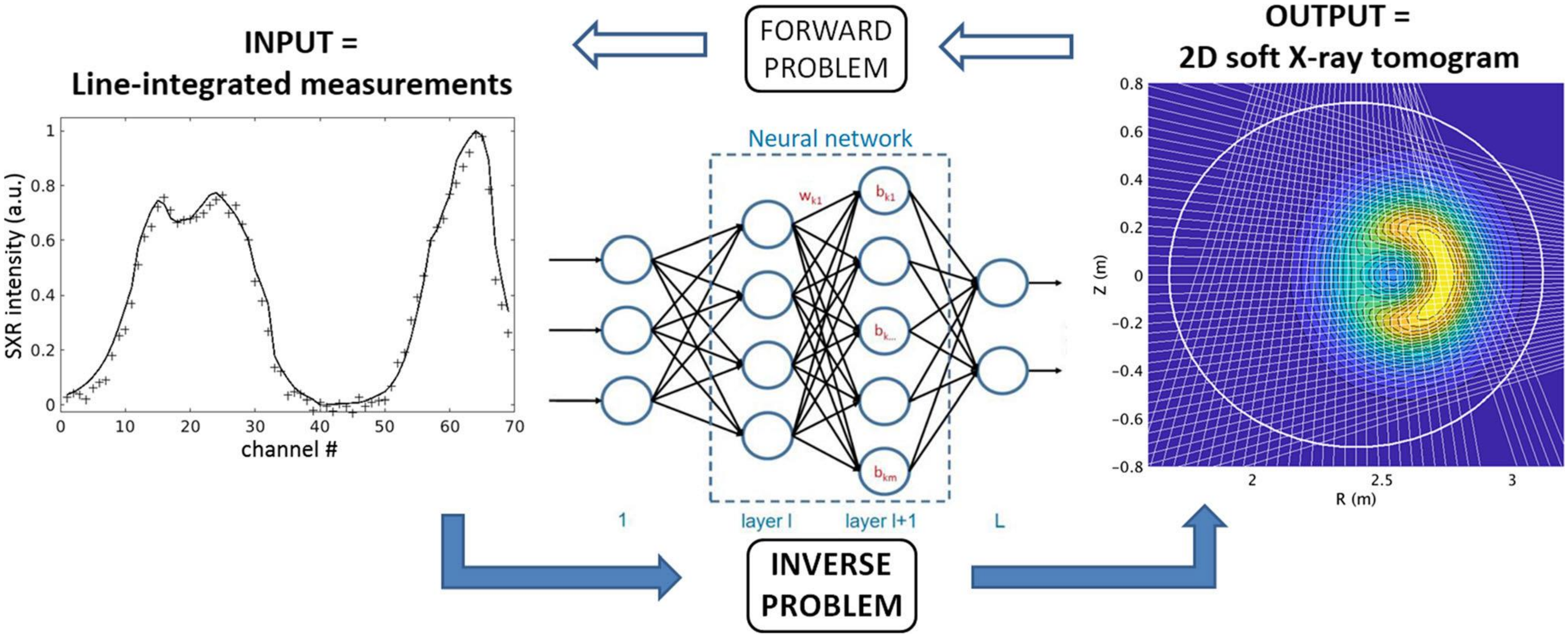


→ Possibility of real-time X-ray tomography?

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.



INPUT =
Line-integrated measurements

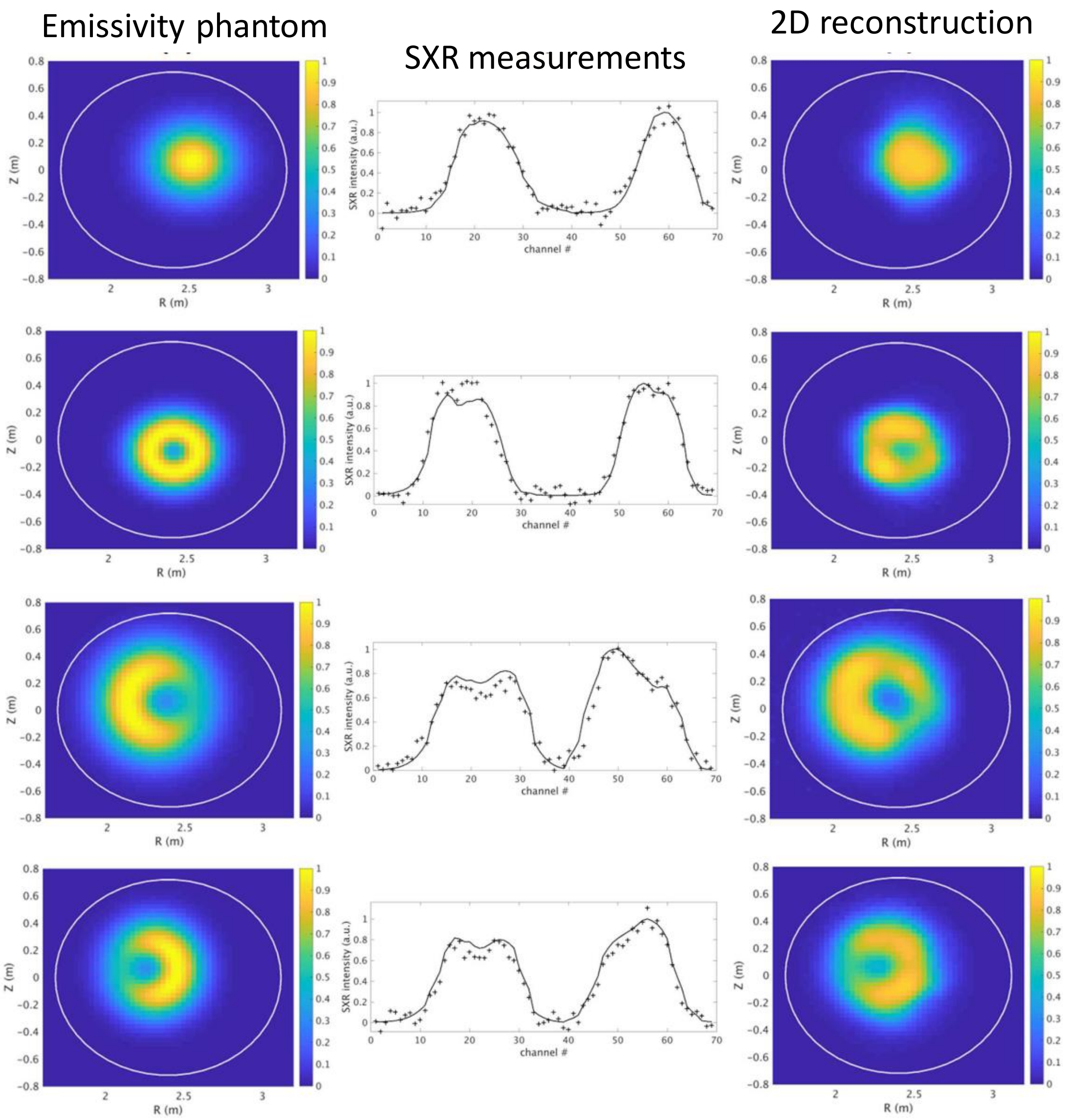
FORWARD PROBLEM

OUTPUT =
2D soft X-ray tomogram

INVERSE PROBLEM

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

Neural networks tests with artificial data

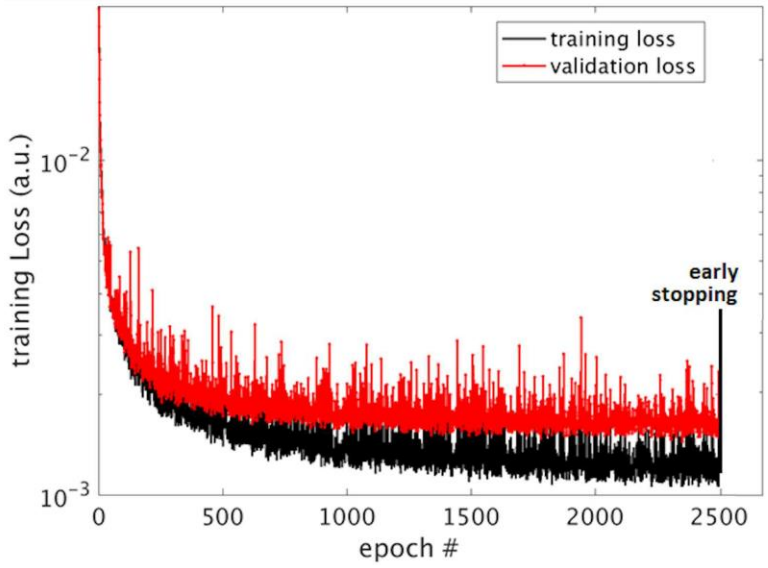

Emissivity phantom

SXR measurements

2D reconstruction

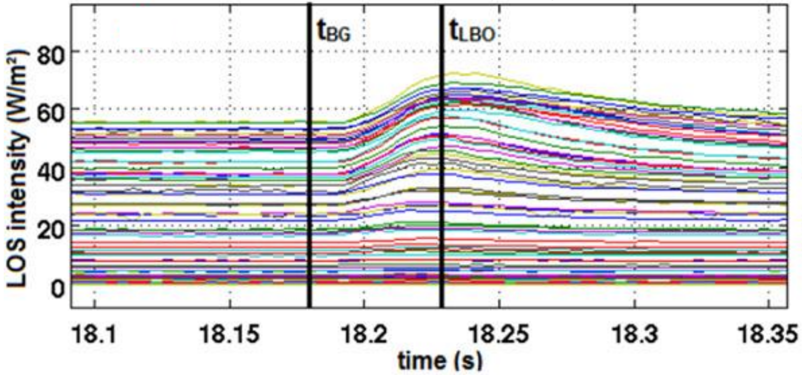
- Large training database to optimize the network parameters ($\vec{w}, b$)
- Minimization of a Cost Function (MSE) with stochastic gradient-descent method:

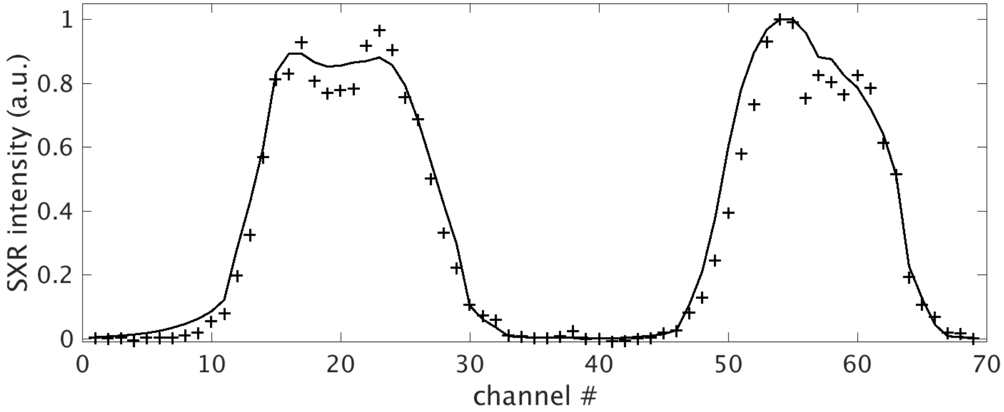
$$C(\vec{w},b)=\frac{1}{2n}\sum_{x}[\underbrace{y(x)}_{\text{desired output}}-\underbrace{a(x,\vec{w},b)}_{\text{output from the network}}]^2$$

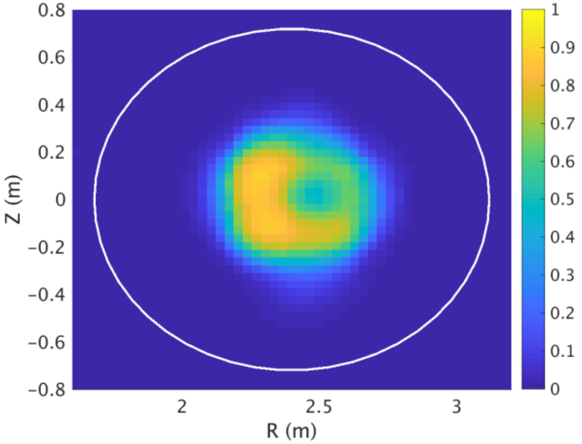


Neural networks experimental test

- ☐ <u>Controlled injection of tunsgen impurities in Tore Supra:</u>


SXR time traces – Tore Supra #46564


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

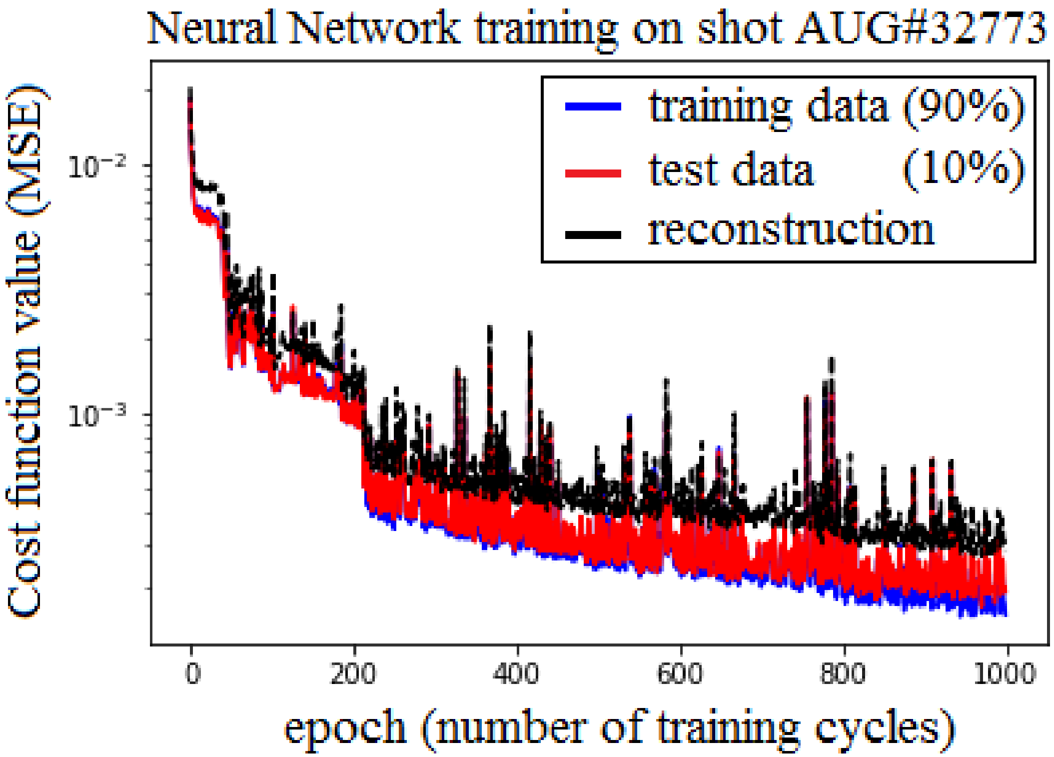

Tomography by neural network

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

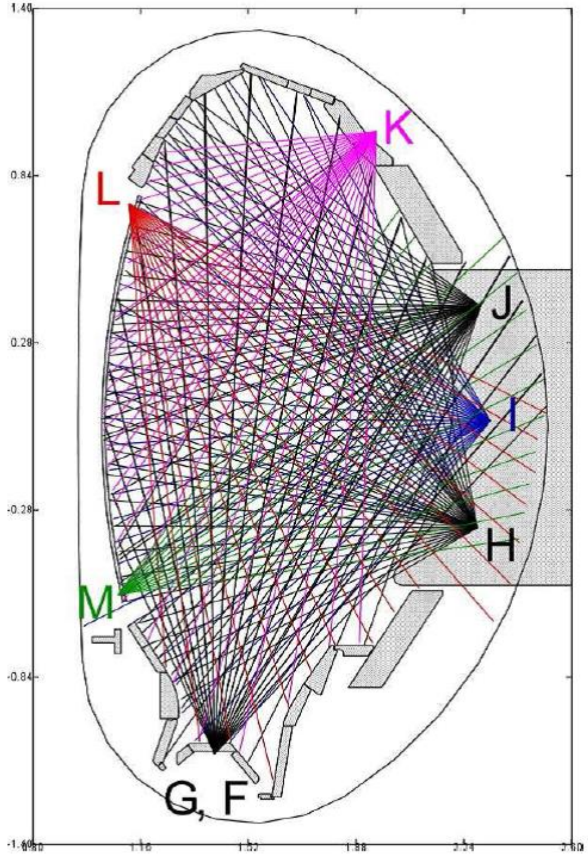
[A. Jardin, J. Bielecki, M. Scholz et al, Acta Phys. Pol. A, 138 (2020) 626-631]

Neural Network training on ASDEX-U (AUG)

- **ASDEX-U discharge AUG#32773**
  → 1st half of discharge used to reconstruct the second half.



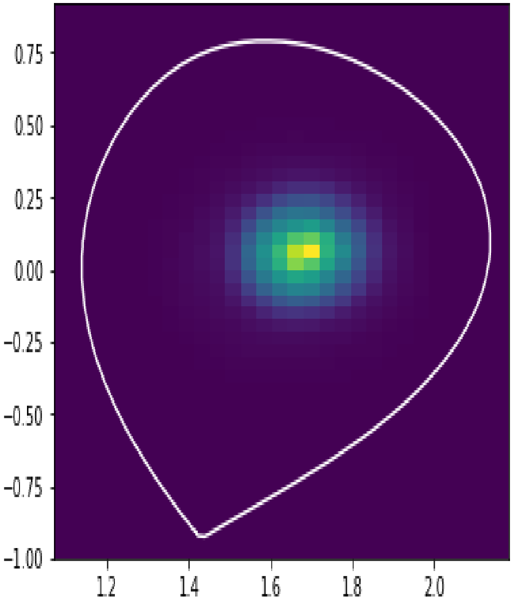
AUG SXR diagnostic

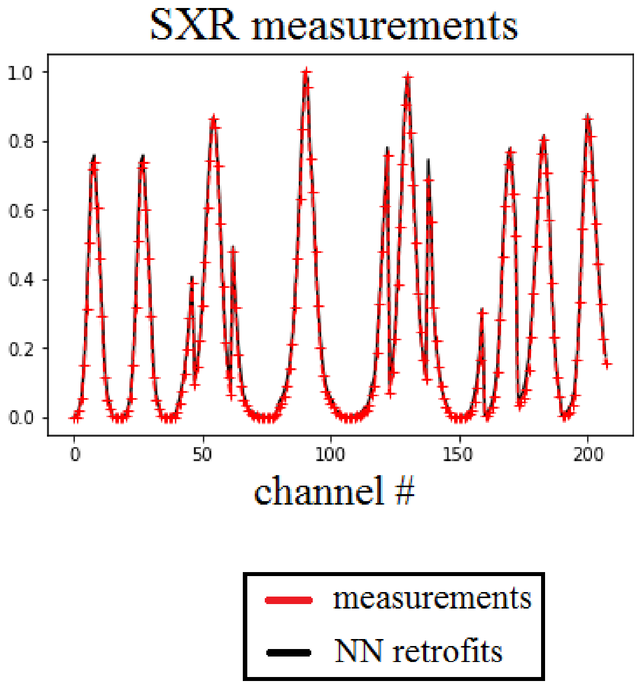


Neural Network – SXR reconstruction

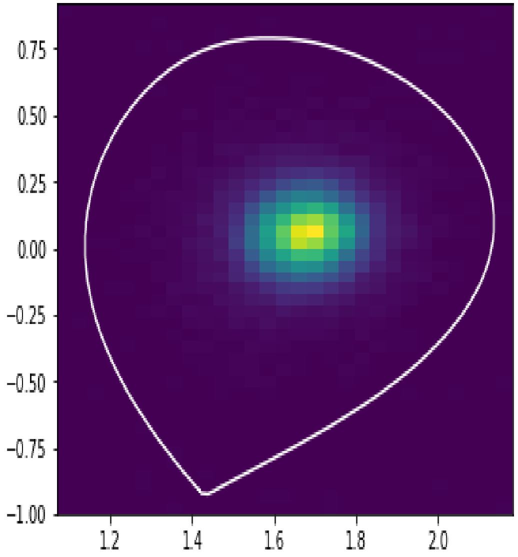
❑ First typical case, peaked distribution → reconstruction OK

Original tomogram





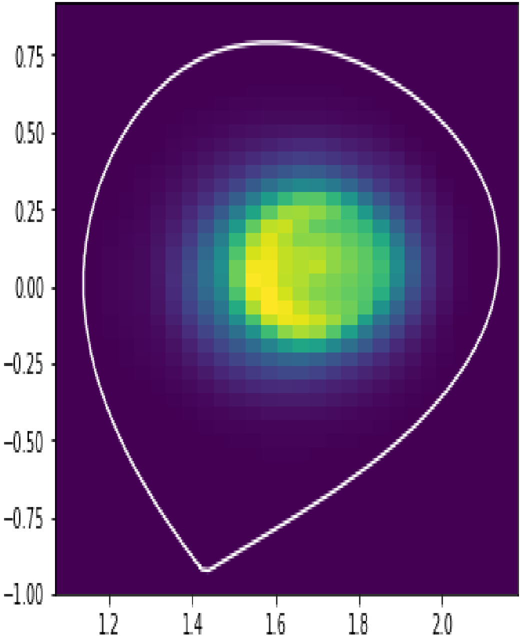
Neural network

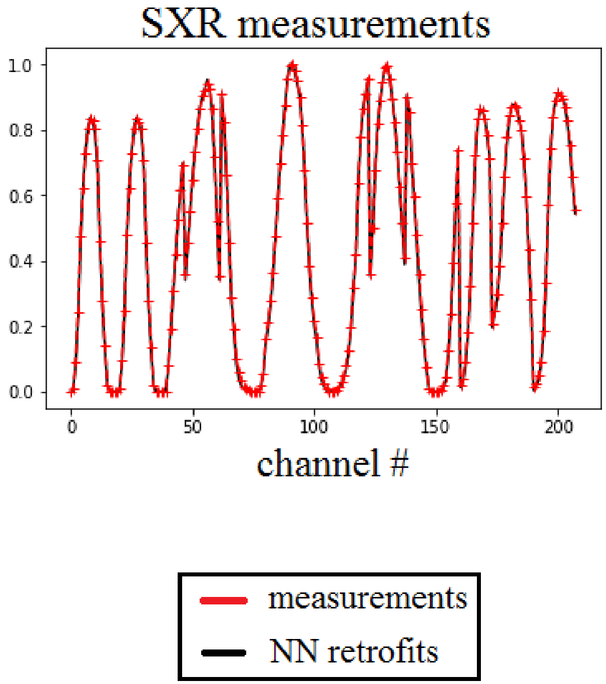


Neural Network – SXR reconstruction

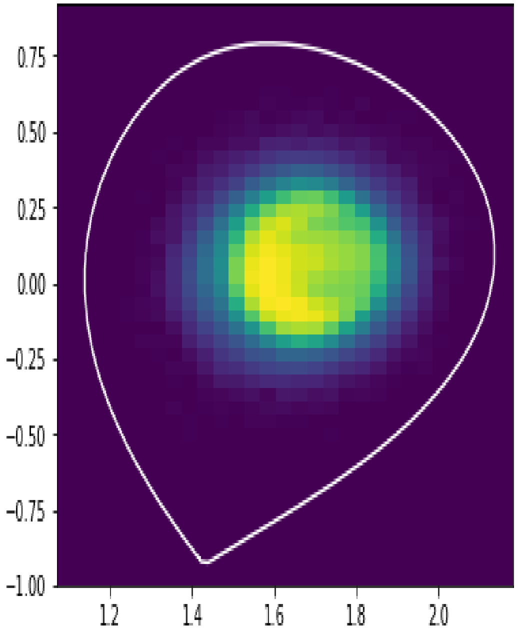
- Second case, HFS asymmetry → reconstruction OK

Original tomogram





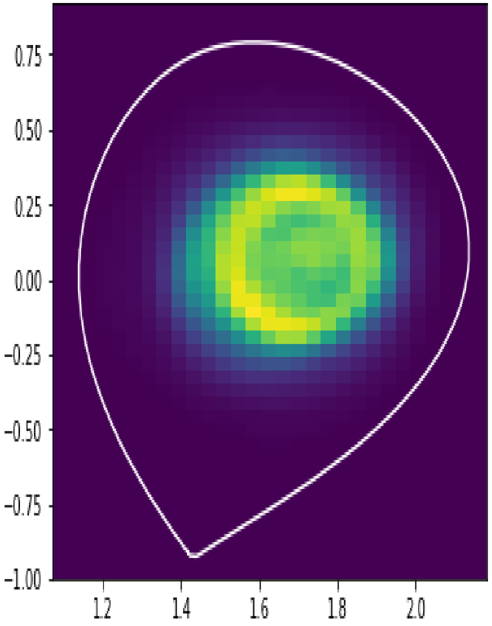
Neural network

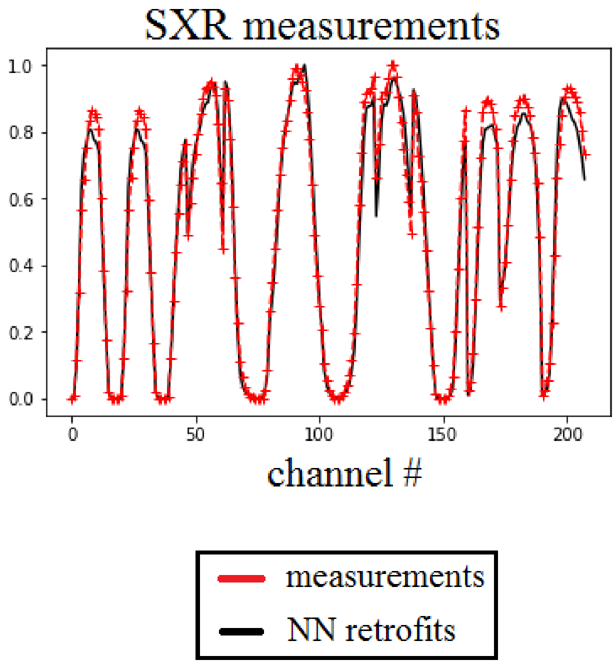


Neural Network – SXR reconstruction

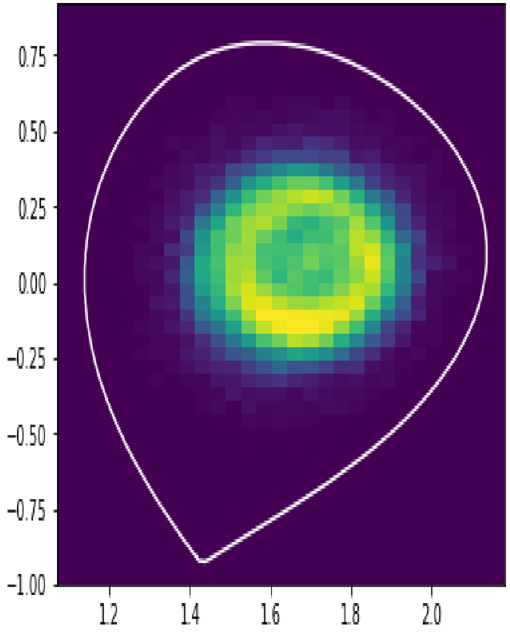
❑ Third case, hollow profile with weak HFS asymmetry
→ <u>reconstruction:</u> hollow shape OK, mismatch in poloidal distribution.

Original tomogram





Neural network



<u>Perspective</u>: use convolutional layers more adapted for image processing, instead of full-connected neuron layers.

Publications

A. Jardin, J. Bielecki, D. Mazon, Y. Peysson, K. Król, D. Dworak and M. Scholz, *Implementing an X-ray tomography method for fusion devices*, Eur. Phys. J. Plus (2021) 136:706, doi: 10.1140/epjp/s13360-021-01483-z

A. Jardin, J. Bielecki, D. Mazon, J. Dankowski, K. Król, Y. Peysson, M. Scholz, *Synthetic X-ray Tomography Diagnostics for Tokamak Plasmas*, J. Fusion Energ., 39 (2020) 240–250, doi: 10.1007/s10894-020-00250-9

A. Jardin, J. Bielecki, D. Mazon, J. Dankowski, K. Król, Y. Peysson, M. Scholz, A. Kulińska, Ł. Marciniak, *X-Ray and Neutron Tomography of Thermonuclear Plasmas*, Acta Phys. Pol. A, 138 (2020) 626-631, doi: 10.12693/APhysPolA.138.626

A. Jardin, J. Bielecki, D. Mazon, J. Dankowski, K. Król, Y. Peysson, M. Scholz, *Neural networks: from image recognition to tokamak plasma tomography*, Laser Part. Beams, 37 (2019) 171-175, doi: 10.1017/S0263034619000296

A. Jardin, D. Mazon, F. Jaulmes, R. Bilato, C. Angioni, K. Król, D. Colette, G. Vogel, ASDEX Upgrade Team, TCV Team, and EUROfusion MST1 Team, *Investigations of the impact of heating schemes and poloidal asymmetries on the heavy impurity transport in AUG and TCV*, proceedings of the 47th EPS Conference on Plasma Physics, P3.1065, June 2021. http://ocs.ciemat.es/EPS2021PAP/pdf/P3.1065.pdf

J. Bucalossi (A. Jardin) et al., Operating a full tungsten actively cooled tokamak: overview of WEST first phase of Operation, Nucl. Fusion 62 (2022) 042007
H. Meyer (A. Jardin) et al., Overview of physics studies on ASDEX Upgrade, 2019 *Nucl. Fusion* 59 112014.
S. Coda (A. Jardin) et al., Physics research on the TCV tokamak facility: from conventional to alternative scenarios and beyond, 2019 *Nucl. Fusion* 59 112023.

J. Walkowiak, A. Jardin, J. Bielecki, Y. Peysson, D. Mazon, D. Dworak, K. Krol, and M. Scholz, *Approximate atomic models for fast computation of the Fokker–Planck equation in fusion plasmas with high-Z impurities and suprathermal electrons*, Phys. Plasmas 29, 022501 (2022)

K. Król, (A. Jardin) et al, *Impact of partial screening effect on fast electron dynamics in WEST tokamak plasmas with high Z impurities*, 47th EPS Conference on Plasma Physics, P2.1072, June 2021 http://ocs.ciemat.es/EPS2021PAP/pdf/P2.1072.pdf

Y. Peysson, D. Mazon, (A. Jardin, K. Król, J. Bielecki, D. Dworak, M. Scholz) et al, *Effect of partially ionized high-Z atoms on fast electron dynamics in tokamak plasmas*, IAEA FEC 2020 - The 28th IAEA Fusion Energy Conference, May 2021 https://hal.archives-ouvertes.fr/cea-03249410/

Y. Peysson, (K. Król, J. Bielecki, A. Jardin, M. Scholz, D. Dworak) et al., *Lower Hybrid Current Drive in High Aspect Ratio Tokamaks*, J. Fusion Energ., 39 (2020) 270–291, doi: 10.1007/s10894-020-00266-1

A. Jardin, J. Bielecki, K. Krol, Y. Peysson, D.Mazon, D. Dworak and M. Scholz, *Study of the mutual dependence between Lower Hybrid current drive and heavy impurity transport in tokamak plasmas*, 2020, IFJ Report No 2105/AP. https://www.ifj.edu.pl/badania/publikacje/raporty/2020/2105.pdf

D. Mazon (A. Jardin) et al., *First GEM measurements at WEST and perspectives for fast electrons and heavy impurities transport studies in tokamaks*, 2022 JINST 17 C01073

D. Colette, D. Mazon, R. Barnsley, A. Sirinelli, A. Jardin, M. O'Mullane, M. Walsh, *Modeling a low voltage ionization chamber based tomography system on ITER*, Rev. Sci. Instrum., 91 (2020) 073504, doi: 10.1063/1.5142909

Thank you for your attention