IAEA
International Atomic Energy Agency
Atoms for Peace and Development

Spectroscopic applications for plasma-wall interaction observations in fusion devices

Kalle Heinola

Joint ICTP-IAEA School on Atomic and Molecular Spectroscopy in Plasmas
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Outline

1. Introduction
   a) tokamak plasma-wall interactions
   b) diagnostic tools

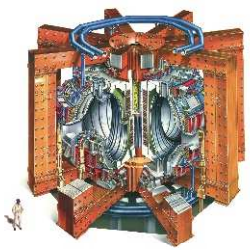
2. Spectroscopic applications in plasma edge
   a) erosion of Be wall material
   b) material migration
   c) plasma-induced erosion of W

3. Divertor spectroscopy and ELMs
   a) ELM-induced erosion of W
   b) plasma-material interactions and ELMs
   c) fuel retention and effect of ELMs

1.a tokamaks and PWI

- present day fusion devices to study plasma properties & plasma-wall interactions (PWI): plasma-surface (PSI) & plasma-material interactions (PMI)
  - experimental results transferred/extrapolated to larger devices
  - plasma power and intensity of PWIs increase with machine size
    - modelling & simulations play a crucial role
    - models to cope with DEMO & Fusion Power Plant conditions
    - plasma physics (A+M data!) and materials science

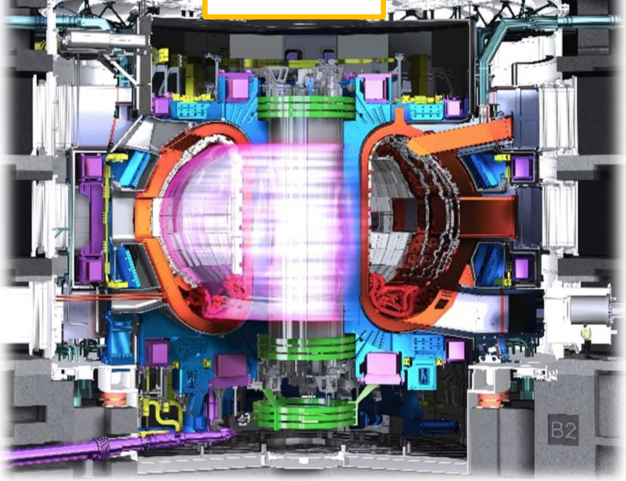
JET



plasma
pulse: few secs to tens secs
volume: 100 m^3
fusion P: 16 MW (Q~0.67)
n damage: <<1 dpa
particle fluence: ~10^{24} m^{-2}

experiments, modelling

ITER

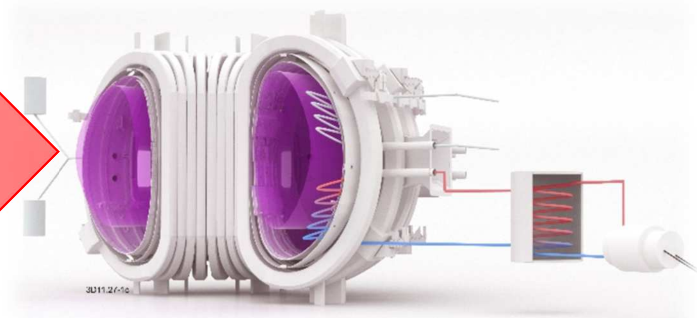


pulse: 400 sec
volume: 840 m^3
power: 500 MW (Q≥10)
n damage: < 2 dpa
particle fluence: ~10^{27} m^{-2}

experiments, modelling

presently only modelling

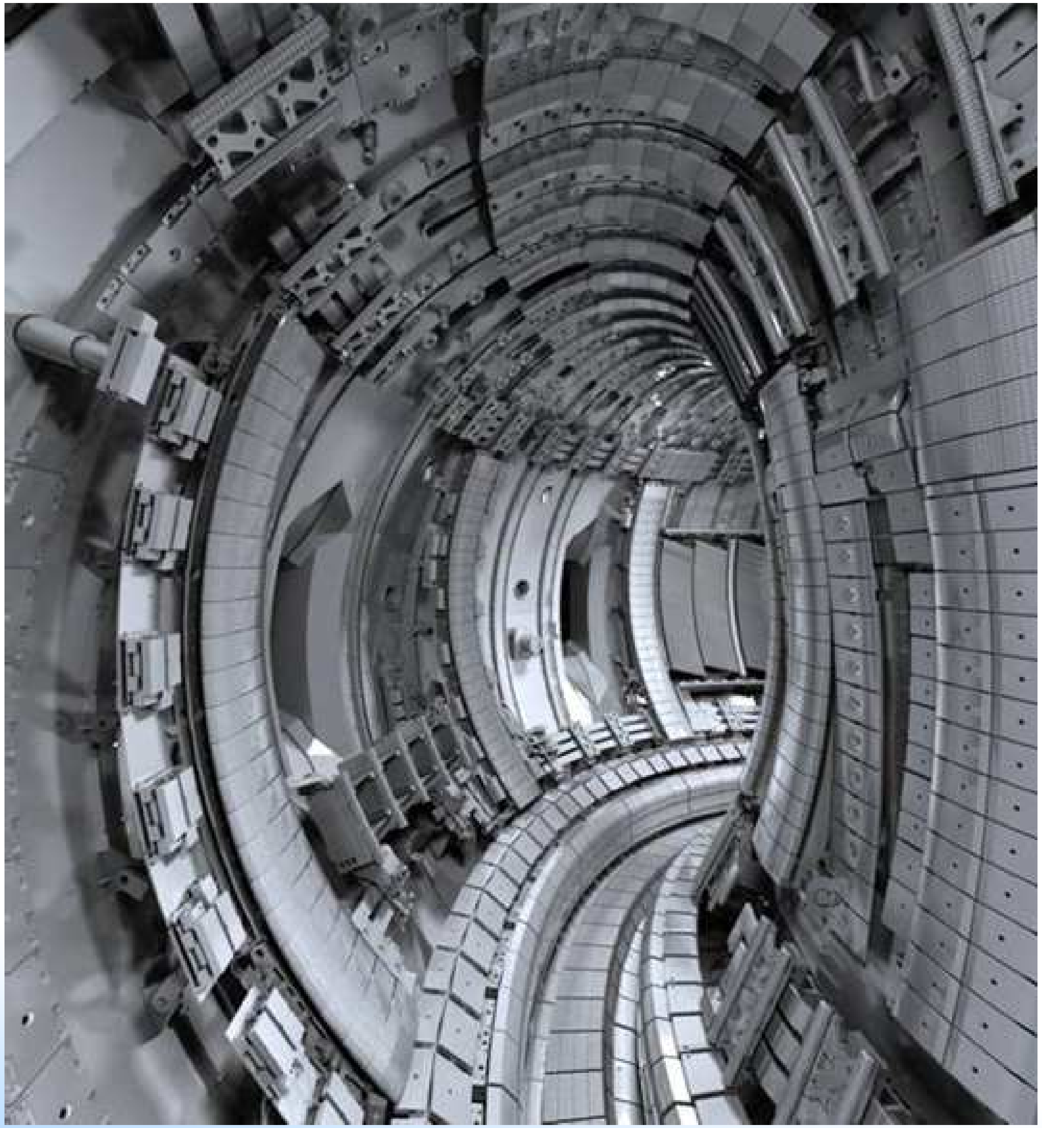
DEMO1

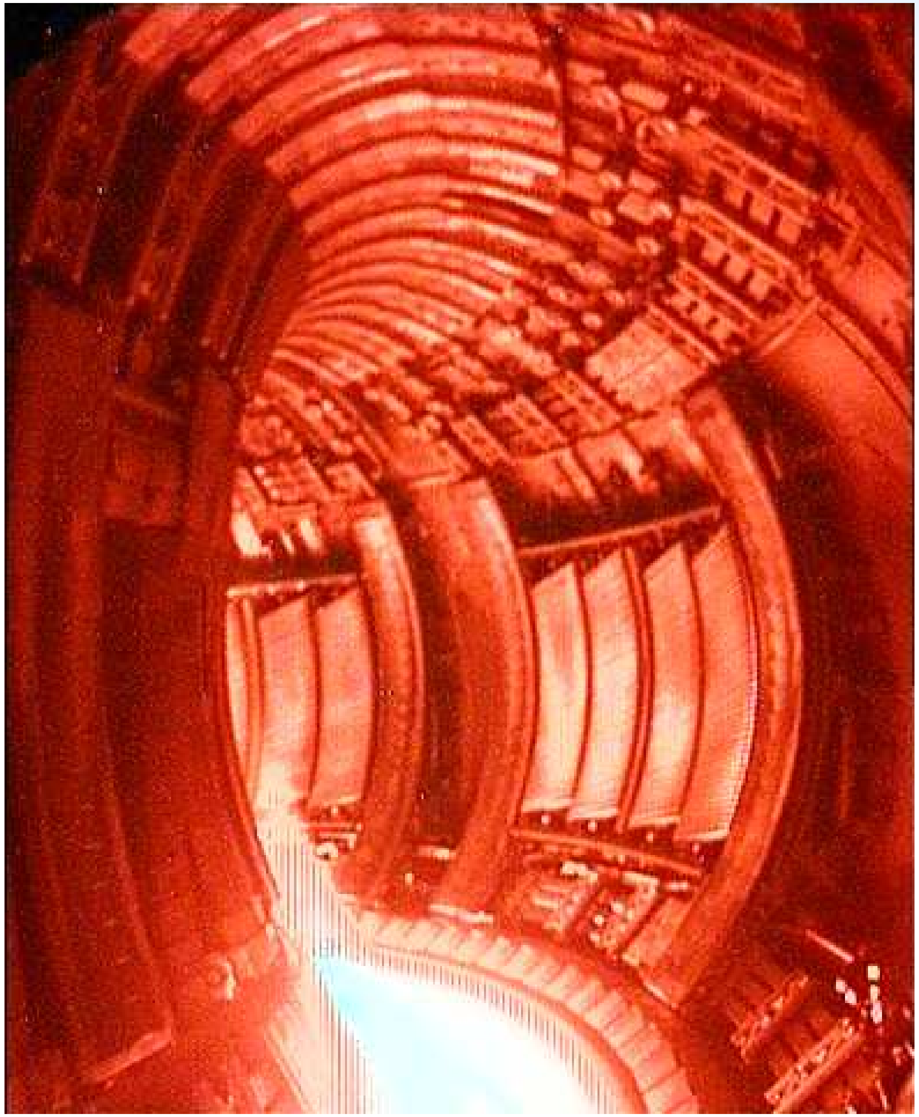


pulse: > 2 hours
volume: ~2500 m^3
power: 2200 MW (Q~30-50), grid 500 MW
n damage: up to 20-50 dpa
neutral particle fluence: ~10^{27} m^{-2}

1.a tokamaks and PWI

- plasma monitoring and control
  - plasma magnetically confined → drifts, etc → plasma-wall interactions (PWIs)





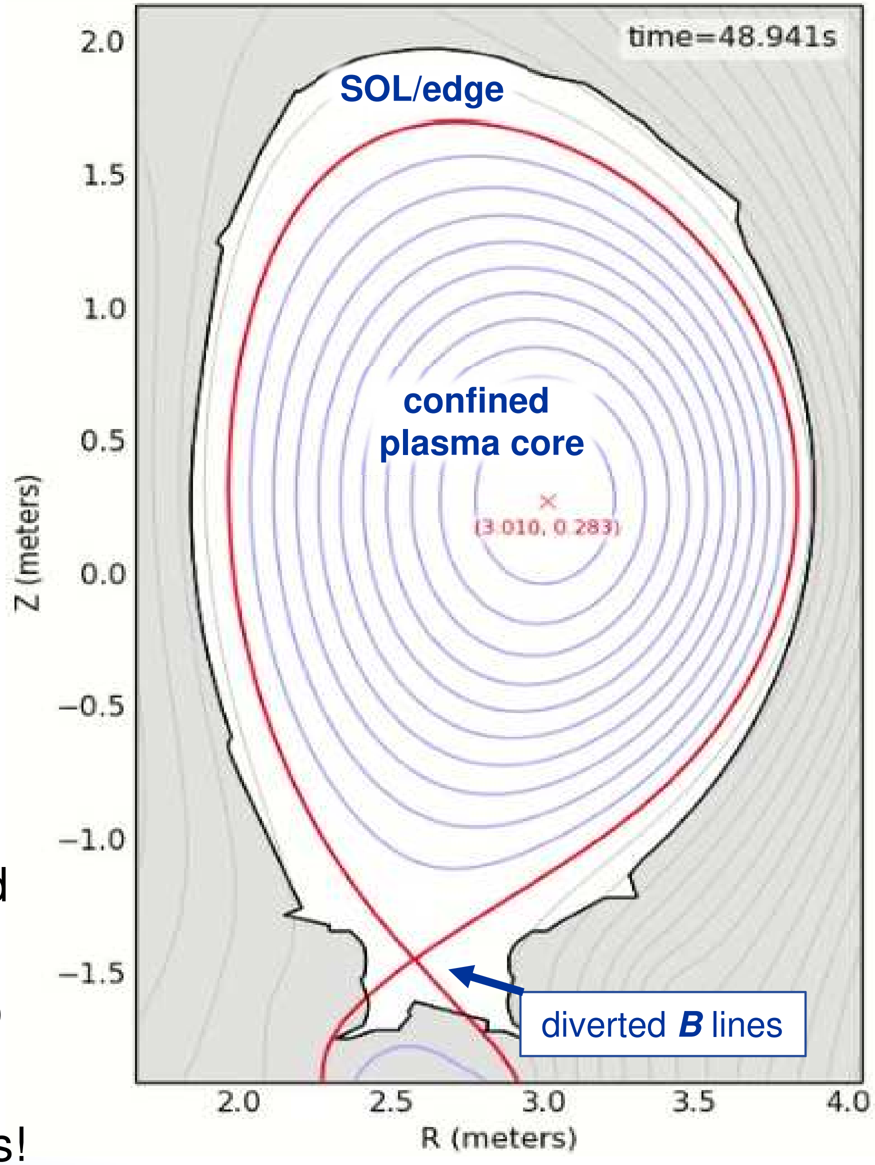
1.a tokamaks and PWI

- plasma monitoring and control
  - plasma magnetically confined → drifts, etc → plasma-wall interactions (PWIs)
  - distinguishable plasma regions:

1. core (closed ***B*** lines):
   - plasma particles confined with ***B***
   - ionized particles and *e*⁻ traverse on helical trajectories around torus
   - energy: up to tens keV
   - collision processes and fusion
   - monitoring of plasma shape, density, temperature, …

2. scrape-off layer (SOL; edge; open ***B*** lines):
   - region of plasma exhaust: particles escaped the core
   - energy: tens of eV (divertor: ELMs several keV)
   - monitoring density, temperature, …
   - interaction with the surrounding components!

Wall lifetime, fuel recycling & retention



1.b diagnostics: core

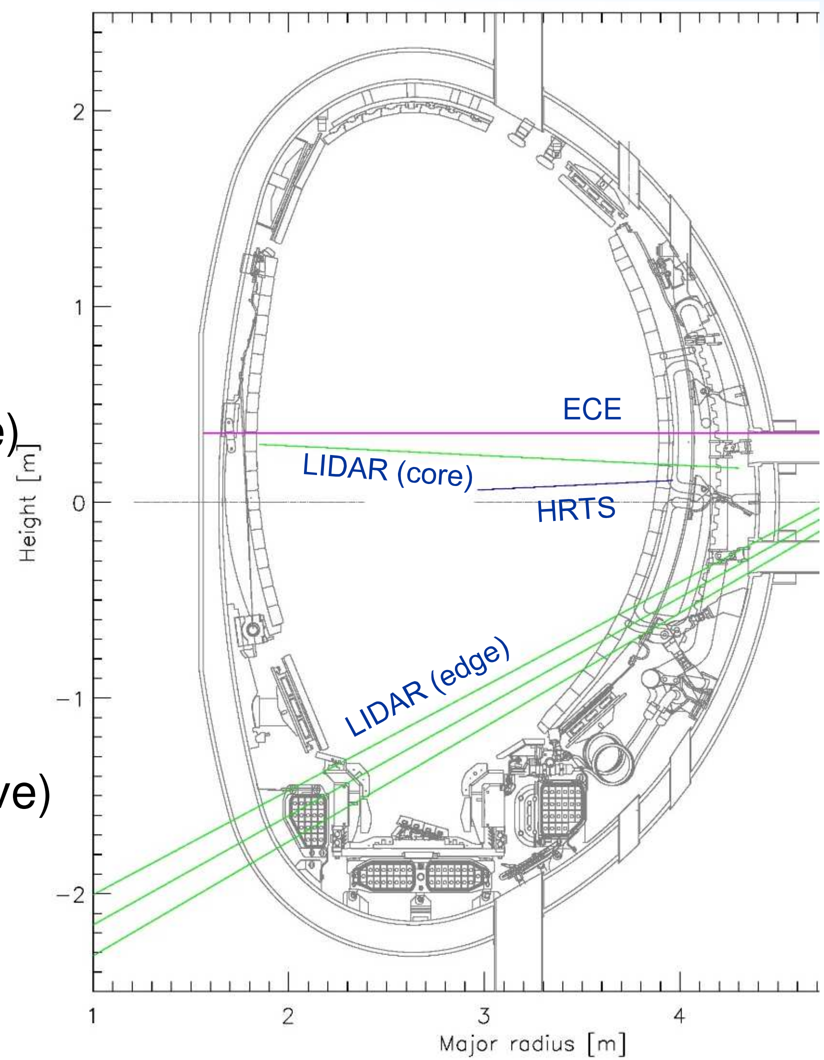
e.g. T_e , n_e in JET (core and edge):

ECE – Electron Cyclotron Emission
HRTS – High-Resolution Thomson Scattering
LIDAR – Light Detection and Ranging (Thomson)

- plasma core
  - several plasma parameters to be monitored
    - ✓ particle temperatures T_i , T_e
    - ✓ particle densities n_i , n_e
    - ✓ plasma shape, flows, and fluctuations

    …
  - tens of plasma diagnostics (active and passive)
    - ✓ T_i , n_i : radiation emitted in charge-exchange (CX) processes with injected neutral plasma particles; radiation emission collisions as *X*-rays, γ-rays
    - ✓ T_e , n_e : Thomson scattering (laser); electron cyclotron emission (ECE; passive)
    - ✓ radiated power: bolometers

    …



1.b diagnostics: SOL and wall

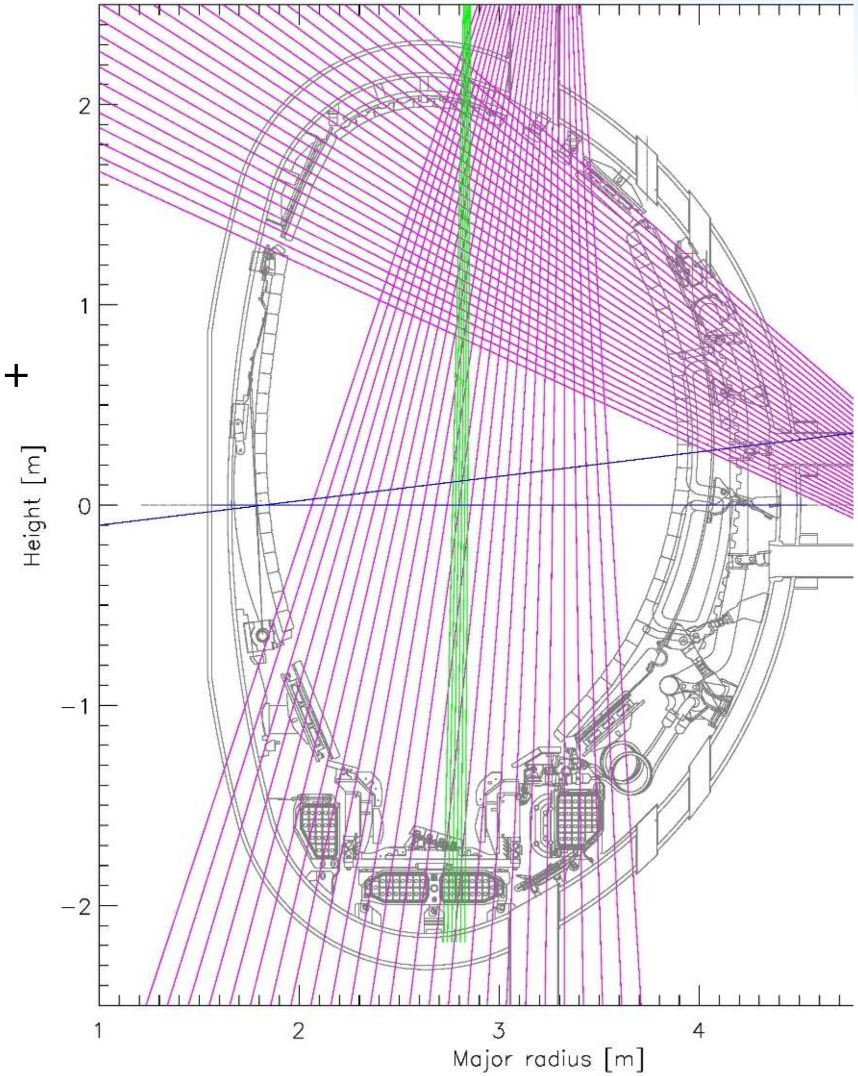
- plasma edge
  - monitoring of plasma SOL/edge and wall surface
    - particle temperatures T_i , T_e
    - particle densities n_i , n_e
    - properties in the main chamber and in the divertor box:
      - wall temperature
      - impinging particles (energies, flux)
      - erosion

    …

1.b diagnostics: SOL and wall

- plasma edge
  - monitoring of plasma SOL/edge and wall surface
  - edge plasma and wall diagnostics (active and passive)
    - ✓ spectroscopic measurements of particle + particle, particle + e^- , etc processes: XUV-VUV

e.g. JET various XUV-VUV spectroscopy (core and edge)



1.b diagnostics: SOL and wall

- plasma edge

  - monitoring of plasma SOL/edge and wall surface

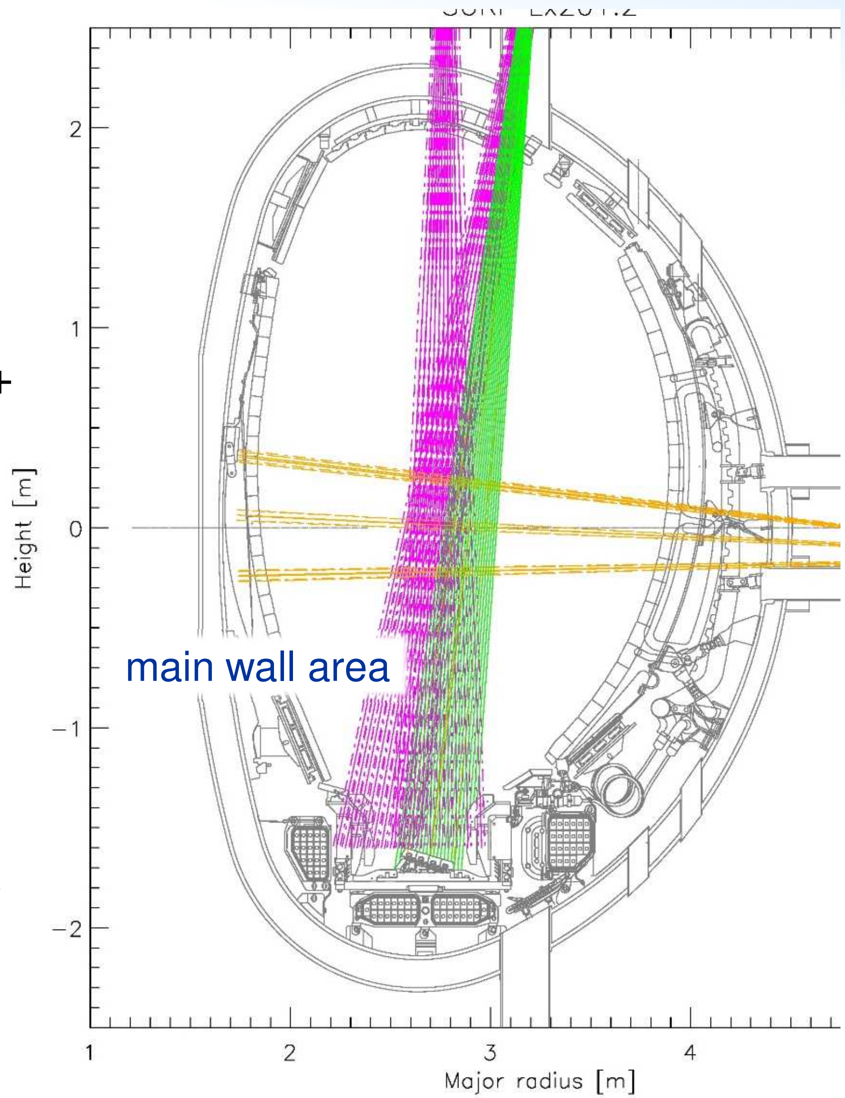
  - edge plasma and wall diagnostics (active and passive)
    - ✓ spectroscopic measurements of particle + particle, particle + e^- , etc processes: XUV-VUV

      optical emission
    - ✓ specific wall areas of interest covered with spectroscopy

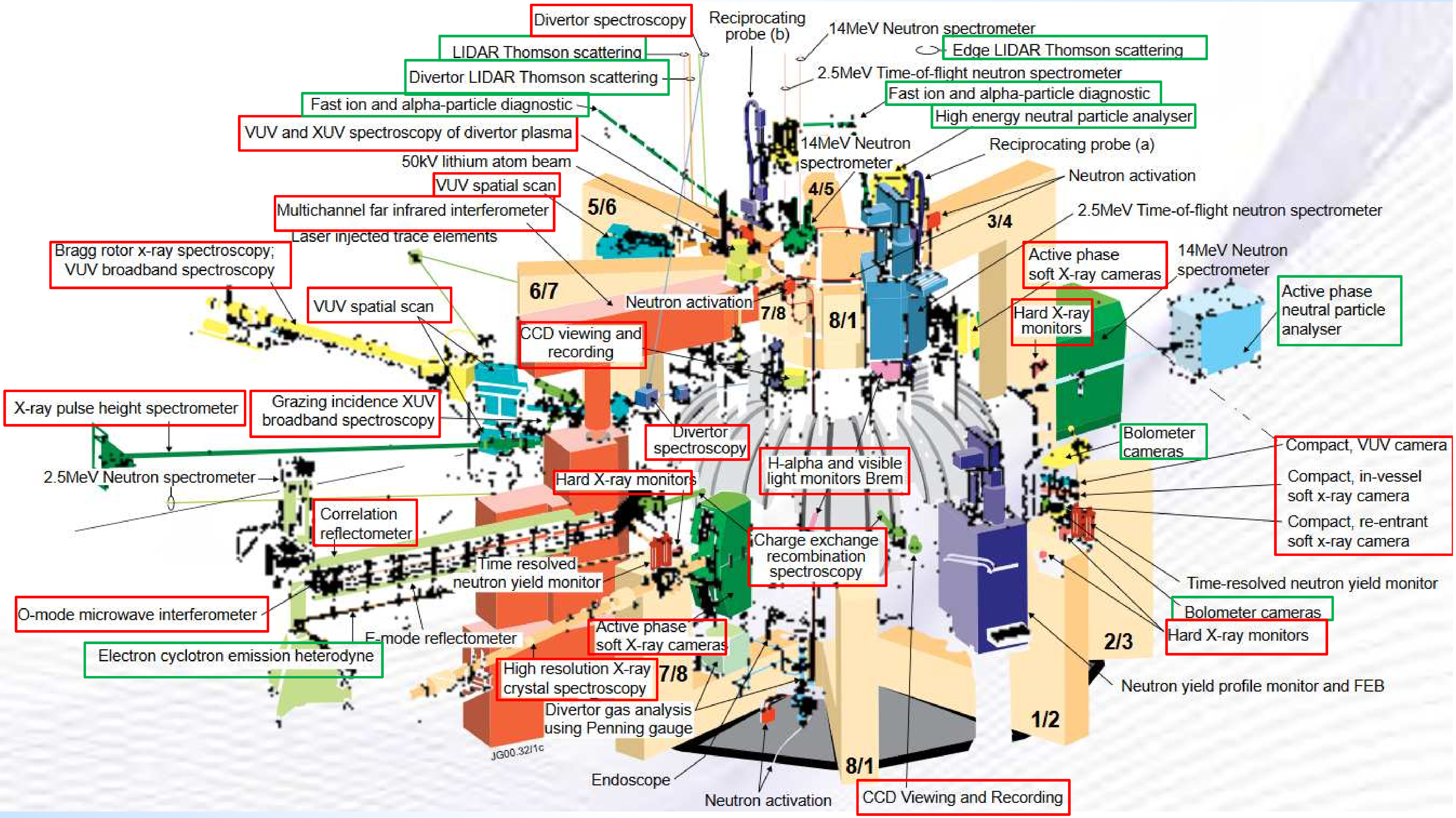
      (JET: D, W, Be, hydrides. Seeded impuri-ties N, Ar, Ne)
    - ✓ other: Langmuir probes for particle flux to wall; thermocouples; Quartz-micro balance; dust monitors; …

  …

e.g. JET optical spectroscopy

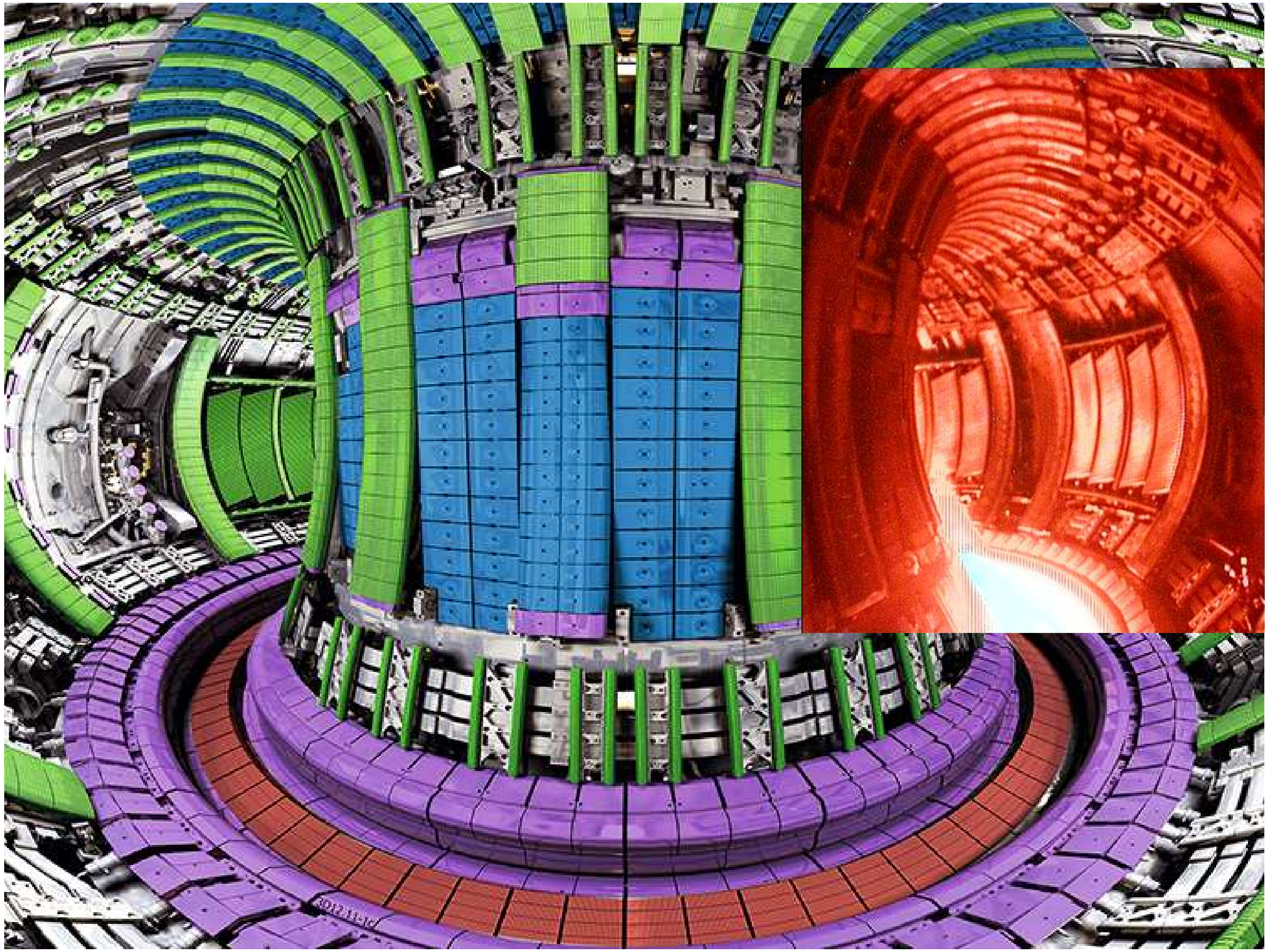


1. diagnostics: JET



2.a Spectroscopy: Be wall erosion

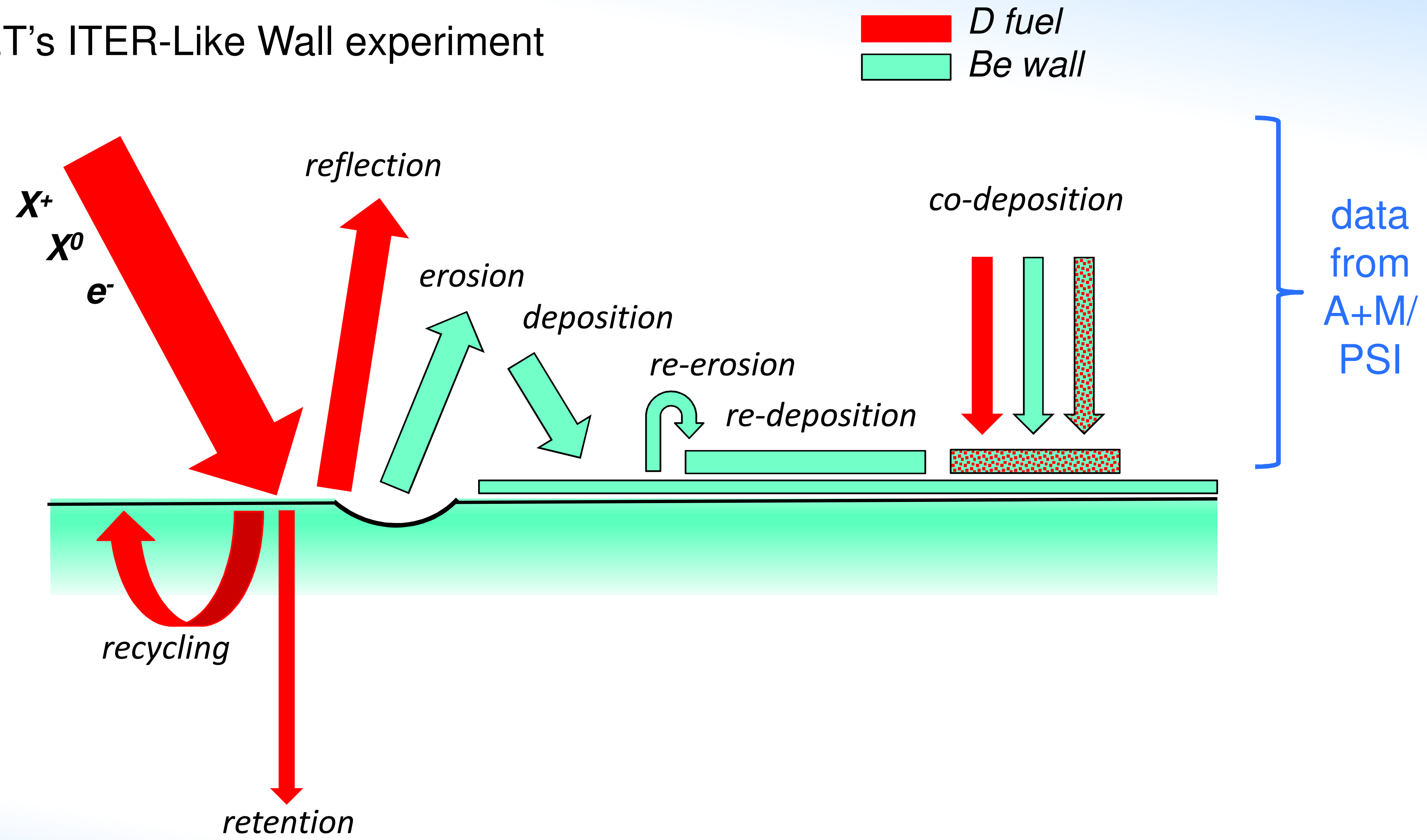
- JET's ITER-Like Wall experiment
  - all metal wall
  - **Be limiters**
    thermal conductivity
    impurity getter
    T_{melt} = 1287˚C
  - **W divertor**
    thermal conductivity
    high erosion threshold
    T_{melt} ~ 3400˚C



Bulk Be PFCs | Be- coated inconel PFCs
Bulk W | W- coated CFC PFCs

2.a Spectroscopy: Be wall erosion

- JET's ITER-Like Wall experiment



S. Brezinsek, Nucl. Fusion 54, 103001 (2014)

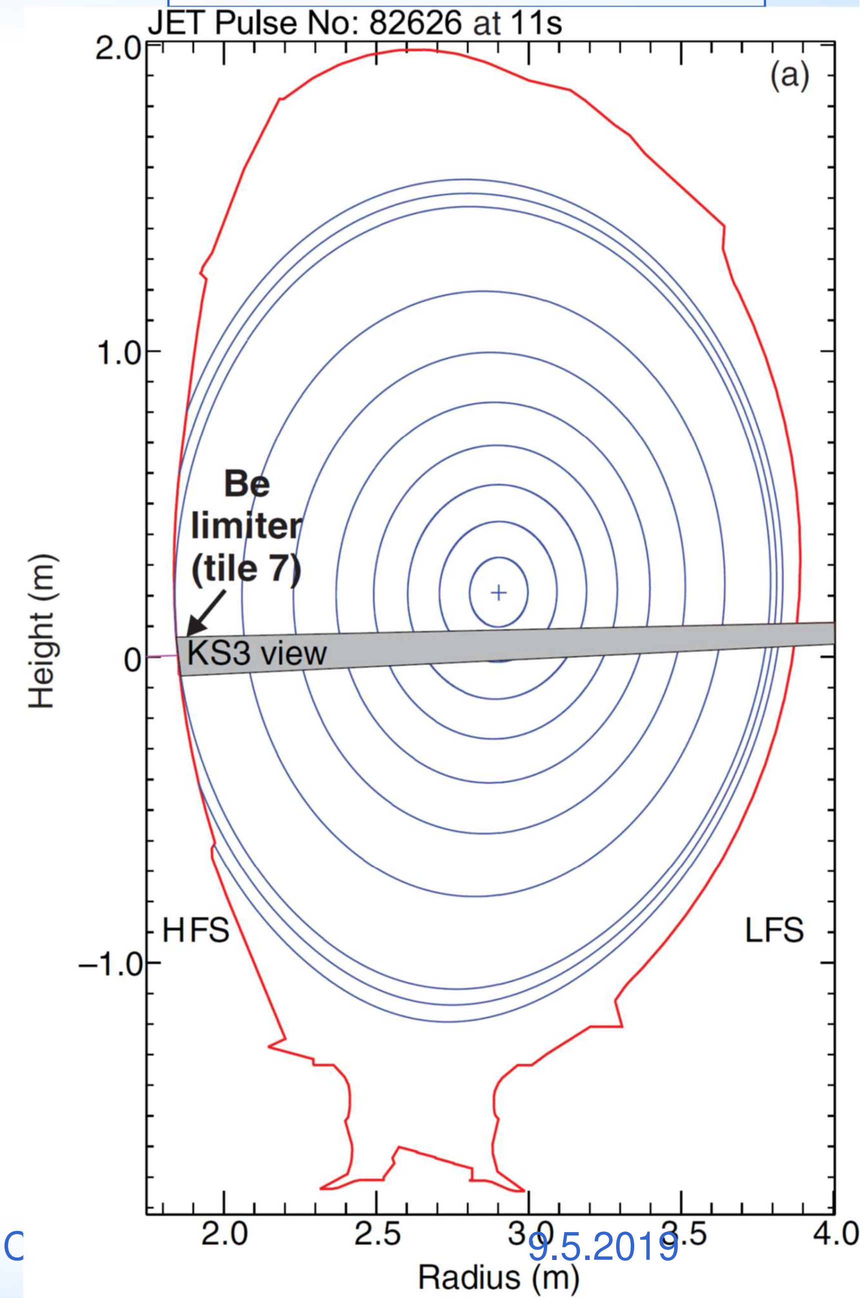
2.a Spectroscopy: Be wall erosion

- ❑ JET's ITER-Like Wall experiment
  - ➢ Be main chamber limiters
  - ➢ W divertor

- ❑ D plasma interactions with limiters
  - ➢ Be erosion and material transport
  - ➢ determination of the amount of sputtered Be crucial

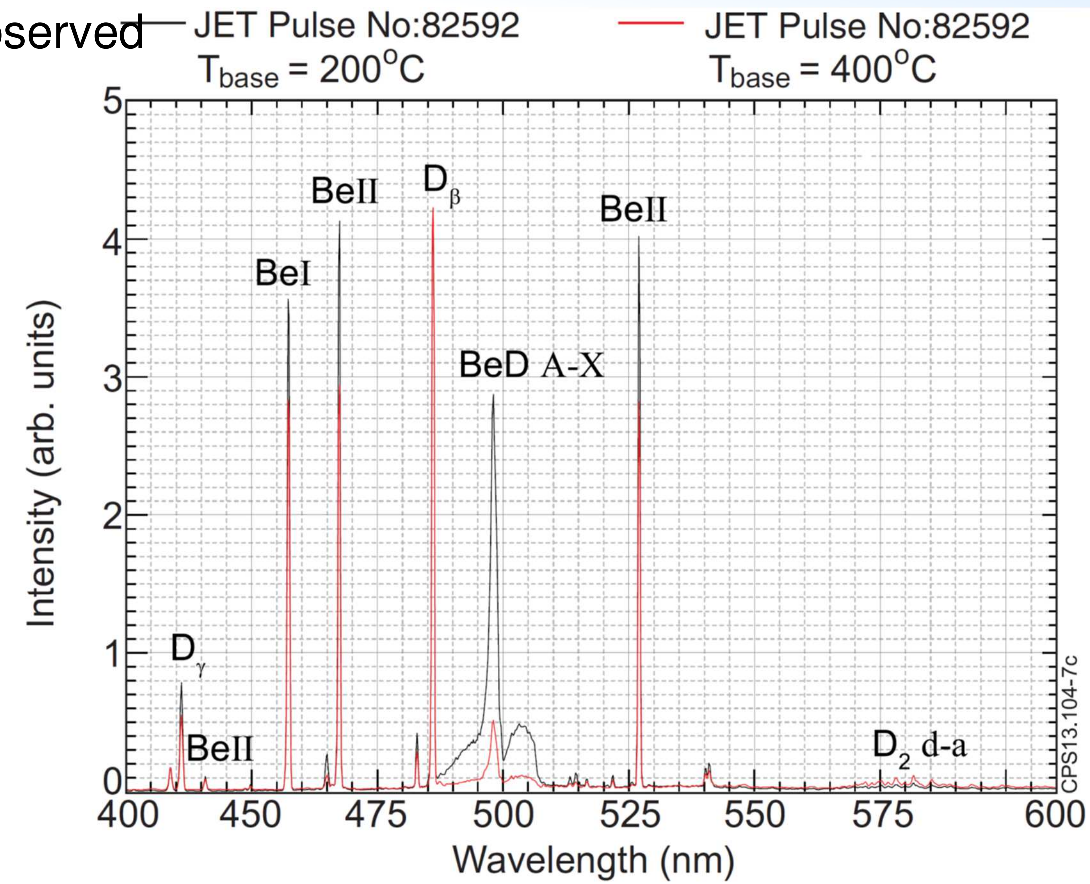
- ❑ *In-situ* optical spectroscopy emission of Be wall
  - ❖ line-of-sight to the plasma contact point
  - ❖ lines: Be II (527 nm, 467 nm 436 nm) and Dγ
  - ❖ Be erosion due to D^+, excitation and ionization in collisions with plasma particles (e^-, D^+)

optical spectroscopy **Be II** and **D**γ



2.a Spectroscopy: Be wall erosion

- *In-situ* optical spectroscopy emission of Be wall
  - Be, D, and formation of D_2, BeD observed
  - temperature effect
    - high T_{base} yields lower BeD
      - desorption of D as D_2



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  - Be, D, and formation of D_2, BeD observed
  - temperature effect
    - high T_{base} yields lower BeD
      - desorption of D as D_2
  - Be sputtering rate Y_{Be} :

$$Y_{Be} = 4\pi \frac{S}{XB} \frac{I_{Be}}{\Gamma_D}$$

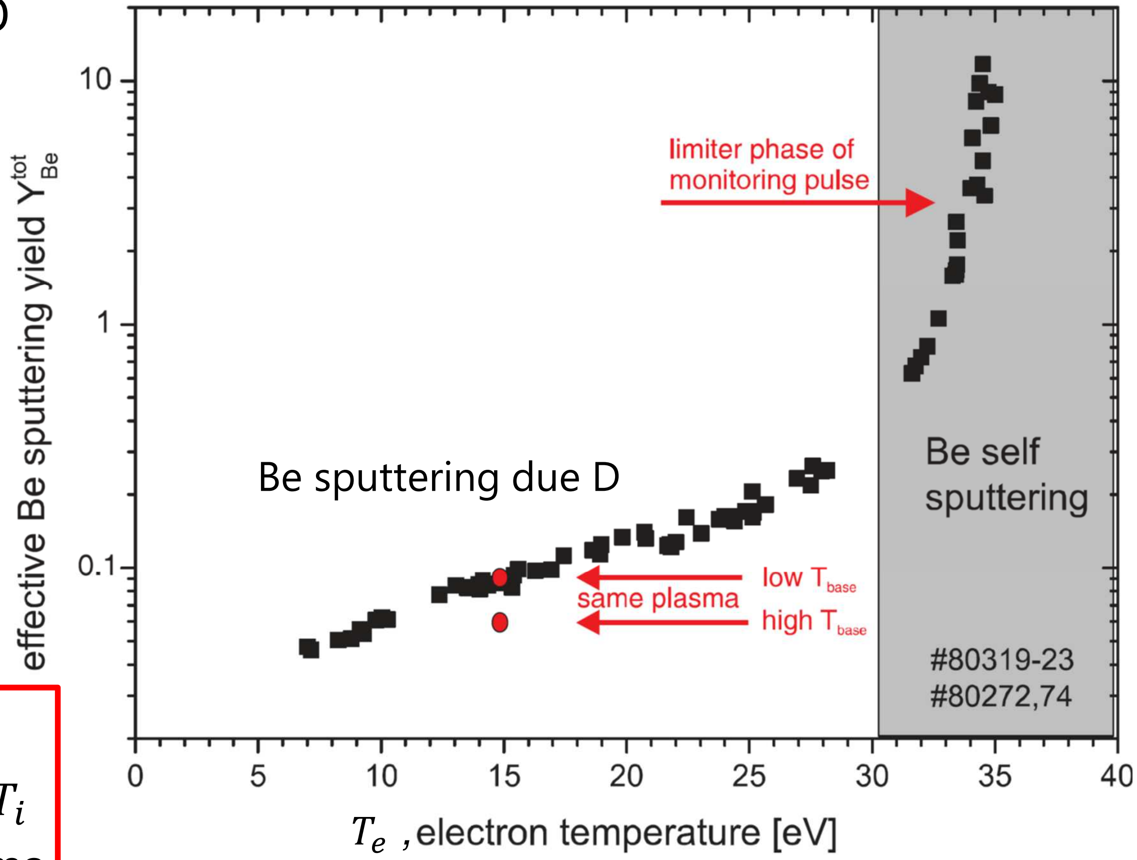
Be II intensity

D^+ flux to wall

(photon production)$^{-1}$

- Spectroscopic findings:
  - Be erosion increases with T_i
  - different erosion mechanisms
  - ✓ assessment for wall lifetime!

Be total sputtering $Y_{Be}^{tot} = Y_{Be}^{chem} + Y_{Be}^{phys}$



$T_i \approx T_e$

S. Brezinsek, Nucl. Fusion 54, 103001 (2014)
S. Brezinsek, Nucl. Fusion 55, 063021 (2015)

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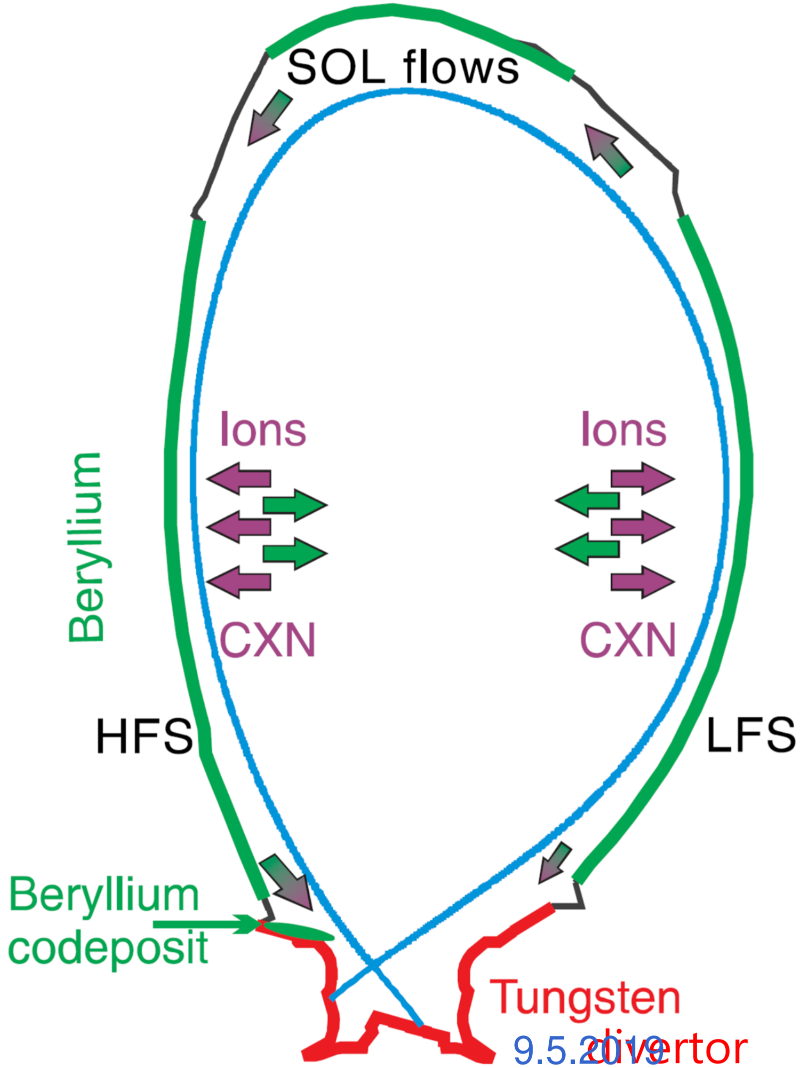
  - different erosion mechanisms
  - ✓ assessment for wall lifetime!

"Big picture"
Be migration in SOL

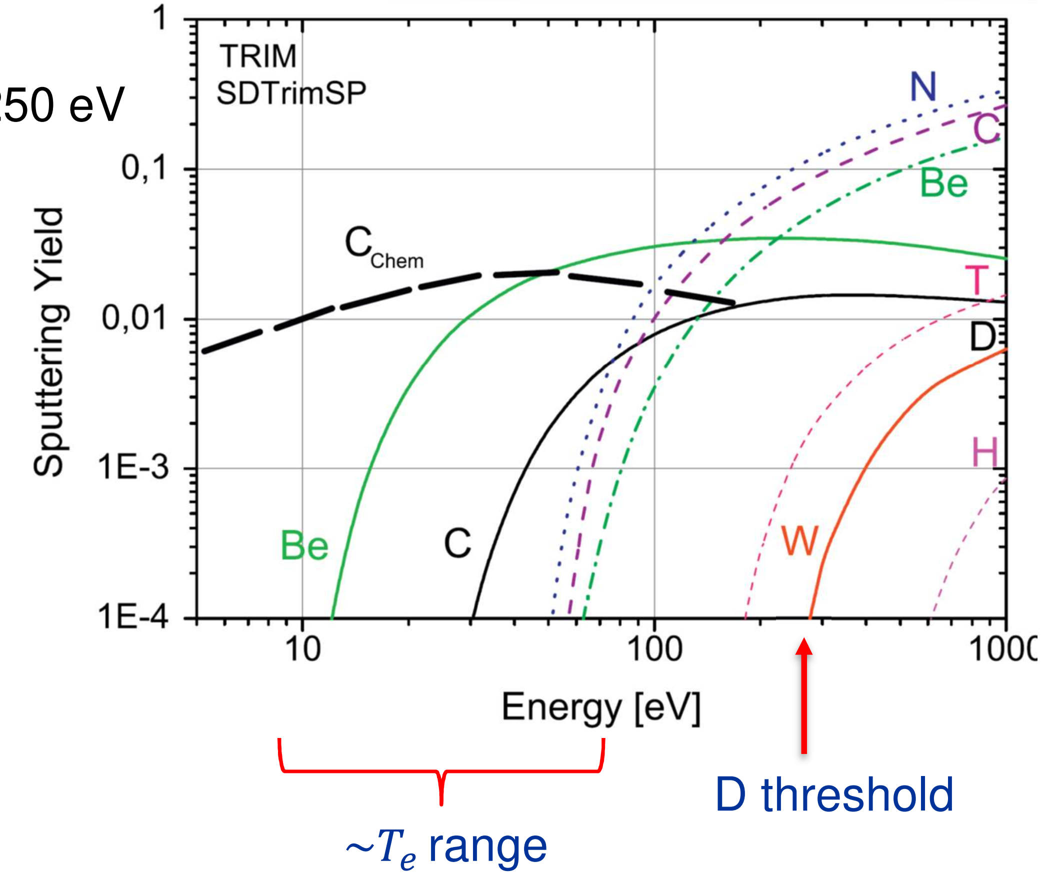


S. Brezinsek, Nucl. Fusion 54, 103001 (2014)
S. Brezinsek, Nucl. Fusion 55, 063021 (2015)

2.b Spectroscopy: divertor PSI

- D plasma-surface interactions in W divertor
  - W sputtering threshold by D approx. 250 eV
  - T_e range low: eV…few tens of eV
    - W erosion unlikely due to D
    - wall eroded Be plays role?

sputtering yields by D



G. J. van Rooij, J.Nucl. Mat. 438, S42 (2013)
S. Brezinsek, J. Nucl. Mat. 463, 11 (2015)

2.b Spectroscopy: divertor PSI

- *In-situ* optical spectroscopy of W divertor
  - line-of-sight to W divertor
  - lines: W I (400.9 nm) and Dε
  - sputtered W get excited and ionized in collisions with plasma particles (e^-, D^+, impurities, ...)

  - W sputtering rate Y_W :

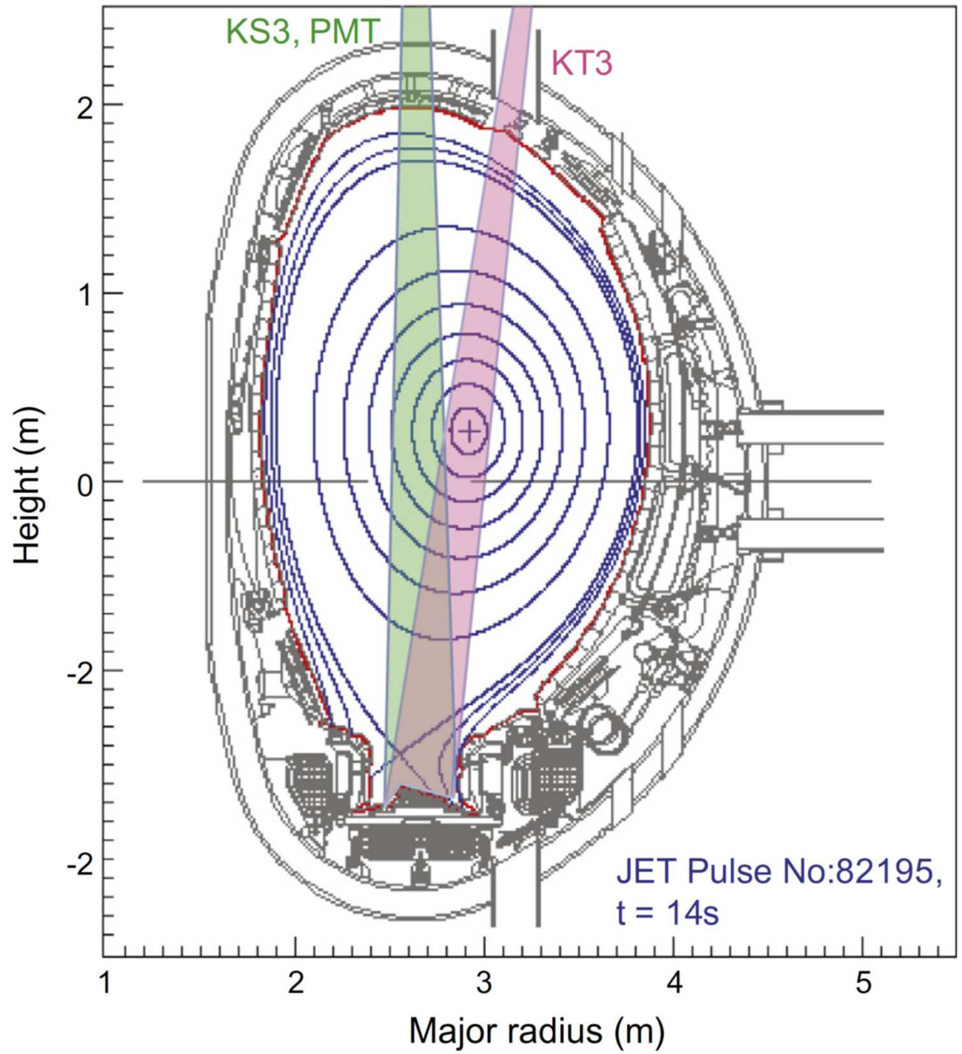
$$Y_W = 4\pi \frac{S}{XB} \frac{I_W}{\Gamma_D}$$

W I intensity

D+ flux to divertor

(photon production)-1

optical spectroscopy **W I** and **Dε**



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  - W sputtering rate Y_W :

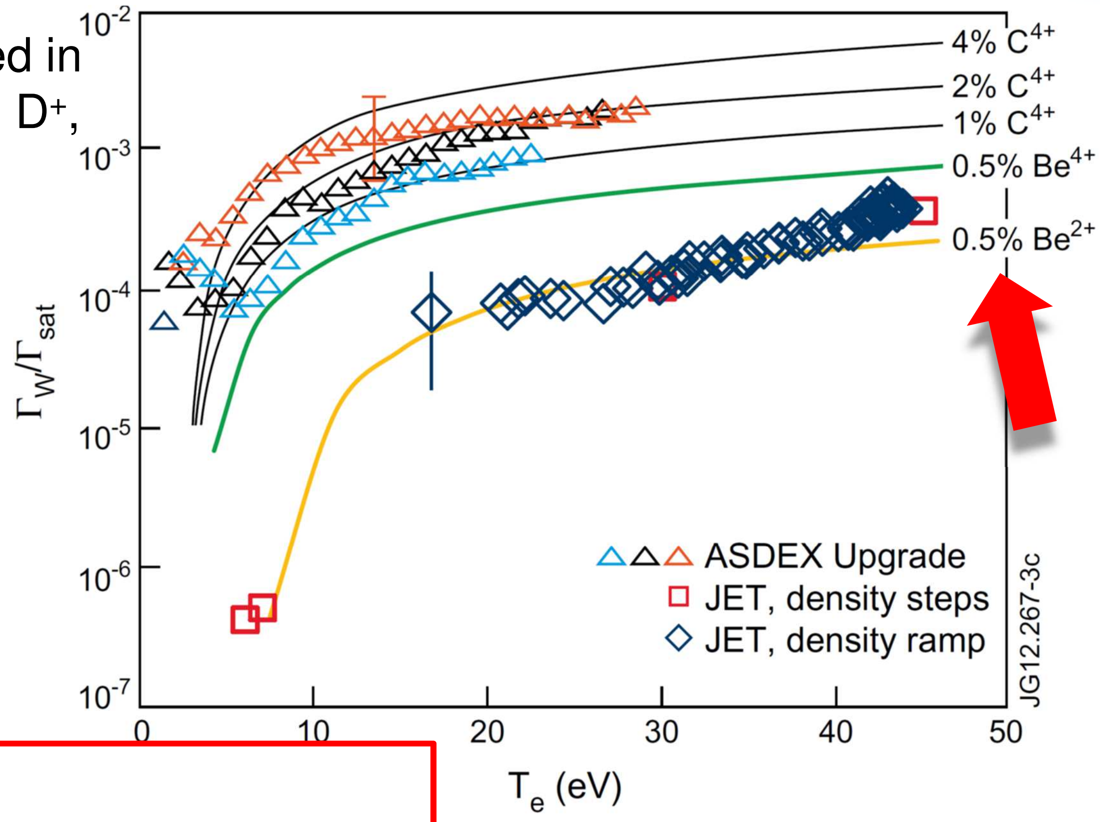
$$Y_W = 4\pi \frac{S}{XB} \frac{I_W}{\Gamma_D}$$

W I intensity

D+ flux to divertor

(photon production)$^{-1}$

W total sputtering $Y_W^{tot} = Y_W^{phys}$



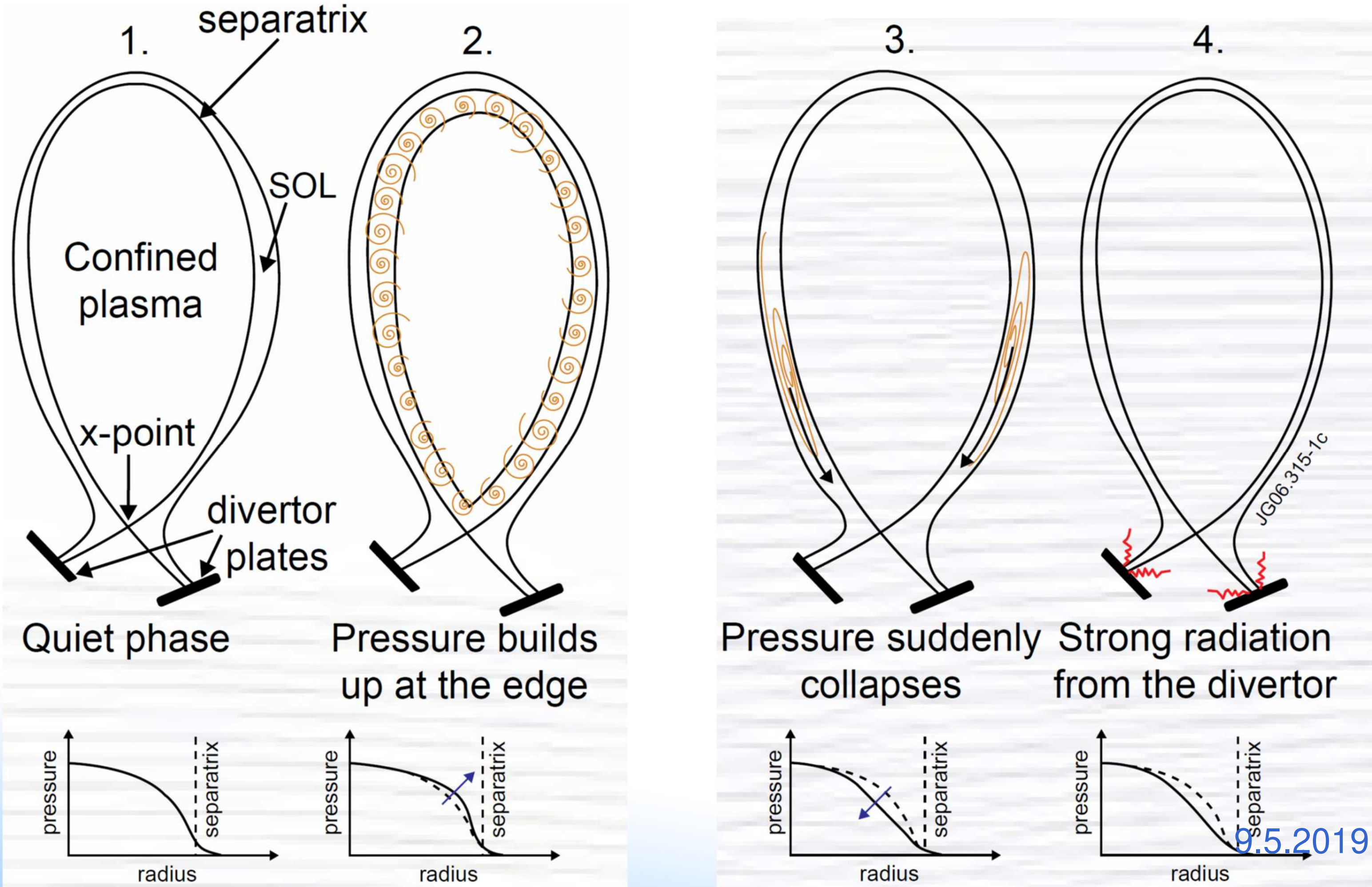
- Spectroscopic findings (low T_e):
  - W erosion: Be dependent, increases with T_i
  - measured 0.5% Be^{2+} corresponds to Be erosion
  - ✓ assessment for divertor sputtering

G. J. van Rooij, J.Nucl. Mat. 438, S42 (2013)
S. Brezinsek, J. Nucl. Mat. 463, 11 (2015)

3.a Spectroscopy: divertor PSI w/ ELMs

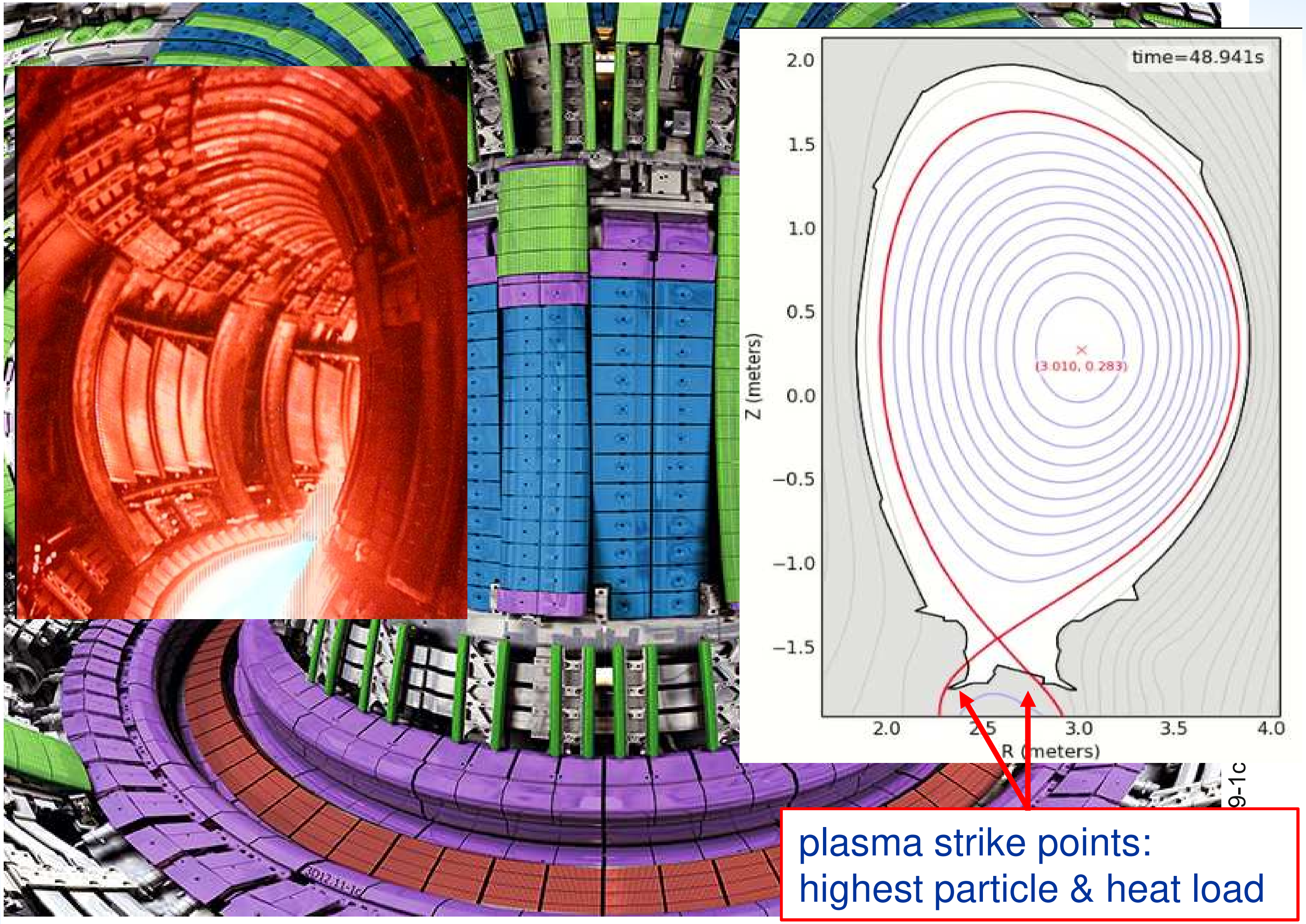
- Plasma edge-localized modes (ELMs)
  - ELMs present in medium-sized to large devices (H-mode)
  - plasma pressure increase at pedestal
  - release to divertor → high *heat* and *energetic* particles!

Δt_{ELM}~ms range



3.a Spectroscopy: divertor PSI w/ ELMs

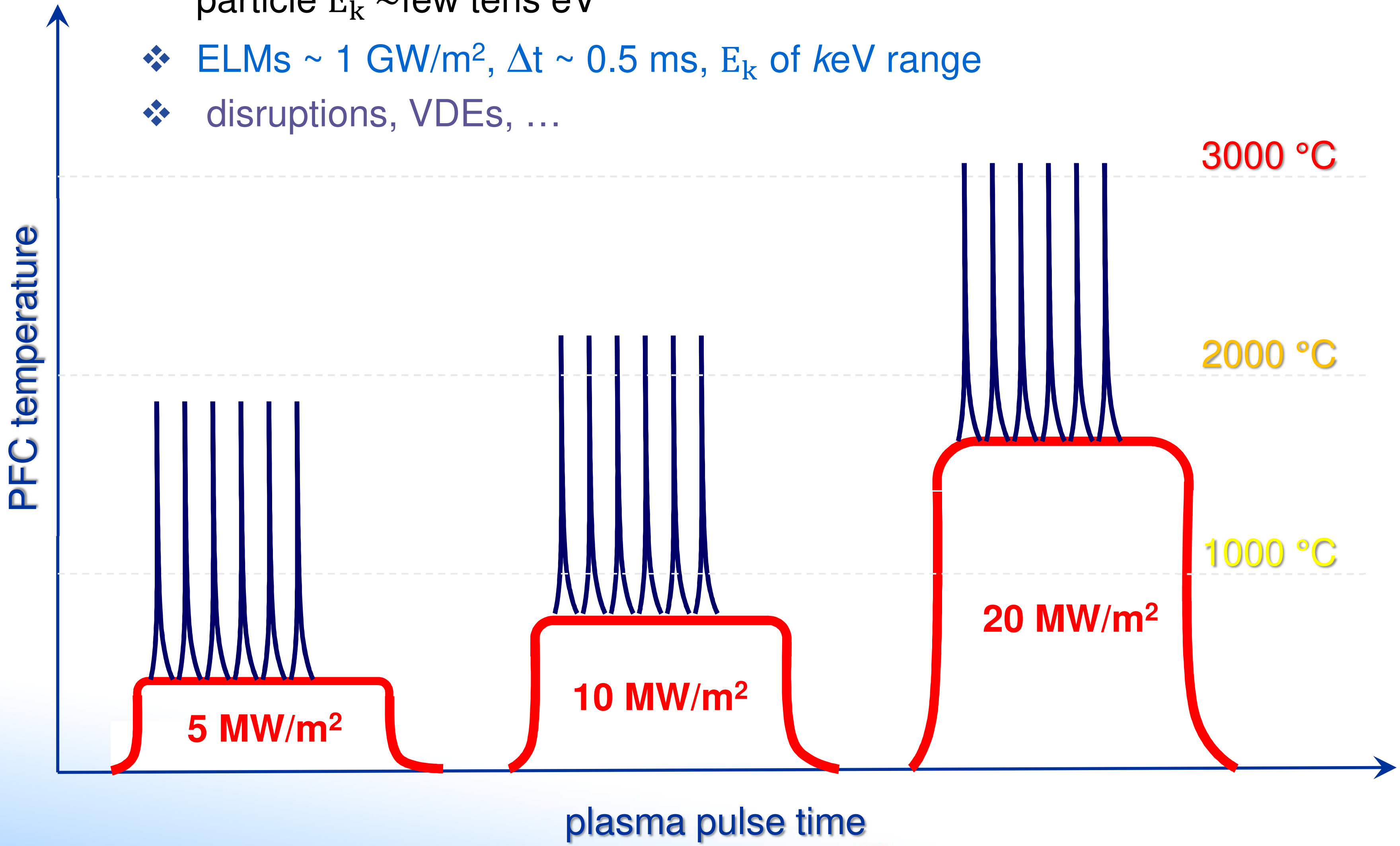
- Formation of magnetic configuration with plasma strike points in divertor



- Bulk Be PFCs
- Be- coated inconel PFCs
- Bulk W
- W- coated CFC PFCs

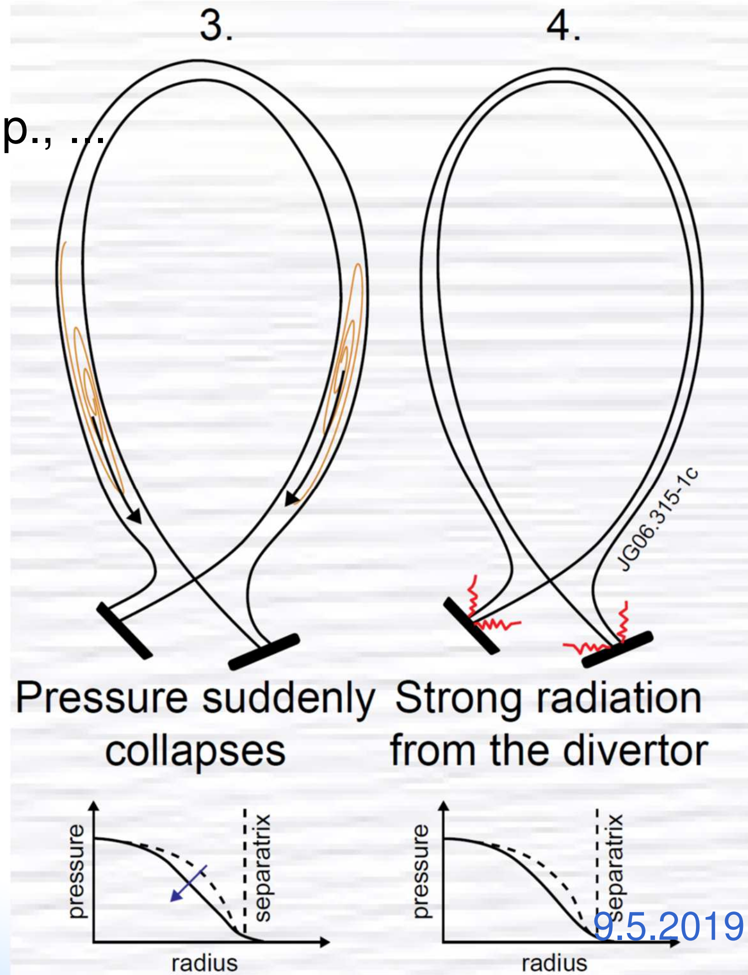
3.a Spectroscopy: divertor PSI w/ ELMs

- Plasma edge-localized modes (ELMs)
  - ITER steady state 10 MW/m², slow transients 20 MW/m², particle E_k ~few tens eV
  - ELMs ~ 1 GW/m², Δt ~ 0.5 ms, E_k of *k*eV range
  - disruptions, VDEs, …



3.a Spectroscopy: divertor PSI w/ ELMs

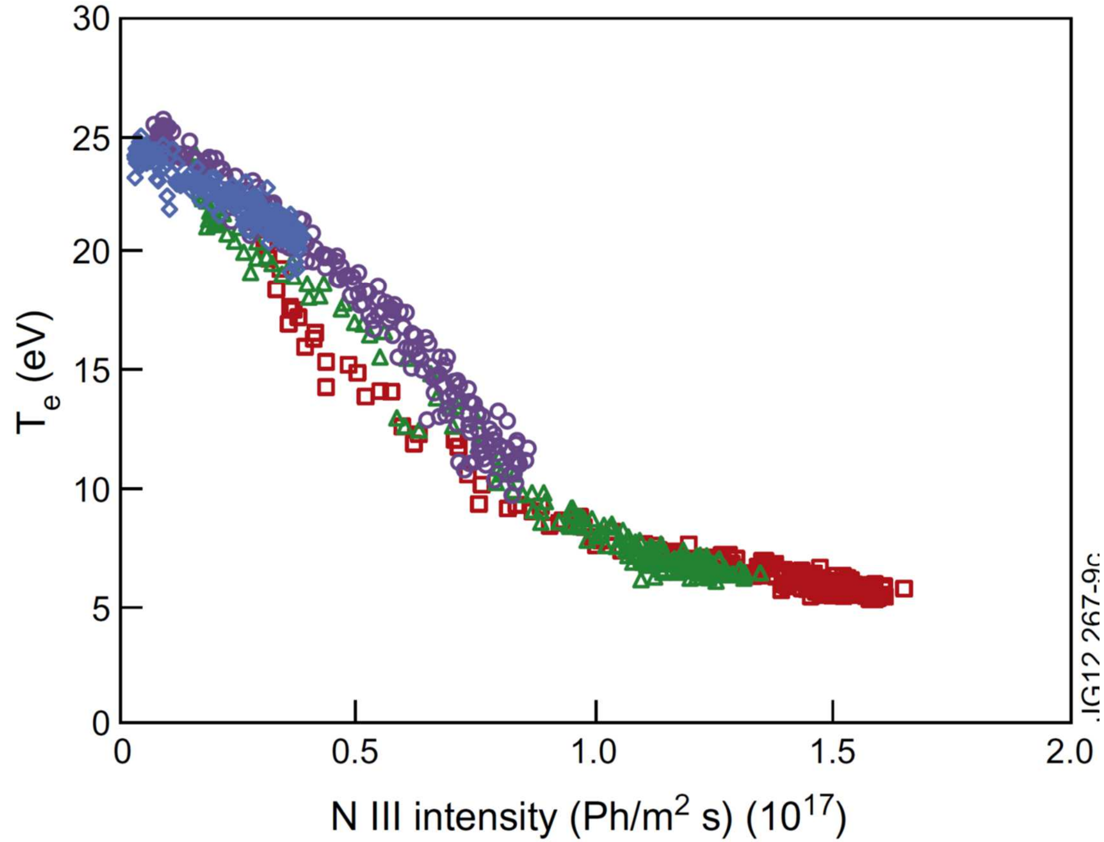
- Plasma edge-localized modes (ELMs)
  - ELMs present in medium-sized to large devices (H-mode)
  - plasma pressure increase at pedestal
  - release to divertor → high *heat* and *energetic* particles
    - monitoring ELMs crucial
    - diagnostic methods for $n_{e,i}$, $T_{e,i}$, temp., ...
    - assessment of wall effects required
      - ✓ plasma operation
      - ✓ wall lifetime
      - ✓ fuel recycling and retention



3.a Spectroscopy: divertor PSI w/ ELMs

- *In-situ* optical spectroscopy of W divertor with ELMs
  - experiment with detached plasma
    (N_2 seeding for divertor plasma mitigation)

T_e ↘ as puffed N_2 ↗ in divertor



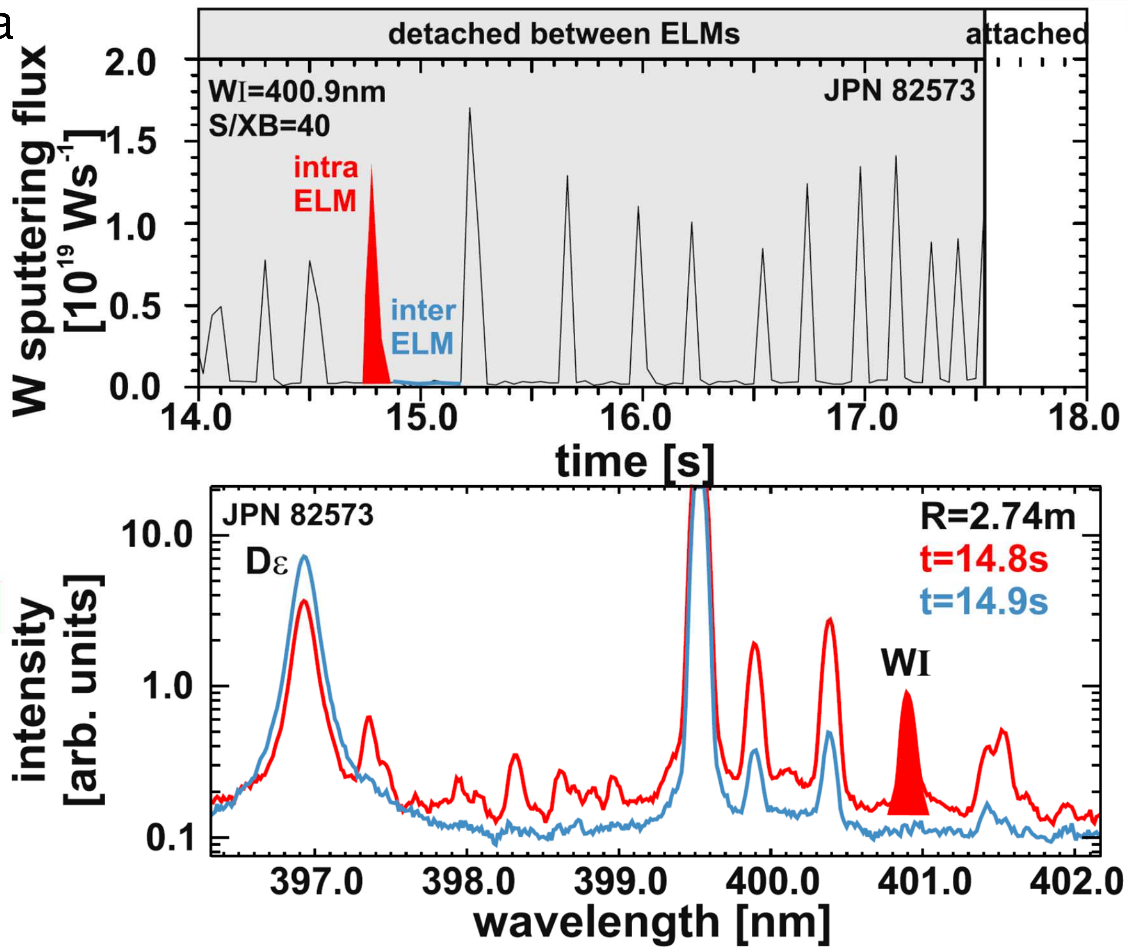
G. J. van Rooij, J.Nucl. Mat. 438, S42 (2013)
S. Brezinsek, J. Nucl. Mat. 463, 11 (2015)

3.a Spectroscopy: divertor PSI w/ ELMs

- *In-situ* optical spectroscopy of W divertor with ELMs

  - experiment with detached plasma (N_2 seeding for mitigation)
  - between ELMs (blue line): no W erosion
  - during ELM (red line): clear W I peak for erosion

- ✓ ELMy plasmas can sputter W efficiently
  - energetic D^+ and impurities from the pedestal



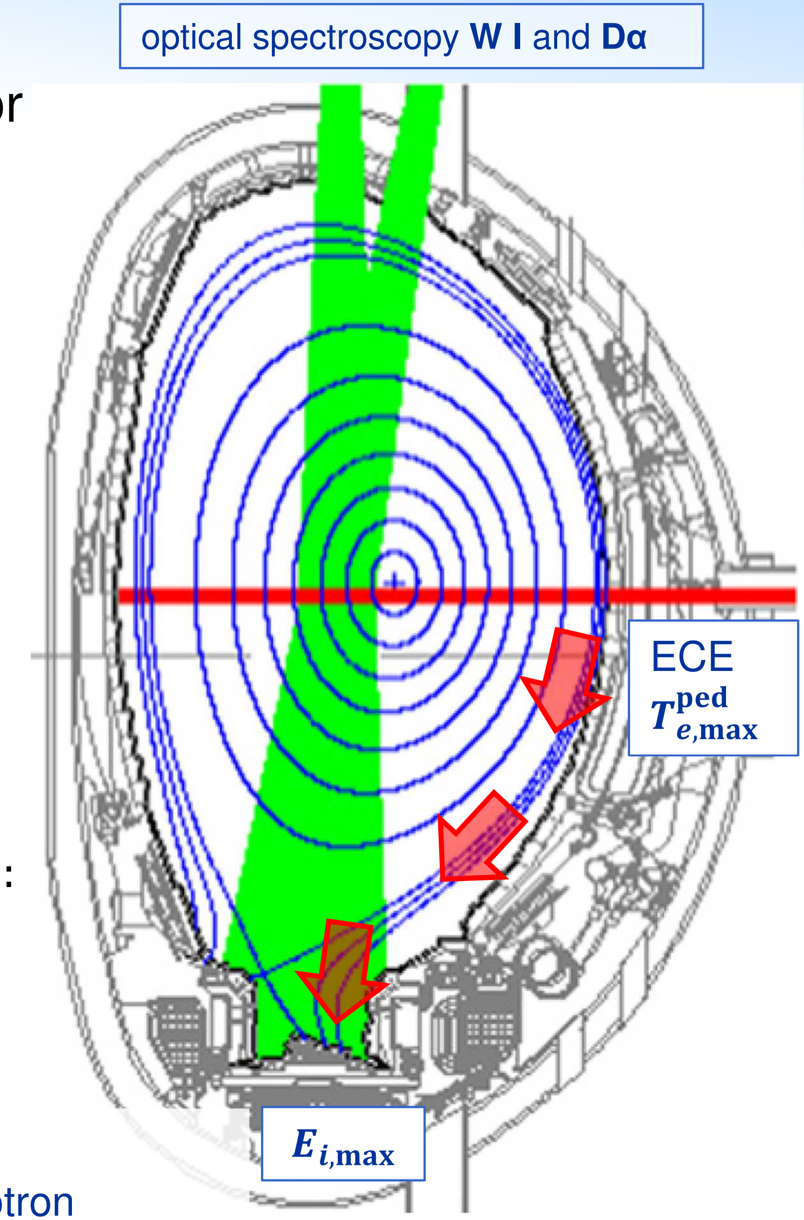
G. J. van Rooij, J.Nucl. Mat. 438, S42 (2013)
S. Brezinsek, J. Nucl. Mat. 463, 11 (2015)

3.a Spectroscopy: divertor PSI w/ ELMs

- ELM-resolved D^+ impact energy (E_i) at W divertor
  (unseeded plasma → no N_2, no mitigation)
  - Why?
    - plasma with 0.5% Be^{2+}
    - D^+ dominant ELM component
  - How?
    - *in-situ* Dα spectroscopy → ion/s at target
    - ECE → maximum T_e at pedestal ($T_{e,\max}^{\mathrm{ped}}$)
    - absorbed power at target
    - ELM impact energy at divertor correlates with T_e in pedestal as ("Free stream model"):

$$\max(E_i + E_e) \approx \alpha T_{e,\max}^{\mathrm{ped}}$$

Dα — power — ECE (electron cyclotron emission $T_e^{\mathrm{ped}} \propto \omega = n\omega_{ce}$)



C. Guillemaut, Phys. Scr. T167, 014005 (2016)
D. Moulton, Plasma Phys. Control. Fusion 55, 085003 (2013)

3.a Spectroscopy: divertor PSI w/ ELMs

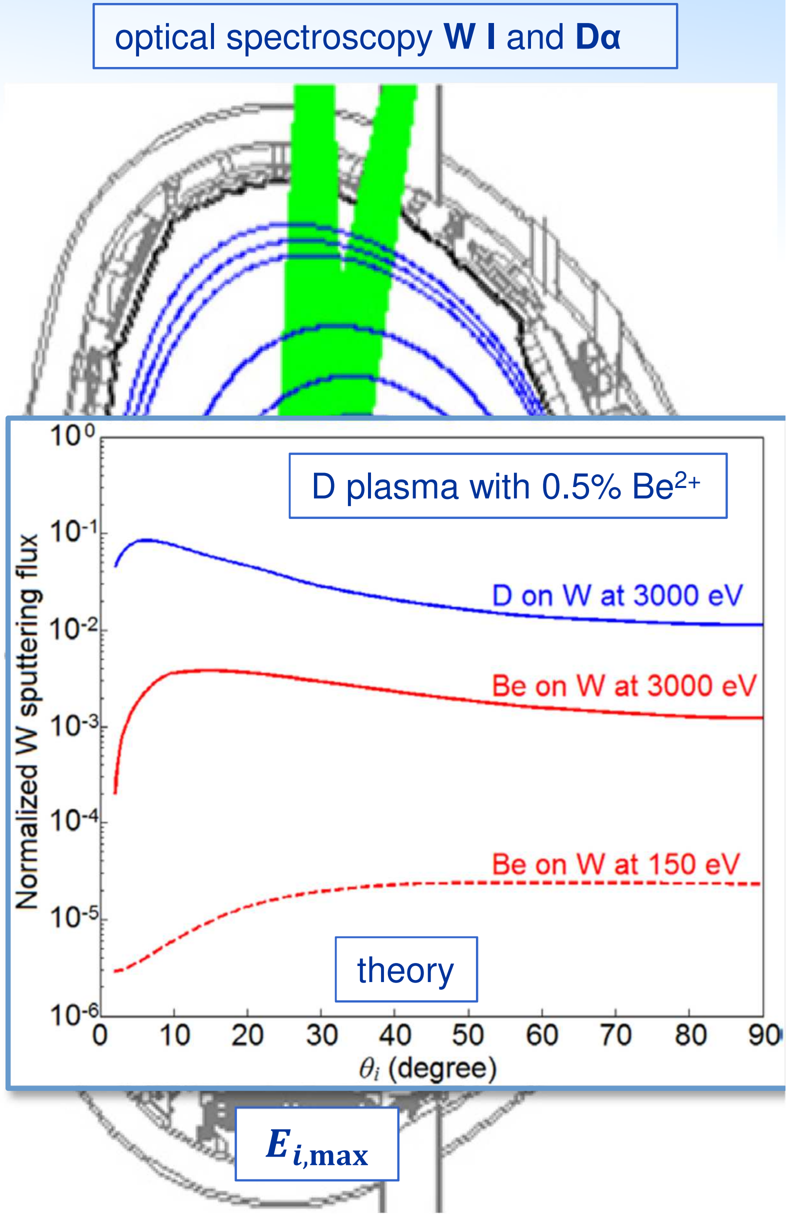
- ELM-resolved D^+ impact energy (E_i) at W divertor
  - How?
    - *in-situ* Dα spectroscopy → ion/s at target
    - ECE → maximum T_e at pedestal ($T_{e,\max}^{\mathrm{ped}}$)
    - absorbed power at target
  - Result
    - $\max(E_i + E_e) \approx \alpha T_{e,\max}^{\mathrm{ped}} \quad (E_e = E_{e,\perp} = T_e^{\mathrm{ped}})$

      $\rightarrow \; E_{i,\max} \approx 4.23 T_{e,\max}^{\mathrm{ped}}$
    - JET: experimental $T_{e,\max}^{\mathrm{ped}} \approx 1\ \mathrm{keV}$ results

      in $E_{i,\max} \approx 3\ \mathrm{keV}$

      → D^+ in ELMs sputter W easily

      → D^+ sputters 20× more W than Be^{2+}



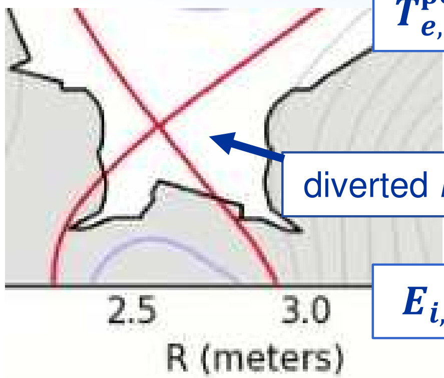
C. Guillemaut, Phys. Scr. T167, 014005 (2016)

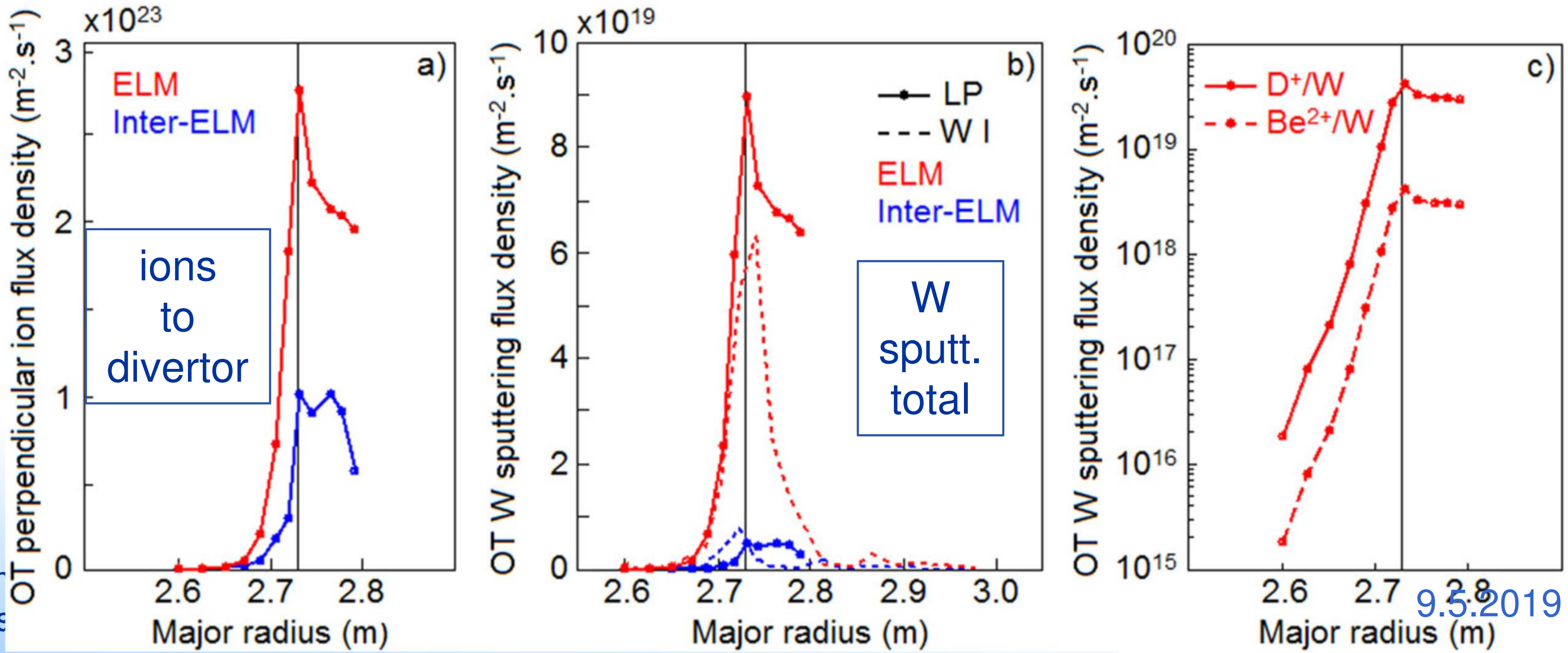
M. Sugihara, Plasma Phys. Control. Fusion 45, L55 (2003)

3.a Spectroscopy: divertor PSI w/ ELMs

- ELM-resolved D^+ impact energy (E_i) at W divertor
  - Result
    - $E_{i,\max} \approx 4.23 T_{e,\max}^{\mathrm{ped}}$
    - JET: experimental $T_{e,\max}^{\mathrm{ped}} \approx 1\ \mathrm{keV}$ results in $E_{i,\max} \approx 3\ \mathrm{keV}$
      $\rightarrow$ D^+ in ELMs sputters W easily
      $\rightarrow$ D^+ sputters 20× more W than Be^{2+}
    - ITER: theoretical $T_{e,\max}^{\mathrm{ped}} \sim 5\ \mathrm{keV}$ $\rightarrow E_{i,\max} \sim 20\ \mathrm{keV}$

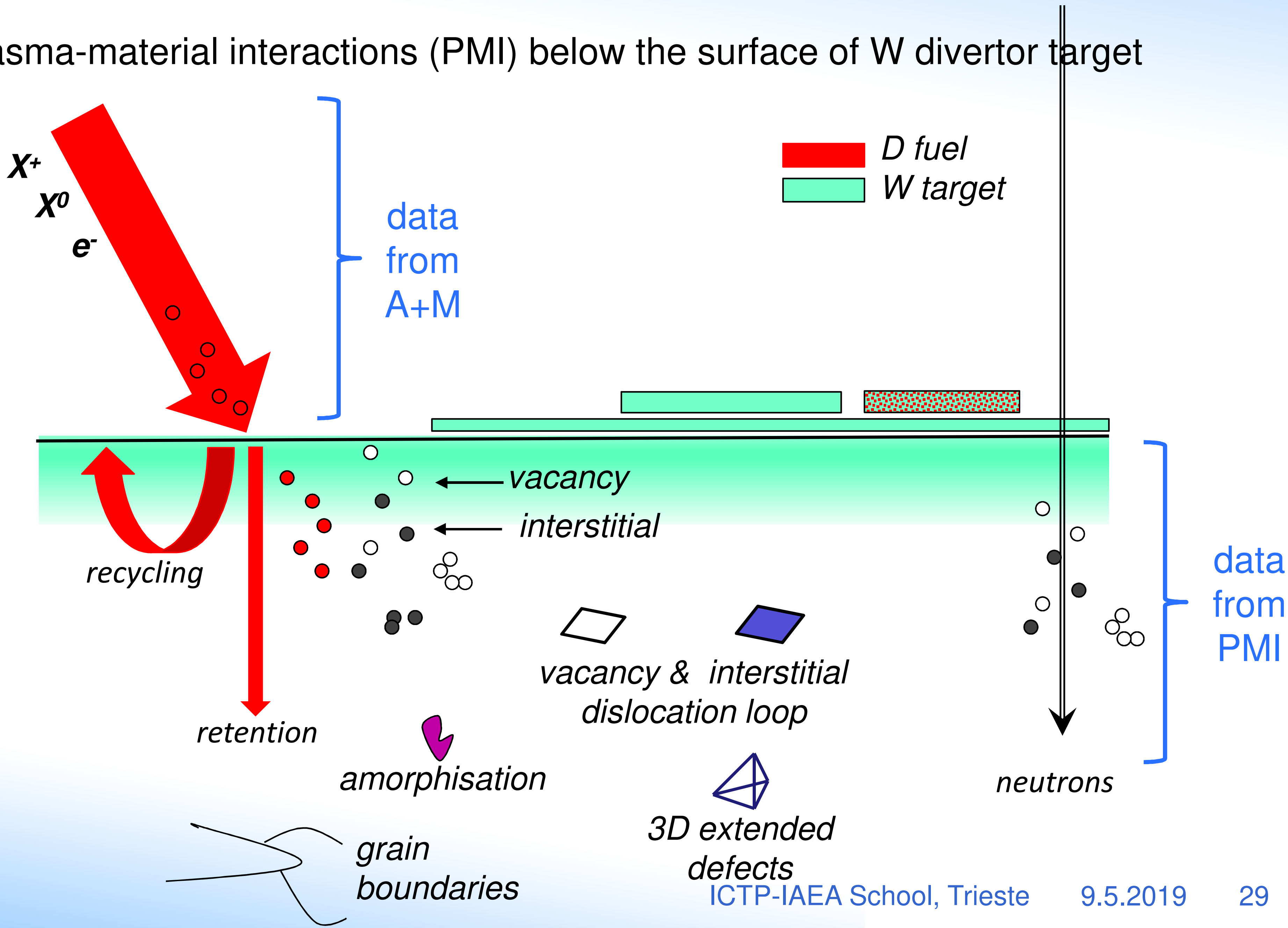
optical spectroscopy **W I** , **Be II** and **Dα**





3.b Divertor PMI w/ ELMs

- Plasma-material interactions (PMI) below the surface of W divertor target



3.c Divertor fuel retention w/ ELMs

- PMI events and reactions, and fuel retention simulated with multi-scale Rate Theory Equation calculations
  - coupled partial differential equations (PDE) for physical processes in the bulk and on the surface

1) D processes inside W
   - diffusion
   - retention, trapping, re-trapping with defects
   - recycling
2) ELM-induced defect evolution inside W
   - nucleation
   - diffusion
   - clustering
   - dissociation
   - …

→ over 300 entities which take part in 3200 exothermic and 300 endothermic reactions

T. Ahlgren, J. Nucl. Mat. 427, 152 (2012)

3.c Divertor fuel retention w/ ELMs

- PMI events and reactions, and fuel retention simulated with multi-scale Rate Theory Equation calculations
  - PDE parametrisation: experiments and computational methods (ab initio, MD)

$$\frac{\partial C_\alpha(x,t)}{\partial t} = D_\alpha \frac{\partial^2 C_\alpha(x,t)}{\partial x^2} + S_\alpha(x,t) \pm \sum_{\beta,\gamma=1}^{N} k^2_{\beta,\gamma} D_\beta C_\beta(x,t) \pm \sum_{\delta=1}^{N} \nu_\delta e^{-E_{A,\delta}/kT} C_\delta(x,t)$$

$$D = D_0 e^{-E_m/kT}$$

source term:
spectroscopy, MD, other

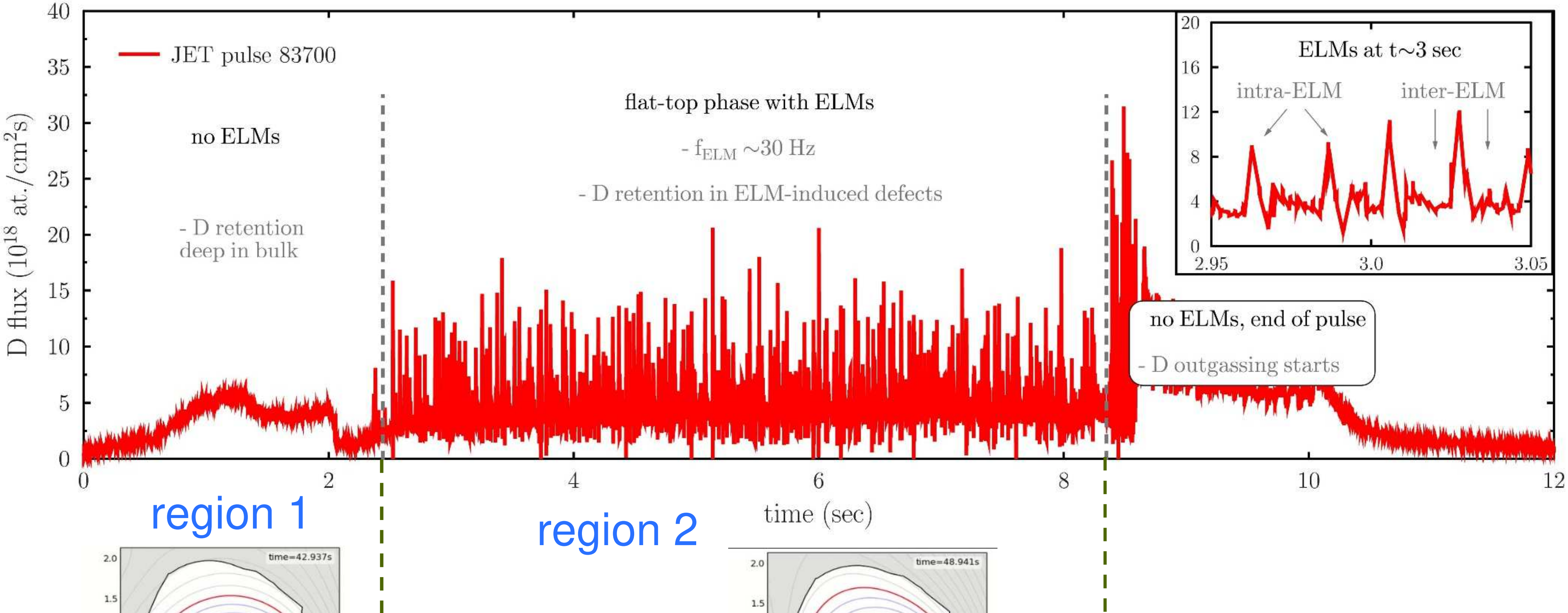
energetics: *ab initio*, MD

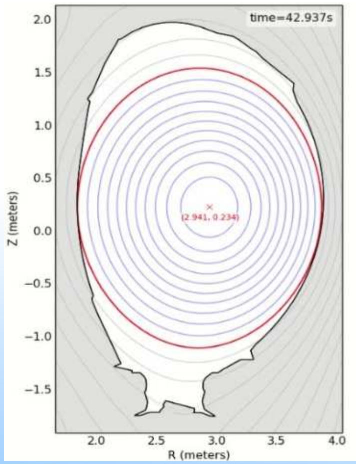
force fields:
sink strength and reaction radii MD

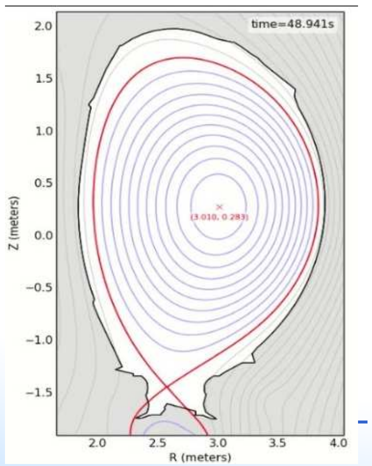
K. Heinola, J. Appl. Phys. 107, 113531 (2010)
K. Heinola, Phys. Rev. B 82, 094102 (2010)
K. Heinola, J. Nucl. Mat. 438, S1001 (2013)
K. Heinola, Phys. Rev. B 81, 073409 (2010)
T. Ahlgren, J. Nucl. Mat. 427, 152 (2012)
K. Heinola, Nucl. Fusion 58, 026004 (2018)

3.c Divertor fuel retention w/ ELMs

- PMI and fuel retention simulation with ELMy plasmas
  - input from D_α (or other method @ divertor)

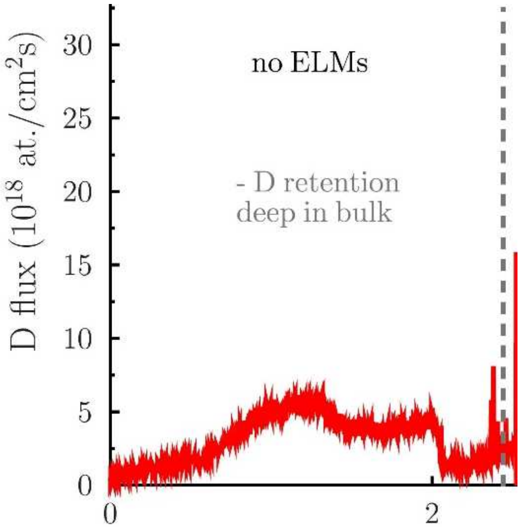






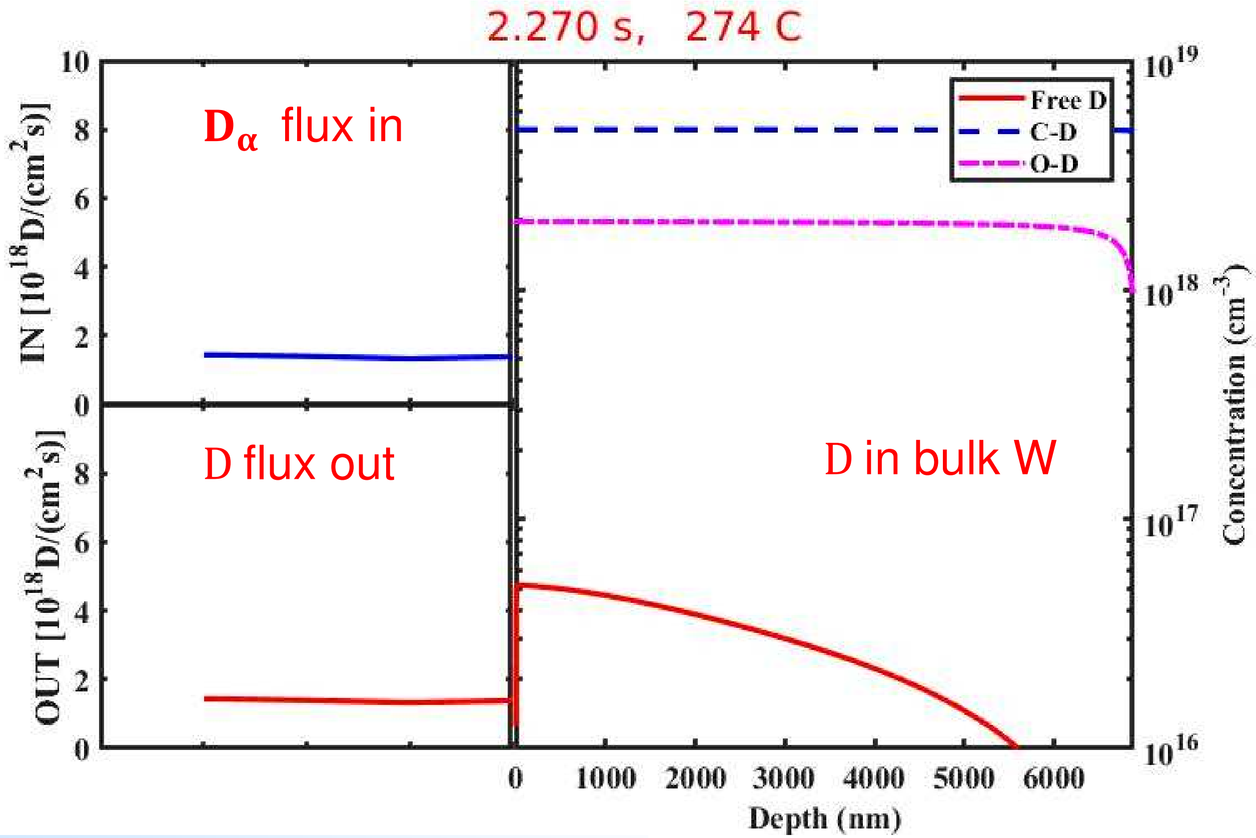
3.c Divertor fuel retention w/ ELMs

- PMI and fuel retention simulation with ELMy plasmas



region 1

- time $0 < t < 2.4$ s
- limiter phase with no ELMs (~40 eV/D)



- ✓ D diffusion deep in the bulk
- ✓ no ELM-damage created
- ✓ D retained at natural impurities of W e.g. C, O

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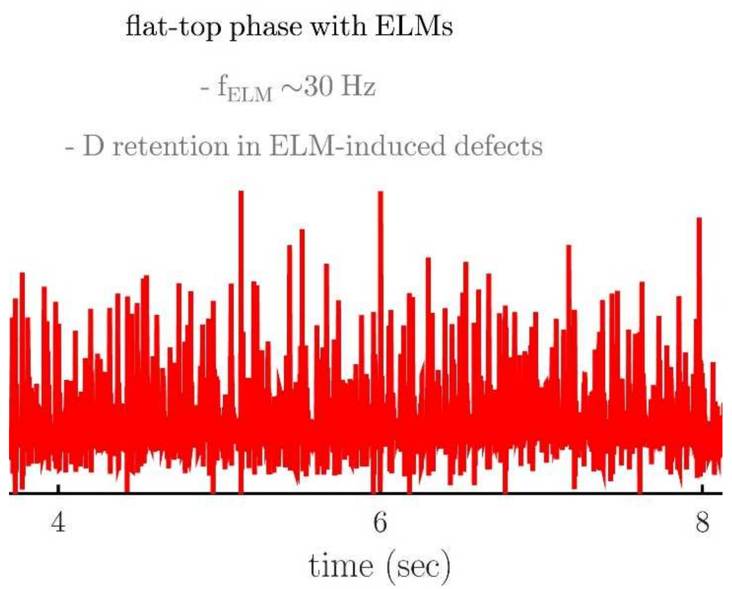
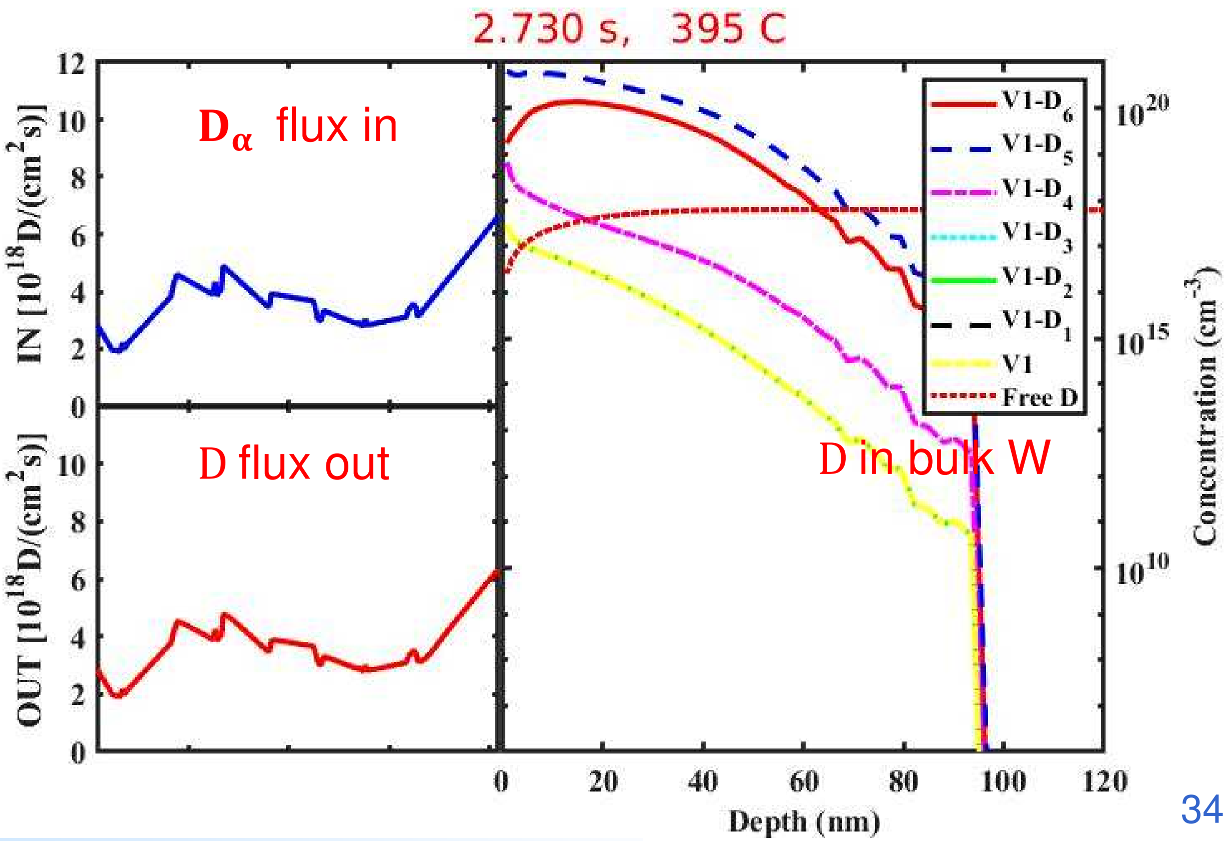
3.c Divertor fuel retention w/ ELMs

- PMI and fuel retention simulation with ELMy plasmas



region 2

- time $2.4 < t < 8$ s
- divertor phase with ELMs (f_{ELM}~30 Hz; 4 keV/D)
- ELM-induced damage, D implantation



- ✓ D retained in near-surface ELM damage
- ✓ effect of target temperature
- ✓ complex dynamics of D trapping/detrapping and mobility of defects

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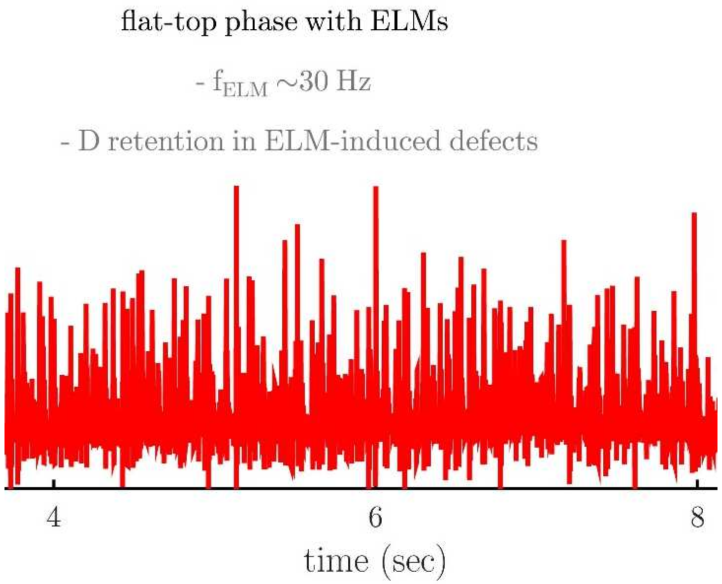
3.c Divertor fuel retention w/ ELMs

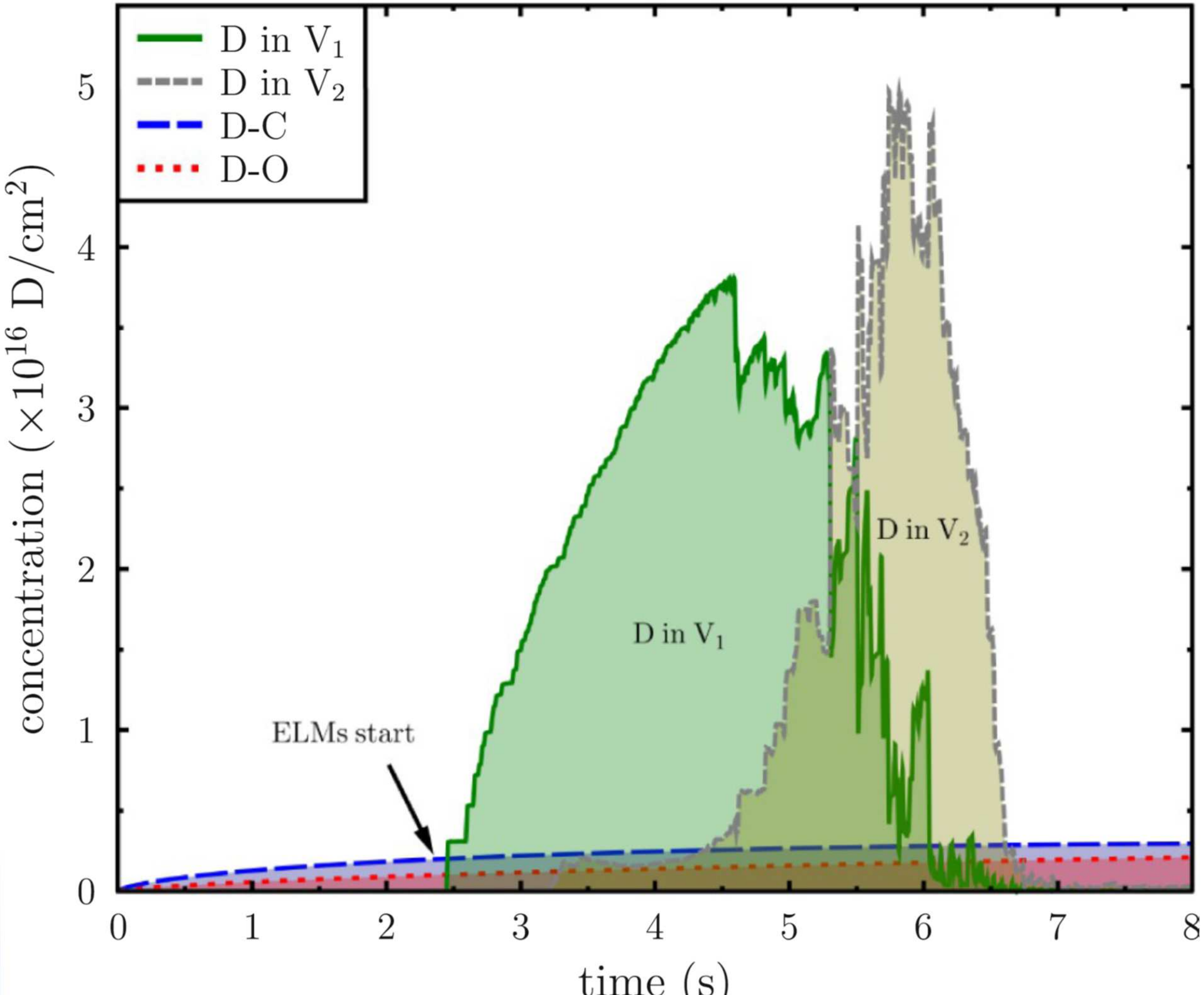
- ❑ PMI and fuel retention simulation with ELMy plasmas



region 2

- ✓ D retained in near-surface ELM damage
- ✓ effect of target temperature
- ✓ complex dynamics of D trapping/detrapping and mobility of defects

- ➢ time $2.4 < t < 8$ s
- ➢ divertor phase with ELMs (f_{ELM}~30 Hz; 4 keV/D)



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IAEA
International Atomic Energy Agency
Atoms for Peace and Development

$$A + M \leftrightarrow PSI \leftrightarrow PMI$$

Thank you!