Introduction into Hydrogen recycling and Tungsten sources in fusion-relevant edge plasmas

IAEA-FZJ Technical Meeting on the Collisional-Radiative Properties of Tungsten and Hydrogen in Edge Plasmas of Fusion Devices

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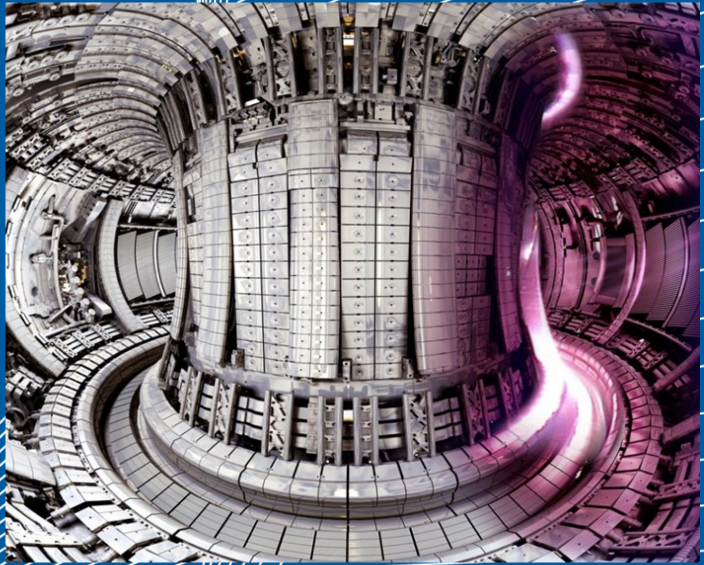
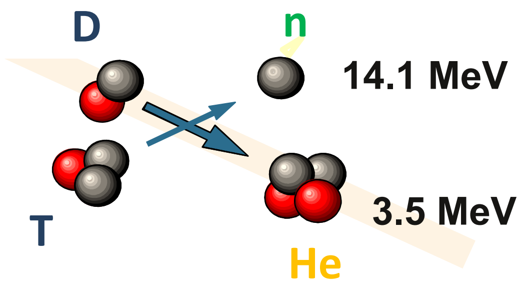


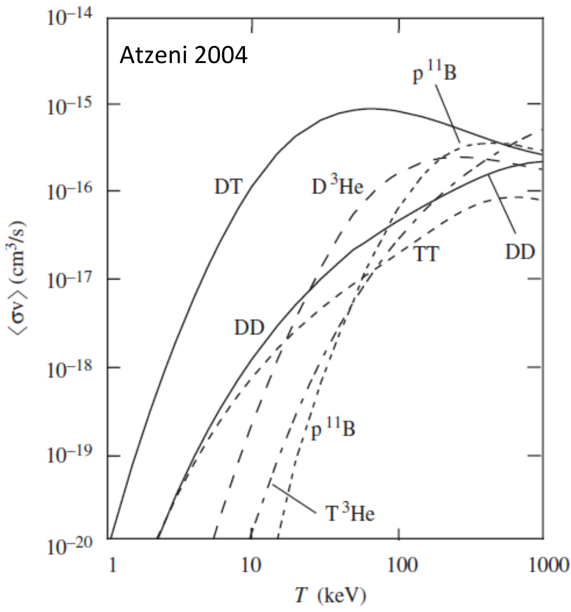
Nuclear Fusion

- Goal: Sustainable and CO_2–free energy source for mankind
- Thermonuclear fusion with largest reaction rate: dt fusion reaction

Maxwell-averaged reaction activity vs ion temperatures for fusion reactions

d + t → α + n + 17.6 MeV





- Measure for fusion power in a 50:50 DT reaction is the triple product:

  ion density (n_i) x ion temperature (T_i) x confinement time (τ_E)
- Ignition in magnetically confined fusion plasmas achievable if:

  n_i [10^{20} m^{-3}] x T_i [10keV] x t_E [5s] ≥ 5x10^{21} keV s m^{-3} (Lawson criterion)

- Requires D and T above 10keV, but the fuel starts as D_2 or T_2 gas or as DT ice pellets entering a cold plasma in eV range. Large gradients in T, n, p!
- Exhaust of He – fusion ash – must be ensured at the cold plasma edge

Outline

- Motivation
- Introduction to Magnetic Confined Fusion
  - Tokamak Functionality
  - Joined European Torus (JET)
  - International Thermonuclear Experimental Reactor (ITER)
  - Power and Particle Exhaust Challenge
- Scrape-Off Layer / Divertor Physics
  - Divertor and Limiter functionality
  - Hydrogen recycling
  - Tungsten sputtering
- Conclusion

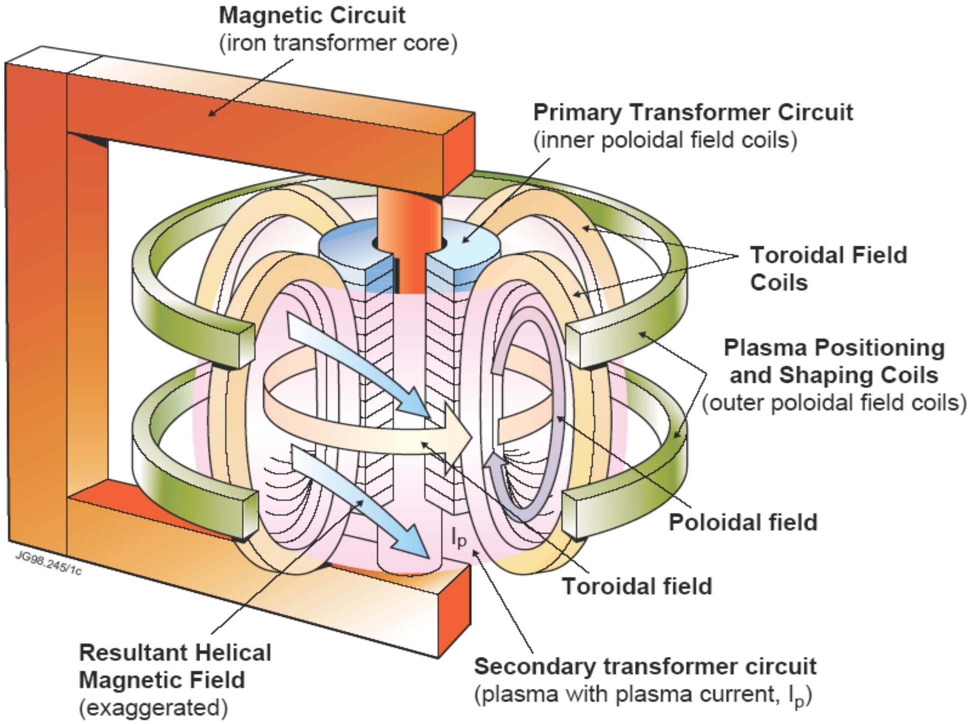
Workshop on Hydrogen in the Plasma Edge (FZJ 10/2000)

1. Molecular hydrogen is formed on the plasma-facing components and is recycled in the plasma edge, where it can be detected spectroscopically. The initial vibrational state of the molecule is important in determining its effect.
2. Theoretical modelling of the dynamics of molecules in plasmas is more complex than just a simple extension of the modelling of atoms.
3. Molecular spectroscopy offers new diagnostic possibilities.
4. The presence of molecules can have an important effect on plasma flows, especially near the plasma edge.
5. Although a considerable amount of molecular data is available for use in plasma modelling, there are important gaps, particularly for HD and D_2, which at present are stopped with intelligent guesses.

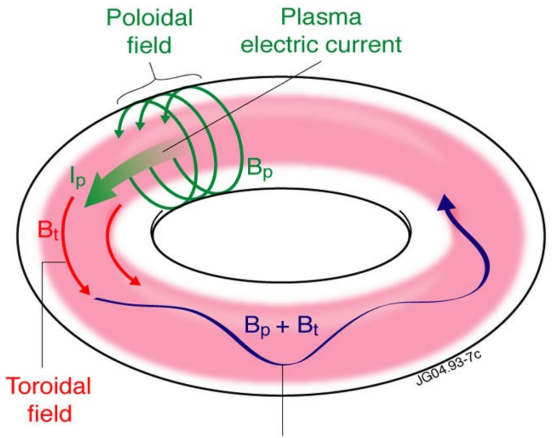
Ph. Mertens and P.T. Greenland
Proceeding in CPP 2002

Magnetically Confined Fusion: Tokamak Principle

- Stable plasma confinement given by a helical, twisted magnetic field structure in torus shape
- Toroidal field component given by large toroidal field coils
- Poloidal field component induced by inductively driven plasma current



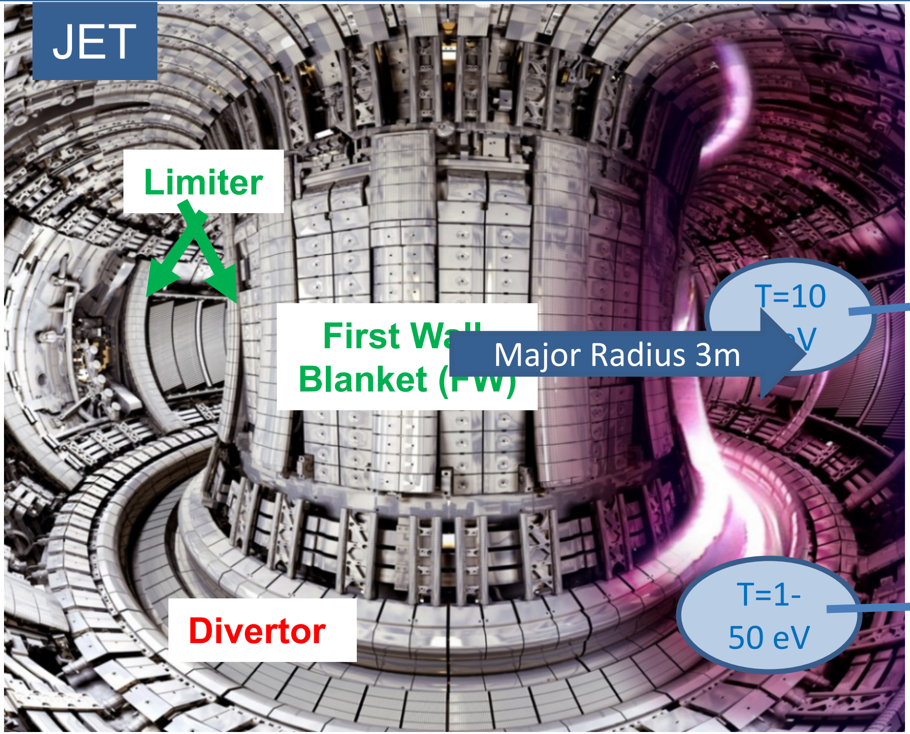
Induced poloidal magnetic field is about 1/10 of toroidal field

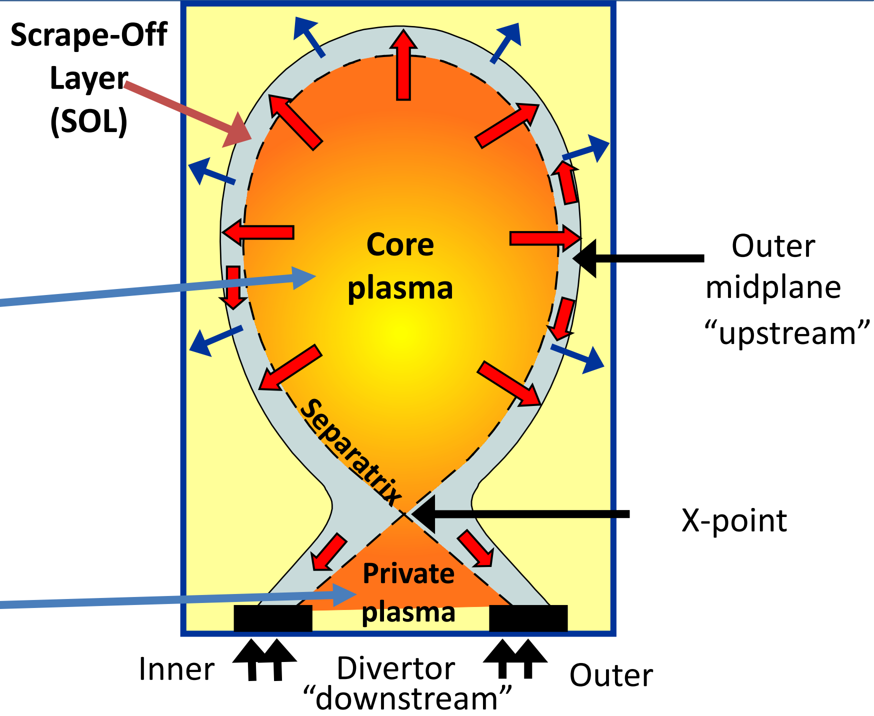


Typically 3-5 toroidal turns for one poloidal turn of a field line

Joint European Torus (JET)

- Largest tokamak currently operating: up to 4.8MA plasma current, 3.45T at max. toroidal field, P_{aux}~40MW
- Joint European Torus (JET) achieved transiently 16MW fusion power in 1997 (with graphite-based wall)
- T_2 plasma experiments currently ongoing |DT experiments with metallic walls start in a few weeks

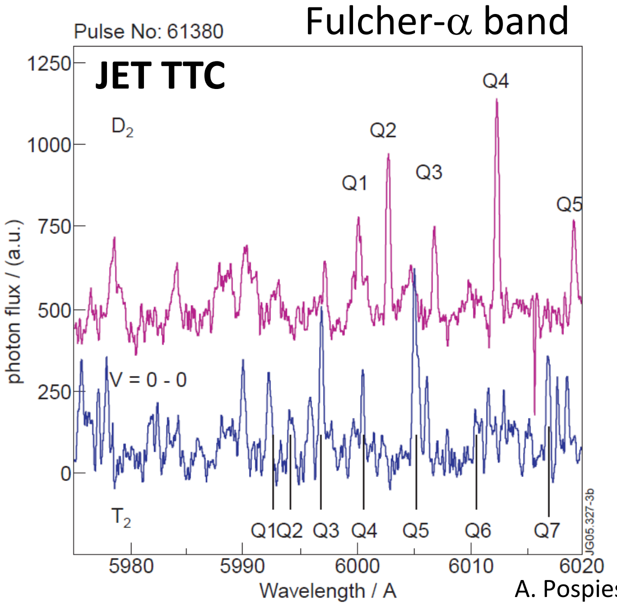




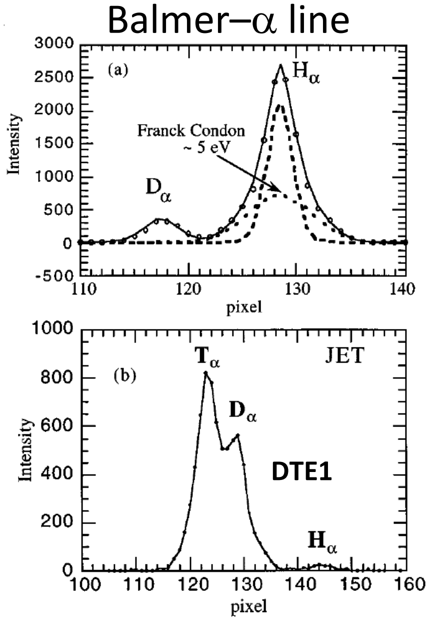
Example of Hydrogen Isotope Emission Spectra in JET

D_2 and T_2 emission spectrum (SOL)

H, D, T emission spectrum (exhaust)



A. Pospieszczyk JNM 2007

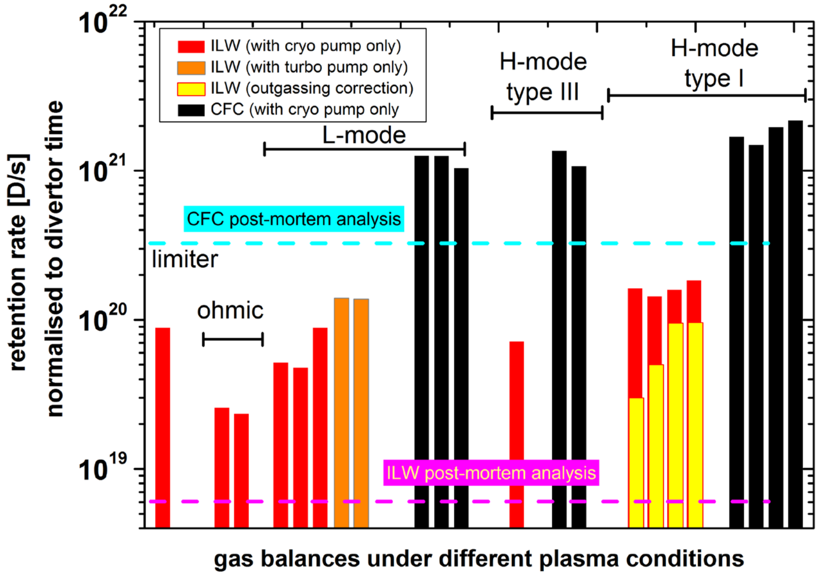


D. Hillis RSI 1999

Cold plasma at the "edges" (T_e=0.1-100eV /n_e=10^{17}-$10^{21}m^{-3}$):
Spectroscopy of (a) fuel H_2, D_2, T_2, HD, HT, DT molecules and H, D, T atoms,
(b) fusion ash, He atoms and ions, and (c) intrinsic (Be, W) and extrinsic impurities (Ne, Ar, N)

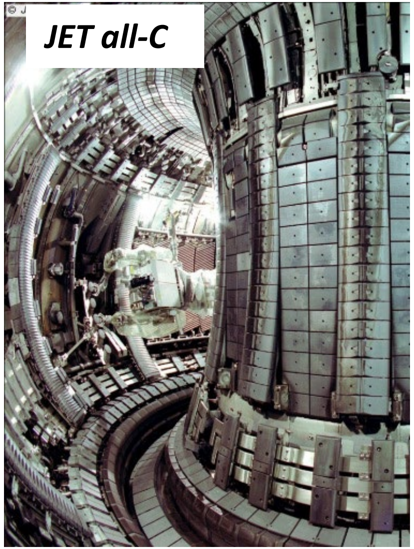
Long-term Fuel Retention: main driver for the change from graphite to metallic plasma facing components

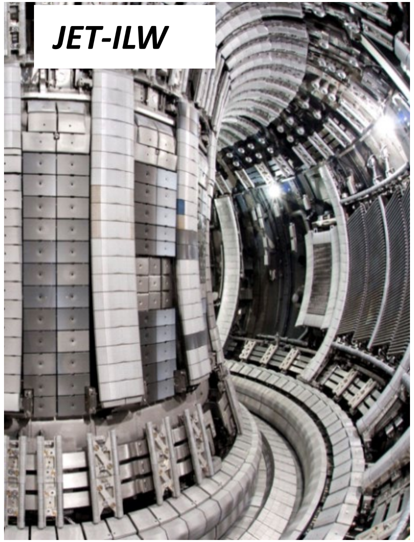
JET confirms reduction in long-term fuel retention with change from **C** to **Be**/**W**



- Lifetime: erosion and melting
- Operation: performance and power exhaust

JET plasma-facing components: from **all-C** to **Be first wall** & **W divertor**

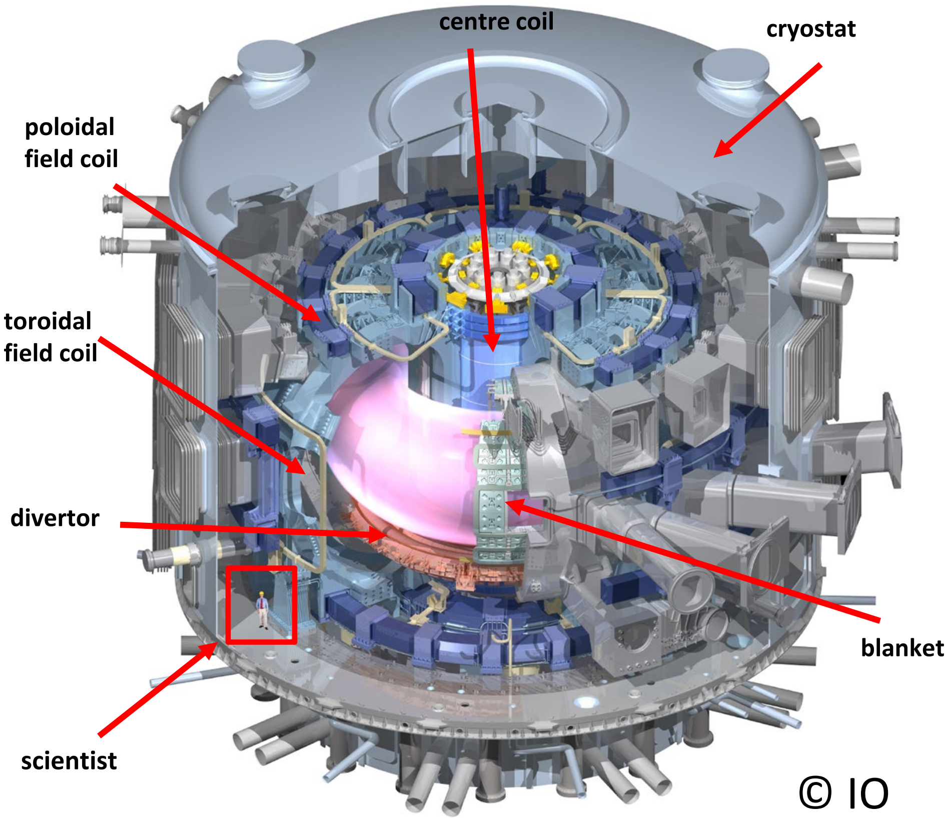




Conclusion: Deuterium plasma operation with graphite walls was rather Deuterium plasma with Carbon seeding resulting in some beneficial properties in the confinement in JET-C!

Next Step Device: ITER

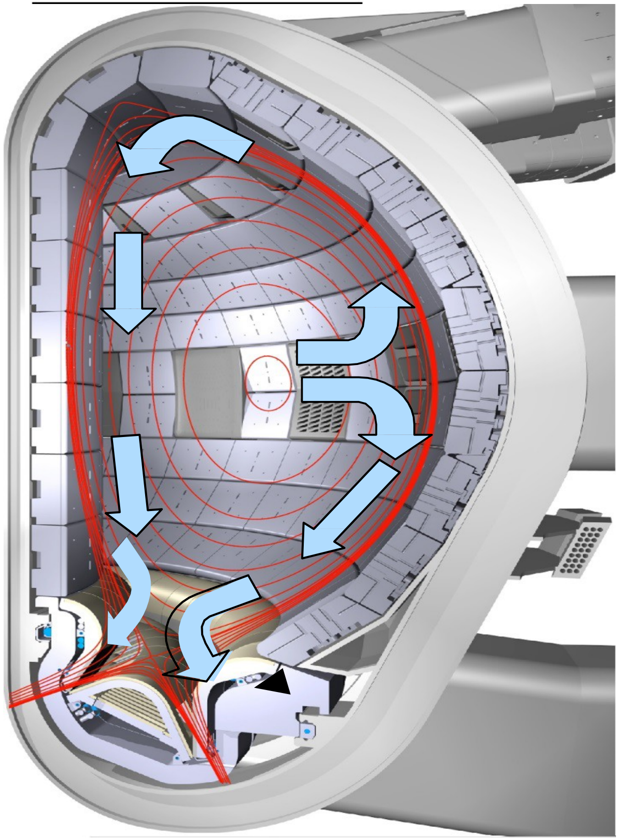
International Thermonuclear Experimental Reactor



- To demonstrate (i) scientific and (ii) technical /plasma-surface interaction feasibility of fusion
- To achieve extended burn in inductively-driven DT plasma operation with Q=10 (400s)
- To demonstrate readiness of essential fusion technologies (incl. breeding blankets)

Major Radius: 6.2 m
Minor Radius: 2.0 m
Plasma volume: 840 m^3
Surface area: 260m^2 W and 620m^2 Be
Plasma current: 15 MA
Magnetic field: 5.3 T (12 T)
Energy content: 350 MJ
Auxiliary heating: 70-100 MW
Height: ~25 m and Diameter: ~26 m

The Power and Particle Exhaust Challenge for ITER



- He-ash is transported out of the plasma on a faster timescale than the energy confinement time
- Particles (**D^+, T^+, He^{2+}, e^-**) are transported (perp B) into the SOL and stream towards the **divertor target plates** at glancing incidence
- In the original scaling law for ITER (unfueled H-mode with 500MW=P_{fus}) one reaches at the target plates more than **40 MW/m^2**
- Divertor plasma solution needs to be adapted to meet material components limit **(~10 MW/m^2)** : radiation-induced detachment
- To enable DT plasma operation: **W concentration** needs to be below 10^{-4} which is linked via transport to the **W** divertor **source**
- Prediction of DD and DT operation (2035) via modelling: SOLPS-ITER => real DT mix modelling pending / T_2 data in EIRENE?

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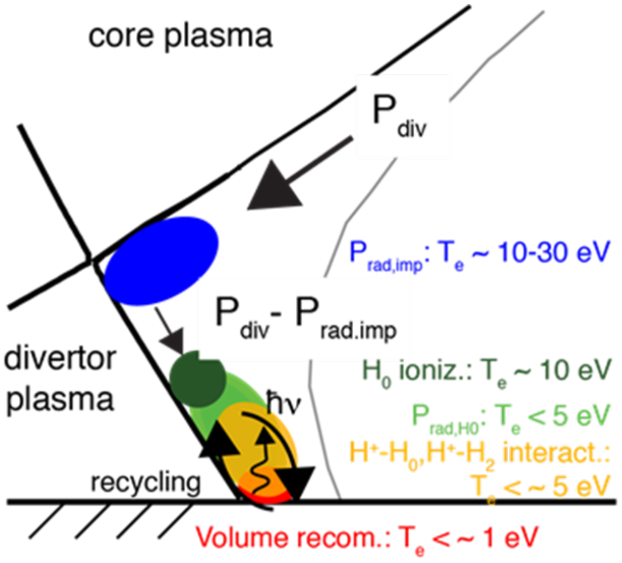
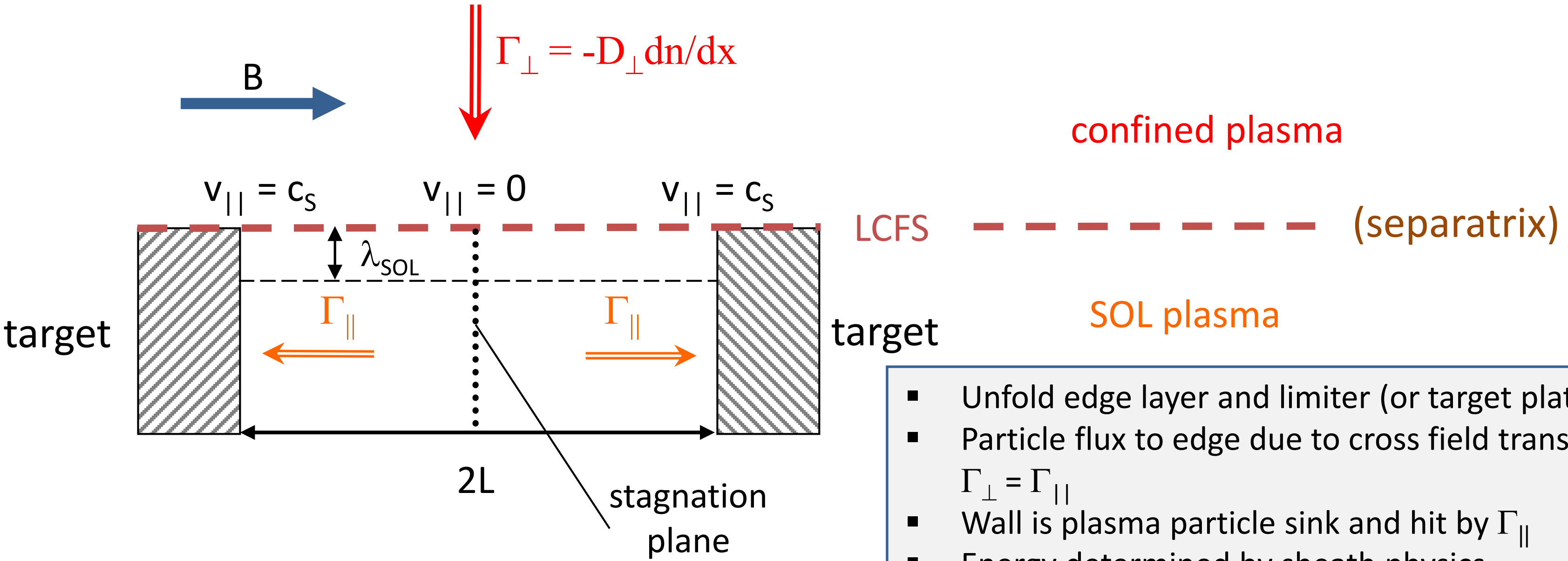
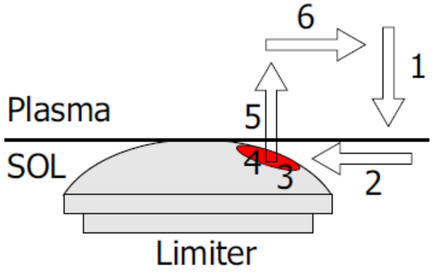


M. Groth et al.

Simple Model for the Edge Plasma



- Unfold edge layer and limiter (or target plate)
- Particle flux to edge due to cross field transport $\Gamma_\perp = \Gamma_{||}$
- Wall is plasma particle sink and hit by $\Gamma_{||}$
- Energy determined by sheath physics
- Plasma-wall interaction processes occur e.g.
  - Recycling of fuel species (e.g. H isotopes)
  - Erosion of wall materials (e.g. W, C)

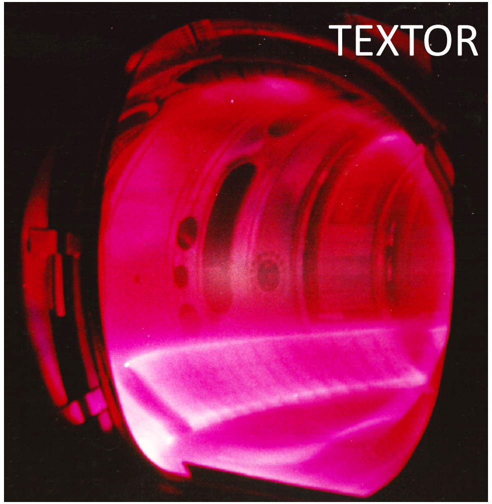


Impact: D^+
Release: D_2, D

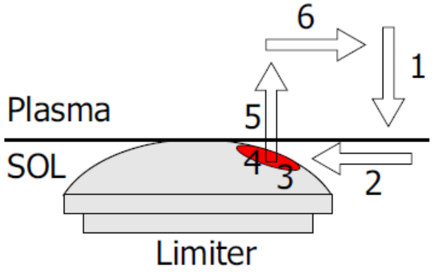
Edge Plasma Emission Interpretation

Colour camera: here mainly

$D\alpha$ + D_2 Fulcher band emission

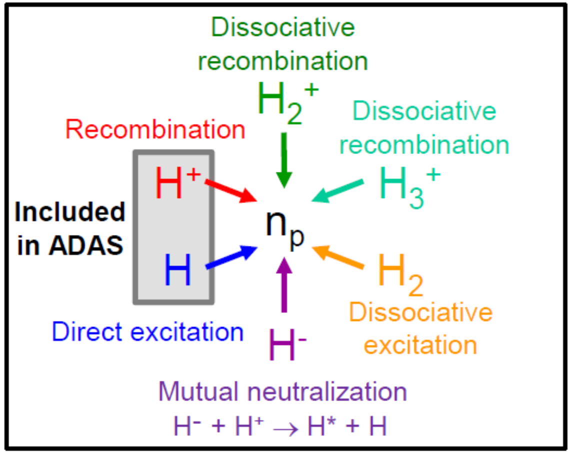


T_e~50eV at LCFS



Impact: D^+

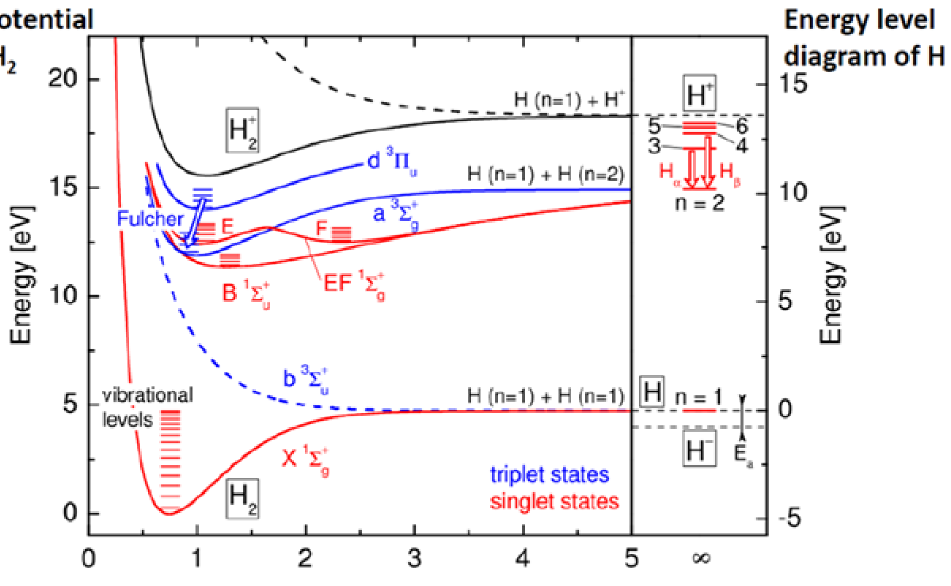
Release: D_2, D



U. Fantz et al.

Interpretation of Balmer alpha complex in cold plasmas!
CRM like EIRENE / YACORA useful

Hydrogen Recycling: Balmer-Line Emission I



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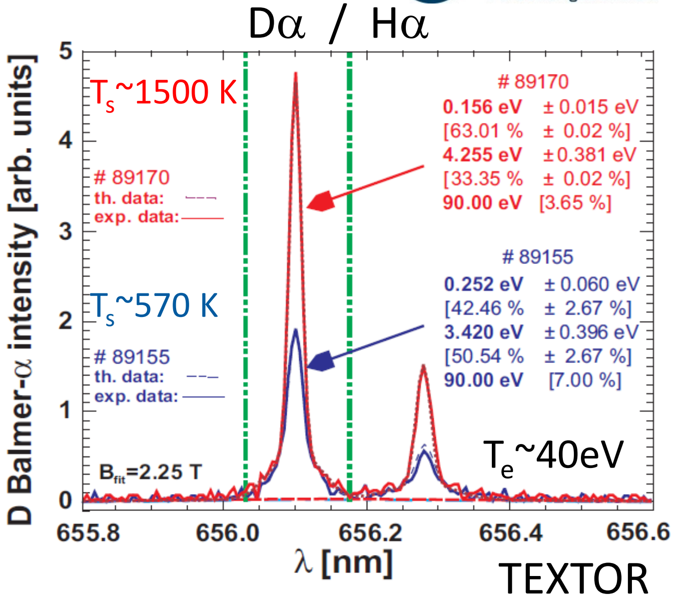
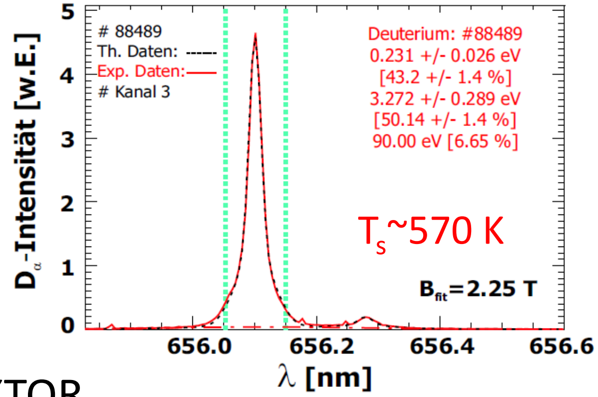


TEXTOR

- Very cold atoms (~0.3eV) in front of graphite surfaces at $T_{surface}$~500K and T_e>> 10 eV plasmas observed
- Atom production mainly via break-up of molecules originating from the wall (graphite)
- Surface conditions can impact the line shape (atom energy) / change of atom to molecular release ratio
- Plasma conditions can impact the line shape and (atom energy) / change of destruction path

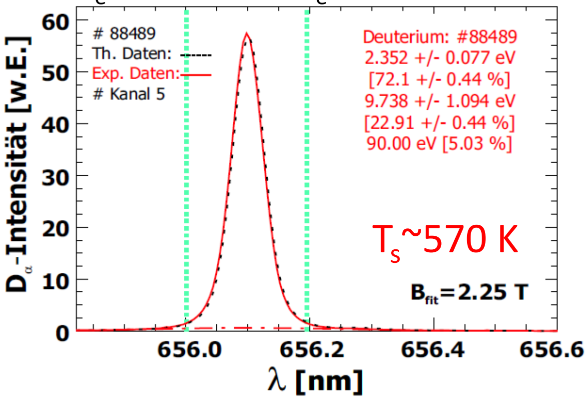
Hydrogen Recycling: Balmer-Line Emission II

T_e=30 eV and n_e=8x10^{18}m^{-3}



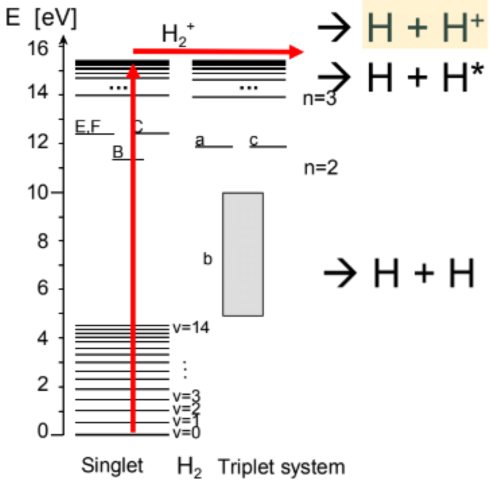
TEXTOR

T_e~^10 eV and n_e=1.2x10^{19}m^{-3}



Attached, low recycling

Te ≥10 eV

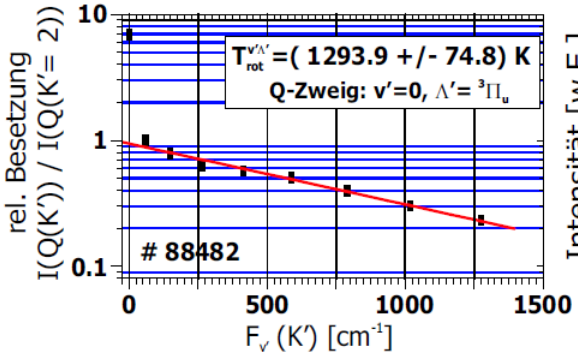


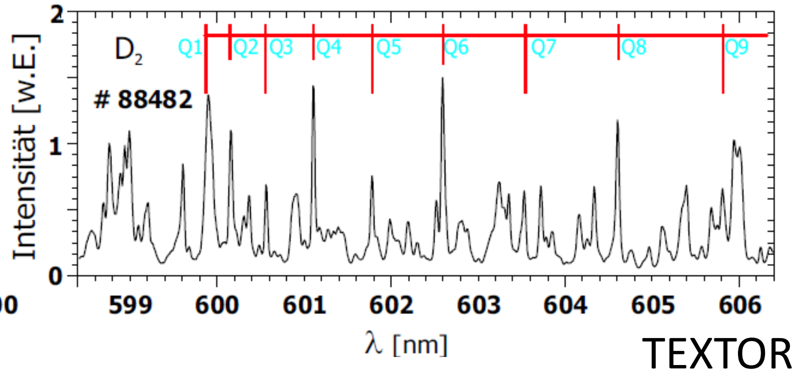
electron impact processes dominant

D_2 Molecules: Rotational Population

Fulcher Band:
3p $^3\Pi_u$ -> 2s $^3\Sigma_g$

Note in fusion:
molecular isotopomers:
T_2, TD, D_2, HD, H_2, HT





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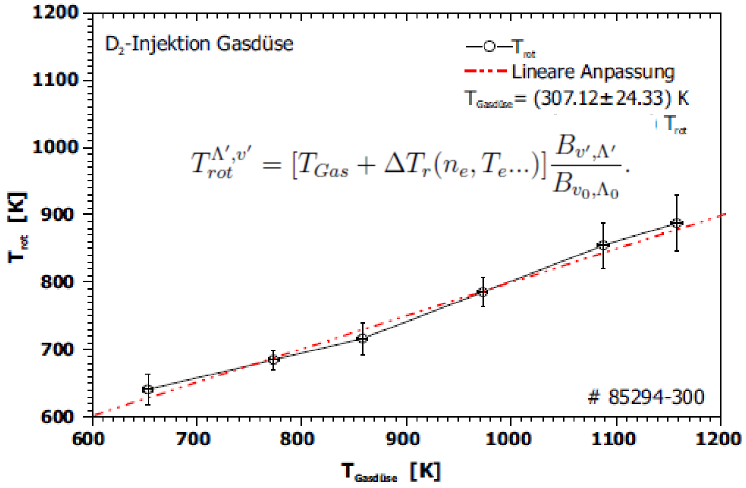
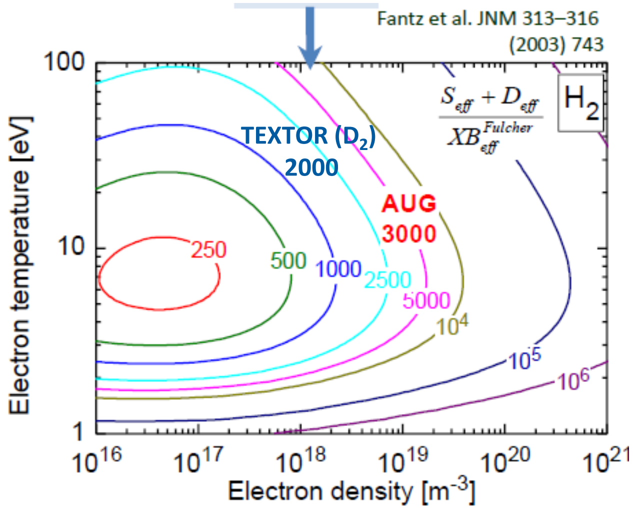


- Rotational analysis of each vibrational level of the upper state shows reduction of T_{rot} with v
- T_{rot} depends on T_e and n_e as well as $T_{gas/surface}$
- T_{rot} is usually not in equilibrium with T_e

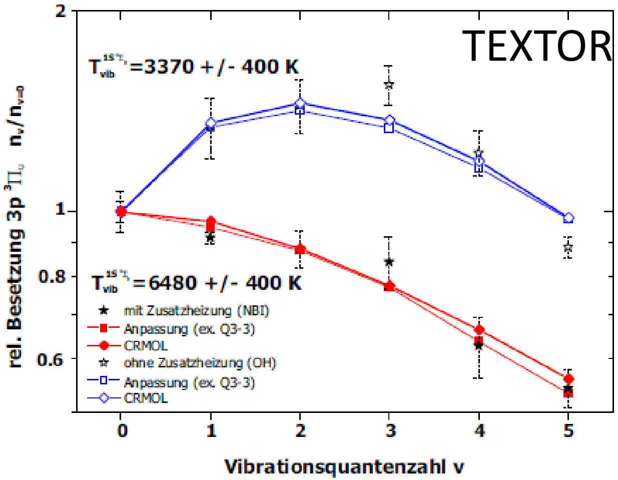
D_2 Molecules: Vibrational Population

- Vibrational population in upper state via Fulcher bands
- Linked to ground state via collision-radiative models CRM (EIRENE, YACORA) for H_2 [and D_2] and T_e in divertor
- Direct measurement of ground state preferable (VUV)
- Surface materials can impact on initial distribution: e.g. a-C:H layers, Ta and cause non-Boltzmann deviations



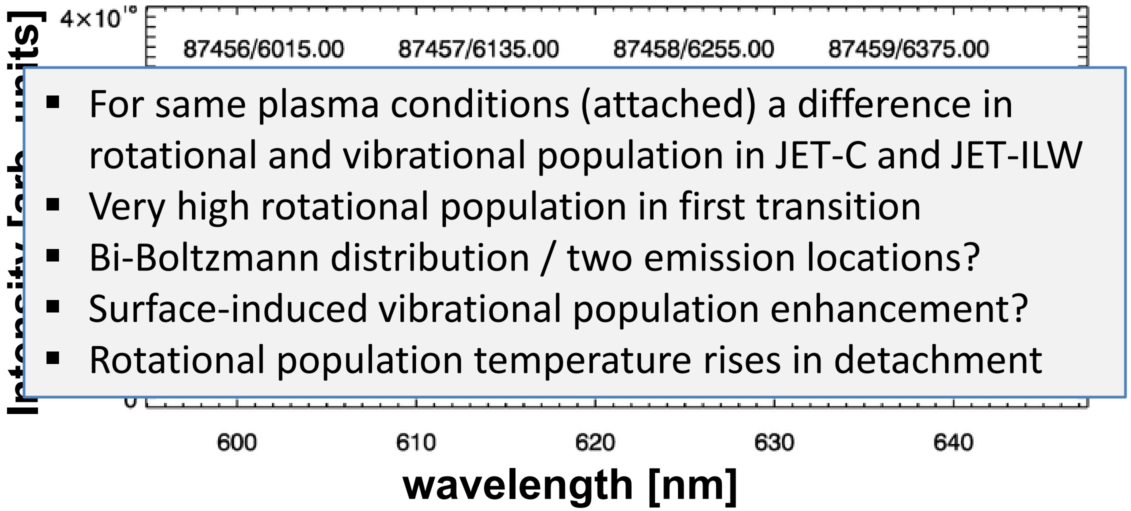
B. Heger et al., U. Fantz et al.

S. Brezinsek PPCF 2005
PT Greenland FZJ report

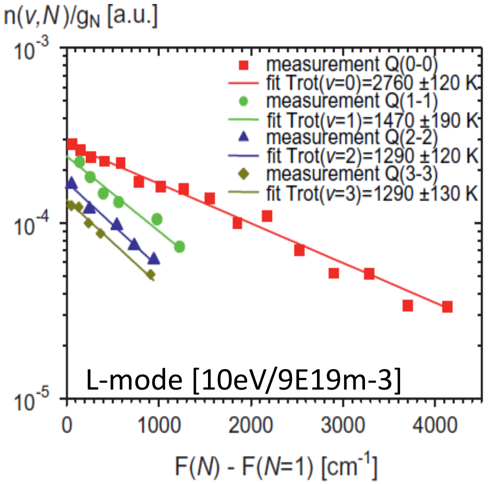


- Conversion of Fulcher band photons into particles via photon efficiencies for the entire electronic transition
- CRMs or experiment required for (D/XB)
- Doable for ionizing plasma conditions, but challenging for recombining plasma conditions

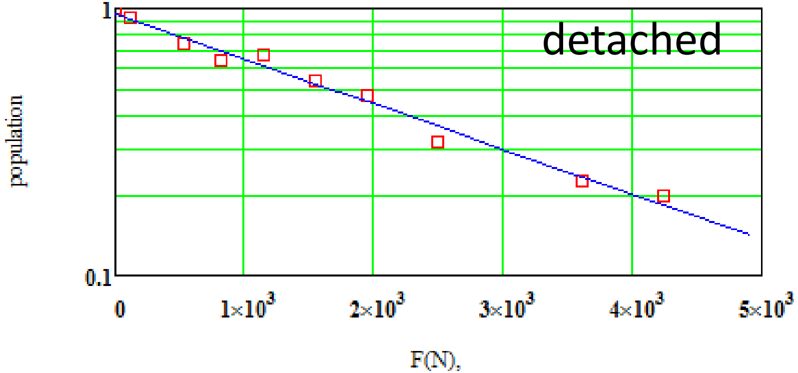
D_2 molecules in JET with W Divertor



- For same plasma conditions (attached) a difference in rotational and vibrational population in JET-C and JET-ILW
- Very high rotational population in first transition
- Bi-Boltzmann distribution / two emission locations?
- Surface-induced vibrational population enhancement?
- Rotational population temperature rises in detachment



G. Sergienko JNM 2013



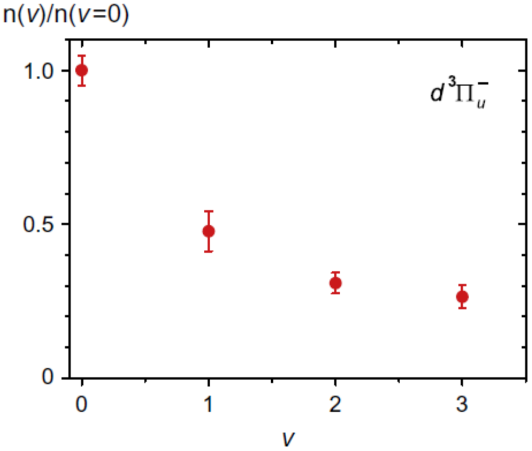
rotational temperature:

$TD_{0,\,picture} = 3.70174 \times 10^{3}$ K

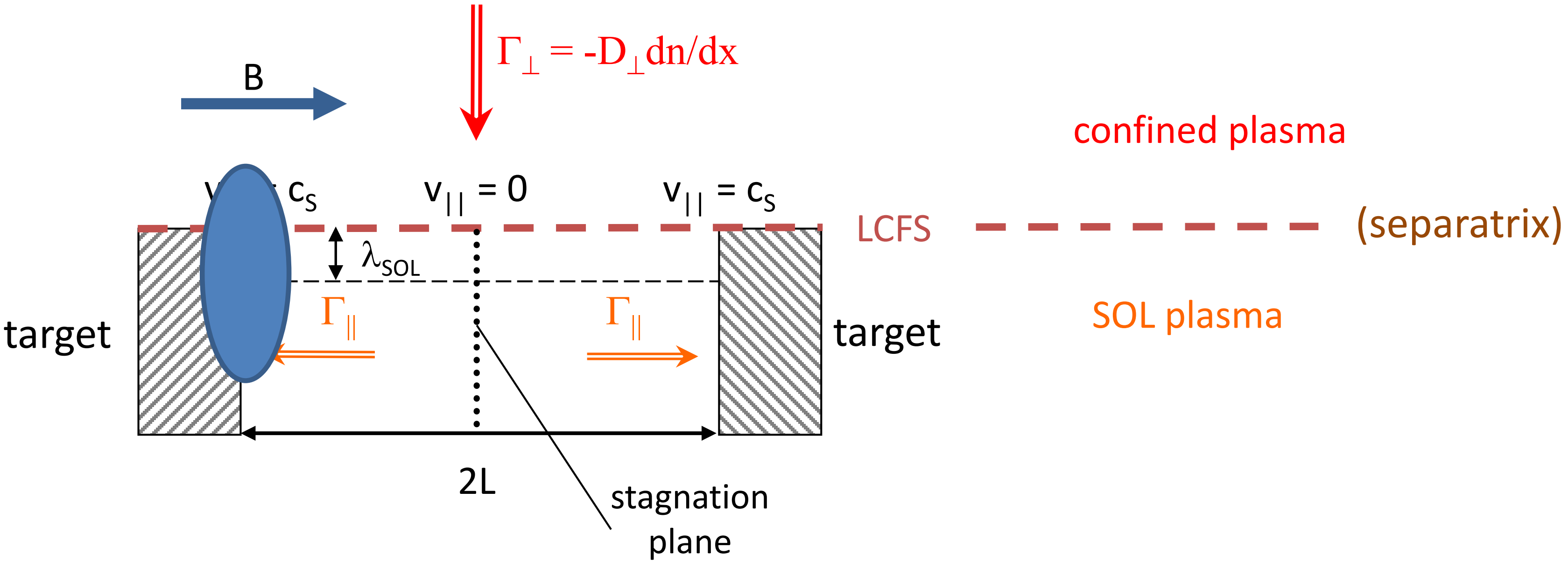
standard deviation of the rotational temperature:

$TD_{2,\,picture} = 174.96425$ K

S. Brezinsek et al.



Simple Model for the Edge Plasma II

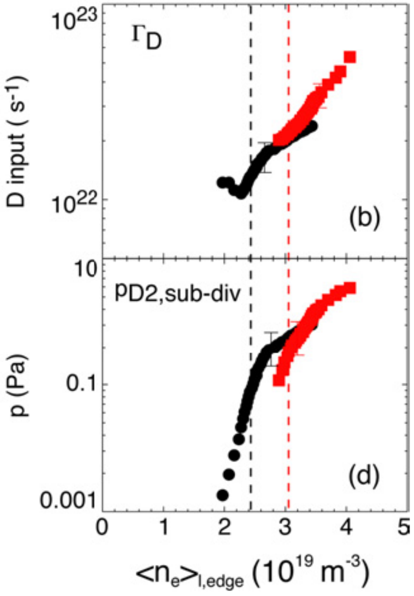


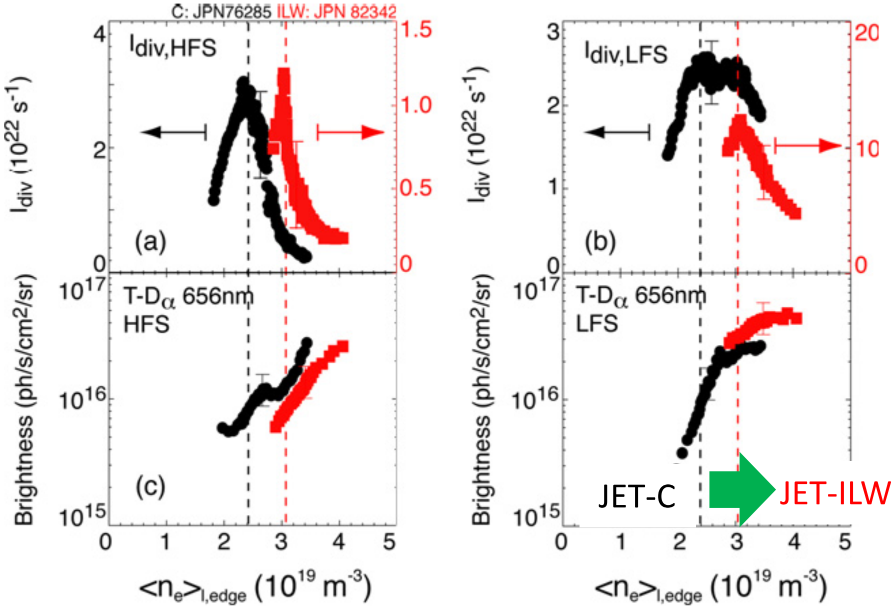
- Formation of a neutral cushion in front of the target plate / loss of momentum of impinging plasma ions along B: Recycling, + Radiation + Friction + Recombination ...
- Shall prevent ions to hit the target plate and deposit power / erosion of target plate by impinging ions

JET L-mode: Complete Detachment in Divertor due D_2

JÜLICH Forschungszentrum

- During a fueling ramp in the divertor one passes all steps from recycling via “ion flux roll over” to detachment



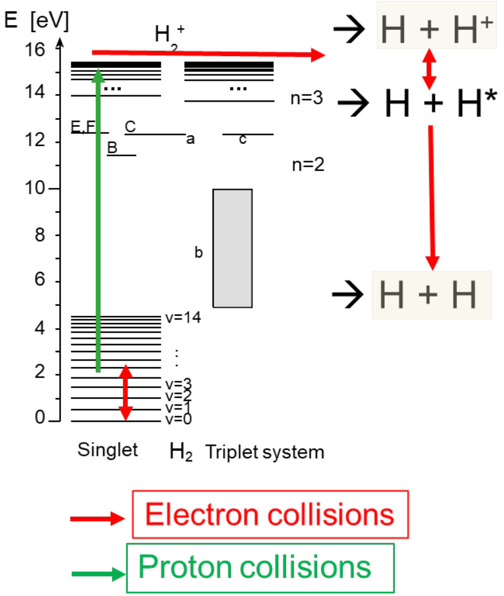


M. Groth et al. Nucl Fus. 2013

Comparison of Relevant Processes in Detachment

Detached

Te ≈ 1 - 3 eV



Molecular **A**ssisted **R**ecombination **MAR**

$H_2(v) + H^+ \Rightarrow H_2^+(v) + H$ — charges exchange with

$H_2^+(v) + e^- \Rightarrow H + H^*$ — dissociative recombination

Molecular **A**ssisted **D**issociation **MAD**

$H_2(v) + H^+ \Rightarrow H_2^+(v) + H$ — charges exchange with

$H_2^+(v) + e^- \Rightarrow H + H^+ + e^-$ — associated dissociation

n_e~10^{19}-10^{21} m^{-3} and T_e~2-10eV

Electron **I**on **R**ecombination **EIR**

$H^+ + e^- + e^- \Rightarrow H + e^-$ — three body recombination or

$H^+ + e^- \Rightarrow H + h\nu$ — radiative recombination

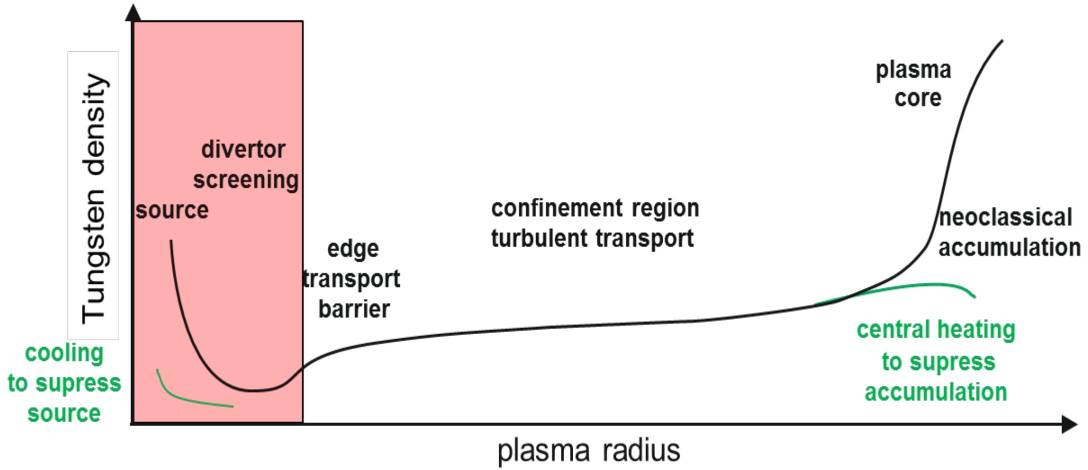
n_e~10^{20}-10^{21} m^{-3} and T_e<1.5eV

See U. Fantz, D. Wünderlich, D. Reiter, R. Janev, K. Sawada etc.

- Competition between different processes sensitive to the plasma conditions => Collisional-radiative models
- Sensitive to (ro-vibrational) ground state population | need for rotational-resolved data
- Sensitive to isotopes | need for isotope-resolved data

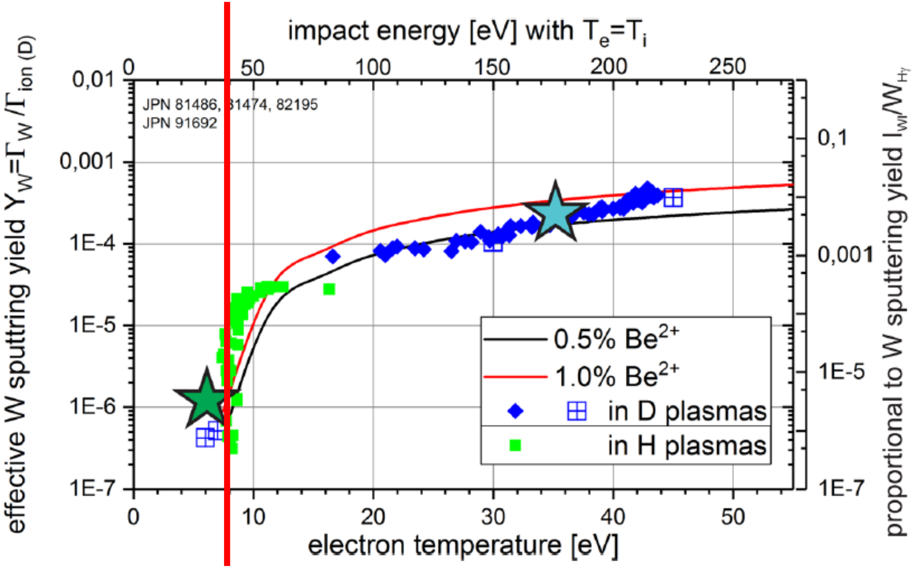
The Challenge of W in Fusion Devices

- High radiation potential (core cooling)
- Prone to accumulate in core (transport)
- Low concentration in core is permitted (ITER ~10^{-4} / DEMO ~10^{-5})
- W control mainly via spectroscopic tools by using divertor cooling by seeding (source) and central heating (core) as actuator

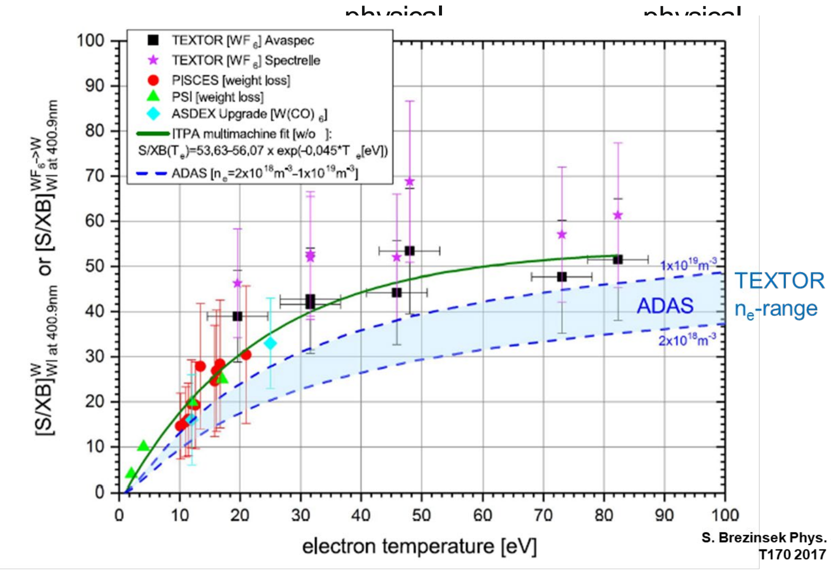


Physical Sputtering of W

- Binary-collision approximation with perpendicular impact of mono-energetic projectiles



W source spectroscopy focused on WI emission at 400.875nm with experimental calibration in cold plasma conditions => S/XBs

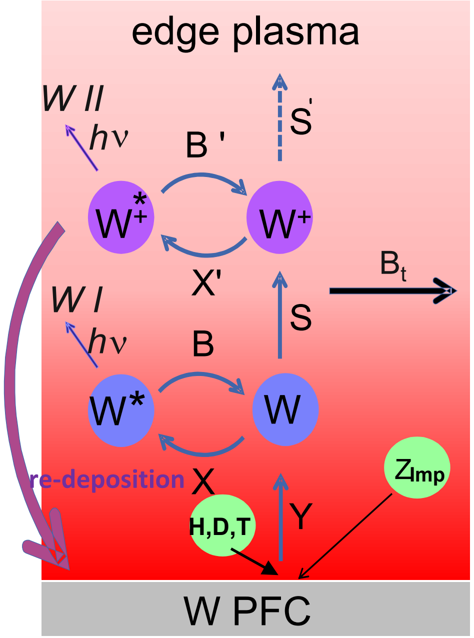


S. Brezinsek Phys. Scrip T170 2017

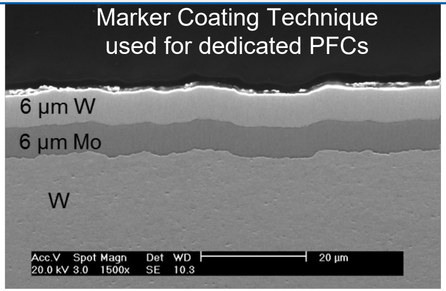
- W sputtering by intrinsic (Be) or seeding impurities (Ne, Ar, N) above threshold energy E_{th}
- Operation in detached divertor inhibits W sputtering

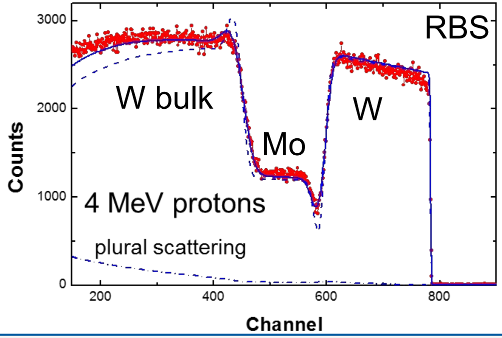
Gross and Net Erosion of W

Optical Emission Spectroscopy (WI):
gross erosion of W [in situ]



Post-Mortem Analysis Techniques:
net erosion of W [ex situ]





M. Mayer et al.
NME 2017

- Difference provides local W balance: eroded, re-deposited, and transported away
- Erosion of W is in general low | local re-deposition high in present-day devices
- JET experiment at high fluence allowed comparison of both methods: >95 % local re-deposited [S. Brezinsek NF 2019]

Challenges in W Spectroscopy and Atomic Data

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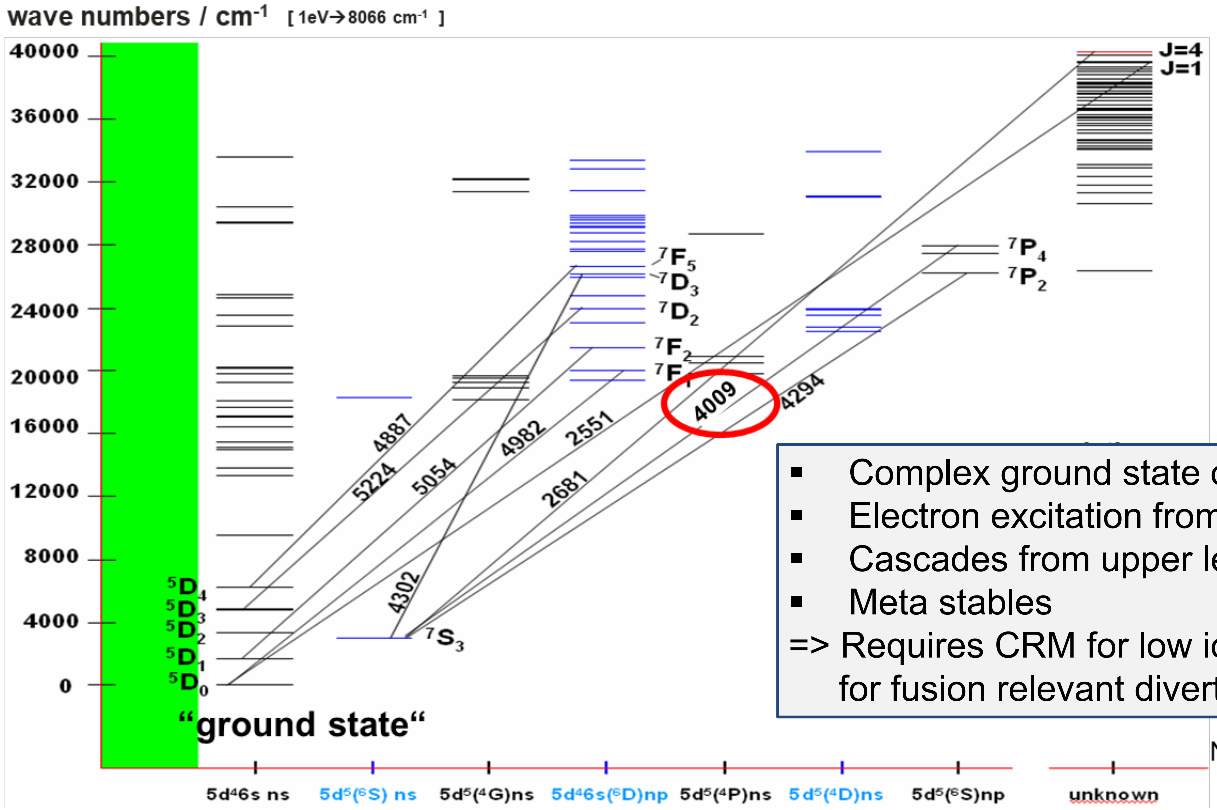


- Complex ground state of neutral W
- Electron excitation from ground state (population?)
- Cascades from upper level
- Meta stables

=> Requires CRM for low ionization levels of W
for fusion relevant divertor conditions

NIST atomic data

Conclusion

Hydrogen recycling and needs for improved CRM

- Need more vibrationally resolved data than currently available
- Need to have rotationally resolved data
- Need to have isotopically resolved data
- Ensure consistency in present data (range of fusion application)
- Synthesize molecular spectrum in model to compare with experiment

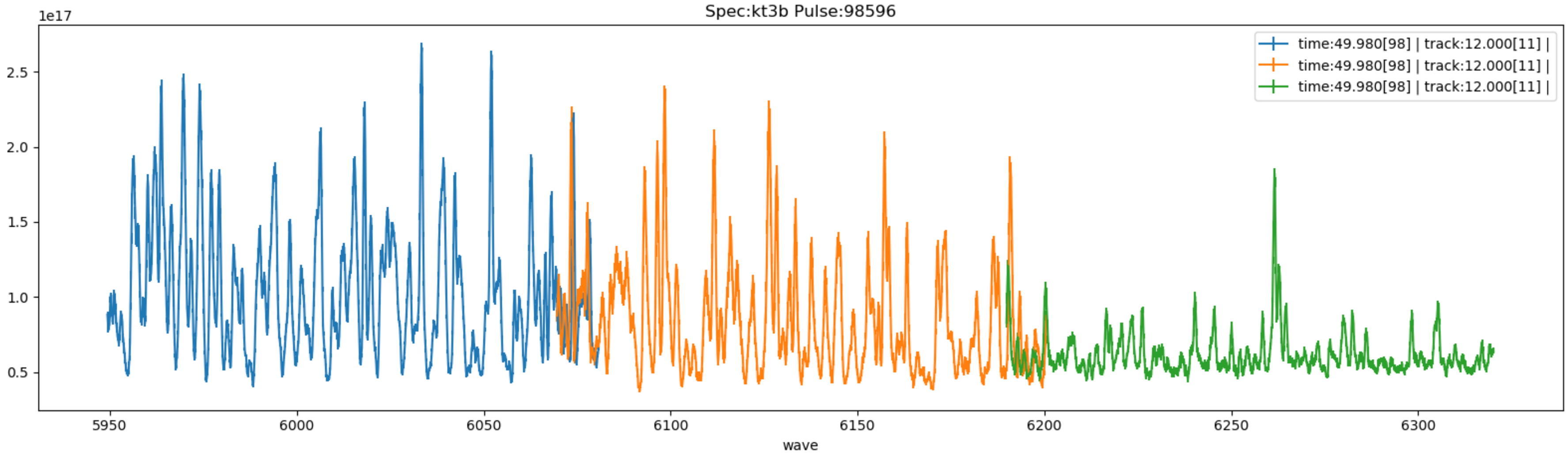
Tungsten erosion and needs for W CRM

- Need to cover complex ground state as well as metastable
- Need to cover low ionization states of W (W, W^{+}, W^{2+}, W^{3+} etc.) relevant for divertor
- Ensure consistency in present data (in the range of fusion application)
- Synthesize atomic spectrum in model to compare with experiment

This meeting will cover the actual status, shall stimulate discussions, identify needs (fusion community) and capabilities in the A&M data community

Spare

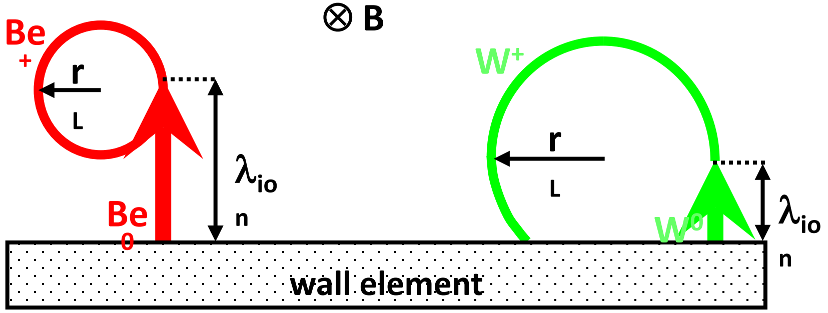
T_2 Fuclher band with HT minority measured in JET-ILW T_2 plasmas



ELM-induced W Sputtering in Detached Conditions

Inter-ELM W source eliminated when impact energies below the threshold for impurities

Intra-ELM W source can burn through the neutral cushion of hydrogen and seed impurities

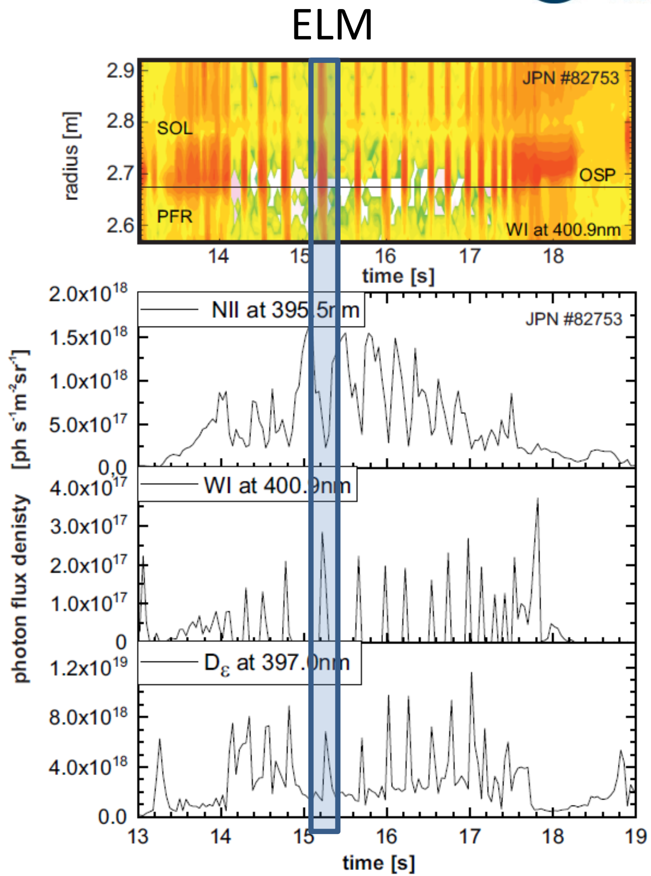


Larmor radius: $r_L = M\cdot v_\perp / q\cdot B$

Ionisation length: $\lambda_{ion} = v_\perp / \langle\sigma v\rangle_{ion} \cdot n_e$

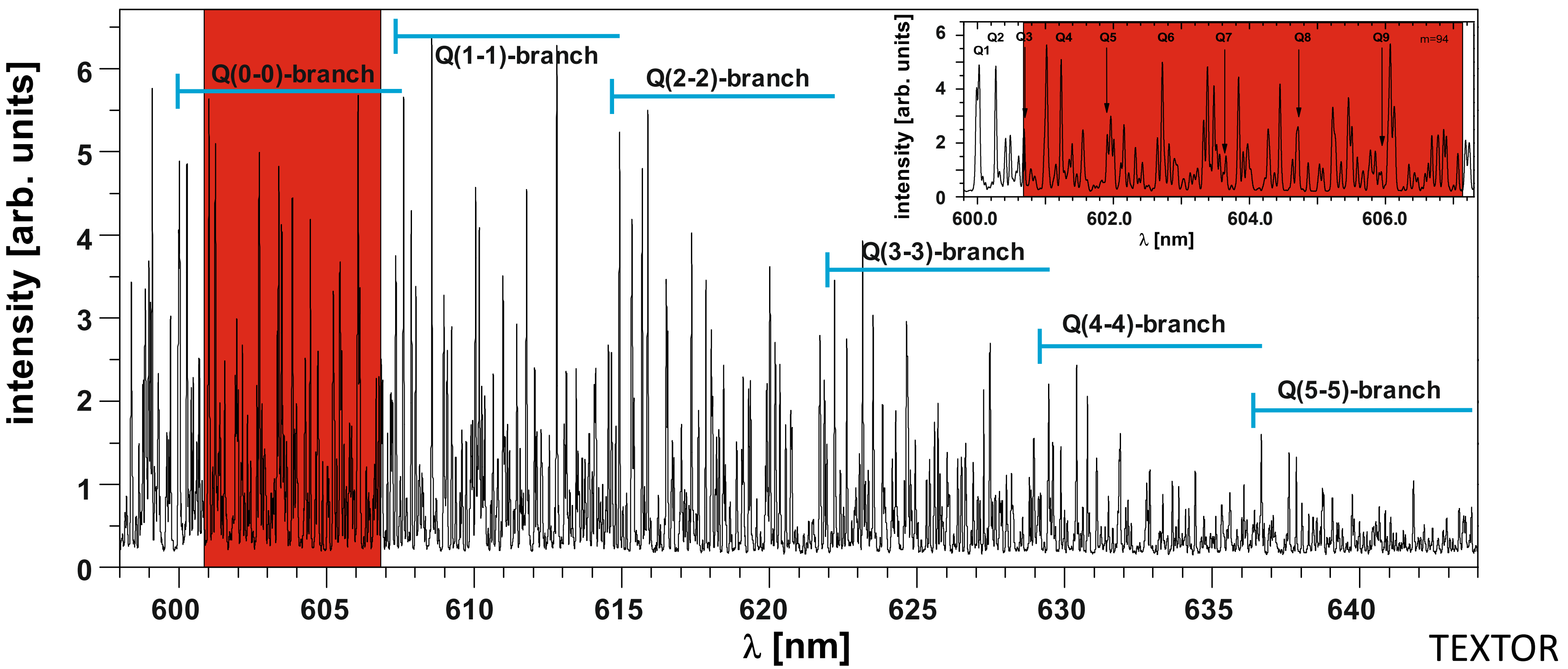
$$\rho_{prompt} = \lambda_{ion}/r_L$$

- Prompt re-deposition of W if $\rho_{prompt} < 1$
- Results in LOW net erosion for W if $\rho_{prompt} < 1$



S.Brezinsek et
NF 2019
A. Kirchner et a
PPCF2019

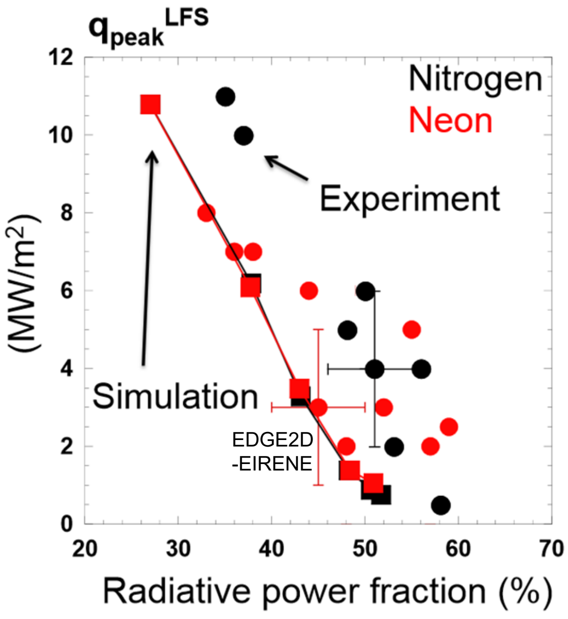
D_2 Fulcher Band: 3p $^3\Pi_u^+$-> 2s $^3\Sigma_g^-$



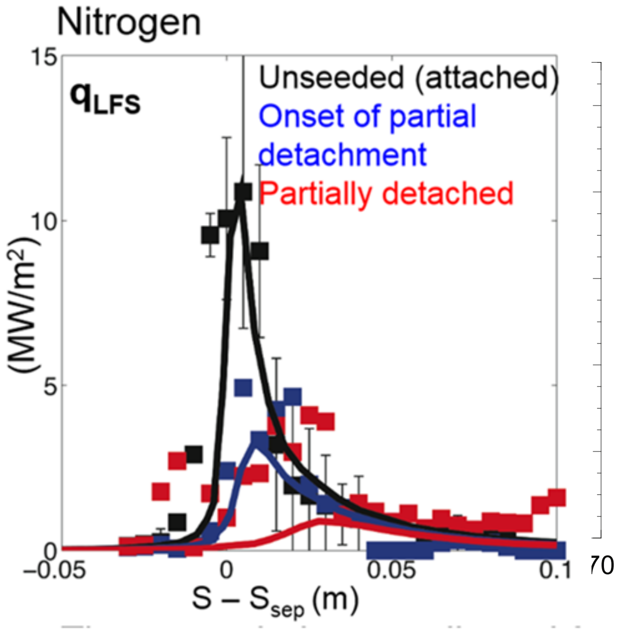
Molecules in the SOL and divertor plasmas of fusion devices!

Divertor Detachement with N_2 Seeding in H-mode

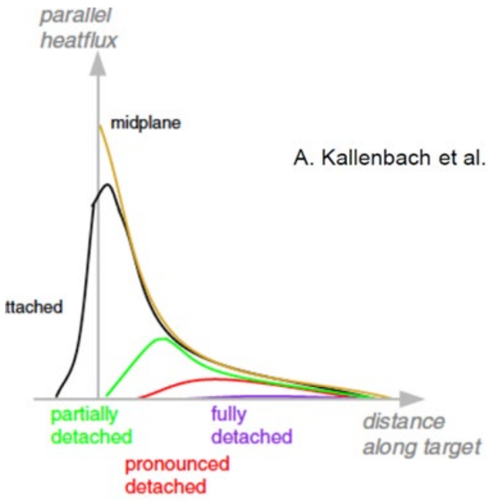
- Full detachment at outer target plate: sequence of power detachment (nitrogen radiation), momentum detachment (D ion-neutral friction) and particle detachment (D volume recombination) reproduced
- Compatibility with power loads and W source for long-pulse operation like in ITER
- Nitrogen radiates predominantly in divertor whereas neon in the edge layer of JET



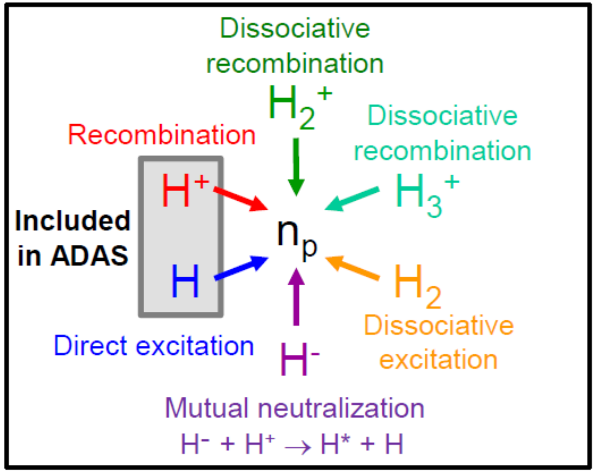
C. Giroud et al.
NF 2014



A. Jarvinen et al.
JNM 2015



Population of Atomic Hydrogen and Line Emission



$$
\begin{aligned}
n(p) = {} & R_H(p)\boxed{n_H}n_e \\
& + R_{H^+}(p)\boxed{n_{H^+}}n_e \\
& + R_{H_2^+}(p)\boxed{n_{H_2^+}}n_e \\
& + R_{H_3^+}(p)\boxed{n_{H_3^+}}n_e \\
& + R_{H_2}(p)\boxed{n_{H_2}}n_e \\
& + R_{H^-}(p)\boxed{n_{H^-}}n_e
\end{aligned}
$$

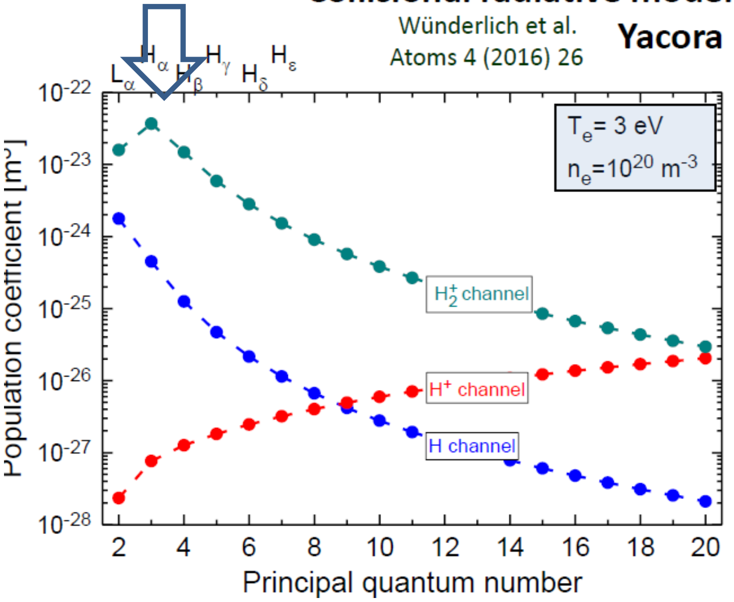
U. Fantz et al.

Interpretation of Balmer alpha very complex in these cold divertor plasmas!

Collisional radiative model

Wünderlich et al.
Atoms 4 (2016) 26

Yacora



Population coefficient **PC**: $R_s = \frac{n_p}{n_e \cdot n_s}$

with n_s= density of H, H^+, H_2^+,...

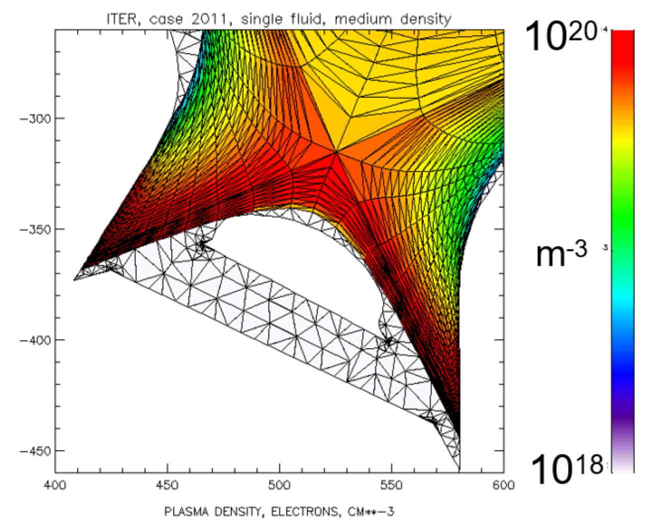
Photon emission coefficient **PEC**: PC·A_{ik}

with A_{ik}= respective Einstein coefficient

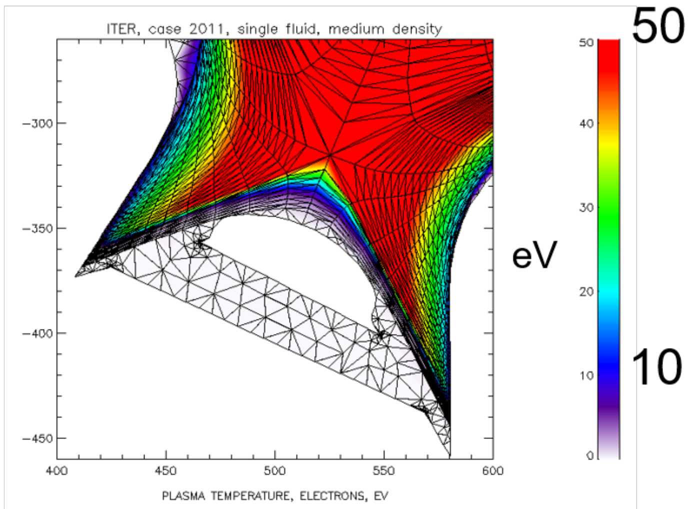
ITER: Divertor Plasmas Solution: SOLPS-EIRENE

- Plasma solution with SOLPS-EIRENE with C exists / Update: SOLPS-ITER for Ne,N_2 and D plasmas
- Self sustained dense, cold plasma layer (≈ 1 – 3 eV) formed in front of divertor components
- Plasma flux drops, despite increased density. Momentum loss predicted.
- ELM burn through not considered / Atomic and molecular data for T, DT not included

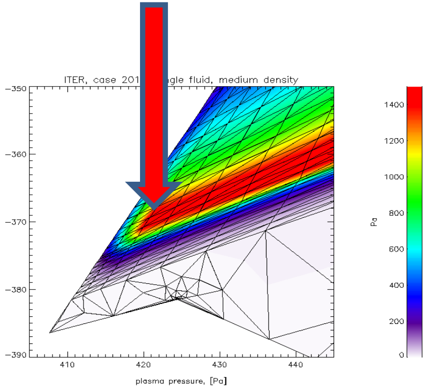
Divertor plasma density
m^{-3}, log scale, 10^{18} - 10^{20}



Divertor electron temperature
eV, lin. scale, 0 – 50 eV

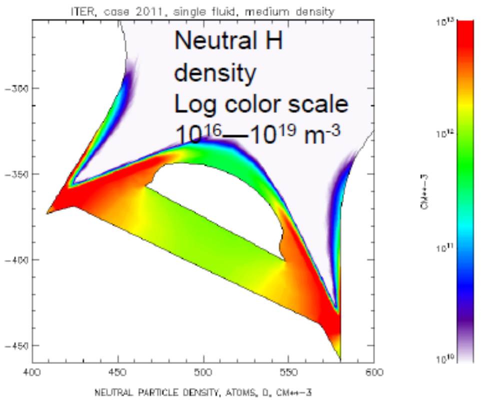


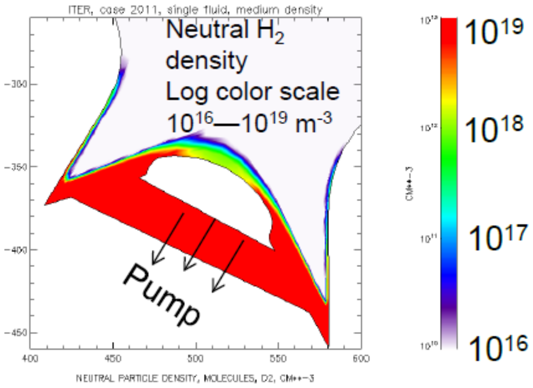
Pressure drop



D. Reiter et al. PSI2018

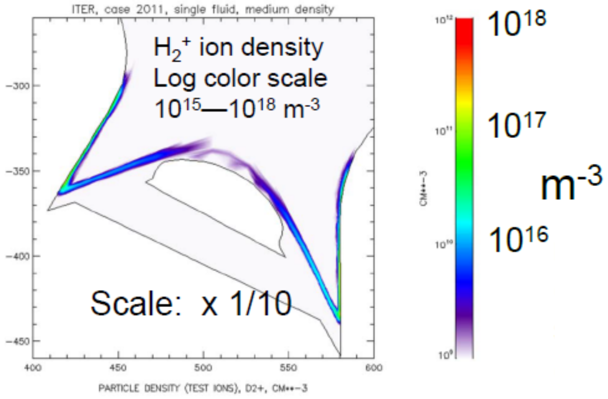
ITER: Self-sustained Neutral Gas Cushion H and H_2

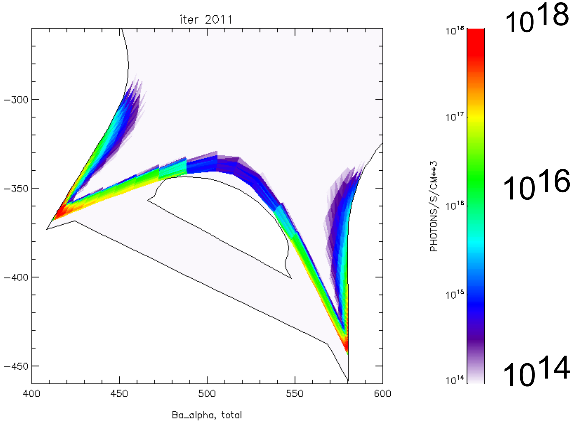




m^{-3}

$n_{H_2^+} << n_{H_2}$ → **no significant H_3^+ formation**
(competing electron collisions on H_2^+ are too strong)





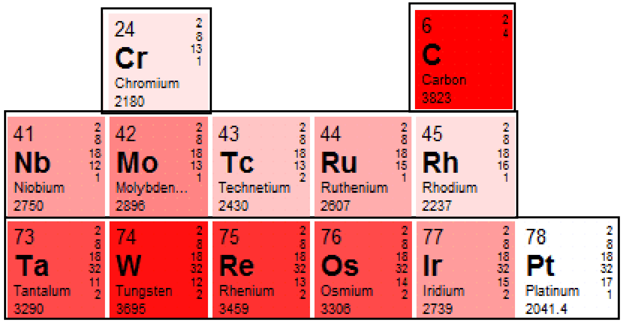
Balmer-alpha

ph s^{-1} cm^{-3}

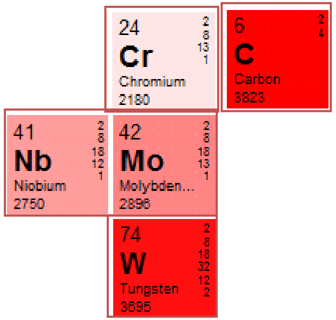
D. Reiter et al. PSI2018

Why do we bother with W?

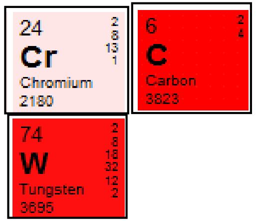
Melting Point >2000 K
Thermal Conductivity >50 W/mK



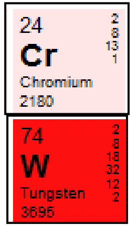
Availability, Cost



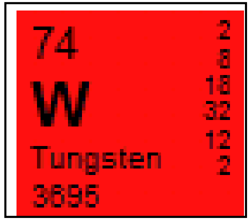
Low/Medium Activation



Erosion Retention

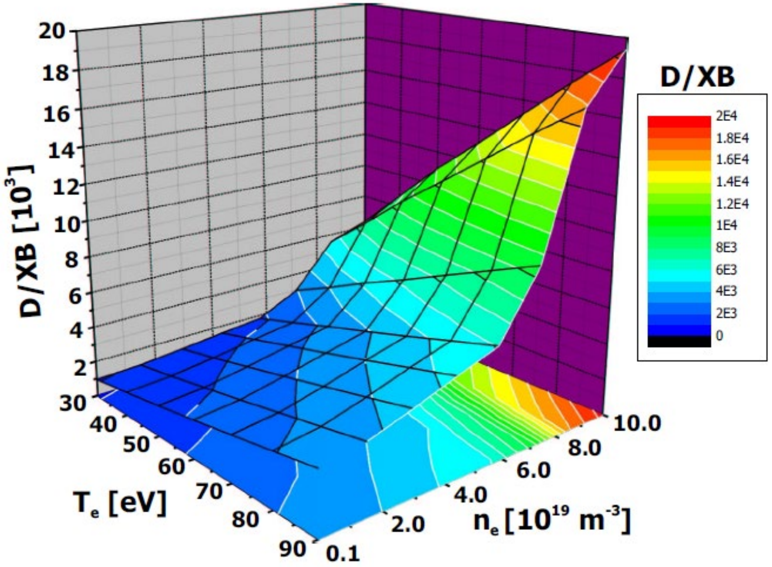


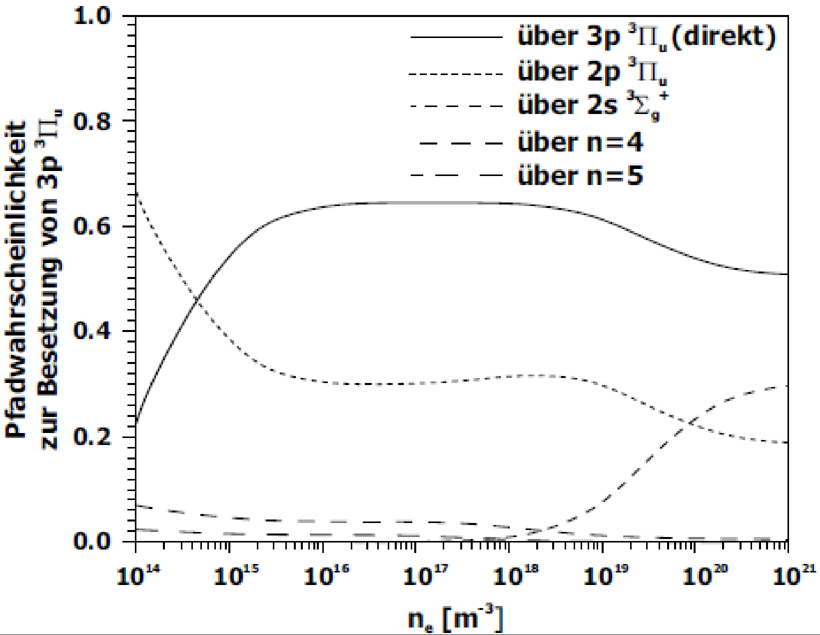
Temperature window (RC)



Photon Efficiency and Population of 3p $^3\Pi_u$

- CRM for hydrogen and deuterium exist meanwhile (e.g. in EIRENE)
- Electronically and vibrationally resolved data available

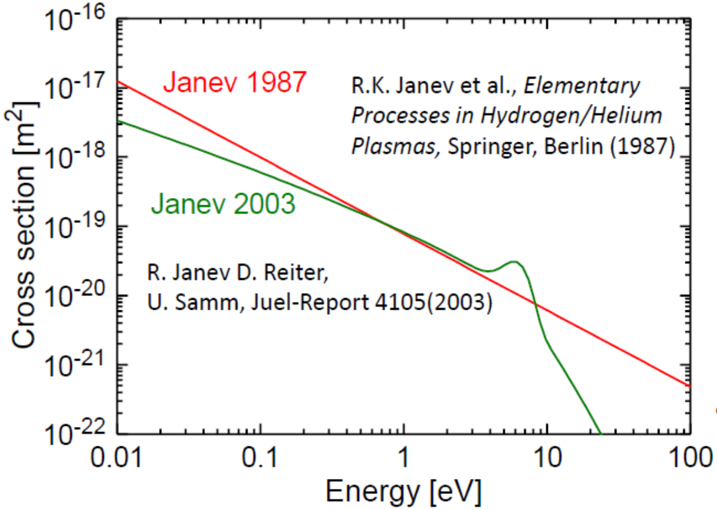




- At the time of work – benchmark by local injection of D_2 and measurement and analysis
- Simulate spectrum => determine T_{rot} (all vib states) => determine T_{vib} => => n tot estimation

Improvement in CRM with Vibrationally Resolved Data

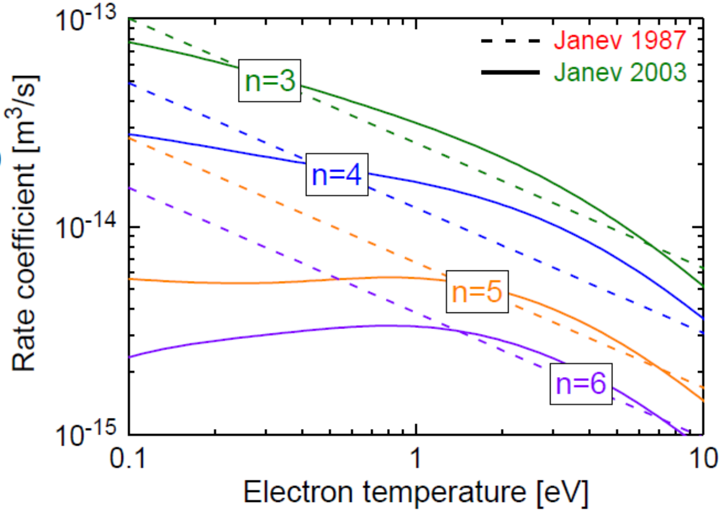
Dissociative recombination $H_2^+ + e \rightarrow H(n) + H$



Janev 1987:
Fixed branching ratio

n=2: 0.1	n=5: 0.12
n=3: 0.45	n=6: 0.69
n=4: 0.22	n>6: $10/n^3$

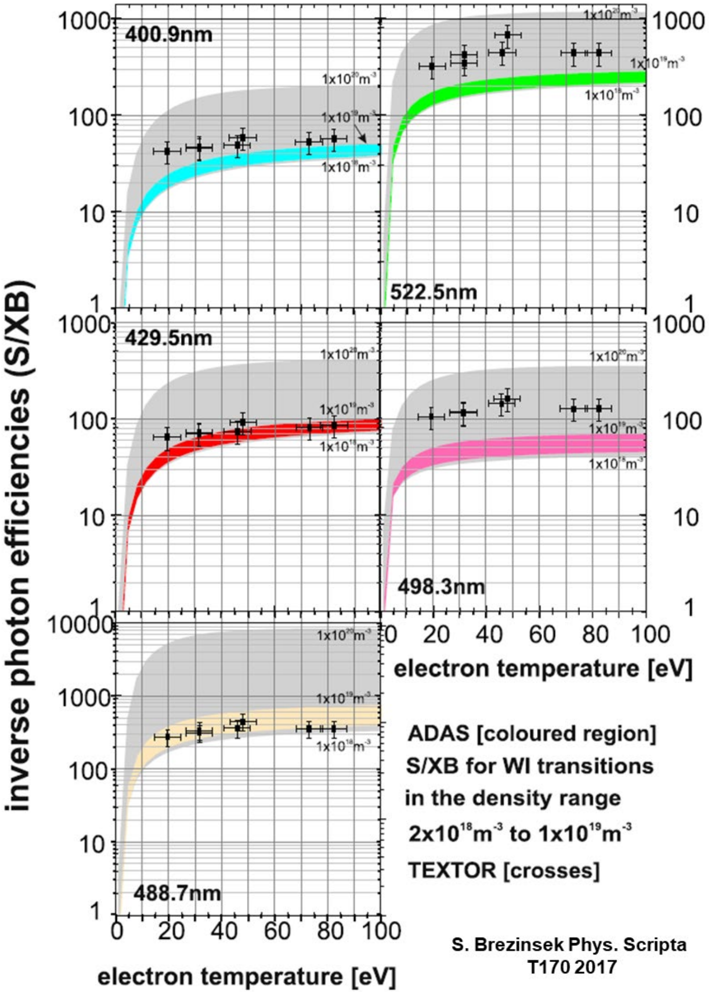
Janev 2003: Branching ratio vibrationally resolved and energy dependent



Comparison of measured line emission to CR modelling results (Yacora):

Much better agreement with Janev 2003 data!

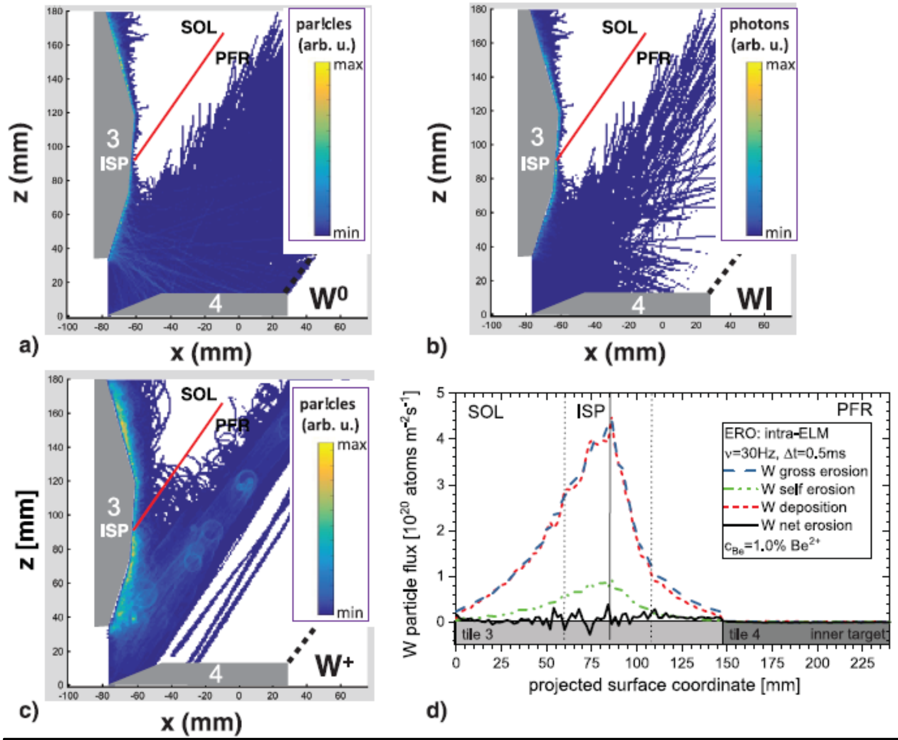
from
U. Fantz

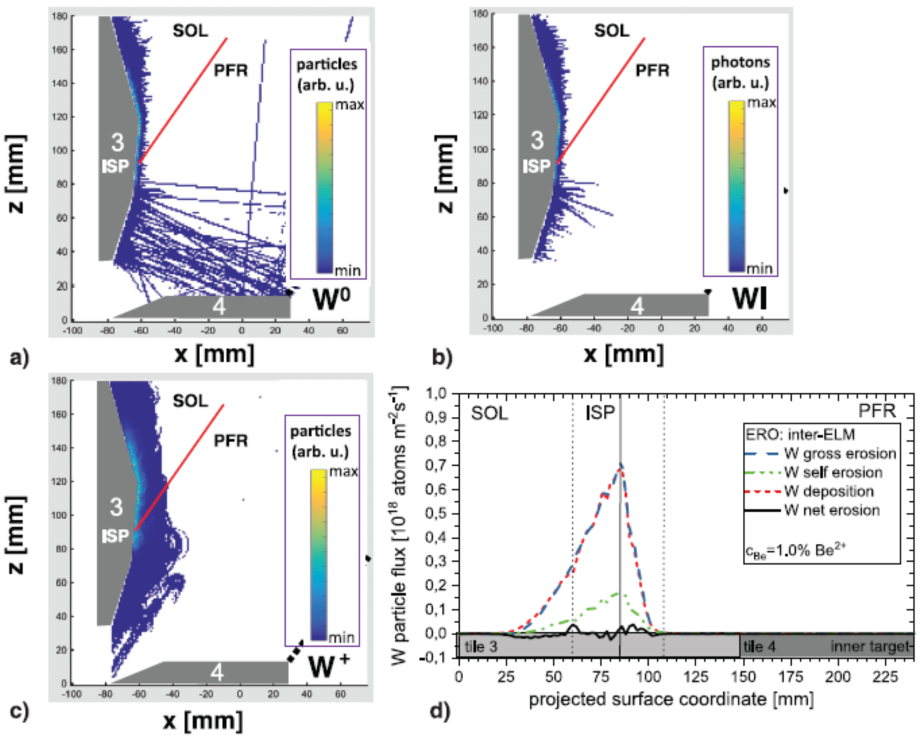


S. Brezinsek Phys. Scripta T170 2017

Simulation of Intra- and Inter-ELM Sputtering of W

JÜLICH Forschungszentrum

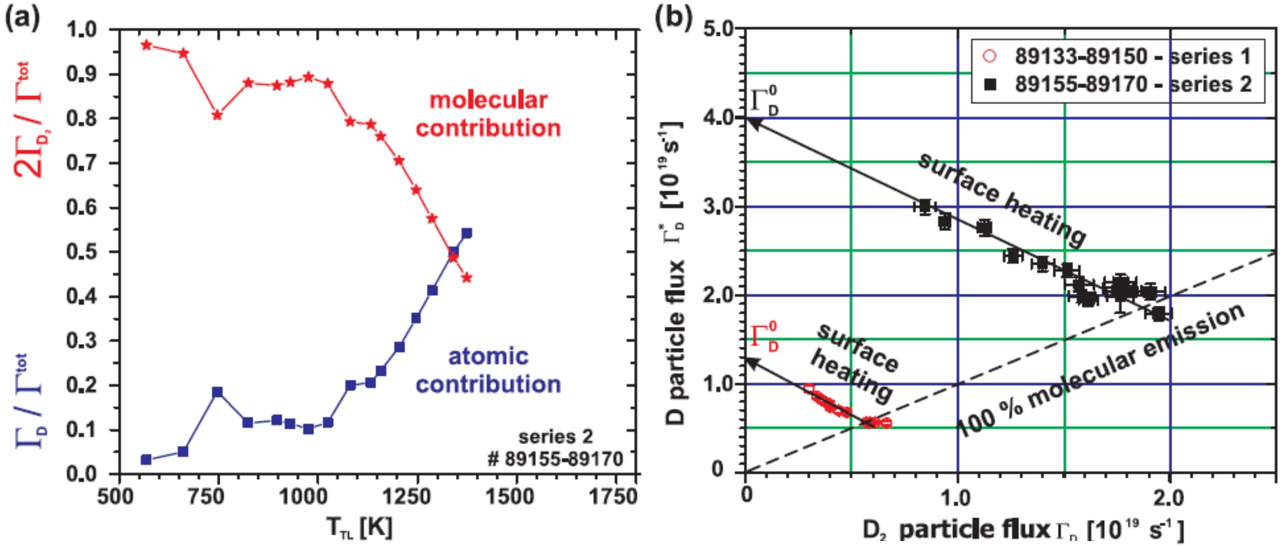




- ERO-modelling (MC+impurity transpot) coupled with PIC simulation of ELM events (1keV, 500ms) reproduces the W sputtering by burn-through in otherwise detached conditions
- More than 95% of W is locally re-deposited in the model => agrees with experiment

Composition of Recycled Deuterium: Ionizing Plasma

- High D^+ flux to the wall (10^{24} D^+ $s^{-1}m^{-2}$), surface saturation in ms and almost 100 % recycling
- Thermal release of D_2 od D from the (graphite) wall and about 10% reflected fast particles



TEXTOR:

Series	Discharge	n_e [10^{18} m^{-3}]	T_e [eV]	T_i [eV]	T_{TL} [K]
1	89133–50	2.8	77	120	620–1380
2	89155–70	5.2	42	150	570–1390

S. Brezinsek
PPCF2002