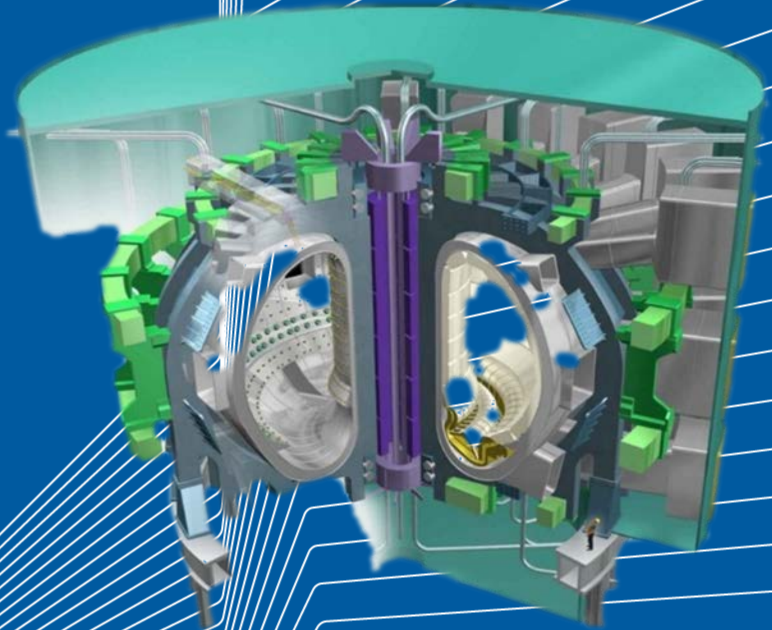
HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

JÜLICH Forschungszentrum

Spectroscopy in Magnetic Confined Fusion Plasmas

PART II

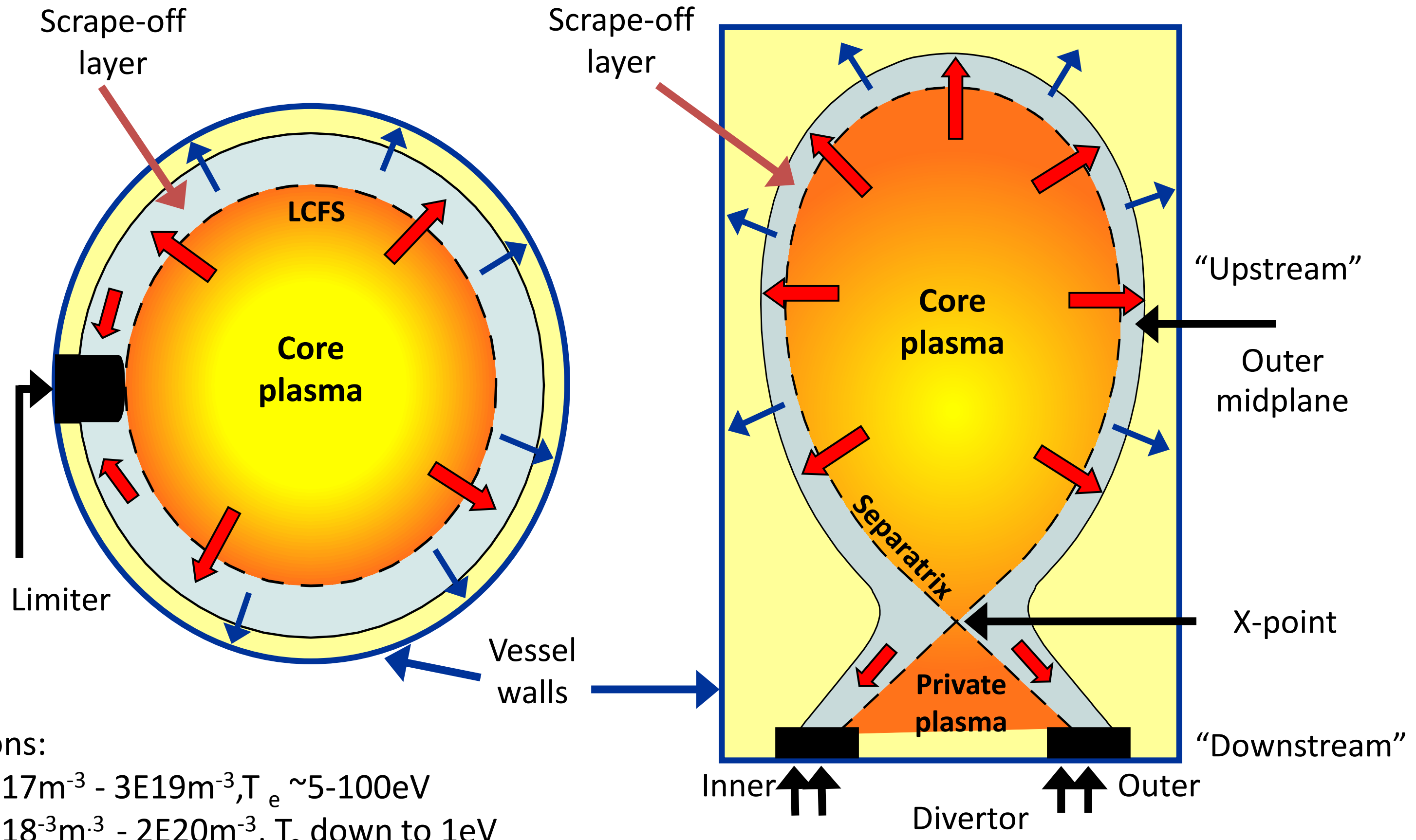


Sebastijan Brezinsek

Institut für Energie und Klimaforschung - Plasmaphysik

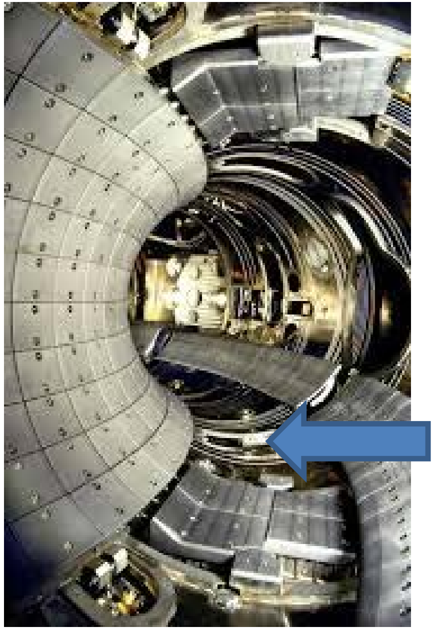
Forschungszentrum Jülich

Regions of Interest



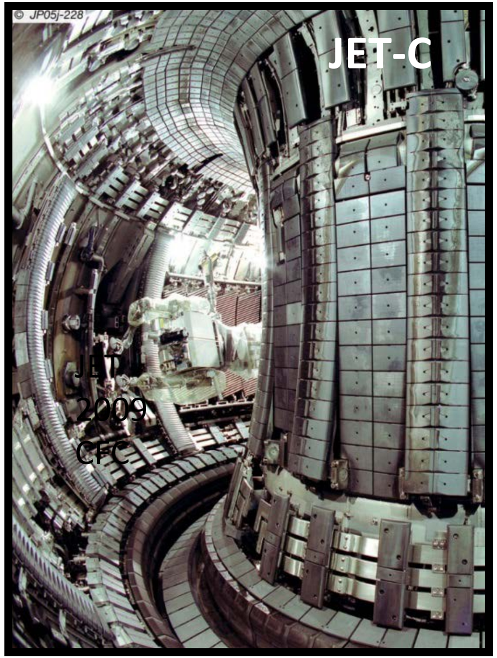
Typical conditions:
FAR SOL: N_e~3E17m^{-3} - 3E19m^{-3},T_e ~5-100eV
Divertor: N_e 1E18^{-3}m$^{.3}$ - 2E20m^{-3}, T_e down to 1eV

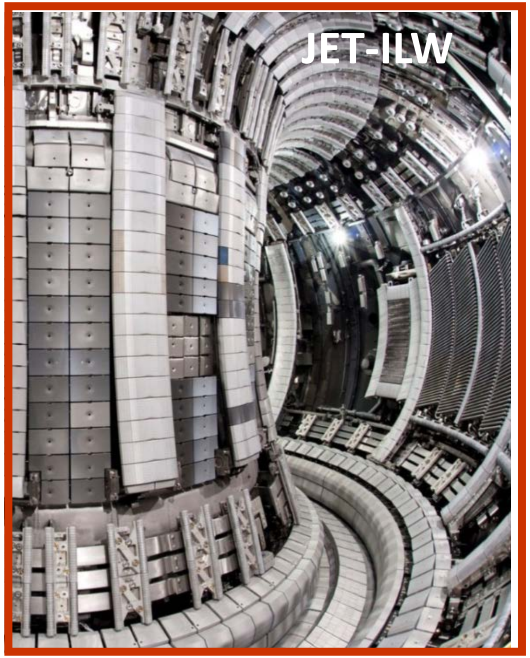
Example Facilities



LOCK
for PSI
studies

TEXTOR shutdown 31.12.2013

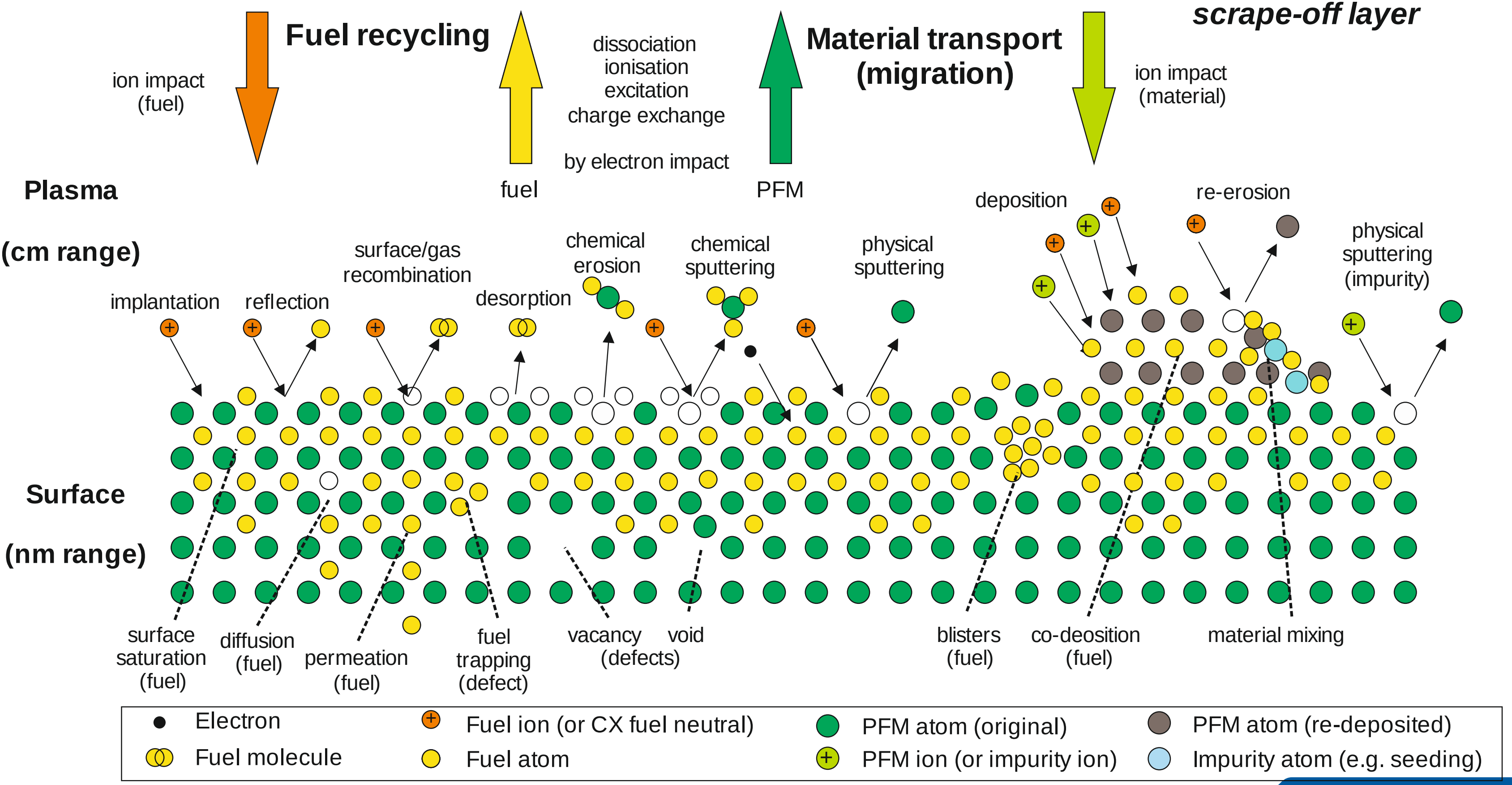




R~1.75m B_t~2.8 T P_{aux}~8MW
a~0.46m I_p~ 0.8MA V_p~10m^3

R~3m B_t: 3.45 T P_{aux} ~40MW
a~1.25m I_p: ~5MA V_p~100m^3

Plasma-Surface Interaction Processes



Plasma-Surface Interaction Processes

Processes to be measured - studied – predicted – controlled - understood:

- Plasma composition (fuel and impurities)
- Erosion, transport, and deposition/mixing
- Impurity source distribution and its strength
- Energy angular distribution of sputtered particles
- Penetration depth and radiation distribution
- Fuelling, recycling, and retention/release
- Plasma conditions
- Ionisation /recombination regime in divertor ....

Input needed for ITER, Reactor in view of operation (radiation/dilution), plasma fueling (fuel cycle), nuclear safety (retention/dust), lifetime (erosion /modification)

Spectroscopy is one of the view methods which permit in-situ access to PSI processes in fusion plasmas as well as plasma conditions at most critical regions

Outline

- Introduction
- Spectroscopic techniques
- Hydrogen (and isotopes) spectroscopy
- Beryllium hydride spectroscopy
- Tungsten spectroscopy
- Hydrocarbon and carbon spectroscopy

Diagnostic Techniques

Mainly passive spectroscopy:

- Determination of particle fluxes
  - Fuel recycling flux (e.g. D, H, D_2, HD, H_2)
  - Intrinsic impurity flux (C, W, O ...)
  - Extrinsic impurity flux (Ar, Ne, N …)
- Energy and velocity distribution
  - Zeeman-splitting analysis
- Molecule characterisation
  - Ro-vibrational population
  - Dissociation chain
- Plasma parameter determination
  - Balmer-line ratios => T_e
  - Stark broadening => n_e
  - Charge-exchange recombination => T_i and n_i

…. and many more ….

Mainly active spectroscopy:

- Local plasma parameters (atomic beams)
- Population of energy levels **(LIF)**
- Impurity concentrations (CXRS - NBI)
- Fuel content and impurity composition of layers (LASER ablation & desorption)
- Molecular densities (CRDS - LASER)

USUALLY:

=> ionising plasma conditions and no opacity

$\Rightarrow$ only divertor can enter recombination and opacity can play a role

Spectroscopy: From Photons to Particles I

Line emission

$$\varepsilon = \frac{1}{4\pi} n_A^* A_{ij}$$

$$n_A^* \sum_{k \le i} A_{ik} = n_A \, n_e < \sigma_{Exg} \, \upsilon_e >$$

with Γ as branching ratio:

$$\Gamma = A_{ik} / \sum_{k \le i} A_{ik}$$

$$\boxed{I_{tot} = \Gamma \frac{h\nu}{4\pi} \int_{r_1}^{r_2} n_A(r) n_e(r) < \sigma_{Exg} \, \upsilon_e > dr}$$

Spectroscopy: From Photons to Particles II

$$\Phi_A = \frac{4\pi}{\Gamma}\frac{I_{tot}}{h\nu}\frac{<\sigma_I \upsilon_e>}{<\sigma_{Exg}\upsilon_e>} = 4\pi\frac{I_{tot}}{h\nu}\frac{S}{XB}$$

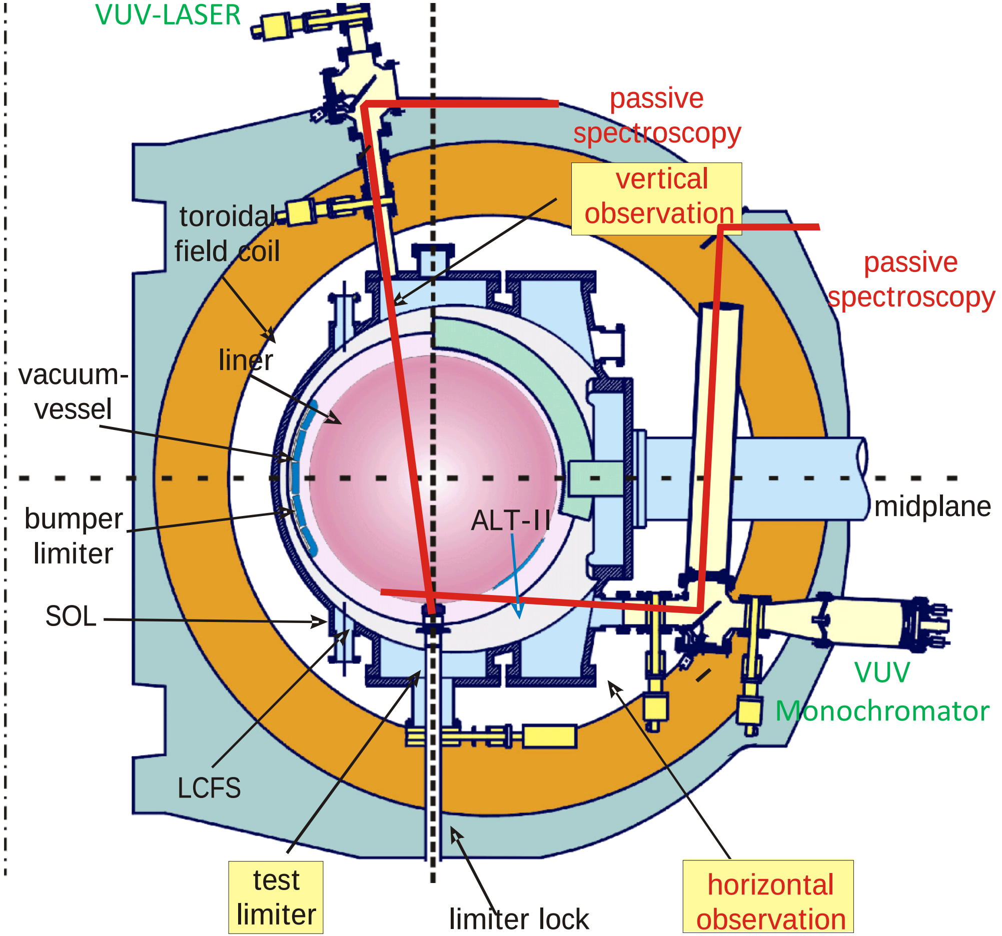
In case of molecular emission:
D/XB with „D“ for Decay =>
Dissociation + Ionisation

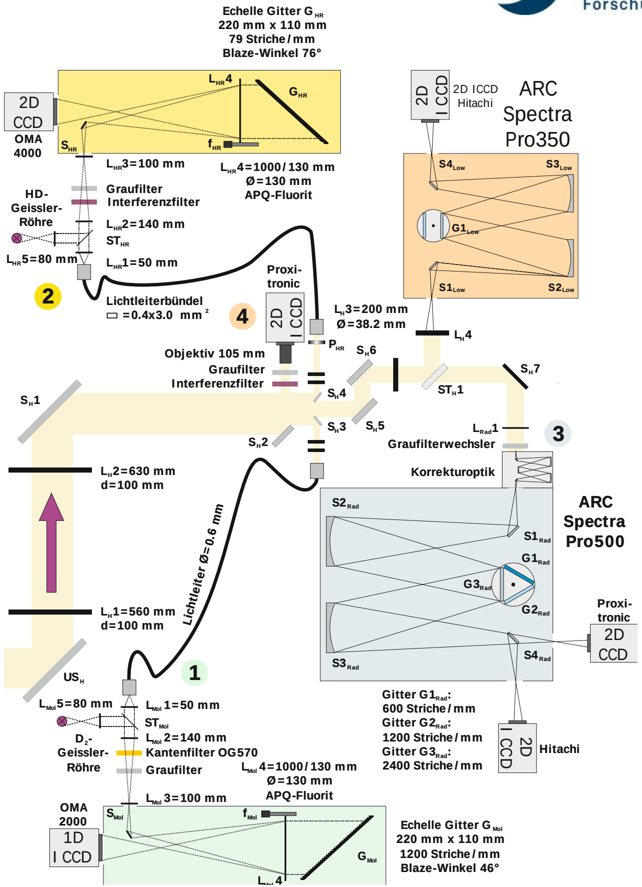
the expression *S / XB* has to be obtained by calculations (including CRM's) or experimentally

$$\frac{<\sigma_I \upsilon_e>}{\Gamma <\sigma_{Exg}\upsilon_e>} = \frac{\Phi_A}{4\pi\left(I_{tot}/h\nu\right)}$$

(OPEN) ADAS – „ionisation events per photon

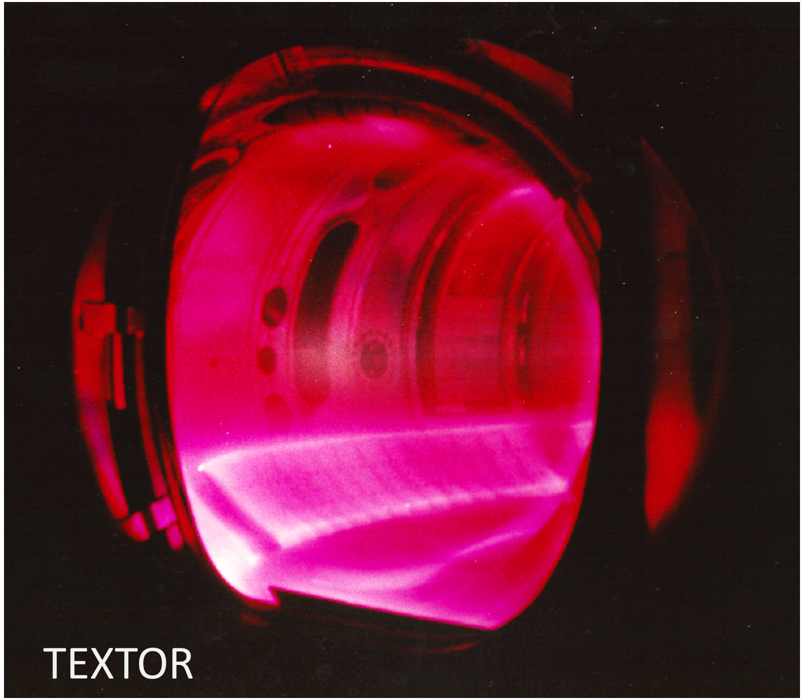
Experiments: Lock Systems in TEXTOR





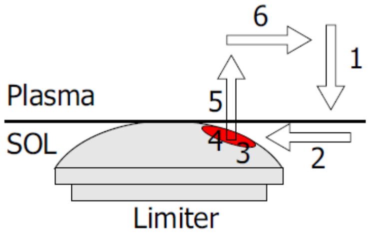
Outline

- Introduction
- Spectroscopic techniques
- Hydrogen (and isotopes) spectroscopy
- Beryllium hydride spectroscopy
- Tungsten spectroscopy
- Hydrocarbon and carbon spectroscopy



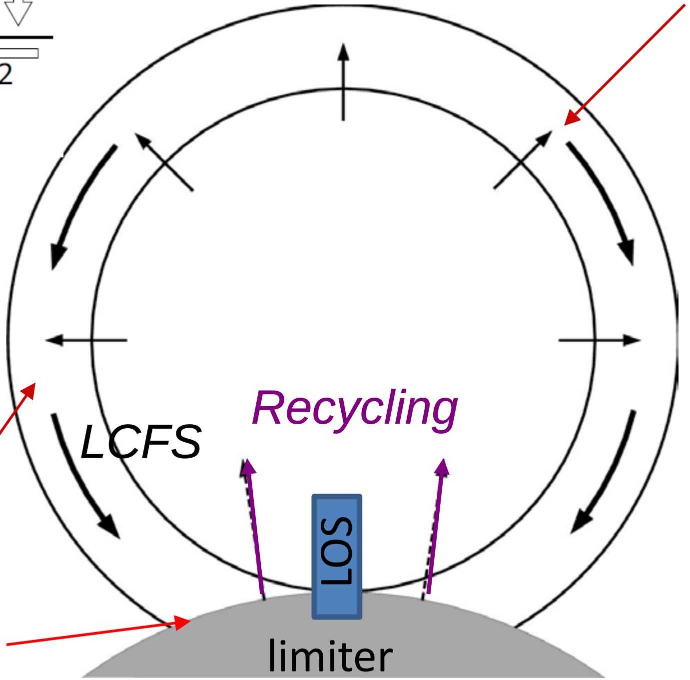
Arrangement / Neutrals Penetration

“Identical“ plasma in T_e and n_e, but photon flux changes with T_{surf}



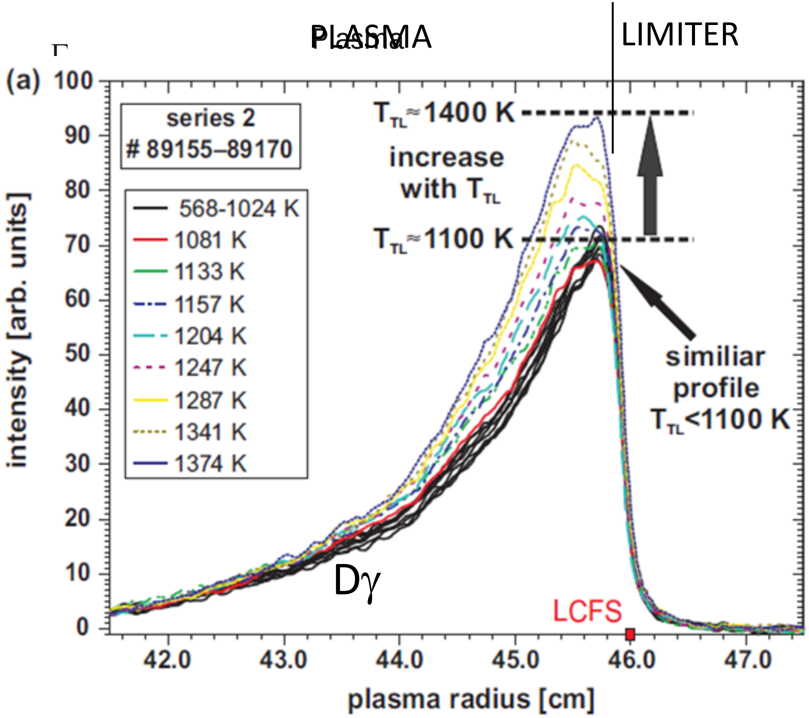
Radial transport in the Scrape-Off Layer (Collsions, Drifts)

Stagnation point

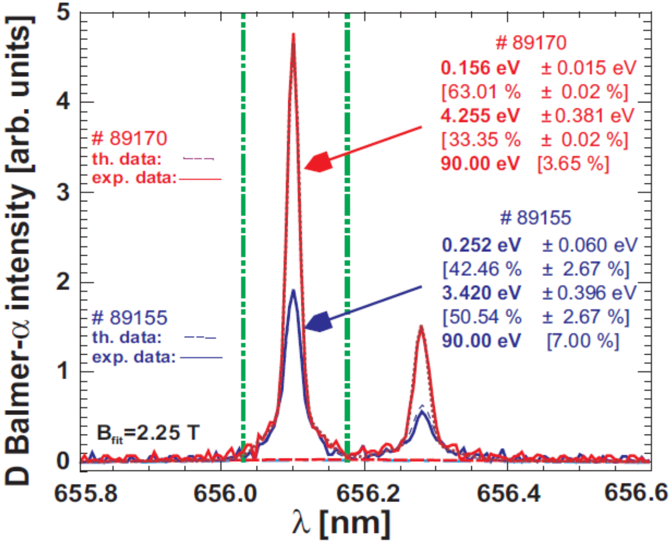


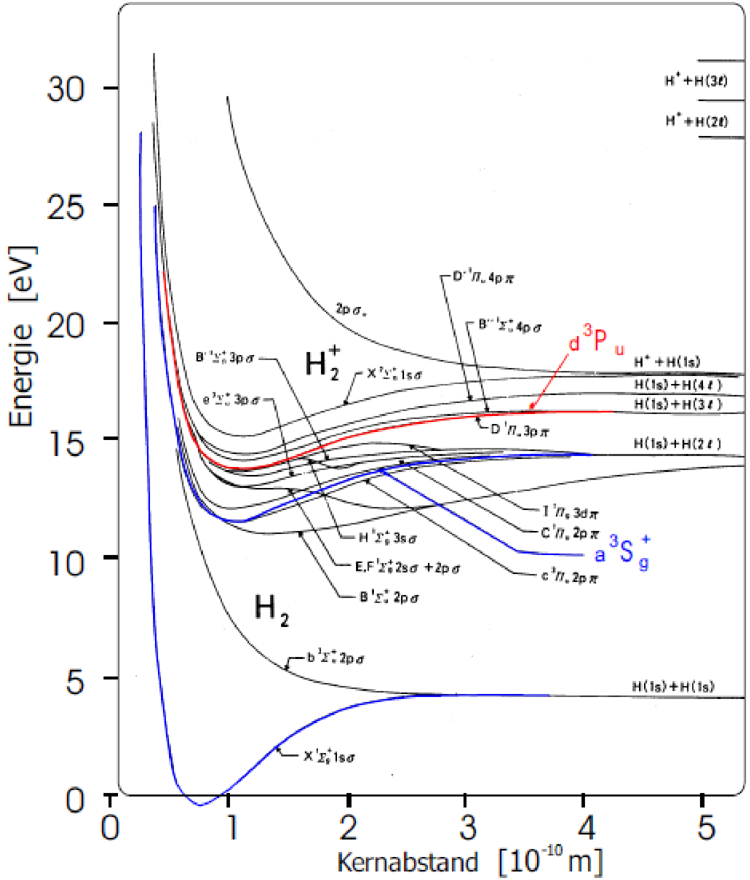
SOL

(Bohm criteria: Ion sound speed)



Atomic Line Shape Analysis



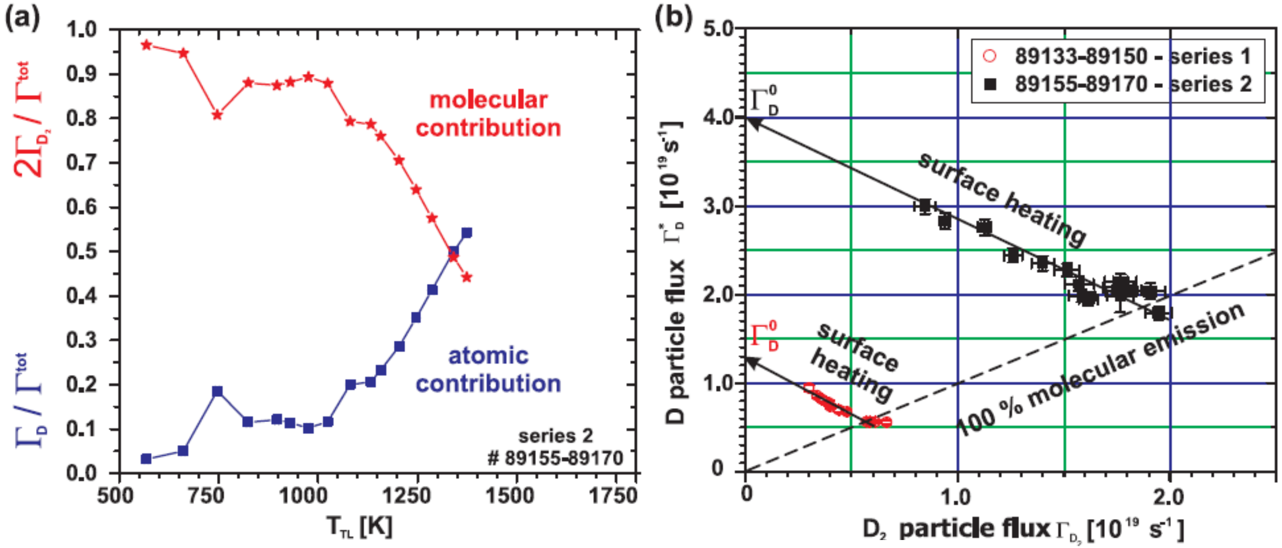


- Zeeman-Splitting analysis reveals: very cold atoms (0.2eV)
- Molecules start from surface: Franck-Condon energy 2.2eV expected

- Change of D_2 destruction mechanism at low T_e
- Destruction path via D_2^+ only dominates above 15eV
- Destruction path via D_2 dissociation dominates below 10 eV

Composition of Recycled Deuterium

- High D^+ flux to the wall (10^{24} D^+ $s^{-1}m^{-2}$), surface saturation, and almost 100 % recycling
- Thermal release of D_2 from the (graphite) wall and some reflected fast particles
- Destruction chain depends on local plasma conditions and surface temperature => atoms at high $T_{surface}$

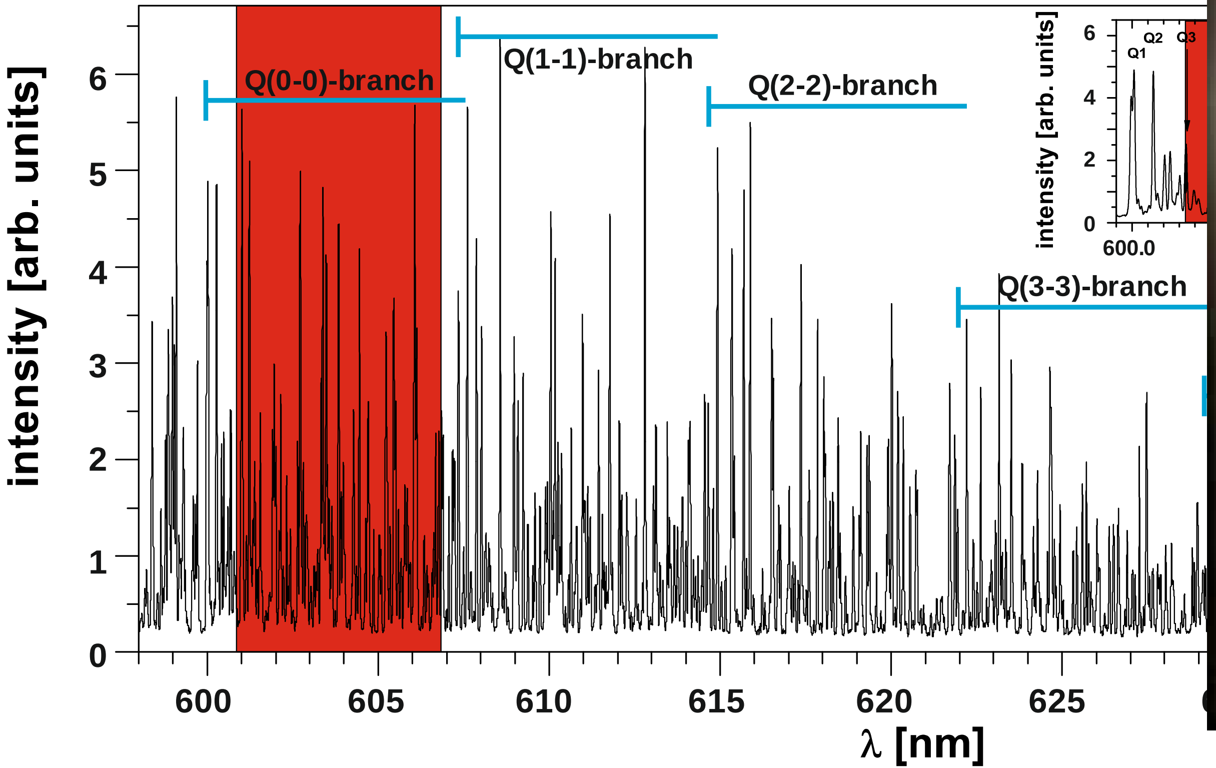


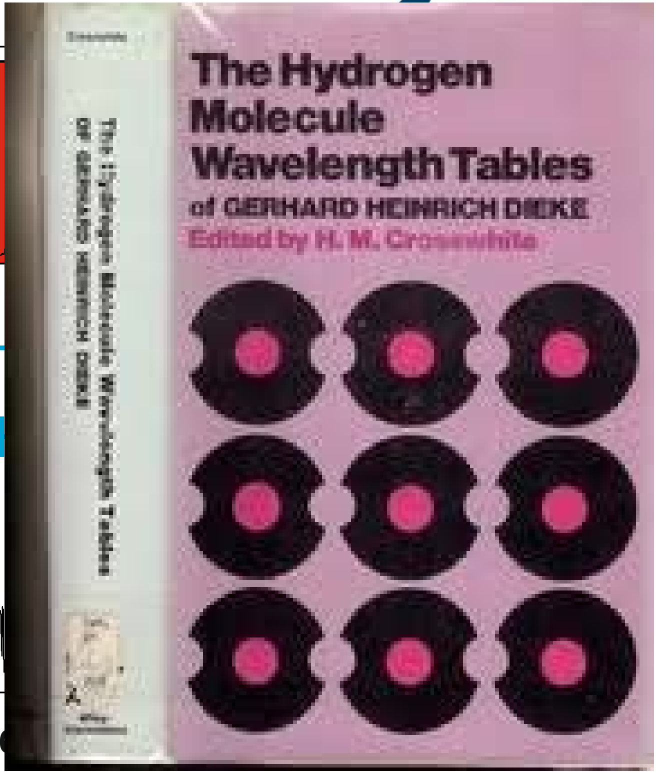
TEXTOR:

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

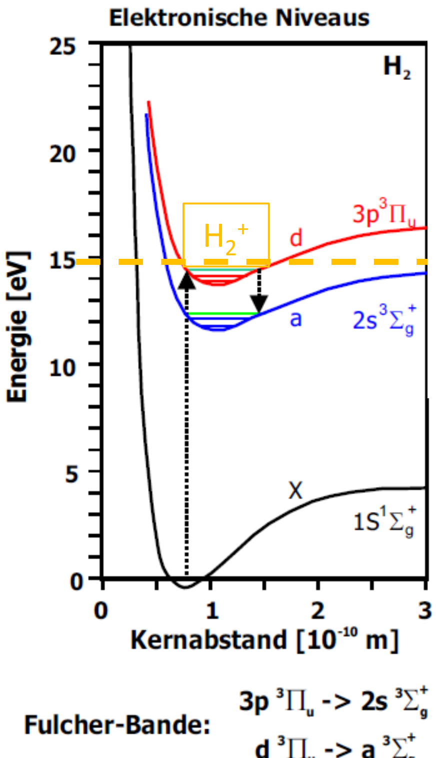
Measurement of D_2 in TEXTOR



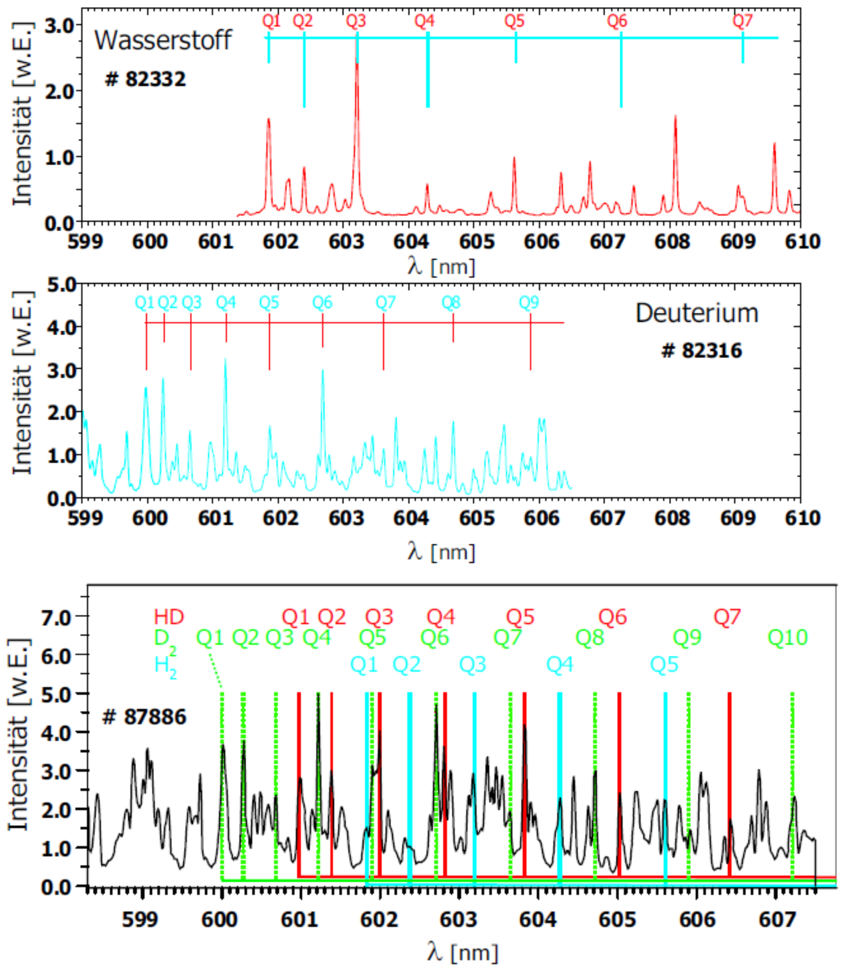


Needs analysis and conversion to total molecular flux from rotational to vibrational to electronic transition….

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



Hund‘s case (b)

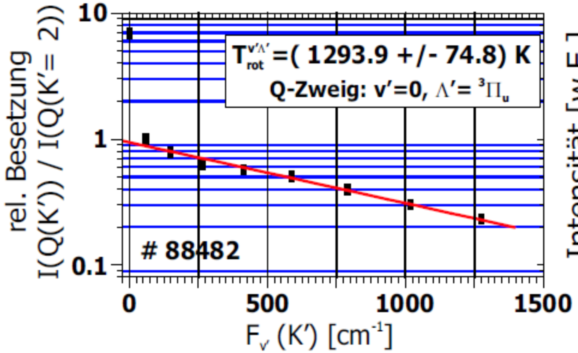


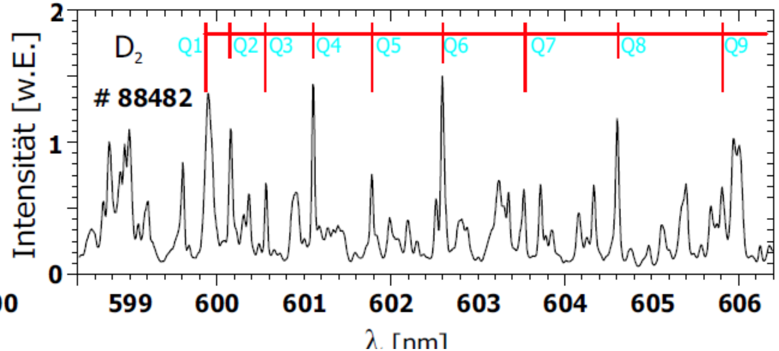
- Electronic transition of highly excited hydrogen molecules
- Direct visability of the impact of nuclear spin! Multiplicity!

Rotational Population Temperatures

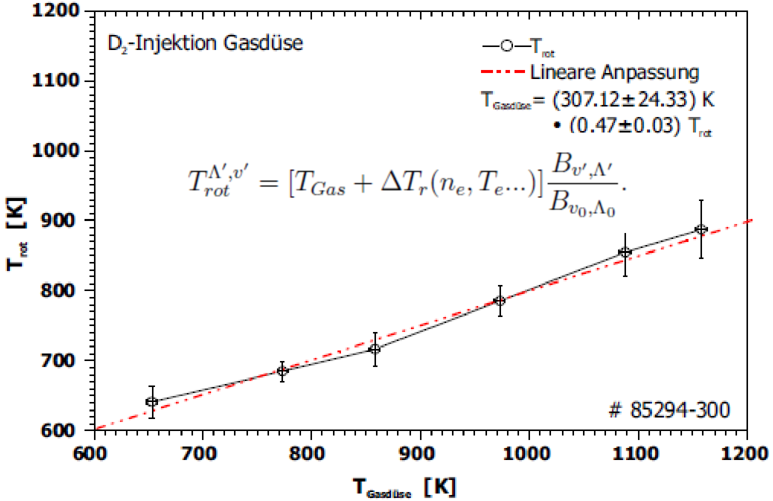
Optical rules applied
P, Q, R branches

Hönl-London Factors





- Rotational and vibrational population according to Boltzmann distribution
- D_2 (injections) for plasma diagnosis (or calibration) otherwise D_2 recycling flux
- T_{rot} and T_{vib} also used for diagnosis of plasmas
- Additional parameter determined by surface properties: $T_{surface}$ / vibrational excitation

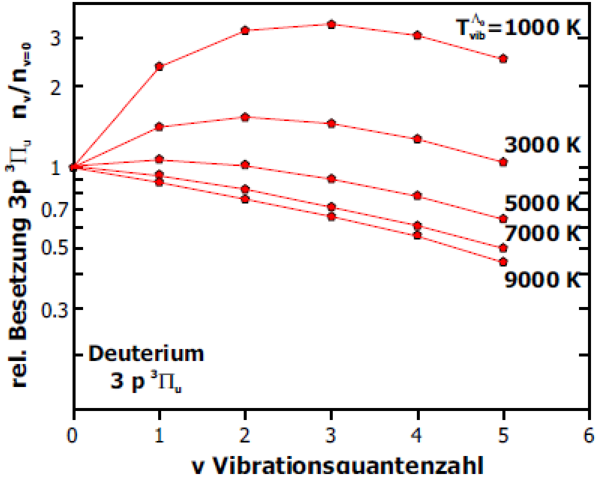


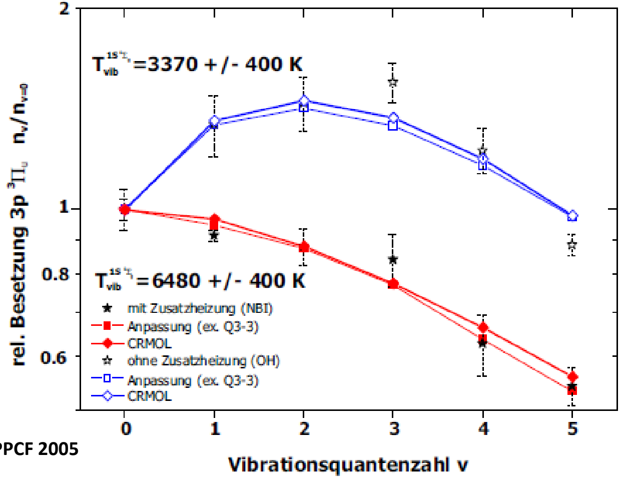
Vibrational Population Temperatures

Optical rules applied
Main diagonals called Fulcher-α bands

Franck-Condon Factors for transfer upper state to ground state population

- Population in upper state can be determined and linked to ground state
- CRM connects excited state with ground state: reproduce “plasma part“
- Surface materials can impact on initial distribution: e.g. C, a-C:H layers, Ta
- Responsible reactions: Eley-Rideal etc.

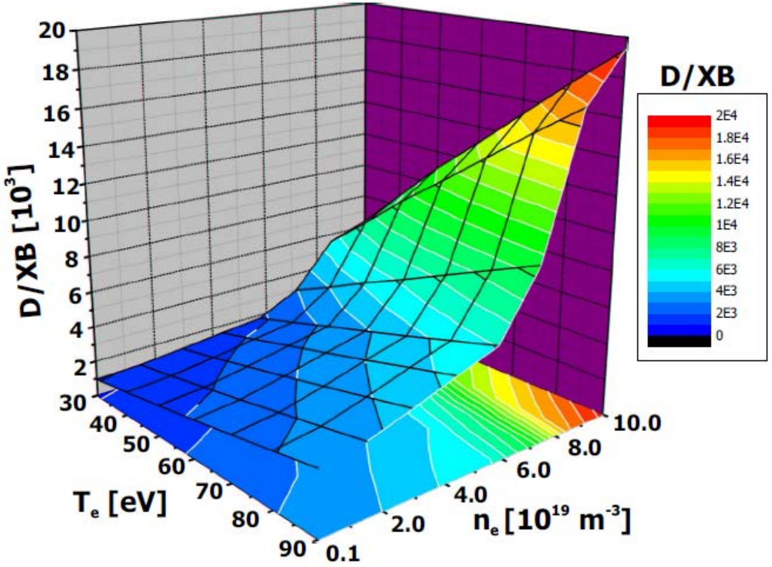


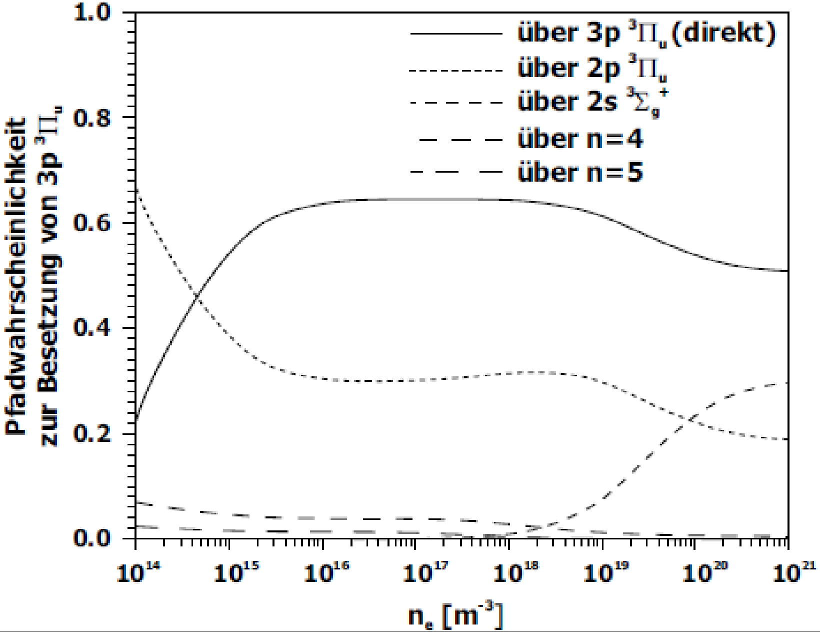


B. Heger et al., S. Brezinsek PPCF 2005
PT Greenland FZJ report

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

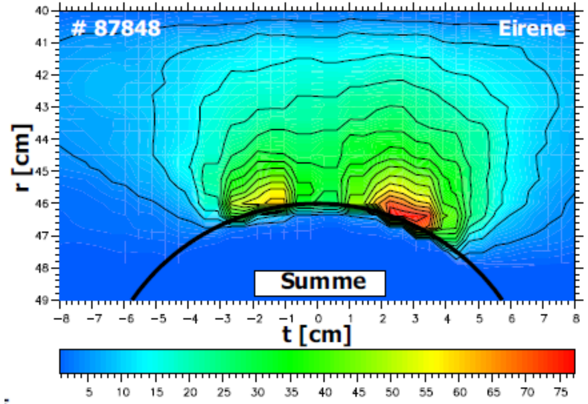




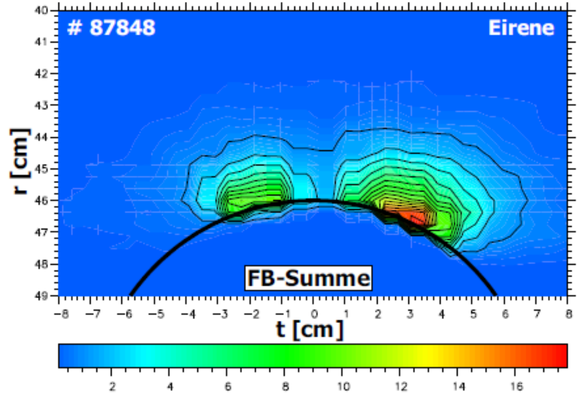
- At the time of work – benchmark by local injection of D_2 and measurement and analysis

- Simulate spectrum => determine T_{rot} (all vib states) => determine T_{vib} => => n tot estimation

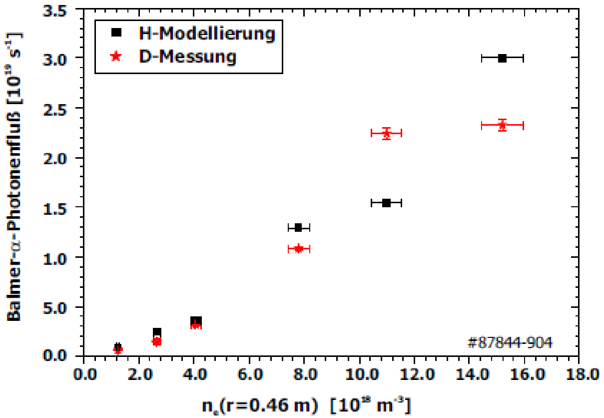
Comparison with EIRENE Code

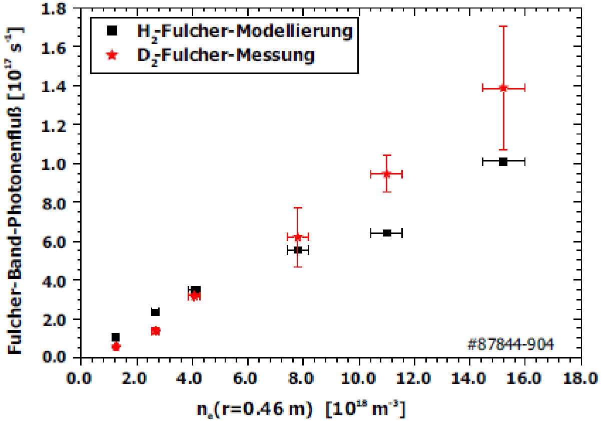


Balmer-α-Photonenfluß [10^{15} Photonen s^{-1} cm^{-2}]



Fulcher-Band-Photonenfluß [10^{14} Photonen s^{-1} cm^{-2}]



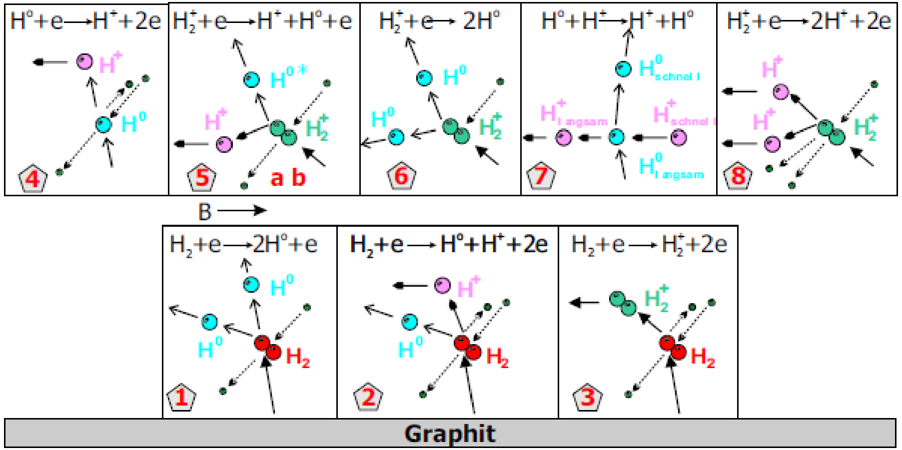


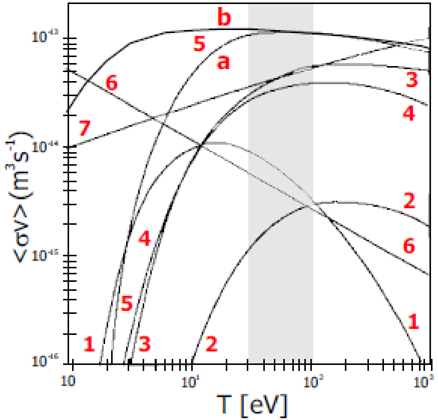
- Good agreement in easy ionizing plasma conditions
- Assuming thermal molecules at start
- Recently D_2 recycled at W showed different behavior

- Next challenge: recombining plasms

Destruction Path for Hydrogen Molecules

Plasma



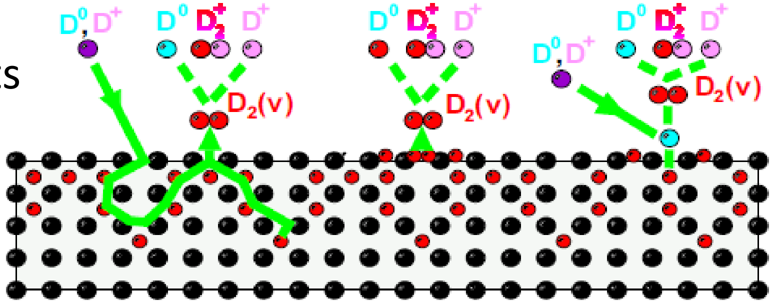


Thermal Release

Langmuir-Hinshelwood

Eley-Rideal

Surface effects

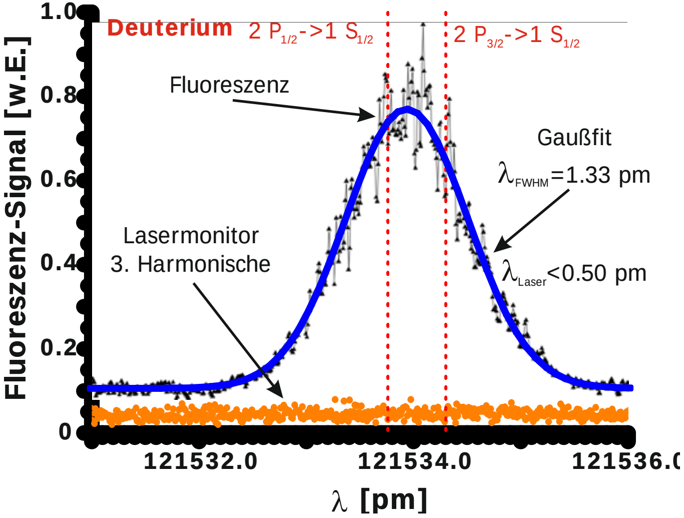


Full set in EIRENE
JUEL-4105 Report

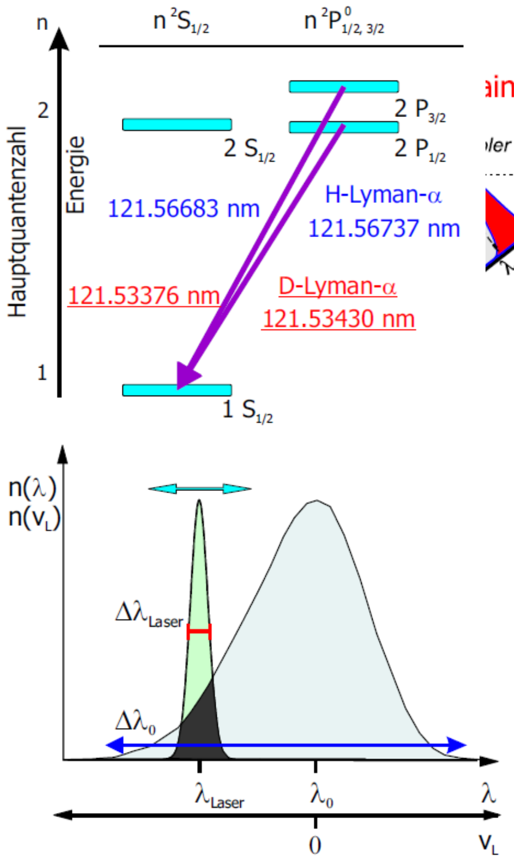
www.eirene.de

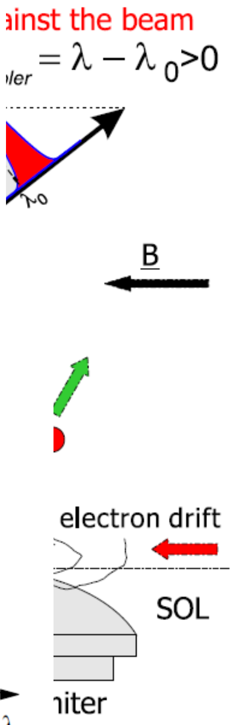
Cold Atoms? Independent Proof via LIF on Ly-α

Lyman-α laser by frequency tripling: Ar/Kr

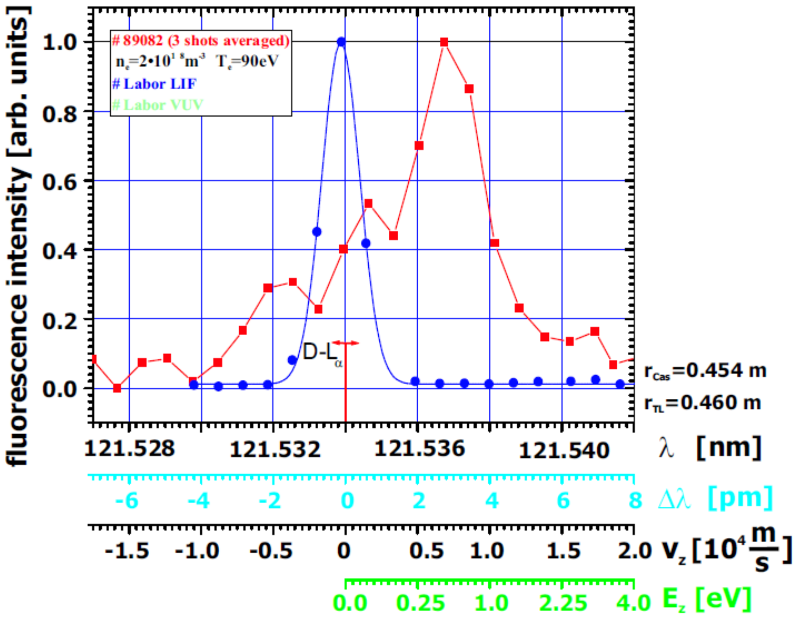


Measure population and energy of atoms in ground state of deuterium

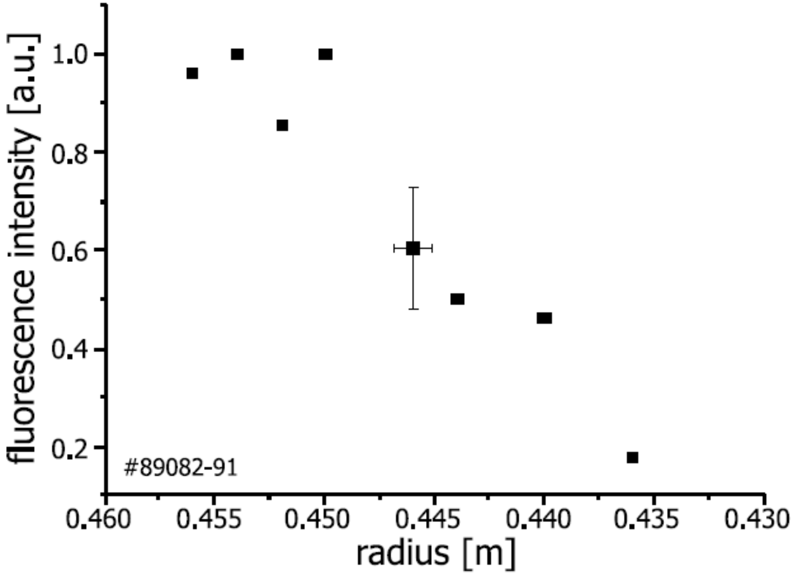




Cold Atoms? Confirmed by LIF on Ly-α



Cold atoms - but method is very, very costly …

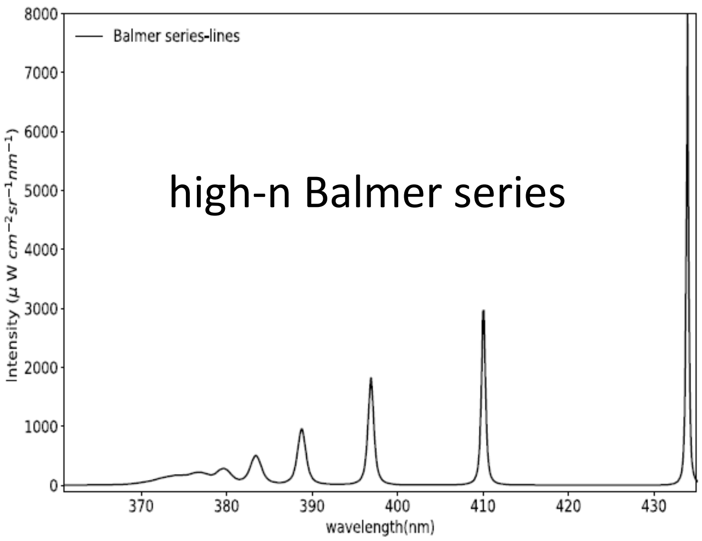


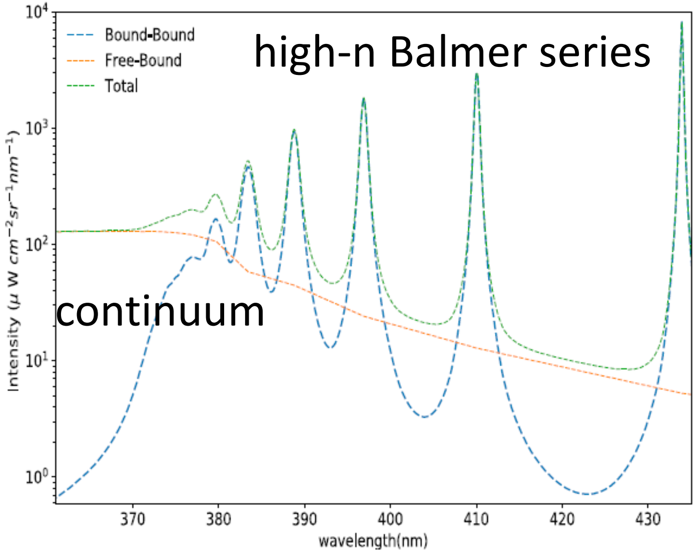
Penetration depth as expected …

N_e and T_e in Recombining D Plasmas

Transfer to complex recombining plasmas

- Balmer and Paschen series recombination used and analysed (compared with ADAS data)
- Line ratio provides T_e, “continuum jump” analysis (Terry et al.)
- Stark broadening for n_e determination (Poetzel et al.)

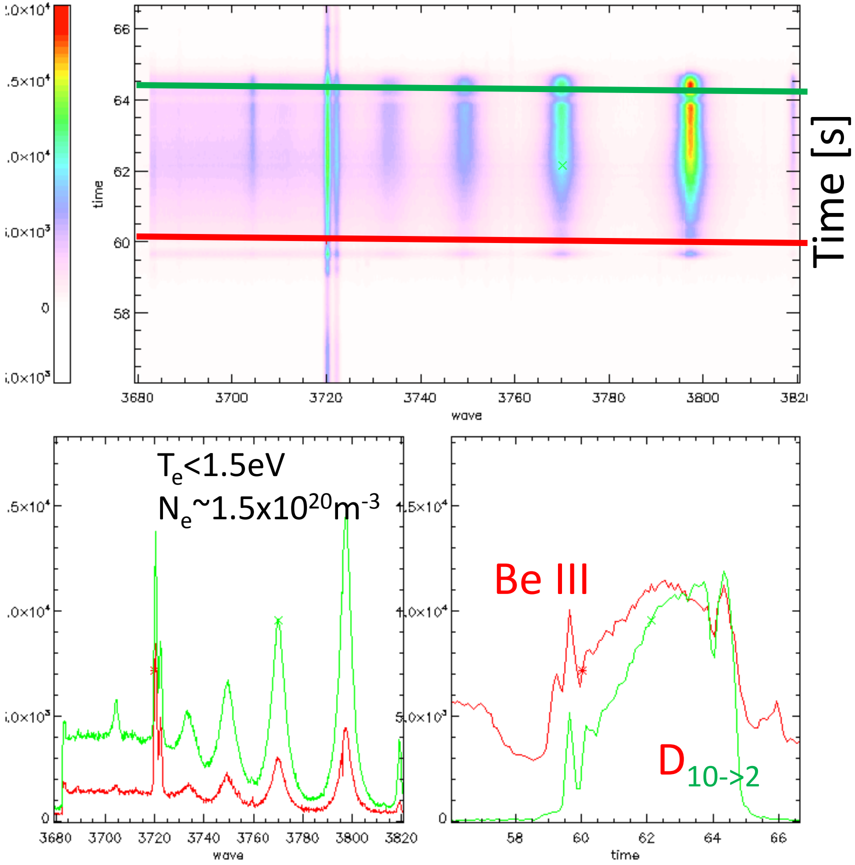




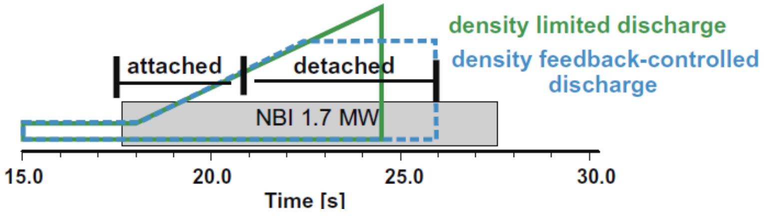
Koubiti 2019

$N_e = 8 \times 10^{20} m^{-3}$, $T_e = 1.1 eV$

JET Divertor: Recombining D Plasmas (JET-ILW)



Density ramp

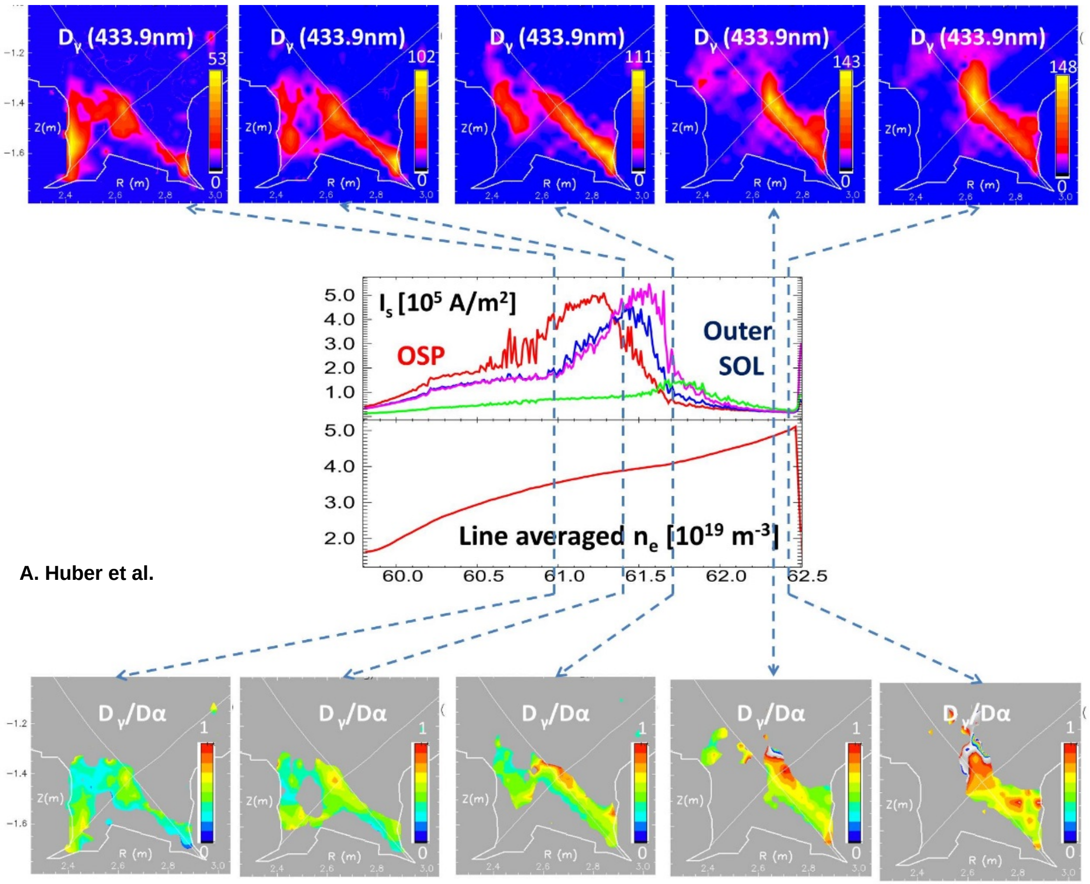


- Provides T_e and n_e from volume recombination in front of target plate
- Detachment indicator

- Issue Ly-α radiation insufficient to explain radiation in these plasmas
- Revisiting data and new diagnostics to check for opacity effects in JET

(B. Lomanowski et al.)

JET Divertor: Recombining D Plasmas



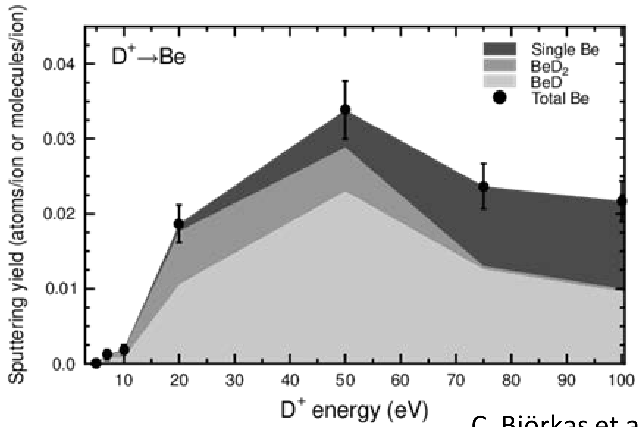
A. Huber et al.

- Interference filtered data used to obtain 2D distribution
- Full detachment at inner divertor leg observed
- Control of ionization front position possible (TCV)

- Multiple cameras with interference filters used to obtain spatially resolved T_e
- Most suitable D_γ over D_α

Outline

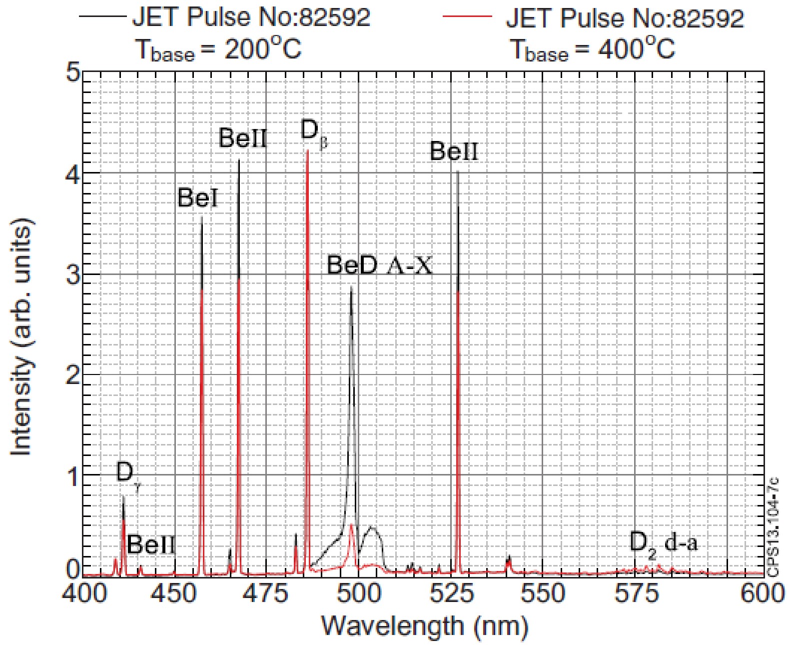
- Introduction
- Spectroscopic techniques
- Hydrogen (and isotopes) spectroscopy
- Beryllium hydride spectroscopy
- Hydrocarbon spectroscopy
- Tungsten spectroscopy



C. Björkas et al.

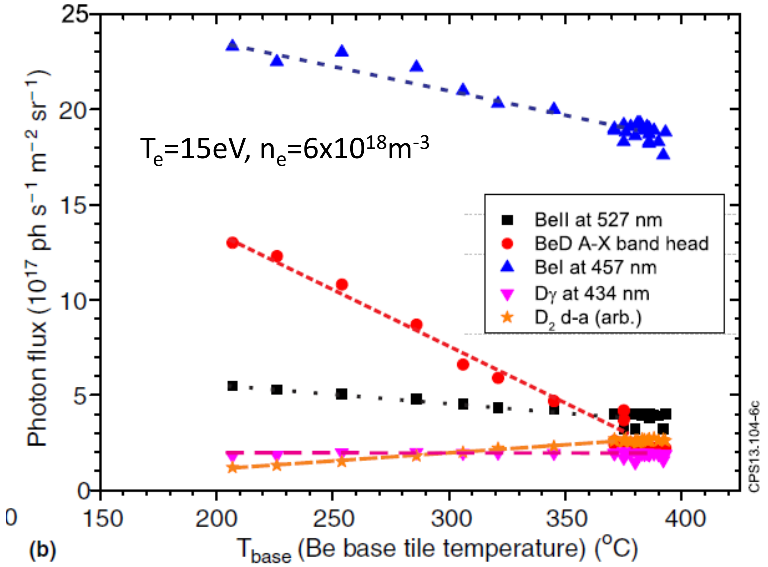
Beryllium Hydride Formation

Chemical (assisted physical) sputtering also observed in JET-ILW at the Be limiters

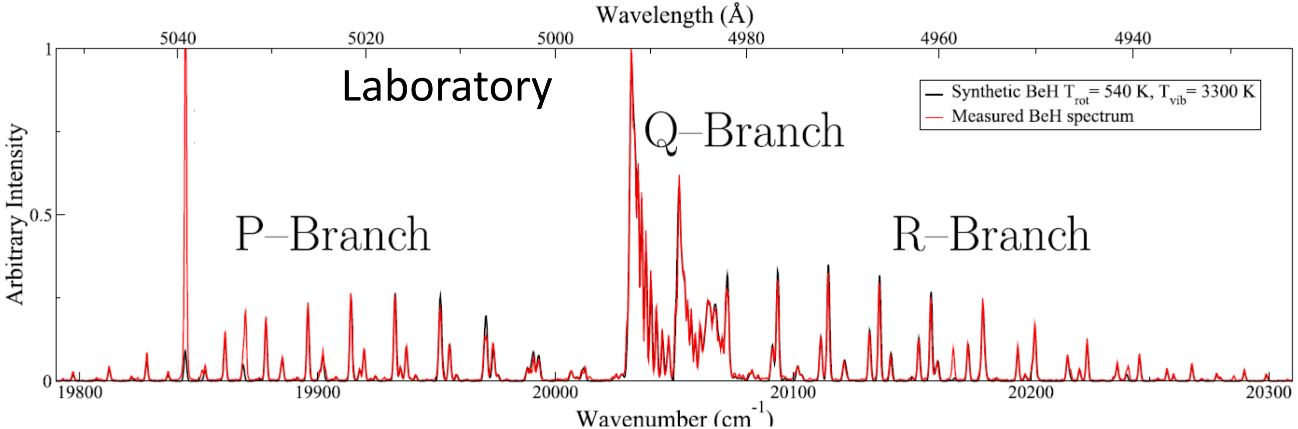


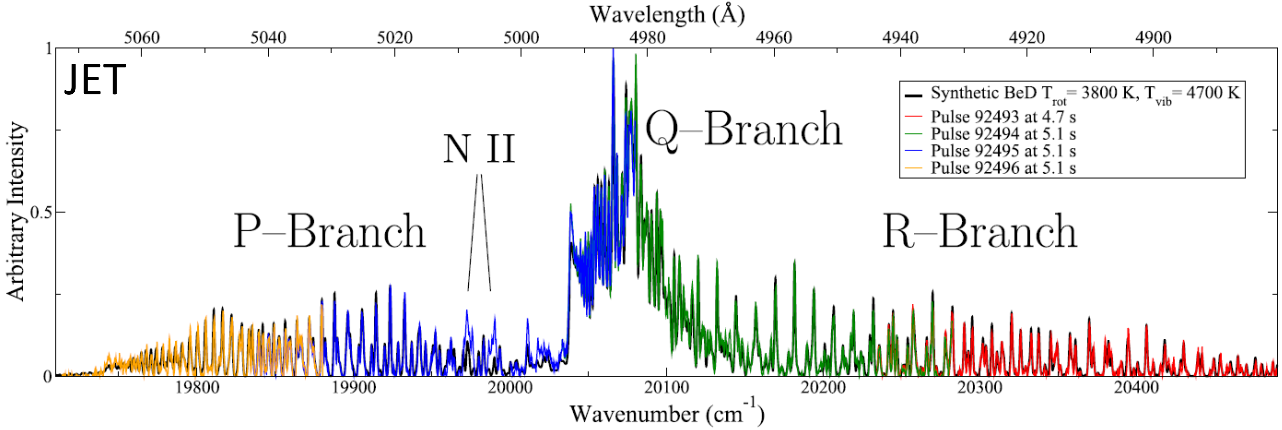
S. Brezinsek NF 2014

- Identical limiter discharges with temperature scan
- BeD observed and decays with T_{surf}
- D_2 increases with T_{surf} (desorption)
- Ratio of Be I and Be II fluxes provide dissociation chain information: 25% via BeD^+ formation



Beryllium Hydride Spectroscopy Modelling



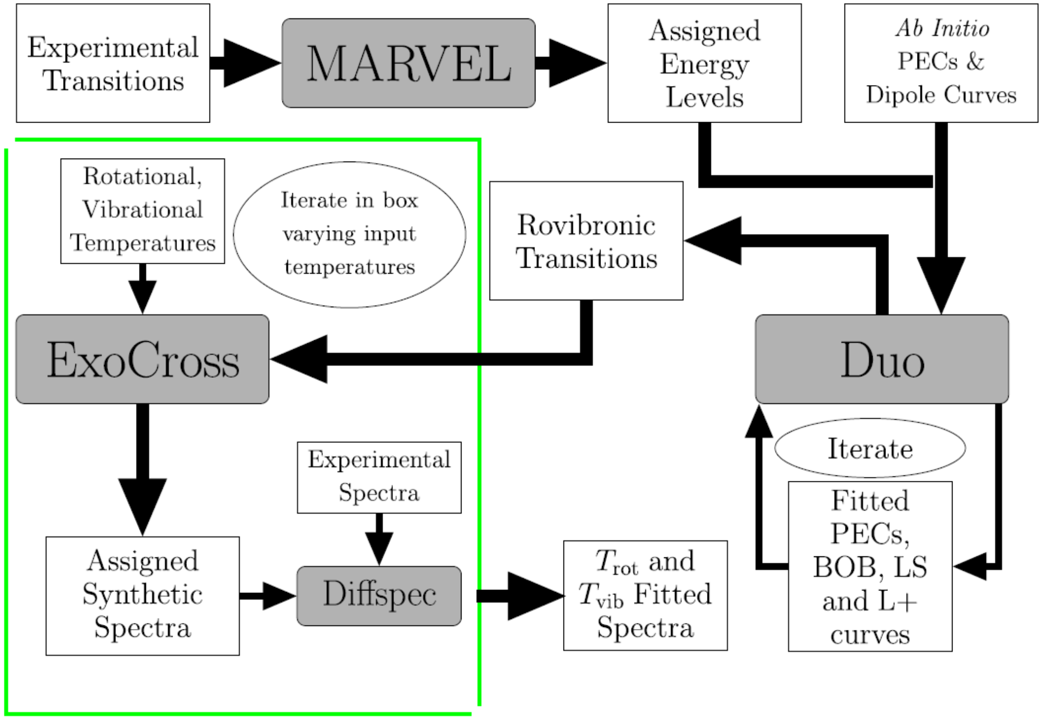


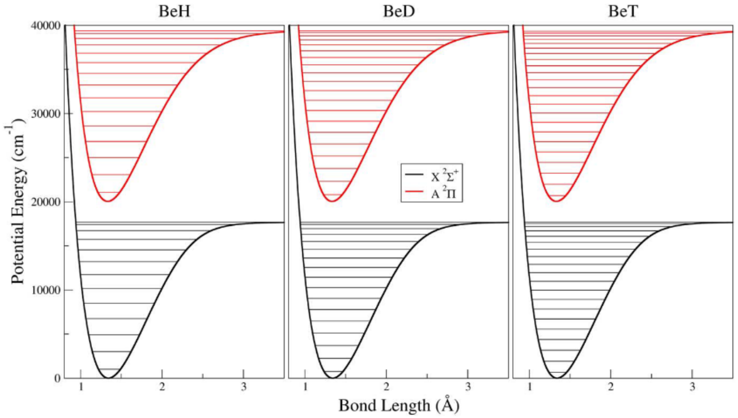
Darby-Lewis 2018

http://exomol.com/

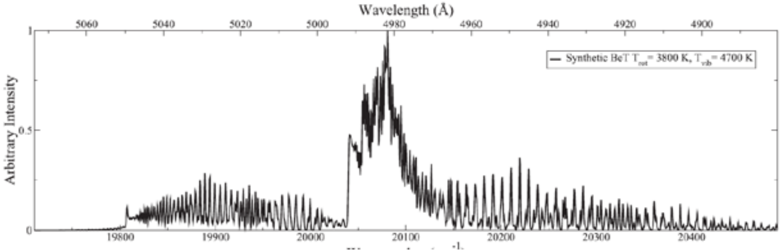
Beryllium Hydride Synthetic Spectra

State-of-the-art procedure to assign energy levels and calculate rovibrionic transitions





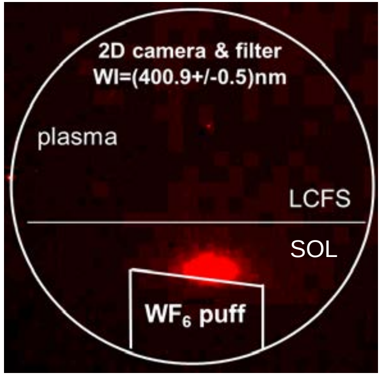
BeT A-X spectrum prediction for JET



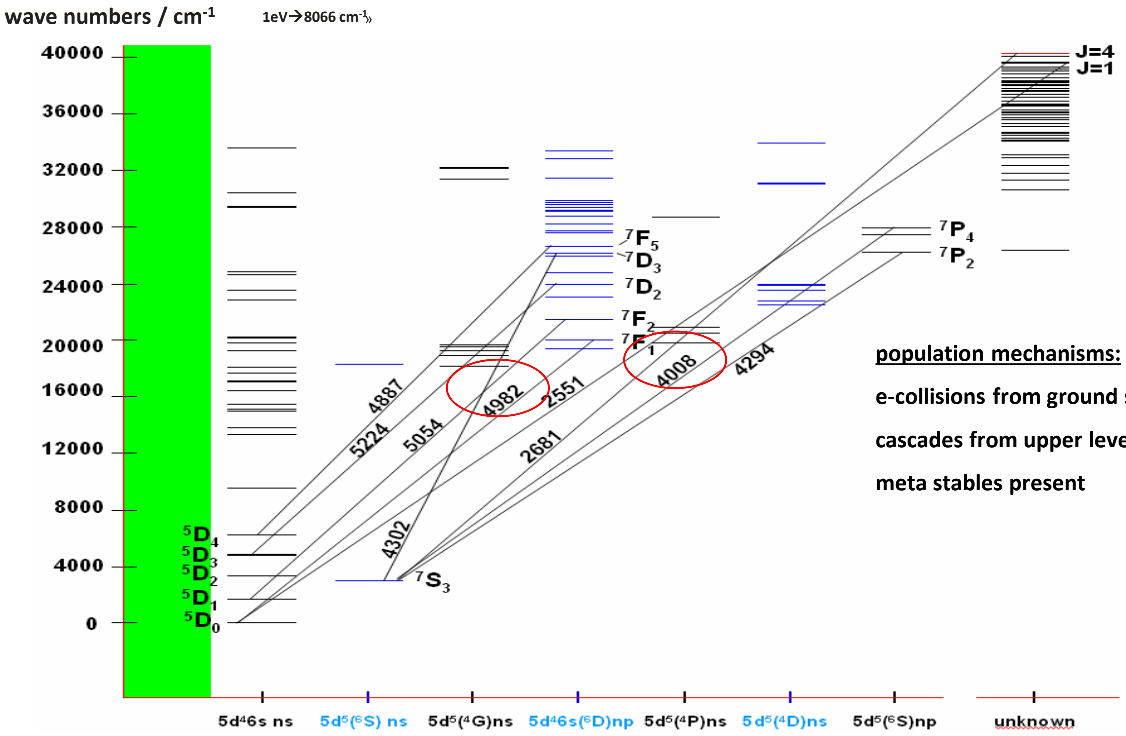
Outline

- Introduction
- Spectroscopic techniques
- Hydrogen (and isotopes) spectroscopy
- Beryllium hydride spectroscopy
- Tungsten spectroscopy
- Hydrocarbon spectroscopy

TEXTOR W calibration



Level Diagram of Neutral W



population mechanisms:

e-collisions from ground state

cascades from upper levels

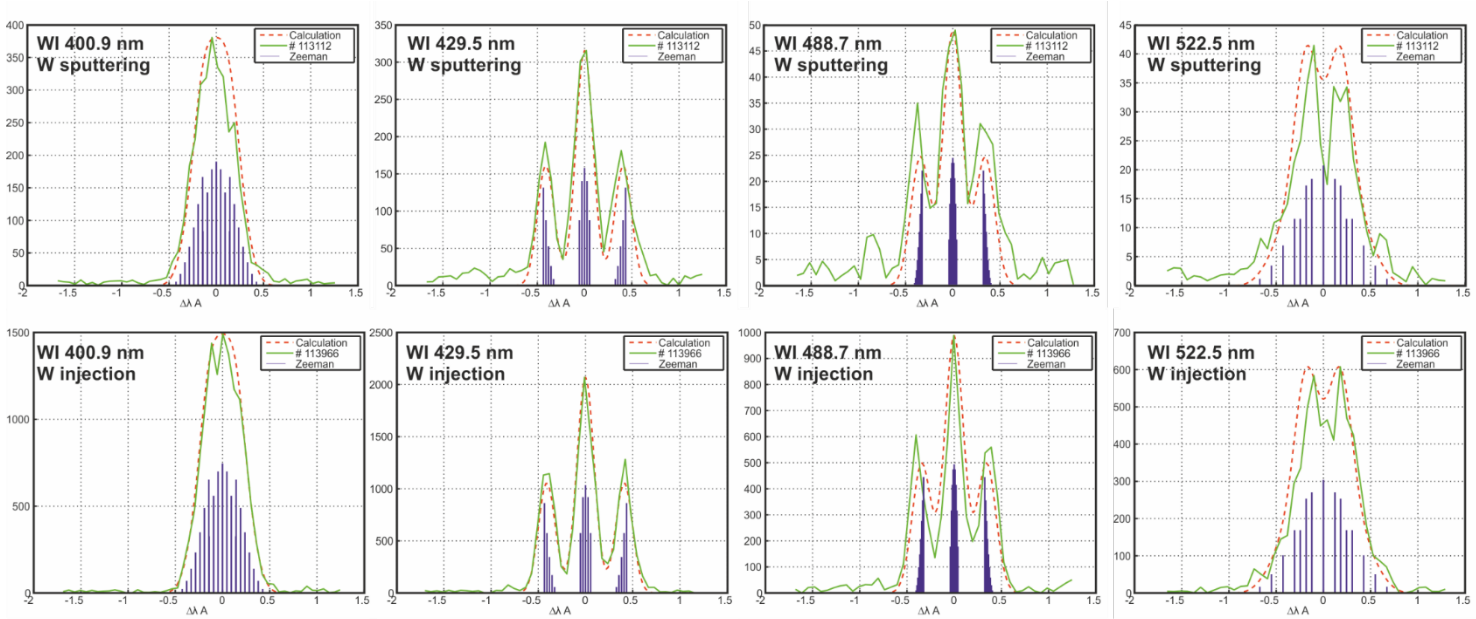
meta stables present

From NIST

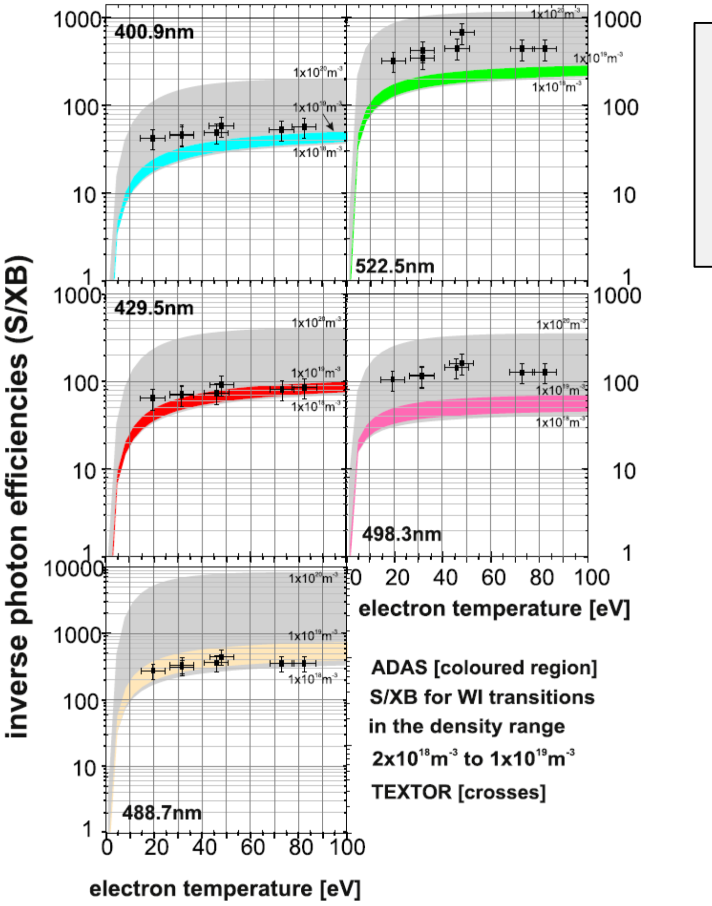
- Prominent transitions in the visible spectral range
- Definition of an artificial ground state ^{5}D population (T_w) in earlier times [Beigman et al.]

Injected W and Sputtered W: WI emission

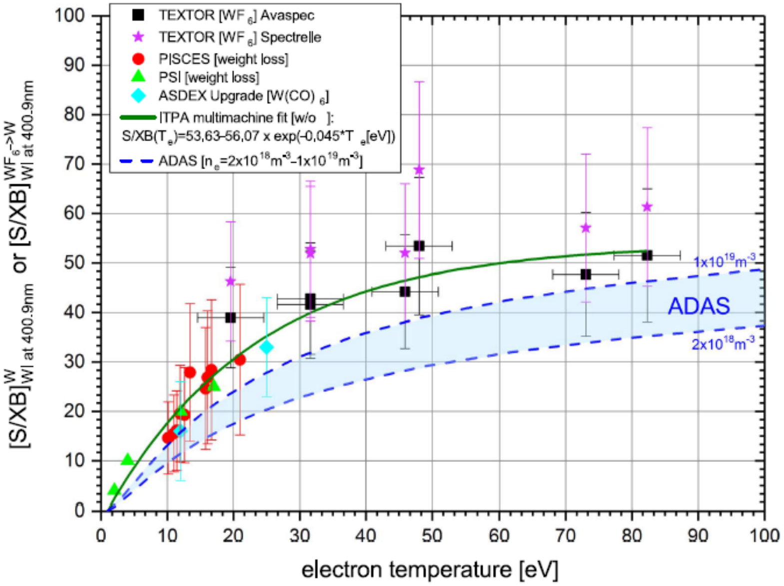
- Calibration of W lines with WF6 injection (dissociation at about T_e~0.1eV)
- W from WF_6 dissociation representative for W from sputtering?
  - No difference in line shape of different WI and WII lines
  - Lines and ratios of WI lines comparable in sputtered and injected W
  - WII lines measured and quantified in WF_6 injections



Photon Effciencies: Experiment and ADAS

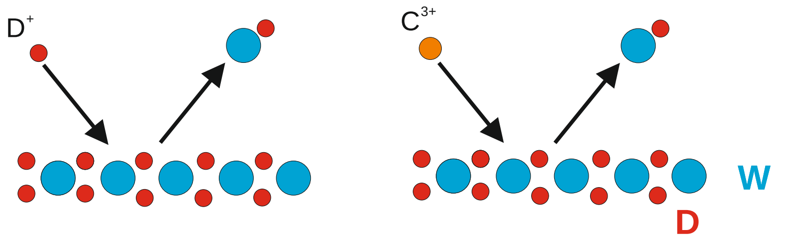


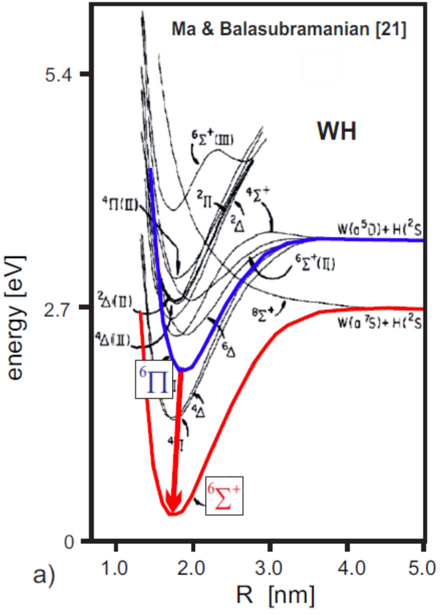
- Experimental data is “effective” assuming WF_6 dissociation is complete
- Experimental data in general in good agreement with ADAS (lower)
- Largest deviation for the “lowest” ground state transition (λ=498.3nm)
- ADAS considers only “real” ground state poppulated (no T_W?)

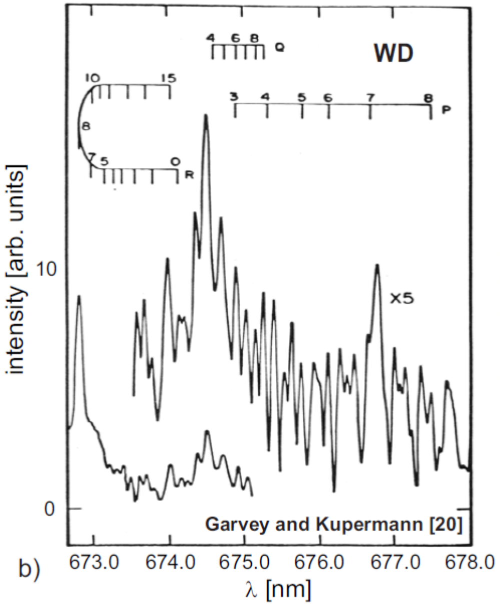


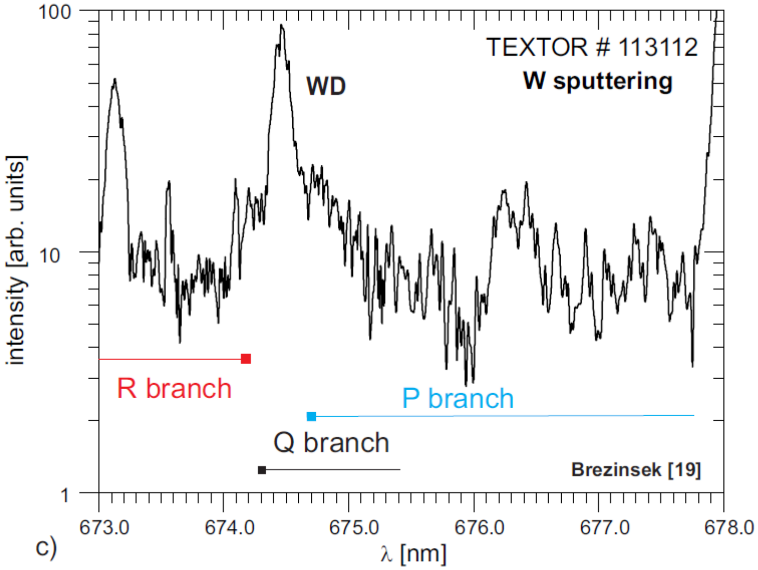
Tungsten Hydride: : $^6\Pi$-$^6\Sigma^+$ Transition

- Observation of WD molecule at very high D^+ fluxes (10^{23} ions $s^{-1}m^{-2}$) on cold W surfaces (<600K)
- Chemically Assisted Physical Sputtering by C ions with sufficient high impact energy (~100eV)









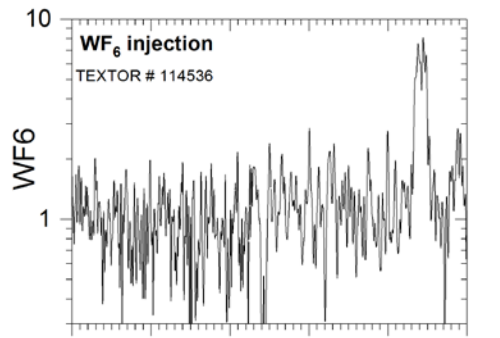
S. Brezinsek NME 2019

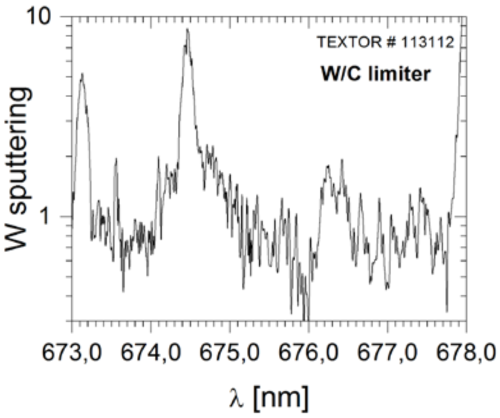
Tungsten Hydride: : $^6\Pi$-$^6\Sigma^+$ Transition

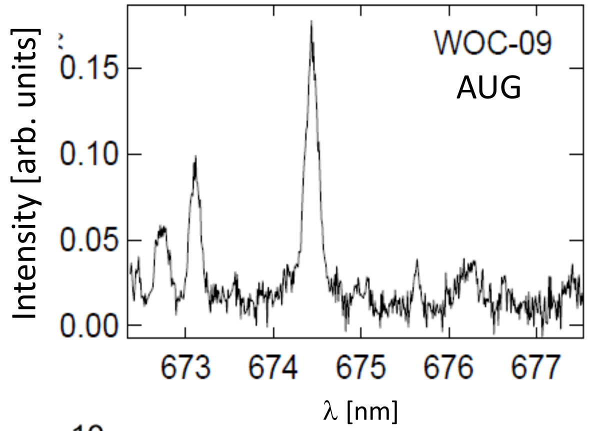
- Not produced in plasma as WF_6 injection in D plasma

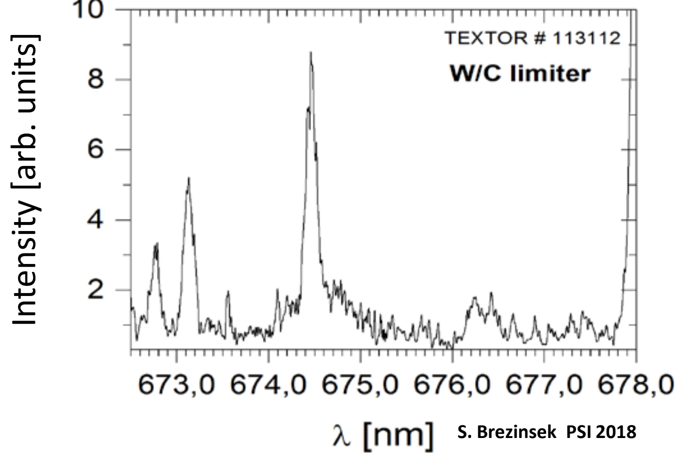
- Observed in ASDEX Upgrade and produced during ELMs too (D^+ ions at high energy)

- Looking forward to see a molecular modelling….





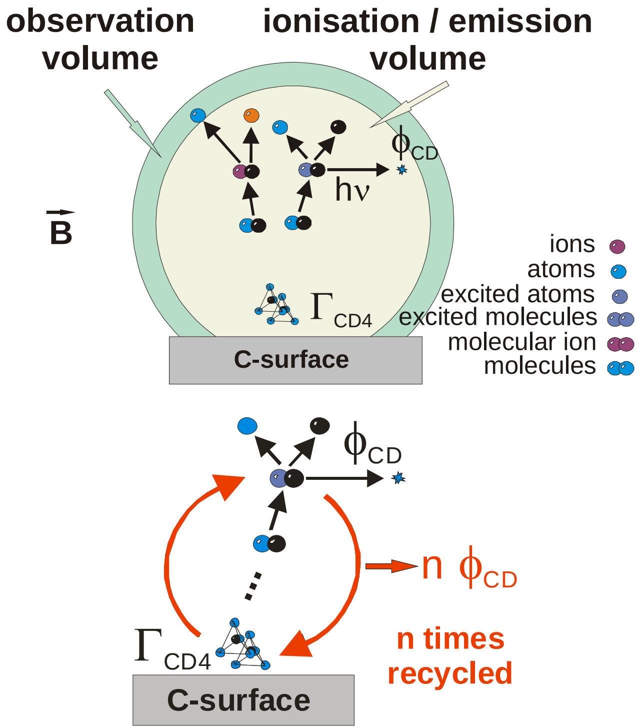




S. Brezinsek PSI 2018

Outline

- Introduction
- Spectroscopic techniques
- Hydrogen (and isotopes) spectroscopy
- Beryllium hydride spectroscopy
- Tungsten spectroscopy
- Hydrocarbon and carbon spectroscopy



Quantification of Sputtering Yields: Example C

(hydro)carbon flux Γ_C ← $Y_{chem} = \dfrac{\Gamma_C}{\Gamma_D}$ → deuterium flux Γ_D

$$\Gamma = \frac{D}{X\,B}\,\phi$$

Γ - particle flux
ϕ - photon flux
D - Decay rate coefficients (ioniSation, dissociation etc.)
X - eXcitation rate coefficient
B - Branching ratio

- composition: CD_4, C_2D_y	- composition: D_2, D
- accessible photon flux ϕ	- accessible photon flux ϕ
CD: Gerö band	*D: Balmer series*
C_2: Swan band	*D_2: Fulcher band*
- inverse photon efficiencies	- inverse photon efficiencies

in-situ plasma parameter determination

- Balmer-line ratios
- Fulcher-α-band analysis

Hydrocarbon break-up chain ↔ *Deuterium recycling*

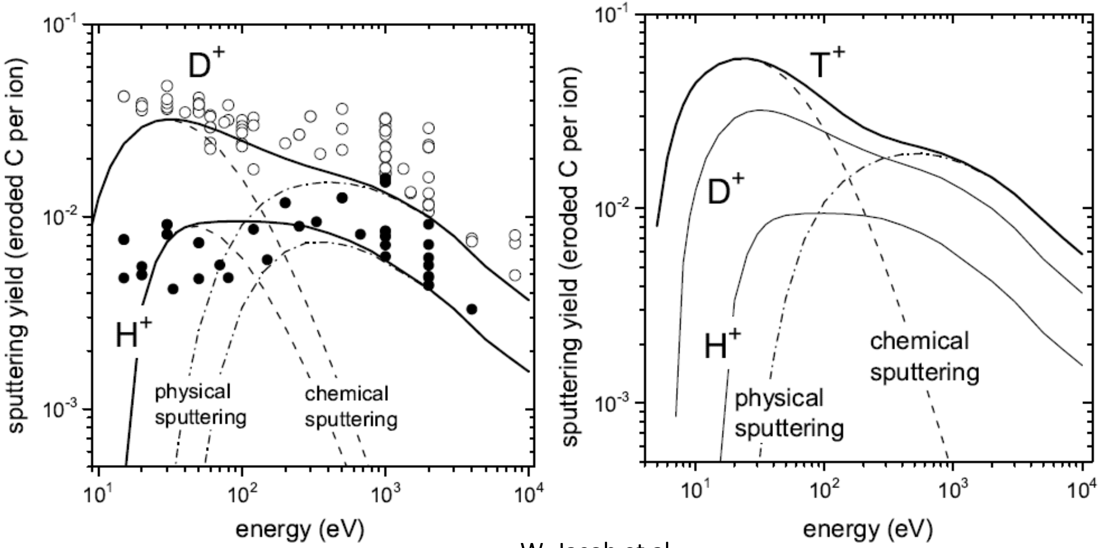
\+ other carbon lines (C II, C III, C IV)

\+ other molecules containing deuterium: BD, HD ...

Identical observation volume and integration time!

Sputtering Yields for Graphite

Chemical (C_xH_y))and physical sputtering (C)of graphite by hydrogen isotopes in ion beam facilities



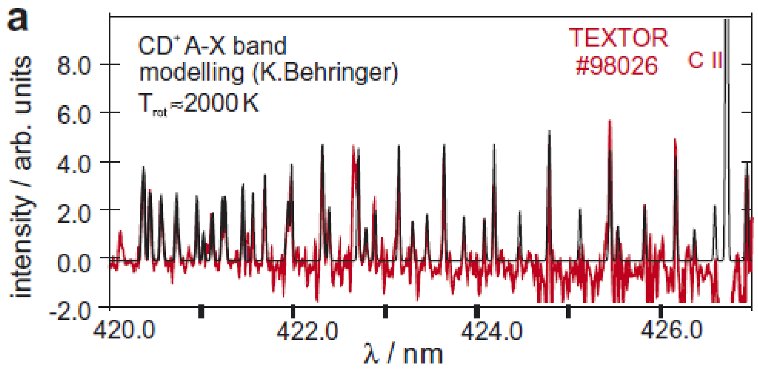
W. Jacob et al.

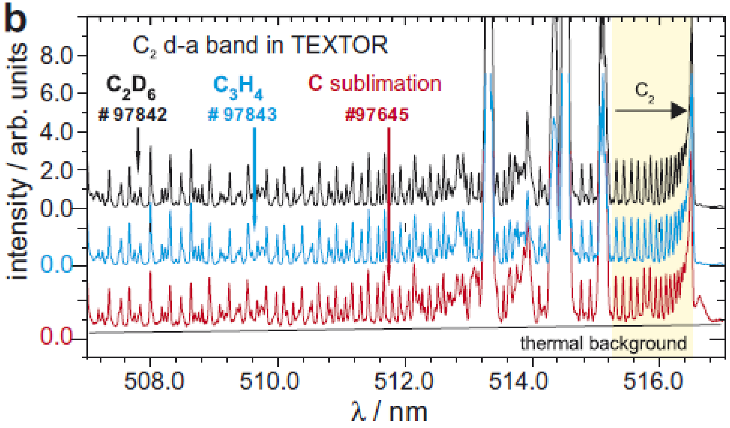
Total yield:

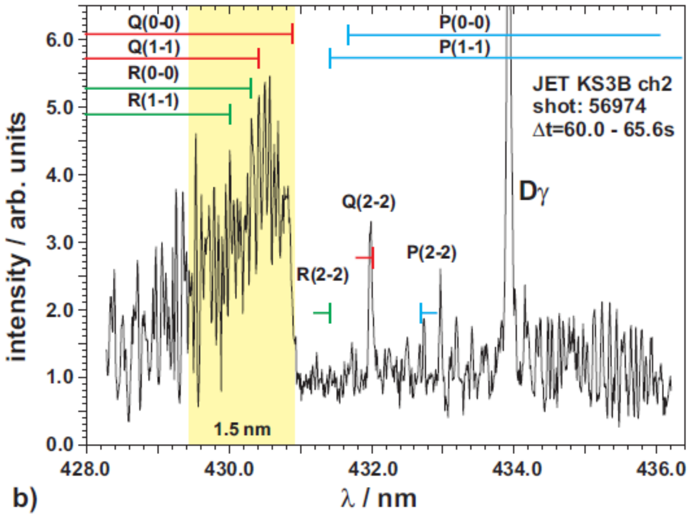
- Still thermal release of chemical erosion contribute below threshold for H^+
- Mass dependence in total erosion yield
- Variation if C layers present

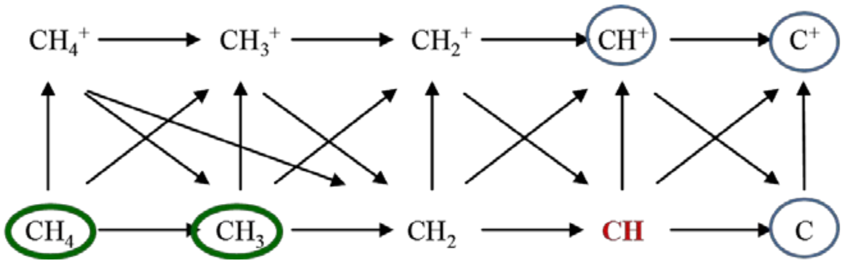
In-situ determination and origin required: chemical or physical sputtering / bulk or carbon layers?

In-situ Measurable Molecular Species: CH, CH^+, C_2



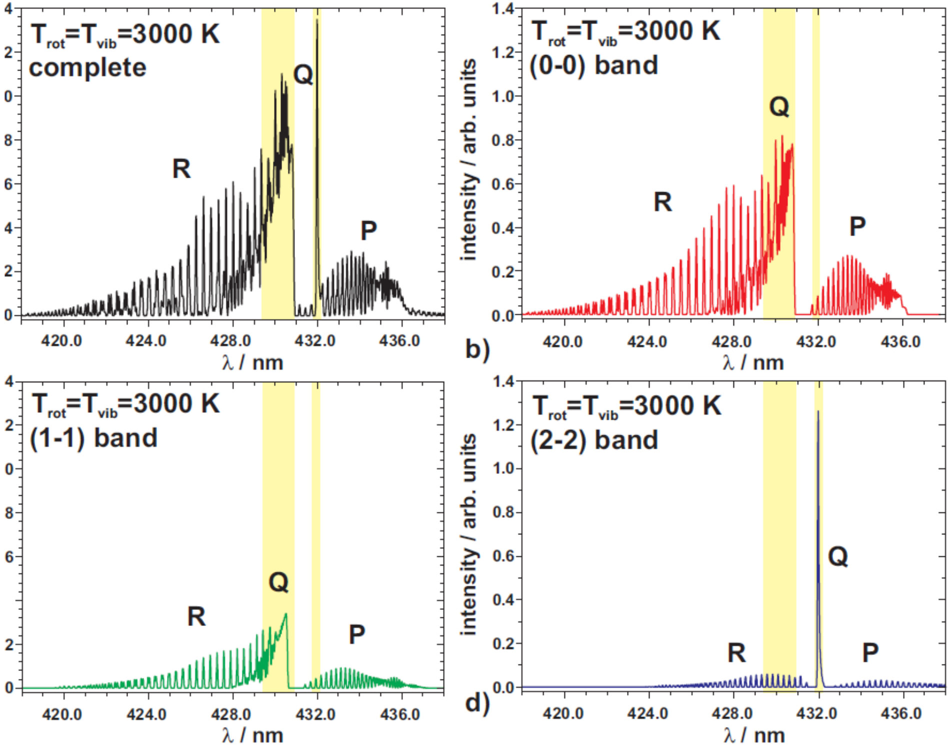


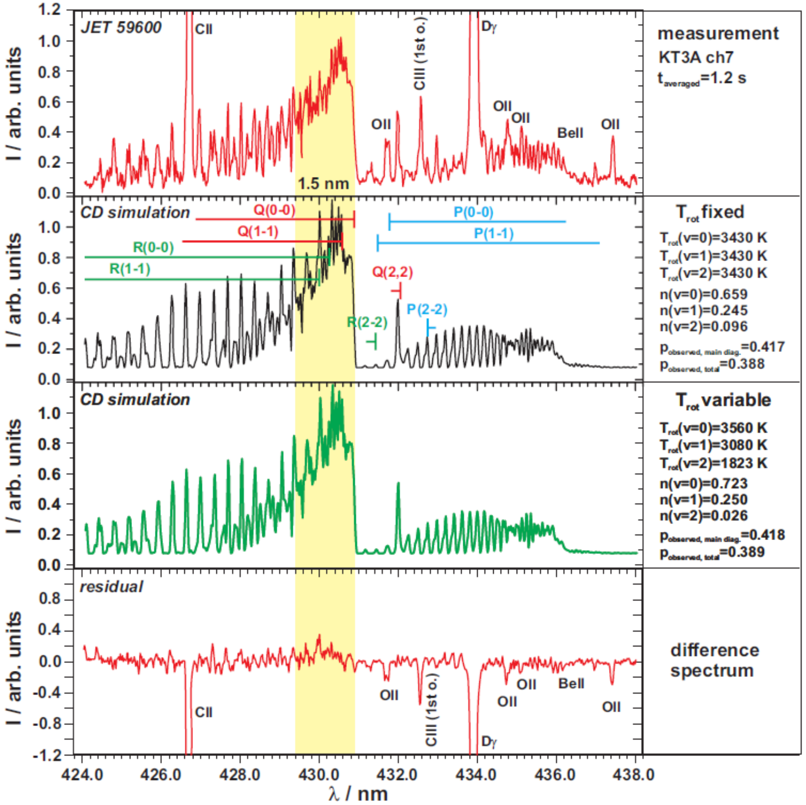




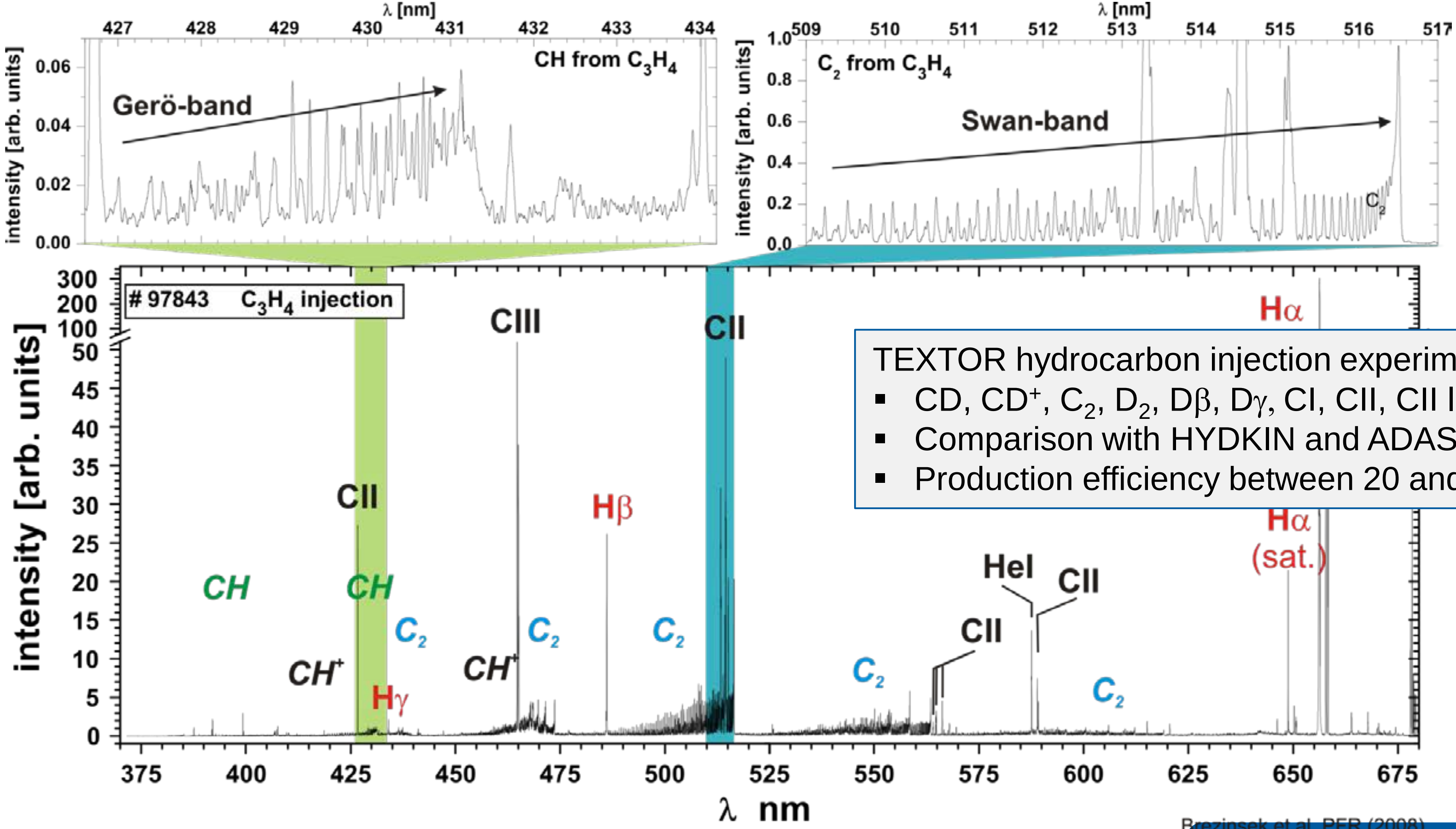
Origin not visible in emission spectroscopy – in-situ calibration to get the footprint

Modelling of the Gerö Band





Hydrocarbon Footprint in Plasmas by C_xH_y Injection



TEXTOR hydrocarbon injection experiments:

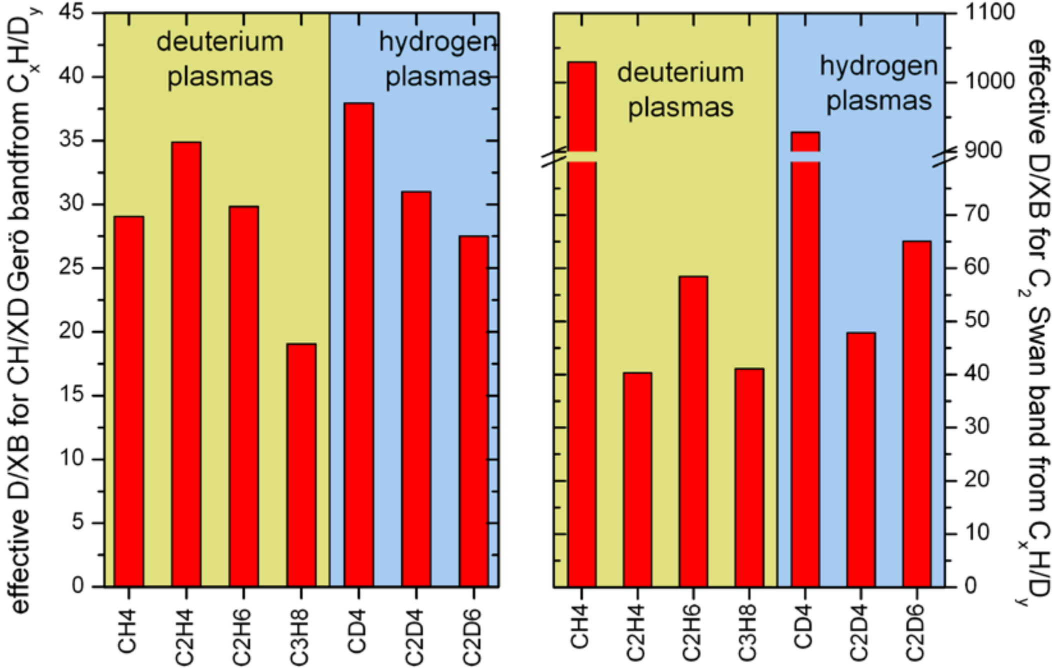
- CD, CD^+, C_2, D_2, Dβ, Dγ, CI, CII, CII lines
- Comparison with HYDKIN and ADAS
- Production efficiency between 20 and 100%

Brezinsek et al. PFR (2008)

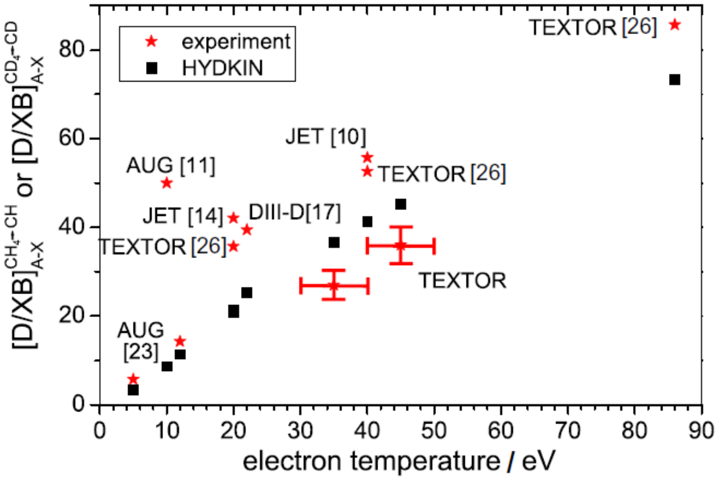
Hydrocarbon Footprint by CxHy Injection in Plasmas

JUEL-3966 Report
JUEL-4005 Report
www.eirene.de

Benchmark of HYDKIN database for hydrocarbon catabolism



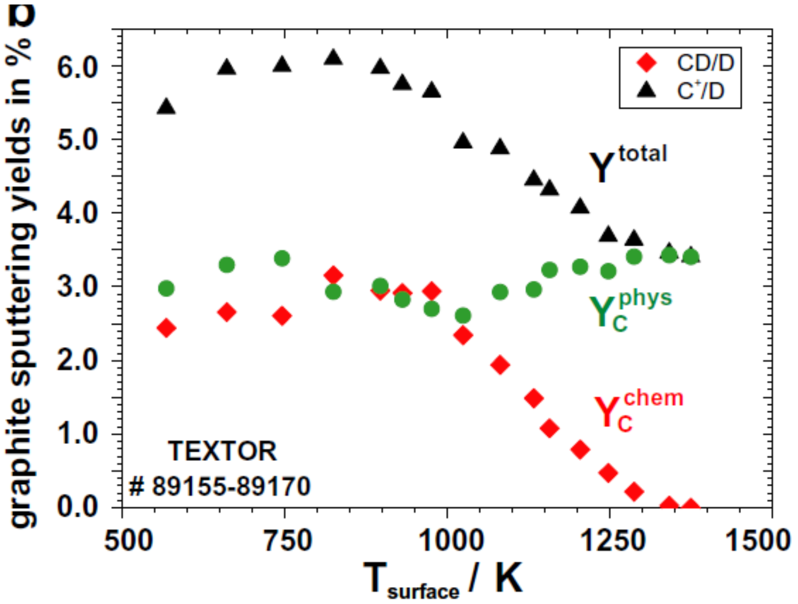
Multimachine comparison of experimental tokamak data



Residual discrepancy – local C recycling and layer formation

C_xH_y in D plasmas: T_e=35 eV, n_e=2.2*$10^{18}m^{-3}$ at the emission location
C_xD_y in H plasmas: T_e=45 eV, n_e=1.8*$10^{18}m^{-3}$ at the emission location

Chemical Erosion: Temperature Dependence

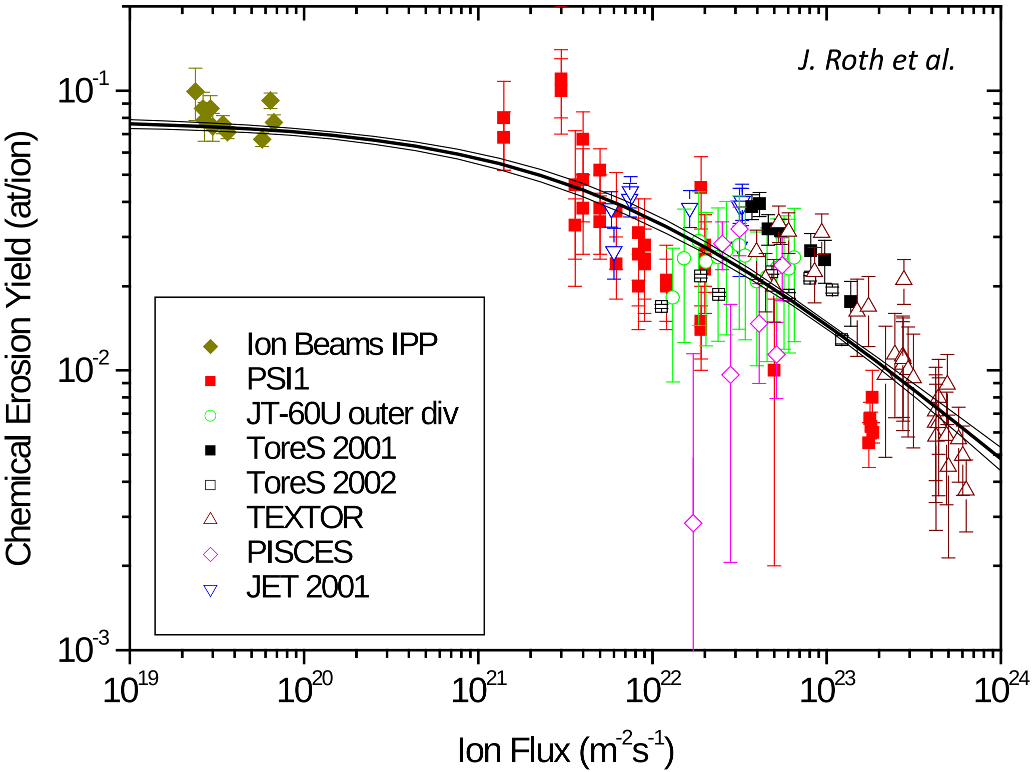


Identical plasmas at T_e~50eVwith external change of surface temperature

Above 1000K chemical erosion drops and vanishes at 1300K

Flux density: ~5x10^{23}ions $s^{-1}m^{-2}$

Chemical Erosion: Flux Dependence



Normalisation:
30 eV T_{surf}(max)

Difficult to decouple from E_{in}

Chemical sputtering decreases with increasing flux

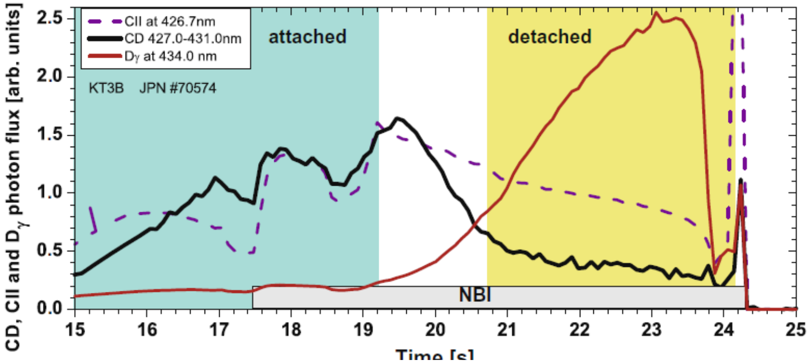
Flux dependence is predicted by model of thermal reaction cycle

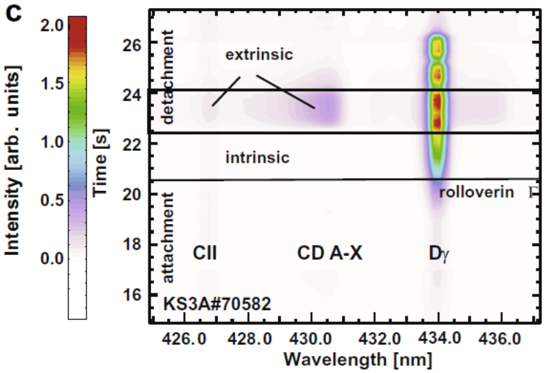
Chemical Sputtering: Energy Threshold

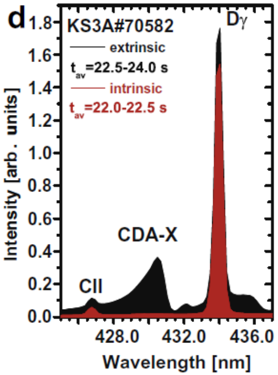
At low impact energies (~2-3eV), the chemical sputtering part of C is almost absent

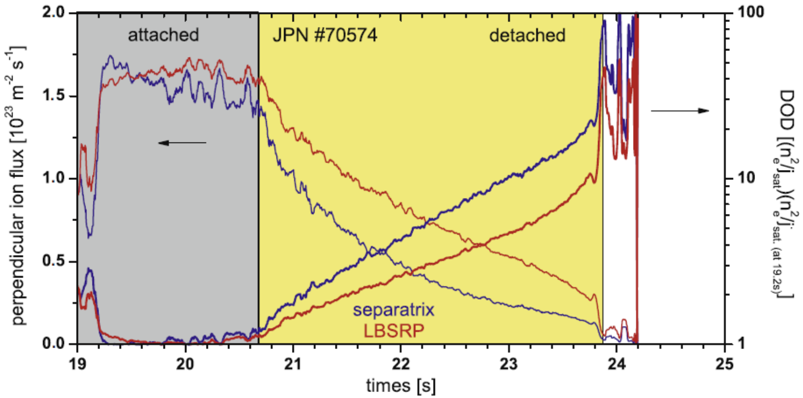
JET-C with CFC divertor

- Erosion zone on graphite
- Divertor detaches and reveals chemical sputtering threshold
- Test with local methane source injection

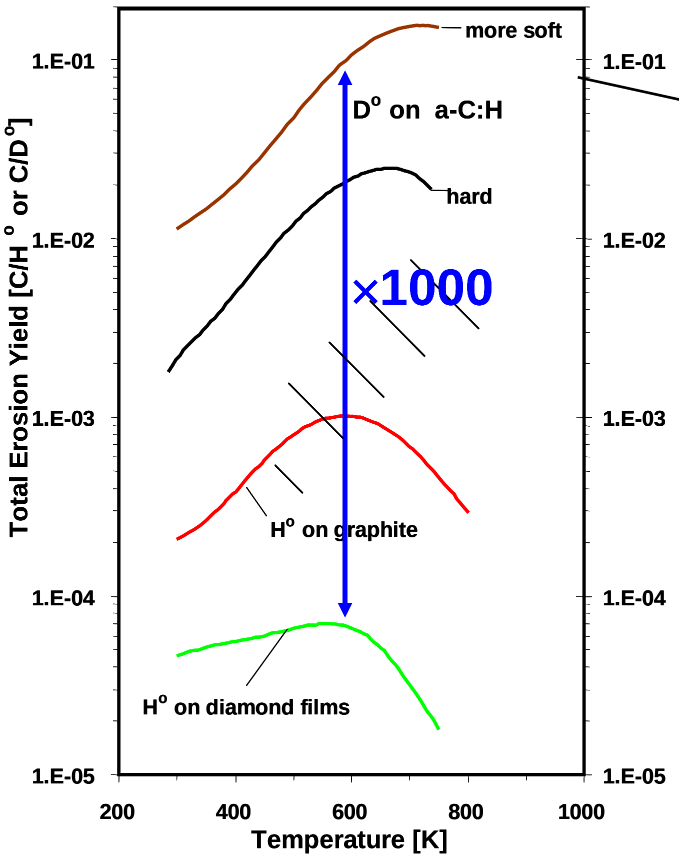








Chemical Erosion: a-C:H layers



a-C:H

amorphous
hydrocarbon layer

- soft (hydrogen-rich) carbon layers suffer from larger chemical erosion
- Lower activation energy for release with high hydrogen content
- Associated with release of higher hydrocarbons

E. Vietzke, J. Nucl. Mat. (1987) 443