



**The Abdus Salam  
International Centre for Theoretical Physics**



**2028-12**

**Joint ICTP/IAEA Workshop on Atomic and Molecular Data for  
Fusion**

*20 - 30 April 2009*

**Plasma-Wall Interaction in Magnetic Fusion  
Erosion Mechanisms (Erosion of Carbon by Hydrogen)**

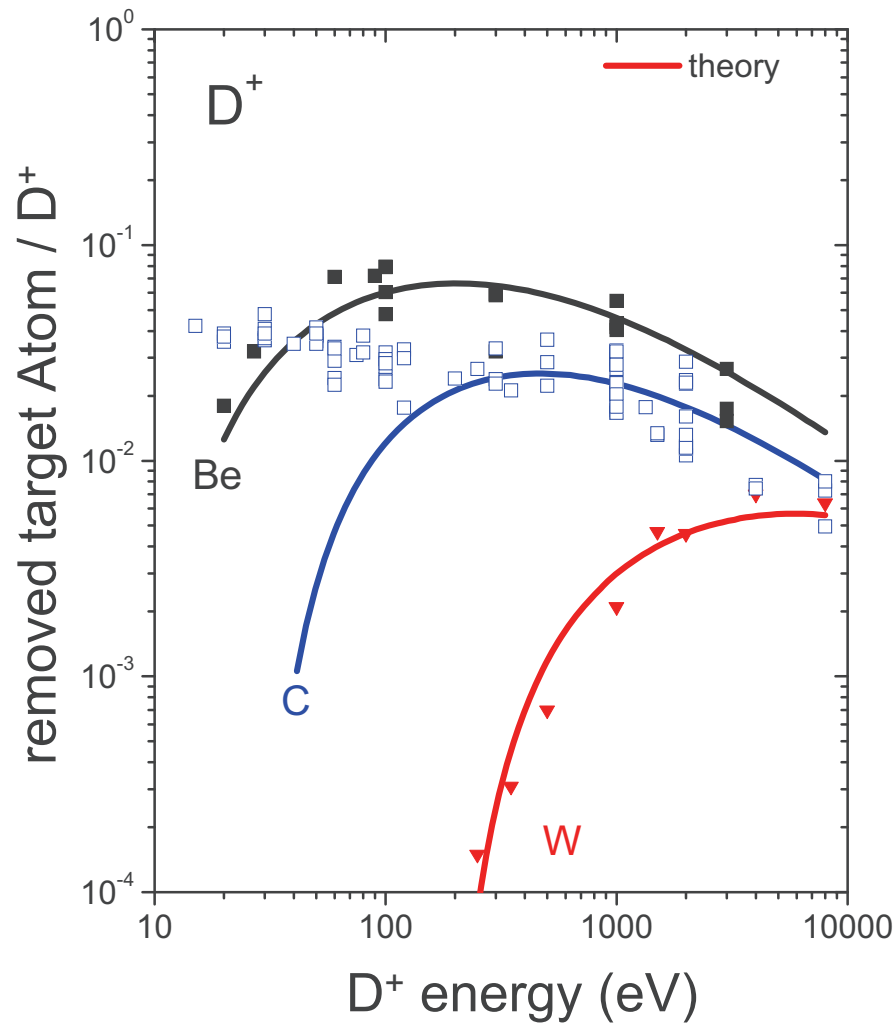
SCHWARZ-SELINGER Thomas  
*Max-Planck-Institut fuer Plasmaphysik  
Boltzmannstrasse 2  
85748 Garching bei Munchen  
GERMANY*

Thomas Schwarz-Selinger

**erosion mechanisms (erosion of carbon by hydrogen)**

- chemical erosion
- physical sputtering
- chemical sputtering

# erosion by hydrogen impact at room temperature



- Advantage for high-Z materials
  - Strong deviation for Carbon based materials
- ⇒ what is different?
- ⇒ chemical reactions between D and C forming volatile hydrocarbons

---

## research groups (experimental): erosion of carbon by hydrogen

---



- **Roth:**
  - IPP, Garching-Germany
- **Jacob:**
  - IPP, Garching-Germany
- **Küppers:**
  - Experimentalphysik III, Universität Bayreuth, Bayreuth-Germany
  - IPP, Garching-Germany
- **Vietzke:**
  - Institut für Chemie, KFA Jülich GmbH, Jülich-Germany
- **Haasz/Davis:**
  - Fusion research group, university of Toronto, Ontario-Canada
  - Institute for Aerospace Studies and Centre for Nuclear Engineering, Ontario-Canada

---

## nomenclature

---

- **Chemical erosion** is a selective removal of surface atoms by *chemical reactions*, forming volatile reactants that can desorb.
- **Physical sputtering** is the *kinetic ejection of surface atoms* by incident energetic ions or atoms *due to collision processes*.  
(playing billiards with surface atoms).
- **Chemical Sputtering** is a process whereby *ion bombardment causes or allows a chemical reaction to occur* which produces a particle that is weakly bound to the surface and hence easily desorbs in the gas phase.

## CHEMICAL EROSION IN FUSION DEVICES:

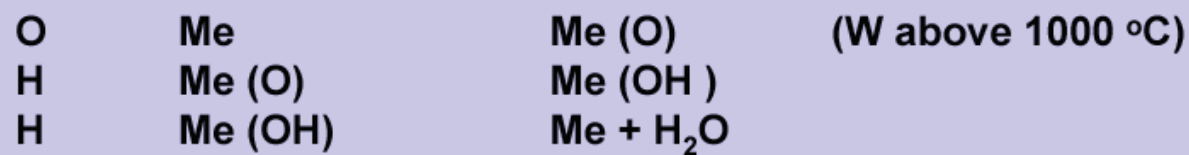
### FORMATION OF HYDROCARBONS:



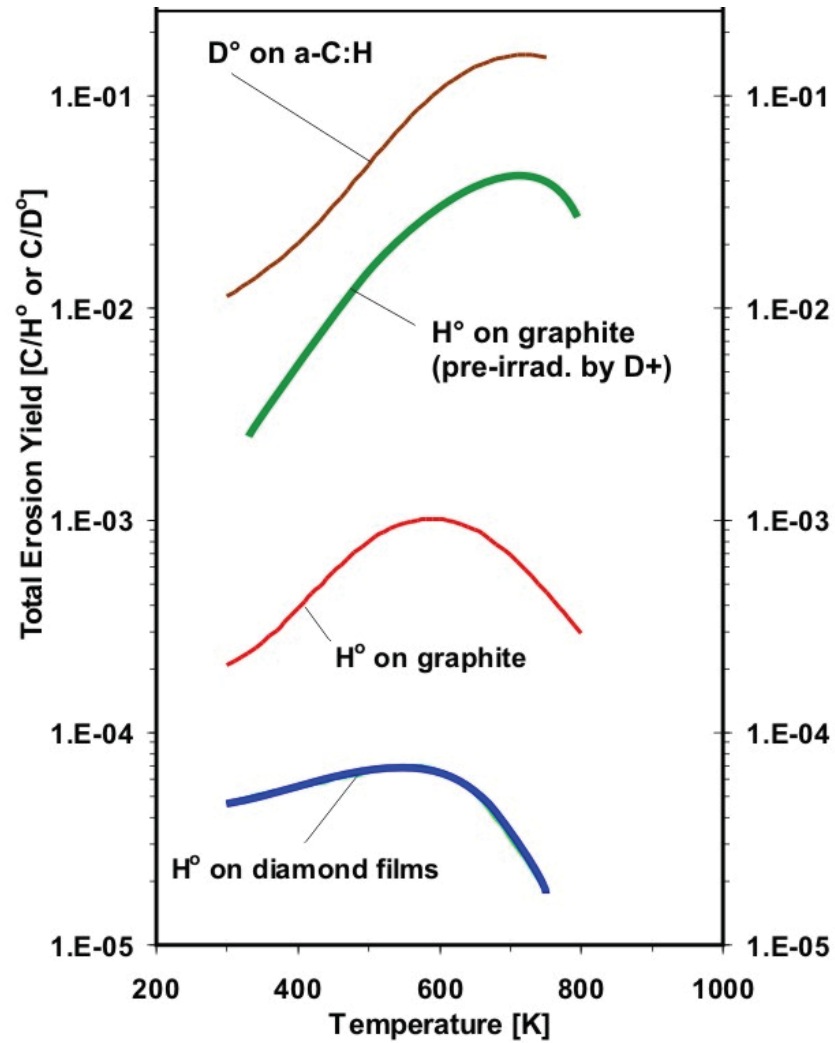
### FORMATION OF CARBON OXIDES:



### REACTIONS WITH SOME METALS:



# chemical erosion of carbon: structure dependence



disorder



1000 x



order

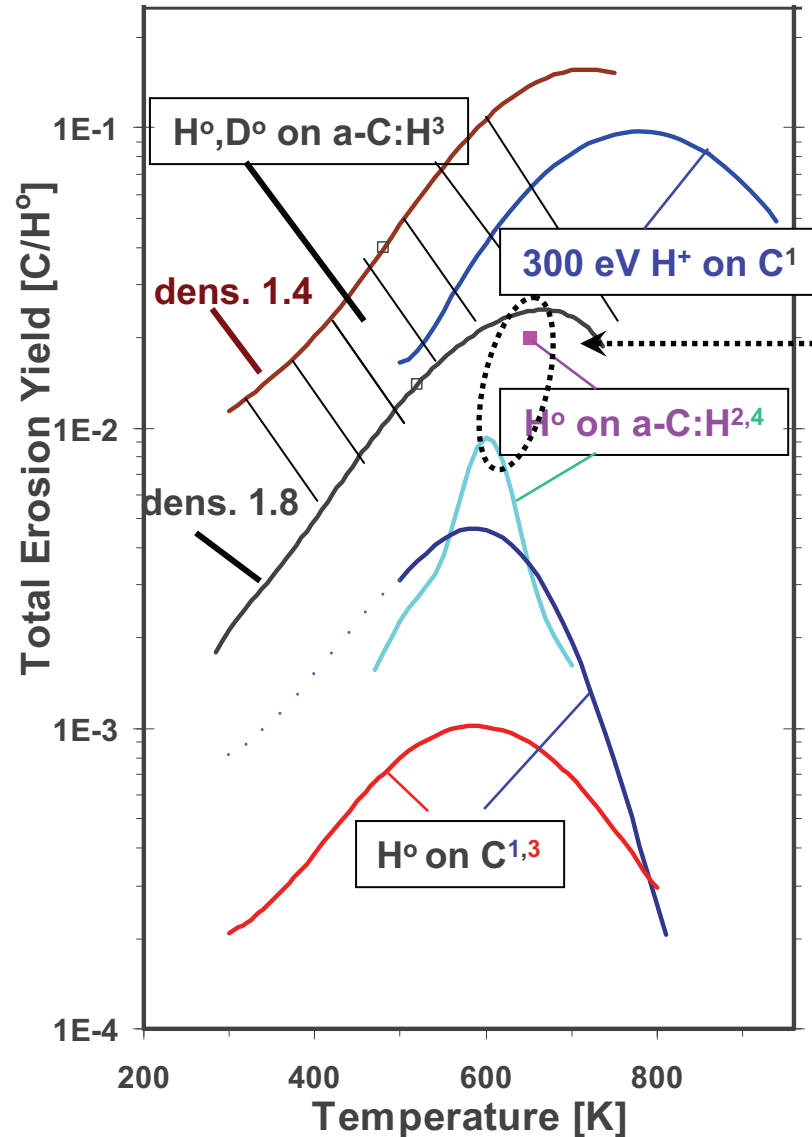
Total Y of H° on films of:

- a-C:H (plasma-deposited),
- pre-irradiated graphite,
- graphite and
- diamond

➤ reactivity of the surface depends critically on the surface structure

*E. Vietzke et al., Surf. Coat. Technol. 47 (1991) 156-161*

# chemical erosion of carbon: structure dependence



- The erosion yield of H<sup>0</sup> on a-C:H reach values of the maximum of H<sup>+</sup> on C
- “Good agreement” of a-C:H (hard)

1. J.W. Davis et al., JNM 155-157(1988)243
2. T. Schwarz-Selinger et al., J. Vac.Sci.Techn. A18 (2000) 995
3. E. Vietzke et al. Fus. Technol. 15 (1989) 108
4. A. Horn et al., Chem. Phys. Lett. 231 (1994) 193



# chemical erosion: microscopic model

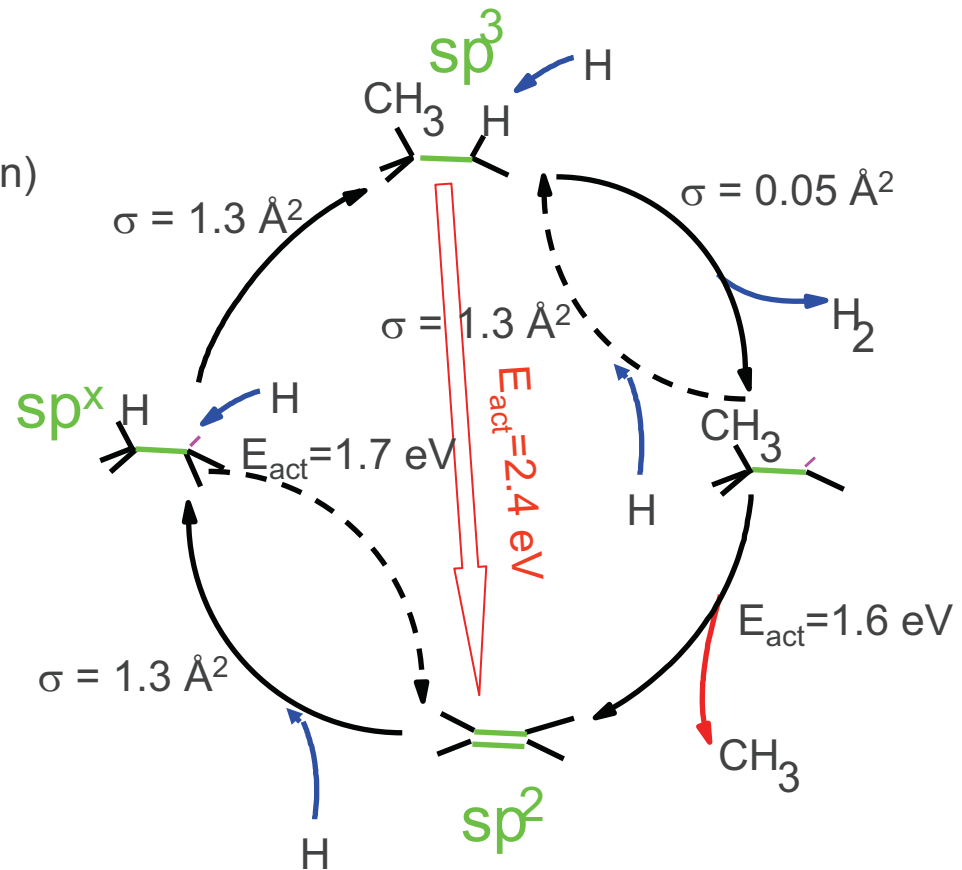


## Hydration and erosion circle:

Horn et al., Chem. Phys. Lett. 231, 193 (1994)

Zecho et al. J. Phys. Chem. B 105 (2001).

- 1) chemisorption of H on  $sp^2$  site
- 2) chemisorption of H on  $sp^x$  site (hydration)
- 3) abstraction of H to form  $H_2$
- 4 a) thermal release of  $CH_3$  radicals from activated sites above 400 K
- 4 b) chemisorption of H on  $sp^x$  site
- 5) relaxation back to  $sp^2$  above 750 K
- 6) direct thermal decomposition to  $sp^2$  above 900 K with  $E_{act}=2.4$  eV



# chemical erosion: microscopic model



## hydration and erosion circle:

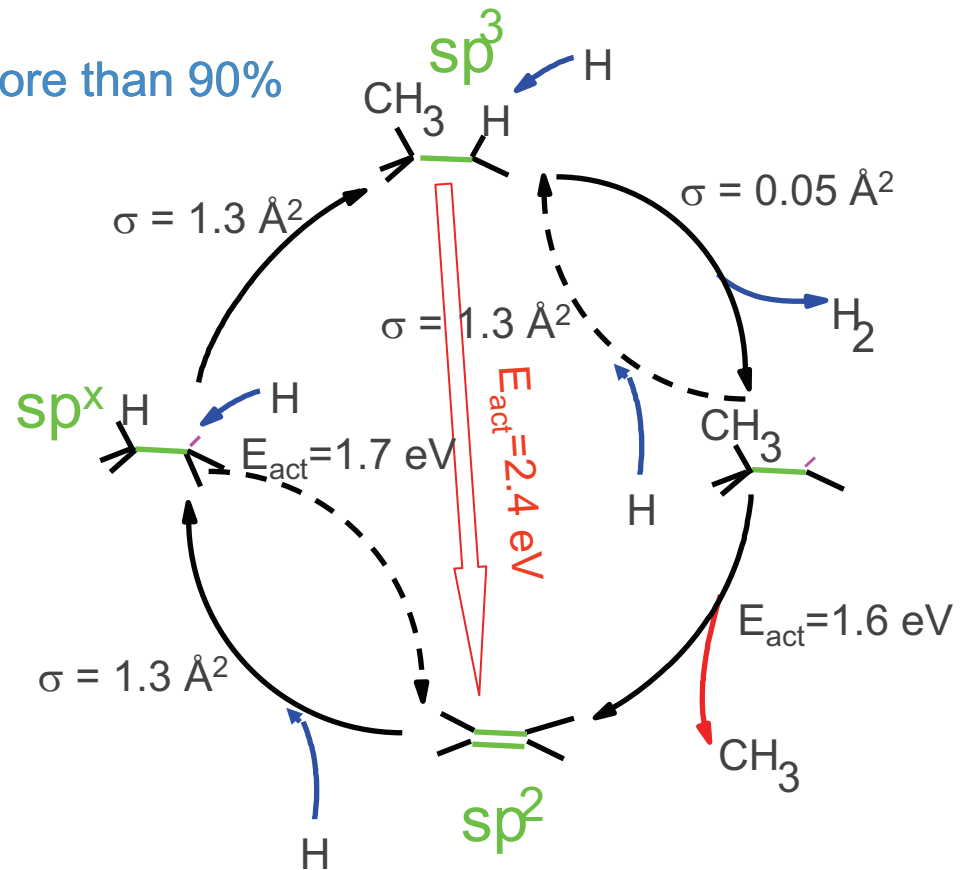
Horn et al., Chem. Phys. Lett. 231, 193 (1994)  
Zecho et al. J. Phys. Chem. B 105 (2001).

- hydration at room temperature of more than 90% of all possible adsorption sites
- erosion maximum
- flux dependence of the erosion maximum

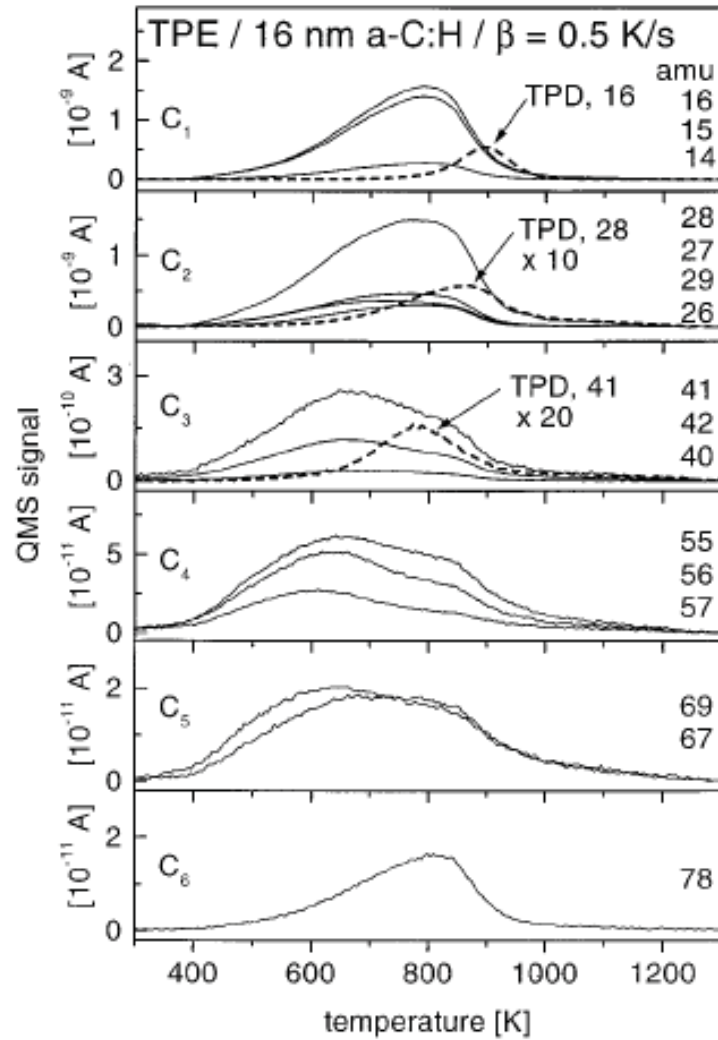
600 K at  $10^{17} \text{ m}^{-2}\text{s}^{-1}$

750 K at  $10^{20} \text{ m}^{-2}\text{s}^{-1}$

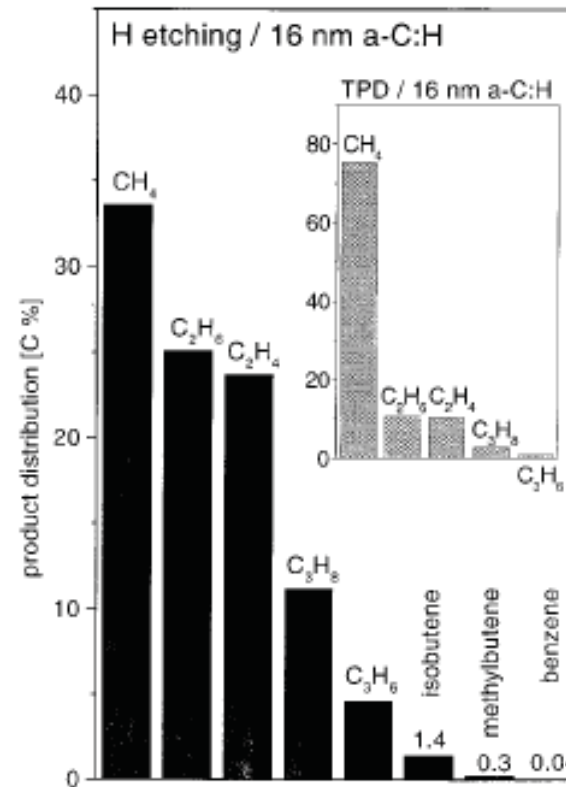
??? K at  $10^{24} \text{ m}^{-2}\text{s}^{-1}$  (ITER)



# chemical erosion: product distribution



Formation of volatile C<sub>x</sub>H<sub>y</sub>:  
Thermal **decomposition** and **erosion**  
**with H<sup>o</sup>** of dense a-C:H film

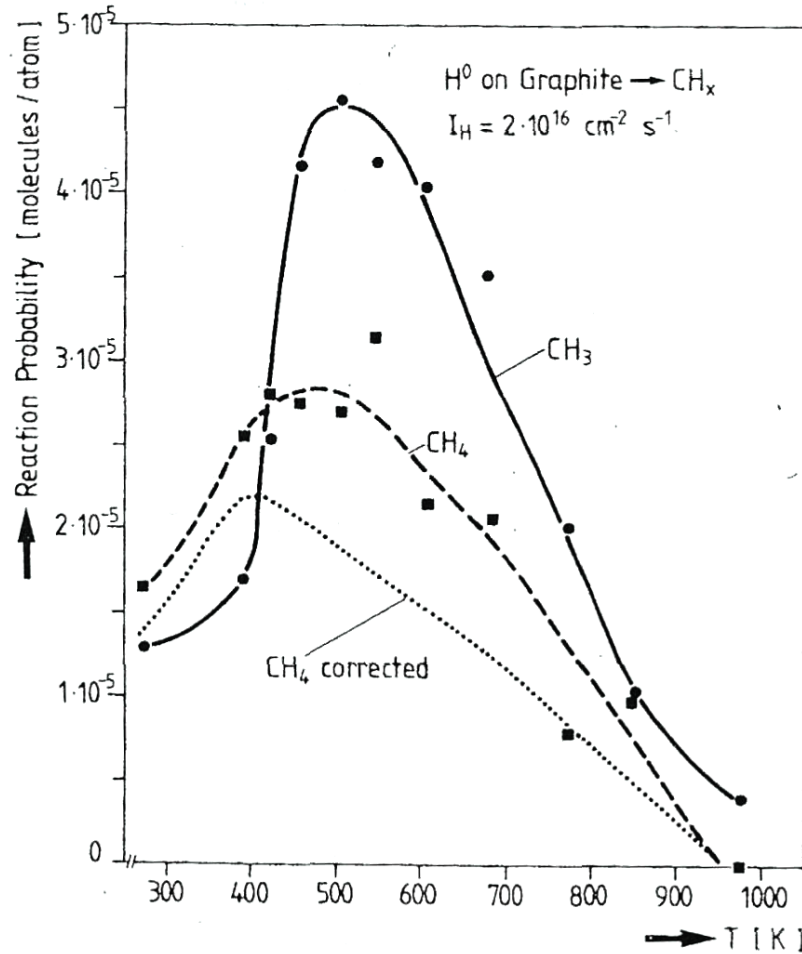


T. Zecho, B. D. Brandner, J. Biener, J. Küppers; *J. Phys. Chem. B* **105** (2001) 6194-6201

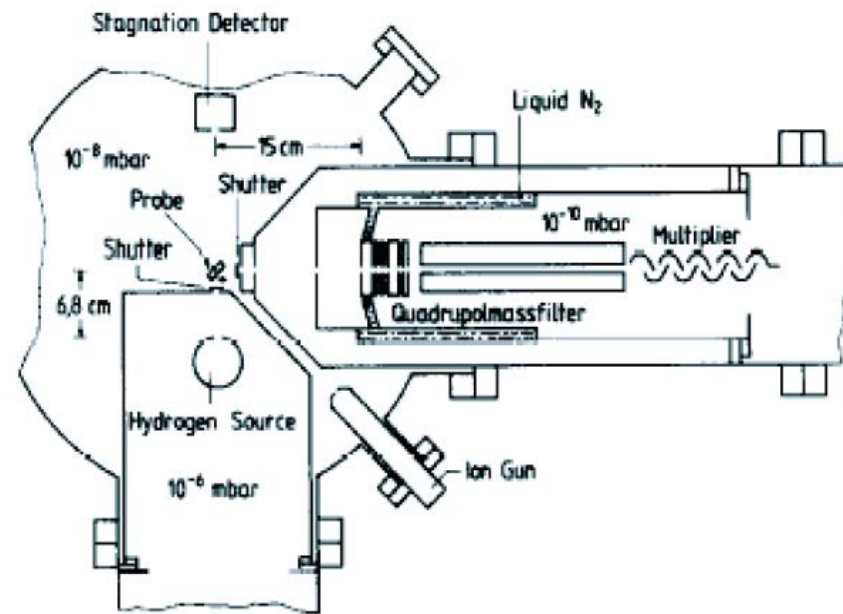
# chemical erosion: direct identification of the precursor



At  $T=500\text{K} \rightarrow$  ratio  $\text{CH}_3/\text{CH}_4 \sim 2$



dedicated experiment to detect reactive products:



E. Vietzke, K. Flaskamp, V. Philipps.; *J. Nucl. Mater.* **128-129** (1984) 545-550

## erosion of dense a-C:H

- Precursor for chemical erosion is a  $\text{CH}_3$  group ( $\text{C}_2\text{H}_x$ ) adjacent to a dangling bond site  
(both are produced by interaction with atomic hydrogen)
- cross section for hydrogenation ( $1.3 \text{ \AA}^2$ ) and abstraction ( $0.05 \text{ \AA}^2$ ) and threshold energies for relaxation (2.4 eV / 1.7 eV) are known (within a factor of 2?)
- nearly all eroded material is transferred into none-reactive volatile products
- shows no isotope effect (generally assumed)

## erosion of soft a-C:H

- thermal decomposition above 600 K and redeposition of up to 50% of the material

---

# chemical erosion: present status

---



## open questions for ITER

- high flux limit of the model
- influence of material mix?
- impact of vibrationally excited molecules on erosion?

- Chemical erosion originates from the formation and release of volatile molecules in the interaction of incident plasma particles and target atoms.
- In fusion application the formation of hydrocarbons in the interaction of hydrogen atoms with carbon surfaces is the dominant example of chemical erosion.
- As chemical reactions are involved, chemical erosion shows a strong temperature dependence in contrast to physical sputtering.
- Chemical erosion can occur with low-energy ions or thermal atoms and does not require a threshold energy.

---

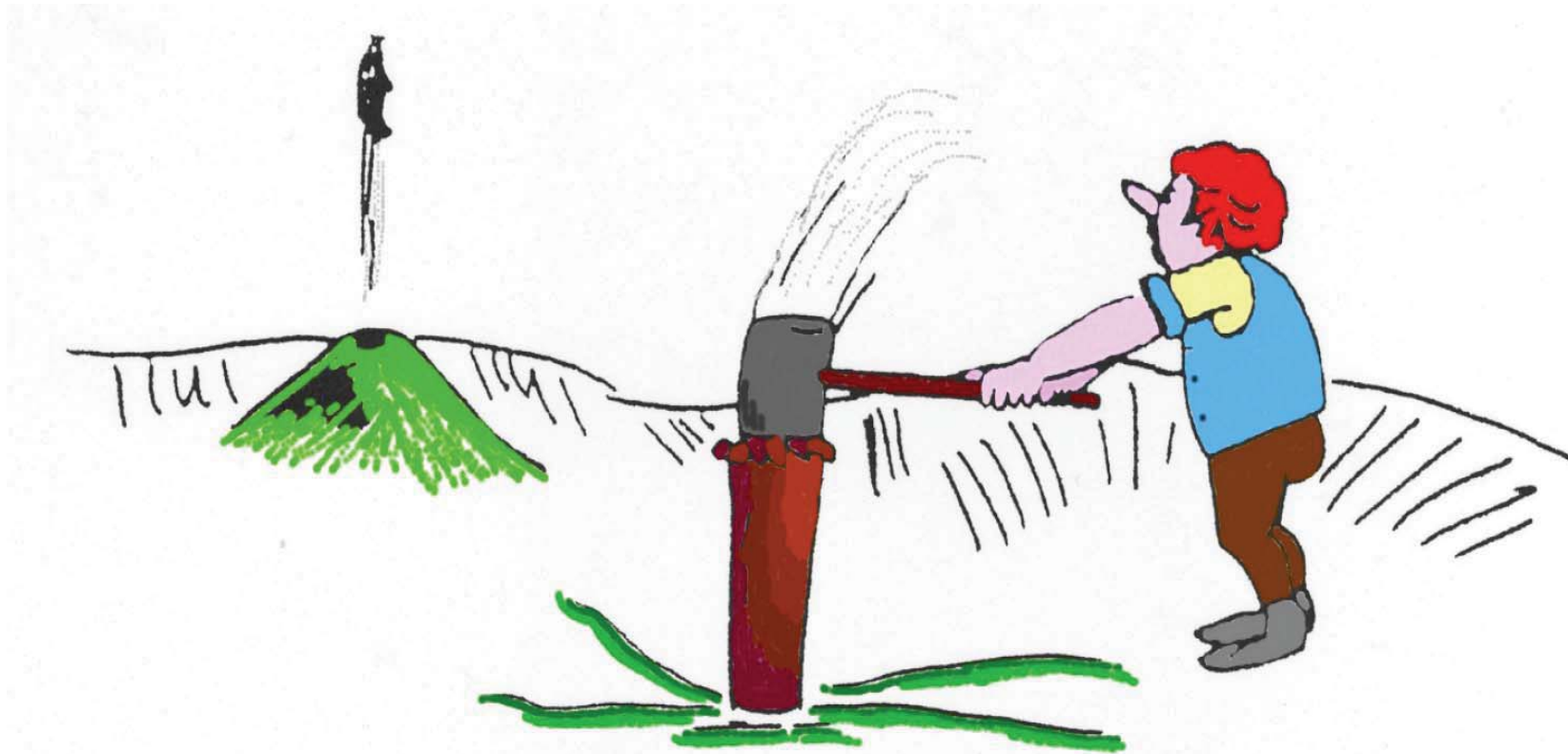
## nomenclature

---

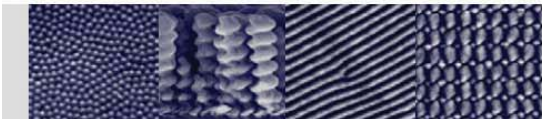
- **Chemical erosion** is a selective removal of surface atoms by *chemical reactions*, forming volatile reactants that can desorb.
- **Physical sputtering** is the *kinetic ejection of surface atoms* by incident energetic ions or atoms *due to collision processes*. (playing billiards with surface atoms).
- **Chemical Sputtering** is a process whereby *ion bombardment causes or allows a chemical reaction to occur* which produces a particle that is weakly bound to the surface and hence easily desorbs in the gas phase.



# physical sputtering



© F. Erler, TU Ilmenau

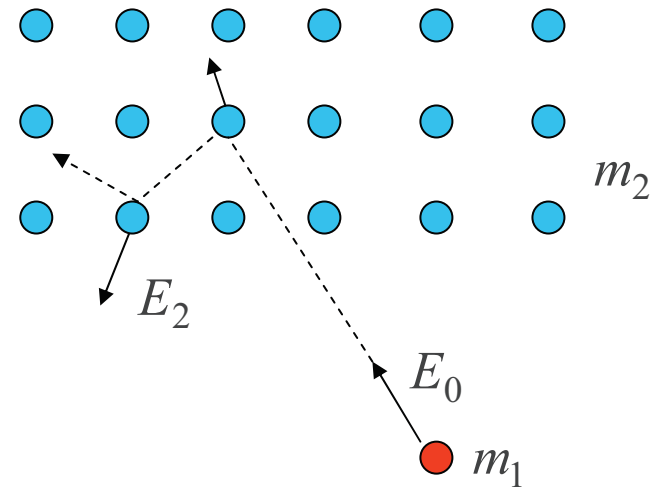


Mühlleithen 2006

Leibniz-Institut für  
Oberflächenmodifizierung e. V.  
Nanostructured Thin Film Group



sputter yield  $Y = \frac{\text{average No of sputtered particles}}{\text{incident ion}}$



energy transfer in central collision:  $\gamma = 4 \frac{m_1 m_2}{(m_1 + m_2)^2}$

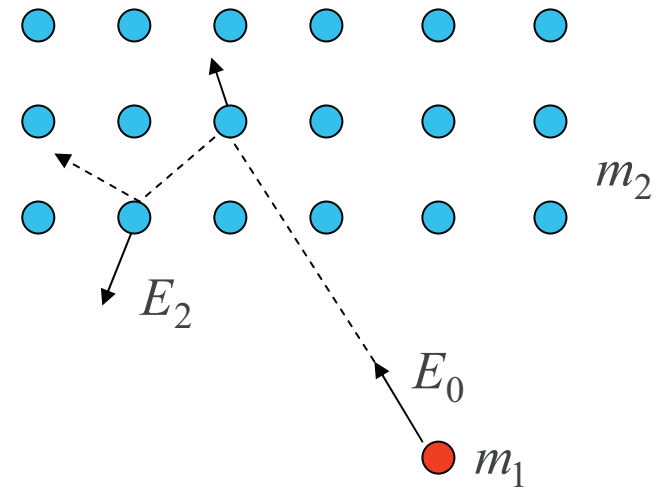
$m_1 < m_2$ , after first collision:  $E_1 = E_0(1 - \gamma)$

transferred energy:  $E_2 = \gamma \cdot E_0(1 - \gamma)$

threshold energy:  $E_{\text{th}} = \frac{E_s}{\gamma(1 - \gamma)}$  ( $E_s$ : surface binding energy)  $3.5 \text{ eV} < E_s < 9 \text{ eV}$

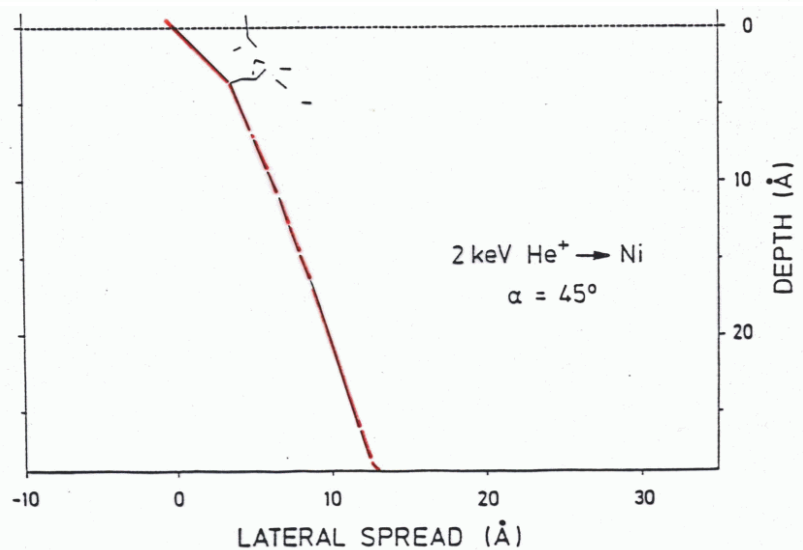
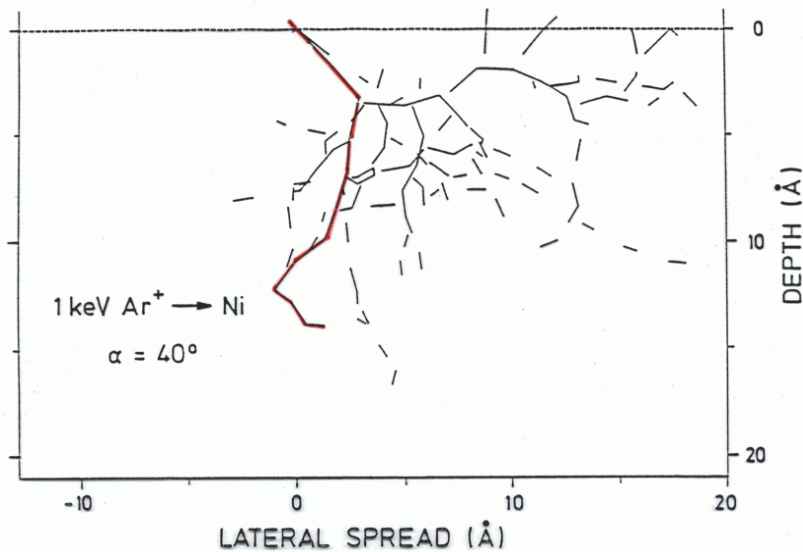
# physical sputtering

sputter yield  $Y = \frac{\text{average No of sputtered particles}}{\text{incident ion}}$



$m_1 = m_2$  (extended collision cascade):  $E_{th} = 4E_s$  (self sputtering),  $3.5 \text{ eV} < E_s < 9 \text{ eV}$

self sputtering: if  $Y > 1$ : unlimited increase of impurity content



- TRIM.Sp Monte-Carlo Code

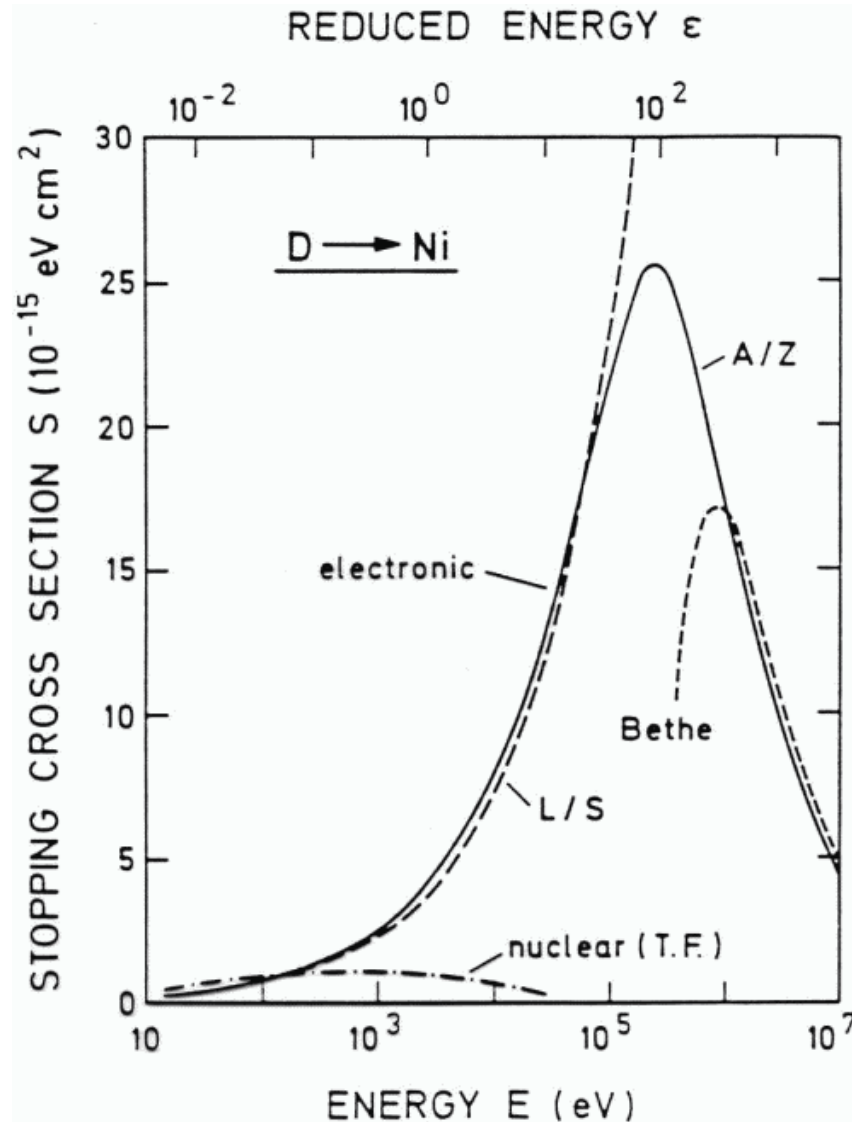
heavy ions:

- large collision cascade
- isotropic velocity distribution
- yield proportional to energy deposited in first two layers

light ions:

- few collisions
- energy transfer in single collision

$$T = E_0 \frac{M_1 M_2}{(M_1 + M_2)^2} \cos^2 \delta$$



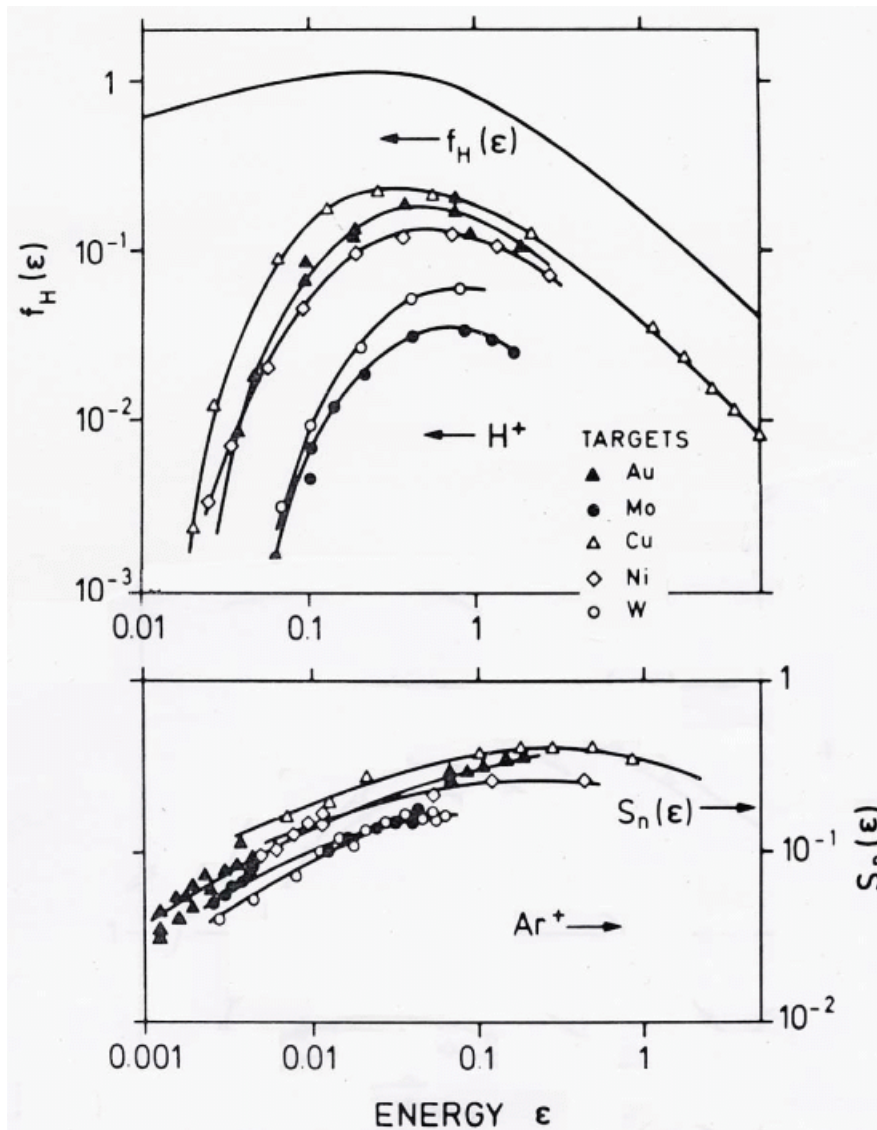
- projectiles and recoil atoms lose energy in elastic collisions (nuclear stopping) and collisions with electrons (inelastic stopping)

- the stopping cross section is a universal function if plotted versus the reduced energy  $\epsilon$

$$\epsilon = E_0 \frac{M_2}{M_1 + M_2} \frac{a}{Z_1 Z_2 e^2} = \frac{E_0}{E_{TF}}$$

$$S_n(\epsilon) = \frac{0.5 \ln(1 + 1.2288\epsilon)}{\epsilon + 0.1728\sqrt{\epsilon} + 0.008\epsilon^{0.1504}}$$

# theory for sputtering in isotropic collision cascades



Ansatz:

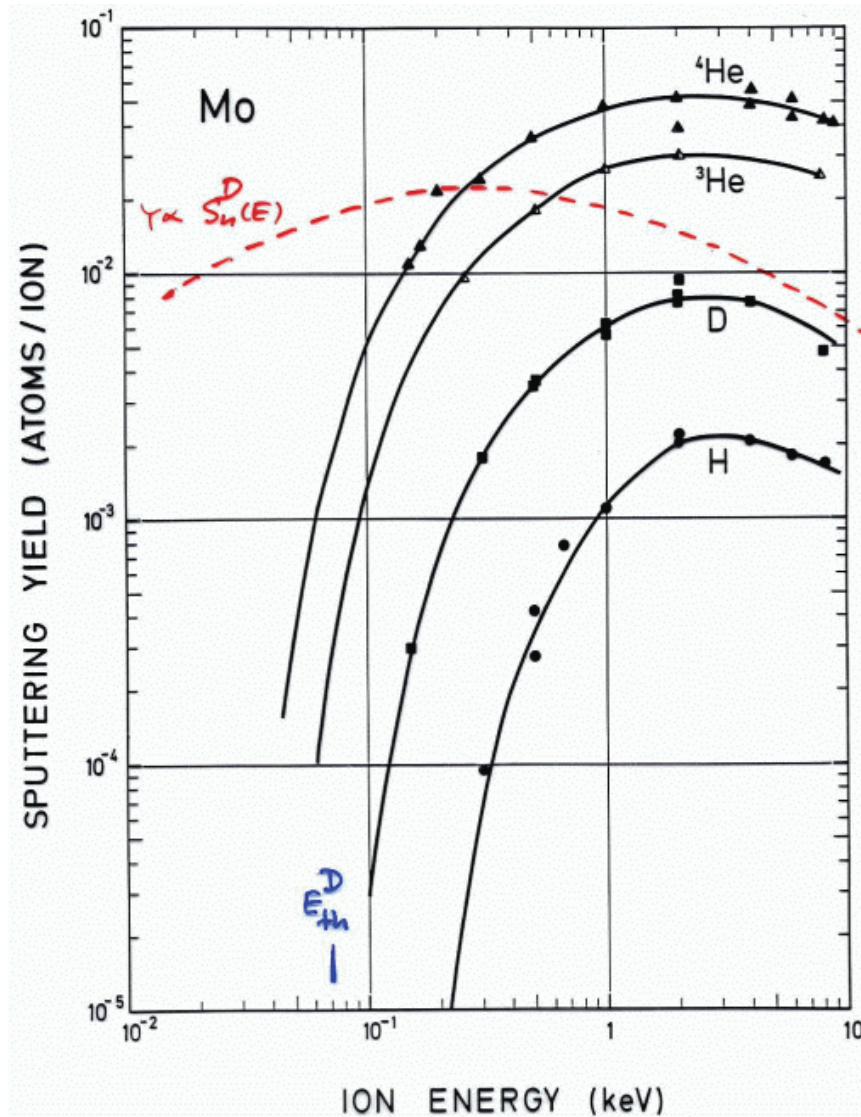
(P. Sigmund (1969))

sputtering yield proportional to the energy deposited into collisions near the surface

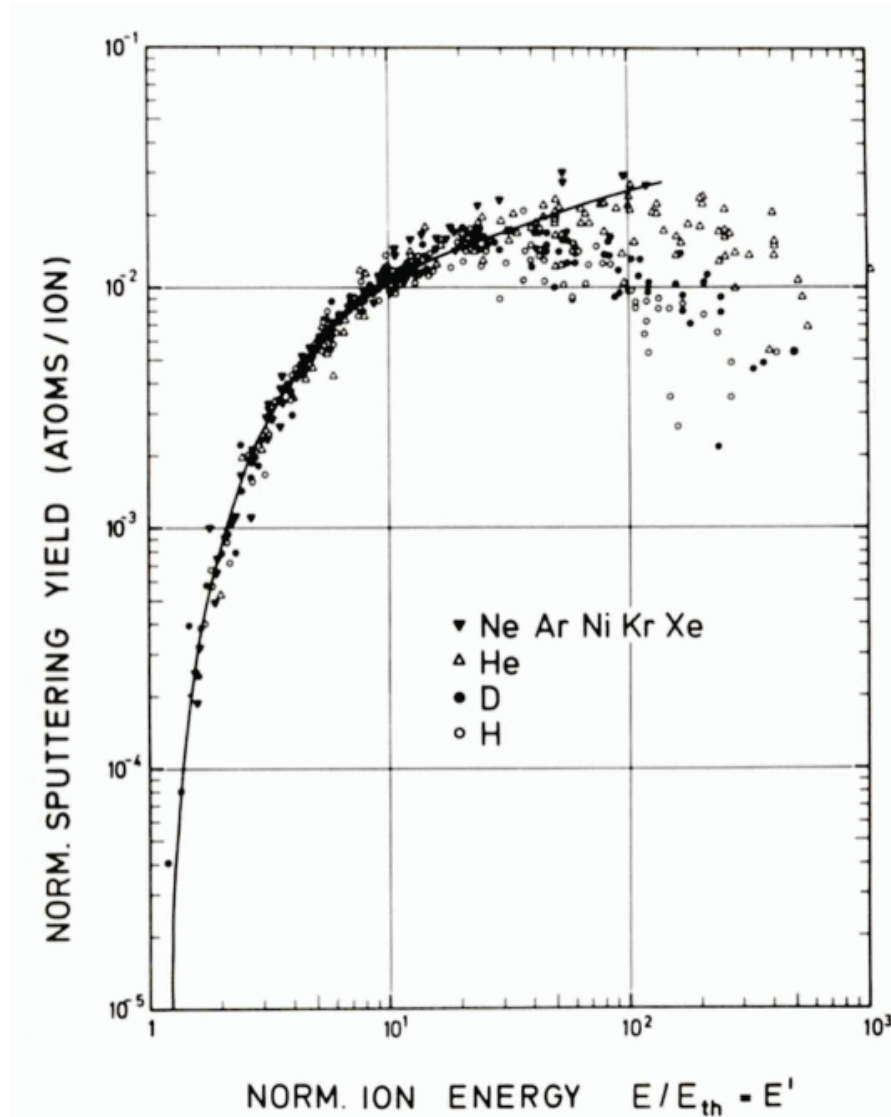
$$Y(\epsilon) \propto S_n(\epsilon)_{x=0}/U_0$$

$$S_n(\epsilon) = f(M_1, M_2, Z_1, Z_2) Y(\epsilon) U_0$$

# threshold regime



- light ion sputtering in fusion application is dominated by threshold effects
- self-sputtering due to re-deposited target atoms can be described by the isotropic collision cascade



- in the threshold regime all experimental data show a similar energy dependence

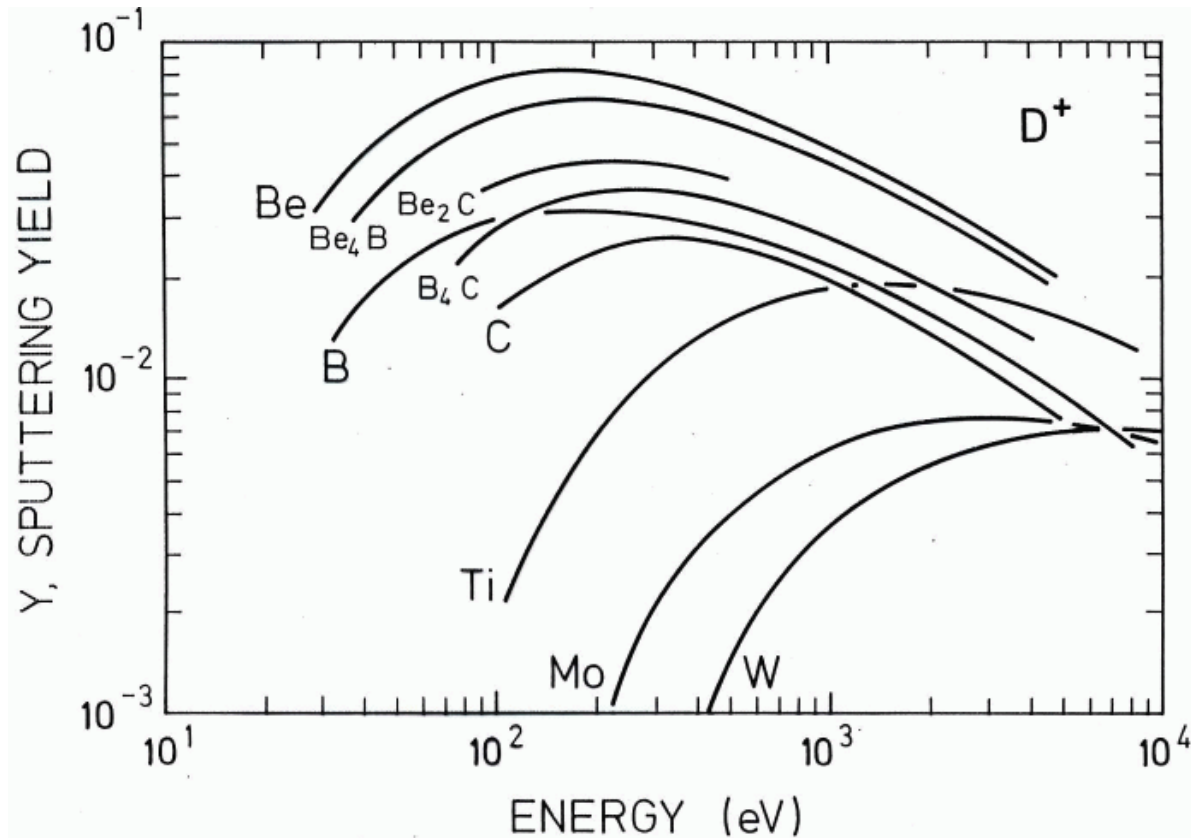
- normalized energy scale  
 $E' = E/E_{th}$

- good fit to universal function with

$$Y(E') = \left(1 - \frac{1}{E'}\right)^{3.5}$$

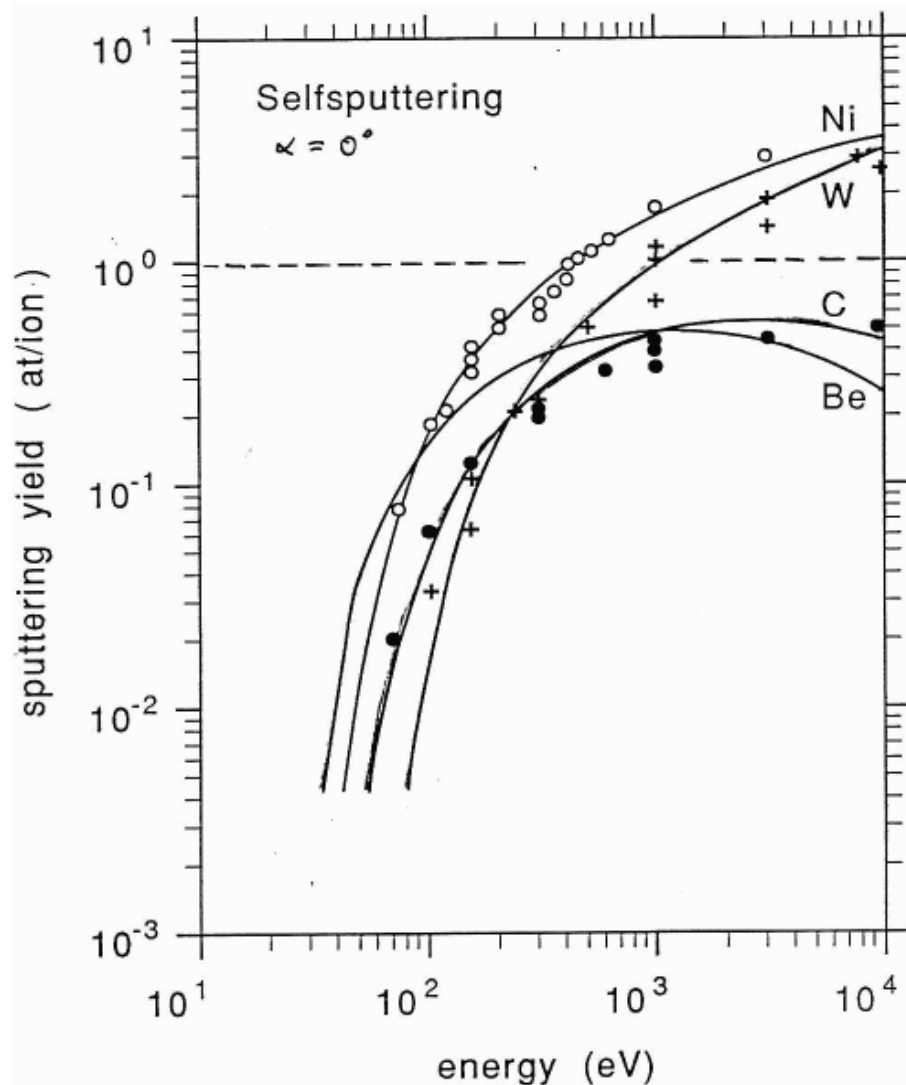


# systematics for light ions



- similar yields in isotropic cascade regime
- strong influence of  $Z_2$  on threshold energy  $E_{th}$

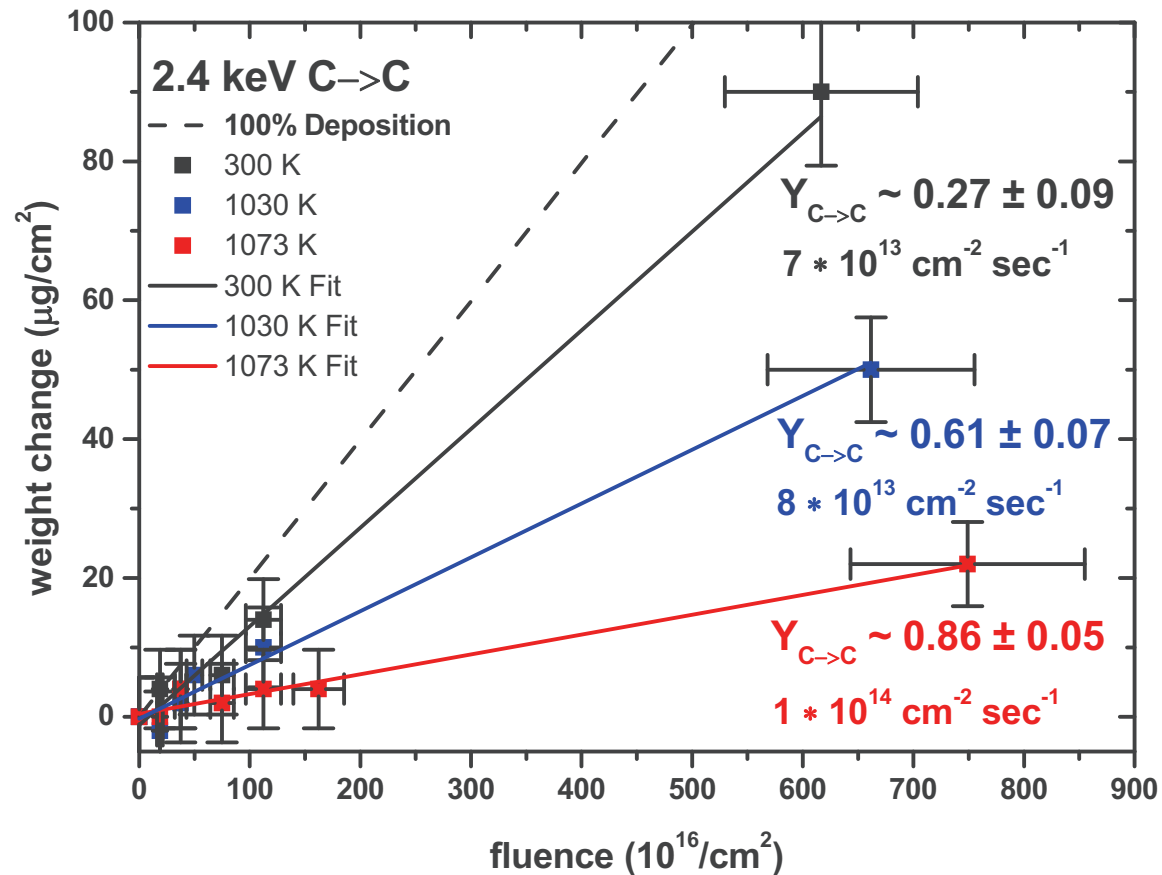
# systematics for self-sputtering



- no dependence of  $E_{th}$  on target mass, but on surface binding energy  $E_s$
- strong dependence of yield on mass in isotropic cascade regime due to nuclear deposited energy.
- most important is the yield range close to unity, as runaway impurity production may occur

$$Y_{eff} = \frac{Y_D}{(1 - Y_{self})}$$

# physical sputtering: temperature dependence



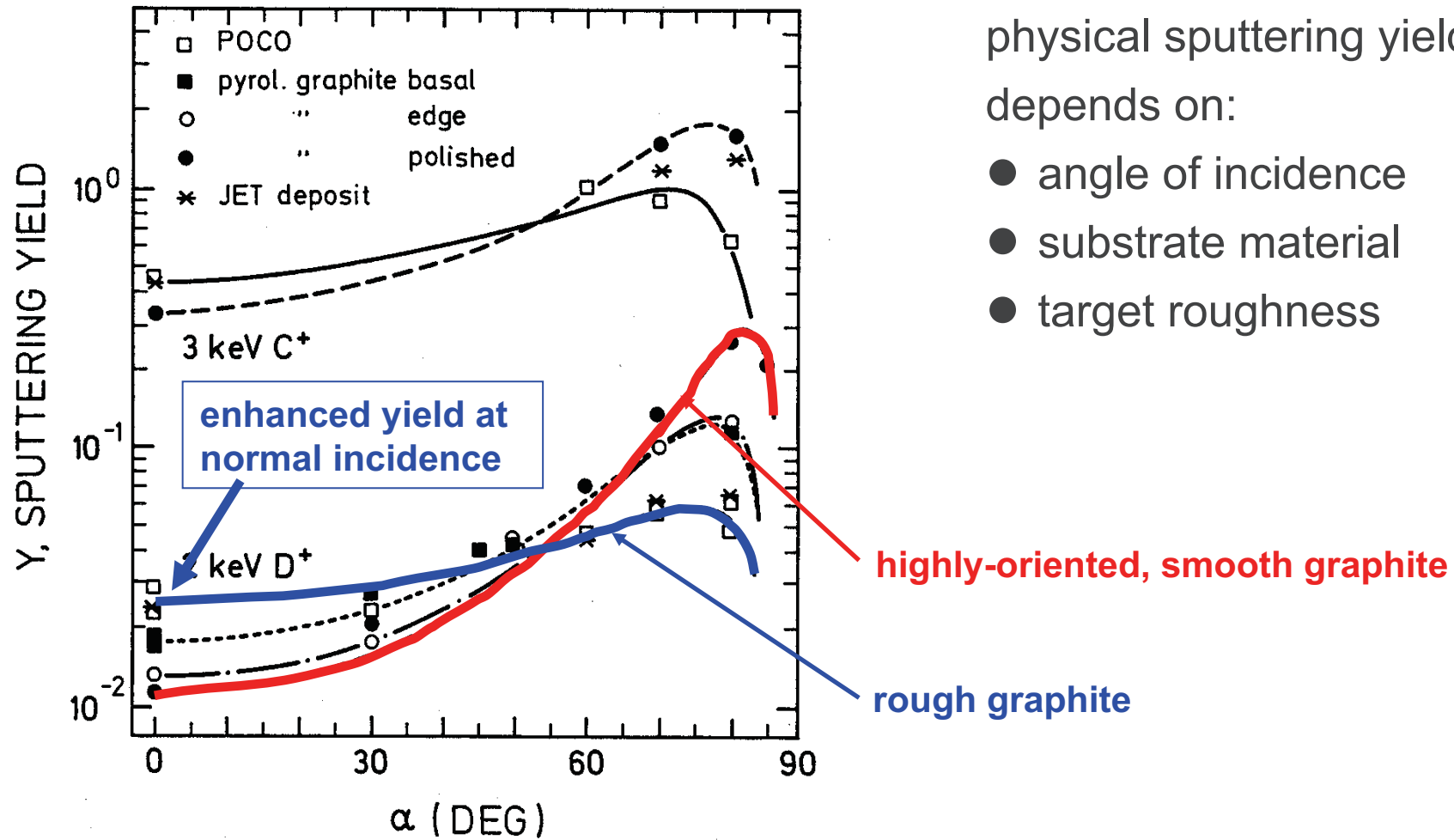
carbon self sputtering

as a function of  
temperature

around 1000 K onset of  
enhanced sputtering

K. Schmid, J. Roth, J. Nucl. Mater. 313-316, 302 (2003)

# physical sputtering: angular dependence

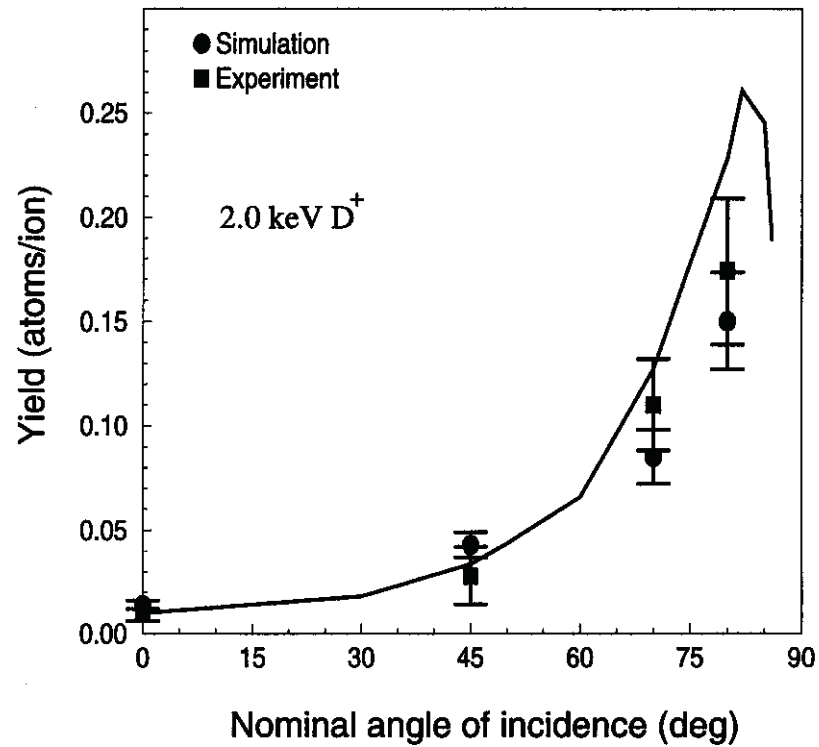


J. Roth, W. Eckstein et al., J. Nucl. Mater. 179-181, 34 (1991)

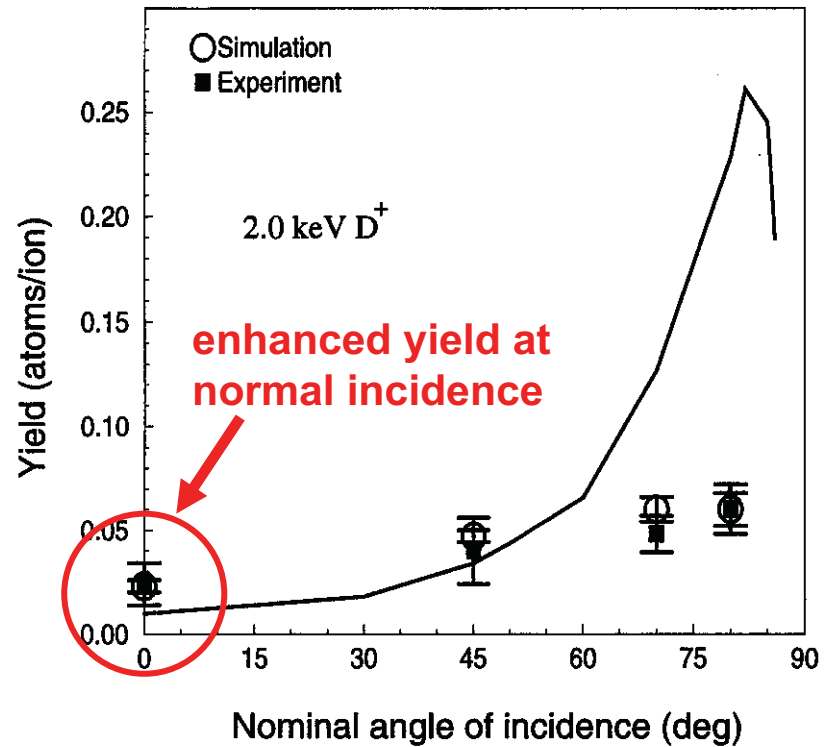
# physical sputtering: angular dependence



highly-oriented, smooth graphite



rough graphite



M. Küstner, W. Eckstein, V. Dose, J. Roth, *Nucl. Instrum. Meth. B* **145**, 320-331 (2000)  
*The influence of surface roughness on the angular dependence of the sputter yield*

- well understood (for the most part)
- key parameter is the surface binding energy  $E_{SB}$  (= 7.4 eV for carbon)
- depends on particle energy
- depends on particle mass
- depends on the particle atomic number

energy transfer:

$$T_{\max} = 4 M_1 M_2 / (M_1 + M_2)^2$$

→ isotope effect

- only weakly T dependent
- threshold energy depends on target/projectile combination
- depends on angle of incidence (roughness)

## open questions / problems:

- surface binding energy for mixed materials
- accuracy of sputter yields close to the threshold
- sputtering at low energies with molecular ions

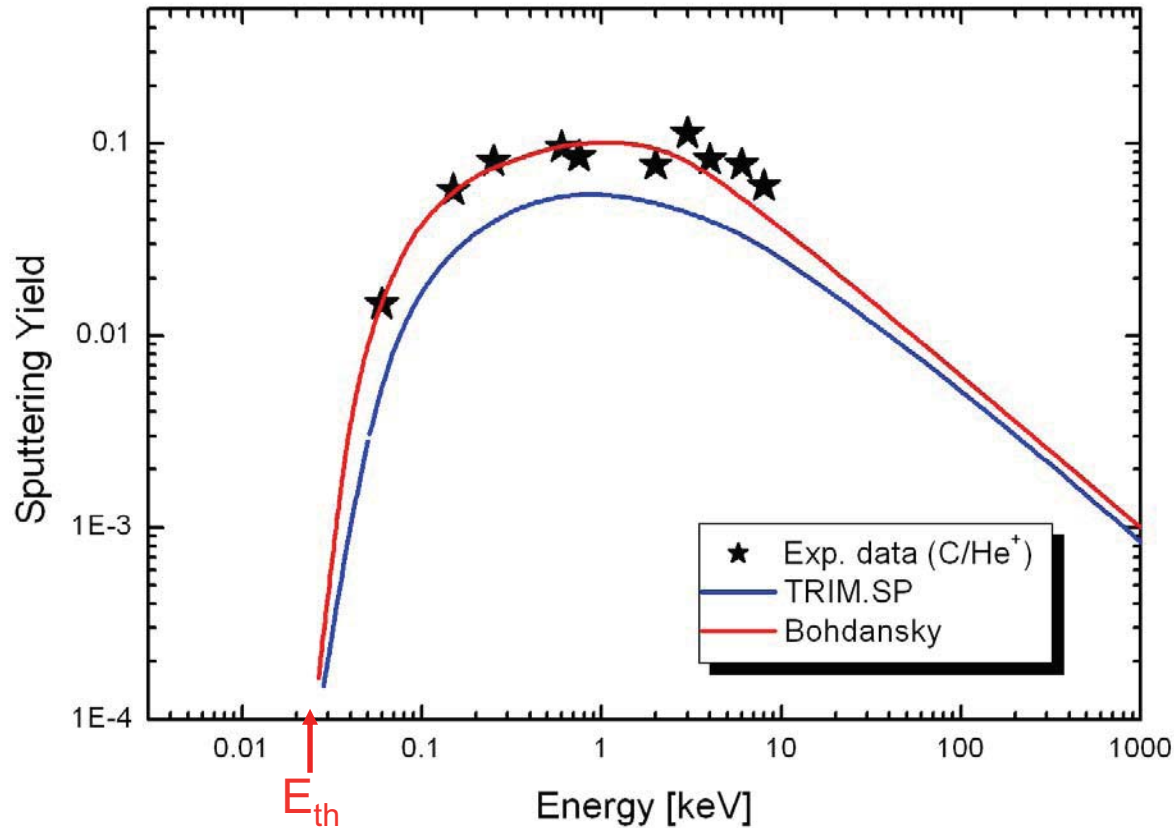
typical experiments are not performed with  $D^+$  but with  $D_2^+$  or  $D_3^+$  ions instead (higher fluxes) but yields are given per atoms assuming:

$$j_{D^+} = 3 \cdot j_{D_3^+} \quad \text{and} \quad E_{D^+} = \frac{1}{3} \cdot E_{D_3^+}$$

surely not valid near the threshold!

- surface roughness (dynamical development during process)

# quantitative description of physical sputtering



the experimental data is fitted with the **Bohdansky** formula:

$$Y = Q \cdot s_n^{TF} \cdot \left( 1 - \left( \frac{E_{th}}{E_o} \right)^{2/3} \right) \cdot \left( 1 - \frac{E_{th}}{E_o} \right)^2$$

$$s_n^{TF} = s_n^{TF}(\mathcal{E})$$

$$\mathcal{E} = E_o \frac{M_{target}}{M_{ion} + M_{target}} \cdot \frac{a_L}{Z_{ion} \cdot Z_{target}}$$

$$Q = 0,169 \text{ [atoms / ion]}$$

$$E_{th} = 25,4 \text{ [eV]}$$

J. Roth, E. Vietzke, A.A. Haasz; *Atomic and Plasma-Material Interaction Data for Fusion, Suppl. to Nuclear Fusion* **1** (1991) 63.

C. Garcia-Rosales, W. Eckstein, J. Roth; *J. Nucl. Mater.* **218** (1994) 8-17.



---

# quantitative description of physical sputtering

---

## Monte Carlo Simulations based on the *binary collision approximation*

- calculating asymptotic trajectories of consecutive collisions between projectile and target atoms
- continuous drag by electronic stopping
- randomly choosing the distance to the next collision partner, the collision parameter, and the azimuth.
- following the projectile and all colliding target atoms that received a certain minimum energy

# quantitative description of physical sputtering



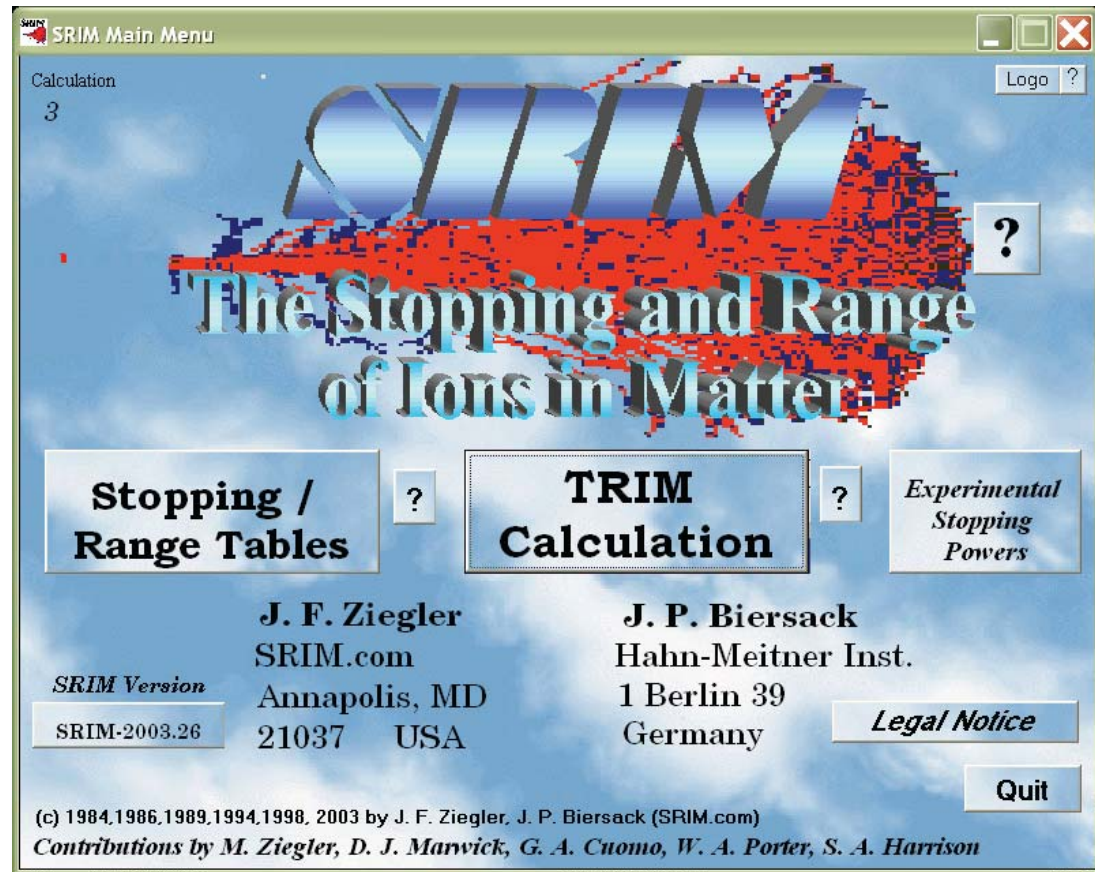
TRIM (transport of ions in matter)  
TRIM.SP (sputtering)  
TRIDYN (dynamic TRIM)

SDTrim available via [SDTrimSP@ipp.mpg.de](mailto:SDTrimSP@ipp.mpg.de)

SRIM (see [www.srim.org](http://www.srim.org))

see exercise

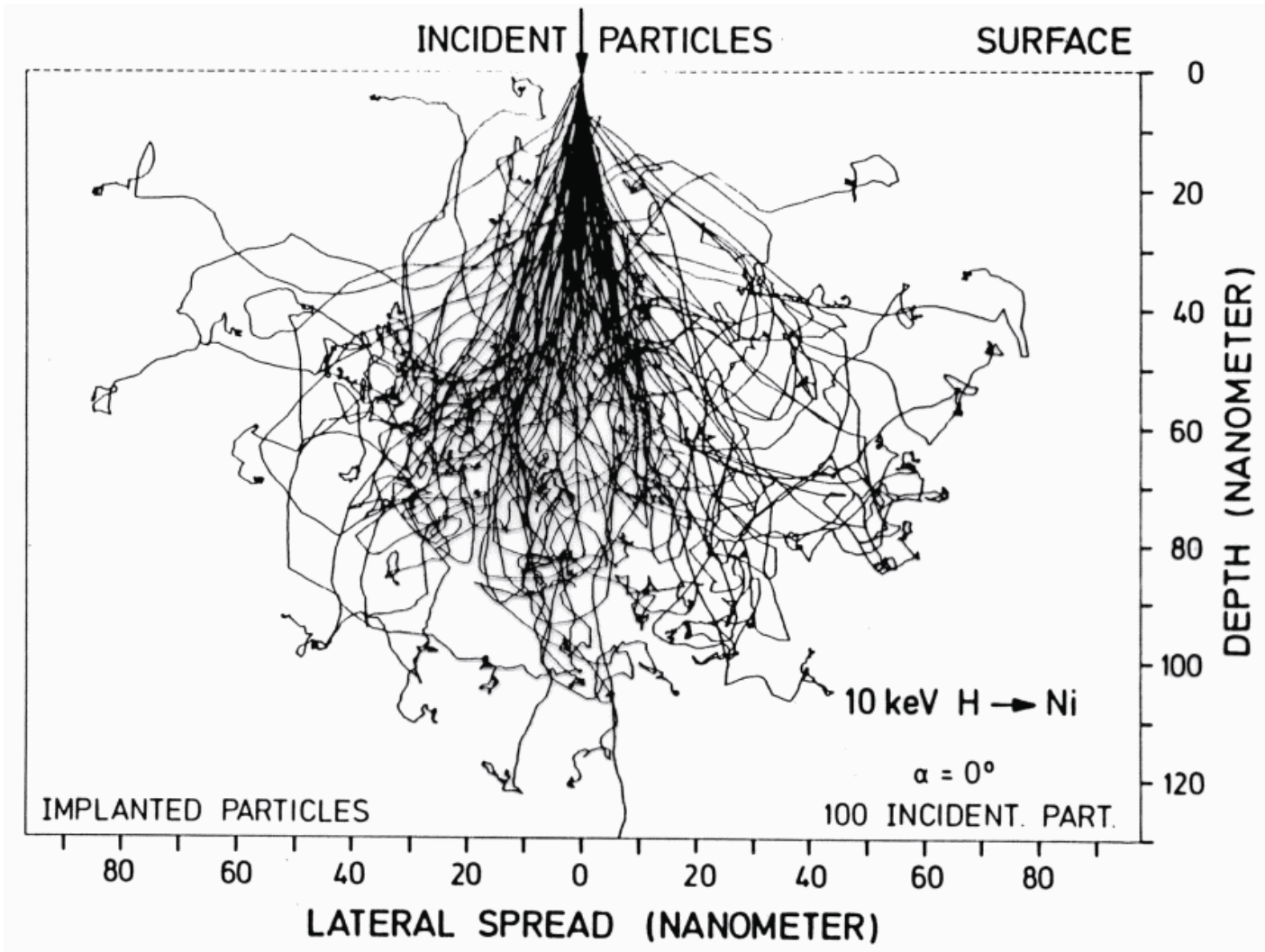
:  
:  
:



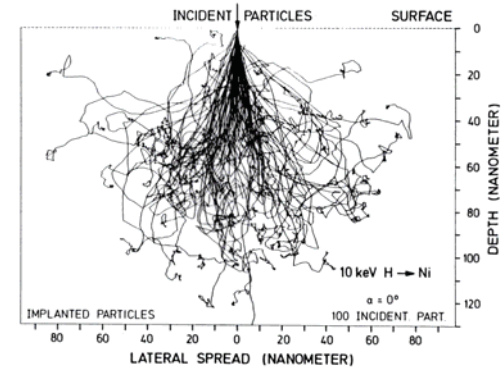
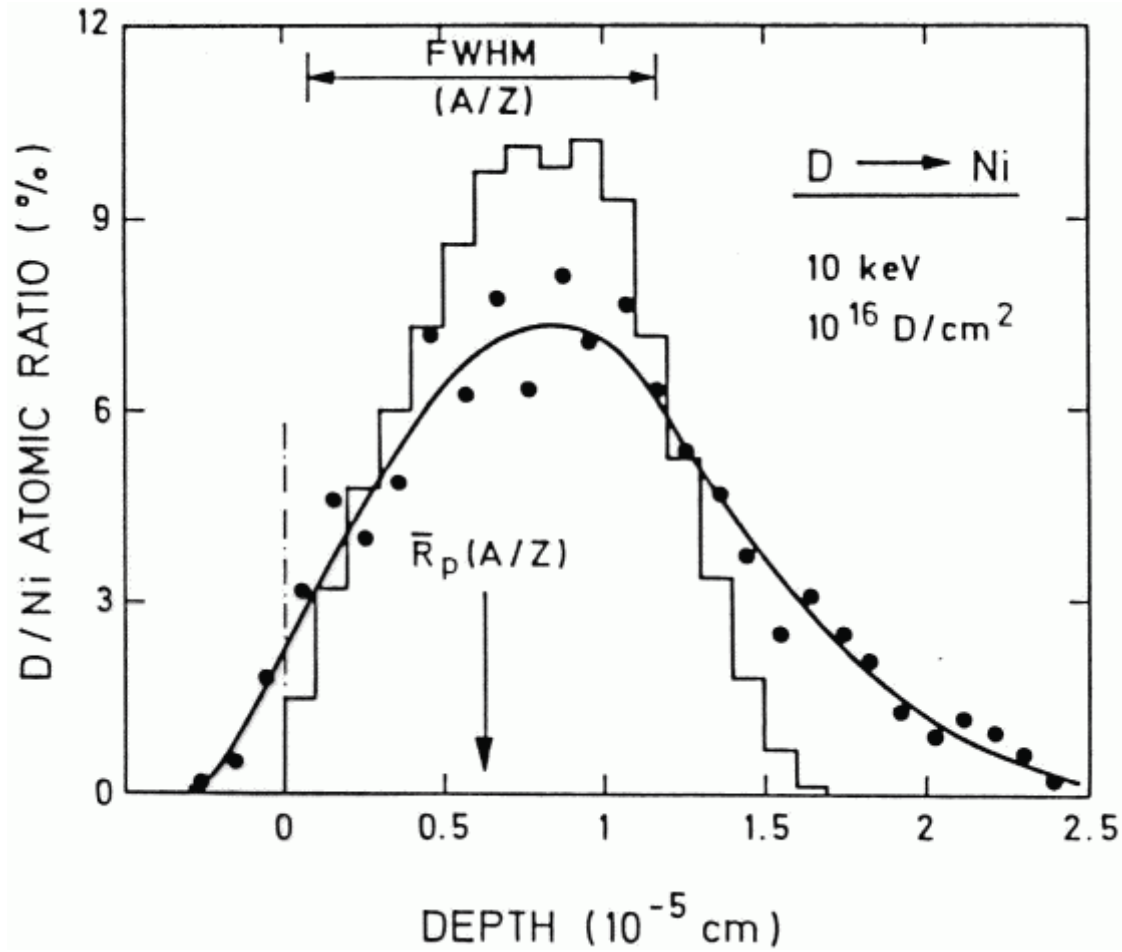
## some remarks on TRIM and its derivatives

- are very powerful tools in describing the collision cascades for nearly every projectile on every target atom out of the elemental table
- they are not ab initio calculations but include fit parameters to describe experimental data like
  - surface binding energy
  - displacement energies
- do not include chemistry effects (bonding of H in C)
- do not include diffusion effects
- often do not change the layer composition (TRIDYN does)

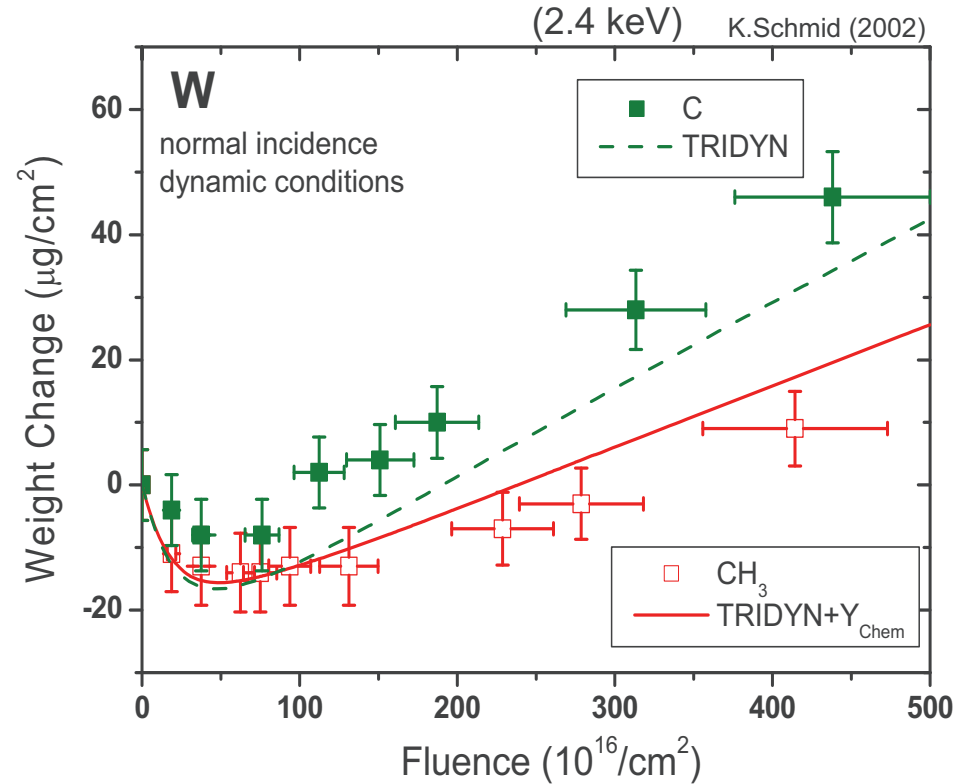
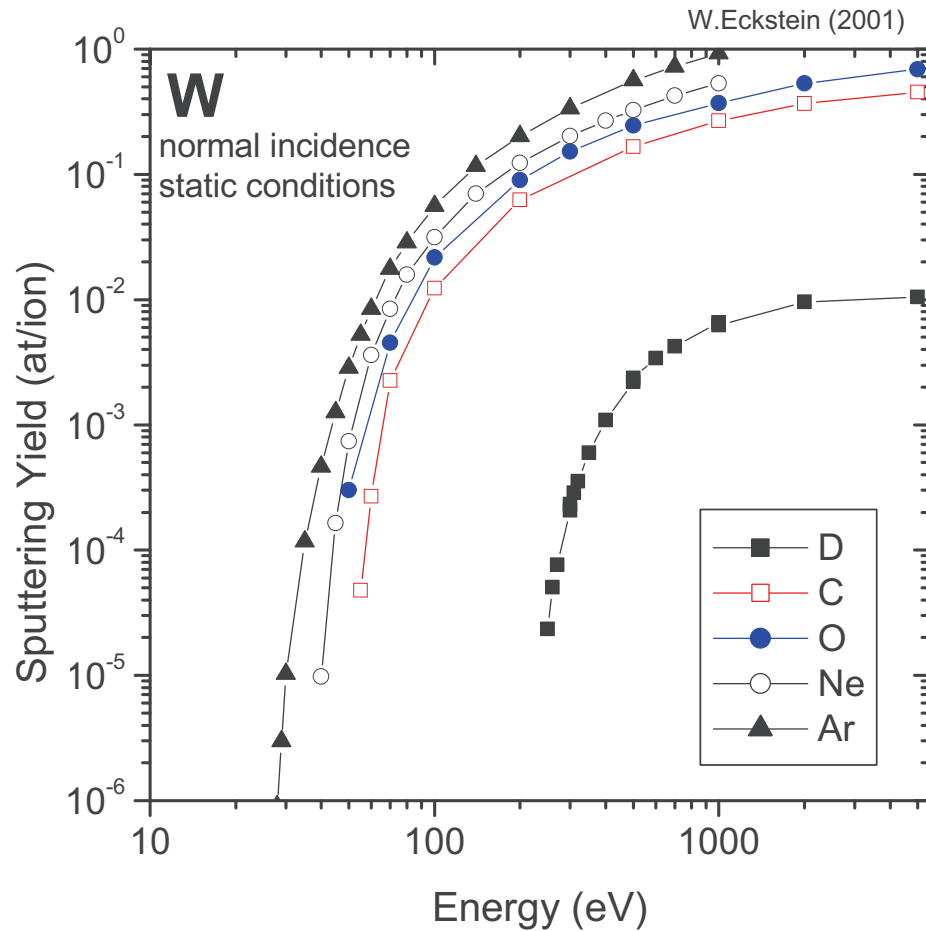
# collision cascade



# range and range distribution



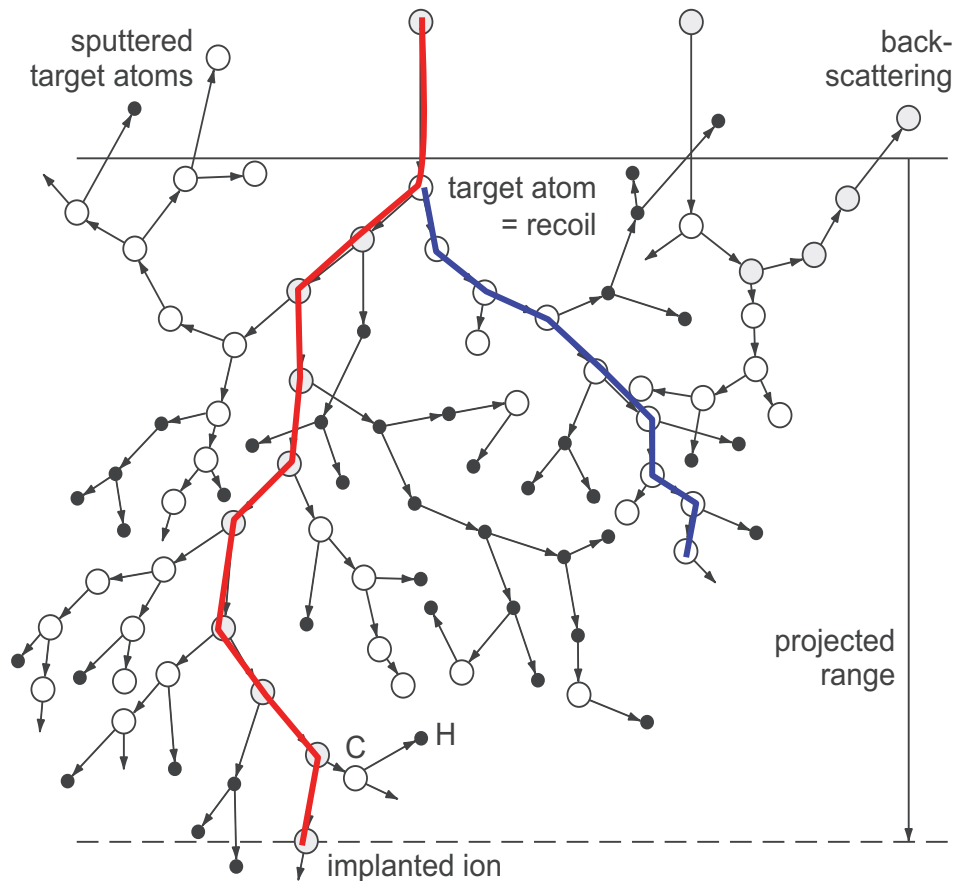
# sputtering by non-recycling ions



- TRIM.Sp for static conditions
- TRIDYN for dynamic conditions
- data base published in

*Atomic and PMI Data for Fusion Vol. 7*  
<http://www-amdis.iaea.org> (AMBDAS)

# physical sputtering: projectile-solid interaction



schematic representation of C impinging on a-C:H

relevant processes:

- sputtering
- implantation
- backscattering
- displacement
- activation

open questions:

- what happens with displaced hydrogen?
- how to incorporate the chemical nature of hydrogen

\*W. Eckstein, 'Computer Simulations of Ion-Solid-Interactions', Springer-Verlag (1991)

W. Jacob, *Thin Solid Films* **326** (1998) 1-41.

---

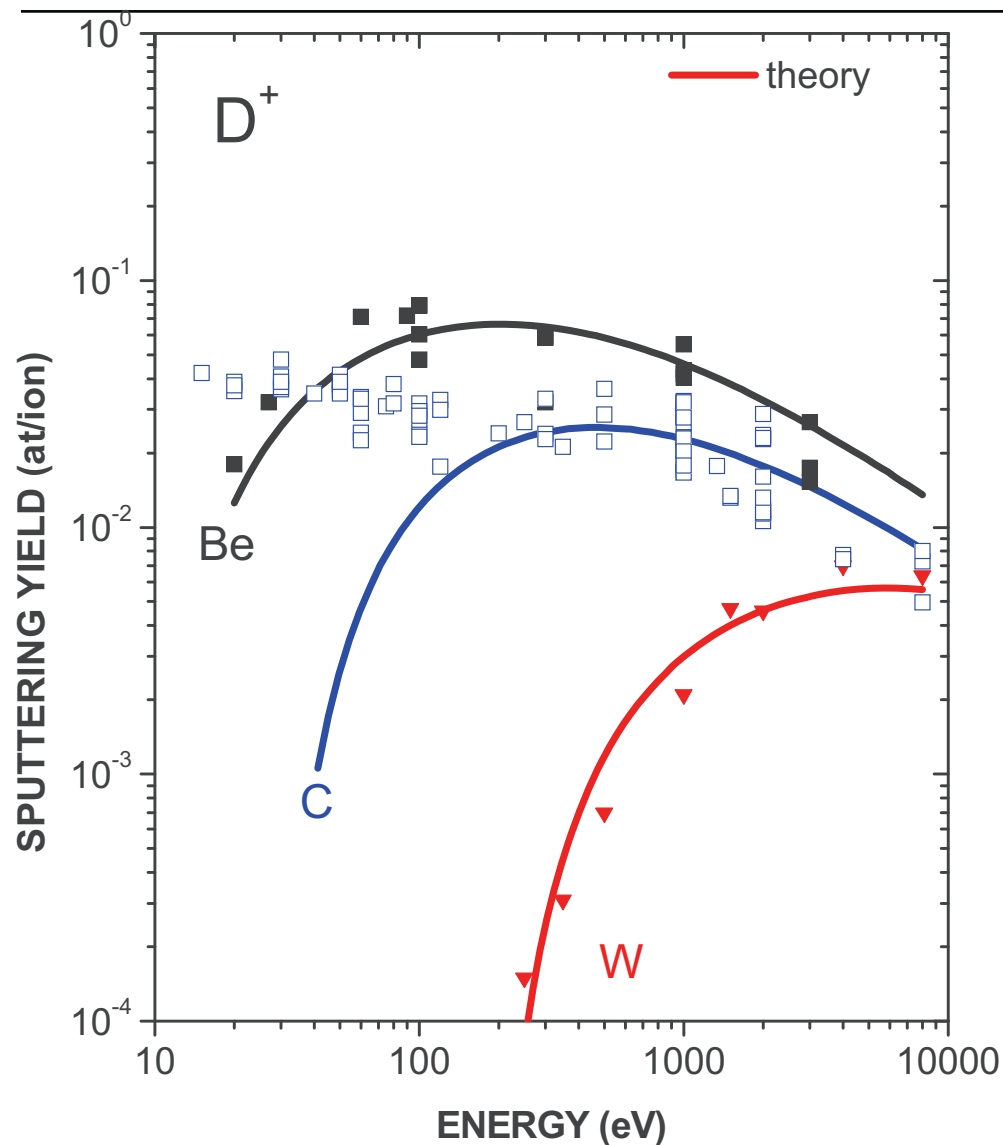
## physical sputtering

---

- Physical sputtering is the ***kinetic ejection of surface atoms*** by incident energetic ions or atoms ***due to collision processes*** (playing pool with surface atoms).
- As surface atoms can escape only if it receives an energy larger than the ***surface binding energy***, a threshold energy for the incident particles is required.
- In fusion application sputtering by hydrogen and helium ions and atoms is important, but also the self-sputtering due to returning impurity atoms.

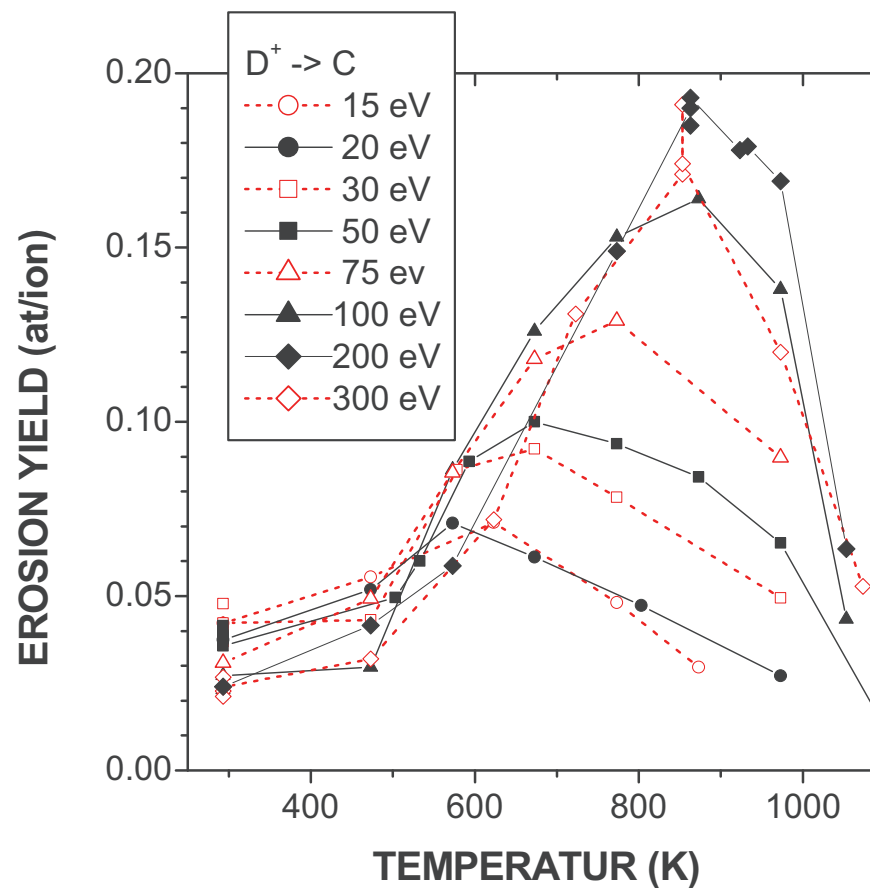
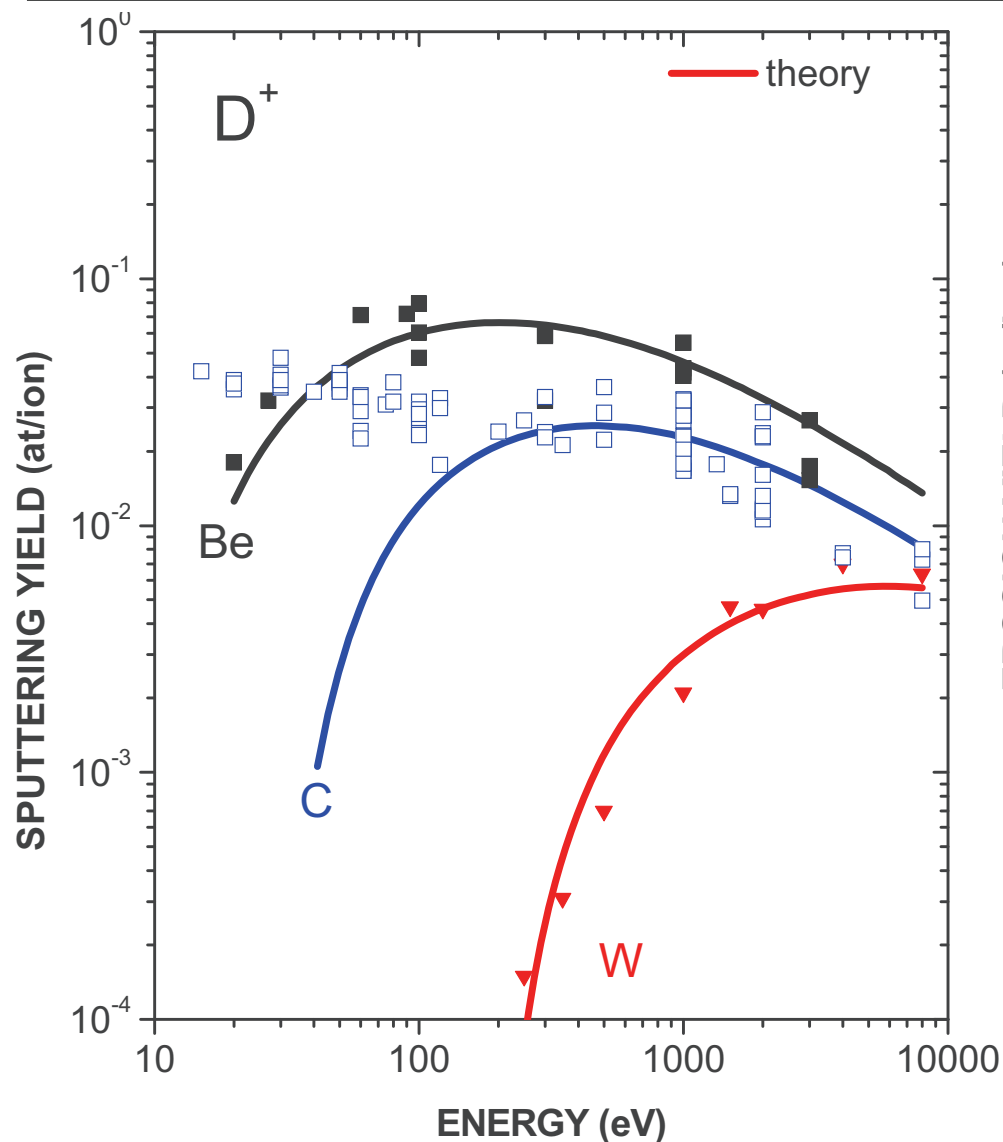


# erosion at room temperature



- advantage for high-Z materials
- strong deviation for Carbon based materials  
⇒ chemical effect?

# erosion of plasma-facing materials



• strong T-dependence: chemistry

---

## nomenclature

---

- **Chemical erosion** is a selective removal of surface atoms by *chemical reactions*, forming volatile reactants that can desorb.
- **Physical sputtering** is the *kinetic ejection of surface atoms* by incident energetic ions or atoms *due to collision processes*. (playing billiards with surface atoms).
- **Chemical Sputtering** is a process whereby *ion bombardment causes or allows a chemical reaction to occur* which produces a particle that is weakly bound to the surface and hence easily desorbs in the gas phase.

# erosion of graphite by energetic hydrogen

*it is not chemical erosion*

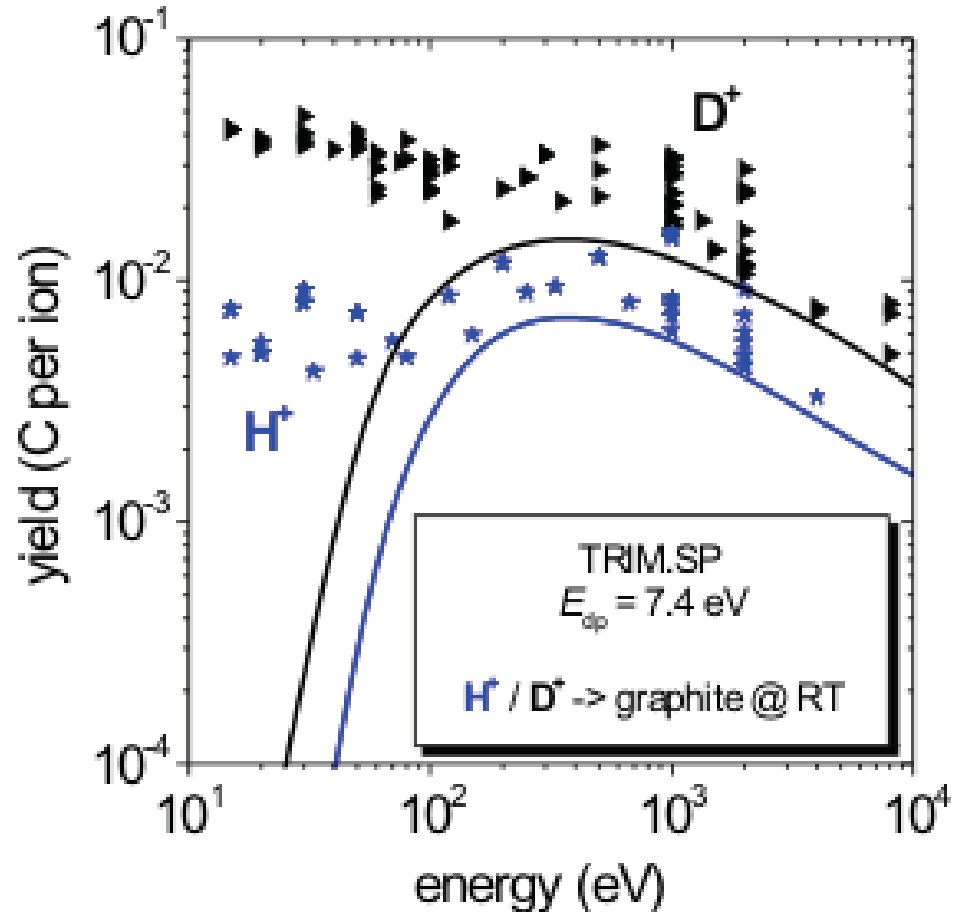
$H^0$  at  $T > 400$  K with a max. at  $\approx 650$  K – 800 K

*it is not physical sputtering*

energetic ions  $E > E_{th}$ ,  
no chemistry

*but its chemical sputtering*

hydrogen ions, low-T, low-E



Data: M. Balden and J. Roth, J. Nucl. Mater. 280 (2000) 39–44

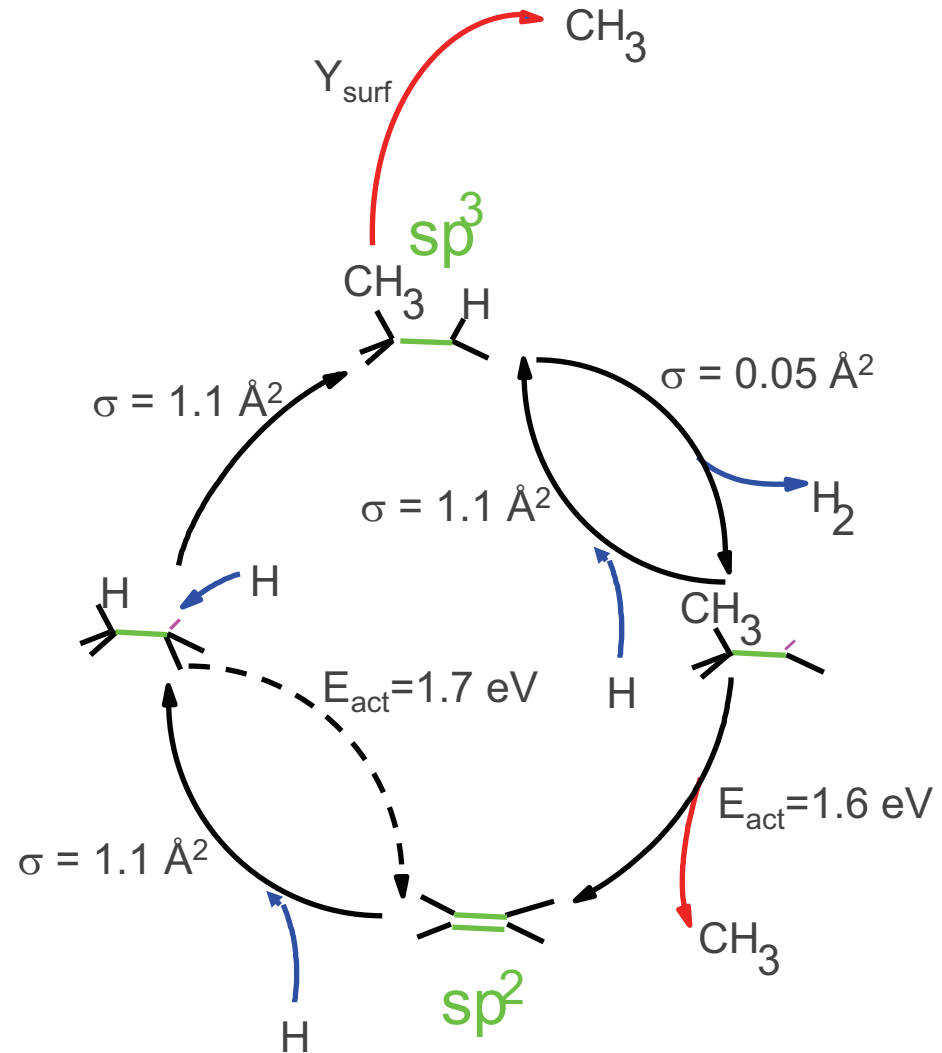
# chemical sputtering: one attempt



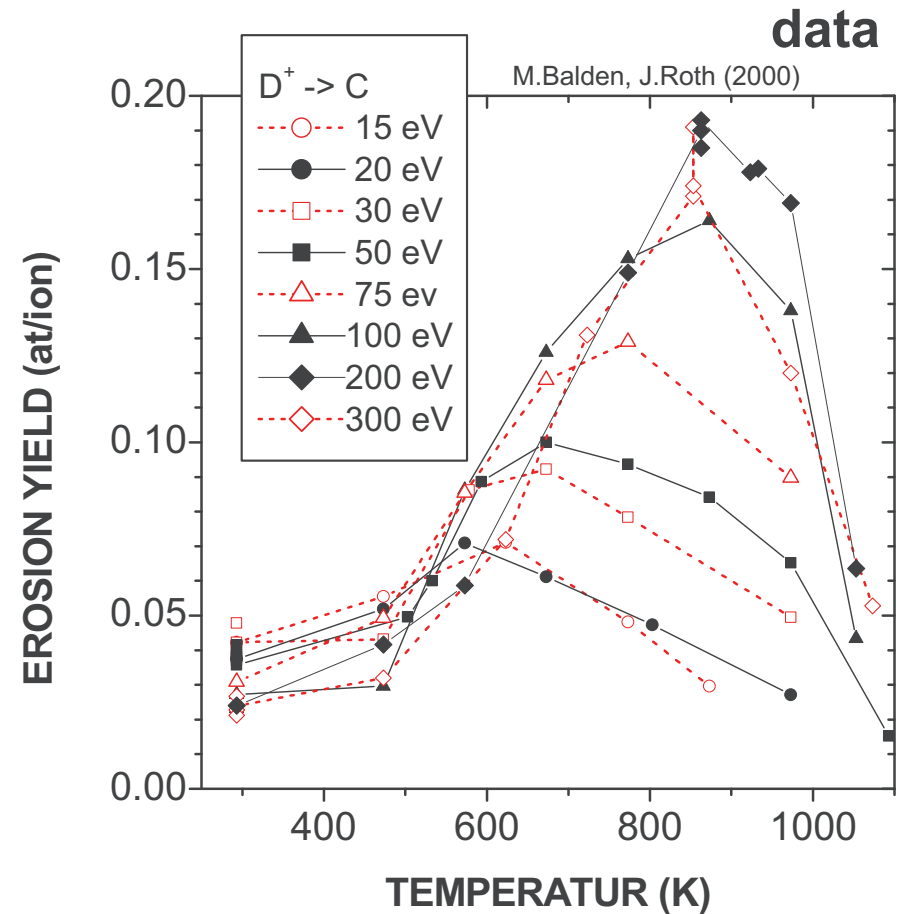
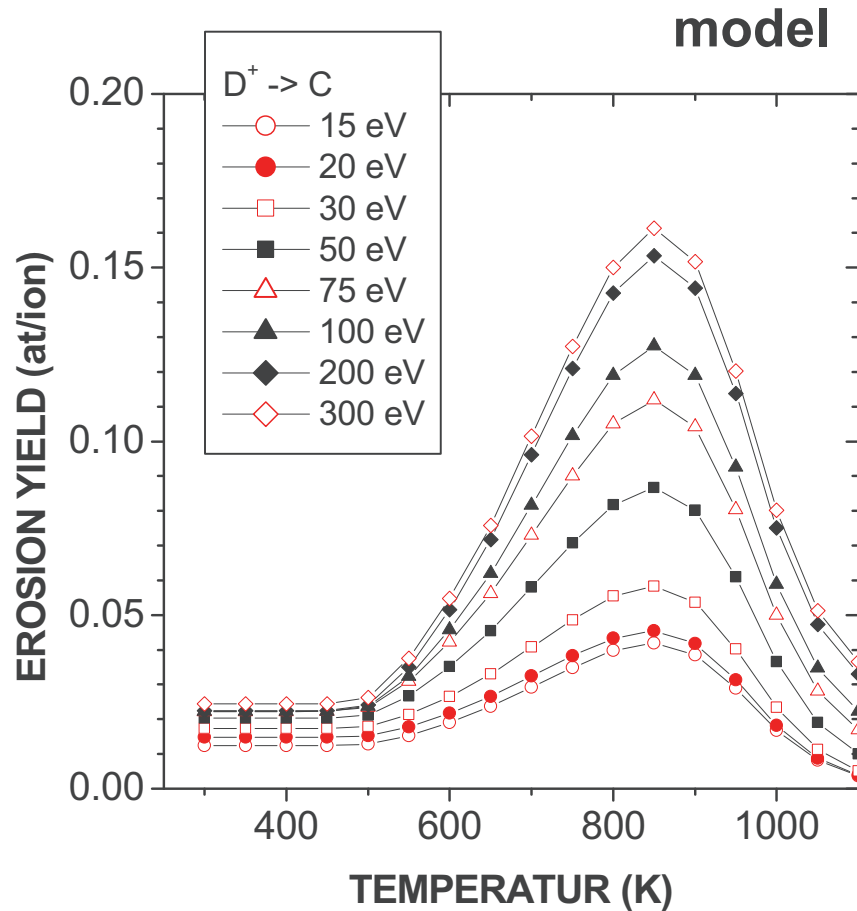
## hydration and erosion circle:

A. Horn et al., Chem. Phys. Lett. 231, 193 (1994)  
J. Roth, J.Nuclear Mat. 266-269, 51 (1999)

- Ion induced release of weakly bound hydrocarbon radicals complexes from the surface



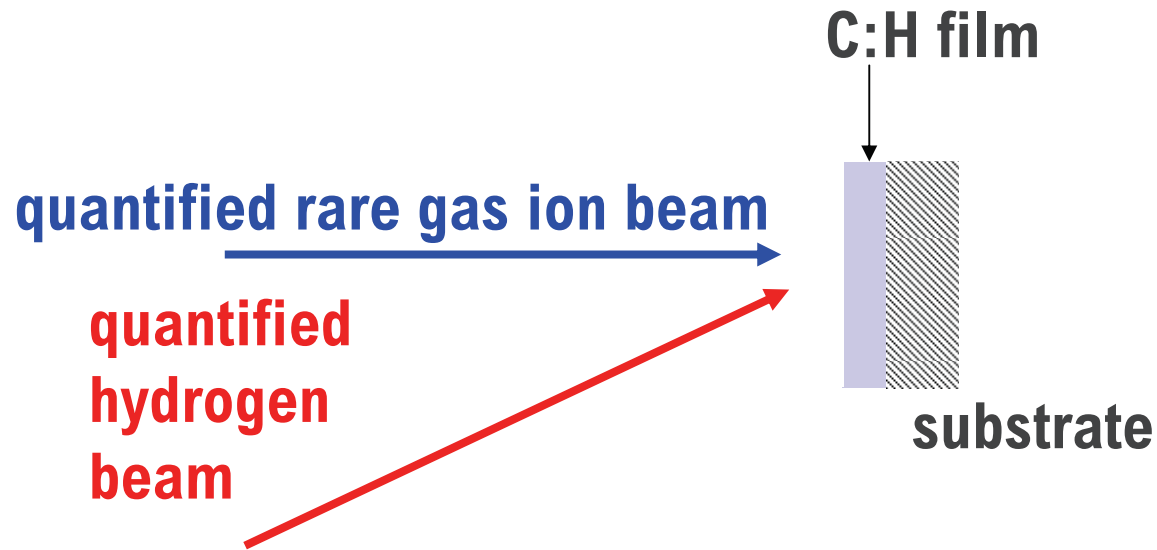
# chemical erosion at elevated temperatures



- adequate modeling of erosion
- does not explain shift of maximum with energy

# Quantified particle-beam experiments: separating physics from chemistry

# measuring erosion yields



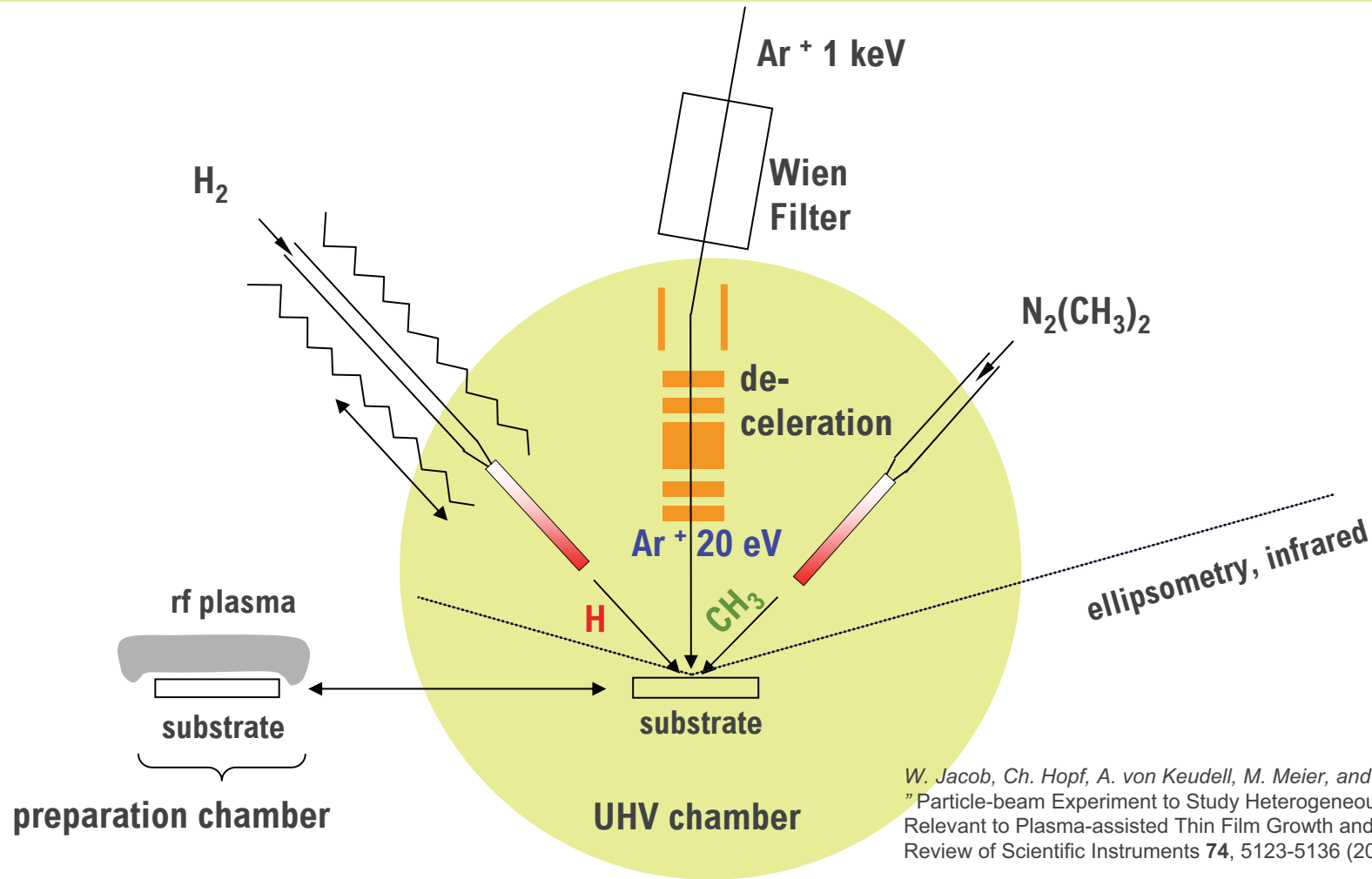
$$\text{erosion yield} = \frac{\text{measured erosion rate in eroded carbon atoms per cm}^{-2}\text{s}^{-1}}{\text{impinging ion flux per cm}^{-2}\text{s}^{-1}}$$



# quantified particle-beam experiments

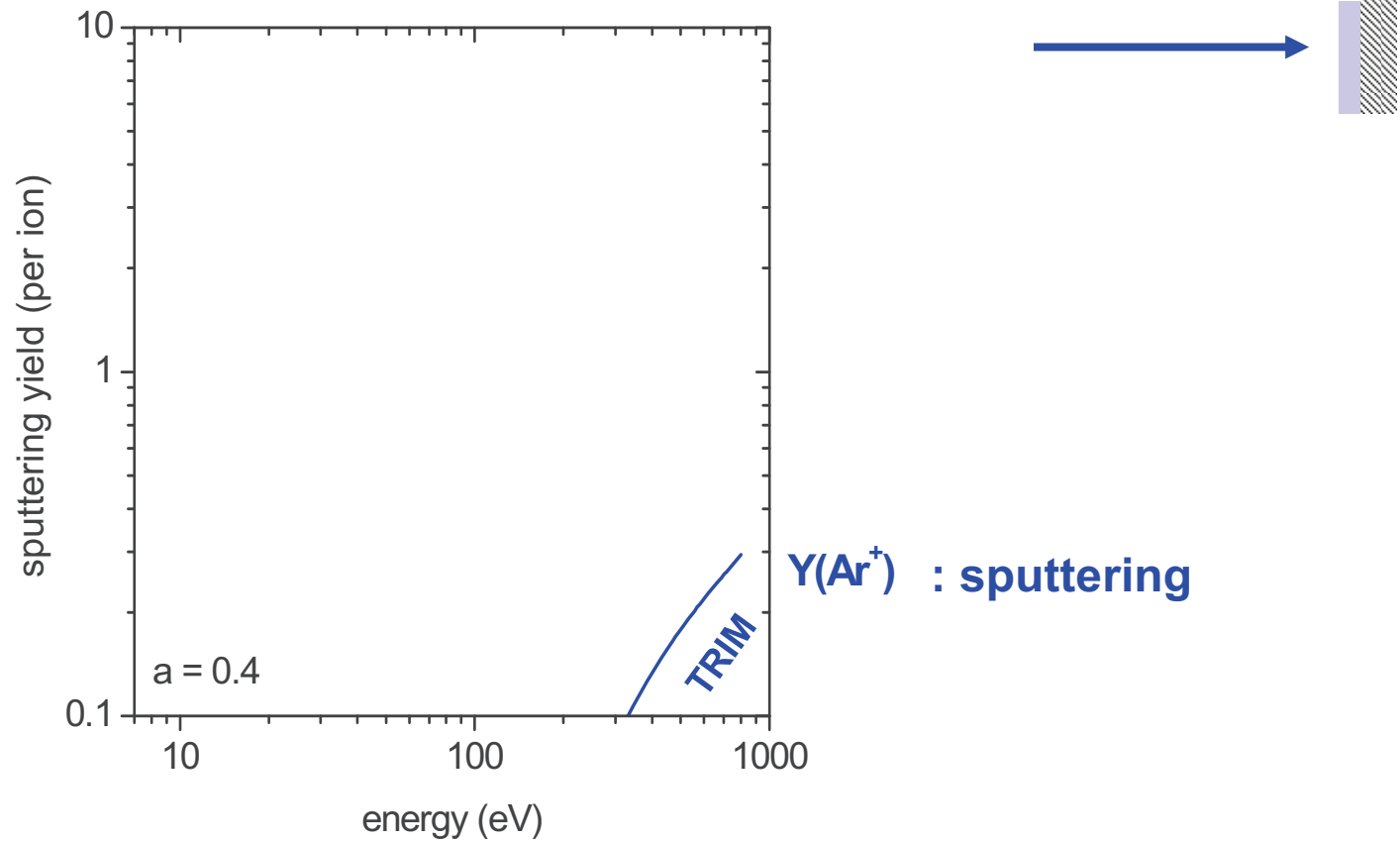


## UHV experiment with 2 radical beam sources and one ion beam source

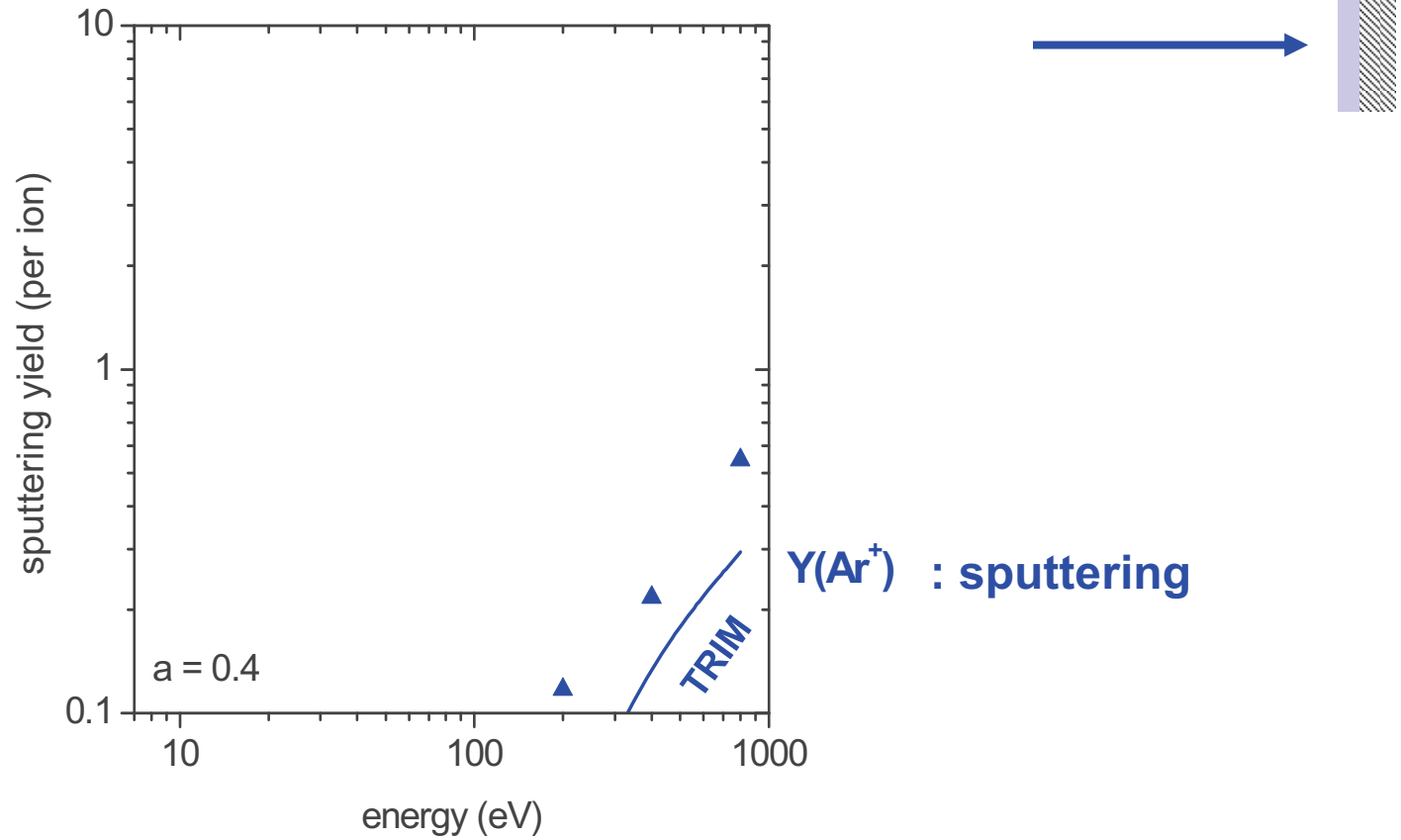


W. Jacob, Ch. Hopf, A. von Keudell, M. Meier, and T. Schwarz-Selinger: "Particle-beam Experiment to Study Heterogeneous Surface Reactions Relevant to Plasma-assisted Thin Film Growth and Etching", Review of Scientific Instruments **74**, 5123-5136 (2003).

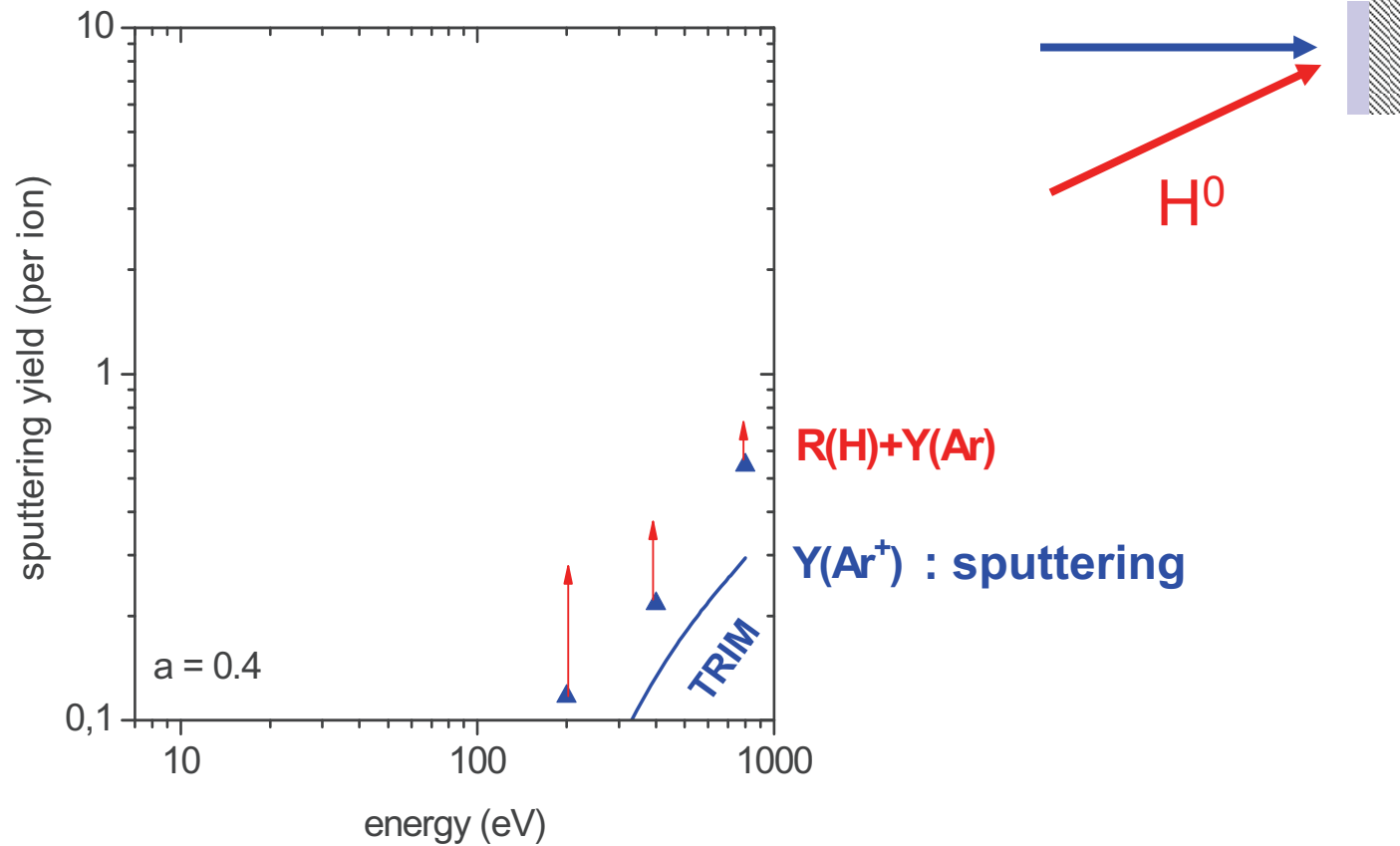
# physical sputtering



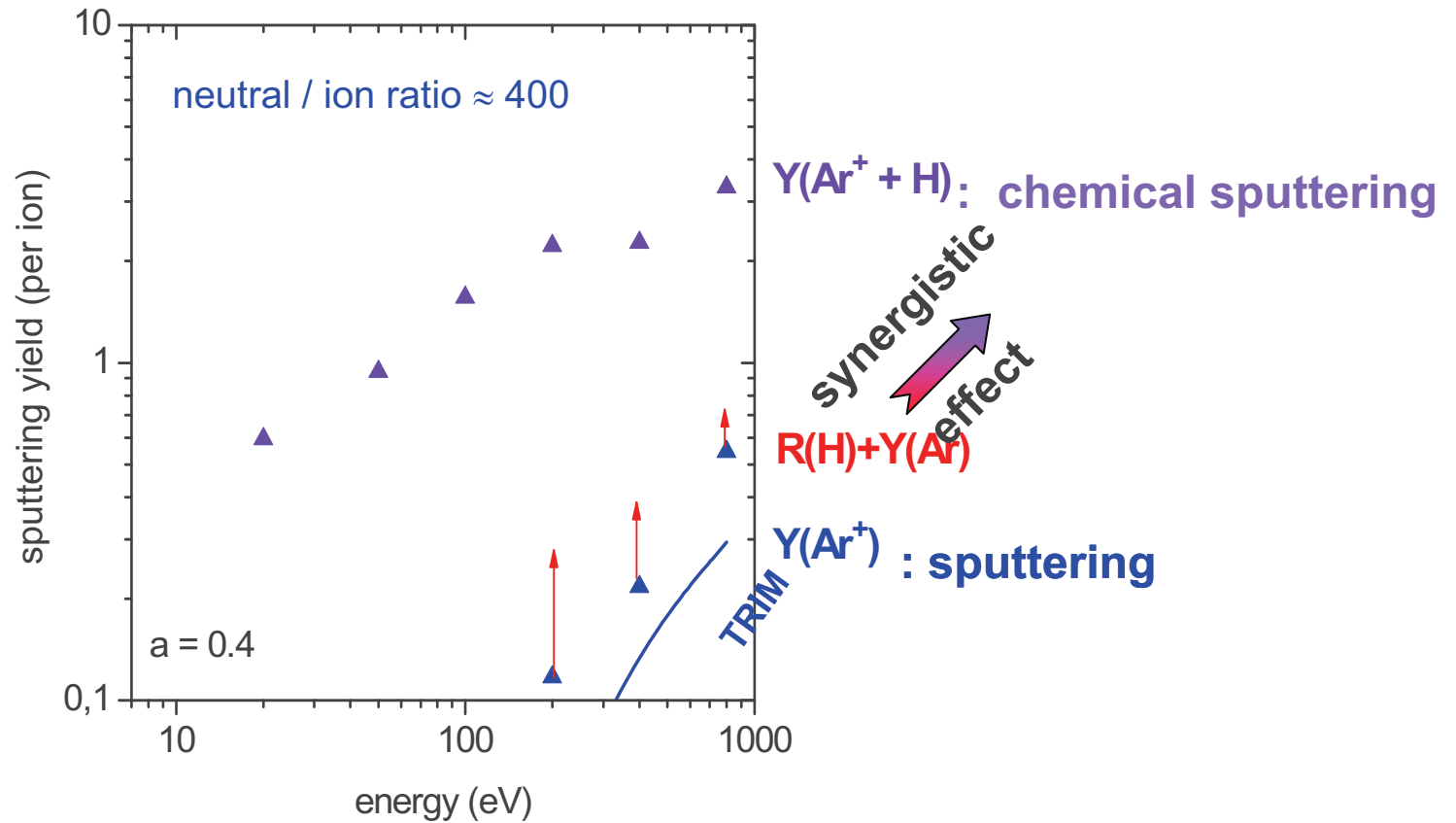
# physical sputtering



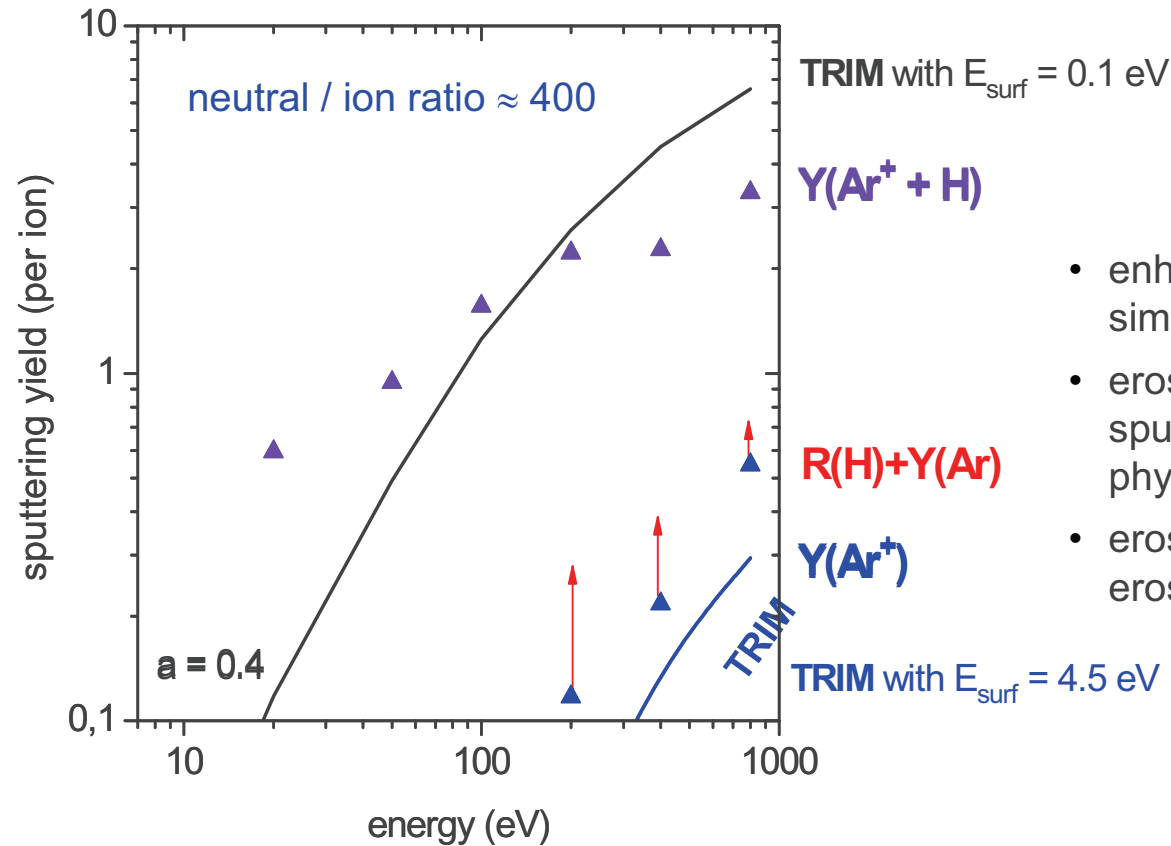
# physical sputtering + chemical erosion



# physical sputtering + chemical erosion

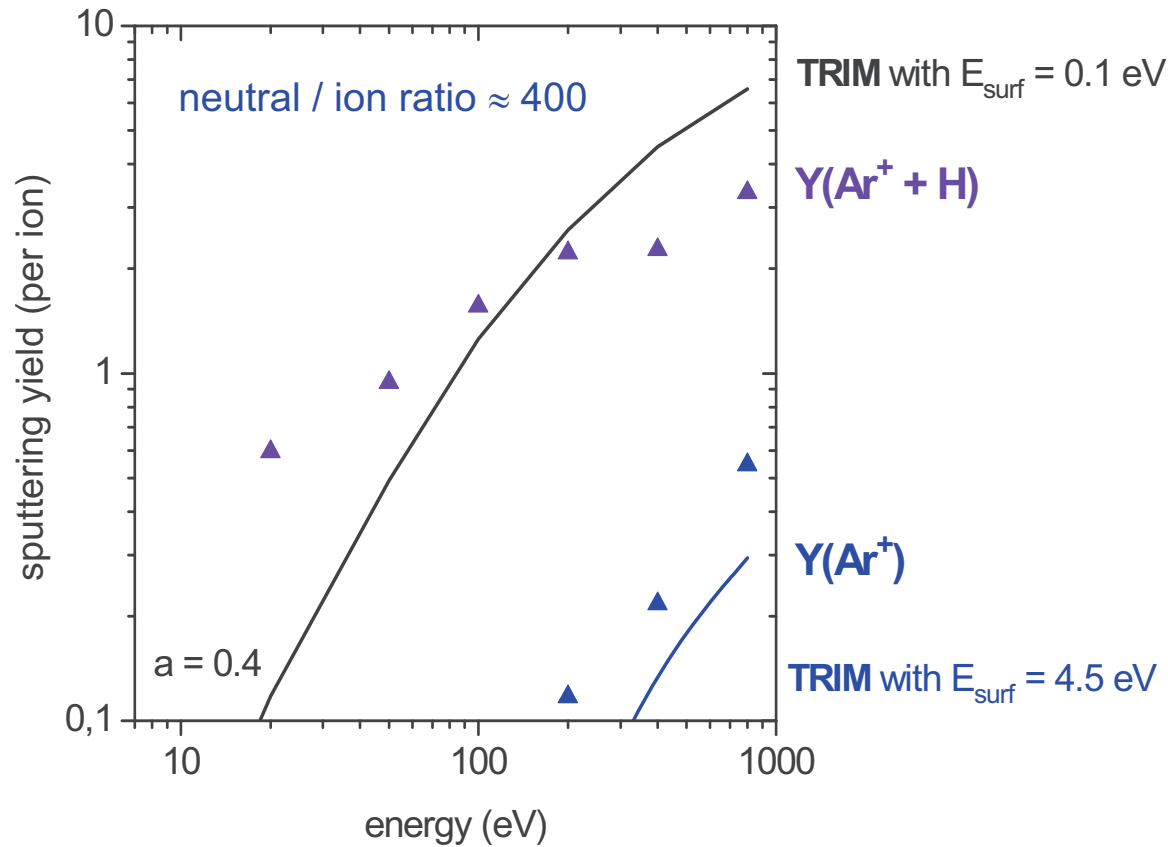


# physical sputtering + chemical erosion



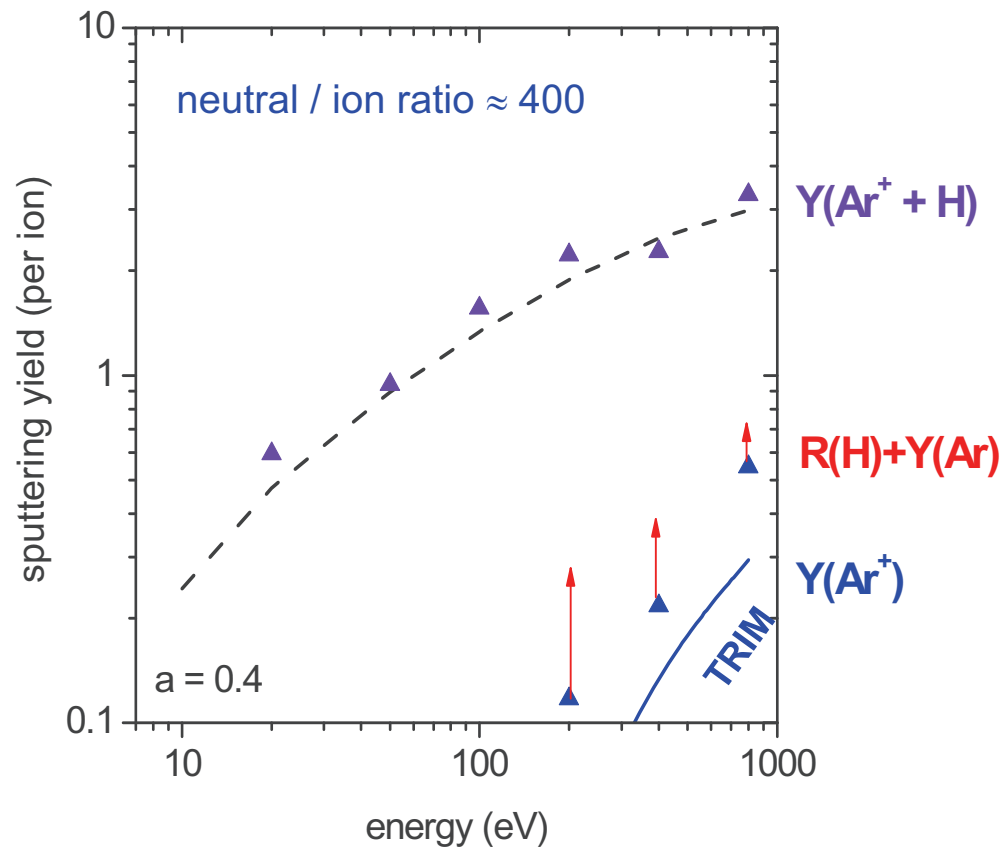
- enhanced erosion above 200 eV for simultaneous interaction
- erosion below threshold for physical sputtering (threshold energy for physical sputtering  $\approx 60 \text{ eV}$ )
- erosion at 20 eV  $\gg$  pure chemical erosion  $\Rightarrow$  '**chemical sputtering**'

# physical sputtering + chemical erosion



sputtering of weakly bound surface radicals seems not to be physical

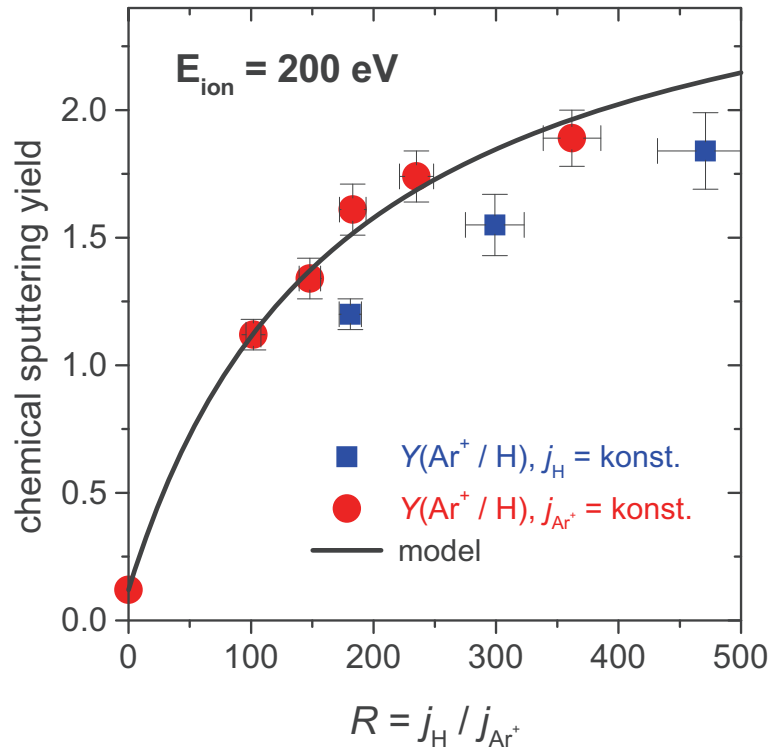
# chemical sputtering



model for chemical sputtering



# Ar<sup>+</sup>|H flux dependence



$$Y_{\text{Modell}} = Y_{\text{phys}}(1 - \Theta_{\text{CH}}) + Y_{\text{chem}}\Theta_{\text{CH}}$$

$$n_0 \frac{d\Theta_{\text{CH}}}{dt} = j_H(1 - \Theta_{\text{CH}})p_{\text{Einbau}}^H - j_{\text{Ion}}\Theta_{\text{CH}}p_{\text{Freisetzung}}^H$$

Mit  $R = j_H / j_{\text{Ion}}$  und  $S = p_{\text{Freisetzung}}^H / p_{\text{Einbau}}^H$

$$Y_{\text{Modell}} = Y_{\text{phys}} + \frac{R}{R + S}(Y_{\text{chem}} - Y_{\text{phys}})$$

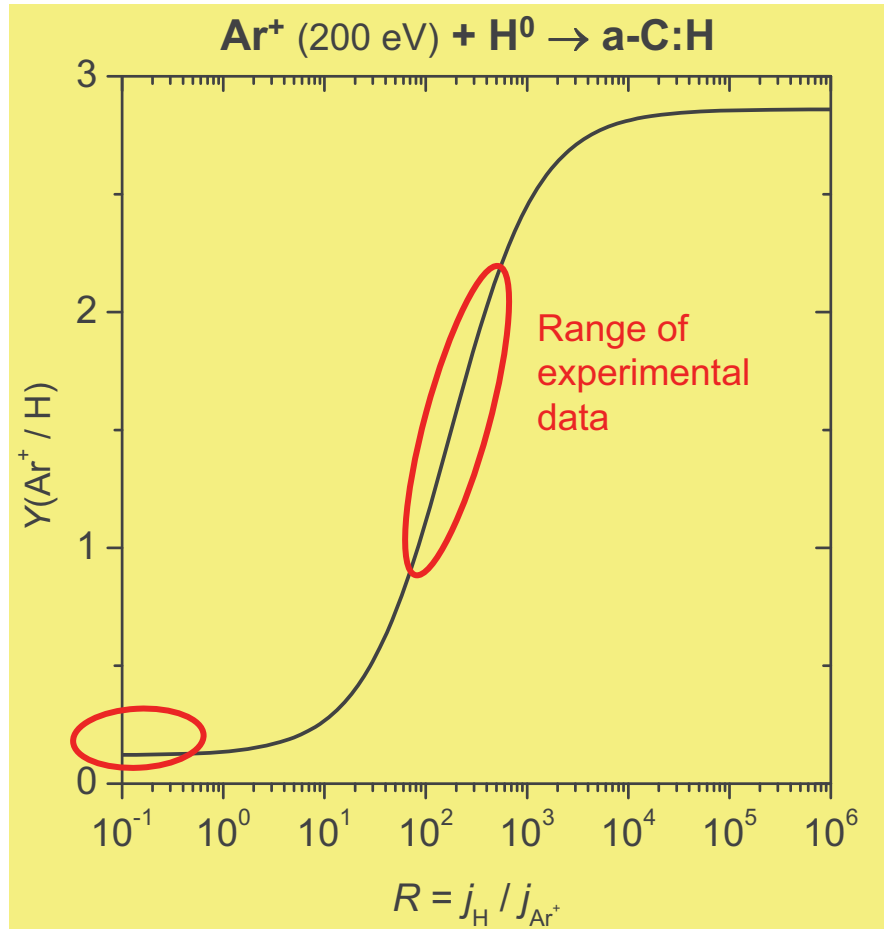
**Fit parameters:**

$$S = 176$$

$$Y_{\text{chem}} = 2.86$$

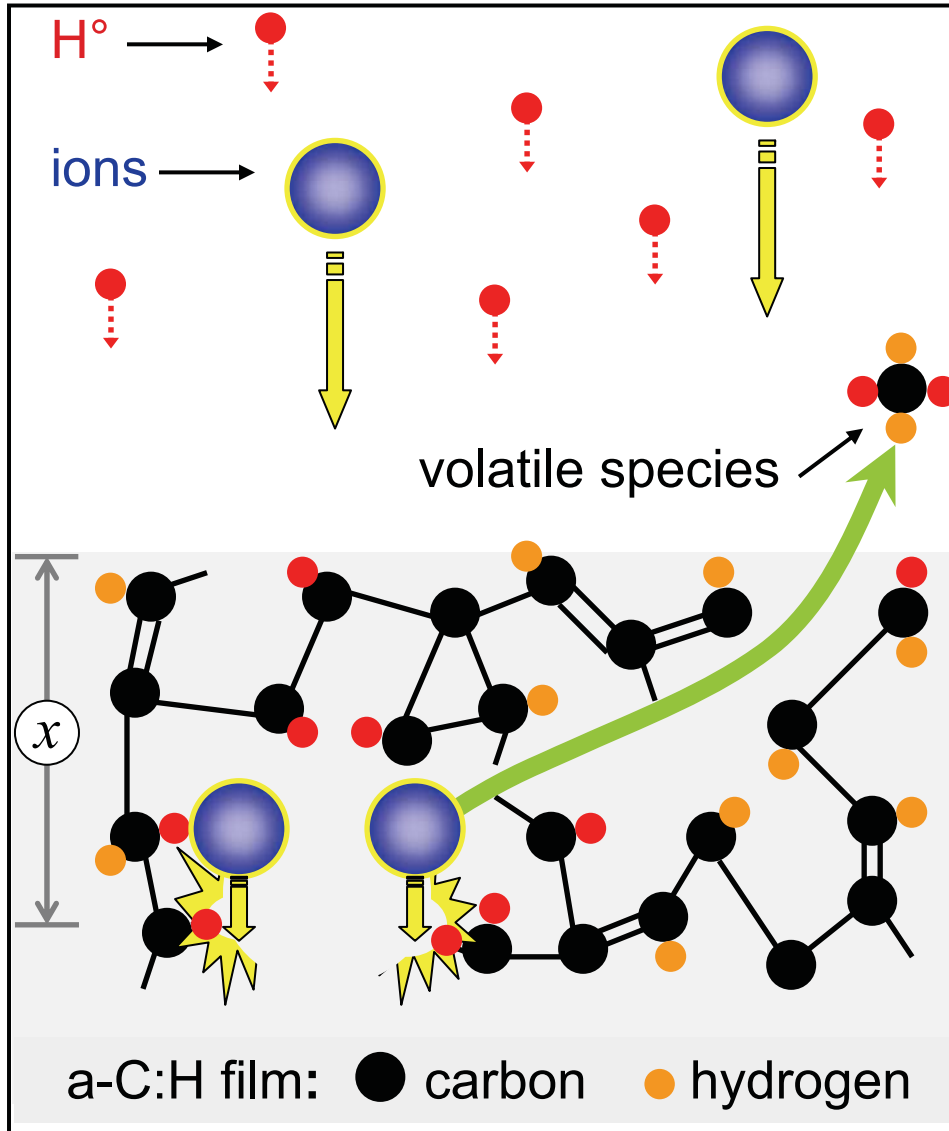
$$Y_{\text{phys}} = 0.12$$

# Ar<sup>+</sup>|H flux dependence



Saturation requires much more H than ions ( $R > 1000$ )

# chemical sputtering mechanism



1. ions break C–C bonds

2. H<sup>o</sup> passivates broken bonds

Repetition of 1 and 2



3. volatile hydrocarbons

diffusion to the surface

desorption

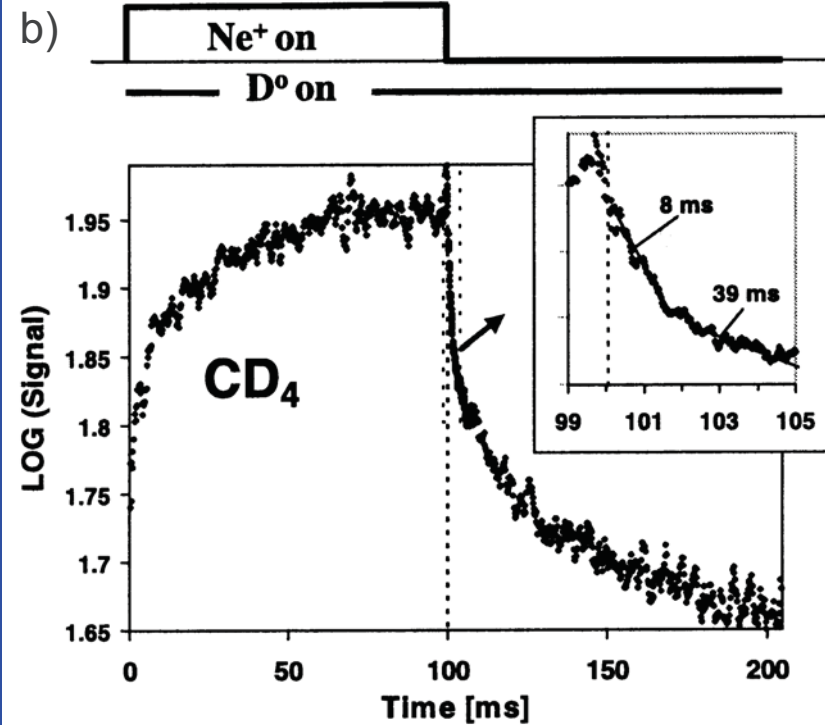
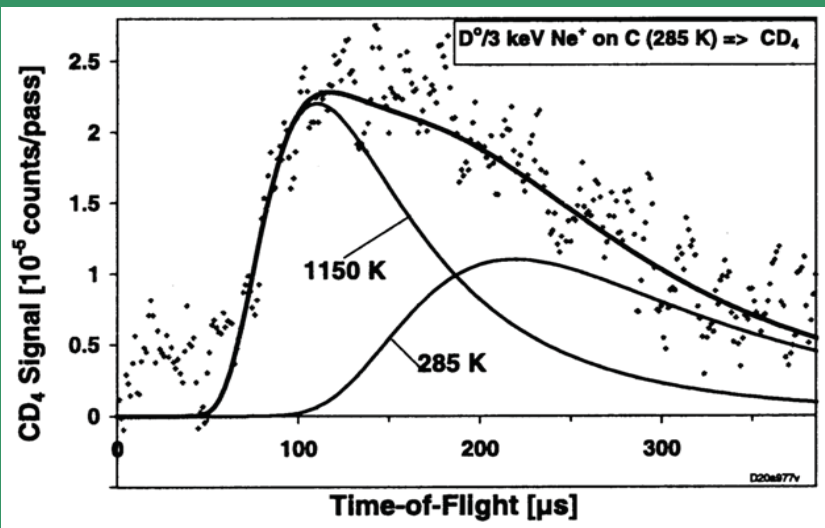
# supporting results from literature

1. CH<sub>4</sub> main (C<sub>1</sub>-) erosion product (Vietzke et al. J. Nucl. Mater. 128&129, 545 (1984))

2. energy distribution of erosions products

3. time delay between end of ion bombardment and end of particle release

from E. Vietzke, J. Nucl. Mater 290, 158 (2001)



# chemical sputtering model



$$Y(\text{ions} | H) \propto \int y_{bb}(x) \cdot p_{pass}(x) dx$$

bond breaking due to ion impact

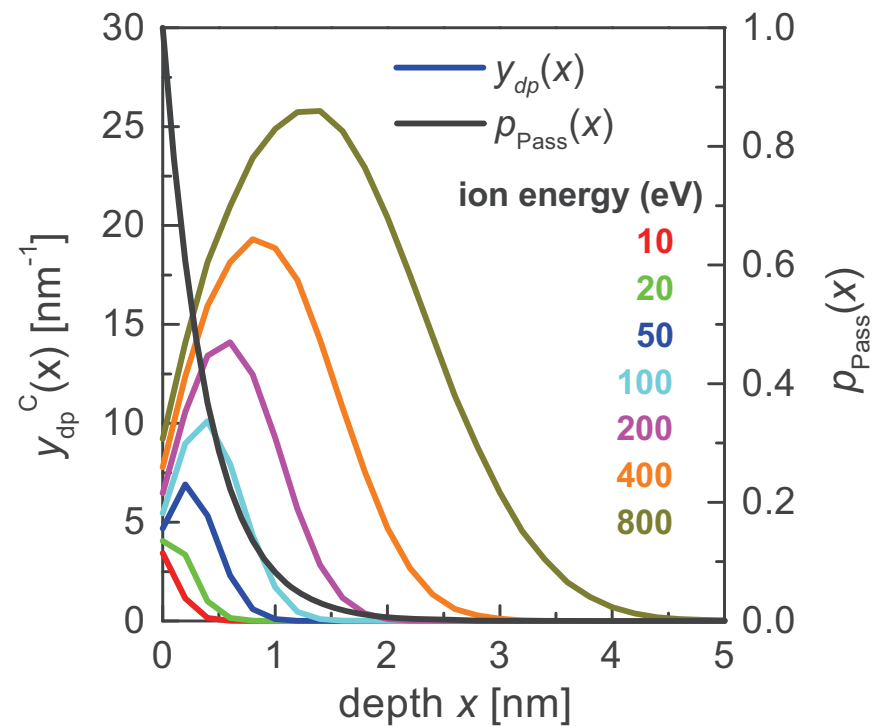
passivation by atomic H

$$Y(\text{ions} | H) = a \cdot \int y_{dp}(x) \cdot e^{(-x/\lambda)} dx$$

displacement events per depth interval calculated by TRIM.SP

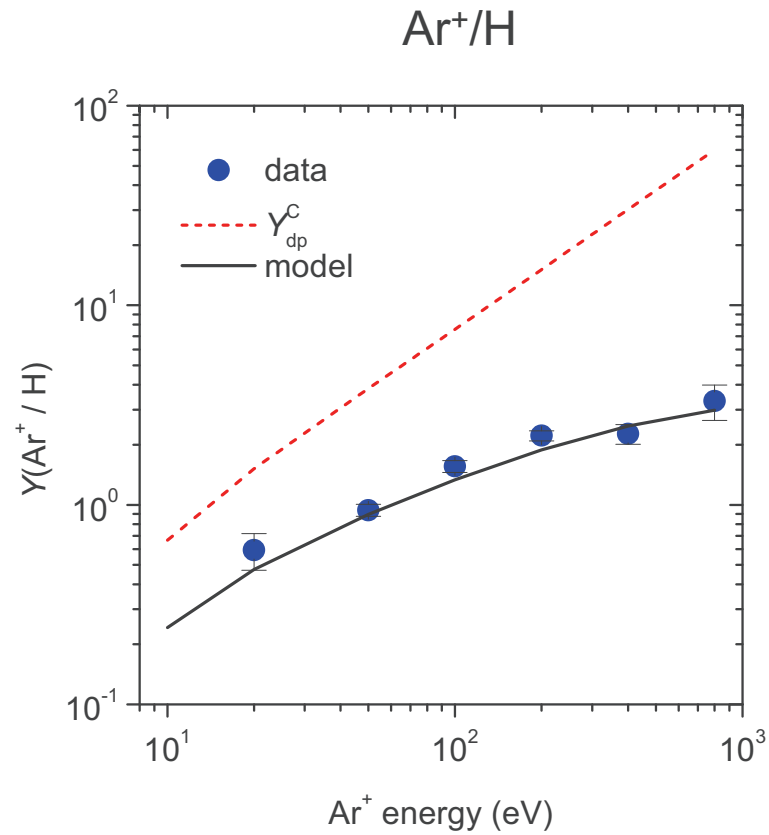
exponential decay, maximum range about 2 nm, known from plasma experiments

a is a fit parameter



$$E_{dp}^C = 5 \text{ eV}, \lambda = 0.4 \text{ nm}$$

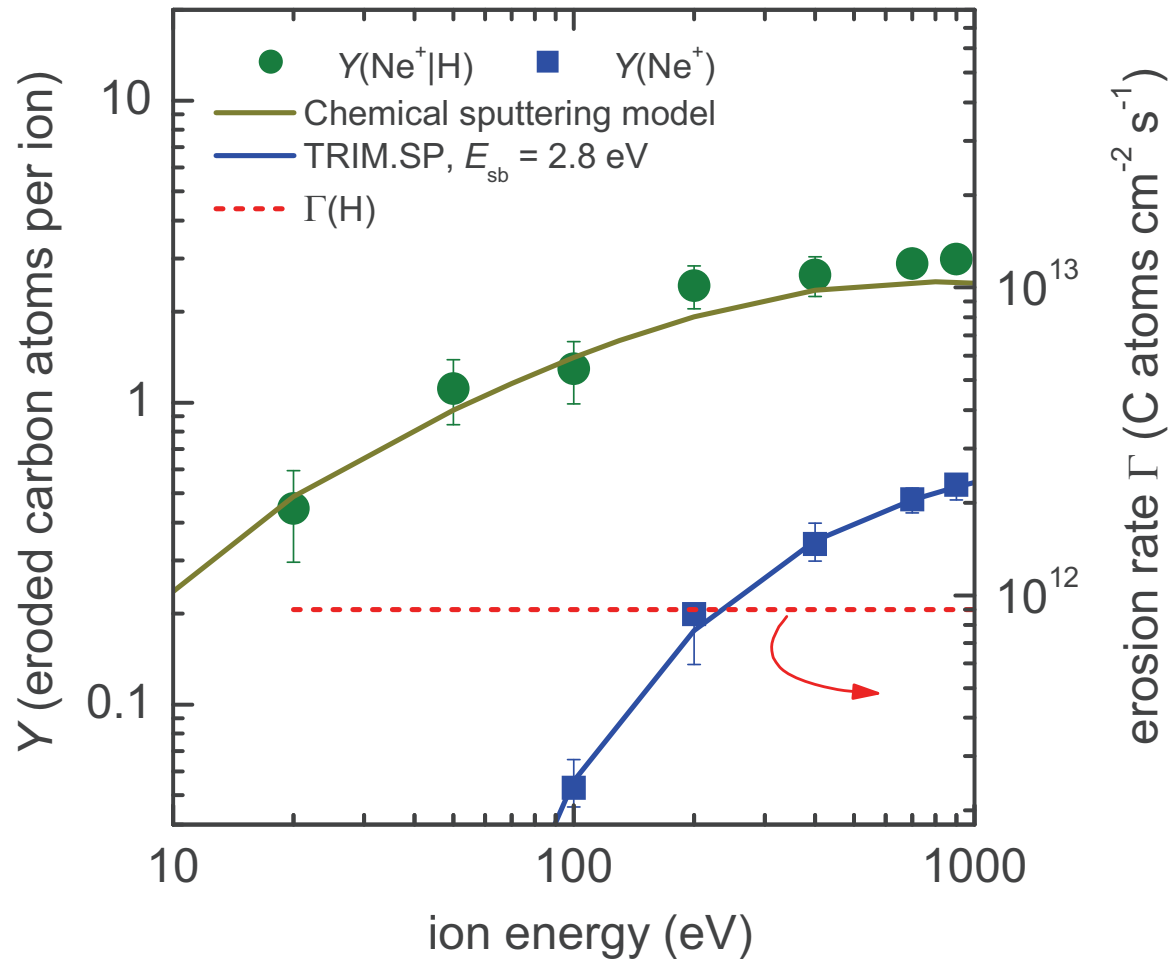
# energy dependence



$$a = 0.4$$

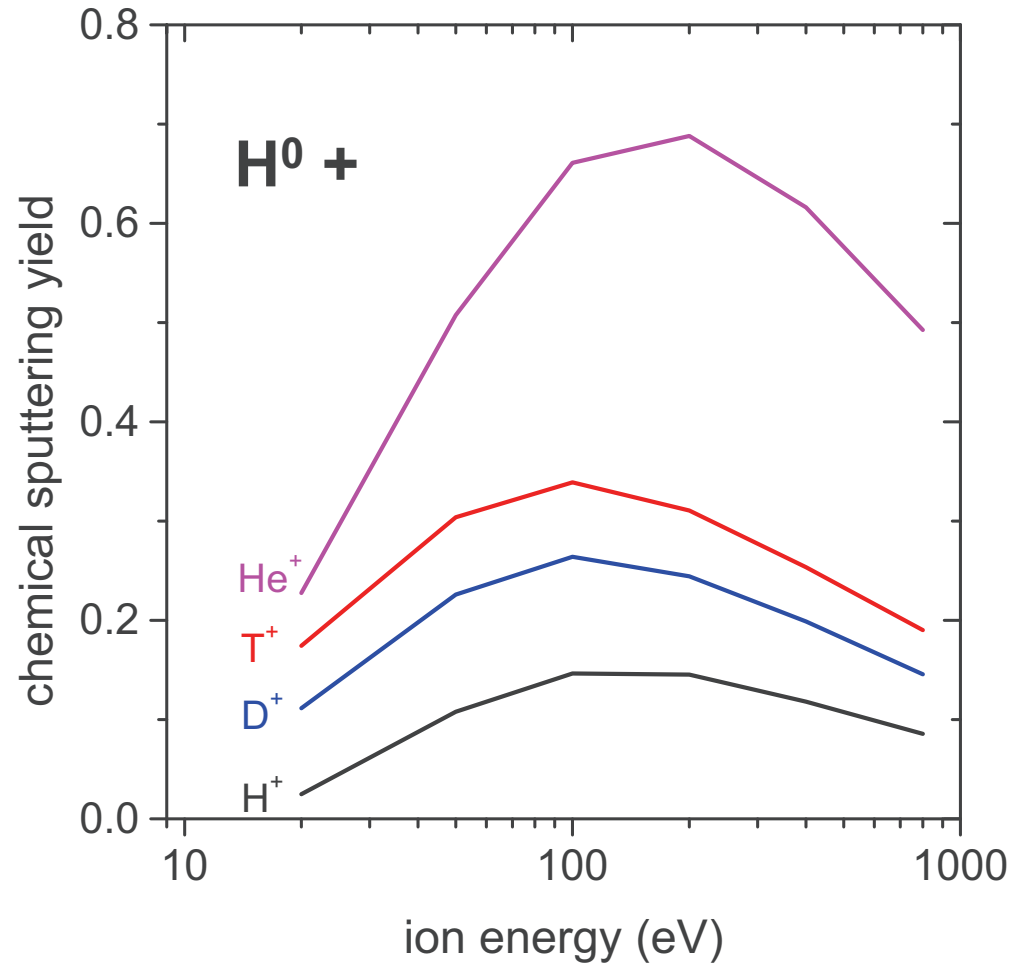
$$j_H = 1.4 \times 10^{15} \text{ cm}^{-2} \text{ s}^{-1}, j_{\text{Ar}^+} = 3.6 \times 10^{12} \text{ cm}^{-2} \text{ s}^{-1}, R = j_H/j_{\text{Ar}^+} \approx 400$$

# : Ne<sup>+</sup> + H



- Excellent agreement between model and data (same parameters as for Ar, i.e., a = 0.4))
- yield > 1 for E<sub>ion</sub> > 50 eV

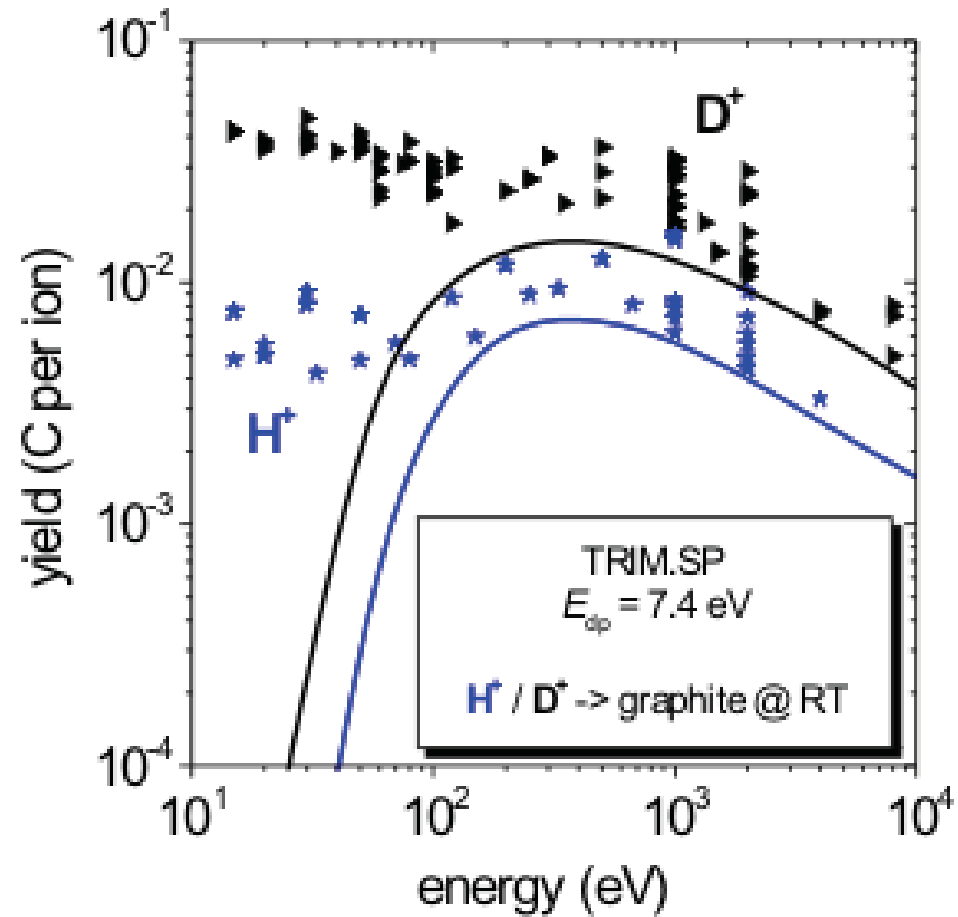
# energy dependence: modeling results



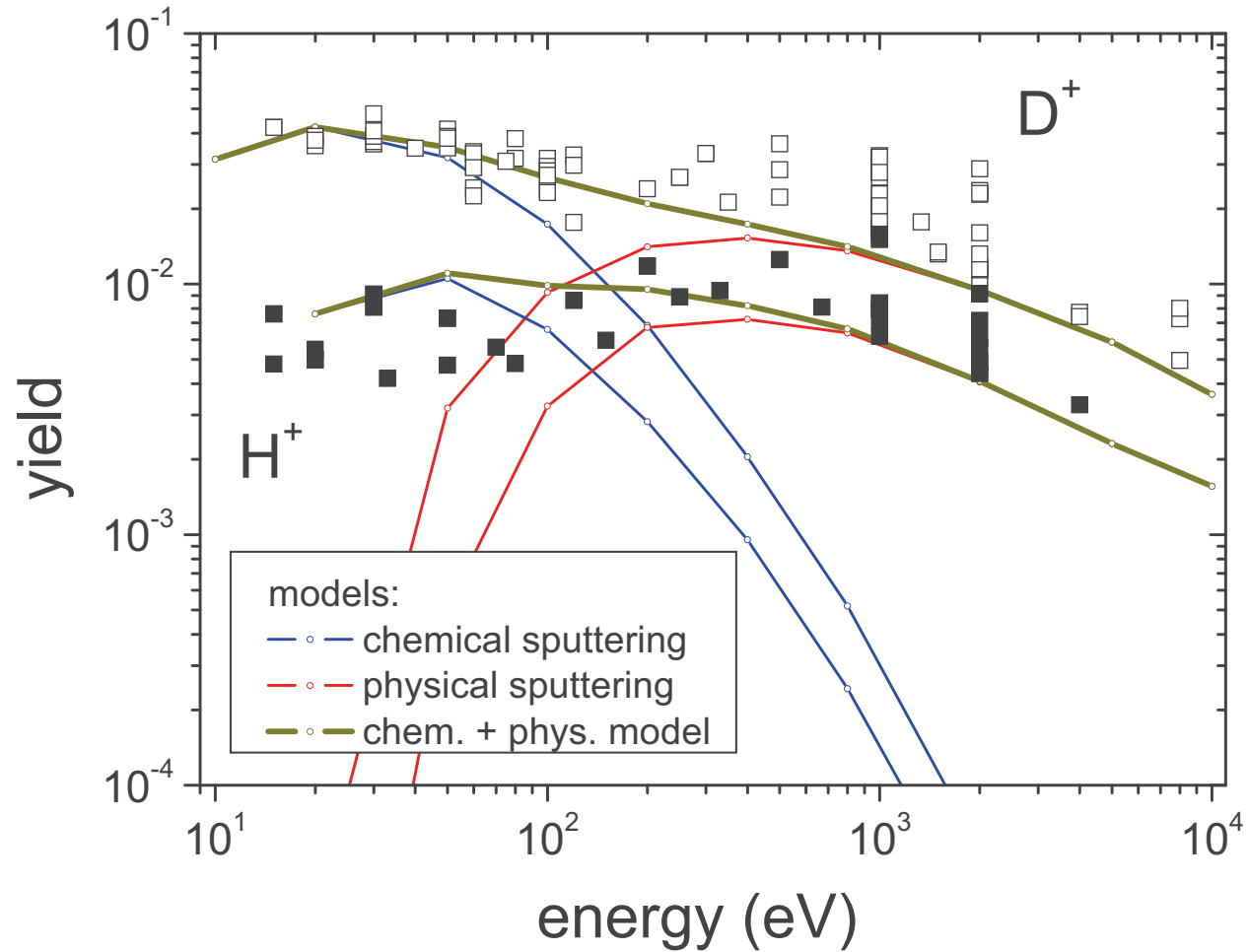
$a = 0.4$   
 $R \approx 400$



# erosion of graphite by energetic hydrogen



# chemical sputtering with reactive ions



C. Hopf and W. Jacob 2005

# chemical sputtering with reactive ions

$$\text{total yield} = \text{chemical sputtering} + \text{physical sputtering}$$
$$Y(E) = \int y_{\text{dp}}^{\text{C}}(x, E) n(x, E) \exp(-x / \lambda) dx + Y_{\text{phys}}(E)$$

$Y_{\text{phys}}(E)$

phys. sputtering yield

TRIM.SP

$y_{\text{dp}}^{\text{C}}(x, E)$

ion induced damage

$E_{\text{sb}}^{\text{C}} = 7.4 \text{ eV}$

$n(x, E)$

implanted hydrogen

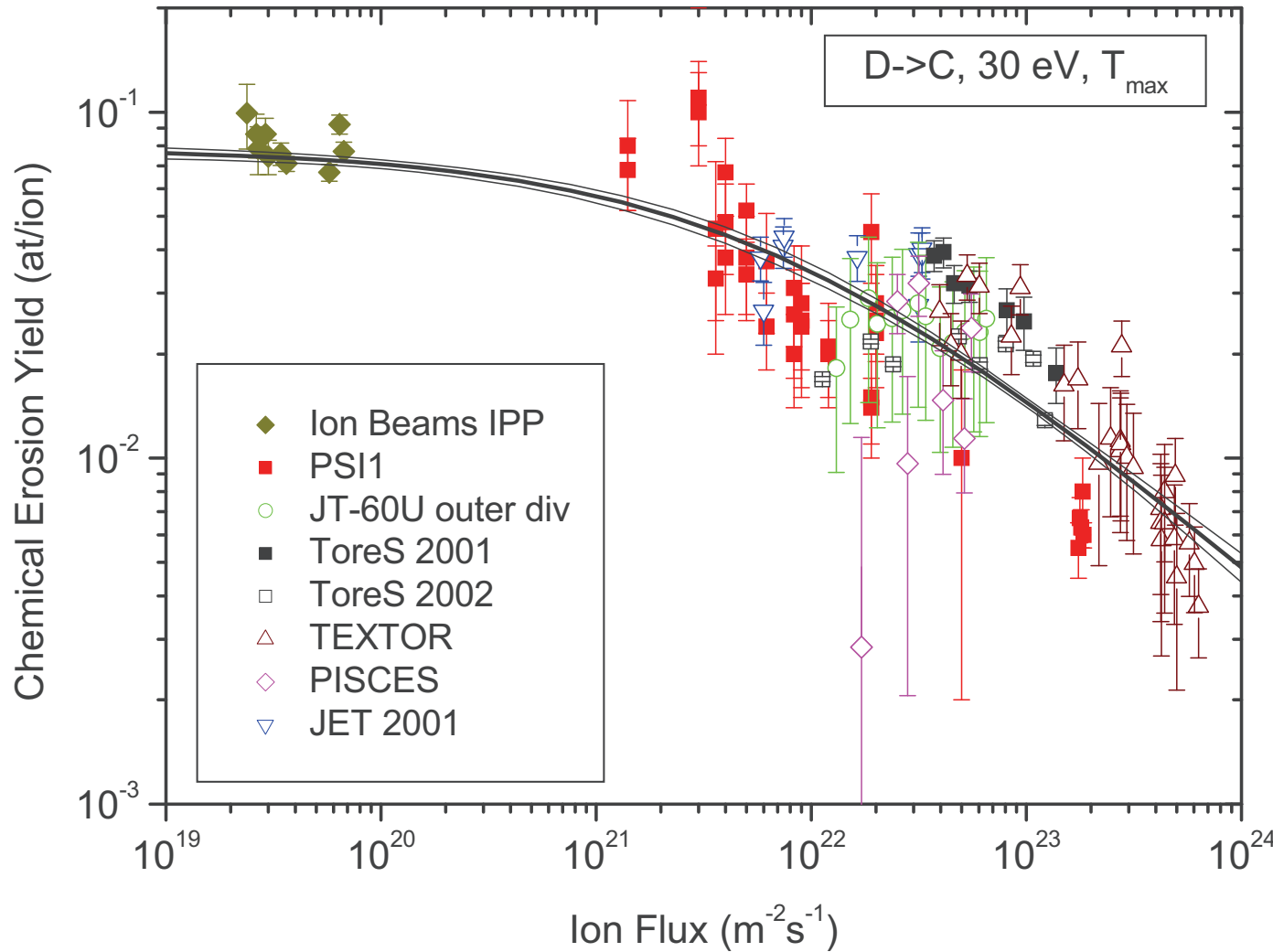
$E_{\text{dp}}^{\text{C}} = 5.0 \text{ eV}$

$\exp(-x/\lambda)$

depth dependent probability  
for outdiffusion of erosion  
products

$\lambda = 0.4 \text{ nm}$

# erosion (Chemical sputtering) at high ion fluxes



fitting formula:  
 $Y = Y_{\text{low}} / (1 + (\Gamma/\Gamma_0)^\epsilon)$

results from fitting:  $Y_{T_{\max}}(\Gamma) = 0.79 / (1 + (\Gamma/6 \times 10^{21})^{0.54})$

## Summary on erosion

- **Physical sputtering:** for the most part well understood
    - well modeled by TRIM.SP (binary collision approximation)
    - energy, projectile mass, angle, roughness
  - **Chemical erosion:** for the most part well understood
    - thermally activated process
    - can be influenced by doping
- 
- ***Chemical sputtering:*** increase of yield and lowering of threshold
  - mechanistic model for *chemical sputtering*
  - flux ratio dependence (rate equation model): high H fluxes required
  - energy dependence: bond breaking  $\times$  passivation
  - predictions for other ions, e.g. H, D, T, He, N<sub>2</sub>, ..
  - temperature dependence of the erosion maximum not understood
  - decrease in erosion rate at high fluxes not understood

---

## exercise 2

---



- Use SRIM to compute the energy dependence of the physical sputtering yields for  $D^+$  on tungsten and carbon, as well as the self-sputtering yields.
- Evaluate the threshold energies for  $D^+$  sputtering of tungsten and of carbon.
- At what energy does the self-sputtering yield equal unity in these two cases.
- compare the yield for  $D^+$  on carbon with the yield for  $D^+$  on a thin (5 nm thick) carbon film on tungsten for an energy of 1 keV. Why is it so different?