The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific and
Cultural Organization

IAEA
International Atomic Energy Agency

2028-18

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

20 - 30 April 2009

WHAT - Can we tend the fire?

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Can we tend the fire?

Three lectures course on plasma surface interaction and edge physics

I Introduction: WHAT happens in a fusion plasma near the walls

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52425 Jülich, Germany

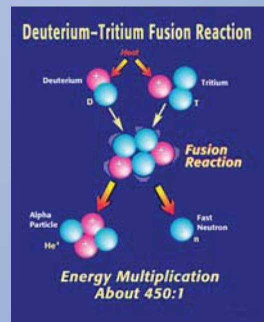
Thanks to: V. Philipps, A. Kirschner, R. Janev

Mankind learning to tend a fire, again….

Fire from processes in atomic shell

Fire from processes in atomic nucleus

100.000 years later….



Chemical process:
$C_xH_y....+O_2+... \rightarrow CO_z + H_2O+...$

Nuclear process:
$d + t \rightarrow He + n$

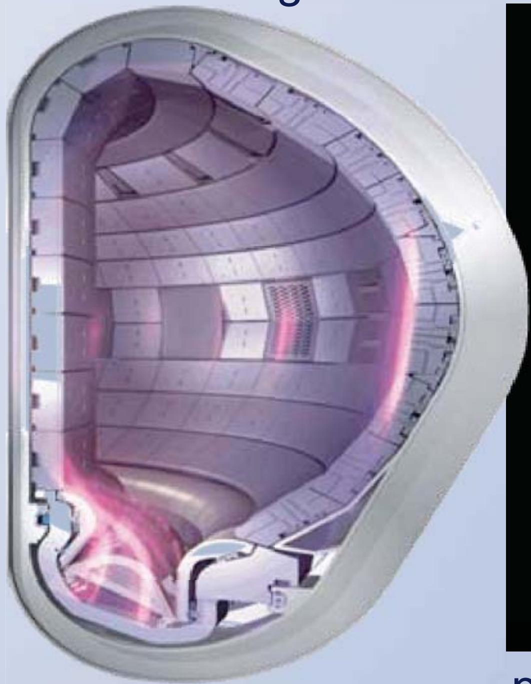
The Energy source of the sun and the stars in the universe is:

Nuclear Fusion

The vision of nuclear fusion research:

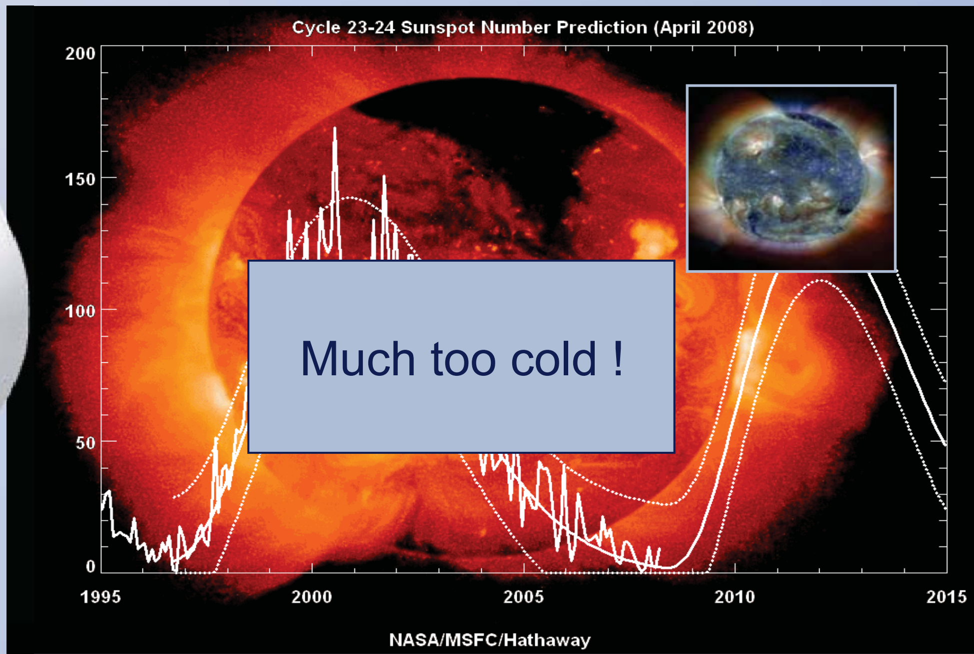
A miniatur star in a solid container

Fusion Reactor:
T=100 Mill. degrees



$d + t \rightarrow He + n$

The Sun: T=15 Mill. degrees in the center



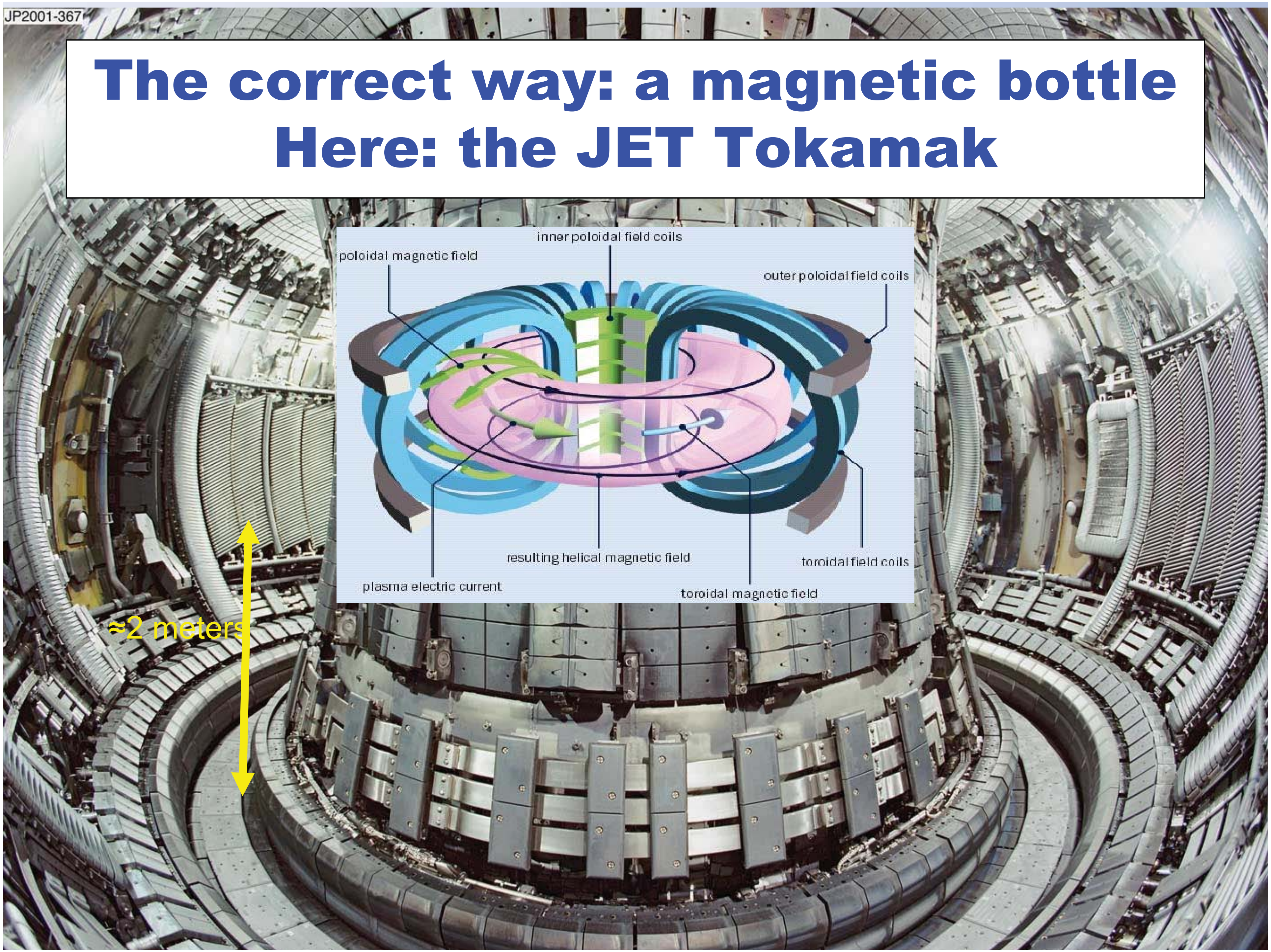
$p + p \rightarrow d$, $d + p \rightarrow He_3$, $He_3 + He_3 \rightarrow He_4 + p + p$,
Reaction time $1/(n_p\langle\sigma v\rangle_{fus})=t_{fus}$ approx. 10^9 years

What these lectures are NOT about:

Fusion reactor

From Robert Zemeckis movie: “Back to the future II”

The correct way: a magnetic bottle
Here: the JET Tokamak



Euratom 26 Fusion Associations

Joint construction of JET (1978)

- **Euratom - CEA** (1958) France
- **Euratom – ENEA** (1960) Italy (incl. Malta)
- **Euratom - IPP** (1961) Germany
- **Euratom - FOM** (1962) The Netherlands
- **Euratom - FZJ** (1962) Germany
- **Euratom - Belgian State** Belgium (1969) (incl. Luxembourg)
- **Euratom - RISØ** (1973) Denmark
- **Euratom – UKAEA** (1973) United Kingdom
- **Euratom - VR** (1976) Sweden
- **Euratom - Conf. Suisse** Switzerland (1979)

- **Euratom - FZK** (1982) Germany
- **Euratom –CIEMAT** (1986) Spain
- **Euratom – IST** (1990) Portugal

- **Euratom - TEKES** (1995) Finland (incl. Estonia)
- **Euratom - DCU** (1996) Ireland
- **Euratom - ÖAW** (1996) Austria
- **Eur - Hellenic Rep** (1999) Greece (incl. Cyprus)
- **Euratom - IPP.CR** (1999) Czech Rep.
- **Euratom - HAS** (1999) Hungary
- **Euratom – MEdC** (1999) Romania
- **Euratom – Univ. Latvia** Latvia (2002)

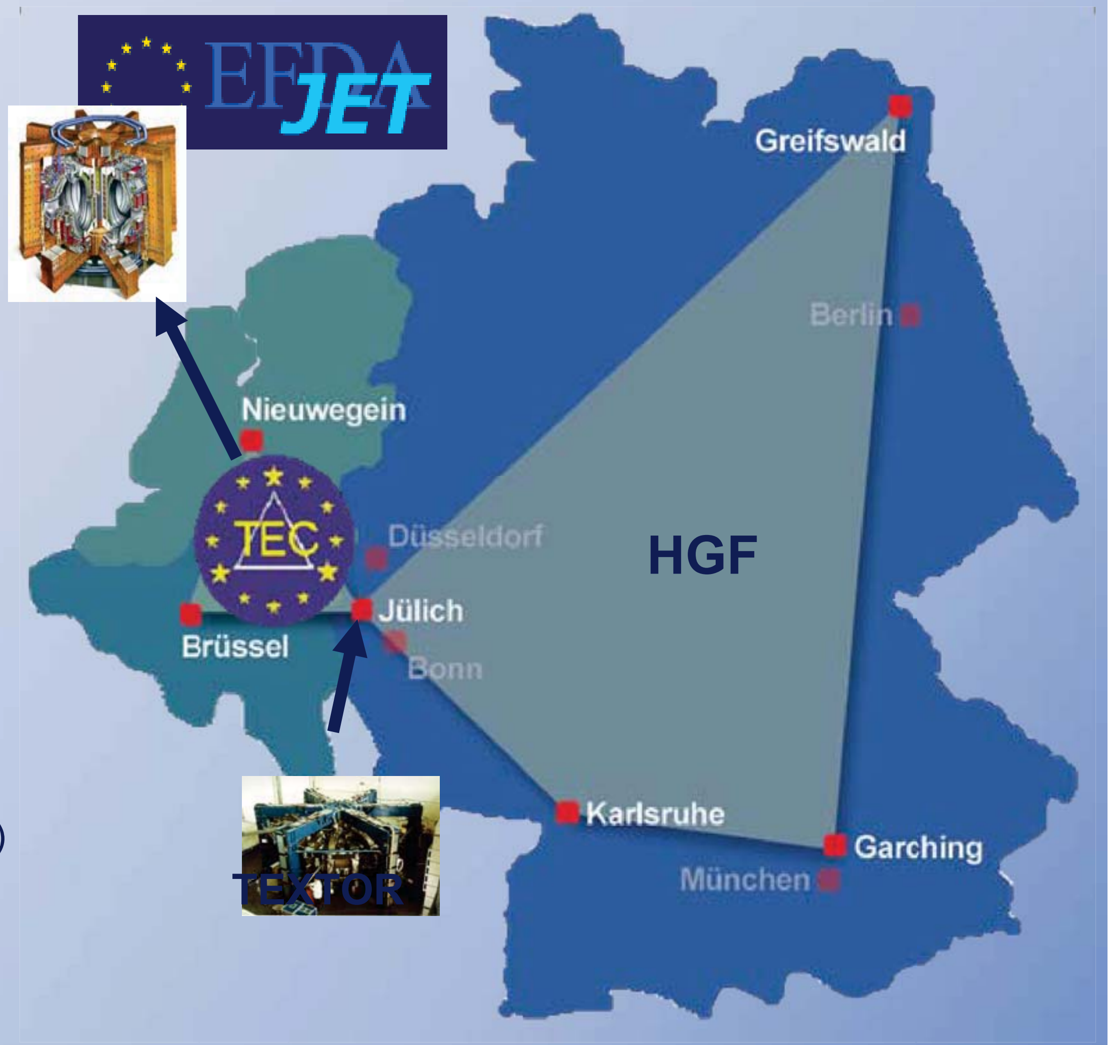
- **Euratom - IPPLM** (2005) Poland
- **Euratom - MHEST** (2005) Slovenia
- **Euratom – CU** (2007) Slovakia
- **Euratom – INRNE** (2007) Bulgaria
- **Euratom – LEI** (2007) Lithuania

FZ Jülich:
in Germany fusion research is organized in the Helmholtz Association

Germany
- Helmholtz Association
- DFG / Universities

Europe
- Trilateral Euregio Cluster (B, Nl, Jül)
- EURATOM Association
- EFDA (JET, Technol.)
- F4E (ITER)

World
- IEA Implementing Agreement
“Plasma-Wall Interaction” (J, USA, Canada)
- ITPA International Expert Groups



Hermann Ludwig Ferdinand von Helmholtz (1821-1894)

1847: precise formulation of the law of conservation of energy

1881: inclusion of chemical processes, “free energy”, “internal energy”

Problem:
what is the source of energy of the sun?
how old is the sun?
how old is the earth at highest?

1854: Theory of Contraction (together with: Lord Kelvin)
The energy radiated by the sun is provided by contraction of the sun (and the stars), freeing the graviational energy, i.e. accounted for in a purely mechanical concept

→ Age of the planet earth: ~ 10 Mill. Years (at highest)

Ca. 1925: Sir Arthur Eddington :

Nuclear Fusion as energy source of the sun and the stars
($E=m\ c^2$)

Ca. 1935: Hans Bethe und Carl Friedrich von Weizsäcker:

final resolution of the nuclear fusion processes in the sun
(“Bethe- Weizsäcker cycle”)

(age of sun and earth: 4-5 billion years well possible)

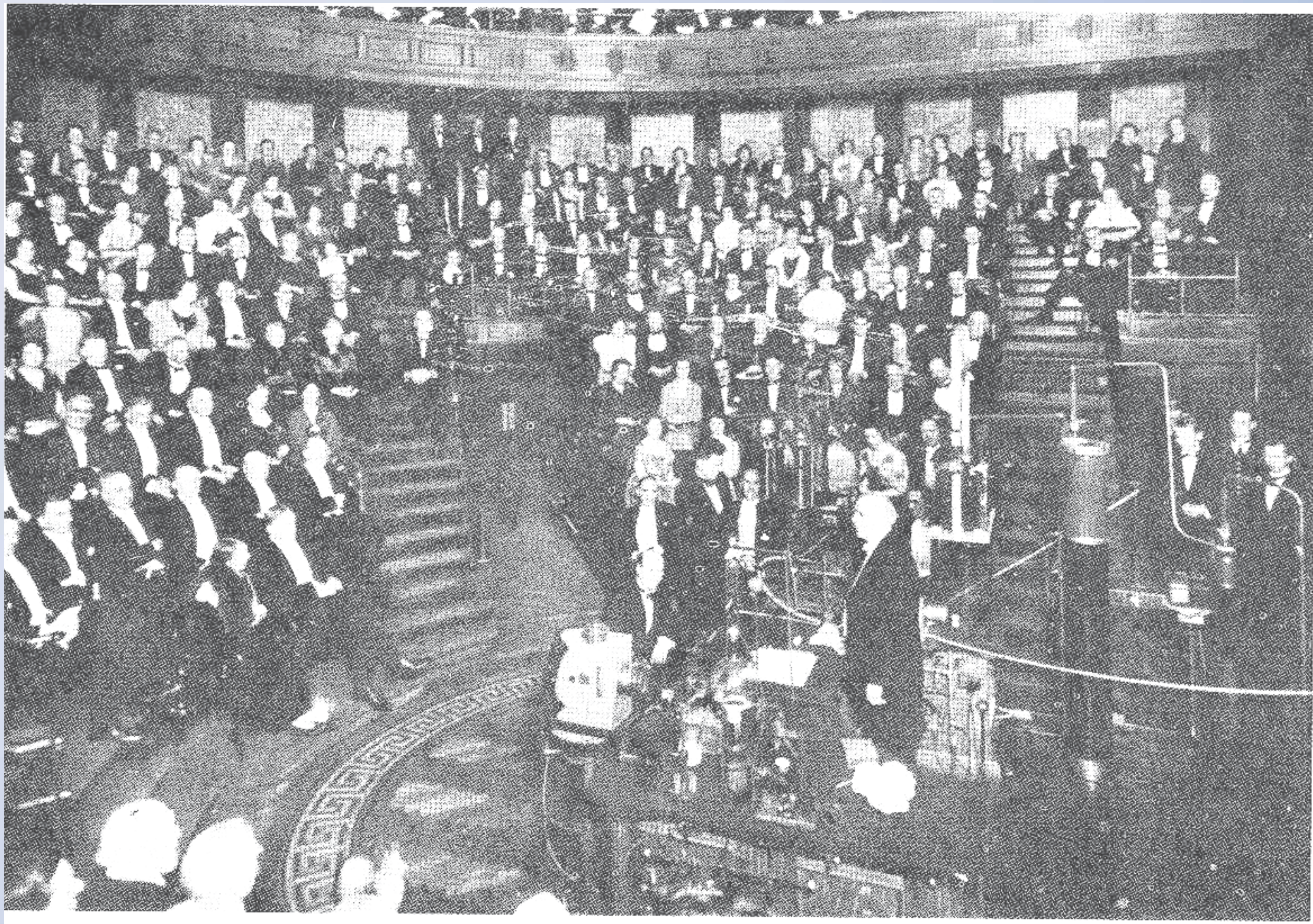
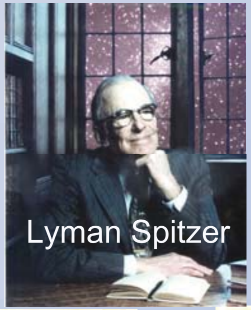


Figure 3.6.3 Rutherford demonstrating deuterium fusion at the Royal Institution, 1934. The Metropolitan-Vickers transformer is to the extreme right of the apparatus. Reproduced by kind permission of Sir Mark Oliphant from his book *Rutherford: Recollections of the Cambridge Days* (Amsterdam: Elsevier, 1972)

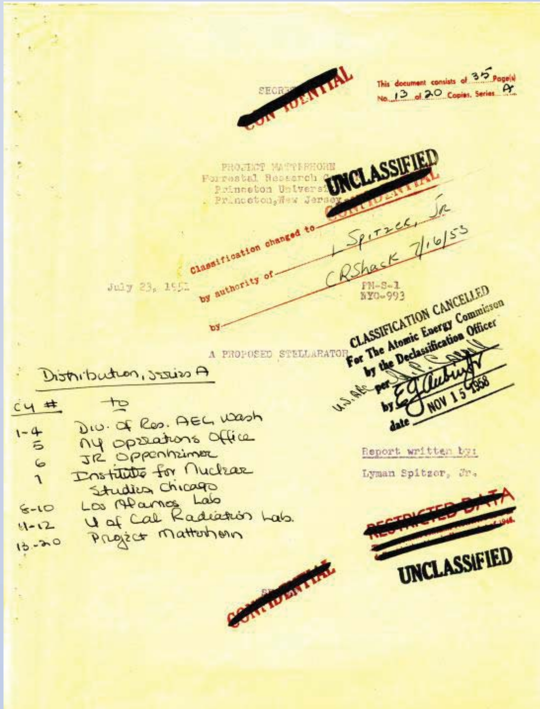
1933: Oliphant und Rutherford fuse Deuteron atoms, discovery of tritium

L. Spitzer “A proposed stellarator”
AEC Report No. NYO-993 (PM-S-1) 1951
US Fusions-Projekt: “Matterhorn”



Known in those days:
- Only magnetic fields can confine the flame
  (Lasers did not yet exist)
- It has to be a toroidal configuration
  (H. Poincare, ~1880)
- The B-field has to be helical

then: → “only a stellarator is possible”



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by authority of
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Spitzer, Jr.
CRShack 7/16/53

July 23, 1951

PM-S-1
NYO-993

A PROPOSED STELLARATOR

CLASSIFICATION CANCELLED
For The Atomic Energy Commission
by the Declassification Officer
NOV 15 1958

Distribution, Series A

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1-4	Div. of Res. AEC Wash
5	NY Operations Office
6	JR Oppenheimer
7	Institute for Nuclear Studies Chicago
8-10	Los Alamos Lab
11-12	U of Cal Radiation Lab.
13-20	Project Matterhorn

Report written by:
Lyman Spitzer, Jr.

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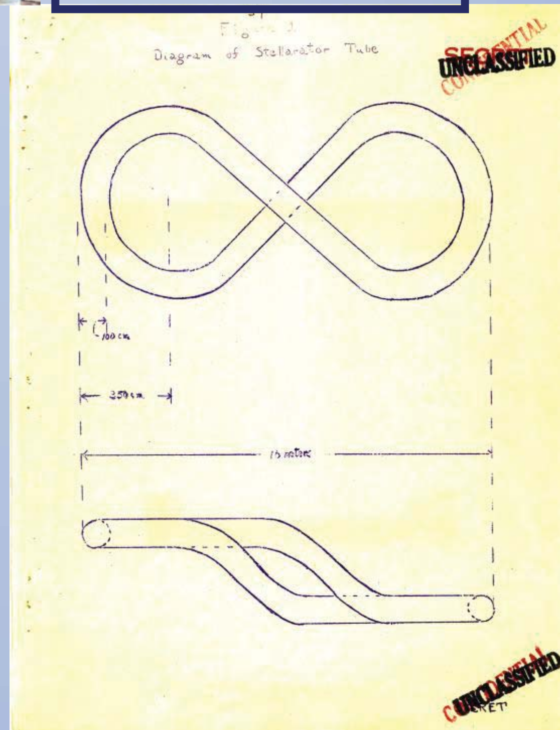
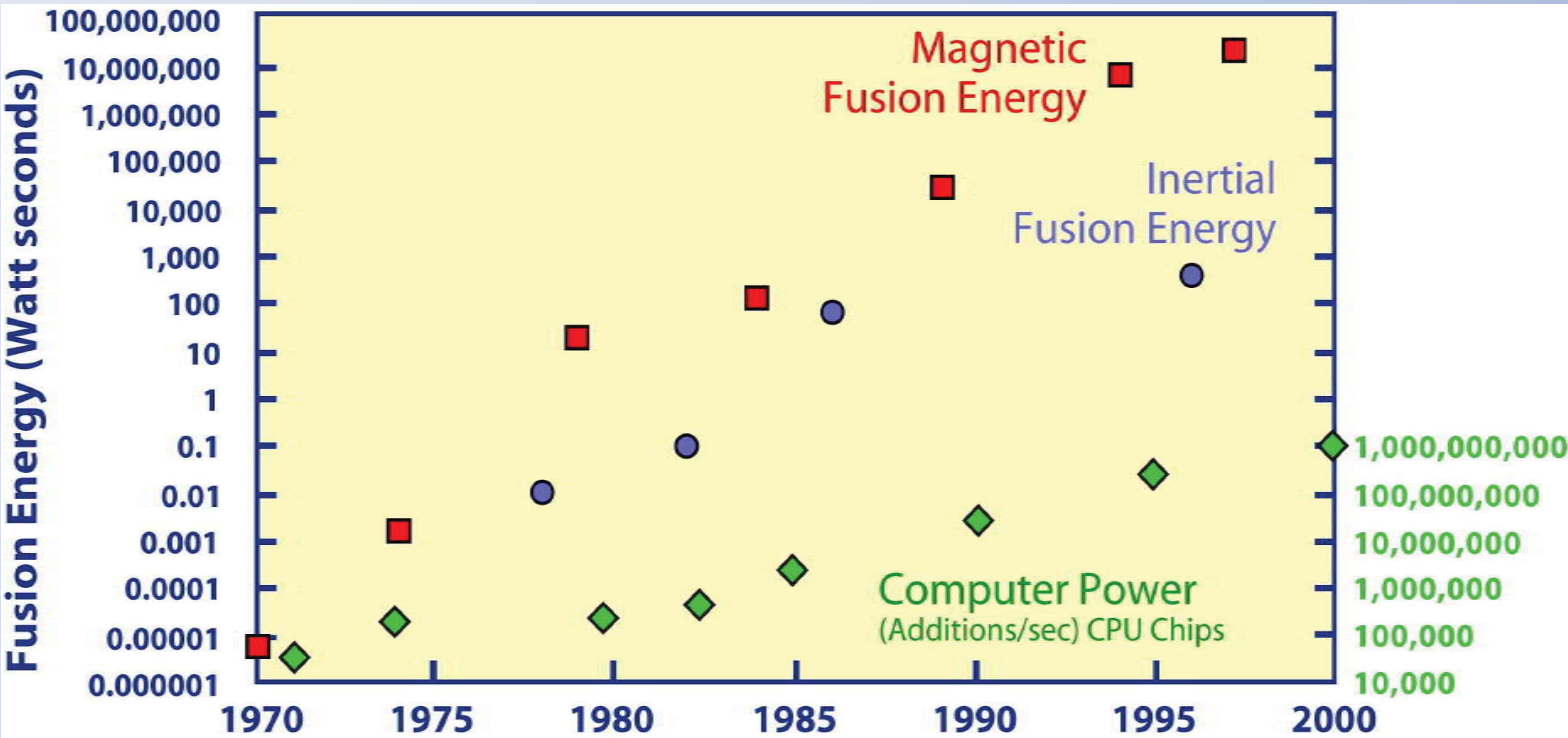
Inventing the stellarator



-1968 : all expectations have been frustrated. All experiments have been gigantic (and costly) failures (Instabilities, sensitivity to small field errors,….)
The final end of nuclear fusion research?
No: a few small experiments in the USSR have shown surprising successes: **Tokamaks**

Progress in Tokamak research:



Compare: Moore’s Law mirco processors

Outline of course:

Introduction: Fusion Research & Plasma-Wall Interaction

I.) WHAT : basic plasma-wall interaction processes

II.) HOW : …can we make the application work? → ITER

III.) WHY : understanding the edge plasma, A&M processes

Role of Edge Plasma Science

Early days of magnetic fusion (sometimes still today?):

Hope that a fusion plasma would not be strongly influenced by boundary:

"The edge region takes care of itself".

Single goal: optimize fusion plasma performance

Now:

man made fusion plasmas are now powerful enough to be dangerous for the integrity of the container:

The edge region does NOT take care of itself.
It requires significant attention!

The ITER lifetime, performance and availability will not only be influenced, it will be controlled by the edge region

Role of Edge Plasma Science, cont.

The layman's response to the idea:

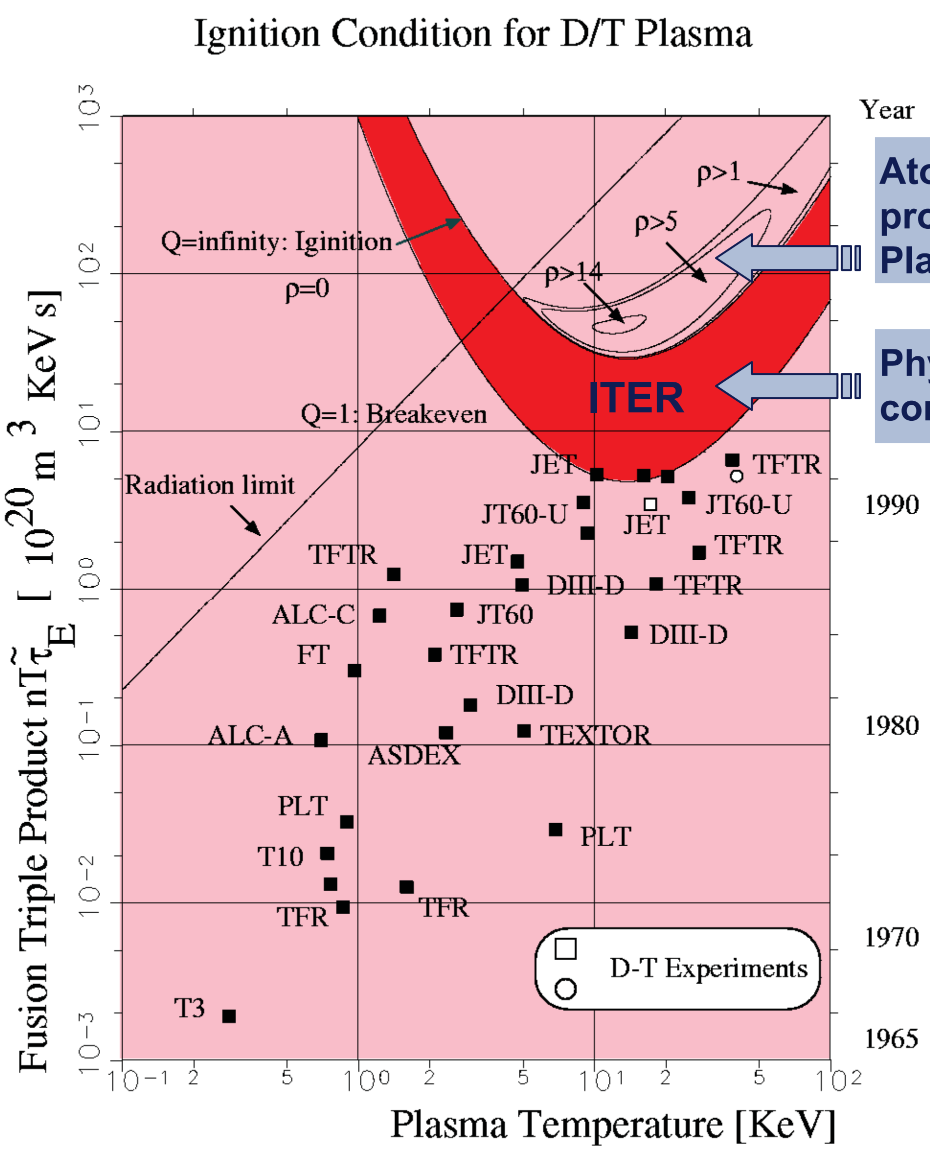
"A miniature star (100 Mill degrees) in a solid container":

THIS MUST BE IMPOSSIBLE !

It turned out unfortunately (early 1990^{th}):

THE LAYMAN IS RIGHT !

Almost...



Atomic/Molecular processes, Plasma material interaction

Physics of hot plasma core

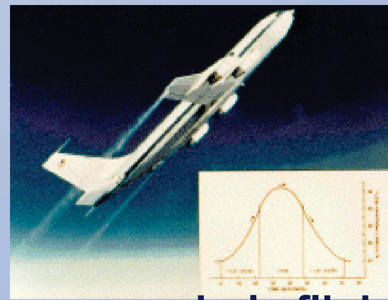
Can we hope that magnetic confinement core plasma physics progress will mitigate plasma-surface problems ?

Candle, on earth

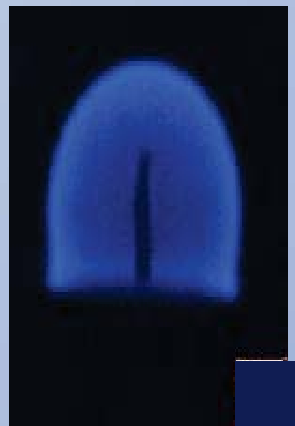
Convection,

driven by buoyancy
(i.e. gravity)

Candle, under mircogravity



e.g.: parabola flight, g ≈ 0

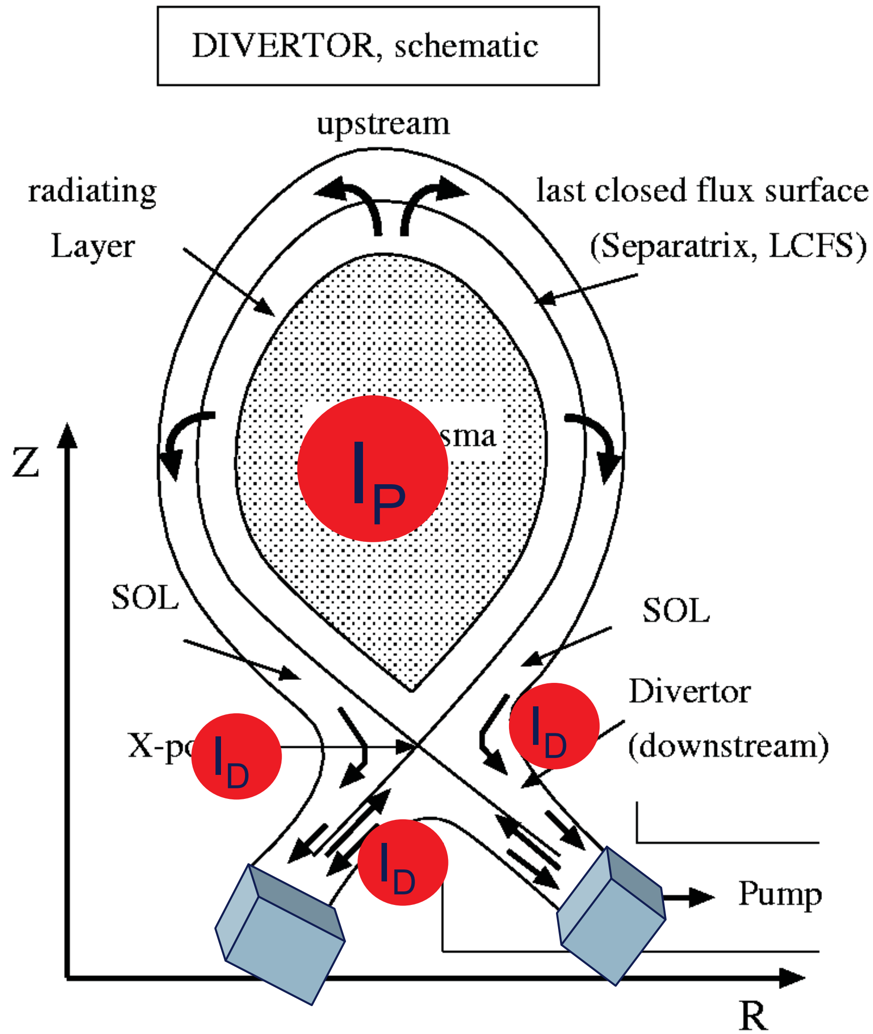


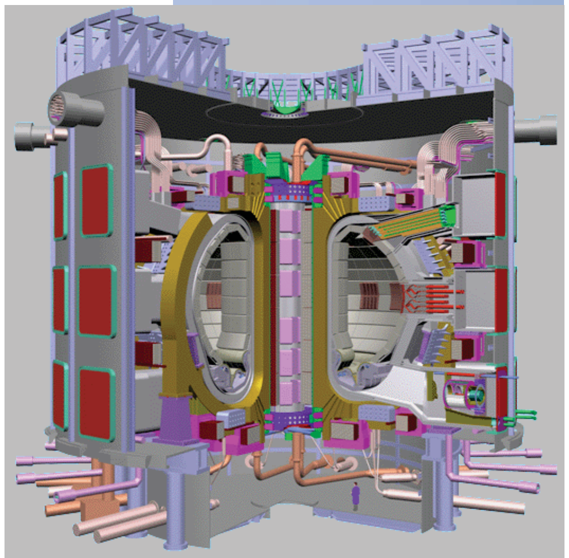
(only small, dim burn, at best)

Only Diffusion

(no convection)

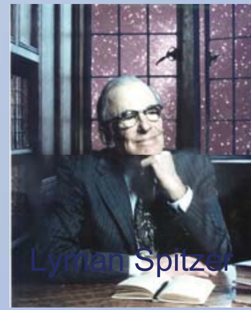
Magnetic Fusion: how to produce convection ? DIVERTOR

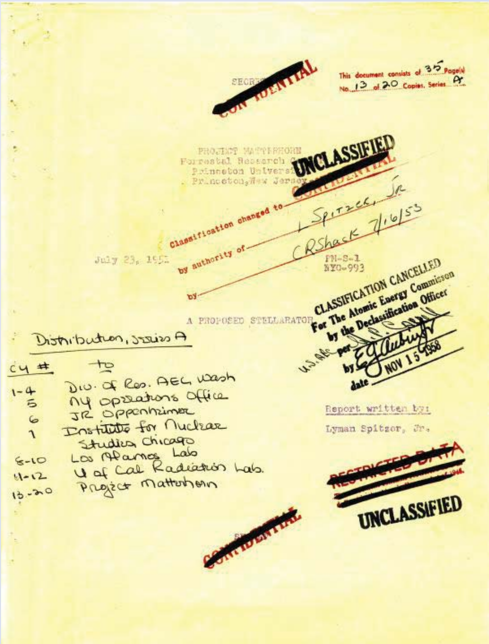




Increase convection → increase plasma surface interaction

L. Spitzer “A proposed stellarator”, US Fusionsprojekt: “Matterhorn”
AEC Report No. NYO-993 (PM-S-1) 1951

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Report written by:
Lyman Spitzer, Jr.

RESTRICTED DATA

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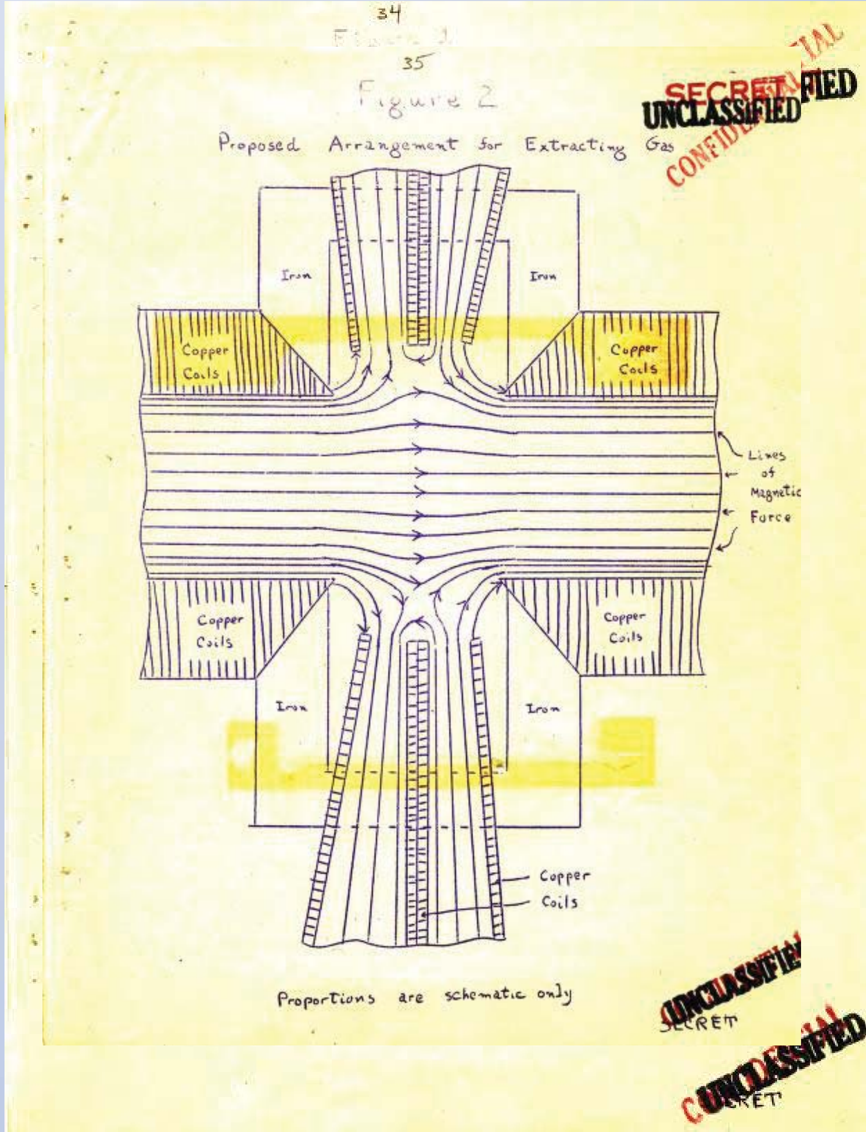
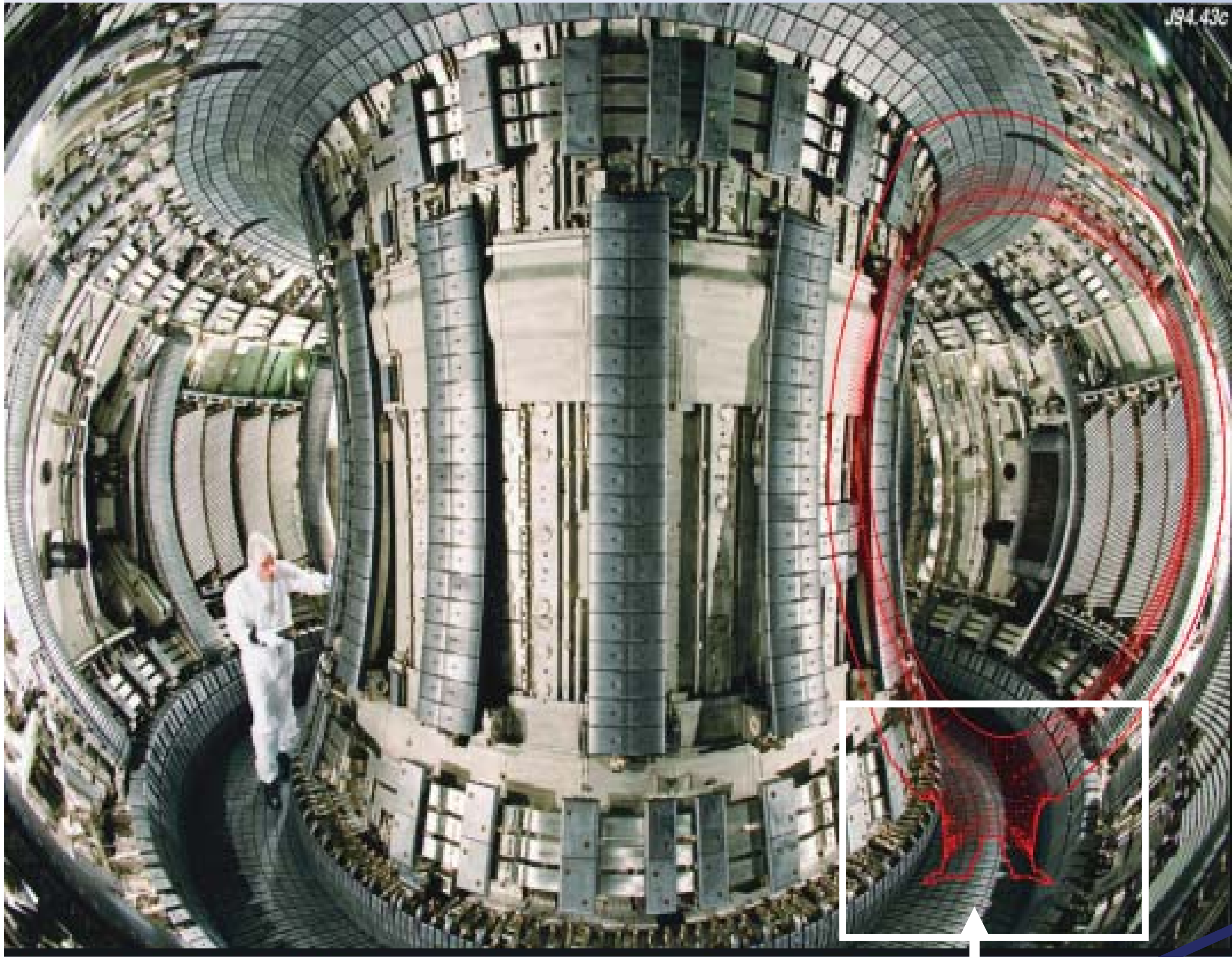
Original report has two figures !



The “Divertor”

To remove wall
Released plasma
Impurities already
from the plasma
boundary,
by a “magnetic
exhaust”

JET (Joint European Torus) :
Ø 8.5 m, 2.5 m high, 3.4 T, 7 MA, 1 min



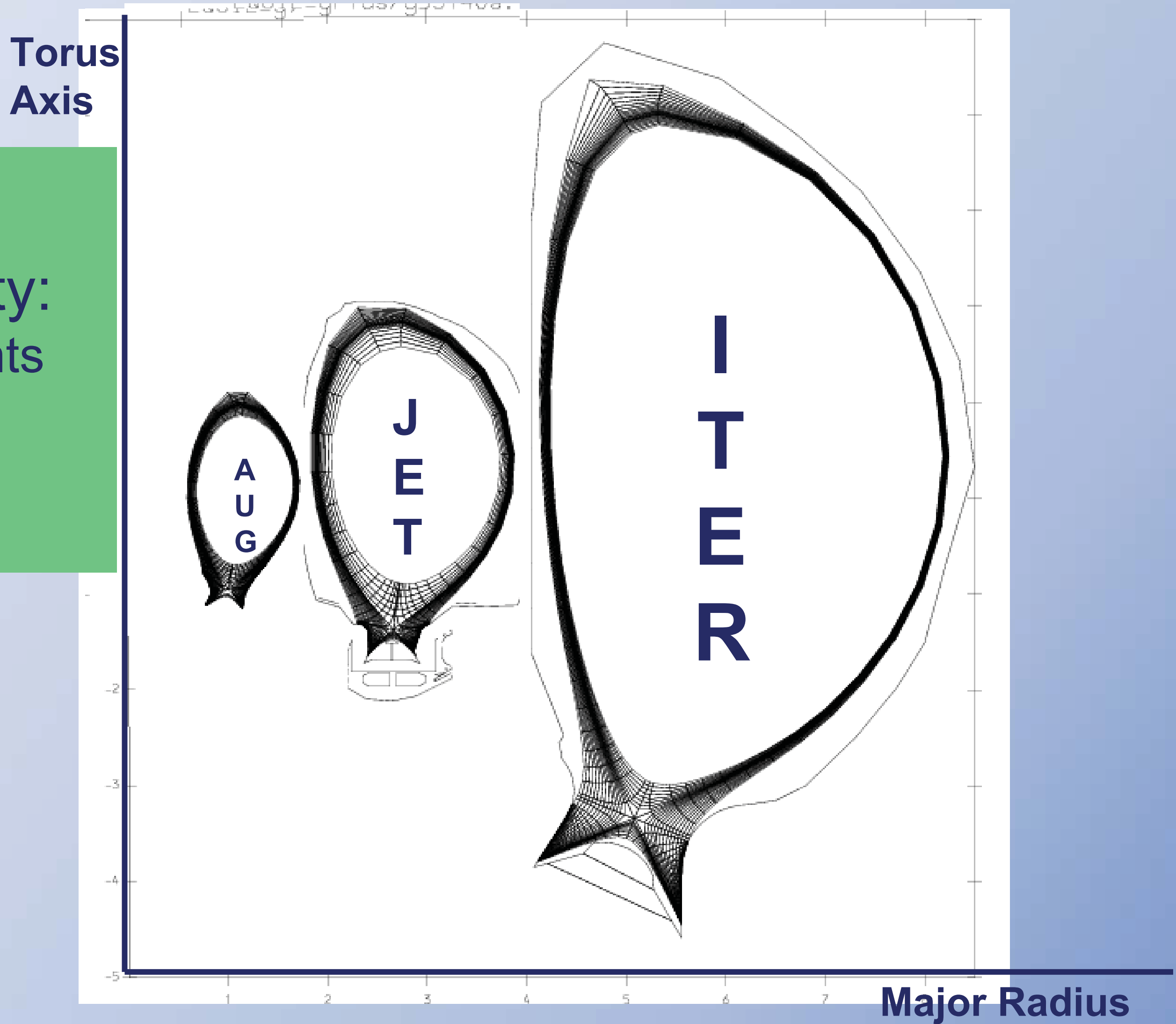
Key area for plasma wall interaction

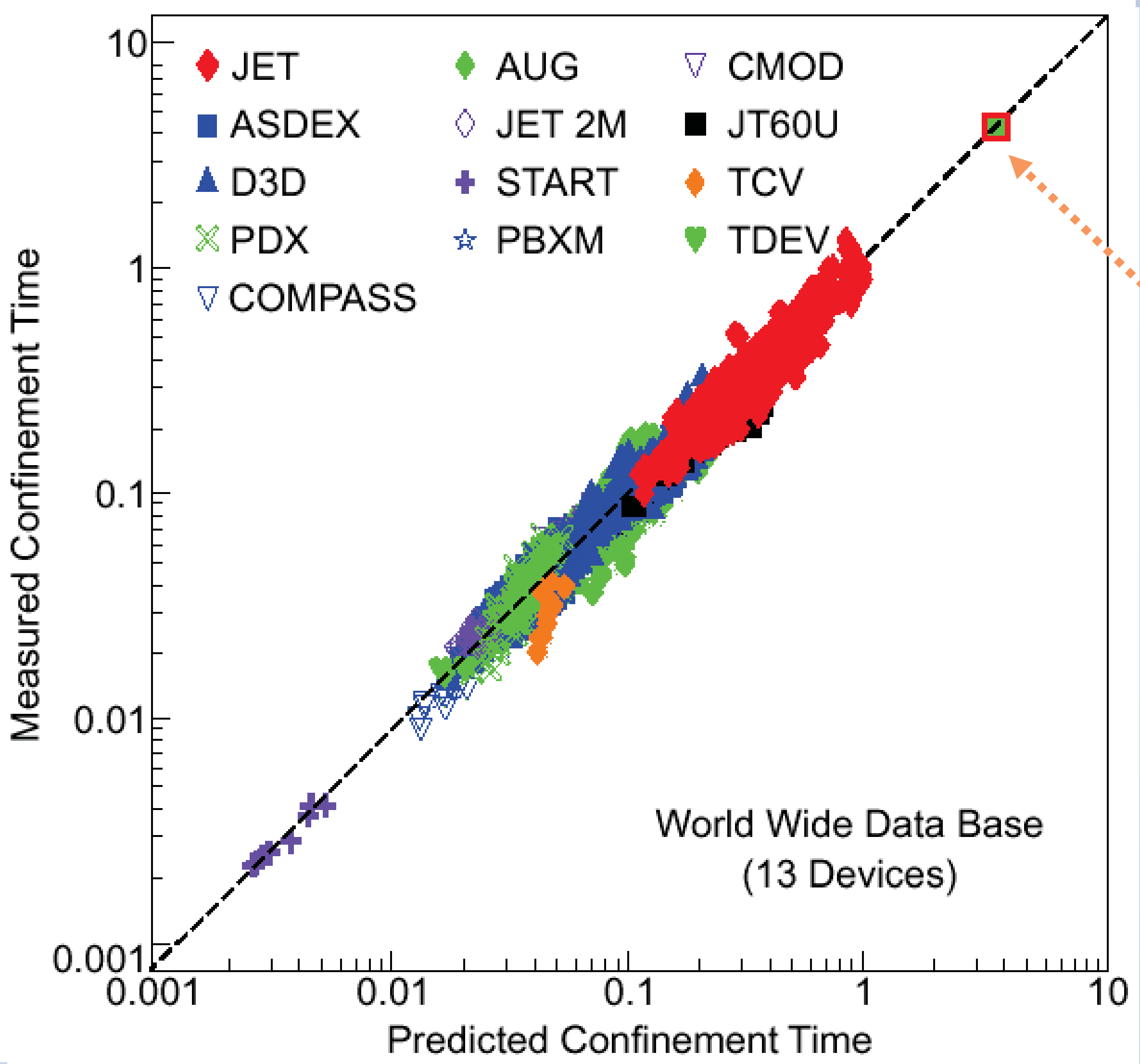
Extrapolation: present experiments ⇒ ITER

Core:

plasma similarity:

present experiments are “wind tunnel experiments” for ITER

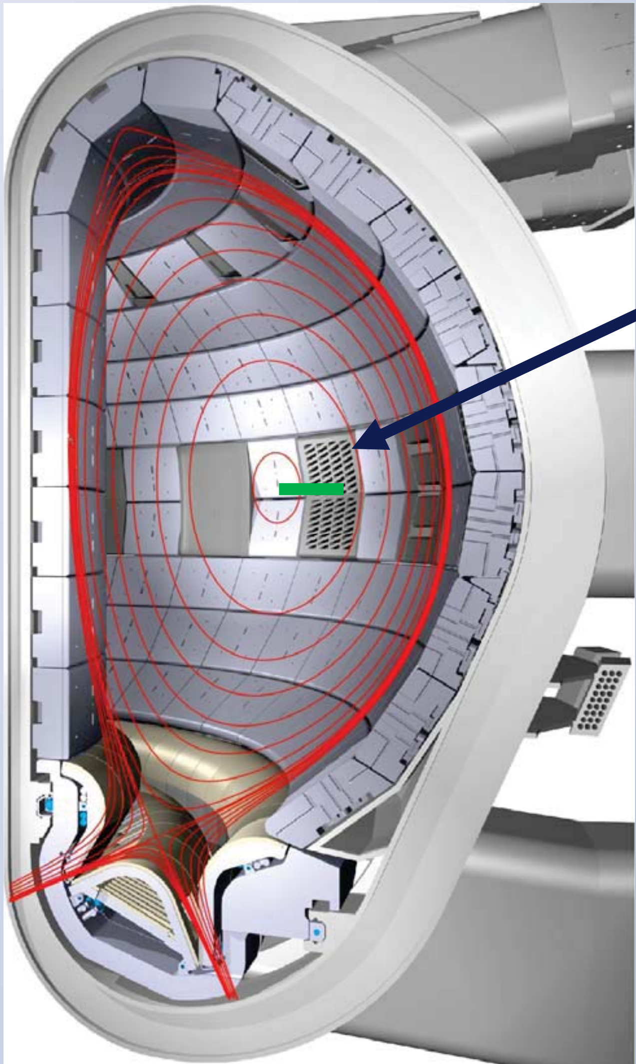




ITER reference scenario

Relative importance of plasma flow forces over chemistry and PWI
I Plasma Core

$\mathrm{div}(nv_{\parallel})+\mathrm{div}(nv_{\perp})=$ ionization/recombination/charge exchange



Core

(collisional +turbulent) cross field flow, $D_{\perp}$, $V_{\perp}$

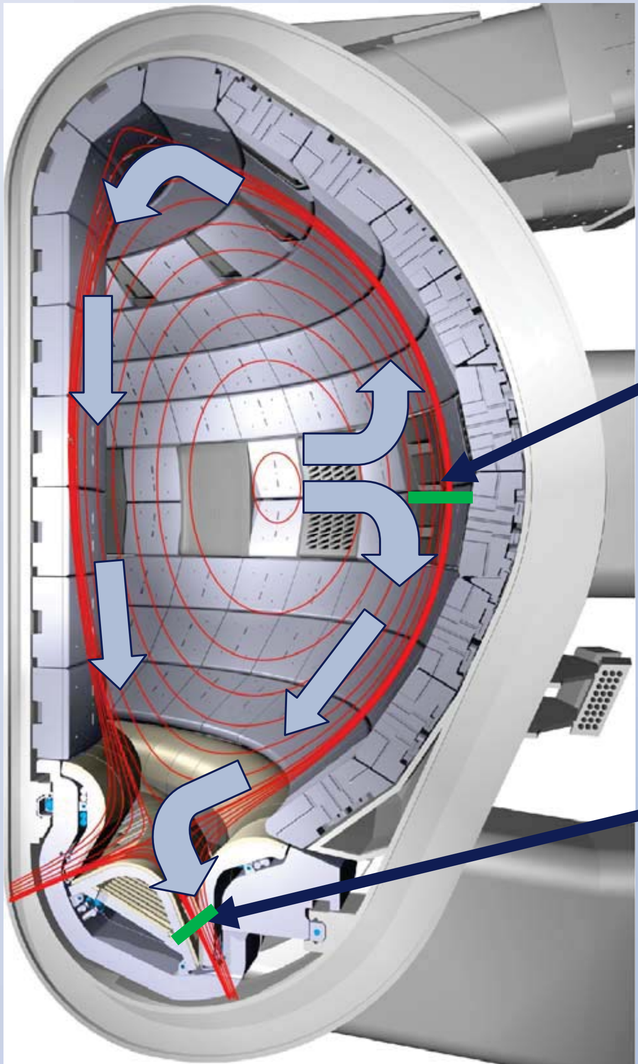
(advanced plasma scenario development)

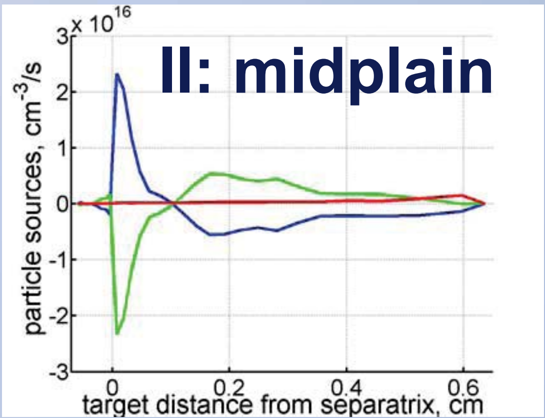
(empirical) ion transport scaling from spectroscopy on surface released impurities (interpretation, line shape modelling):

Spectroscopy : nZ^*
CR Model : $nZ^* \rightarrow nZ$
Transport Model : $nZ \rightarrow D_{\perp}$, $V_{\perp}$

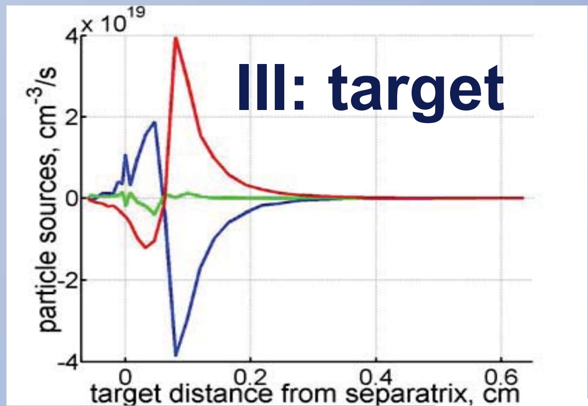
Relative importance of plasma flow forces over chemistry and PWI
II edge region → III divertor

$\mathrm{div}(nv_{\parallel})+\mathrm{div}(nv_{\perp})=$ ionization/recombination/charge exchange



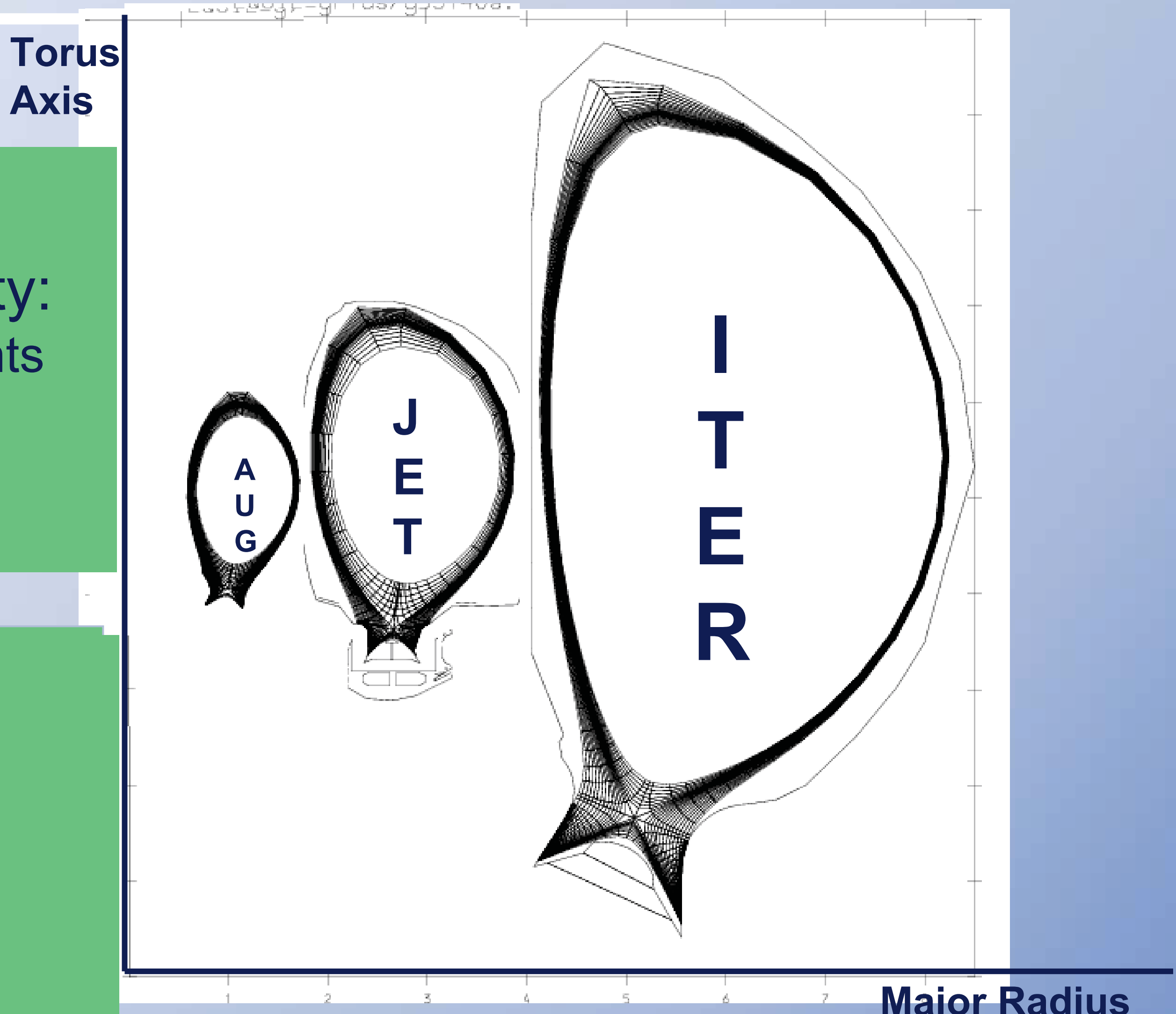


parallel vs.
(turbulent)
cross field
flow



parallel vs.
chemistry
and PWI
driven flow

Extrapolation: present experiments ⇒ ITER



Core:

plasma similarity:

present experiments are "wind tunnel experiments" for ITER

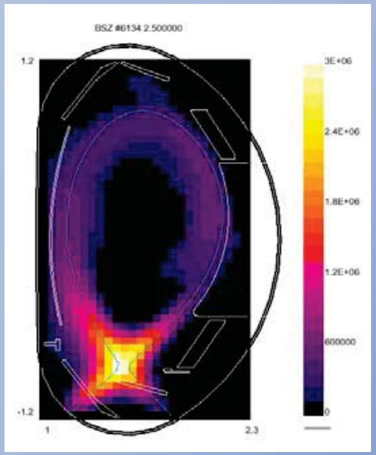
Edge:

Computational plasma edge modelling (lecture III)

Edge/divertor science

- interdisciplinary
- already a highly integrated field

- plasma physics	fusion, technical-, astro plasmas
- CFD	fluid-dynamics
- rarefied gas dynamics	aero-dynamics, vacuum
- opacity	lighting, inertial fusion
- plasma wall interaction - atomic physics - molecular physics	Atomic & Surface data (database: IAEA fusion data unit)
-	



this lecture I

Plasma-wall interaction in fusion devices

<u>**Impinging plasma and impurity particles**</u>

- erosion of wall elements

  $\Rightarrow$ lifetime of wall elements is reduced

- eroded wall particles can penetrate into core plasma

  $\Rightarrow$ dilution and radiation cooling of core plasma

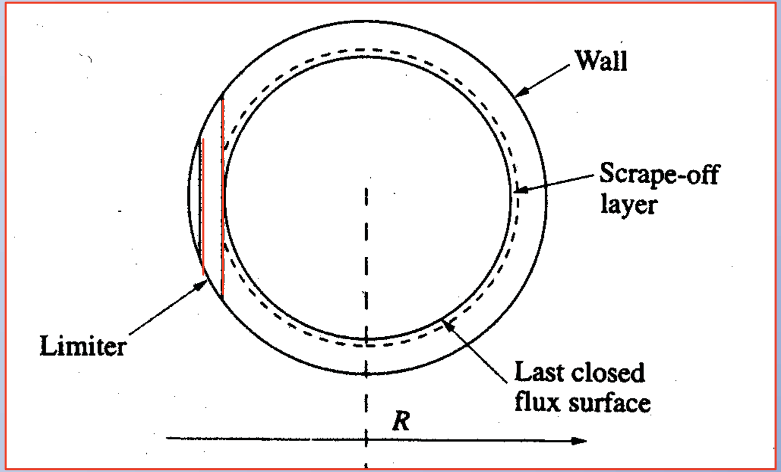
- re-deposition of eroded particles

  $\Rightarrow$ tritium retention in deposited layers
  (retained T has to be limited to 350g due to safety rule in ITER)

Erosion, transport and redeposition of impurities is a crucial (show stopping ?) issue in fusion research

Control of plasma-wall interaction: the limiter concept

Limiter:
A material piece protruding from the main wall intercept the closed field lines to extract power and particles.



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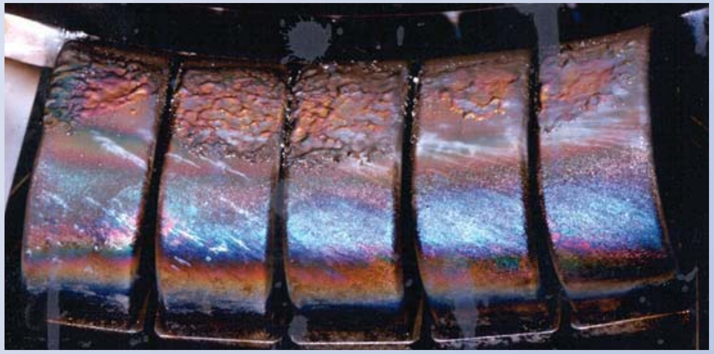
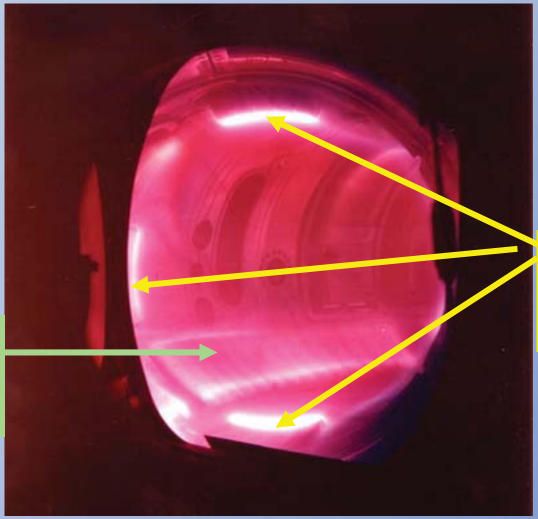


Poloidal limiter

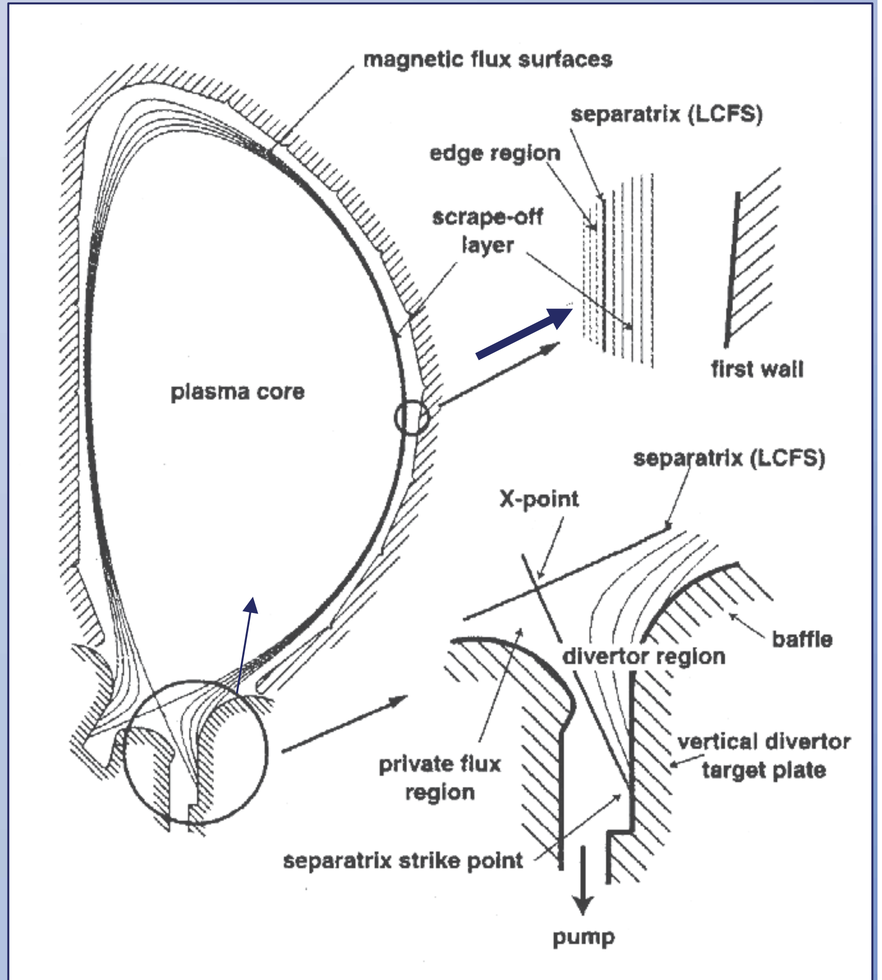


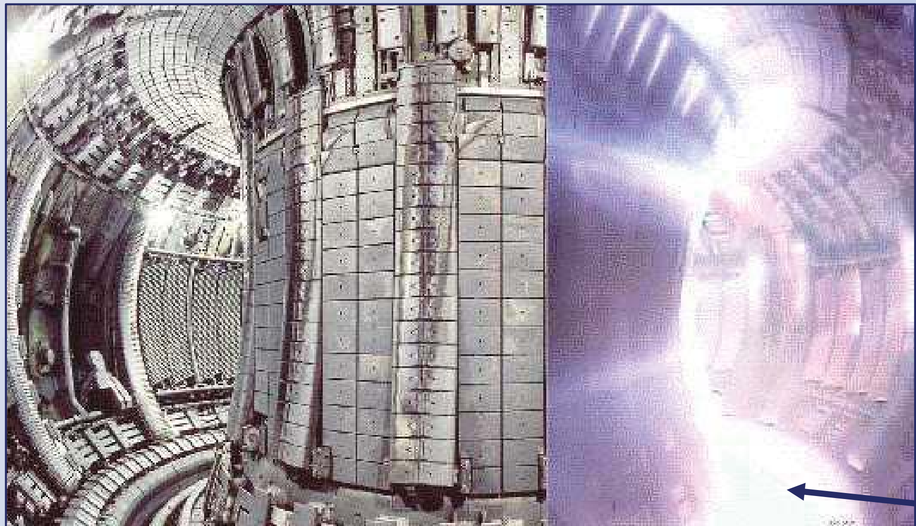
Toroidal belt pump limiter

Poloidal limiters

Control of plasma-wall interaction: the divertor concept

Divertor:
A separate chamber in the vacuum vessel to which particles and energy are directed



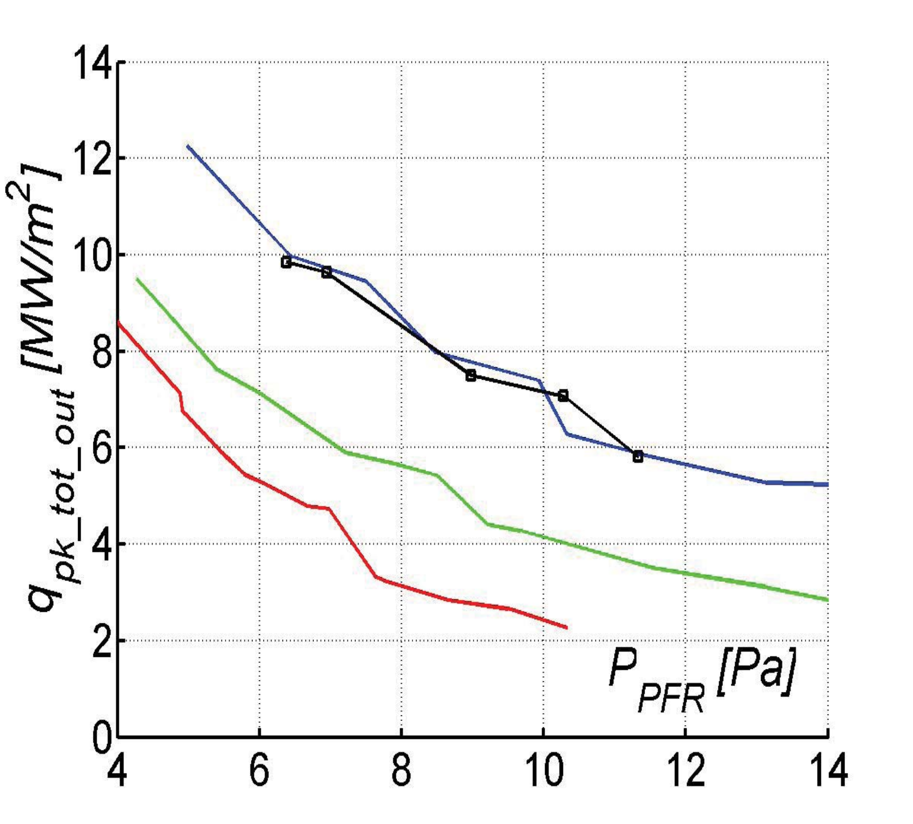


JET divertor

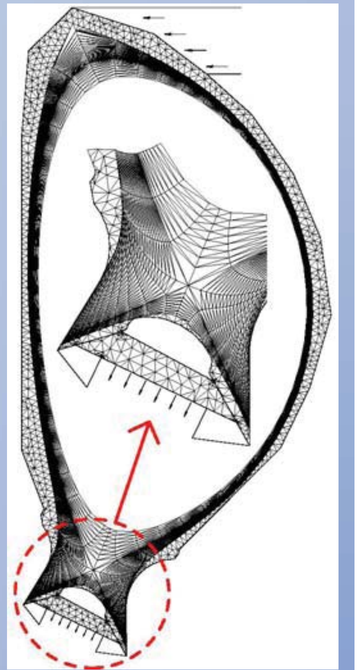
Next 2 slides:
JUMPING AHEAD
see again 3rd lecture

Consequences for ITER design (B2-EIRENE): shift towards higher divertor gas pressure to maintain a given peak heat flux (Kotov et al., CPP, July 2006)

ITER divertor engineering parameter:
target heat flux vs. divertor gas pressure



— 1996
(ITER physics basis1999)
— 2003, neutral - neutral collisions
— ….+ molecular kinetics ($D_2(v)+D^+$, MAR)
— 2005, + photon opacity



P_{PFR}: average neutral pressure in Private Flux Region

ITER design review 2007-2009:
“Dome“ re-design now ongoing

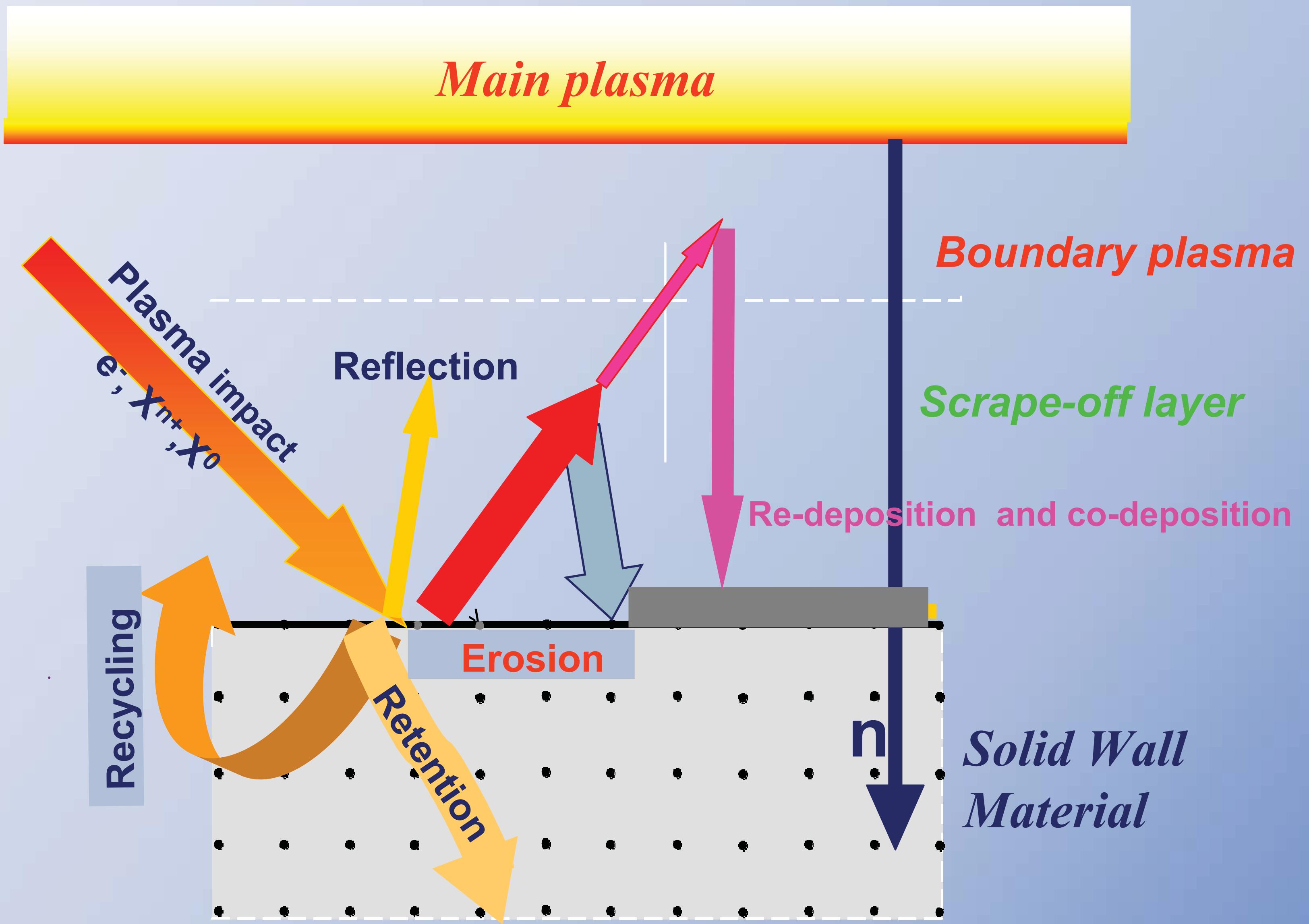
Compare: re-entry problems
e.g. Space shuttle)

~10 MW/m^2,

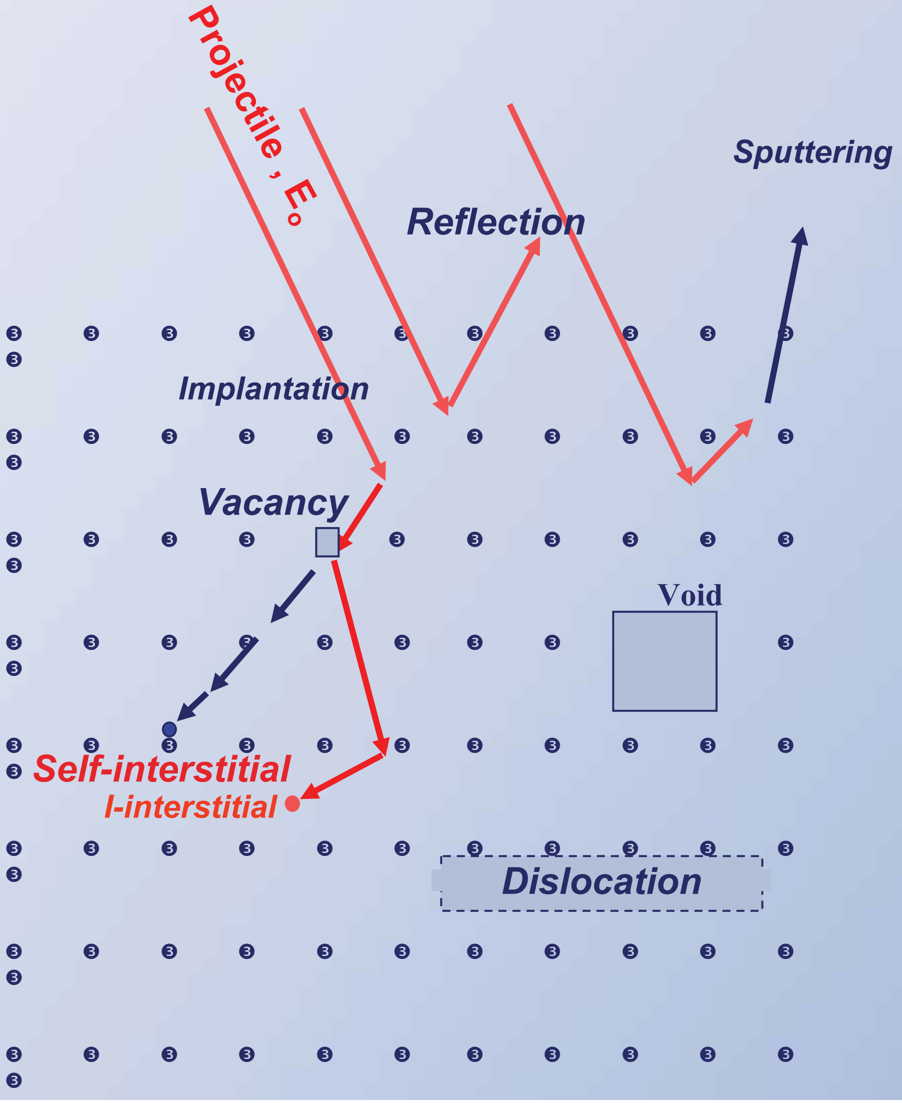
for some minutes

10 MW/m^2 stationary: perhaps tolerable, but not trivial

Plasma - Wall Interactions



Basic Processes Induced in Materials by Plasma Particle Impact



Energy dissipation by elastic (with atoms) and ineleastic (with electrons) collisions

(10^{-13} sec, range 10^{-7} m, 200 eV D^+)

Elastic collisons: Creation of vacancies and interstitials

elastic collisions

(energy transfer > threshold energy for damage)

Diffusion of vacancies and interstitials

voids, dislocations, swelling, radiation, embrittlement

Sputtering of surface atoms

(energy transfer > surface binding energy)

Transmutation

formation of nuclear reaction products (including H isotopes and He)

The 14 MeV fusion neutrons heat an external material (for energy conversion) and they breed Tritium in the blanket.

Unfortunately:

14 MeV fusion neutrons also produce volumetric radiation damage, and change and deteriorate the material properties

heat conductivity	lattice defects scattering of phonons
swelling	void formation, gas bubbles agglomeration of vacancies and helium
ductility	neutron and helium induced embrittlement densification of dislocation network, agglomeration of helium bubbles on grain boundaries
composition	transmutation products

→ Science of irradiated materials (not further discussed here)

Basic PSI Processes

I.) Sublimation

II.) Physical sputtering

III.) Chemical erosion

IV.) Radiation Enhanced Sublimation (RES)

V.) Backscattering

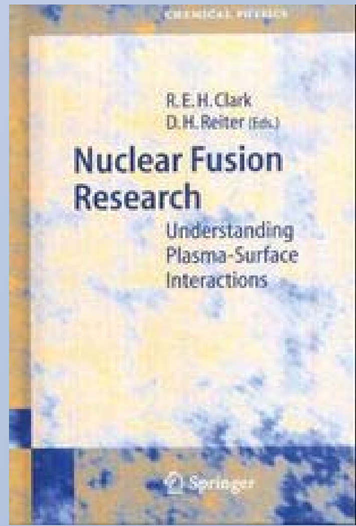
Only briefly discussed here:

VI.) Retention (hydrogen isotopes)

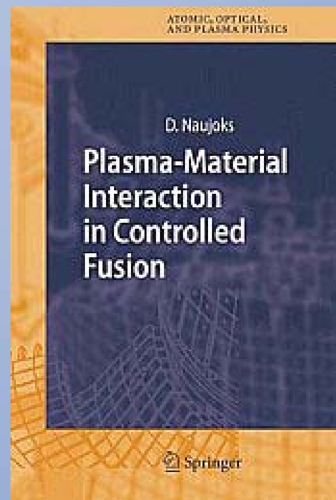
VII.) Desorption/Adsorption

VIII.) Blistering

IX.) Secondary electron emission



Springer, 2005



Springer, 2006

I.) Sublimation

Power exhaust *steady state heat loads*

Plasma input : Q (W/m^2)

Armor material: thickness d with thermal conductivity λ

Water cooling

Monoblock concept

Heat diffusion time

$t = d^2/2D$

D: diffusivity

$D = \lambda / \rho c$

conductivity density heat capacity

~ 4 s

$\sim 5\ 10^{-5}\ m^2/s$

In steady state

$$T_s - T_w = \Delta T = Q * d / \lambda$$

$Q = 10\ MW/m^2$, $\lambda = 200 [W/(m\ K)]$, $d = 0.02 m$

$\rightarrow \Delta T = 1000\ °C$

Power exhaust *transient heat loads (1)*

In transient events, like disruptions or ELMs, part of the plasma stored energy is deposited in very short pulses to the walls

example: type I Elms in ITER:

$W_{thermal}$ (Plasma)	350 MJ
energy loss during ELM	2-6 %
Energy per ELM	~ 20 MJ (~30 hand grenades at 150g TNT each)
deposition time	~ 0.2 ms
deposition area	~10 m^2
→ power density	10 GW/m2

transient heat loads (2)

In transient events the energy must be absorbed by the heat capacity (inertial cooling)

$$T(t) = P * (2 / \pi\ \lambda\ \rho\ c)^{0.5} * t^{0.5}$$

temperature power conductivity density heat capacity

$t = 0.25$ ms $\rightarrow$ $Ts_{max} = 6000$ C Penetration depth: 0.15 mm

Sublimation threshold: 2200 C

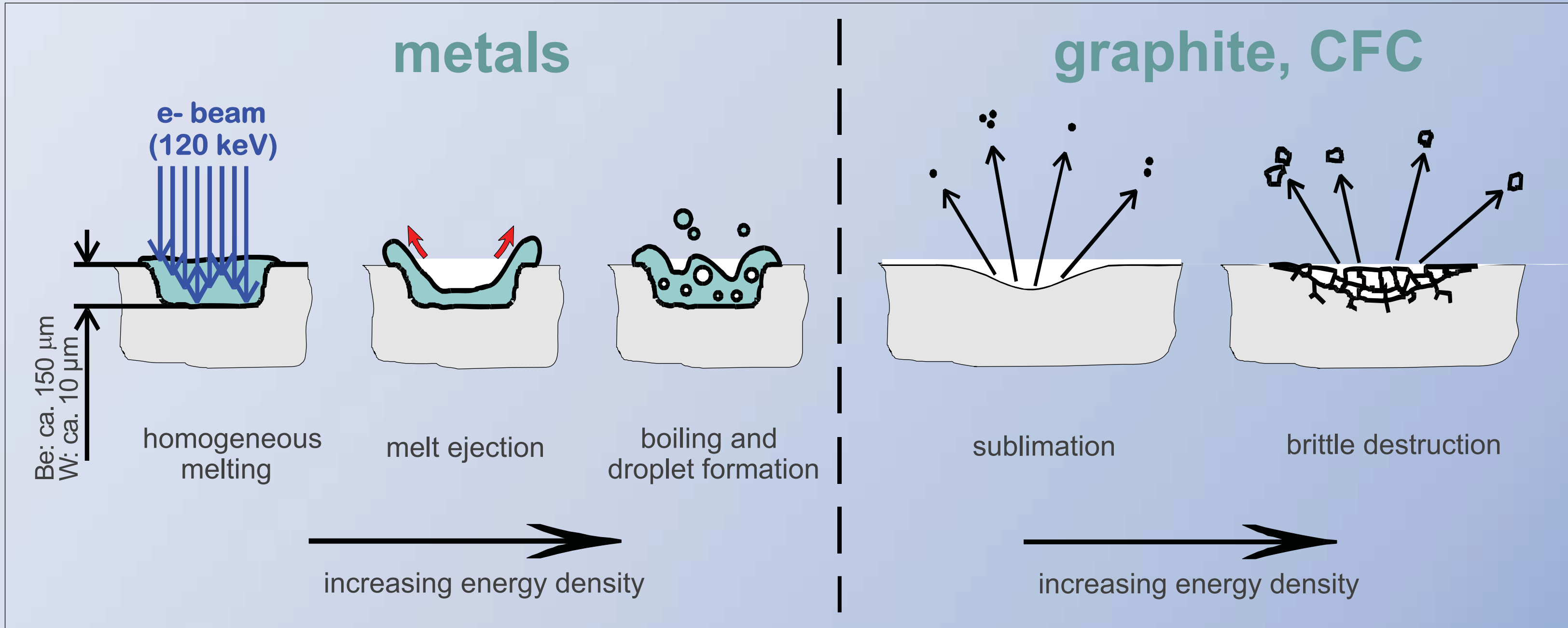
Graphite Target will sublimate quickly

With duration of 0.2 ms and area 10 m^2 the maximal energy per ELM in ITER must limited to < 1-2 % of stored energy to avoid material loss by sublimation

Metals will melt leading to loss of melt layer by MHD effects in melt layer

Type I ELM operation critical for ITER

Material Behaviour under Extreme Power Loads



Effects of interaction

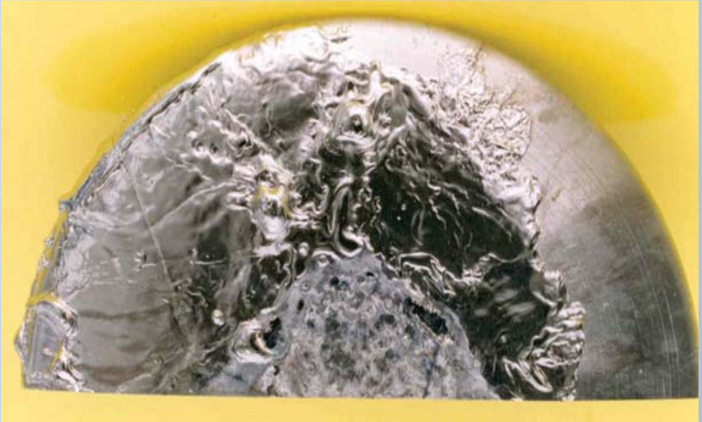
FOR METALS:
Splashing
Formation of droplets
Formation of dust

FOR CARBON:
Above a certain power load (threshold) emission of debris occurs = BRITTLE DESTRUCTION

MELTING observed commonly in present machines

Beryllium antenna screen at JET

$T_m(Be) = 1278\ ^{o}C$



Limiter from FTU TZM coated with 2 mm VPS Tungsten

TEXTOR: Melting of 170 mm B4C coating on copper

ASIDE:

The **TEXTOR PWI Test Facility** with air lock
a tool (user facility) for PWI research

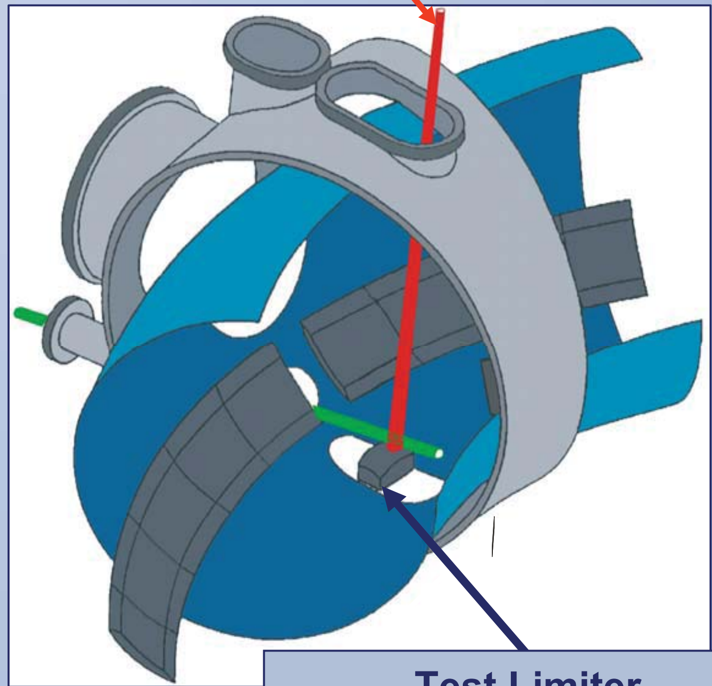
Air locks for PWI components

- < 15 cm diameter (enlargement foreseen)
- external heating (up to 1800K) or cooling (down to RT)
- radial movement (+- 5 cm around LCFS)
- rotatable
- electrical biasing of limiters
- exchange time for samples <½ day
- local gas injection systems

Comprehensive diagnostics

- overview spectroscopy (UV-VIS-IR)
- 2D imaging (Dα, CII etc.),
- high resolution spectroscopy
- laser-induced fluorescence
- 2D thermography, thermocouples
- colorimetry
- laser desorption/ablation
- edge diagnostics for ne, Te (Langmuir probes and atomic beams)

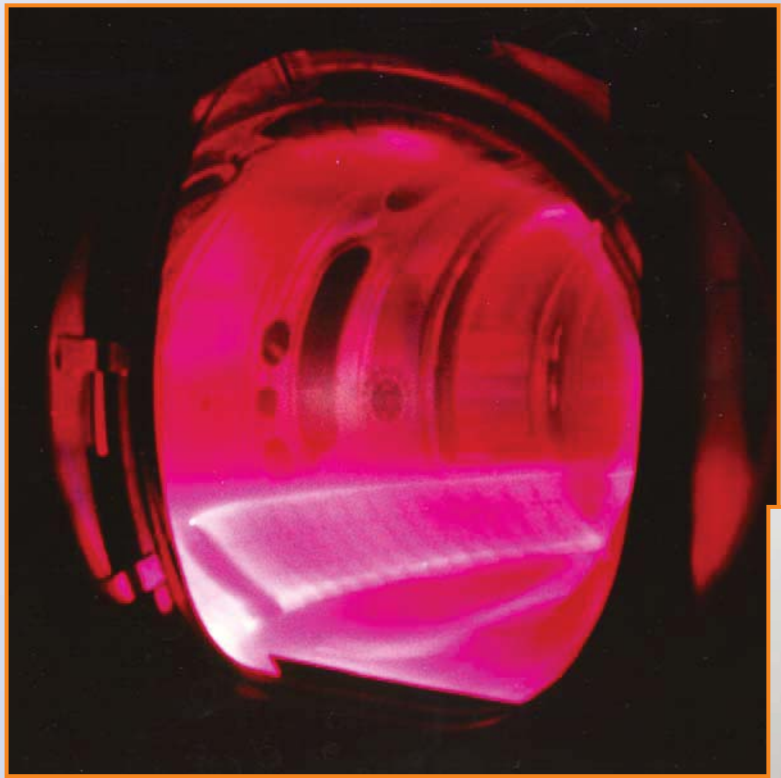
TEXTOR PWI Test Facility

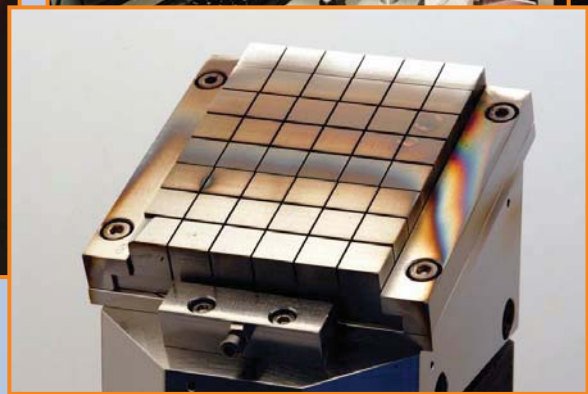


Presently used in cooperation with Japan (TEXTOR-IEA), VR, IPPWL, Slovenia, Universities,….

Inside the TEXTOR Tokamak @ FZ-Jülich

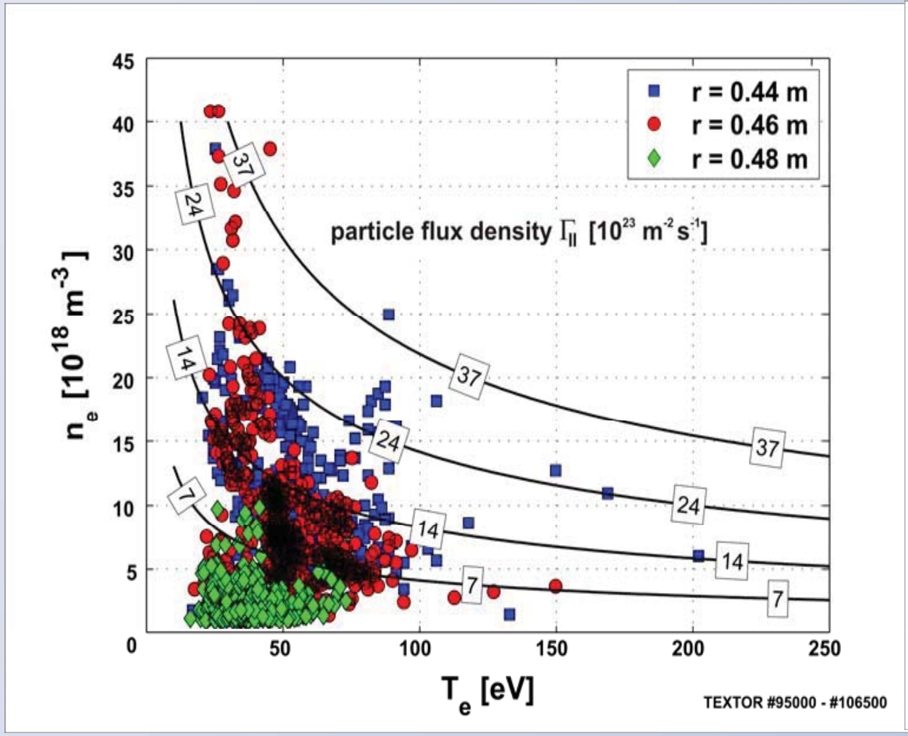
Focus on Plasma Surface interaction research

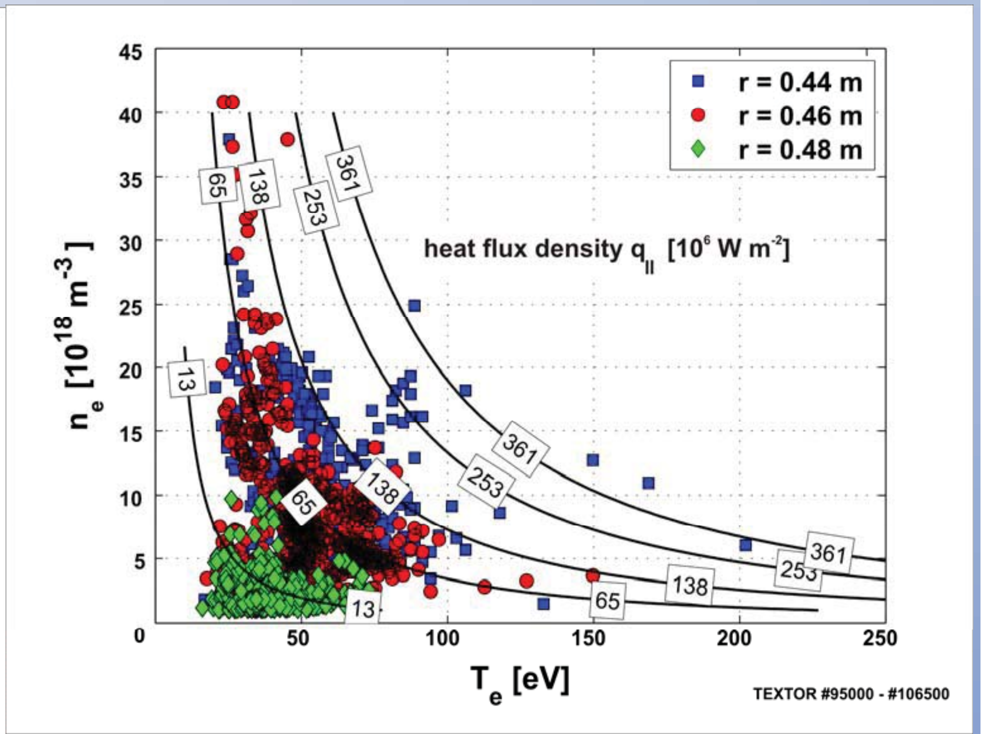




Plasma parameters at the TEXTOR **PWI Test Facility:**

Exceeds ITER particle and heat fluxes





parallel particle fluxes: up to 4 x10^{24}/m^2 s

particle fluencies: up to 2 10^{26} /m^2 per day (150 s plasma per TEXTOR operation day)

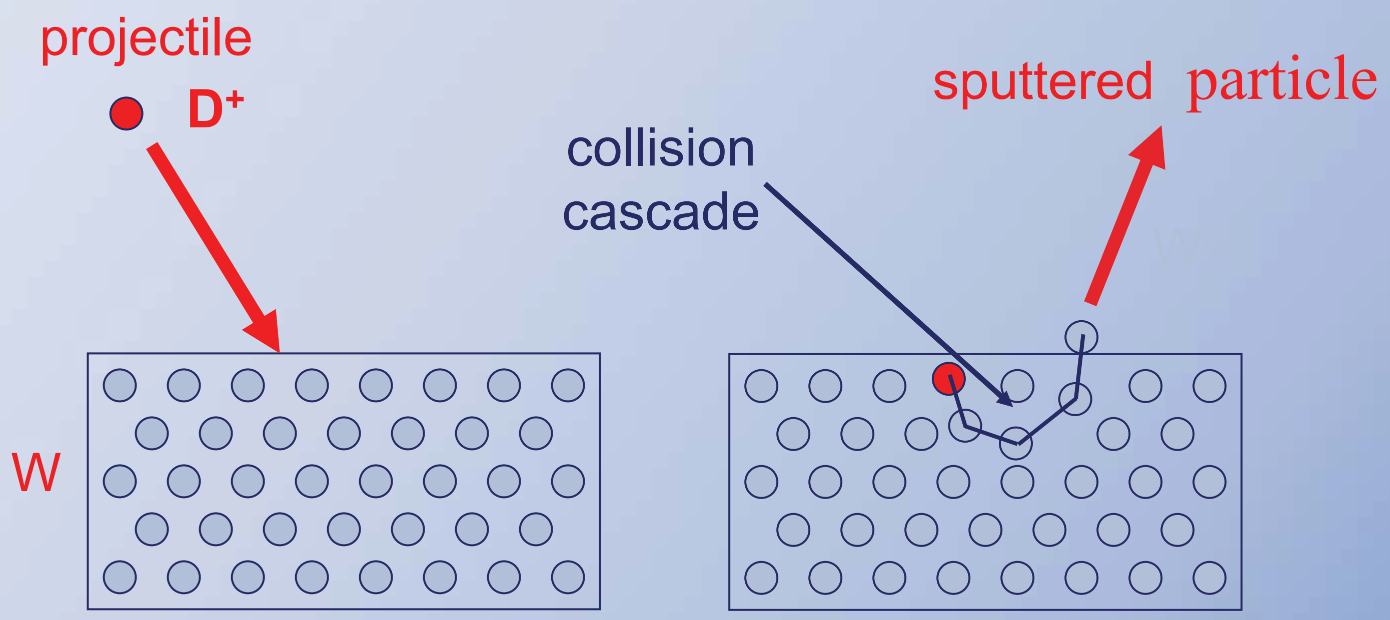
parallel power fluxes: up to 200 MW/m^2

⇒ Melting of bulk W limiters in ≈ 4 sec

II.) Physical sputtering

II.) Physical sputtering

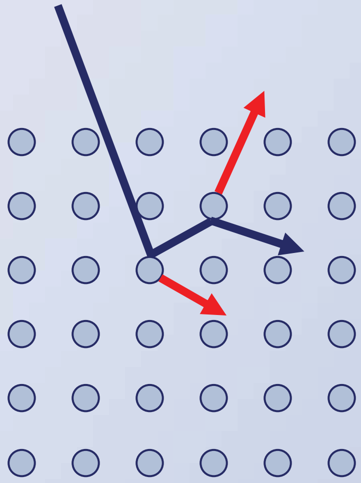
Mechanism: energy transfer from projectile to solid atom at surface



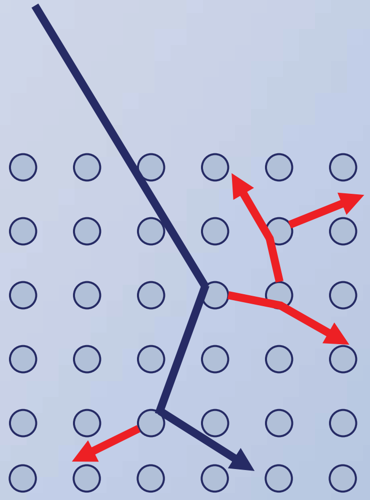
Impinging projectile ion initiates collision cascade inside the solid ⇒ energy transfer to surface solid atom which is released

II.) Physical sputtering

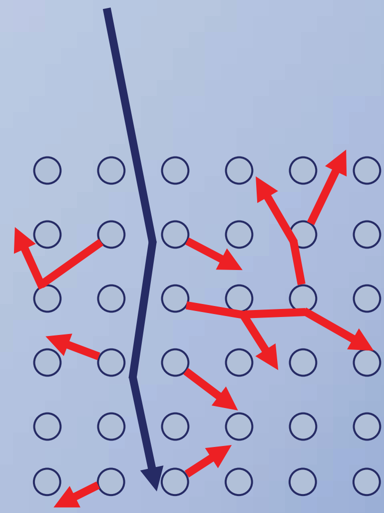
Collision cascades: different regimes



single collision regime



linear cascade regime



thermal spike regime

Single collision: light ions at low energies, atomic motion stopped after few collisions, binary collision approximation (BCA) valid

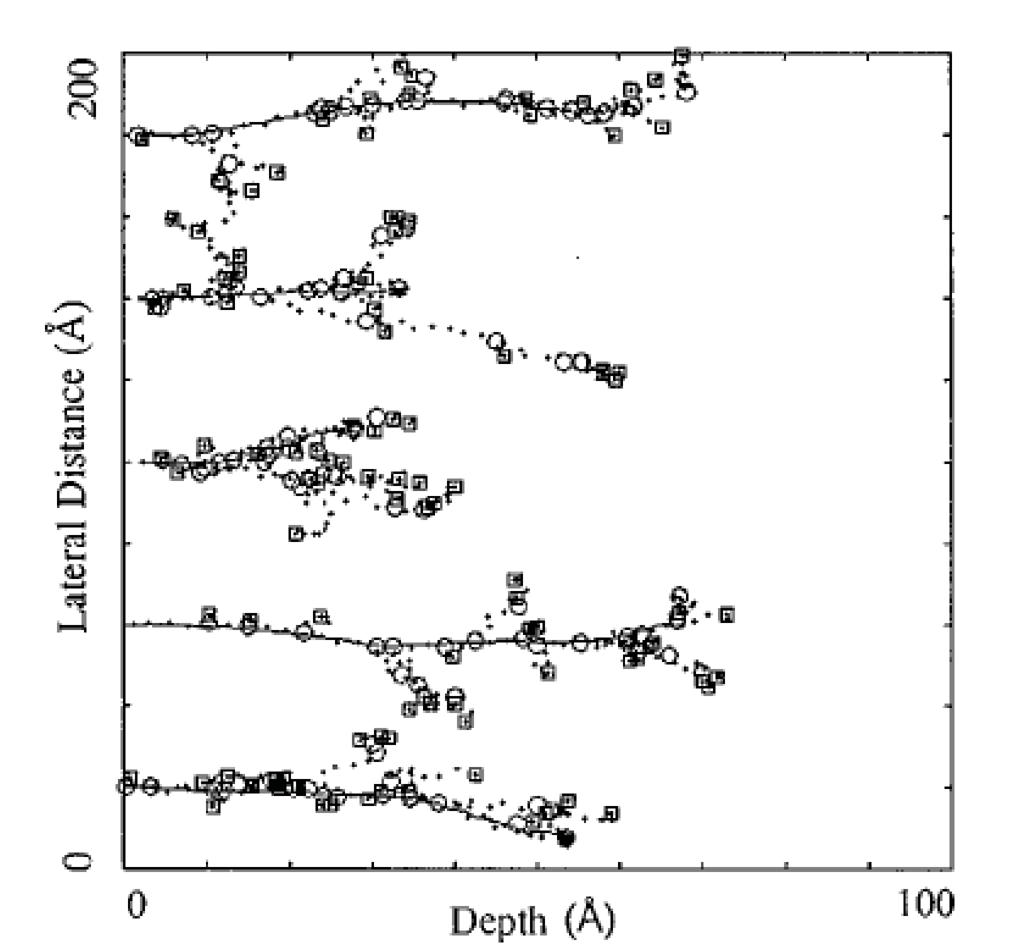
Linear cascade: collisions only between fast particles and atoms at rest, BCA

Thermal spike: dense cascade, collisions between fast particles important

II.) Physical sputtering

Simulation of collision cascades: example "linear cascade" regime

Monte Carlo simulation, Binary Collision Approximation



5 typical cascades of 3 keV Ar^+ ions into graphite

— Ion trajectory
O Vacancies
☐ Interstitials
\+ Phonons

II.) Physical sputtering

In general: definition of erosion yield Y

Erosion yield Y:

average number of eroded target atoms per incident projectile

Impinging flux of projectiles: $\Gamma_{\mathrm{in}} = \dfrac{\text{number of incoming projectiles}}{\text{area} \times \text{time}}$

Emitting flux of eroded particles: $\Gamma_{\mathrm{ero}} = \dfrac{\text{number of eroded particles}}{\text{area} \times \text{time}}$

Erosion yield Y: $Y = \dfrac{\Gamma_{\mathrm{ero}}}{\Gamma_{\mathrm{in}}}$

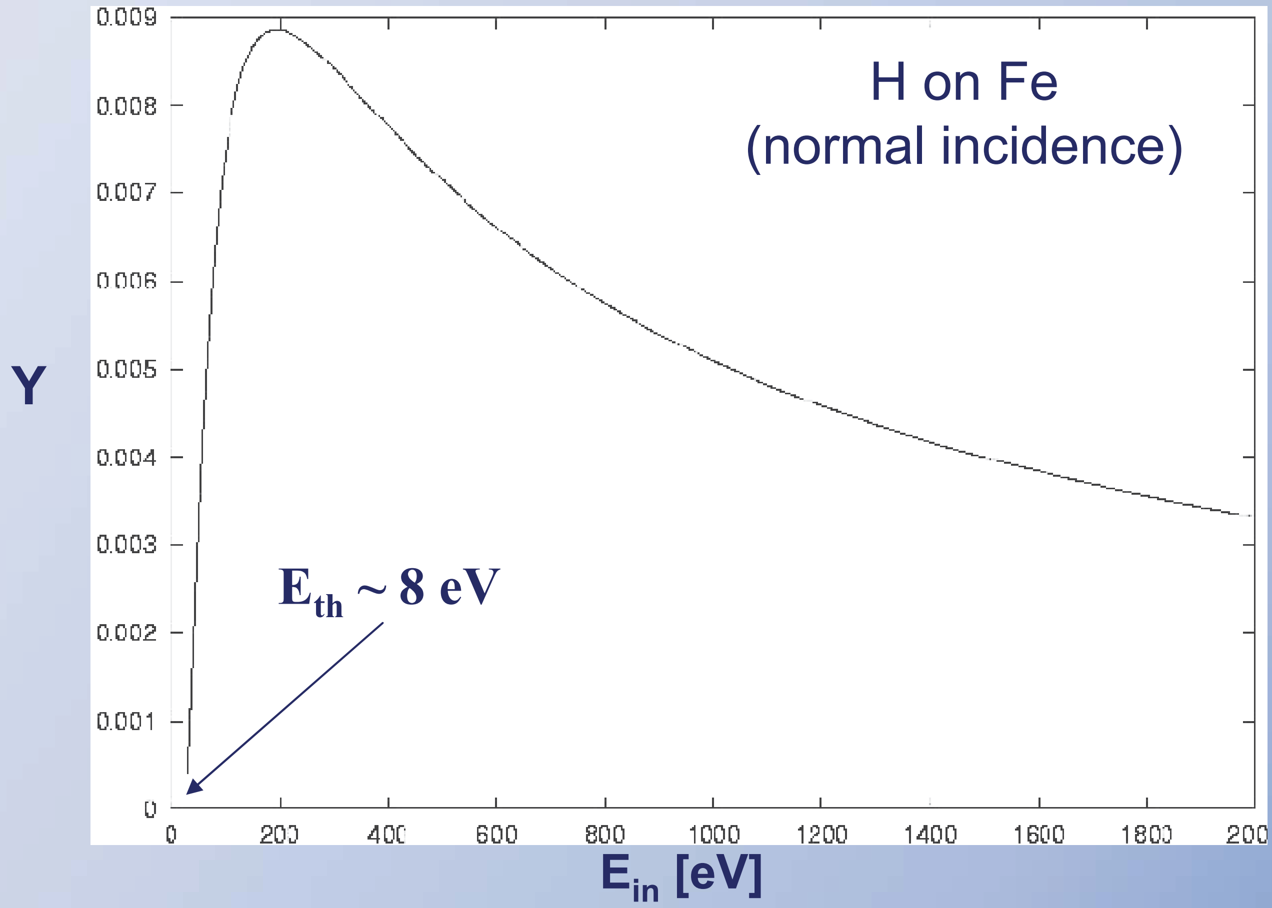
II.) Physical sputtering

Main features of physical sputtering

- Occurs for all combinations of projectile – substrate
- Existence of threshold energy E_{th}. If $E_{in} < E_{th}$: $Y_{sputter} = 0$
- Sputter yield $Y_{sputter}$ depends on energy and angle of incoming projectile
- Sputter yield $Y_{sputter}$ depends on projectile – material combination. Maximal energy transfer factor $\gamma = 4\, M_1 M_2 / (M_1 + M_2)^2$
- No significant dependence of $Y_{sputter}$ on surface temperature
- Sputtered species: atoms or small clusters of substrate particles

II.) Physical sputtering

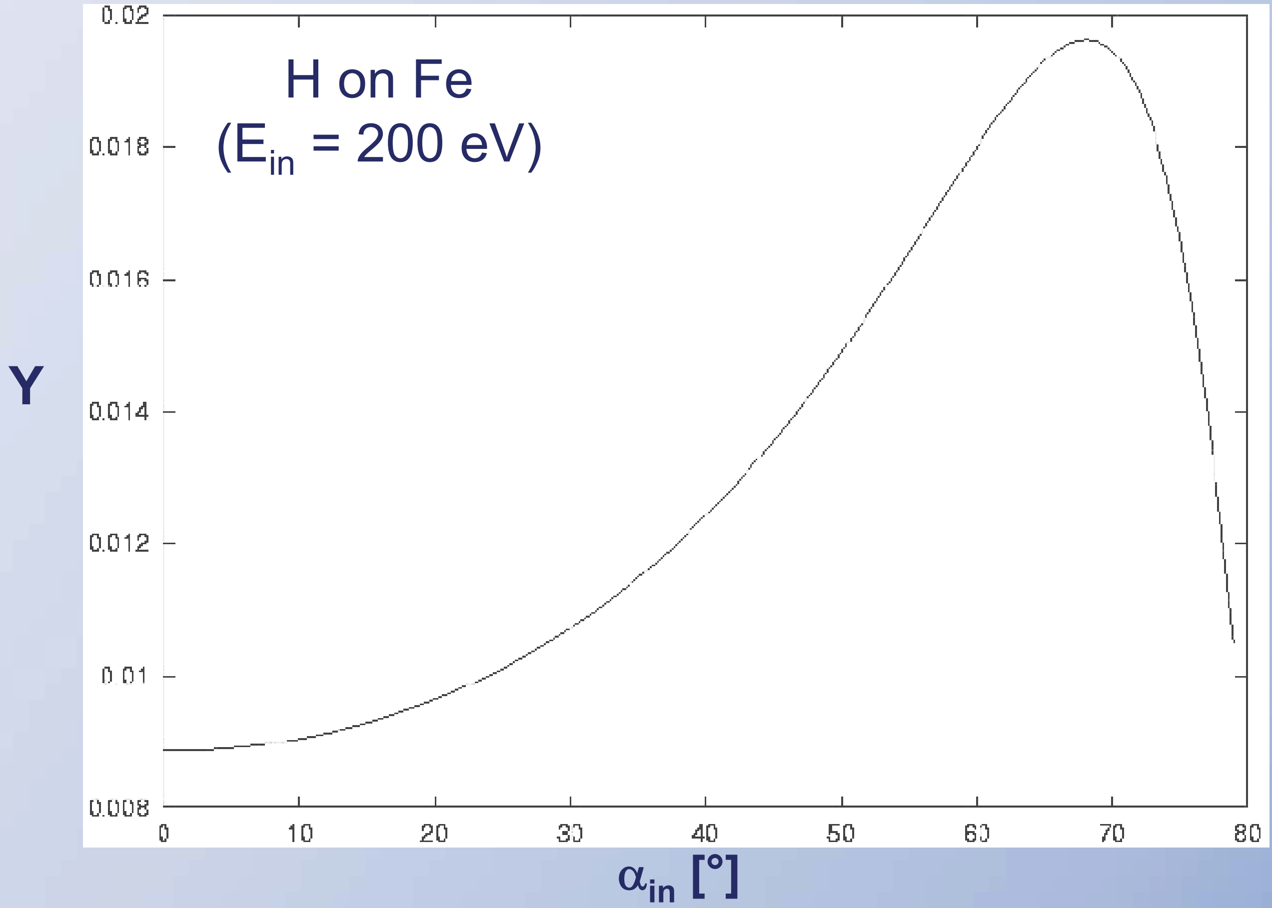
Typical dependence of sputter yield Y on incident energy of projectile

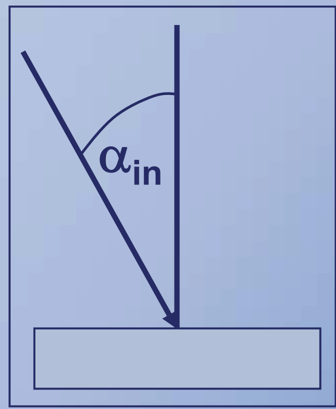


$E_{in} < E_{th}$: Y = 0. Increasing $E_{in} \Rightarrow$ Y increases until maximum. Further increase of $E_{in} \Rightarrow$ Y decreases (collision cascade penetrates deeper into solid).

II.) Physical sputtering

Typical dependence of sputter yield Y on incident angle of projectile



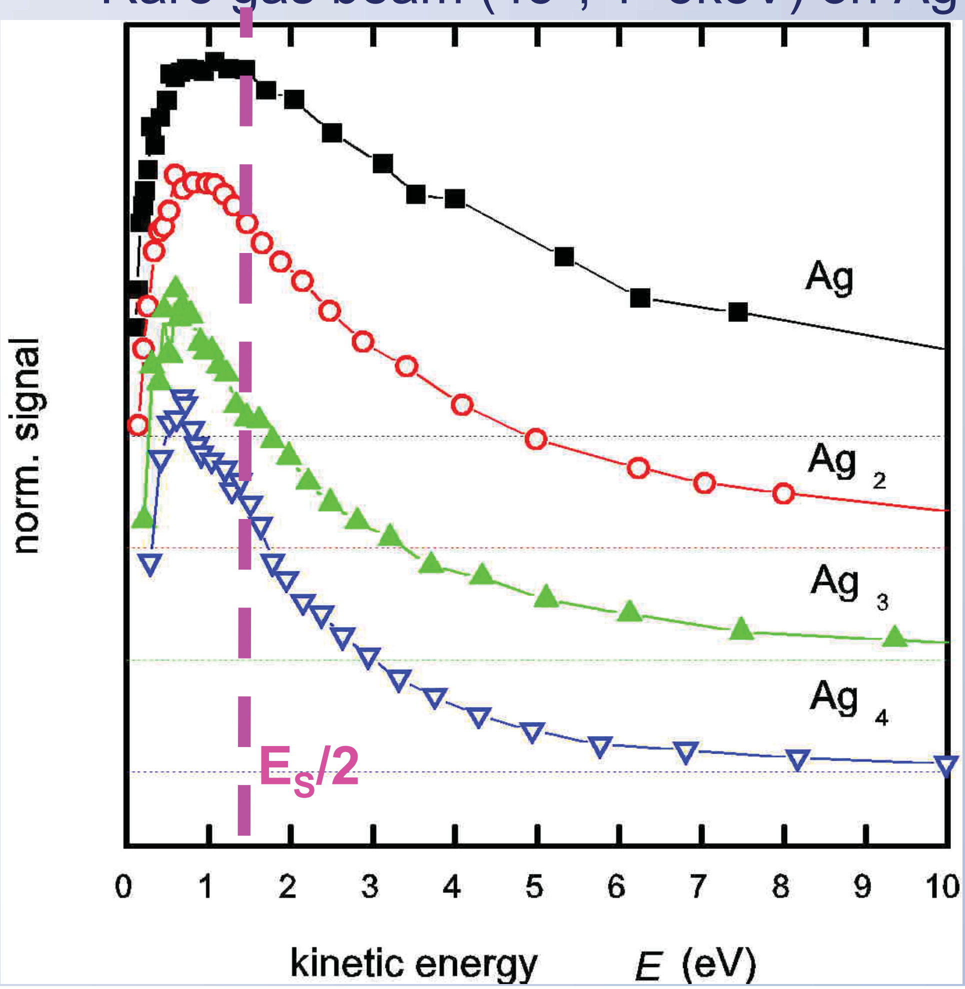


Y first increases with increasing α_{in} (with grazing incidence more energy is deposited near surface). After reaching maximum $\Rightarrow$ Y decreases (reflection).

II.) Physical sputtering

Energy distribution of sputtered particles

Rare gas beam (45°, 1–5keV) on Ag



<u>In many cases:</u>

sputtered particles have **Thompson distributed energy**

$$N(E) \propto E/(E + E_S)^3$$

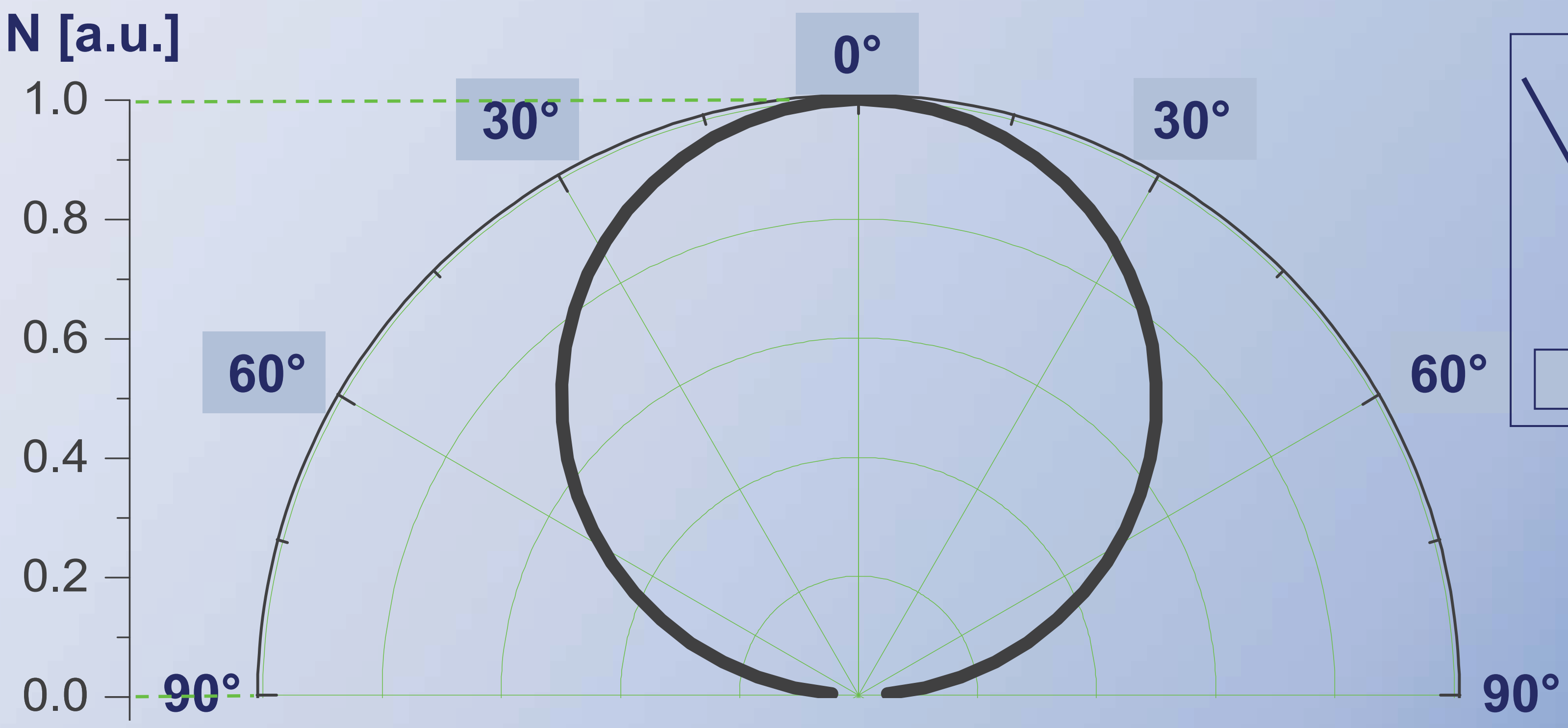
E_S: sublimation energy

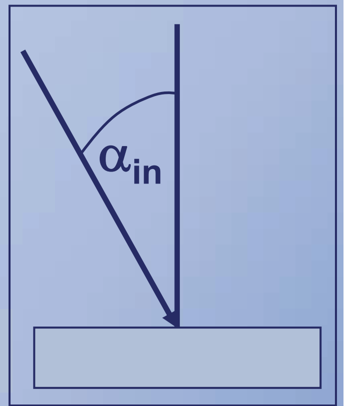
Most probable energy $E = E_S/2$

Deviations from Thompson distribution for light ion bombardment and/or non-normal incidence

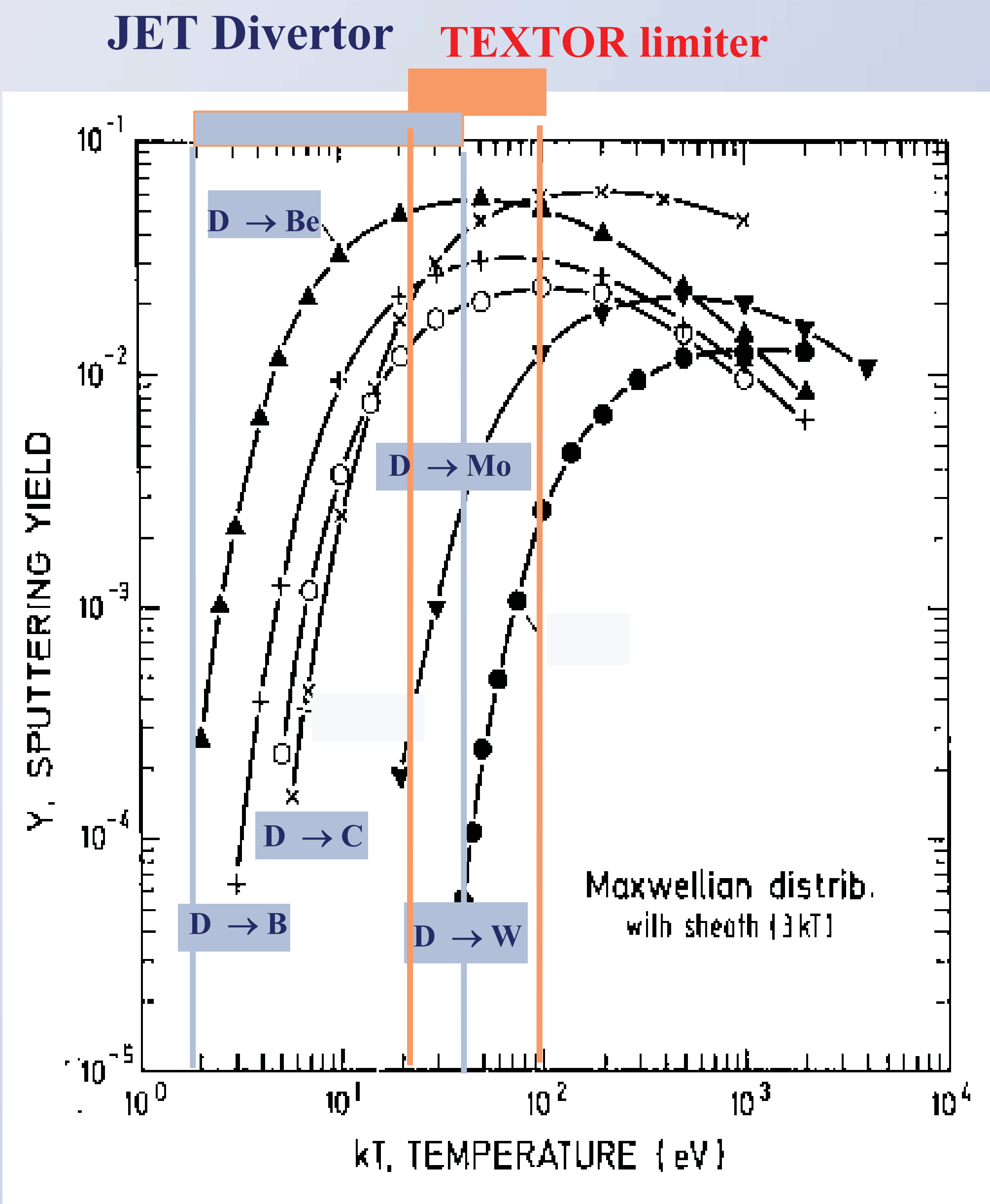
II.) Physical sputtering

Angle distribution of sputtered particles





In many cases: **sputtered particles have cosine distribution**
Deviations: for light ions and non-normal incidence



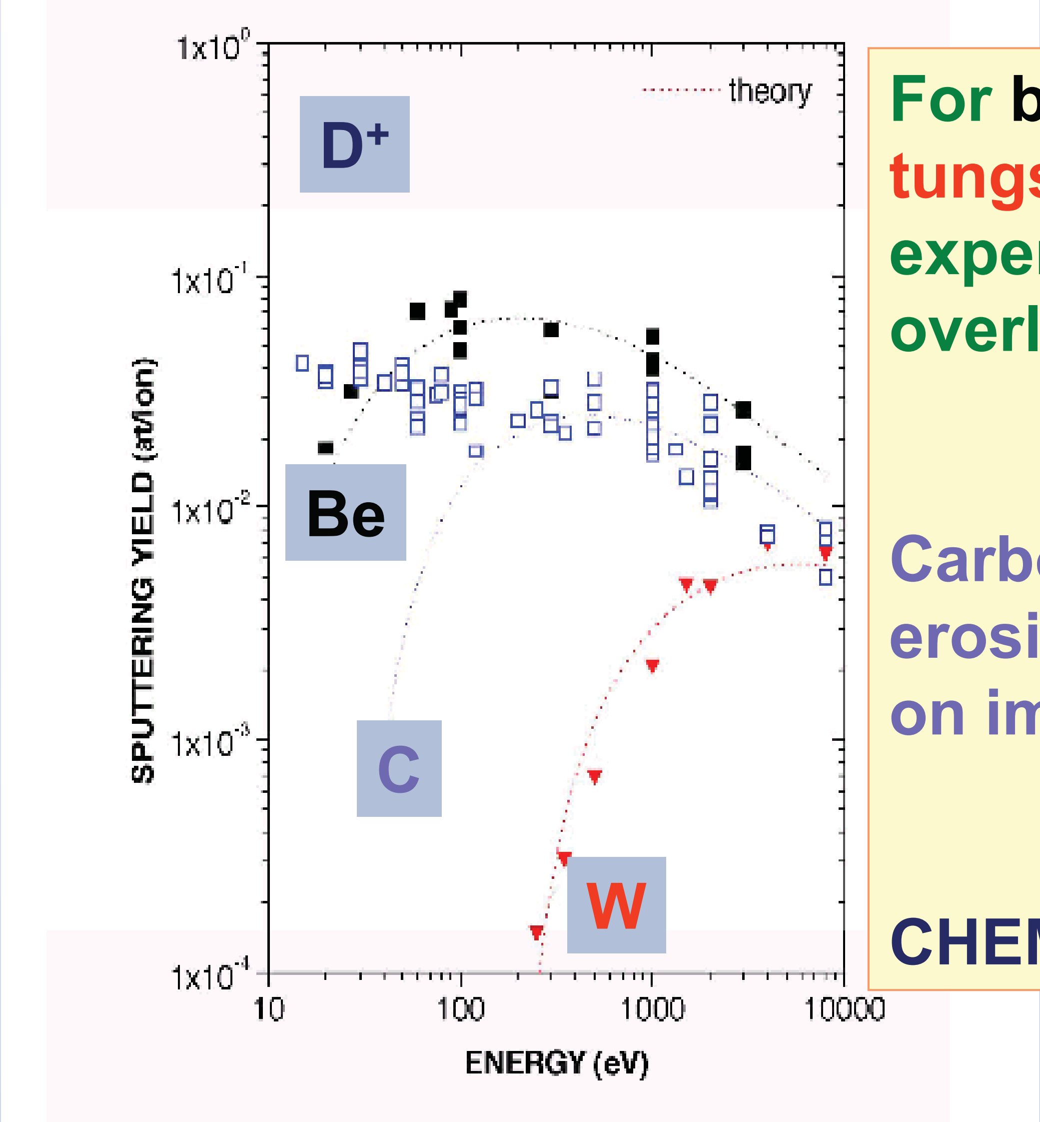
Physical sputtering : deuterium impact on different first wall materials

- Maxwellian energy distribution shifted by the sheath potential (3 kT_e): E_{in} ~ 6-7 kT_e
- largest physical sputter yields and low threshold for Be
- small yields and large threshold for high Z materials

threshold for D impact

Be	C	W
3 eV	8 eV	80 eV

Total erosion Yield of Graphite, Be and W by D impact



For beryllium and tungsten theoretical and experimental curves overlap.

Carbon shows additional erosion, not dependent on impact energy.

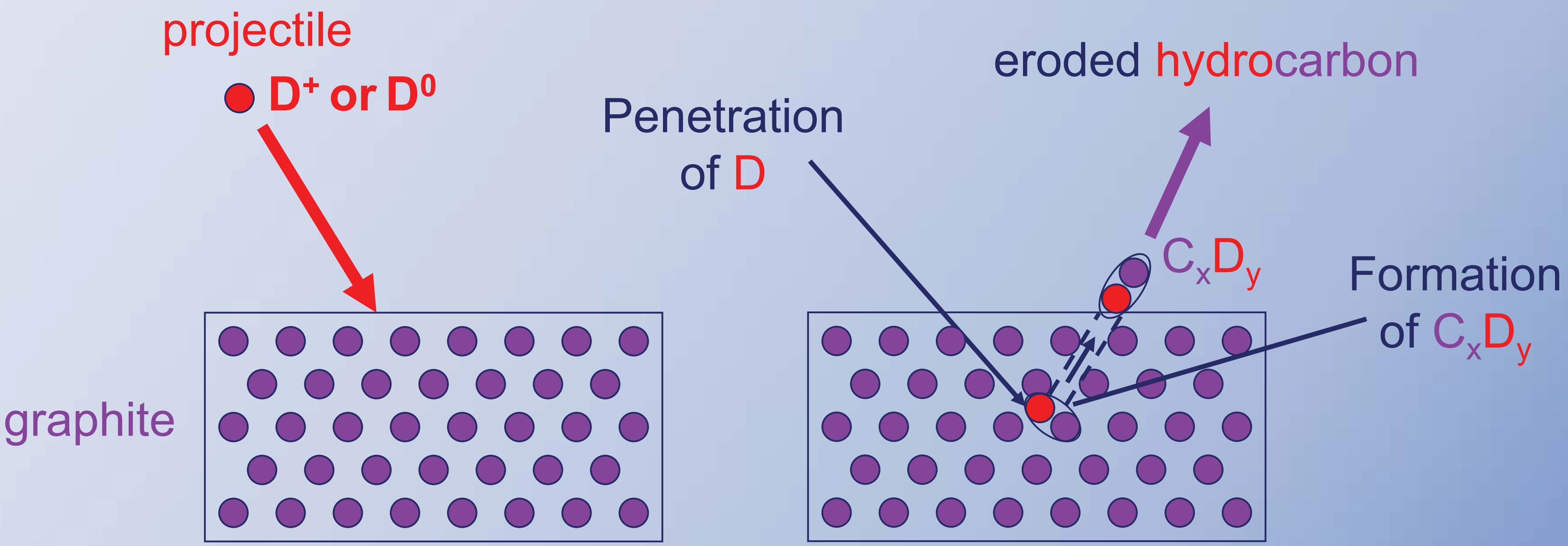
⇓

CHEMICAL EROSION

III.) Chemical erosion

III.) Chemical erosion

Mechanism: formation of molecules from projectiles and solid atoms



Impinging deuterium penetrates into graphite and forms hydrocarbon molecule after thermalisation ⇒ molecule “diffuses” through porosity to surface of the solid and desorbs

III.) Chemical erosion

Main features of chemical erosion

- Occurs only for special combinations of projectile – substrate (most important: hydrogen on graphite, oxygen on graphite)
- No (or very low) threshold energy
- Strong dependence of erosion yield Y_{chem} on surface temperature T_{surf}
- Dependence of erosion yield Y_{chem} on hydrogen content in solid
- Synergetic effects caused by energetic ions
- Sputtered species: molecules formed from projectile and substrate atoms

III.) Chemical erosion

Fusion research: Importance of chemical erosion of carbon-based materials

Main disadvantage of carbon-based materials:

- **chemical erosion** due to hydrogen & its isotopes even at lowest plasma T_e
- **in a fusion reactor: tritium (T)** as fuel ⇒ erosion of C_xT_y molecules

⇒ **re-deposition of C_xT_y molecules** leads to formation of T-containing layers. Amount of permitted **radioactive T limited to 350g in ITER**

⇒ **removal of T-containing layers** necessary after having reached 350g

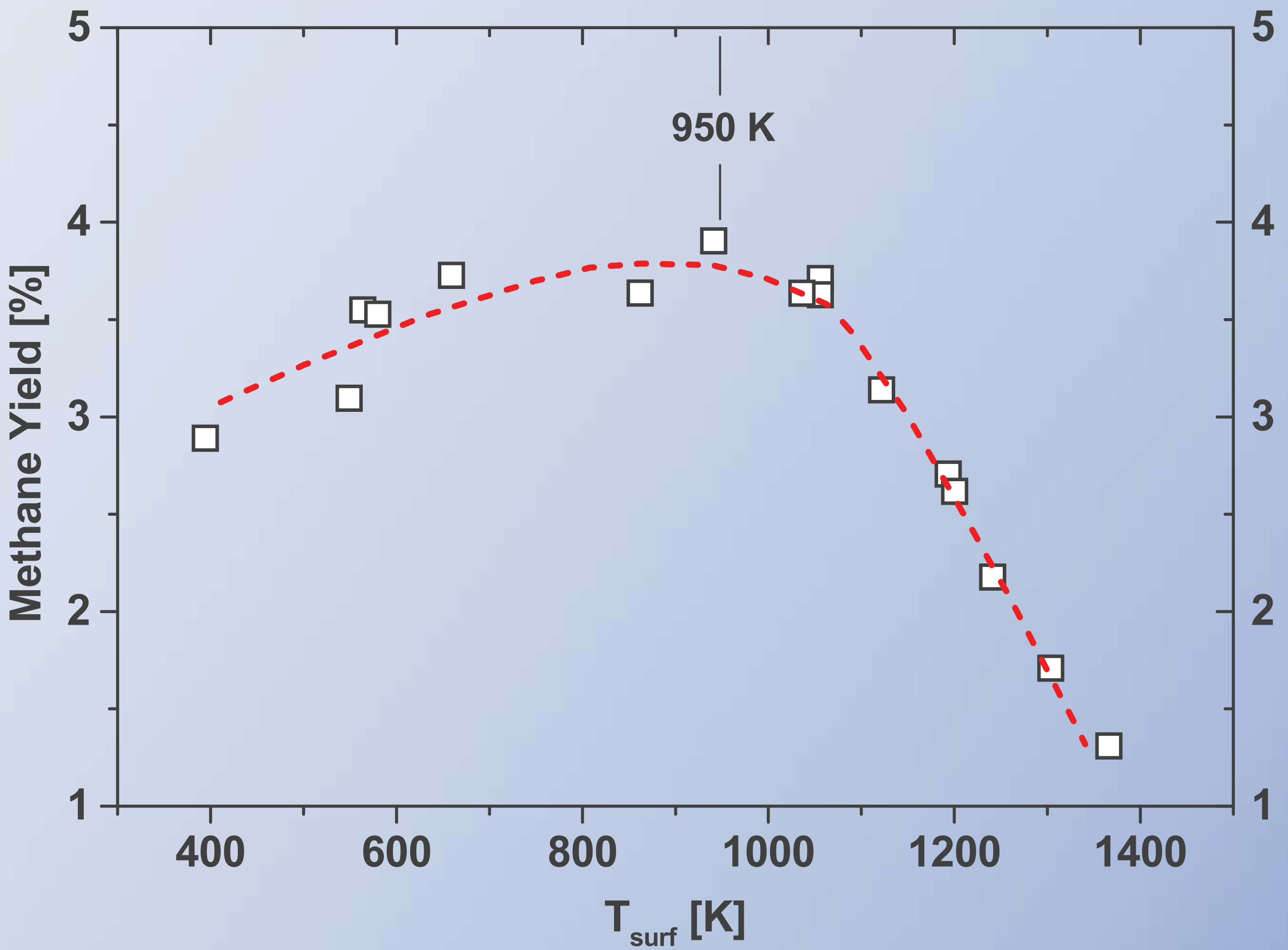
Advantages of carbon-based materials:

- **no melting** even under extremely high power loads (in ITER: 10 MW/m^2)
- **high sublimation temperature** (~3800°C)

⇒ therefore carbon-based materials are foreseen to use at areas of high power loads in ITER (divertor plates)

III.) Chemical erosion of carbon-based materials

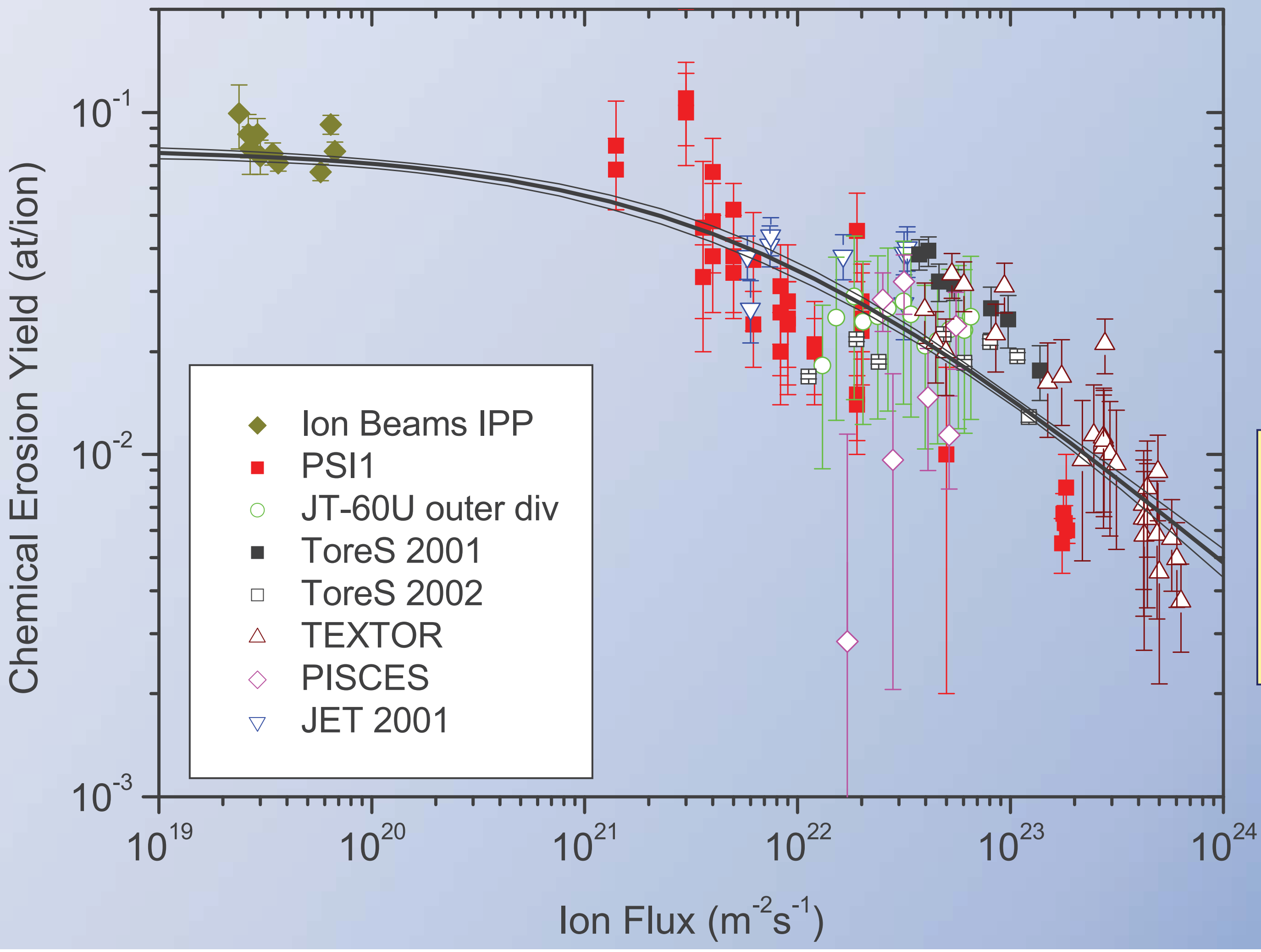
Dependence of chemical erosion yield on surface temperature T_{surf}



- Maximum erosion yield @ ~950K
- Erosion yield decreases with elevated T_{surf}

III.) Chemical erosion of carbon-based materials

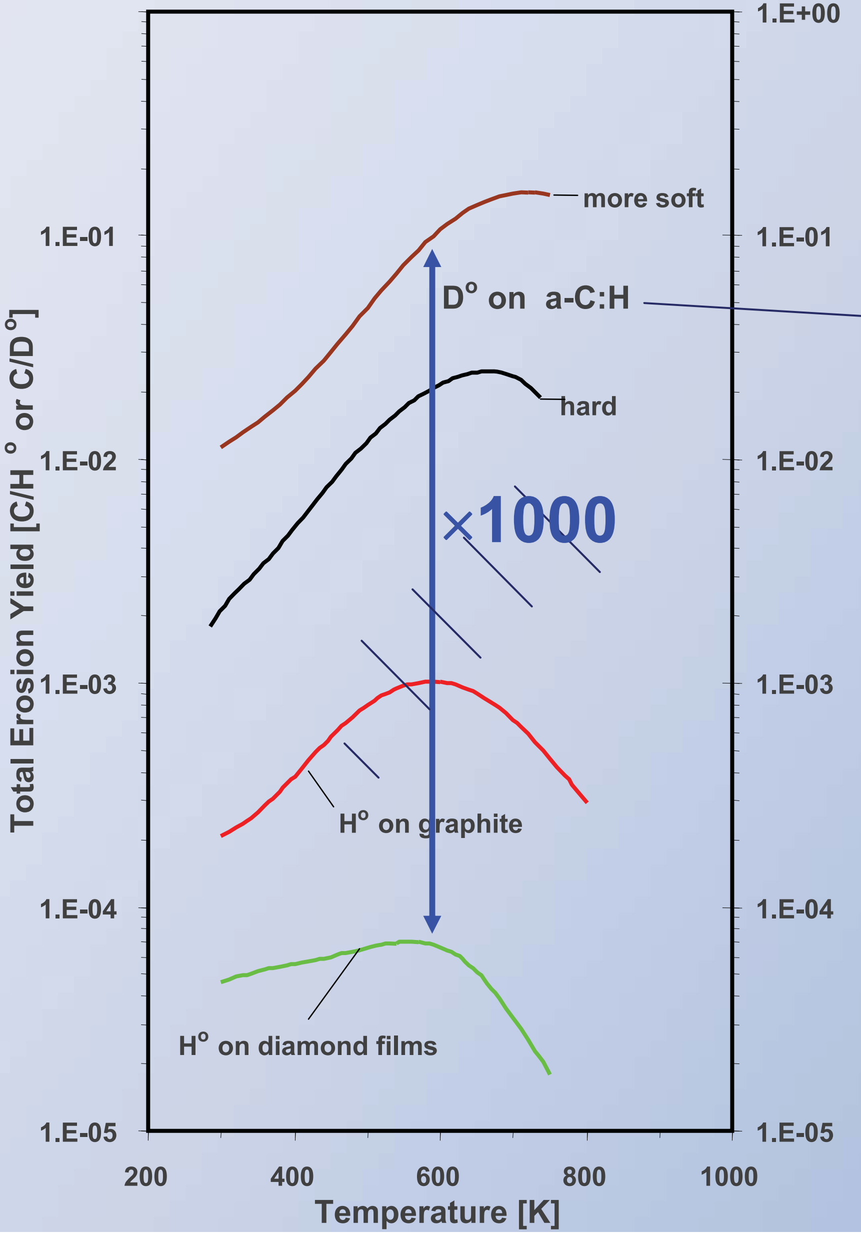
Flux dependence of chemical erosion yield



Chemical erosion yield decreases with increasing deuterium flux

III.) Chemical erosion of carbon-based materials

Chemical erosion yield in dependence on properties of carbon material



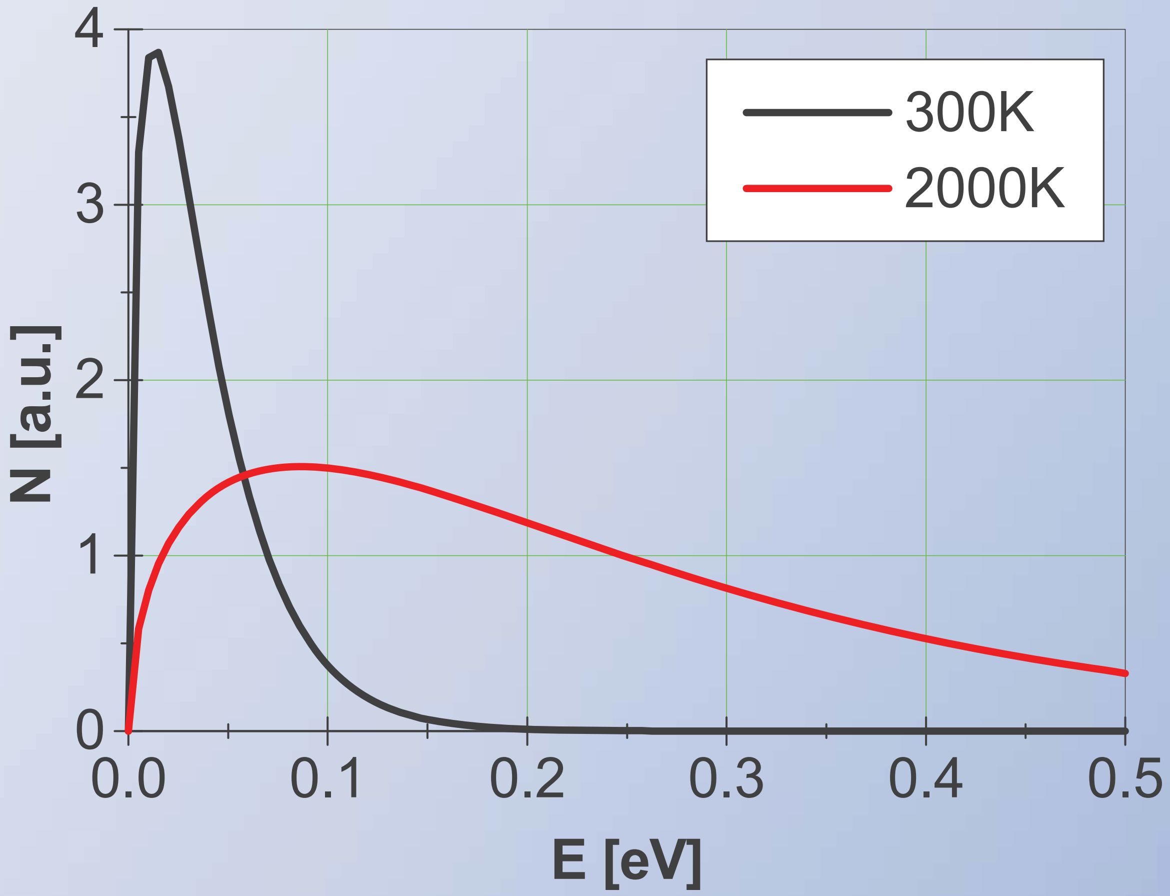
a-C:H

amorphous hydrocarbon layer

Soft (hydrogen-rich) carbon layers suffer from an enhanced chemical erosion

III.) Chemical erosion of carbon-based materials

Energy and angle distribution of eroded particles



Chemically eroded particles have **Maxwell distributed energy**

(E ~ kT_{surf} ~ 0.05 eV @RT)

Angle distribution of chemically eroded molecules:

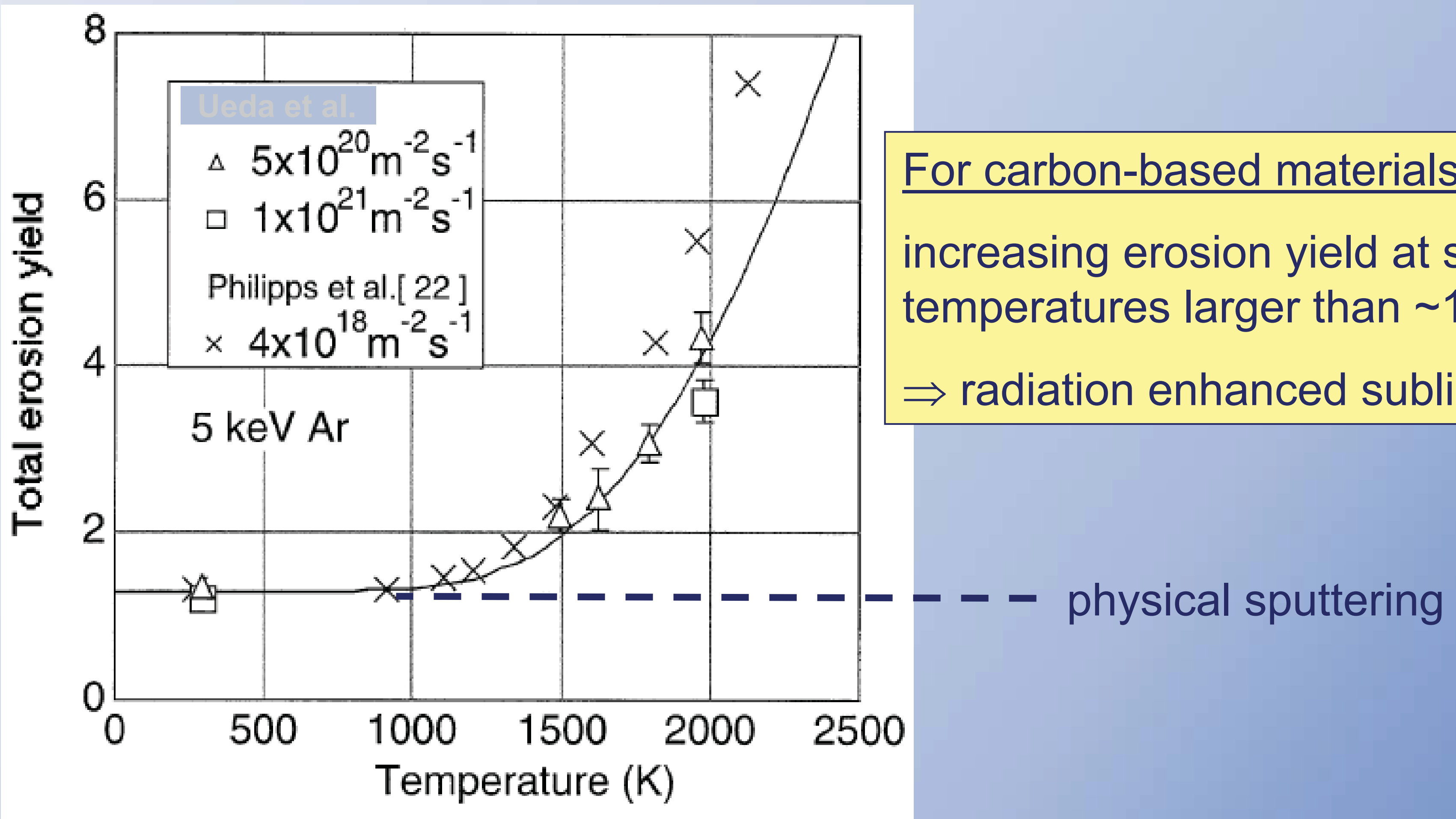
as for physical sputtering: good choice **cosine** distribution

IV.) Radiation Enhanced Sublimation (RES)

IV.) Radiation Enhanced Sublimation (RES)

Erosion yield from beam experiments in dependence on surface temperatures

5 keV Ar^+ on graphite



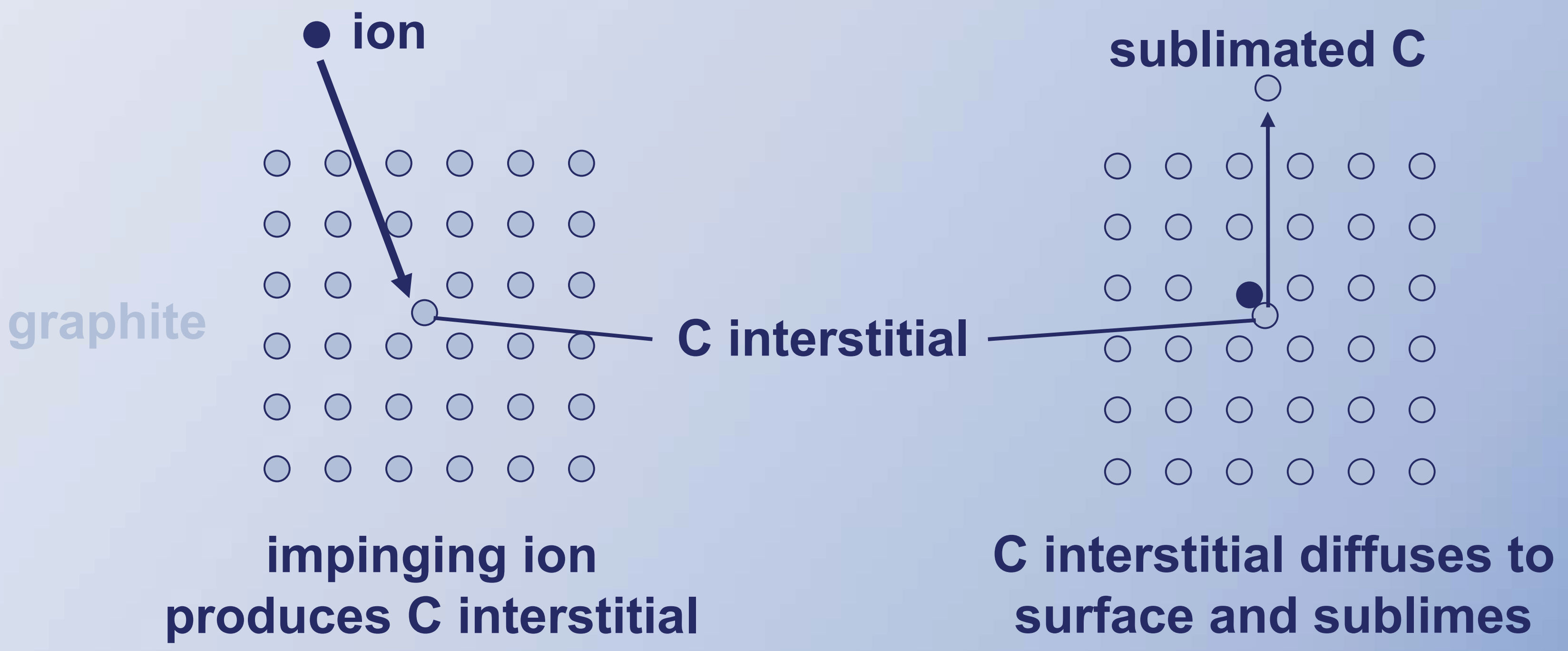
For carbon-based materials:

increasing erosion yield at surface temperatures larger than ~1000K

⇒ radiation enhanced sublimation

IV.) Radiation Enhanced Sublimation (RES)

Mechanism of RES

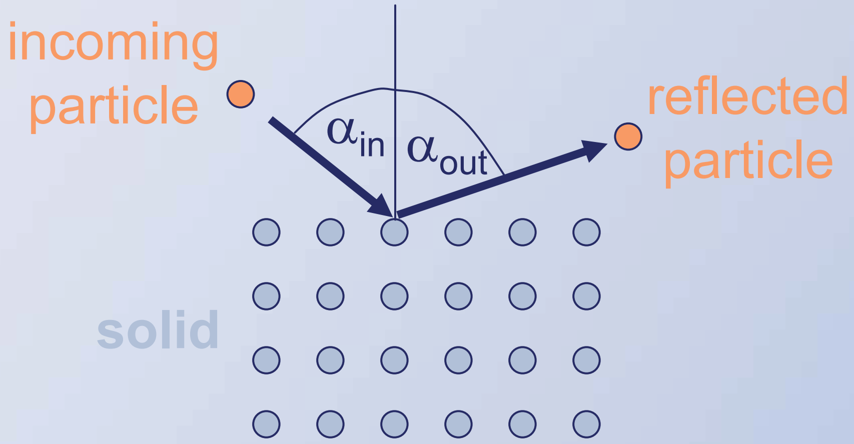


- During diffusion of C interstitials to surface: probability of recombination with vacancies or stable defects ($\Rightarrow$ annihilation of interstitial)
- Density of vacancies increases with increasing ion flux
  $\Rightarrow$ flux dependence of RES
- So far **RES not clearly seen in tokamak** experiments (not yet clarified)

V.) Backscattering

V.) Backscattering

Reflection of impinging particles at the surface



Reflection coefficient R:

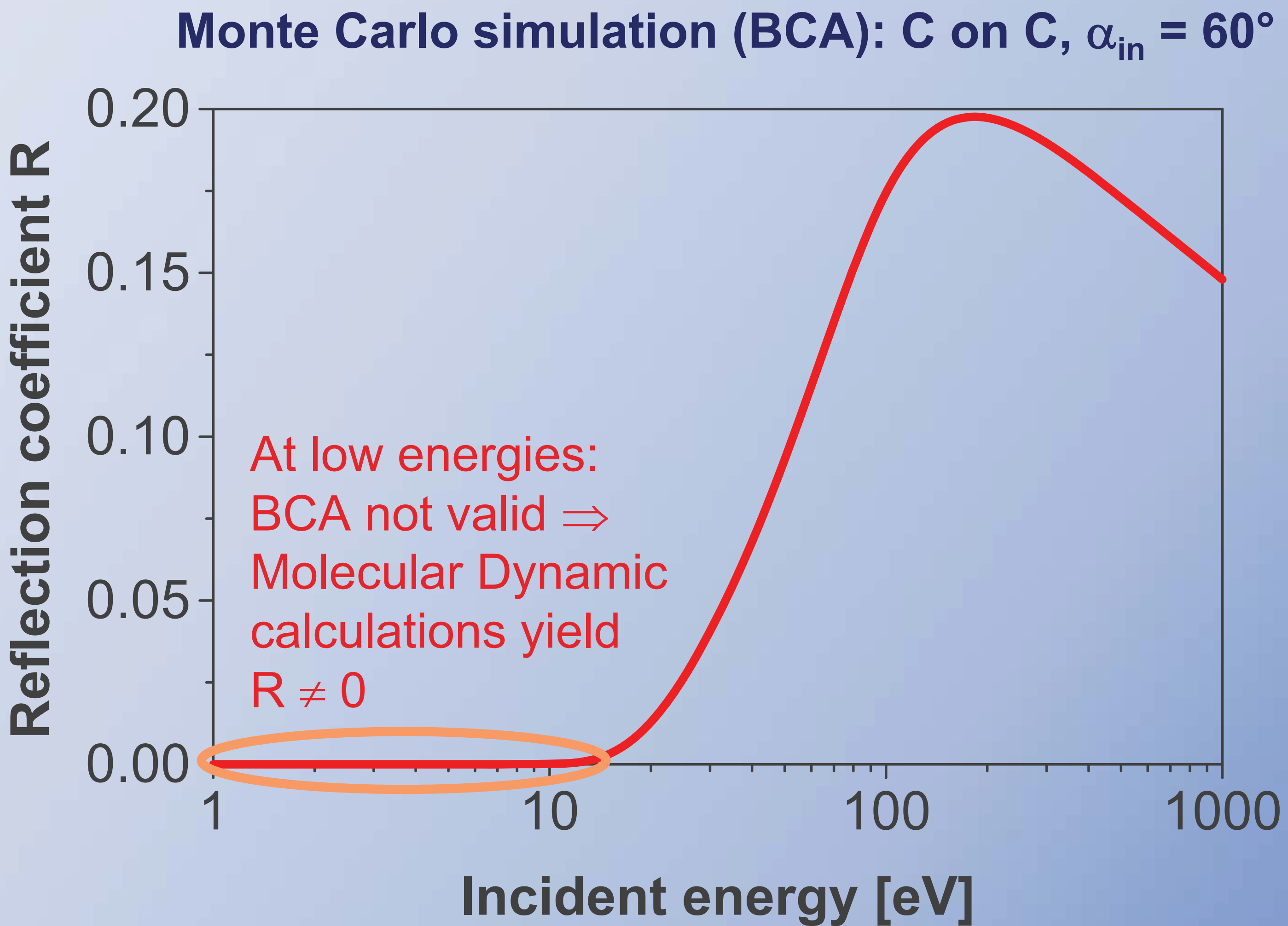
$$R = \frac{\text{amount of reflected particles}}{\text{amount of incoming particles}}$$

Deposition = 1 - R

- In most cases: reflected particles are neutrals
- Reflection coefficient depends on:
  - mass of projectile and target
  - energy and angle of incident particles

V.) Backscattering

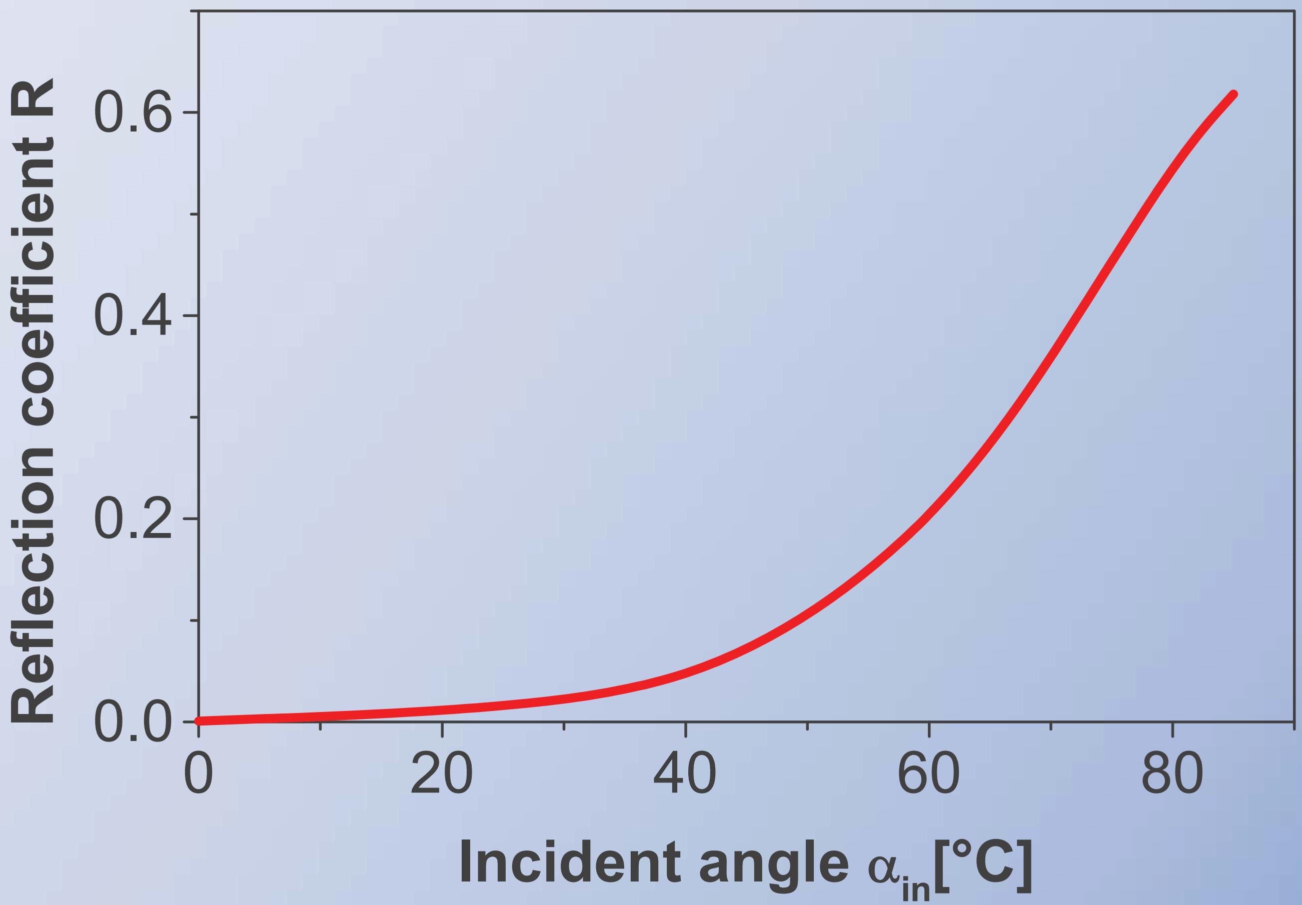
Dependency of reflection coefficient on incident energy

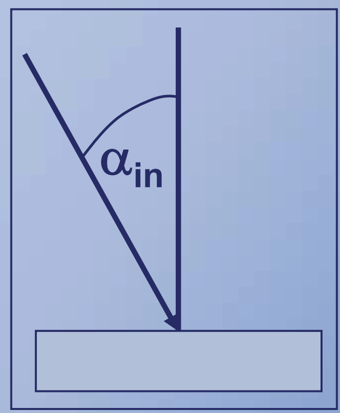


V.) Backscattering

Dependency of reflection coefficient on incident angle

Monte Carlo simulation (BCA): C on C, E_{in} = 100 eV





V.) Backscattering

Energy and angle distribution of reflected particles

Reasonable assumptions:

Energy: exponential decrease for reflected particles if incoming particle energy is Maxwell-distributed

Angle: cosine distribution for reflected particles if isotropic bombardment

further important Plasma-Wall Interaction Processes

VI.) Retention

Hydrogen retention in graphite and co-deposited layers

Licensing: in-vessel tritium inventory in ITER limited to 350g

Four retention mechanisms have been identified:

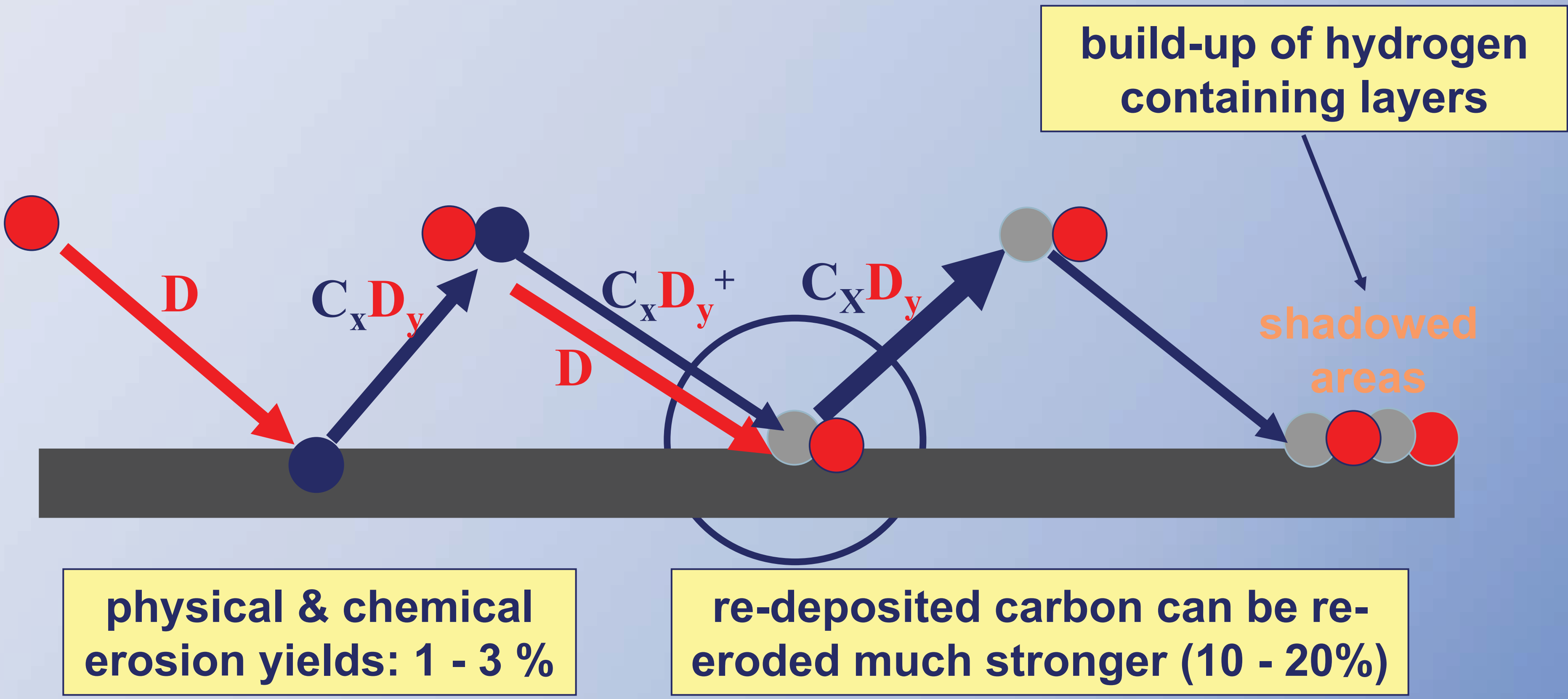
- **Build-up of a saturated surface layer** during hydrogen implantation
- **Chemisorption** on grain boundaries and inner porosity surfaces
- **Intergranular diffusion and trapping** at temperatures > 1000K
- **Co-deposition** of hydrogen with carbon

Based on experimental data:

- **Co-deposition is expected to be most important mechanism for long-term tritium retention in ITER**

V.) Retention

Hydrogen retention via co-deposition



VII.) Adsorption/Desorption

Definition of the processes

Adsorption: binding of particles or molecules to a solid surface (adsorption from residual gas O_2, H_2O, CO …or from impurities segregated at surface at elevated temperatures)

physisorption: binding due to van der Waals forces (E_B <~0.5eV)

chemisorption: binding via exchange/sharing of electrons (E_B ~ eV)

Desorption: adsorbed species leave the surface and return into gas phase

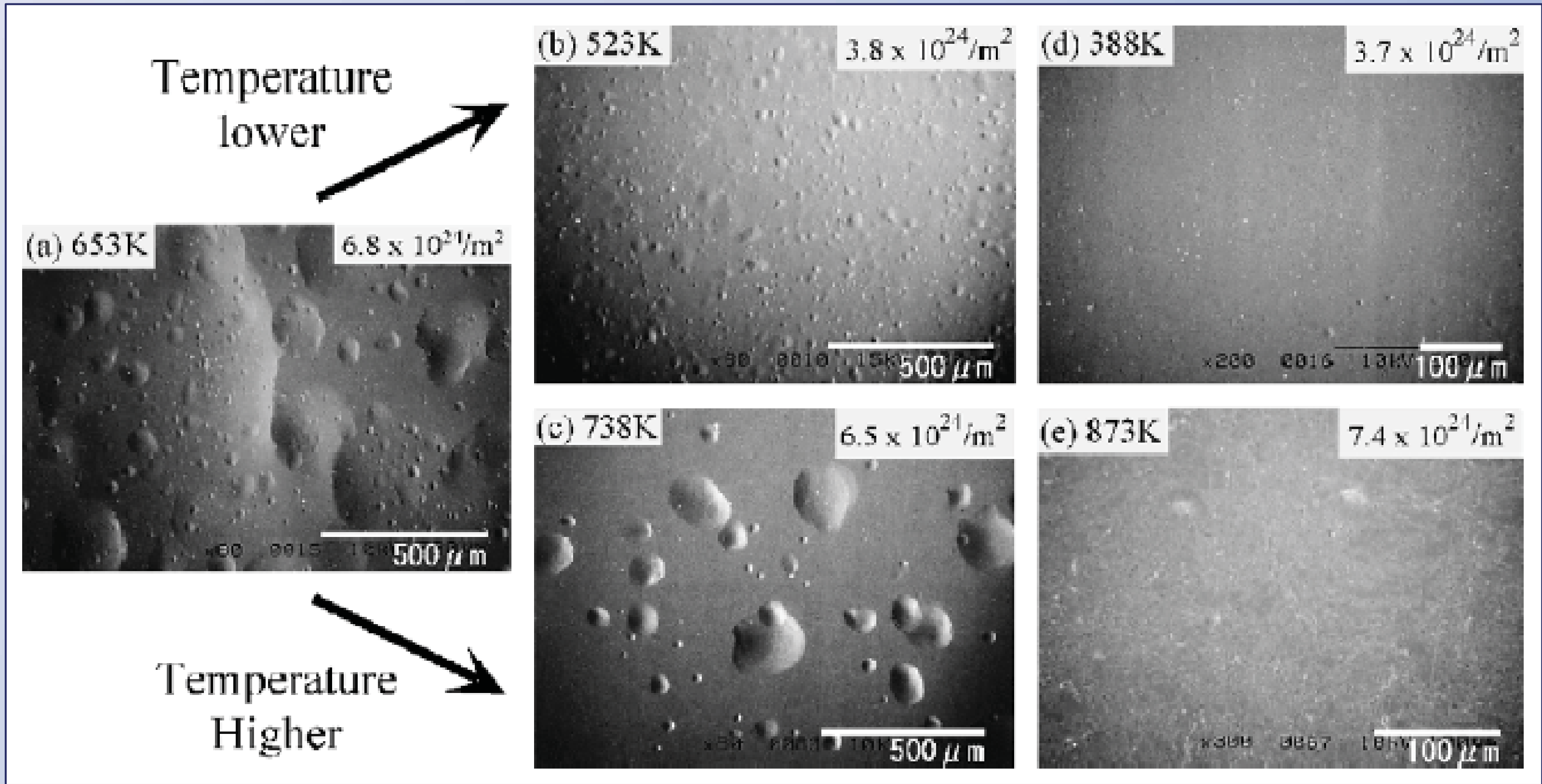
⇒ impurity release process

Ion-induced desorption most important desorption process for fusion.

VIII.) Blistering

Trapping of gas atoms in bubbles of high pressure

Example: blistering in tungsten



Pressure in bubble too high ⇒ repetitive exfoliation of micron-thick flakes

IX.) Secondary Electron Emission

Mechanisms of secondary electron emission

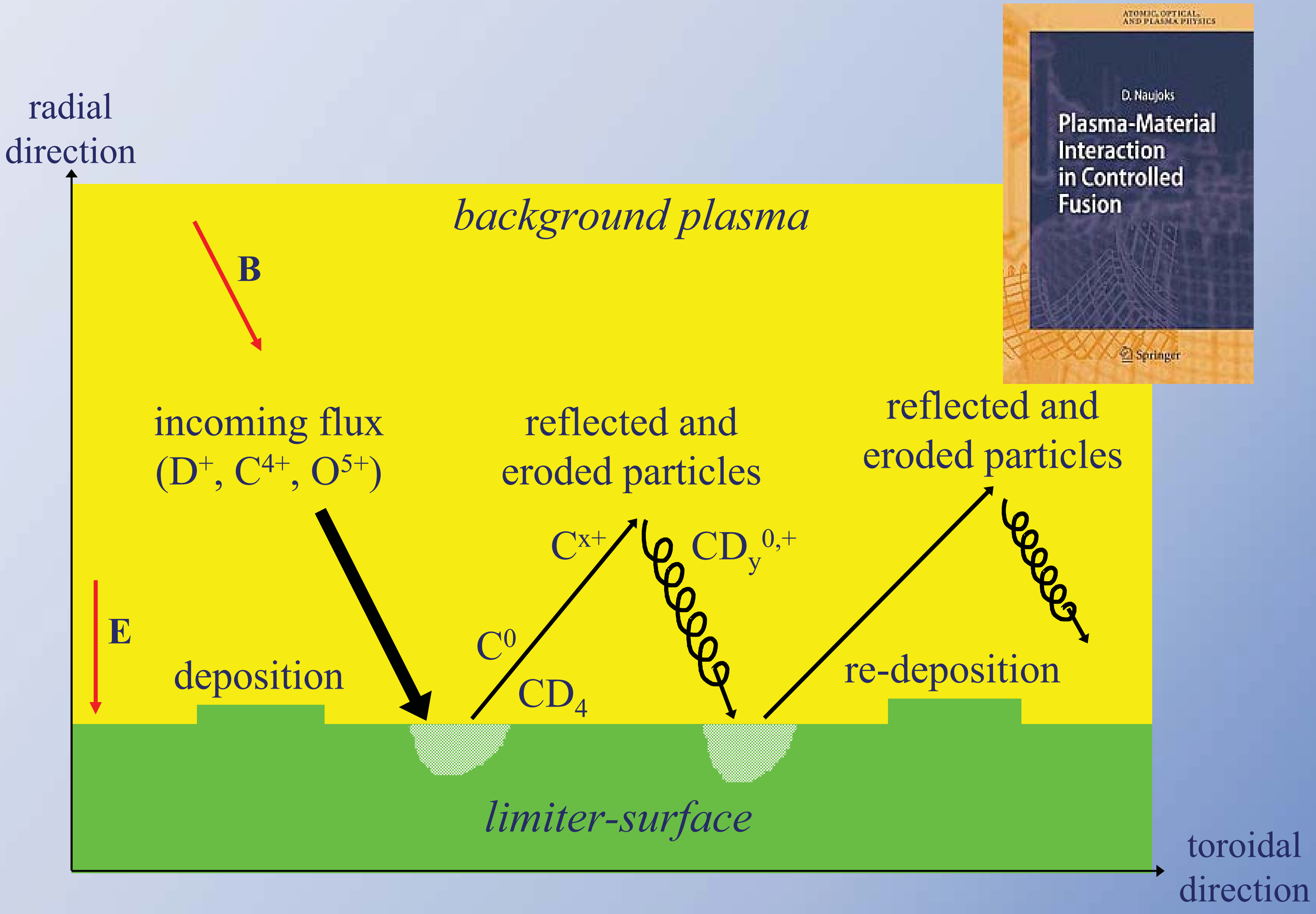
- **reflection of electrons** which impinge the surface, mostly elastic scattering
- **true electron-induced secondary electron emission** from the solid
- **ion-induced electron emission**

Why important in fusion research?

Secondary electron emission coefficient influences the **the sheath potential** in front of target surface exposed to plasma (later in these lectures …)

Detailed book-keeping of PWI processes (and local transport)

The Impurity Transport Code ERO: see also: lecture III



Plasma wall interaction is unavoidable and necessary for particle and energy exhaust

WHAT happens:

Low Z materials are favourable since higher concentrations can be tolerated in the plasma due to lower radiation losses but the erosion of low Z materials is stronger. A compromise between impurity release and acceptable impurity concentration must be found, which is connected by impurity transport.

> **Graphite has large advantages for off- normal heat loads in ELMS and disruptions, since it does not melt, but the disadvantage of high erosion and which can lead to large fuel retention by co-deposition**

High Z metals have much lower erosion and show much lower hydrogen retention but metal walls can suffer from melt layer loss in off normal heat loads.

Next lecture: HOW can we make ITER work despite these issues