

# ACCELERATOR TECHNIQUES AND NUCLEAR DATA NEEDS FOR ION BEAM ANALYSIS OF WALL MATERIALS IN CONTROLLED FUSION REACTORS

Marek Rubel<sup>1</sup>, Daniel Primetzhofer<sup>2</sup>, Per Petersson<sup>1</sup>  
Sotirios Charisopoulos<sup>3</sup>

<sup>1</sup>Fusion Plasma Physics, KTH Royal Institute of Technology

<sup>2</sup>Physics and Astronomy, Uppsala University

<sup>3</sup>IAEA – Physics Section

rubel@kth.se

INTERNATIONAL CONFERENCE ON

## ACCELERATORS FOR RESEARCH AND SUSTAINABLE DEVELOPMENT

From good practices towards socioeconomic impact



**23–27 May 2022**

IAEA Headquarters, Vienna, Austria

Our conference is a complex and fascinating mosaic of topics:  
*from fundamentals to medical physics and environmental science.*

This contribution belongs to energy research.

Goal 7 (*Affordable & Clean Energy*) with great impact on the whole mosaic of Goals.

*A brief introduction to the title and topic of this talk is needed:*

1. *Controlled Fusion and Devices*
2. *Plasma-Facing Materials and Components*



# Controlled Thermonuclear Fusion: The Goal and "Boundary Conditions"

**The ultimate goal of controlled fusion research is to construct and operate a power generating system.**



# Controlled Thermonuclear Fusion: The Goal and "Boundary Conditions"

**The ultimate goal of controlled fusion research is to construct and operate a power generating system.**

- **Under terrestrial conditions the fuel (plasma) must be surrounded by walls of a vacuum vessel.**



# Controlled Thermonuclear Fusion: The Goal and "Boundary Conditions"

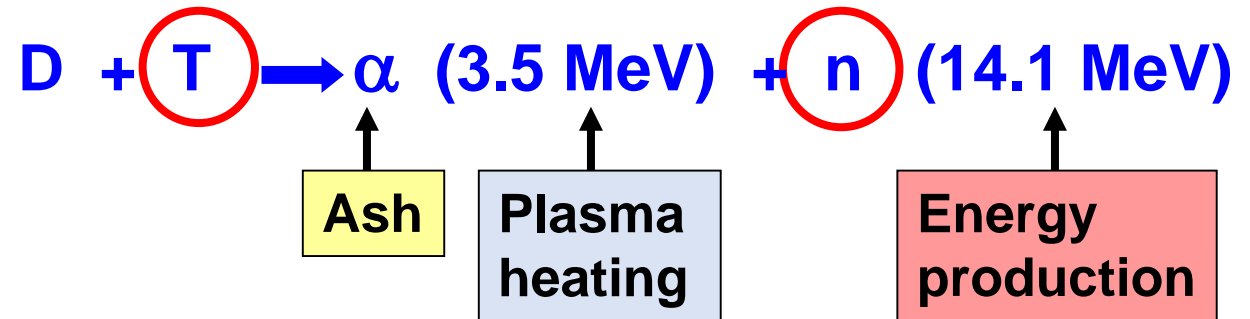
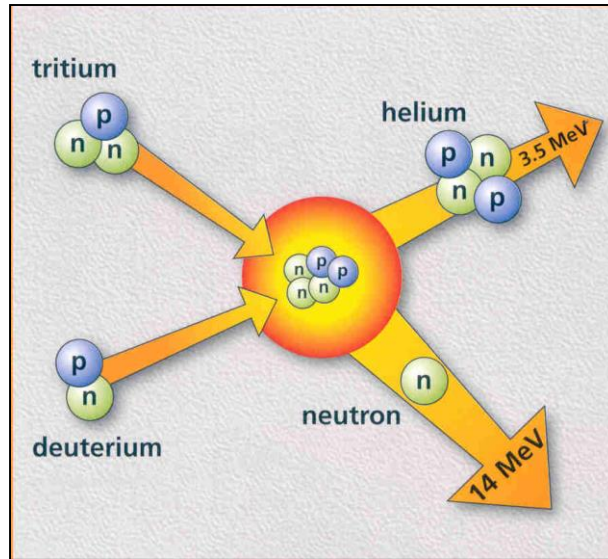
**The ultimate goal of controlled fusion research is to construct and operate a power generating system.**

- **Under terrestrial conditions the fuel (plasma) must be surrounded by walls of a vacuum vessel.**
- **Temperature gradients between the plasma and the surrounding wall in fusion devices are (probably) the largest in the Universe.**
- **Issues of power handling and radioactivity are universal for ALL confinement schemes realised for energy generation.**
- **Fusion reactor is a nuclear device.**



# Nuclear and Material Aspects of Deuterium – Tritium Fusion

*Choice based on analysis of reaction cross-sections*



**Reaction of 1 g of equimolar mixture:  
 $1.2 \times 10^{23}$  events**

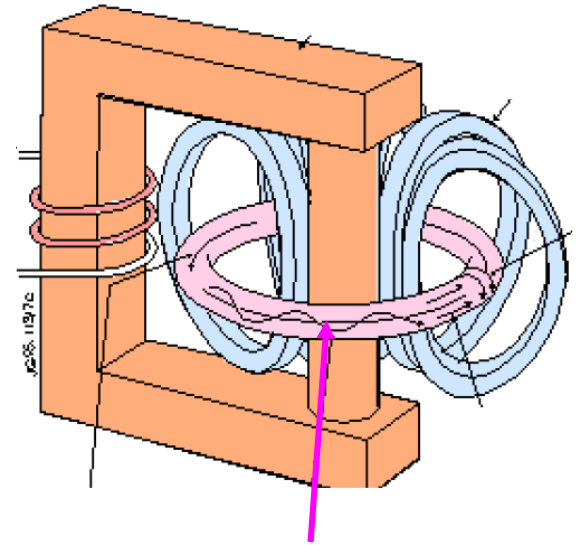
$\alpha$	<b>67.5 GJ</b>
$\text{n}$	<b>271.8 GJ</b>

**Important consequences in a reactor operation:**

- Power and particle exhaust
  - Radioactivity
- } Impact on wall materials**

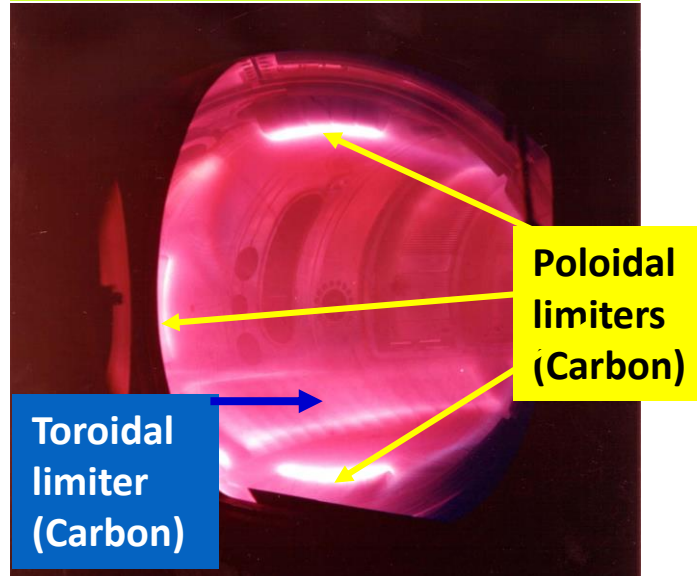
# Plasma-facing wall in fusion devices: Tokamaks

A "transformer" where the secondary circuit is the plasma current.

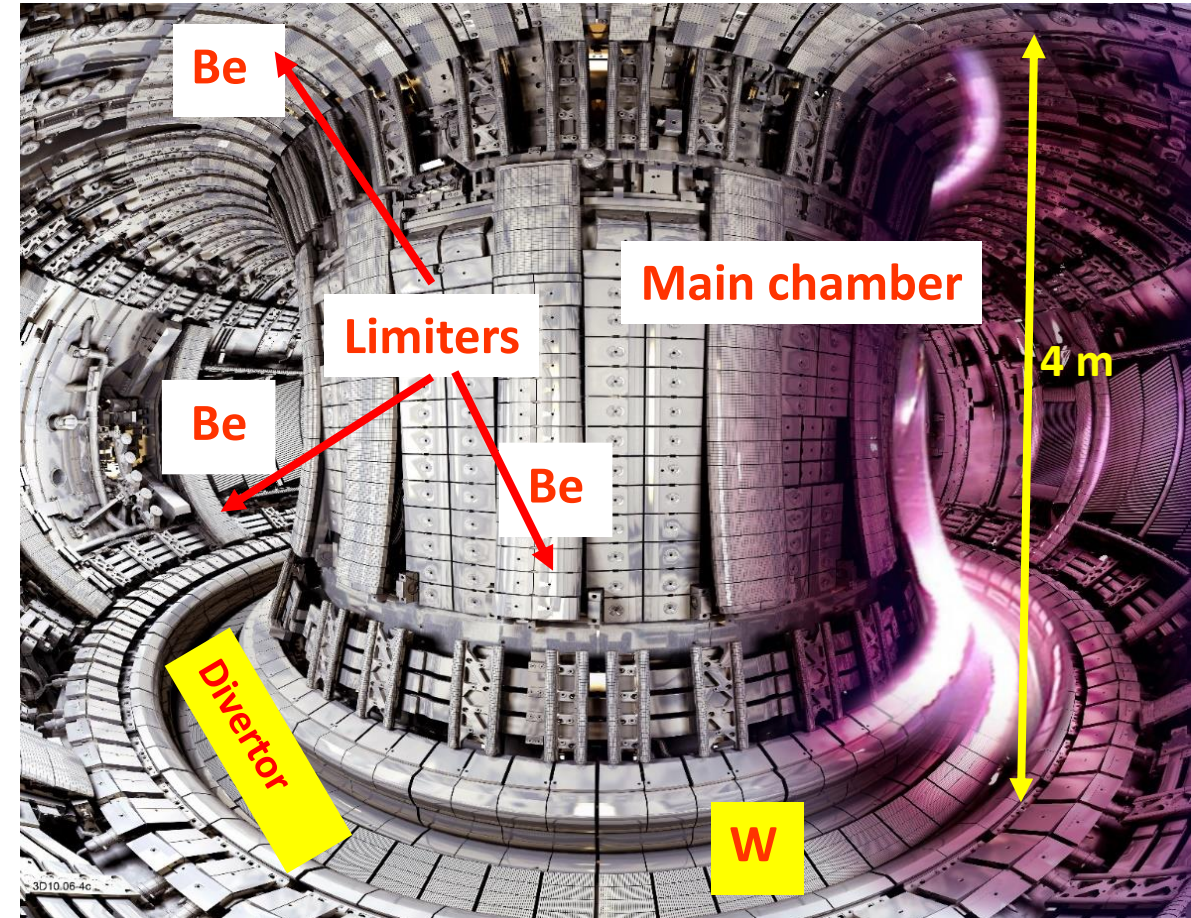


*Plasma in the toroidal vessel*

TEXTOR: operation 1982-2013



JET: Joint European Torus: *the largest tokamak (since 1983)*



High complexity of the plasma-facing wall: composition and structure.

# Structure of the talk

- What is to be determined/analysed?
- Why is it to be determined/analysed?
- How is the examination carried out?
  - The Tools*
  - The Physics*

Material analysis is not an isolated aim of research.

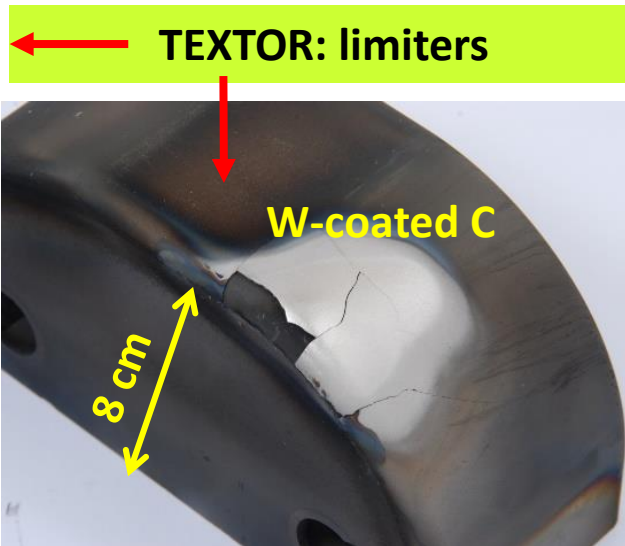
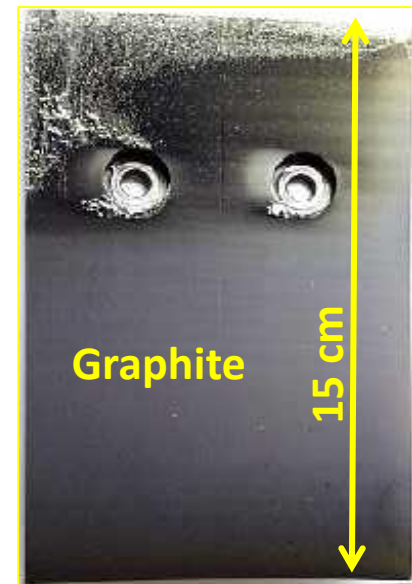


# What do we study?

## Components retrieved from fusion devices

A large number of:

- *limiter plates*
- *divertor plates*
- *long-term probes*
- *short-term probes*
- *optical components*
- *dust*



JET with ITER-Like Wall: castellated limiter



COMPASS: divertor



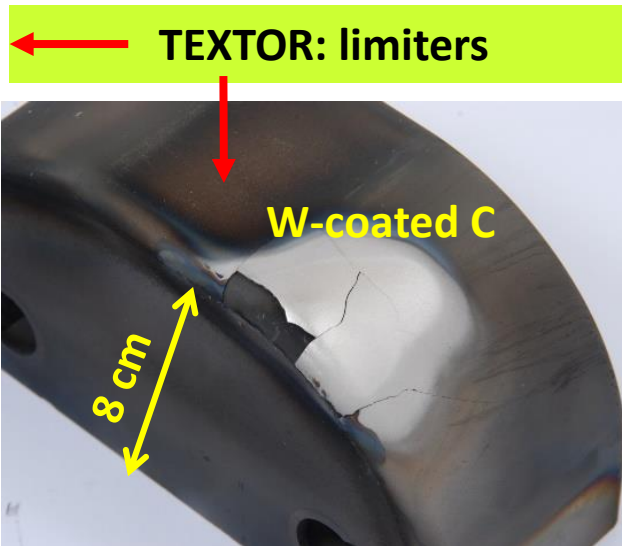
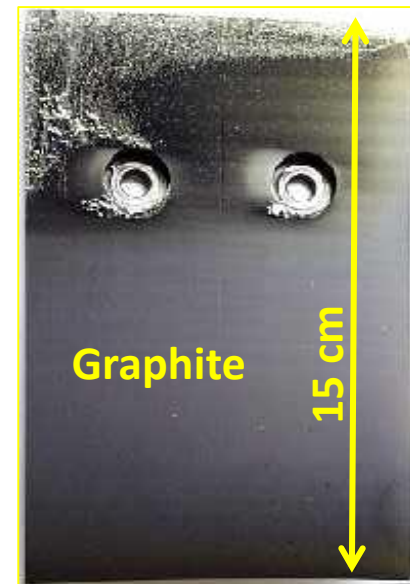
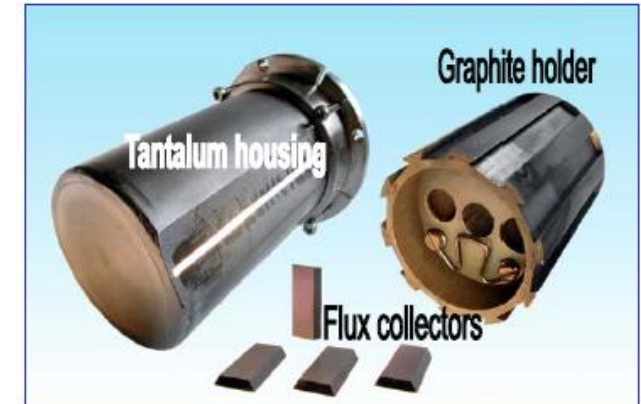
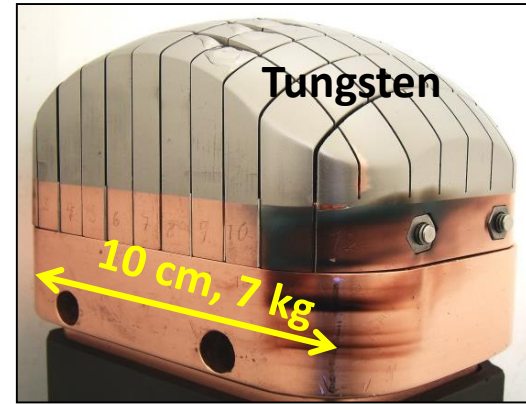
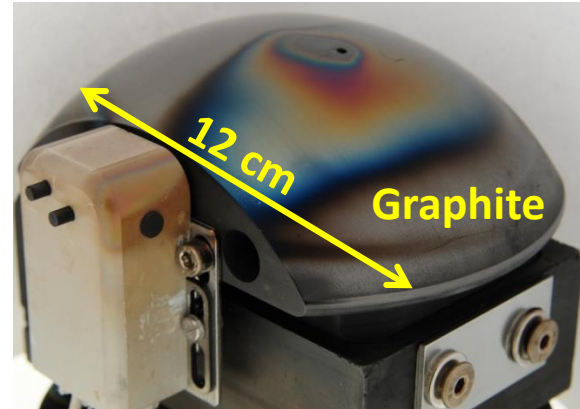
# What do we study?

## Components retrieved from fusion devices

A large number of:

- *limiter plates*
- *divertor plates*
- *long-term probes*
- *short-term probes*
- *optical components*
- *dust*

**TEXTOR:** *test limiters and collector probes*



**JET with ITER-Like Wall: castellated limiter**



**Results from JET:**  
*Anna Widdowson, Session 9A*  
*Laura Dittrich, Poster 89*

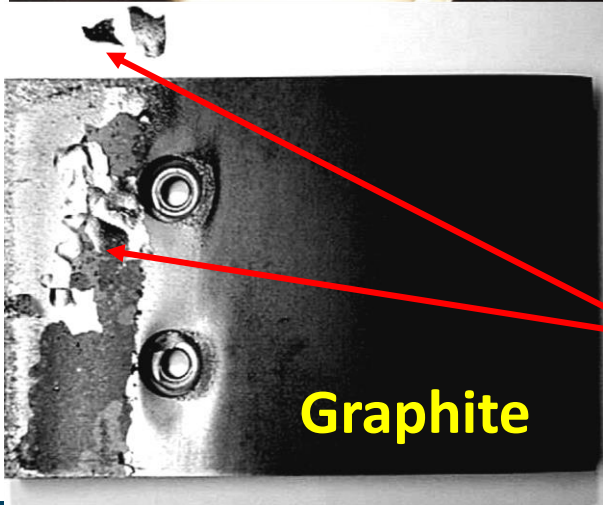
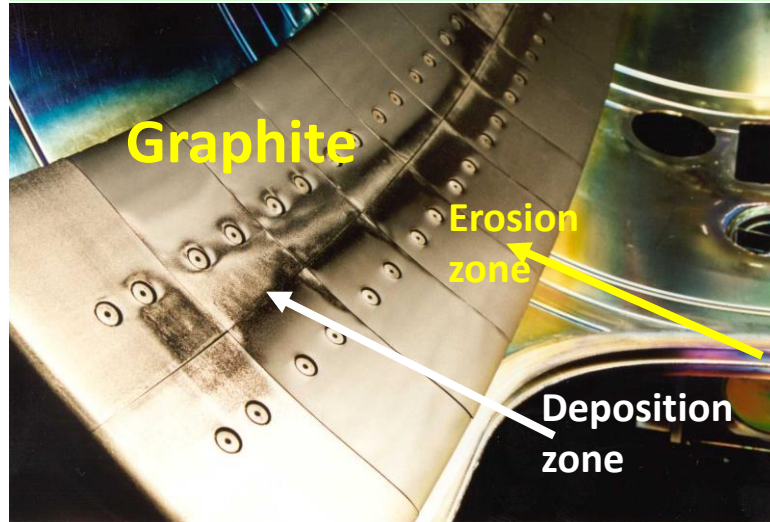
**COMPASS: divertor**



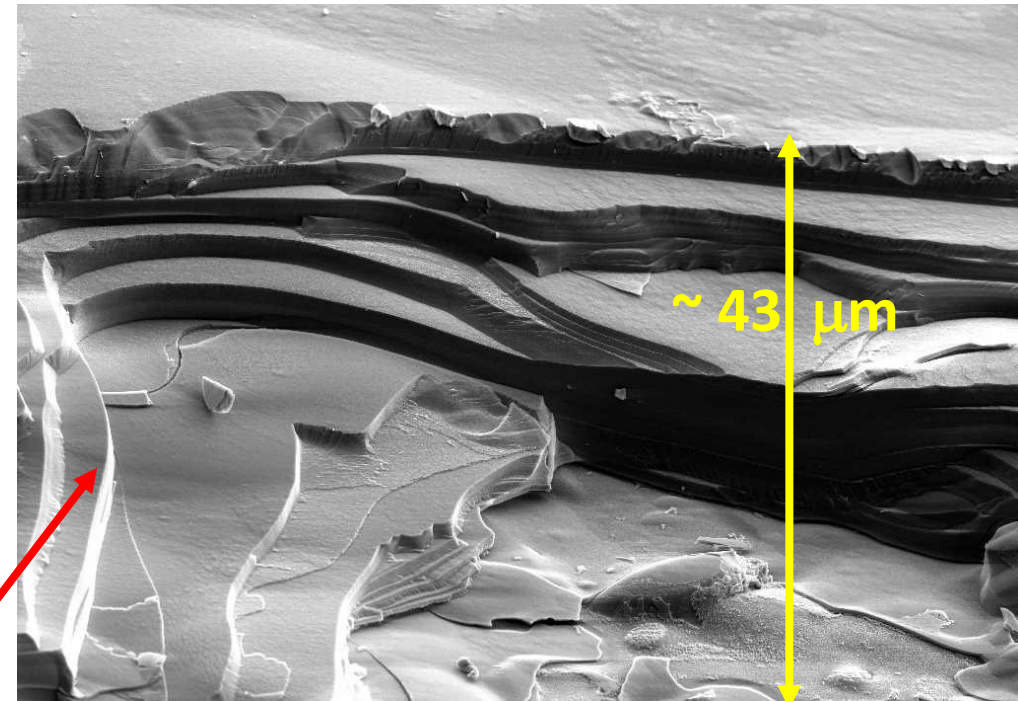
# Material Migration: Erosion & Deposition

Example from the TEXTOR tokamak operated till December 2013.

Tiles of a toroidal limiter



Cross-section of a re-deposited layer



*Large amount of deuterium and tritium fuel can be retained in such layers.*

***How does it happen??***

# Plasma – Wall Interactions

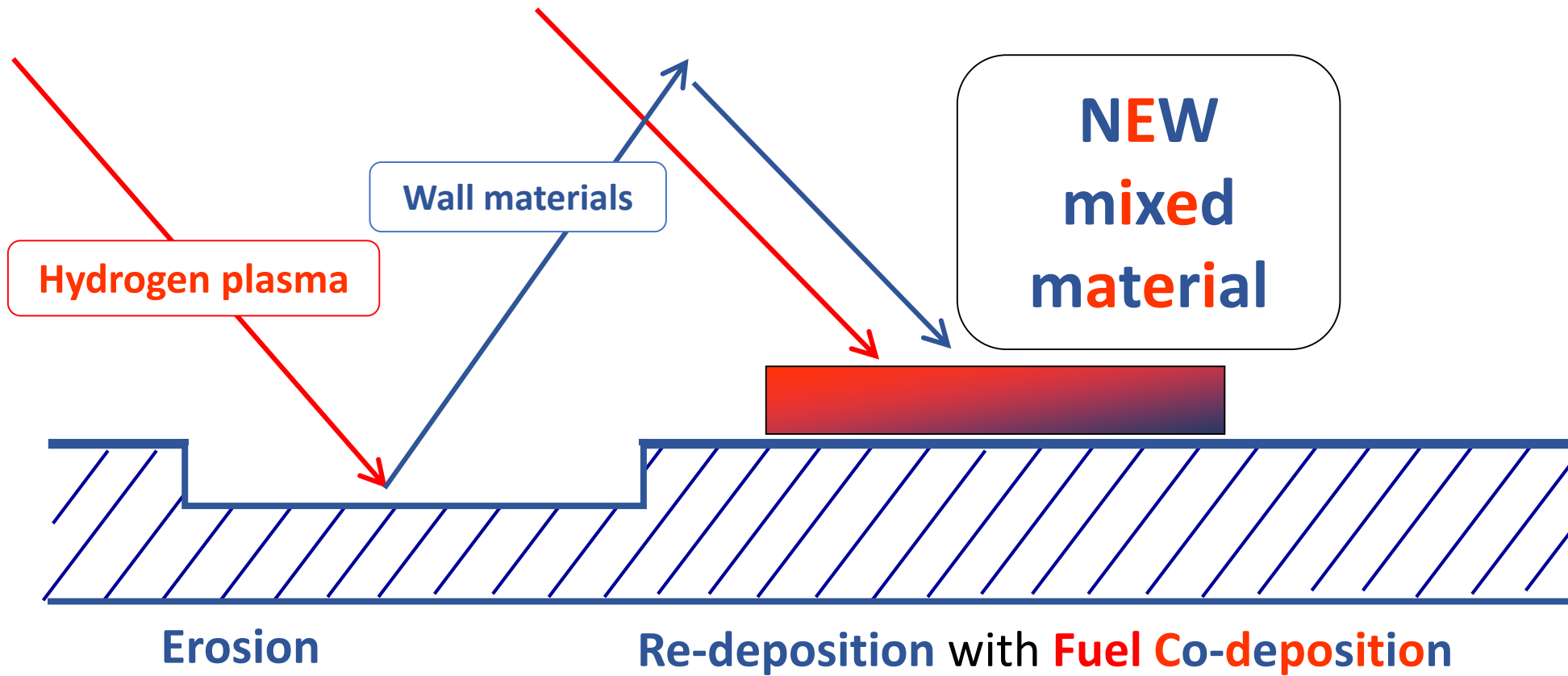
*All processes involved in the exchange of mass and energy between the plasma and the material surface.*

- *Sputtering*
- *Chemical erosion*
- *Reflection*
- *Implantation*
- *Ionisation*
- *Recombination*
- *Gas retention*
- *Desorption*
- *Arcing*
- *Compound formation*
- *Melting*
- *Cracking*
- *Splashing*
- *Activation*
- *Transmutation*
- *... all dynamic.*



# Plasma – Wall Interactions

*All processes involved in the exchange of mass and energy between the plasma and the material surface.*

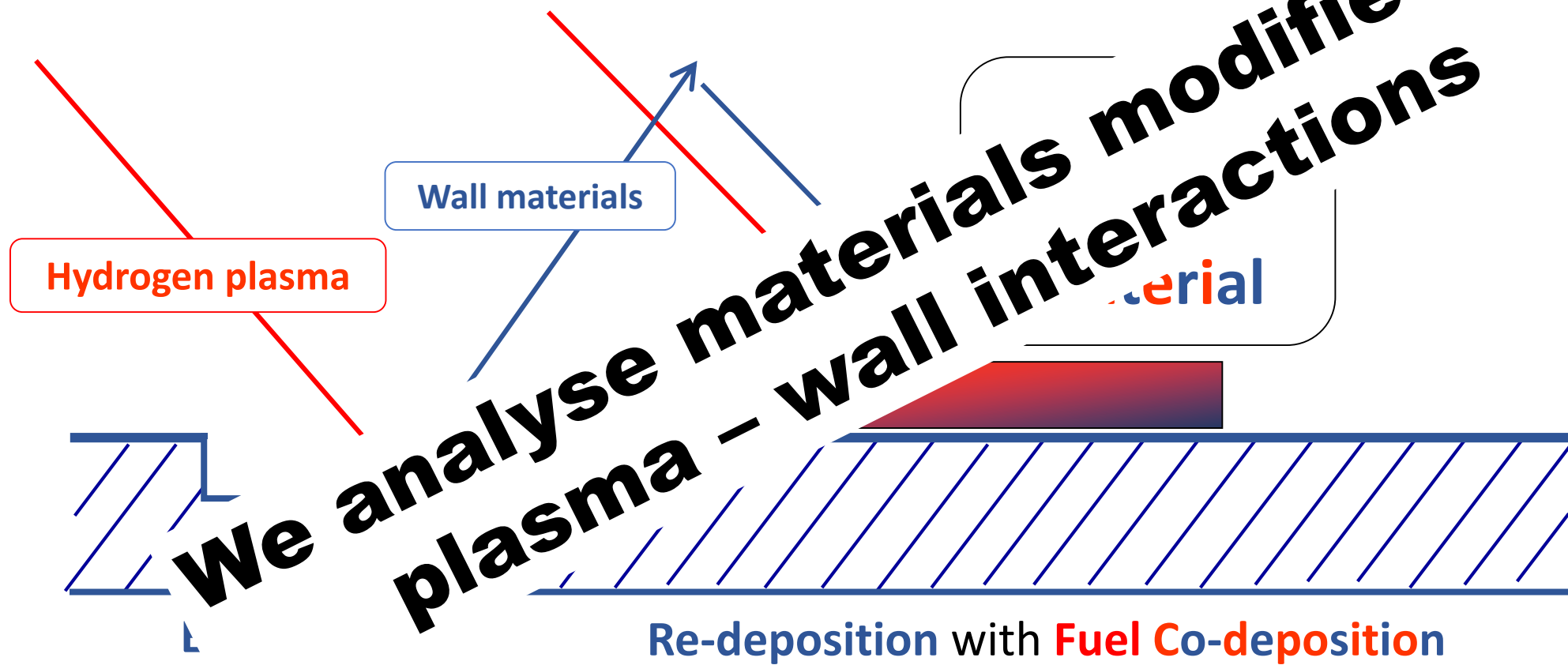


- Sputtering
- Chemical erosion
- Reflection
- Implantation
- Ionisation
- Recombination
- Gas retention
- Desorption
- Arcing
- Compound formation
- Melting
- Cracking
- Splashing
- Activation
- Transmutation
- ... all dynamic.

**Consequences: Modification of fusion plasma and material properties.**

# Plasma – Wall Interactions

*All processes involved in the exchange of mass and energy between the plasma and the material*



Consequences: Modification of fusion plasma and material properties.

Species to be analysed / determined

**FUEL**

**Z = 1 (H D T)**

**ASH**

**Z = 2 (<sup>4</sup>He)**



Species to be analysed / determined

**FUEL**

**Z = 1 (H D T)**

**ASH**

**Z = 2 (<sup>4</sup>He)**

**ERODED SPECIES: PLASMA IMPURITY ATOMS**

**Z > 2**

*For instance:*

**Li <sup>9</sup>Be <sup>10</sup>Be <sup>10</sup>B <sup>11</sup>B <sup>12</sup>C <sup>13</sup>C <sup>14</sup>C <sup>14</sup>N <sup>15</sup>N <sup>16</sup>O <sup>18</sup>O Ne**  
**Si Ni Cr Fe Mo W Re**



# Key Questions in Material Migration Studies

- ***Where*** are the erosion zones ?
- ***Where*** are the eroded species re-deposited? (Migration !)
- ***How*** are materials modified by erosion & re-deposition ?
- ***How*** much fuel is retained in wall components? (Fuel inventory is be strictly controlled.)
- ***What*** is the impact of wall materials on material migration?

The whole picture depends on the wall composition/materials.

Talk in 9A: ***Anna Widdowson***

Poster 89: ***Laura Dittrich***



# What are the materials?

## Main plasma-facing materials in fusion devices world-wide:

### Carbon

*(graphite, fibre composites)*

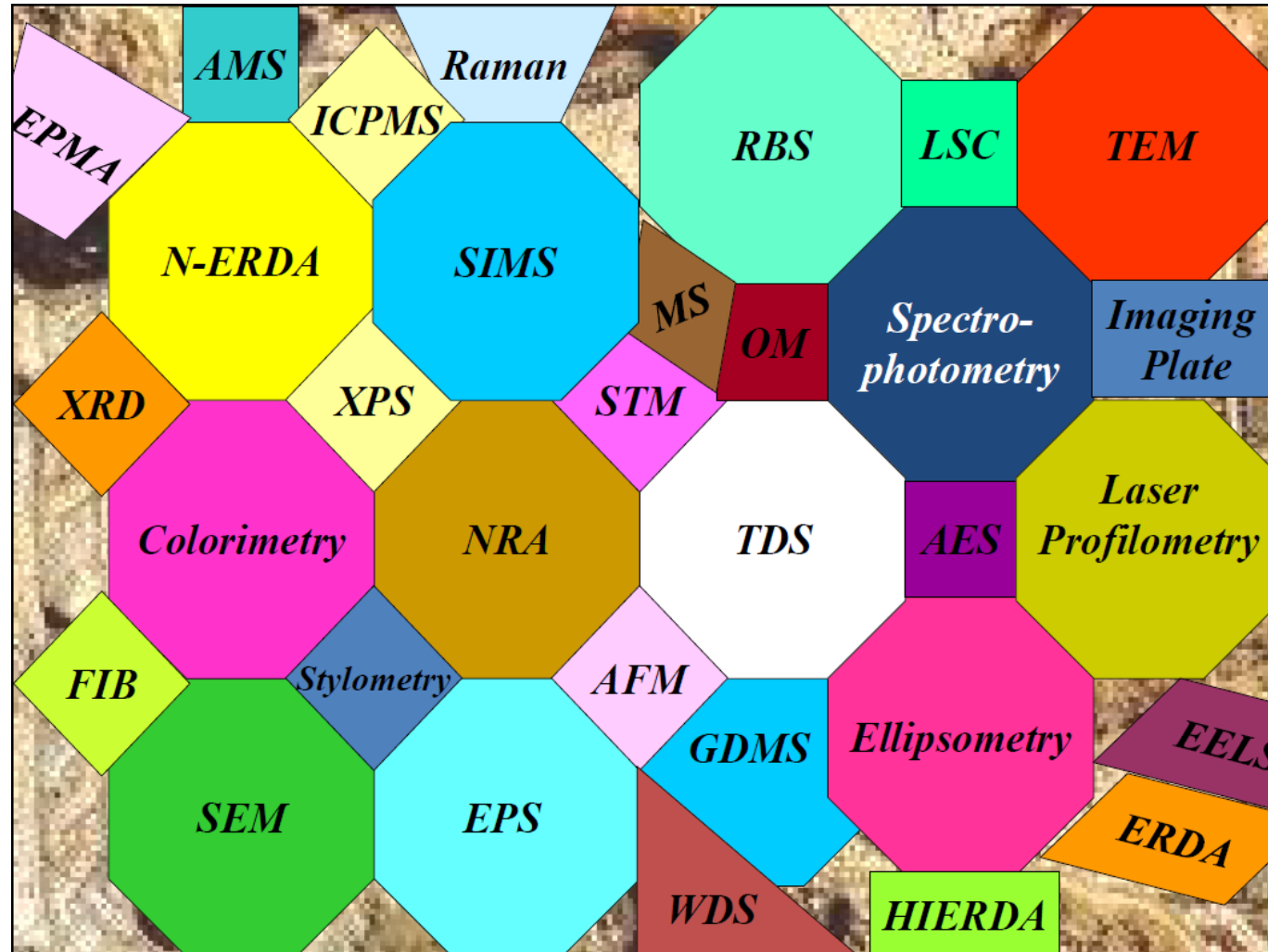
### Beryllium

### Tungsten

	Advantages	Drawbacks
<b>C</b>	Excellent power handling & no melting	Chemical erosion $\rightarrow C_xH_y$
<b>Be</b>	Low-Z, no chemical erosion	Low $T_m$
<b>W</b>	High $T_m$ , low sputter erosion	High-Z plasma contaminant

# How?

A mosaic (alternatively: "ZOO") of over 50 different methods has been used in our studies of wall components from many controlled fusion devices.

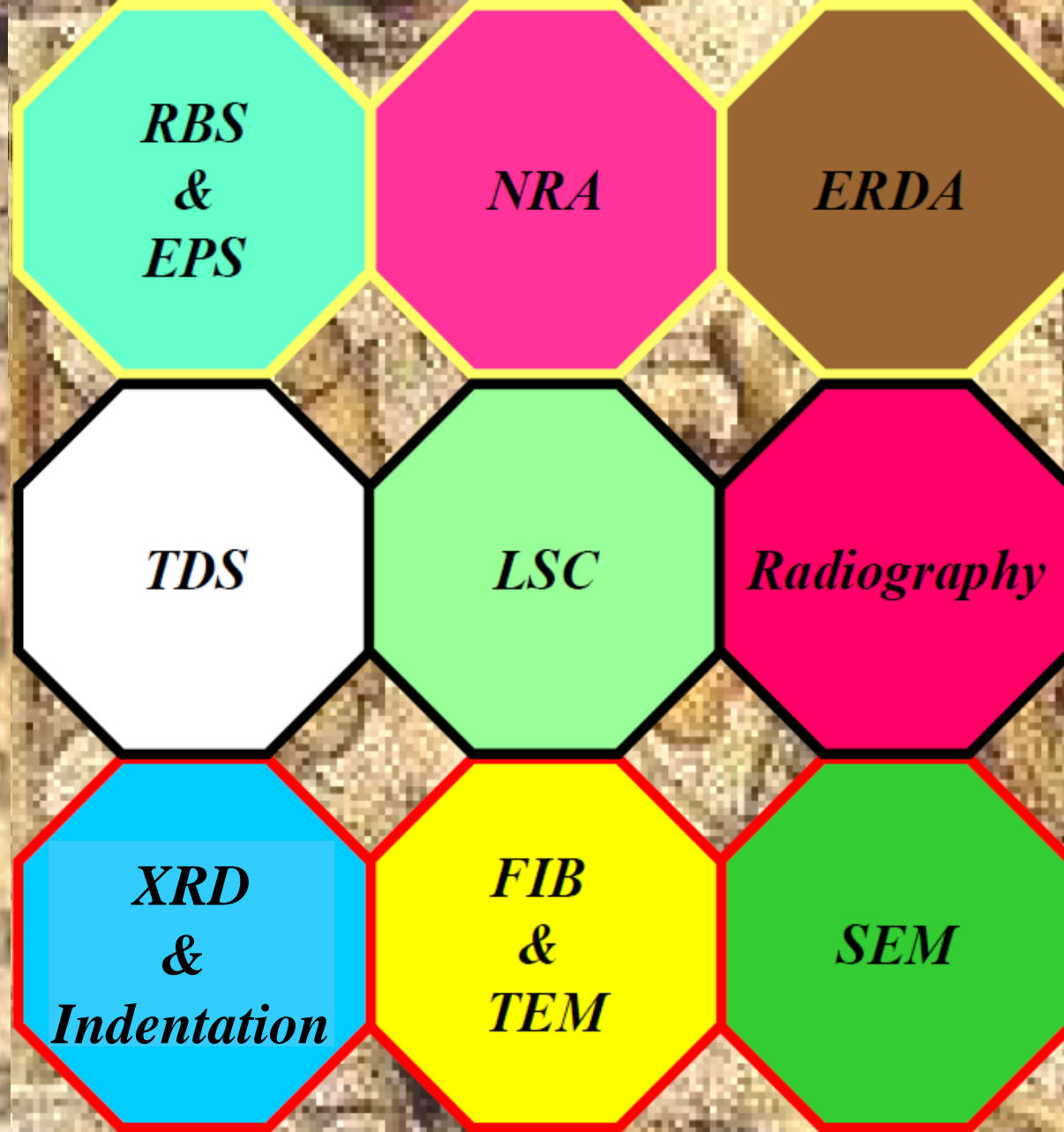


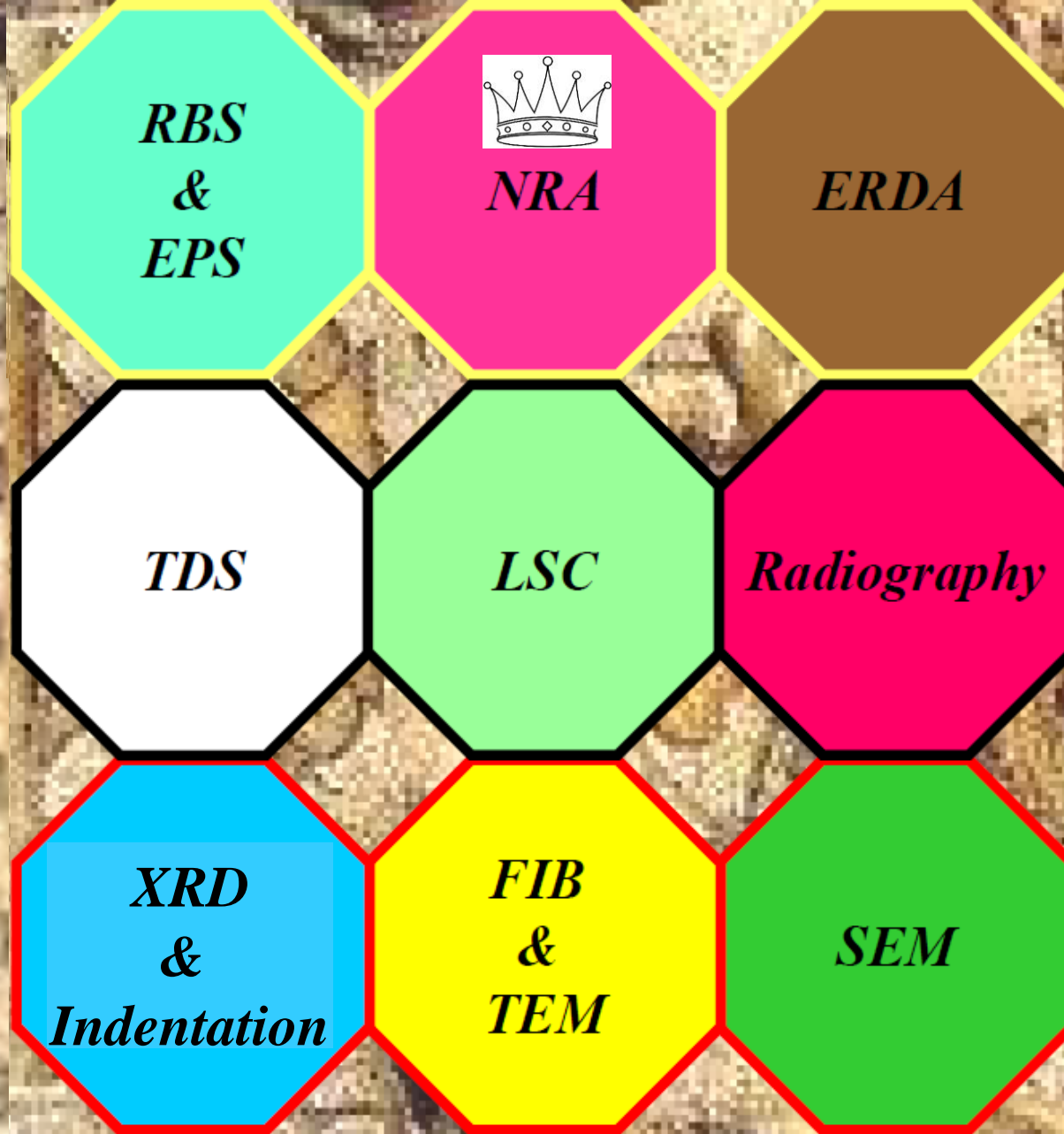


*RBS  
&  
EPS*

*NRA*

*ERDA*





# Nuclear Reaction Analysis with $^3\text{He}$

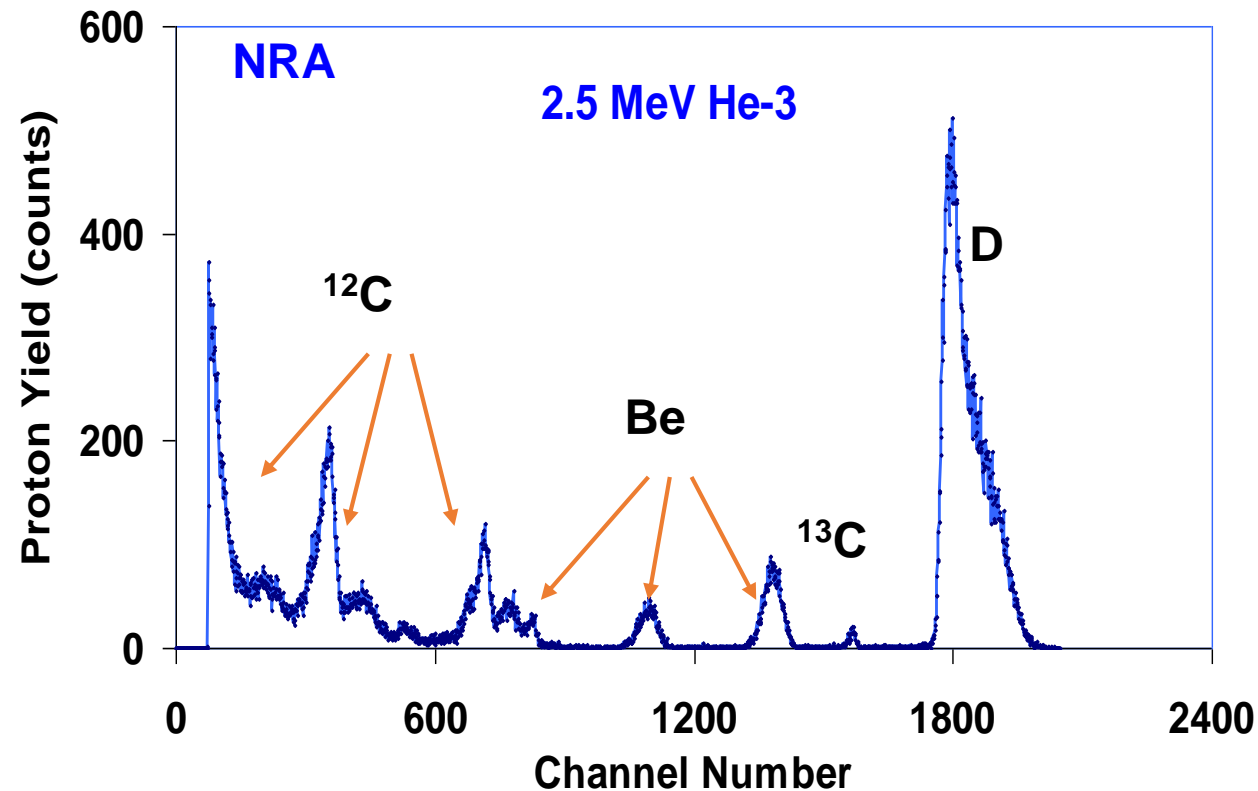
Advantage:

*Simultaneous determination of  $^2\text{H}$ ,  $^9\text{Be}$ ,  $^{12}\text{C}$ ,  $^{13}\text{C}$  (also B, N)*

$^2\text{H} (^3\text{He}, p) ^4\text{He}$  *The main tool in fuel retention studies in devices operated with deuterium.*

$^9\text{Be} (^3\text{He}, p) ^{11}\text{B}$

$^{12}\text{C} (^3\text{He}, p) ^{14}\text{N}$

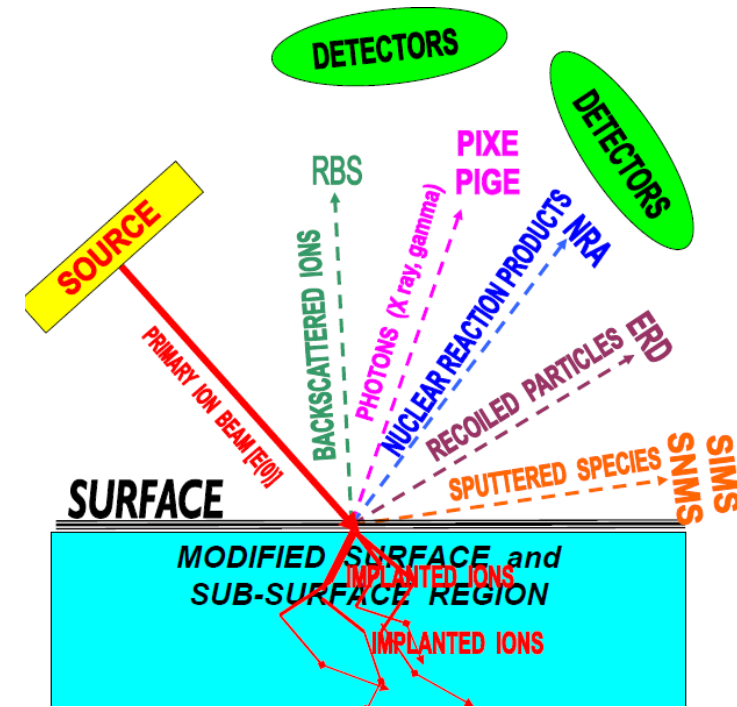


*About fuel retention:  
Anna Widdowson, Session 9A  
Laura Dittrich, Poster 89*

# Why accelerator-based IBA techniques?

- **Efficiency:**

- *Combination of various techniques in one system.*
- *Analysis of many elements and isotopes in the same system.*
- *Relatively quick analysis over large areas.*



# Why accelerator-based IBA techniques?

- **Efficiency:**

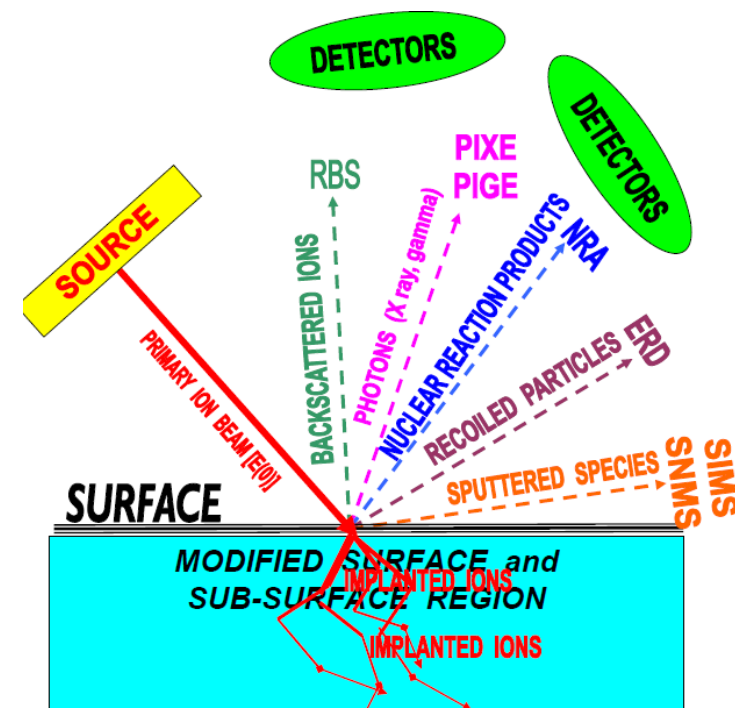
- *Combination of various techniques in one system.*
- *Analysis of many elements and isotopes in the same system.*
- *Relatively quick analysis over large areas.*

- **Sensitivity & Selectivity & Quantification** (*no standards*).

- **Neither special sampling nor sample preparation needed** (*in many cases*).

- **Depth profiling** (*limited in some cases*).

- **Chemical state of atoms is often of secondary importance.**  
(*materials retrieved from devices are transported in air*).



# If accelerator-based IBA techniques...

... then we need people and tools:

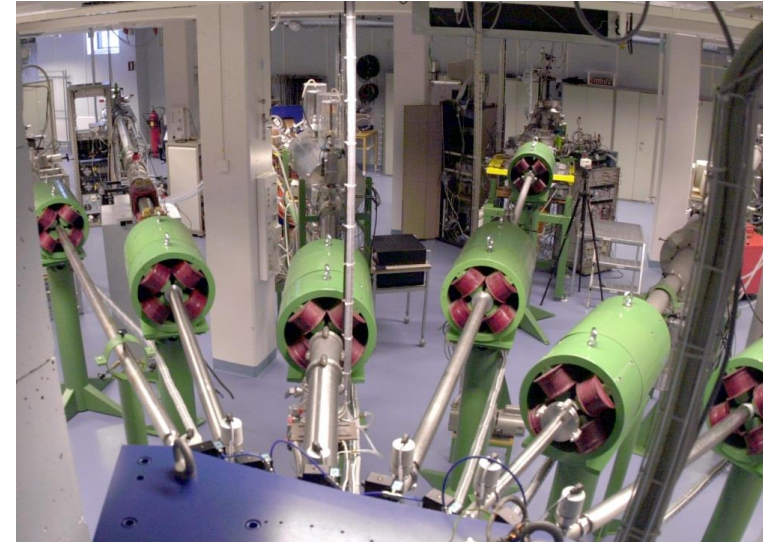
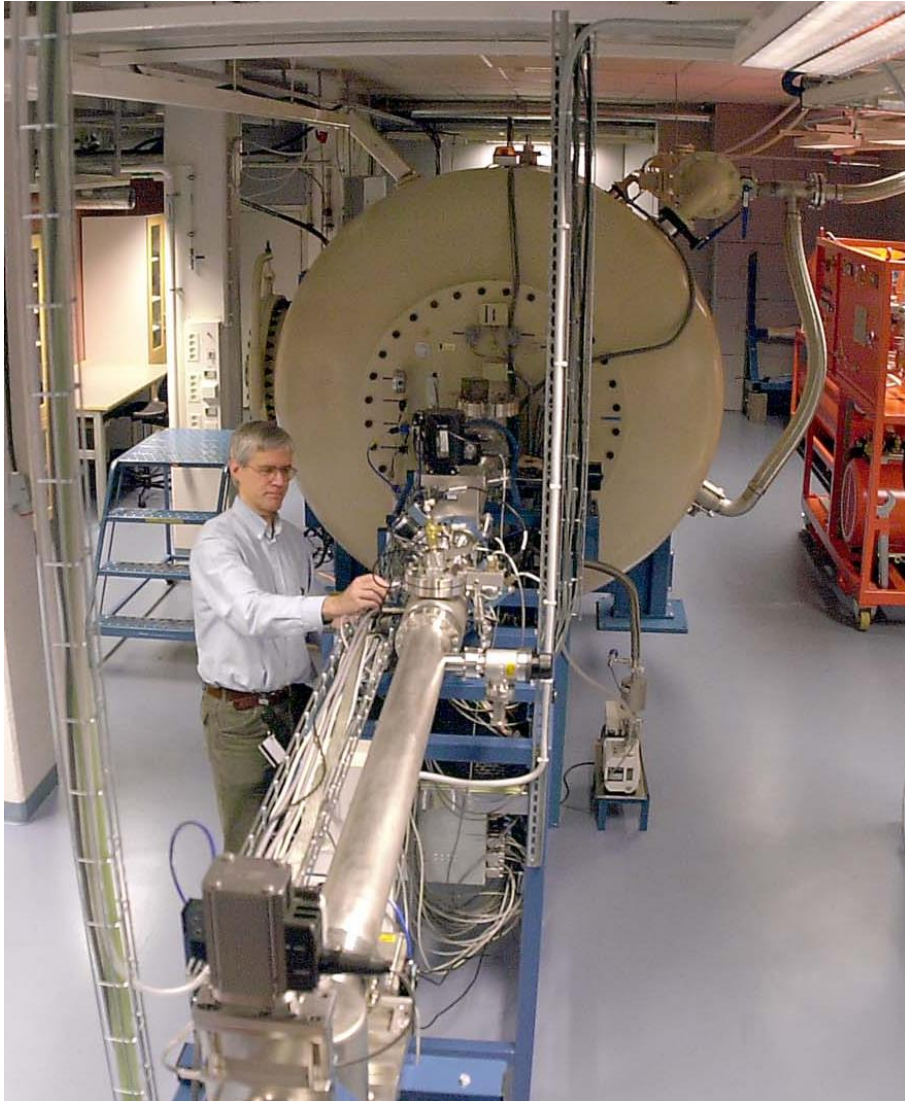
- ❖ *competent personnel,*
- ❖ *laboratories with relevant hardware,*
- ❖ *material handling capabilities,*
- ❖ *robust physics basis,*
- ❖ *data libraries,*
- ❖ *spectra analysis softwares,*
- ❖ *etc.*



# The Tandem Laboratory at Uppsala University

5 MeV Tandem

Beam lines with quadrupoles



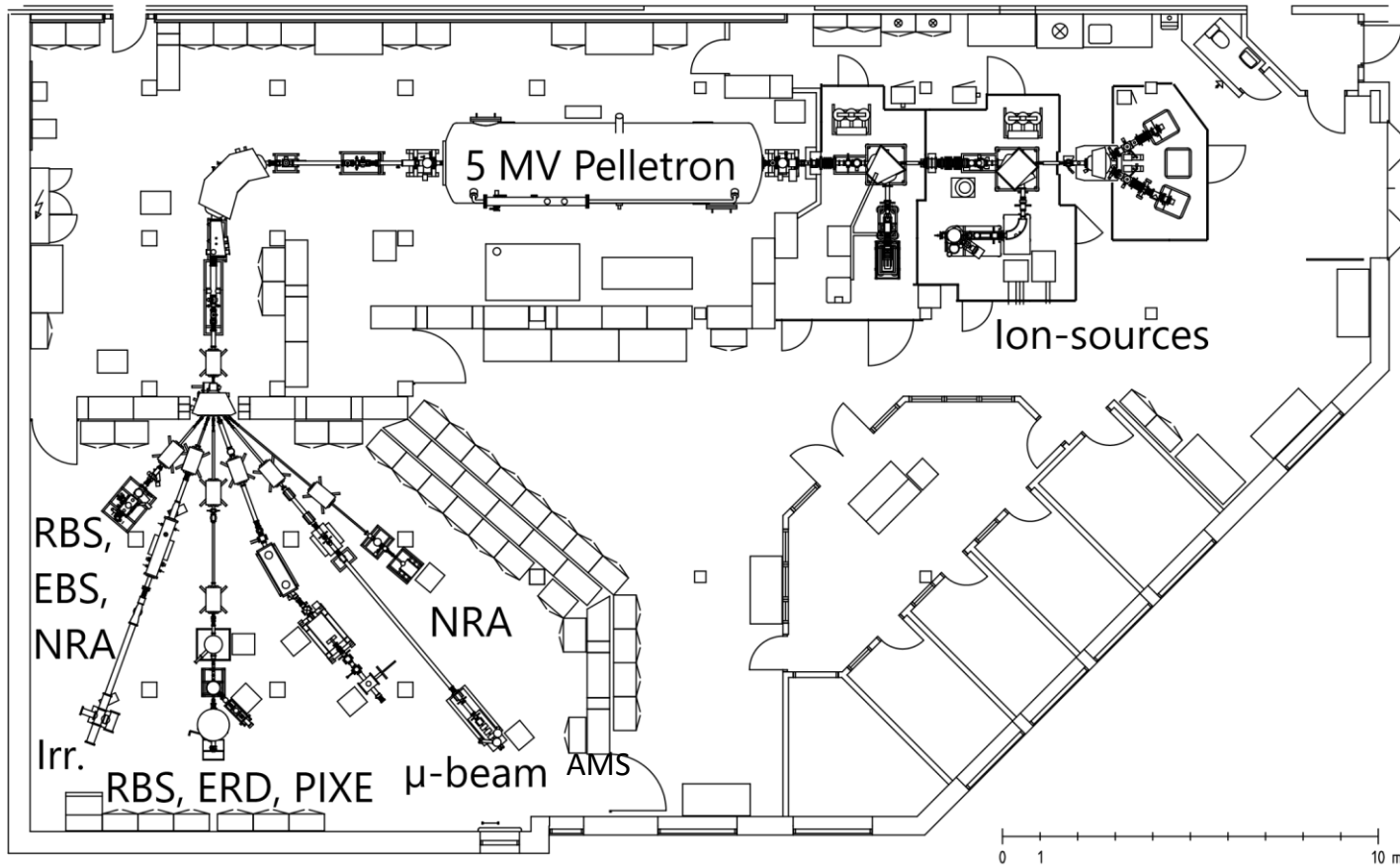
Surface analysis station



150 – 200 mm ports

# The Tandem Laboratory at Uppsala University

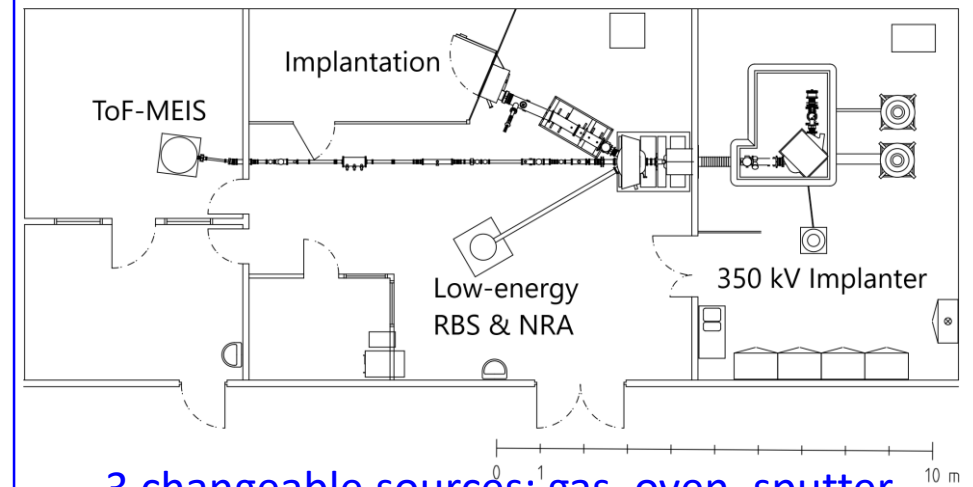
## 5 MV 15-SDH2 pelletron accelerator



2 gas & 2 sputter ion sources – beams of H, D,  $^3\text{He}$ ,  $^4\text{He}$ , C, N, O, Cu, Br, I, Au

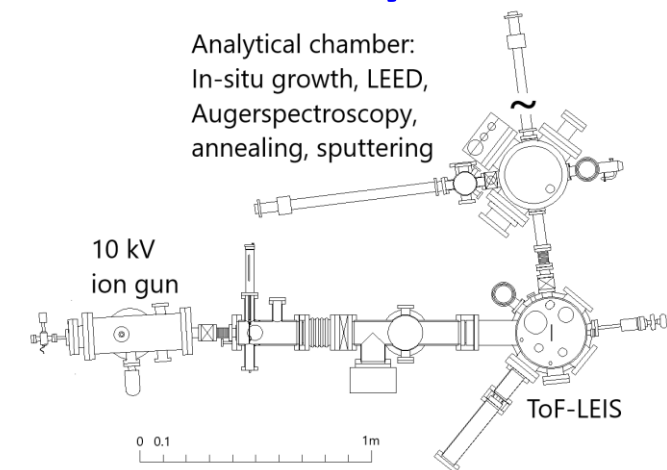
**Fusion-related research is carried out in all systems.**

## 350 kV Danfysik implanter



3 changeable sources: gas, oven, sputter

## ToF-LEIS system



# Ion Beam Analysis of Fusion Reactor Materials

## IAEA-initiated "inventory" of laboratories and capabilities

**"Ion Beam Analysis of fusion plasma-facing materials and components: Facilities and Research Challenges"**

*M. Mayer, S. Möller, M. Rubel, A. Widdowson, S. Charisopoulos et al., Nucl. Fusion 60 (2020) 025001.*

### Overview of:

- *13 laboratories with over 20 systems.*
- *Simulation softwares.*
- *Handling of contaminated materials.*
- *Impact of surface roughness.*
- *Discrepancy in the data bases.*
- *Future research needs.*

### A list of issues to address and solve:

- ☐ *Provision of facilities for handling of hazardous materials (T, activated samples, Be) for existing and future experiments, e.g. ITER.*
- ☐ *Standardisation of measurement and evaluation procedures;*
- ☐ *Determination and possibly evaluation of cross-sections and stopping powers for elements and isotopes with relevance for fusion;*
- ☐ *Round-robin test with fusion relevant samples.*

**Nucleation of CRP in that area.**



# Ion Beam Analysis of Fusion Reactor Materials

## IAEA-initiated "inventory" of laboratories and capabilities

**"Ion Beam Analysis of fusion plasma-facing materials and components: Facilities and Research Challenges"**

*M. Mayer, S. Möller, M. Rubel, A. Widdowson, S. Charisopoulos et al., Nucl. Fusion 60 (2020) 025001.*

### Overview of:

- 13 laboratories with over 20 systems.
- Simulation softwares.
- Handling of contaminated materials.
- Impact of surface roughness.
- *Discrepancy in the data bases.*
- *Future research needs.*

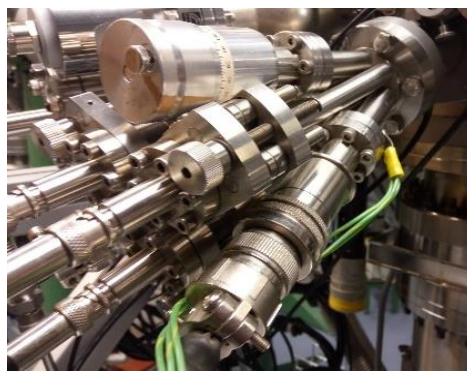
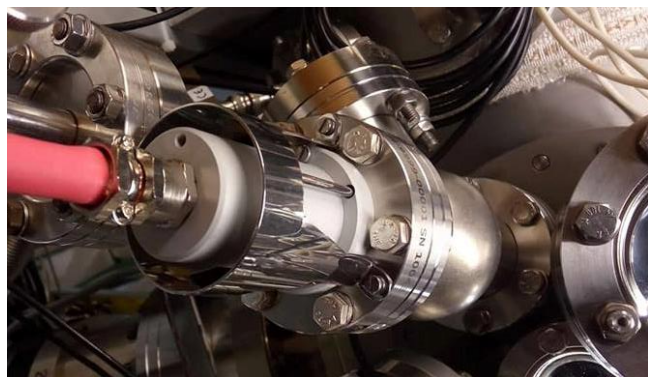
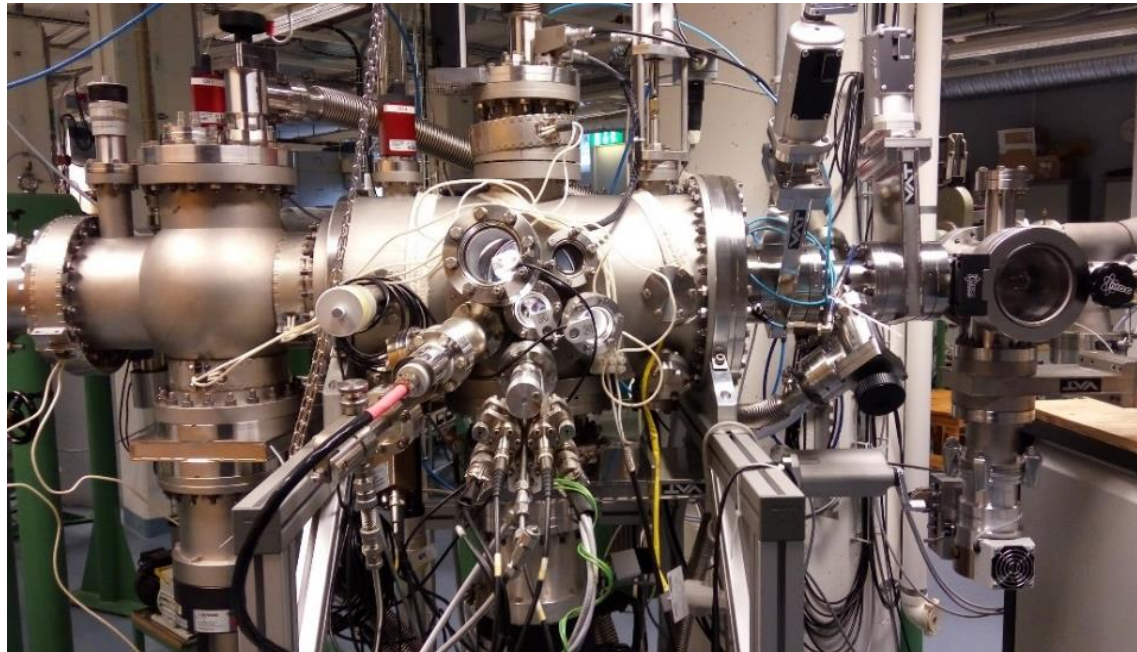
### A list of issues to address and solve:

- ❑ *Provision of facilities for handling of hazardous materials (T, activated samples, Be) for existing and future experiments, e.g. ITER.*
- ❑ *Standardisation of measurement and evaluation procedures;*
- ❑ *Determination and possibly evaluation of cross-sections and stopping powers for elements and isotopes with relevance for fusion;*
- ❑ *Round-robin test with fusion relevant samples.*



# The Tandem Laboratory at Uppsala University: Recent developments

## Multi-method capabilities: *In-situ* IBA & target modification



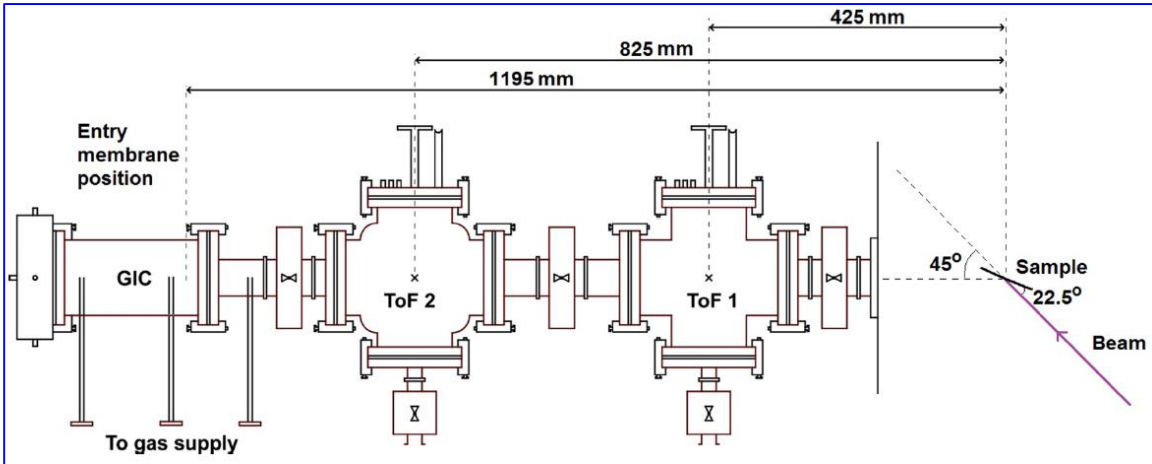
- IBA with light & heavy ions – RBS, NRA, PIXE, PIGE, ToF-ERDA
- Beam energies: 2 – 50 MeV
- Large viewport (e.g. optical characterization)
- Evaporation: 3 evaporation cells
- Sputtering: 1 – 5 keV ion gun
- Implantation
- Annealing & thermal desorption spectroscopy
- Gas analysers
- Gas feeds

*K. Kantre et al., Nucl. Instr. Meth. B (2020)*  
*P. Ström, D. Primetzhofer, JINST (2022)*

**Talk: Petter Ström, Session 9A**

# The Tandem Laboratory at Uppsala University: Recent developments

## Time of Flight Heavy Ion ERDA with a gas ionization chamber detector

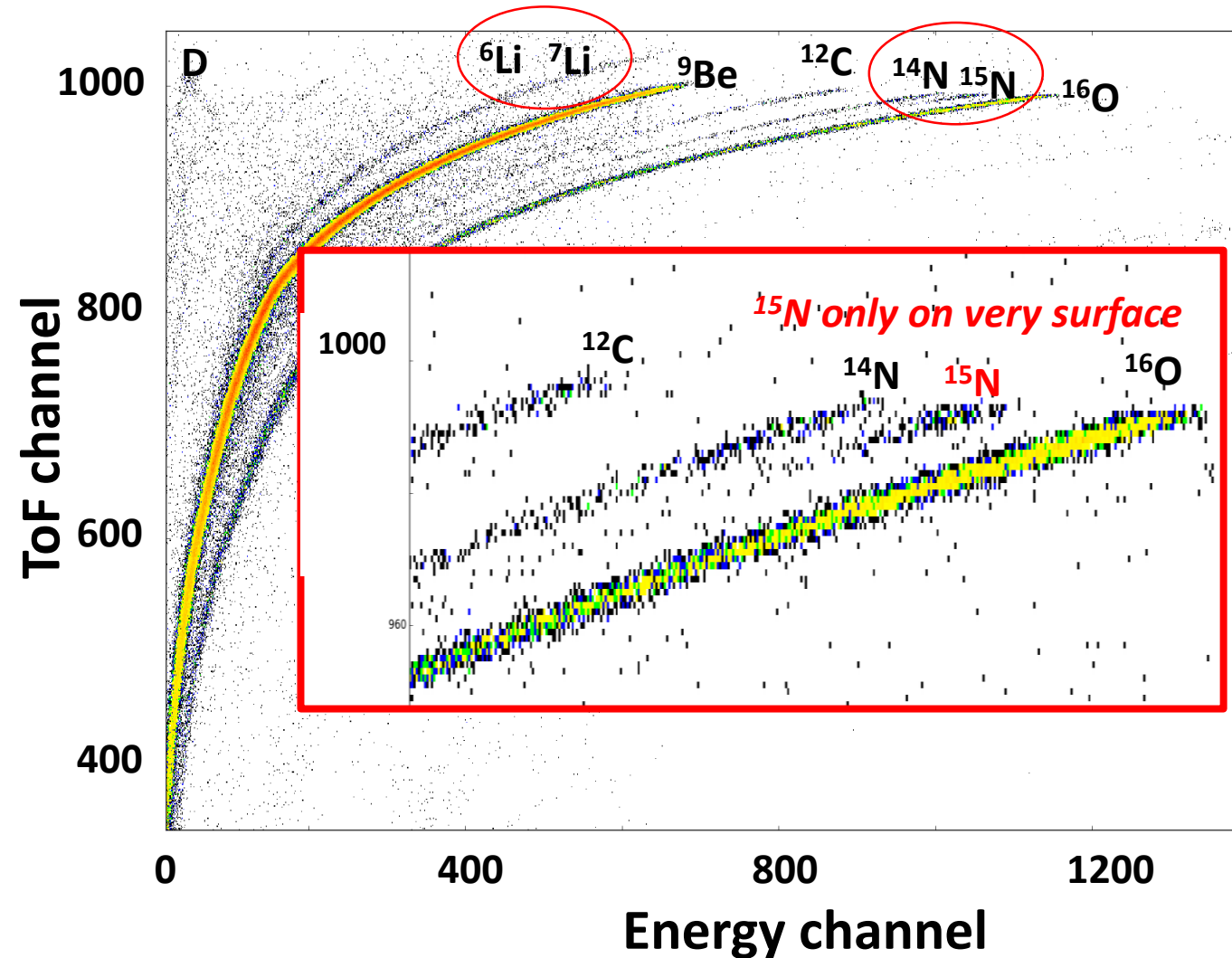


A perfect tool in material migration studies with tracer species:

$Li$ ,  $^{13}C$ ,  $^{15}N$ ,  $^{18}O$ ,  $^{21}Ne$

Talk: *Petter Ström (Session 9A)*

Poster: *Laura Dittrich (89)*



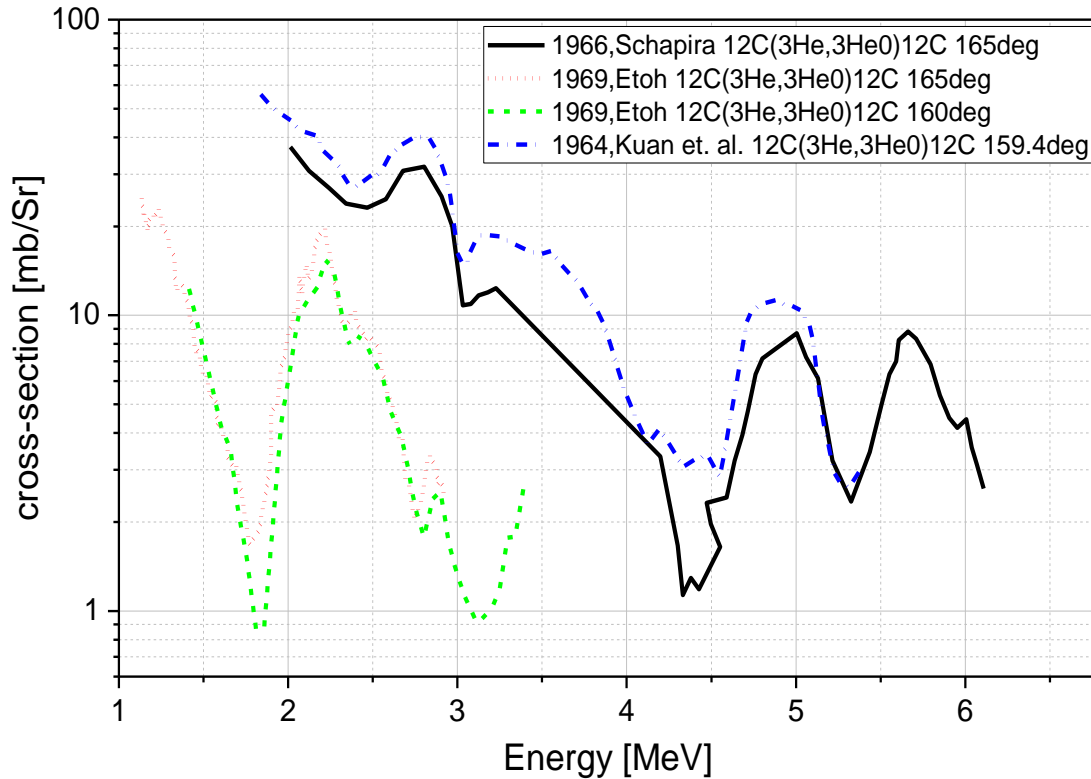
# ***Cross-sections***

# The role and impact of IAEA CRP: Definition of High Priority Measurements

Cross-section measurements of <sup>3</sup> He-induced reactions								
Target isotope:			<sup>7</sup> Li	<sup>9</sup> Be	<sup>10</sup> B	<sup>11</sup> B	<sup>12</sup> C	<sup>13</sup> C
³He beam energy range and recommended energy step			1 – 6 MeV (Step: ≤ 100 keV) Caution: consider resonance width, when found					
Range of angles to measure			120° – 175°					
Stopping power measurements								
Target element:			W		Be		Min. data points	
Beam	H	Beam energy range	20 keV – 2 MeV			30		
	He		40 keV – 8 MeV			25		
	Cu		1 -25 MeV			20		
	I		2 – 40 MeV			15		
Target type:			thin film, layer or bulk					

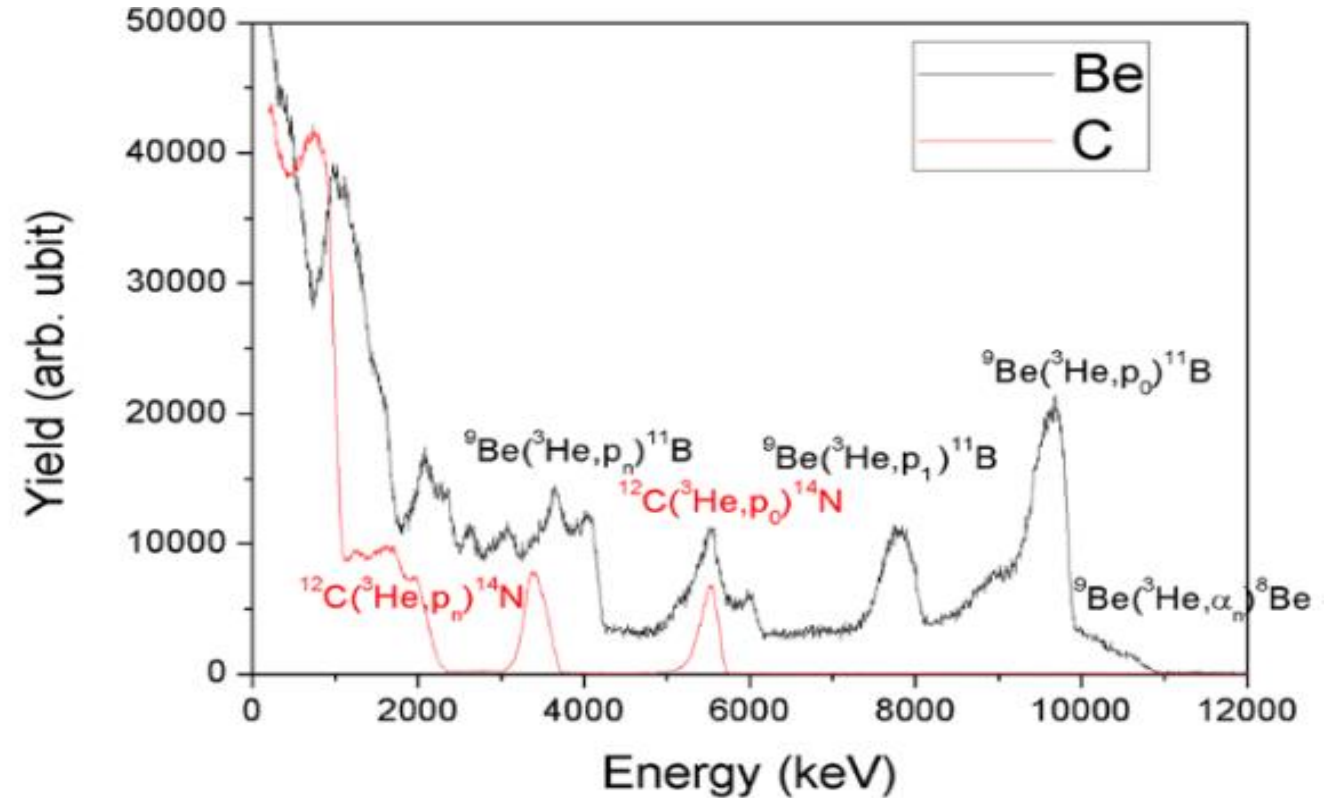
# IBA on C and Be: Motivation for research

## Non-Rutherford elastic scattering of $^3\text{He}$ on $^{12}\text{C}$



The cross-sections available on IBANDL exhibit differences over orders of magnitude in spite of similar conditions.

## 3MeV $^3\text{He}$ on pure targets: $^{12}\text{C}$ and $^9\text{Be}$

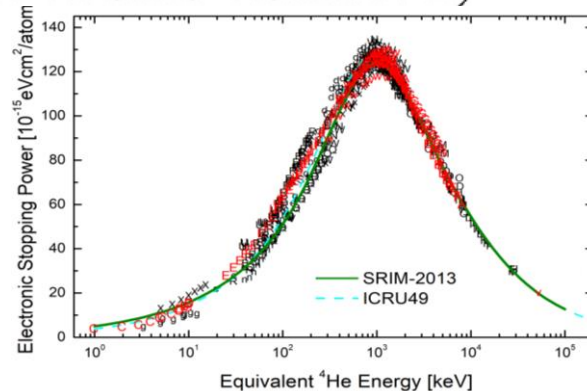
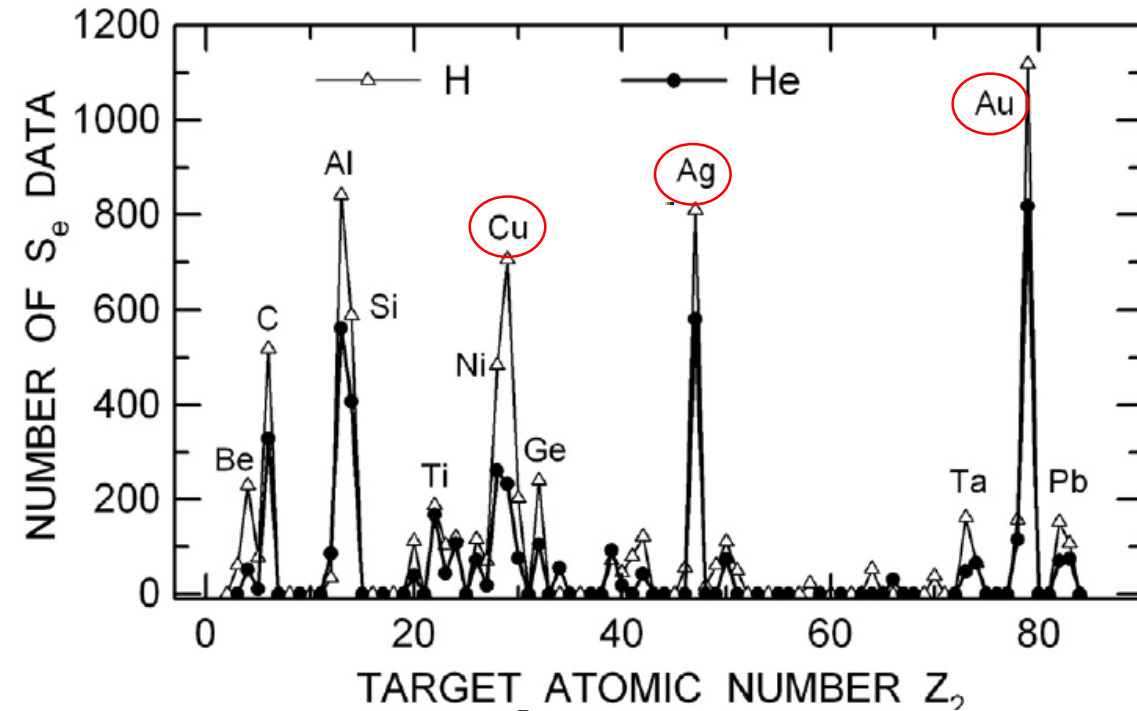


NRA spectra for  $^{12}\text{C}(^3\text{He}, p)^{14}\text{N}$  and  $^9\text{Be}(^3\text{He}, p)^{11}\text{B}$ , (scattering angle  $170^\circ$ ).

→ Not possible to determine C on the Be-rich surface.

# Why still studying stopping power?

Availability of data and predictions.



$^3,^4\text{He}$  on Au

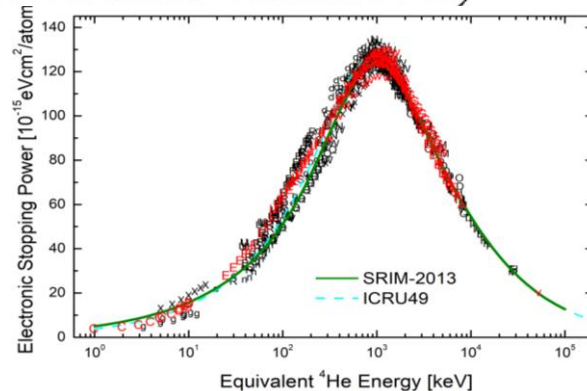
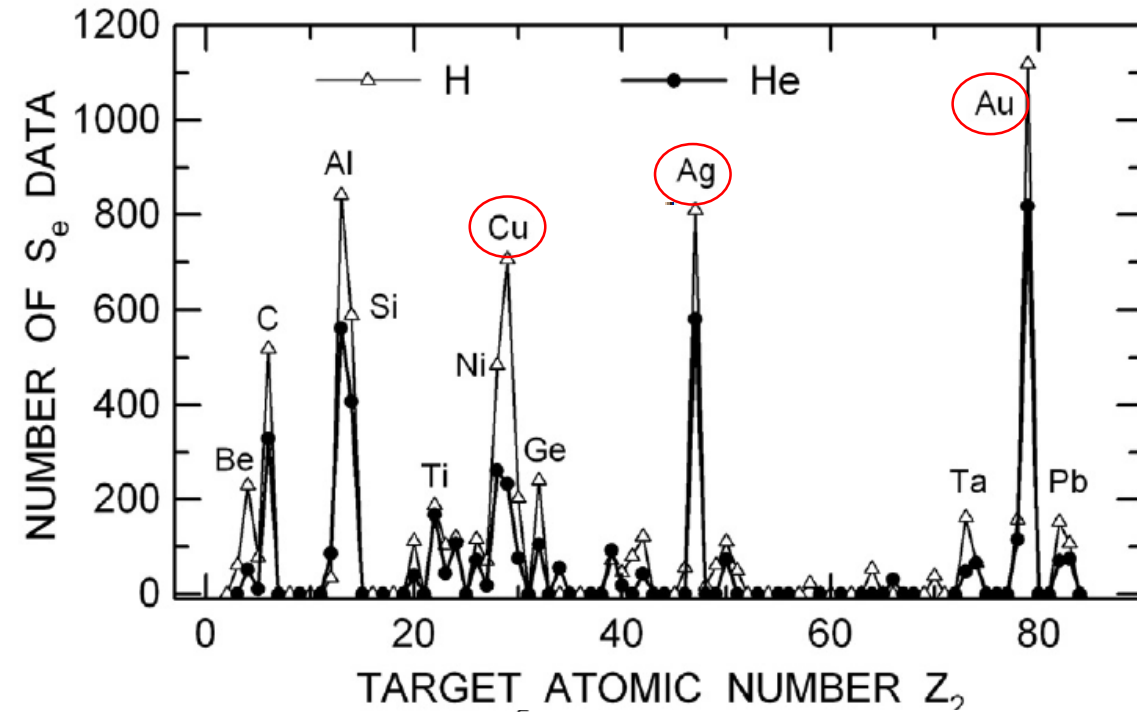
Exp. 1950-1989 → 580

Exp. 1990-today → 250

K. Wittmaack, *NimB* (2016)

# Why still studying stopping power?

Availability of data and predictions.



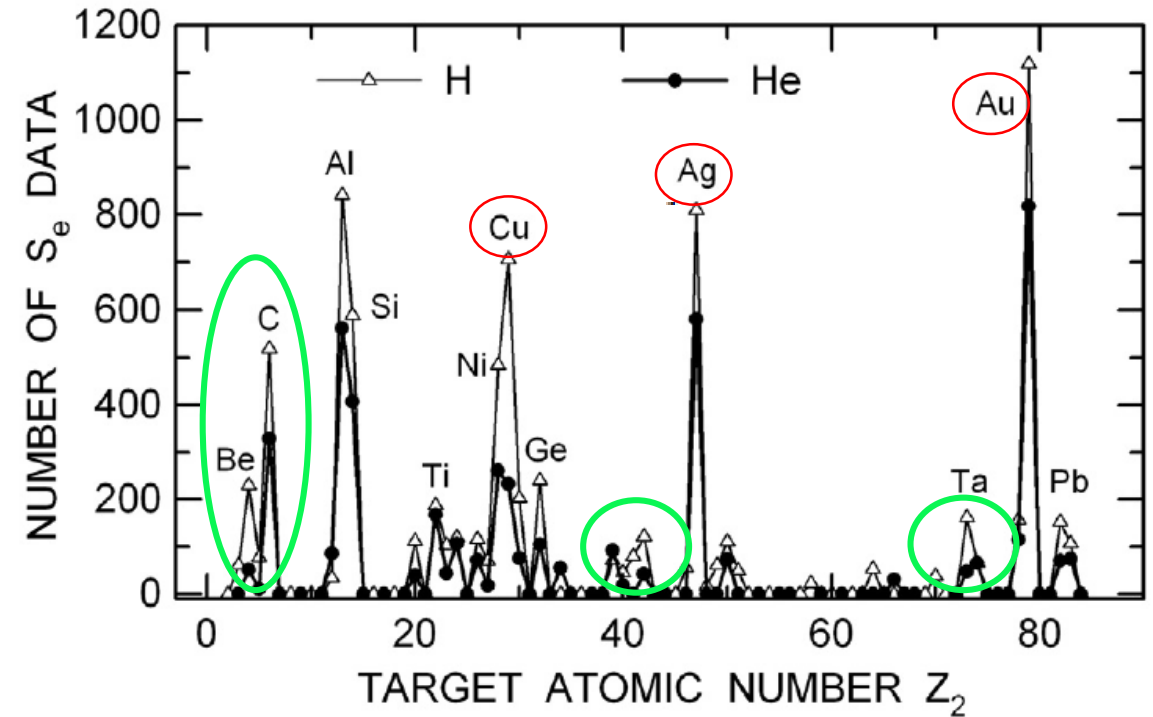
$^3\text{He}$ ,  $^4\text{He}$  on Au

Exp. 1950-1989 → 580

Exp. 1990-today → 250

K. Wittmaack, *NimB* (2016)

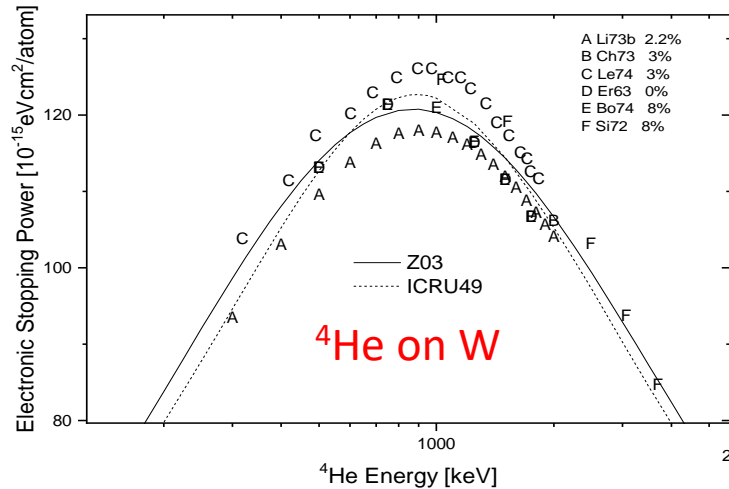
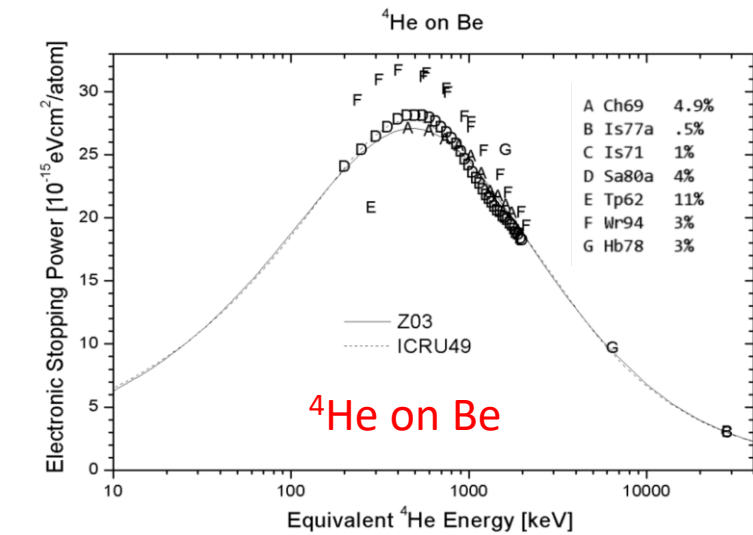
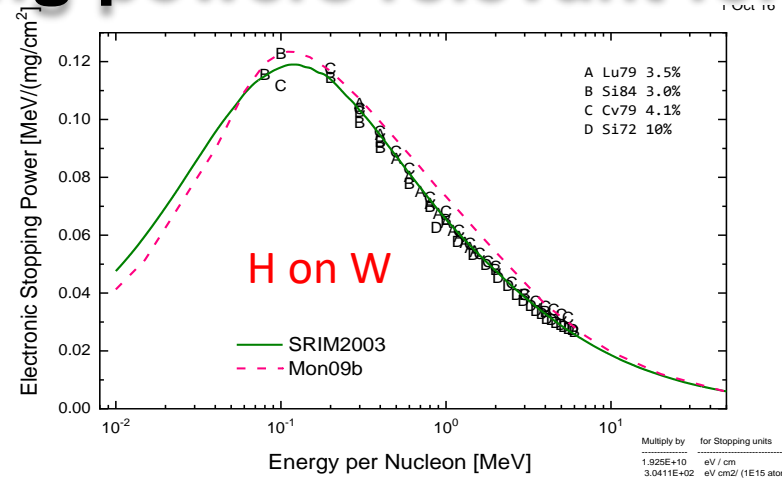
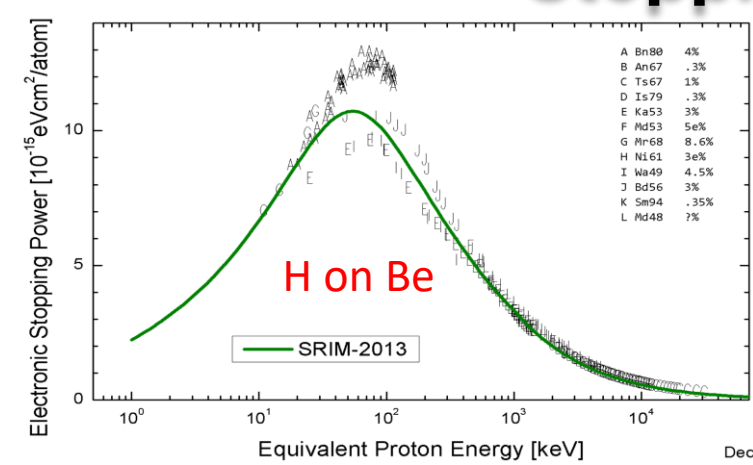
Situation in the fusion world...



Needs: Be, W (and Mo)

Poster: Norberto Catarino

# Stopping powers relevant for fusion

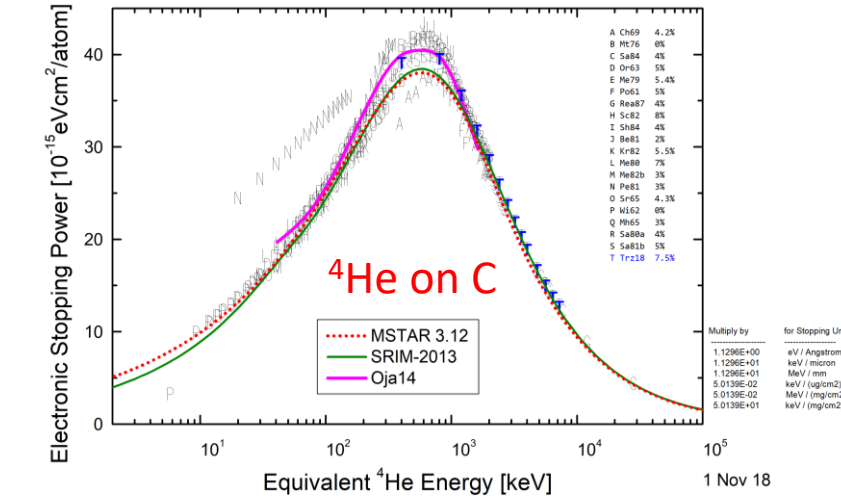
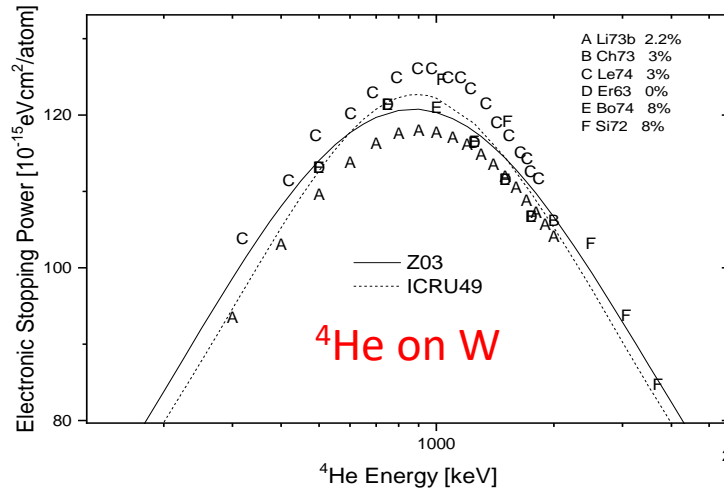
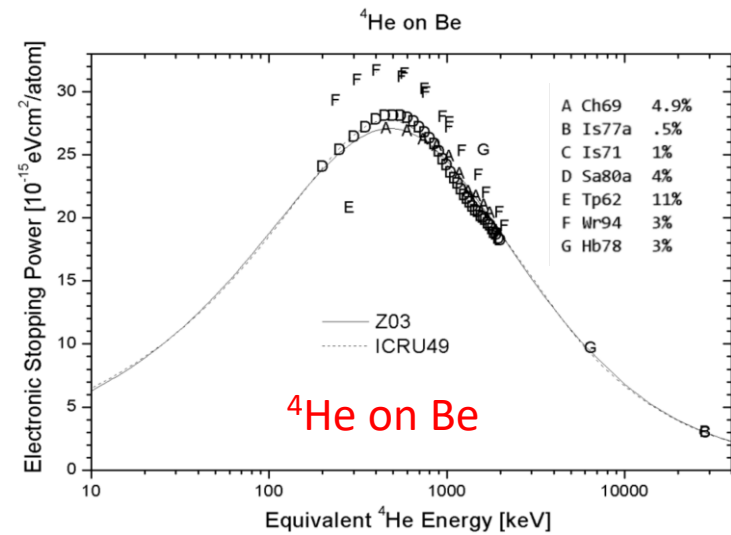
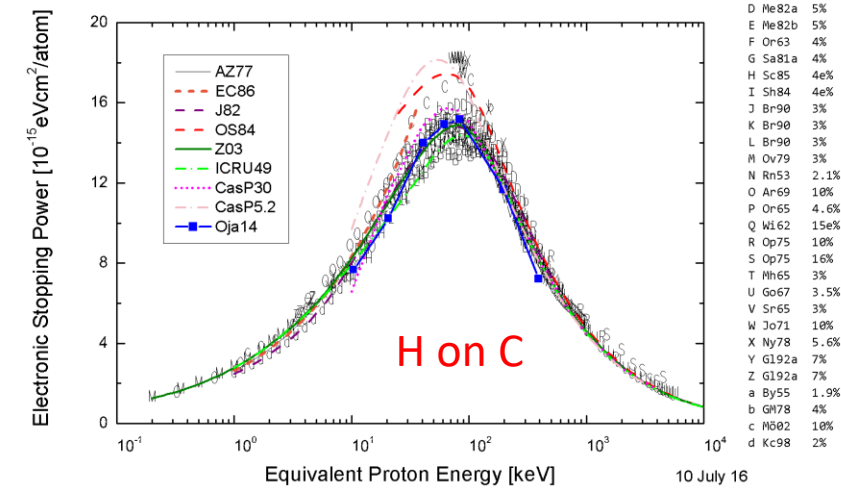
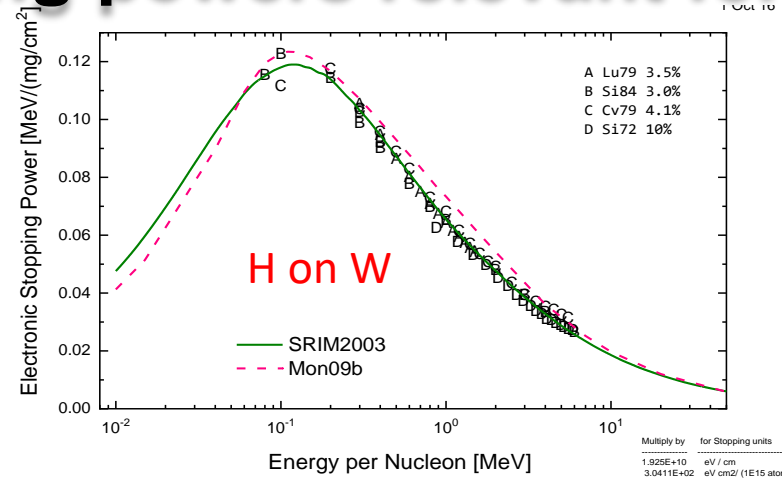
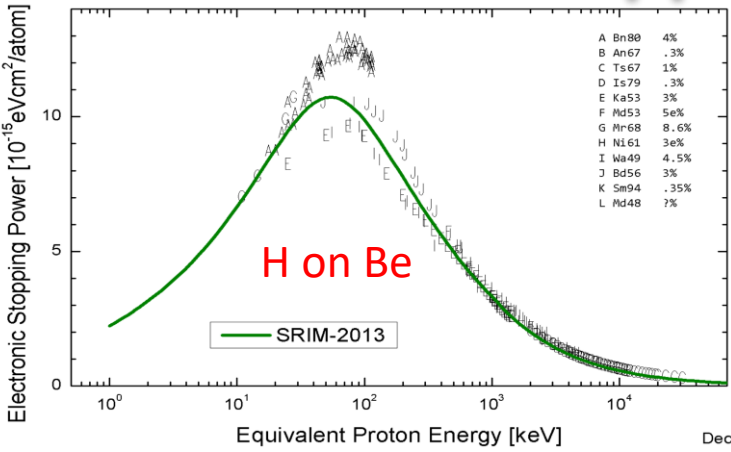


- Be, W (and Mo): *Limited data at low energies for both protons and He-ions.*
- *For classical IBA-energies two distinct datasets – SRIM represents an average.*

# Stopping powers relevant for fusion

Amorphous C

A	Be81	4e%
B	Kr82	10%
C	He80	6%
D	He82a	5%
E	He82b	5%
F	Or63	4%
G	Se81a	4%
H	Sc85	4e%
I	Sh84	4e%
J	Br90	3%
K	Br90	3%
L	Br90	3%
M	Ov79	3%
N	Rn53	2.1%
O	Ar69	10%
P	Or65	4.6%
Q	Wi62	15e%
R	Op75	10%
S	Op75	16%
T	Mh65	3%
U	Go67	3.5%
V	Sr65	3%
W	Jo71	10%
X	Ny78	5.6%
Y	GL92a	7%
Z	GL92a	7%
a	By55	1.9%
b	Gr78	4%
c	M082	10%
d	Kc98	2%



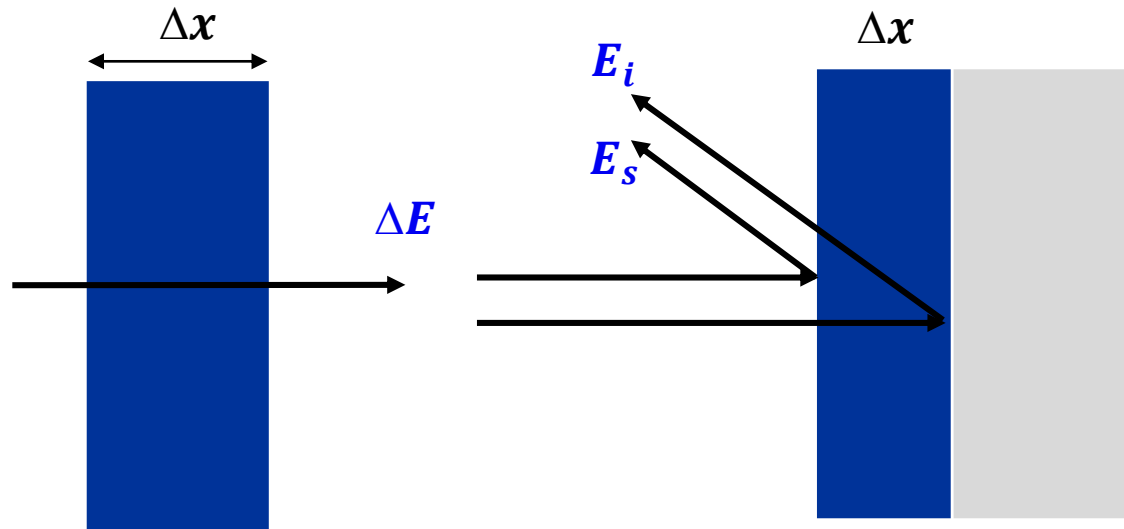
- Be, W (and Mo): Limited data at low energies for both protons and He-ions.
- For classical IBA-energies two distinct datasets – SRIM represents an average.

- Rich data base for protons.
- Limited data base for He low energies.
- Discrepancy by differences in C structure



# Stopping powers: measurements and sources of discrepancy

Transmission, backscattering, relative measurements, ...



$$\frac{dE}{dx} \approx \frac{\Delta E}{\Delta x}$$

$$\Delta E_{\text{RBS}} = n\Delta x[\varepsilon] \quad H = \frac{A}{\Delta E_{\text{RBS}}} / \propto \frac{d\sigma/d\Omega}{[\varepsilon]}$$

Most straightforward approach

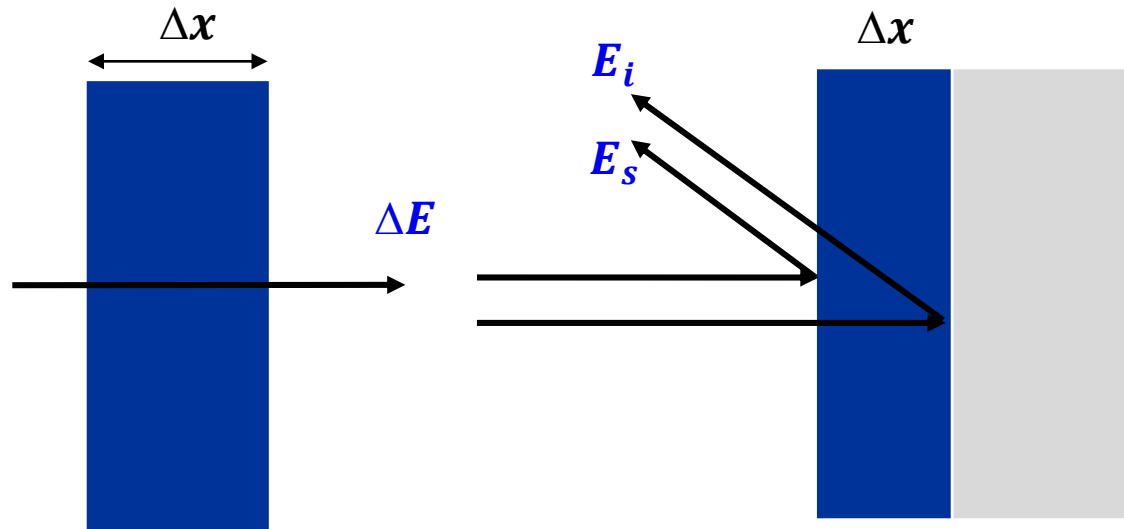
- A bit more complex formalism

Requires self-supporting films

- Films on backing sufficient

# Stopping powers: measurements and sources of discrepancy

Transmission, backscattering, relative measurements, ...



$$\frac{dE}{dx} \approx \frac{\Delta E}{\Delta x}$$

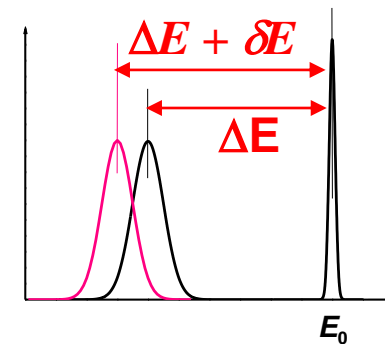
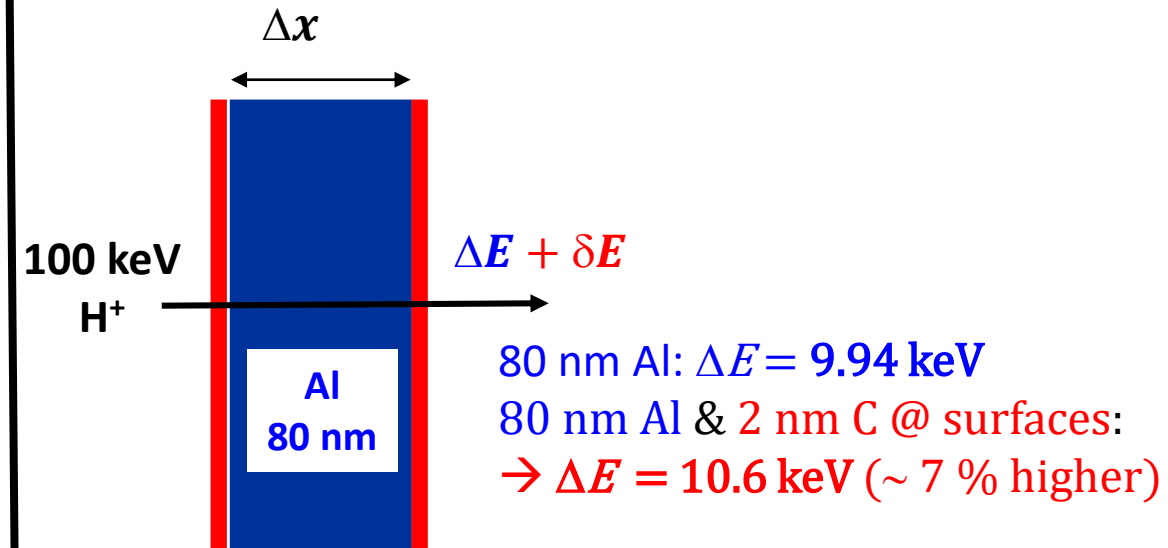
$$\Delta E_{\text{RBS}} = n\Delta x[\varepsilon] \quad H = \frac{A}{\Delta E_{\text{RBS}}} / \propto \frac{d\sigma/d\Omega}{[\varepsilon]}$$

Most straightforward approach

Requires self-supporting films

- A bit more complex formalism
- Films on backing sufficient

Issues with surface purity.



$$\frac{dE}{dx} \approx \frac{\Delta E + \delta E}{\Delta x}$$

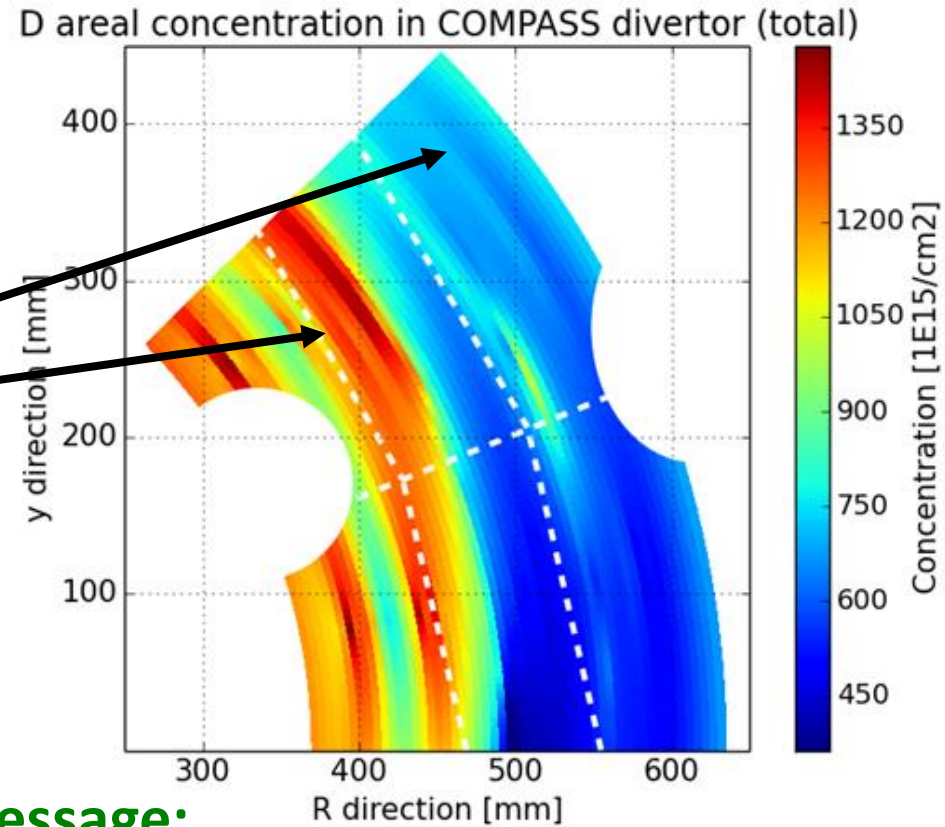
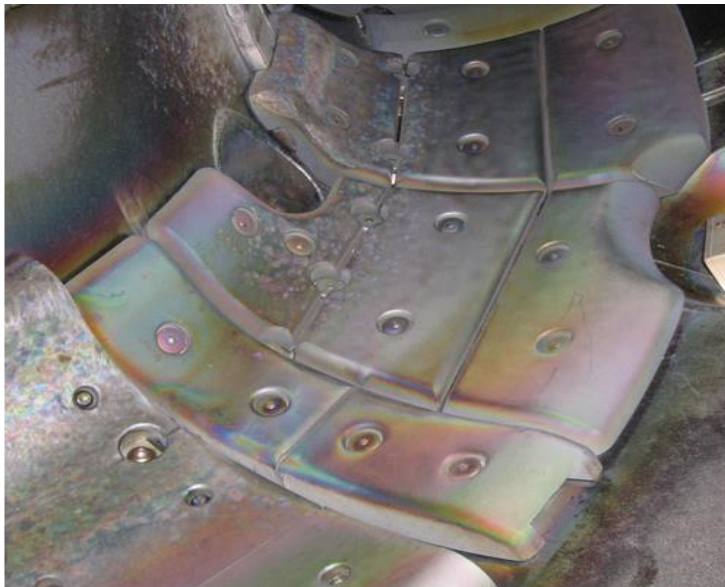
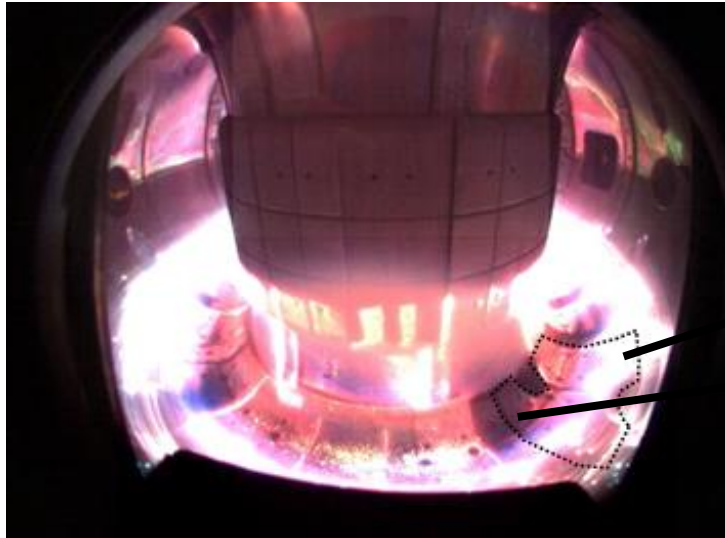
# Stopping powers: reasons for inaccurate data

- **Sample purity and cleanliness:**
  - ❖ *bulk contaminants,*
  - ❖ *surface contaminants.*
- **Sample microstructure:**
  - ❖ *channeling and texture,*
  - ❖ *material density issues.*
- **Treatment of nuclear stopping & multiple scattering:**
  - ❖ *how to evaluate?*
  - ❖ *what to subtract?*
- **Generally extensive characterization using ERD and/or NRA is highly recommended.**



# ***Knowledge in practice***

# COMPASS tokamak: Deuterium retention pattern



**Message:**  
Highly non-uniform D distribution.

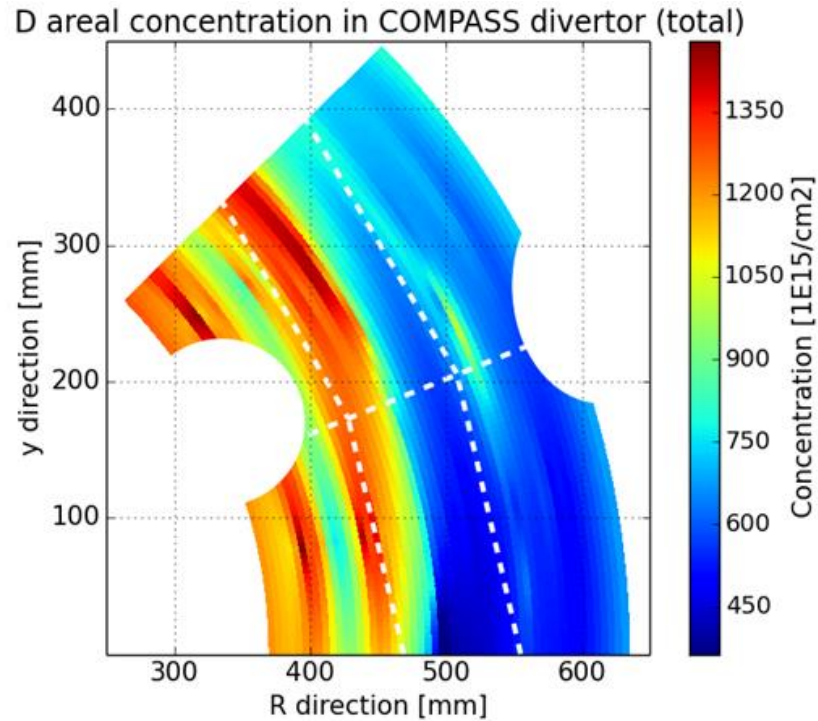
*A Weckmann et al.,  
Fusion Eng. Des. 2022*

## Questions:

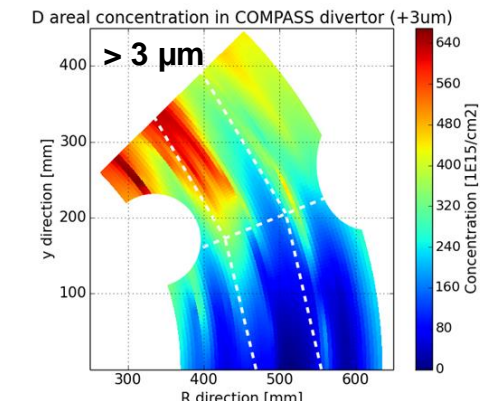
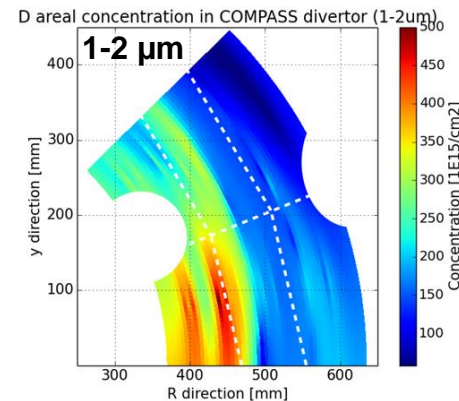
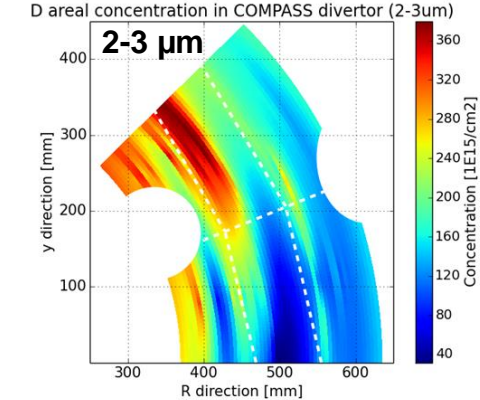
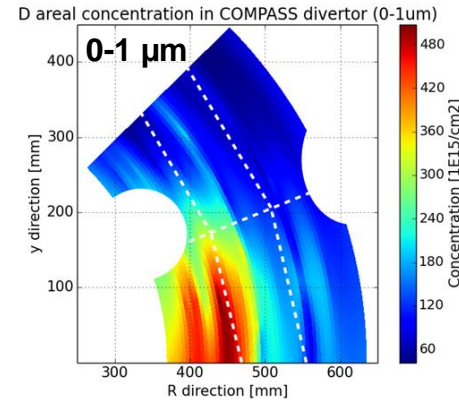
Is there a correlation with operation parameters?  
What is the impact of the operation scenario?

# COMPASS tokamak: Deuterium retention studies

## Total pattern



## Details of deposition: In depth



## Why the pattern has changed?

- The change of magnetic field direction in the middle of experimental campaign.
- This is how IBA contributes to the integrated picture: impact of operation history (archeology).

*A Weckmann et al.,  
Fusion Eng. Des. 2022*

# Pitfalls and traps in IBA of reactor materials

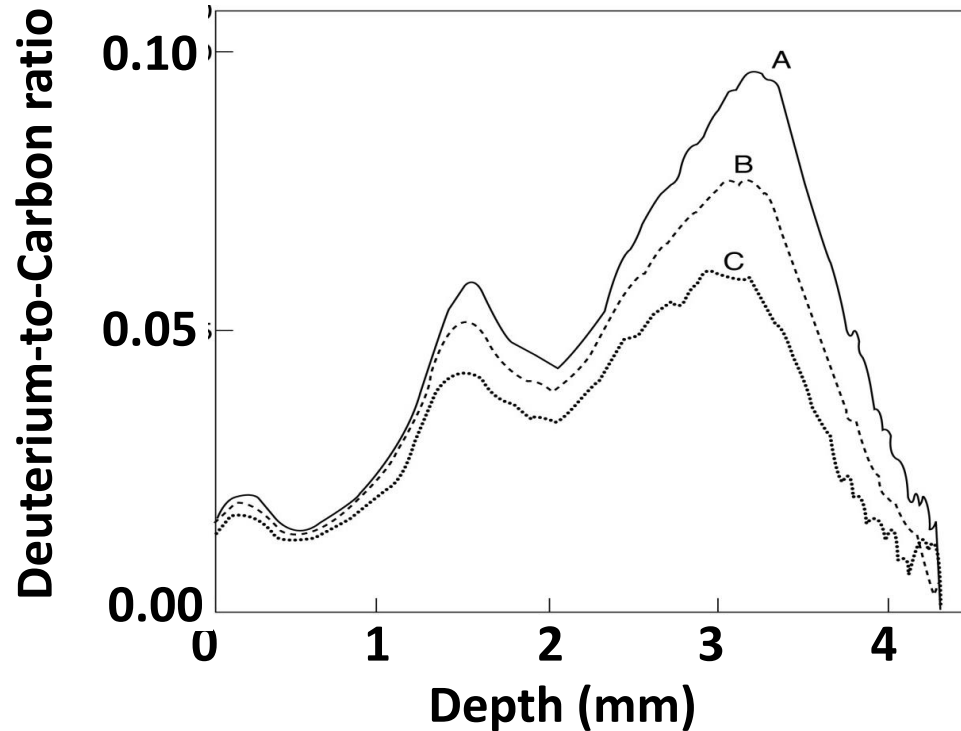
Are there any banana peels?



- Ion-induced detrapping of deuterium in NRA:  $d(^3\text{He}, p)^4\text{He}$
- Surface roughness: primary and induced

# $^3\text{He}$ -induced detrapping of deuterium

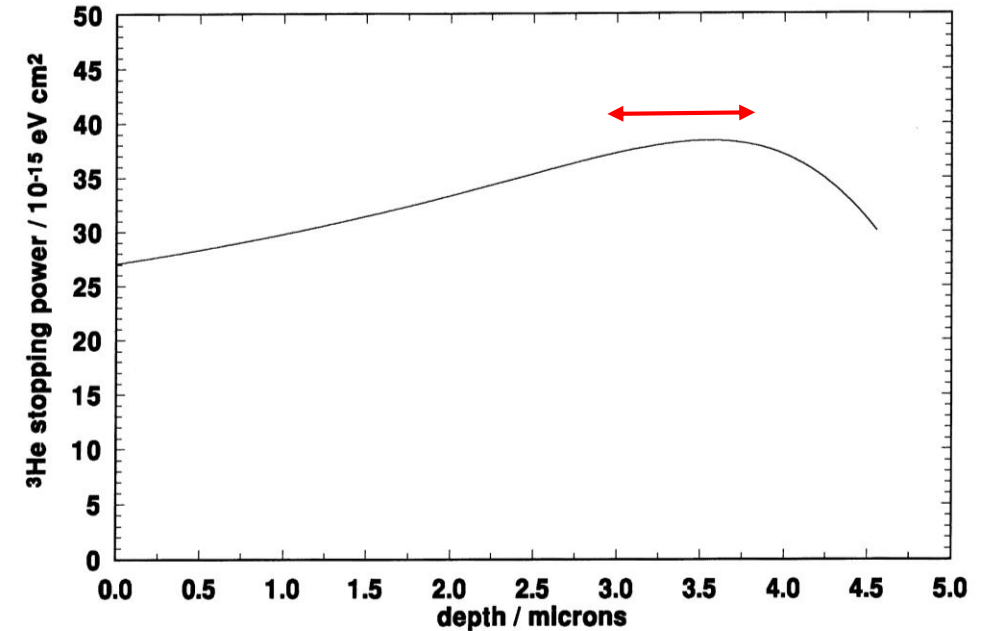
The change of D profile under irradiation with increasing dose of  $^3\text{He}^+$ , 1500 keV



- A.  $\Phi = 4.7 \times 10^{14} \text{ cm}^{-2}$   $C_D = 2.57 \times 10^{18} \text{ cm}^{-2}$   
C.  $\Phi = 4.7 \times 10^{16} \text{ cm}^{-2}$   $C_D = 1.40 \times 10^{18} \text{ cm}^{-2}$

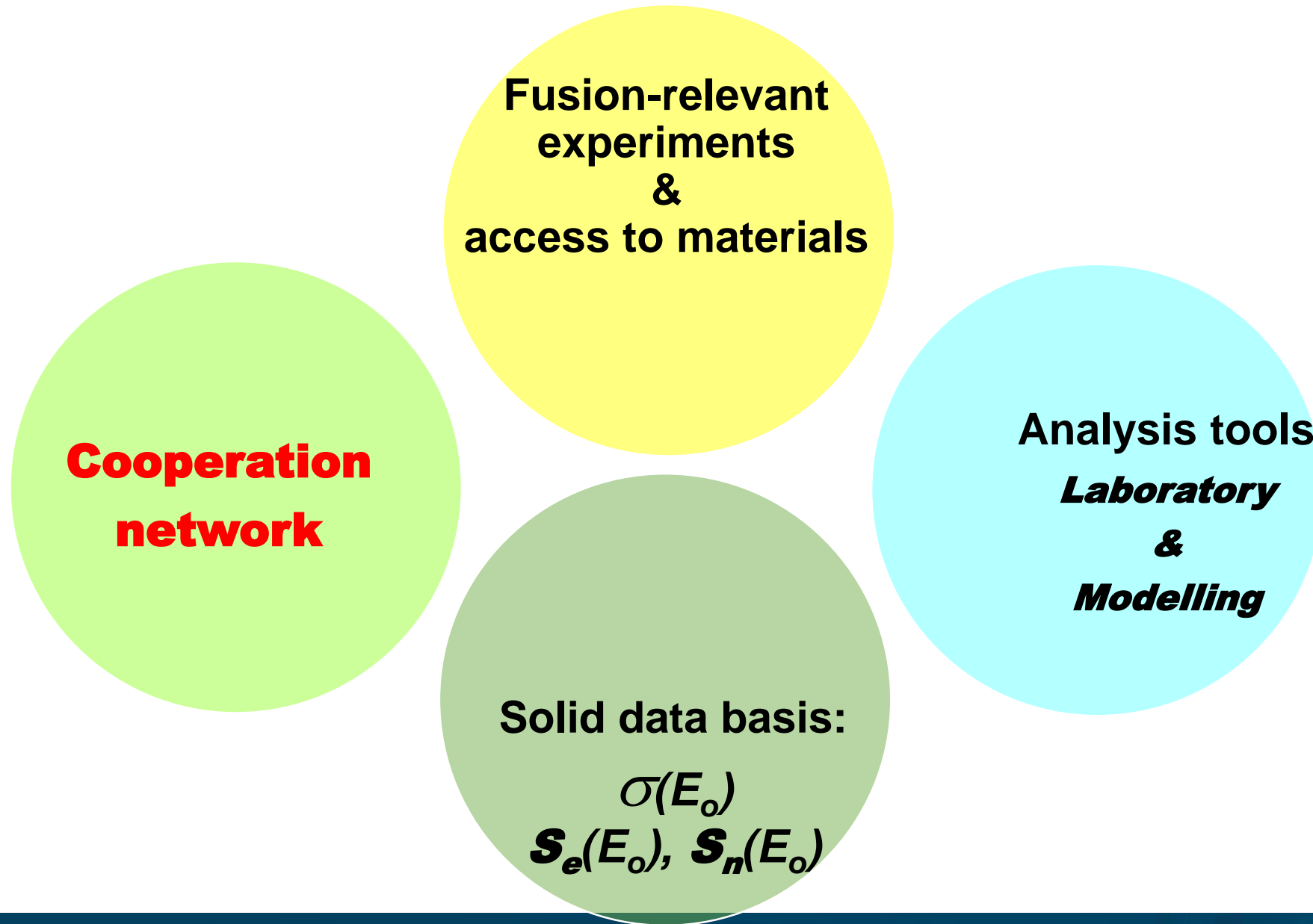
> 45 % deuterium detrapped.  
Maximum release at 3.2-3.4  $\mu\text{m}$

$^3\text{He}$  electronic stopping in carbon matrix

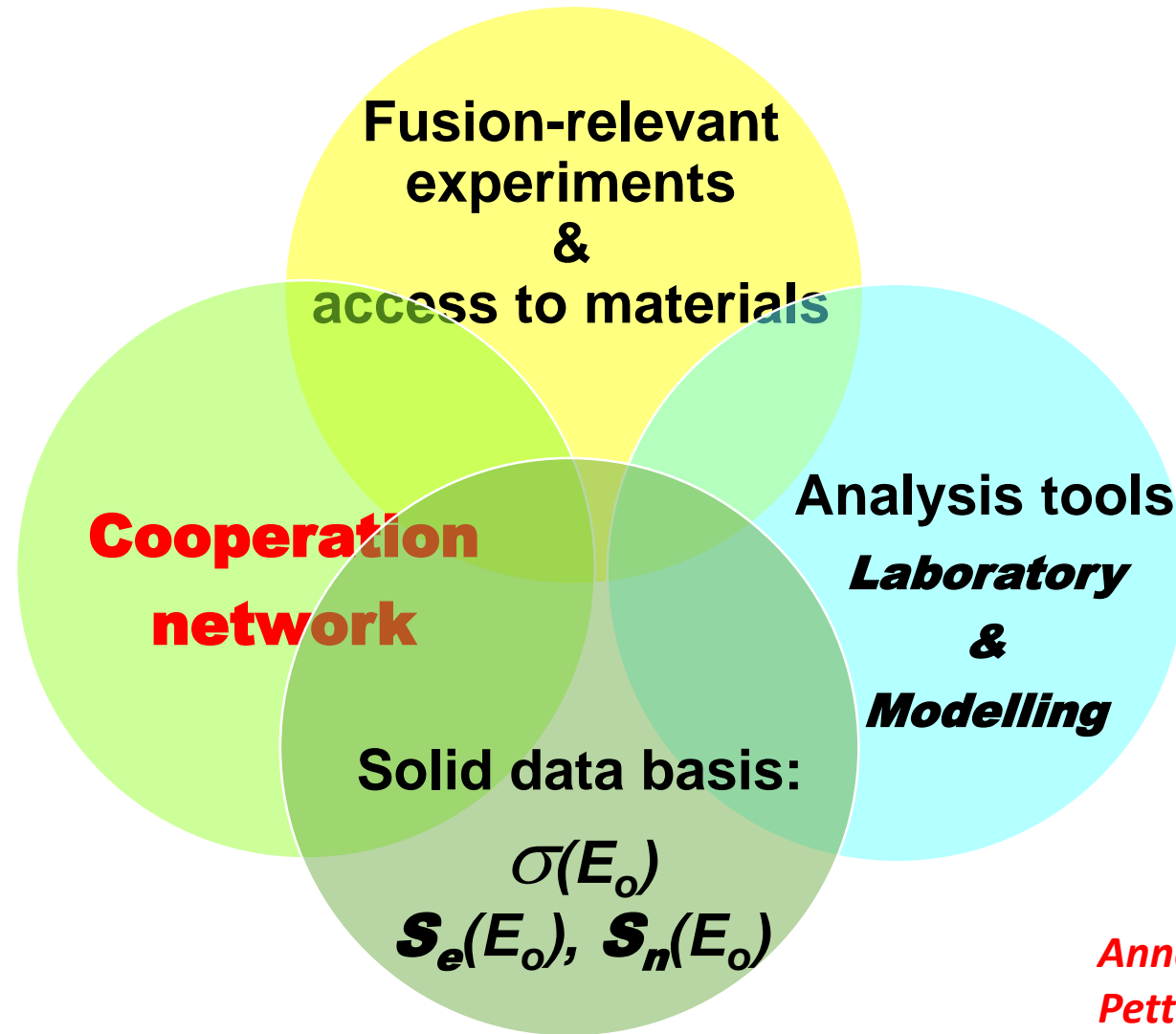


*Detrapping occurs mostly  
via electronic excitation.*

# Integrated program on studies of plasma-facing materials and components



# Integrated program on studies of plasma-facing materials and components



*Anna Widdowson, Session 9A*  
*Petter Ström, Session 9A*  
*Laura Dittrich, Poster*

Thank you

## Acknowledgements

The IAEA support is highly acknowledged.

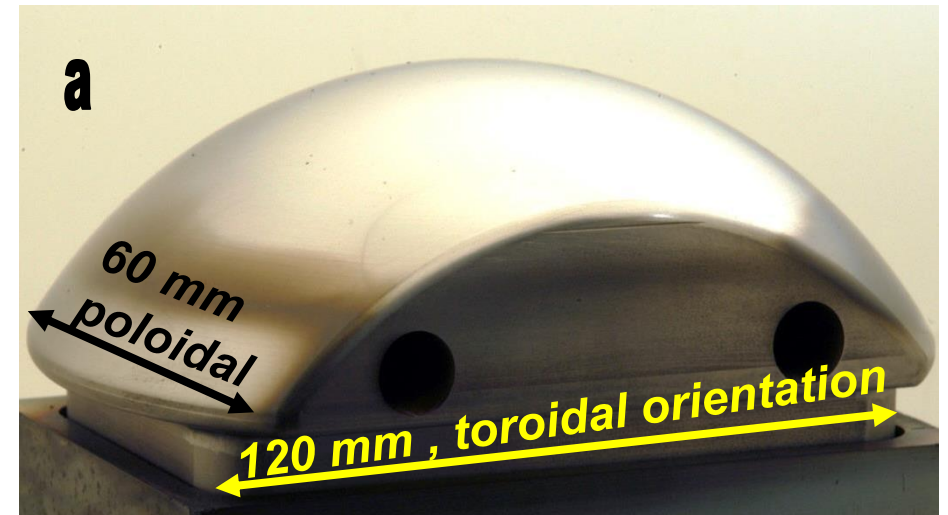
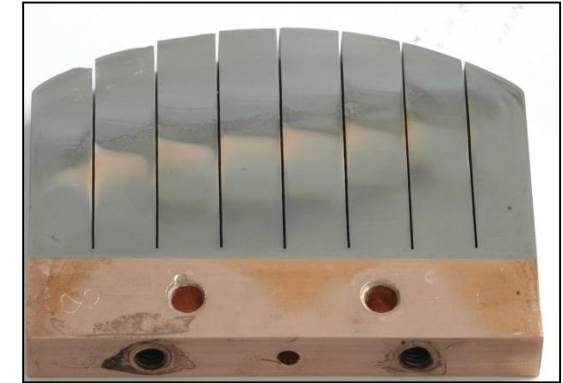
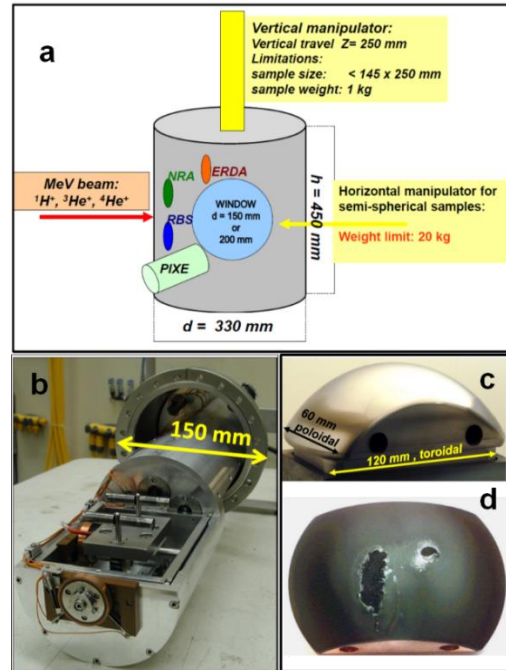
INTERNATIONAL CONFERENCE ON

# ACCELERATORS FOR RESEARCH AND SUSTAINABLE DEVELOPMENT

From good practices towards socioeconomic impact



# What do we study?



# Stopping powers relevant for fusion: Analysis of the situation

Target	H-ions	He-ions
Be	No data below 10 keV – no reliable data below 1 MeV	No data below 200 keV
C	Lot's of data	Lot's of data – but limitations at low energies
Mo	No data below 50 keV – data spread in the stopping maximum	Only one low-energy dataset – spread in the stopping maximum
W	No data below 100 keV	No data below 300 keV – 2 datasets differing by 10% at classical IBA energies