APPLICATION OF ACCELERATOR TECHNIQUES FOR CHARACTERISATION OF WALL MATERIALS IN CONTROLLED FUSION REACTORS

Marek Rubel[1,2], <u>Sotirios Charisopoulos</u>[3], Per Petersson[1], Eduardo Pitthan[2], Daniel Primetzhofer[2], Anna Widdowson[4]

[1]KTH Royal Institute of Technology, Stockholm, Sweden

[2]Physics and Astronomy, Uppsala University, Uppsala, Sweden

[3]International Atomic Energy Agency, Physics Section, Vienna, Austria

[4]Culham Centre for Fusion Energy, Abingdon, United Kingdom

Int. Topical Meeting on Nuclear Applications of Accelerators

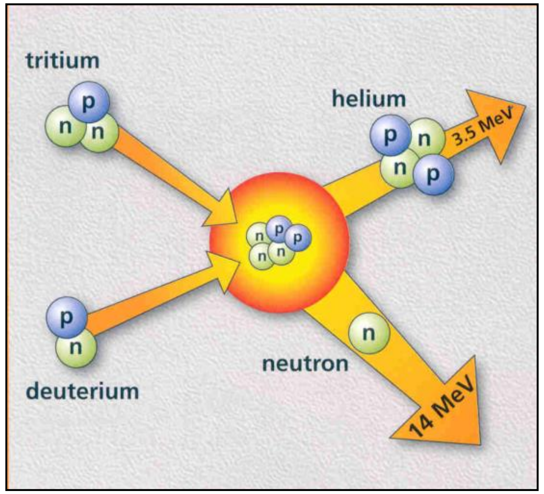
Norfolk, March 2024

A brief introduction to the title and topic of the talk

- ***Controlled Fusion and Devices***
- ***Plasma-Facing Materials and Components***

Nuclear and Material Aspects of Deuterium – Tritium Fusion

Choice of process is based on analysis of reaction cross-section.



D + T → α (3.5 MeV) + n (14.1 MeV)

- α → **Ash**
- 3.5 MeV → **Plasma heating**
- 14.1 MeV → **Energy production**

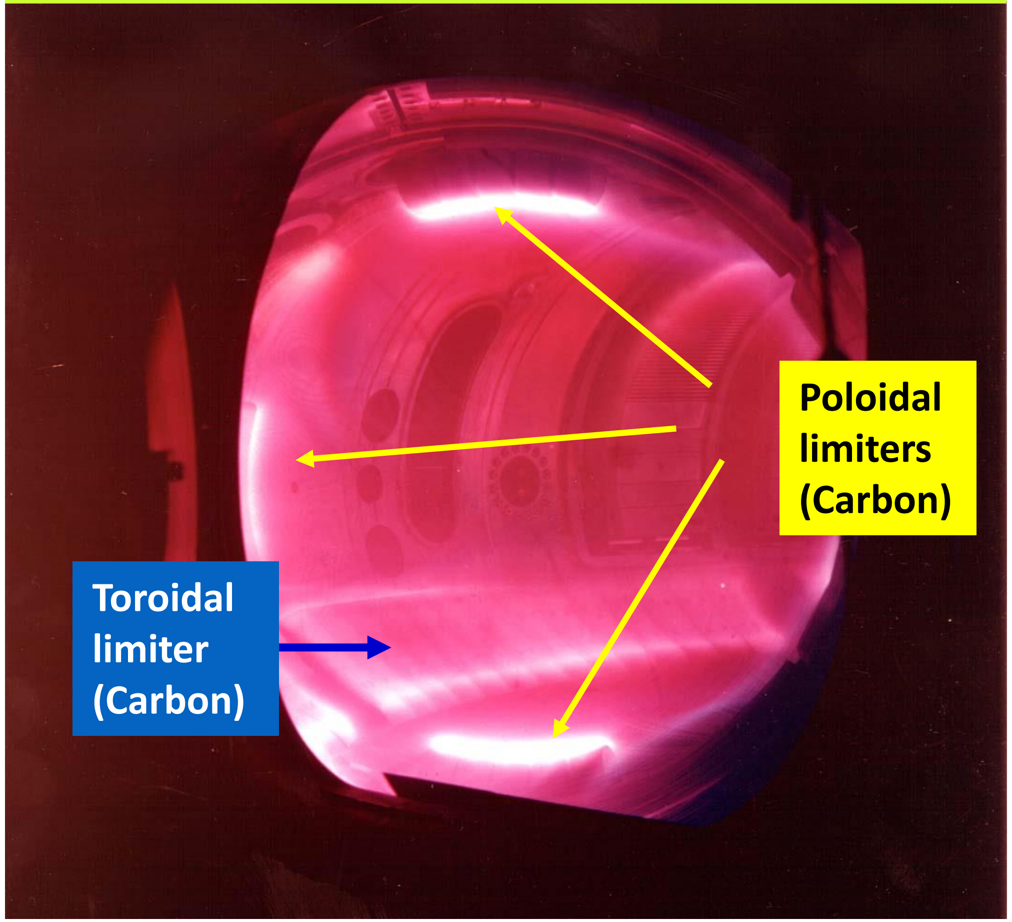
Important consequences in reactor operation:

- **Power and particle exhaust**
- **Radioactivity**

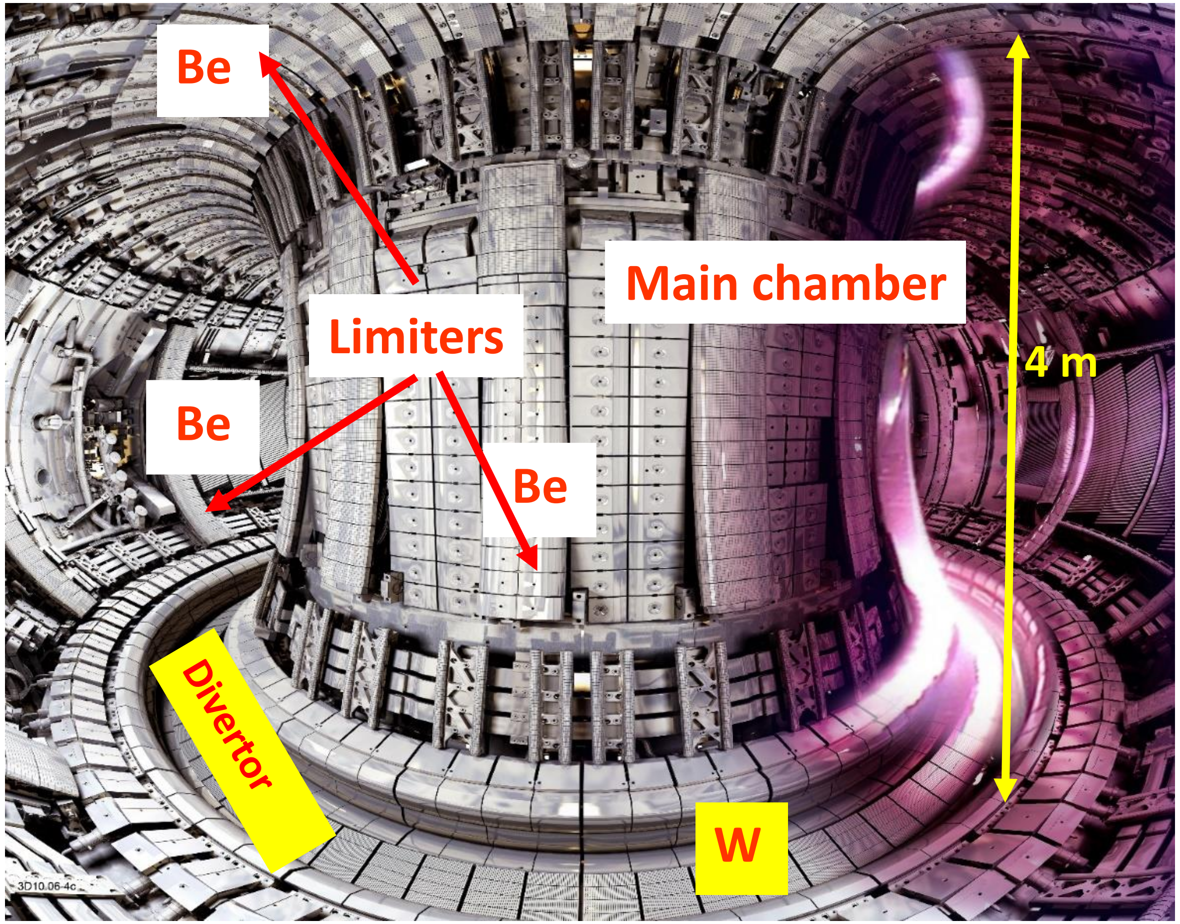
} **Impact on wall materials**

Plasma-facing wall in fusion devices: Tokamaks

TEXTOR: *operation 1982-2013*



JET: Joint European Torus: *the largest tokamak (1983- 2023)*

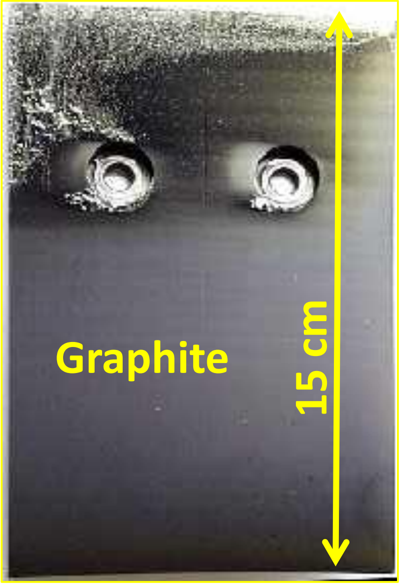


High complexity of the plasma-facing wall: composition and structure.

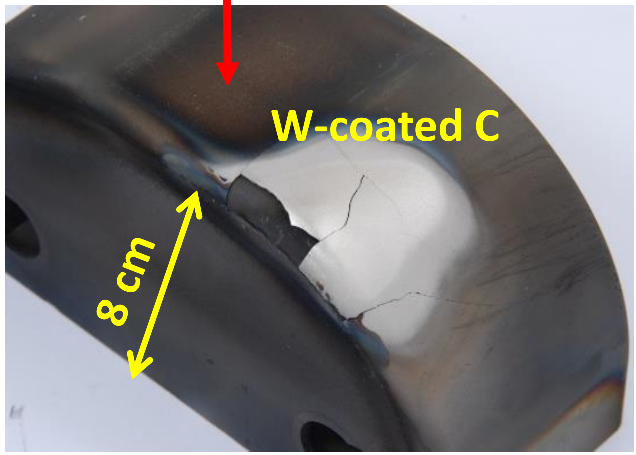
Structure of the talk

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

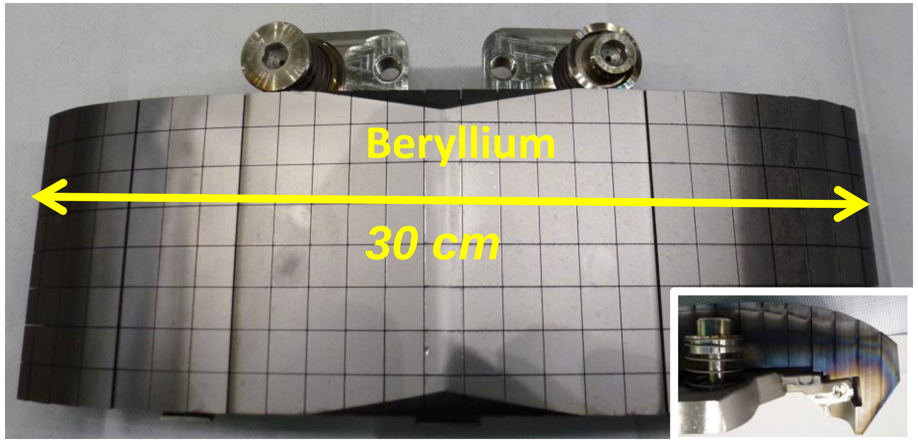
What do we study?
Components retrieved from fusion devices



TEXTOR: limiters



JET with ITER-Like Wall: castellated limiter

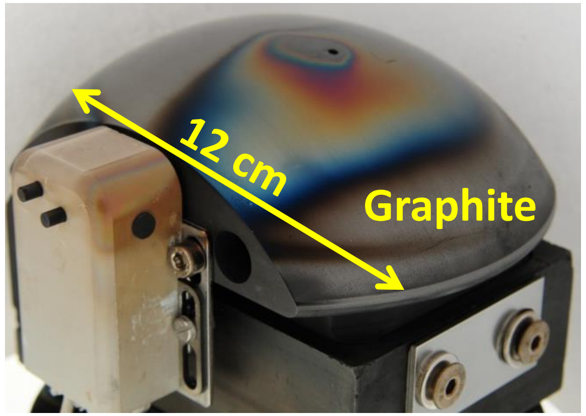


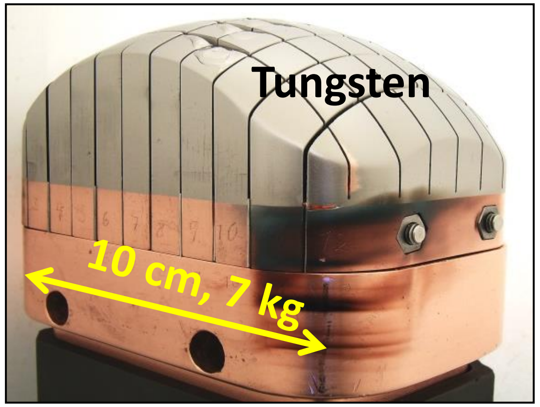
COMPASS: divertor

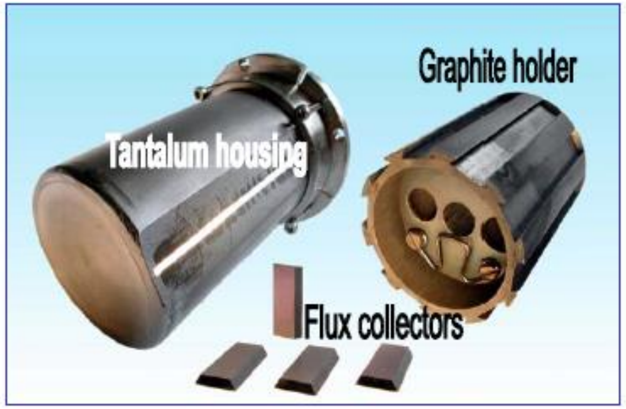
A large number of:

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

TEXTOR: *test limiters and collector probes*



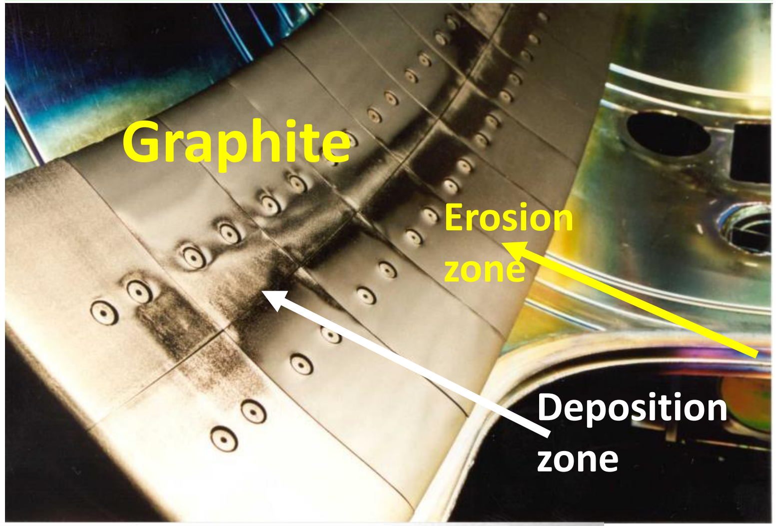


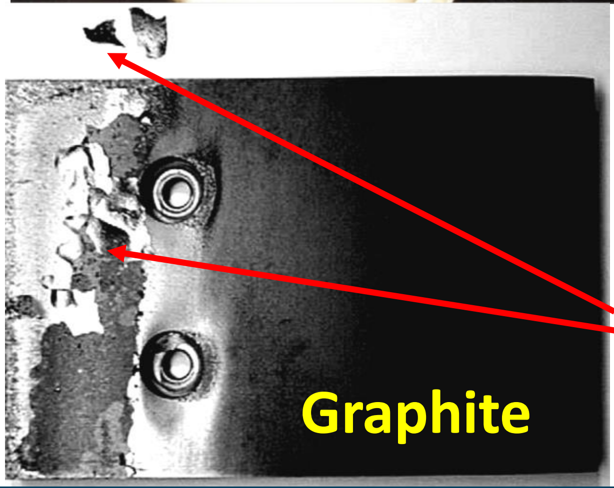


Material Migration: Erosion & Deposition

Example from the TEXTOR tokamak operated till December 2013.

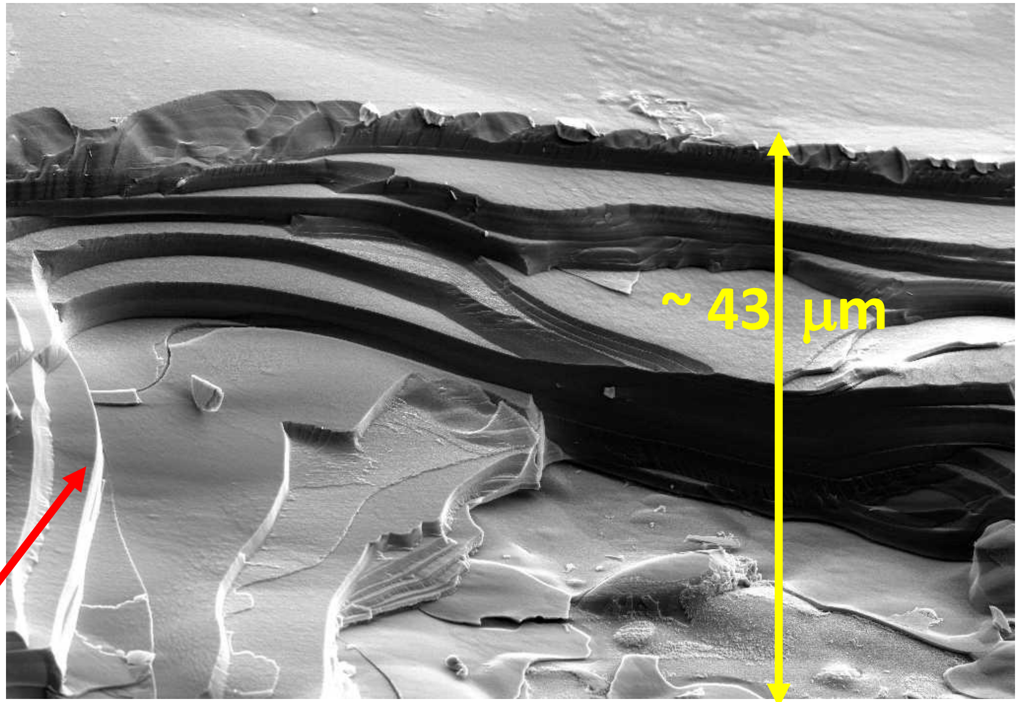
Tiles of a toroidal limiter





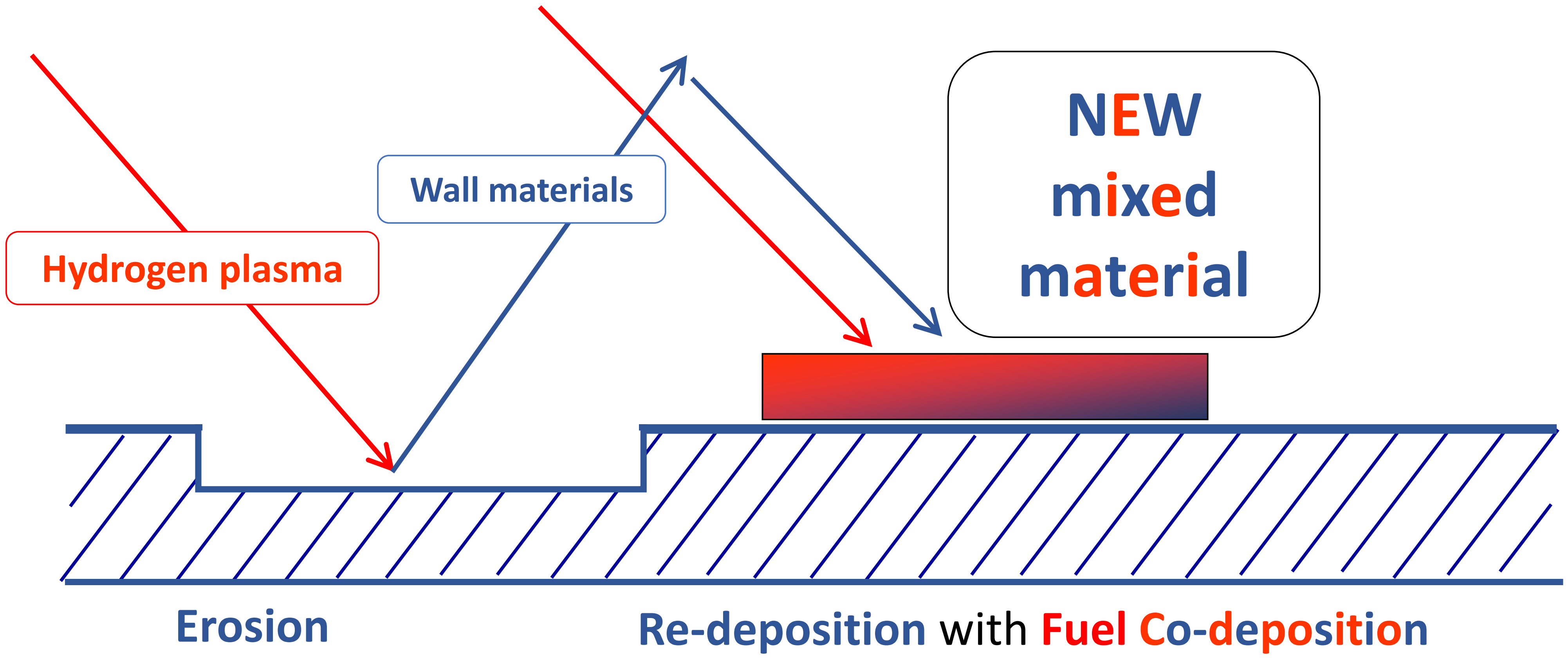
Flaking re-deposited layer & dust

Cross-section of a re-deposited layer



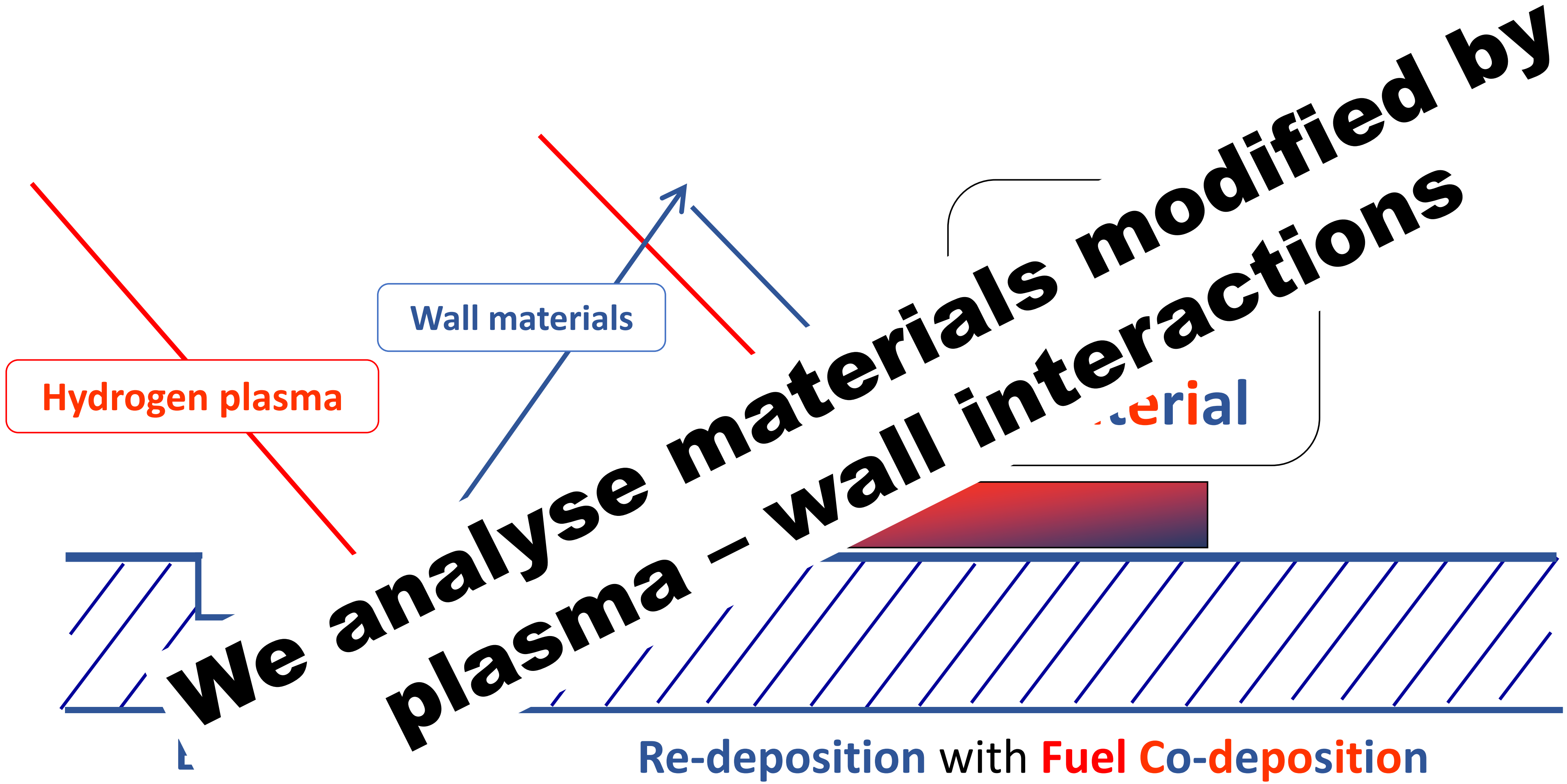
Large amount of deuterium and tritium fuel can be retained in such layers.

Plasma – Wall Interactions: Material Migration



Consequences: Modification of fusion plasma and material properties.

Plasma – Wall Interactions: Material Migration



Consequences: Modification of fusion plasma and material properties.

Species to be analysed / determined

Z = 1: HYDROGEN ISOTOPES (*H D T*)

Z = 2: HELIUM ASH (^{4}*He*)

ERODED SPECIES: *PLASMA IMPURITY ATOMS*

Z > 2

For instance:

^{3}He ^{6}Li ^{7}Li ^{9}Be ^{10}Be ^{10}B ^{11}B ^{12}C ^{13}C ^{14}C ^{14}N ^{15}N ^{16}O ^{18}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 must be strictly controlled.)*
- ***What* is the impact of wall materials on material migration?**

The whole picture depends on the wall composition/materials.

What are the wall materials?

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

Carbon
(graphite, fibre composites)

Beryllium

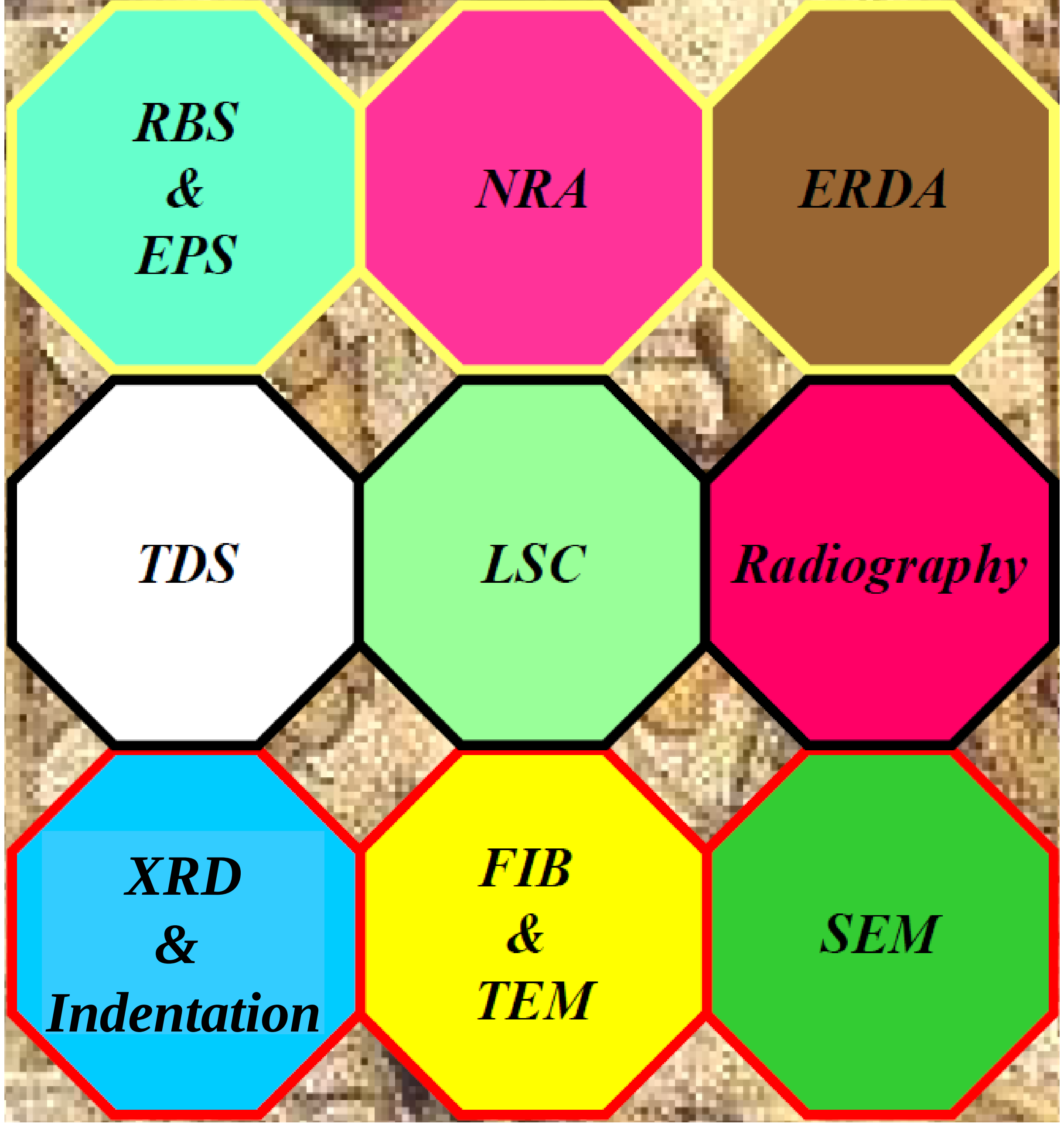
Tungsten

	Advantages	Drawbacks
C	Excellent power handling & no melting	Chemical erosion → C_xH_y
Be	Low-Z, no chemical erosion	Low T_m
W	High T_m, low sputter erosion	High-Z plasma contaminant

Material characterization: Methods

Over the years more than 40 different analysis methods have been used in studies of wall materials.

IBA methods play particular role.


RBS
&
EPS
NRA
ERDA
TDS
LSC
Radiography
XRD
&
Indentation
FIB
&
TEM
SEM

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).

Nuclear Reaction Analysis with ^{3}He

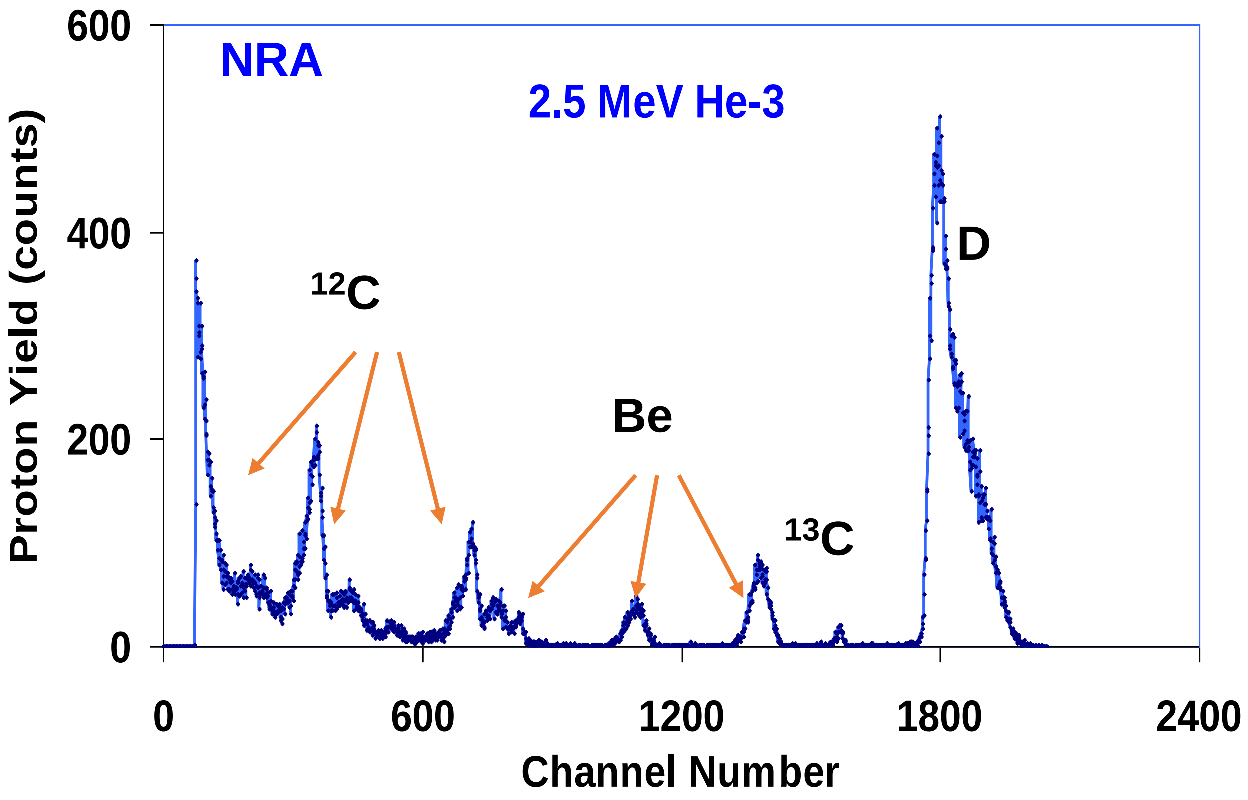
Advantage:

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

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

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

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



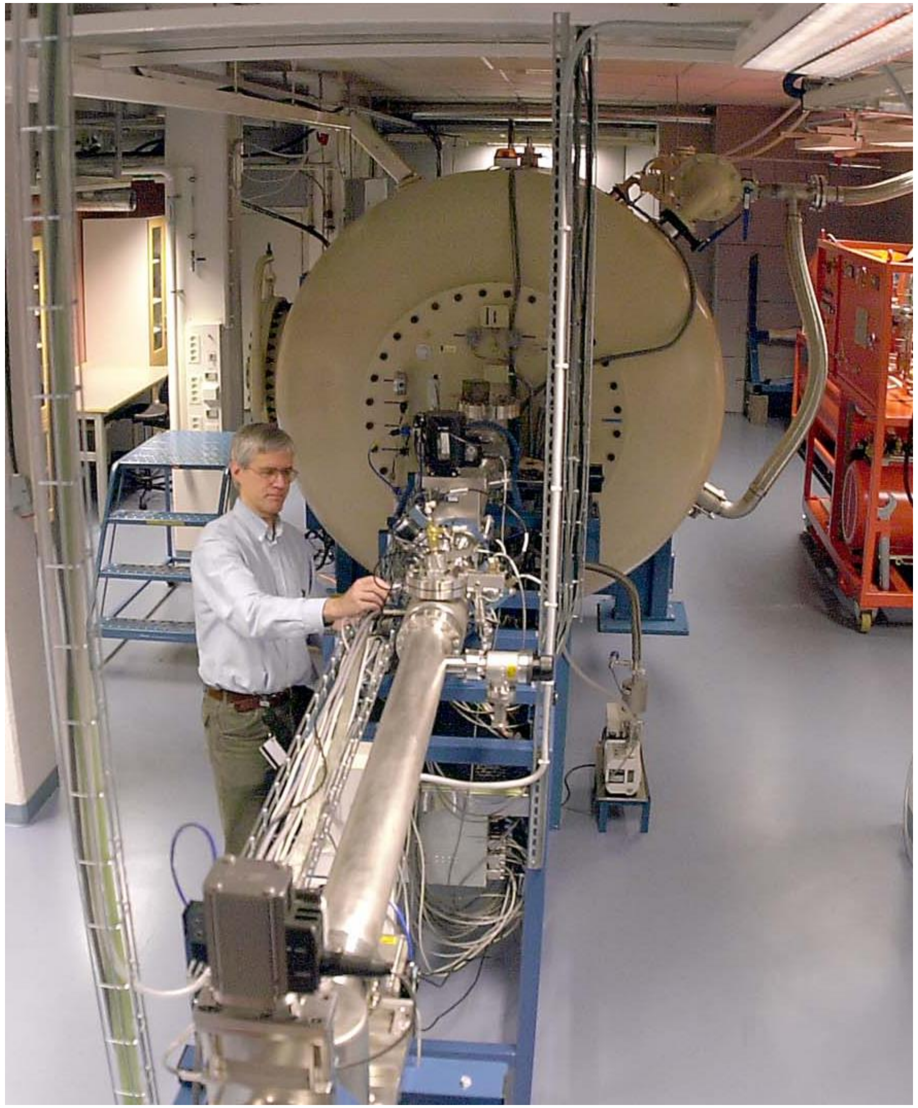
If accelerator-based IBA techniques…

… then we need people and tools:

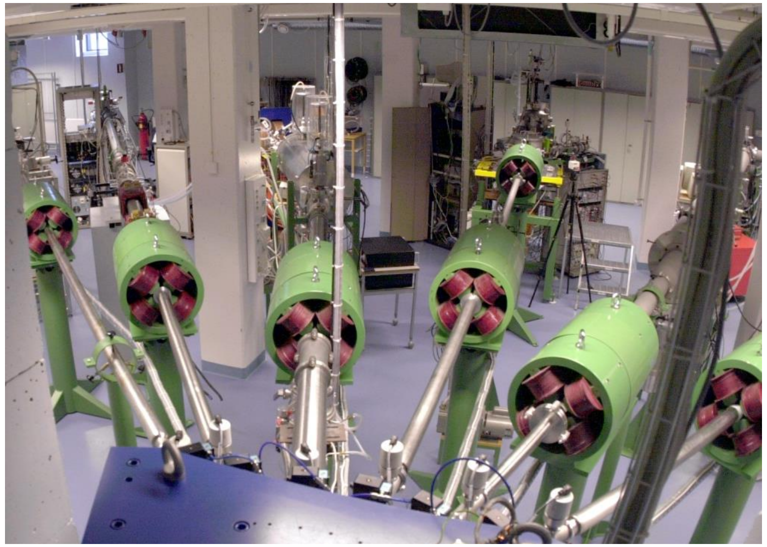
- ❖ *competent personnel,*
- ❖ *laboratories with relevant hardware,*
- ❖ *material handling capabilities,*
- ❖ *robust physics basis,*
- ❖ *data libraries,*
- ❖ *spectra analysis softwares,*
- ❖ *etc.*

The Tandem Laboratory at Uppsala University

5 MeV Tandem



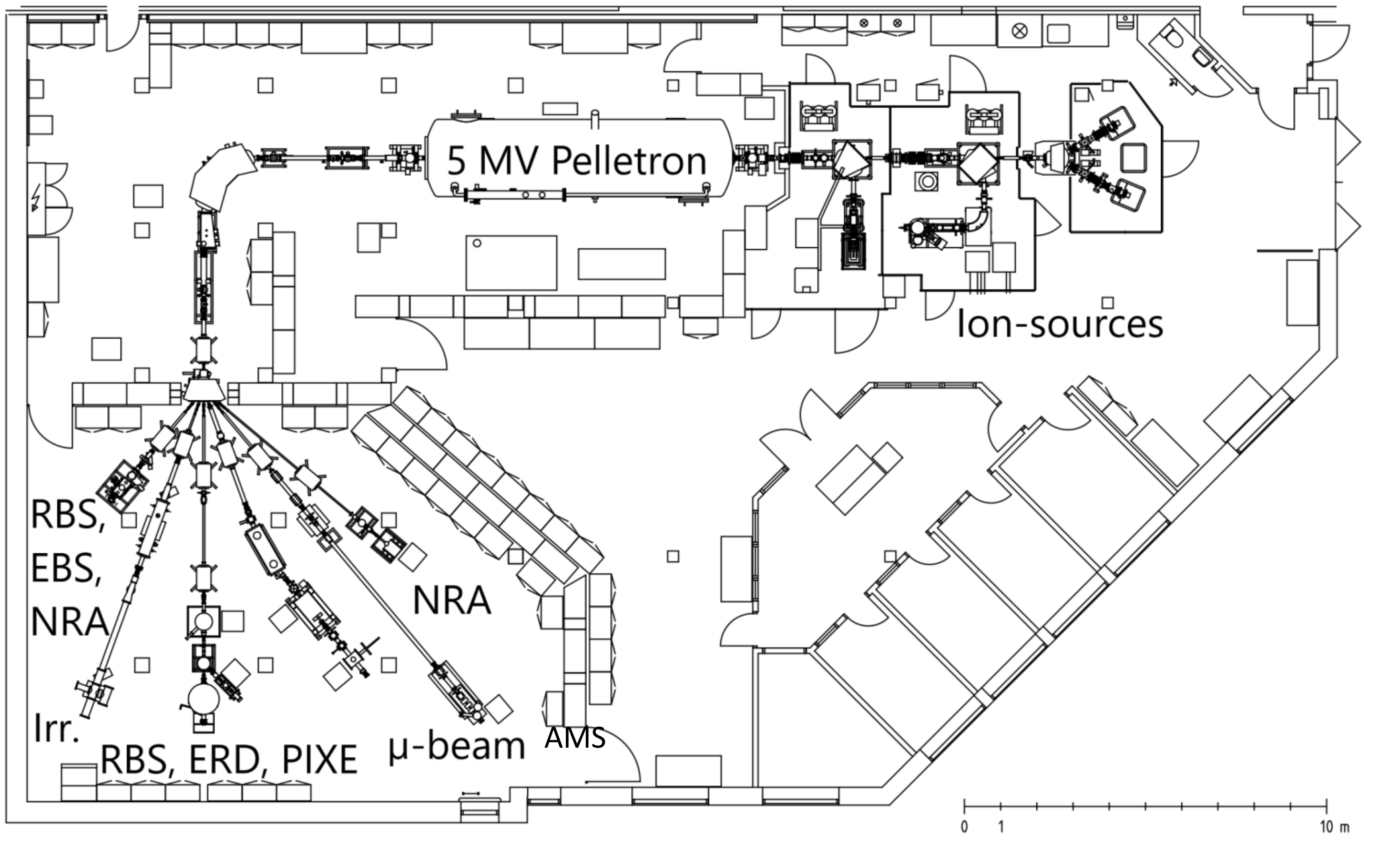
Beam lines with quadrupoles



Surface analysis station

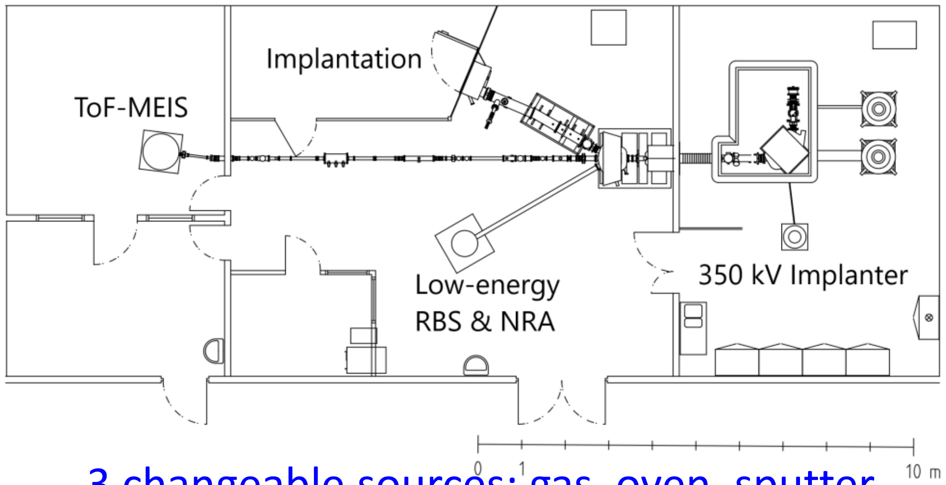
The Tandem Laboratory at Uppsala University

5 MV 15-SDH2 pelletron accelerator



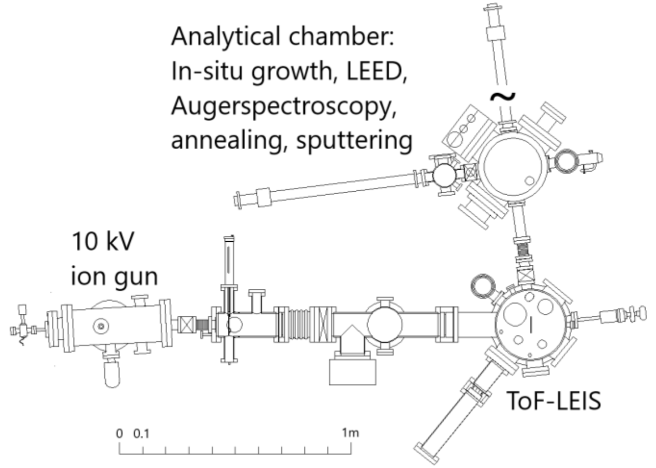
2 gas & 2 sputter ion sources – beams of H, D, ^{3}He, ^{4}He, C, N, O, Cu, Br, I, Au

350 kV Danfysik implanter



3 changeable sources: gas, oven, sputter

ToF-LEIS system



Fusion-related research is carried out in all systems.

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.*

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.*

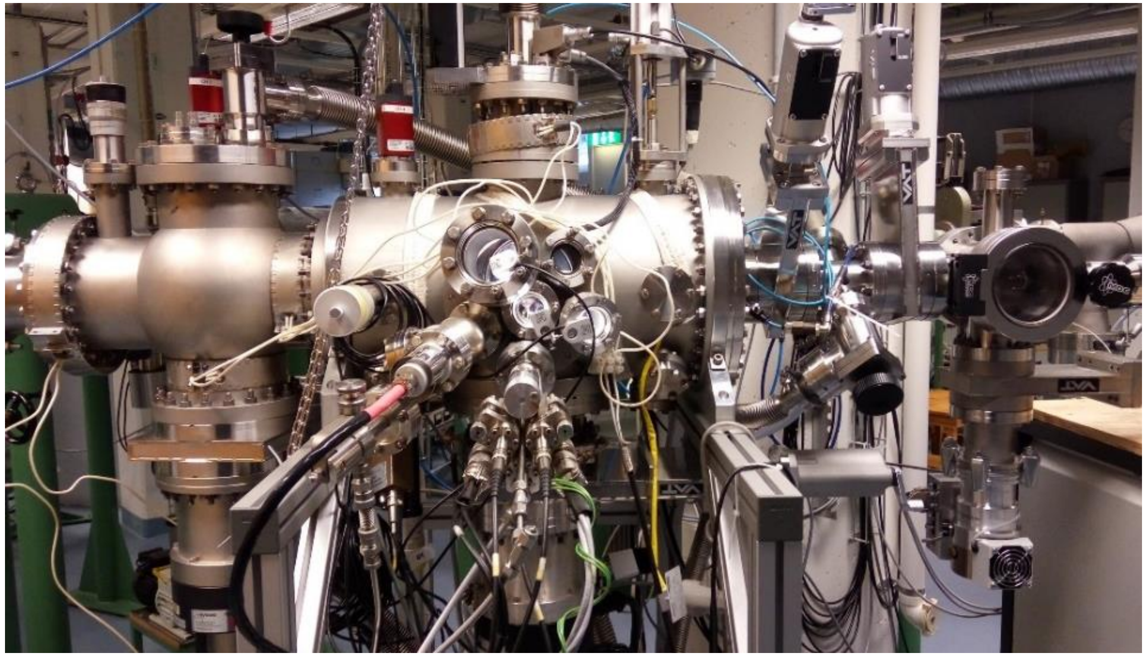
A list of issues to address and solve:

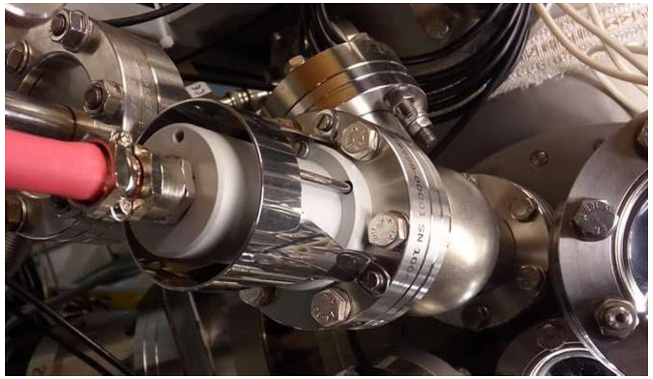
- *Provision of facilities for handling of hazardous materials (T, activated samples, Be) for existing and future experiments, e.g. ITER.*
- *Standardisation of measurement and evaluation procedures;*
- *Determination and possibly evaluation of cross-sections and stopping powers for elements and isotopes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

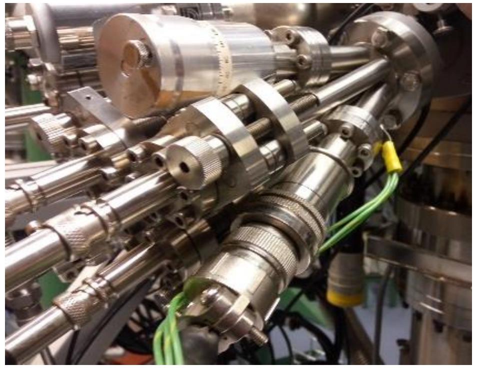
IAEA CRP in that area.

The Tandem Laboratory at Uppsala University: Recent developments

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





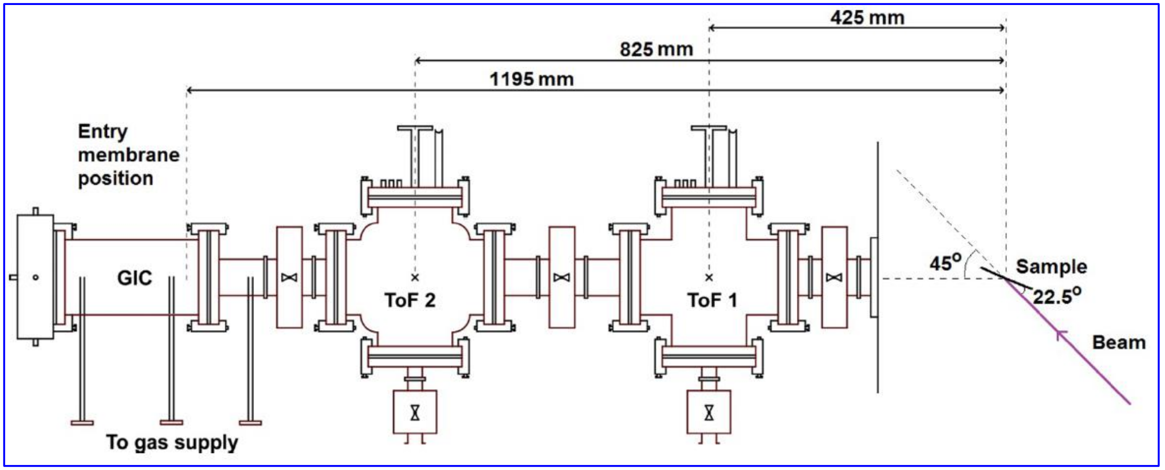


- **IBA with light & heavy ions – RBS, NRA, PIXE, PIGE, ToF-ERDA**
- **Beam energies: 2 – 50 MeV**
- **Large viewport** (e.g. optical characterization)
- **Evaporation:** 3 evaporation cells
- **Sputtering:** 1 – 5 keV ion gun
- **Implantation**
- **Annealing & thermal desorption spectroscopy**
- **Gas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

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

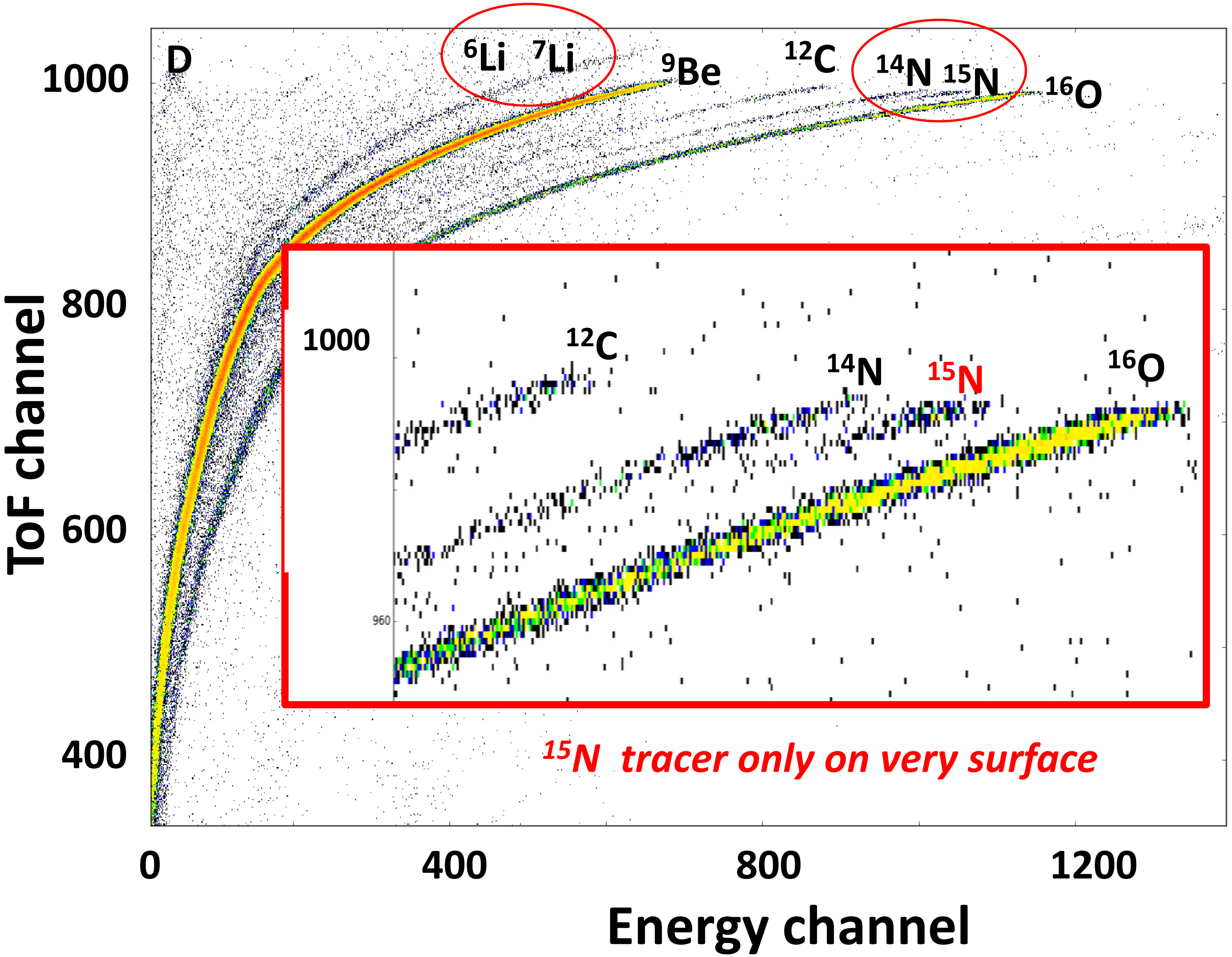
The Tandem Laboratory at Uppsala University: Recent developments

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



Cross-sections

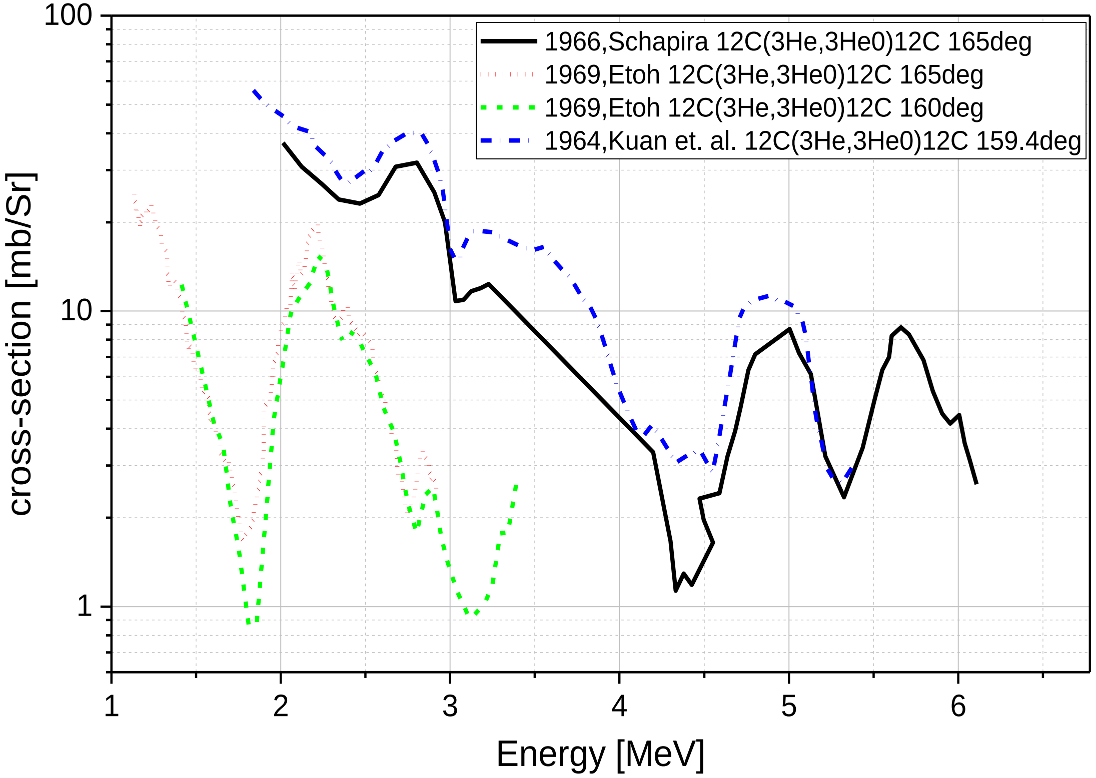
The role and impact of IAEA CRP: Definition of High Priority Measurements

Cross-section measurements of ^{3}He-induced reactions						
Target isotope:	^{7}Li	^{9}Be	^{10}B	^{11}B	^{12}C	^{13}C
^{3}He beam energy range and recommended energy step	1 – 6 MeV (Step: ≤ 100 keV) Caution: consider resonance width, when found					
Range of angles to measure	$120^O – 175^O$					

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		

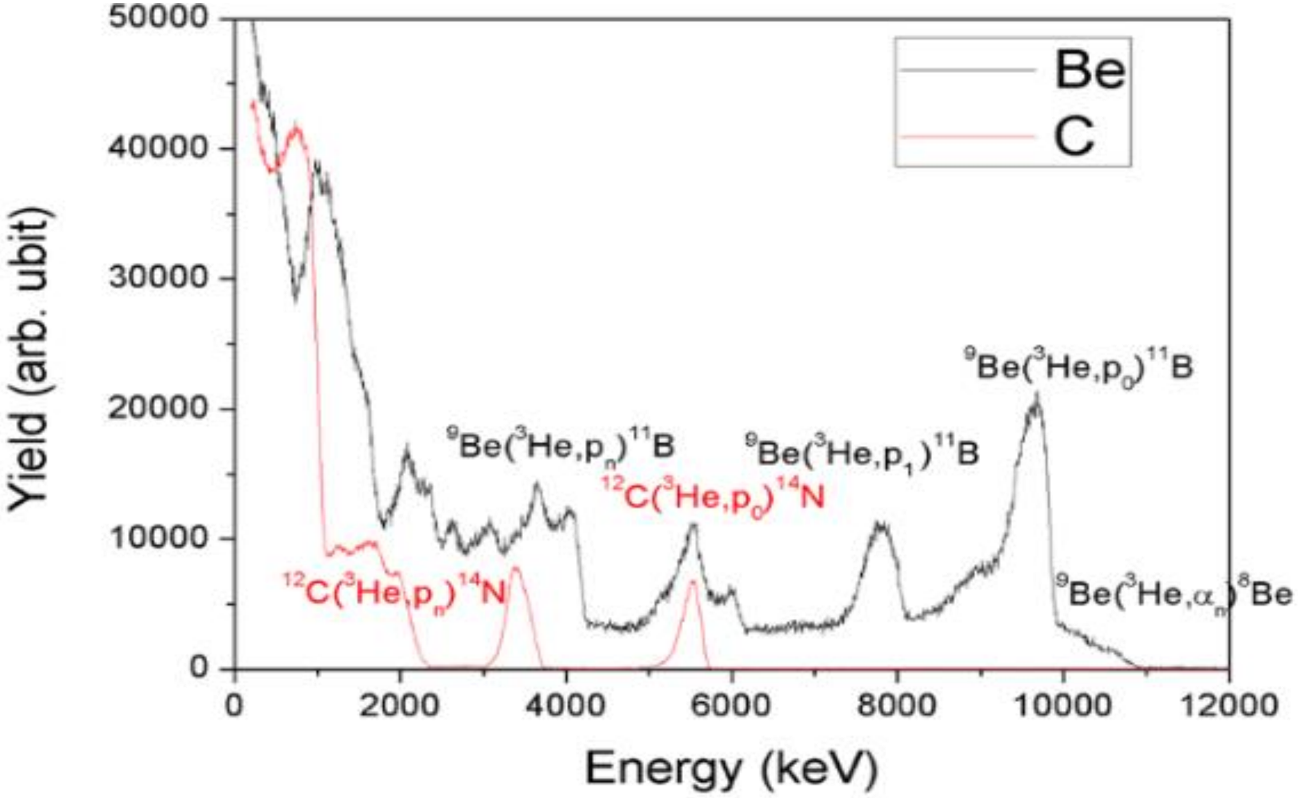
IBA on C and Be: Motivation for research

Non-Rutherford elastic scattering of ^{3}He on ^{12}C



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

3MeV ^{3}He on pure targets: ^{12}C and ^{9}Be

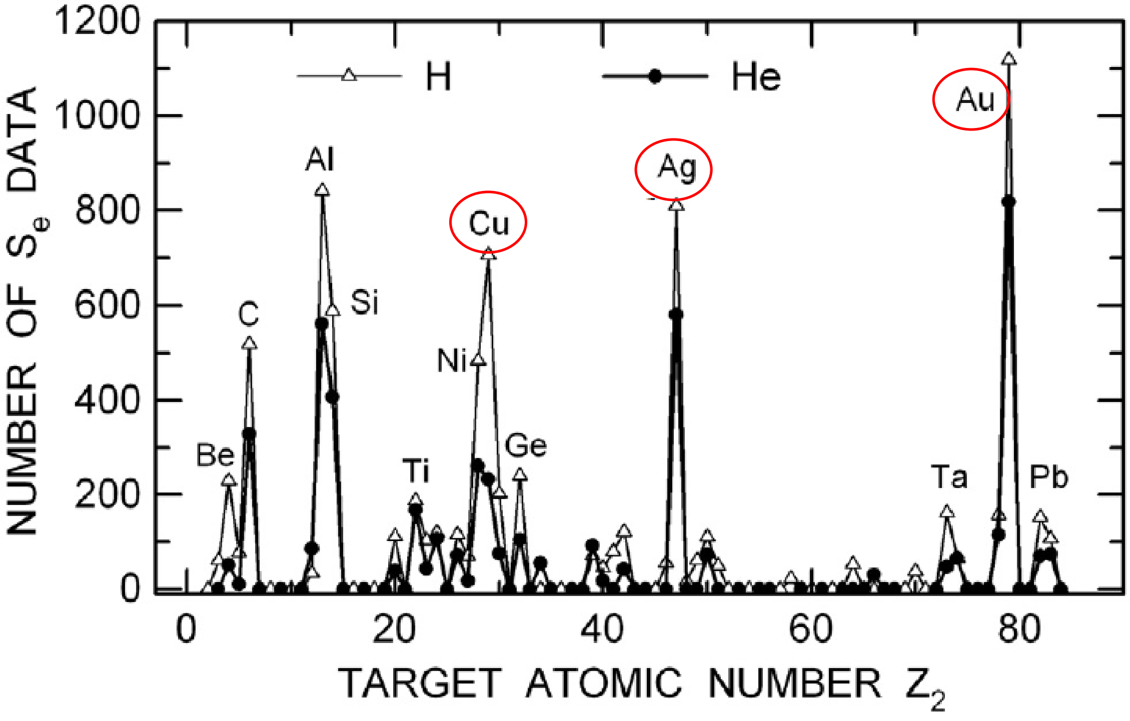


NRA spectra for $^{12}C(^{3}He,p)^{14}N$ and $^{9}Be(^{3}He,p)^{11}B$, (scattering angle 170°).

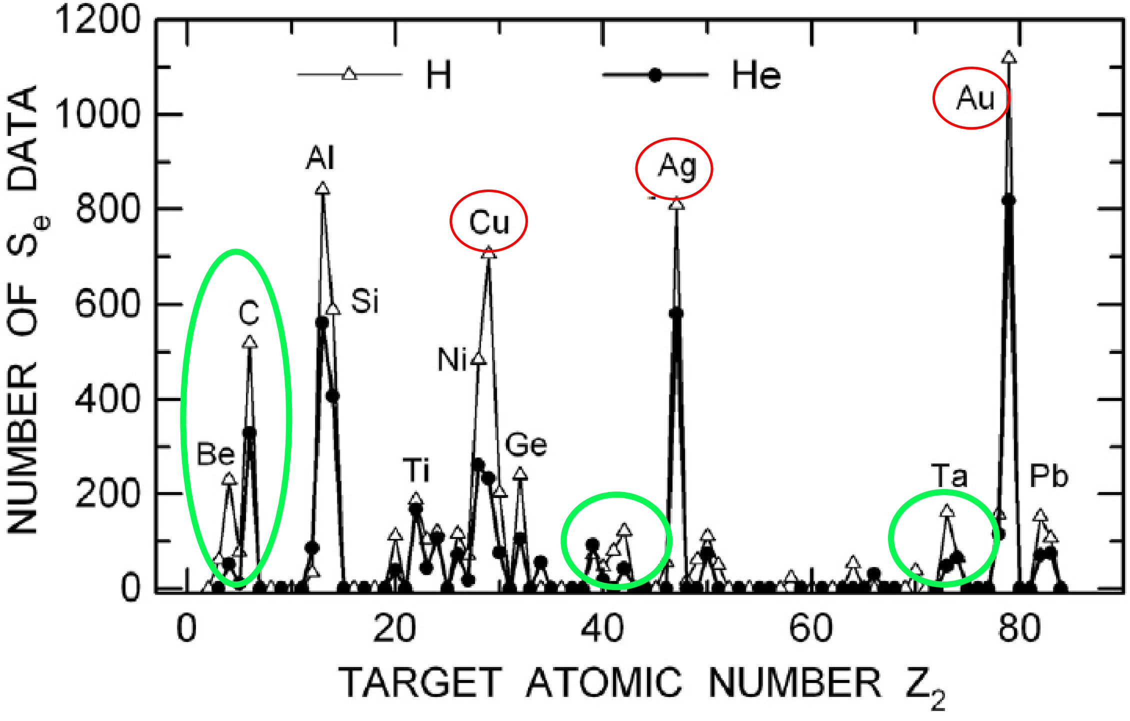
→ Not possible to determine C on the Be-rich surface.

Why still studying stopping power?

Availability of data and predictions.

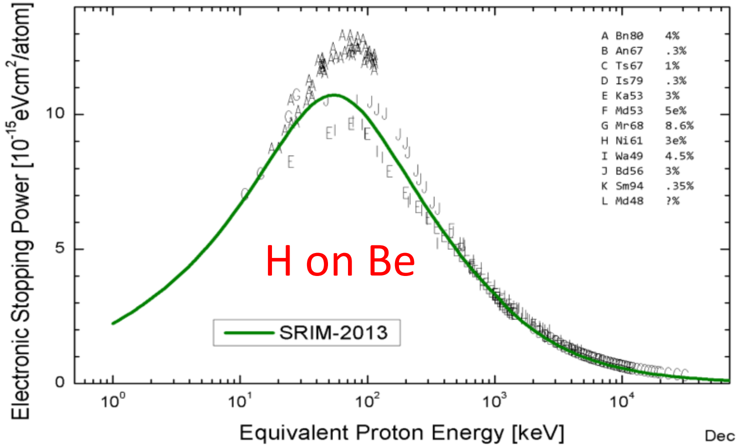


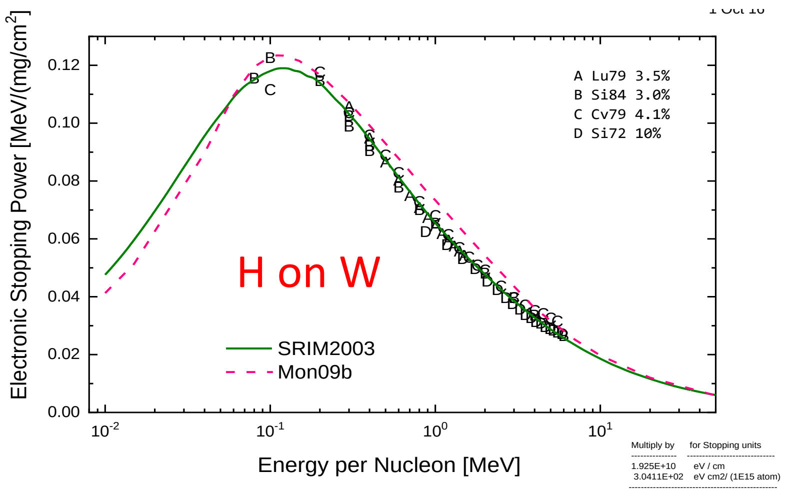
Situation in the fusion world…

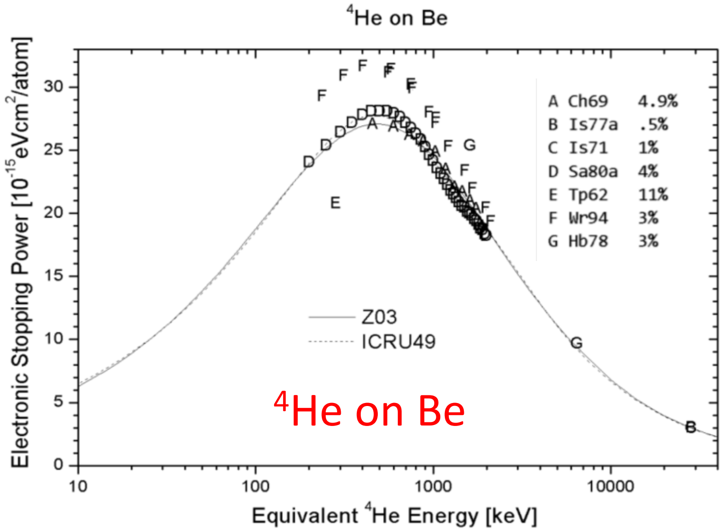


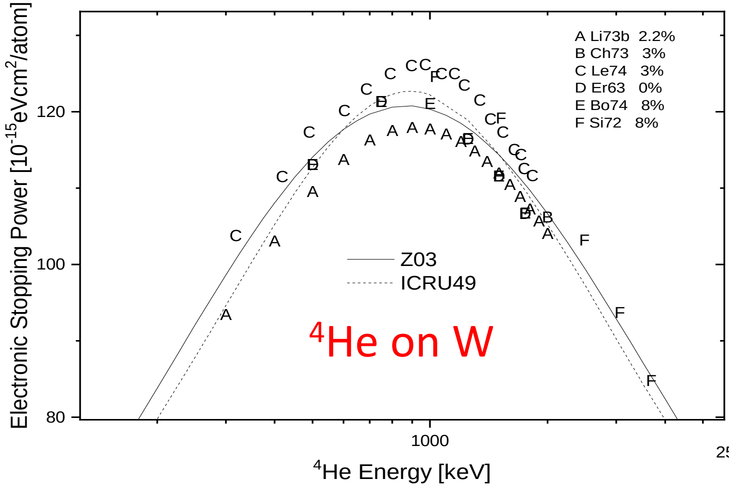
Needs: Be, B, W (and Mo)

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: 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.**

Integrated program on studies of plasma-facing materials and components

Analysis tools

Laboratory

&

Modelling

Fusion-relevant experiments
&
access to materials

Solid data basis:

$\sigma(E_o)$

$S_e(E_o)$, $S_n(E_o)$

Cooperation network

Thank you