ANALYSIS OF PLASMA FACING MATERIALS

IN CONTROLLED FUSION DEVICES

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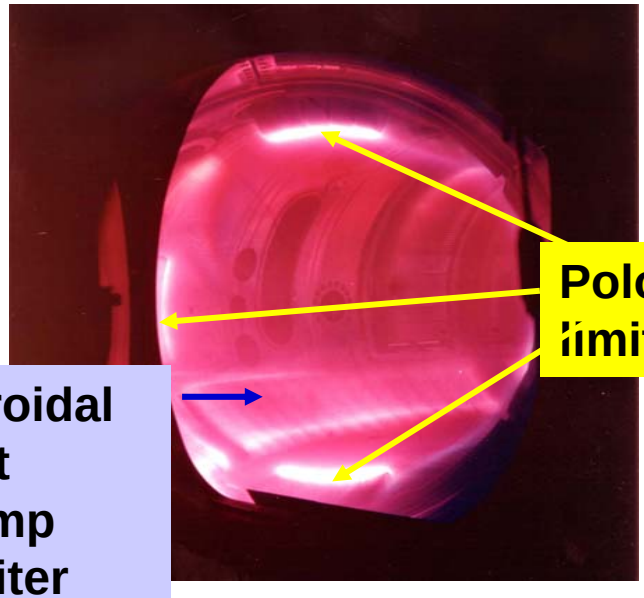
STRUCTURE OF THE TALK

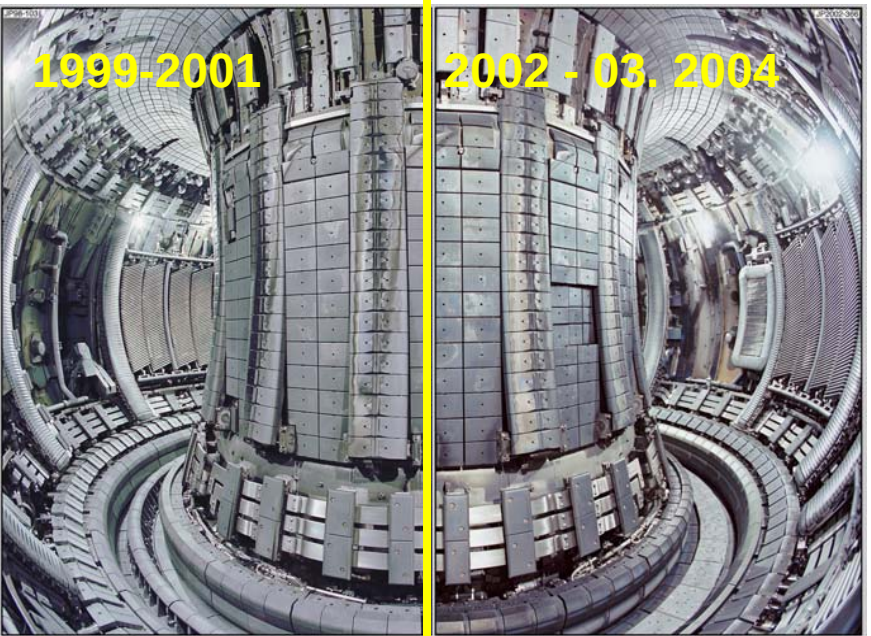
- **What is to be analysed?**
- **Why is it to be analysed?**
- **How is the analysis carried out?**

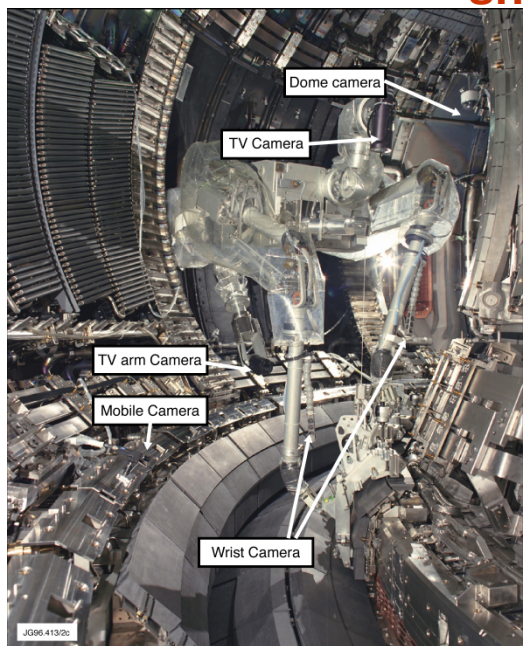
What is to be analysed ?



A large number of:

- limiter plates
- divertor plates
- other wall components
- optical components
- instrumented tiles
- long-term probes
- short-term probes

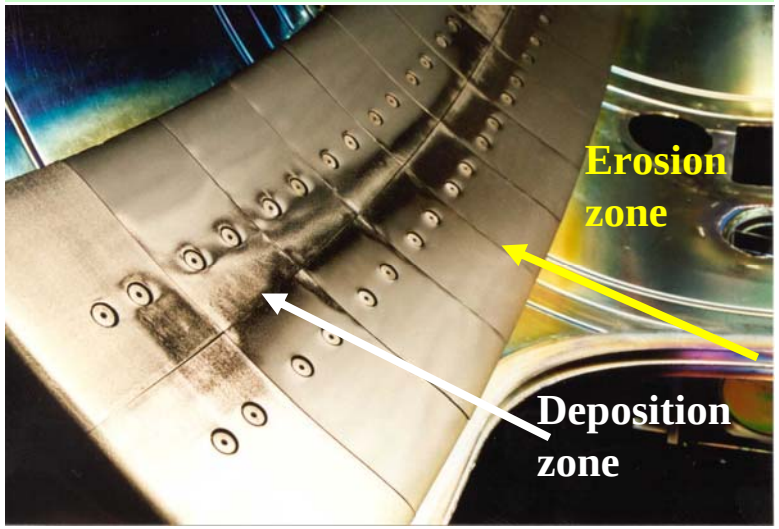


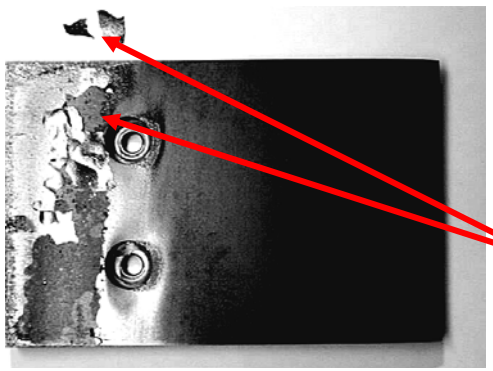


[At least tiles from one poloidal cross section.]

Layers of Re-deposited Material

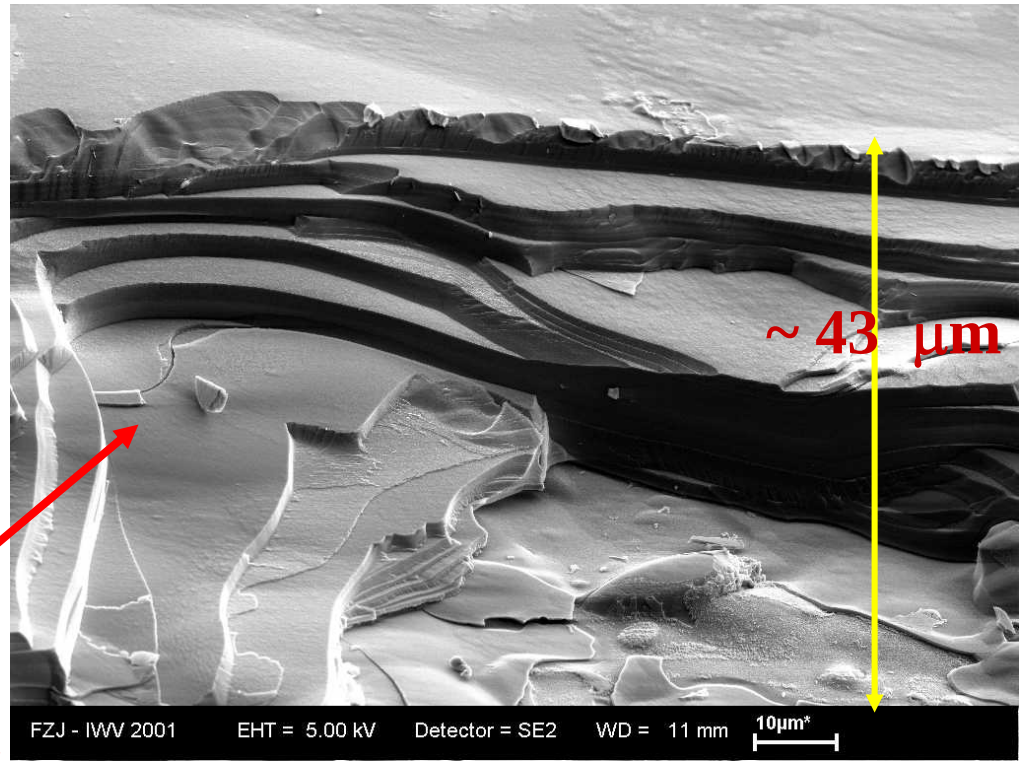
Tiles of a toroidal limiter



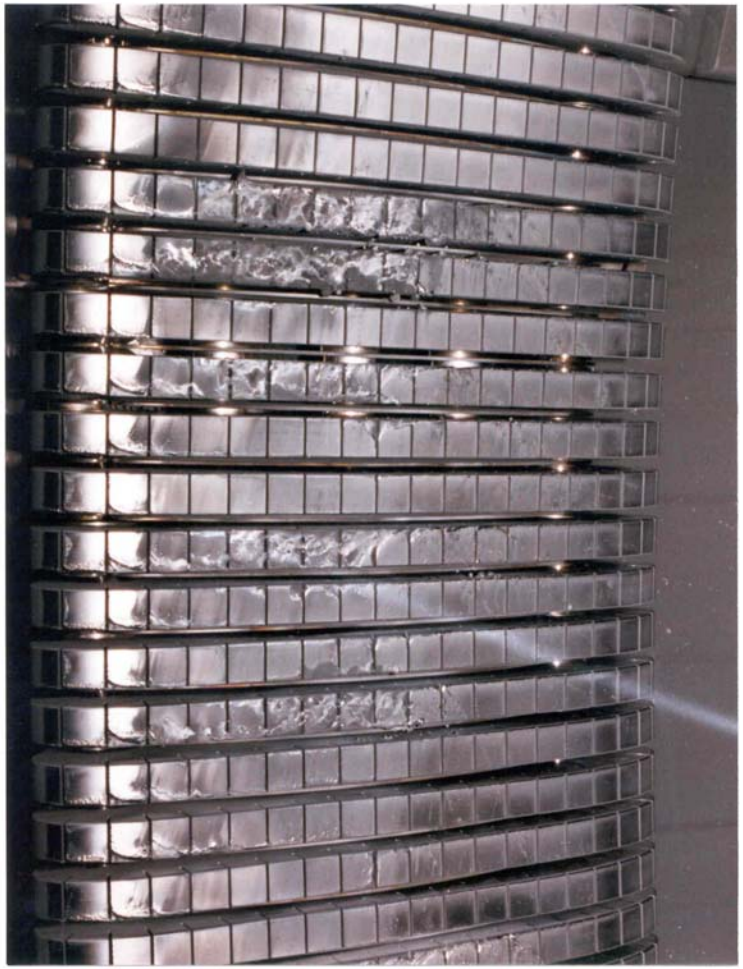


Flaking re-deposited layer

Cross-section of a re-deposited layer

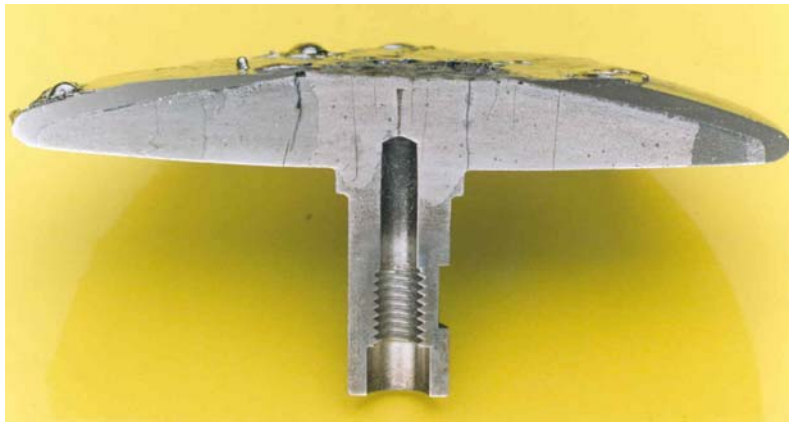


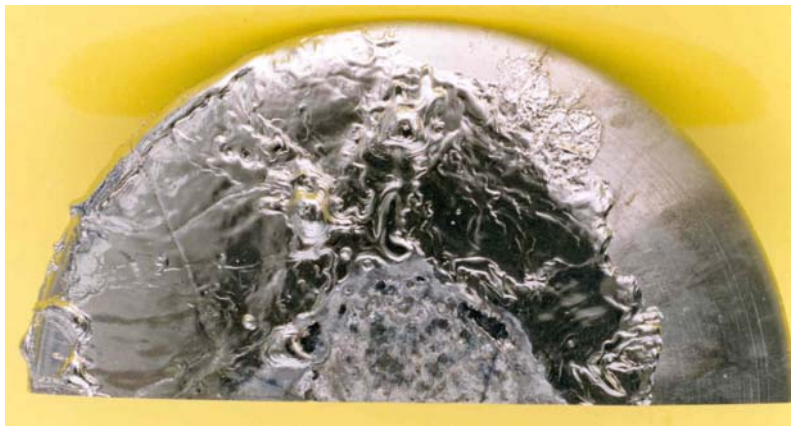
EROSION BY MELTING



Beryllium antenna screen at JET

$T_m(Be) = 1278\ ^oC$





Limiter from FTU
TZM coated with 2 mm VPS Tungsten

$T_m(W) = 3683\ ^oC$

Atoms to be Analysed in Re-deposited Layers

FUEL

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

PLASMA IMPURITY ATOMS:
Eroded species

$Z > 2$

For instance:

Li Be ^{10}B ^{11}B ^{12}C ^{13}C ^{14}C *Si Ni Cr Fe Mo W Re*

We are to answer some basic questions !

What has happened ?

Why has it happened ?

How to deal with the problem ?

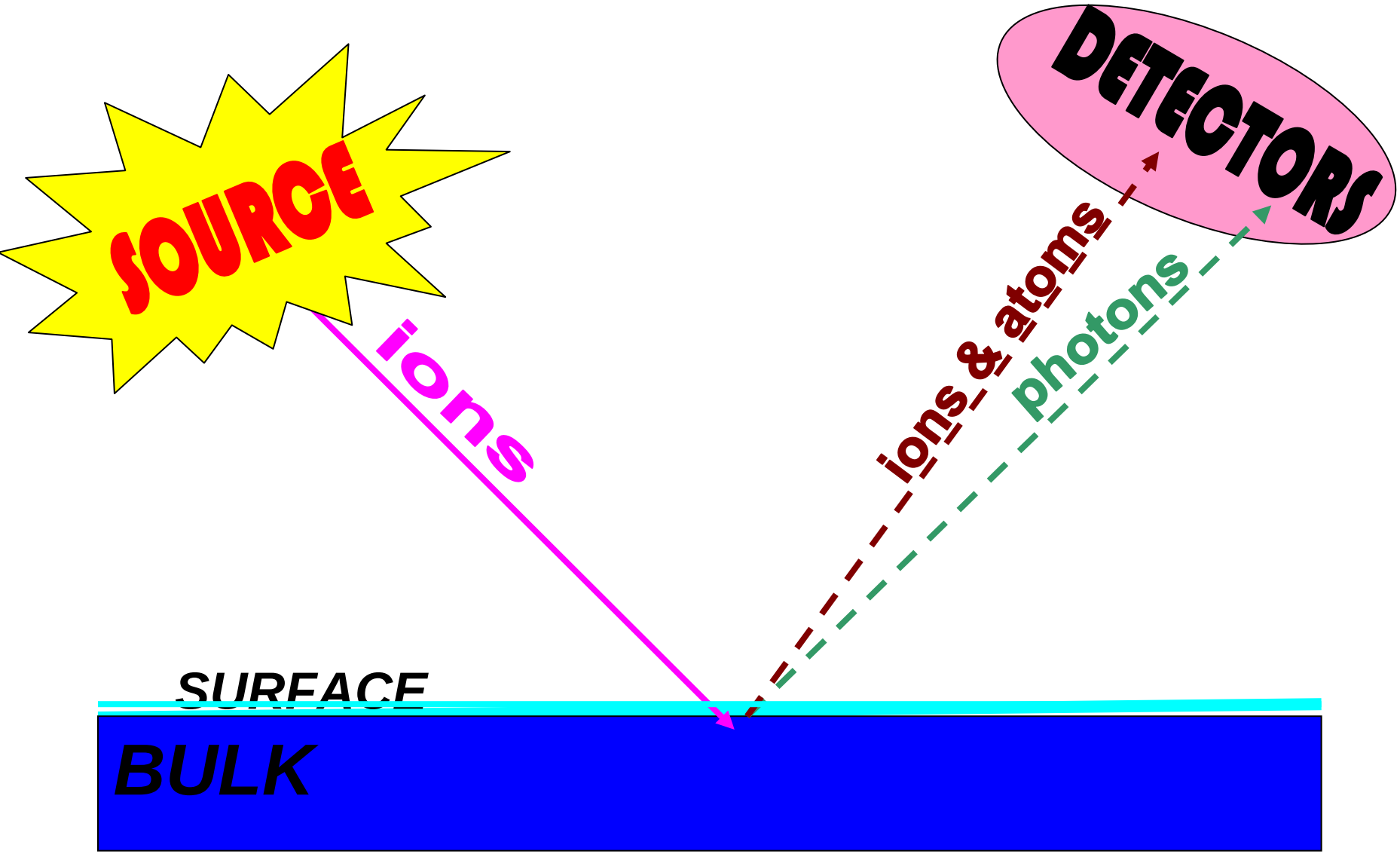
We are paid NOT only to find and emphasize problems but TO FIND AND PROVIDE SOLUTIONS.

How ??

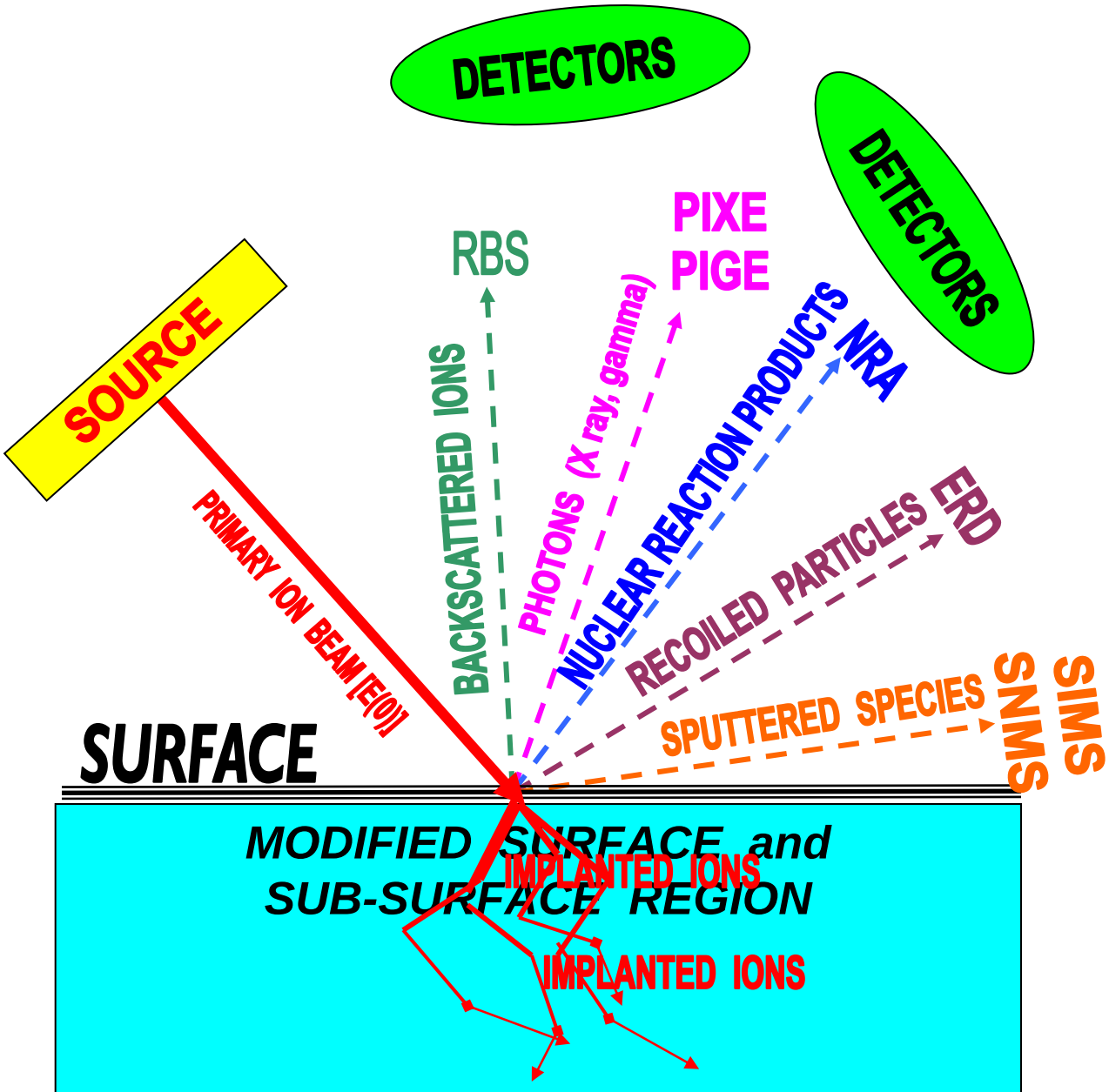
ANALYSIS

Methods, selected Results & Instrumentation

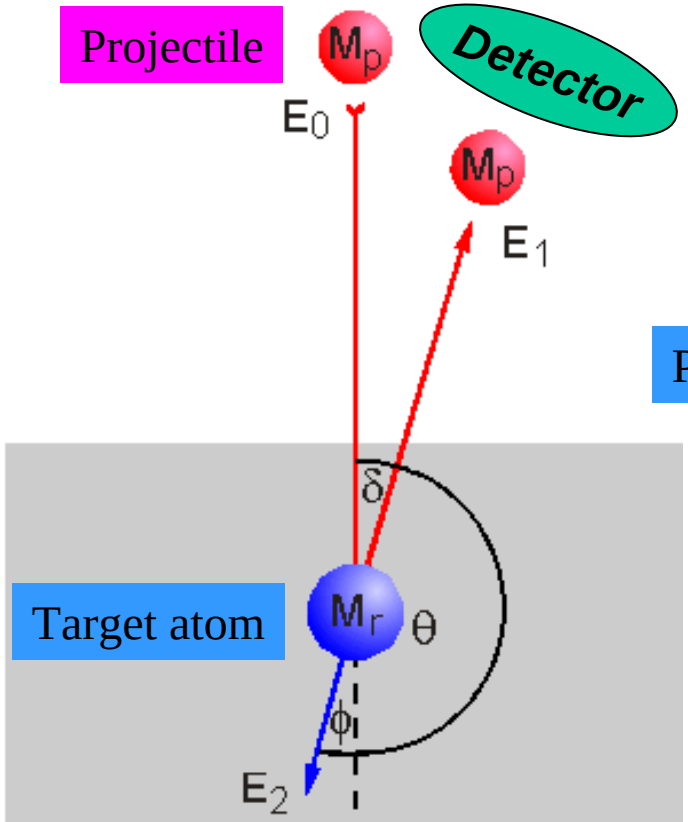
ION BEAMS for Material Characterisation

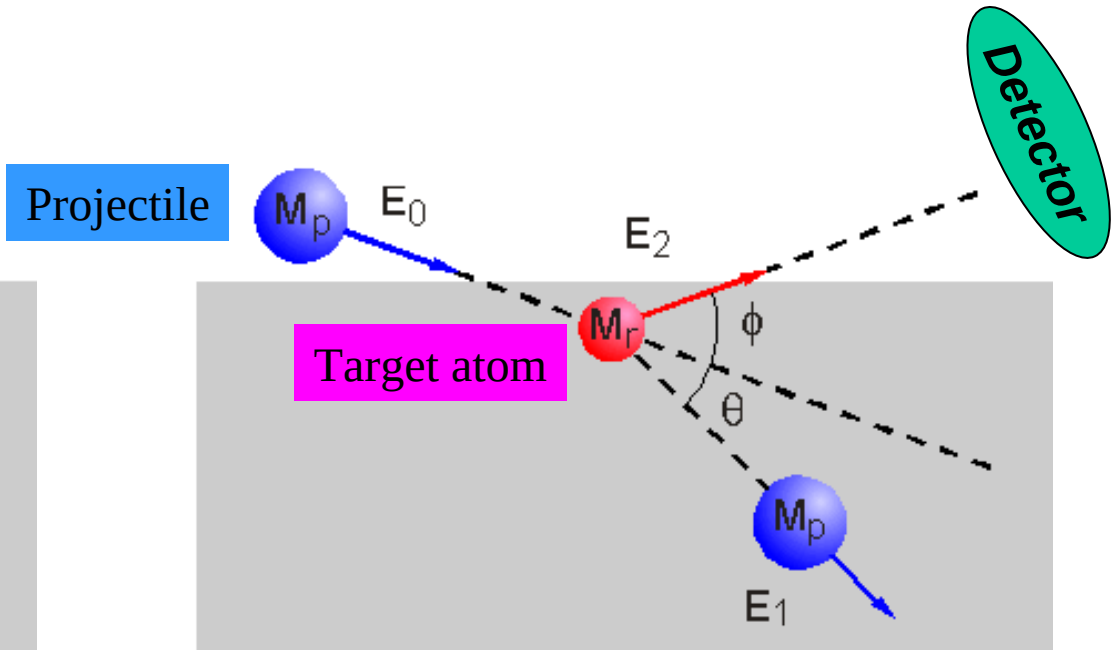


Methods Based on Ion – Surface Interactions



Collisions & Scattering



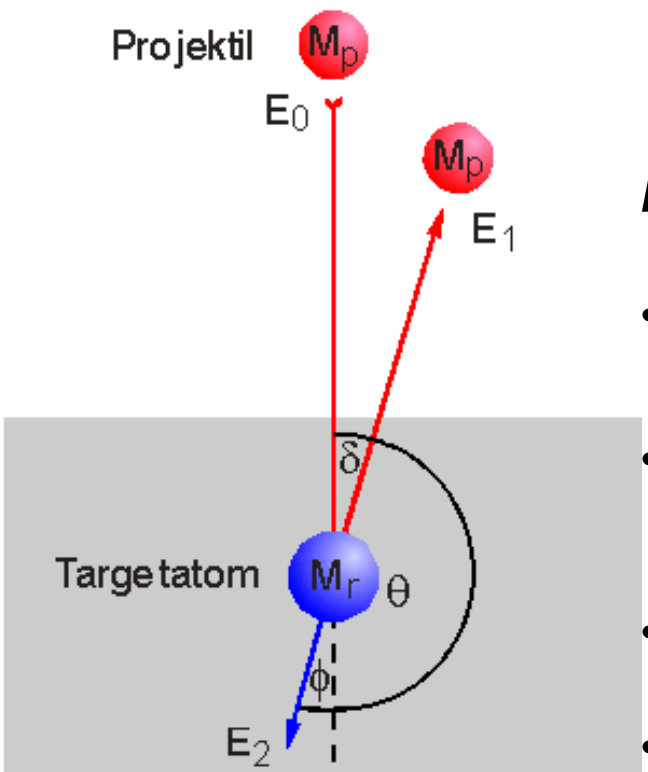


RBS & (EPS)

ERDA & (HI-ERDA)

Kinematic Factor

$$k_p = \left(\frac{M_p / M_r \cos\theta + \sqrt{1 - (M_p / M_r)^2 \sin^2\theta}}{1 + M_p / M_r} \right)^2$$



k_p is unique for a given M_p - M_r combination:

- ***unambiguous determination of a given mass in the spectrum***
- ***for a given M_p mass separation decreases for increasing M_r.***
- ***better separation of larger M_r with heavier M_p***
- ***only target atoms heavier than projectiles can be determined***
- ***for $M_p \geq M_r$ only forward scattering possible***
- ***k_p increases with Θ.***
- ***better detection at large scattering angles.***

Efficiency in RBS: Differential Cross-section

$$\frac{d\sigma_p}{d\Omega} \propto \left(\frac{Z_p Z_r e^2}{2E_0}\right)^2 (\Theta, M_p, M_r)$$

σ_p *cross-section*

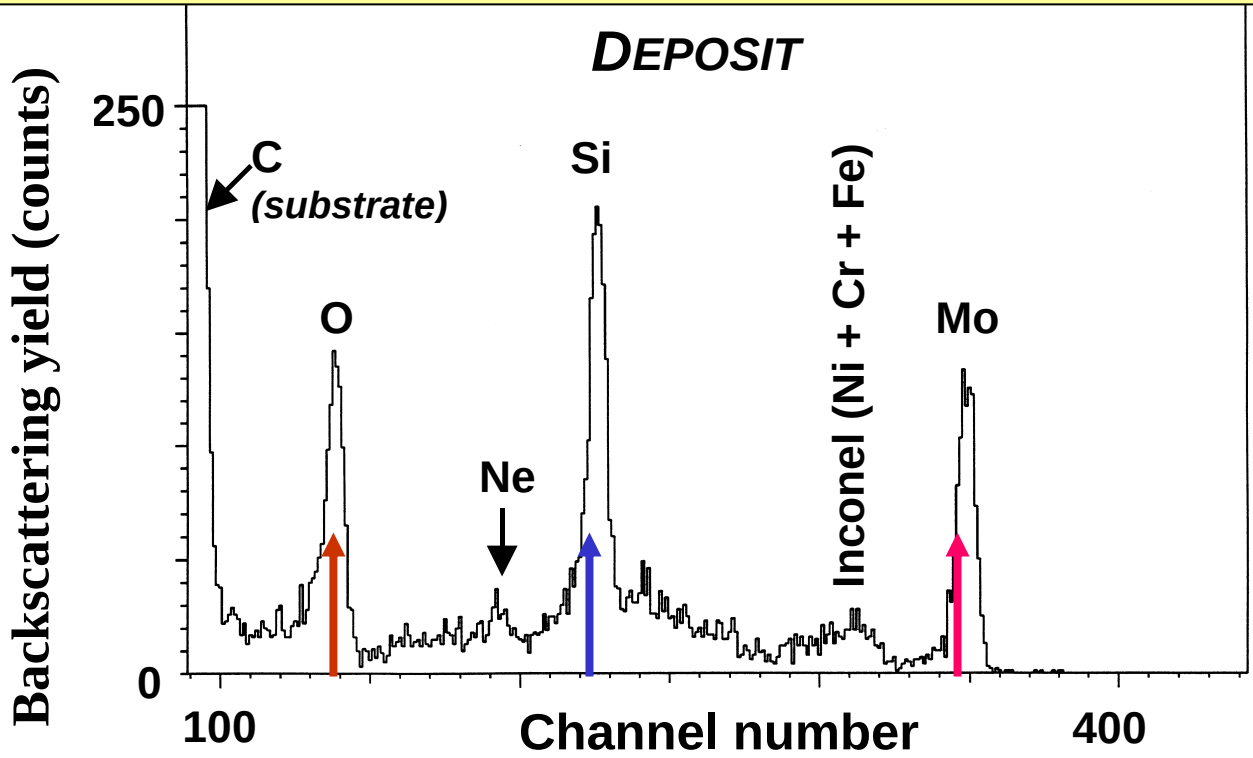
Ω *solid angle in detection system*

Z_p, Z_r *atomic numbers*

Important: For a given projectile σ_p scales with $(Z_r / E_0)^2$

→ higher sensitivity for heavy elements and at lower E_0.

Rutherford Backscattering Spectrum *($^4He^+$ beam)*: Elements Co-deposited on Graphite PFC



$N_O = 10^{17}\ cm^{-2}$

$N_{Si} = 10^{15}\ cm^{-2}$

$N_{Mo} = 10^{14}\ cm^{-2}$

Good separation of low masses, poorer for medium and high.

No detection of deuterium with a $^4He^+$ beam.

Very difficult (not possible) to detect co-deposited boron on the graphite target.

High sensitivity for heavy elements.

Quantification

$$N_t = A/\sigma \Omega \, Q$$

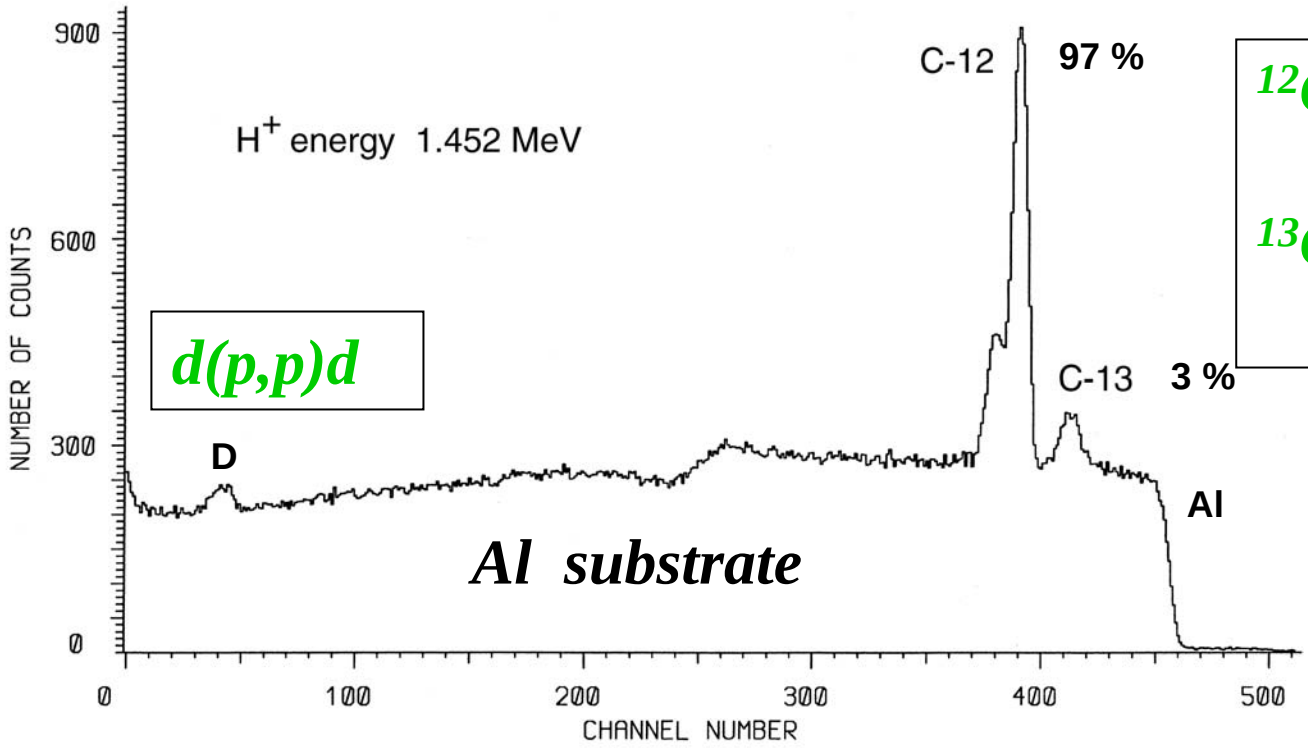
N_t	*concentration of species*
A	*number of counts in multi-channel analyser*
Q	*ion dose measured by current integrator*
σ_p	*cross-section*
Ω	*solid angle in detection system*
Z_p, Z_r	*atomic numbers*

All parameters in the system are directly measured (Q, A) and independently calculated (Ω, σ) knowing the scattering geometry, detector active area, atomic masses and numbers.

- **There is no free parameter left.**
- **RBS is an absolute quantitative method.**
- **No standards for calibration are required.***

NUCLEAR RESONANCE & ENHANCED PROTON BACKSCATTERING:
C-13 Resonance and C-12 enhanced scattering

Carbon transport studies by tracer techniques



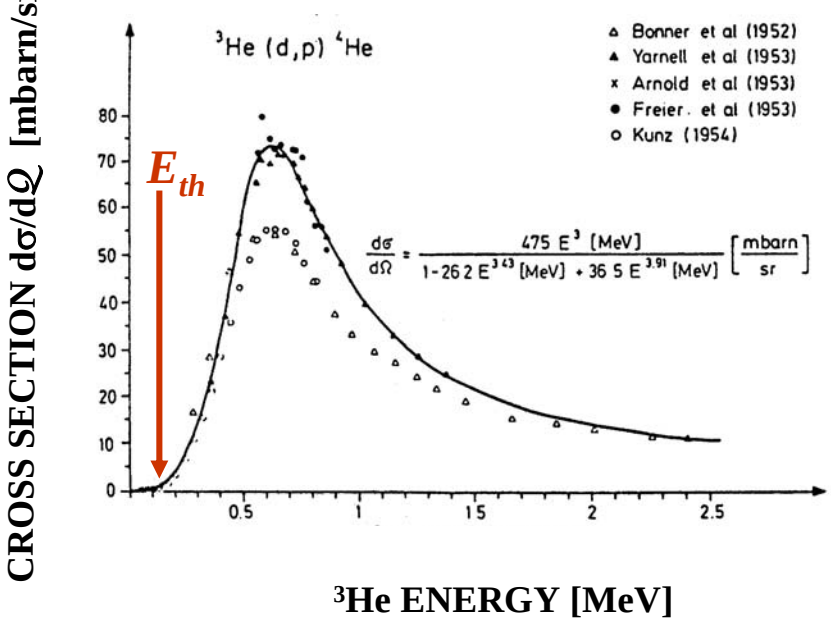
- *Very good separation of small masses (but hopeless for high).*
- ***High sensitivity for low-Z (not attainable with a ^{4}He beam).***

$^3He(d,p)^4He$

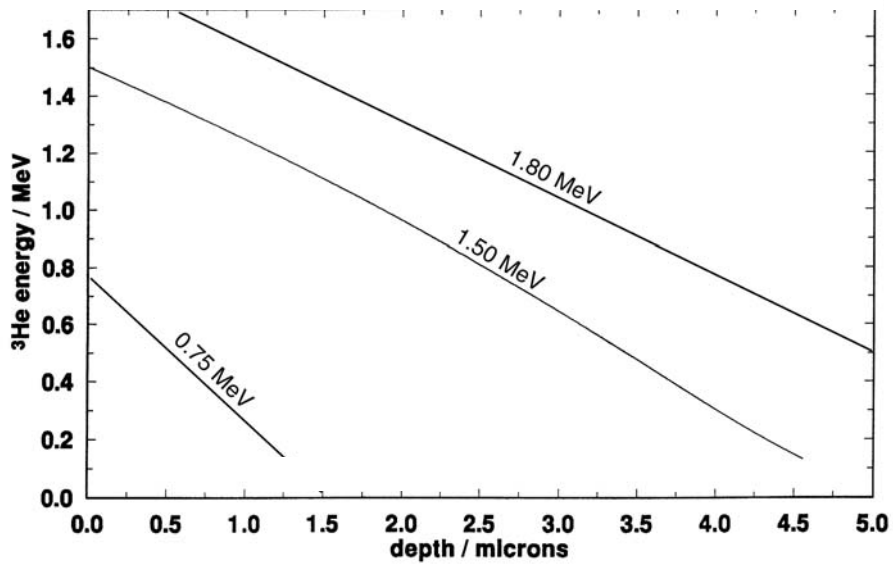
Q = 18.3636 MeV Detected particle: proton 11 – 14 MeV range

Proton spectrum can be converted into a deuterium depth profile.

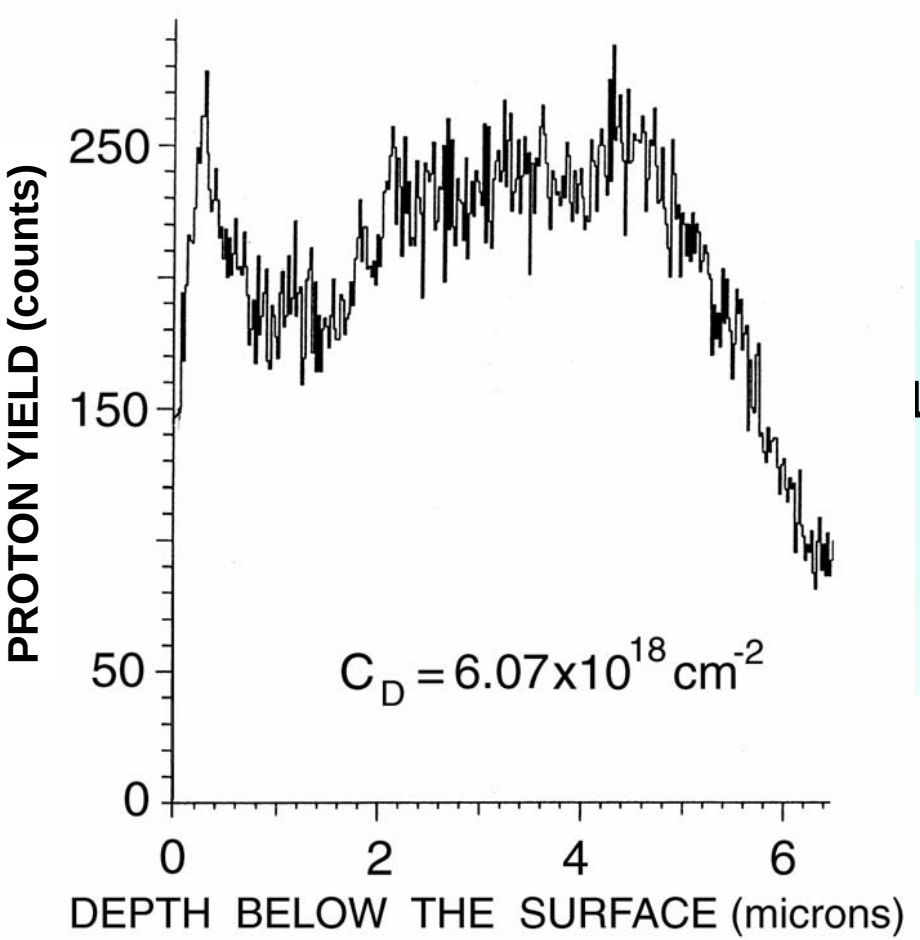
Cross- section *versus* energy



Information depth in C matrix



Nuclear Reaction Analysis
depth profile of deuterium in a flake from the ALT II tile



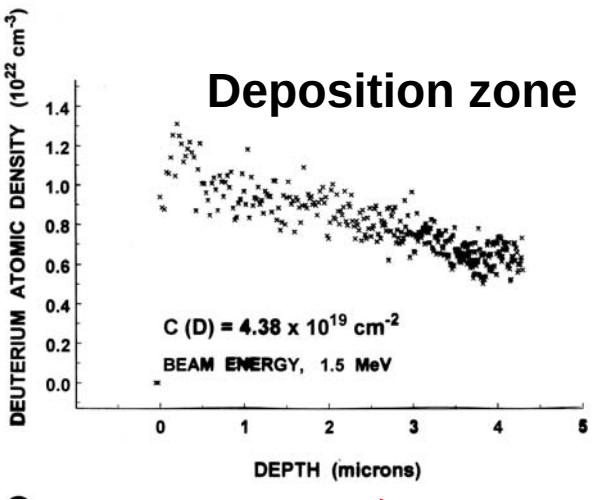
^{3}He beam 1.8 MeV

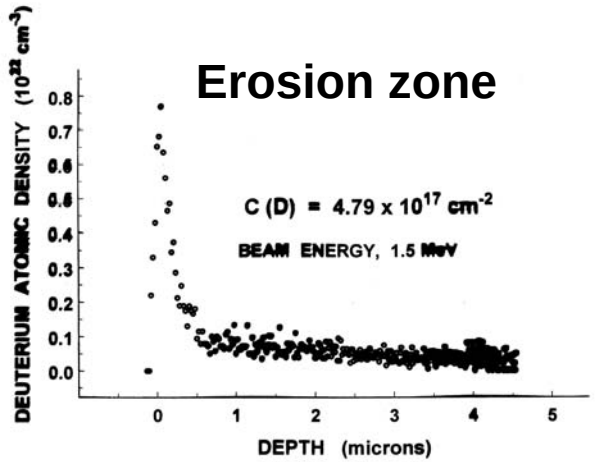
Layer Structure and D concentration:

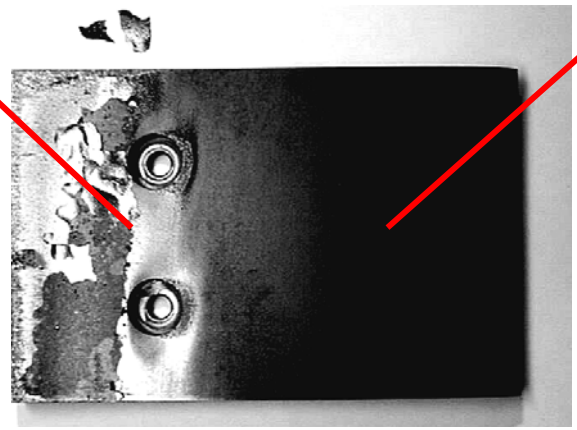
9×10^{17} D at μm^{-1} = 9×10^{21} D at / g C

D/C = 0.1

Deuterium Depth Profiles in Plasma Facing Components

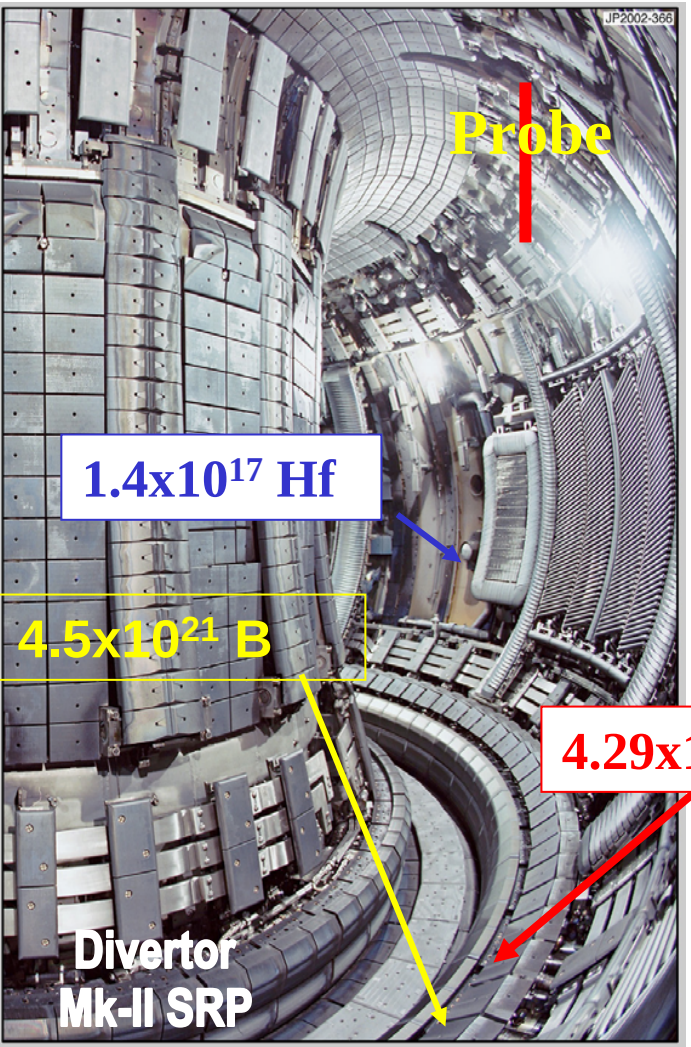






Forschungszentrum Jülich

MATERIAL MIGRATION STUDIES: TRACER TECHNIQUES



How is carbon transported and where is it re-deposited?

How to answer these questions?

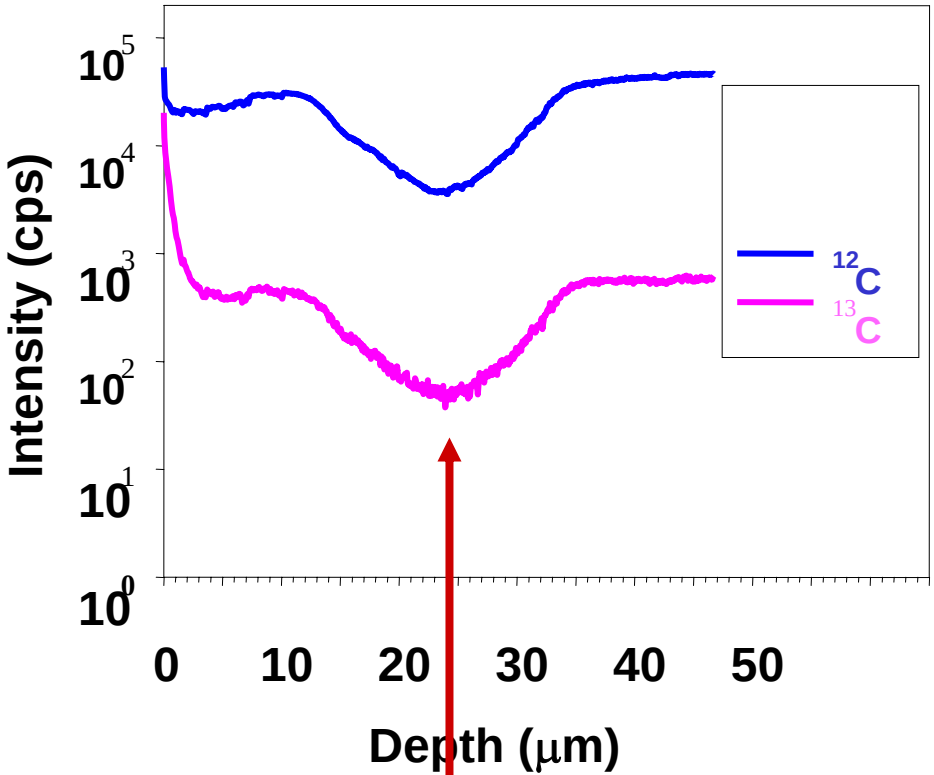
- **Controlled injection of ^{13}C tracer.**

- **Analysis of tiles to quantify the amount of ^{13}C tracer re-deposited in different locations.**

Why accelerator-based IBA techniques ? Summary

- **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.**
- **Depth profiling (limited in some cases).**
- **Chemical state of atoms is of secondary importance.**

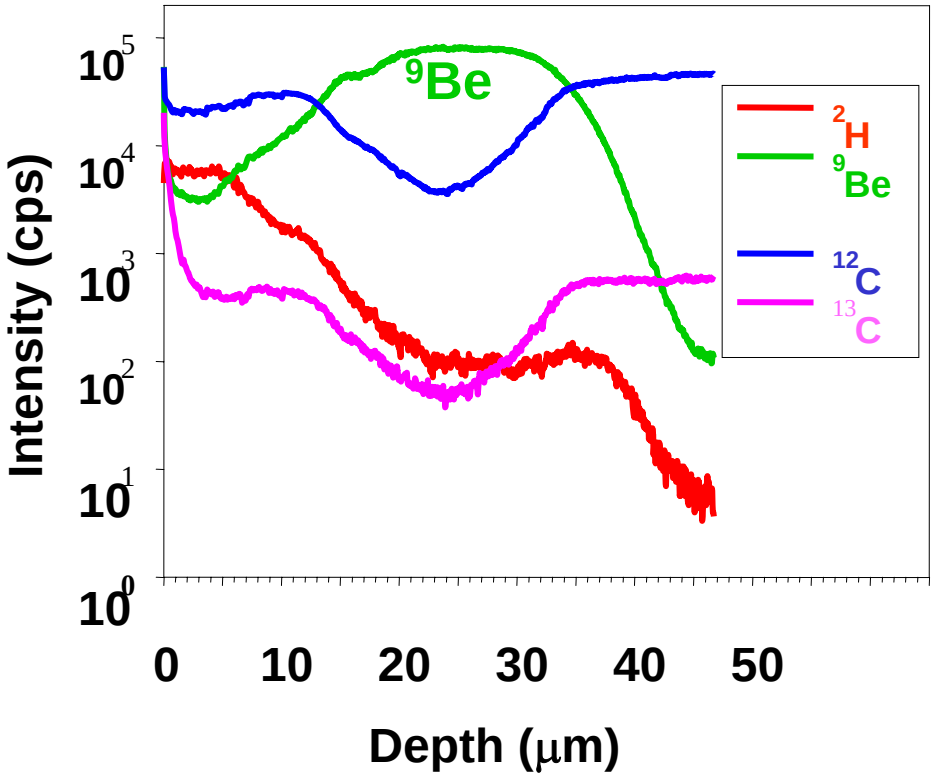
SIMS Analysis of Tracer Experiment: Depth Distribution of Re-deposited ^{13}C



Message: vast amount of C-13 is found in a thin surface layer (< 2 μm).

Question: Why are the carbon profiles hollow?

SIMS: Depth Distribution of Species



Secondary Ion Mass Spectrometry: Advantages and Limitations

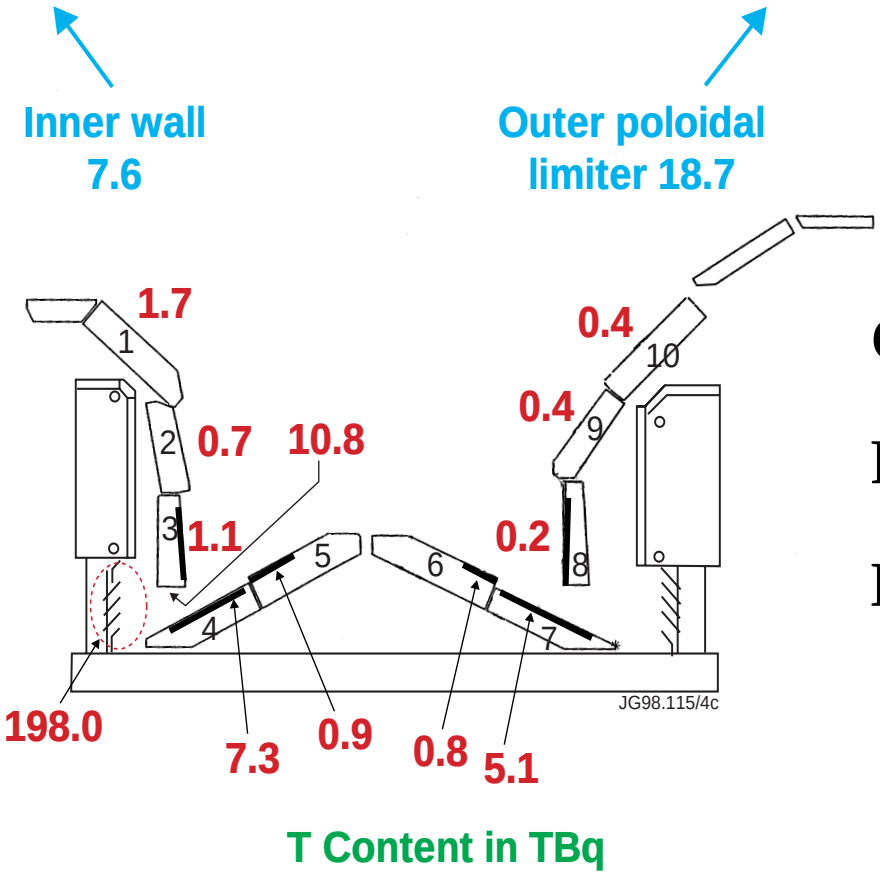
- **Ultra-high sensitivity. Unbeatable in qualitative analysis.**
- **Depth profiling.**

- **Poor quantification because of matrix and crater effects.**

TRITIUM ANALYSIS

- ***LIQUID SCINTILLOGRAPHY (LSC) OF TRITIATED WATER***
- ***IMAGING PLATE (IP)***
- ***BETA-INDUCED X-RAY SPECTROSCOPY (BIXS)***

JET Divertor: Tritium retention after D-T Operation



T Content in TBq

How was the analysis performed?

Coring

Full combustion

Liquid scintillography of Q_2O

$Q_2 = DT, HT, T_2$

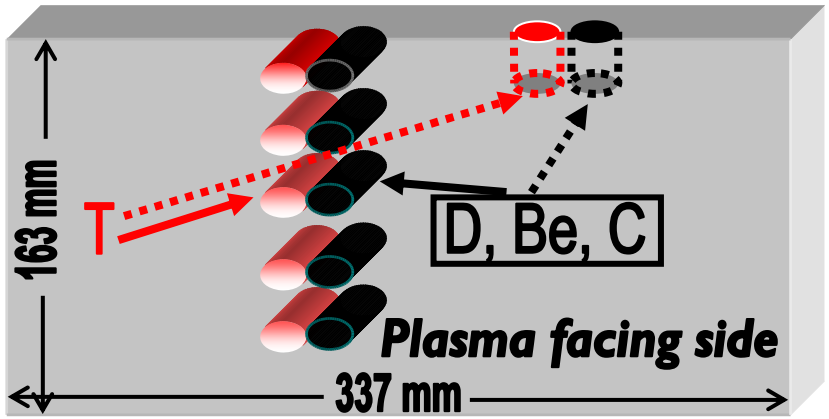
UKAEA Fusion

R-D Penzhorn, N Bekris, FZK, Karlsruhe

Sampling and Analysis

Example of a divertor tile

TRITIUM:
- *Full combustion*
- *LSC of Q_2O*



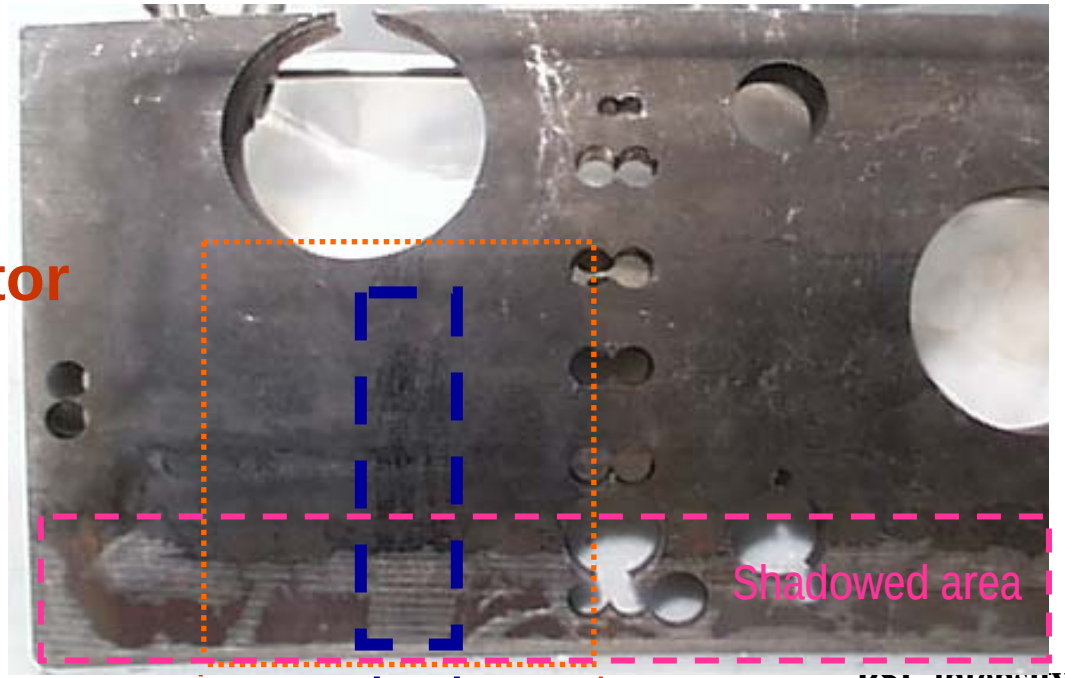
D, Be and C:
NRA with a $^3He^+$ beam

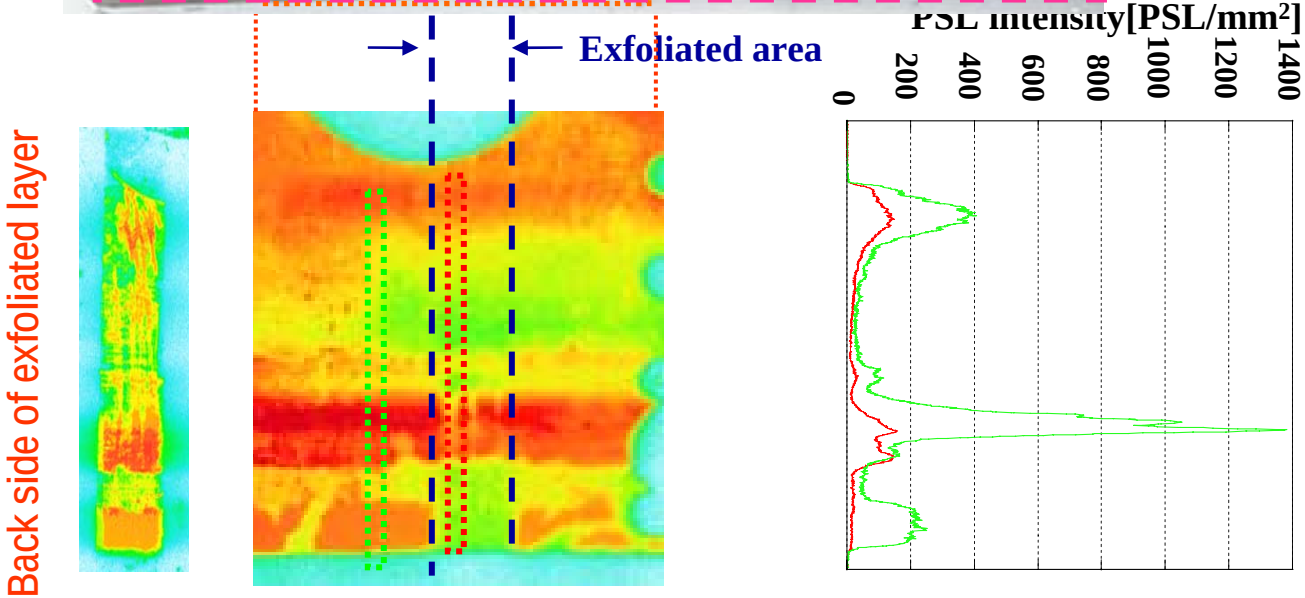
The aims of sampling:

- ***Reduction of total radioactivity to be handled in further studies***
- ***Comparative analysis of D and T***

Imaging Plate Technique for Tritium Analysis

Tritium on the divertor plate from JET





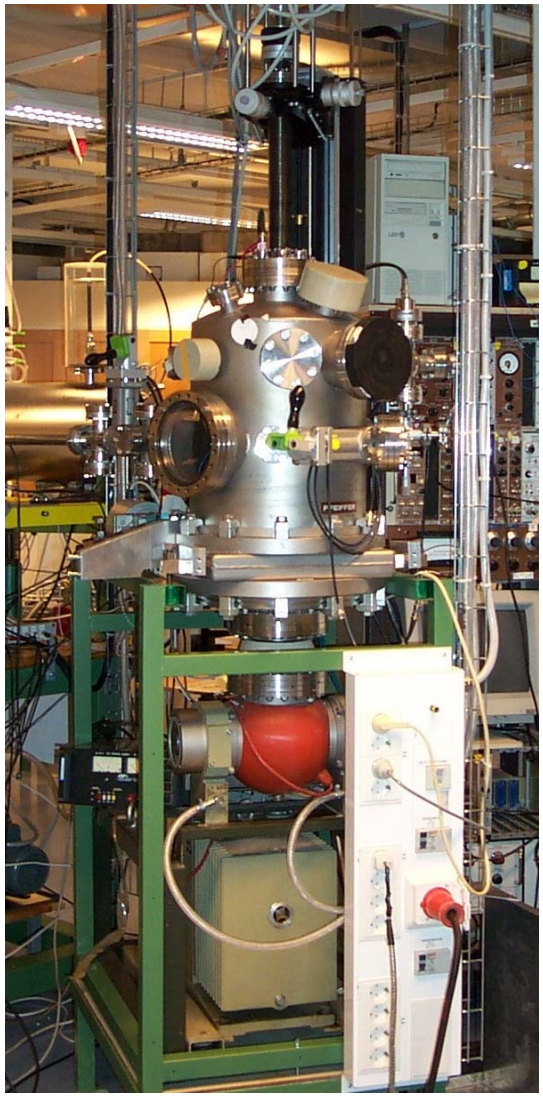
Courtesy: Tetsuo Tanabe, Kyushu University, Japan

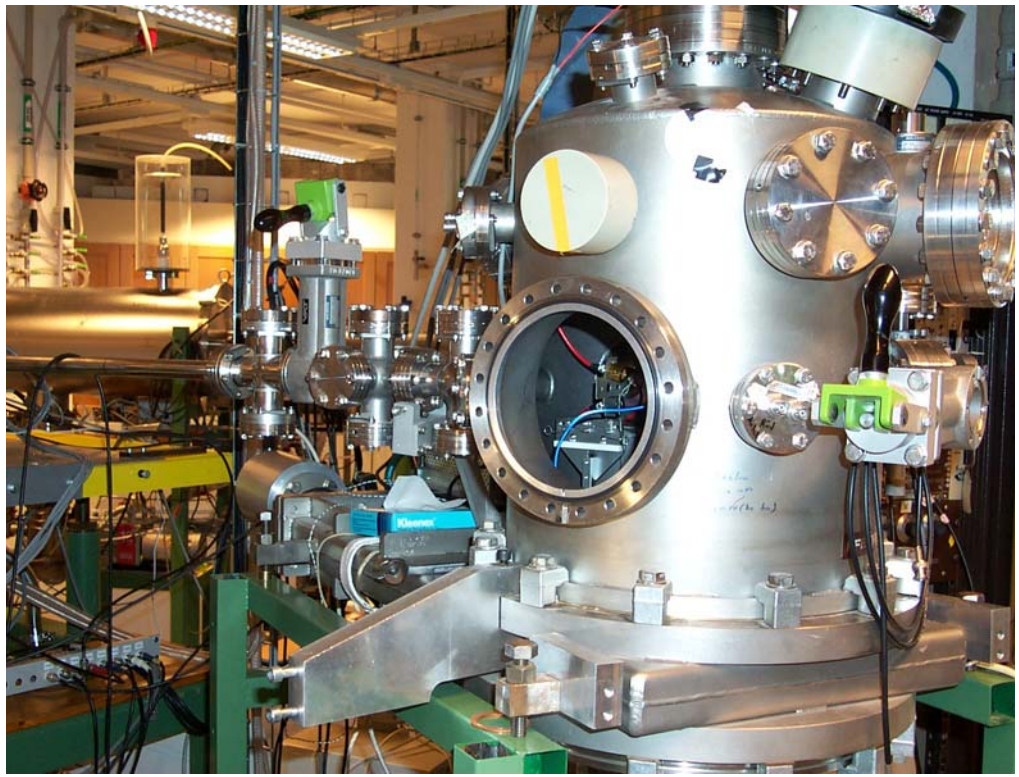
INSTRUMENTATION

INSTRUMENTATION FOR ANALYSIS OF PFM

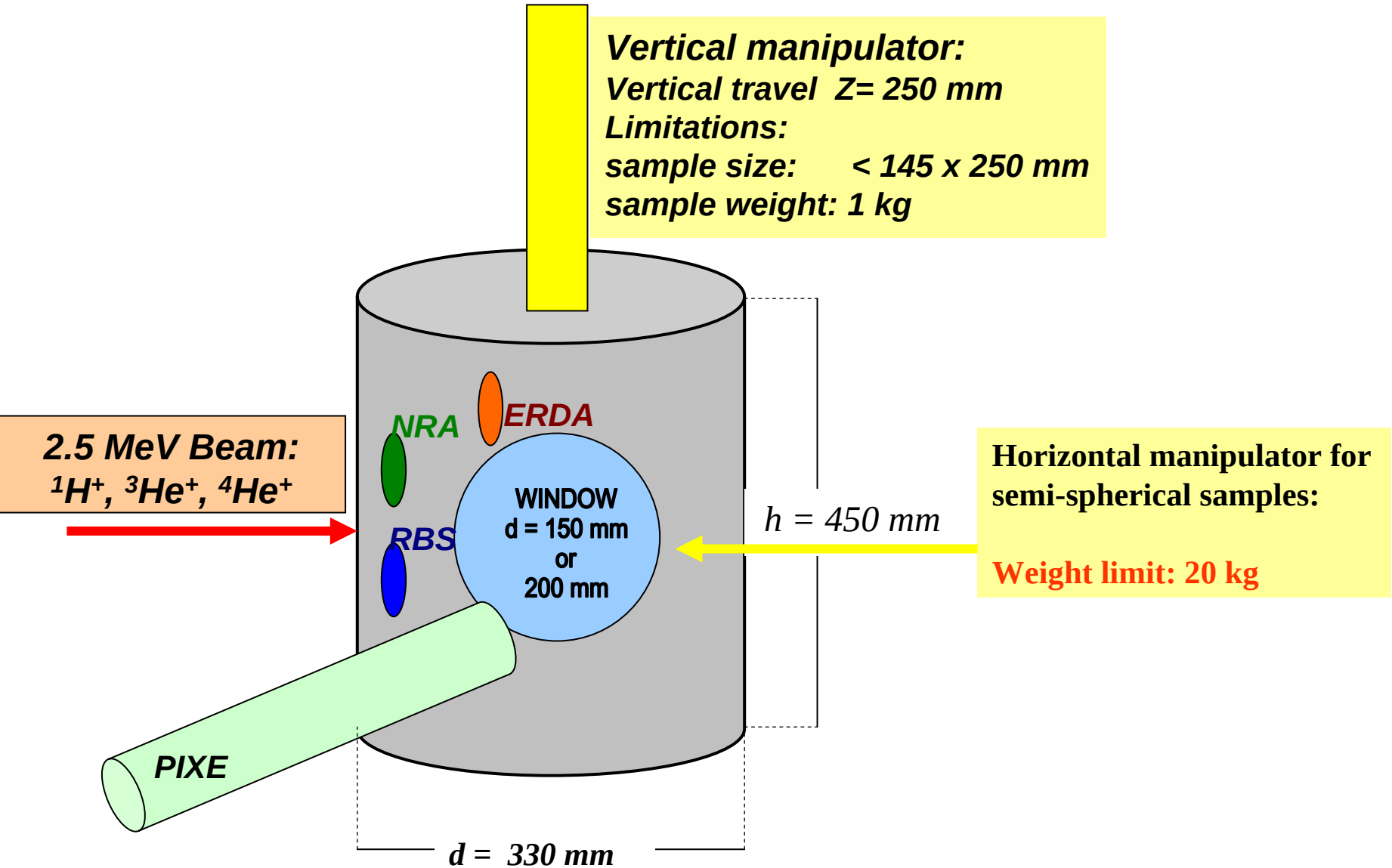
- ***Accelerator***
- ***Analysis chamber with detectors***
- ***Targets***

Instrumentation: Analysis chamber

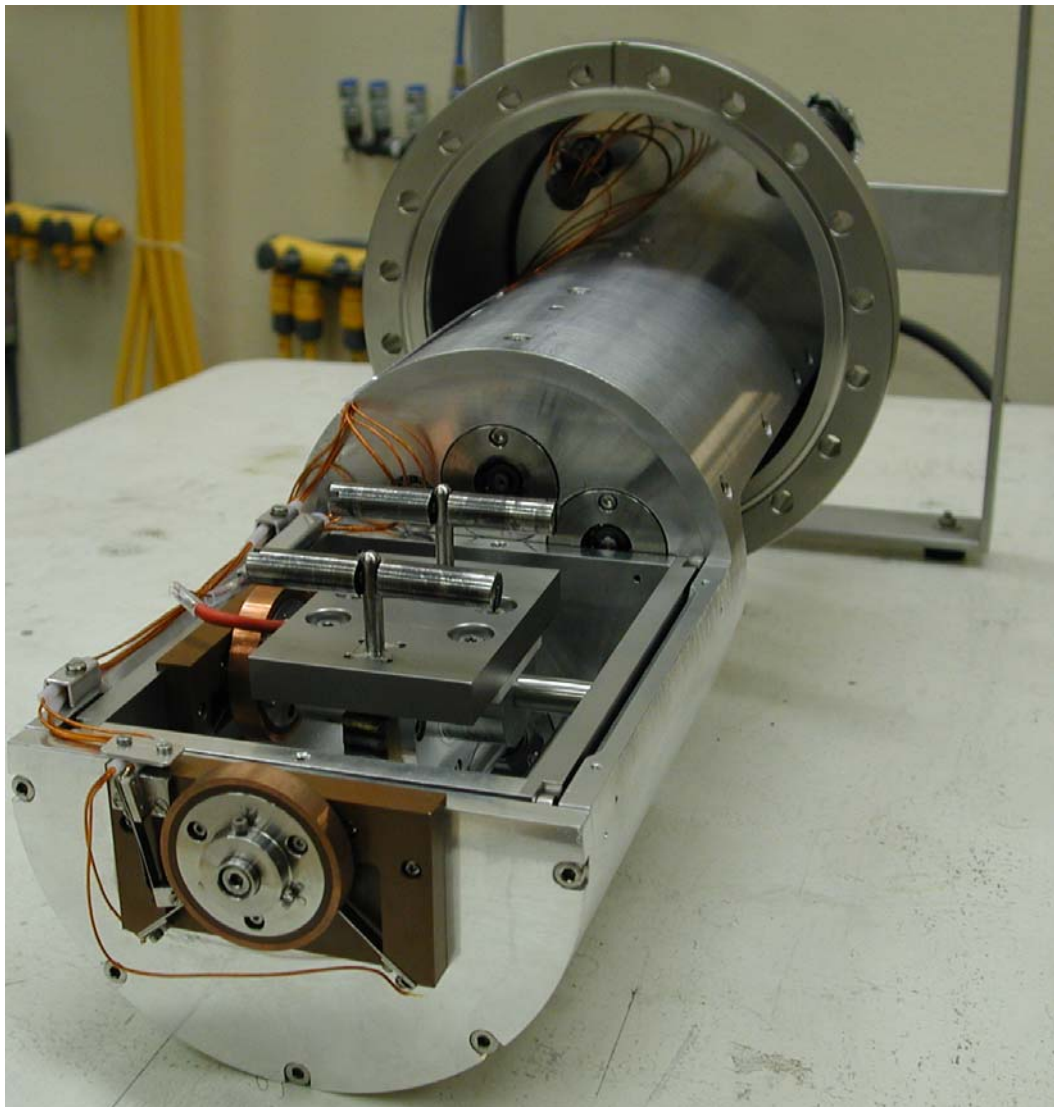




Analysis chamber



Instrumentation: Limiter manipulator



Weight: 23 kg

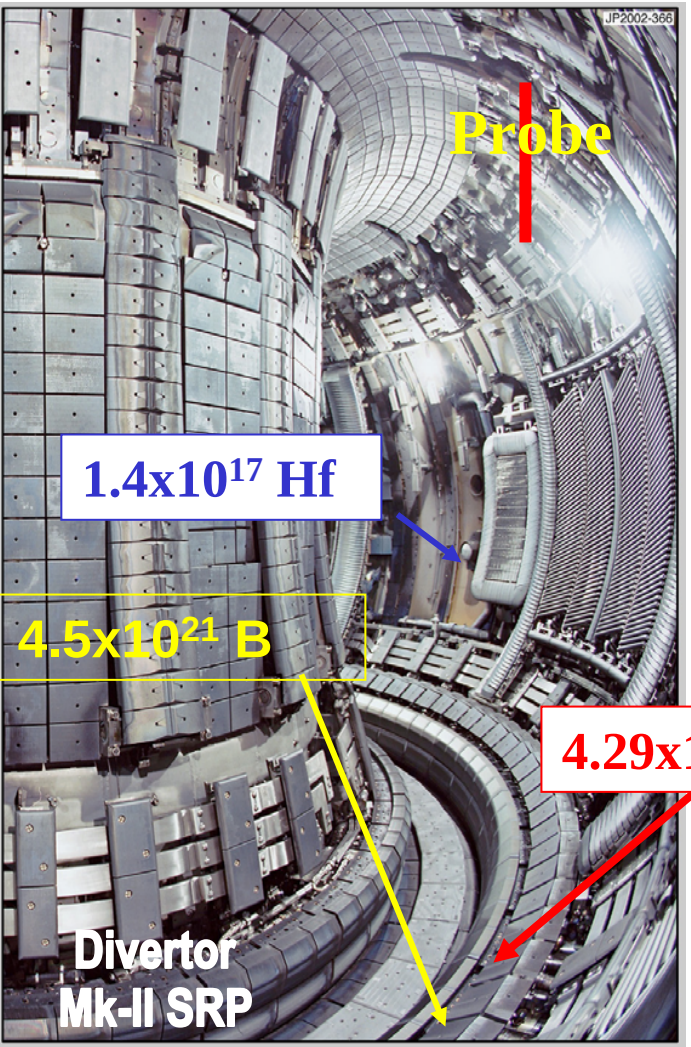
Capabilities:

Probes up to 20 kg

Rotation X and Y: 180^{o}

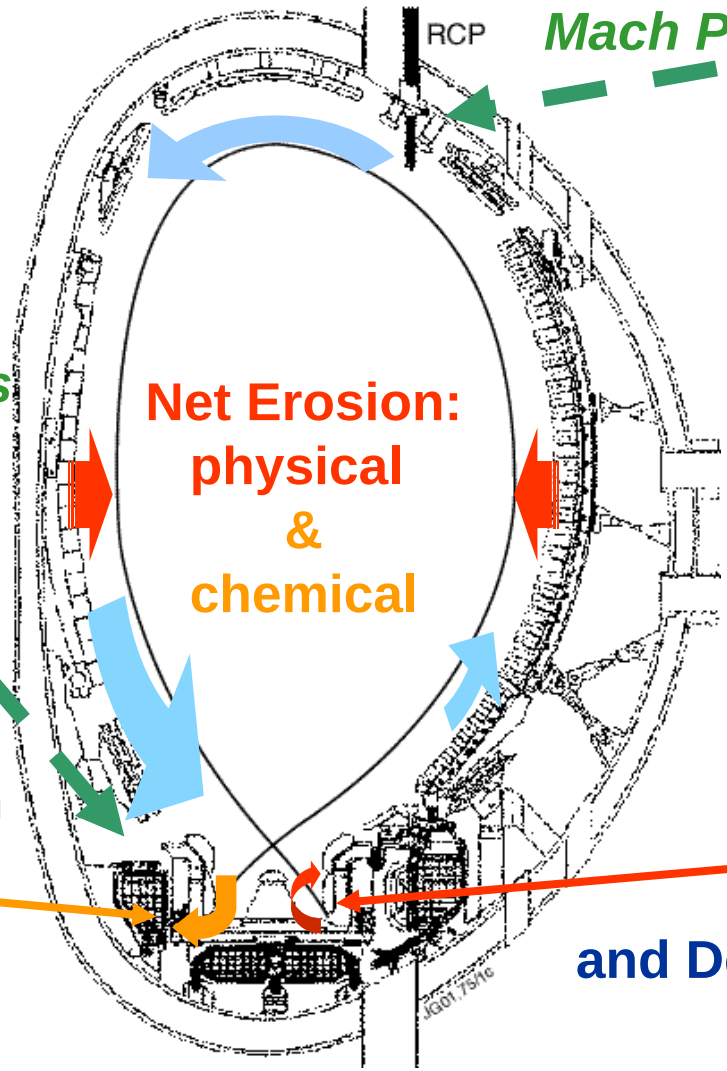
Positioning: ± 50 μm

MATERIAL TRANSPORT STUDIES: TRACER TECHNIQUES and COLLECTOR PROBES



Collector probe before and after exposure

Concluding Remarks: Overview of Material Migration in JET



This picture is based on:

- Tile analysis
- Tracer injection experiments
- Probe measurements
- Quartz micro-balance data

Simple concluding remarks and recommendations

Use a relevant set of methods for solving a given problem.

NEVER EVER claim that ”MY METHOD” solves all problems (possible and impossible).

Cross-check your results !

There is NO single method that can answer all questions but there are methods that can provide answers to specific questions.

CO-OPERATE !!

Thank you for listening