KTH ROYAL INSTITUTE
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Material characterization for magnetically confined fusion: Surface analysis and method development

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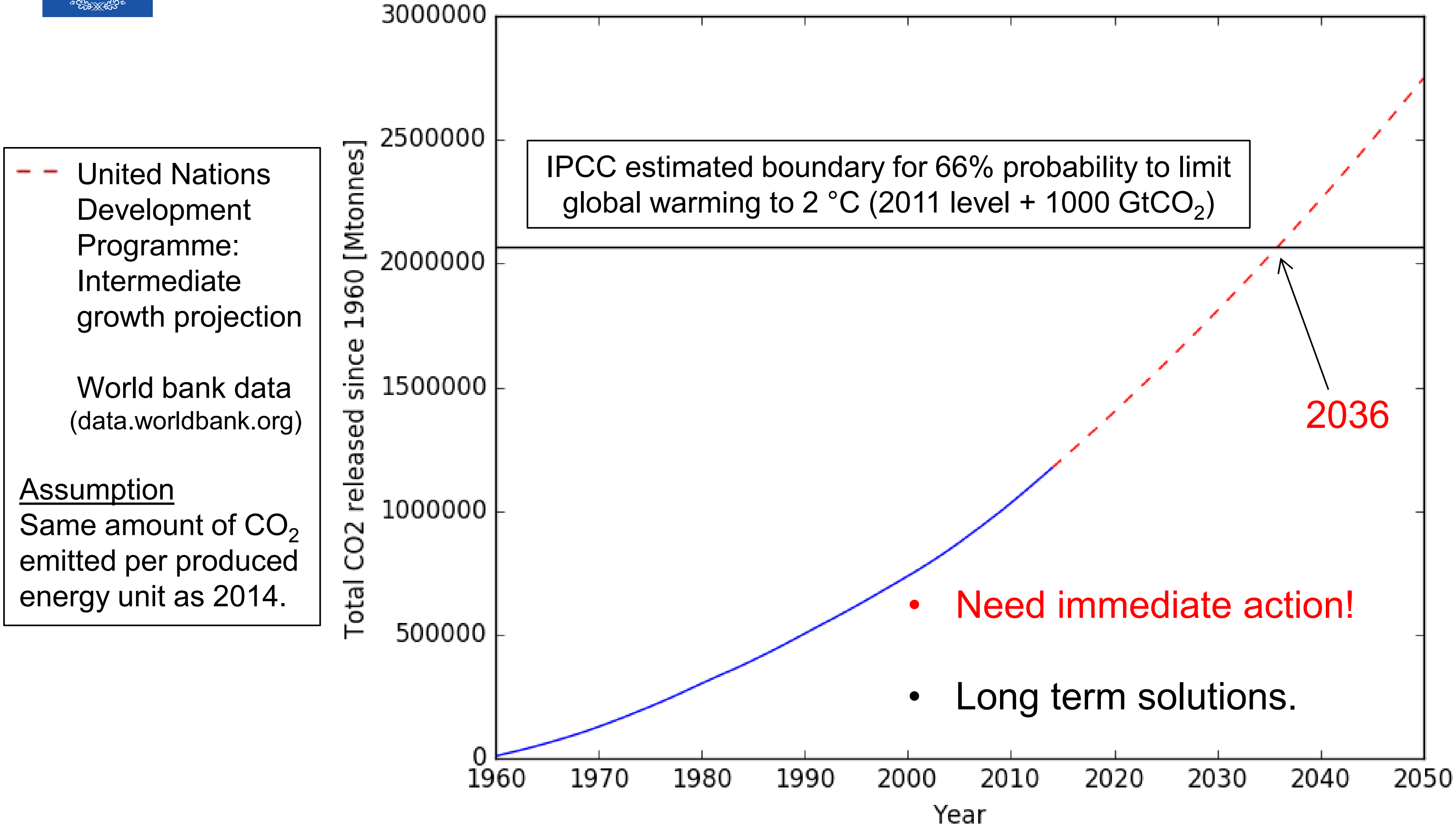
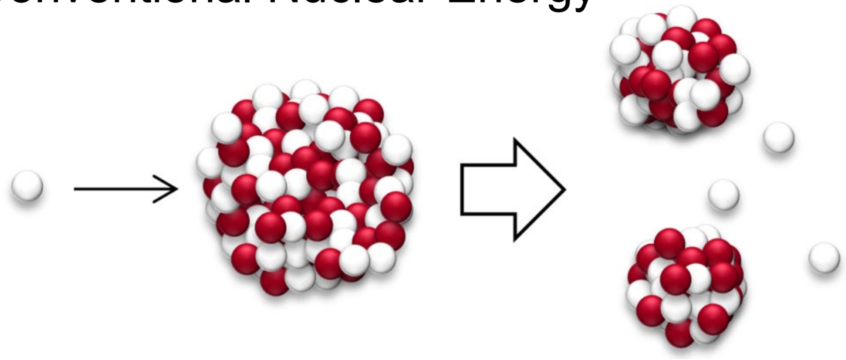
Total CO_2 Released after 1960



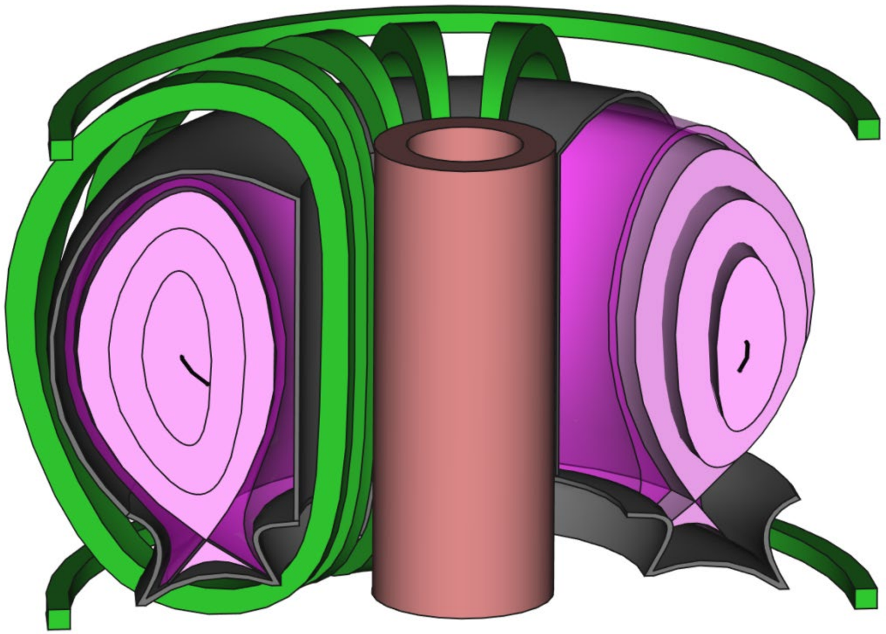
- Need immediate action!
- Long term solutions.

Long Term Carbon-Neutral Energy Mix

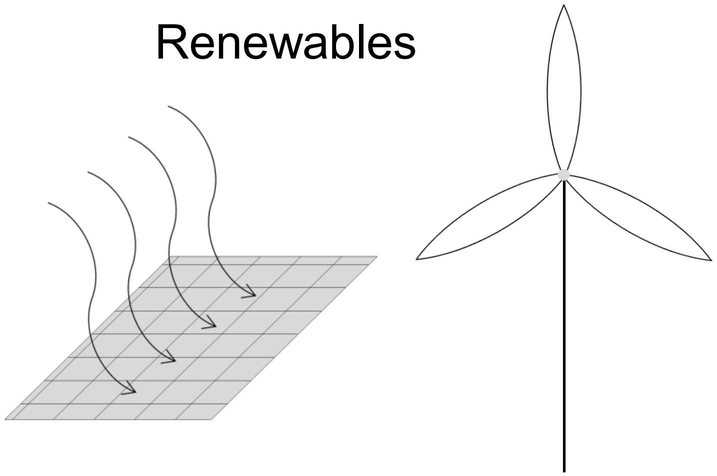
Conventional Nuclear Energy



Nuclear Fusion

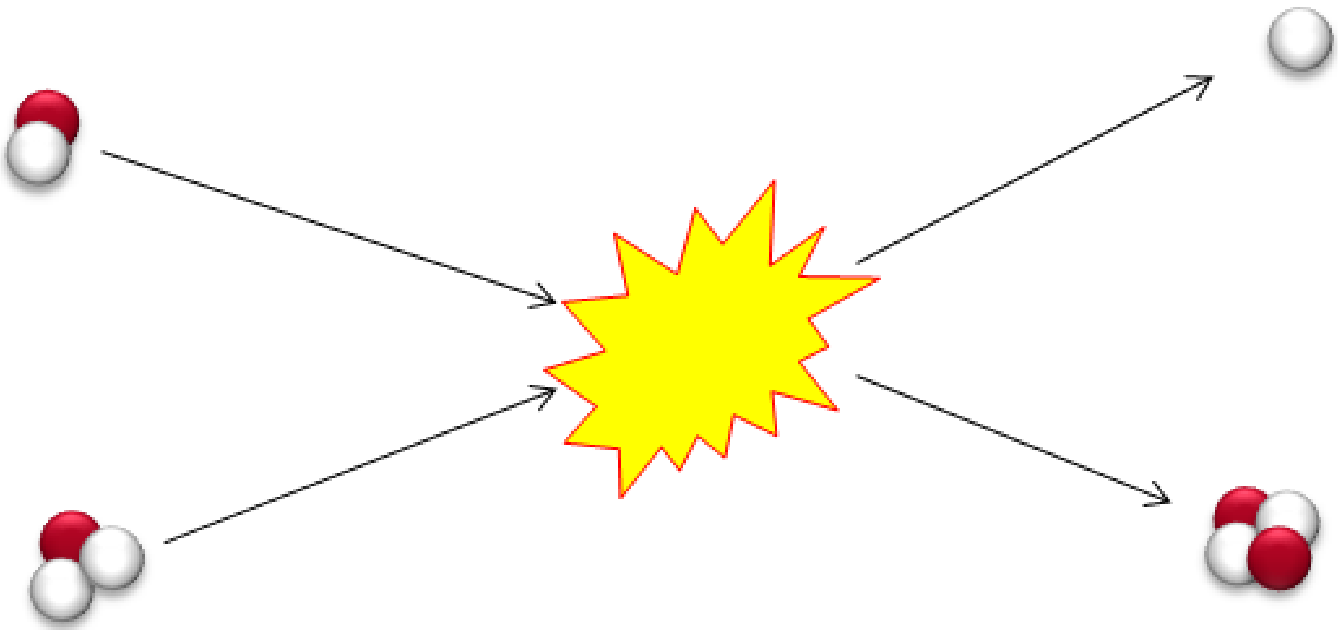


Renewables



Nuclear Fusion

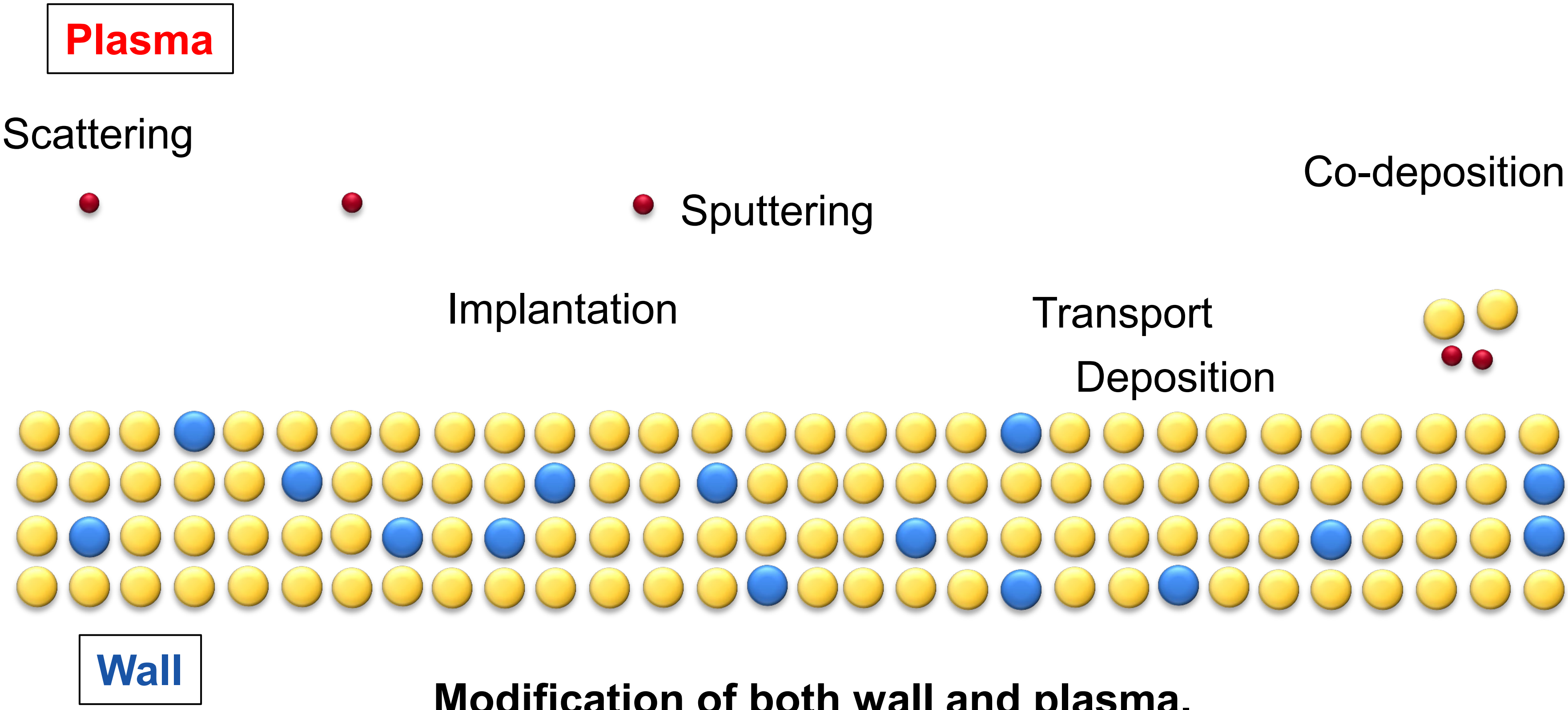
May cause material damage and activation!



$D + T \rightarrow {}^4He + n + 17.6\ MeV$

Present machines operate mainly with deuterium plasma.

Plasma-Material Interactions



Modification of both wall and plasma.

Notable issue: Fuel atom (●) retention.

Aims

General objectives

- Improve our knowledge about plasma-material interaction in fusion devices: Erosion, transport and deposition.

- Investigate methods and possible development to this end.

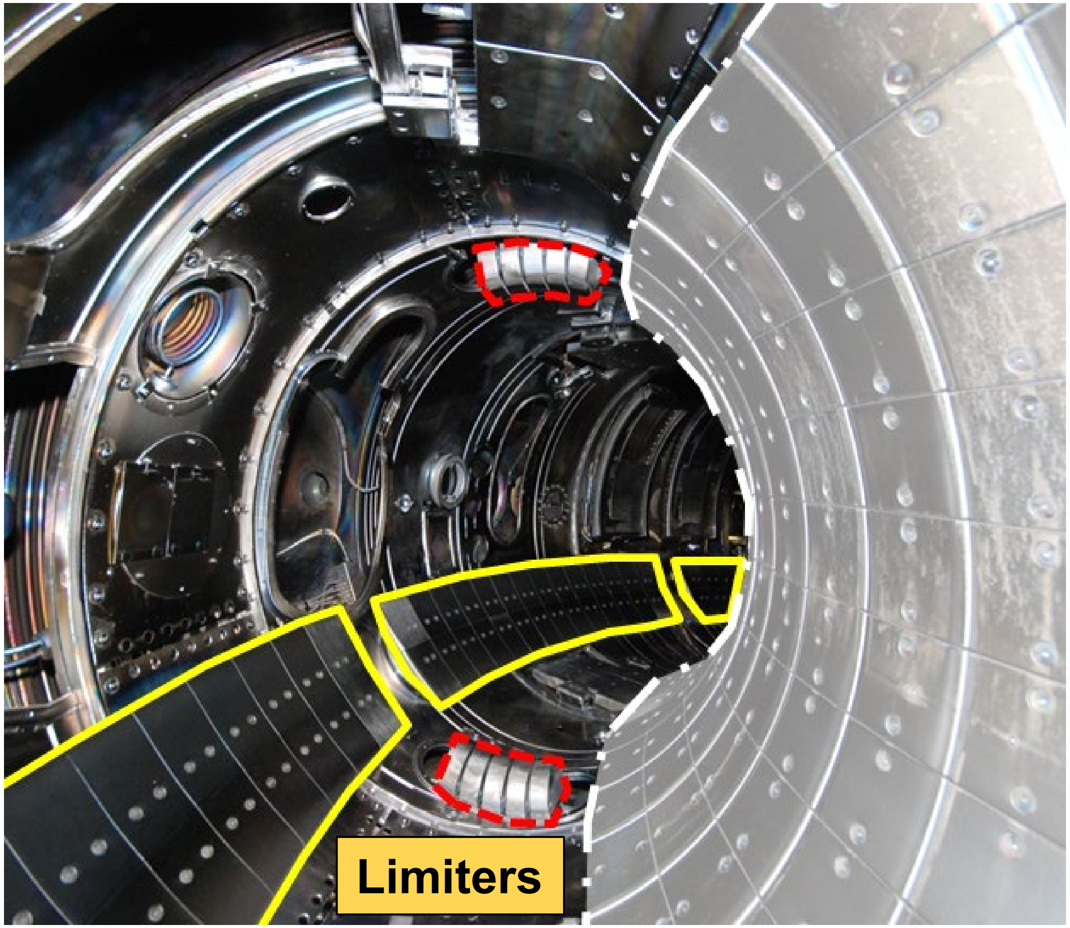
Specific: Papers I and VI

- Determine rate/direction of material transport in two tokamaks
  $\rightarrow$ Differences between different elements.
  $\rightarrow$ Relevance of geometry, component position.

- Obtain information about thickness and composition of deposits.

- Quantify retention of fuel atoms.

Studied Tokamak Devices



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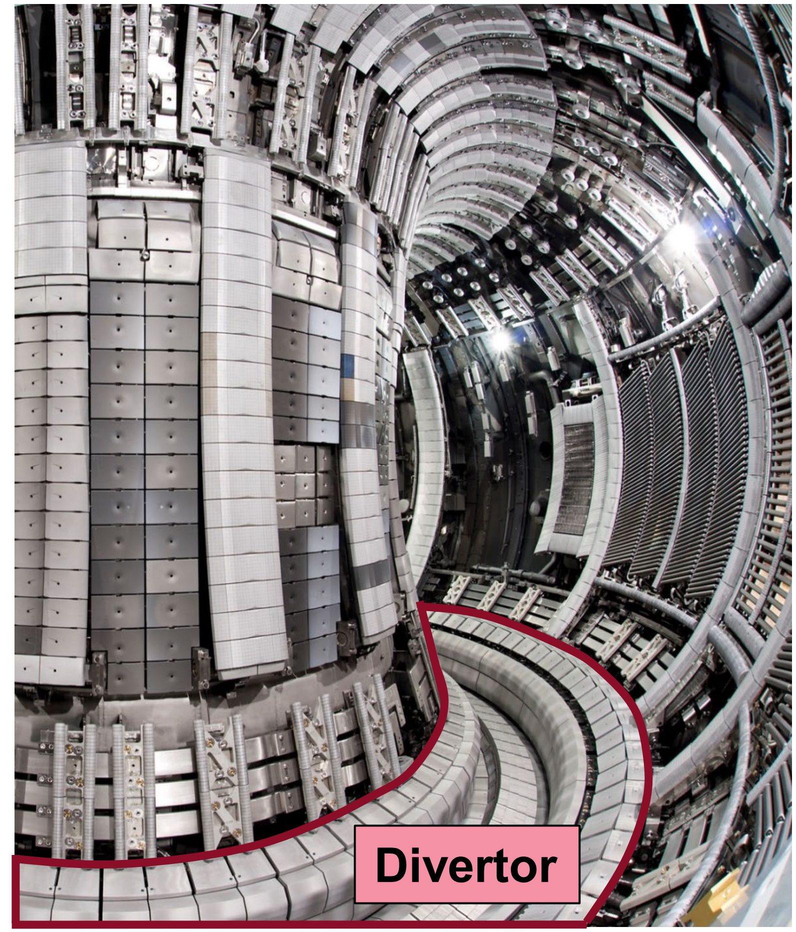
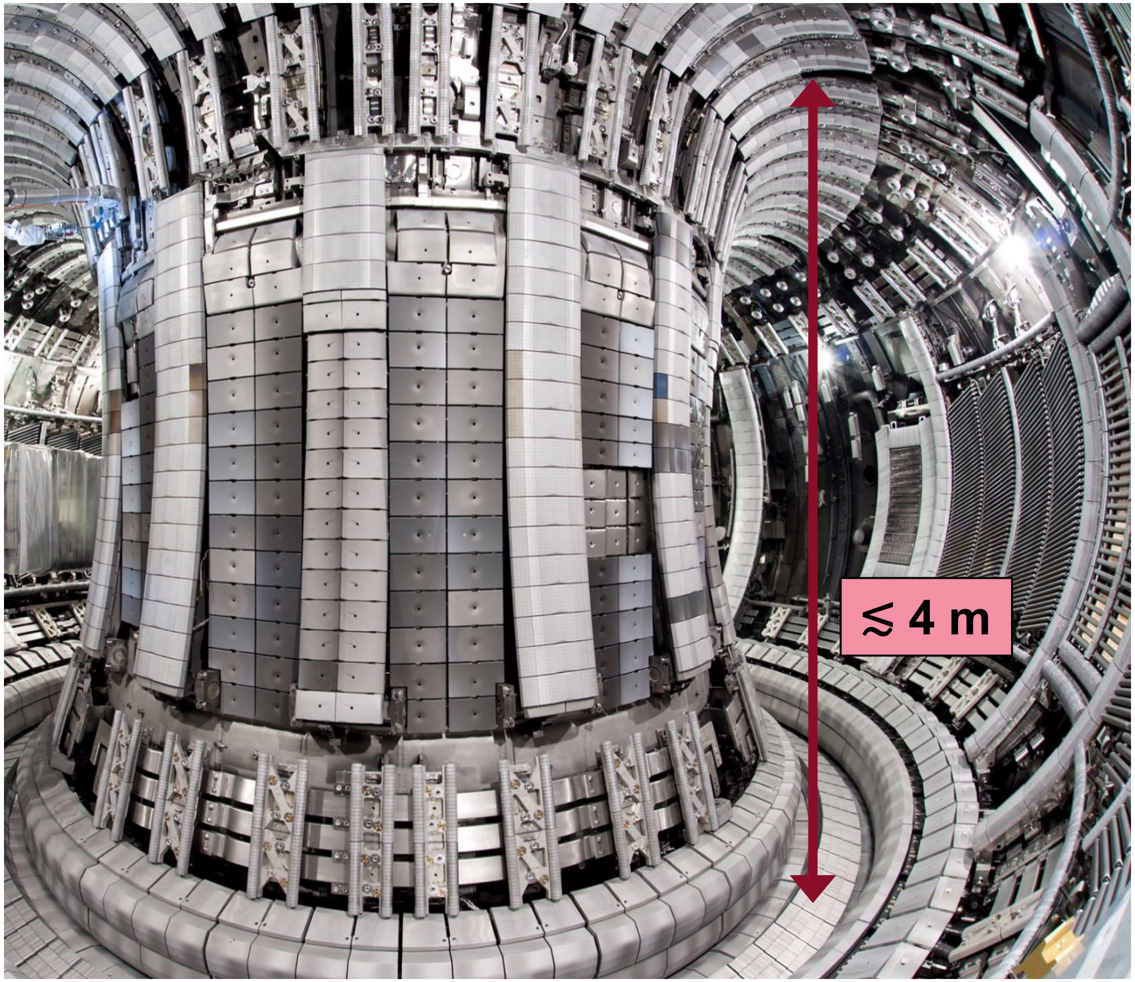


JET

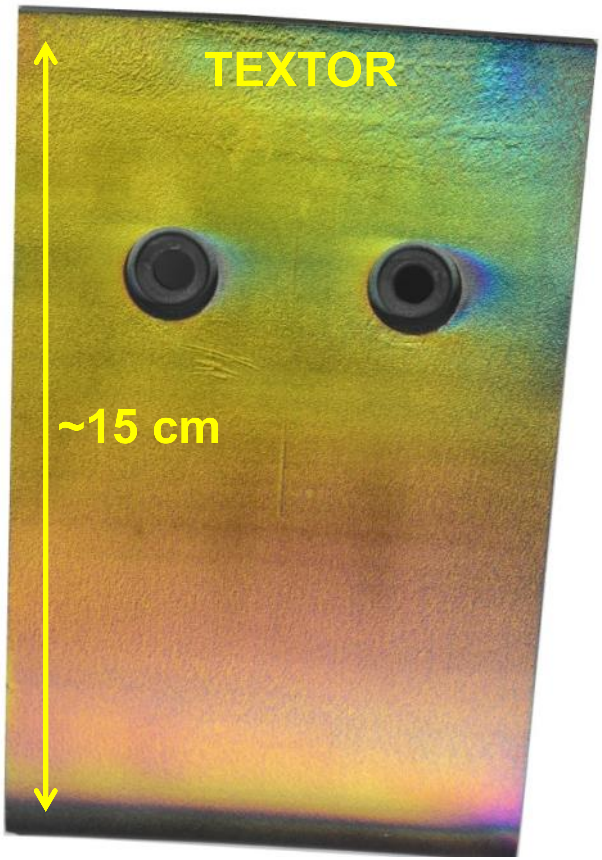
Size Scales



Erosion, Transport and Deposition Studies

Methods: a) Monitoring of fusion plasma during machine operation.

b) Ex-situ surface analysis of plasma-exposed components.



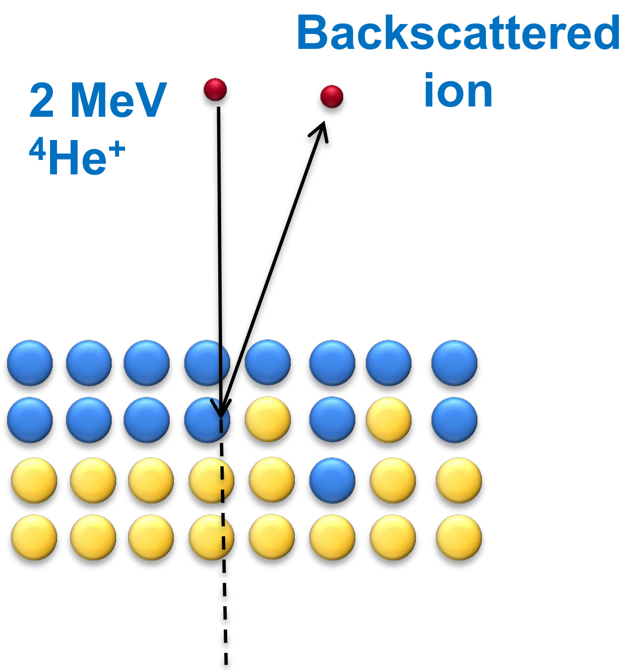
Techniques used in this work

- Rutherford Backscattering Spectrometry
- Medium-Energy Ion Scattering
- Nuclear Reaction Analysis
- Elastic Recoil Detection Analysis
- Optical Surface Profiling
- Optical Microscopy
- Atomic Force Microscopy
- Scanning Electron Microscopy with Energy Dispersive X-ray Spectroscopy

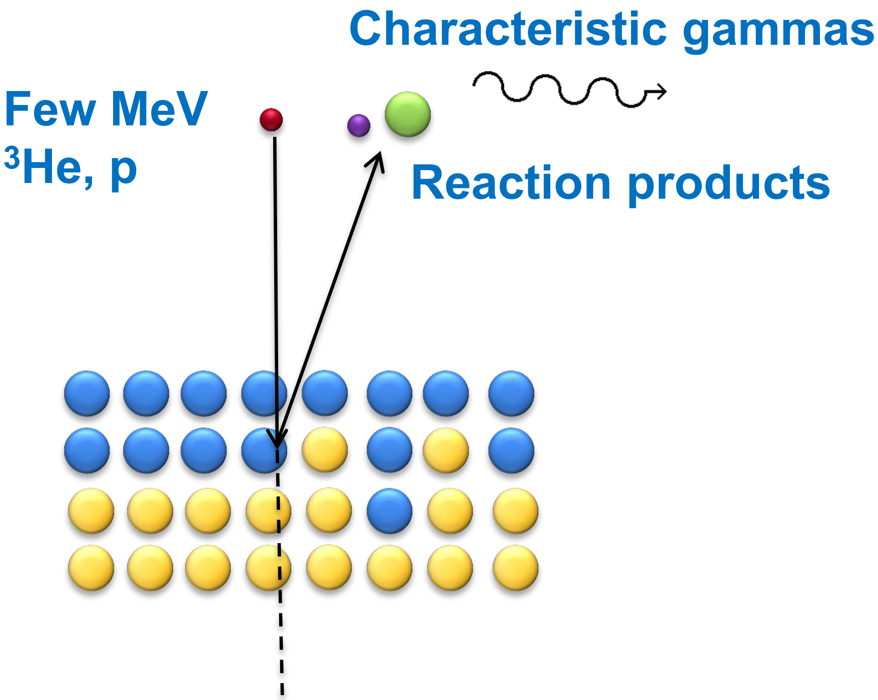
Every technique has specific pros & cons

Ion Beam Analysis Techniques

Rutherford Backscattering Spectrometry



Nuclear Reaction Analysis

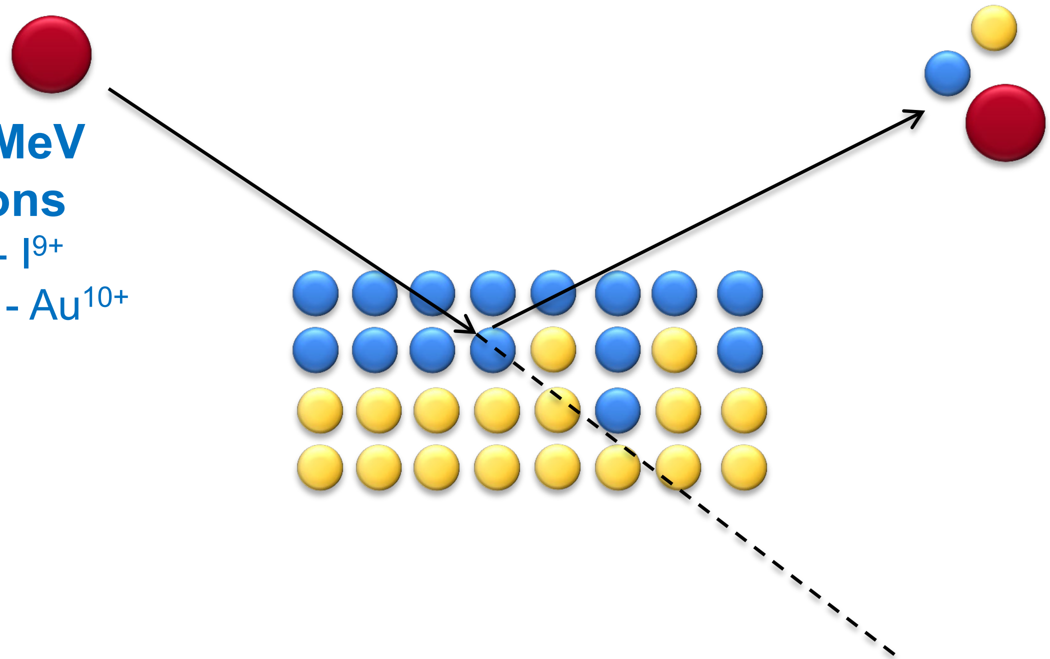


$^{3}He + D \rightarrow {}^{4}He + p$

$^{3}He + {}^{9}Be \rightarrow {}^{11}B + p$

Elastic Recoil Detection Analysis

30 – 40 MeV
Heavy ions
Iodine I^{7+} - I^{9+}
Gold Au^{7+} - Au^{10+}

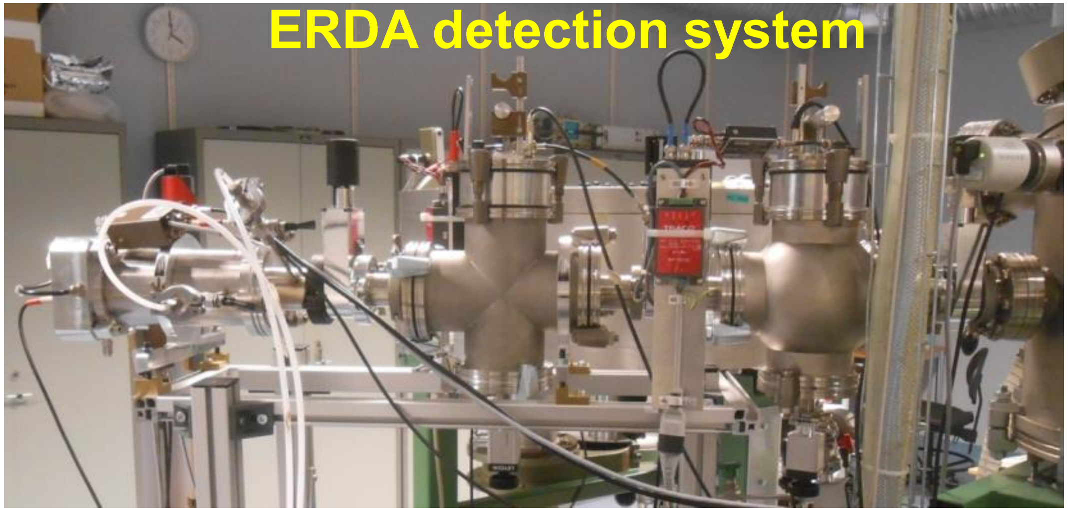


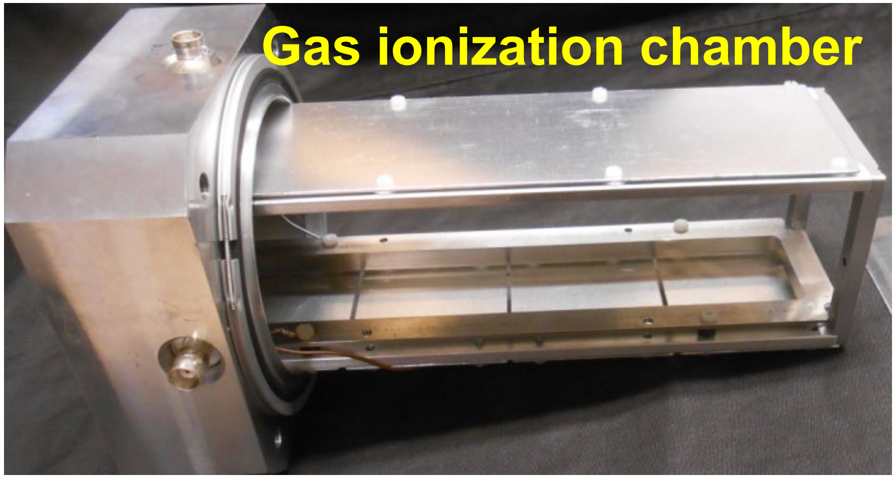
Recoil ions

Forward scattered primary ions

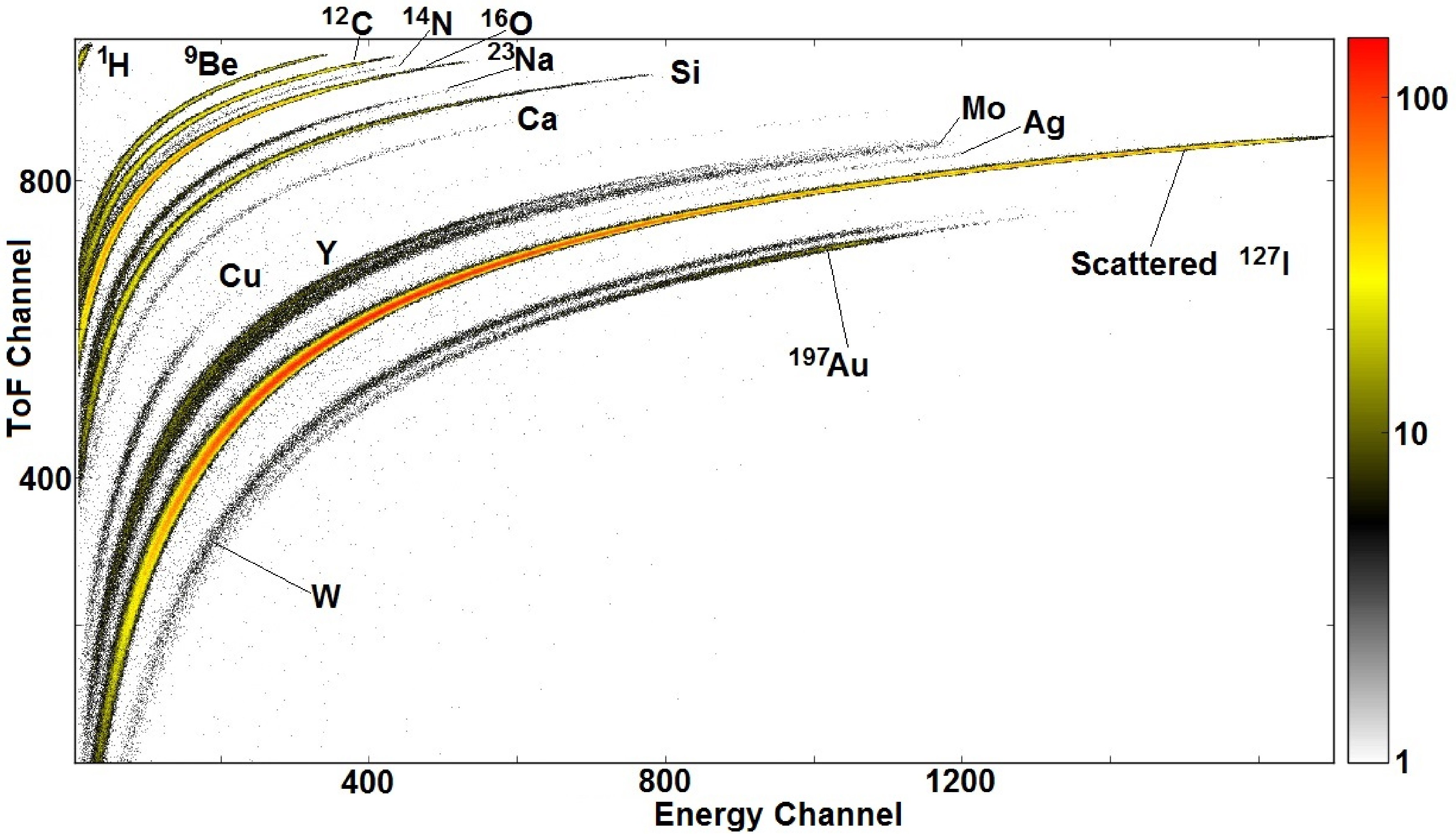
Mesurement of recoil ions' velocity and energy
→ Depth resolved quantification of all elements and isotopes present in sample

Uppsala University Tandem Laboratory



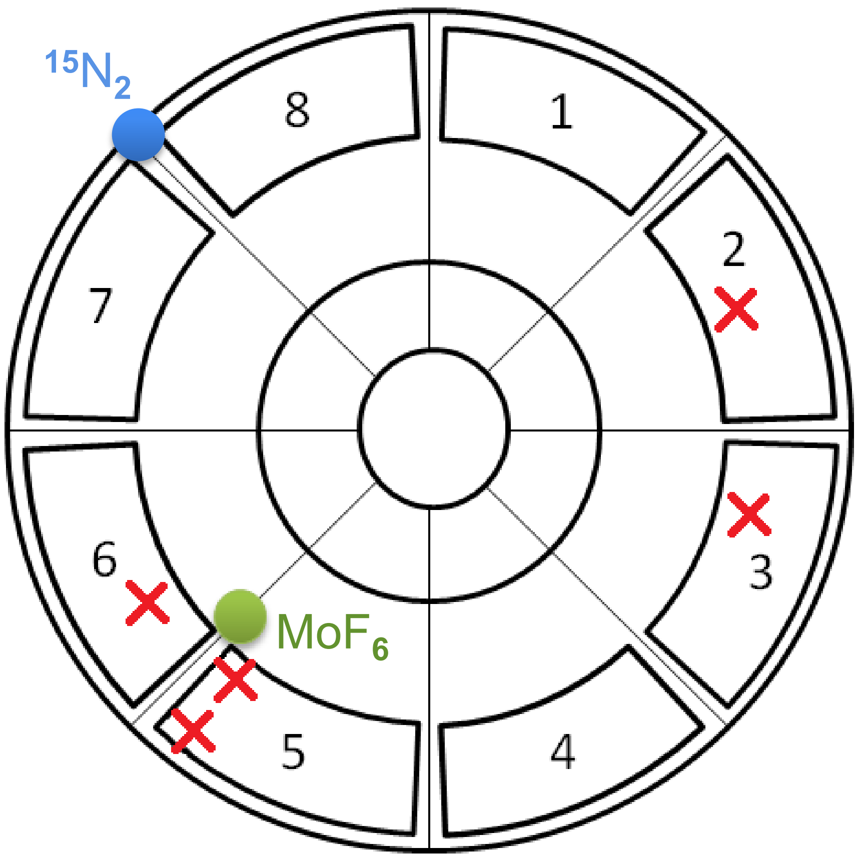


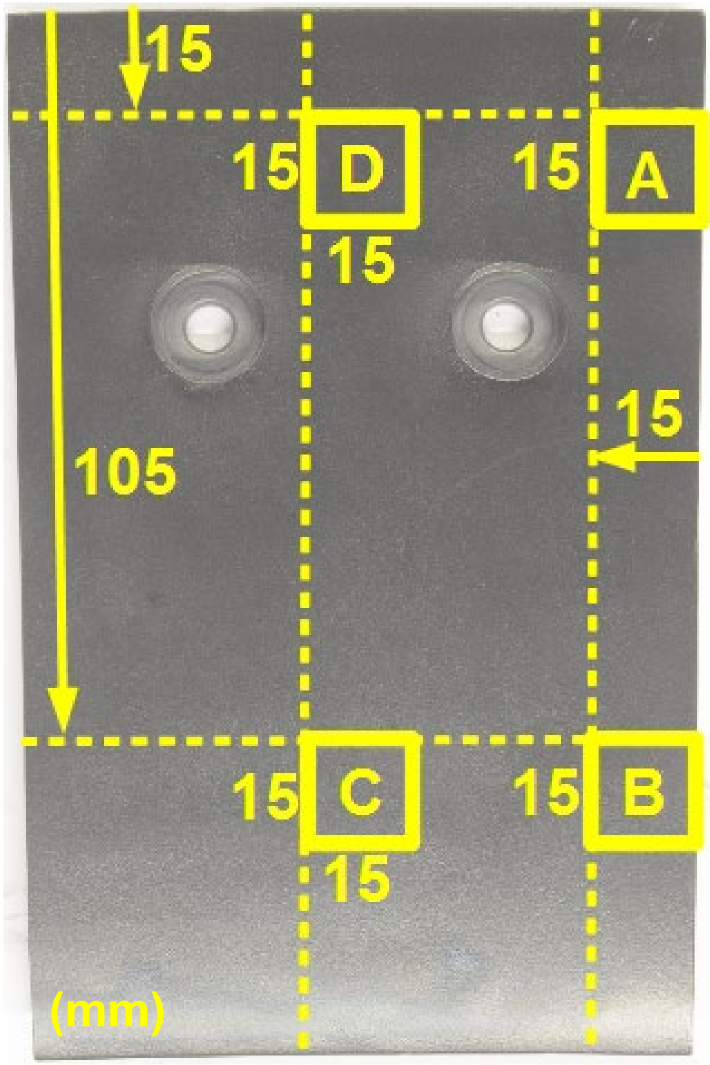
ERDA Detection System Performance



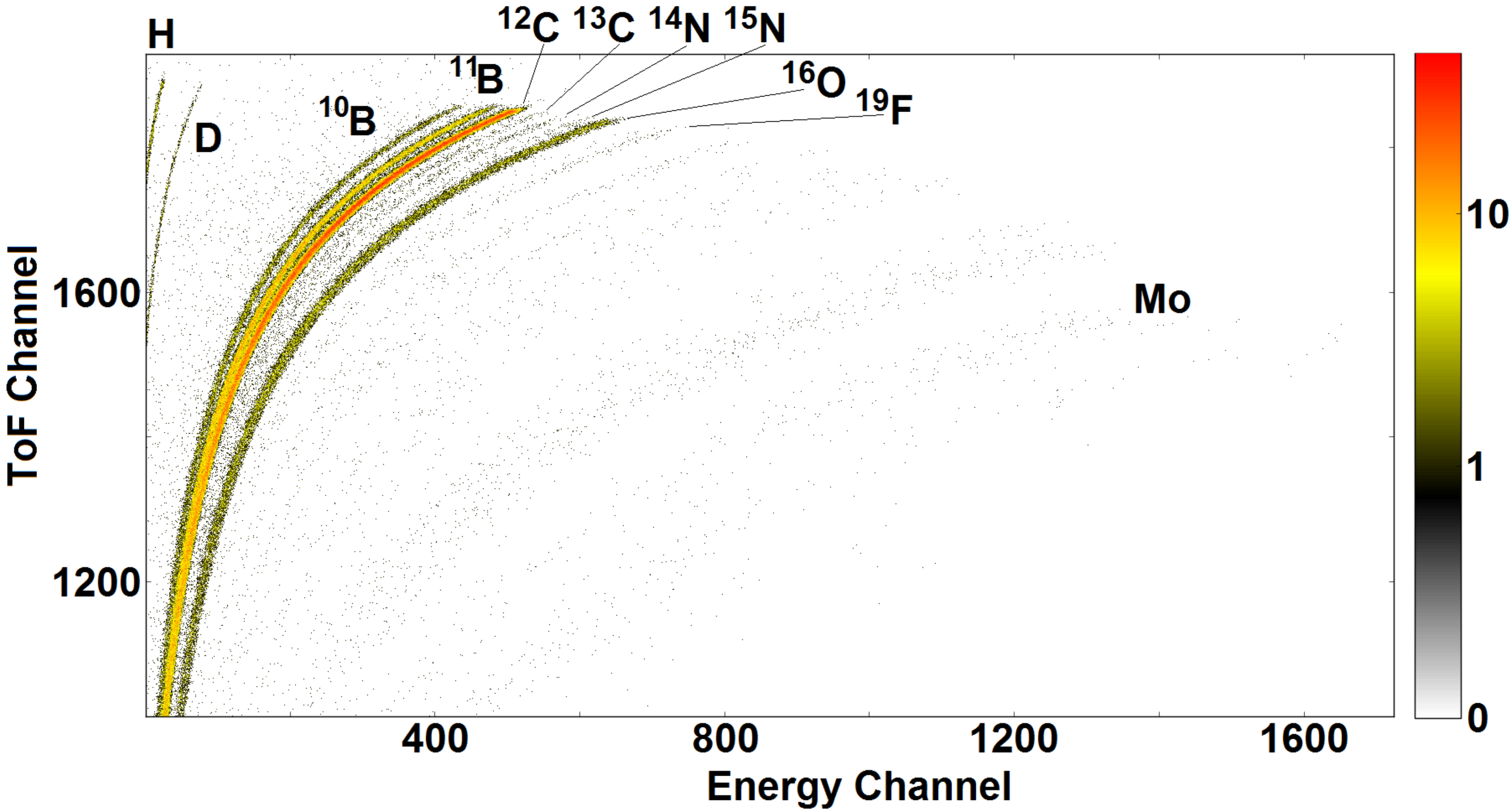
Some Measurements and Results

Paper I: Material Analysis After TEXTOR Shutdown



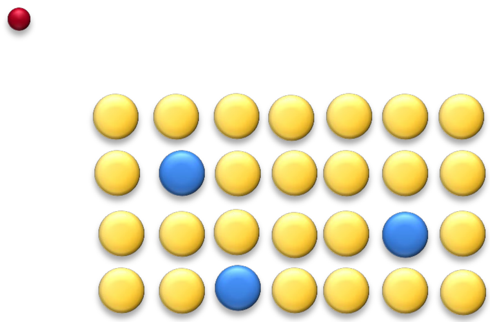


Paper I: ERDA Measurements



Paper I: Summary

- A lot of molybdenum deposited rather close to injection point
  → **Prompt deposition, erosion, prompt re-deposition.**

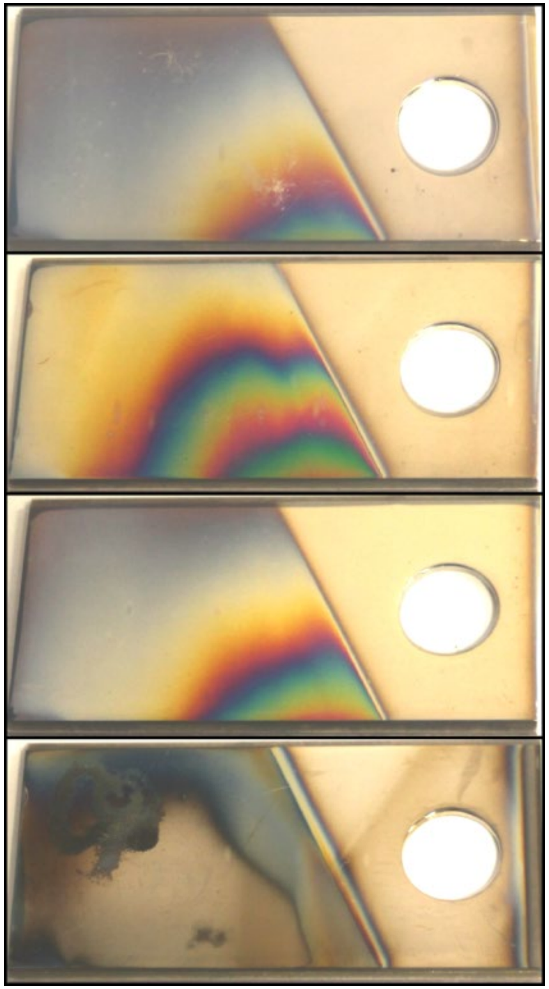


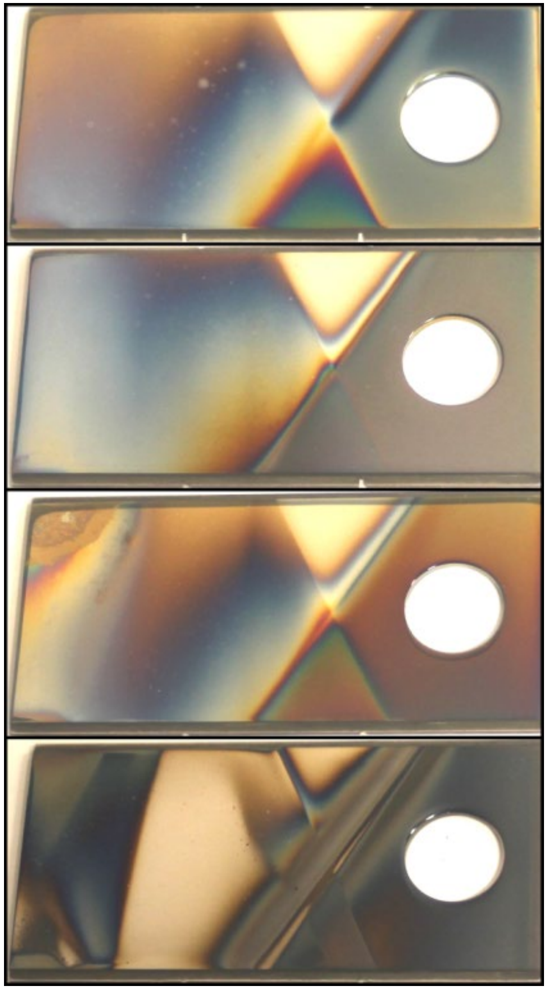
Note: Properties of deposits radically different from original material.

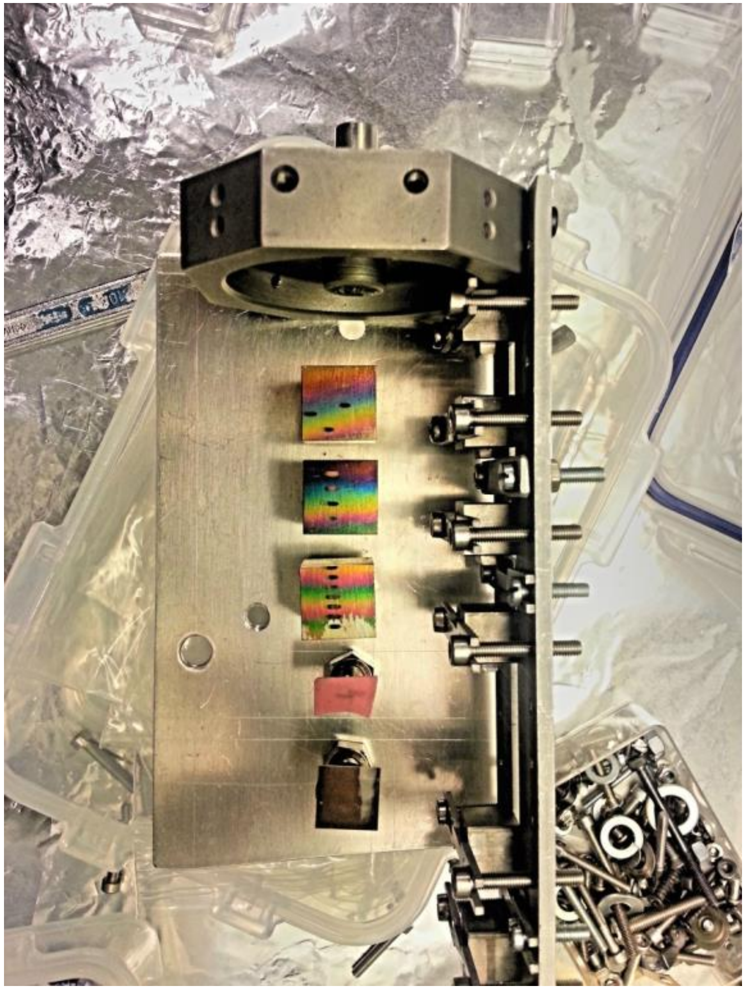
- Larger fraction of fluorine found on opposite side of machine
  → **Verified: prompt deposition less effective for light elements**.

- ^{15}N found with molybdenum despite different injection location
  → **Deposition locally enhanced by MoF_6 injection.**

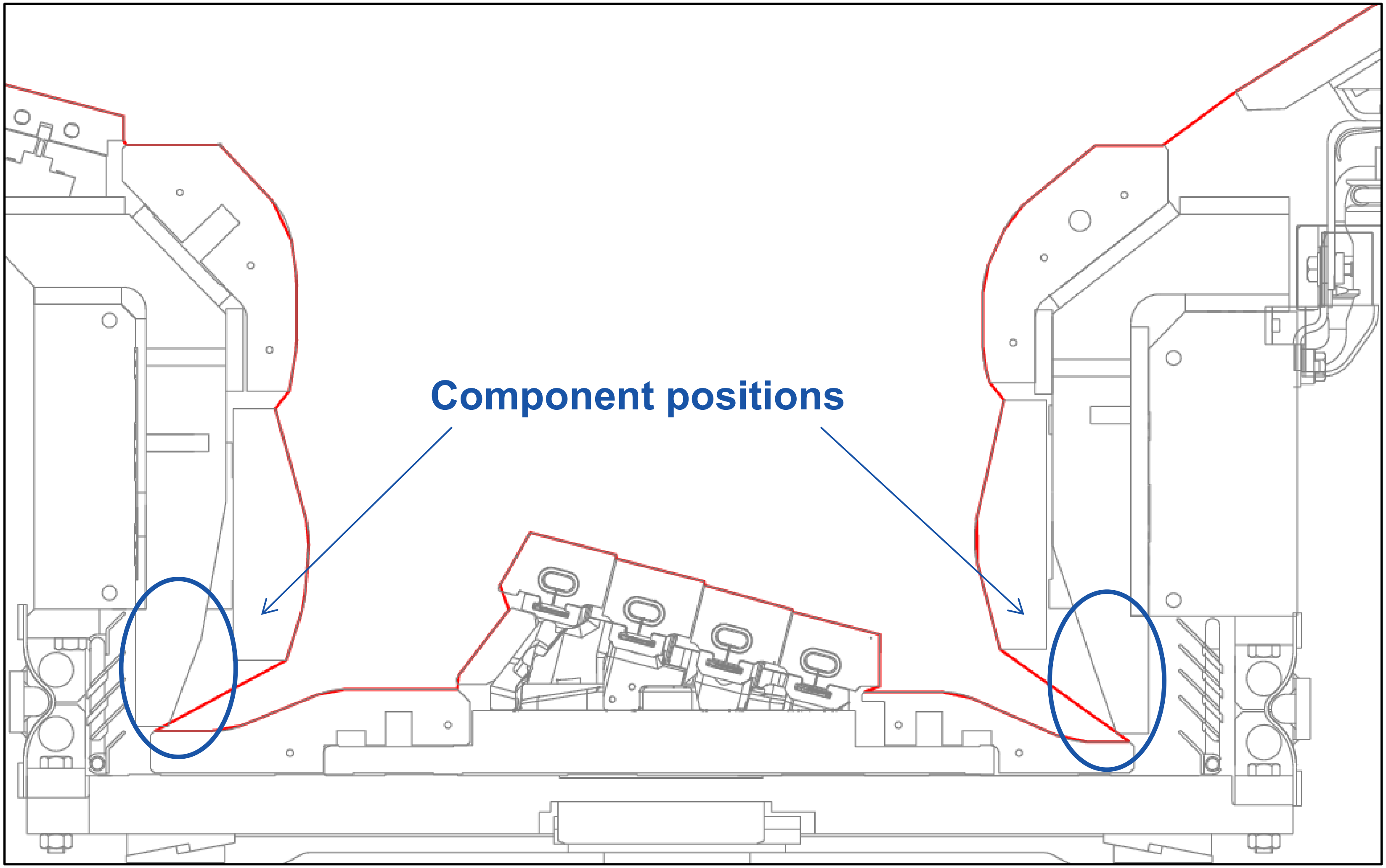
Paper VI: Deposits In JET Divertor Corners





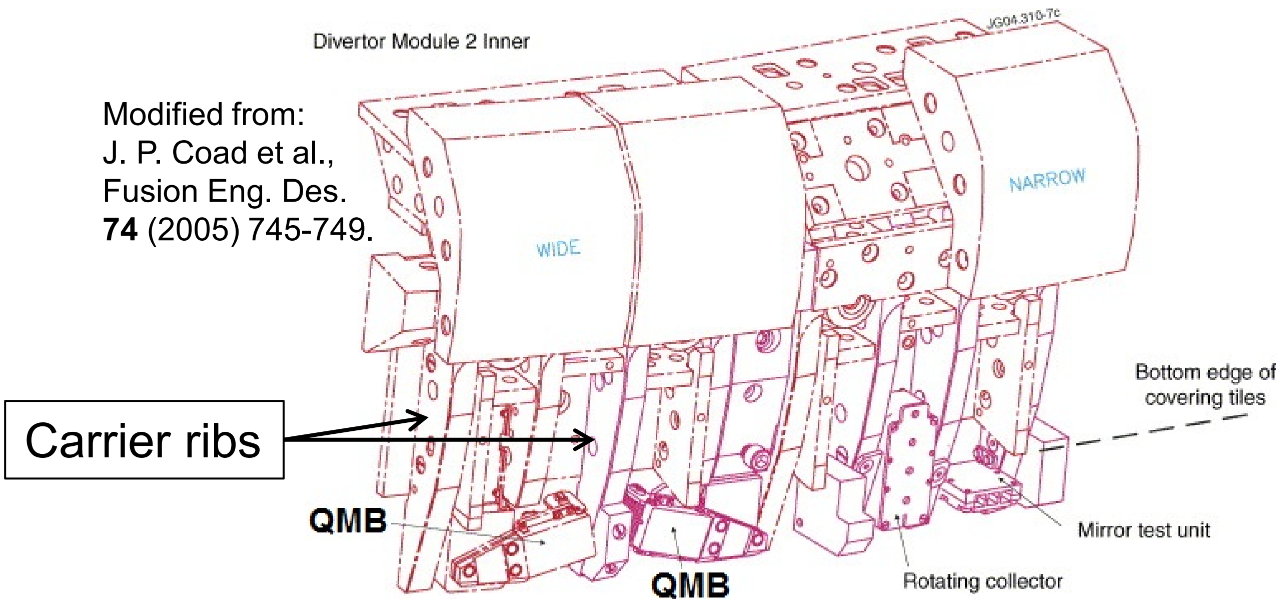


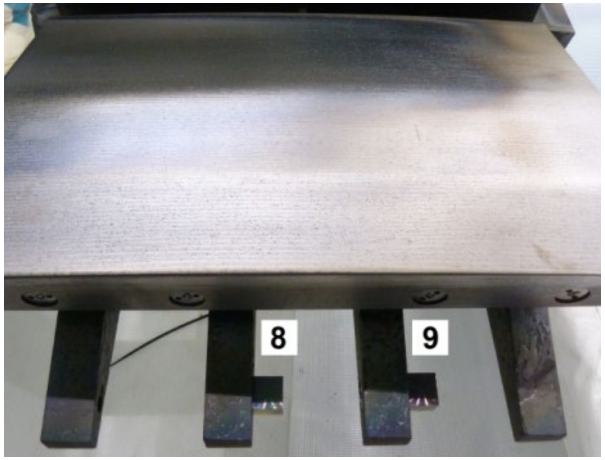
JET Divertor Cross Section



Wall Probes on Divertor Carrier

Modified from:
J. P. Coad et al.,
Fusion Eng. Des.
74 (2005) 745-749.





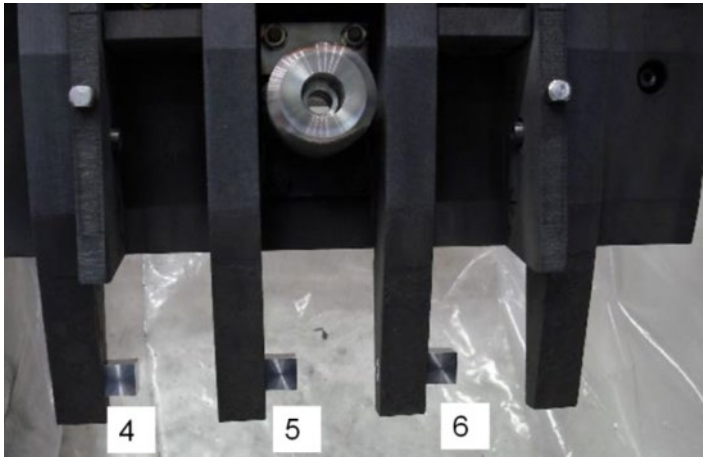


Photo credit:
A. Widdowson
K. Heinola

Paper VI: Summary

- Typical layer thickness in divertor corners: a few hundred nanometers
  → **Reduction of one order of magnitude compared to JET-C.**
- Carbon/deuterium co-deposition indicated on blocks.
- Carbon not present on instrument covers
  → **Carbon from divertor carrier ribs only moved a few centimeters.**
- High deuterium fraction in beryllium/oxygen layers.
- ^{18}O detected, tracer for oxidation studies.
- ^{15}N not detected in divertor corners.

Papers III-V: The role of reduced activation steel

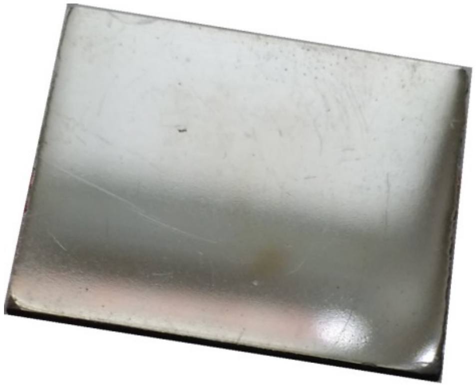
Structural material for Fusion Reactors

- Reproduce mechanical properties of Cr-Mo ferritic steels
- Avoid neutron activation (cannot use Nb, Ni, Mo)

Possible side effect

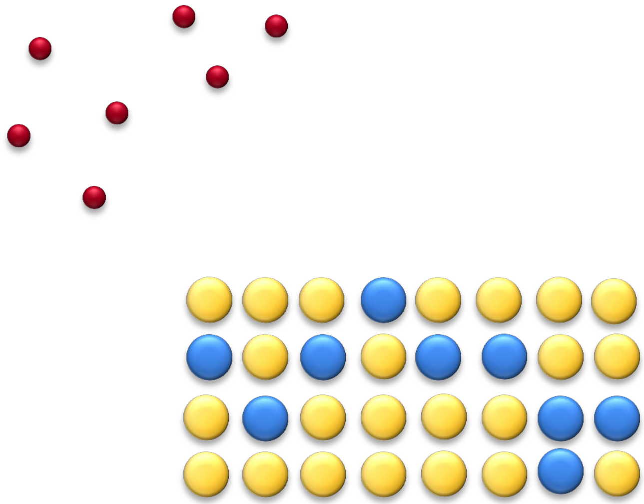
- Tungsten and tantalum → Erosion resistance

Element (weight %)	EUROFER97
Fe	89
Cr	8.9
W	**1.1**
Mn	0.47
V	0.20
Ta	**0.14**
C	0.11
Si	< 0.10



EUROFER97

Mechanism for Increased Erosion Resistance

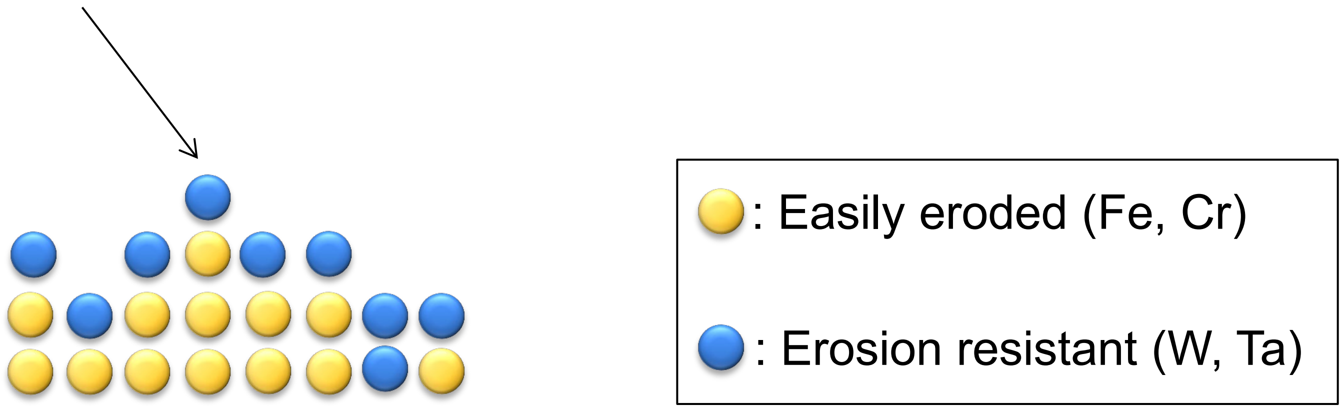


: Easily eroded (Fe, Cr)

: Erosion resistant (W, Ta)

Mechanism for Increased Erosion Resistance

“Armor” layer enriched with
erosion resistant component



Aims: Paper III-V

- EUROFER97 exposed to 600 eV D_3^+ ions; measure
  - Layer thickness
  - Atomic composition

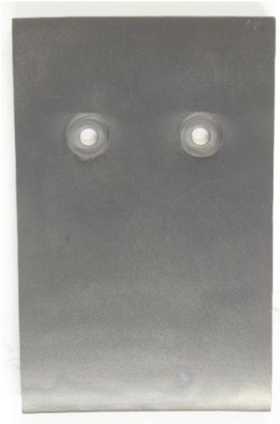
- Correlate with changes in surface morphology.

Papers III-V: Summary

- 600 eV D_3^+ bombardment → Surface enrichment with tungsten and tantalum.
- Fluence of ~10^{23} D/m^2 or higher required to yield measurable effect.
- Surface tungsten fraction increases with increasing eroding ion fluence
→ **Increase by factor up to 25 for 10^{24} D/m^2.**
- Layer thickness after 10^{23} D/m^2: ~ 5 nm.
- Significant roughening of surface occurs at higher fluences
→ **Depth profiling with ion beams becomes difficult.**
- Characteristic height of roughness after 10^{24} D/m^2: ~ 20 nm

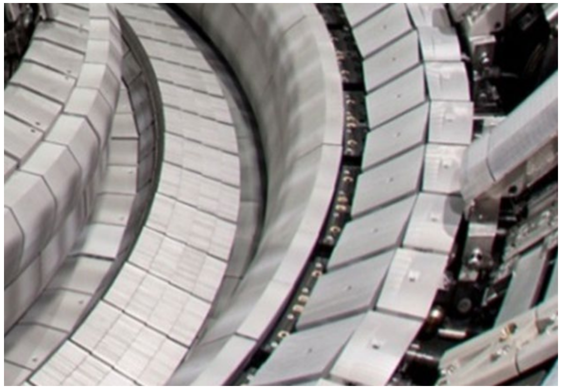
General Summary

Material characterization



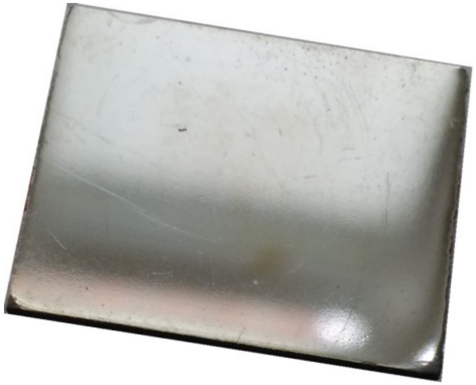
Past
Carbon

→



Present
Tungsten, beryllium

→



Future?
Reduced activation steel

ERDA detector: Applications

Presently 28 citations on Google Scholar.

- Hf-C and Ta-C hard coatings
- Multilayered coatings
- Electrochromic films
- Stopping of ions in matter
- Metal nitride coatings
- Photochromic films

Thank you for your attention!