Fusion Technology at CIEMAT
Overview of Material Irradiation Activities

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RaDIATE Collaboration Meeting . May 19, 2014

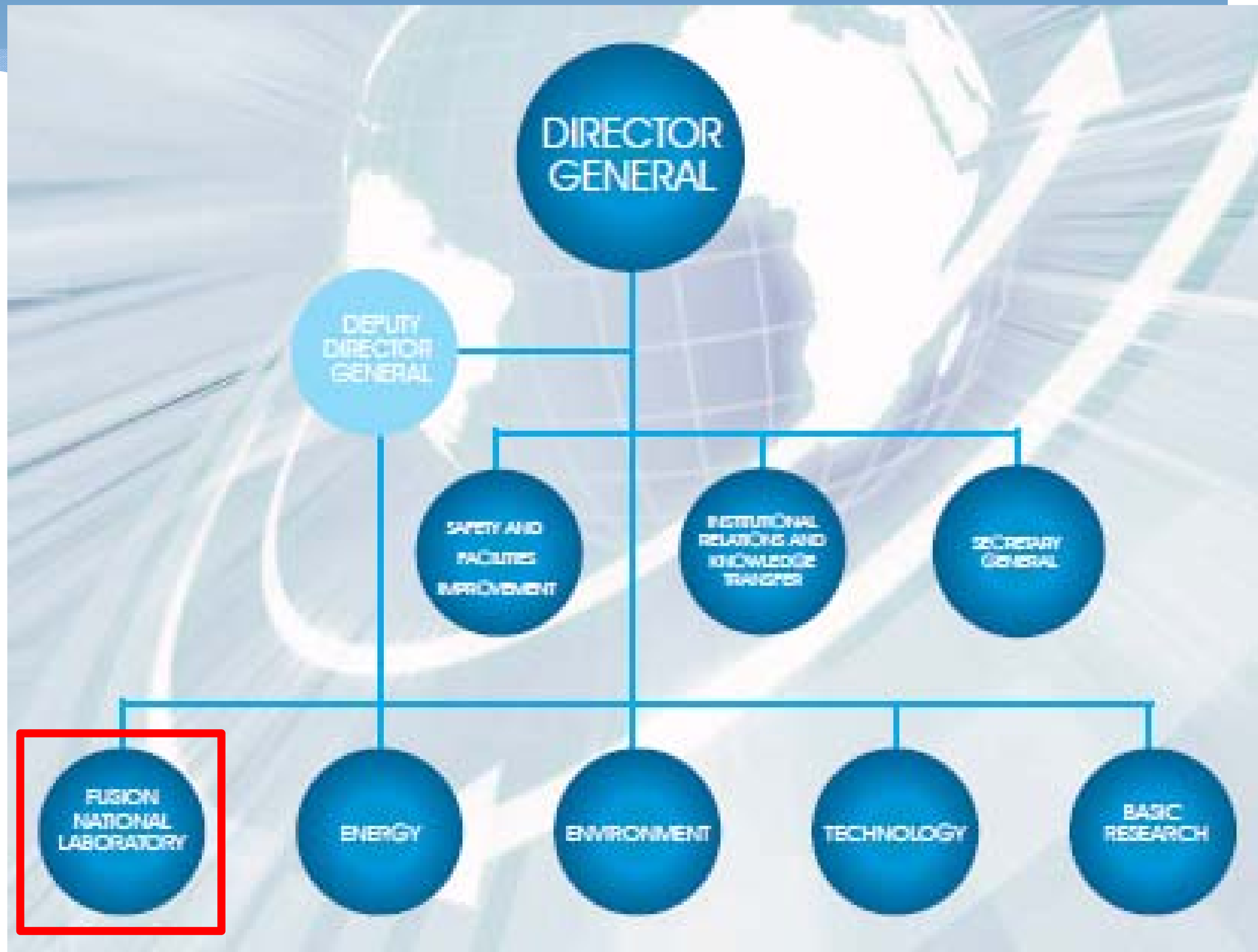
GOBIERNO DE ESPAÑA
MINISTERIO DE ECONOMÍA Y COMPETITIVIDAD

Ciemat
Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

LABORATORIO NACIONAL de FUSIÓN
ASOCIACIÓN EURATOM-CIEMAT

CIEMAT

- **CIEMAT** is a public research entity focused on energy and environmental problems, founded more than 50 years ago (initially focused on nuclear research).
- Several centres around Spain (main one in Madrid). Staff of around 1500 people and yearly budget around 100 M€.
- CIEMAT activities are organized in 5 technical departments (ENERGY, **FUSION,** ENVIRONMENT, TECHNOLOGY, and BASIC RESEARCH) and 3 transversal departments.

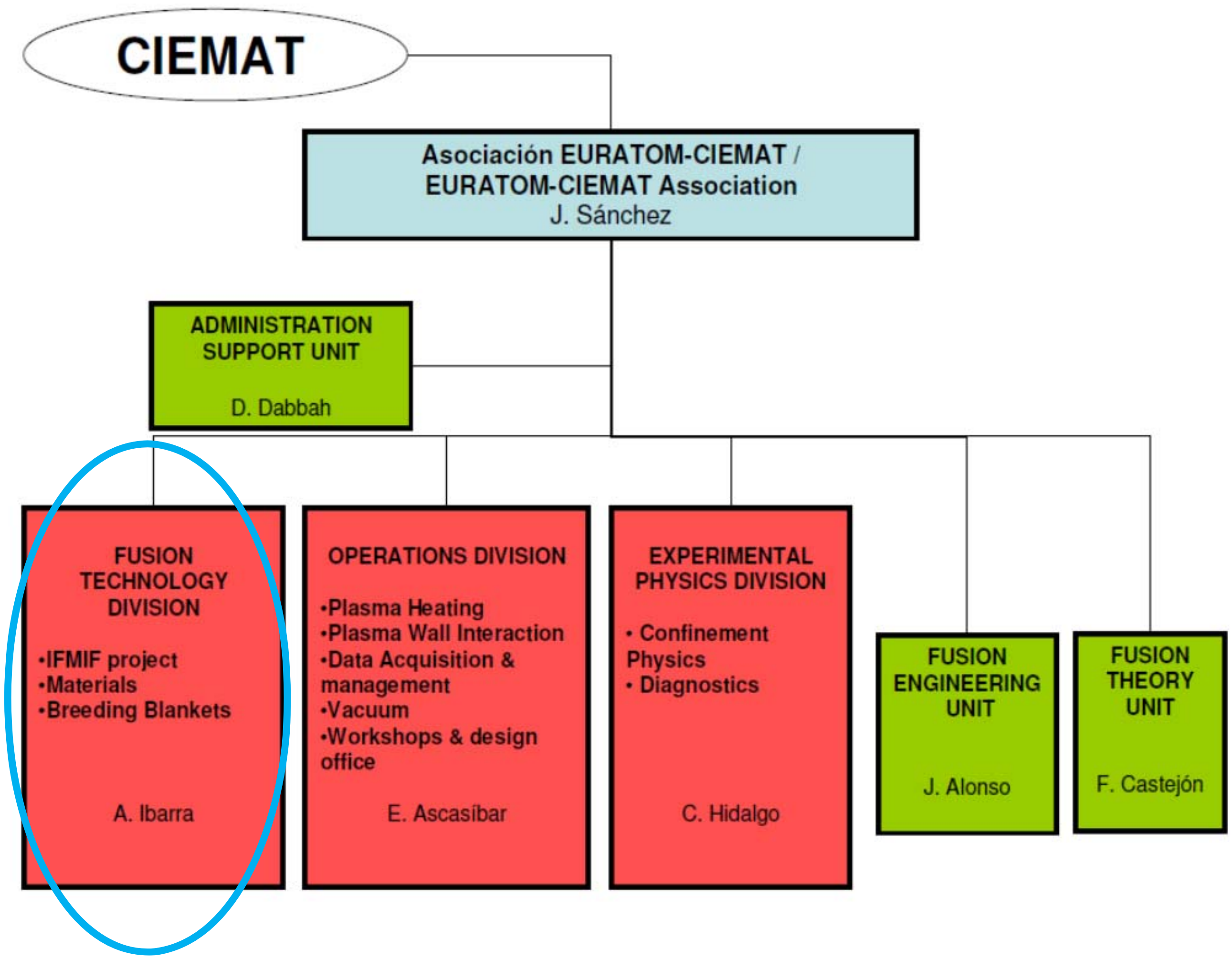


Fusion National Laboratory (FNL)

➤ The FNL of CIEMAT carries out R&D for the development of magnetic confinement fusion as a future energy resource and coordinates the Spanish fusion research carried out as part of the EU Fusion Programme.

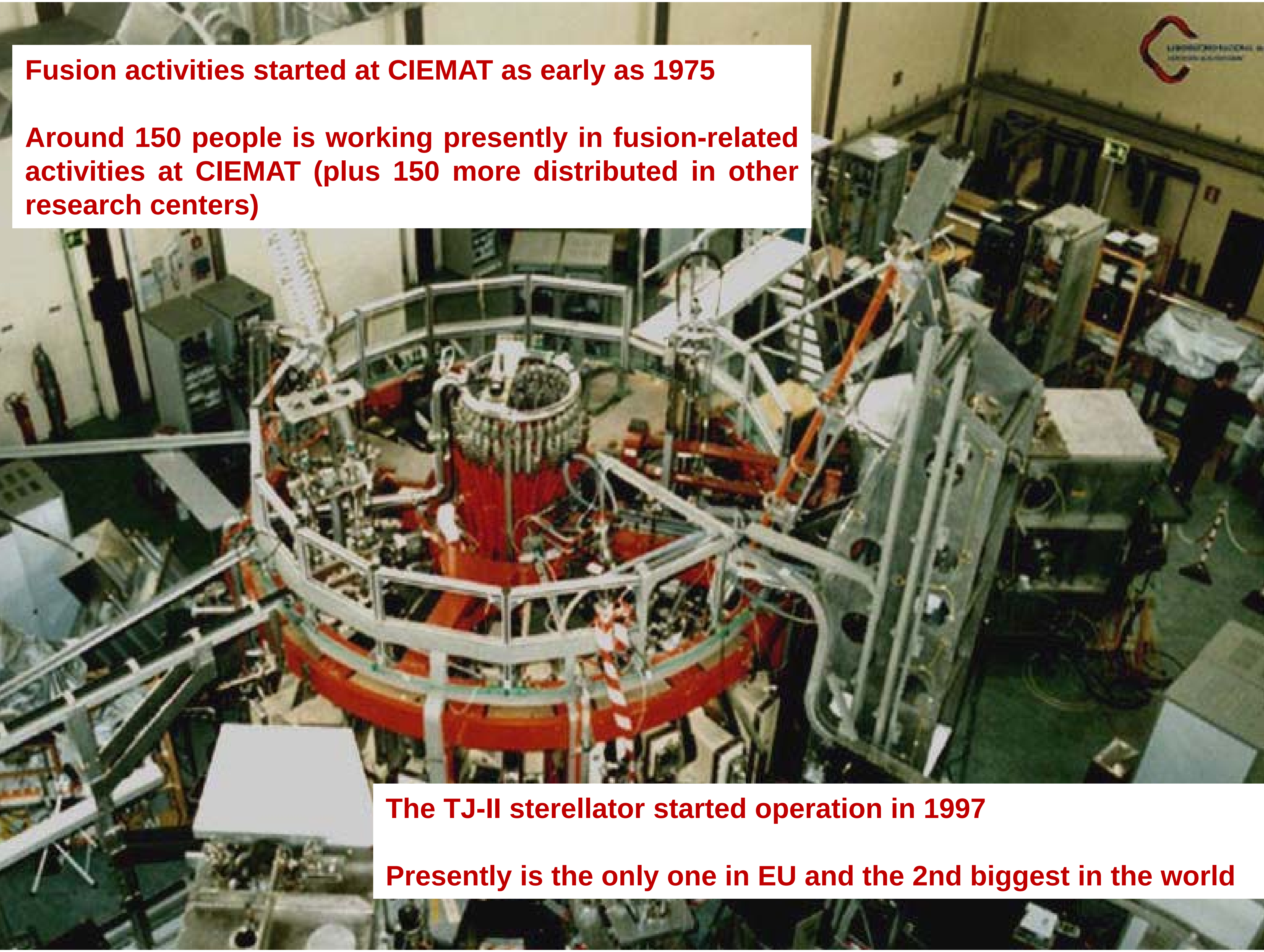
The main goals of the Spanish fusion programme are:

- The development of the "stellarator" concept, through the exploitation of the TJ-II device
- The participation in the large world fusion experiments (JET, LHD, W7X, ITER, JT60 and IFMIF)
- The development of knowledge and technologies needed for DEMO and the Power Plant.



Fusion activities started at CIEMAT as early as 1975

Around 150 people is working presently in fusion-related activities at CIEMAT (plus 150 more distributed in other research centers)



The TJ-II sterellator started operation in 1997

Presently is the only one in EU and the 2nd biggest in the world

Fusion Technology activities

Activities on Fusion Technology started many years ago (early 80´s) around the study of radiation effects on insulator materials. Only recently a significant expansion take place. Presently, around 50 people at CIEMAT and 70-80 distributed in other research centers.

The different research activities are focused along the following lines:

- ✓ **DEMO Design** (mainly breeding blankets)
- ✓ **Development of breeding blankets technologies** (mainly those related to liquid metals)
- ✓ **Fusion Materials Fusion Development** (Functional and Structural materials, including production and characterization including irradiation effects)
- ✓ **Modelling,** mainly of radiation damage effects
- ✓ **New facilities**
  - ✓ **Participation in the IFMIF/EVEDA project**
  - ✓ **Development of new Spanish Facilities for fusion**

Fusion Technology activities

Most of the activities carried out at the CIEMAT group have a common background: **the study of the radiation effects**

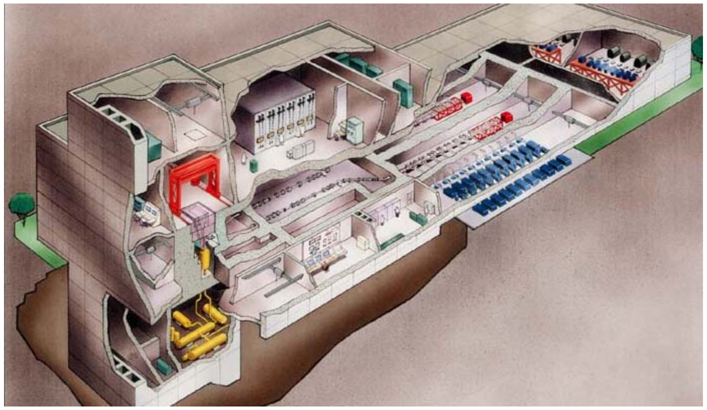
- ✓ **Modelling and validation experiments**
  - ✓ Evaluation of damage, MD, Montecarlo methods, rate theory methods
  - ✓ Benchmarking experiments (resistivity recovery, desorption, …)
- ✓ **Physical phenomena during irradiation (RIC, RIED, FL, OA, RL, RID, …)**
- ✓ **Radiation effects on structural materials**
- ✓ **Development of new irradiation facilities**
  - ✓ IFMIF
  - ✓ Ion irradiation

New irradiation facilities

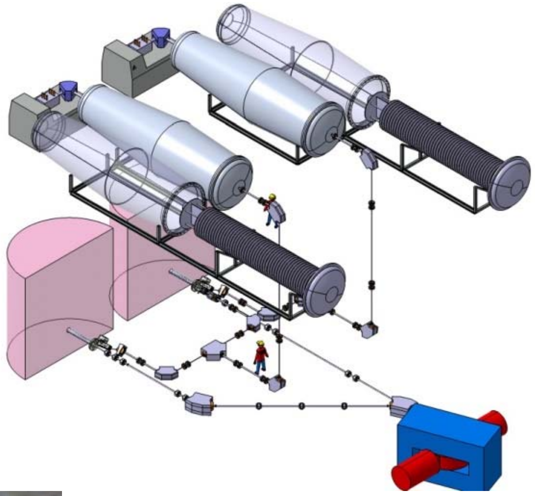
Presently there are no irradiation sources similar equivalent to DEMO

IFMIF Project

To better understand radiation effects in materials, to be able to make predictions



Spain heavily involved through the IFMIF-EVEDA Project included in the BA Agreement



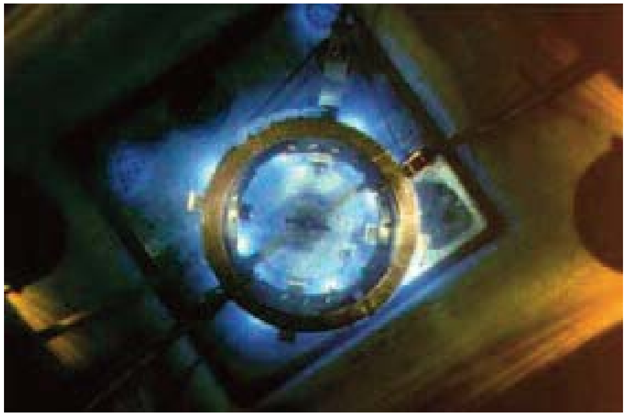
Electron, Gamma and Ion Irradiation Facilities

2 MeV Van de Graaf electron Accelerator

Collaboration with CMAM (UAM)
5 MeV Tandem Accelerator

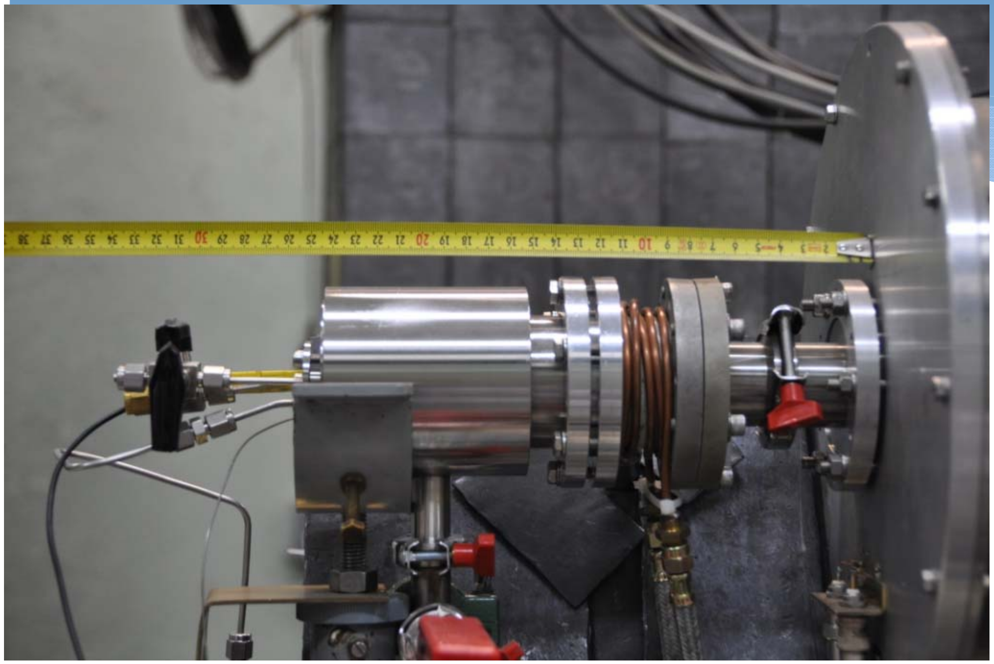
60 keV Ion Implantator

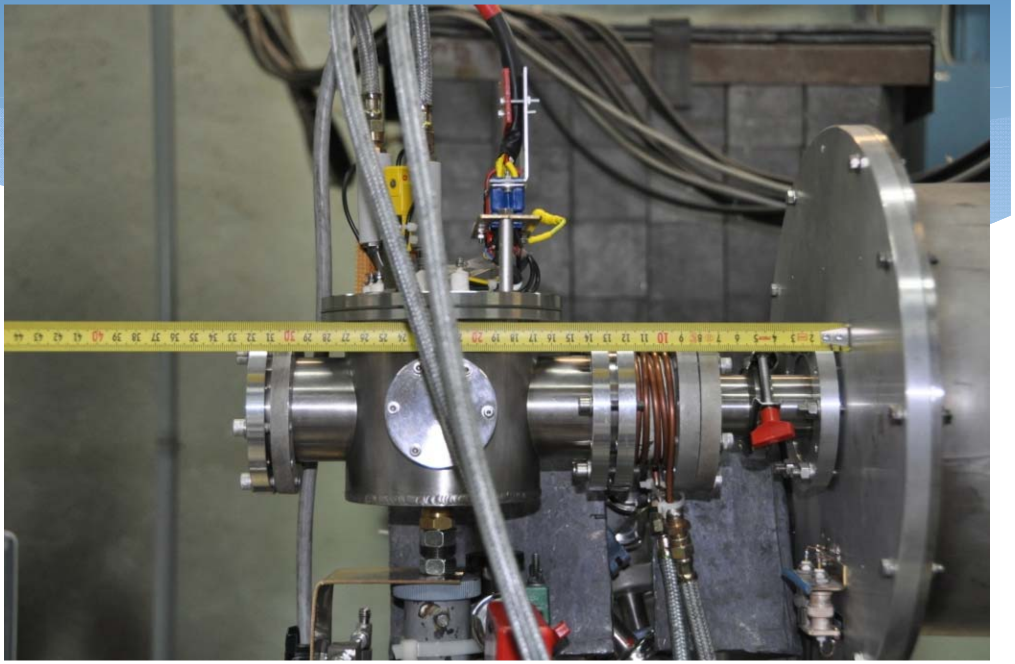
NAYADE: Co60 γ-source



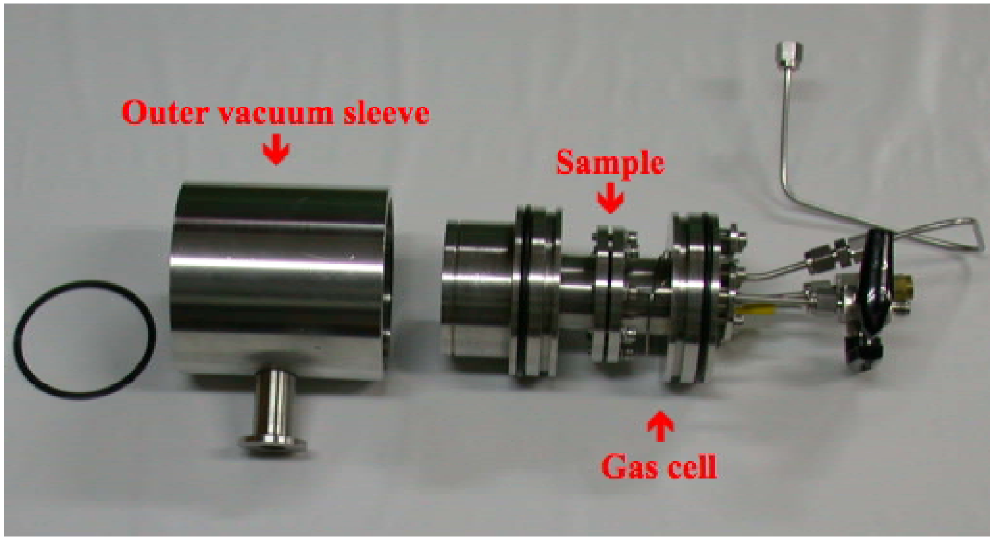
Radiation Enhanced Permeation Chamber.

Radiation Enhanced Desorption Chamber.





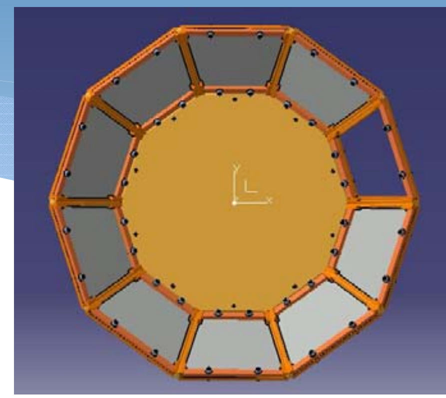
Very significant capabilities for in-beam measurements *(later)*

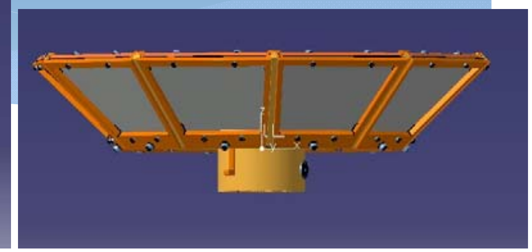


implantation beam line of CMAM

(I) Design and prototyping of an energy degrader for triple beam irradiations.

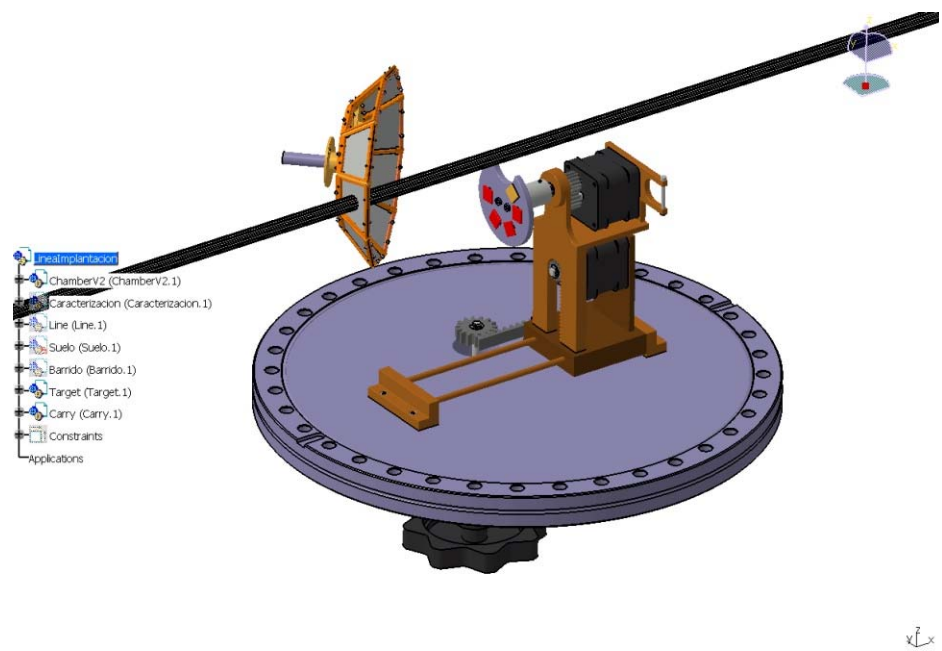
- Design and manufacture of a ion beam energy degrader (H: 3.8 MeV; He: 15 MeV).
- Rotating wheel with 10 Al sheets of different thicknesses (0 - 50 µm).





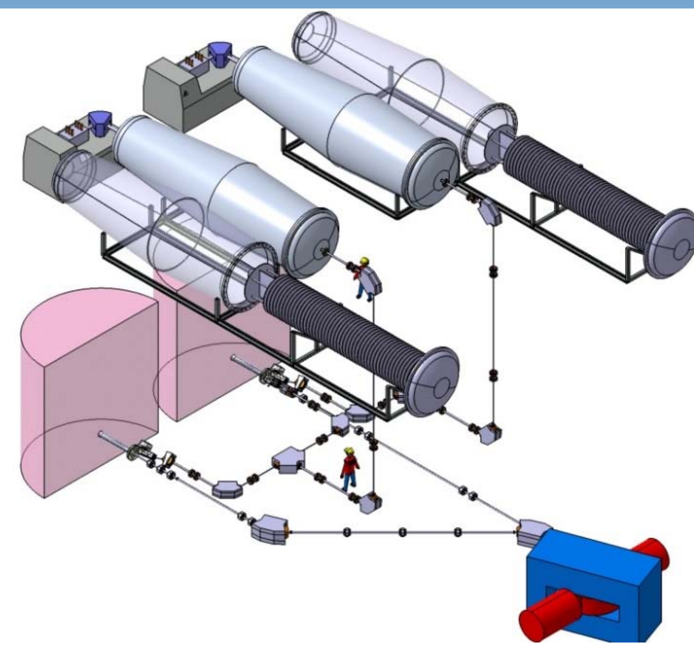
(II) Development of the implantation beam line and a sample holder at CMAM

- Completed and tested a sample holder (useful area of 10 x 10 cm2).
- Wide range of temperature (LN2 to 500 C)
-
- 4 Faraday Cups to control the beam current during the scanning. Irradiation test performed on steels, studying the beam scanning with Luminescent Silica, with very satisfactory results.



TF-triple beam facility

Presently in standby, but conceptual design is finished and available

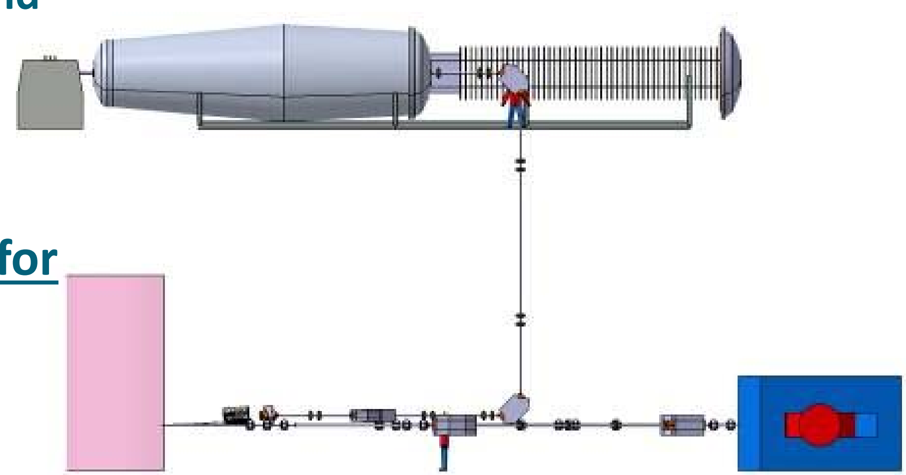


A Facility to contribute to the evaluation of radiation effects on fusion materials

Three simultaneous ion accelerators will emulate the neutron irradiation effects

Includes:

- **Two light ions tandem-type, electrostatic accelerators (mainly for He and H irradiation)**
- **One heavy ion cyclotron (isochronous type) accelerator (Fe -400 MeV-, W -400 MeV-, Si -300 MeV-, C -100 MeV-, … and k = 110)**
- **Also experiments under high-field magnet**

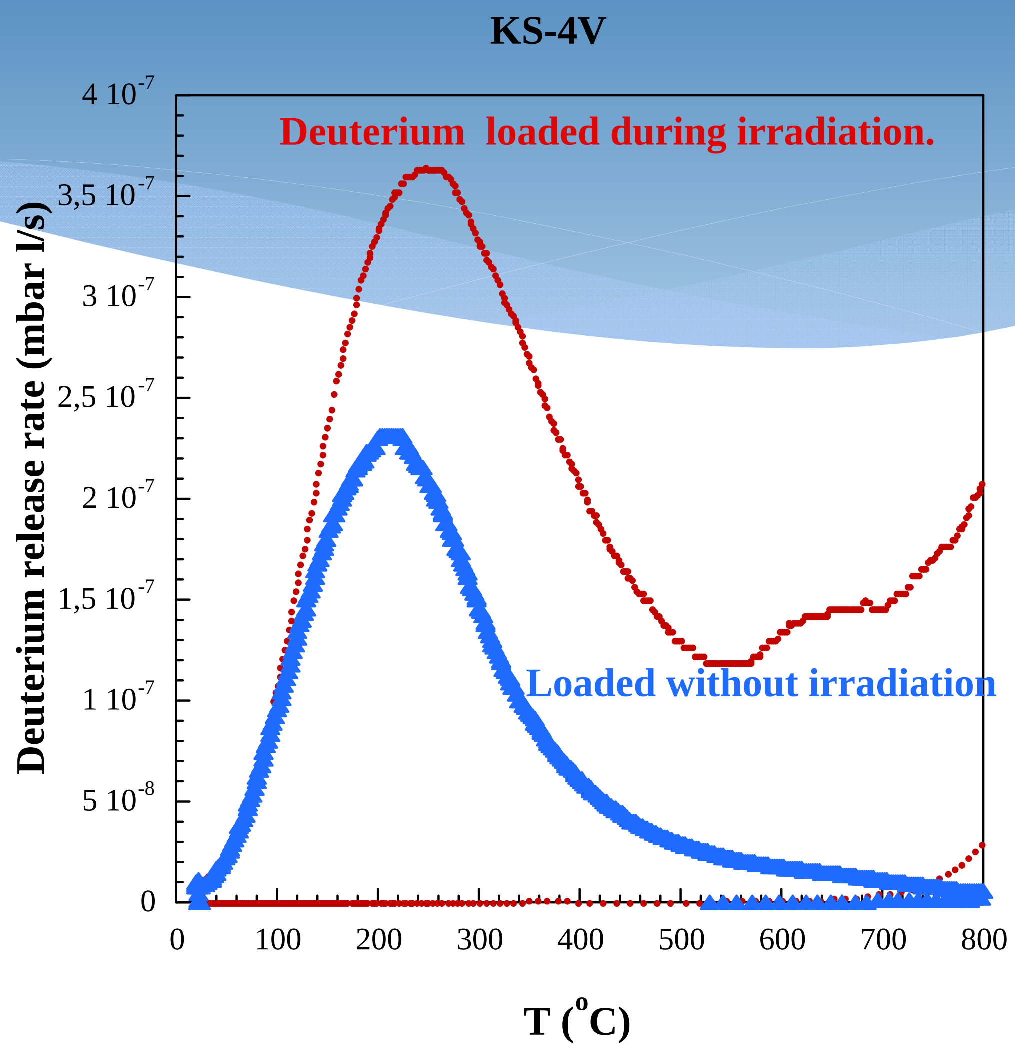


<u>Irradiation volume up to tens of microns –relevant for volume effects-</u>

Physical phenomena during irradiation

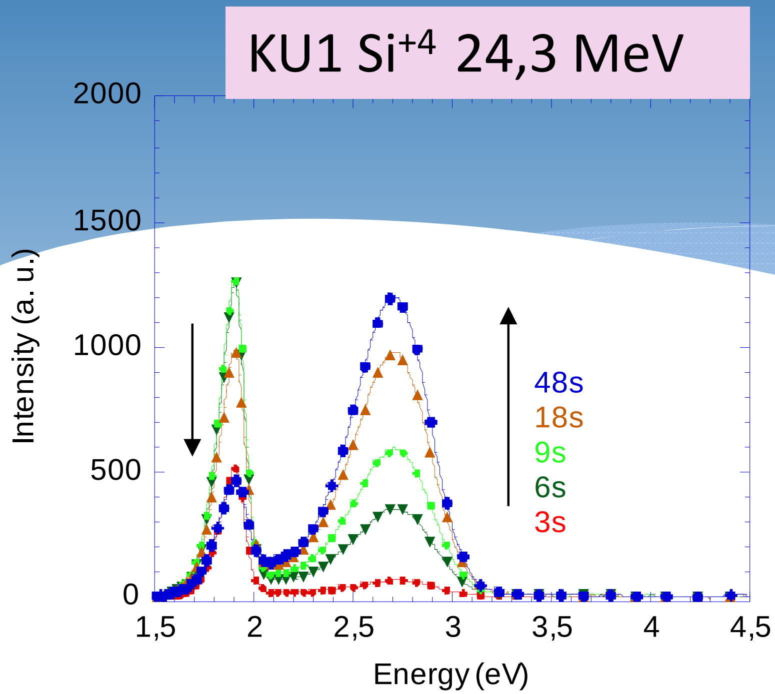
* Generally speaking, physical properties of materials (specially non-metallic materials) are different **during** irradiation
* For example: electrical conductivity (RIC), optical absorption (RIA), dielectric properties,…
* And a lot of new phenomena can appear: radiation induced diffusion, radiation induced electrical degradation (RIED), radioluminescence, radiation induced corrosion,…

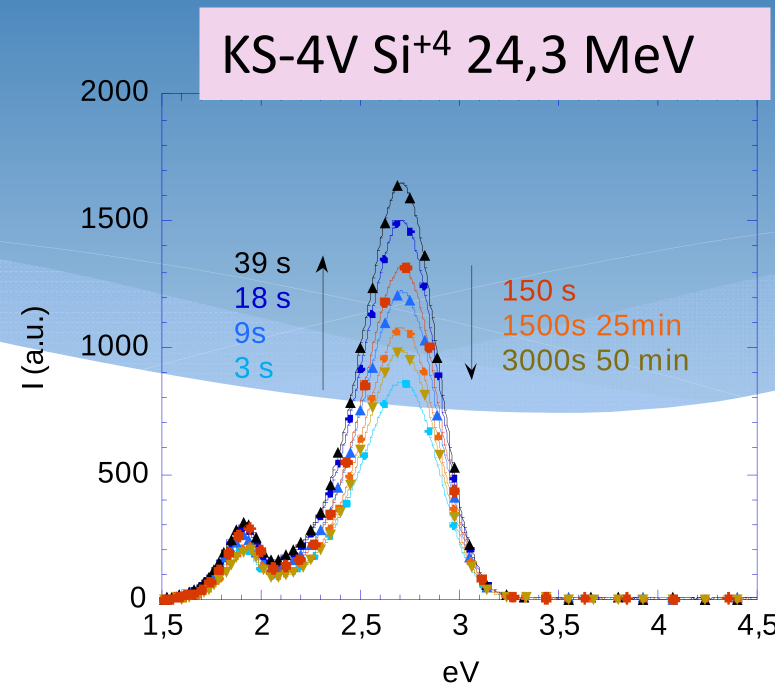
Irradiation chamber and accelerator.

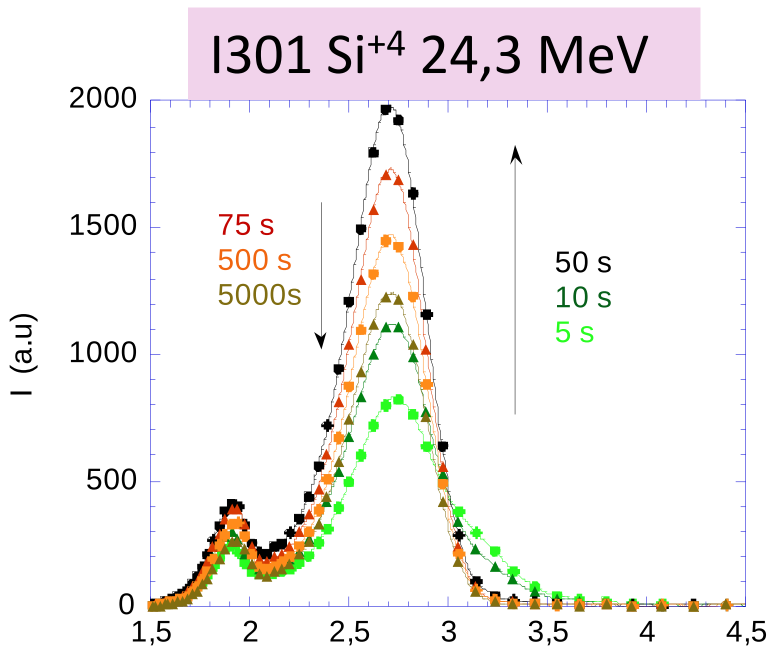


Radiation enhanced deuterium absorption for KS-4V.

Ionoluminescence Si^{+4} implanted silica

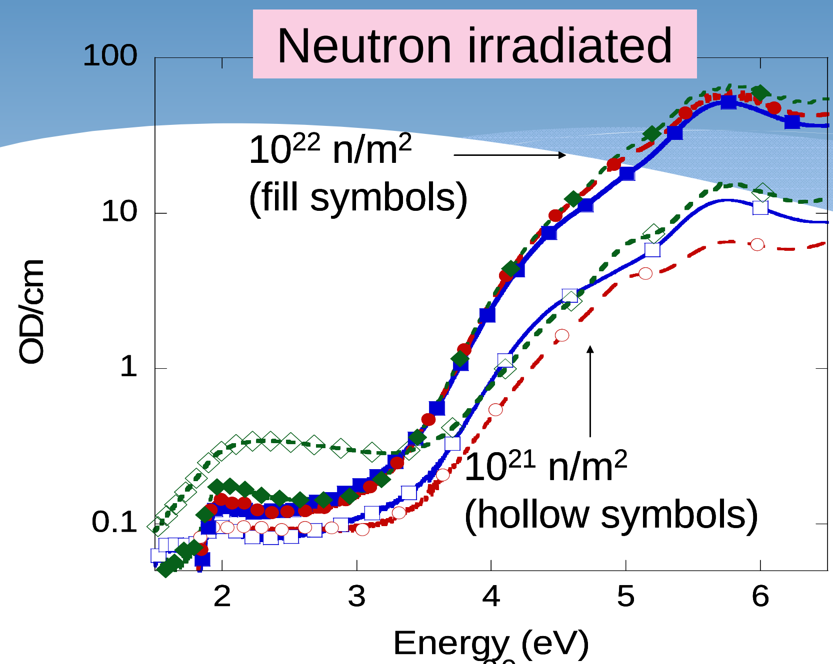


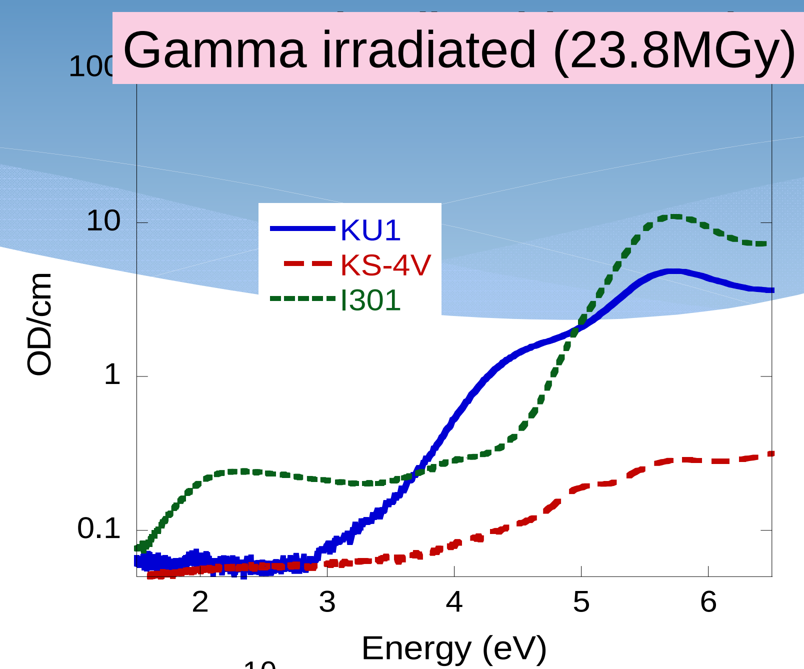




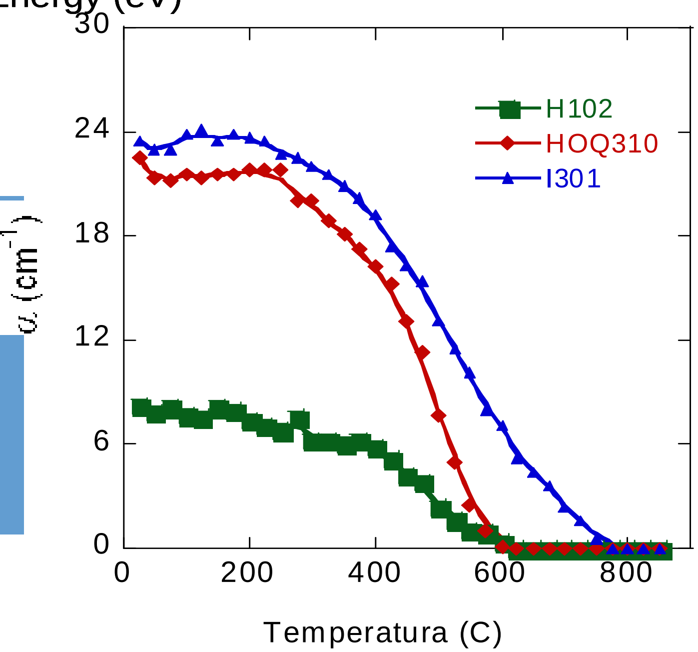
IL measured during ion irradiation to study the evolution of different defects

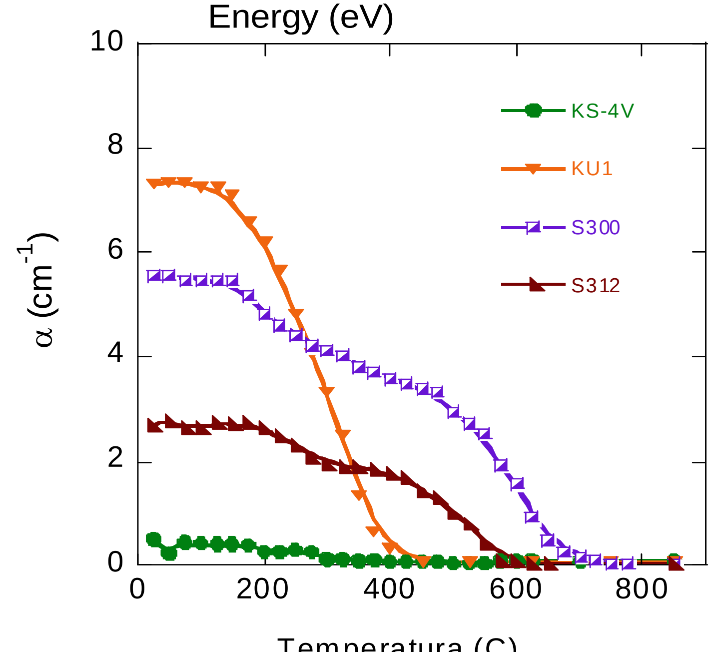
Fused silica: Optical Absorption comparison





Thermal stability of gamma irradiation induced E´ defect (5.8eV) for different fused silicas



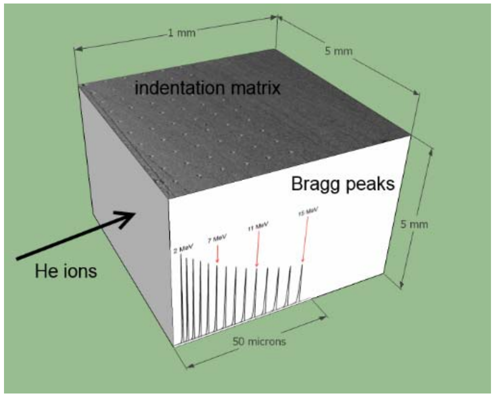


Radiation effects on structural materials

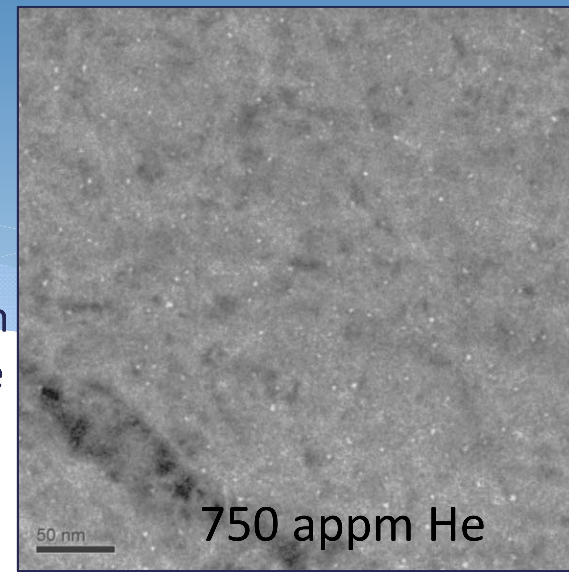
Evaluation of He and self-ion implantation on EUROFER97 and EU-ODS EUROFER by nanoindentation and TEM

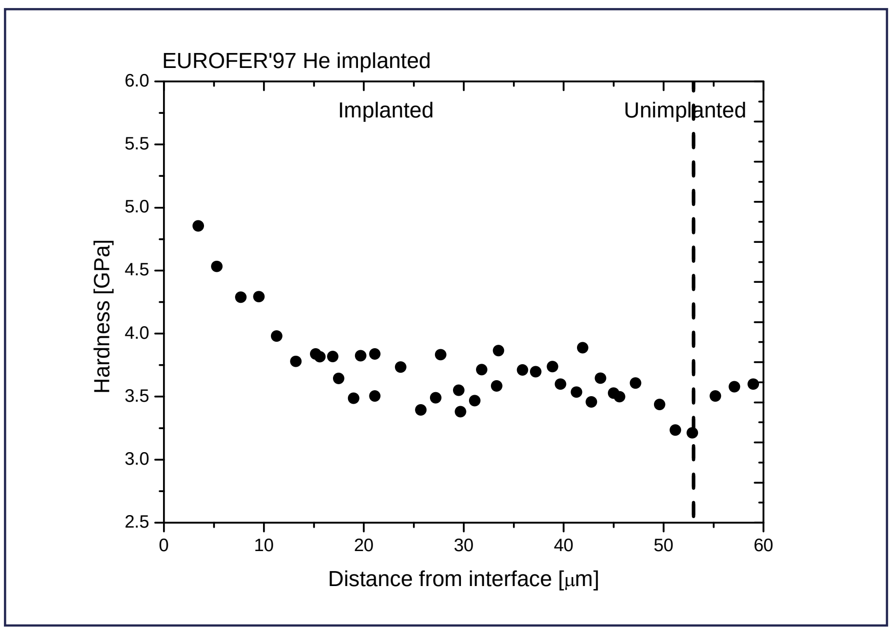
- He

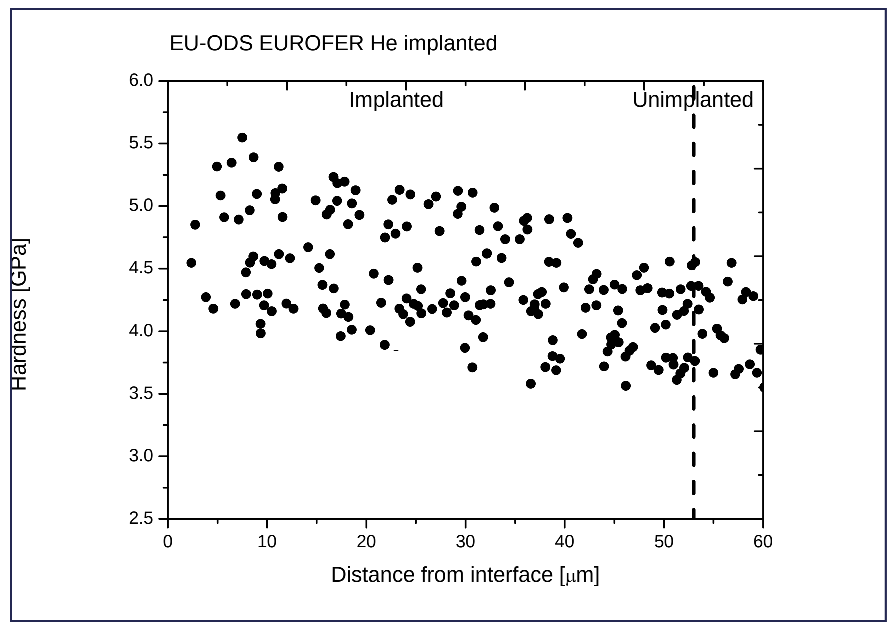
- EUROFER & EU-ODS - 3-15 MeV at RT, 1,67e15 ions/cm^2, 0.625 appm He/s



- Nanoindentation on transversal surface. Measuring increase in hardness due to increment in He.
- Nanobubbles observed in both steels with a size around 2 nm.







Hardness increase observed in both steels, being more pronounce on EUROFER97.

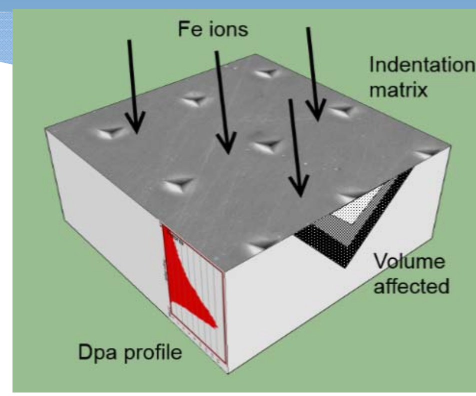
Evaluation of He and self-ion implantation on EUROFER97 and EU-ODS EUROFER by nanoindentation and TEM

Fe implantation:

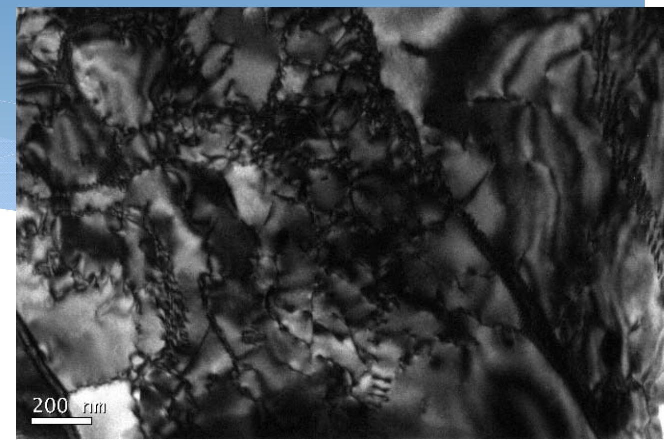
EUROFER & EU-ODS - 0.05 to 30 dpa at RT.

Comparative study on mechanical properties between EUROFER97 and EU-ODS EUROFER in as received, 0.2 and 6.5 dpa status.

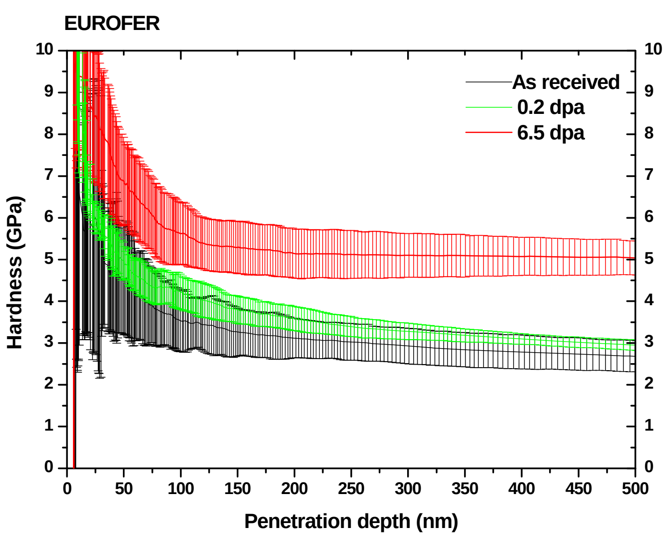
From 10 to 30 dpa: in progress.

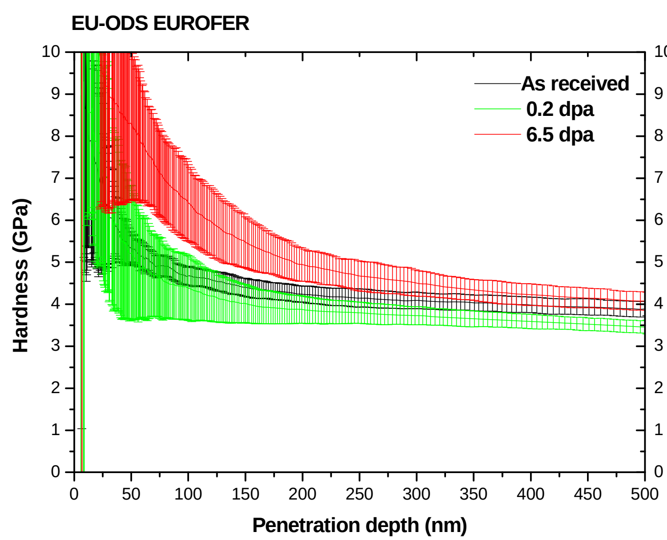


Nanoindentation on normal surface to ions



Dislocation network due to self ion irradiation



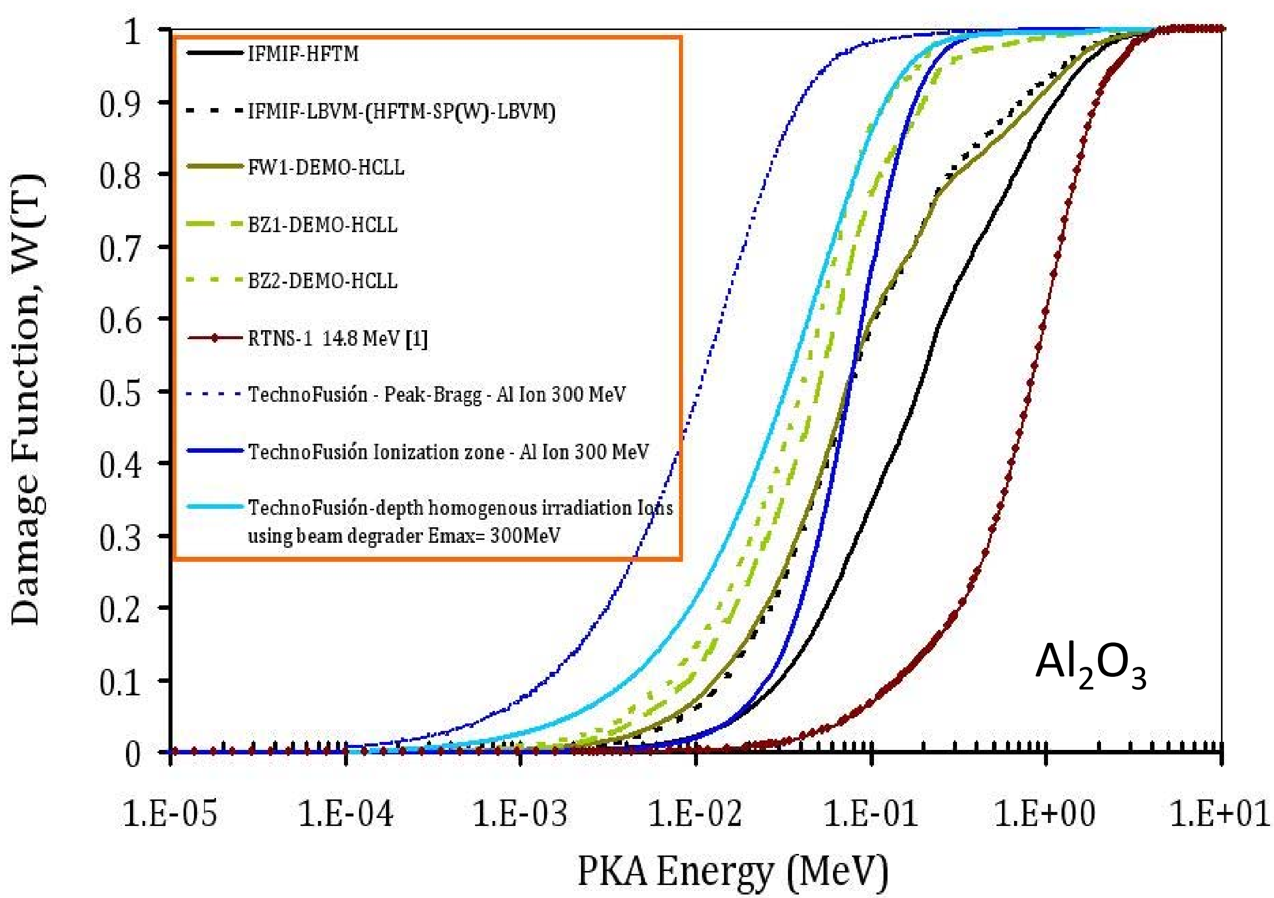


Increase in hardness observed in EUROFER97. EU-ODS EUROFER shows more resistance to the same damage.

Modelling

Radiation damage evaluation and its comparison with the expected damaged by neutrons in a fusion reactor

A methodology to calculate damage (PKA spectra and, consequently, dpa and He, H generation) for different radiation sources (neutrons, ions,…electrons?) has been developed

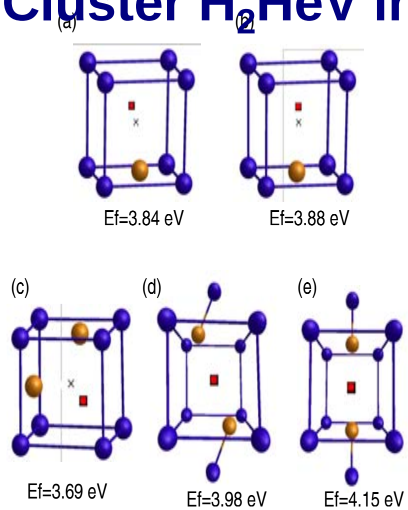


- ✓ A combination of neutron transport codes (MCNP5/MCNPX), processing of nuclear libraries (NJOY) and approximation of binary collisions (MARLOWE) is used.
- ✓ MARLOWE code has been modified to estimate the stopping of ions in materials with energies of MeV (or even GeV).
- ✓ This methodology is also able to take into account recombination of defects by means of an effective capture radius I-V (based on MD calculations).

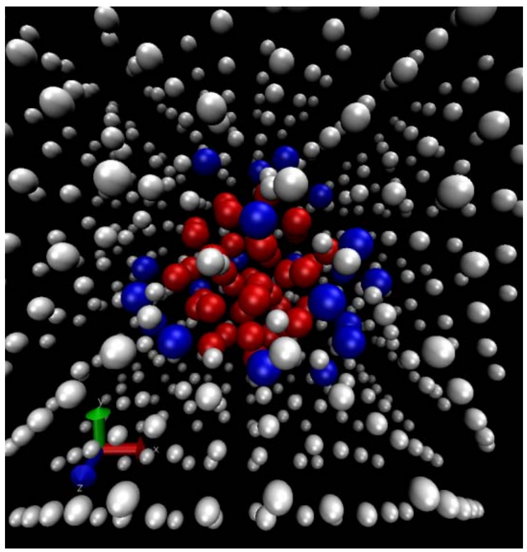
Molecular Dynamics: The case of H-He-V in Fe

Large amounts of H and He form in steels under neutron irradiation and agglomerate with vacancies into bubbles.

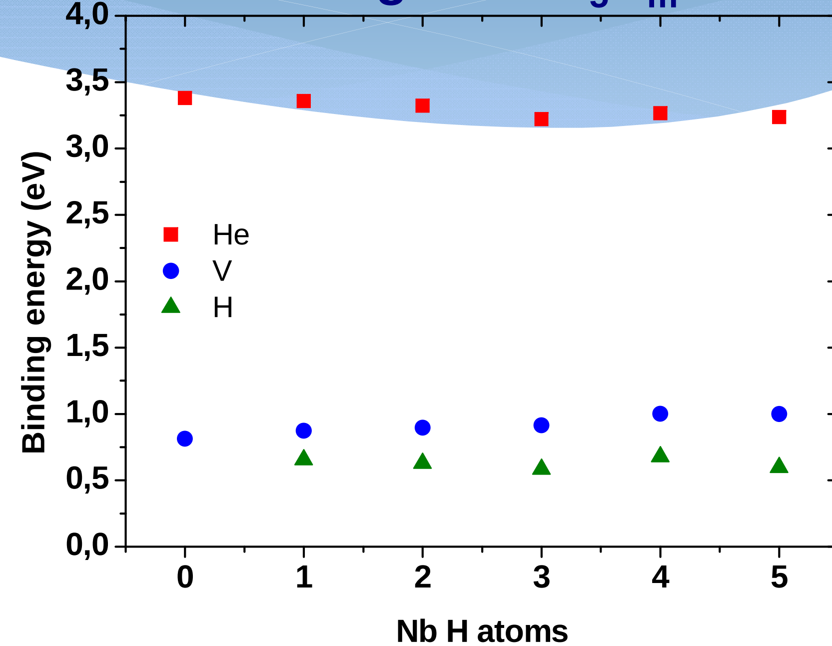
Cluster H_2HeV in Fe



Bubble of H-He in Fe



Binding to HeV_5H_m



• With MD it is calculated the binding energy of H, He and V. This allows to calculate the frequency at which they dissociate, which is used in kinetic models (OkMC or Rate Theory).

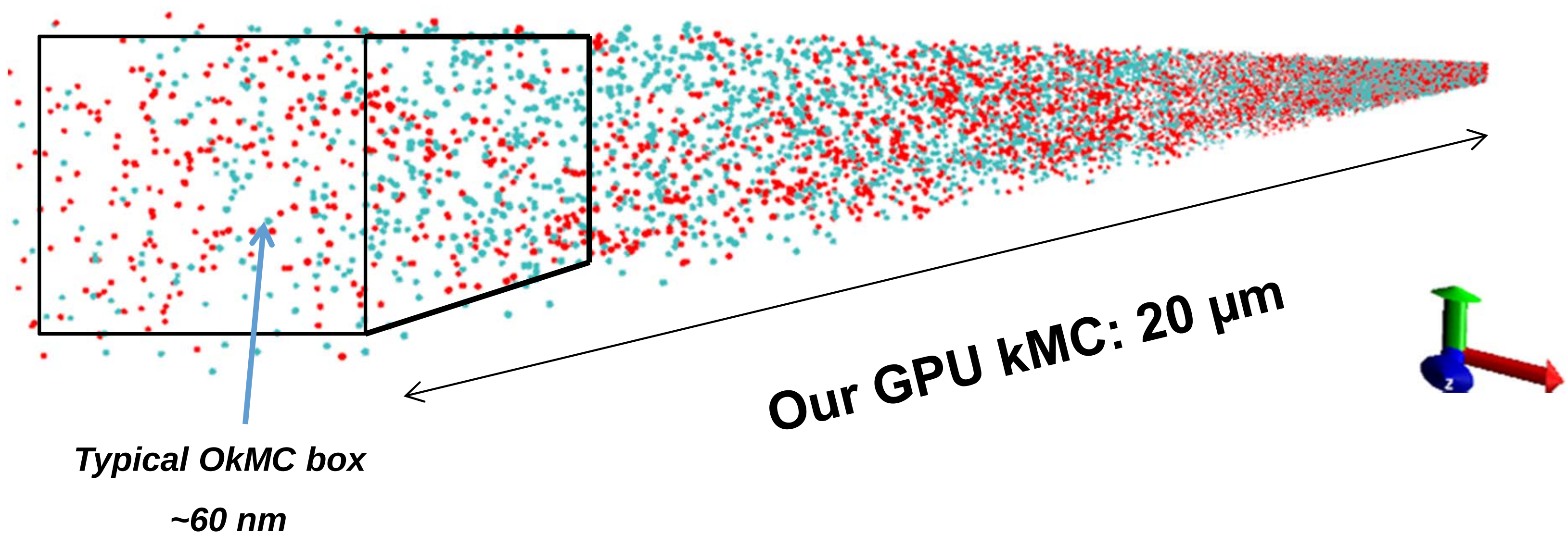
• MD calculations reveal the structure of H-He bubbles. He is contained in a core (red spheres), surrounded by a shell of H atoms (blue spheres).

A GPU-Object kMC for the evolution of defects

• The kinetic Monte Carlo is a computer simulation method intended to simulate the evolution of a set of objects, knowing the type of event those objects can perform and the probability for each event to occur.
•Can treat difficult issues such as correlation between defects and inhomogeneities.

• CPU time of classical OkMC simulations too slow (days – weeks). Limited to 100000-200000 defects. Only allows to explore small piece of material.

• We explore the possibility to use GPU (graphics card) programming. Thousands of cores !



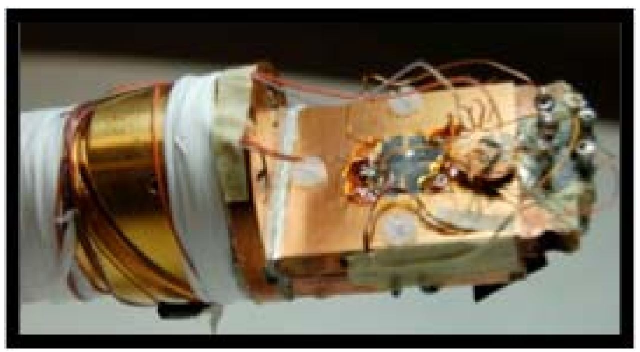
Our GPU-OkMC is able to simulate evolution of millions of particles in only few hours. Allows to simulate evolution of defects in a realistic piece of materials.

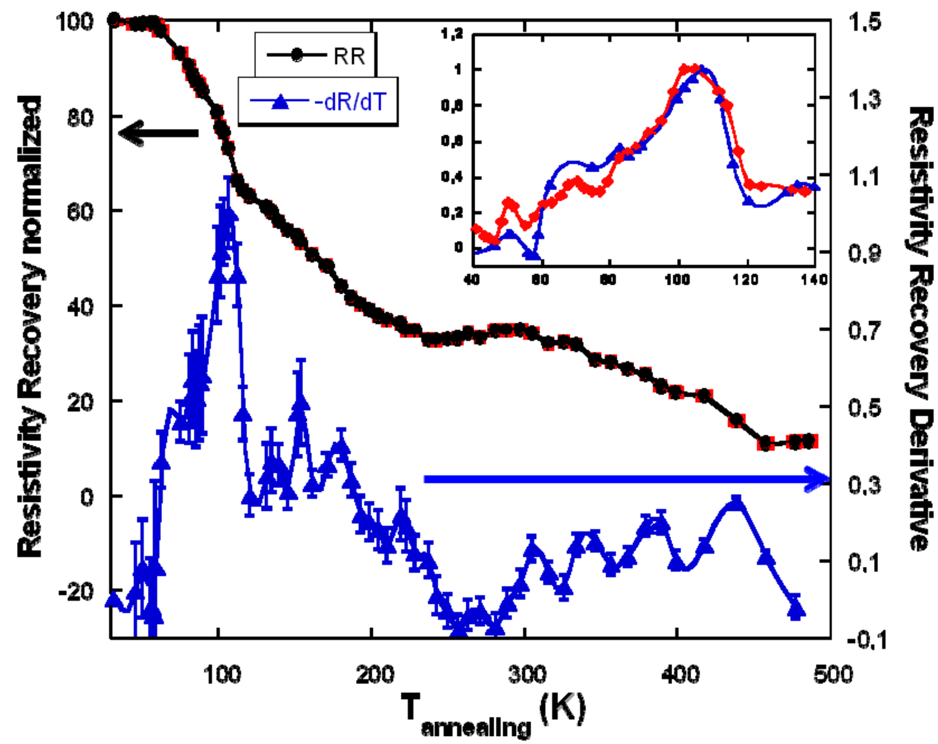
Resistivity Recovery Experiments on Fe-Cr

(III) H^+ Irradiation of Fe-Cr samples and its diagnosis by resistivity recovery.

A “Resistivity Recovery (RR)" system has been developed by Ciemat, reaching a new method of irradiation and measure that provides cleaner results than the classical method. RR spectra have been obtained in samples Fe_{100-x} Cr_x (x = 5, 10, 14) irradiated with H^+ of to 5 MeV.

Very important for the experimental validation of the computational simulations of damage by radiation in steels.





Conclusions

* FT group at CIEMAT has a long tradition on the study of radiation effects from the point of view of fusion materials needs
* Our work is organized along the following main lines: development of new facilities, radiation effects on functional and strucutural materials, modelling and validation experiments
* We are open to collaborations if something of common interest can be identified

Thanks for your kind attention!