Resistivity Recovery of Fe-Cr alloys after low-temperature proton irradiation

G. Apostolopoulos[a,*], K. Mergia[a], A. Salevris[a], S. Messoloras[a], A. Lagoyannis[b]

[a]Institute of Nuclear Technology and Radiation Protection,
[b]Institute of Nuclear Physics,
National Centre for Scientific Research “DEMOKRITOS”, Athens, Greece

Introduction

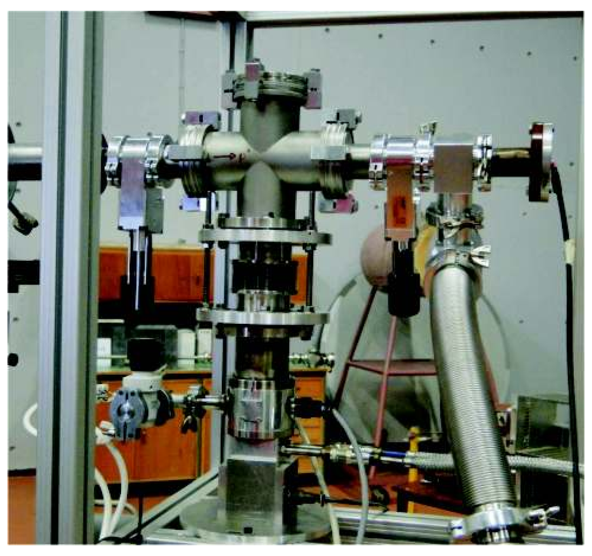
Motivation

- The behavior of Fe-Cr alloys under irradiation is of crucial technological importance for fusion technology since Cr is the main alloying element in EUROFER steels.
- Currently, extensive theoretical work is being undertaken to deepen the understanding of radiation damage in Fe-Cr.
- Electrical resistivity has been widely used for the study of radiation damage in metallic materials due to its high sensitivity to irradiation defects.
- With controlled post-irradiation annealing, valuable information can be extracted for the properties and kinetics of defects and their interactions.

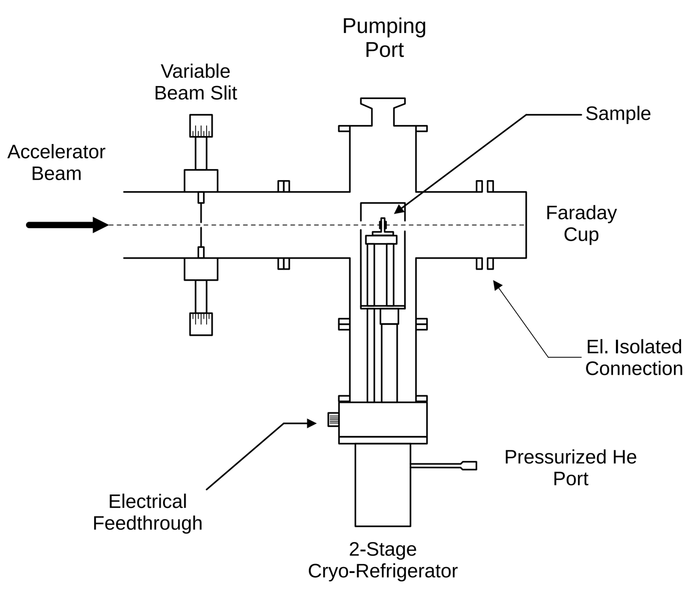
Current work

- A low-temperature ion irradiation facility with simultaneous in-situ resistivity measurement has been developed at the “Demokritos” TANDEM accelerator.
- One of the first applications of the facility concerns the nature and behavior of radiation defects produced in pure Fe-Cr model alloys.
- The present experiments will provide valuable experimental validation of theoretical predictions.

Ion Irradiation Facility

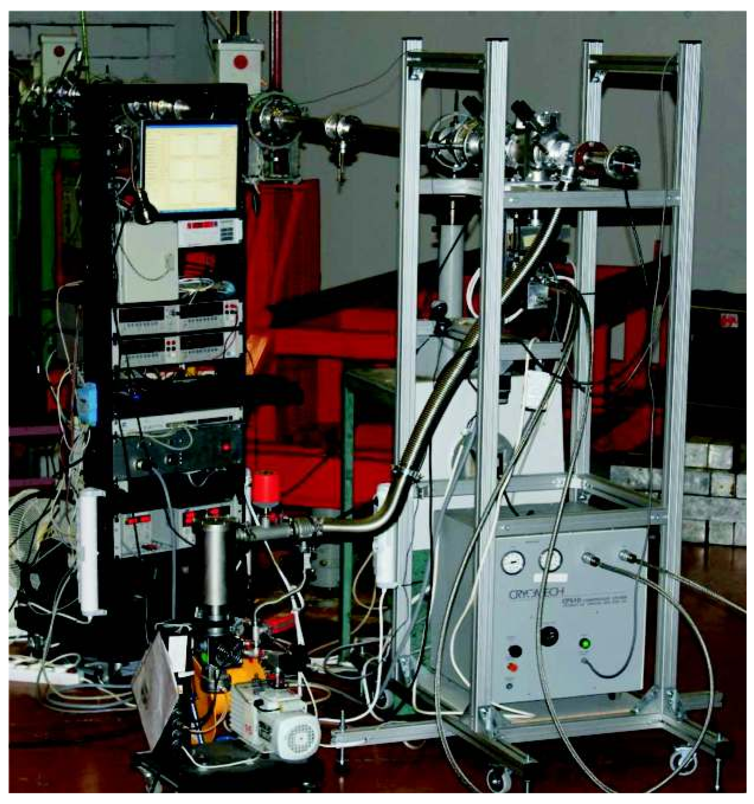


Sample stage with Cold-head



Beam-line integration

- 5MV TANDEM accelerator, producing H, D, He and light ions up to O
- Closed-cycle He refrigerator coupled into the accelerator beam line
- Base T = 10K, during irradiation 20 < T < 50 K due to beam heating
- Beam area 1 x 1 cm^2, current up to 0.5 μA
- In-situ electrical resistance measurement with 10^{-7} Ω resolution

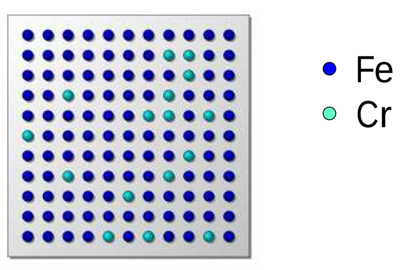


The Irradiation facility during operation

Experimental Results

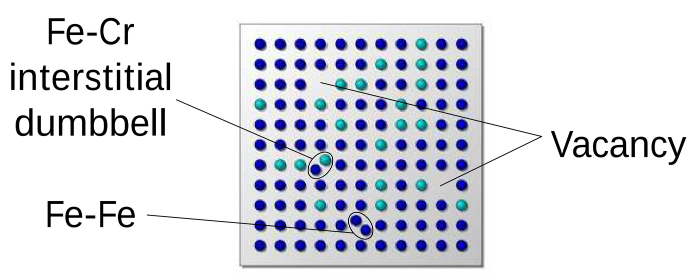
Sample preparation

- Pure Fe-Cr alloys fabricated by induction melting
- Cr concentrations 10 and 15 wt. %.
- Thin foils of 50 μm thickness obtained by cold-rolling
- Strips of 15 x 2 mm^2 were cut and instrumented with potential leads for the electrical measurements
- Residual resistivity of both alloys ~ 13.5 μΩ-cm
- Resistivity is due to electron scattering at the randomly distributed Cr atoms in the Fe matrix (alloy resistivity)

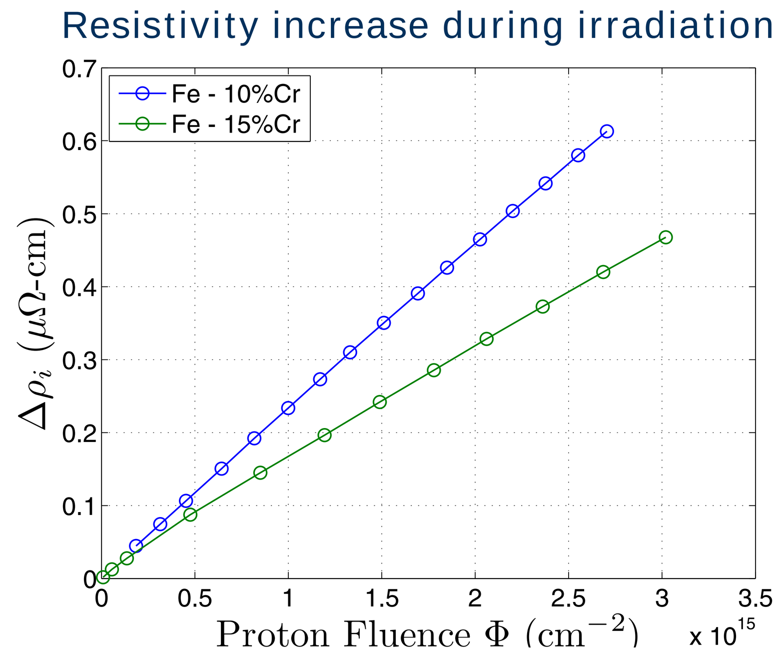


Irradiation

- 5 MeV protons, max fluence 3x10^{15} cm^{-2}
- Penetrate through the 50 μm sample
- Sample T = 50 K during irradiation
- Radiation damage mainly in the form of isolated Frenkel pairs (interstitial - vacancy)
- Resistivity increases due to scattering at these defects



Resistivity increase during irradiation

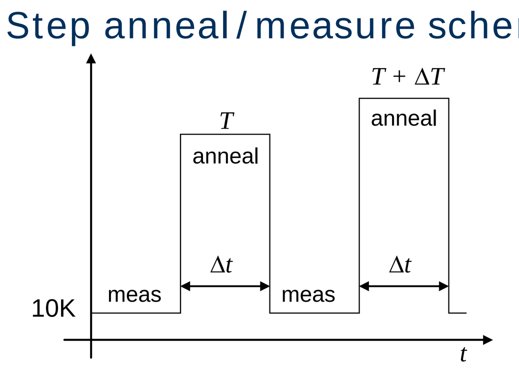


- Linear resistivity increase with dose - no saturation effects
- Damage rate is Cr concentration dependent - 50% higher in the lower concentration alloy
- Cannot be attributed to differences in damage efficiency since Fe & Cr interaction with proton is very similar.
- May be due to increased damage recovery in the 15% Cr alloy which occurs during irradiation.

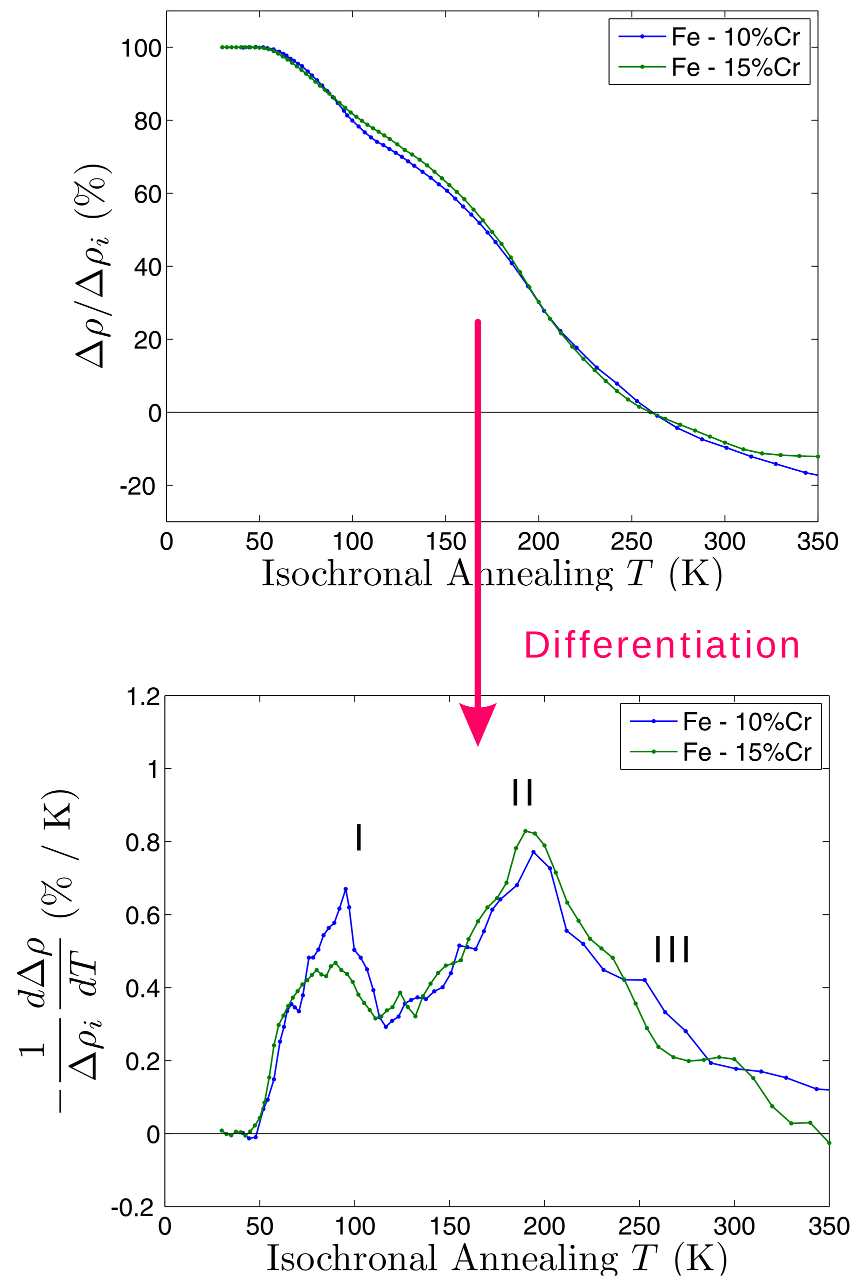
Post-irradiation annealing

- Sample is subject to isochronal annealing steps at successively higher temperature
- Between annealing steps the sample returns to 10 K for measurement of the residual resistivity

Step anneal / measure schema



- During the annealing time defects become mobile and may either recombine, interact with other defects, or annihilate at defect sinks (disslocations, grain boundaries, etc.)
- All these processes lead to a gradual reduction of the number of defects and consequently to the recovery of the residual resistivity.



Conclusions

- The rate of damage recovery peaks at specific temperature regions
- These recovery stages are best exemplified in the differential recovery spectrum, marked with I (~100 K), II (~200K), III (~250K)
- A direct analogy of these stages exists with the ones observed in pure Fe which have been previously identified as
  - I : Frenkel pair recombination, interstitial migration
  - II : migration of interstitial clusters
  - III : migration of vacancies
- The presence of Cr affects the position of the stages relative to Fe (I shifts to lower, II to higher T)
- The recovery peaks are wide, overlapping and they generally show a rich substructure. This can be attributed to the multitude of possible defect combinations (e.g. Fe-Fe, Fe-Cr, Cr-Cr interstitial dumbbell configurations) which result in a distribution of activation energies.
- Only the amplitude of stage I is Cr concentration dependent.
- Above stage III the resistivity goes below the pre-irradiation value. This is due to radiation-enhanced alloy ordering caused by the mobile vacancies in stage III.

Future work

A systematic dataset of resistivity recovery at different Cr concentrations and irradiation doses will be completed. The results will be compared to recent theoretical results

* e-mail: gapost@ipta.demokritos.gr