Radiation Damage in Fe-Cr Alloys for Fusion Applications

G. Apostolopoulos

National Center for Scientific Research “Demokritos”,
Athens, Greece

Outline

- Fusion
  - Introduction & Status
  - Basic material problems
- Fe-Cr alloys and their importance for Fusion
- Low-T ion irradiations at “Demokritos” TANDEM facility with in-situ resistivity measurements

People

G. Apostolopoulos
K. Mergia
S. Messoloras

X-Ray & Neutron Scattering, Transport properties

E. Devlin
N. Moutis

Mössbauer Spectroscopy

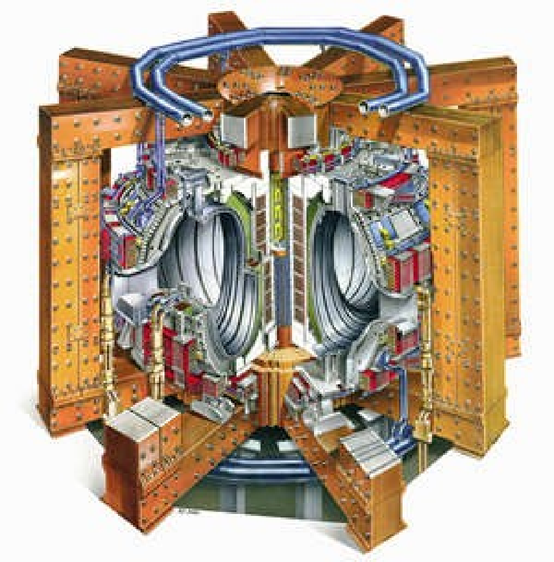
M. Gjoka
V. Nousiou
K. Mergia

Magnetic Measurements

A. Lagoyannis
Th. Merzimekis

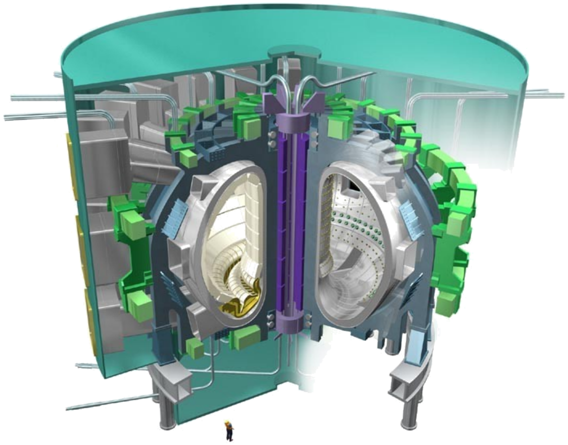
Ion Irradiations

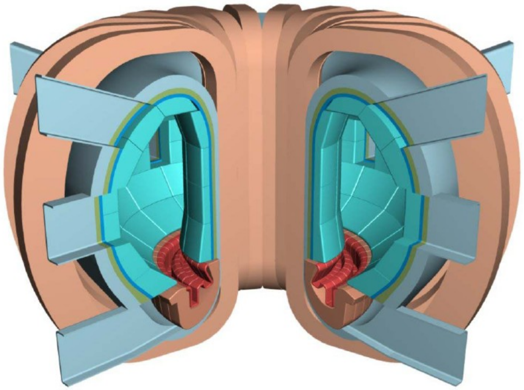
Fusion Energy



- Fusion is a potential alternative energy source
  - Low carbon emissions
  - Abundant fuel, high efficiency
  - No long-lived radio-active waste, safe & reliable operation
- Energy production has been demonstrated (JET, UK)
  - Magnetically confined plasma in a TOKAMAK
  - $D+T \rightarrow {}^4He$ (3.517 MeV)+n (14.069 MeV)
  - Closed Tritium fuel cycle!
- Main roadblock to fusion power:
  - Materials to withstand the high radiation (n) doses in future power plants
- Current International Fusion Roadmap:
  - International Thermonuclear Experimental Reactor (ITER) (to operate by 2018)
  - International Fusion Materials Irradiation Facility (IFMIF) (expected operation ~ 2030)
  - Demonstration power plant (DEMO), ~2050

Indicative Dose levels

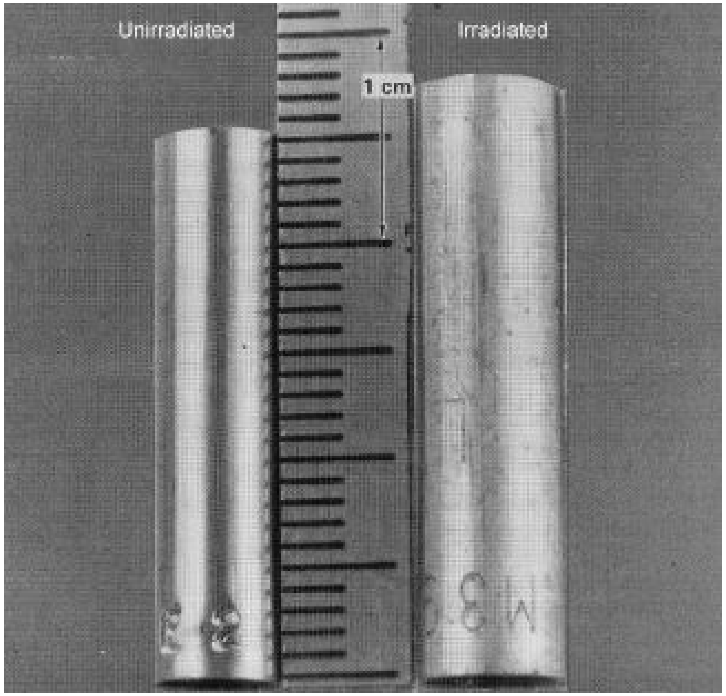




	First Wall	Dose (dpa)	Temperature	
ITER	Austenitic steel	<3 dpa	<300 °C	
DEMO	EUROFER	50-89 dpa	<550°C	
Power Plant	ODS Ferritic Steels	100-150 dpa	<750 °C	
Power Plant	SiC_f/SiC Composites	100-150 dpa	upto 1100°C	

First Wall Materials – Requirements/Problems

- High temperature operation
- High neutron radiation levels
- Low Activation
- He, H production
  - voids, embrittlement
- Radiation damage (atom displacement)
  - Degrade mechanical properties
  - Swelling



Candidate first wall materials

- Steels
  - **Reduced Activation Ferritic/Martensitic** (RAFM) steel
  - Oxide dispersion strengthened (ODS) steel
- Other materials:
  Vanadium alloys, SiCf/SiC composites
- Behavior under DEMO doses is **unknown**
- IFMIF will provide neutron beams relevant to fusion conditions (*but not in near future*)
- Theoretical Modelling of radiation damage with quantitative prediction capability is highly desired

Fe-Cr model alloy

- The base of the RAFM alloy steels
- Alloy phase stability and Irradiation behavior is currently studied theoretically by a number of methods (ab-initio, molecular dynamics, kinetic monte-carlo, …) in a multi-scale approach
- Experimental validation is a crucial part of this effort
- "Demokritos" participates actively to the Fe-Cr exp. validation by a number of studies

Electrical resistivity under irradiation

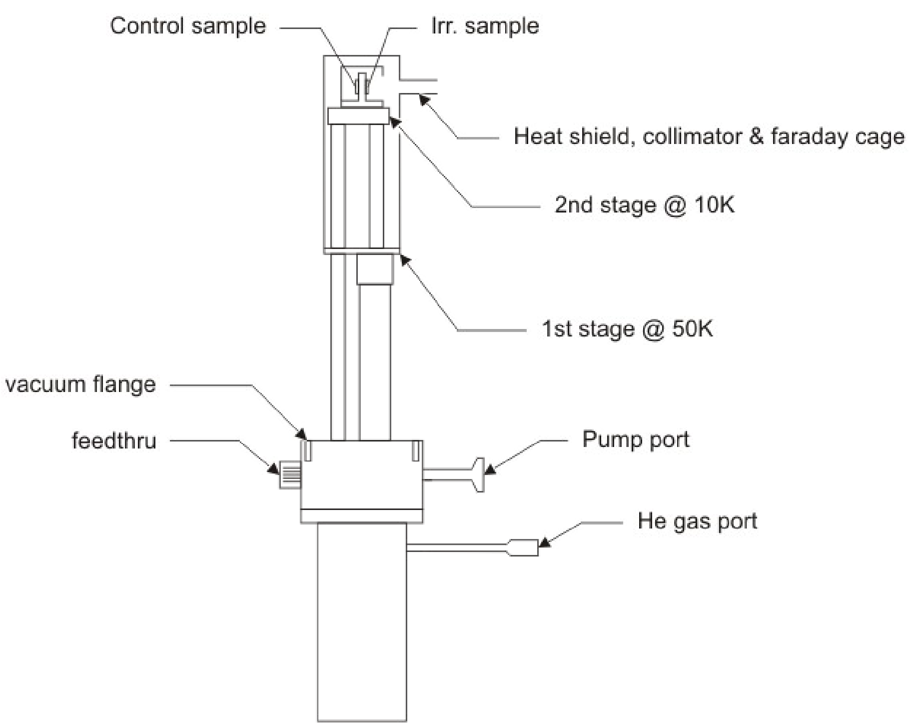
Scope:

Development of a low-temperature ion irradiation facility with in-situ resistivity measurements at the “Demokritos” TANDEM accelerator

- El. Resistivity is very sensitive to irradiation defects (vacancies, interstitials)
- Low-T prevents instantaneous annihilation of mobile defects
- Controlled post-irradiation annealing reveals kinetics of the defects

Experimental setup

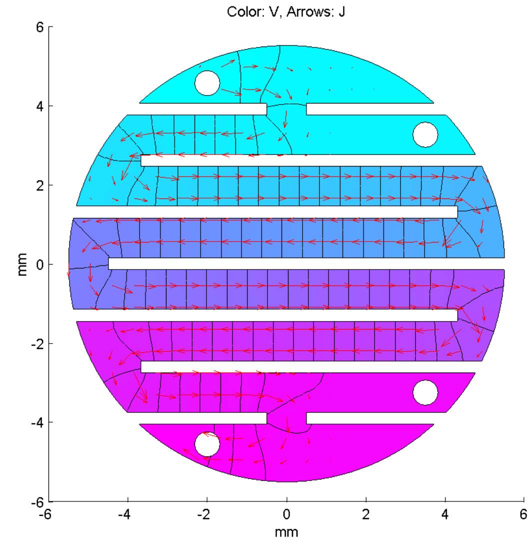
- A closed cycle He refrigerator installed at a beam line of “Demokritos” TANDEM accelerator



- 2-stage refrigerator provides 1W of cooling @ 10K (base temp.)
- Cryogen free, continuous unattended operation

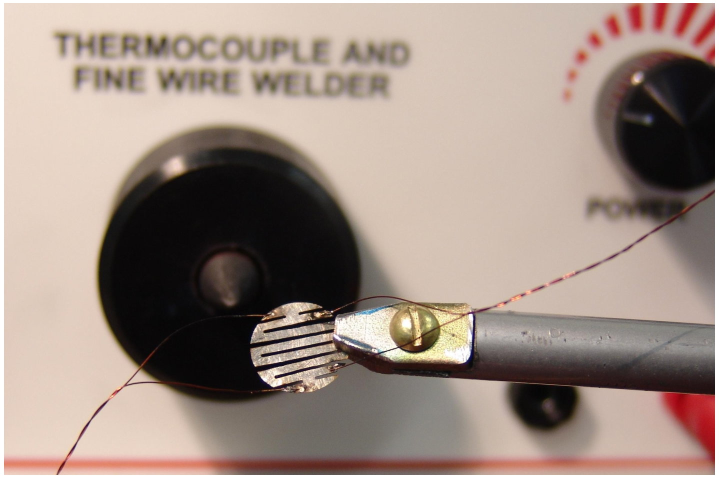
Sample preparation

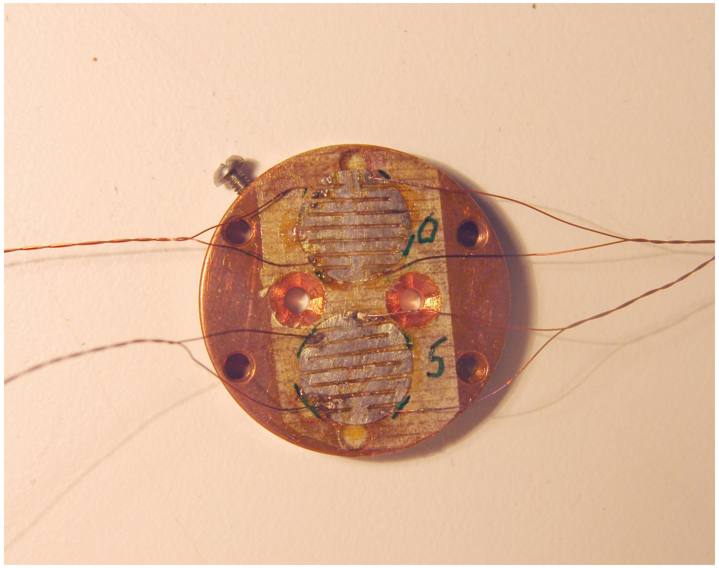
- Thin disks of ~11mm diameter are prepared from model alloy bars by cutting and thinning/polishing
- Target thickness is 50 μm (optimized for irradiation / measurement)
- Meander shape cut with spark erosion
  - optimize geometrical factor for resistivity measurement
  - provide contact locations for current/voltage leads



Electrical connections & thermal anchoring

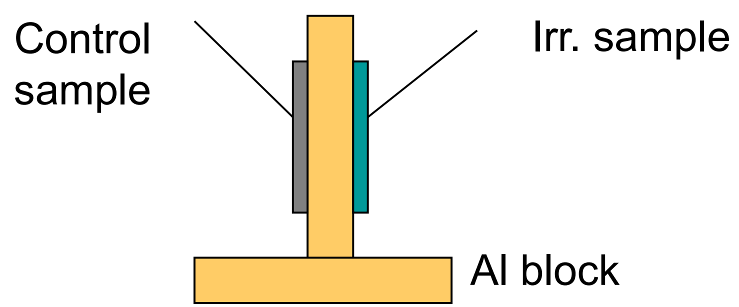
- Spot-welding of current and potential leads
- Thermal anchoring on the cryostat's copper block by low-T varnish

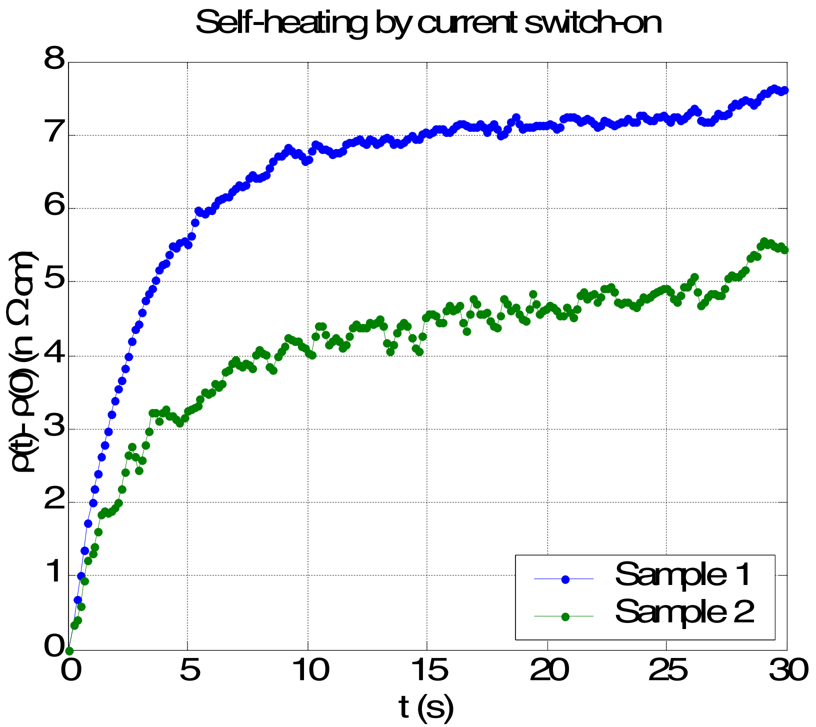




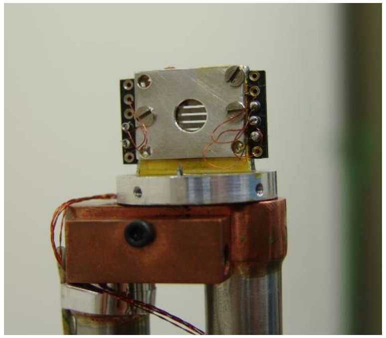
Resistivity measurement

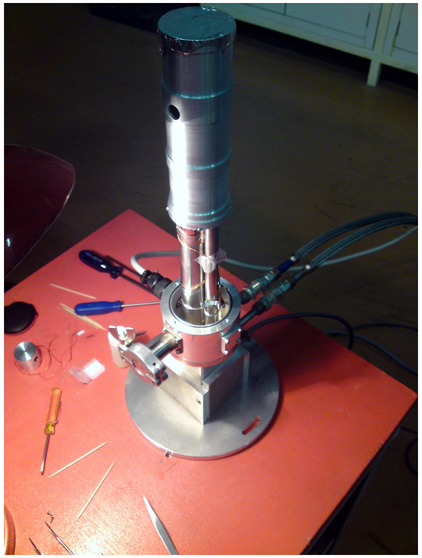
- State of the art, fast & accurate instrumentation
- Resolution:
  - resistance < 10^{-6} Ω
  - resistivity (typical sample dimensions) 10^{-10} Ω-cm
- 2 samples measured simultaneously @ 7 pts/s
  - control + irradiated sample

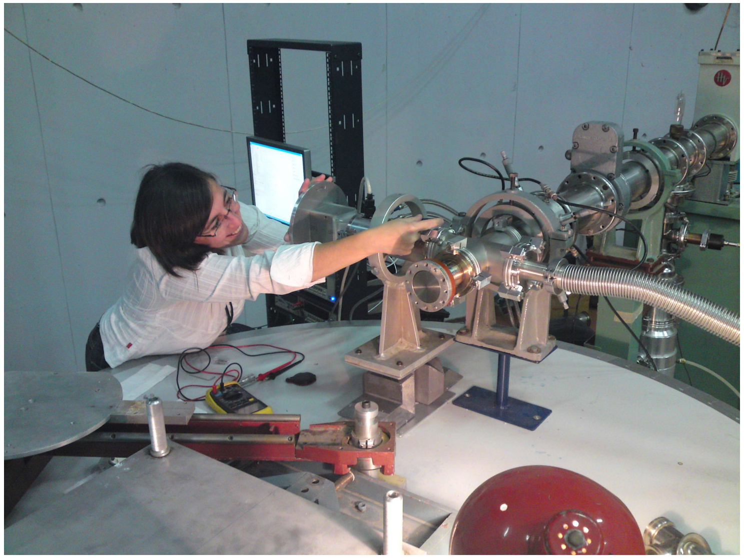


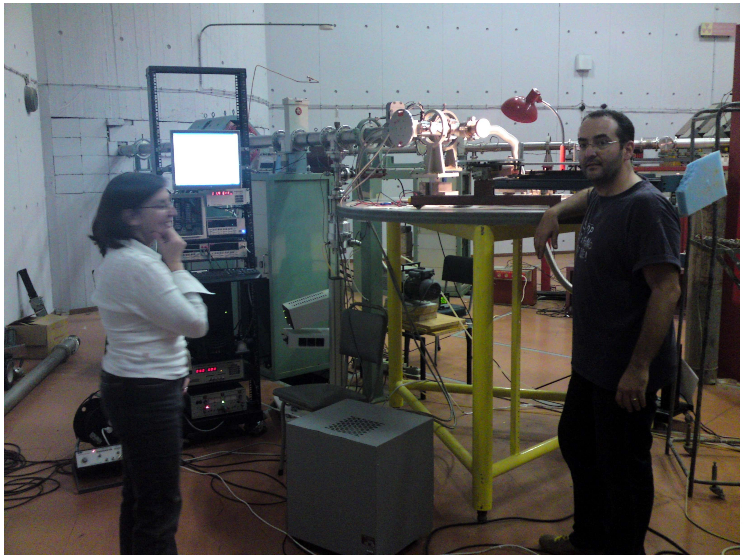


Integration in the TANDEM Beam-line

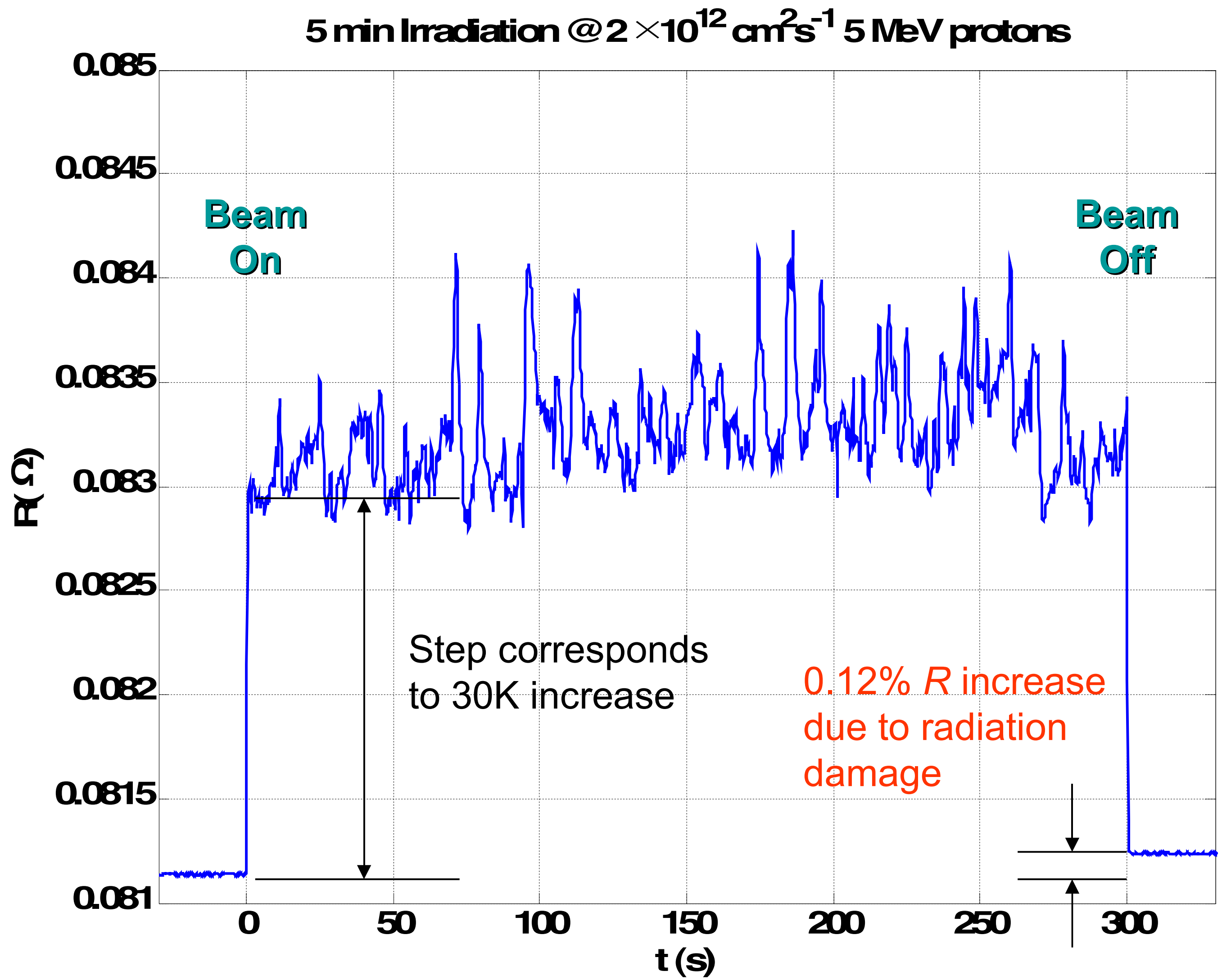




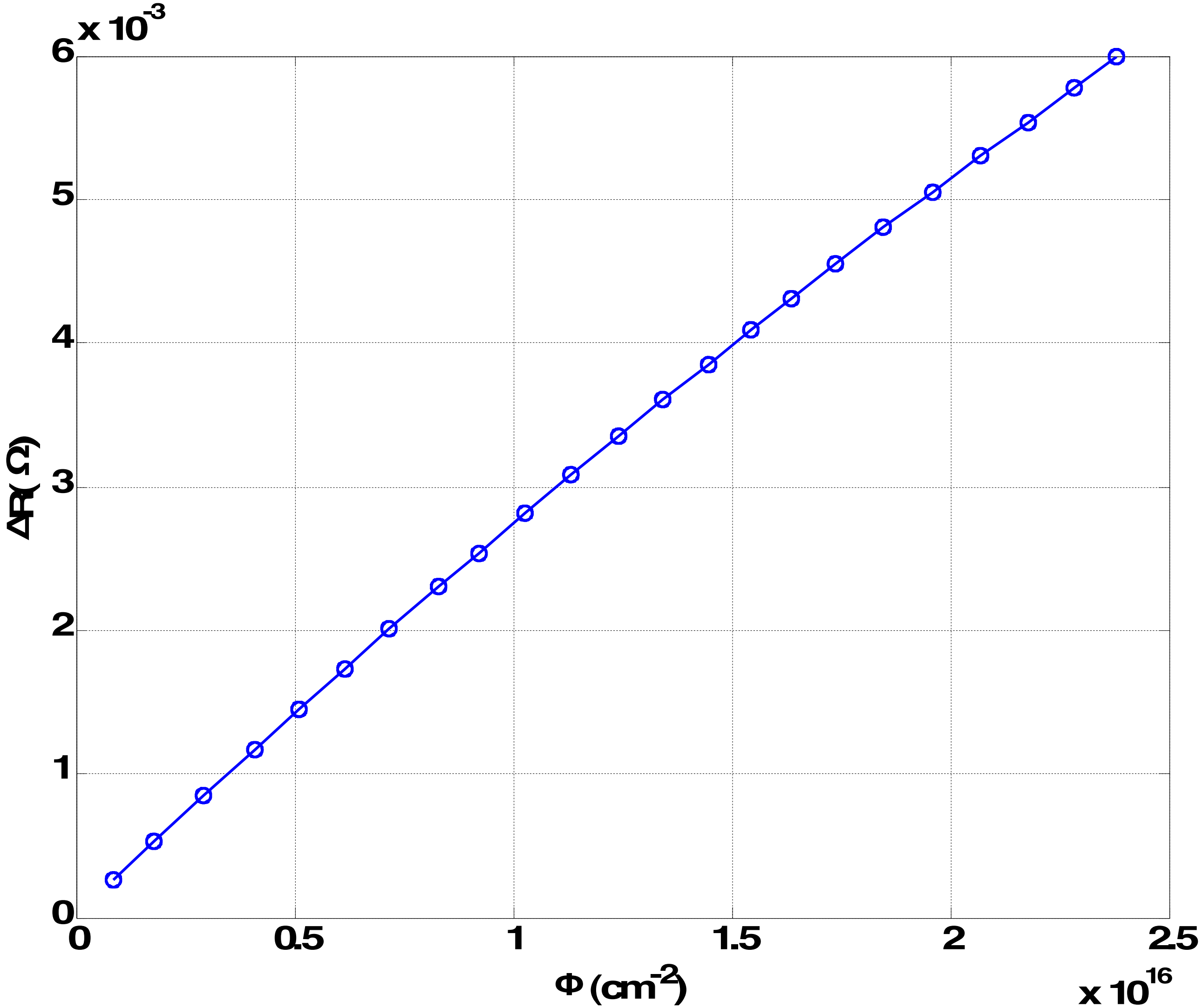




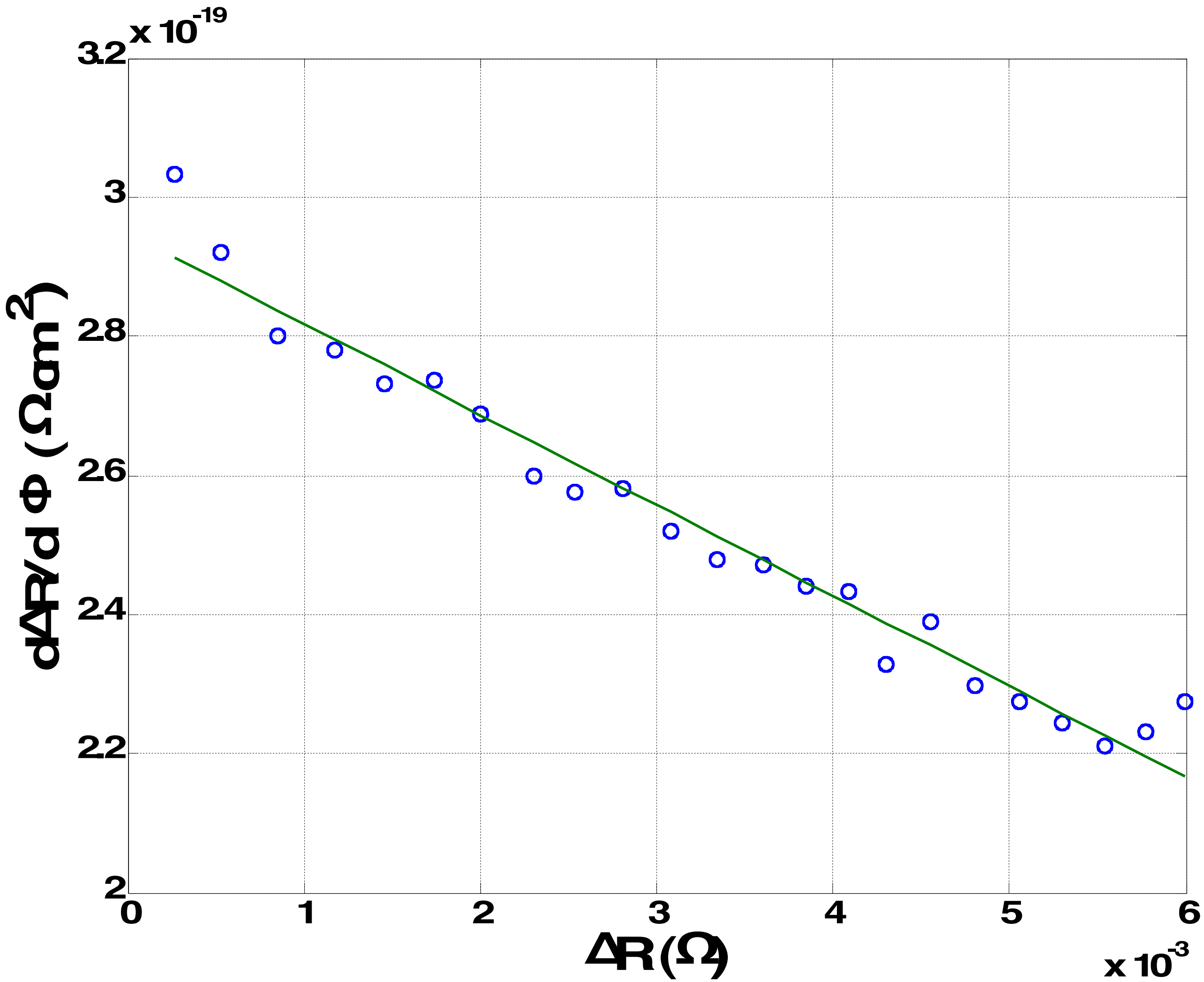
1st irradiation experiments



Resistance increase vs Dose



Damage Rate evolution



Defect production & recombination

$$\frac{dN_d}{d\Phi} = \sigma_d \left(1 - v_0 N_d\right)$$

- N_d : defect concentration
- σ_d : defect production cross-section
- v_0 : recombination volume

$$\Delta R \propto \rho_d N_d$$

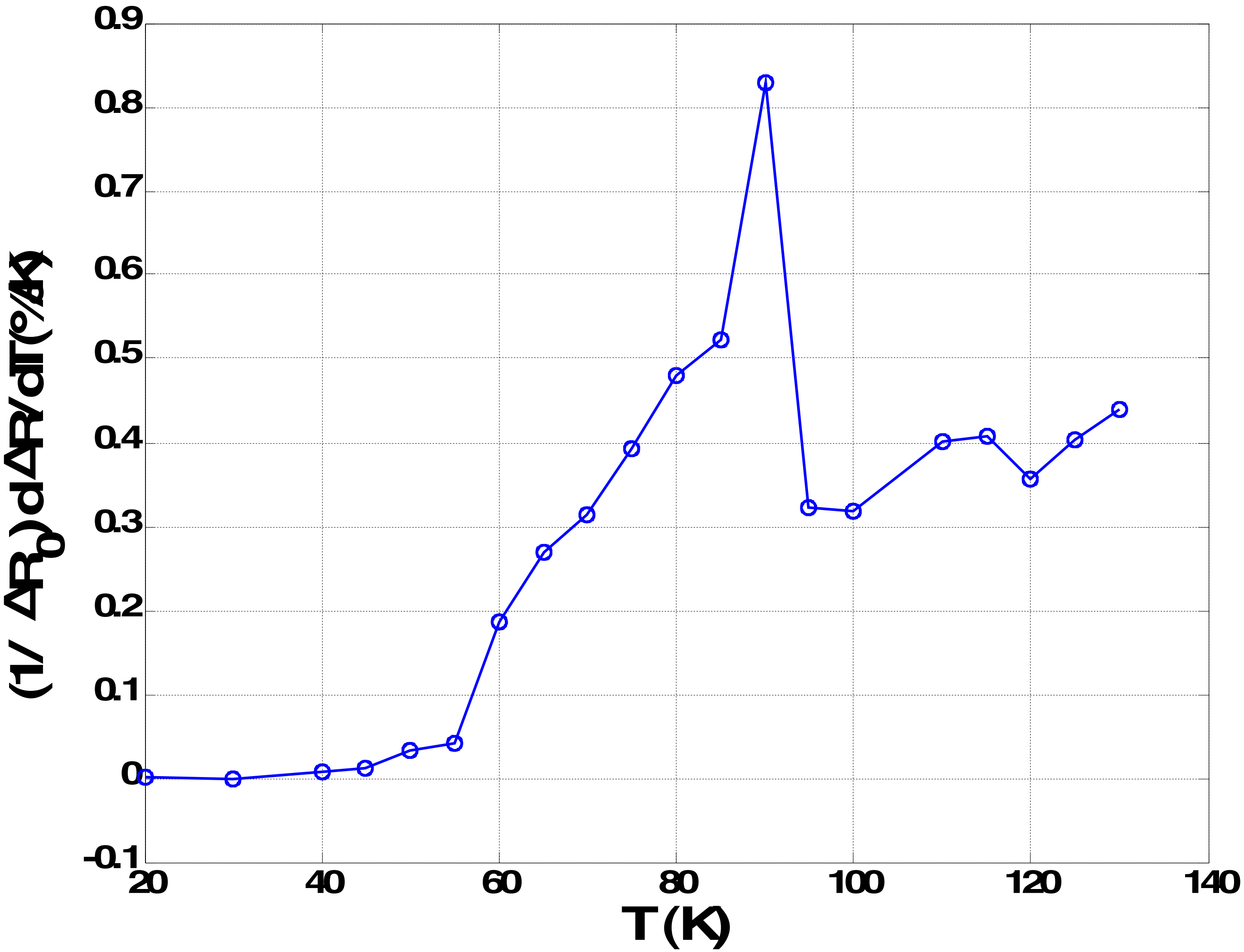
Summary

- Understanding of radiation damage in Fe-Cr alloy is crucial for the Fusion Materials program
- An in-situ low-T resistivity set-up under ion irradiation has been successfully operated at “Demokritos”
- Radiation damage in Fe-Cr will be studied under proton irradiation
- The annealing system for Resistivity recovery measurements will be developed next

Thank you for your attention …

Additional Material

Post-irradiation annealing / Res. Recovery



Group Activities in Fe-Cr Alloys

- Structural properties
  - Short Range Ordering (SRO), phase stability, Cr clustering studied by means of Mössbauer spectroscopy, SANS, X-Ray diffraction
  - Correlation with magnetic properties, Magnetic measurements, SANS

- Transport properties
  - Resistivity of un-irradiated alloys
  - Ion irradiation and resistivity recovery studies