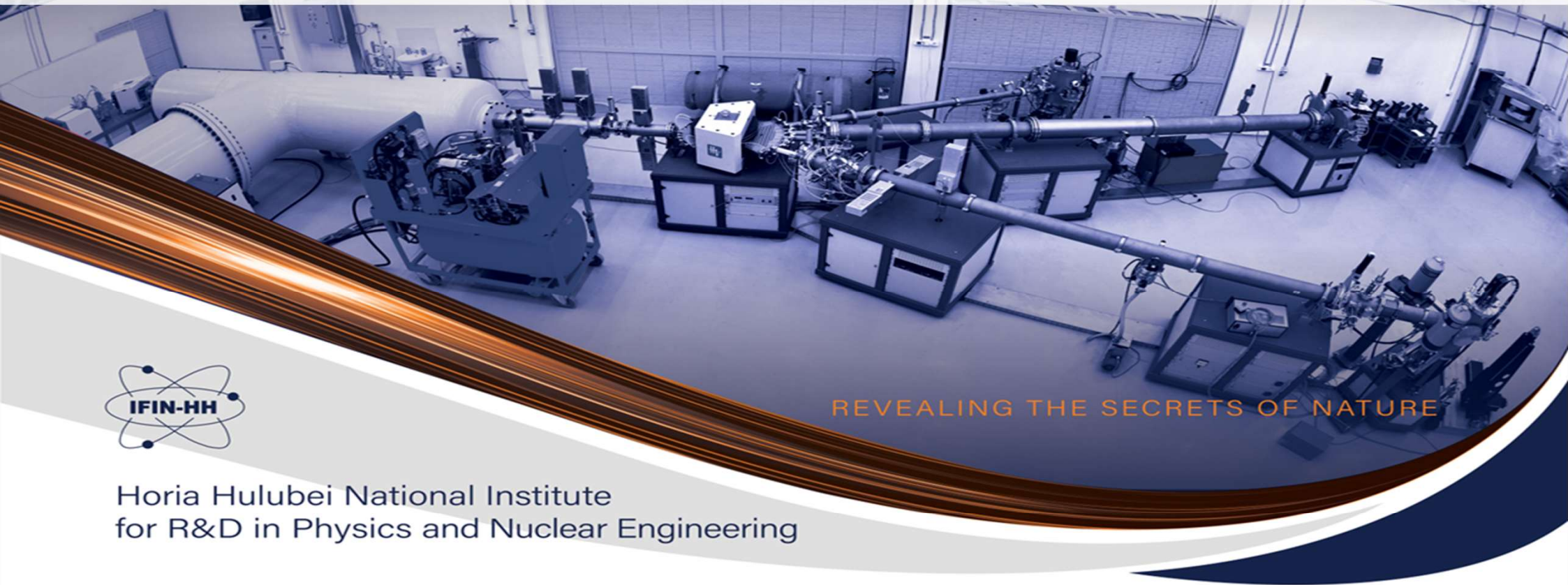


First Steps in the IFIN-HH–GSI MAT Collaboration: Investigating Irradiation-Induced Phase Transformations in Ga_2O_3 under Extreme Electronic Excitation



Horia Hulubei National Institute
for R&D in Physics and Nuclear Engineering

<https://www.nipne.ro/>

REVEALING THE SECRETS OF NATURE



Gihan Velişa

MAT Collaboration Meeting 2026

gihan.velisa@nipne.ro

3 MV Tandem Accelerator USER FACILITY IFIN-HH

The present structure of PAC is as follows:

Members:

- Primoz Pelicon
- Zsolt Podolyak
- Norbert Pietralla
- Georgi Georgiev
- Silvia Leoni
- Timo Sajavaara
- Anna Mackova

Secretary:

Sorin Pascu (sorin.pascu@nipne.ro)



**Beam request until
25th of October 2026,**
while the PAC meeting is scheduled for
the 12th – 13th of November 2026.



IFIN-HH

National Institute for Nuclear Physics
and Engineering

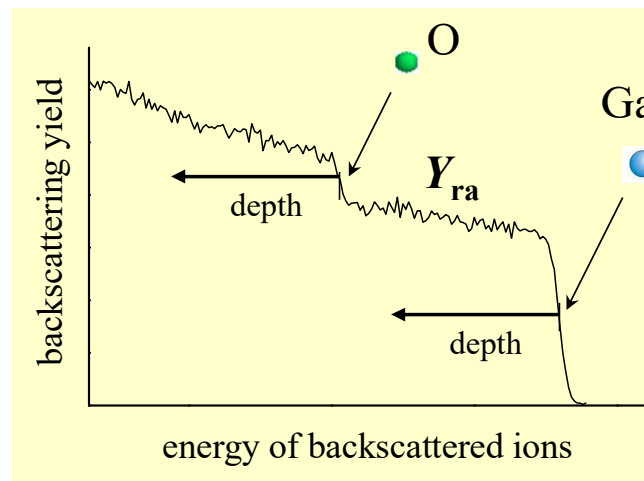
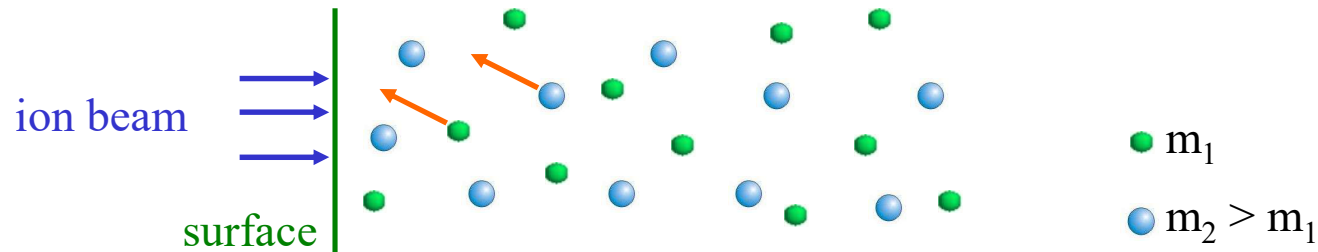


**Applied Nuclear
Physics Department
(DFNA)**
IFIN-HH (NIPNE)

RBS spectra of non-crystalline solids

energy spectra of backscattered ions: Y_{ra} *random yield*

(ions incident in amorphous targets or in random direction of crystalline targets)

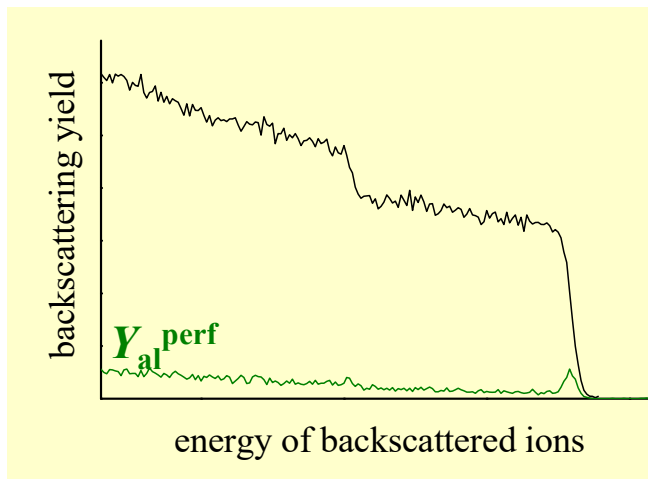
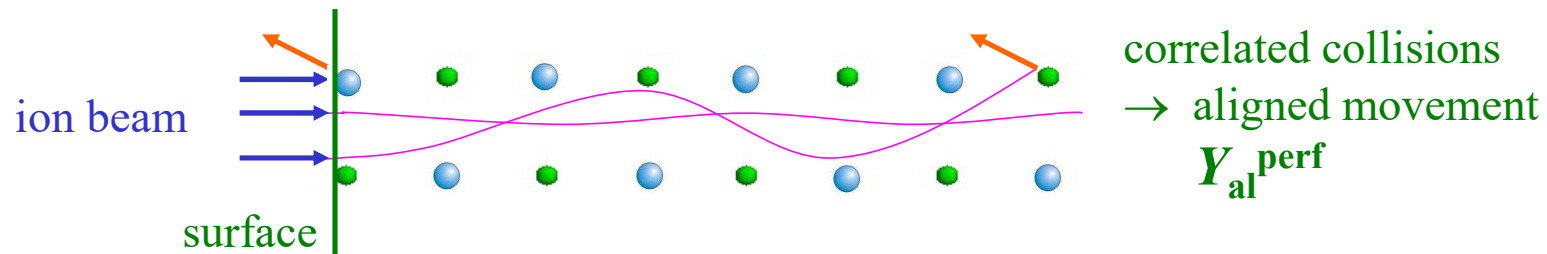


RBS/C spectra of pristine crystal

energy spectra of backscattered ions: Y_{al} *aligned yield*

(ions incident in crystalline targets along low-index axes)

perfect crystal



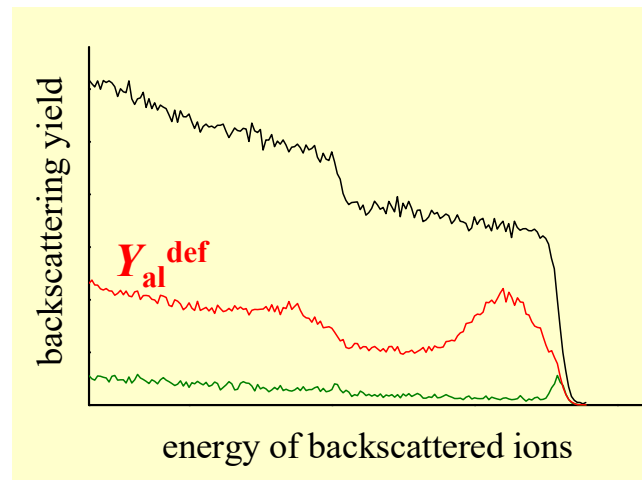
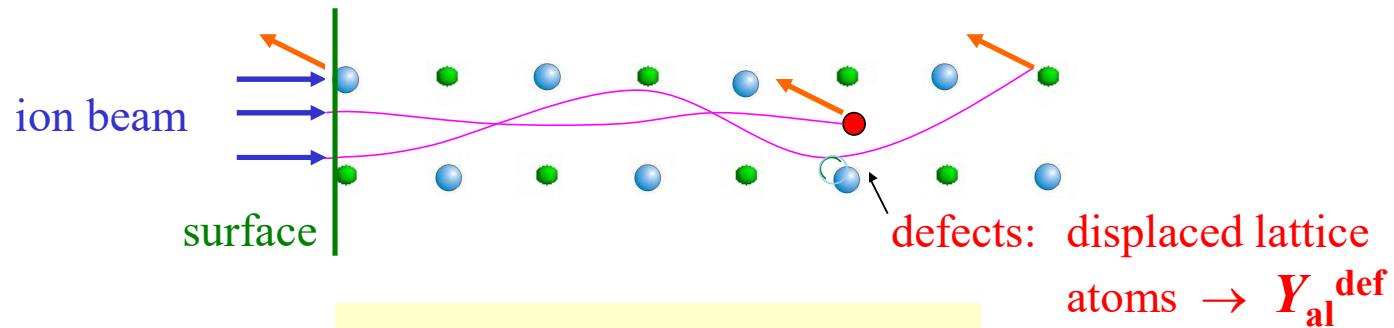
- guidance of the ions by the periodic potentials of the lattice atoms (channelling)
 - low probability for direct backscattering of ions
 - much lower yield of backscattered ions in channelling direction (aligned-spectrum) compared to random incidence (random-spectrum)

RBS/C spectra of defective crystal

energy spectra of backscattered ions: Y_{al} *aligned yield*

(ions incident in crystalline targets along low-index axes)

crystal with defects

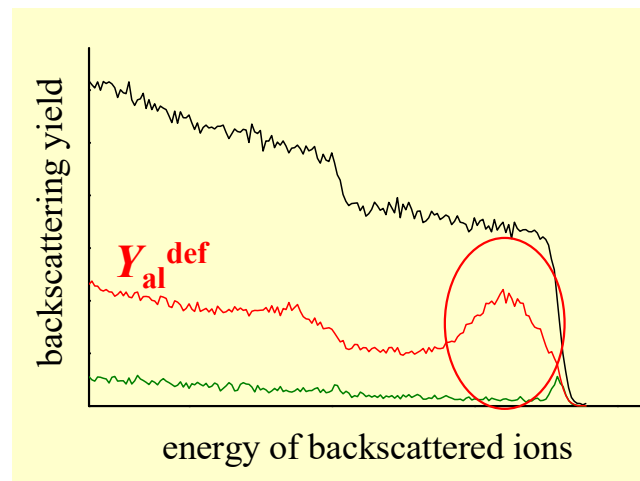
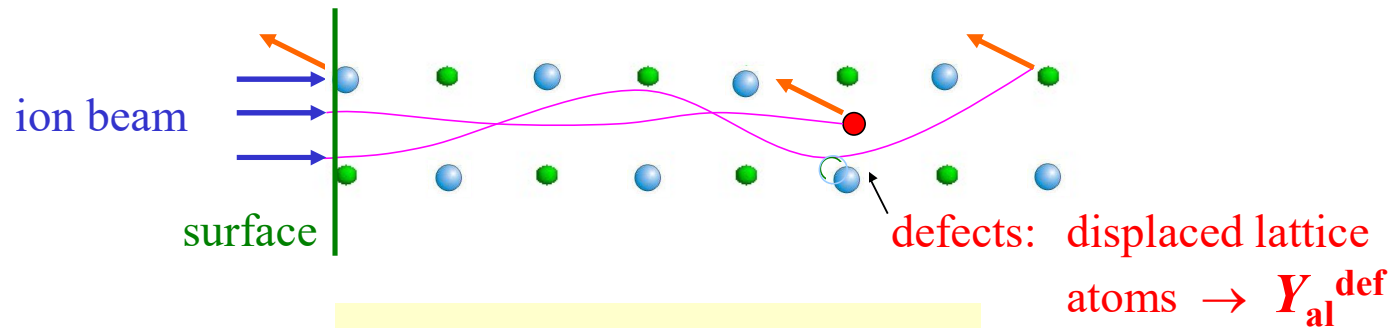


RBS/C spectra of defective crystal

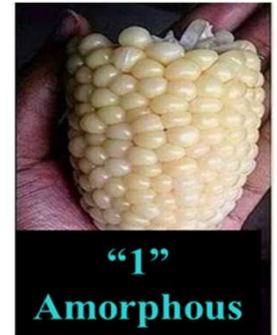
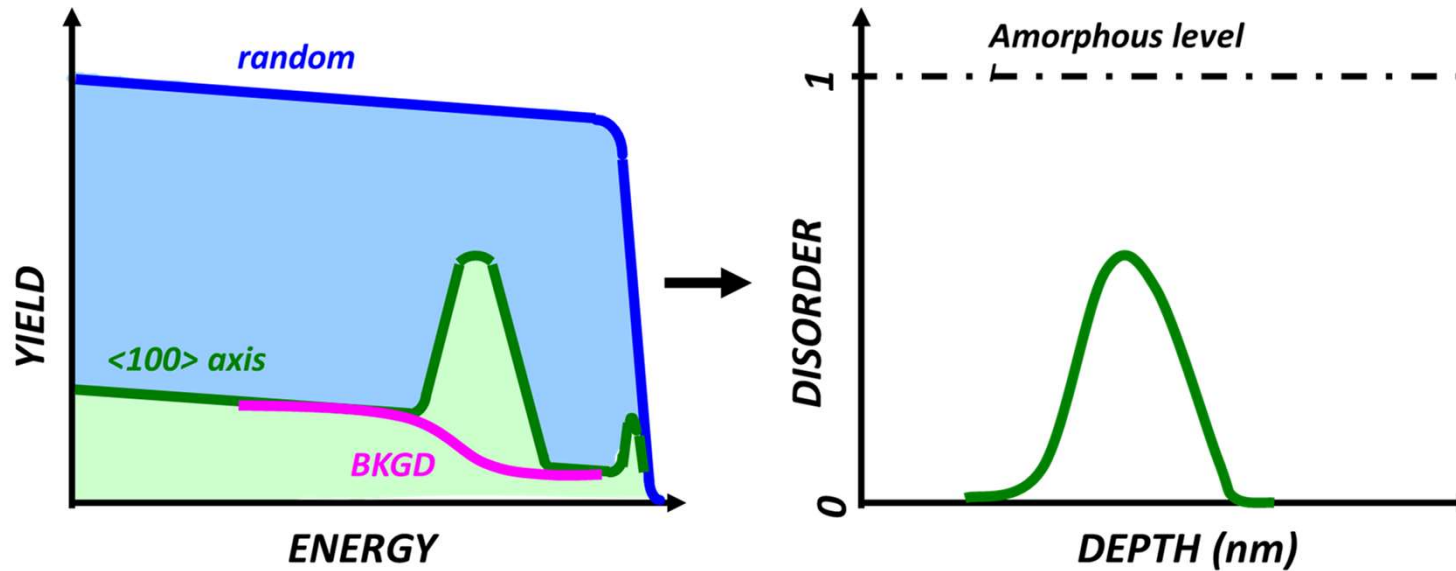
energy spectra of backscattered ions: Y_{al} *aligned yield*

(ions incident in crystalline targets along low-index axes)

crystal with defects



Analysis of RBS/C spectra



Schematic illustration of data analysis using iterative procedure: (left) subtracting dechanneling background from RBS spectra, and (right) relative disorder profiles.

Introduction remarks

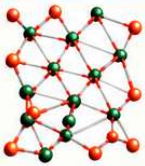
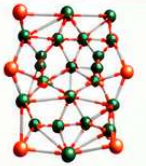
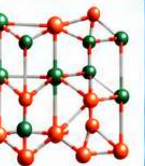
1 Ga₂O₃: Now a Polymorphic Material

- ✓ Ga₂O₃ joins the class of **polymorphic materials** with multiple crystalline phases.
- ✓ The irradiation-induced **γ-phase** is metastable but highly **robust**.
- ✓ Opens new opportunities for **radiation-hard electronics** and extreme environment applications.

Ga

O

2 Polymorphs of Ga₂O₃

α-Ga ₂ O ₃	β-Ga ₂ O ₃ (stable phase)	δ-Ga ₂ O ₃	γ-Ga ₂ O ₃ (newly created phase)
			
Monoclinic (P2 ₁ /m)	Monoclinic (C2/m)	Orthorhombic (Pna2 ₁)	Cubic (Ia $\bar{3}$)

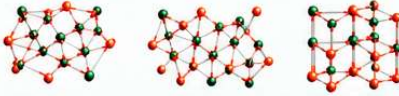
Increasing structural symmetry →

3 Irradiation Response: β-Phase vs Newly Created γ-Phase

β-Ga₂O₃ (initial phase)

- Under irradiation, β-Ga₂O₃ accumulates defects.
- Disorder increases continuously with dose.
- Tendency toward amorphization.

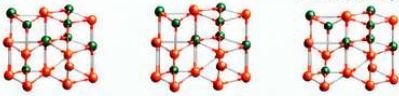
Low dose → Increasing dose → High dose



γ-Ga₂O₃ (irradiation-induced phase)

- Under irradiation, β-Ga₂O₃ transforms into γ-Ga₂O₃.
- The γ-phase maintains its crystal structure even at very high doses.
- No amorphization observed.

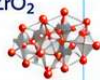
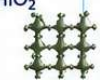
Low dose → Increasing dose → Very high dose (hundreds of dpa)



The β → γ transformation can suppress amorphization under specific irradiation conditions, enabling exceptional radiation tolerance of the γ-phase.

⚠ **Not universal:** β-Ga₂O₃ amorphization has been observed under other irradiation conditions. Radiation tolerance is irradiation-condition dependent!

4 In Contrast to Other Polymorphic Materials

Material System	Polymorphic Phases	Effect of Irradiation
ZrO ₂ 	Monoclinic Tetragonal Cubic	Irradiation induces disorder and amorphization
HfO ₂ 	Monoclinic Tetragonal Cubic	Amorphization observed at high damage
TiO ₂ 	Rutile Anatase Brookite	Amorphization observed under low damage

How can we improve the crystalline quality of the newly converted γ-phase?

Two annealing strategies:

In-situ annealing (during irradiation)

Simultaneous irradiation and annealing. At temperatures above ~300 °C, dynamic annealing is active and suppresses the γ → β phase reversion. (*J. Vac. Sci. Technol. A* 41, 023101 (2023))


β-Ga₂O₃
(before irradiation)

Irradiation + Heating
→


β-Ga₂O₃
(suppressed reversion)

T > ~300 °C

Limitation: Dynamic annealing prevent defects accumulation and hence the γ-phase formation is prevented.

Ex-situ annealing (after irradiation)

Post-irradiation annealing to reduce defects and improve crystallinity.


γ-Ga₂O₃
(as-irradiated)

Annealing
→


β-Ga₂O₃
(recrystallized)

Limitation: At temperatures approaching or exceeding ~1000 K, the γ-phase can recrystallize back to the stable β-phase.

Key References

1. A. Tracy, et al. *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*, Volume 374, pp. 40–44 (1 May 2016).
2. A. Azarov, et al. *Universal radiation tolerant semiconductor*. *Nature Communications* 14, Article 4855 (2023), DOI: 10.1038/s41467-023-40588-0.

★ Documents amorphization of β-Ga₂O₃ under other irradiation conditions, including 946 MeV Au swift-heavy-ion irradiation (amorphous ion tracks).

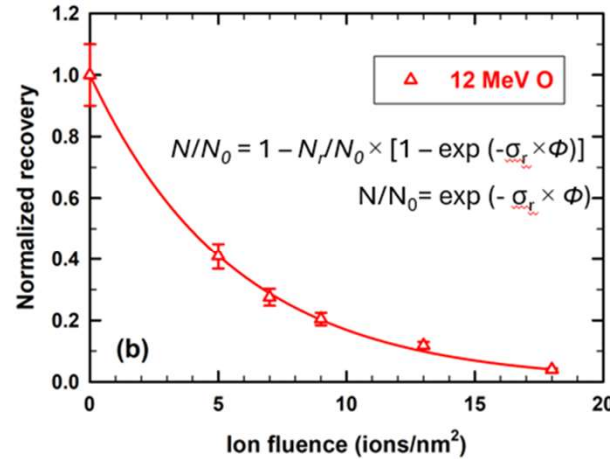
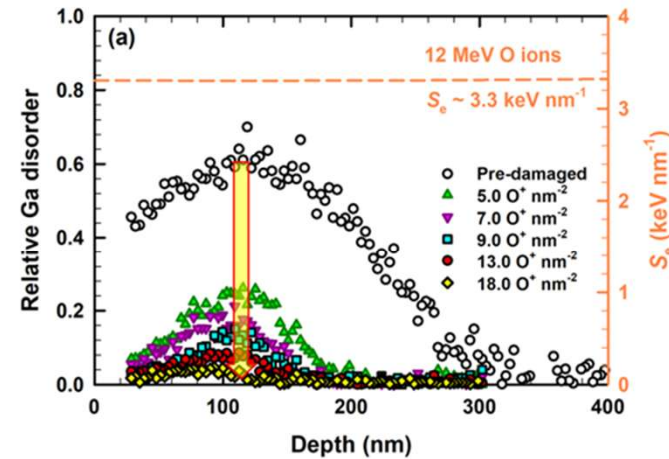
★ Supports the γ/β double-polymorph Ga₂O₃ structures tolerating disorder equivalent to hundreds of dpa under room-temperature implantation conditions.

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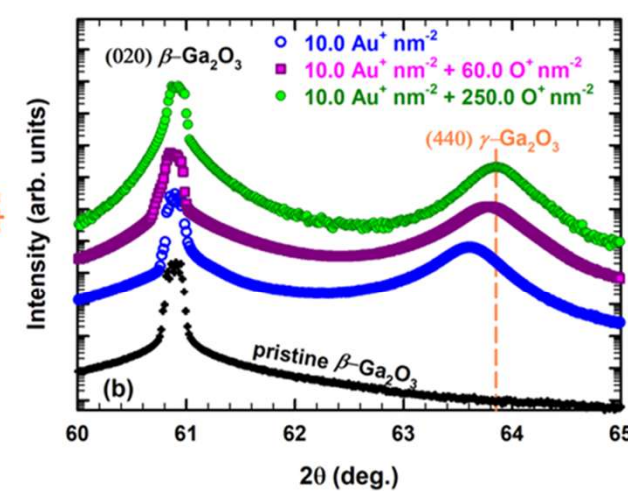
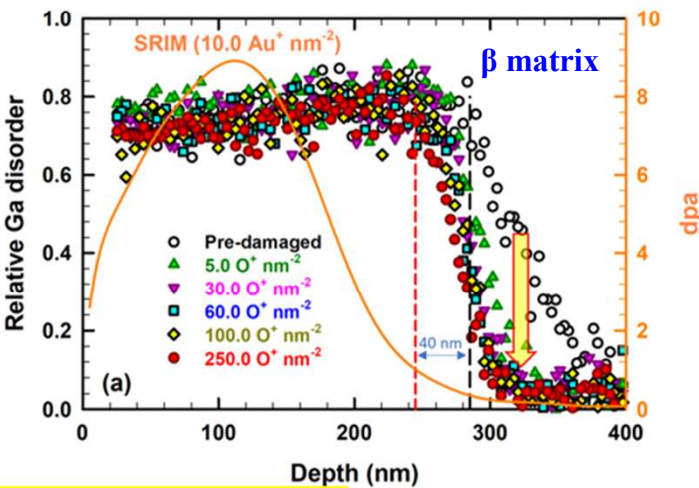
What about:

Athermal ionization-induced annealing (AIIA)?

Ionization-induced healing and atom reordering in Ga₂O₃ @ RT



- Evolution of Ga disorder upon 12 MeV O irradiation at 300 K.
- Normalized disorder recovery yielding a recovery cross-section (σ_r) of $\sim 0.17 \text{ nm}^2$.
- Relative Ga disorder profiles and selected XRD θ - 2θ scans of γ/β -Ga₂O₃ bilayer prior to and following 12 MeV O ions irradiations.
- The **orange** dashed line marks the (440) γ -Ga₂O₃ for an as-grown film.
- The narrowing of the disordered layer (by $\sim 40 \text{ nm}$) and the shift of the (440) diffraction peak toward the reference position indicate improved crystallinity and interface sharpening of the γ layer under ionizing irradiation.



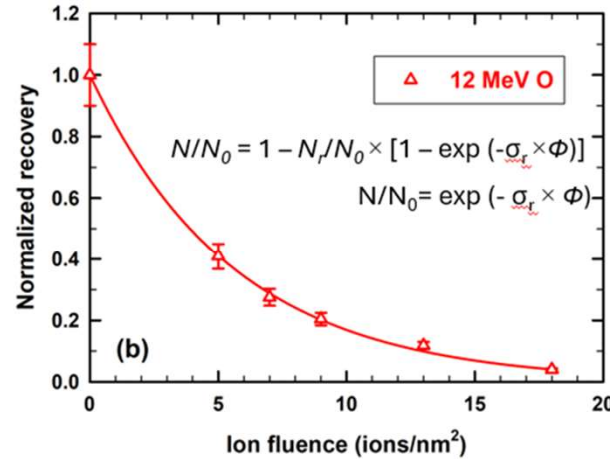
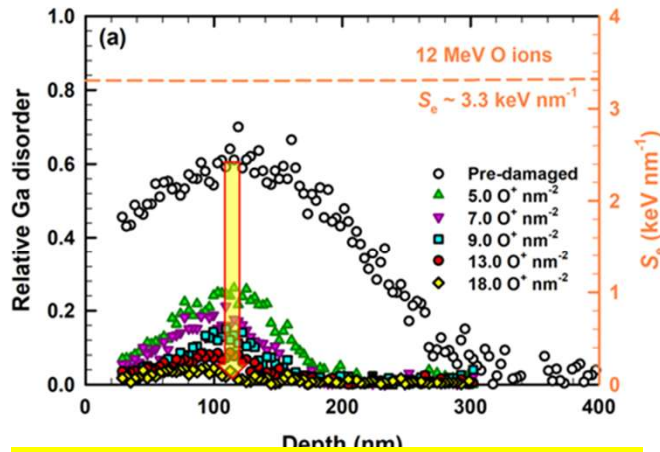
In Ga₂O₃, ionization anneals the existing damage and improves crystallinity!

Ga₂O₃: 1+1 < 2

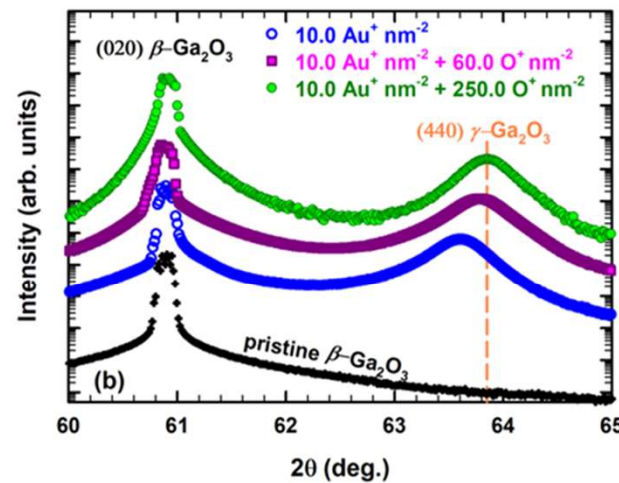
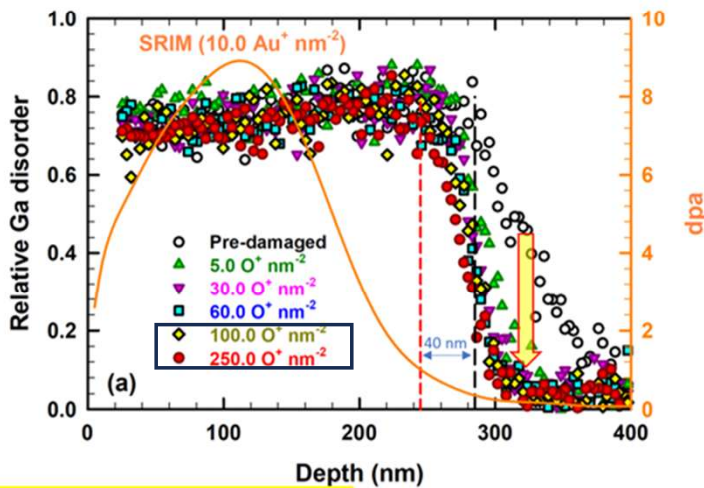
1 (nuclear) + 1 (electronic) << 2 Competitive

Curtesy of Y. Zhang

Ionization-induced healing and atom reordering in Ga_2O_3 @ RT



Unreasonably high fluence!!!



- Evolution of Ga disorder upon 12 MeV O irradiation at 300 K.
- Normalized disorder recovery yielding a recovery cross-section (σ_r) of $\sim 0.17 \text{ nm}^2$.
- Relative Ga disorder profiles and selected XRD θ - 2θ scans of γ/β - Ga_2O_3 bilayer prior to and following 12 MeV O ions irradiations.
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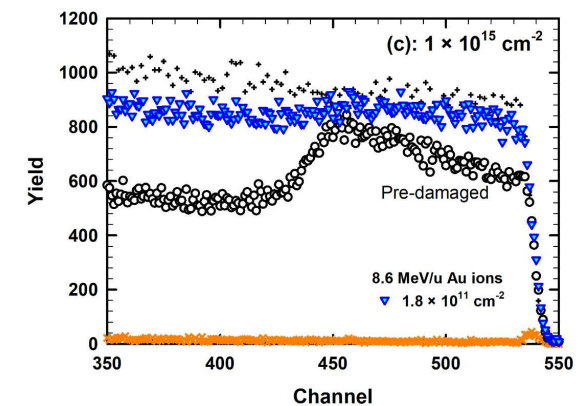
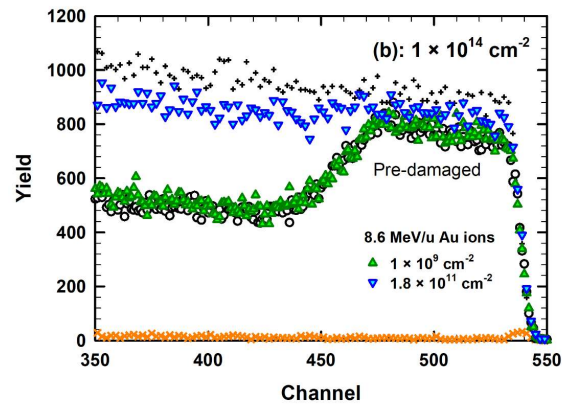
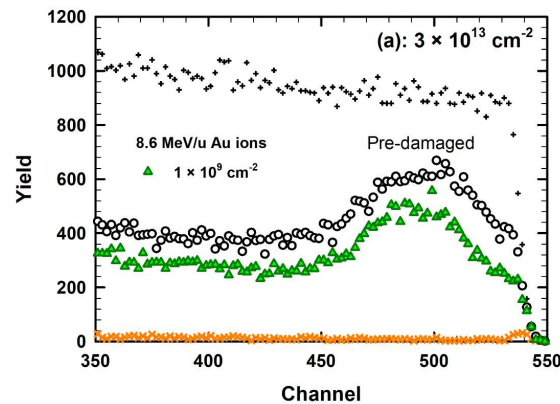
In Ga_2O_3 , ionization anneals the existing damage and improves crystallinity!

Ga_2O_3 : 1+1 < 2

1 (nuclear) + 1 (electronic) << 2 Competitive

Courtesy of Y. Zhang

First tests at GSI using much more Extreme Electronic Excitation



Acknowledgments:

Wagner Michael

Toimil Molares Maria Eugenia

For more details:

please see the Poster of Andrei Hotnog - No. 8

FAIR-RO Grand Application & PAC Proposal

Ga₂O₃-The New Kid in the Class of Radiation Tolerant Semiconductors (ATOM)

08/07/2024 – 31/12/2025

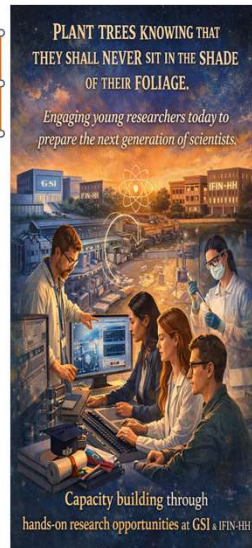
Project Director: Gihan VELIŞA
gihan.velisa@nipne.ro

Programme / Sub-programme / Module	5.9/5.9.2/FAIR-RO		
Project type	RD		
Experiment	BIOMAT / MAT	Scientific Domain	APPA
Project title / Acronym	Ga ₂ O ₃ -The New Kid in the Class of Radiation Tolerant Semiconductors (ATOM)		
Project duration	30 months		

From fundamental physics to applications

Horia Hulubei National Institute for R&D in Physics and Nuclear Engineering (IFIN-HH)

ISAB FAIR-RO 2024-2025: 26 January 2026



PROJECT OBJECTIVES

Three interconnected objectives designed to advance discovery, develop capabilities, and strengthen collaboration.

01: Advance understanding of electronic energy dissipation and defects



02: Invest in the next generation of scientists



03: Establish a creative and dynamic partnership between IFIN-HH & GSI



GSI Helmholtzzentrum für Schwerionenforschung GmbH

GATE (GSI)

My Proposal

New proposal

Proposal list

Personal section

Personal data

Change password

Change username

Disable / delete account

Campus registration

Handbook

Glossary

Logout

GATE (GSI) - Gihan Velisa

You have

- 1 active proposals (in review or on schedule)

Active proposals

Proposal	Action	Title	Proposer	Facility	ET alloc.	Schedule
M-24-00318		Multiple pathways to study the effects of intense electronic excitation on β/γ -Ga ₂ O ₃ phase transformation dynamics: Real-time vs. Offline observations	Gihan Velisa, NIPNE, RO	2.1-U: M2	4 Shifts	
				2.2-U: M3		



Acknowledgments

Koch Frieder

Simon Pascal

Toimil Molares Maria Eugenia

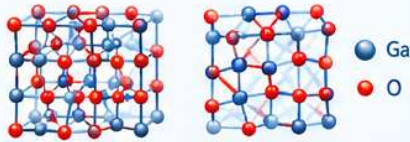
Ion-Beam Modification of Defective β -Ga₂O₃ and Pre-converted γ -Ga₂O₃

Competing Effects – Healing vs. Ion-Track Formation – Across Different Ion Velocities

Material & Irradiation

β -Ga₂O₃
(defective)

γ -Ga₂O₃
(pre-converted)



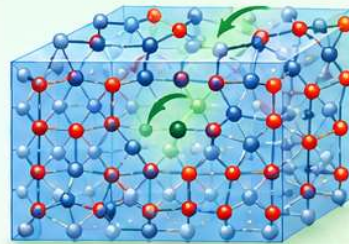
Ionizing irradiation

- MeV ions (low, intermediate, high velocities)
- 3 MV accelerator (our facility)
- GSI (test, high-velocity regime)
- Madrid (intermediate energies)
- GANIL (high-velocity regime)

Two Competing Effects

Damage healing

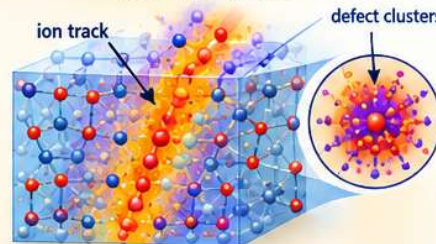
Recombination of defects and restoration of crystalline order



Restored structure

Ion-track formation

Electronic energy deposition
→ thermal spike → amorphous track and/or defect clusters



Amorphous track / defect clusters

Energy threshold

Ion velocity / energy regime

Low velocity
(our 3 MV accelerator)

Intermediate velocity
(Madrid)

High velocity
(GANIL + GSI test)



Damage healing

(> threshold: limited track formation)



Both effects accessible
(near threshold)



Track formation

(damage healing may still occur)

Key Findings



Two competing effects
(damage healing and ion-track formation) can coexist in the same material, separated by an **energy threshold**.



Both effects are accessible in the low-velocity regime using the **3 MV accelerator**.



A test at GSI indicates that the same processes may also occur in the **high-velocity regime**.



We applied for beam time at Madrid to access the **intermediate-energy region**.



We are also interested in extending the study to the high-velocity regime at GANIL.

Project Opportunity



3 MV accelerator
(low velocity)

+



Madrid
(intermediate energy)
– applied for beam time

+



GANIL
(high velocity)
– future extension

+



GSI
(high velocity)
– test results

Expected Impact



Tailored defect engineering in Ga₂O₃ (β and γ phases)



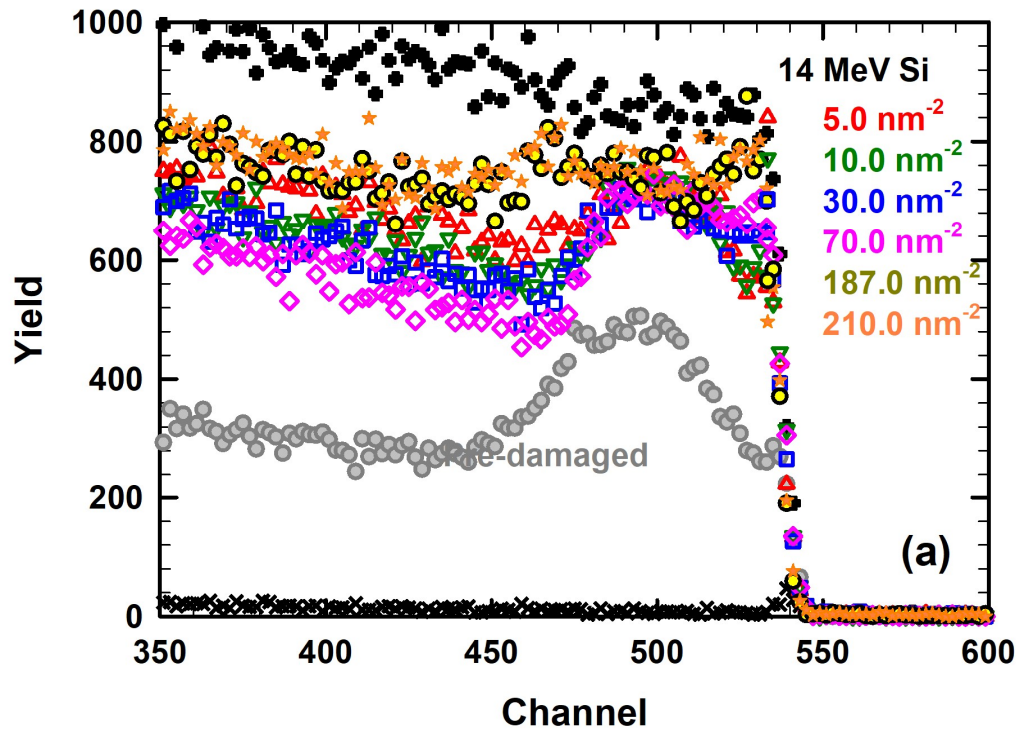
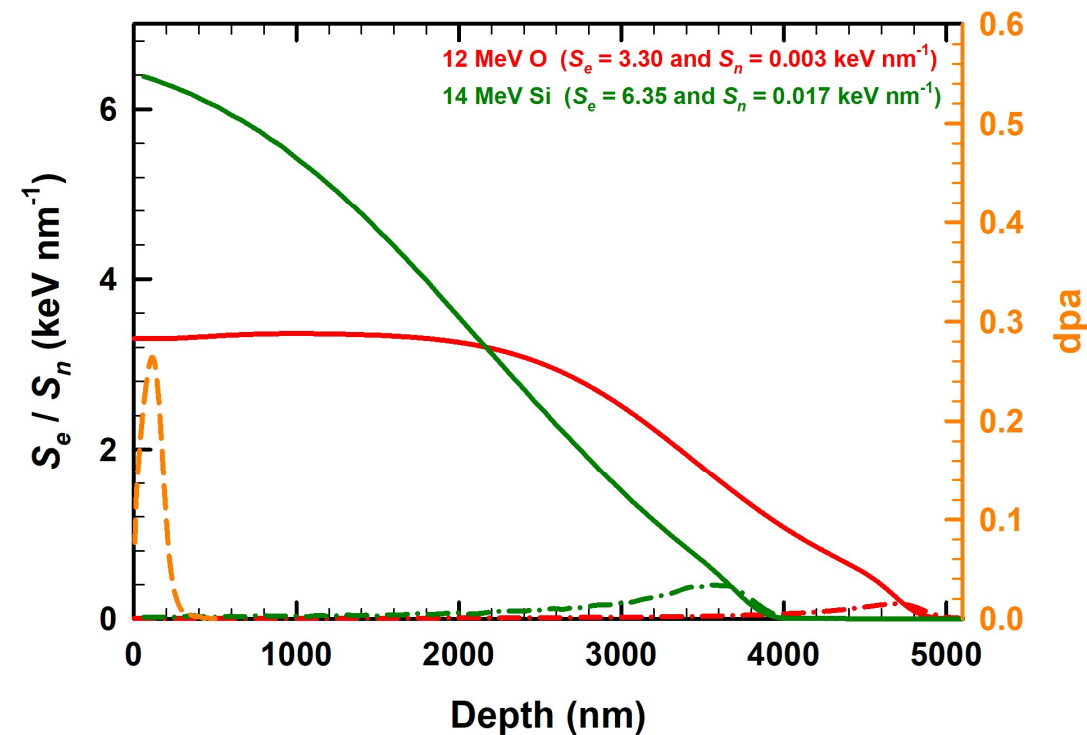
Improved radiation tolerance and device performance



Guidance for next-generation power and optoelectronic devices

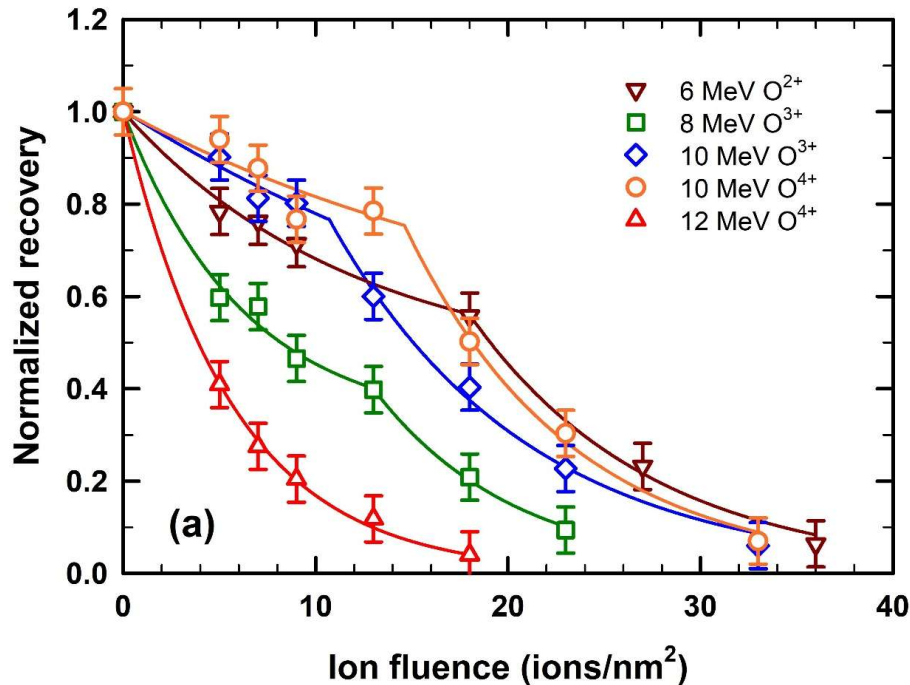
Understanding defect dynamics → Controlling damage and healing → Enabling advanced Ga₂O₃-based technologies

S_e -dependent defect healing and ion-track formation



Synergistic effect is **ACTIVE!**
Increase in S_e value leads to the enhancement of damage!!!

Ionization-induced annealing kinetics dependence on E



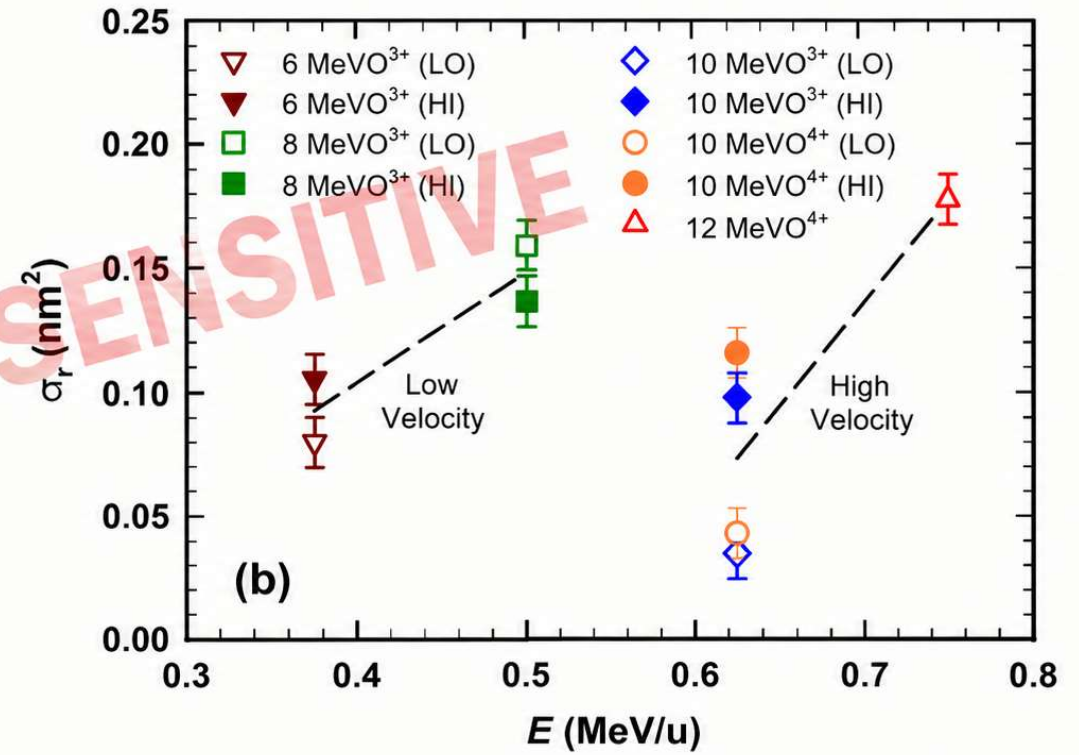
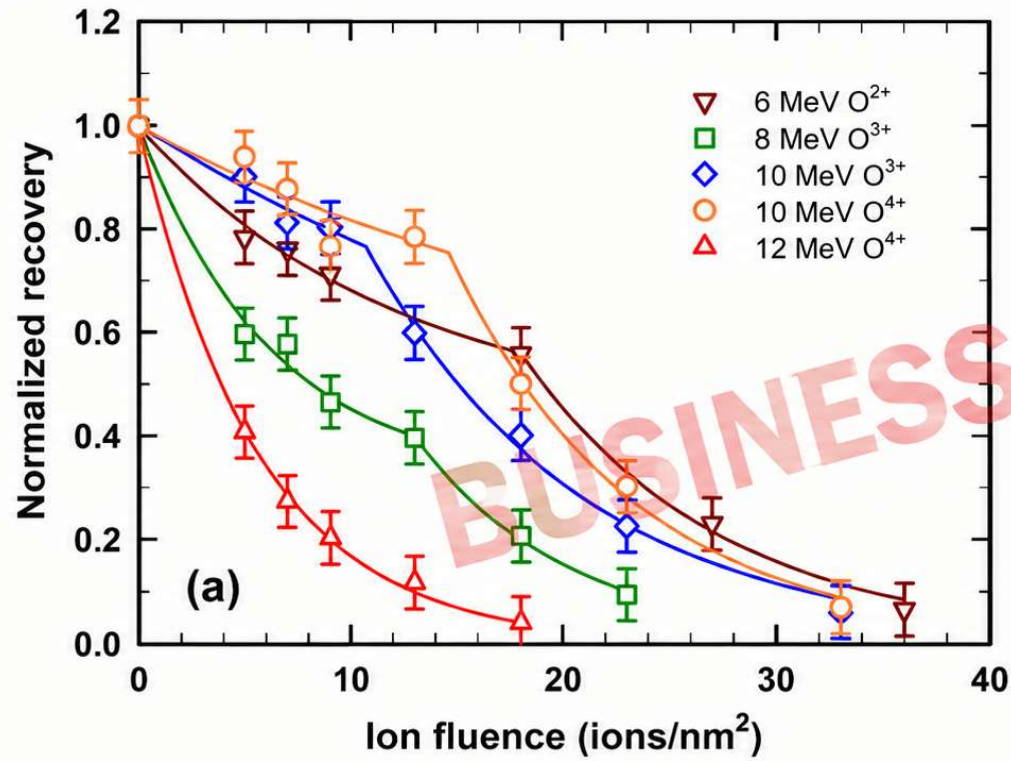
For the low fluences (and the 12 MeV O data), the model used is: $N/N_0 = 1 - N_r/N_0 \times [1 - \exp(-\sigma_r \times \Phi)]$. In the case of 12 MeV O, N_r/N_0 is 1.0.

For the high fluences, the model used is $N/N_0 = N^*/N_0 \times \exp(-\sigma_r \times \{\Phi - \Phi_T\})$, where N^*/N_0 is the normalized recovery at the incubation dose, Φ_T .

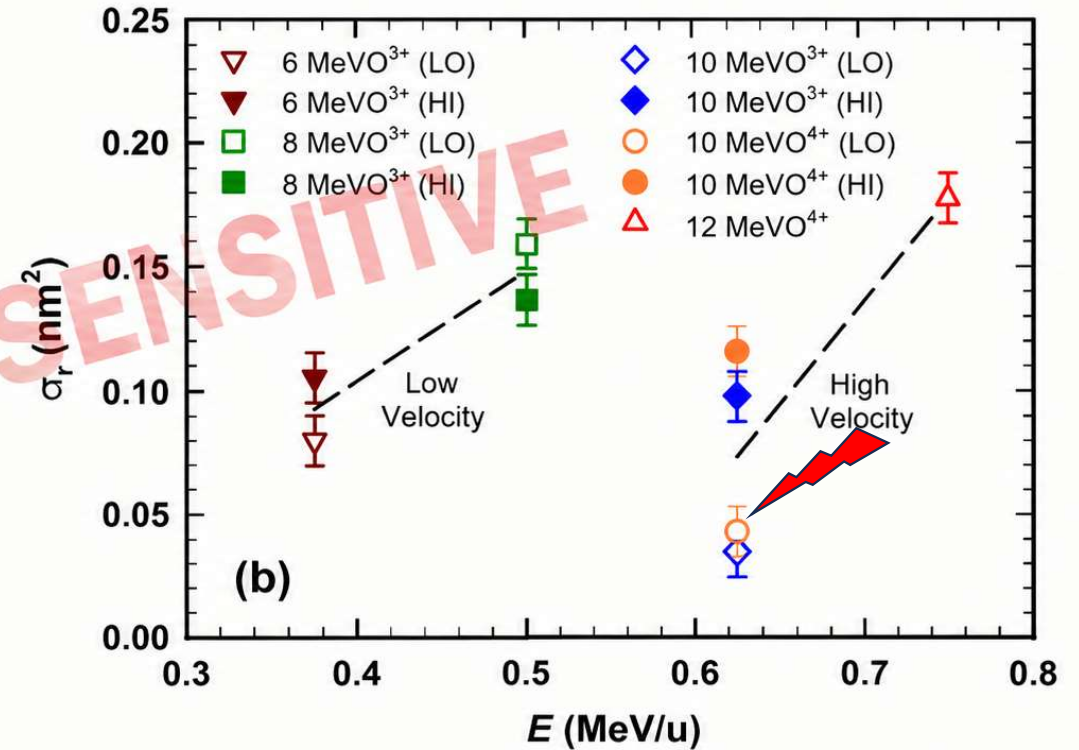
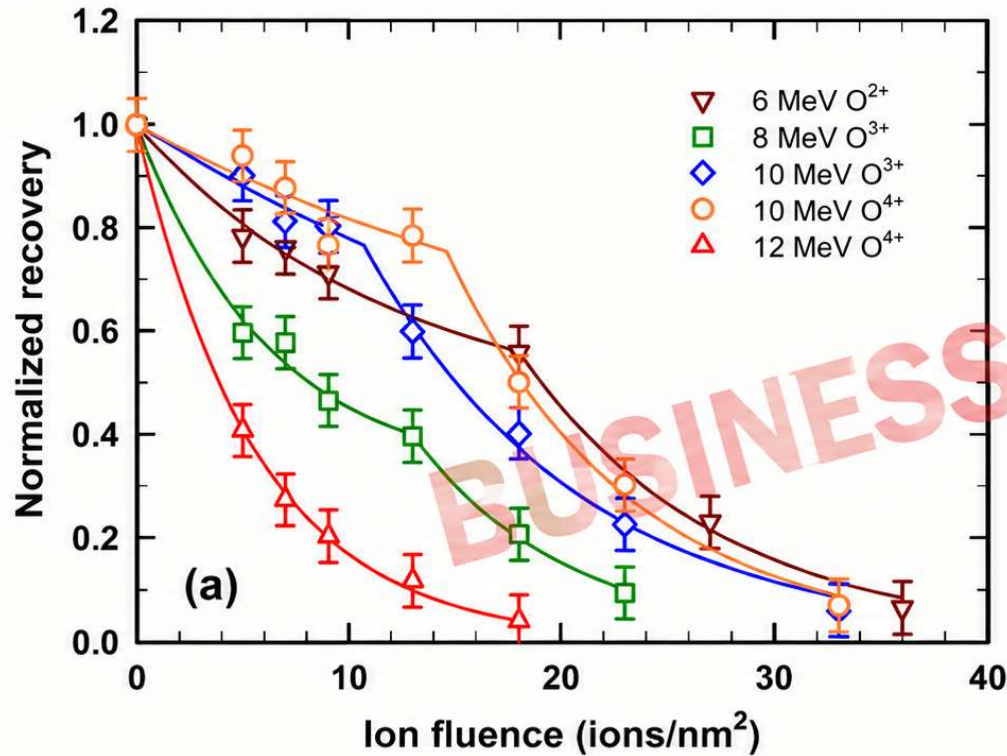
12 MeV O ions: **ONE** recovery stage

6, 8 and 10 MeV O ions: **TWO** different recovery stages

σ_r vs. E



σ_r vs. E



We did find this via AI: Resonant Transfer Excitation (RTE):

This process involves the simultaneous capture of a target electron by the projectile ion and the excitation of the ion into a resonant state. These resonant states can then decay, potentially affecting the energy deposition profile and the shape of the Bragg peak. Based on this, if the 10 MeV oxygen ions capture an electron, this might temporarily reduce their charge state and S_e .

COLLABORATORS

D. Iancu, A. Hotnog
IFIN-HH, Magurele (Romania)

W.J. Weber
UTK, Knoxville (USA)

Y. Zhang
Queen's University (Canada)

E. Zarkadoula
ORNL, Oak Ridge (USA)

Wagner Michael, Koch Frieder, Simon Pascal, Toimil Molaes Maria Eugenia
GSI (Germany)

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