RBI Accelerator Facility and Applications

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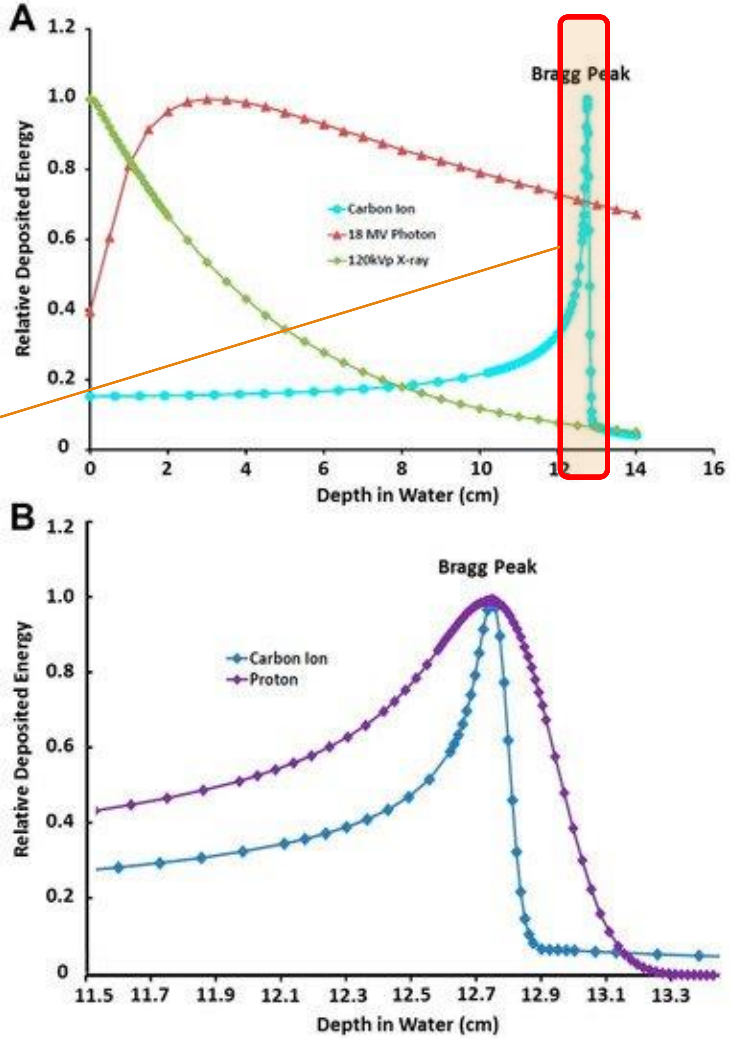
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101008548

OUTLINE

- RBI Electrostatic accelerators
- Ion beam analysis – reactions, scattering, ionization,
- Ion beam interactions - applications relevant to hadron therapy (MeV C ions)
- Staff, users, funding



From: Osama Mohamad et al. Cancers 2017, 9(6), 66; https://doi.org/10.3390/cancers9060066

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RBI electrostatic accelerators

Ion beam interactions with material

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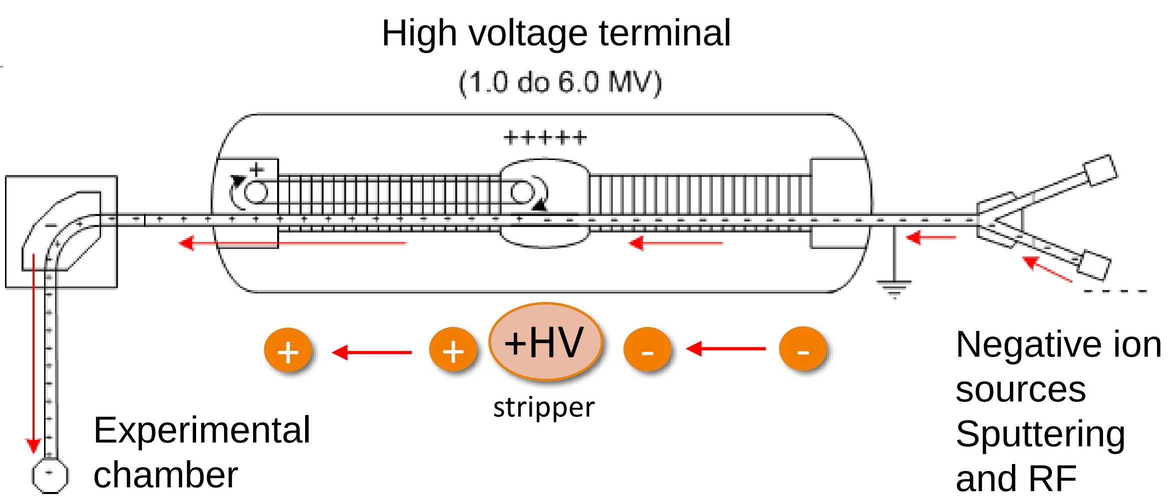
RBI electrostatic accelerators

1 MV Tandetron



6 MV Tandem van de Graaff

- Ion source create <u>continuous</u> negative ion beam, such as H^-, Li^-, C^-, Si^-...
- MV potential attracts negative ions; in stripper channel they change polarity; MV potential repulse positive ions to the MeV energy
- Ion beam is directed to the scattering chamber to perform analysis or irradiation

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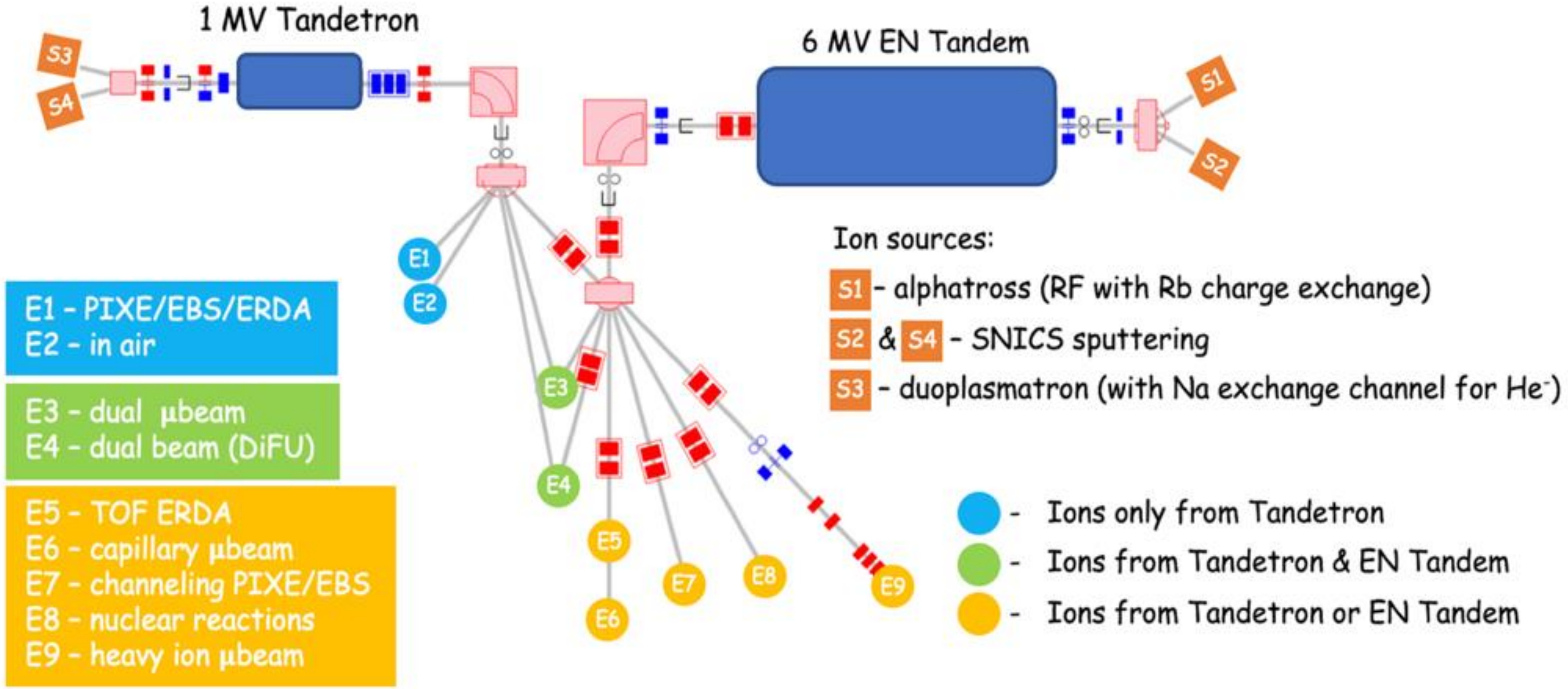
RBI electrostatic accelerators:
beam lines



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RBI electrostatic accelerators:
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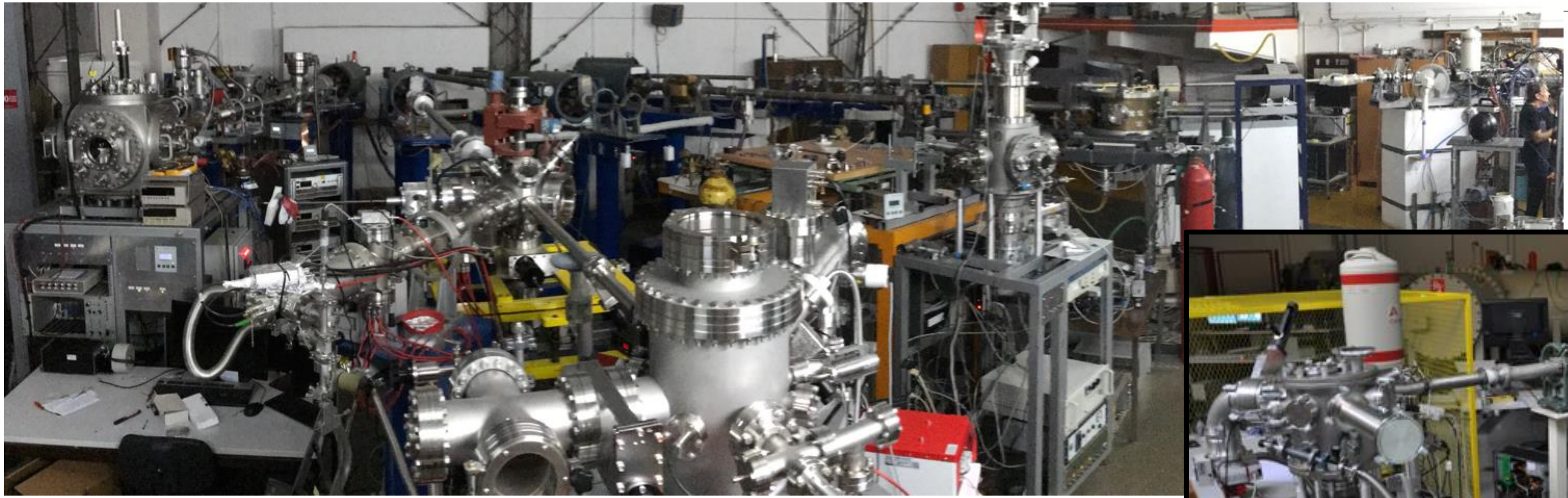

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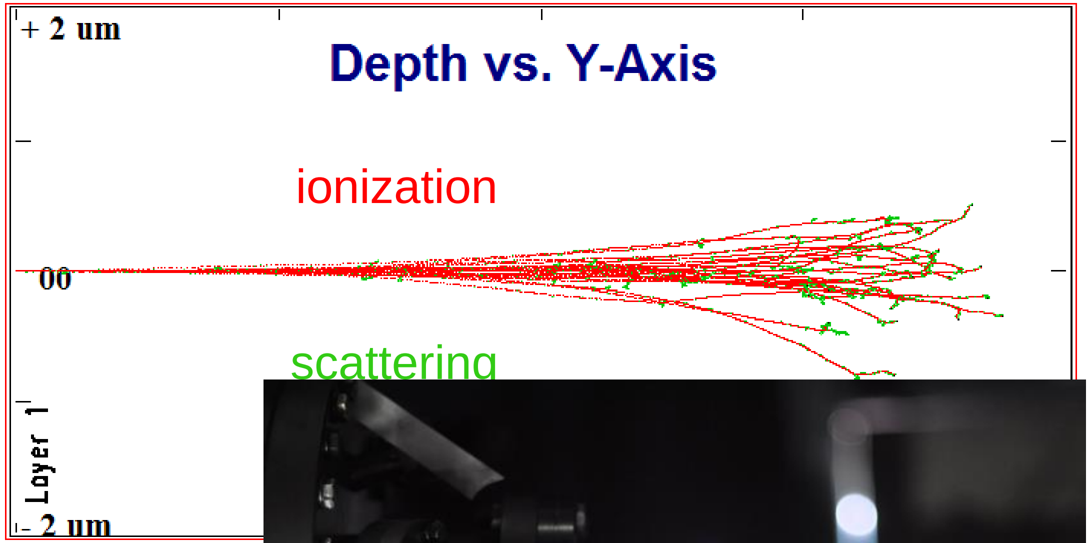
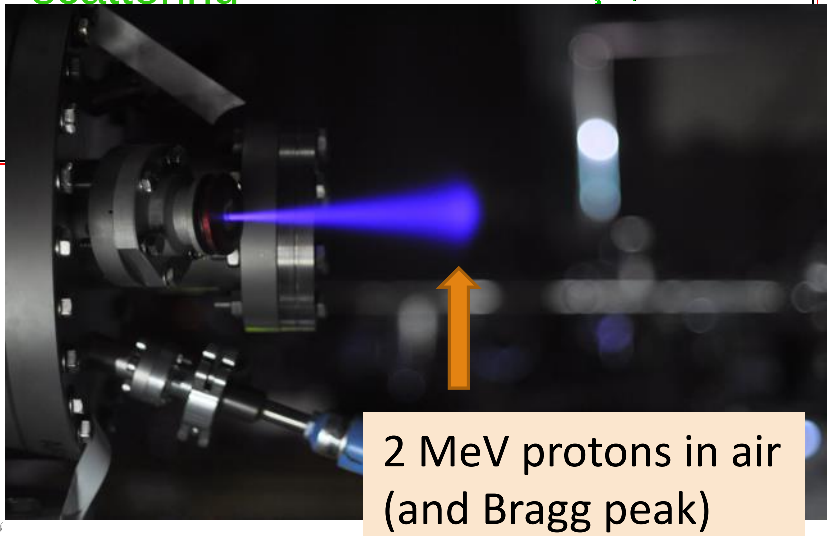
Ion beam interactions with material





2 MeV protons in air
(and Bragg peak)

Main processes (listed in order of importance):

a) **Ionization of atoms and molecules (scattering with electrons)**
b) Scattering with atomic nuclei
c) Nuclear reactions

Every process lead to one or more analytical techniques: ION BEAM ANALYSIS, or it can be used for MATERIALS MODIFICATION in target through radiation damage and/or ion implantation

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Ion Beam Applications:

Ion Beam Analysis & ~~Ion Beam Materials Modification~~

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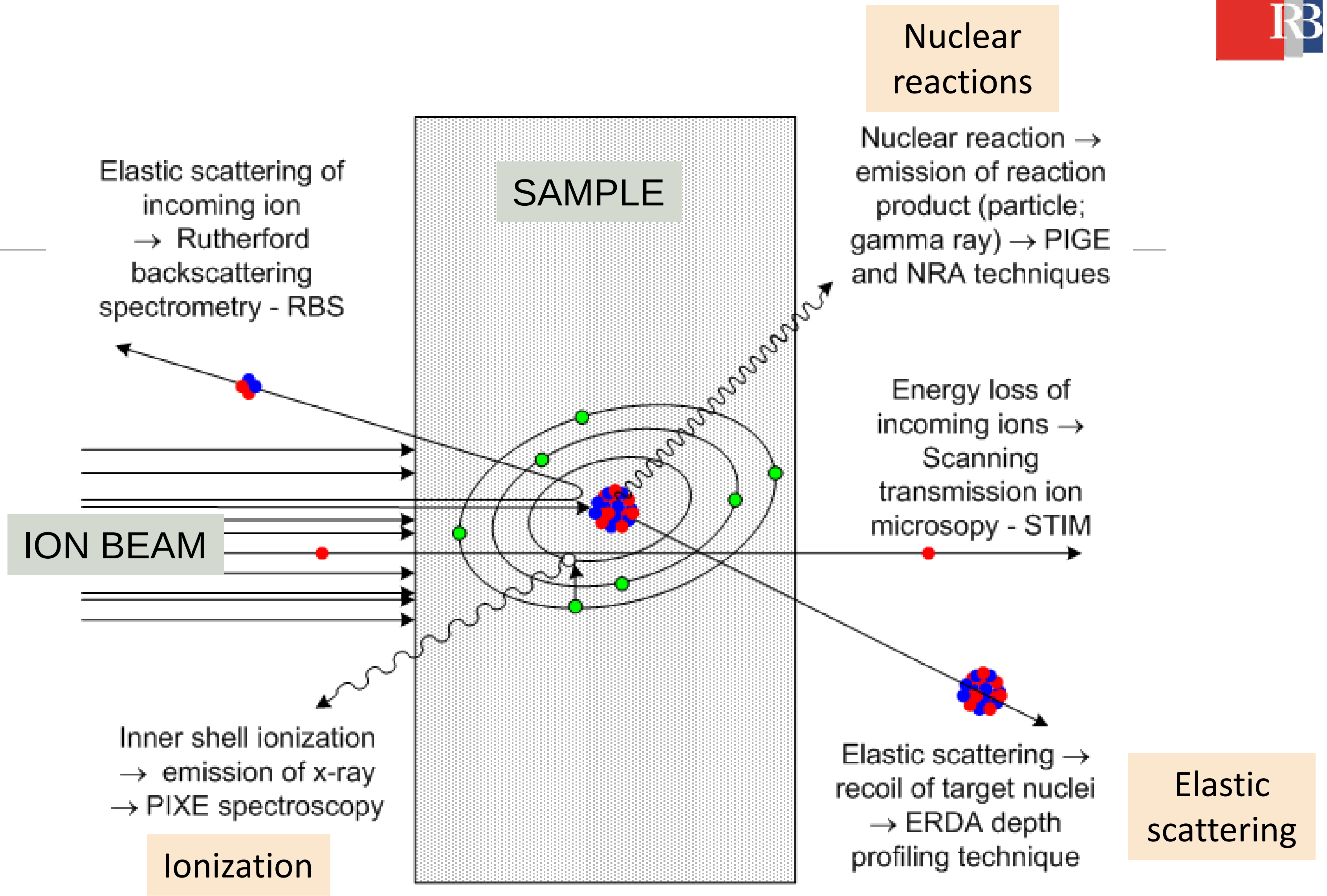
Ion beam analysis

1. We understand the nature of the physical processes that occur during the ion beam irradiation of material
2. By detection of products we perform energy or mass spectroscopy of interaction products

3. Using 1 & 2 we extract a quantitative information – elemental analysis of unknown sample / target



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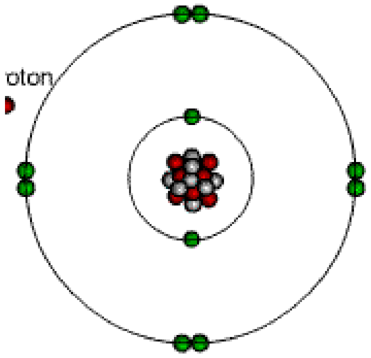
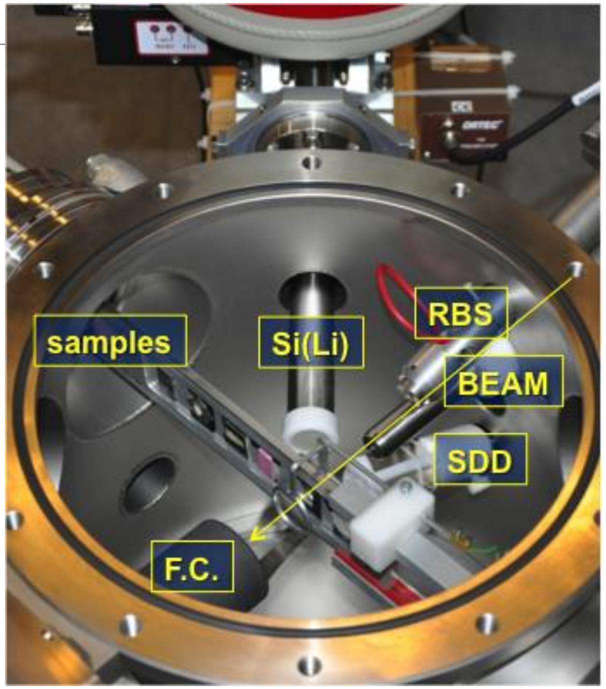
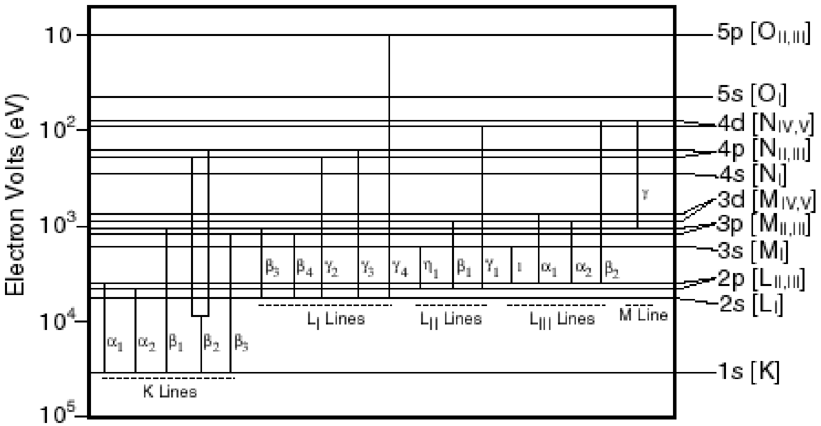
IONIZATION of atoms & molecules



PIXE (Proton Induced X-ray Emission) spectroscopy





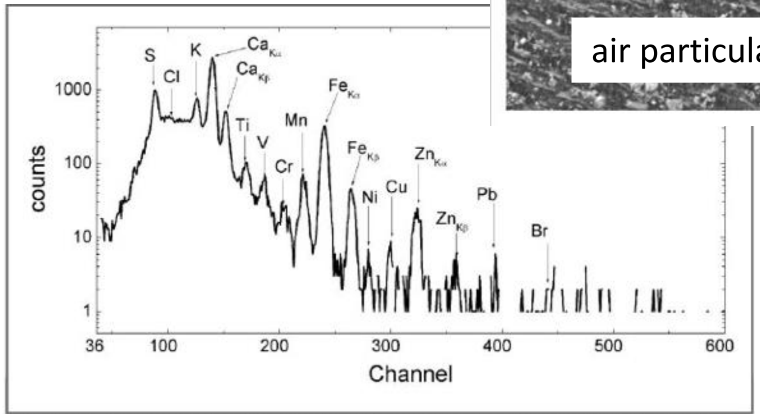


Figure 2. Representative PIXE spectra of the fine airborne particulate matter collected in the sampling site.

From the observed x-ray intensities, elemental concentrations in the sample exposed to the proton beam can be determined

Excited atoms emit characteristic x-rays, which are detected by silicon detector

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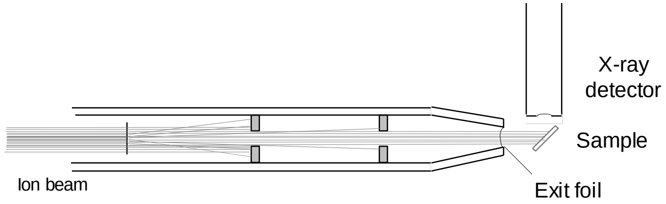
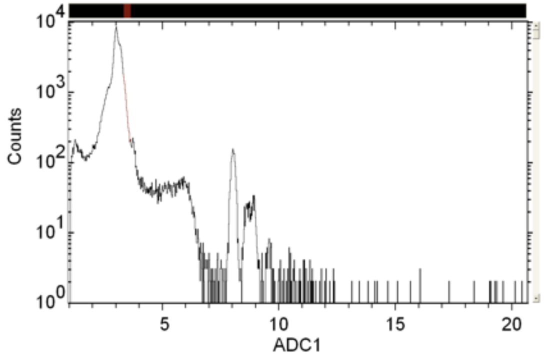
IONIZATION of atoms & molecules

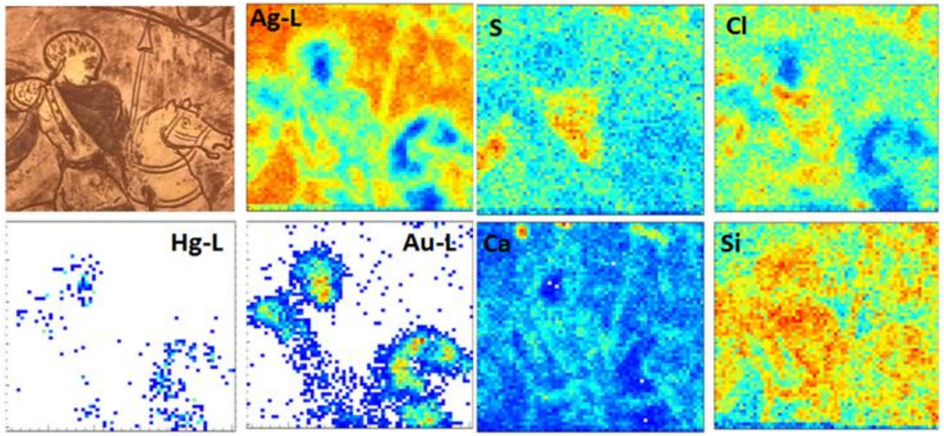
PIXE (Proton Induced X-ray Emission) spectroscopy – in air

Simple external beam setup:
- Robust Al foil exit window
- No additional vacuum pump
- Classical Si(Li) x-ray detector
- Computer controlled XYZ table

Example:
Analysis of Roman silverware found in area of Vinkovci







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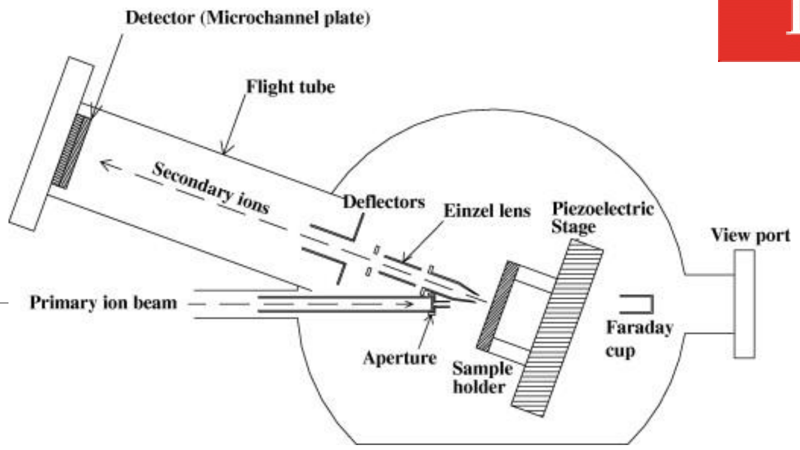
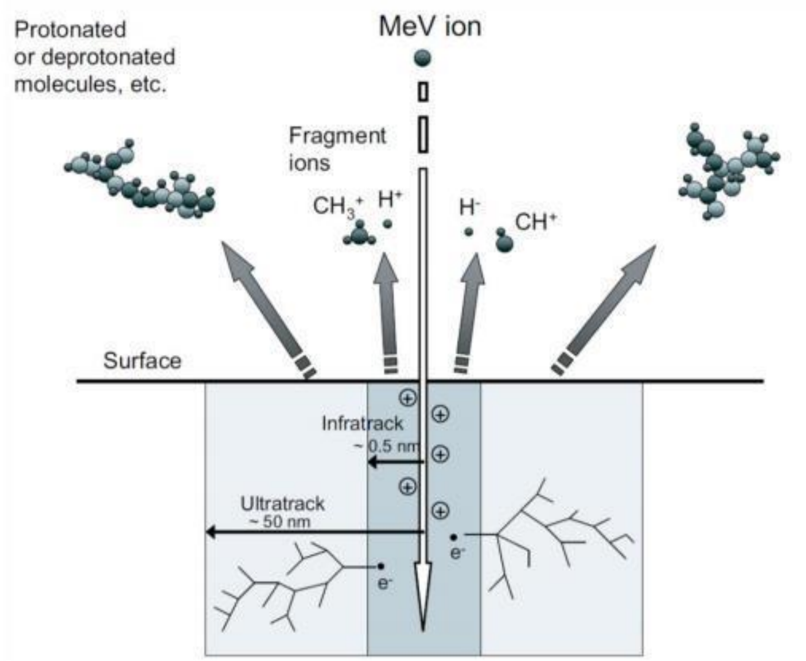
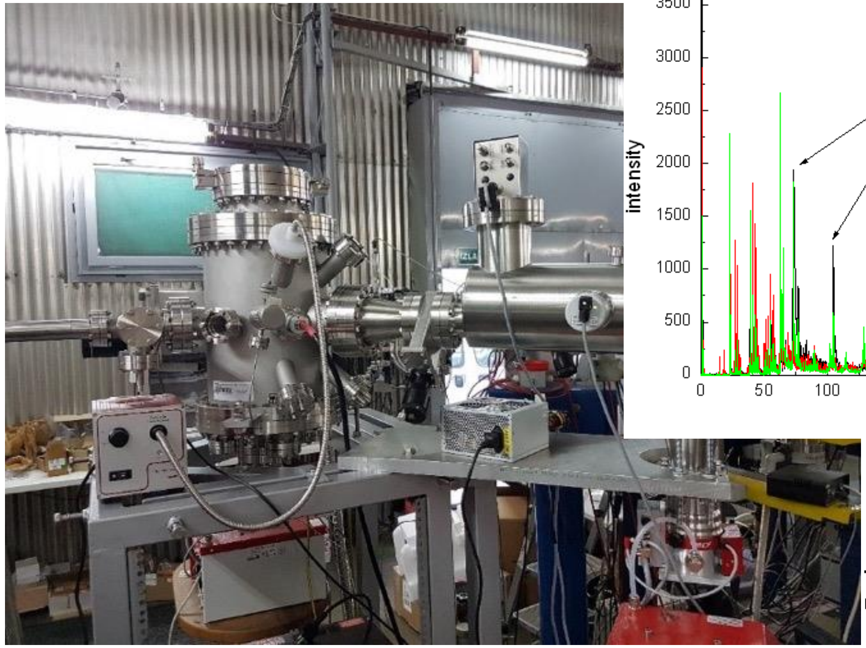
IONIZATION of atoms & molecules

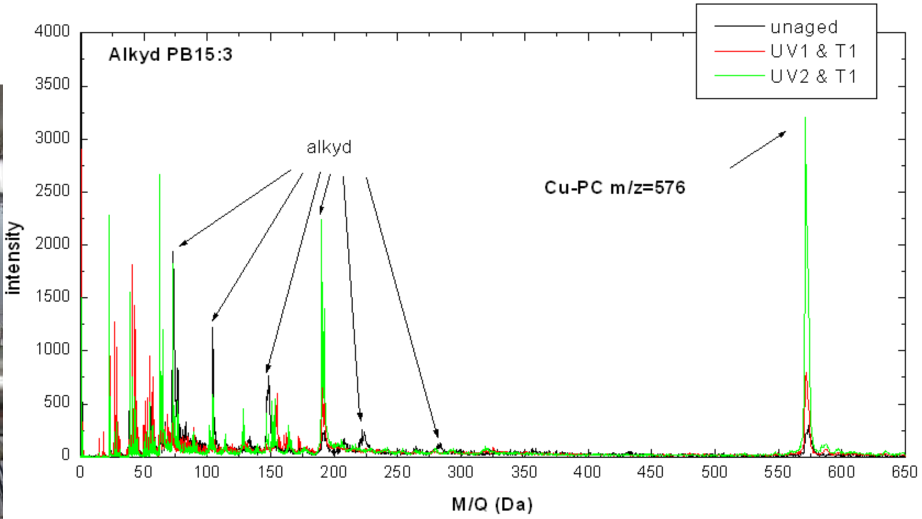


MeV SIMS (Secondary Ion Mass Spectroscopy)

Molecular ions are emitted from the target surface when it is hit by MeV energy heavy ion







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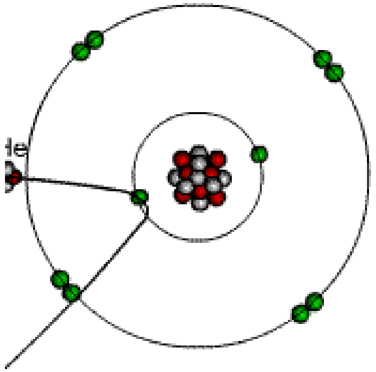
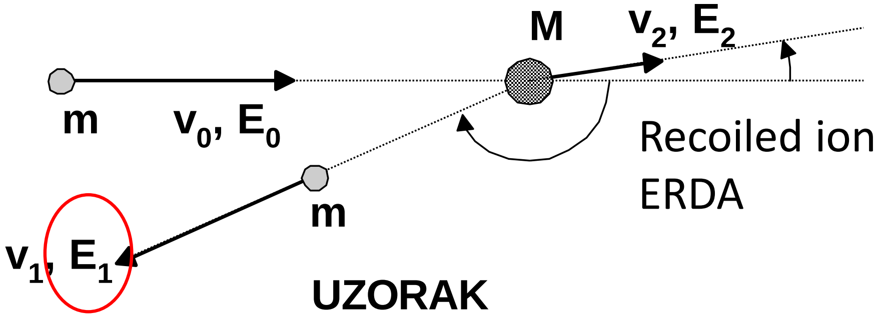
ELASTIC SCATTERING of beam ions and **RECOILS** of target nuclei

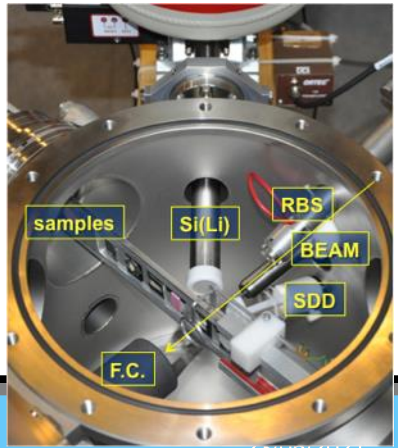
RBS Rutherford Backscattering spectrometry





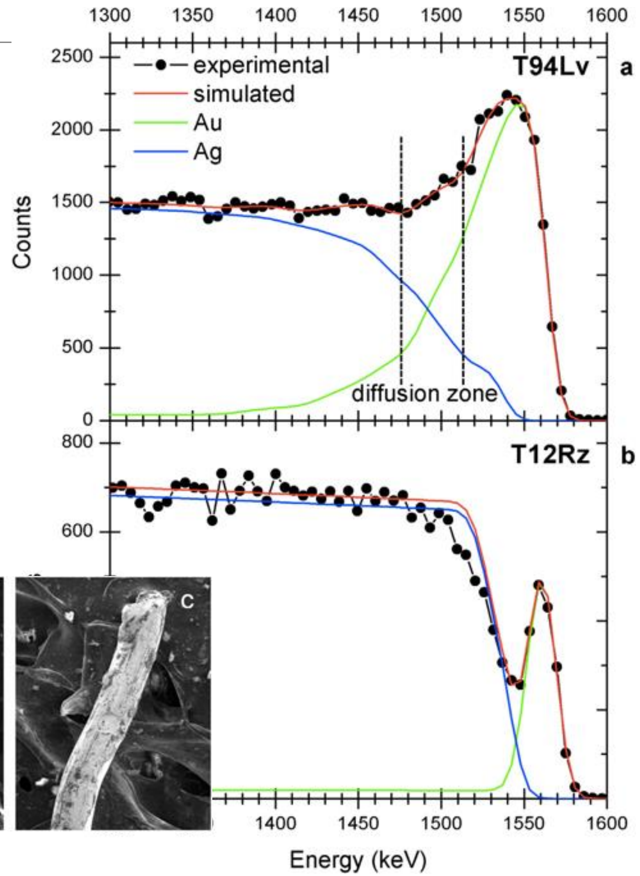
Recoiled ions
ERDA

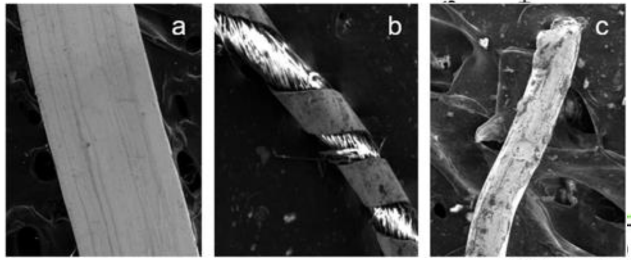
Scattered ions
- RBS



By detecting energy of scattered ion, while knowing kinematics of Rutherford scattering, unknown mass M of the target atom can be determined

Example:
Analysis of gilding technology in production of ancient metal threads in textiles





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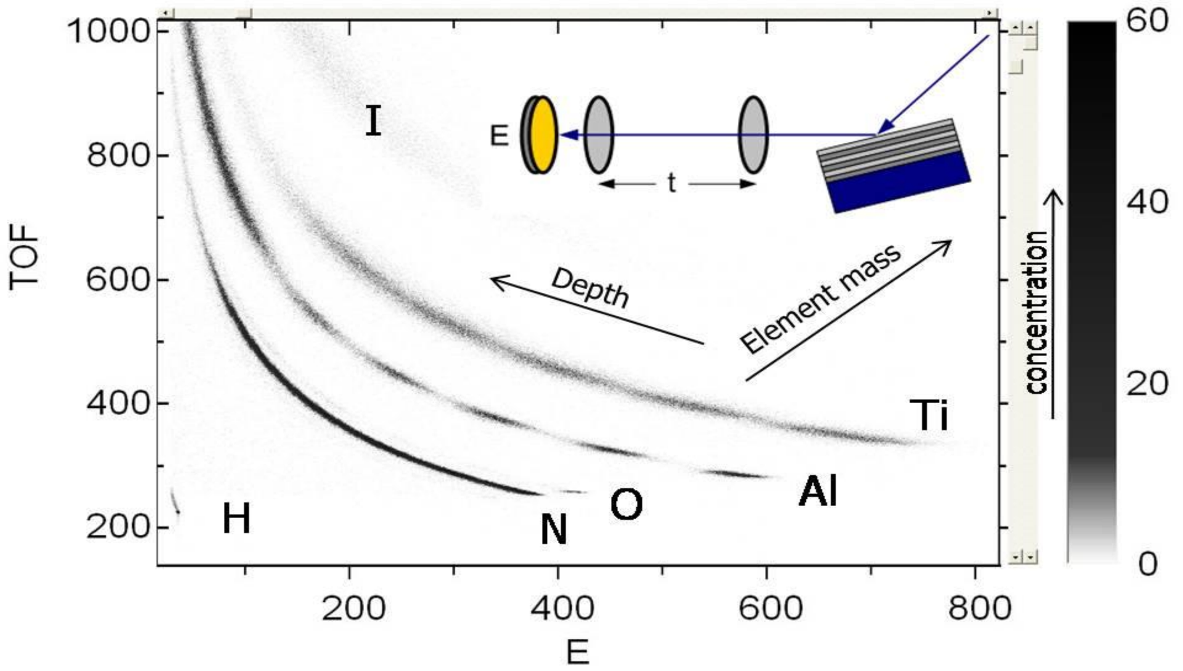
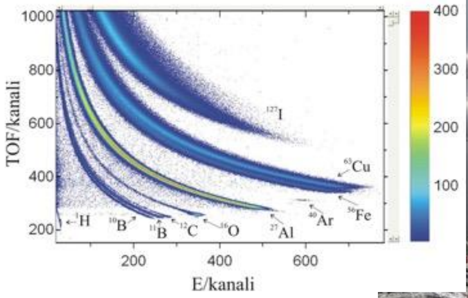
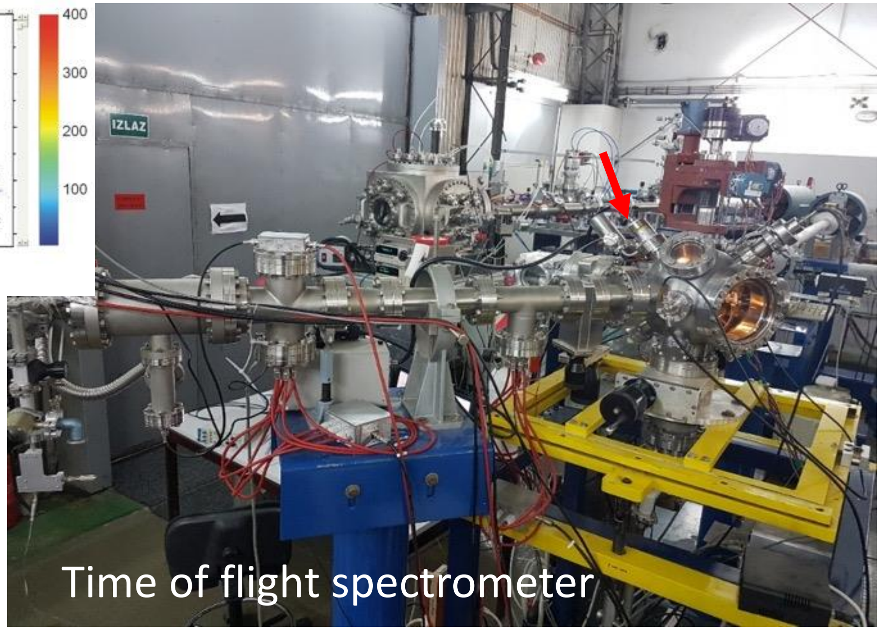
ELASTIC SCATTERING of beam ions and **RECOILS** of target nuclei



ERDA (Elastic Recoil Detection Analysis)



Sample:
20 nm multilayers
TiN/AlN



Heavy ion beam – e.g. 20 MeV Iodine ions

- sensitivity 10^{15} /cm^2
- 2 nm depth resolution, up to 500 nm probe depth
- all elements are resolved

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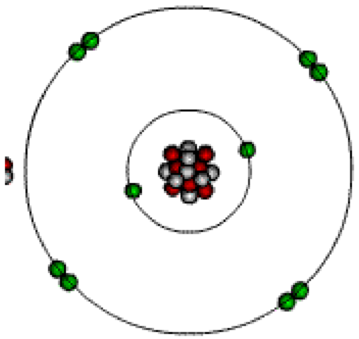
NUCLEAR REACTIONS
(detection of emitted particles)

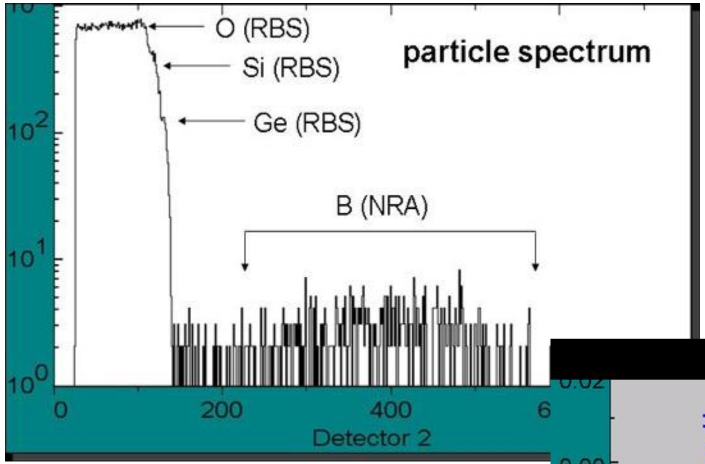
NRA (Nuclear Reaction Analysis)



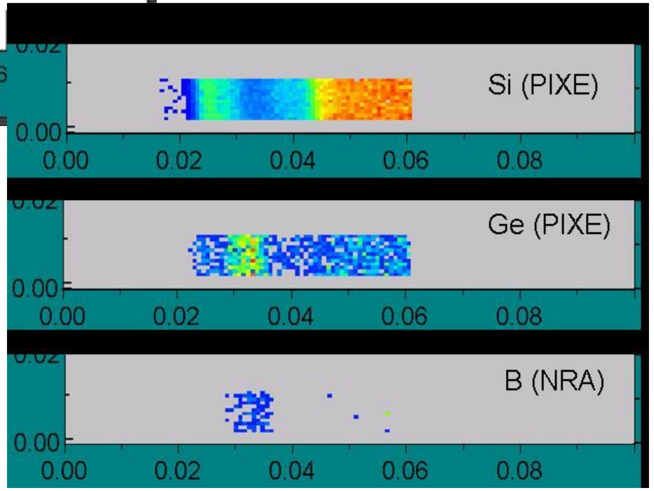
Irradiation of light elements by H or He nuclei can induce nuclear reactions that result in:

- Emission of particles – NRA spectroscopy
- Gamma ray emission – PIGE spectroscopy

NRA and PIGE - ideal for light nuclei isotopes: H, He, Li, B, Be, etc.



Reaction: $^{11}B(p,\alpha)^{8}Be$,
Q=8.582 MeV
Beam – 0.9 MeV protons



Example: Boron in optical coatings
Dopants are changiing optical properties –NRA + PIXE imaging

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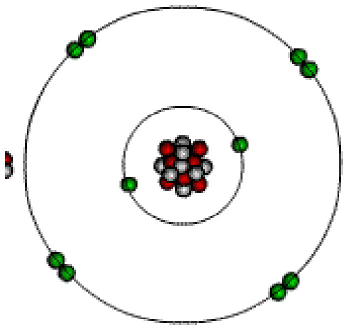
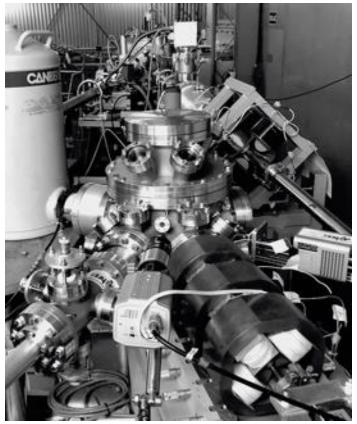
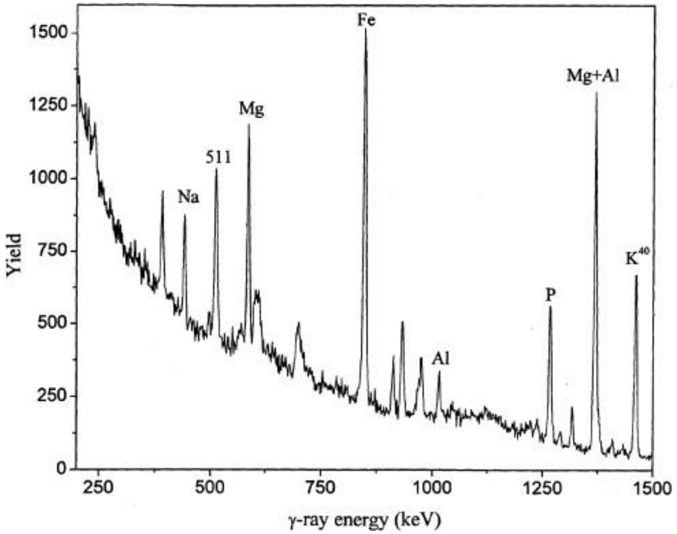
NUCLEAR REACTIONS
(detection of gamma rays)



PIGE (Particle Induced Gamma Emission)





element	Eγ (keV)	γ-ray yield (counts/μCsr) x 10^5			reaction
		1.7 MeV	2.4 MeV	3.1 MeV	
Li	429	-	-	9.2	$^7Li(p,n_1\gamma)^7Be$
	478	8.6	26.0	56.0	$^7Li(p,p_1\gamma)^7Li$
Be	3562	-	0.02	2.5	$^9Be(p,\alpha_1\gamma)^6Be$
B	429	0.9	3.5	7.2	$^{10}B(p,\alpha_1\gamma)^7Be$
	718	-	0.12	1.3	$^{10}B(p,p_1\gamma)^{10}B$
	2125	-	-	4.8	$^{11}B(p,p_1\gamma)^{11}B$
F	110	0.1	7.2	11.0	$^{19}F(p,p_1\gamma)^{19}F$
	197	0.2	20.0	37.0	$^{19}F(p,p_2\gamma)^{19}F$
	1236	-	3.0	5.4	$^{19}F(p,p\gamma_{3-1})^{19}F$
	1349	-	1.3	2.1	$^{19}F(p,p\gamma_{4-1})^{19}F$
	1357	-	1.4	4.2	$^{19}F(p,p\gamma_{5-2})^{19}F$
	1459	-	0.9	3.9	$^{19}F(p,p_4\gamma)^{19}F$
	6129	2.6	67.0	95.0	$^{19}F(p,\alpha_2\gamma)^{16}O$
Na	440	0.8	9.6	16.0	$^{23}Na(p,p_1\gamma)^{23}Na$
	1634	0.2	9.9	19.0	$^{23}Na(p,\alpha_1\gamma)^{20}Ne$
Mg	1369	0.1	0.9	5.1	$^{24}Mg(p,p_1\gamma)^{24}Mg$
Al	844	-	0.1	2.3	$^{27}Al(p,p_1\gamma)^{27}Al$
	1014	-	0.3	4.6	$^{27}Al(p,p_2\gamma)^{27}Al$
Si	1779	-	-	1.2	$^{28}Si(p,p_1\gamma)^{28}Si$
P	1266	-	1.6	5.2	$^{31}P(p,p_1\gamma)^{31}P$
Cl	1219	-	0.2	1.5	$^{35}Cl(p,p_1\gamma)^{35}Cl$

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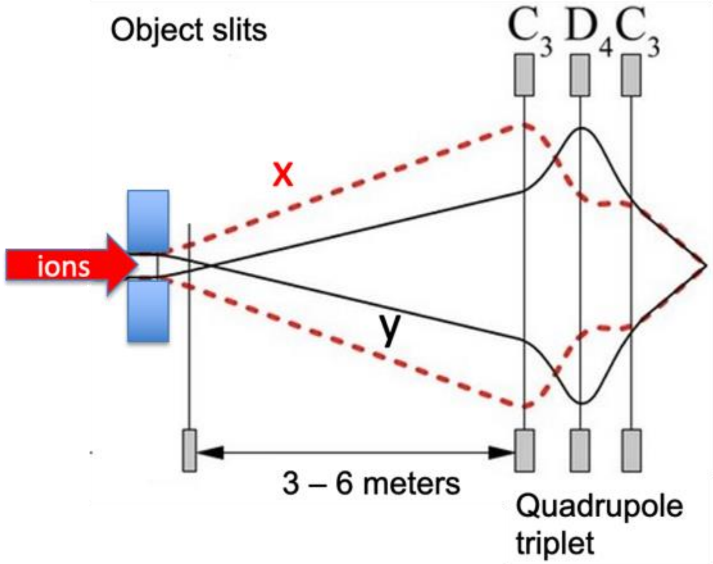
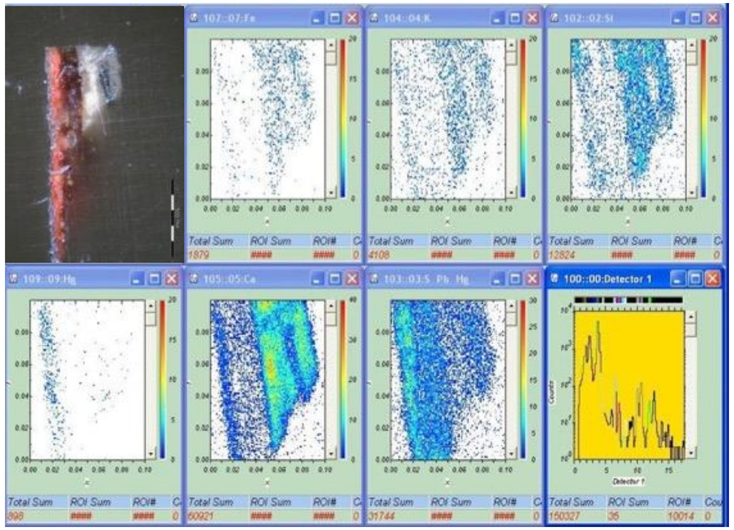
NUCLEAR Microprobe
imaging using scanning focused beam & Ion Beam Analysis techniques



- Ion (proton) beam is focussed to 1 µm spot size
- It can be scanned over 1 x 1 mm sample surface
- In vacuum & in air

Elemental micro-imaging



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Applications relevant to hadron therapy (at RBI facility)

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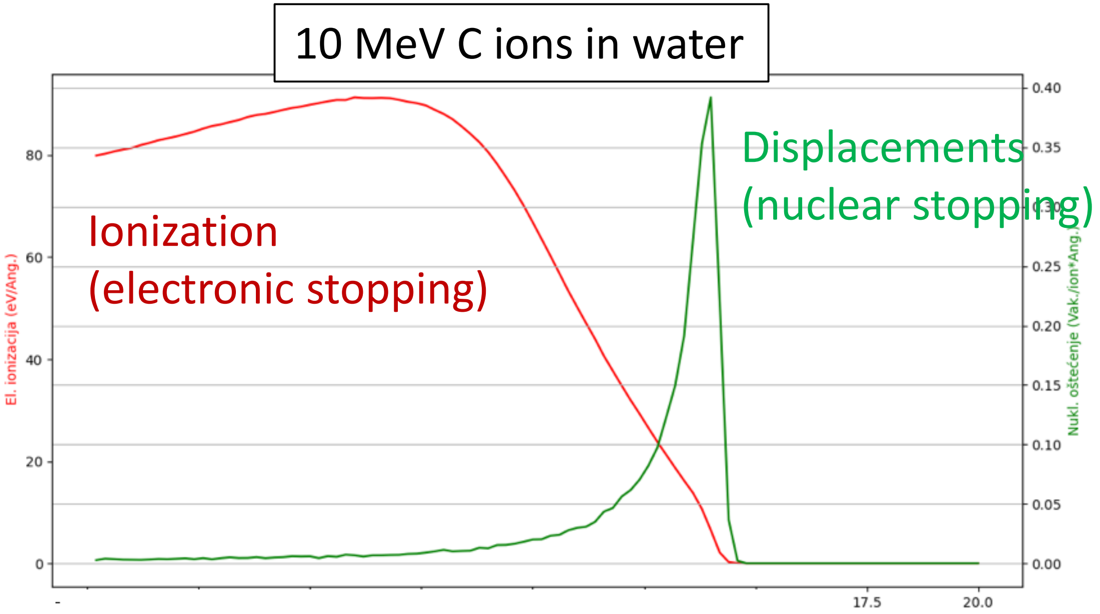
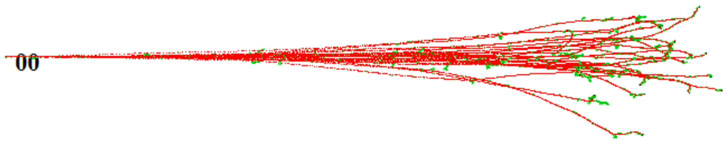
Ion stopping

(nuclear and electronic energy loss)





What we do with low energy C-ions ?

- Calibration of microdosimeters
- Irradiation of living cancer cells

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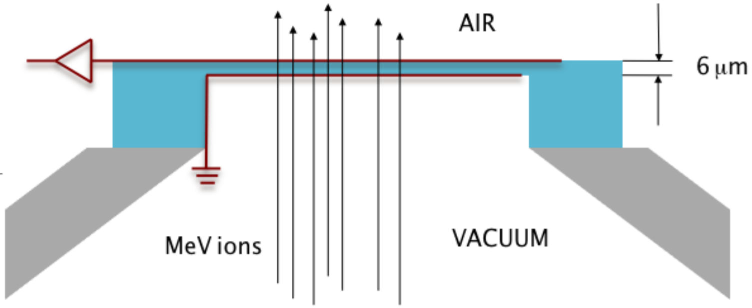
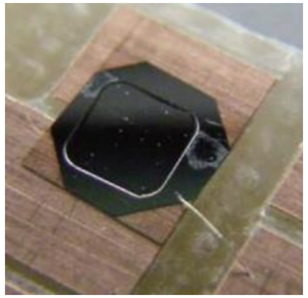
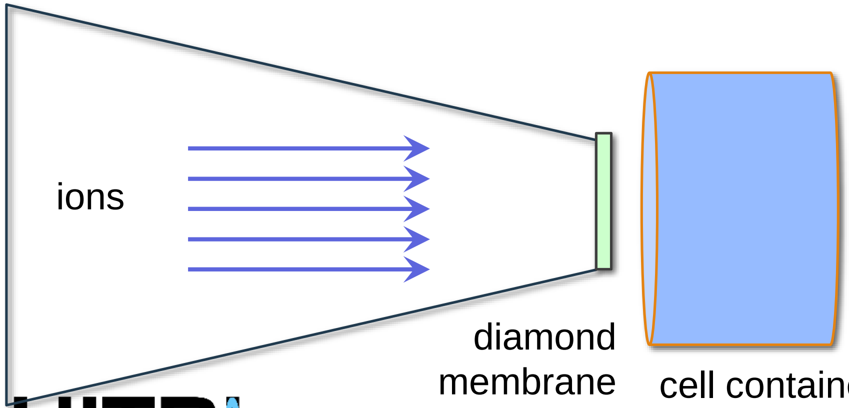
Irradiation of cancer cells

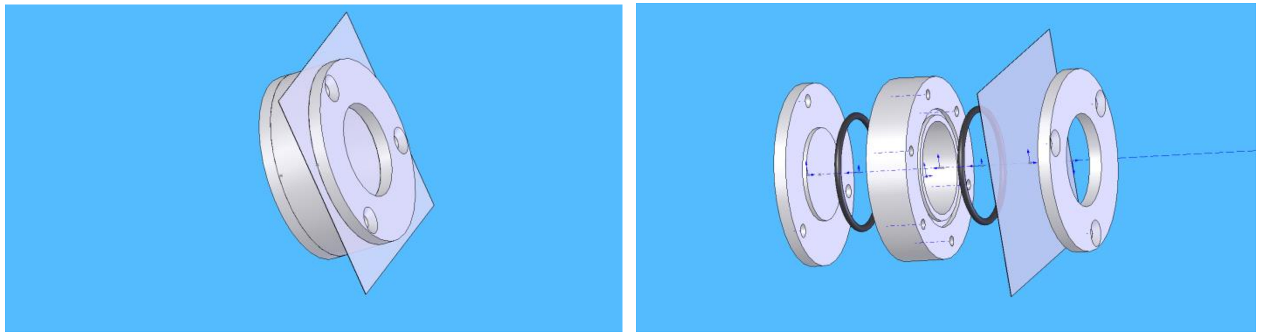


- ❑ Ion beam passes through the diamond membrane detector that is used:
  - As a vacuum – air window
  - As a counter of ions that pass to the container of cancer cells
- ❑ Cells are grown in contaner with thin Mylar window where most of the cells grow.
- ❑ Combination of chemotherapy and radiotherapy was explored (as it can synergistically induce cancer cell death)



Diamond membrane detector





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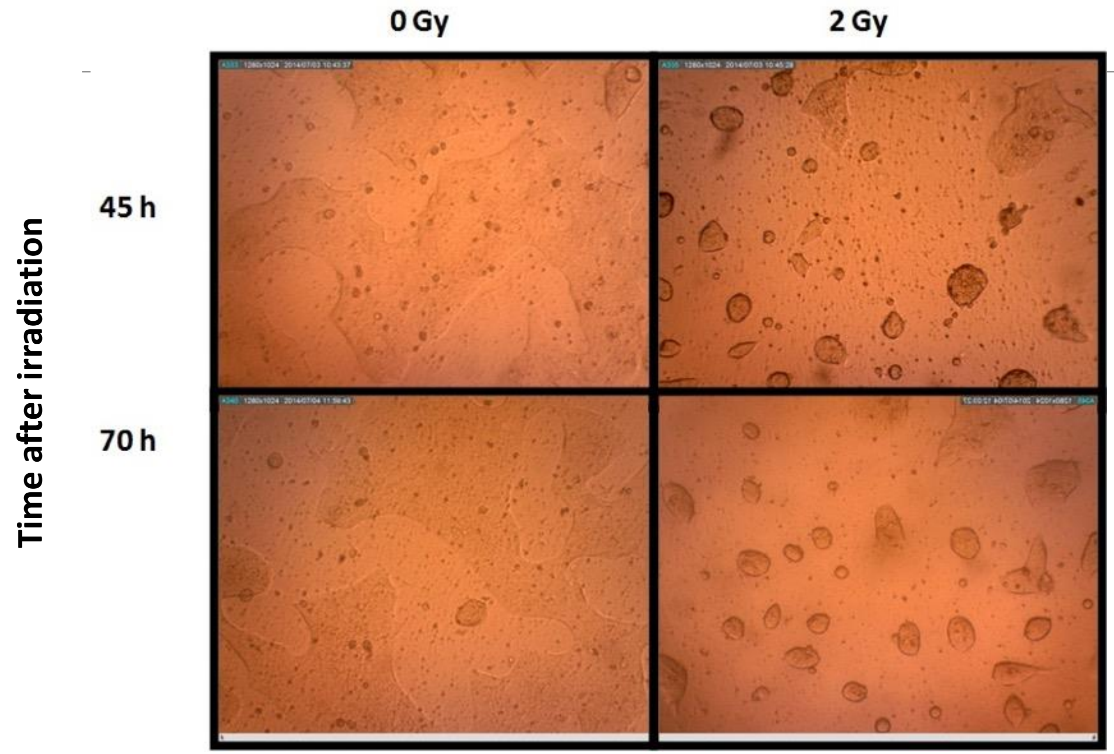
Irradiation of cancer cells



The attachment of cells to Mylar (left) and survival after 2 Gy proton irradiation (right)

- ❑ These cancer cells grow in islands (left) while irradiated cells grow in very small islands (right) and more cells die (detached cells)

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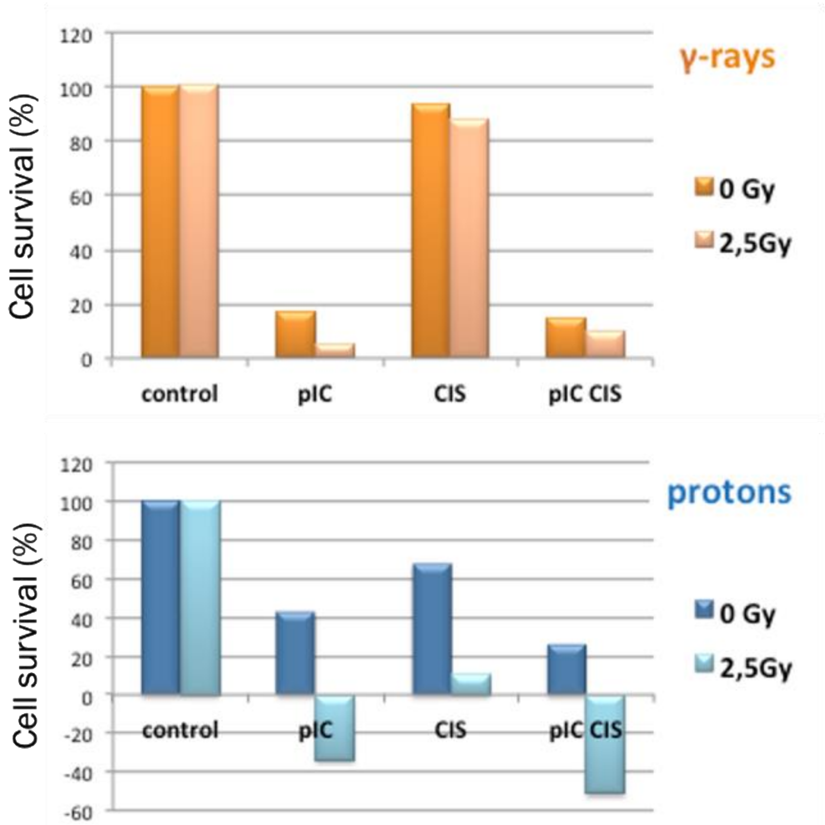
Irradiation of cancer cells



Control - untreated cells

pIC - cells where protein Toll-like receptor 3 is activated and the consequence is cell death

CIS - Cisplatin, a well known chemotherapeutic

pIC CIS - combined treatment of pIC and cisplatin

What next?
- Microbeam irradiation of single cells

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IBIC technique

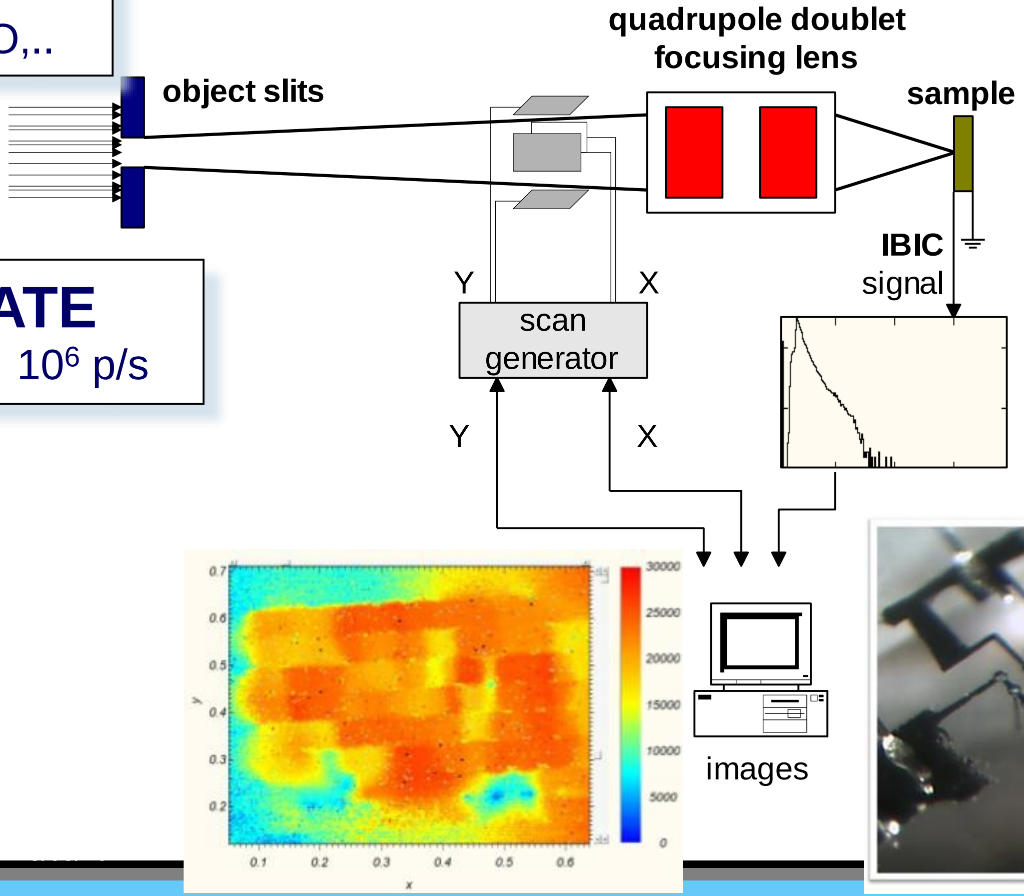
microscopic imaging of charge transport in detectors

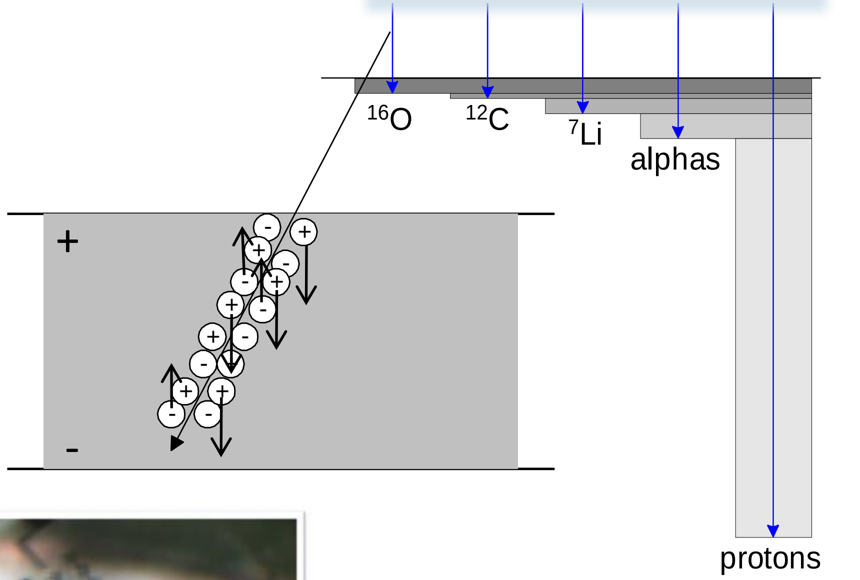
❶ IONS
- p, α, Li, C, O,..

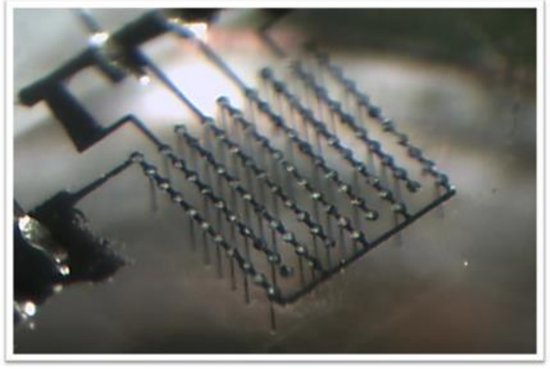
❷ ION RATE
- currents 0 - 10^6 p/s

❹ ION POSITION
- focusing and scanning

❸ RANGE
- from 2 to 500 μm







scCVD sample

Courtesy of CERN

ceived funding from the European Union's Horizon 2020
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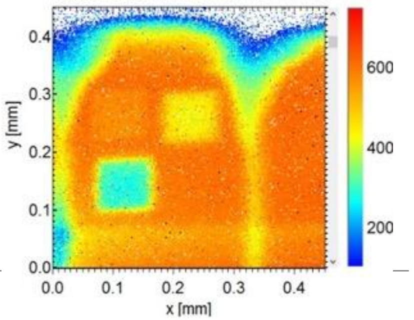
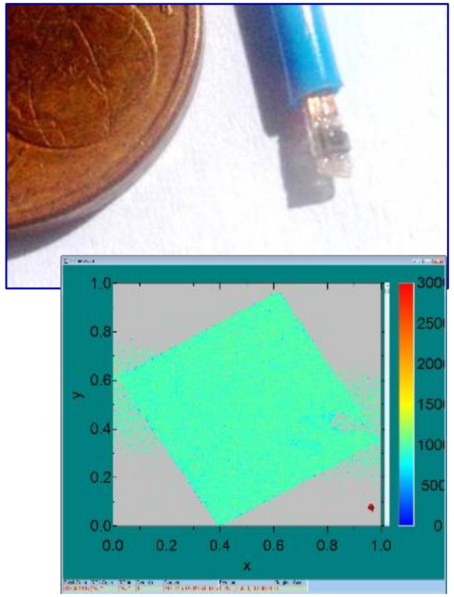
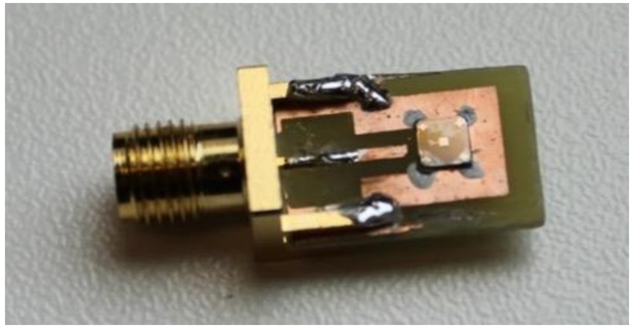
IBIC investigation of microdosimeters

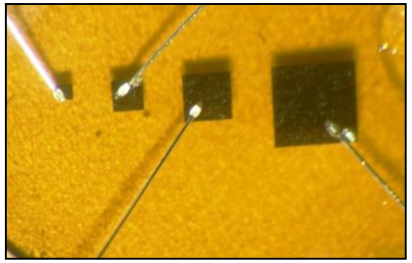


- **AIDA-2020-RBI-2016-1**

  IBIC characterization of single crystal diamond based Shottky diodes for microdosimetry application, Claudio Verona, 'Tor Vergata' University, **Italy**



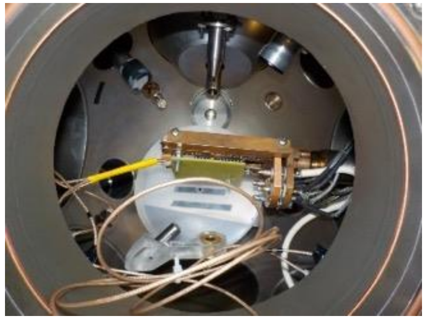


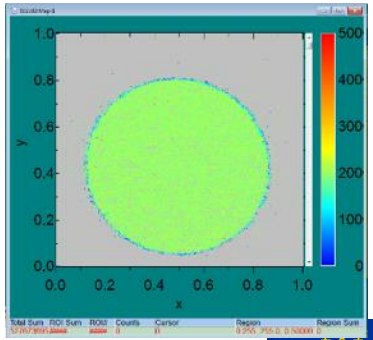


Università di Roma
Tor Vergata

- **AIDA-2020-RBI-2016-2**

  Microbeam tests of silicon telescope for clynical dosimetry, G. Magrin, Austron, **Austria**





MedAustron

POLITECNICO MILANO

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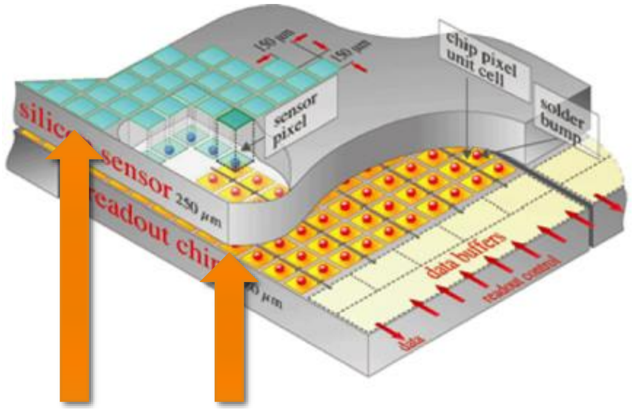
IBIC in air – CMS pixel detector

AIDA-2020-RBI-2018-1

Single event effects in CMS pixel ROC

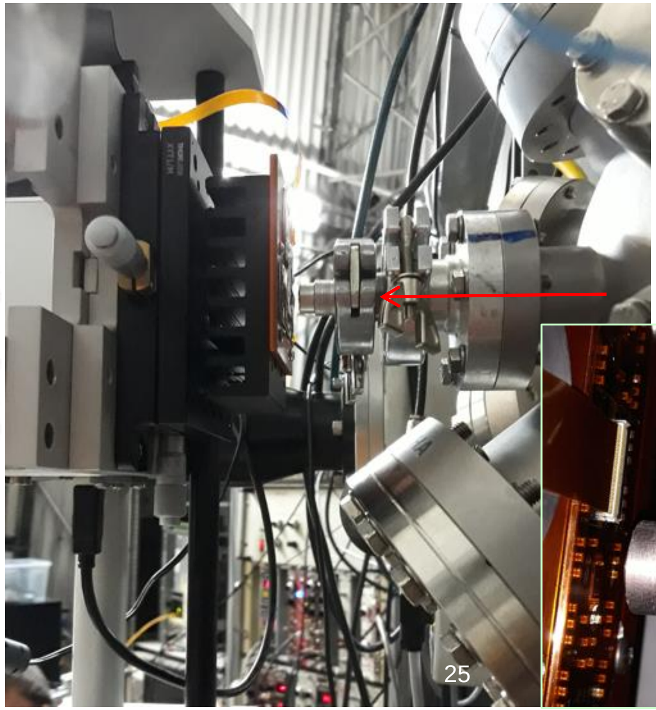
W. Erdemann, PSI, Switzerland

- The CMS (Compact Muon Solenoid) inner barrel pixel detector has integrated silicon pixels and readout chip (ROC), where occasional memory soft errors occur.
- Total 48 million pixels in CMS
- Minimum ionizing particles are supposed to be responsible for SEU in pixel readout chain (tested at PSI)



Long range
6 MeV protons
(chip alignment)

Short range
heavy ions – 16 MeV C ions
(single event upsets)



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Staff, users, funding…

…and sustainability in South East Europe society ?

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Staff

Scientists (5): Milko Jakšić, Stjepko Fazinić, Iva Bogdanović Radović, Tonči Tadić, Zdravko Siketić
Postdocs (4): Iva Božičević, Georgios Provatas, Matea Krmpotić, Mauricio Rodriguez
Professional associates (3): Donny Domagoj Cosic, Milan Vićentijević, Fares Boussahoul
Doctoral students (4): Marko Barac, Andreo Crnjac, Marko Brajković, Toni Dunatov
Technicians (4): Željko Periša, Damir Španja, Andro Kovačić, Zvonko Kolar

+ Incoming and outgoing mobility
- Low salaries
+ international staff
+ attractive research subjects

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Attracting users

Strategy:

- To be equiped with all standard ion beam techniques

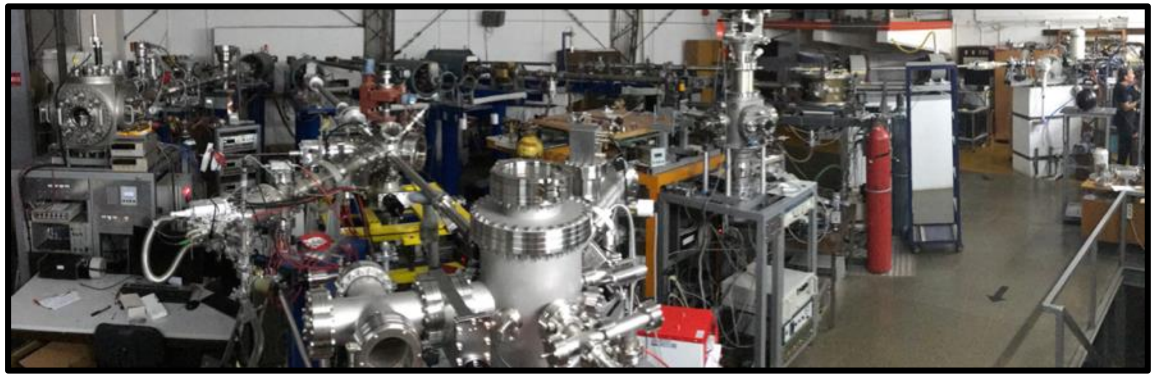
PIXE, RBS, ERDA, NRA, PIGE, STIM, IBIC, Channeling,… & microprobe !!

- To have several unique end stations:
    - High Resolution PIXE setup (APXS on Mars)
    - Dual Beam Irradiation (EuroFusion)
    - Dual microbeam (only in the world)
    - TOF ERDA (commercial applications)
    - IBIC system (high energy physics)
    - Micro MeV SIMS (forensics and cultural heritage)

Funded access to beam lines:

Today: CERIC-ERIC consortium;

H2020 project RADIATE; IAEA CRP



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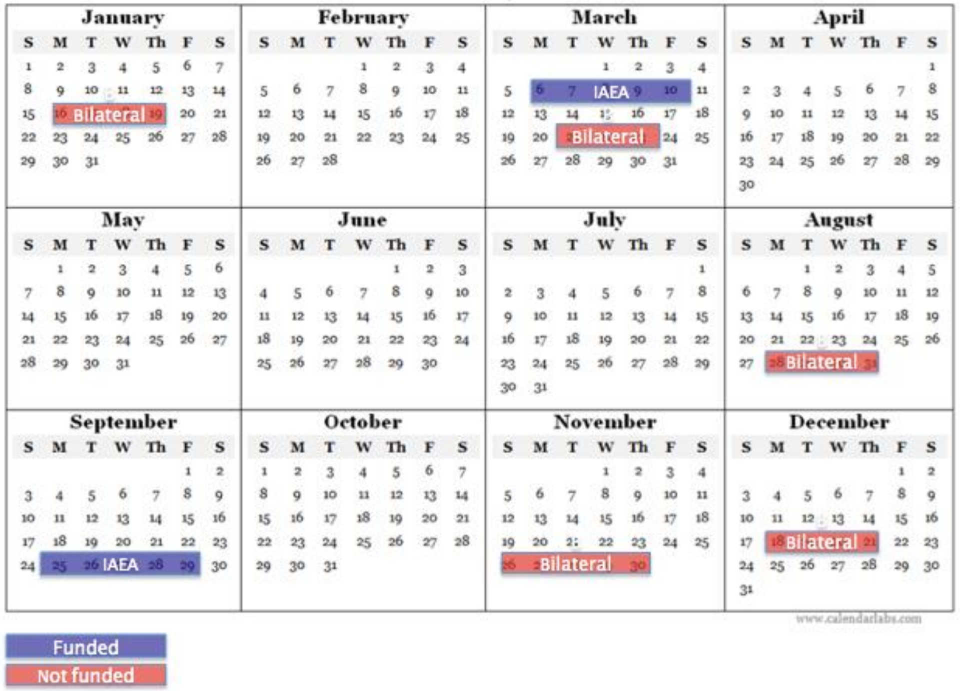
Users

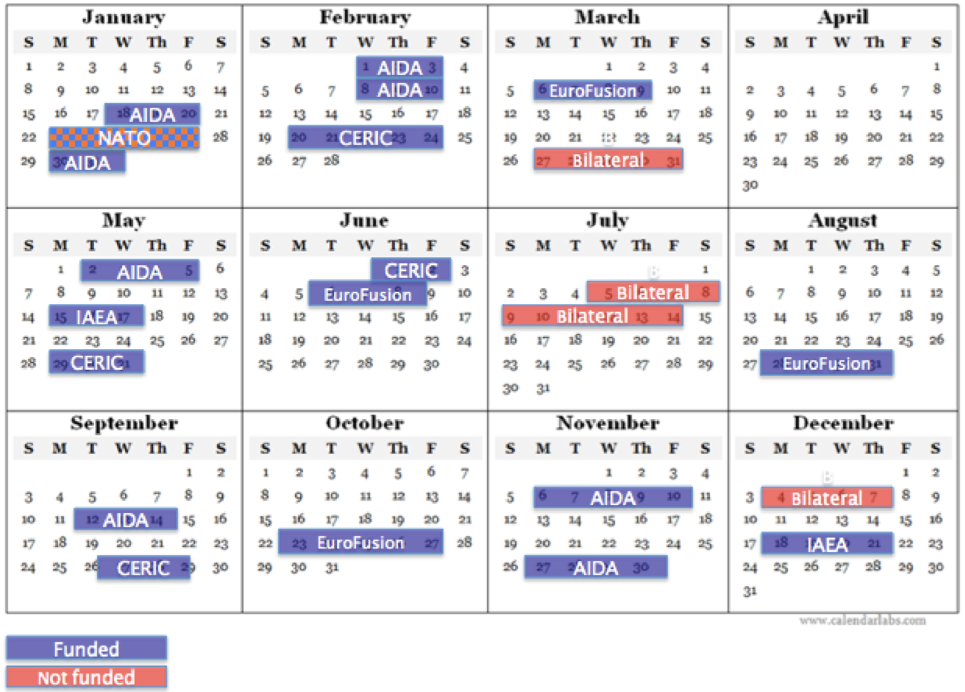
Foreign researchers at RBI accelerator facility:

2007



Foreign researchers at RBI accelerator facility:

2017



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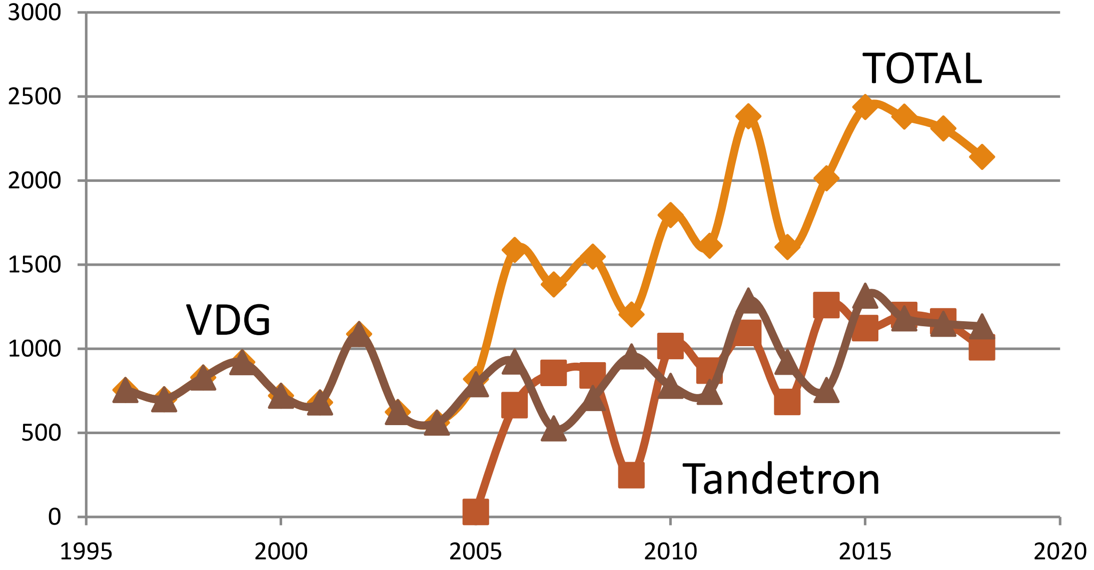
Funding:

Projects 1990-2009

Projects 2010-2020

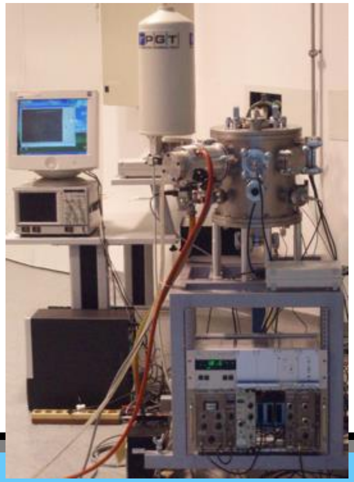
Beam time (on target):



IAEA International Atomic Energy Agency

Ministry of science

Donations & internal constructions



European Union European Regional Development Fund

AIDA 2020

CERIC Central European Research Infrastructure Consortium

RADIATE

EUROfusion

CDSE

hrzz Hrvatska zaklada za znanost

CEMS Center of Excellence for Advanced Materials and Sensing Devices

European Nuclear Science and Applications Research ENSAR

The NATO Science for Peace and Security Programme

AIDA innova

IAEA International Atomic Energy Agency

DONES Preparatory Phase

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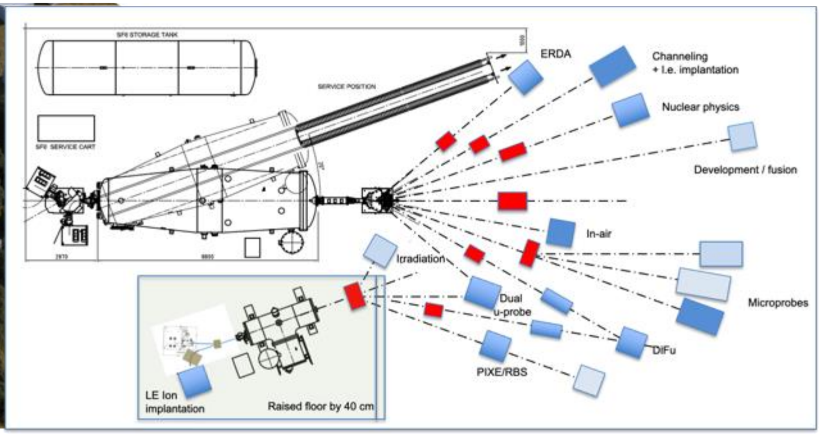
Future:

Structural funds project:
O-ZIP (just started)



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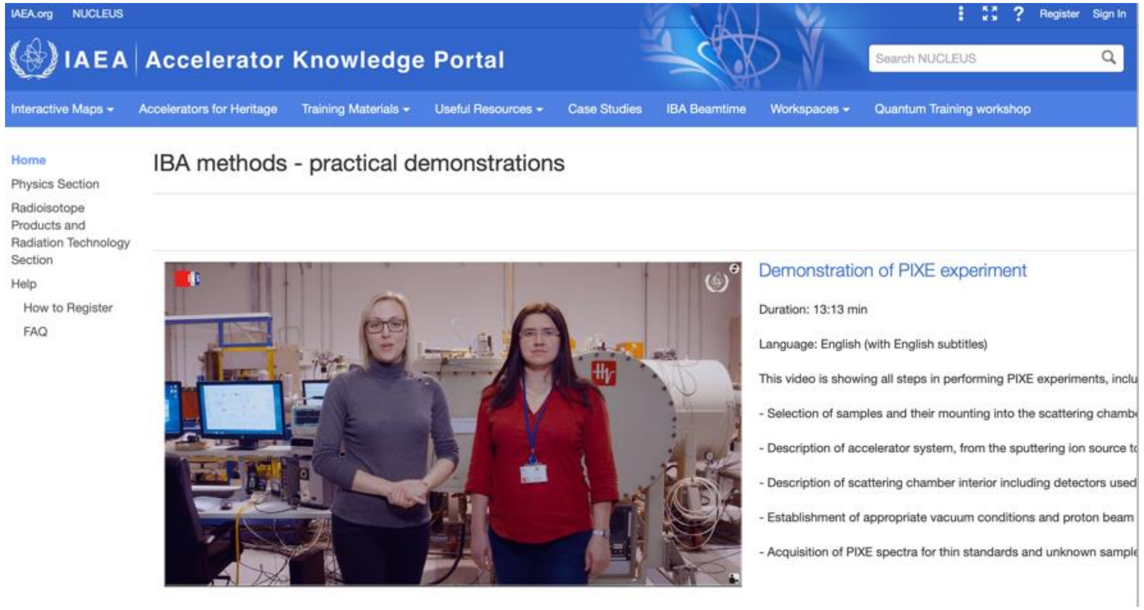
Videos about practical IBA - at IAEA site



https://nucleus.iaea.org/sites/accelerators/Pages/IBA-video-demonstrations.aspx

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Conclusions

Electrostatic accelerators (and associated beam lines) are excelent instruments for:

- Education and training (nuclear physics, detectors, electronics, vacuum technology, etc.)
- Basic research in physics
- Applied research in many interdisciplinary areas
- Commercial applications (analysis, irradiation)

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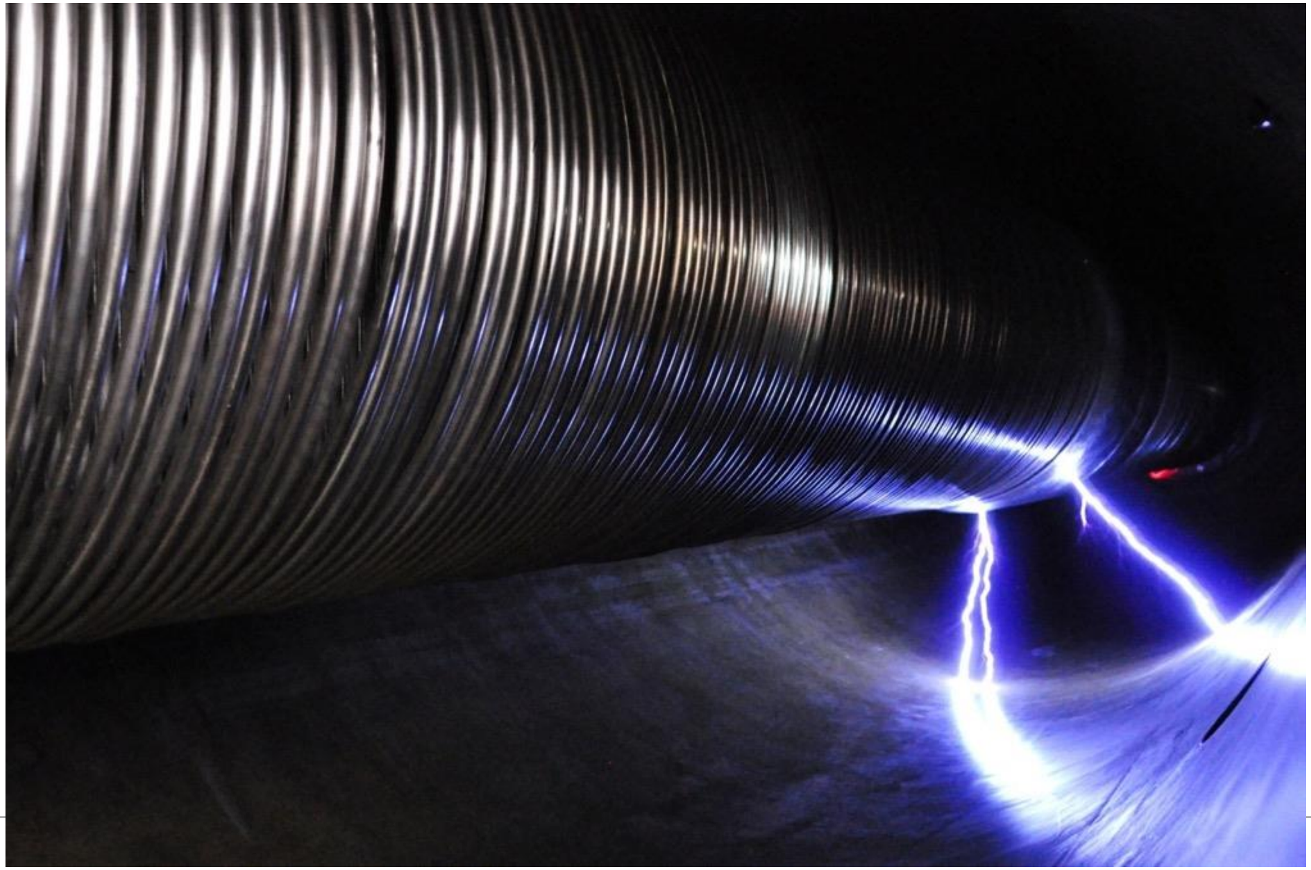
Thank you !!



This material was prepared and presented within the HITRIplus Heavy Ion Therapy MasterClass school, and it is intended for educational purposes to facilitate students; people interested to use any of the material for any other purposes (such as other lectures, courses etc) are kindly requested to please contact the author Milko Jakšić at jaksic@irb.hr

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