

Sustainability of the Tandem accelerator facility at the Ruđer Bošković Institute

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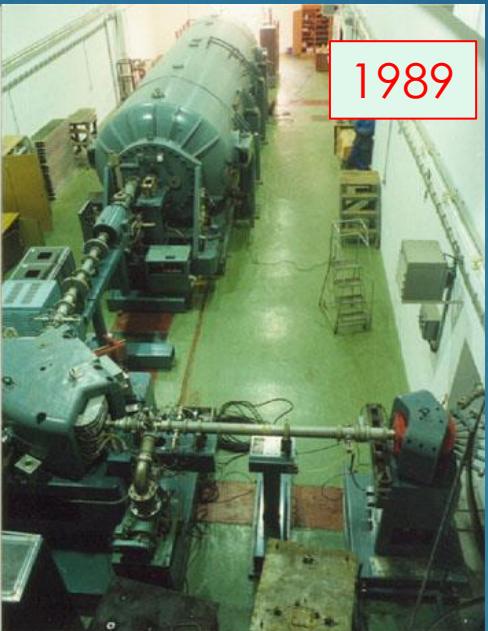
Outline

- Tandem accelerator facility
- Strategy, staff
- Routine ion beam analysis techniques
- Development of unique capabilities for analysis and irradiation of materials
- Internationalisation; funding
- Conclusions

Facilities: Tandem van de Graaff accelerator

History (6.0 MV EN Tandem):

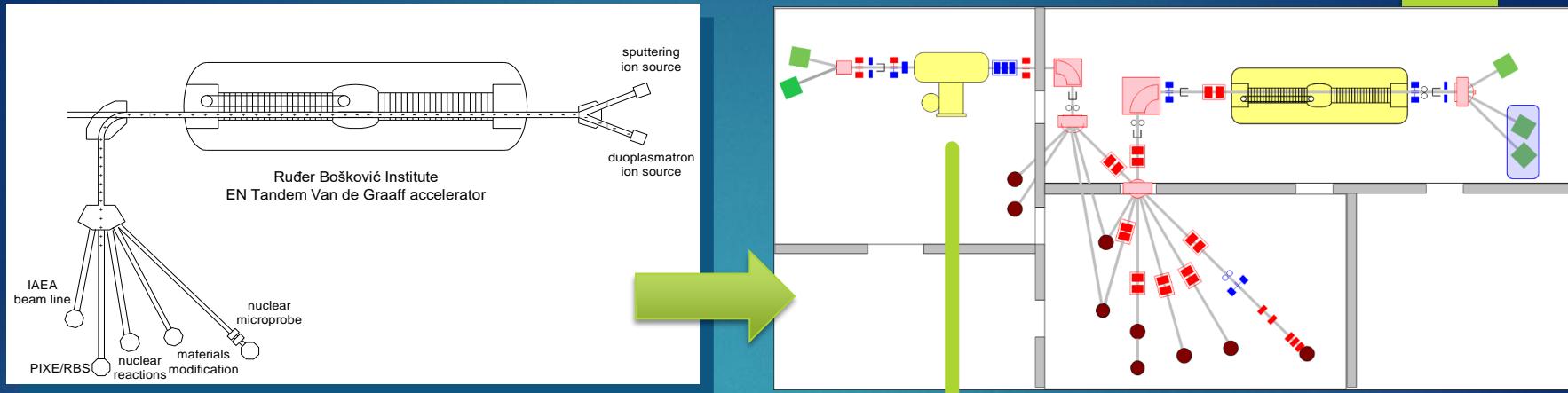
- 1962, installed at Rice University, Houston, Texas
- 1984, moved to Zagreb
- 1987, first beam at RBI
- Major upgrades:
 - Cryopumps (early '90)
 - Turbopumps (late '90)
 - Computer control (2005&2019)
 - SNICS 40 (2006)



Today:

- Runs with old belts; approximately 1000 hours per year
- Limitations in high voltage (4 MV max) due to leak in vacuum tubes at higher insulation gas pressures (<10 bar N₂, CO₂)
- To be closed after installation of new 5 MV tandem in 2024!

Upgrades and expansion (2004 and further)



Problems:

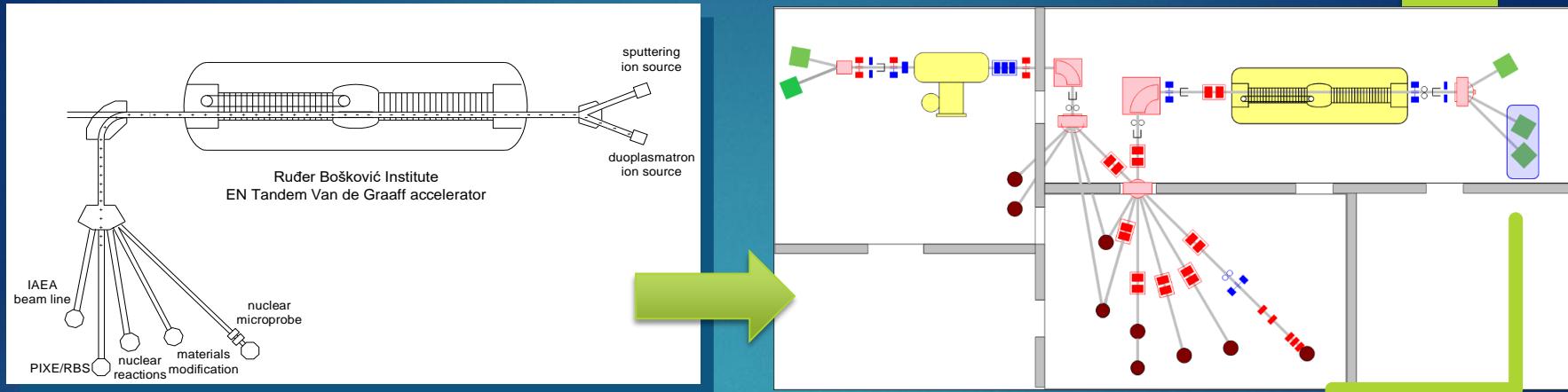
- Would EN tandem survive much longer ?
- Limited number of beam lines !

Solutions:

- IAEA project to make an upgrade -> new 1.0 MV Tandetron !
- New ion sources (IAEA and EU projects)
- New independent beam lines & Dual beam line possibility (EU projects)!!



Upgrades and expansion (2004 and further)

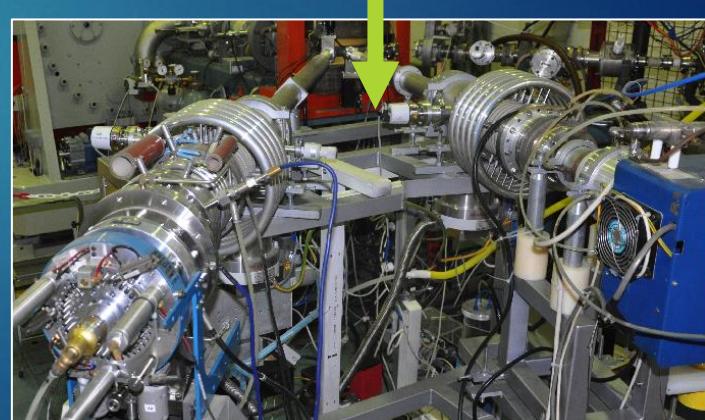


Problems:

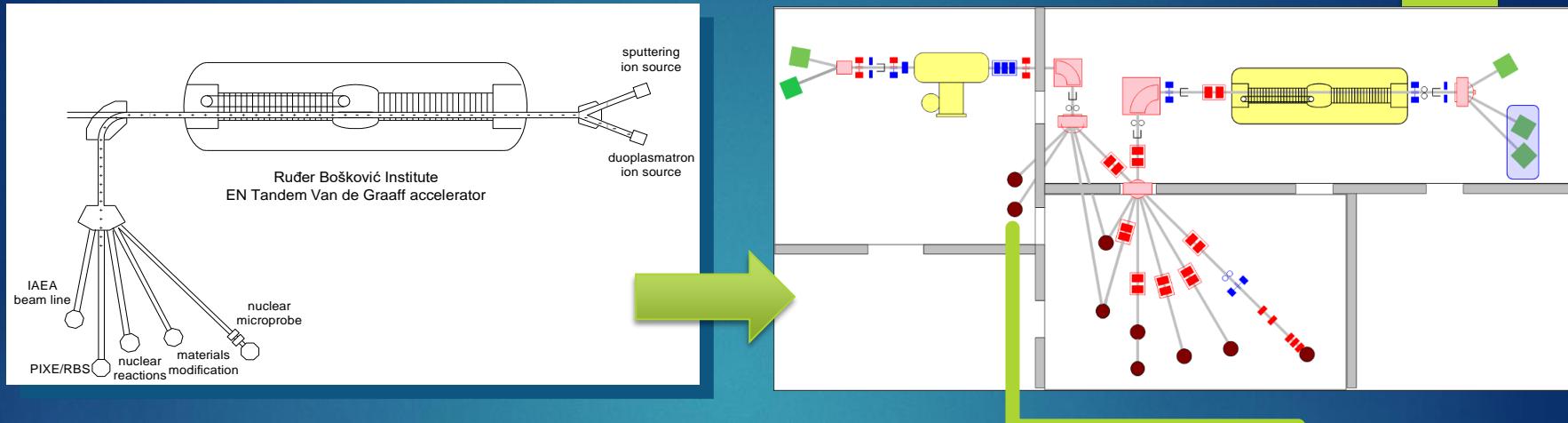
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Upgrades and expansion (2004 and further)



Problems:

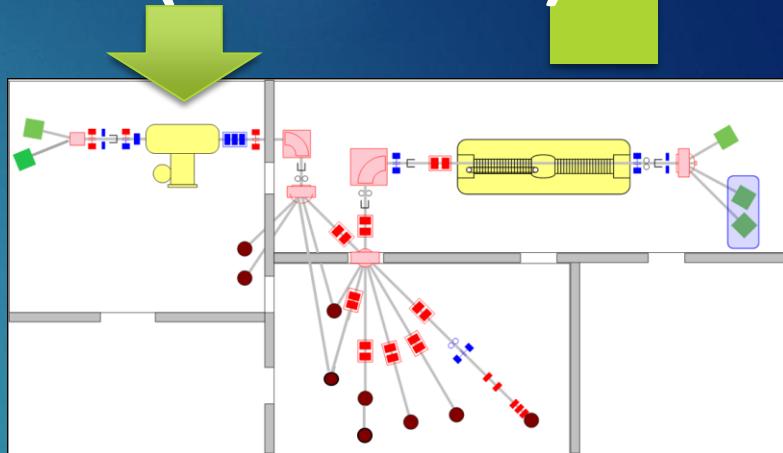
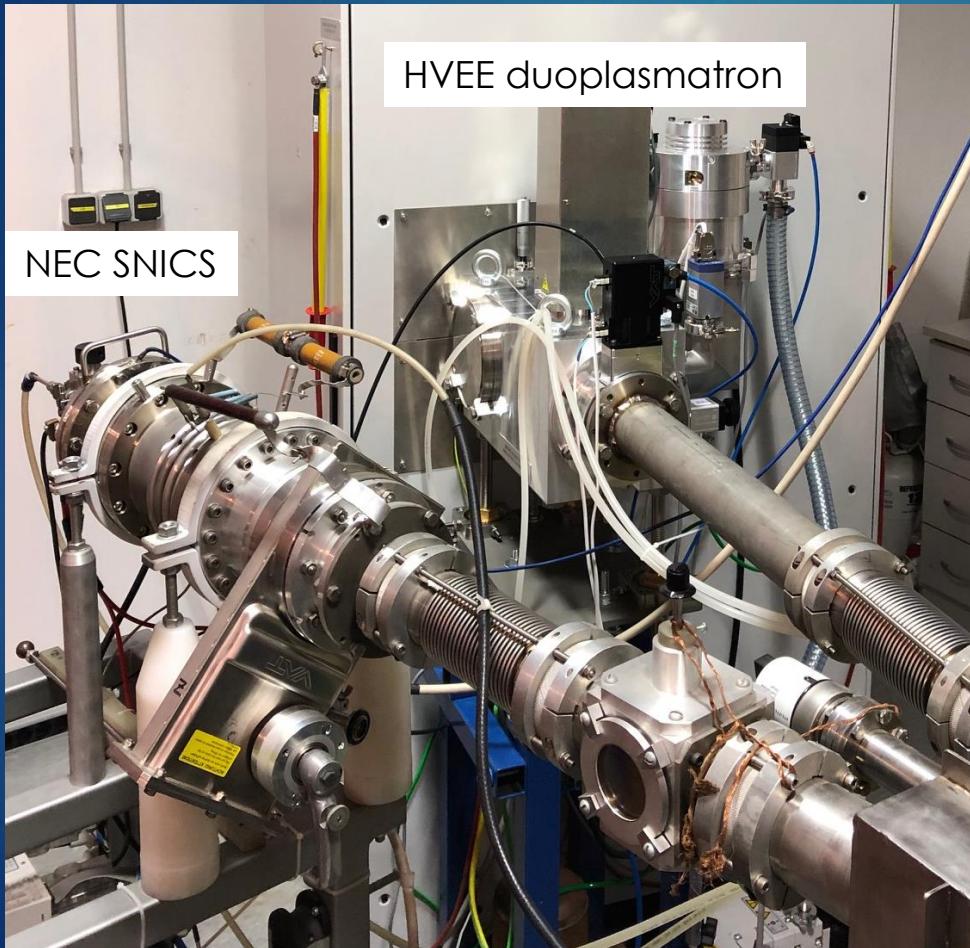
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Example: Tandetron ion sources (IAEA & EU)



- **NEC SNICS:** Obtained through IAEA and EU projects in 2008, typical ion beams: H, Li, C, O, Si, Cu, etc.
- **HVEE duoplasmatron** with Na charge exchange: IAEA procurement in 2017, used for He (3 and 4) and high brightness H with direct extraction

Laboratory for ion beam interactions

- **Strategy, general (RBI):**

- globally relevant basic scientific research
- orientation toward research of strategic national importance
- participation in higher education
- transfer of knowledge to other areas of public and economic life

- **Strategy, specifics (on Laboratory level):**

- Staff (quantity and quality), more postdocs and PhD students
- New research areas (detectors, fusion, surfaces, quantum appl.)
- **Classical IBA + unique capabilities !!**
- More competitive projects (EU) !!

2005: all staff – only 8 !!



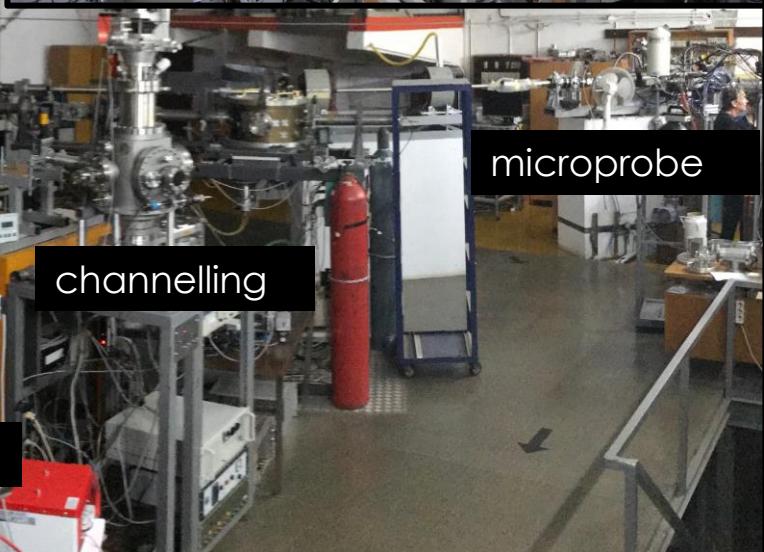
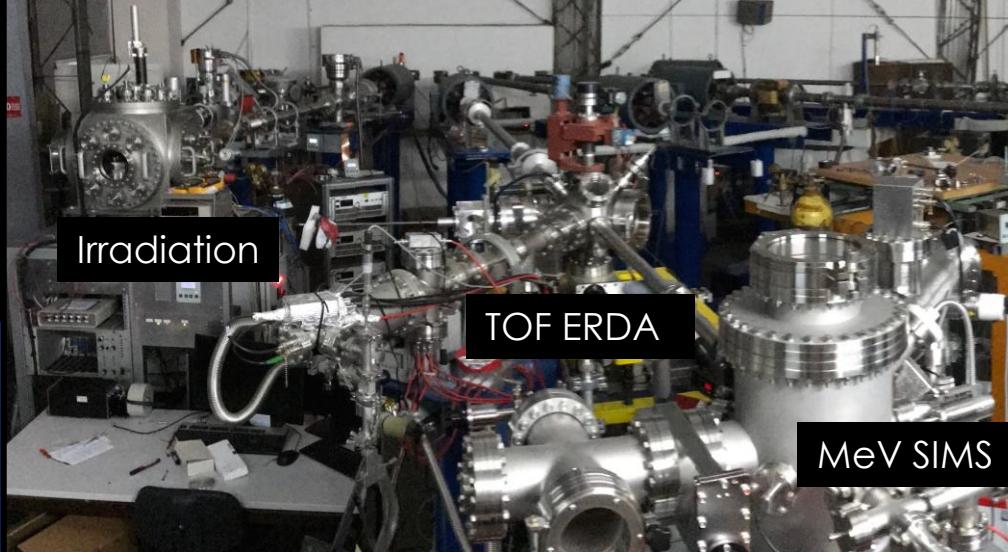
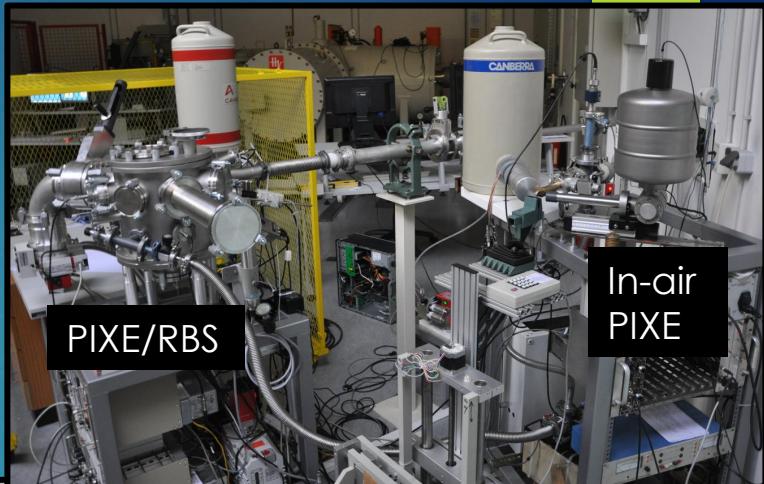
2022: all staff – 21 !!
7 researchers (5 seniors)
3 postdocs
7 PhD students
4 technical associates
and technicians



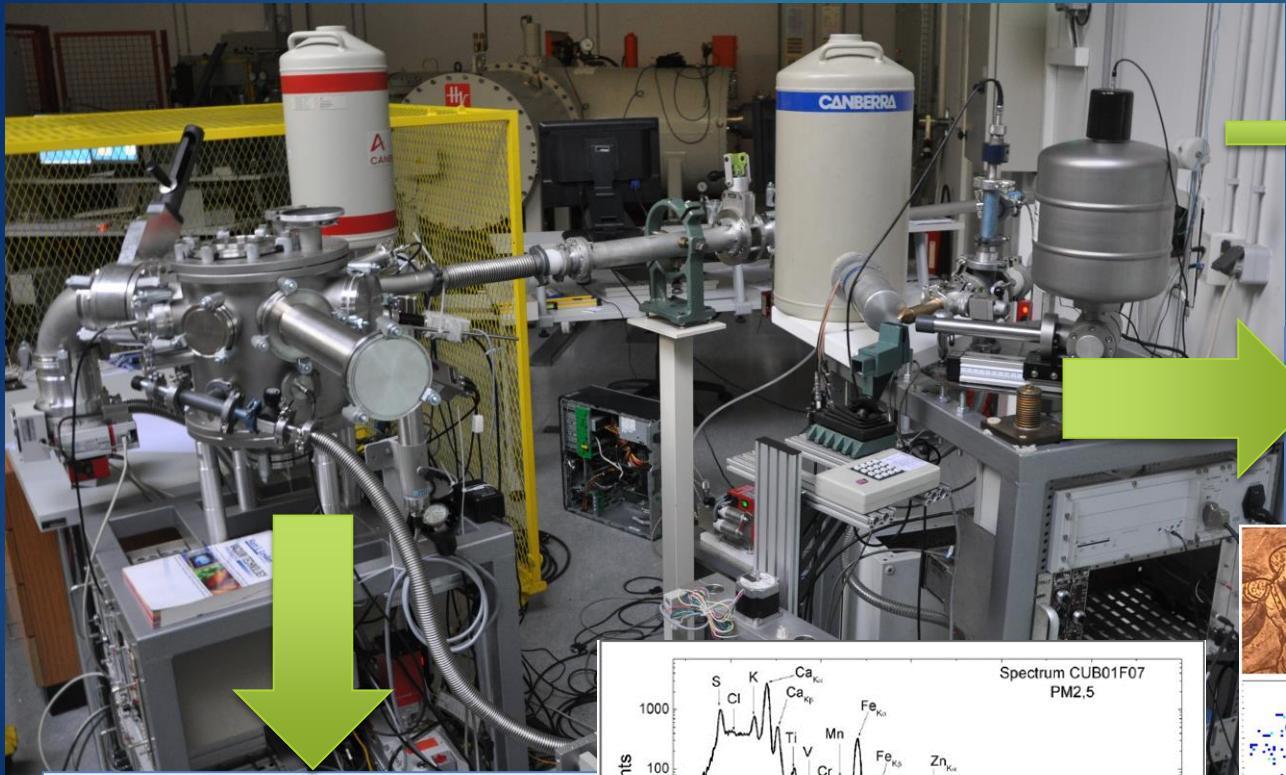
Introduction of all IBA techniques

Target rooms today !!

Target room as it was in 2001



Routine IBA: PIXE & RBS



Routine PIXE/RBS
(for air particulates)

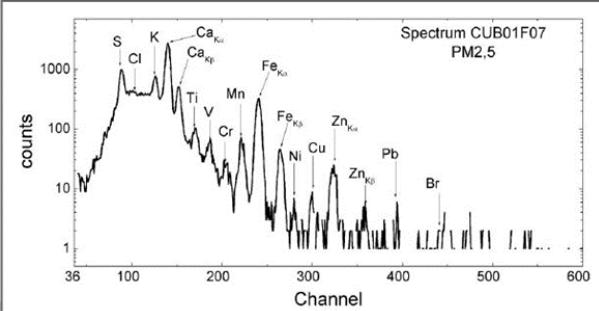
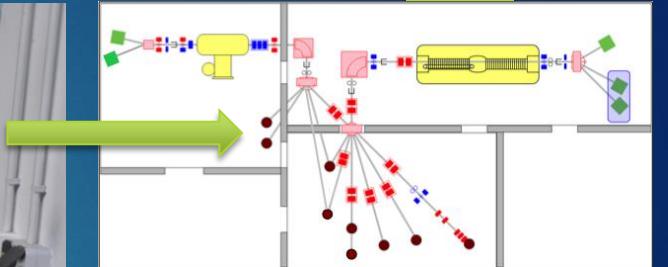
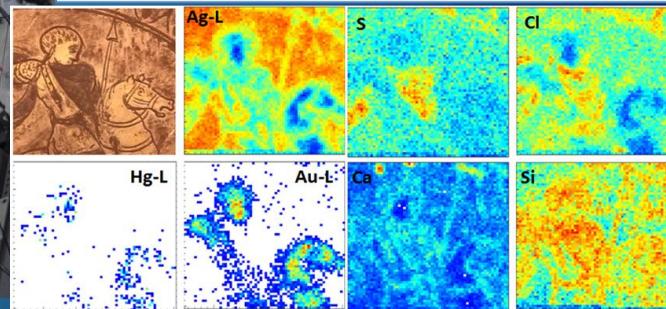


Figure 2. Representative PIXE spectra of the fine airborne particulate matter collected in the sampling site.

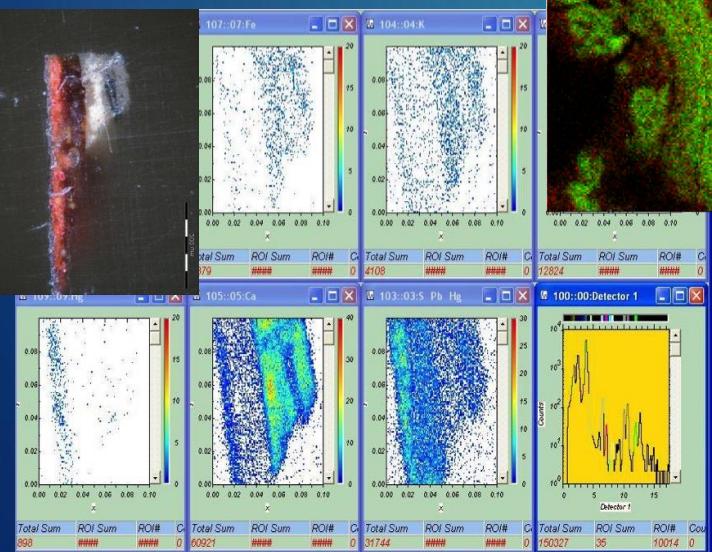
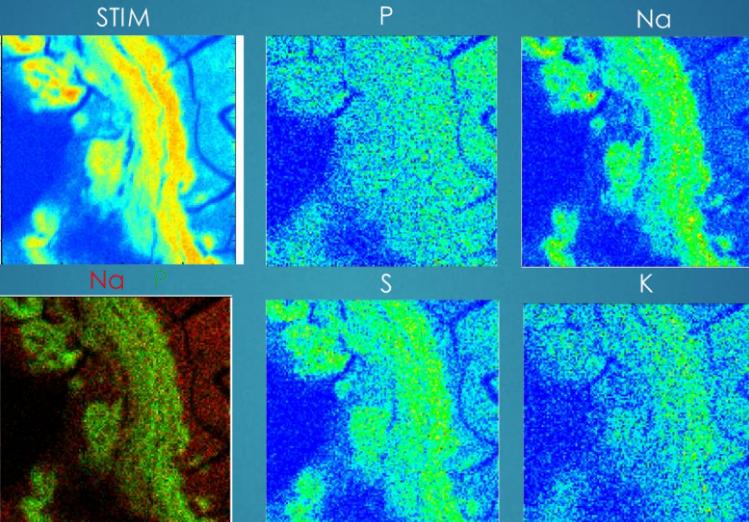


In air PIXE
(imaging of large objects
with 0.5 mm beam)

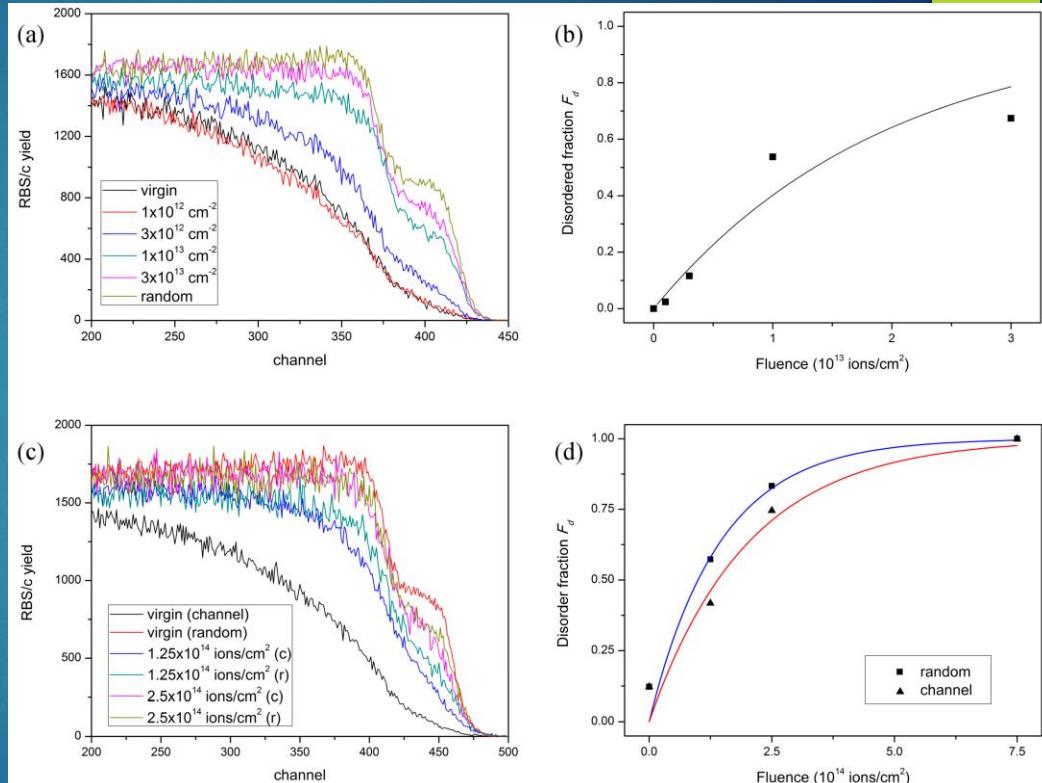
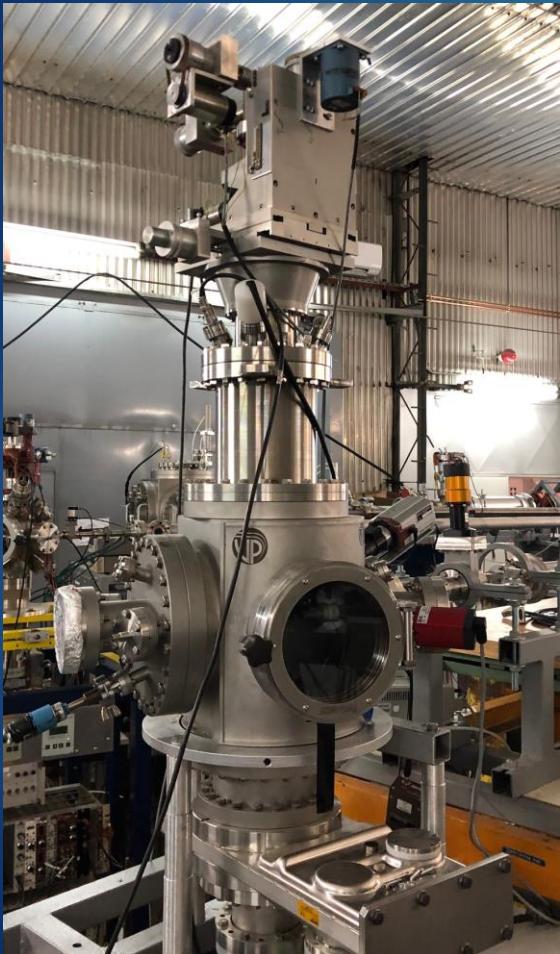


Routine IBA: microprobe PIXE&RBS

microPIXE: Numerous applications for cultural heritage, environment, geology, biomedicine, etc.



Routine IBA: RBS channeling

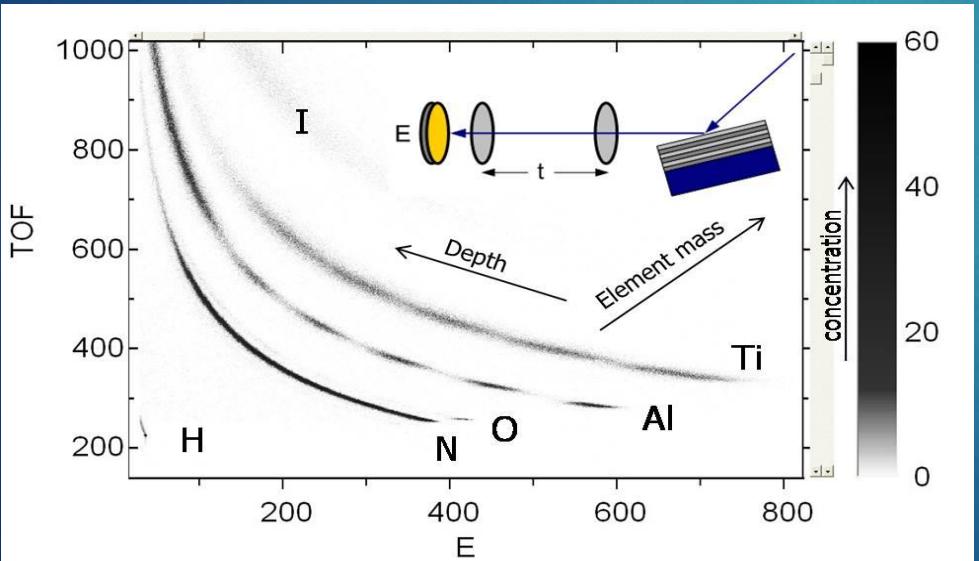


M. Karlušić et al. Monitoring ion track formation using In Situ RBS/c, ToF-ERDA and HR-PIXE, Materials 10 (2017) 1041

Towards state of the art: TOF-ERDA

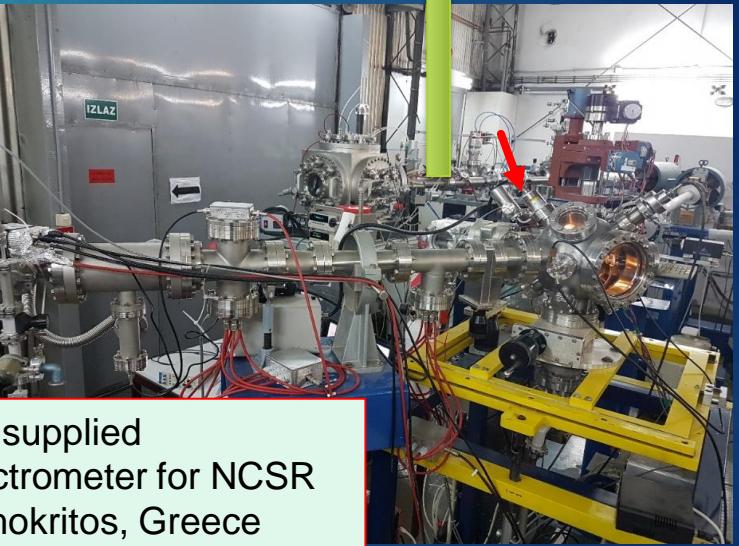
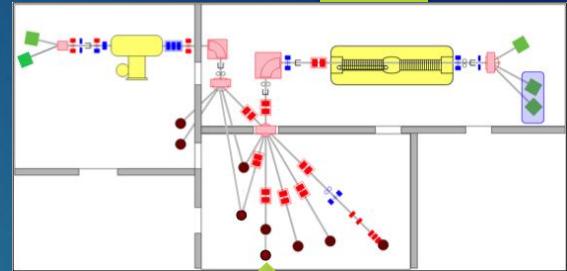
Heavy ion beam – e.g. 20 MeV Iodine ions

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



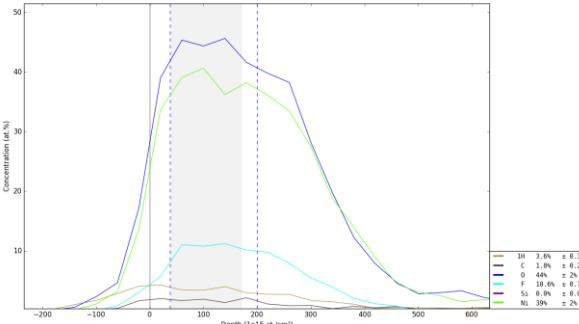
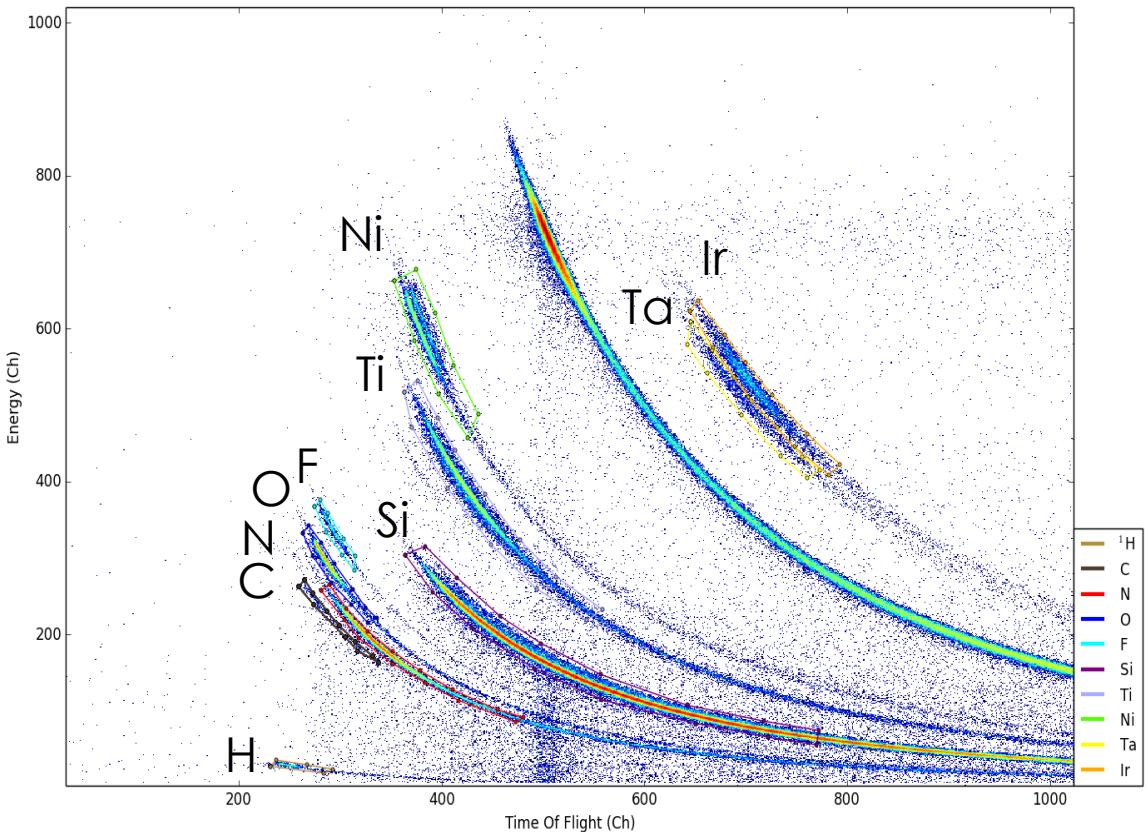
RBI supplied
spectrometer for NCSR
Demokritos, Greece

Z. Siketić, I. Bogdanović Radović, M. Jakšić, Thin Solid Films, 518 (2010) 2617-2622



TOF-ERDA applications – industrial partners

Quality control of production proces – NiO films (23 MeV iodine beam)



Element	Total Number of 10^{15} at/cm ²
H	15.2
C	6.6
O	158.7
F	33.5
Ni	141.8

Florine contamination found

Other unique capabilities – IBIC

Scholar ibic

About 9,600 results (0.03 sec)

My profile My library

IBIC investigations on CVD diamond
C Manfredotti, F Fizzotti, E Vittone, M Boero... - Nuclear Instruments and ..., 1995 - Elsevier
A 3 MeV proton microbeam has been used for the first time both to investigate the transport properties and to probe the electrical field in a CVD diamond sample of detector grade. Qualitative results concerning the spatial distribution of charge collection efficiency and ...
Cited by 43 Related articles All 4 versions

The effect of ion induced damage on IBIC images
MBH Breese, GW Grime, M Dellich - ... in Physics Research Section B: Beam ..., 1993 - Elsevier
Ion induced damage limits the number of charge pulses which can be measured in an IBIC (ion beam induced charge) image because the average measured charge pulse size decreases with cumulative beam dose. The cause and effects of MeV light ion induced ...
Cited by 28 Related articles All 4 versions

IBIC analysis of CdTe/CdS solar cells
E Colombo, A Bosio, S Calusci, L Giuntini... - Nuclear Instruments and ..., 2009 - Elsevier
This paper reports on the investigation of the electronic properties of a thin film CdS/CdTe solar cell with the Ion Beam Induced Charge (IBIC) technique. The device under test is a thin film (total thickness around 10 μm) multilayer heterojunction solar cell, displaying an ...
Cited by 22 Related articles All 13 versions

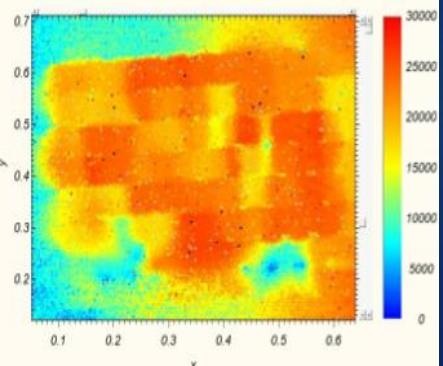
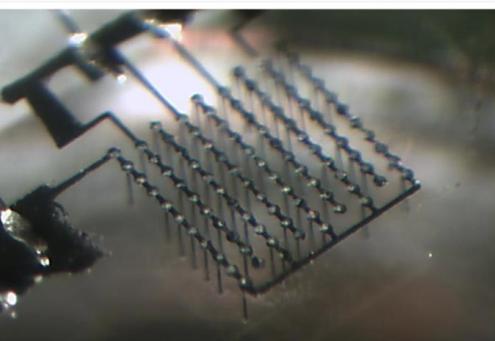
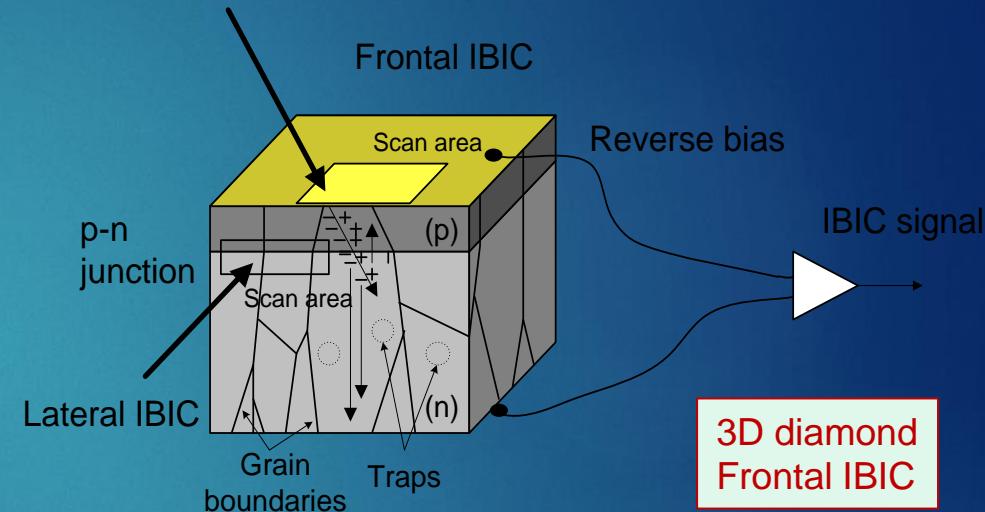
Focused ion beam fabrication and IBIC characterization of a diamond detector with buried electrodes
P Olivero, J Forneris, M Jakšić, Z Pastuović... - Nuclear Instruments and ..., 2011 - Elsevier
This paper reports on the fabrication and characterization of a high purity monocrystalline diamond detector with buried electrodes realized by the selective damage induced by a focused 6 MeV carbon ion beam scanned over a pattern defined at the micrometric scale. A ...
Cited by 24 Related articles All 14 versions

Investigation of 4H-SiC Schottky diodes by ion beam induced charge (IBIC) technique
C Manfredotti, F Fizzotti, AL Giudice, C Paolini... - Applied surface ..., 2001 - Elsevier
Ion beam induced charge technique has been used in order to investigate the charge collection properties of 4H-SiC epitaxial Schottky barrier nuclear detectors. In this work, 2 MeV He ions microbeam about 2 μm spot size scanned the total surface area of the detector ...
Cited by 19 Related articles All 9 versions

Characterisation of SiC by IBIC and other IBA techniques
M Jakšić, Ž Bošnjak, D Gracin, Z Medunić... - Nuclear Instruments and ..., 2002 - Elsevier
Several new technological applications of silicon carbide have attracted significant attention in recent years. As a wide gap semiconductor it has the capability to be used as a room temperature radiation detector. For most applications, material properties like homogeneity ...
Cited by 17 Related articles All 10 versions

IBIC and IBIL microscopy applied to advanced semiconductor materials
C Manfredotti, F Fizzotti, P Polesello, E Vittone... - Nuclear Instruments and ..., 1998 - Elsevier
A new version of the classical IBIC technique is presented together with a comparison between IBIC and IBIL microscopy with the aim of obtaining maps of radiative recombination centers in technologically advanced materials. In some cases (Si, CdTe) the method is ...
Cited by 19 Related articles All 7 versions

Ion Beam Induced Charge imaging of charge collection in detectors (and other devices)



Unique capabilities – high resolution PIXE



Parametrisation of He induced x-ray spectra using HR PIXE spectrometer – important for calibration of APXS Alpha Particle X-Ray Spectrometer (APXS) spectrometer on Mars

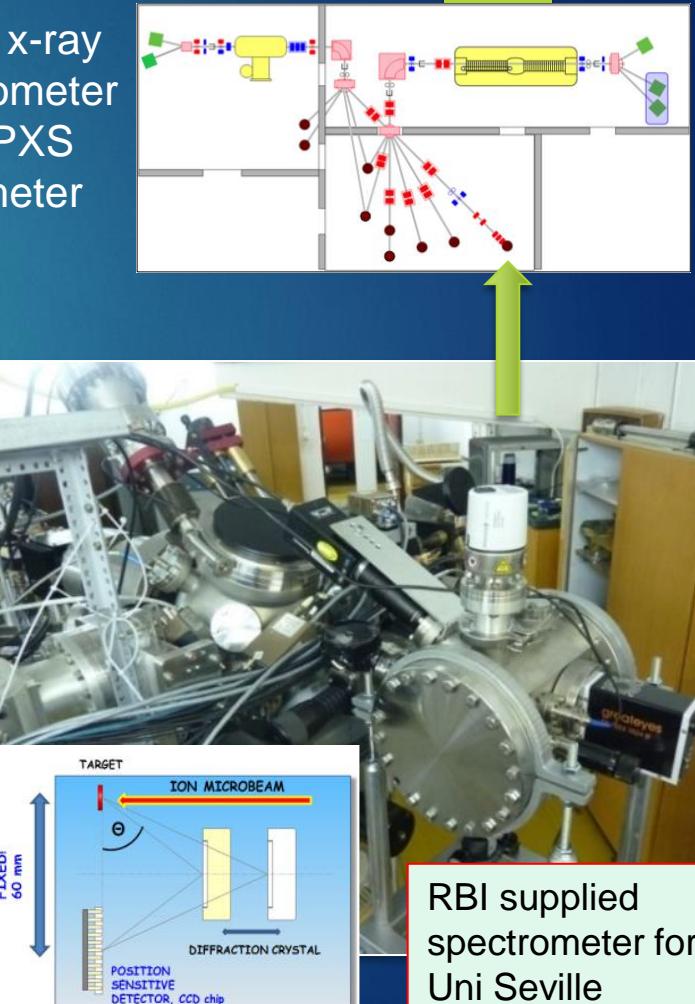
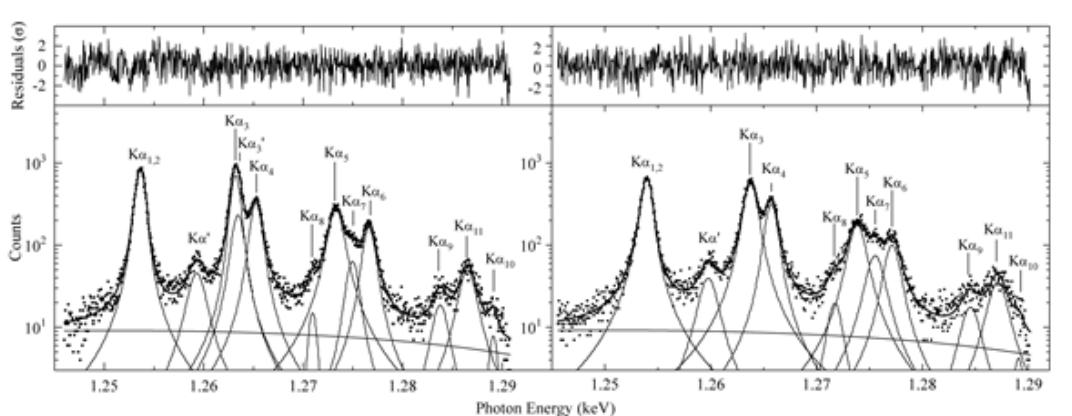
Fazinić et al, NIMB363 (2015) 61

Božičević MI et al., JAAS 31 (2016) 2293

Karlušić et al, Materials 10 (2017) 1041

3 MeV He \rightarrow Mg

3 MeV He \rightarrow MgO

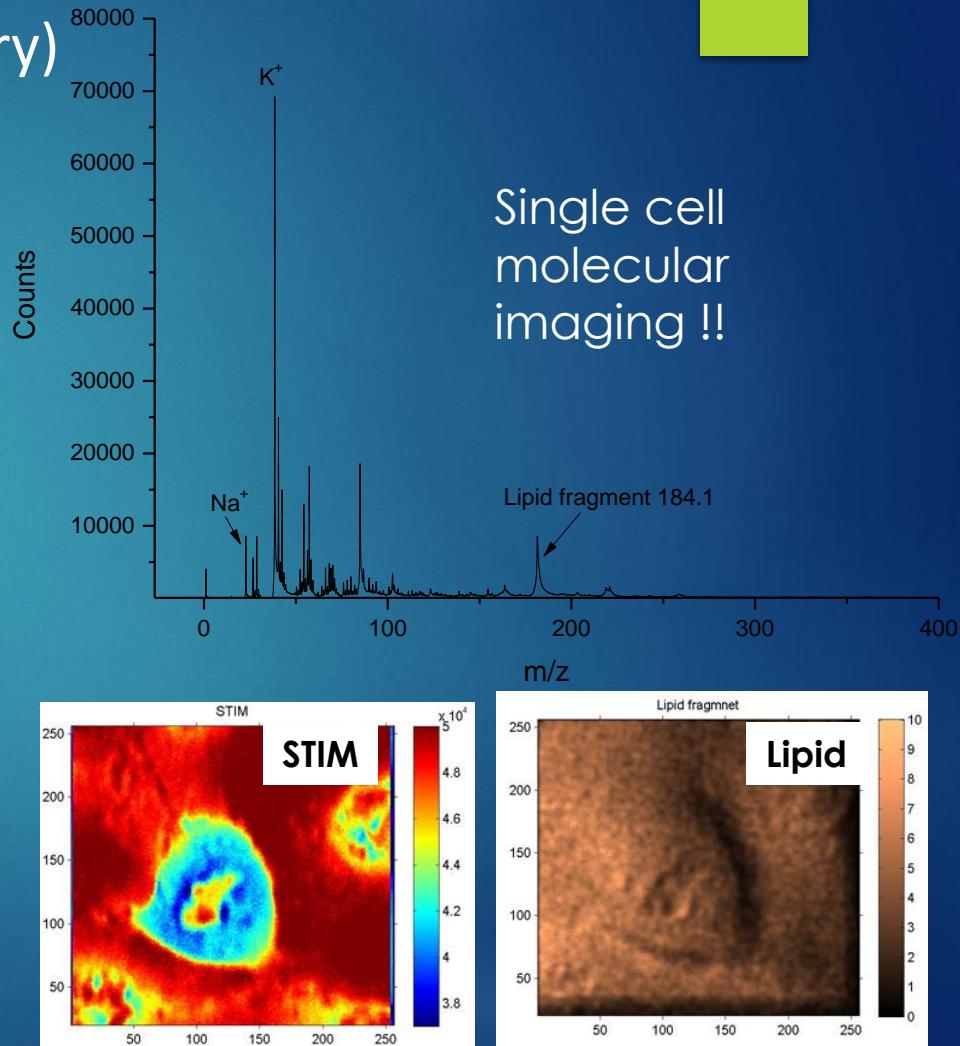
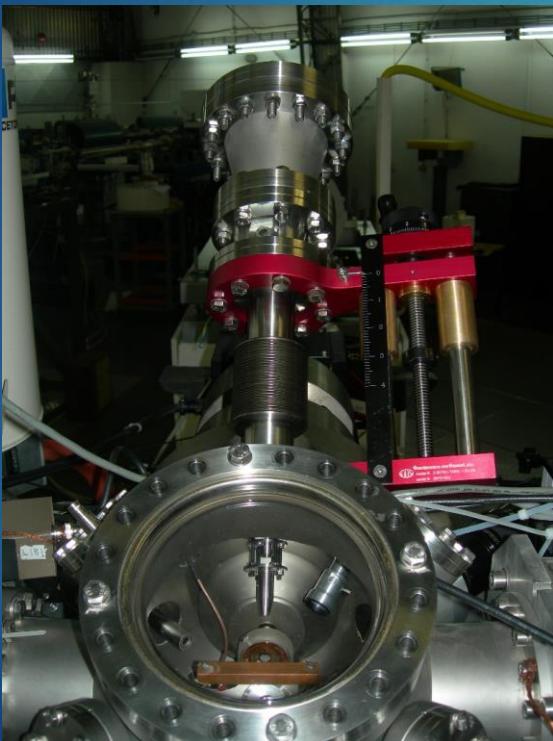


RBI supplied
spectrometer for
Uni Seville

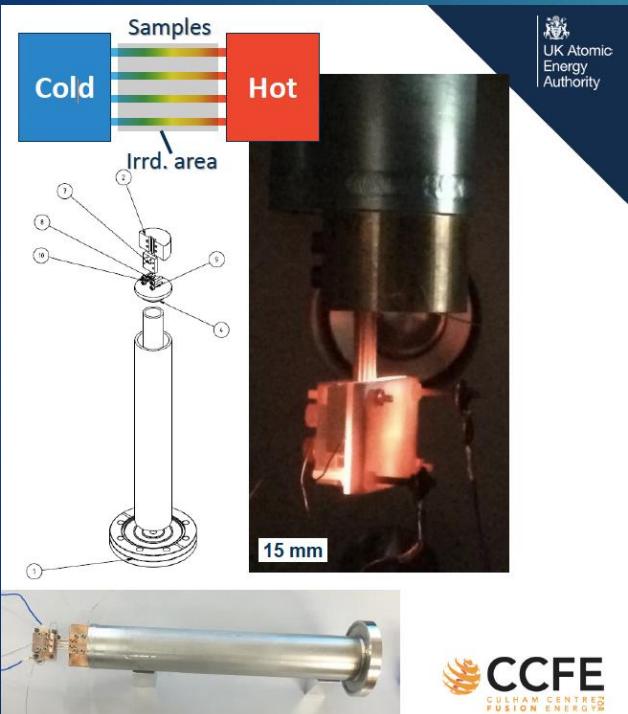
Unique capabilities – MeV SIMS

(secondary ion mass spectrometry)

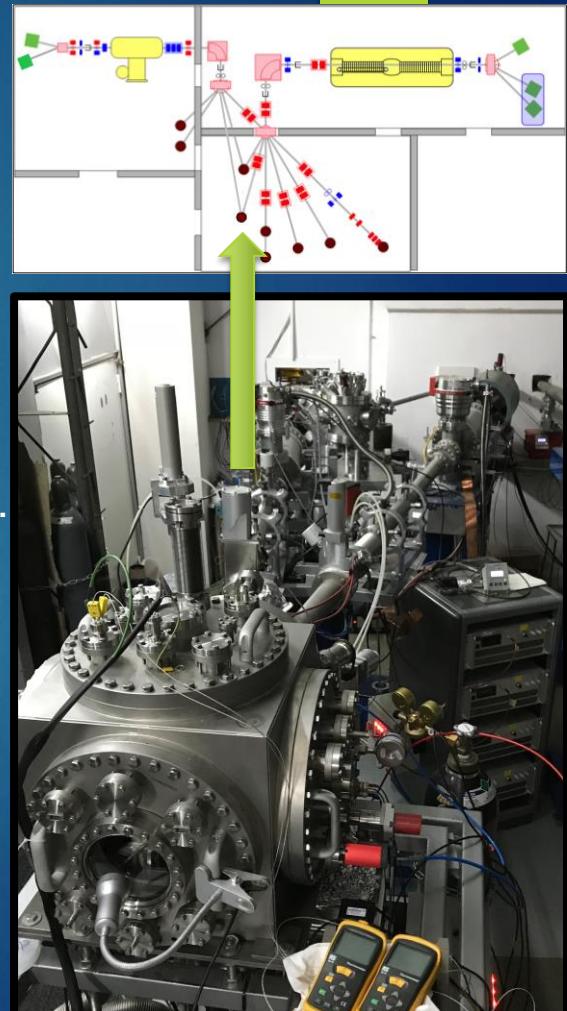
- The first MeV SIMS system:
- Microprobe – TOF MeV SIMS & imaging
(0.5 μm resolution)



Unique capabilities – Dual beam irradiation (for fusion research – DIFu)

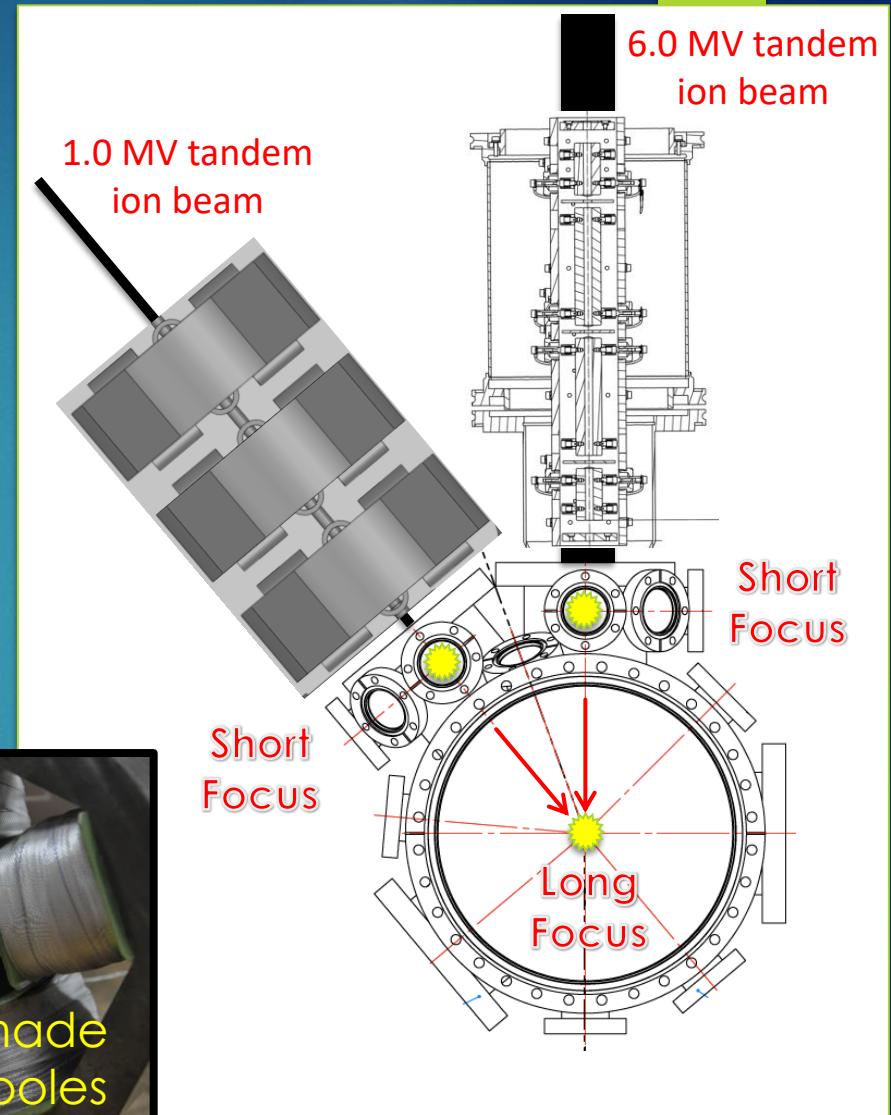
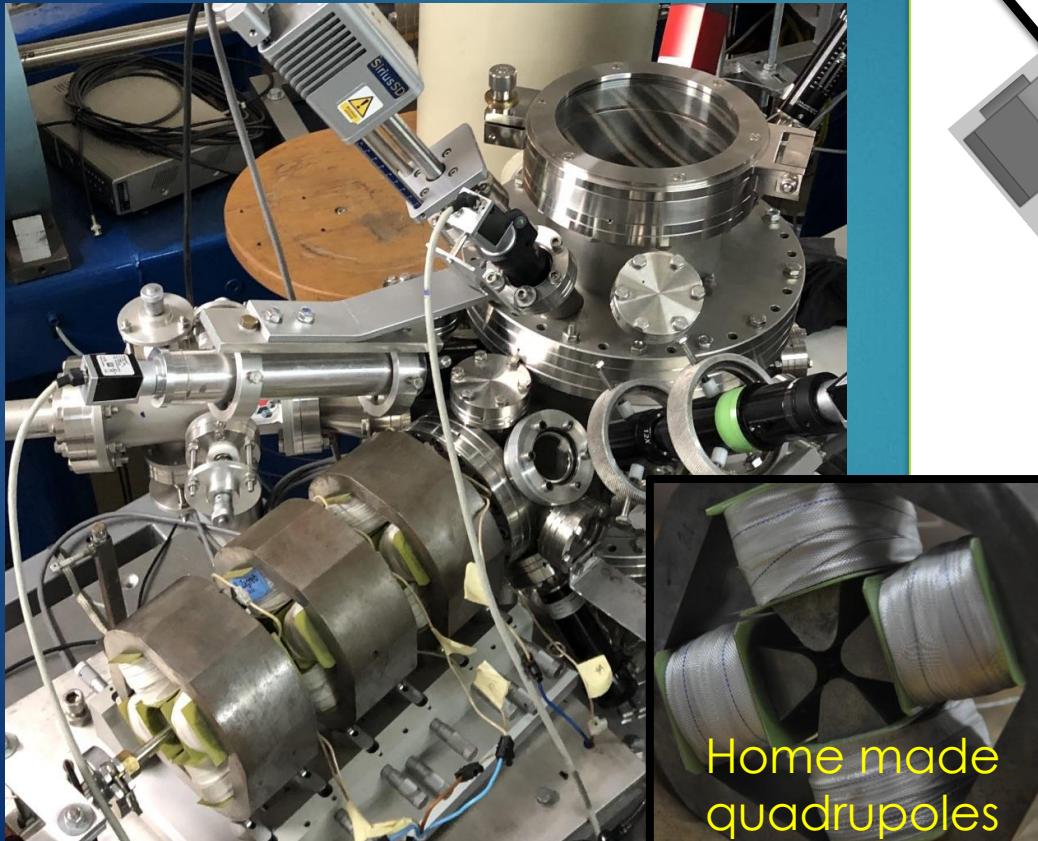


- Only 4 dual beam irradiation facilities in Europe
- Simulation of fusion reactor irradiation by: H or He from small tandem + self ions (e.g. Fe, W) that simulate neutron radiation
- Sample heating & control of sample temperature by IR camera and TCs
- Used also for all other irradiation / implantation tasks



Unique capabilities – Dual microprobe

2 microbeams from
2 accelerators to one area



Research output – articles 2020&2021

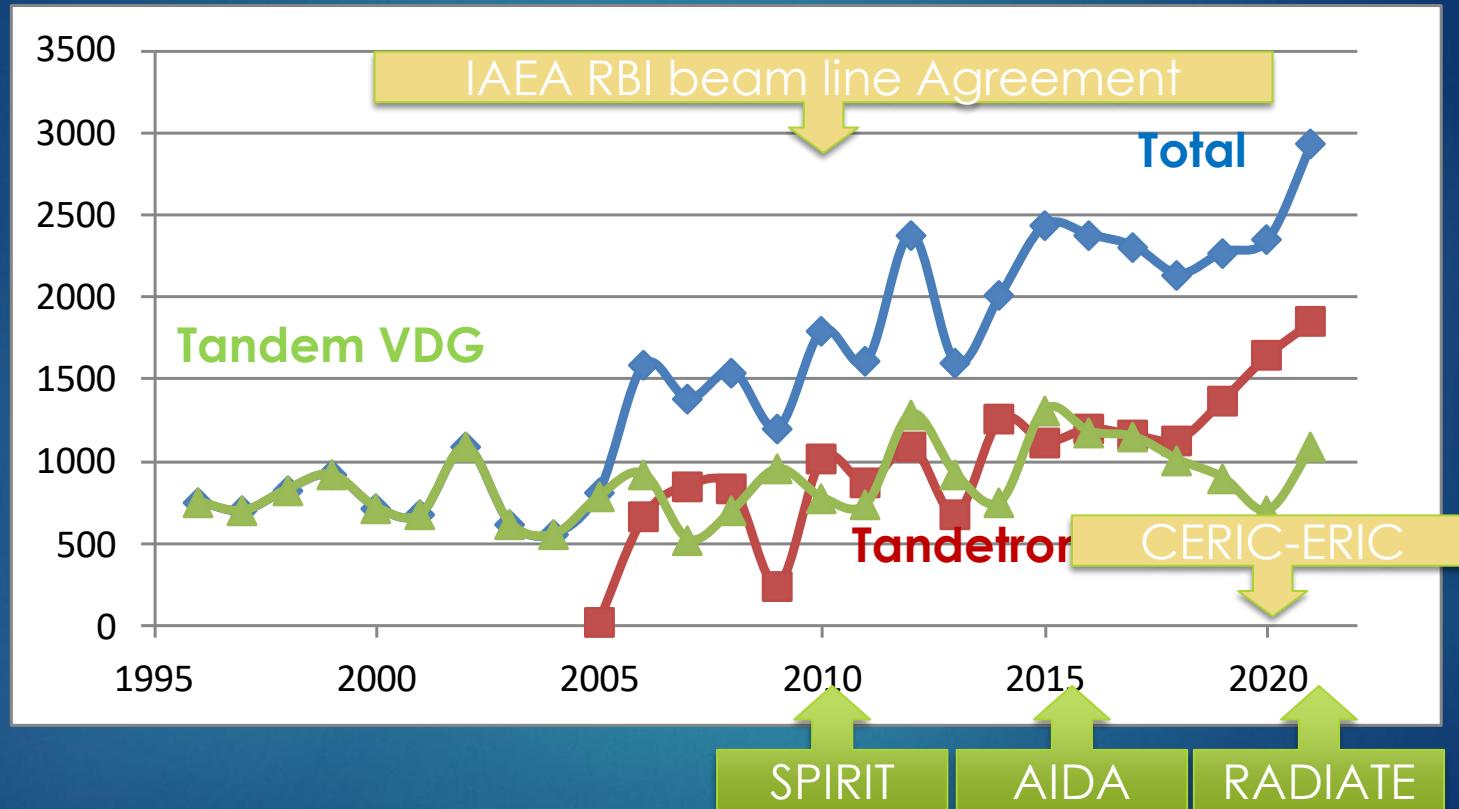
2022.

1. Omer Kaspi, Osnat Israelsohn-Azulay, Yigal Zidon, Hila Rosengarten, Matea Krmpotić, Sabrina Gouasmia, Iva Bogdanović Radović, Pasi Jalkanen, Anna Liski, Kenichiro Mizohata, Jyrki Räisänen, Olga Girshevitz, Hanoch Senderowitz, Inter-laboratory workflow for forensic applications: Classification of car glass fragments, *Forensic Science International* 331 (2022) 111216, DOI: 10.1016/j.forsciint.2022.111216
2. M. Barac, A. Filko, M. Brajković, Z. Siketić, A. Ledić, I. B. Radović, Comparison of optical techniques and MeV SIMS in determining deposition order between optically distinguishable and indistinguishable inks from different writing tools, *Forensic Science International* 331 (2022) 111136, DOI: 10.1016/j.forsciint.2021.111136
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4. M. R. Ramos, A. Crnjac, D. Casic, M. Jakšić, Ion Microprobe Study of the Polarization Quenching Techniques in Single Crystal Diamond Radiation Detectors, *Materials* 2022, 15, 388, DOI: 10.3390/ma15010388

2021.

1. I. Božičević Mihalić, S. Fazinić, M. Barac, A. Karydas, A. Migliori, D. Doračić, V. Desnica, D. Mudronja and D. Krstić, 2021. Multivariate analysis of PIXE + XRF and PIXE spectral images. *Journal of Analytical Atomic Spectrometry*, (2021), 36(3), 654-667. DOI: 10.1039/DJAA00529K
2. M. Brajković, I. Bogdanović Radović, M. Barac, D. D. Casic, Z. Siketić, Imaging of Organic Samples with Megaelectron Volt Time-of-Flight Secondary Ion Mass Spectrometry Capillary Microprobe, *J. Am. Soc. Mass Spectrom.* 2021, 32, 10, 2567–2572, DOI: 10.1021/jasms.lc00200
3. M.R. Ramos, A. Crnjac, G. Provatas, V. Grilj, N. Skukan, M. Pomorski, M. Jakšić, Characterization of ion beam induced polarization in scCVD diamond detectors using a microbeam probe, *Nucl. Instr. and Meth. B* 504 (2021) 21–32, DOI: 10.1016/j.nimb.2021.07.013
4. A. Crnjac, M. R. Ramos, N. Skukan, M. Pomorski, M. Jakšić, Charge transport in single crystal CVD diamond studied at high temperatures, *J. Phys. D: Appl. Phys.* 2021, 54, 465103, DOI: 10.1088/1361-6463/ac1e4e
5. M. Barac, M. Brajković, I. Bogdanović Radović, J. Kovač, Z. Siketić, MeV TOF SIMS Analysis of Hybrid Organic/Inorganic Compounds in the Low Energy Region, *J. Am. Soc. Mass Spectrom.* 2021, 32, 3, 825–831, DOI: 10.1021/jasms.lc00006
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7. M. Karlušić, M. Mičetić, M. Kresić, M. Jakšić, B. Šantić, I. Bogdanović Radović, S. Bernstorff, H. Lebius, B. Ban-d'Estat, K. Žužek Rožman, J.H. O'Connell, U. Hagemann, M. Schleberger, Nanopatterning surfaces by grazing incidence swift heavy ion irradiation, *Applied Surface Science* 541 (2021) 148467, DOI: 10.1016/j.apsusc.2020.148467
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12. M. Gloginjić, M. Erich, M. Kokkoris, E. Liarokapis, S. Fazinić, M. Karlušić, K. Tomić Luketić, S. Petrović, The quantitative 6H-SiC crystal damage depth profiling, *Journal of Nuclear Materials* 555 (2021) 153143, DOI: 10.1016/j.jnucmat.2021.153143
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Internationalization - providing the transnational access to RBI beam lines!



- Proposals for experiments through EU projects are reviewed !!

Internationalization - providing the transnational access to RBI beam lines!

Transnational access (+industry) is today main source of accelerator operation funding !!

RBI was partner in these EU projects:



Support of Public and Industrial Research using Ion Beam Technology



Advanced European Infrastructures for Detectors at Accelerators

Users from industry:



RBI is partner in current projects and agreements:

Central European Research Infrastructure Consortium – CERIC-ERIC



Research And Development with Ion Beams – Advancing Technology in Europe



Beam line Agreement with IAEA



Upgrades and expansion (future !!)

Problems and solution:

- Increased number of users (mostly international) require more reliable facility (Tandem replacement) !
- National and IAEA funding are insufficient, need for EU funding !

Foreign researchers at RBI accelerator facility:

2007

January							February							March							April							
S	M	T	W	Th	F	S	S	M	T	W	Th	F	S	S	M	T	W	Th	F	S	S	M	T	W	Th	F	S	
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22	23	24	25	26	27	28	19	20	21	22	23	24	25	19	20	21	22	23	24	25	26	27	28	29	30	31		
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May							June							July							August							
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7	8	9	10	11	12	13	4	5	6	7	8	9	10	2	3	4	5	6	7	8	9	10	11	12	13	14	15	
14	15	16	17	18	19	20	11	12	13	14	15	16	17	9	10	11	12	13	14	15	16	17	18	19	20	21	22	
21	22	23	24	25	26	27	18	19	20	21	22	23	24	16	17	18	19	20	21	22	23	24	25	26	27	28	29	
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September							October							November							December							
S	M	T	W	Th	F	S	S	M	T	W	Th	F	S	S	M	T	W	Th	F	S	S	M	T	W	Th	F	S	
3	4	5	6	7	8	9	8	9	10	11	12	13	14	5	6	7	8	9	10	11	12	13	14	15	16	17	18	
10	11	12	13	14	15	16	15	16	17	18	19	20	21	12	13	14	15	16	17	18	19	20	21	22	23	24	25	
17	18	19	20	21	22	23	22	23	24	25	26	27	28	19	20	21	22	23	24	25	17	18	19	20	21	22	23	
24	25	26	27	28	29	30	29	30	31					16	17	18	19	20	21	22	23	24	25	26	27	28	29	30

Funded
Not funded

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Foreign researchers at RBI accelerator facility:

2017

January							February							March							April								
S	M	T	W	Th	F	S	S	M	T	W	Th	F	S	S	M	T	W	Th	F	S	S	M	T	W	Th	F	S		
1	2	3	4	5	6	7	1	2	3	4	5	6	7	1	2	3	4	5	6	7	1	2	3	4	5	6	7		
8	9	10	11	12	13	14	8	9	10	11	12	13	14	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	
15	16	17	18	19	20	21	12	13	14	15	16	17	18	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	
22	23	24	25	26	27	28	29	30	31					5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	
29	30	31					26	27	28	29	30	31		19	20	21	22	23	24	25	26	27	28	29	30	31			
May							June							July							August								
S	M	T	W	Th	F	S	S	M	T	W	Th	F	S	S	M	T	W	Th	F	S	S	M	T	W	Th	F	S		
1	2	3	4	5	6	7		1	2	3	4	5	6	7	1	2	3	4	5	6	7	1	2	3	4	5	6	7	
8	9	10	11	12	13	14	4	5	6	7	8	9	10	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	
15	16	17	18	19	20	21	11	12	13	14	15	16	17	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	
22	23	24	25	26	27	28	18	19	20	21	22	23	24	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	
29	30	31					25	26	27	28	29	30	31	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	
September							October							November							December								
S	M	T	W	Th	F	S	S	M	T	W	Th	F	S	S	M	T	W	Th	F	S	S	M	T	W	Th	F	S		
3	4	5	6	7	8	9	8	9	10	11	12	13	14	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
10	11	12	13	14	15	16	15	16	17	18	19	20	21	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
17	18	19	20	21	22	23	22	23	24	25	26	27	28	19	20	21	22	23	24	25	26	27	28	29	30	31			
24	25	26	27	28	29	30	29	30	31					17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	

Funded
Not funded

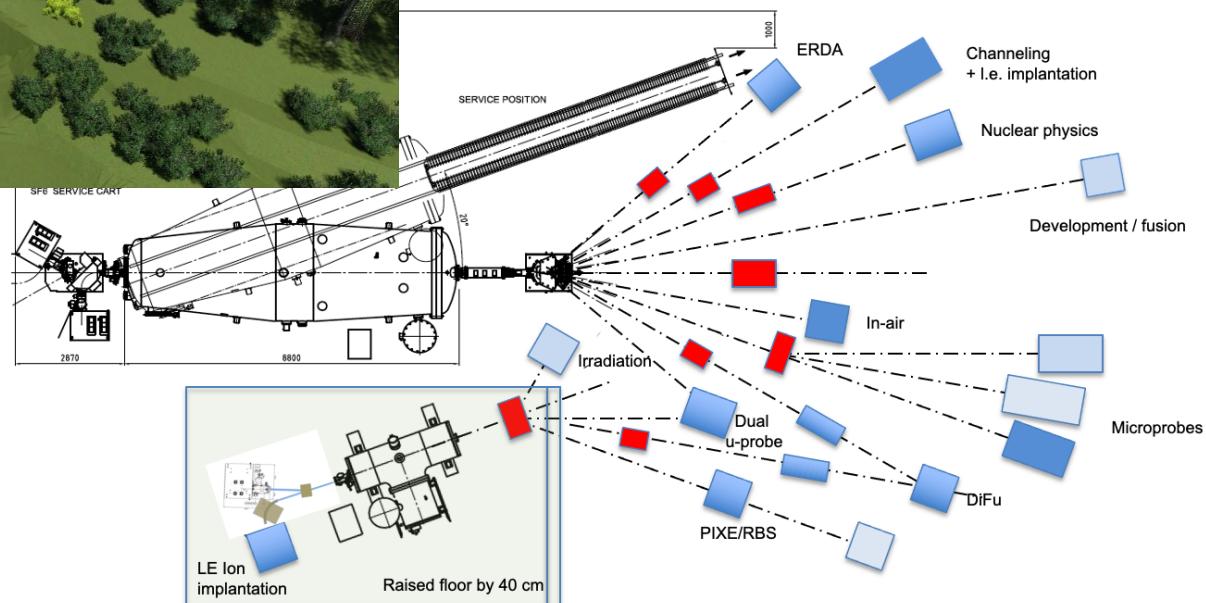
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Upgrades and expansion (future !!)

RBI structural funds project O-ZIP – 72 MEur



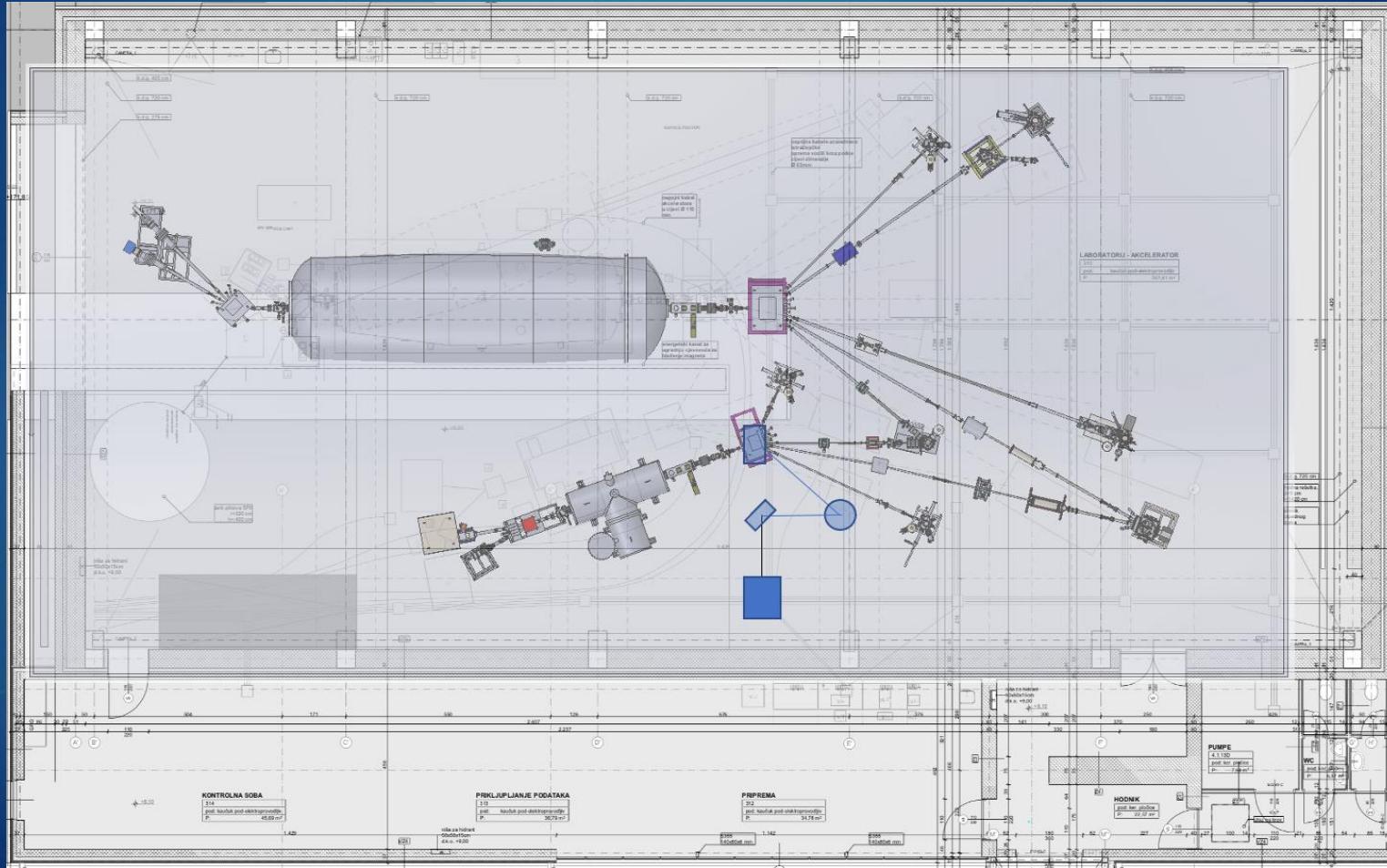
New accelerator building



Renovation of existing
building with addition of
auxiliary laboratories

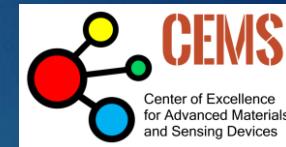
Upgrades and expansion (future !!)

RBI structural funds project O-ZIP – 72 MEur



Conclusions, or how to fund accelerator facility

- National (Croatia) funding – can provide only salaries and utilities !
- Accelerator maintenance per year is > 200 kEur !
- Need for the development of state of the art techniques – **to attract international users and funding!**
- Increased support through high quality internal research:
 - 3 national projects (HRZZ)
 - National Centre of excellence for Advanced Materials and Sensing Devices (CEMS)
 - 2 European Regional Development Fund projects
 - Partner in EuroFusion project
 - ERA (European Research Area) Chair project: Paradesec - Expanding Potential in Particle and Radiation Detectors, Sensors and Electronics in Croatia – CDSE
 - AIDAinnova
 - Industry



Thank you for your attention !!

