

Research at JSI 2MV Tandem

Primož Pelicon, Jožef Stefan Institute, Ljubljana

Outline

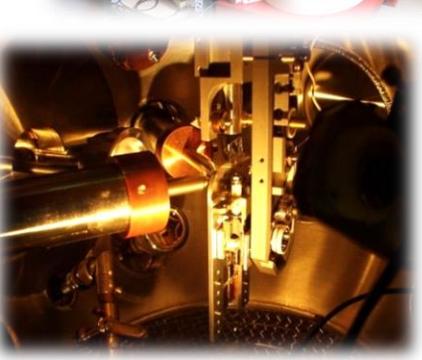
1. Introduction: Department of low and medium energy physics
2. Tandem ion accelerator at JSI
3. Research and applications with ion beams
4. Transnational access programme to JSI accelerator/beams
5. Conclusion

Department of Low and Medium Energy Physics, Jožef Stefan Institute

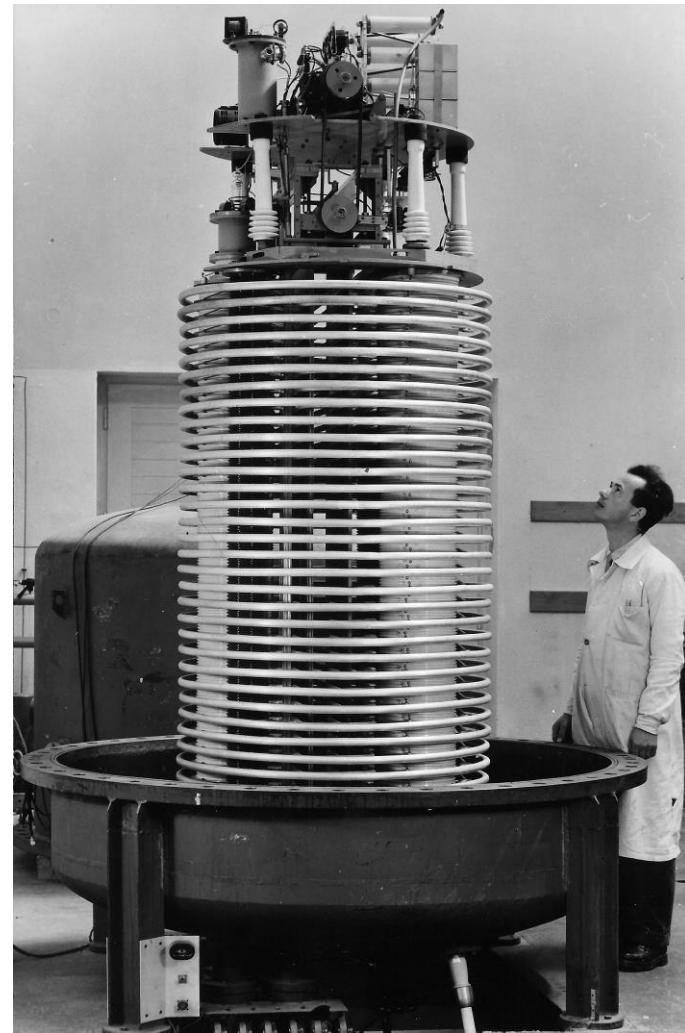
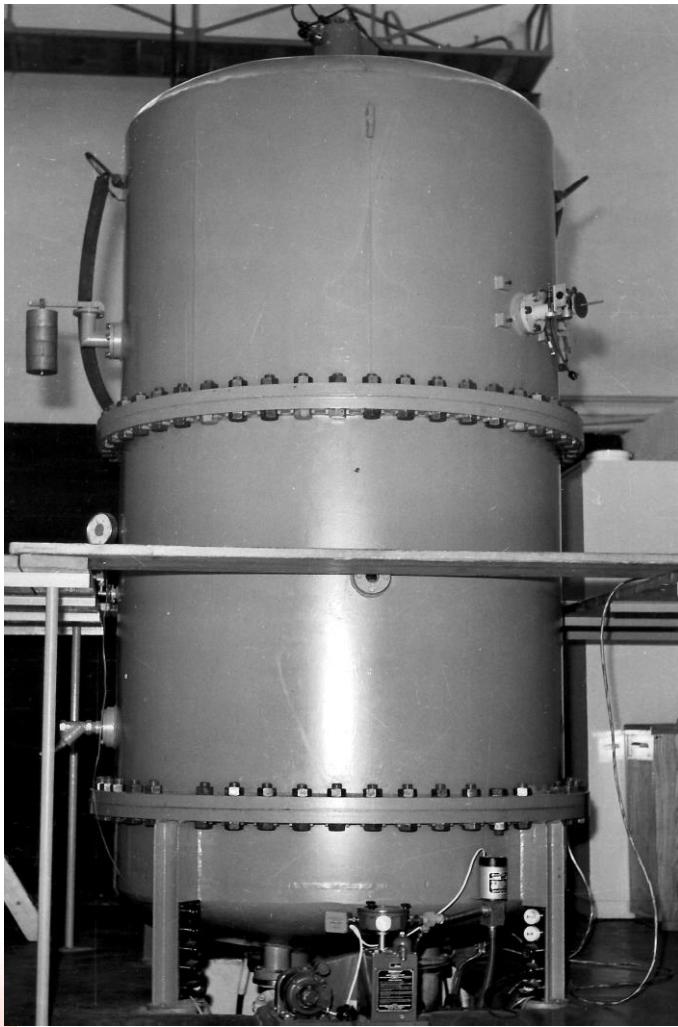
<https://f2.ijs.si/en>

Personnel: 50, budget 3.5 MEUR

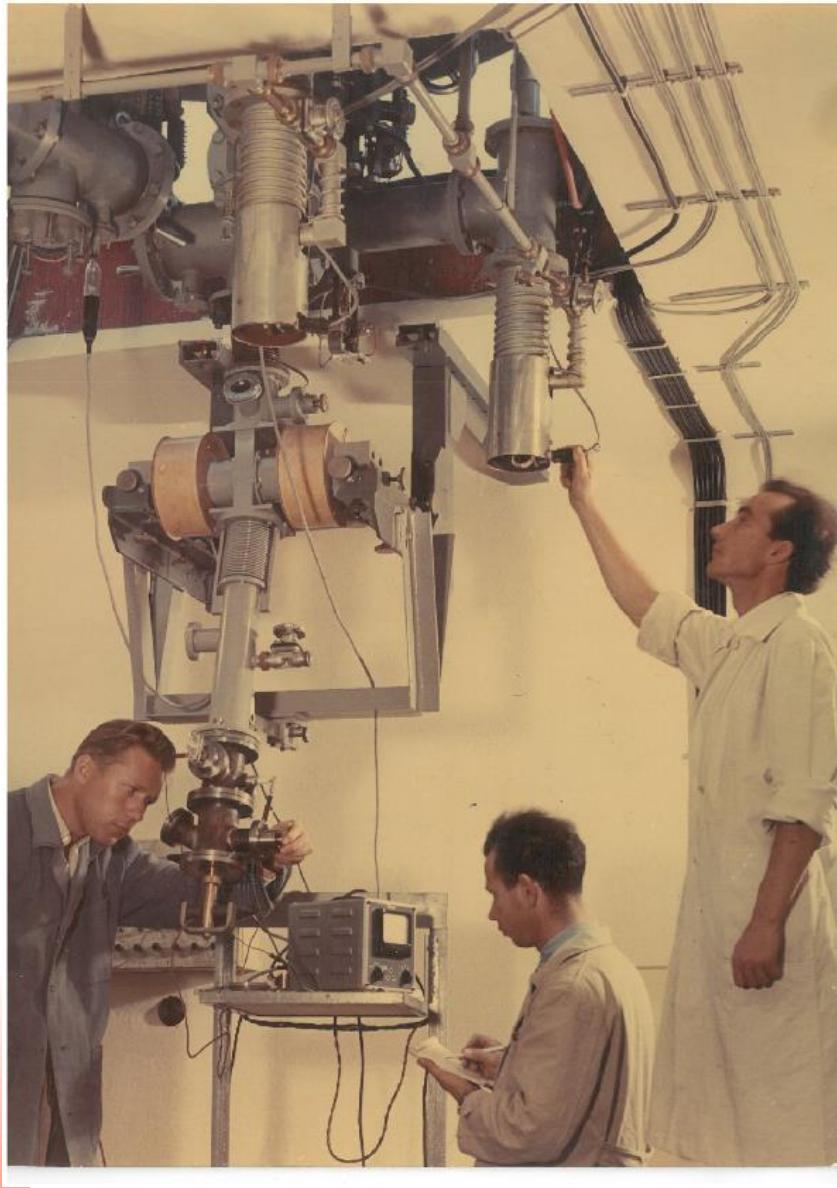
- Basic research in nuclear and atomic physics
- Environmental radiological monitoring
- Ion accelerator laboratory
- Calibrated radiation fields (gamma, X-ray)
- Research with charge particle and photon beams at large experimental facilities worldwide



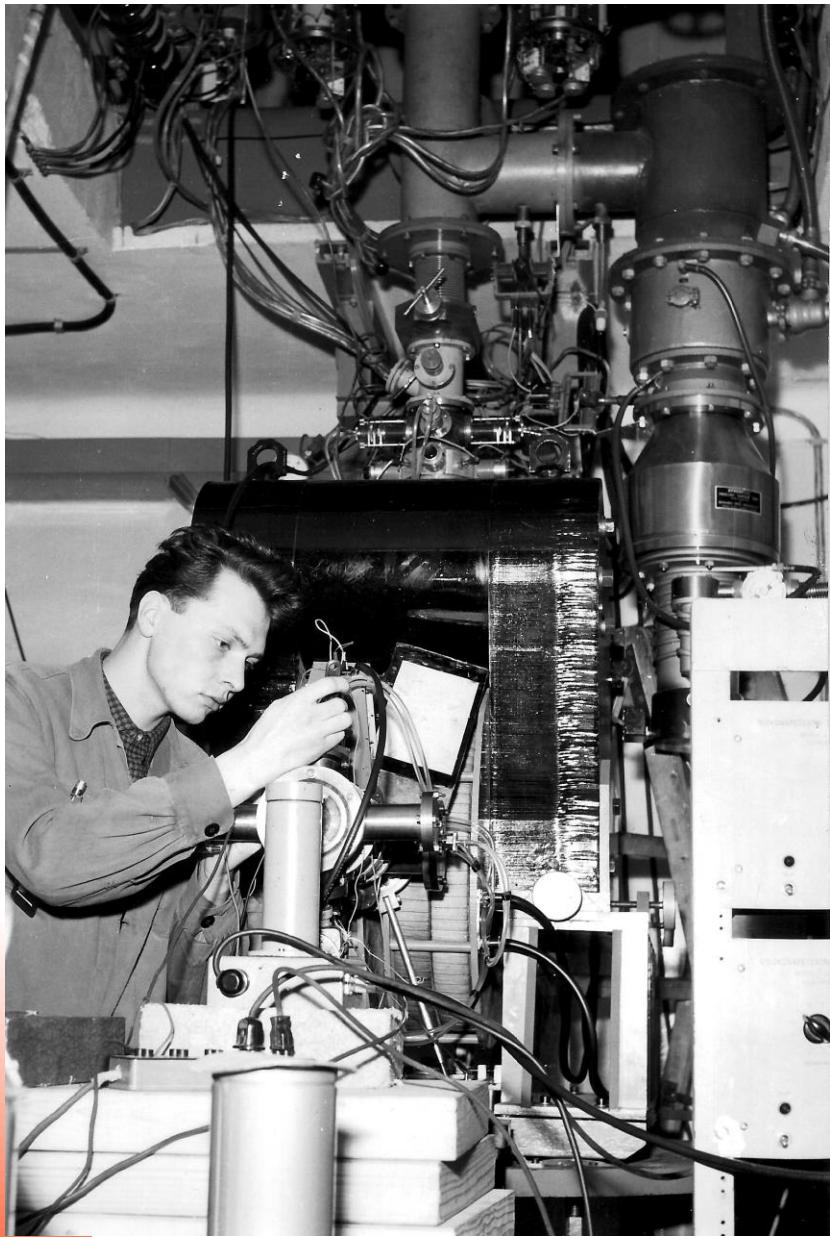
2. Tandem ion accelerator at JSI



Electrostatic Van de Graaff accelerator with accelerating voltage of 2MV has been constructed at Jožef Stefan Institute according to own technical drawings in the years 1953 - 1957. The project was headed by Eng. Edvard Cilenšek. The first successful formation of accelerated ion beam took place in May 1956. Van de Graaff accelerator at Jožef Stefan Institute operated successfully until 1999.

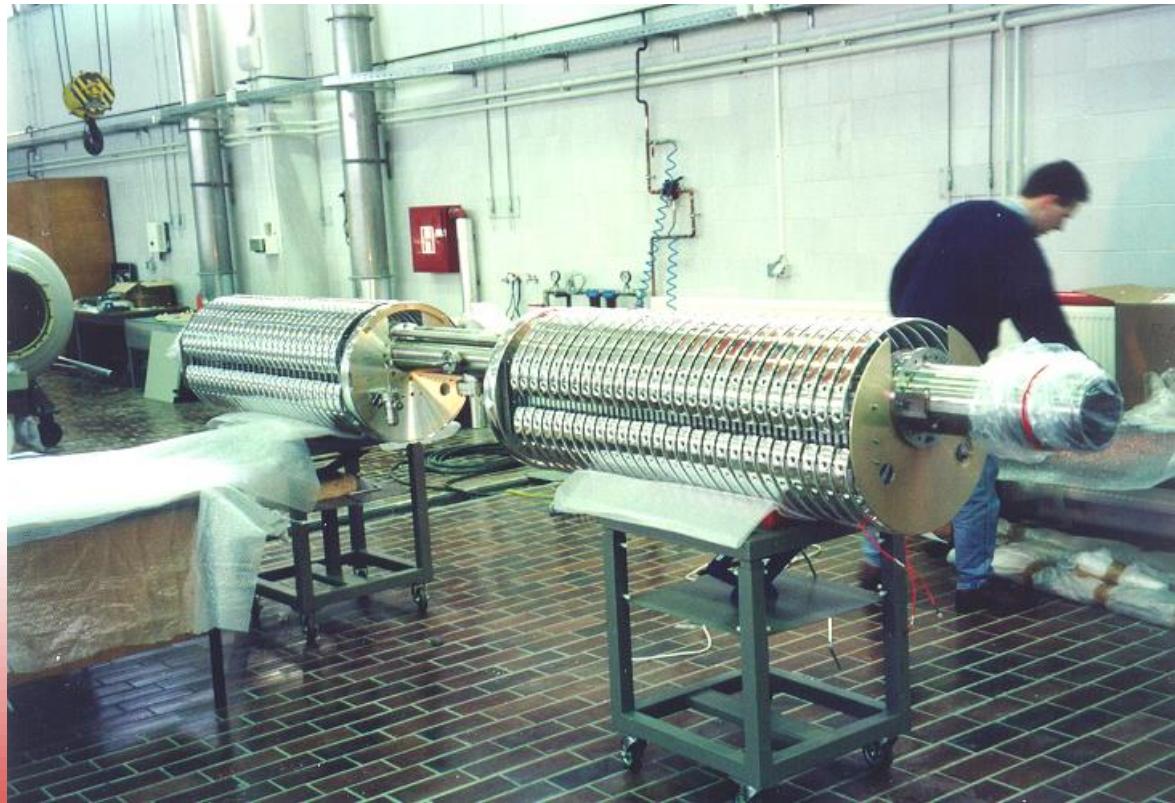


The first successful formation of accelerated ion beam took place in May 1956.
Van de Graaff accelerator at Jožef Stefan Institute operated successfully until 1999.



In 1972: first experiments in Particle-Induced X-ray Emission (PIXE) at JSI VDG accelerator.
(First PIXE conference: Lund 1976)

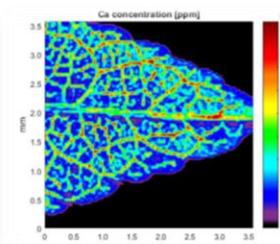
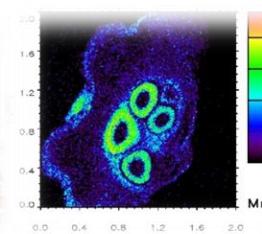
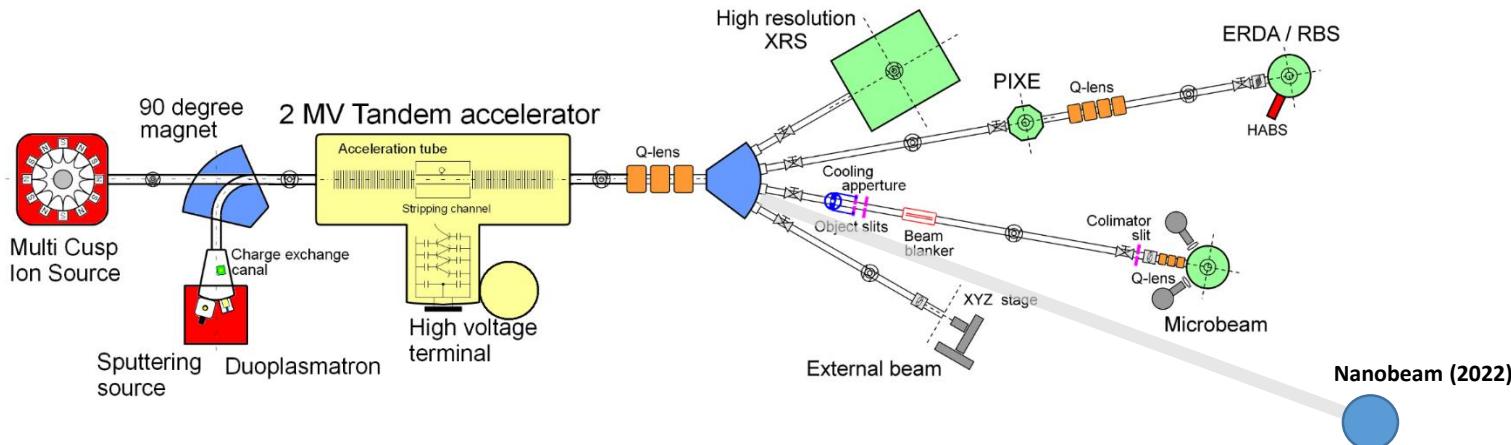
1997: Installation of 2 MV tandemron accelerator



Microanalytical centre

Member of ARIE, TNA provider within EU projects RADIATE, ReMade@ARI:

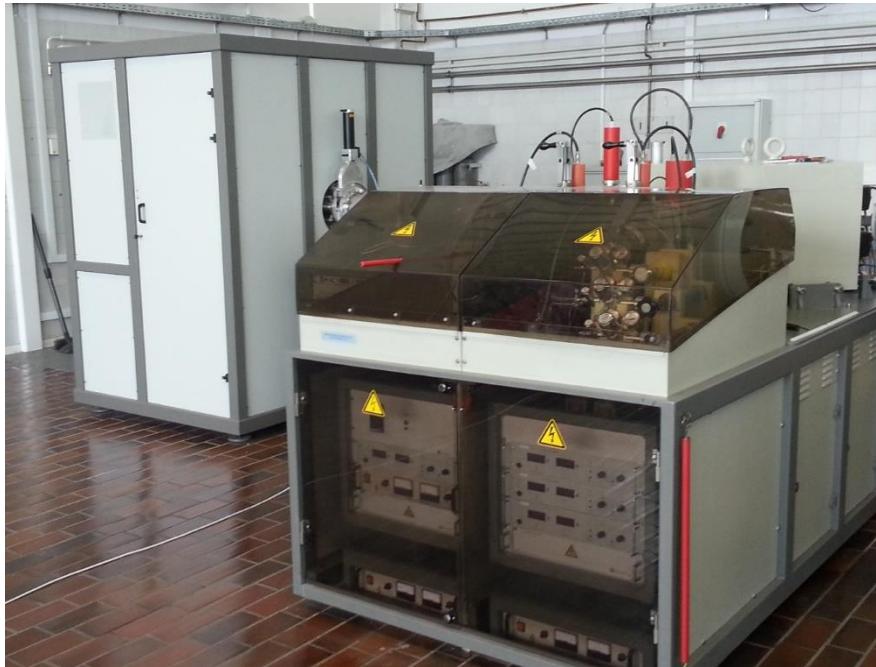
2 MV tandemron accelerator with 3 ion sources, 5 beamlines



Accelerator with beamlines



Ion sources



Multicusp SO120 (protons) , Sputter source 860A (any ion type) and Duoplasmatron 358 (3He) manufactured by HVEE Amersfort, NL. We are able to form (almost) any ion species from periodic table, and used them for ion implantation/IBA analysis.

Ion beam analysis toolkit

IBA (Ion Beam Analytical) methods, standard:

- RBS (Rutherford Back Scattering)
- Ion channeling (RBS-C, NRA-C, PIXE-C)
- ERDA (Elastic Recoil Detection Analisys)
- NRA (Nuclear Reaction Analisys)
- PIXE (Proton Induced X-ray Emission)
- PIGE (Proton Induced Gama-ray Emission)

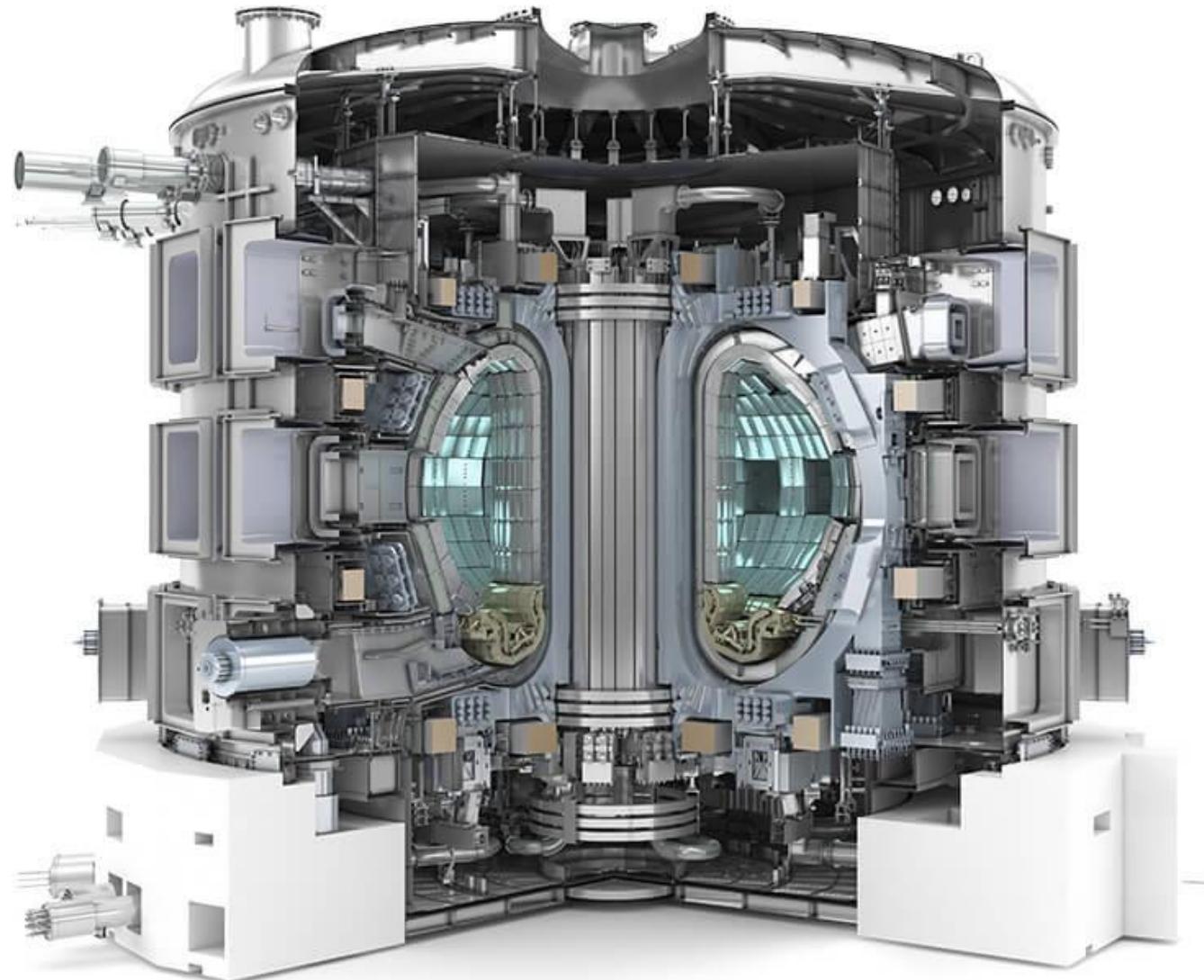
In-house developed instrumentation/ techniques:

- MeV SIMS (MeV Secondary Ion Mass Spectroscopy)
- HR-XRS (High Resolution X-ray Spectrometry)
- Three beamlines with high energy focused ion beams: in-air, microbeam, nanobeam



3. Research and applications with ion beams

Fusion

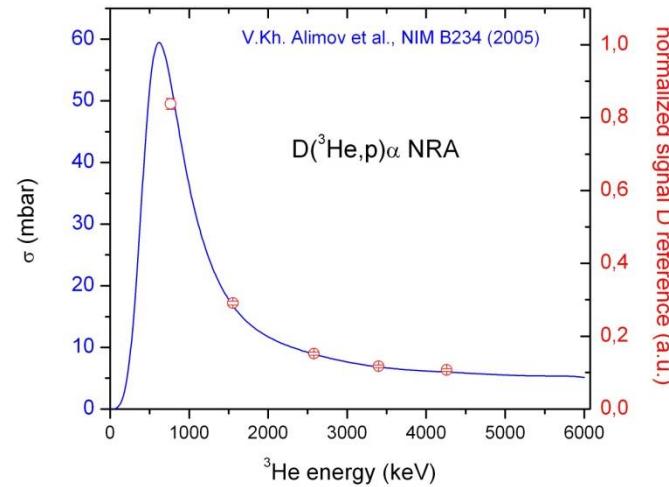
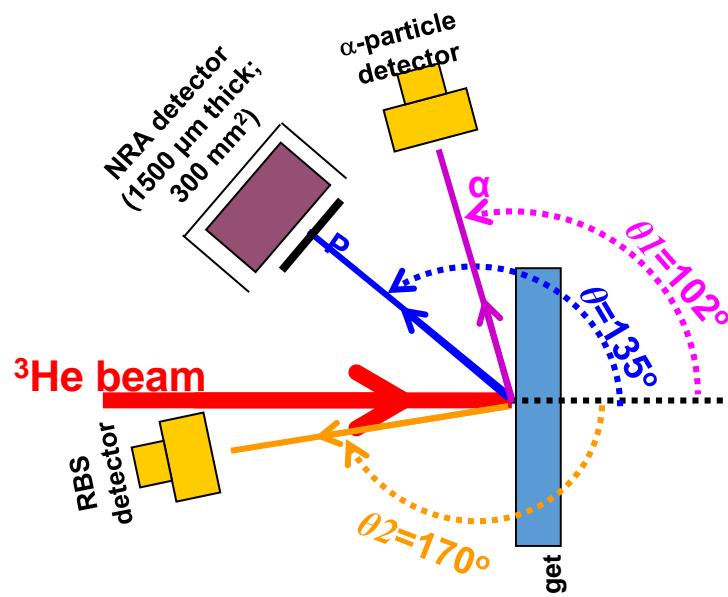


ITER, Cadarache

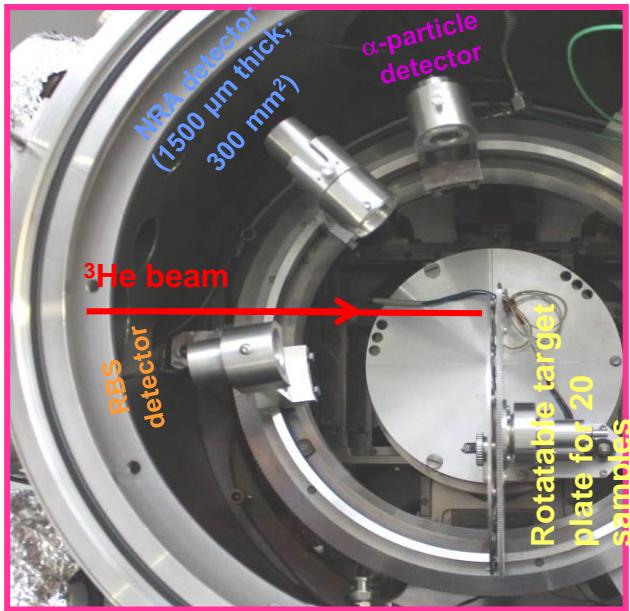
Plasma facing components, fusion fuel dynamic in wall materials

The ${}^3\text{He}$ NRA method:

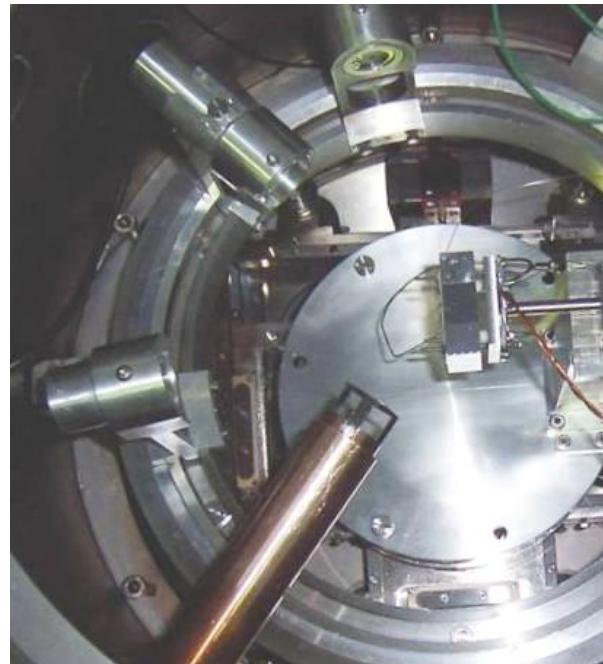
- Analyzing protons from nuclear reaction $\text{D}({}^3\text{He}, \text{p}){}^4\text{He}$ at ${}^3\text{He}$ energies from 650 (500) keV up to 4.5 MeV
- D depth profile up to 8 μm in W;
- D-concentration in near-surface layer by $\text{D}({}^3\text{He}, \alpha)\text{H}$ reaction at lowest ion beam energy – energy analyzed α particles, detected under a shallow scattering angle of 102° (V.Kh. Alimov, M. Mayer and J. Roth, Nucl. Instr. and Meth. in Phys. Res. B 234, (2005) 169)
- First measurements at on standards: a-C:D layer (60 nm) at five different ${}^3\text{He}$ energies (766, 1555, 2580, 3399, 4322 keV)



Two modes of NRA measurements:



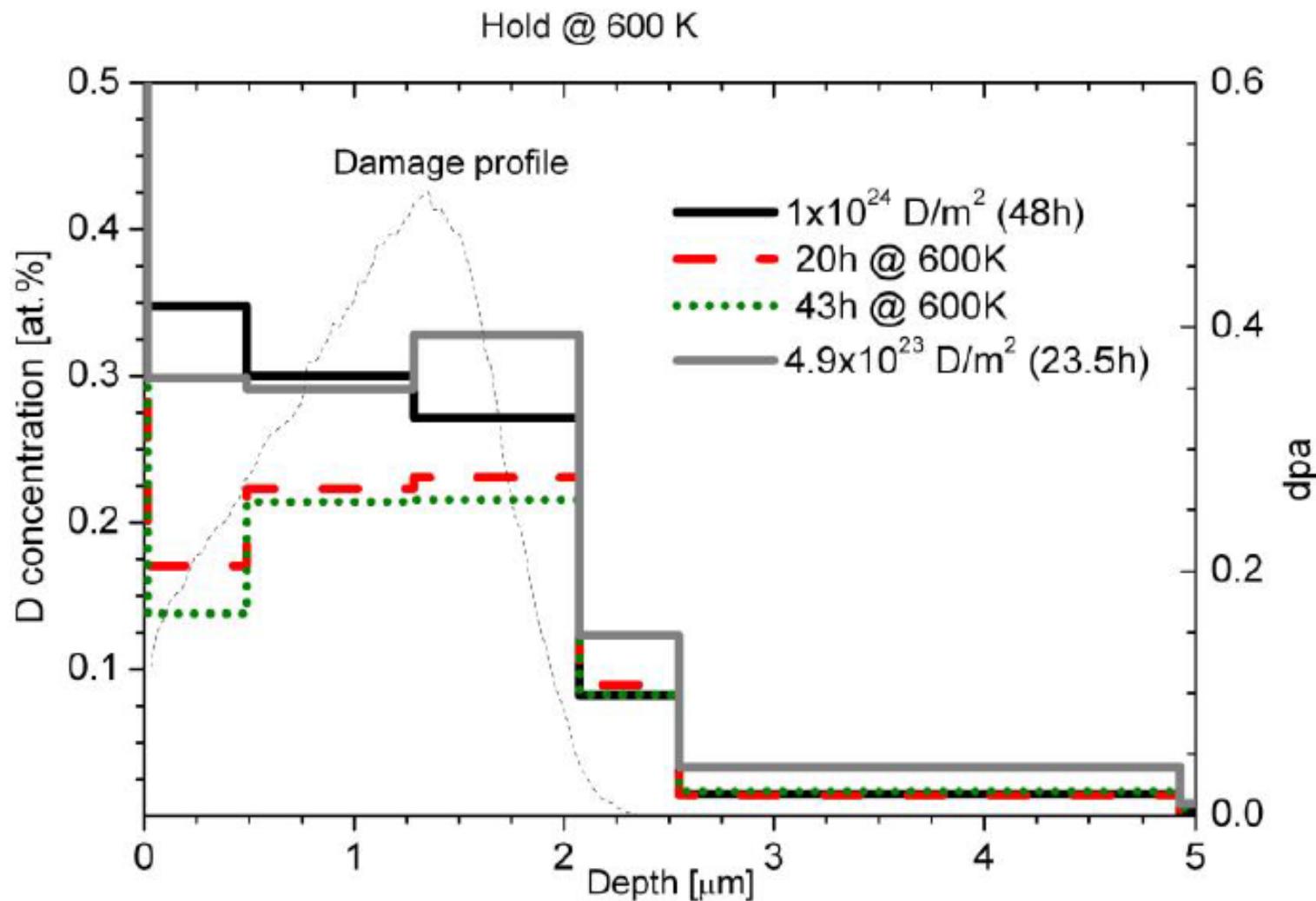
Static mode allows fast analyses of D-depth profile and sample structure for a bunch of samples in an automatic mode.



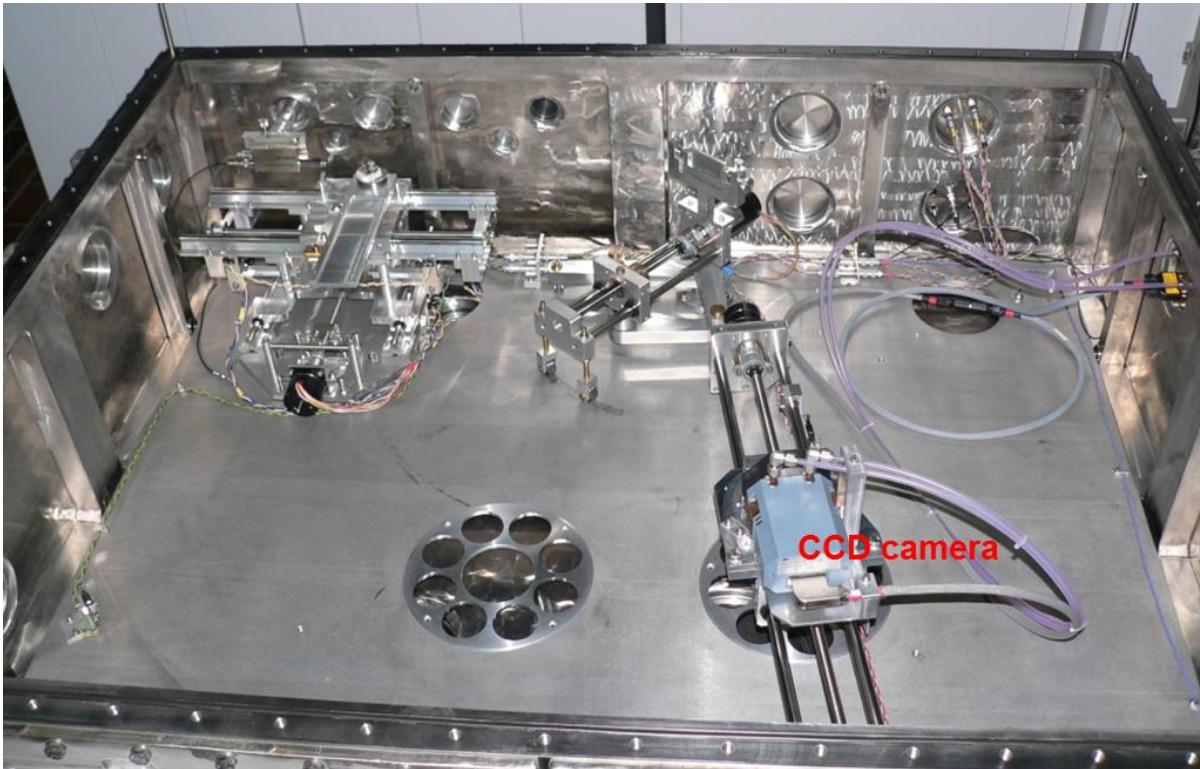
In situ NRA/RBS allows dynamic experiments on plasma interaction with materials.

T control, hydrogen atomic beam gun, plasma gun, residual gas analysis for TDS

Deuterium concentration profiles in structurally damaged tungsten after plasma exposure (Sabina Markelj et al.)



Chemical speciation by ion-induced X-ray emission (PIXE)

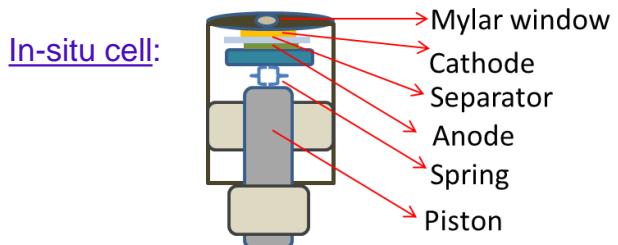


Curved-crystal x-ray emission spectrometer in
Johansson geometry

Project leader at JSI: Matjaž Kavčič

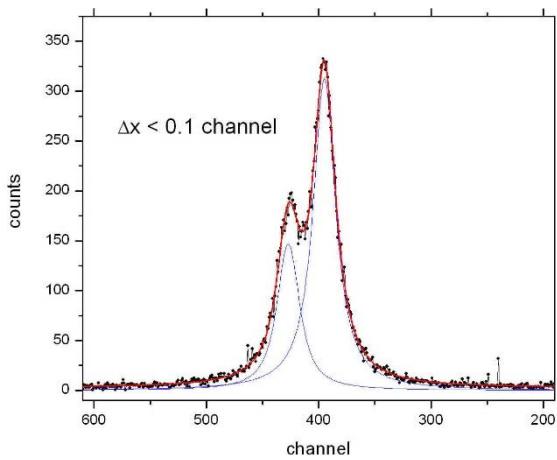
Marie Curie ITN SPRITE PhD: Marko Petric

In-situ (in-operando) S K α PIXE measurements on Li-S battery:

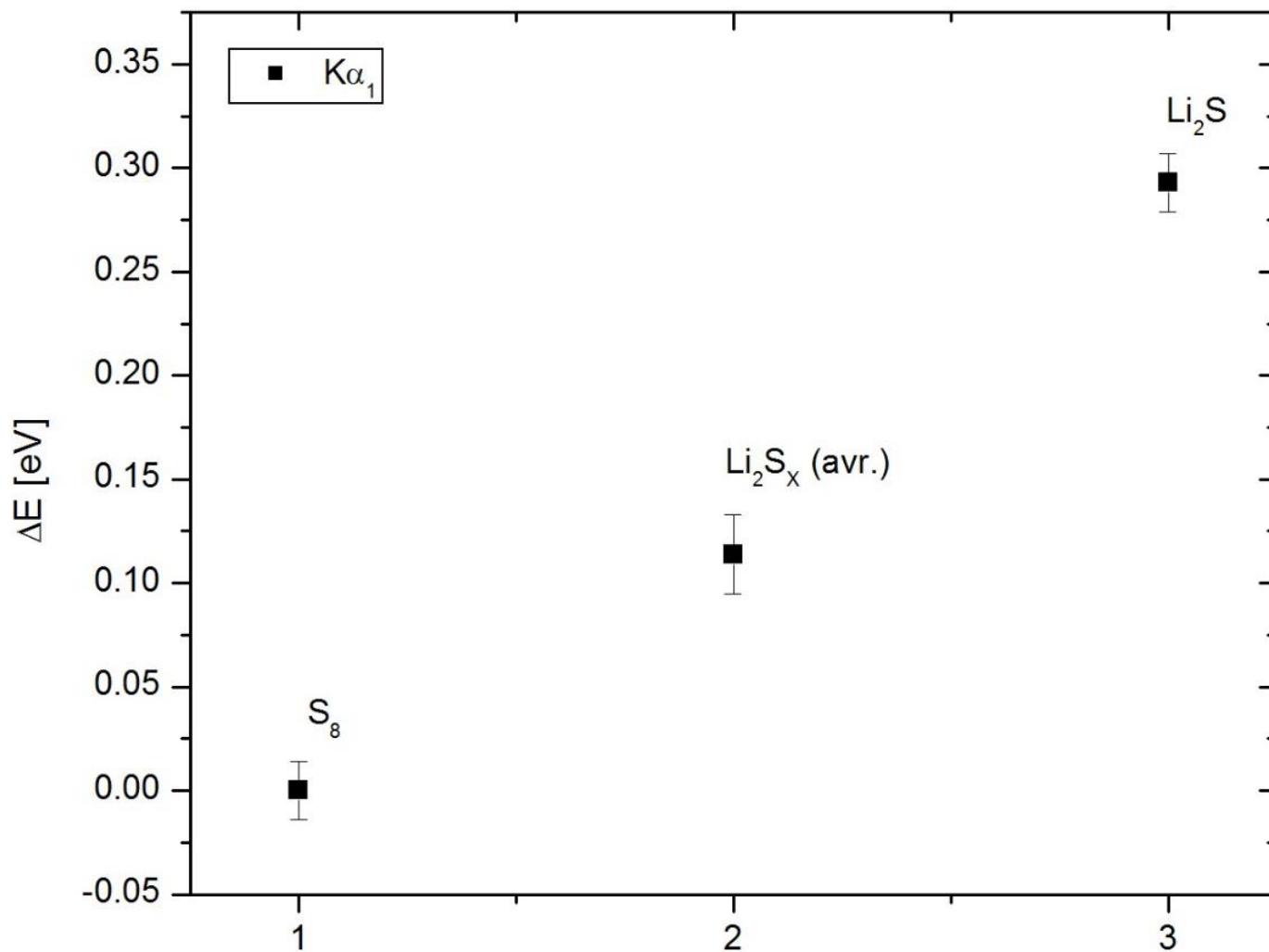


HR-PIXE measurements:

$E_p = 2 \text{ MeV}$, $I_p = 40 \text{ nA}$
 $t_{\text{acq}} = 30 \text{ min}$

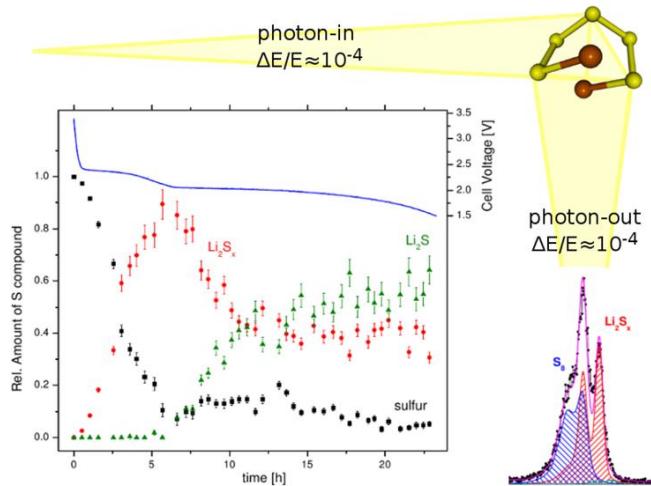
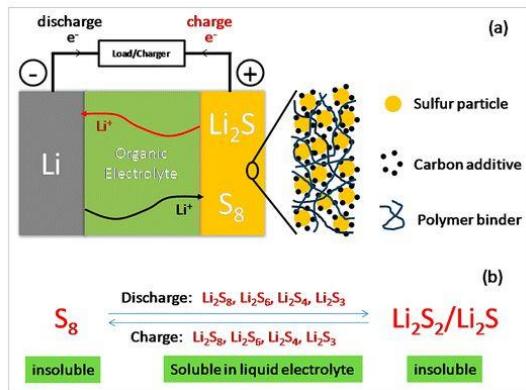


K α XES measurements on Li $_2$ S $_X$ standards:



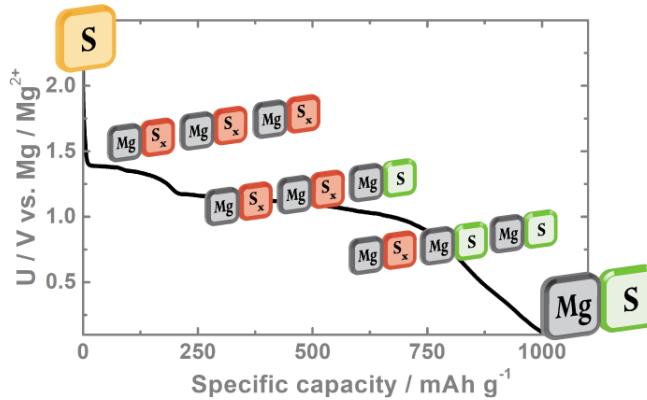
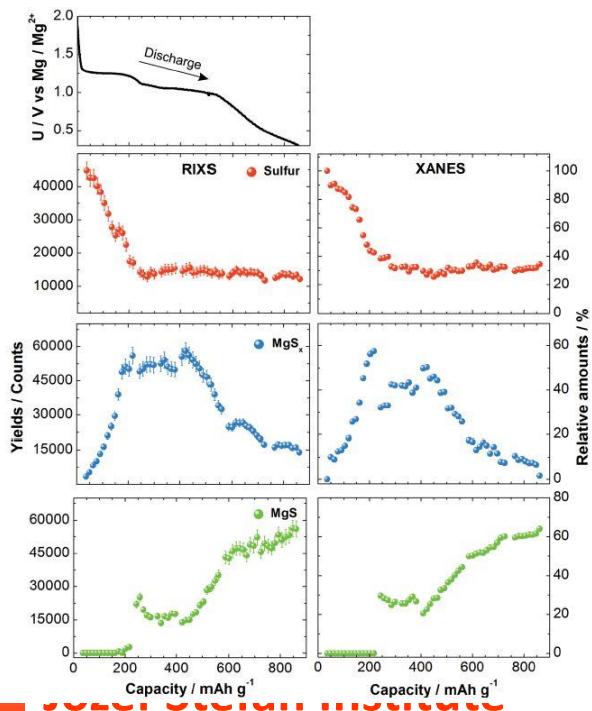
In operando analysis of batteries

Li-S:



M. Kavčič, K. Bučar, M. Petrić, M. Žitnik, I. Arčon, R. Dominko, A. Vižintin, *J. Phys. Chem. C*, **120**, 24568 (2016).

Mg-S:



A. Robba, A. Vizintin, J. Bitenc, G. Mali, I. Arčon, M. Kavčič, M. Žitnik, K. Bučar, G. Aquilanti, I. C. Martineau-Corcos, A. Randon-Vitanova, and Robert Dominko, *Chem. Mater.*, **29**, 9555–9564 (2017).

Matjaž Kavčič et al

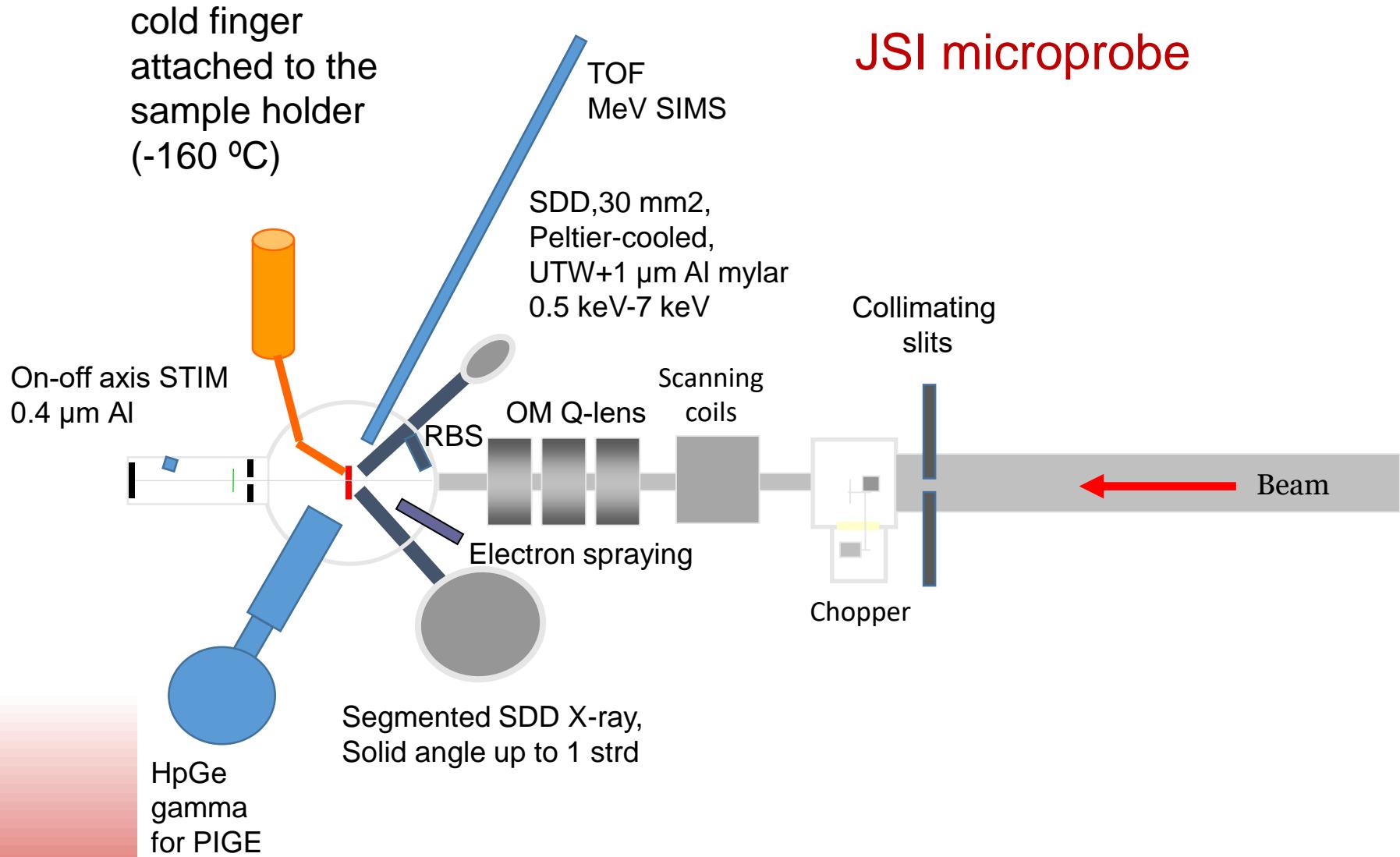
- Biomedicine

Laboratory is a member of national node of the

EU ESFRI Eurobioimaging ERIC

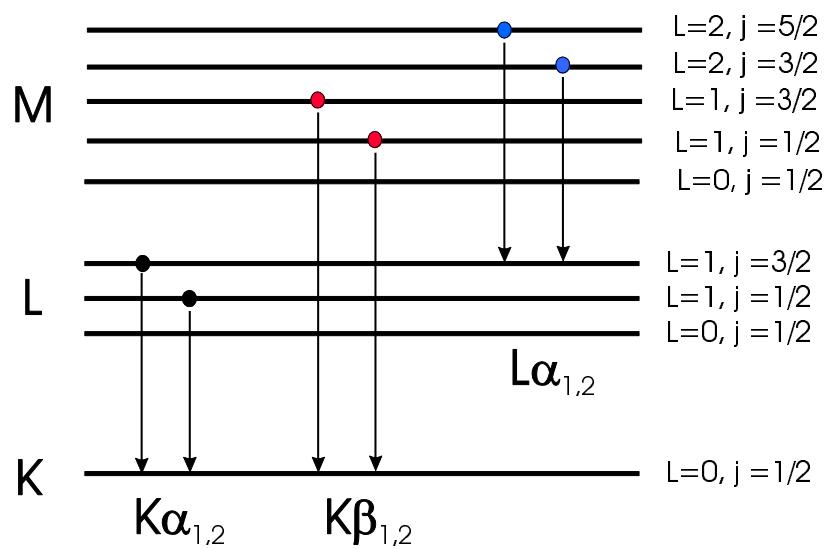
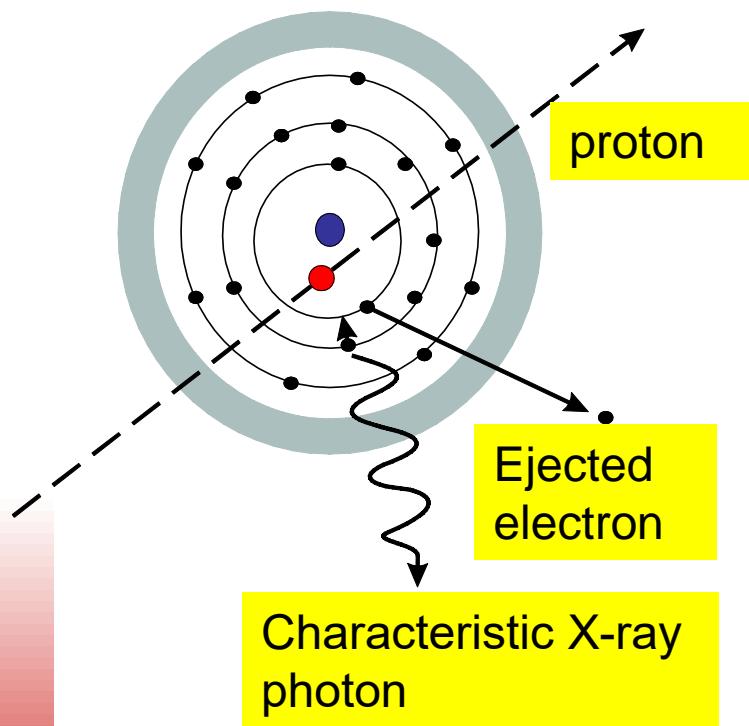
(elemental imaging with micro-PIXE, molecular imaging with MeV-SIMS)

JSI microprobe

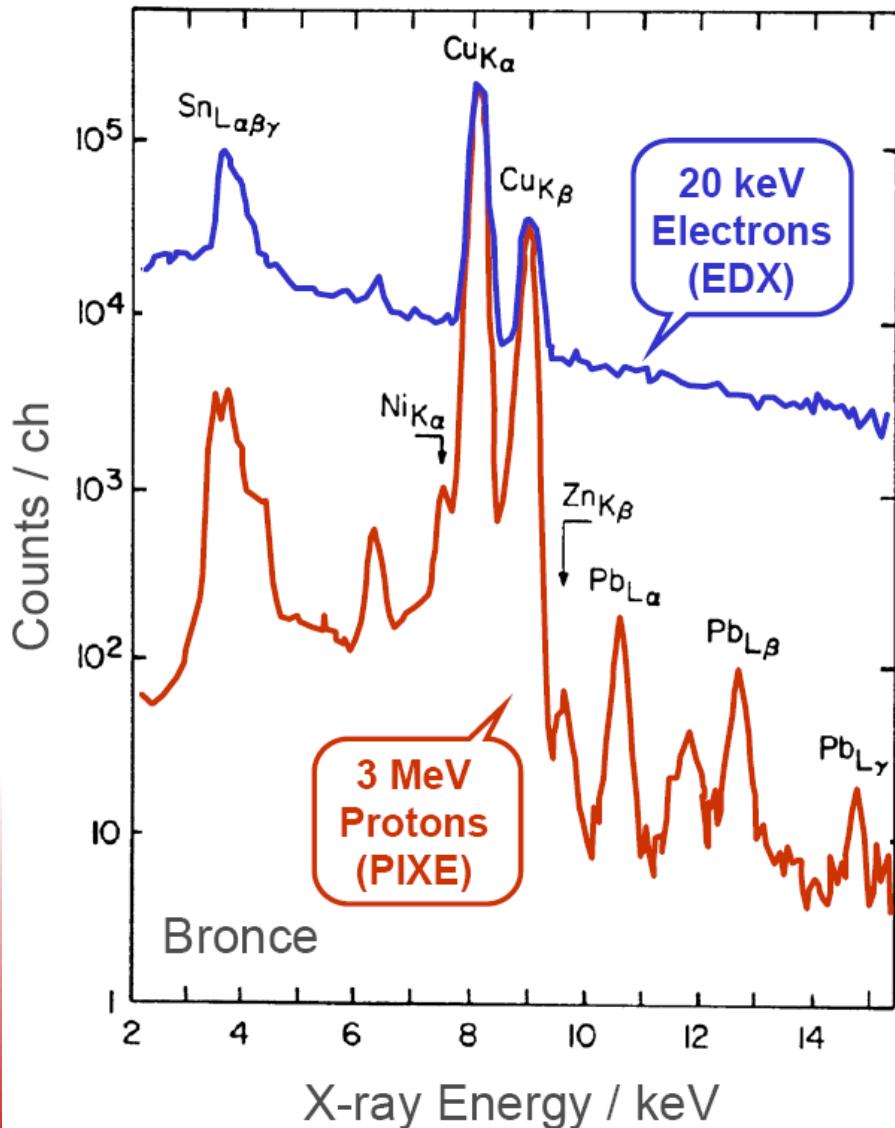


During the analysis, biological tissue in freeze-dried or frozen hydrated state

PIXE – Proton-Induced X-ray Emission



PIXE similar to the Energy Dispersive X-ray emission (EDX), available at scanning electron microscopes (SEM). Comparison:



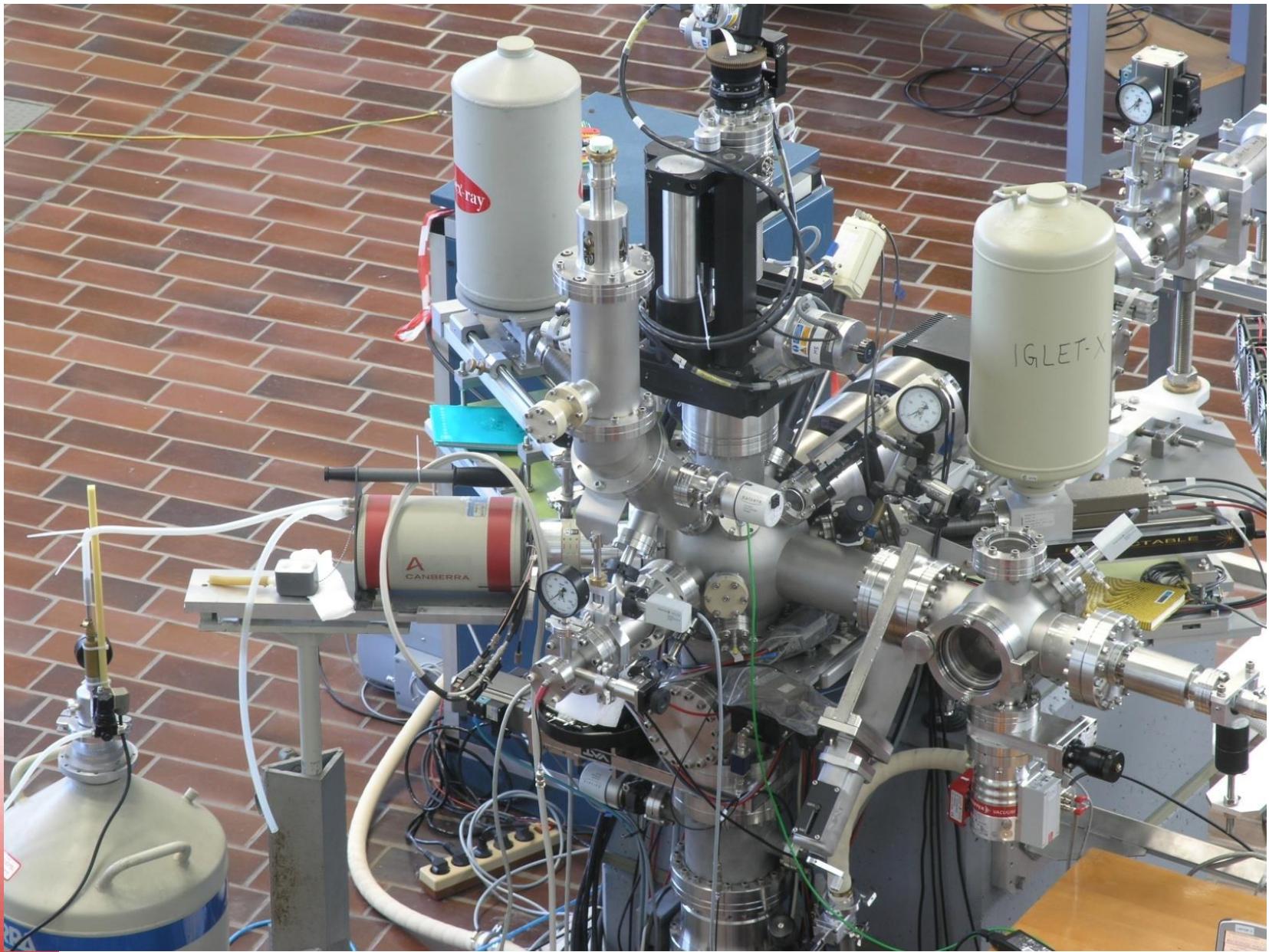
EDX: electron 20 keV
PIXE: proton 3 MeV

Bremsstrahlung intensity
by primary particle
proportional to $(1/m)^2$

$m_p/m_e = 1836$

Background
intensity much lower
with protons

EDX: LOD 1000 ppm
PIXE: LOD 0.2 ppm Zn
1 ppm Fe
10 ppm Pb



$j=\sigma T^4$

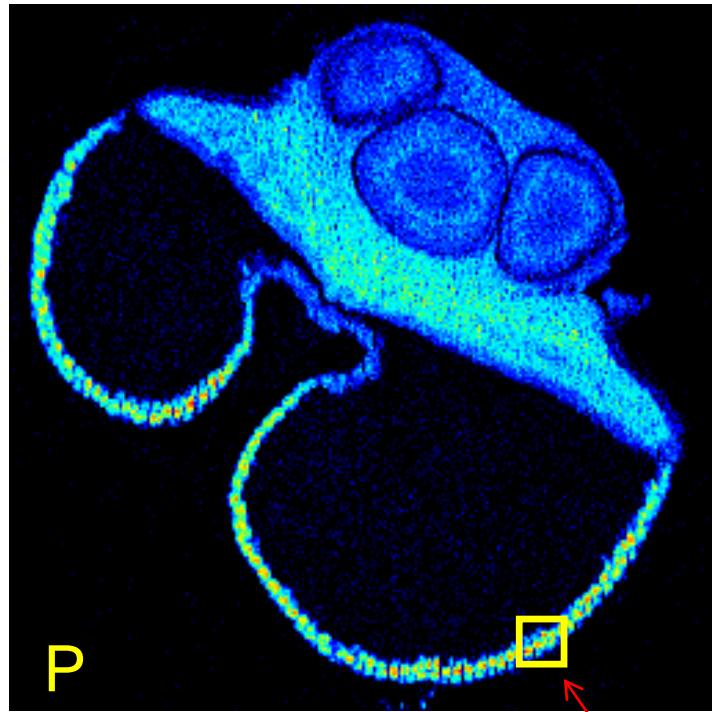
Jožef Stefan Institute

Nuclear microprobe at JSI

Micro-PIXE is very suitable to determine the quantity and the distribution of minerals in the grains of cereals

Uptake of soil minerals by wheat:
elemental distribution in wheat grain



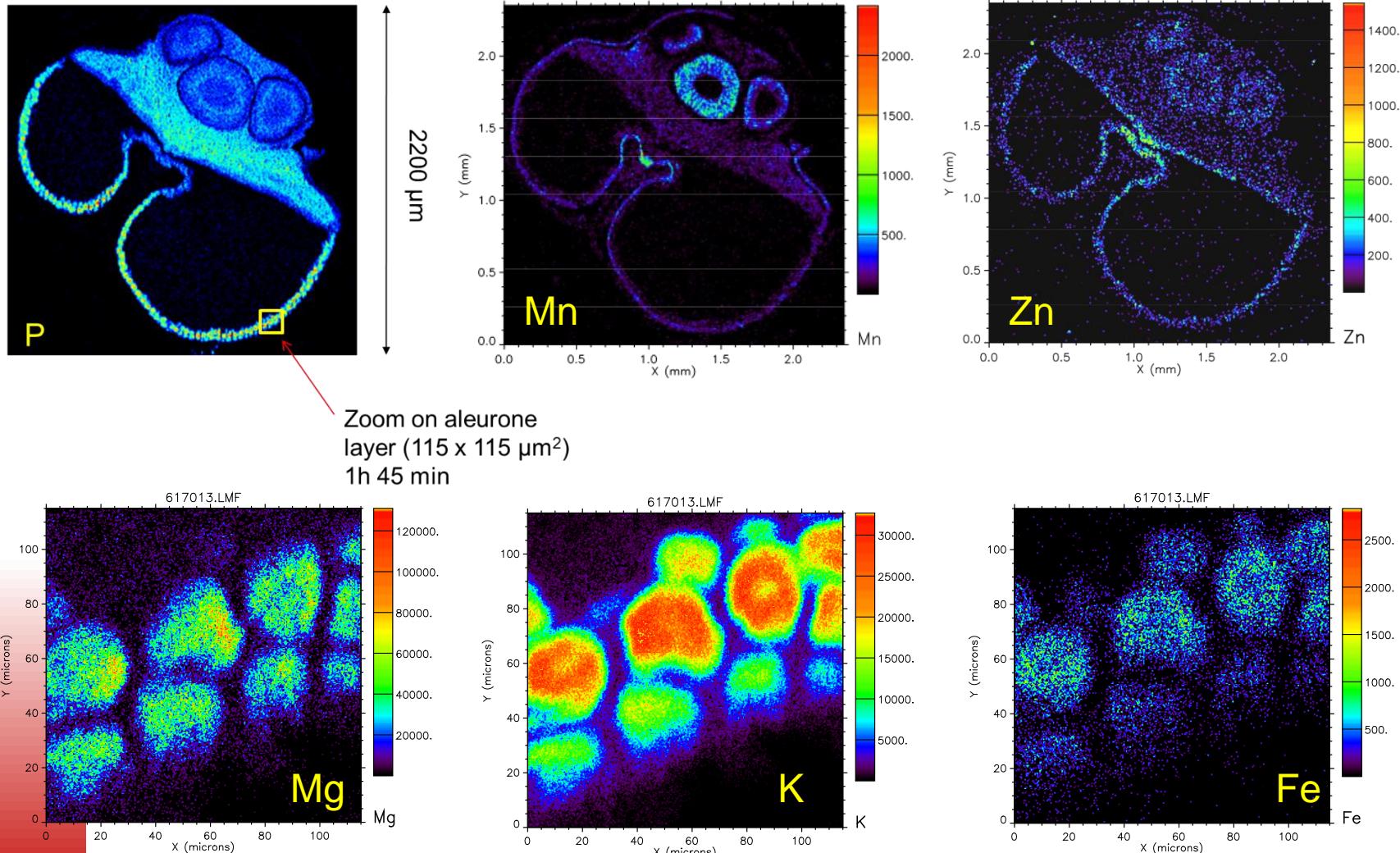


2200 μm

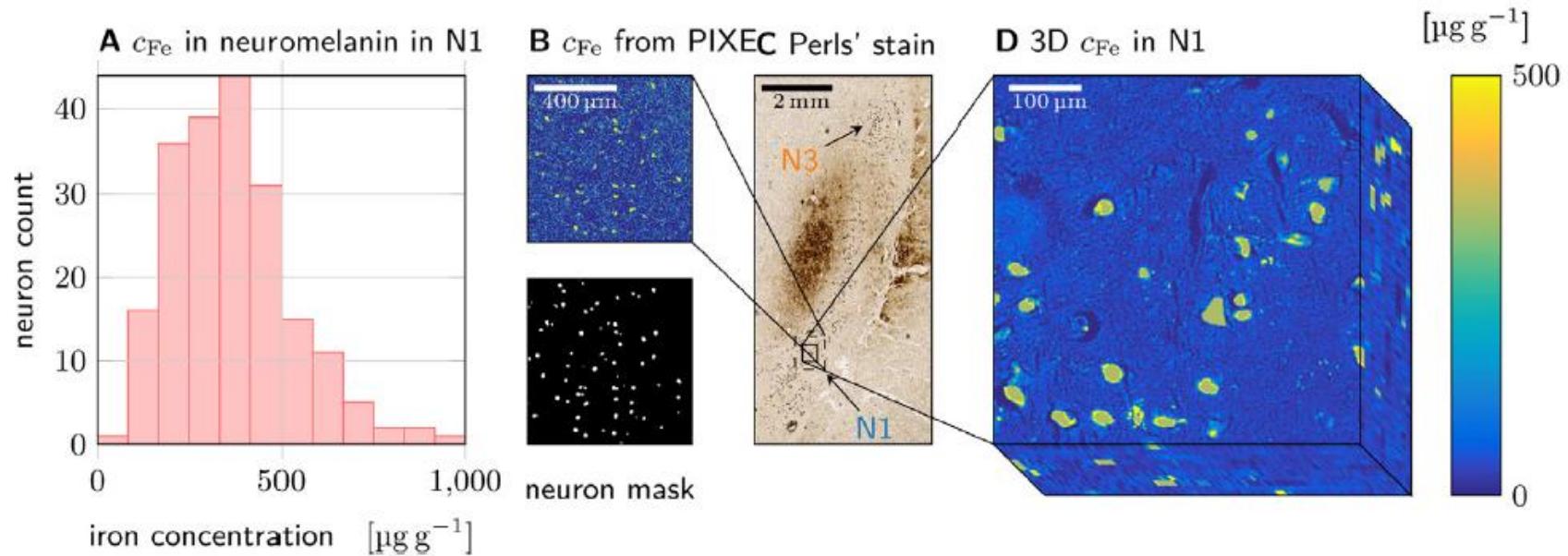
Zoom on aleurone
layer ($115 \times 115 \mu\text{m}^2$)
1h 45 min

Cross section of wheat grain

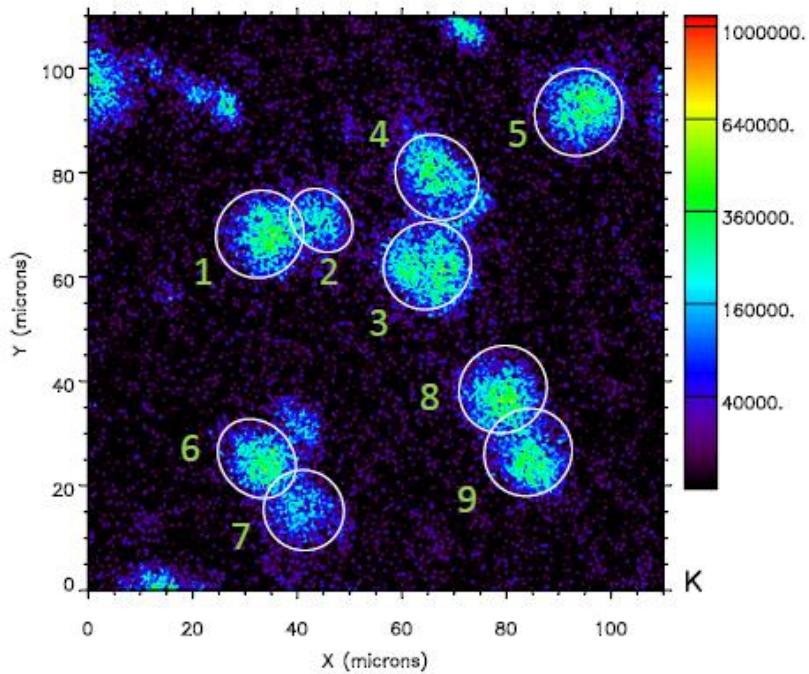
(Singh et al, Jour. Exp. Bot. 2013, Pongrac et al, Jour.Royal Soc.Interf. 2013)



Elemental imaging of human brain tissue: iron distribution (collaboration with Max Planck Institute for cognitive sciences, Leipzig)

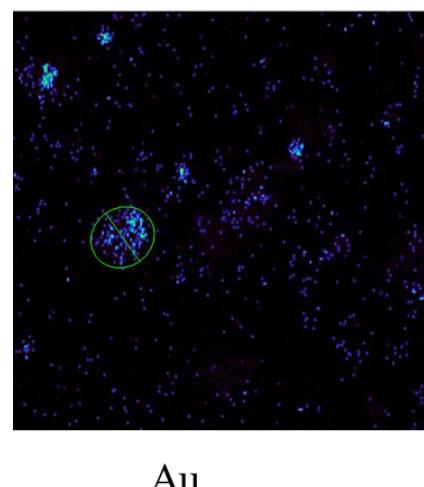
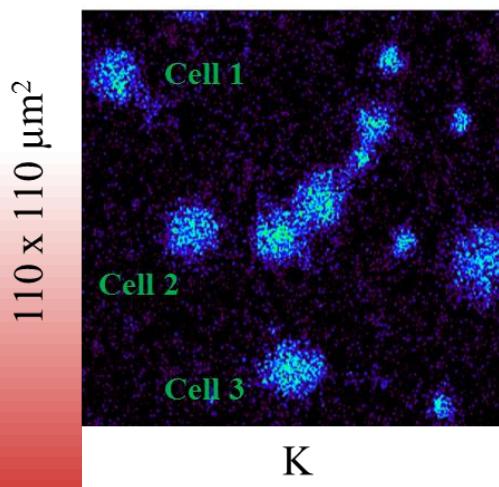


Quantitative iron histology of *post mortem* human brain tissue with micro-PIXE
in search for early markers for Parkinson's disease
(Malte Brammerloh, Tilo Reinert et al, Neuroimage 2021).



Micro-PIXE:

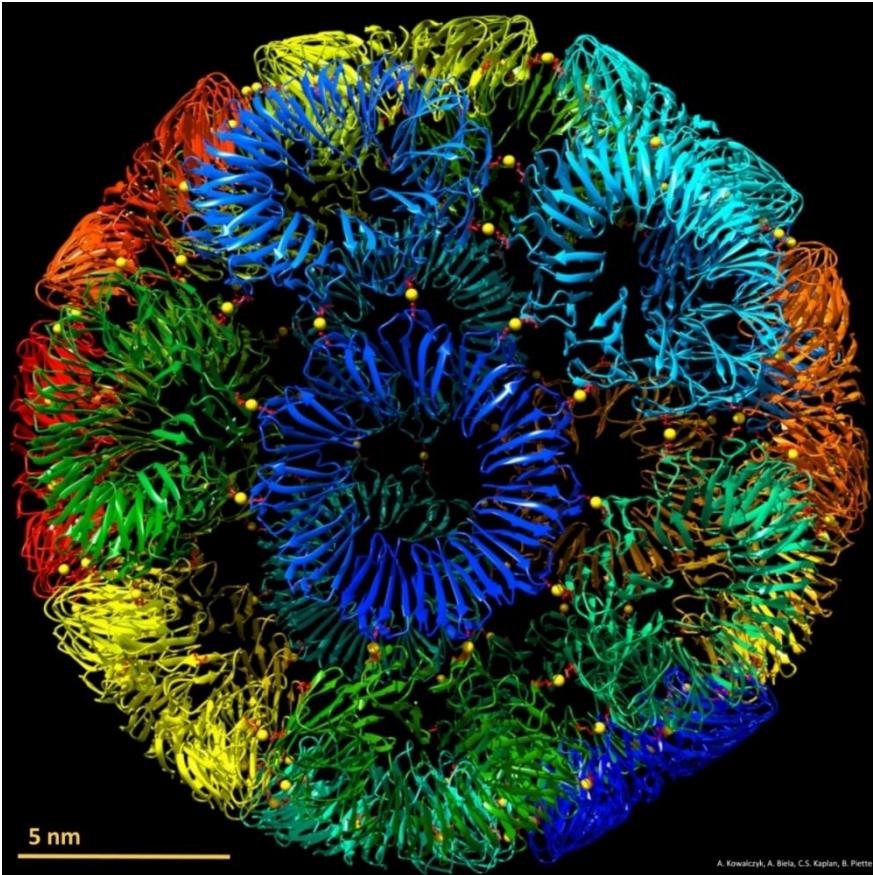
Determination of mass of particular element in individual cells, precision 1 pg (10^{-12} g): nanotoxicology, nanomedicine, pharmacy.



Cell 2:
 (3.3 ± 0.5) pg K
 (21.1 ± 2.5) pg Au

Example: Uptake of Au nanoparticles in human cells

Tomić et al, Plos One 2014



LETTER

<https://doi.org/10.1038/s41586-019-1185-4>

An ultra-stable gold-coordinated protein cage displaying reversible assembly

Ali D. Malay^{1,14}, Naoyuki Miyazaki², Artur Biela^{3,4}, Soumyananda Chakraborti³, Karolina Majsterkiewicz^{3,5}, Izabela Stupka^{3,5}, Craig S. Kaplan⁶, Agnieszka Kowalczyk^{3,7}, Bernard M. A. G. Piette⁸, Georg K. A. Hochberg^{9,15}, Di Wu⁹, Tomasz P. Wrobel¹⁰, Adam Fineberg⁹, Manish S. Kushwaha⁹, Mitja Kelemen^{11,12}, Primož Vavpetič¹³, Primož Pelicon¹¹, Philipp Kukura⁹, Justin L. P. Benesch⁹, Kenji Iwasaki^{2,13} & Jonathan G. Heddle^{1,3*}

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24 modified trap rings in a cage

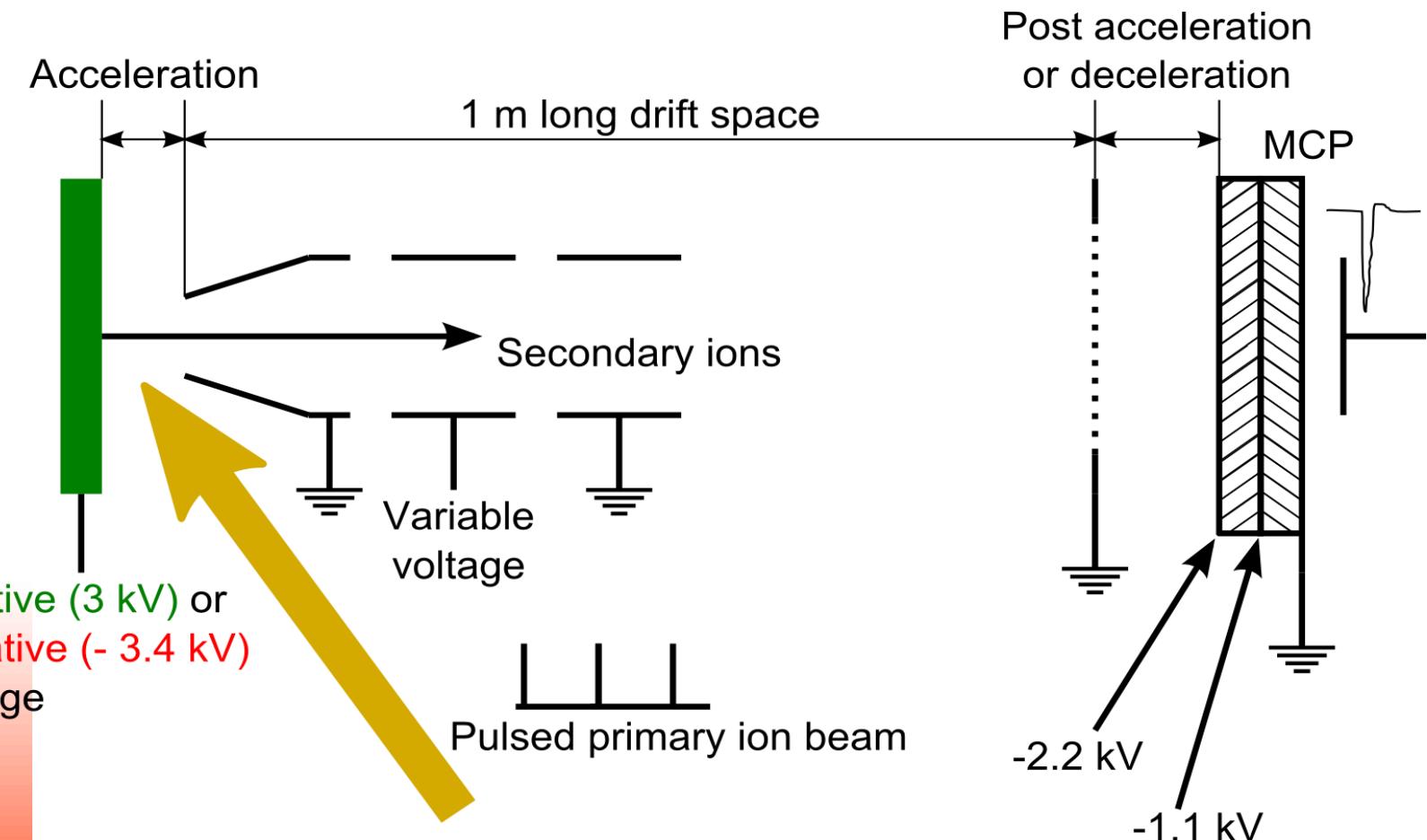
Each ring contains
11 monomeres with
1 cisteine and 1 methionine.
So each cage contains
 $24 \times 11 \times 2 = 528$
sulphur atoms.

Five neighbours are involved in binding to a selected ring by altogether 10 thiols, one thiol remains unused. Thus the S:Au ratio would be in this case **528/120 = 4.4**

There is
24 x 10 cisteines that form the thiol bonds. If gold is bonded also on the eleventh thiol group and not linked with another ring, S:Au ratio would be in this case **528/144 = 3.7**

Our result: **6 (1 ± 0.15)**

MeV-SIMS at JSI



Comparison: MeV SIMS vs. keV SIMS

keV SIMS: 25 KeV Bi_3^+ beam at TOF.SIMS 5 spectrometer (IONTOF)

MeV-SIMS: 5.8 MeV $^{35}\text{Cl}^{6+}$ beam.

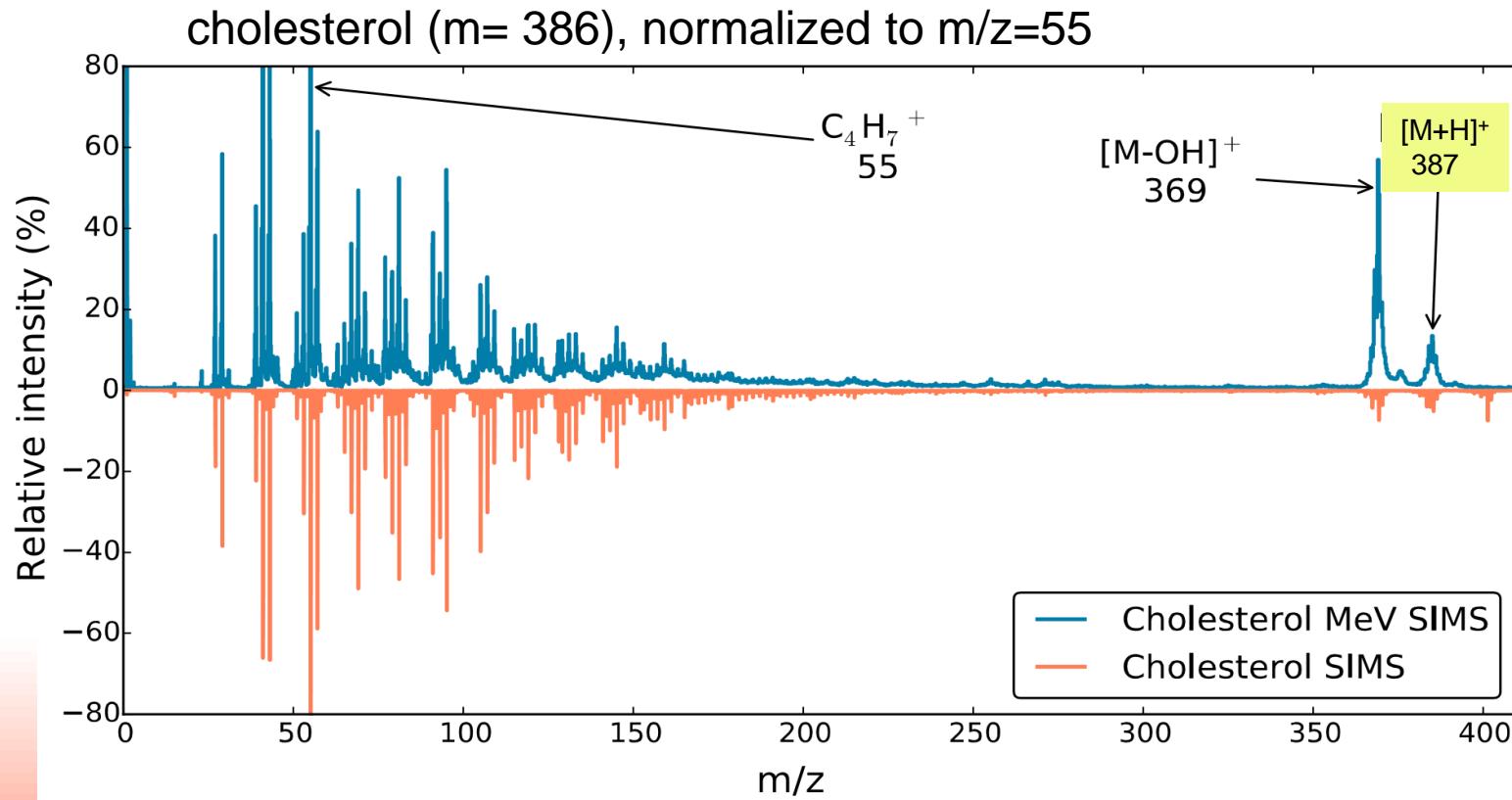
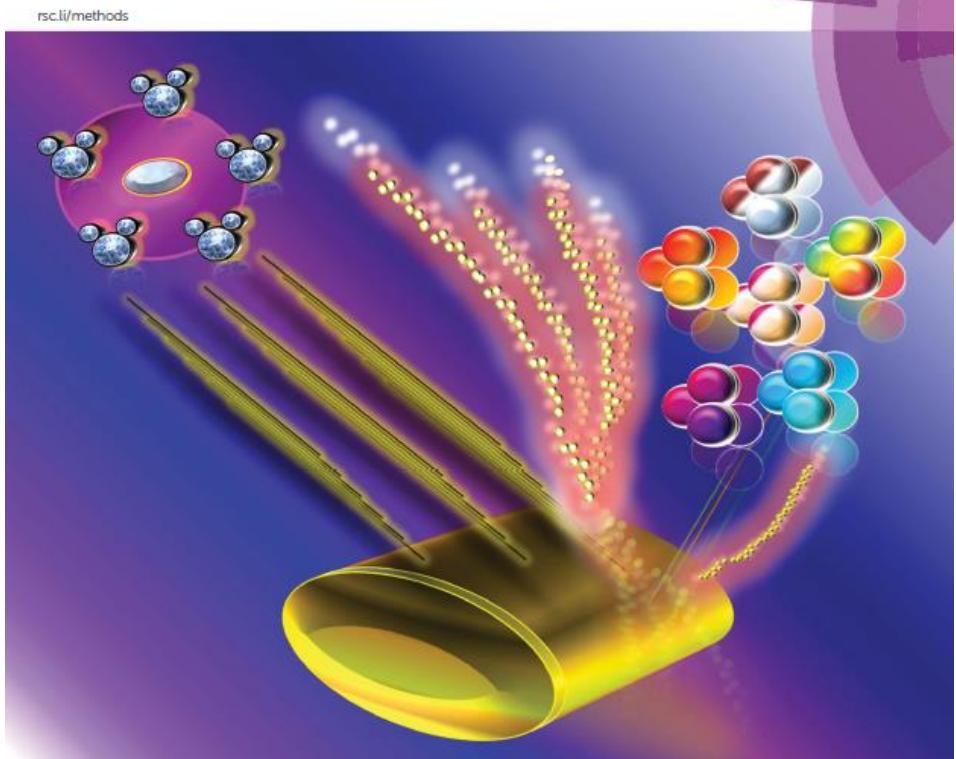


Figure 5.10: Comparison of Cholesterol mass spectra acquired with 25 keV Bi_3^+ beam (SIMS, lower spectrum) and 5.8 MeV $^{35}\text{Cl}^{6+}$ beam (MeV SIMS, upper spectrum). Both spectra were acquired from the same sample. Molecular peak is clearly present as well as even more abundant signal of molecule loosing hydroxyl group at $m/z = 369$. The relative intensities are normalized to the fragment $[\text{C}_3\text{H}_7]^+$ at $m/z = 55$ present in both spectra.

Analytical Methods

Human hair:

medium containing record on drug abuse, pharmaceutical treatment, etc.



ISSN 1759-9679



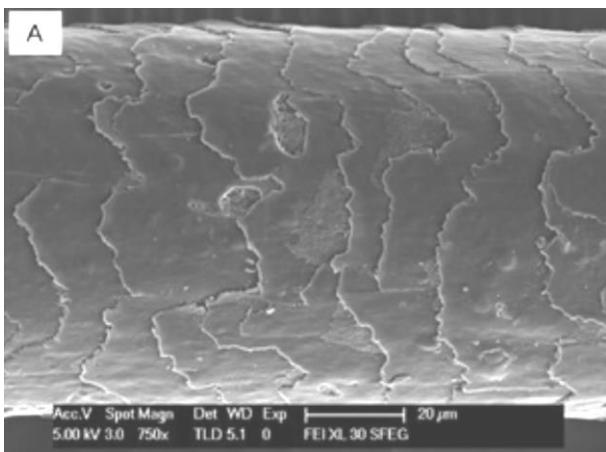
ROYAL SOCIETY
OF CHEMISTRY

COMMUNICATION

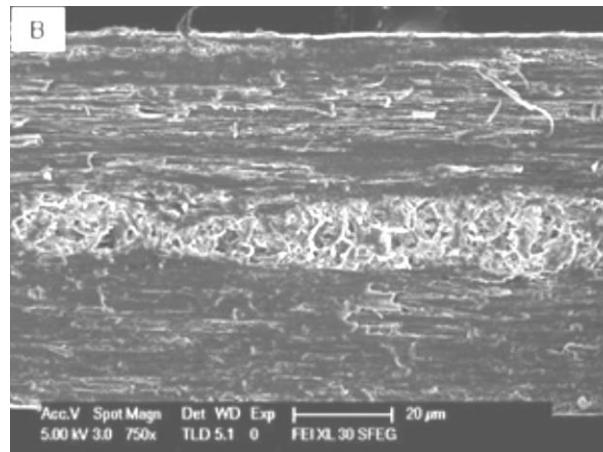
Karen J. Cloete *et al.*
Detection of lithium in scalp hair by time-of-flight secondary ion mass spectrometry with high energy (MeV) primary ions

MeV-SIMS: a novel Imaging Mass Spectrometry (IMS) technique is under development within the Ion Beam Analysis Community. It features several niche advantages in respect to the more known IMS techniques (MALDI, DESI, SIMS): high sensitivity for larger organic molecules, no needed surface preparation, high lateral resolution (less than 1 micrometer), ...

The case of cocaine incorporation in human hair:



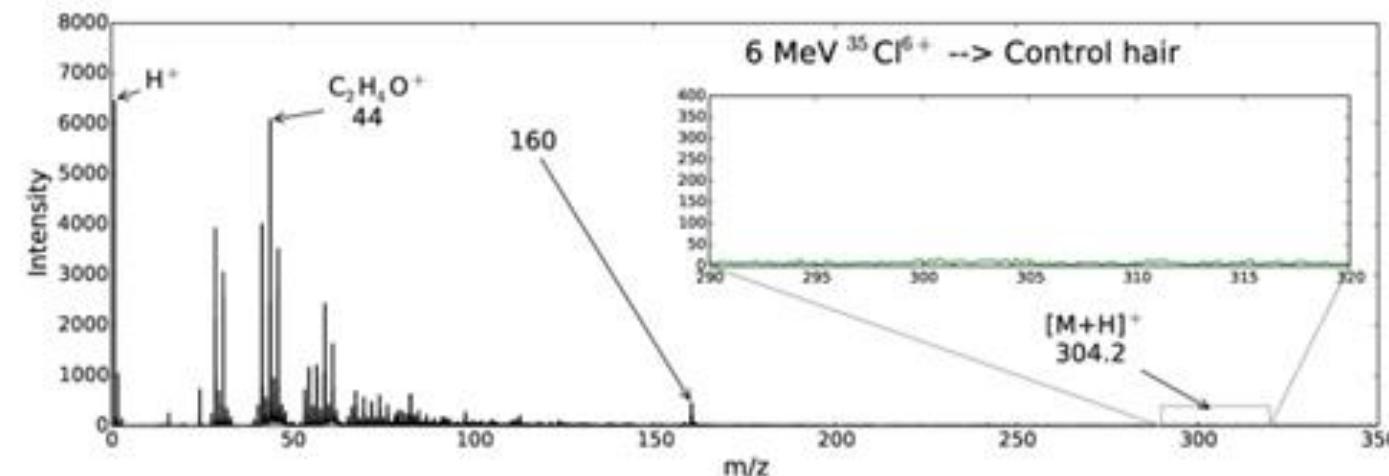
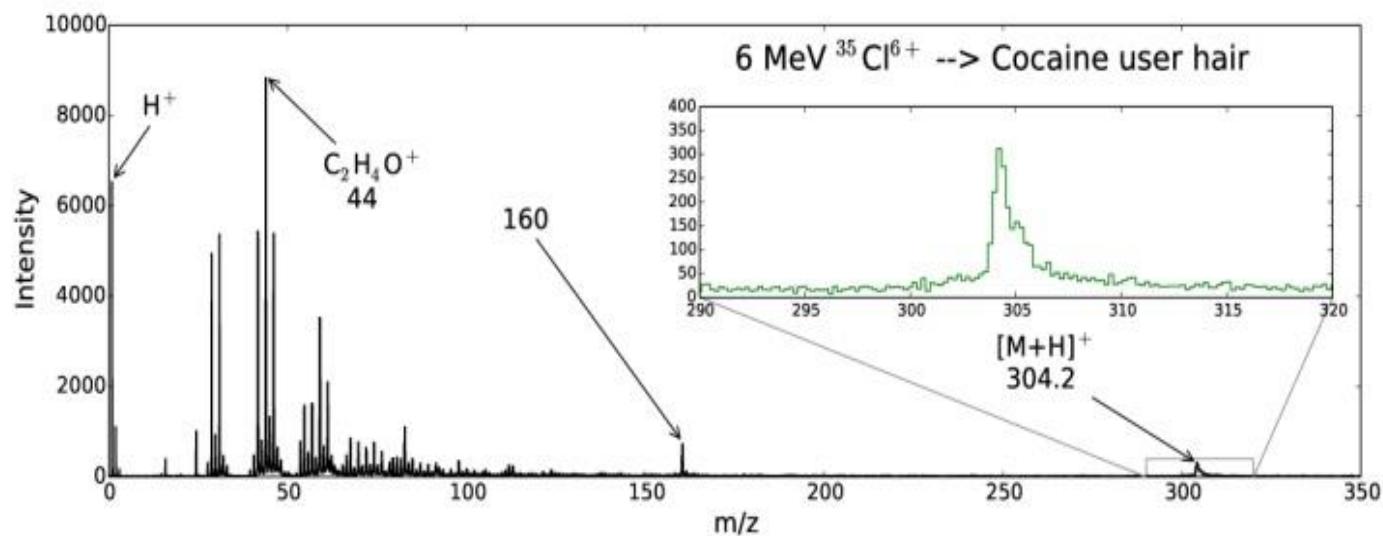
Before cutting

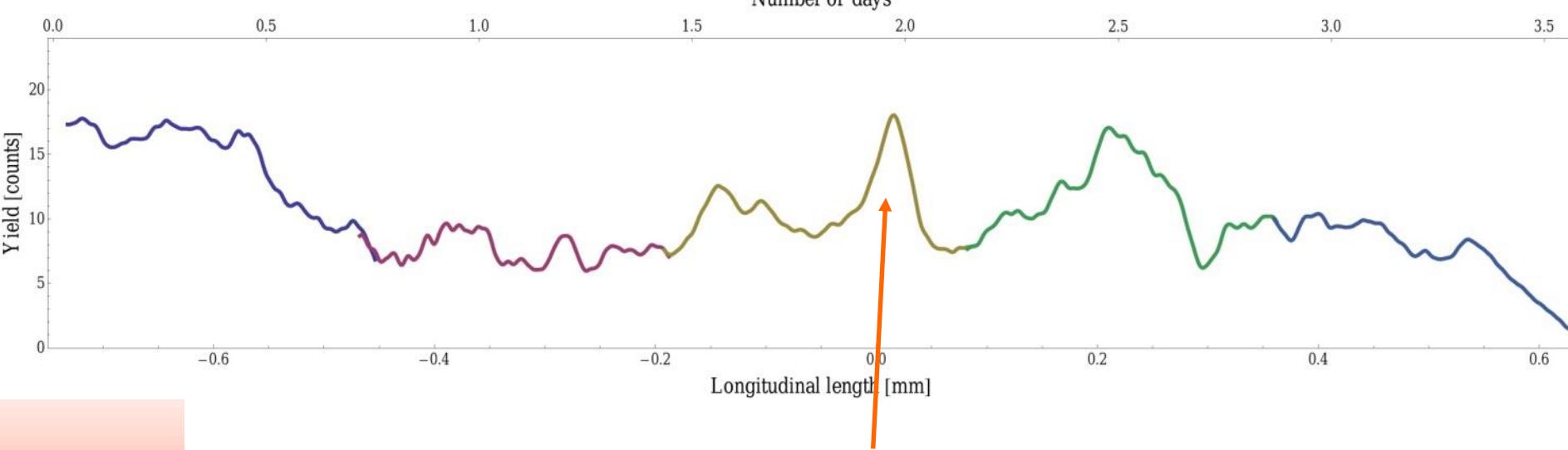
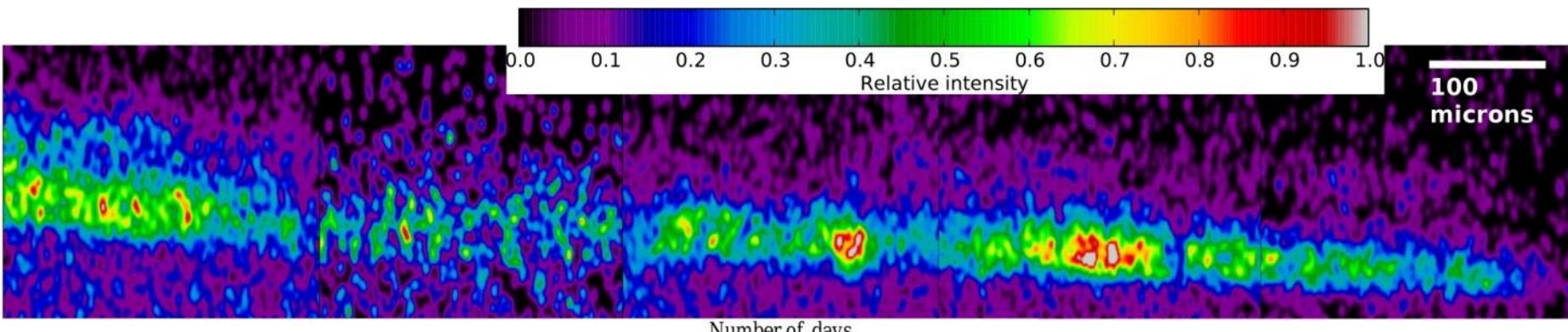


After cutting

Flinders et al, Drug Testing and Analysis 2014

Cocaine $[M+H]^+$ at $m/Z = 304$





width of this peak corresponds
to the hair growth time of 3 hours

4. Transnational access programme to JSI accelerator/beams

H2020 No. 824096 »RADIATE«, 2019-2023

End of proposal portal: 31.3.2023

End of project: June 31, 2023

All ion beam applications

<https://www.ionbeamcenters.eu/radiate/>



ReMade@ARI, 2022-2026

<https://remade-project.eu/>

Ion beam application on circular economy



EUROBIOIMAGING

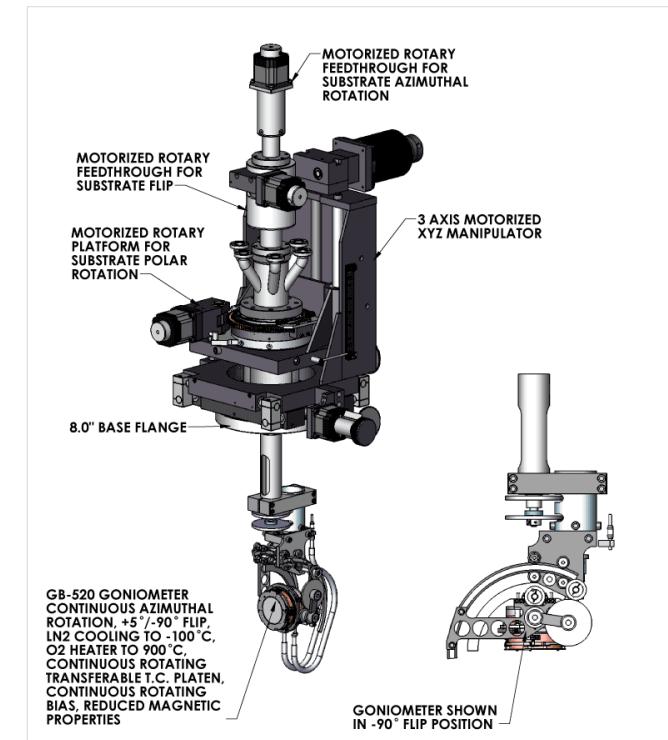
Application in life sciences

<https://www.eurobioimaging.eu/>



5. Conclusions

6-axis channeling goniometer



Resolution in rotation: 0.01 degrees
Sample platen heating to 1200°C continuous
Liquid nitrogen cooling
Maximum sample bias 500 V
Sample size 4 cm
Data acquisition system for 5 detectors with computer and program for spectra collection
Additional: Load-lock chamber with magnetic arm



Nanobeam at JSI: in march 2023 beam diameter < 300 nm

