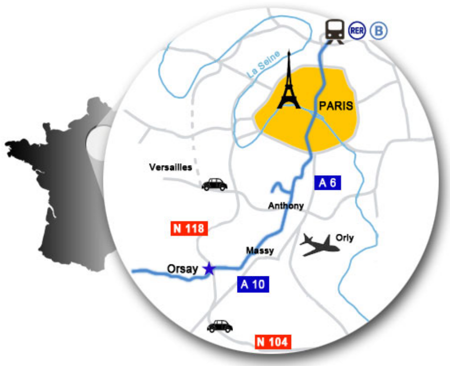
Ion traps for advancing nuclear physics in Orsay

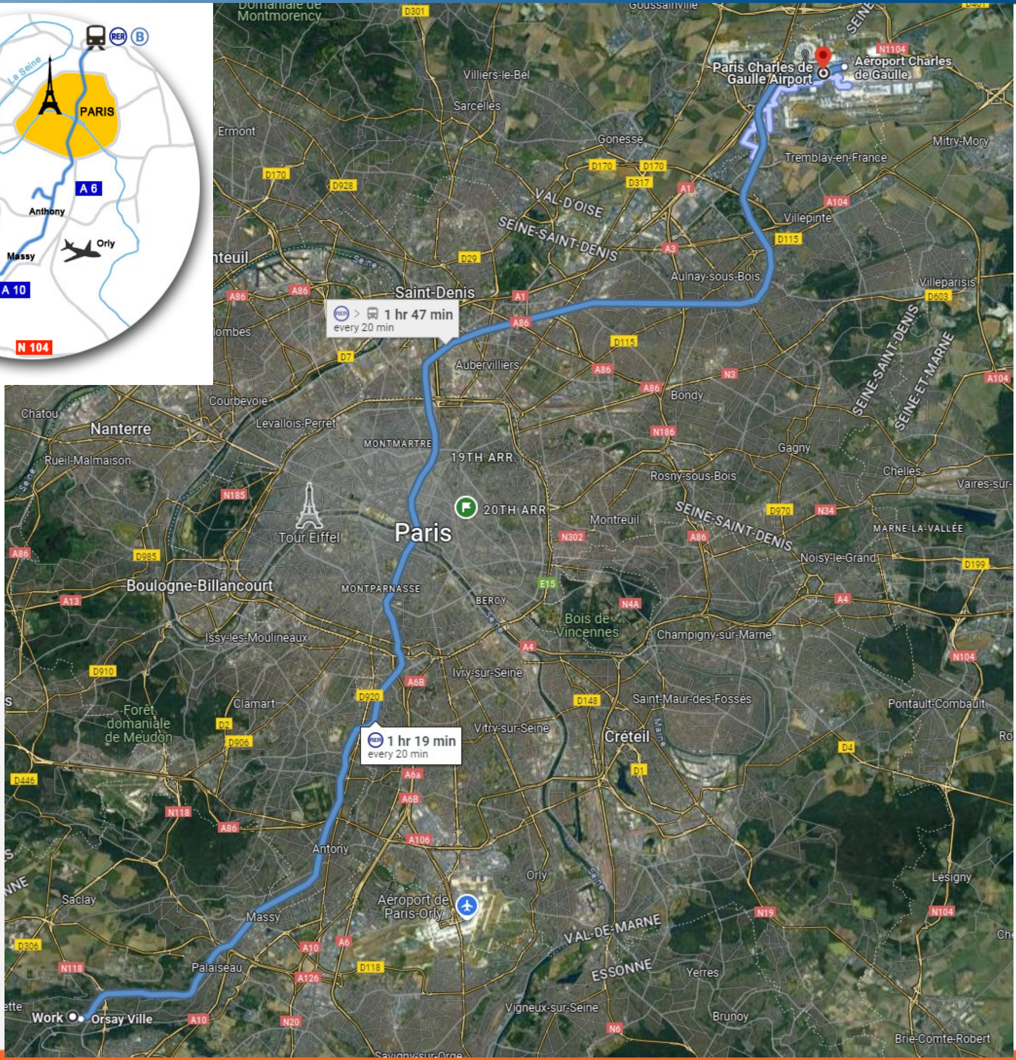
Sarah Naimi

IJCLab/CNRS-IN2P3/ Paris-Sacaly University

LEES2024 Sendai Oct.28--Nov. 1, 2024

Where is Orsay Campus (Paris-Saclay University)



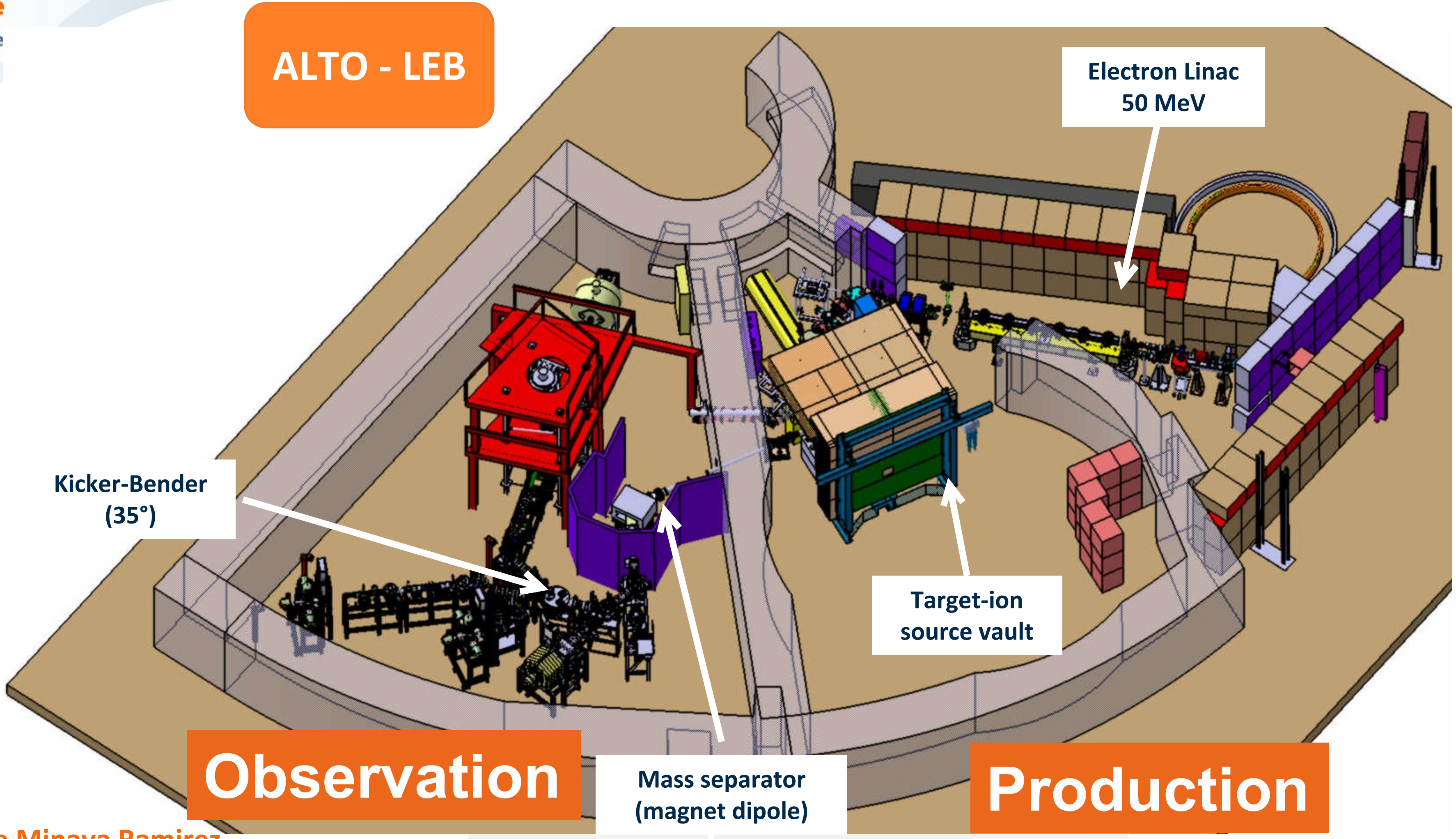


The ALTO research platform of IJCLab

Accélérateur Linéaire et Tandem à Orsay

Courtesy to Enrique Minaya Ramirez

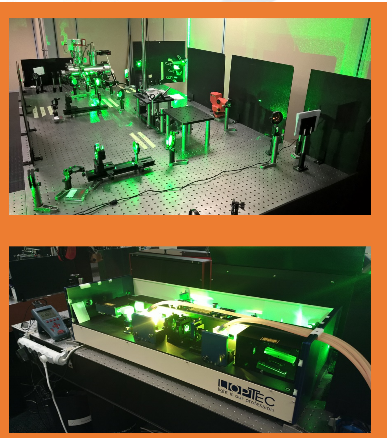
General presentation of the platform



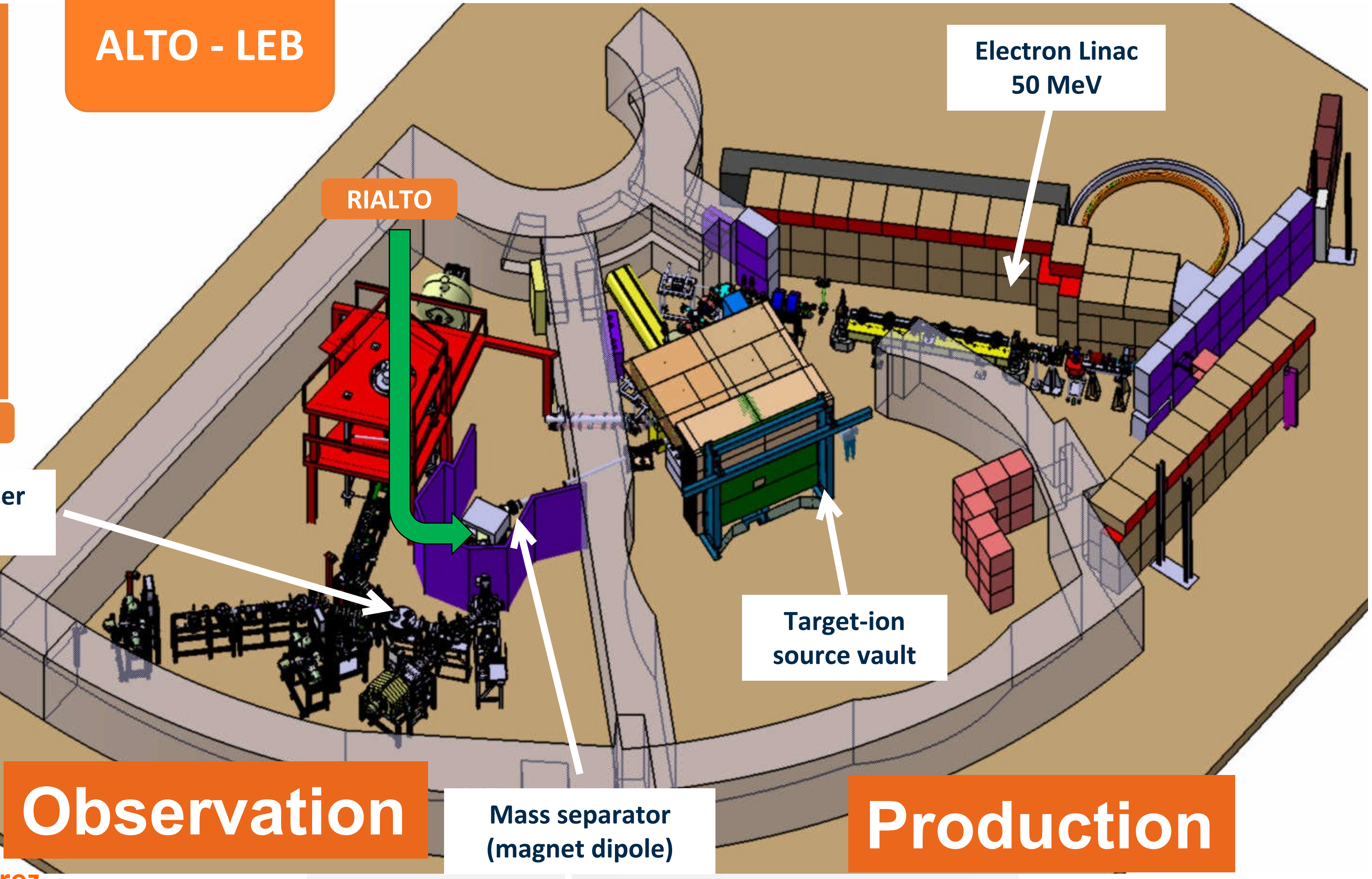
Courtesy to Enrique Minaya Ramirez

General presentation of the platform

ALTO - LEB



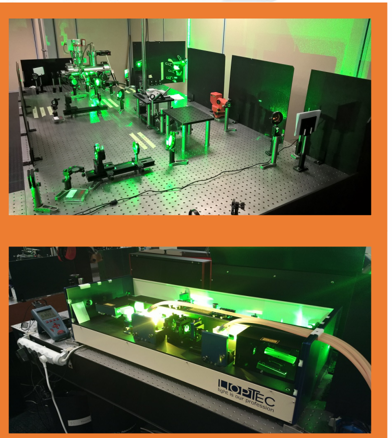
RIALTO



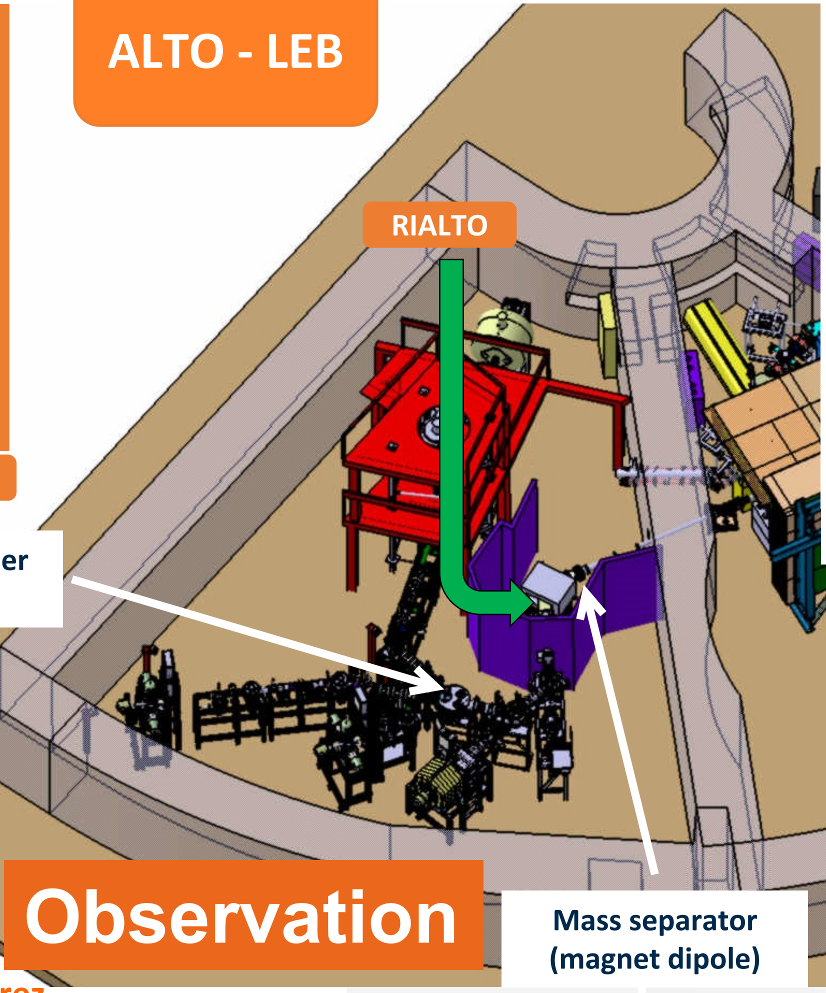
Courtesy to Enrique Minaya Ramirez

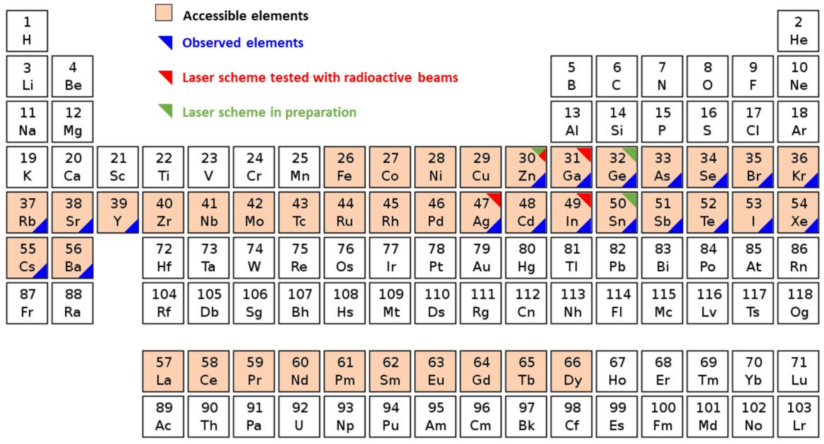
General presentation of the platform

ALTO - LEB



RIALTO





https://alto.ijclab.in2p3.fr/en/facility/alto-leb/production/

Courtesy to Enrique Minaya Ramirez

MLLTRAP project in France

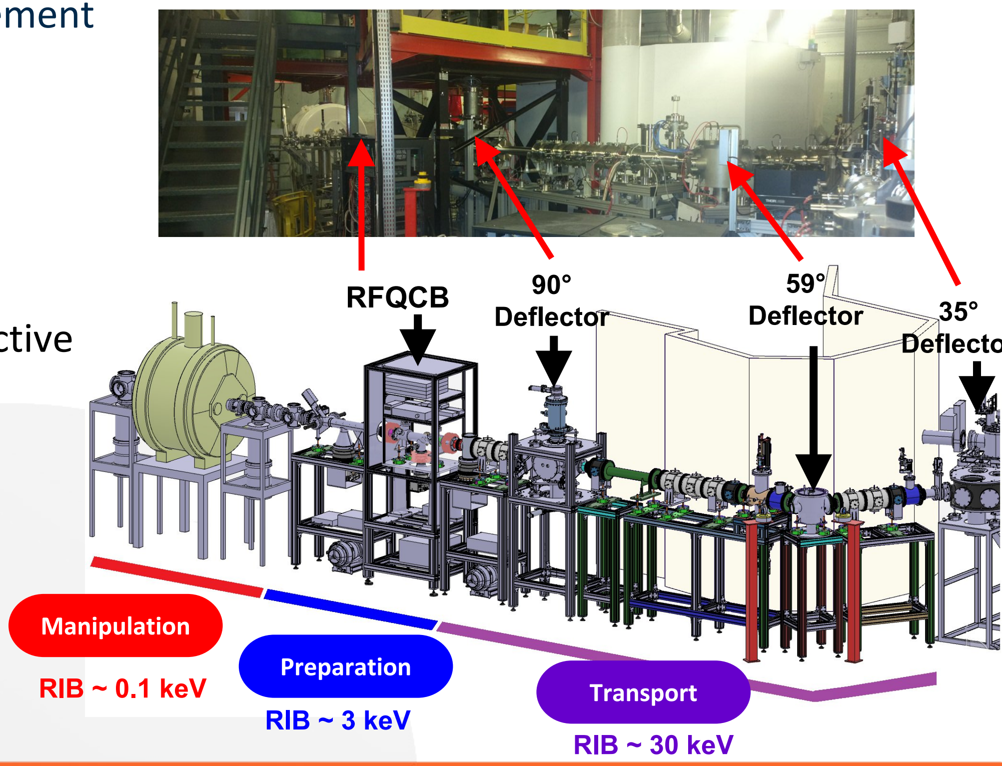
MLLTRAP → Spiral2 DESIR

Framework : "adaptation of experimental devices for their use with DESIR"

2016 - 2026 : Commissioning and upgrade of MLLTRAP + mass measurement campaign @ ALTO (silver beams commissioned end of 2023 at ALTO).

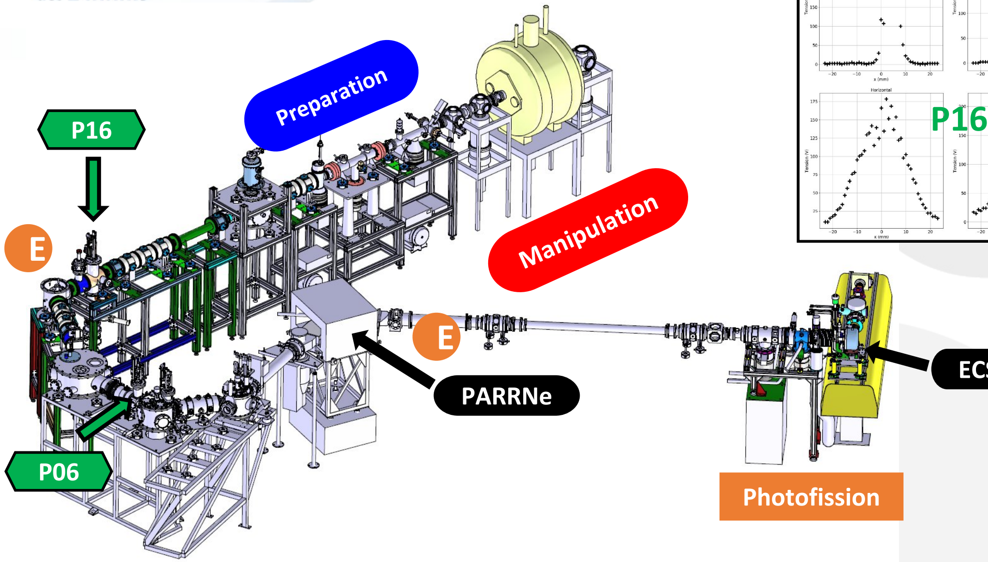
The goal of the MLLTRAP @ ALTO is to :

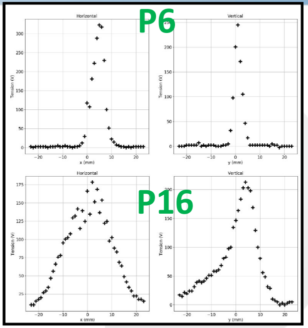
- Characterize the preparation and manipulation sections with radioactive ions
- Test the resolving power of Penning traps with low production rates
- Continue the In-trap project R&D

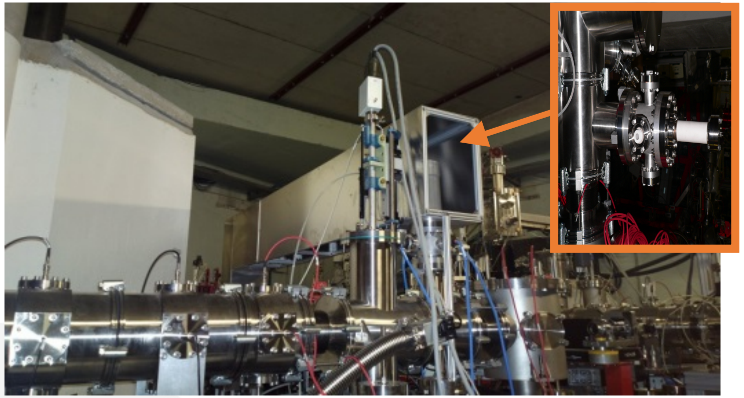


Courtesy to Enrique Minaya Ramirez

MLLTRAP : High-precision mass spectrometer

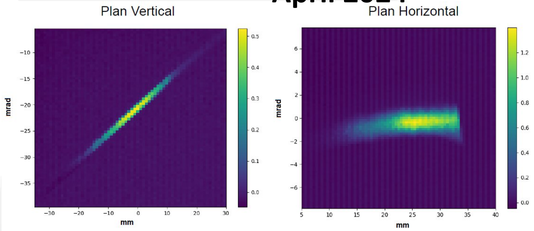




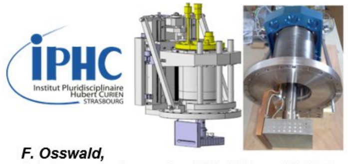


- Optimization of stable beam in the transport in section (M3).
- New campaign of emittance measurements to compare beam dynamics calculations from the ECS to the RFQCB entrance. The new simulated values of the voltages to be applied will be tested this autumn.
- A new high voltage source is under commissioning.

April 2024

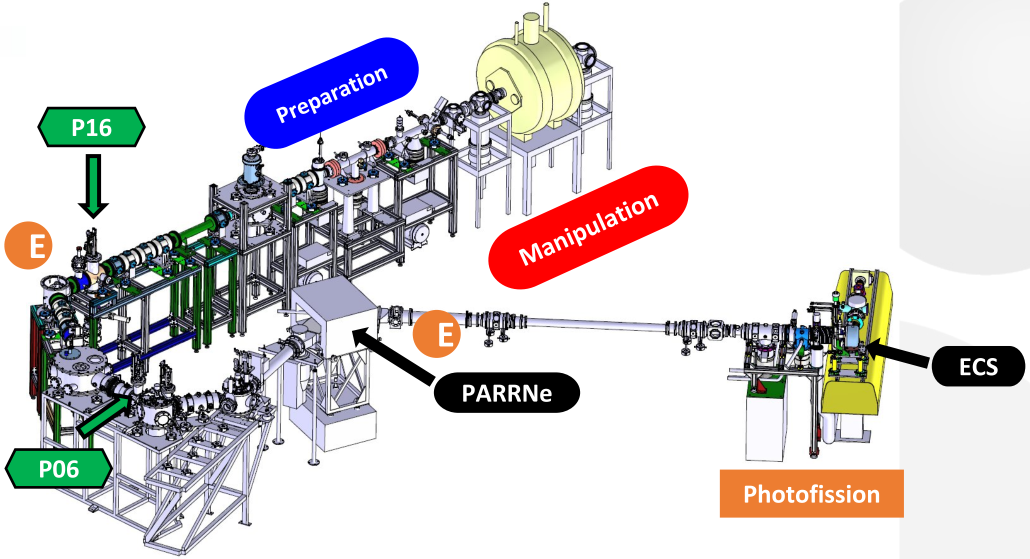


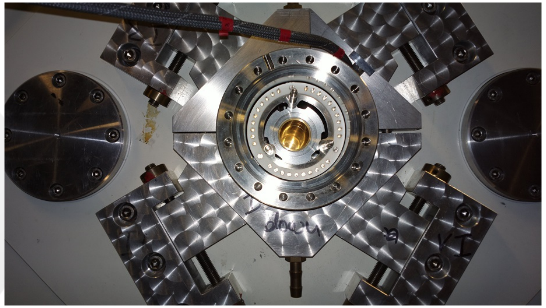
Emittancemeter

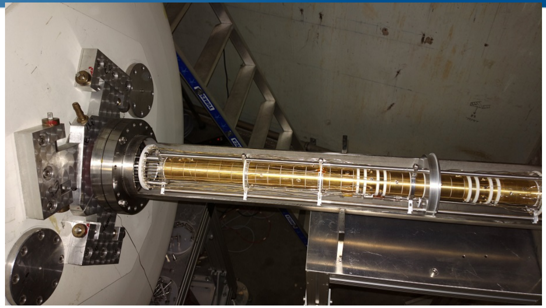


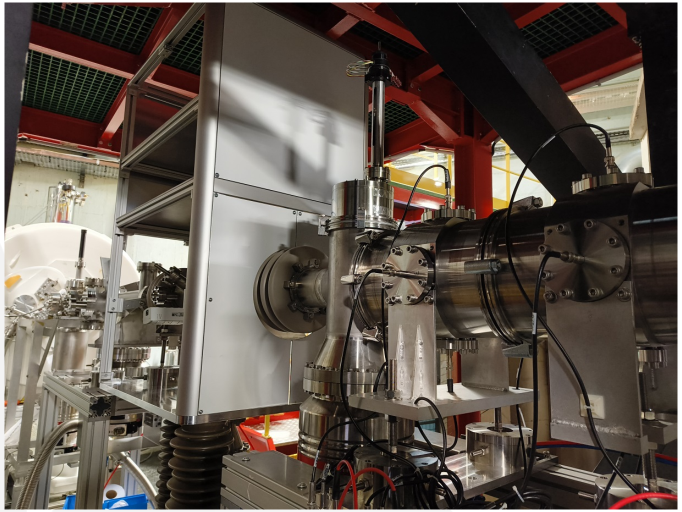
F. Osswald, Int. Beam. Instrum. Conf (2019) tupp007 293

MLLTRAP : High-precision mass spectrometer



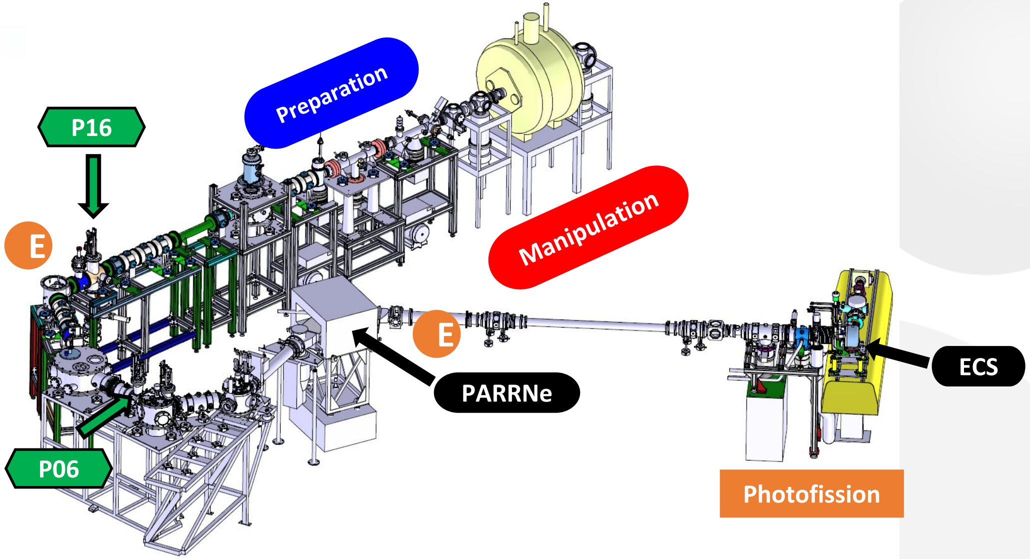


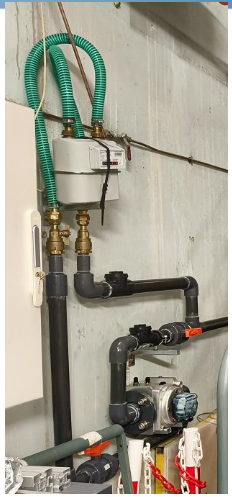


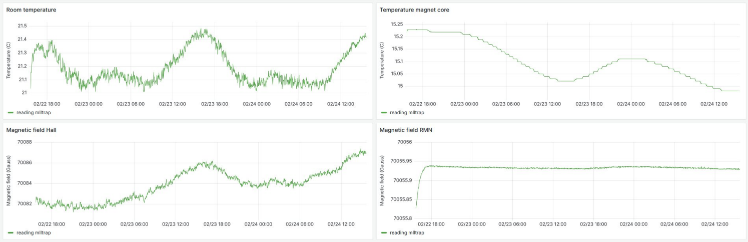


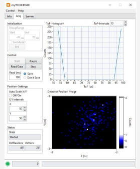
- Penning traps installed and aligned. Preparation section installed and aligned. All the sections are connected.
- All the electronics for the preparation section is being installed and tested.
- All the diagnostic have been installed.

MLLTRAP : High-precision mass spectrometer



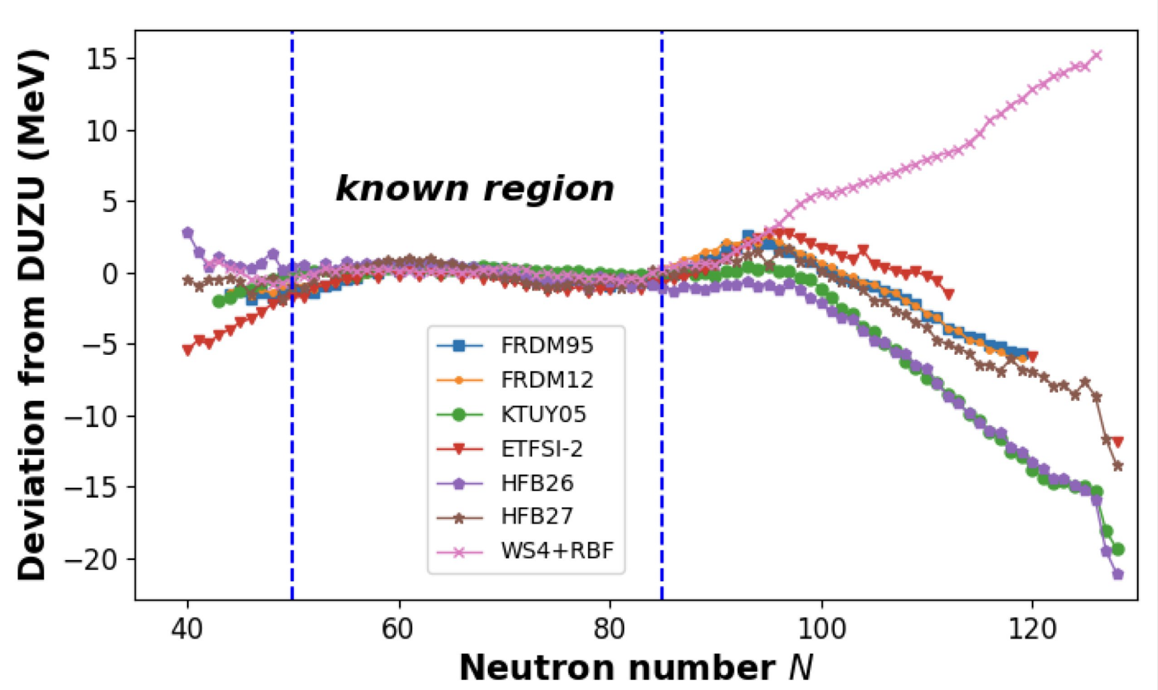


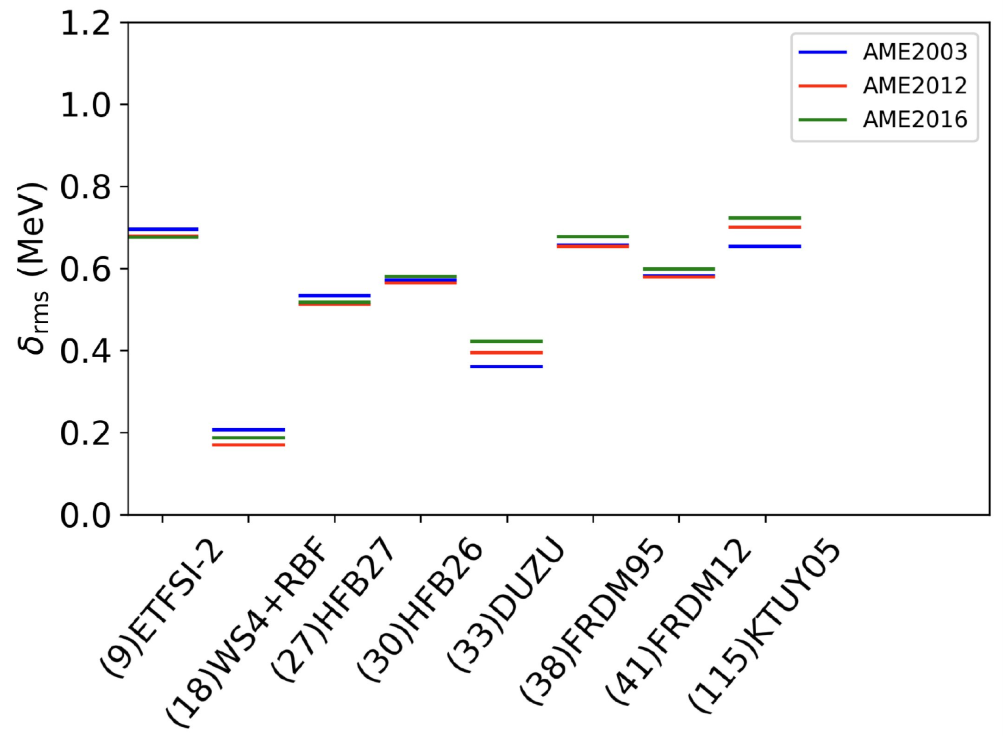




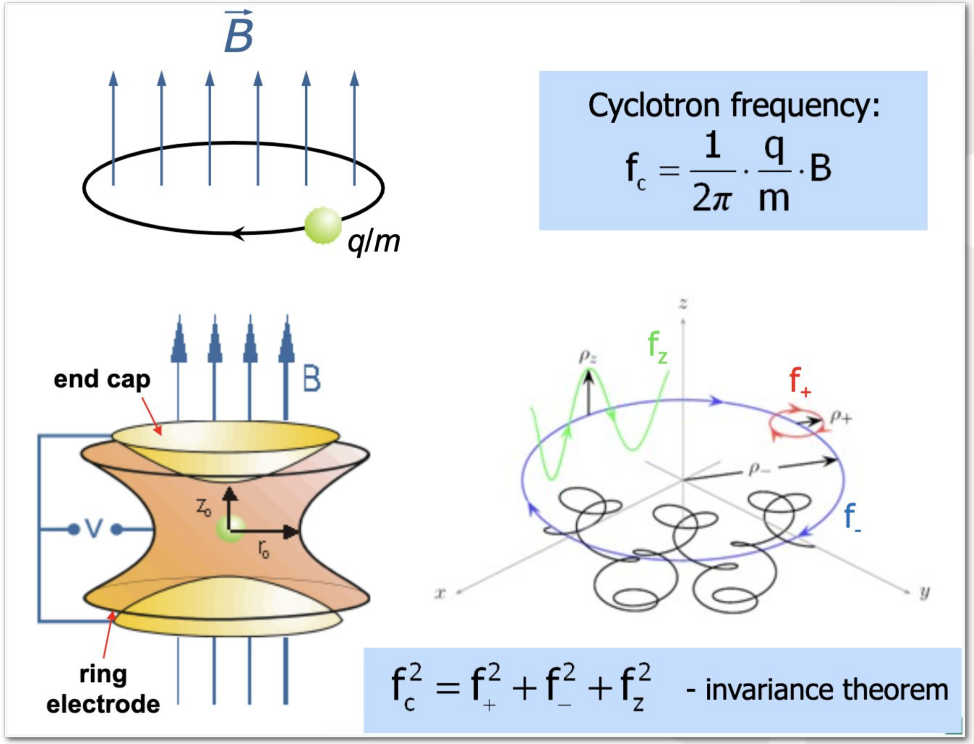
- Temperature stabilization system inside the magnet validated
- Installation of a helium recovery line
- Control system based on CS++ (GSI): integration of all new equipment, Grafana interface for some devices.
- Magnetic probe to track the strength of the magnetic field evolution in real time is also integrated in the CS++

Why measure masses of exotic nuclei ?





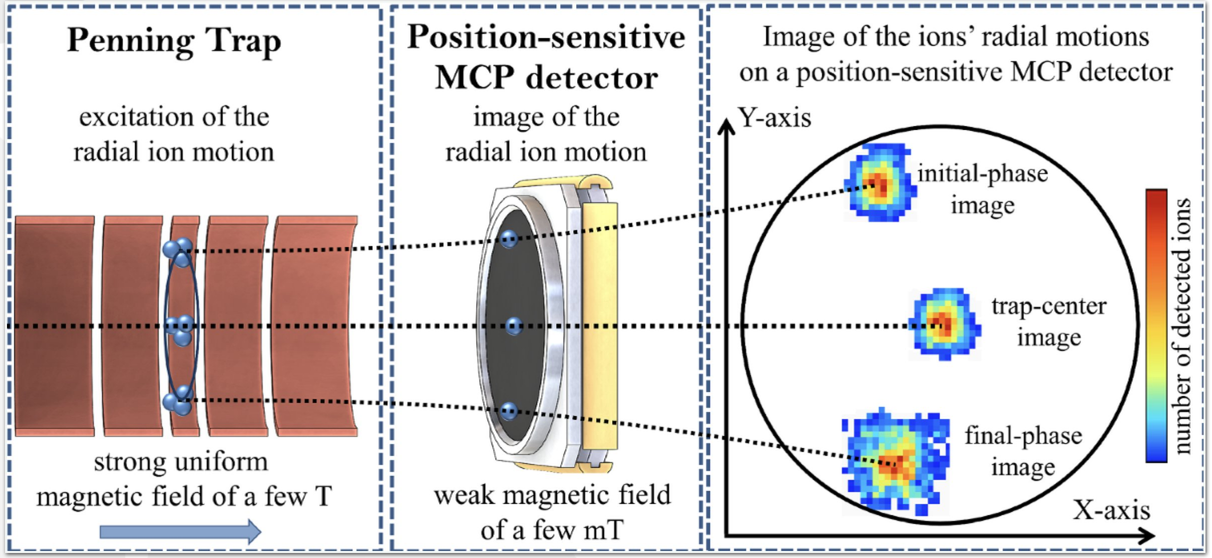
Mass measurement principle



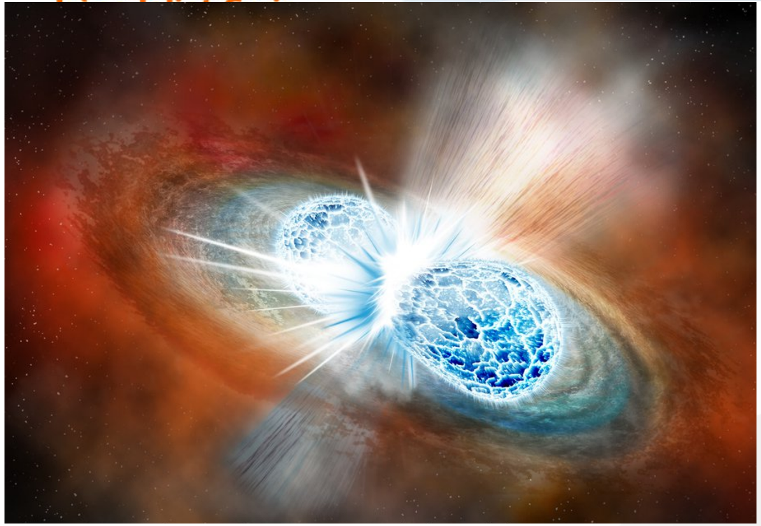
Cyclotron frequency:

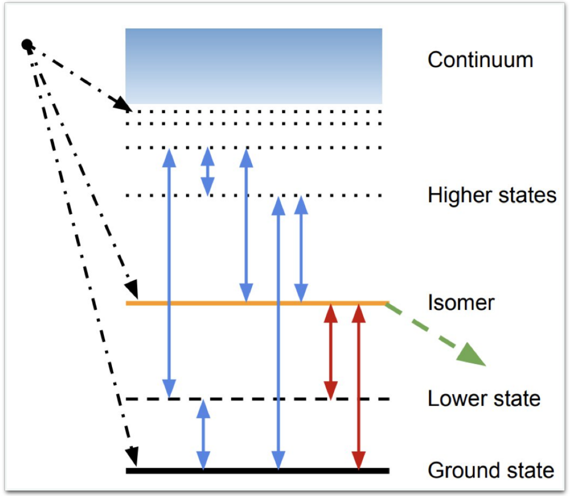
$$f_c = \frac{1}{2\pi} \cdot \frac{q}{m} \cdot B$$

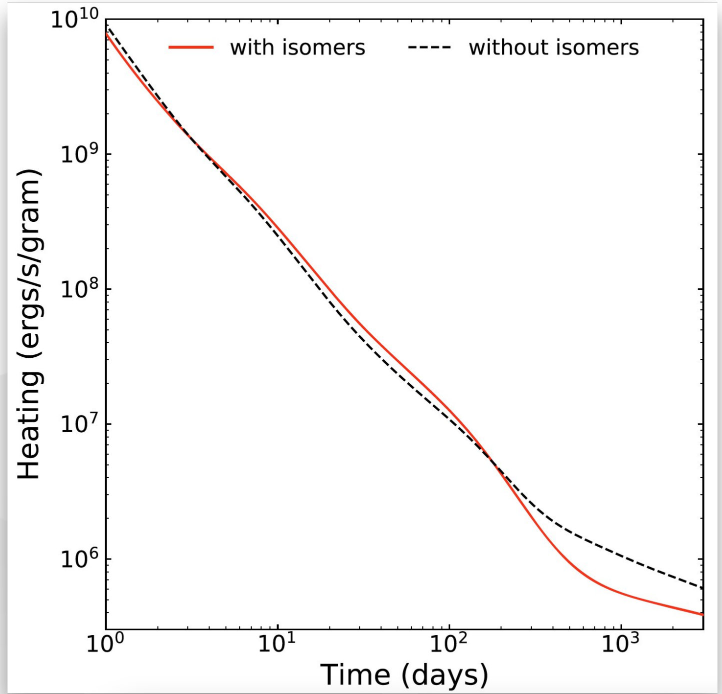
$$f_c^2 = f_+^2 + f_-^2 + f_z^2$$ - invariance theorem



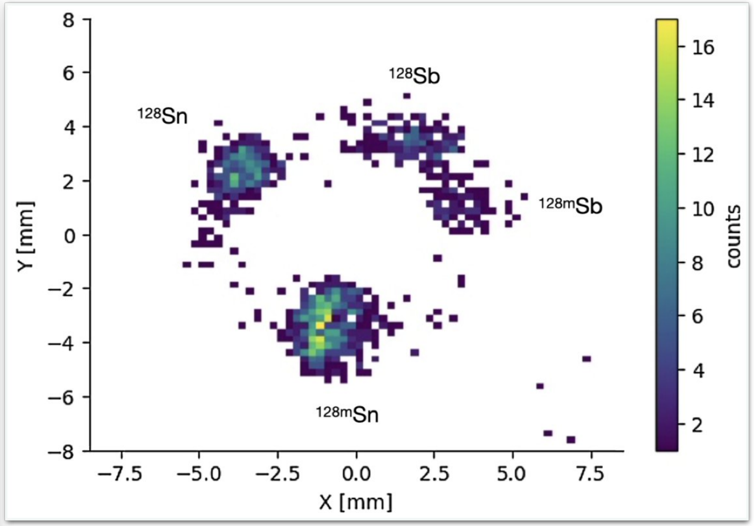
Mass spectrometry and isomers







Misch et al., ApJS 252 2 (2021)

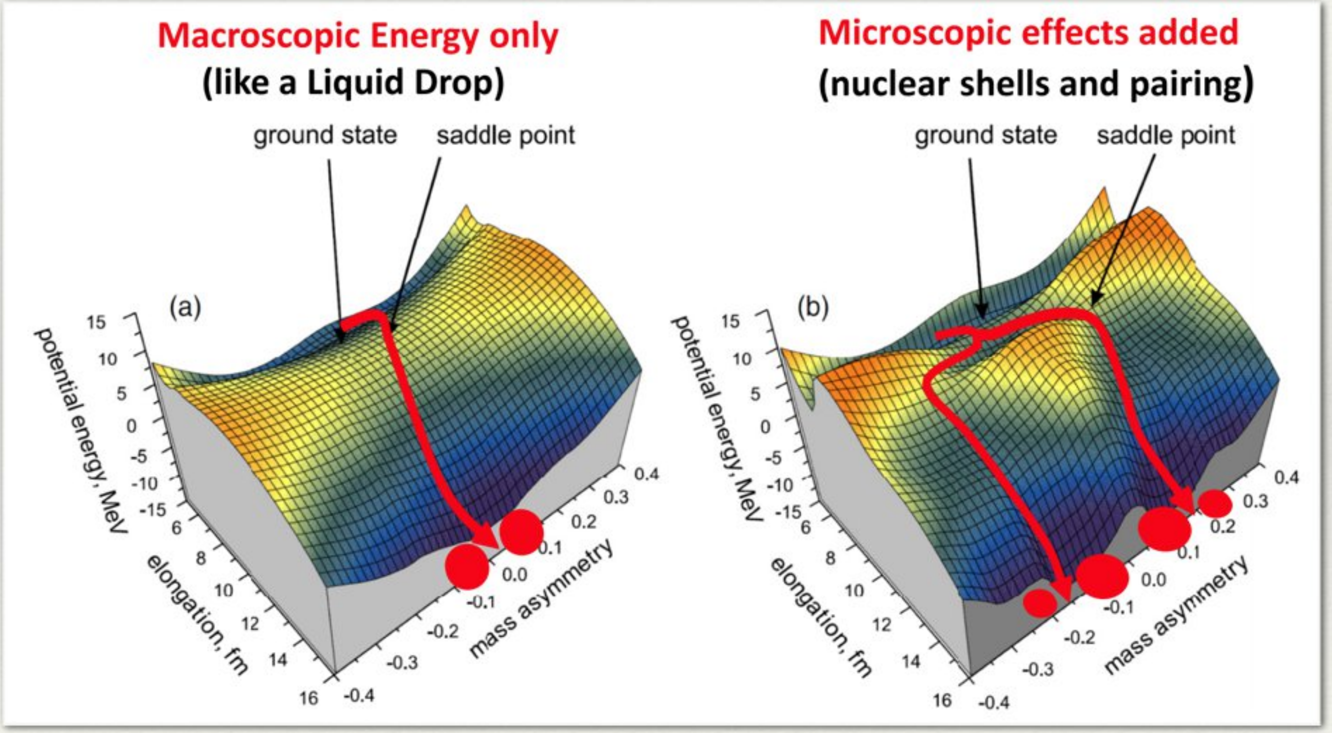


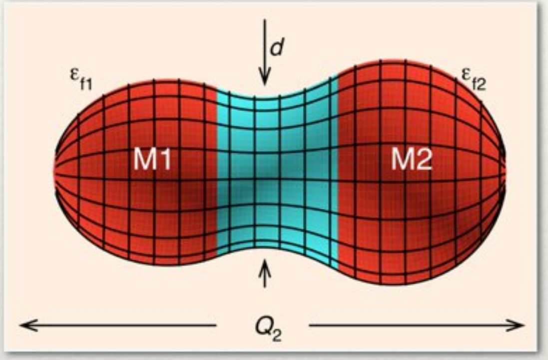
Species	$r = (\nu_c^{cal}/\nu_c)$	Mass excess (keV) this Letter	Mass excess (keV) evaluated
$^{128}Sb^+$	0.962407089(17)	-84608.8 ± 2.1	-84630 ± 19[a]
$^{128m}Sb^+$	0.962407444(20)	-84564.8 ± 2.5	-84620 ± 18[b]
	Excitation energy	43.9 ± 3.3	10 ± 6[b]

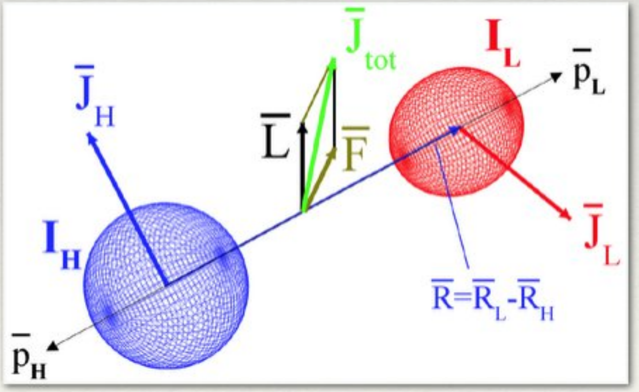
Hoff et al, PRL131 (2023)
during r-process ^{128}Sb is populated in 10min (1keV)
Conclusion: ^{128m}Sb is an astromer and accelerant
($t_{1/2}$ 10min vs. gs 9h)

Andreyev et al., Rep. Prog. Phys. 81 (2018)

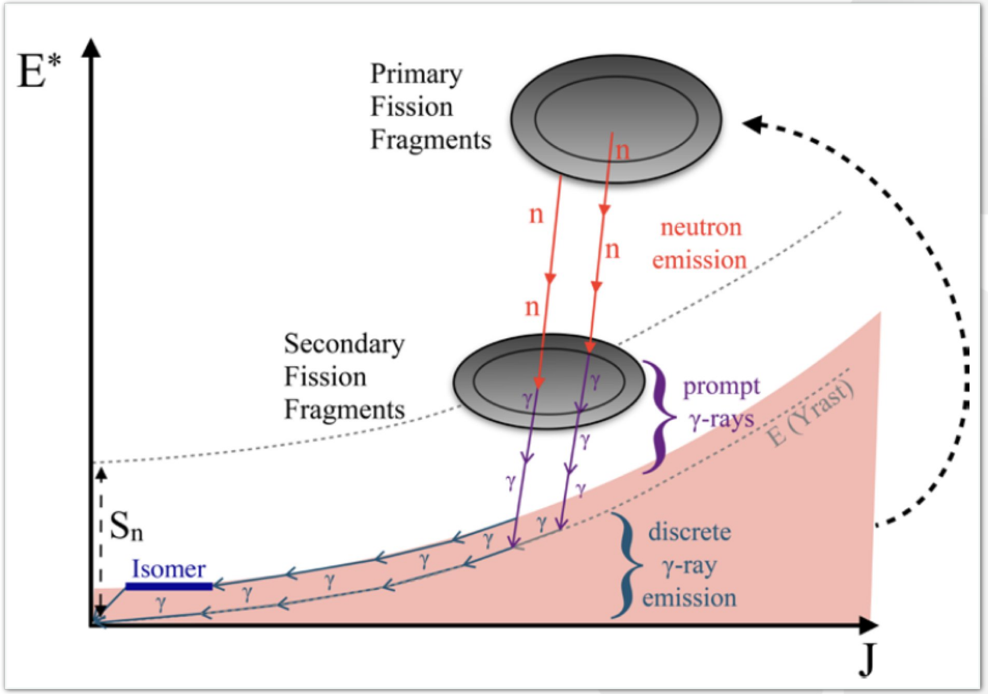
Open question in fission: What is the origin of angular momentum?

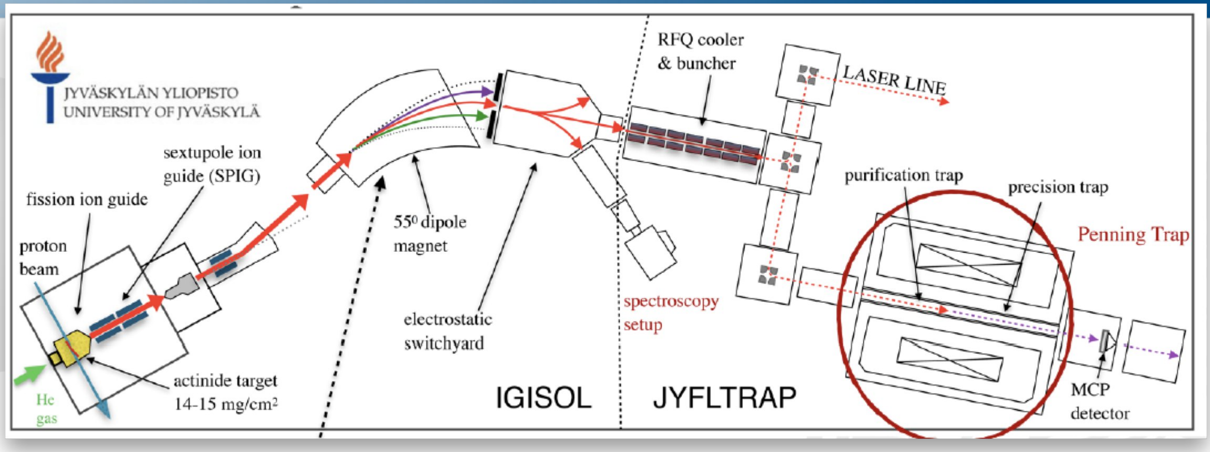


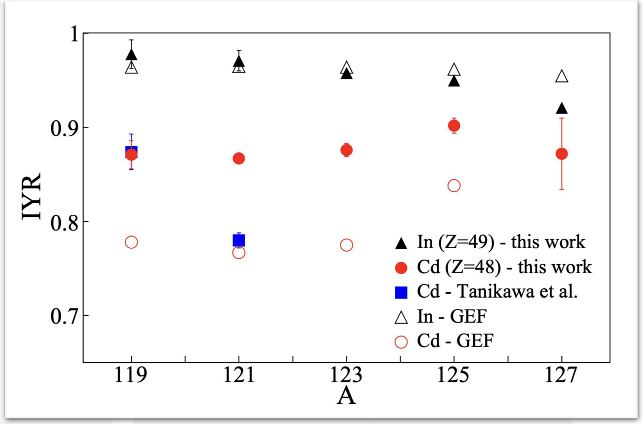


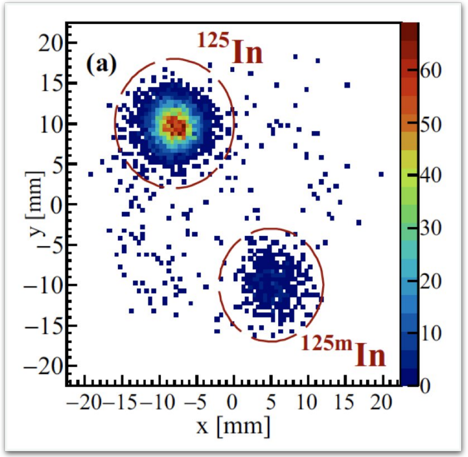


Mass spectrometry and fission study



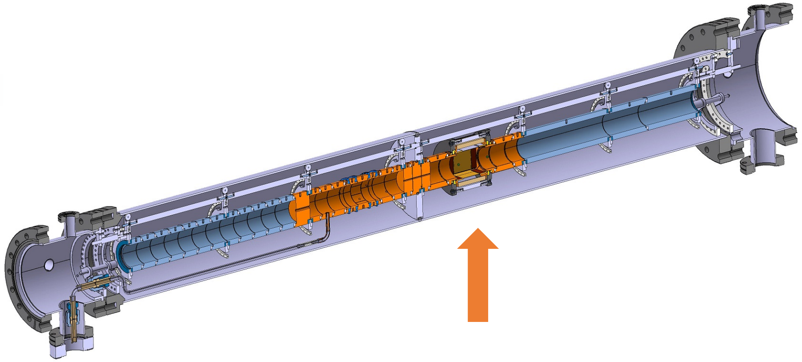






Rakopoulos et al., PRC98(2018)
Isomeric ratios of fission fragments of proton induced fission on U and ^{232}Th @IGISOL

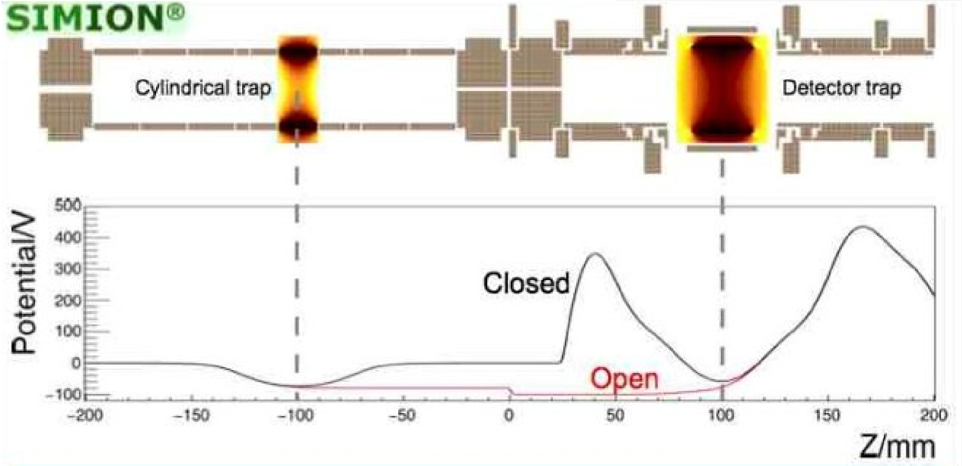
What about the photofission?

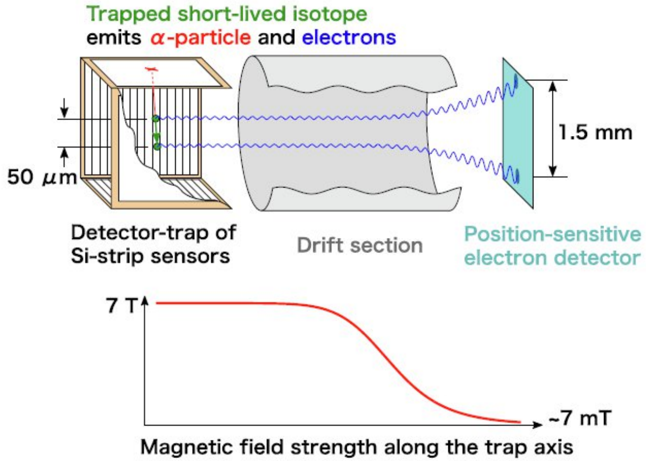


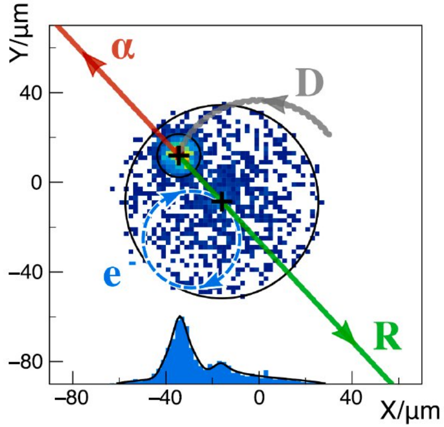
In-trap decay spectroscopy for MLLTRAP

- Decay experiments with carrier-free particles stored in a Penning trap enable studies on ideal ion samples.
- The improved energy resolution can be exploited for high-resolution α- and electron-decay spectroscopy.

DARING (Decay And Recoil imagING) technique to measure lifetimes of first excited nuclear states populated by α decay.

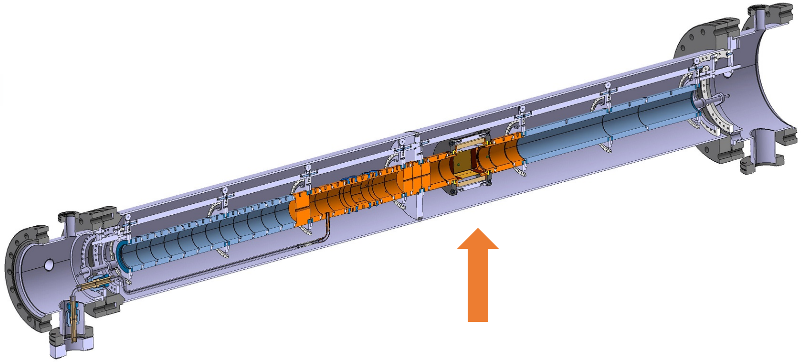






P. Chauveau et al., NIMB 982 (2020) 164508
P. Chauveau et al., NIMB 463 (2020) 371

MLLTRAP – R&D for Beam manipulation



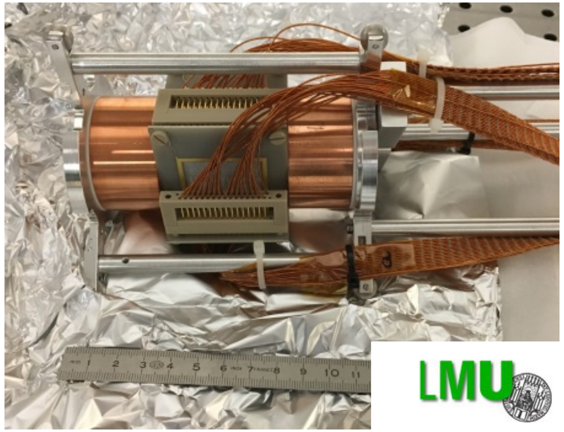
In-trap decay spectroscopy for MLLTRAP

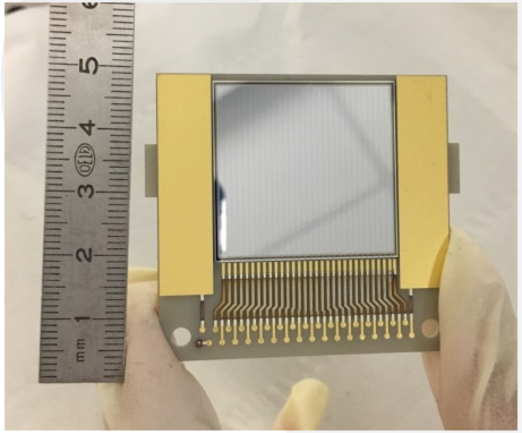
- Penning trap as high-resolution mass separator to prepare state-selected pure sample
  - clean spectra
  - detailed nuclear structure information in one experiment

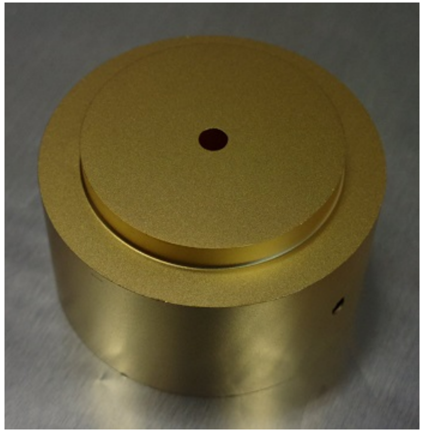
à Design fixed, all mechanical parts and insulators received in 2020.

à Gold plating of all the electrodes performed in October 2022.

à The next step is to finalize the mechanical assembly in 2024.







MOSAIC platform (Stable beams)

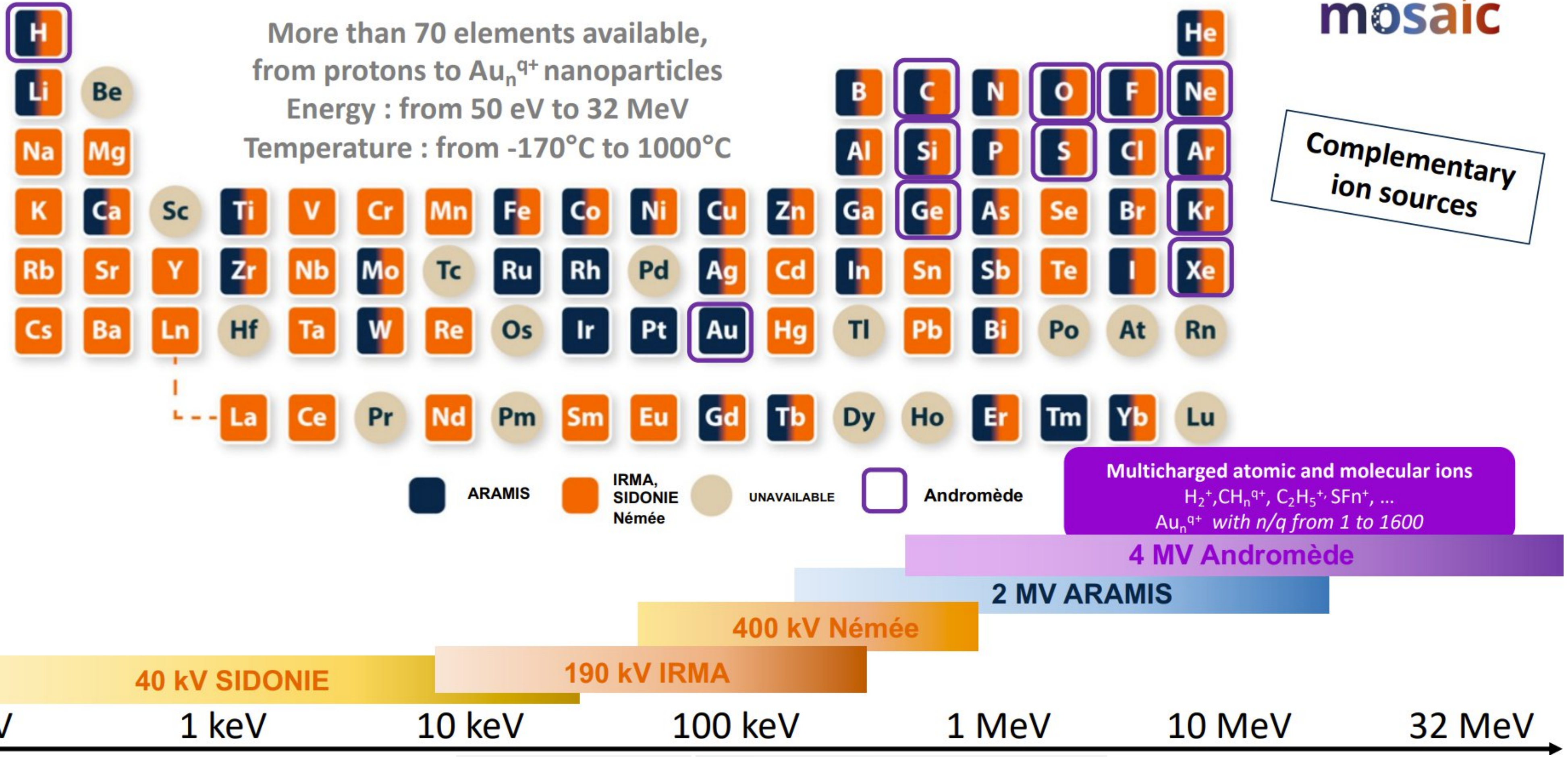
mosaic

Ion beams for …

… synthesis, modification, and analysis of materials,

… and ion-matter interactions studies

A large variety of elements and energies available

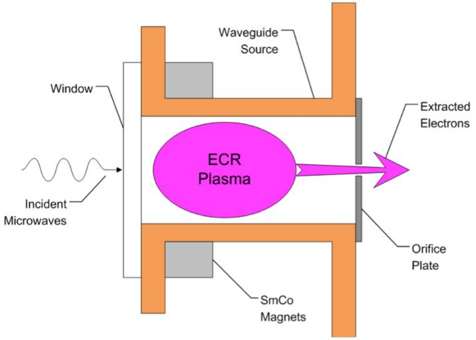


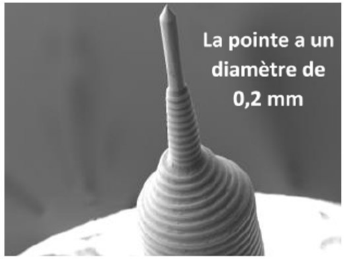
MOSAIC platform (Stable beams)

TMI: Study ion trapping techniques for nuclear physics

TMI
Techniques de Manipulation d'Ions

HINA
GBAR
DESTIN@ PERLE



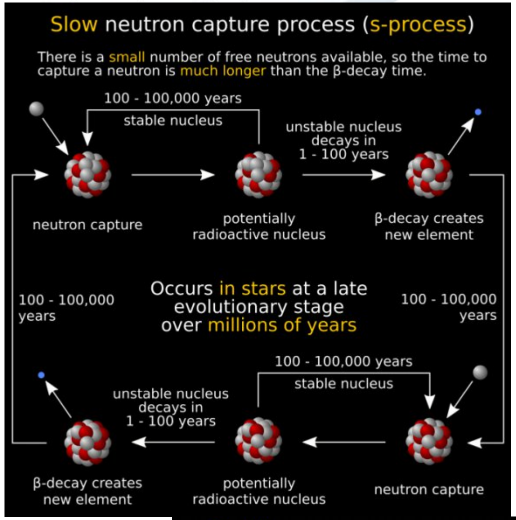


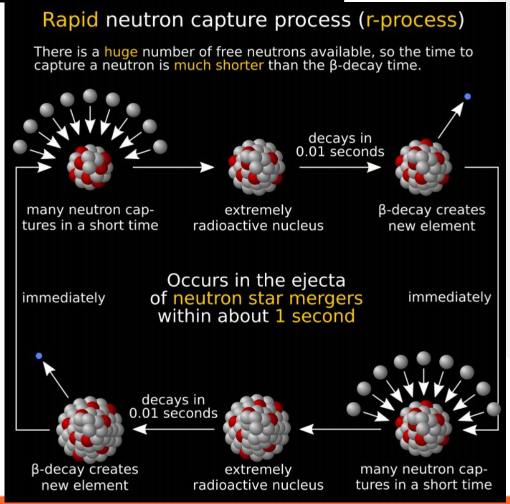
Liquid metal ion source

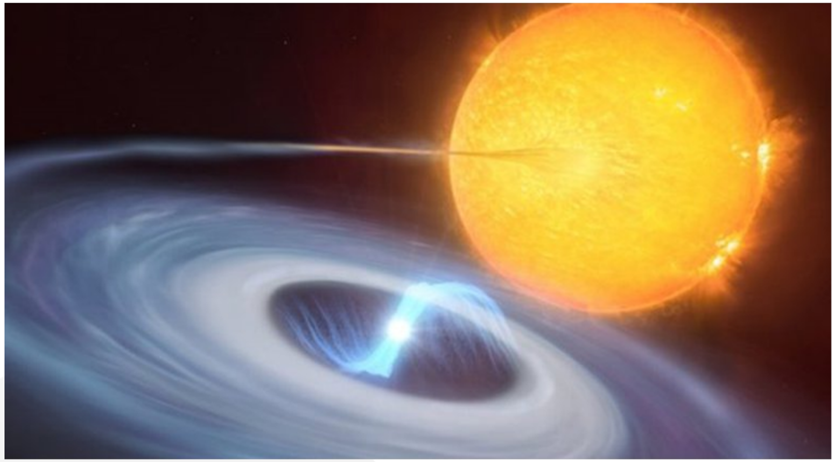
HINA Project

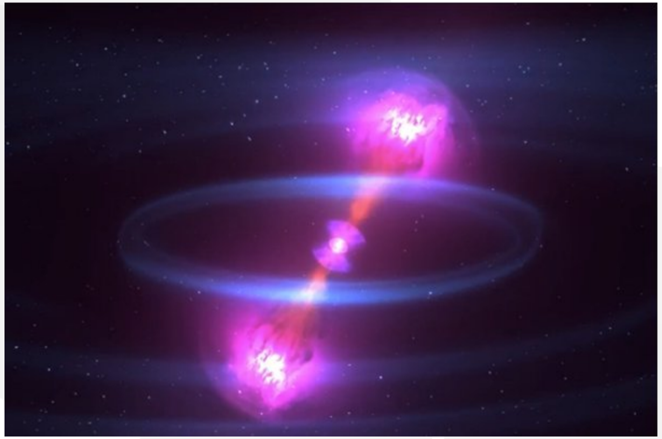
(**H**ighly charged **I**ons for **N**uclear physics and **A**strophysics)

Highly charged ions naturally present in the stellar medium

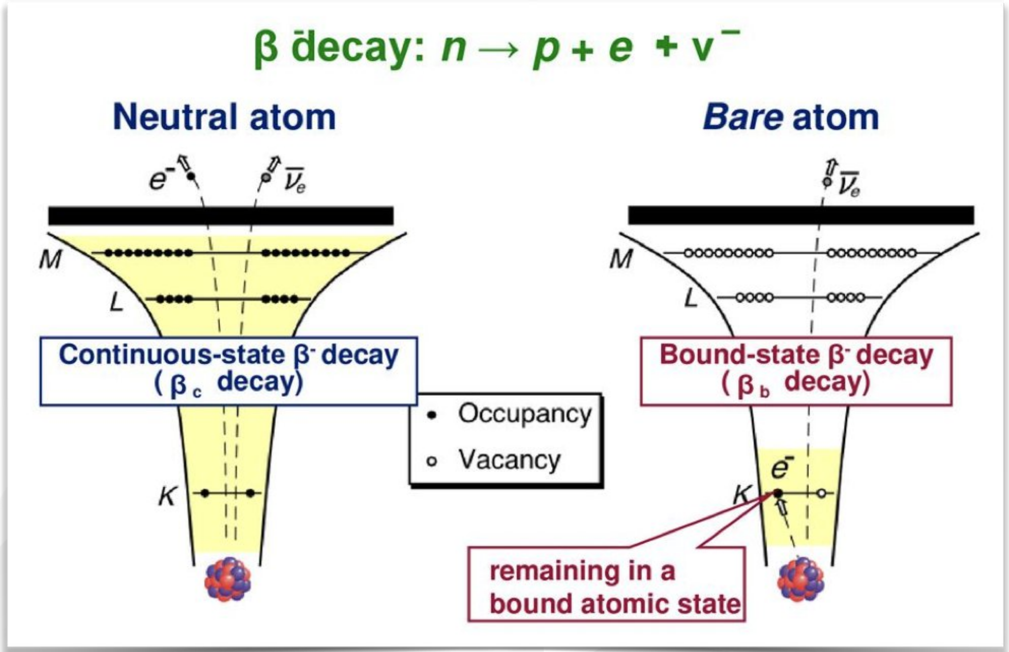








Bound state beta decay



$$Q_{\beta_b}(\mathrm{K, L, \ldots}) = Q_{\beta_c^-} - |\Delta B_{e^-}| + |B_{e^-}^{\mathrm{K,L\ldots}}|$$

$^{163}Dy^{0}$ **stable** $^{163}Dy^{66+}$ **instable** **49keV** **-2,8keV** **13keV** **65keV**

J. Phys. Radium **8**, 238-243 (1947)

SUR LA POSSIBILITÉ D'EXISTENCE D'UN TYPE PARTICULIER DE RADIOACTIVITÉ PHÉNOMÈNE DE CRÉATION *e*

Par RAYMOND DAUDEL, MAURICE JEAN et MARCEL LECOIN.
Institut du Radium, Laboratoire Curie, Paris.

Sommaire. — Dans cet article, on montre la possibilité théorique d'existence d'un type nouveau de désintégration β. On étudie, en se plaçant toujours d'un point de vue entièrement théorique, les particularités qui caractériseraient le phénomène.

$$Q_{\beta_b}(\mathrm{K, L}, \ldots) = Q_{\beta_c^-} - |\Delta B_{e^-}| + |B_{e^-}^{\mathrm{K,L}\ldots}|$$

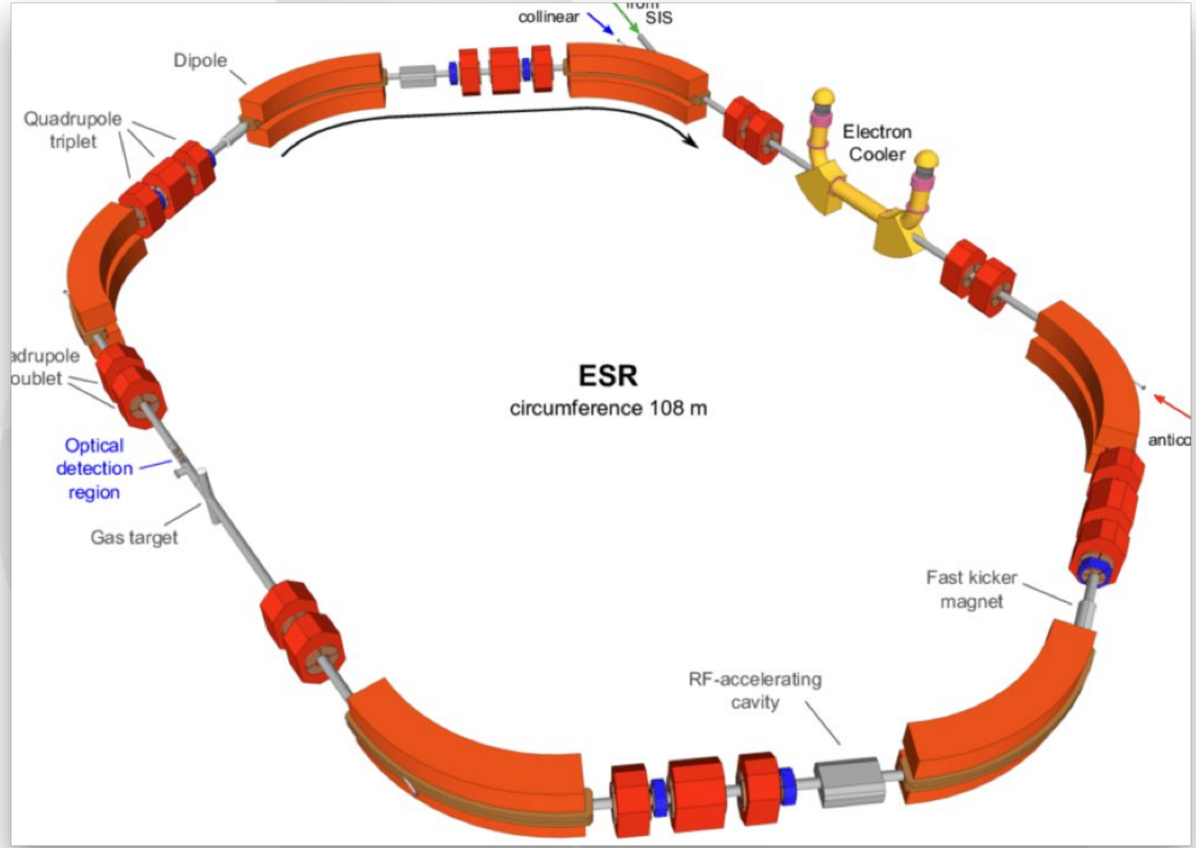
$^{163}Dy^{0}$ **stable** $^{163}Dy^{66+}$ **instable** **49keV** **-2,8keV** **13keV** **65keV**

VOLUME 69, NUMBER 15 PHYSICAL REVIEW LETTERS 12 OCTOBER 1992

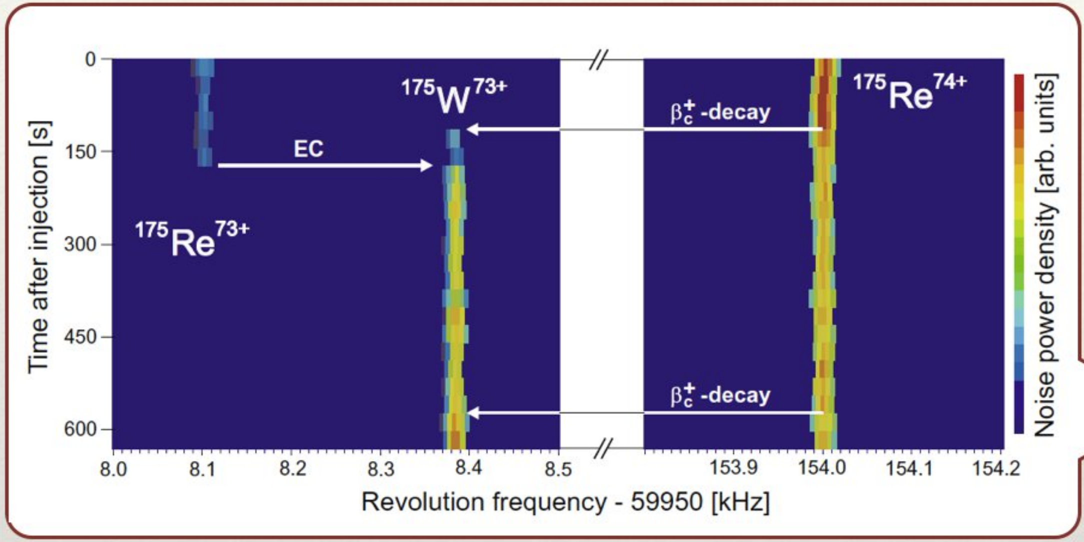
First Observation of Bound-State β^- Decay

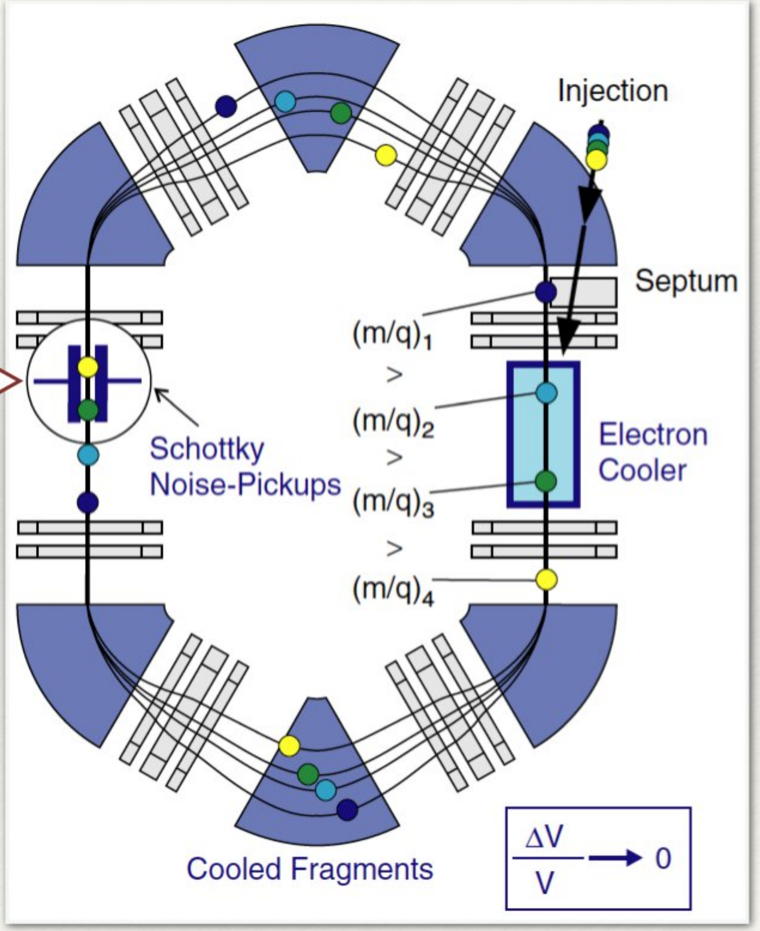
M. Jung, F. Bosch, K. Beckert, H. Eickhoff, H. Folger, B. Franzke, A. Gruber, P. Kienle, O. Klepper, W. Koenig, C. Kozhuharov, R. Mann, R. Moshammer, F. Nolden, U. Schaaf, G. Soff, P. Spädtke, M. Steck, Th. Stöhlker, and K. Sümmerer

Gesellschaft für Schwerionenforschung (GSI), D-6100 Darmstadt, Germany



Lifetime measurements in the ESR



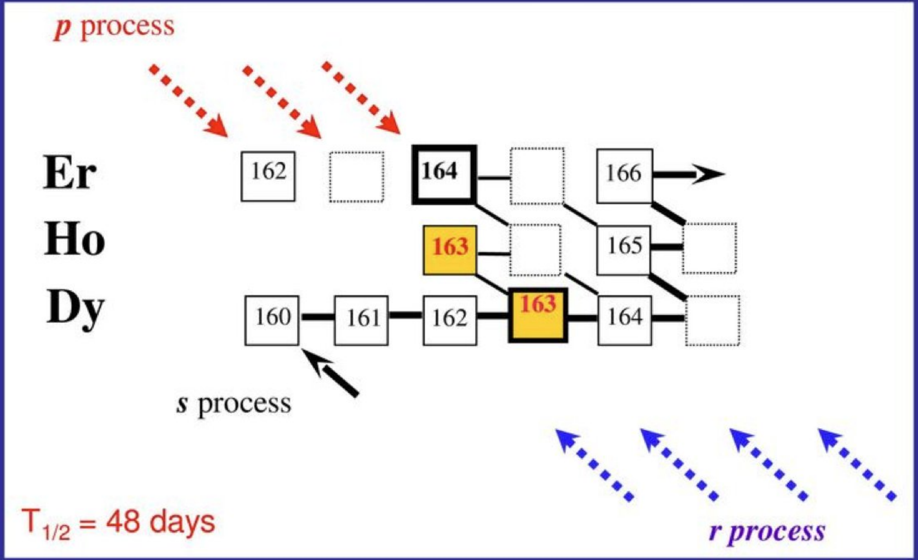


2~10 min storage time in the ESR

Bound state beta decay in astrophysics

Bound-State β-decay of ^{163}Dy

s process: slow neutron capture and β- decay near valley of β stability at kT = 30 keV; → high atomic charge state → bound-state β decay

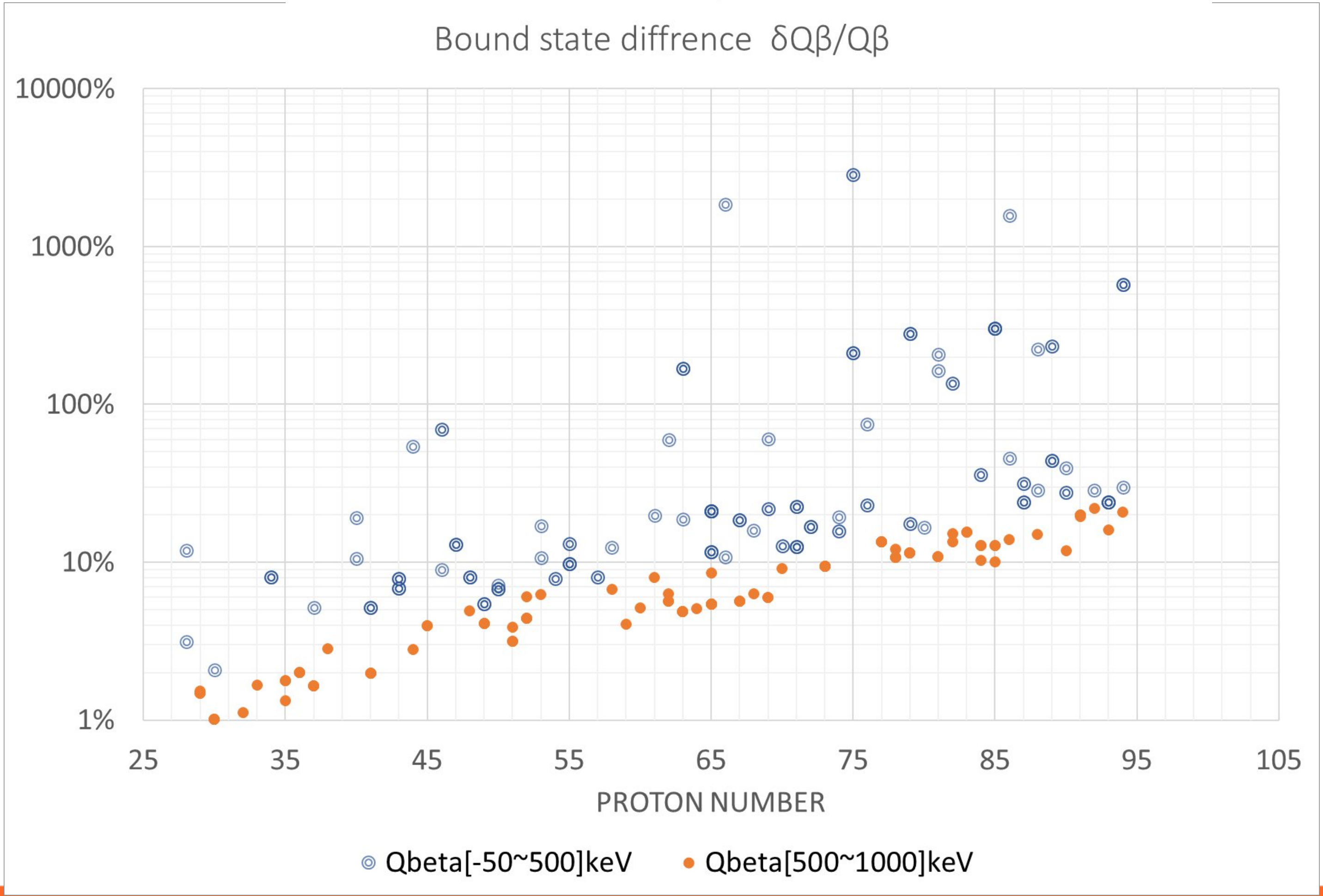


branchings caused by bound-state β decay

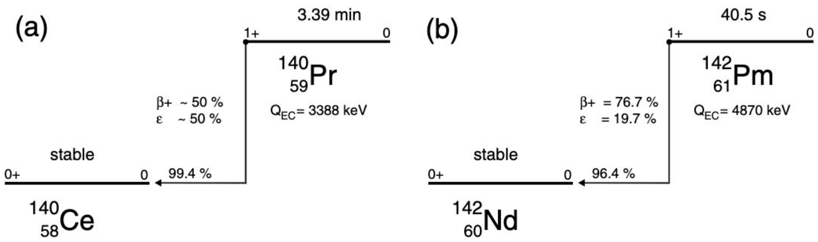
M. Jung et al., Phys. Rev. Lett. 69 (1992) 2164

Bound state beta decay: a lot needs to be done

$$Q_{\beta_b}(\mathrm{K}, \mathrm{L}, \ldots) = Q_{\beta_c^-} - |\Delta B_{e^-}| + |B_{e^-}^{\mathrm{K},\mathrm{L}\ldots}|$$



EC decay of H- and He-like atoms

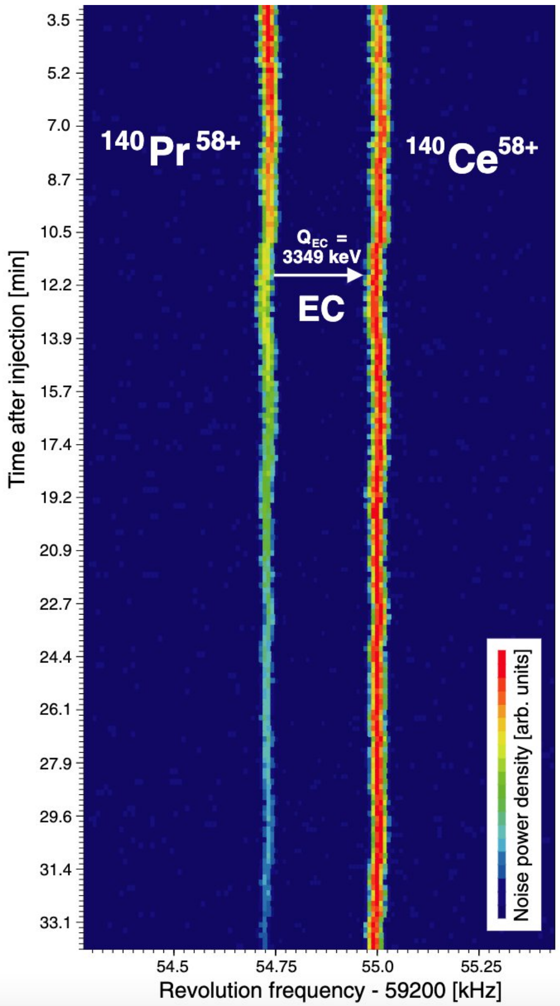


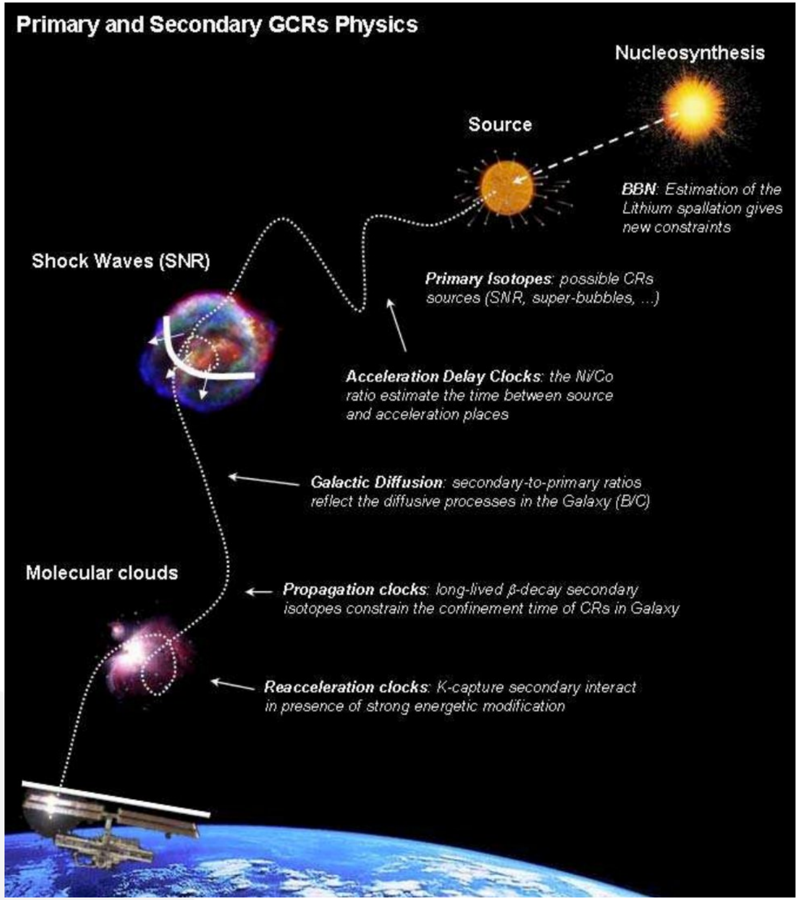
Measured @GSI

Ion	λ_{β^+} (s^{-1})	λ_{EC} (s^{-1})	$\frac{\lambda_{EC}}{(\lambda_{\beta^+} + \lambda_{EC})}$
$^{140}Pr^{58+}$	0.001 61(10)	0.002 19(6)	$(57.6 \pm 2.3)\%$
$^{140}Pr^{57+}$	0.001 54(11)	0.001 47(7)	$(48.8 \pm 3.1)\%$
$^{140}Pr^{0+}$	0.001 74(5)	0.001 65(5)	$(48.7 \pm 1.8)\%$
$^{142}Pm^{60+}$	0.012 6(3)	0.005 1(1)	$(29.0 \pm 1.3)\%$
$^{142}Pm^{59+}$	0.013 9(6)	0.003 6(1)	$(20.2 \pm 1.0)\%$
$^{142}Pm^{0+}$	0.013 2(5)	0.003 9(5)	$(22.9 \pm 2.7)\%$

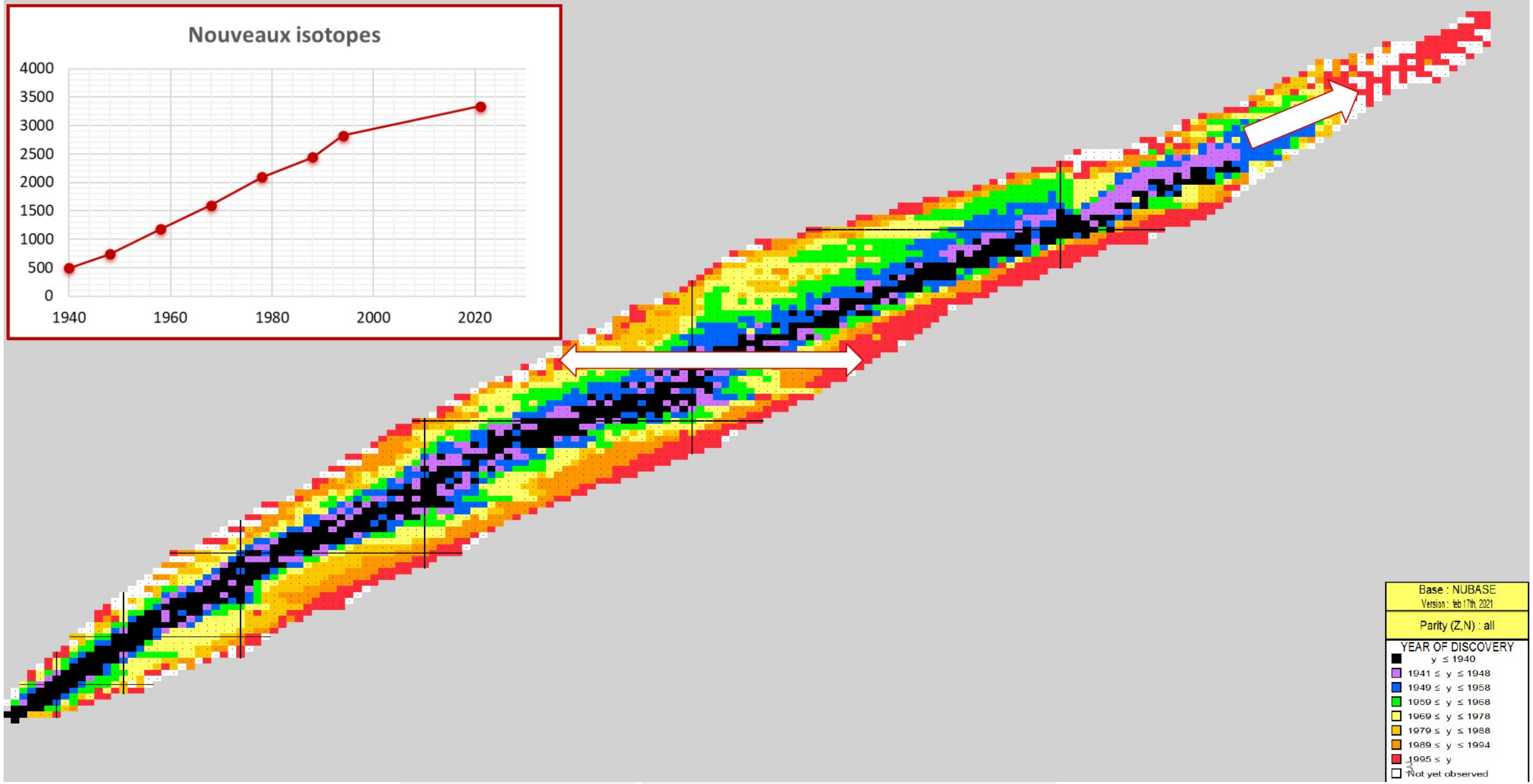
EC rate depends on the occupied electron shells

Z. Patyk et al. PRC77, 2008



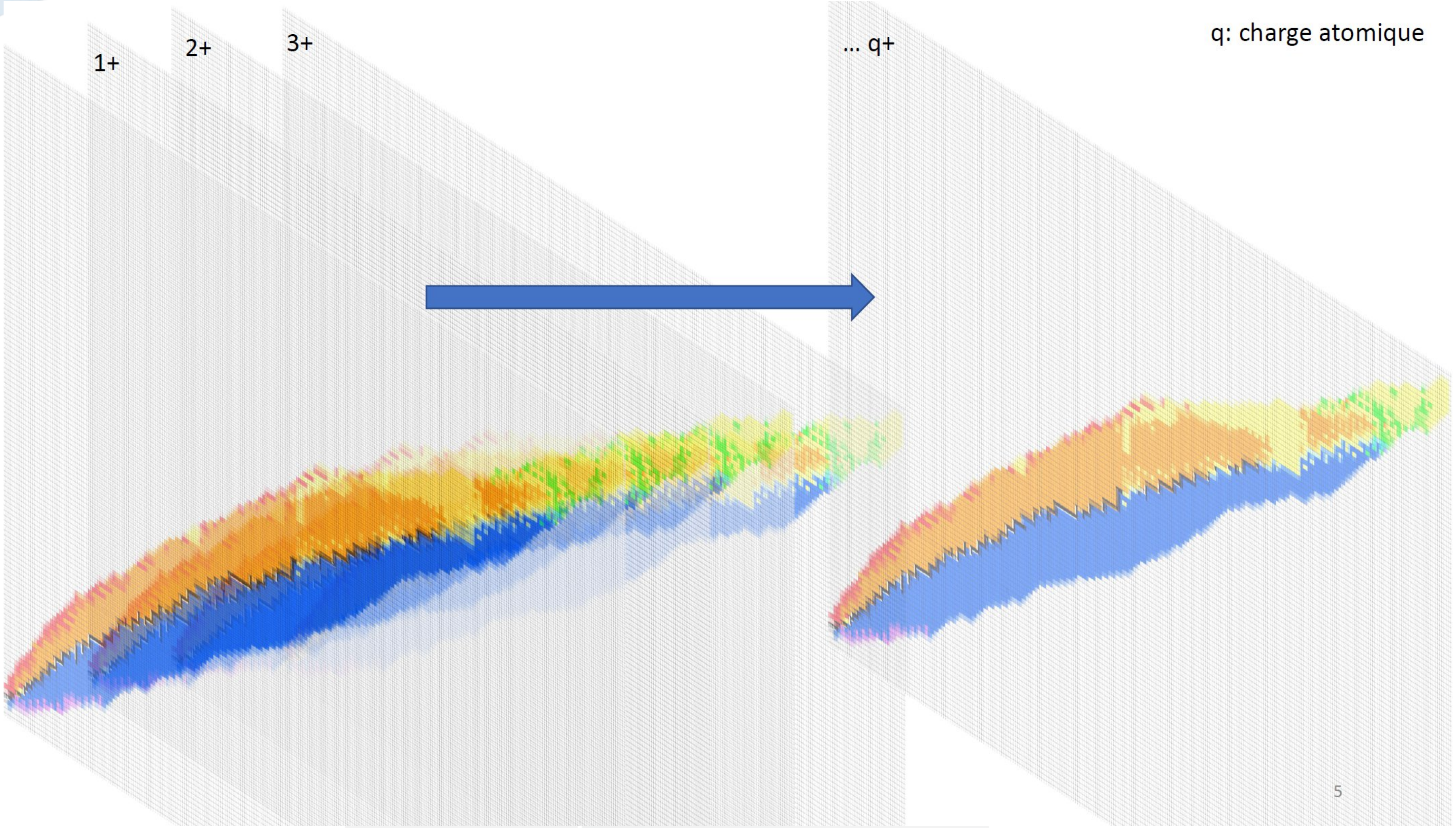


New way to explore properties of atomic nucleus

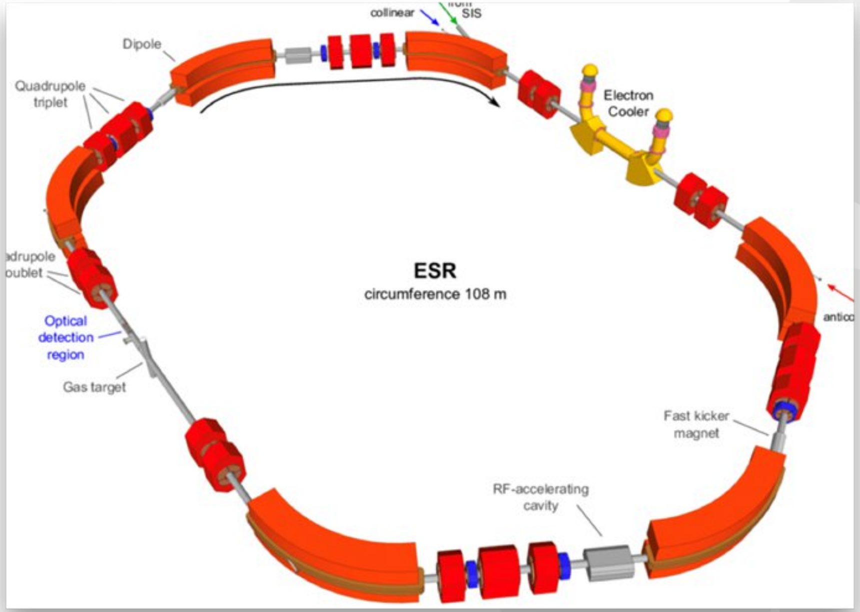


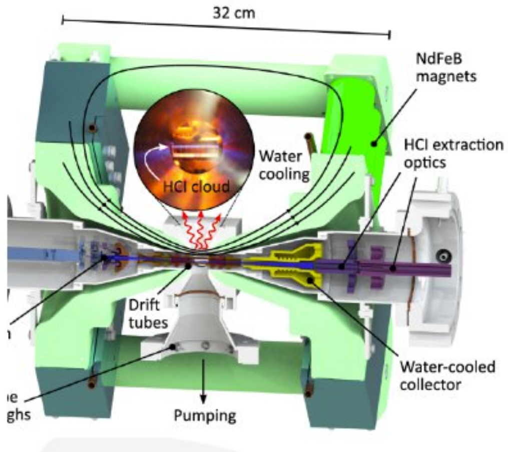
New way to explore properties of atomic nucleus

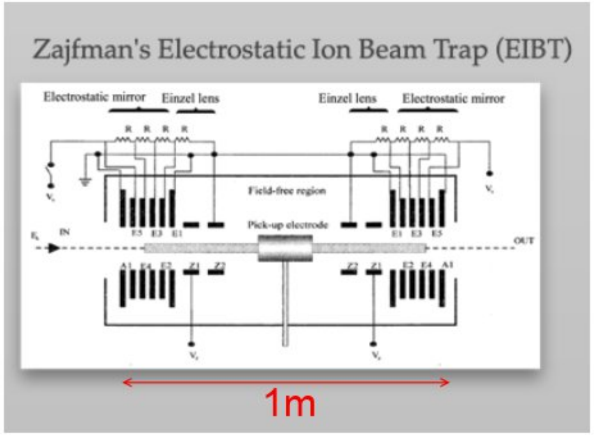
HINA



Traps as alternative to Storage Rings







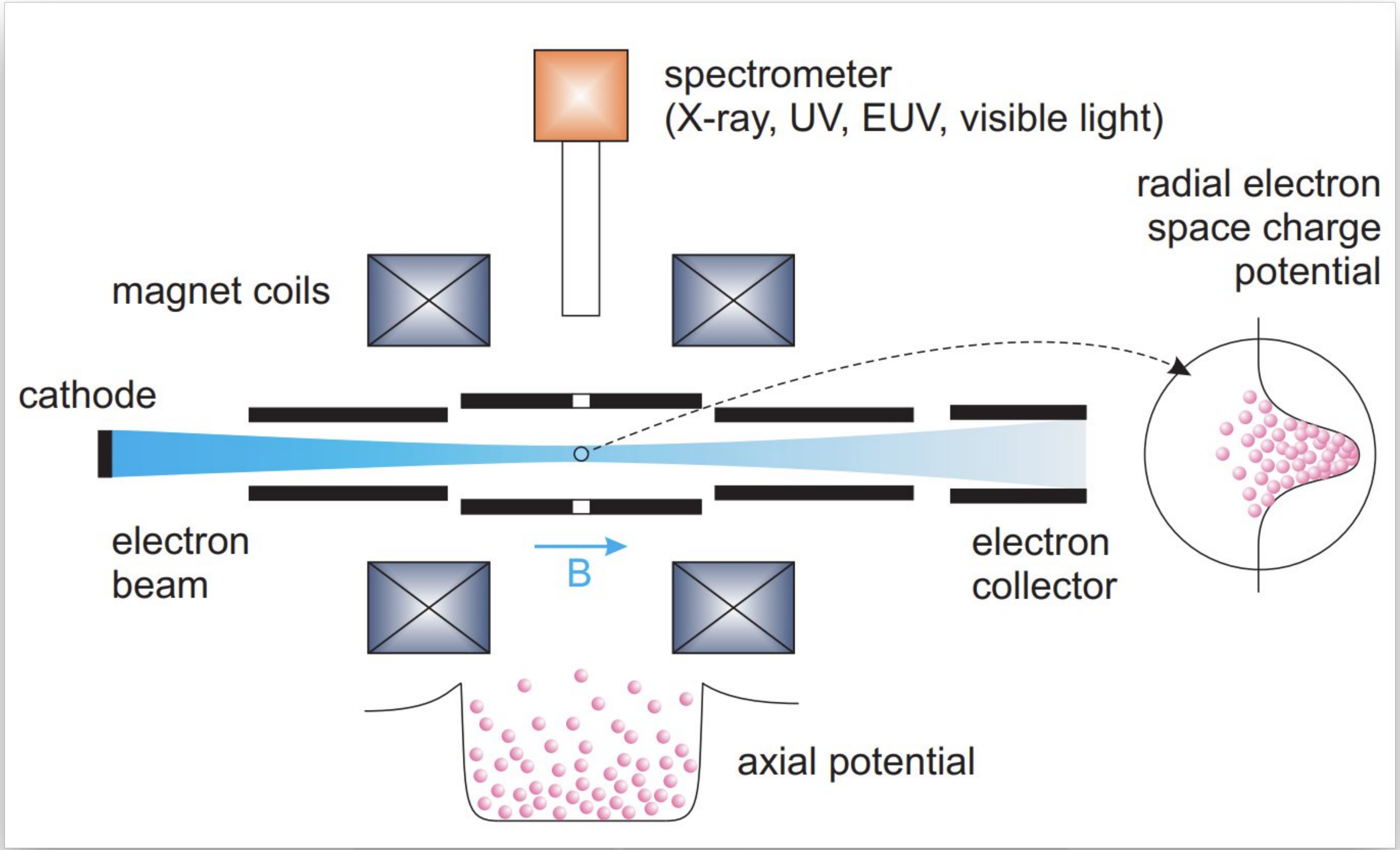
Advantages:

Eco / cost
Confinement is small space
—> radiation detection around the trap

Issues:

confinement in small space
—> space charge effects

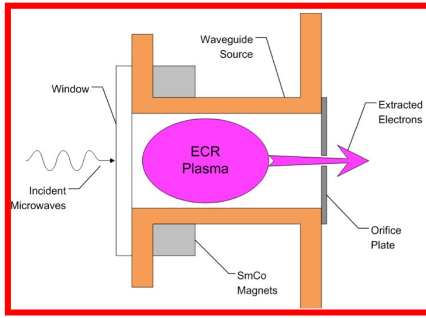
Charge breeding: EBIT

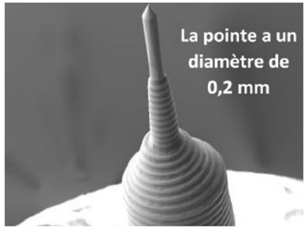


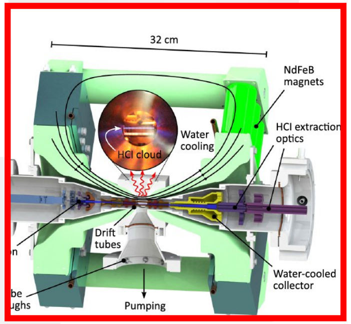
Tools to be developped at IJCLab

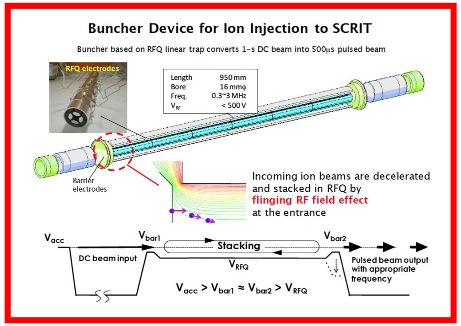
mosaic

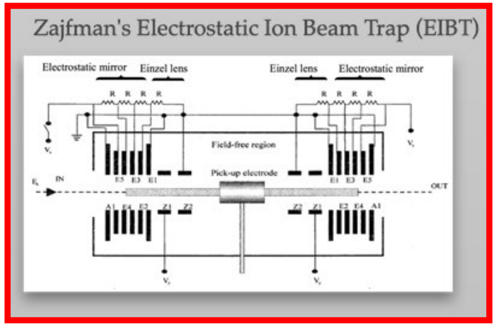
Production (ECR/LMIS) → Charge breeding → Accumulate Cool → Trapping Observation





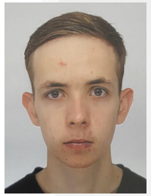






Serge Della Negra

Amelle Khamkham (M1)



Damien Jacquemin (L3)

Michele Sguazzin (postdoc in2p3)

David Lunney

Maroua Benhatchi PhD (IJCLab)

Sarah Hussein (M1)

Maxime Duval (L3)

Production of multicharged ions @Tancrède

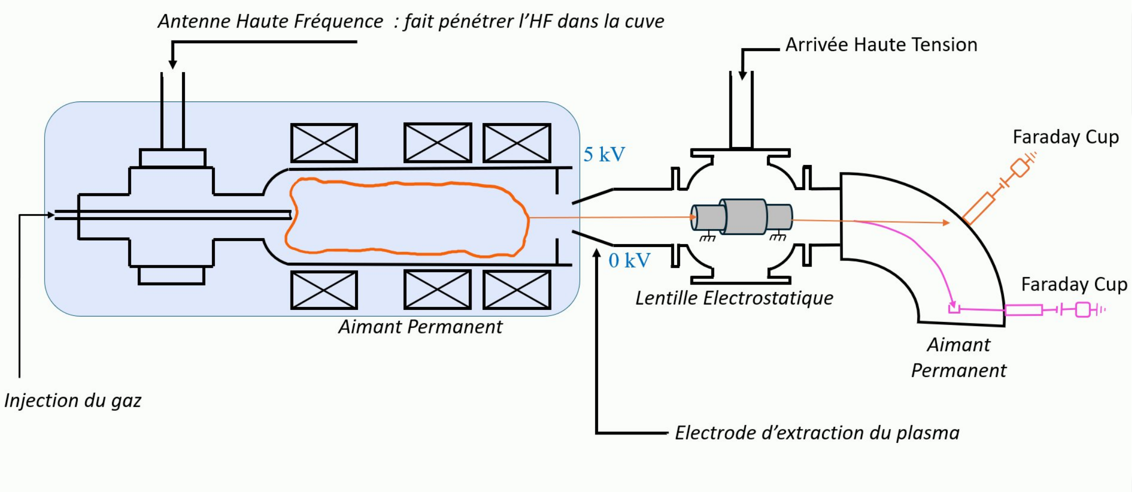
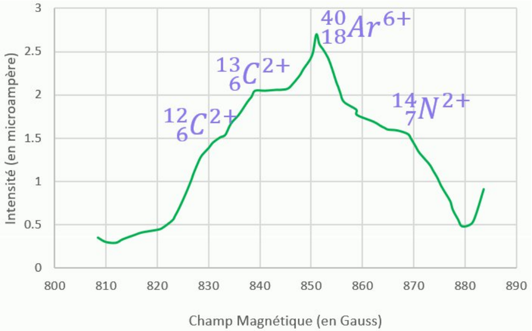
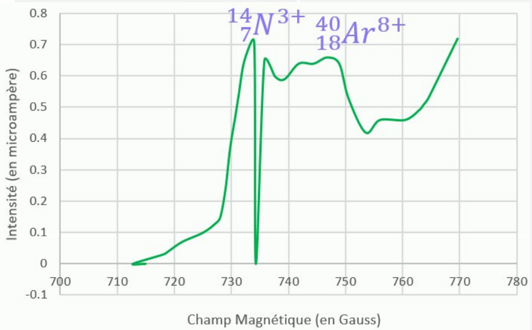
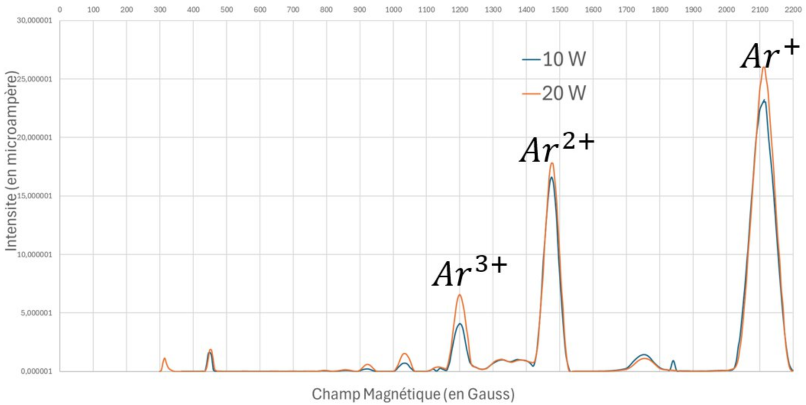


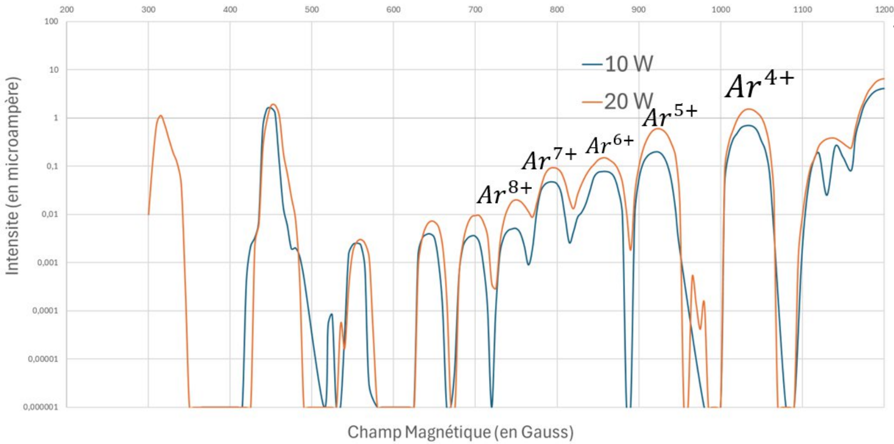
Schéma de la source TANCREDE

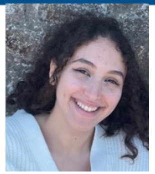






Spectre Argon multi-chargé (courant en fonction du champ magnétique)
Comparataison entre 10 W et 20 W de puissance, à 10 kV



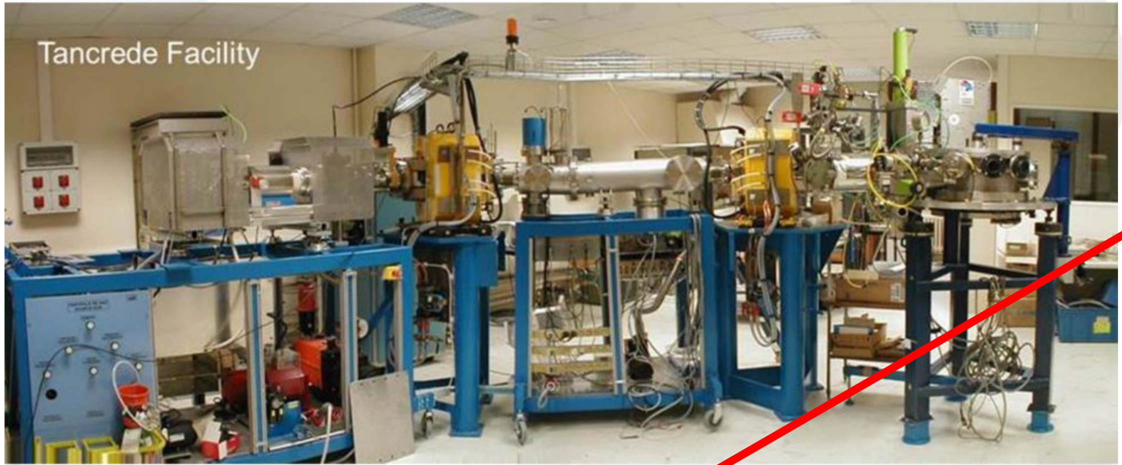


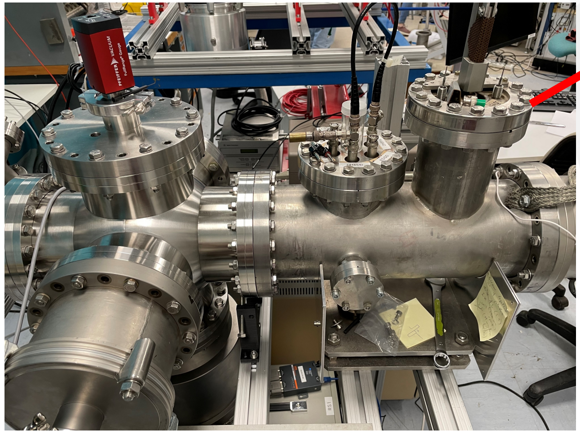
Amelle Khamkham (M1)

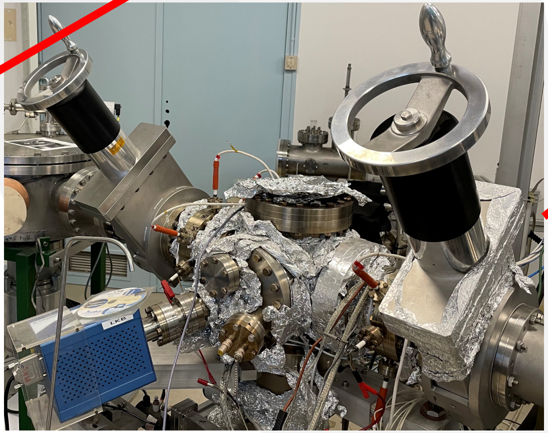
Michele Sguazzin (postdoc in2p3)

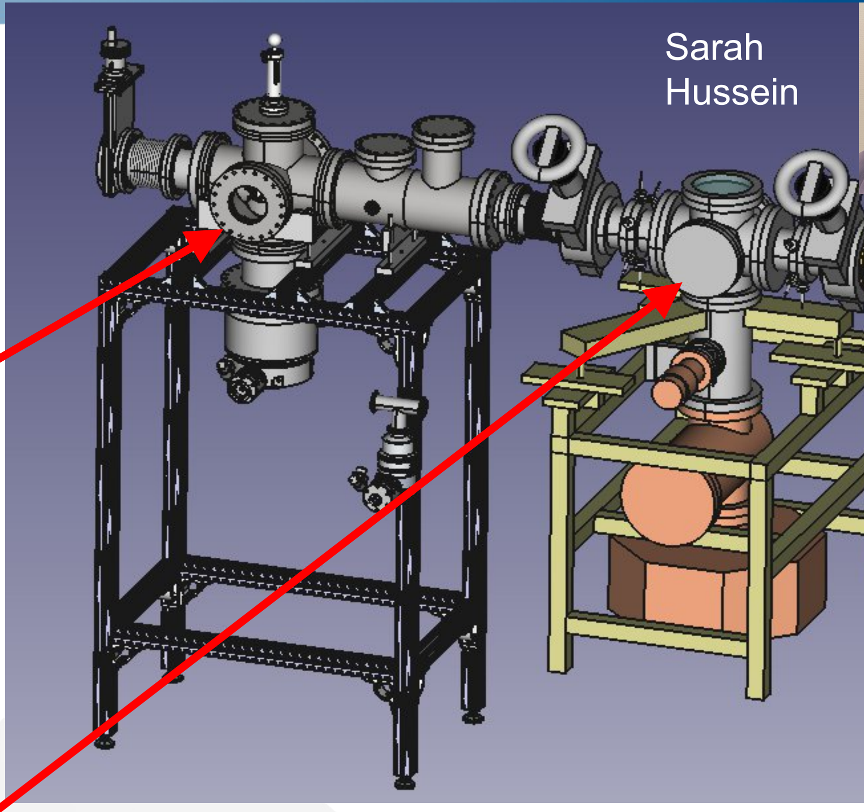
HINA beamline @Tancrède (ongoing)

mosaic

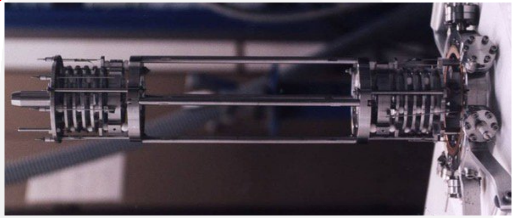








Sarah Hussein



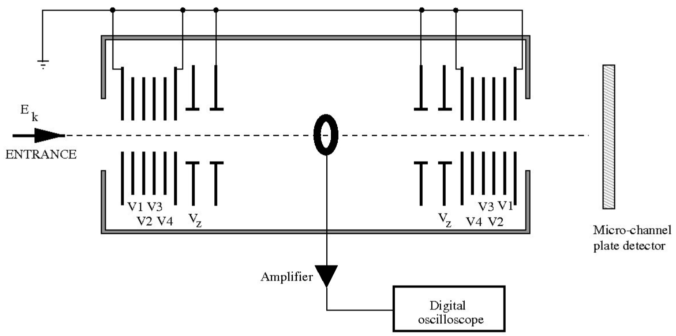
Maroua Benhatchi (PhD)

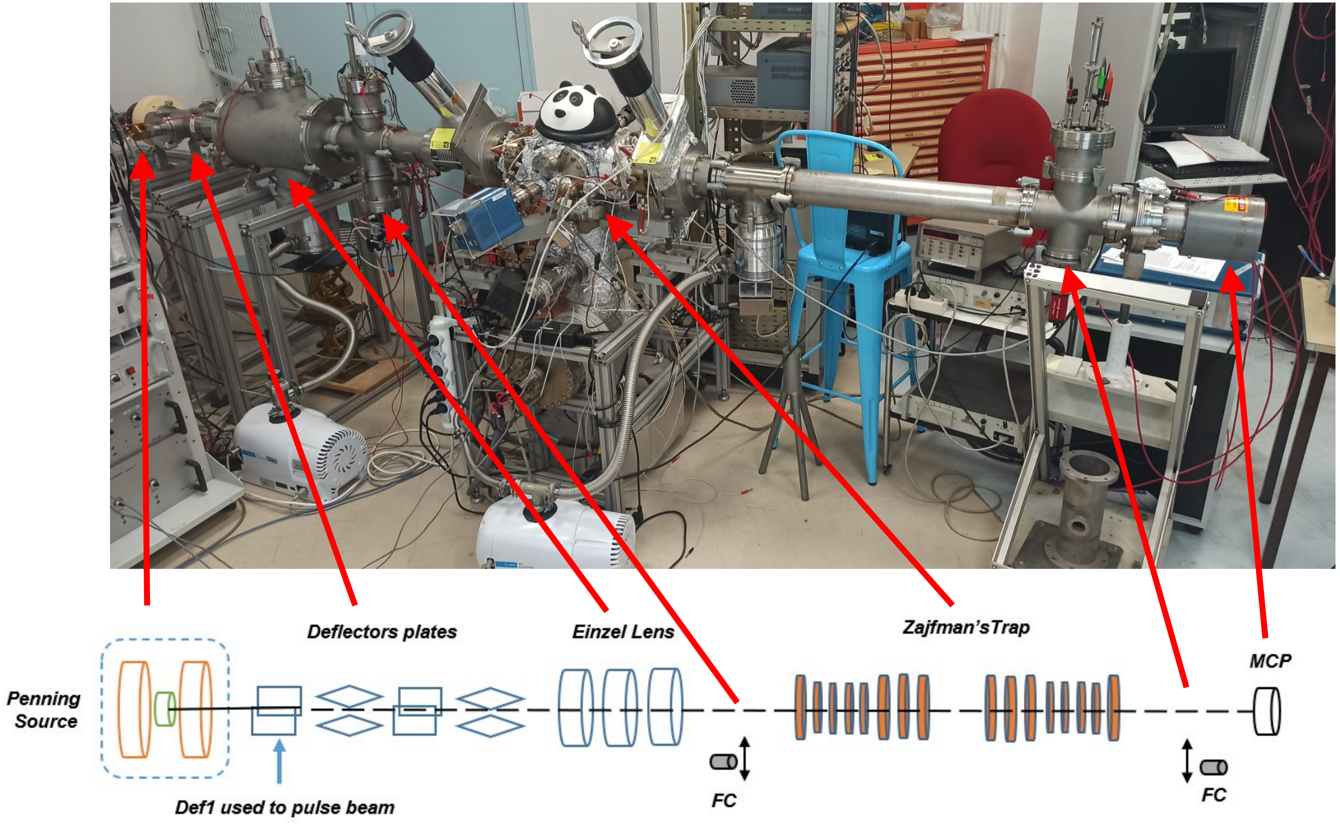
Maxime Duval (L3)

Offline test setup

- Developement Set up:
  - penning source to create ions (energy spread ~100eV)
  - different optical devices to pulse and optimise ion beam
  - Zajfman's Trap
  - diagnostic devices

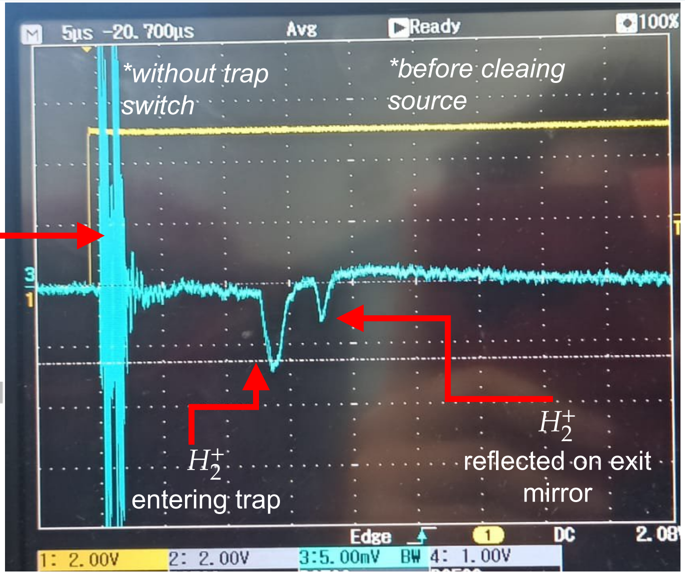
D. Zajfman et al. / International Journal of Mass Spectrometry 229 (2003) 55–60





First test of trapping with Zajfman trap

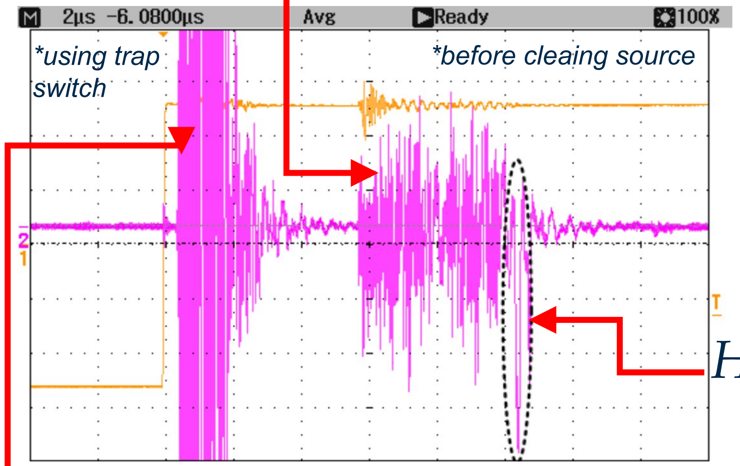
- With H_2^+:
  - at $E_k \approx 2\text{KeV}$:
    - *V1 = 2826V, V2 = 2168V, V3 = 2168V, V4 = 661V, Vz = 1850V*
    - *Trapping time up to 80us ~ 40 revolutions (very low signal)*



Buncher switch noise

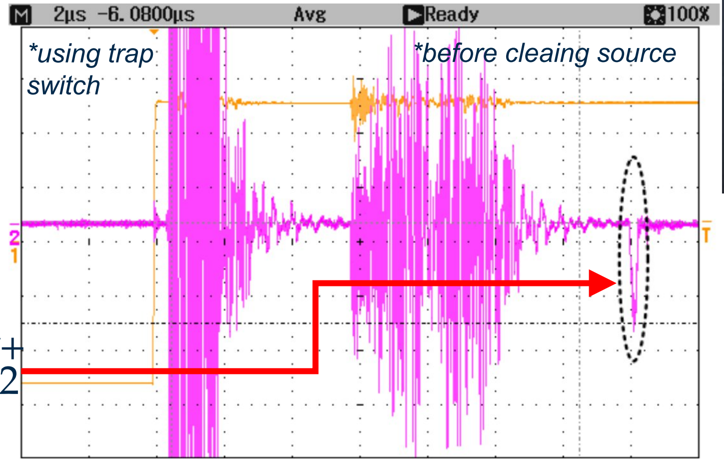
Signal on MCP for one revolution, ToF = 13,69us.

Trap switch noise



Signal on MCP for a shoot throught, ToF = 10,85us.

H_2^+



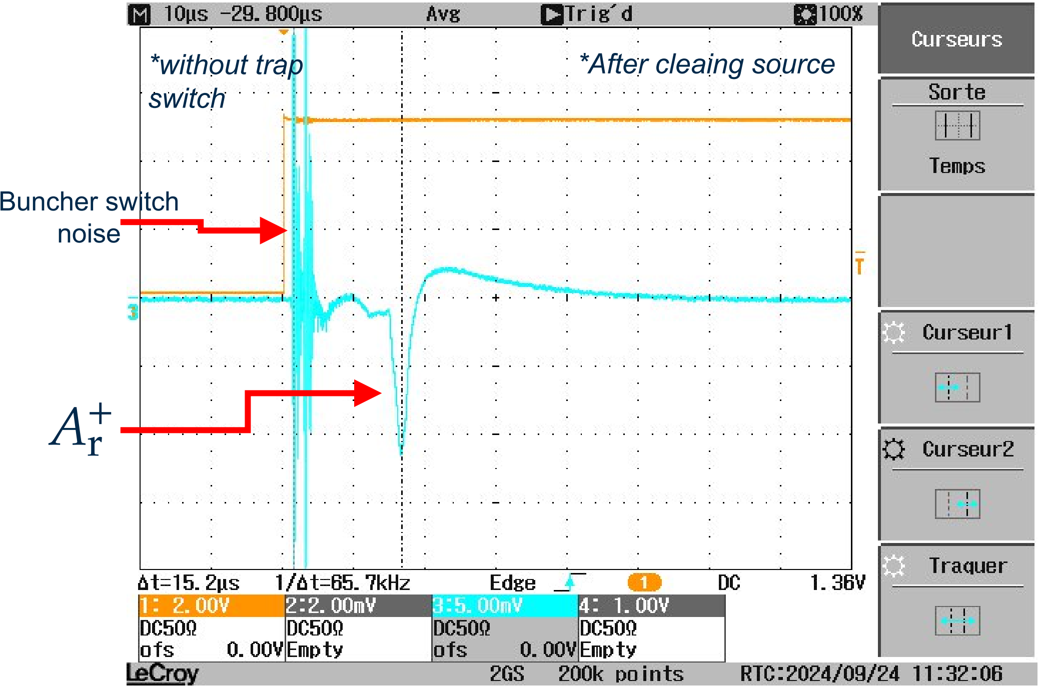
Signal on MCP for one revolution, ToF = 13,69us.

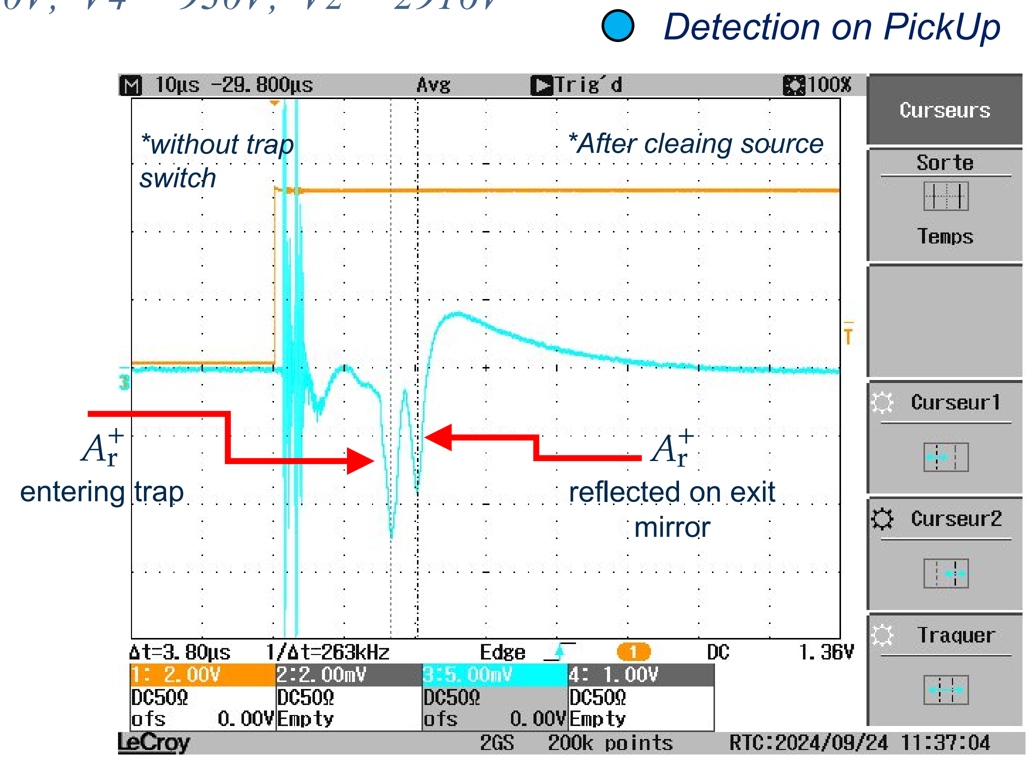
Buncher switch noise

- *Detection on PickUp*
- *Detection on MCP*

Courtesy of Maxime

- With Ar^+:
  - at $E_k \approx 3KeV$:
    - *Trap entry : V1 = 4760V, V2 = 3528V, V3 = 3535V, V4 = 959V, Vz = 2908V*
    - *Trap exit : V1 = 4754V, V2 = 3543V, V3 = 3510V, V4 = 930V, Vz = 2916V*
    - *Trapping for half a revolution (~ 4us)*

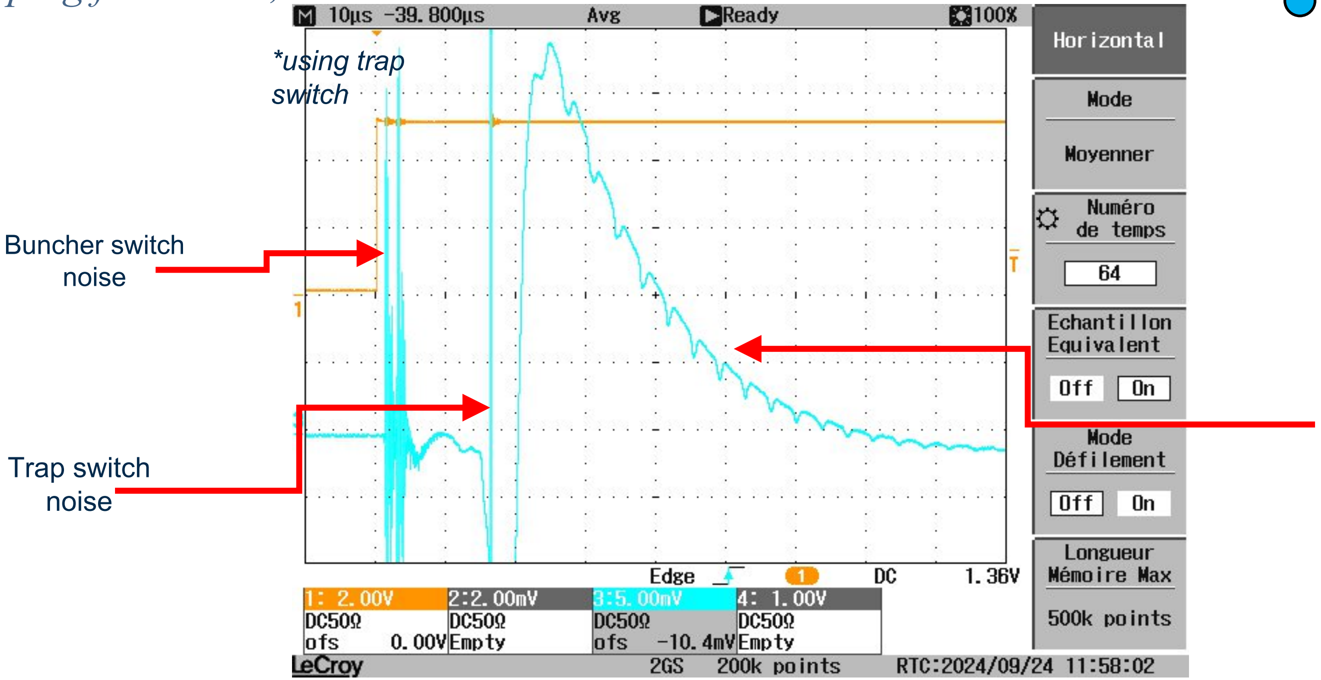




Courtesy of Michele

Measurements with pickup electrode

- With Ar^{+}:
  - at $E_k \approx 3\text{KeV}$:
    - *Trap entry : V1 = 4756V, V2 = 3570V, V3 = 3399V, V4 = 925V, Vz = 2663V*
    - *Trap exit : V1 = 4730V, V2 = 3553V, V3 = 3345V, V4 = 928V, Vz = 2699V*
    - *Trapping for ~ 80us, 10 revolutions*



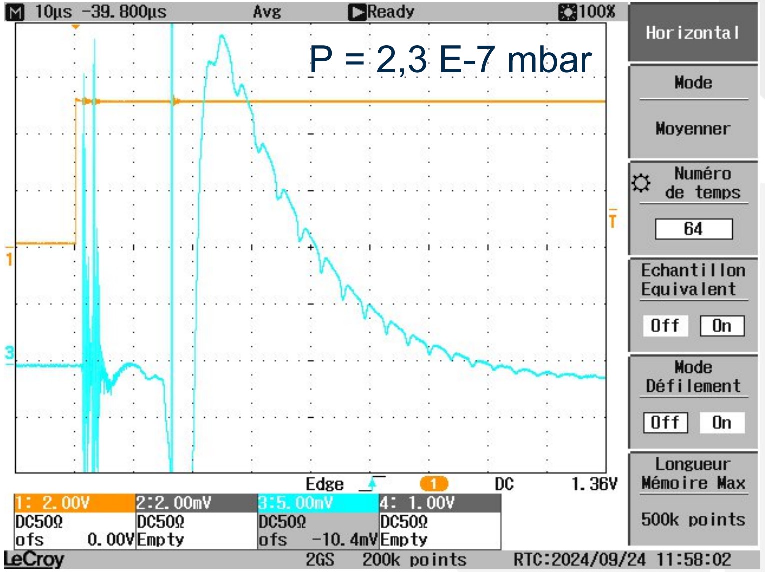
Detection on PickUp

A_r^+ ion bunch decaying over time !

Courtesy of Michele

Measurements with pickup electrode

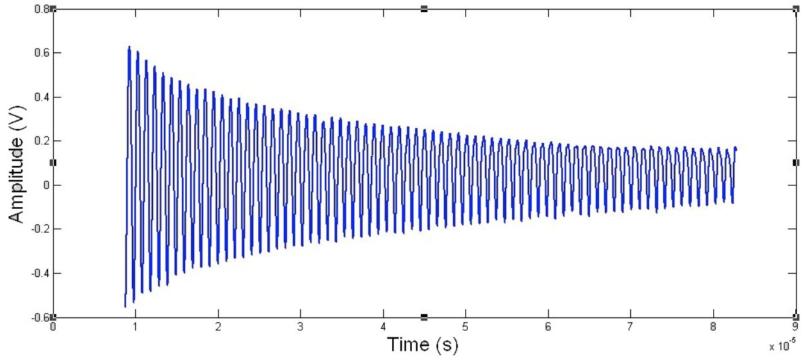
- Our's



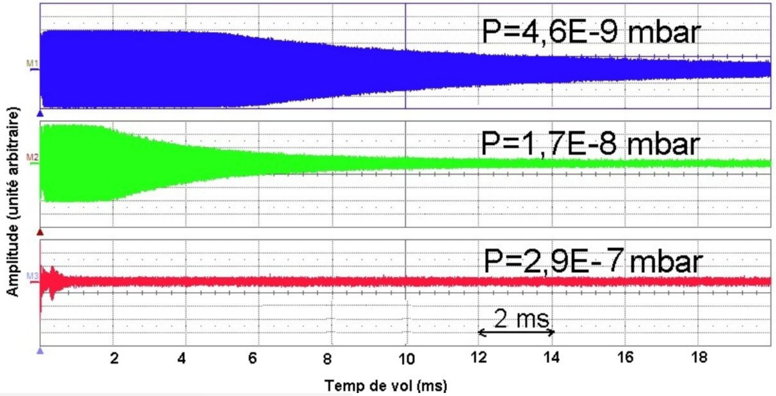
Trapping of A_r^{+} ions

clean signal
and
higher vaccum
needed !!!

- Dina's



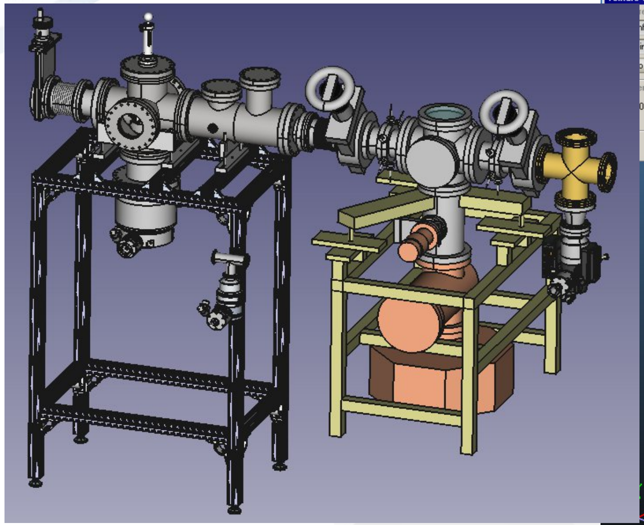
Trapping of A_r^{10+} ions

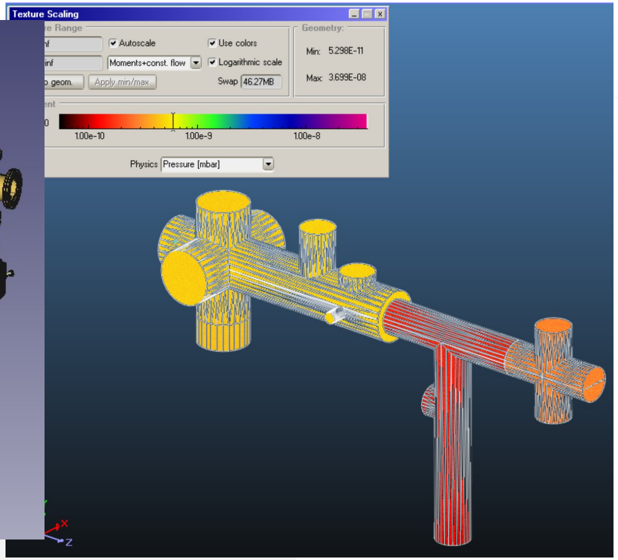


Trapping of A_r^{11+} ions

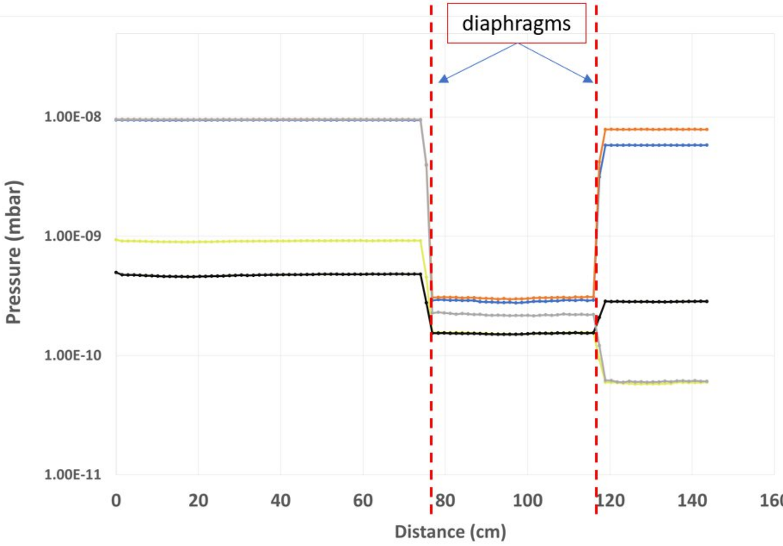
Simulation for vacuum (Molflow) @Tancrede

Michele Sguazzin (postdoc in2p3)

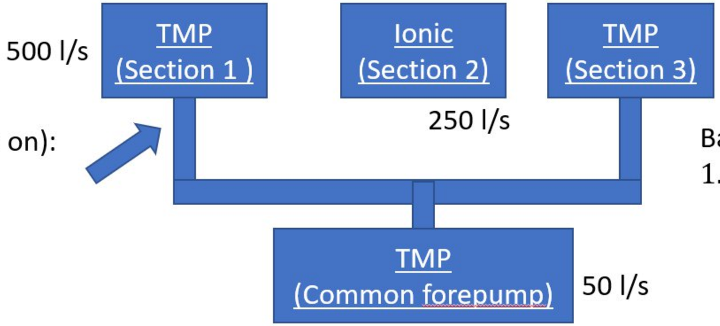




Partial pressure of H_2



Back pressure (pumps on): $1.3 \cdot 10^{-4}$ mbar

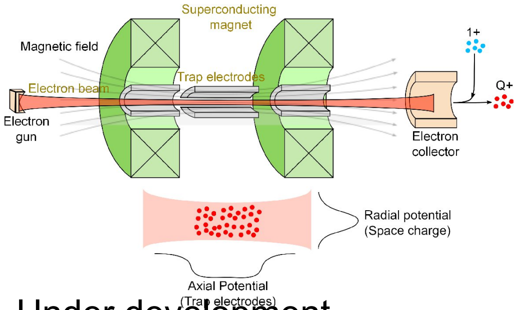


Back pressure (pumps on): $1.3 \cdot 10^{-4}$ mbar

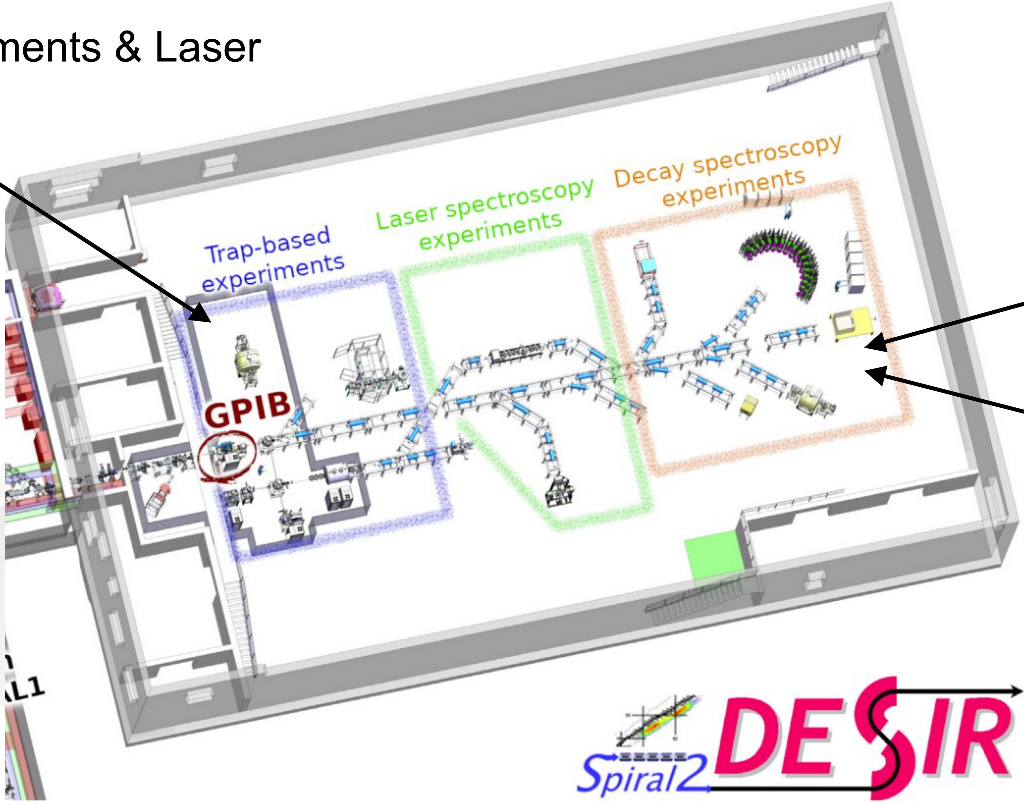
HINA project (**H**ighly charged **I**ons for **N**uclear physics and **A**strophysics)

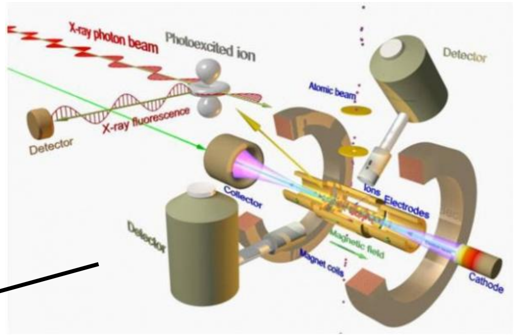
High precision mass measurements & Laser spectroscopy

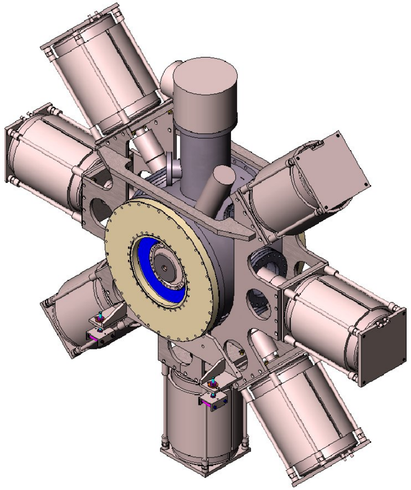
$$\frac{m}{\Delta m} \propto \frac{q \cdot B}{m} \cdot T_{RF}\sqrt{N}$$



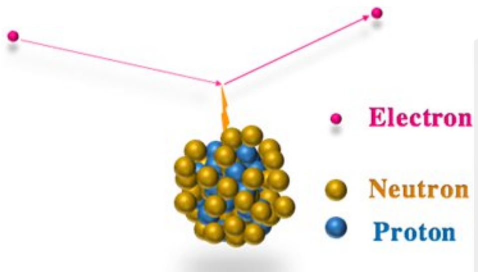
Under development @IJCLab



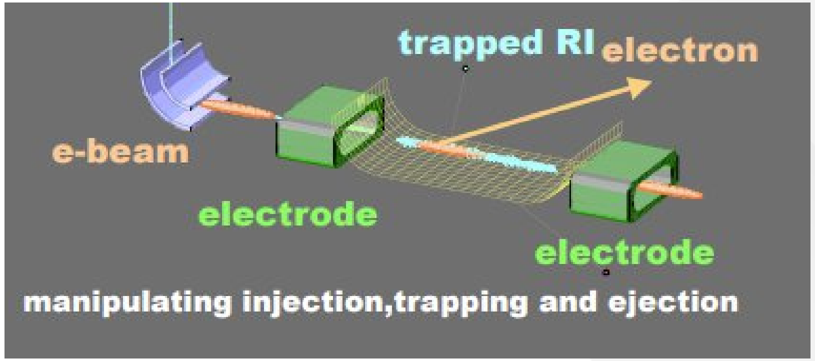




TMI: Study ion trapping techniques for nuclear physics



Electron scattering off neutron-rich exotic nucleus



TMI

Techniques de Manipulation d'Ions

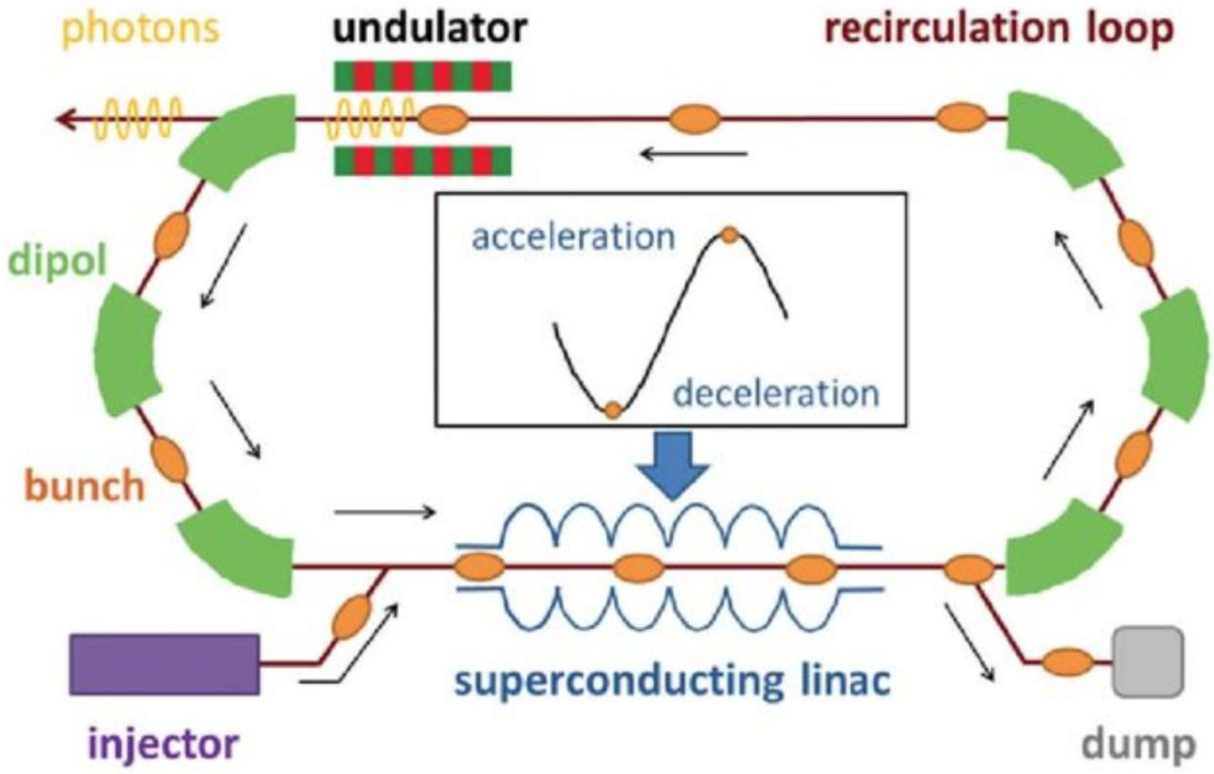
HINA

GBAR

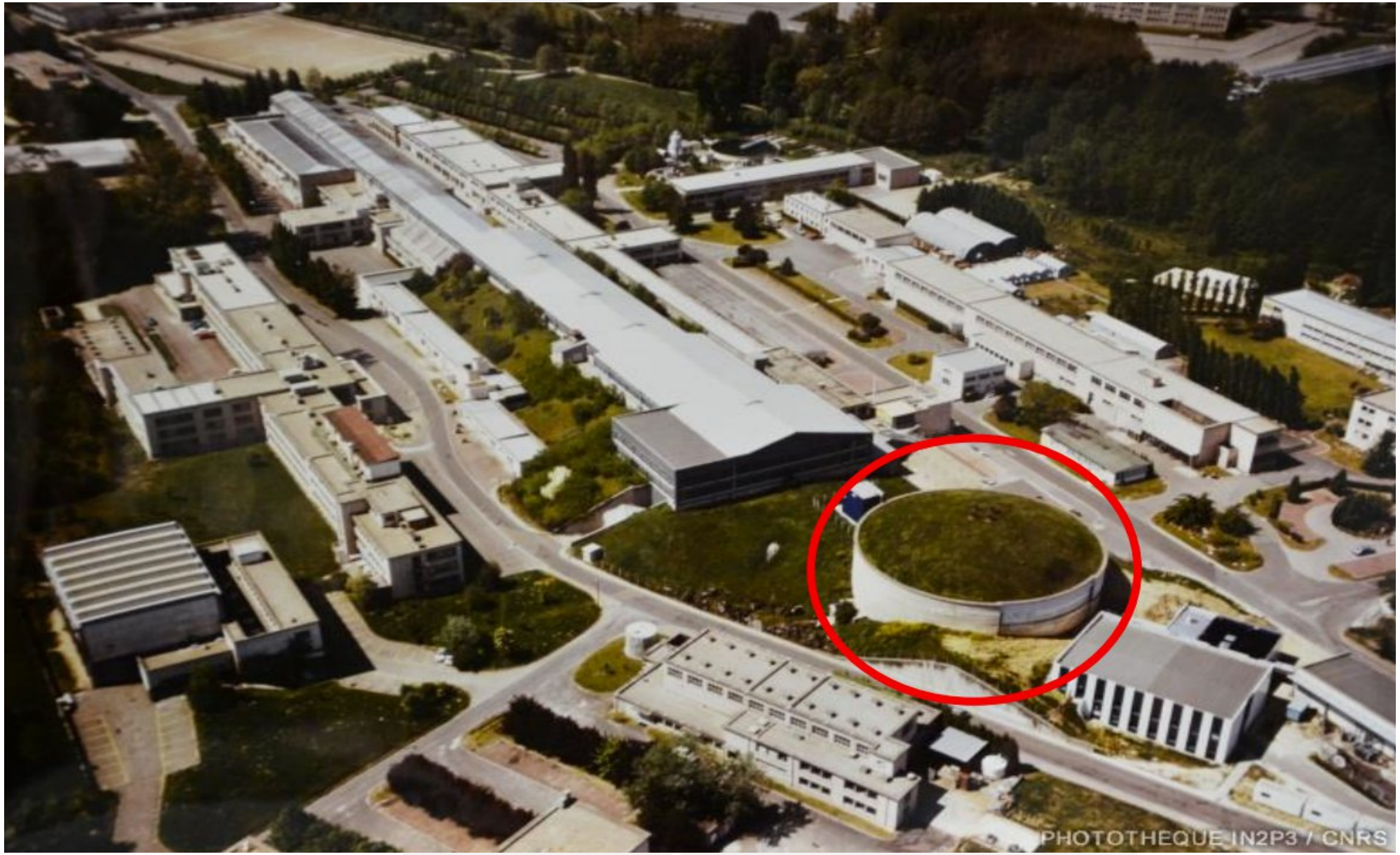
DESTIN@PERLE

DESTIN@PERLE is an ideal place for R&D
—> trap techniques could be developed @TMI

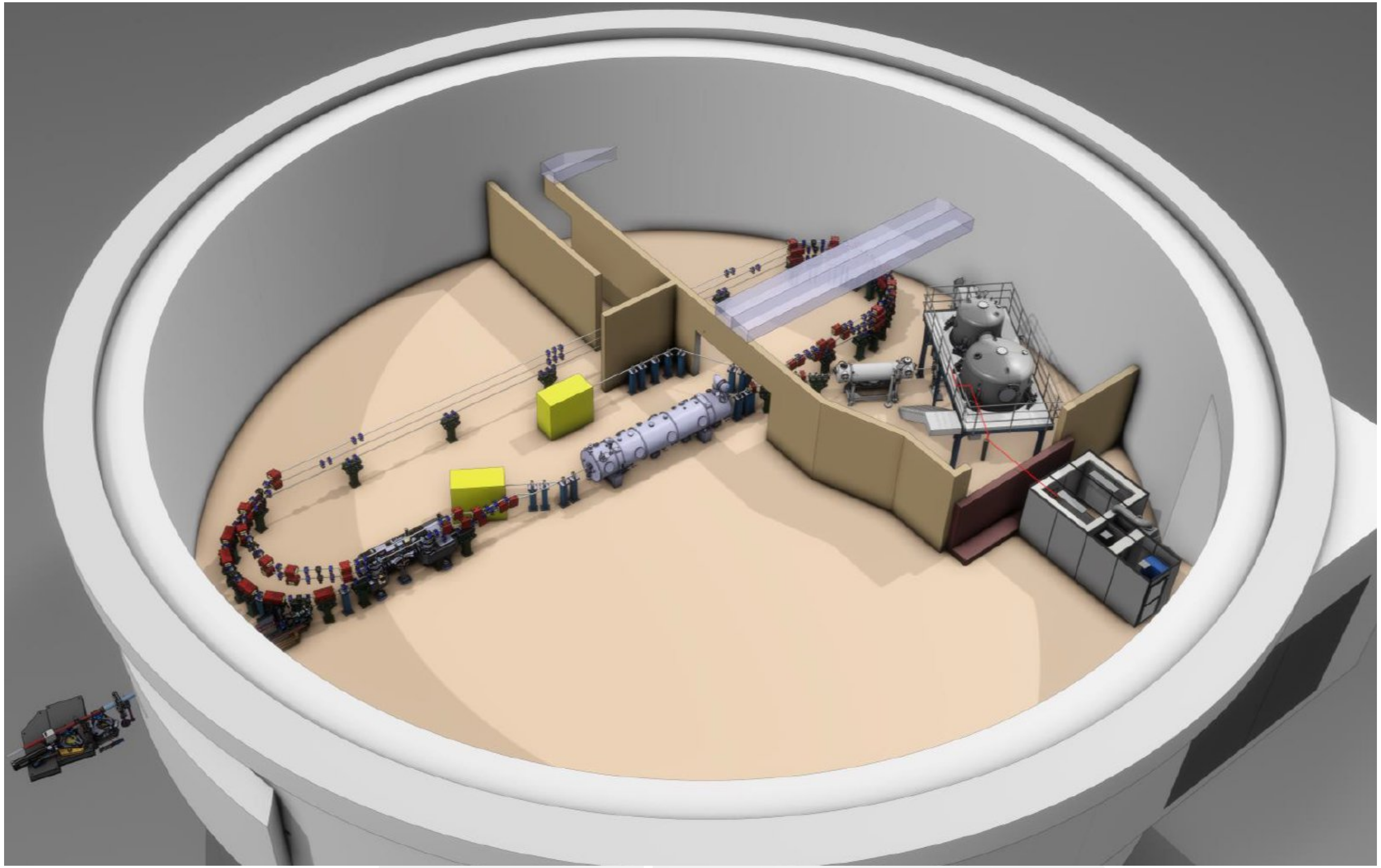
Principle of ERL



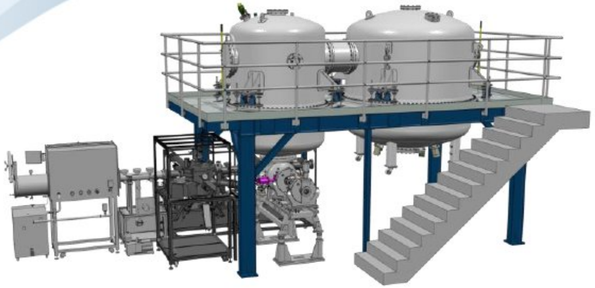
PERLE project @ORSAY (energy recovery LINAC)

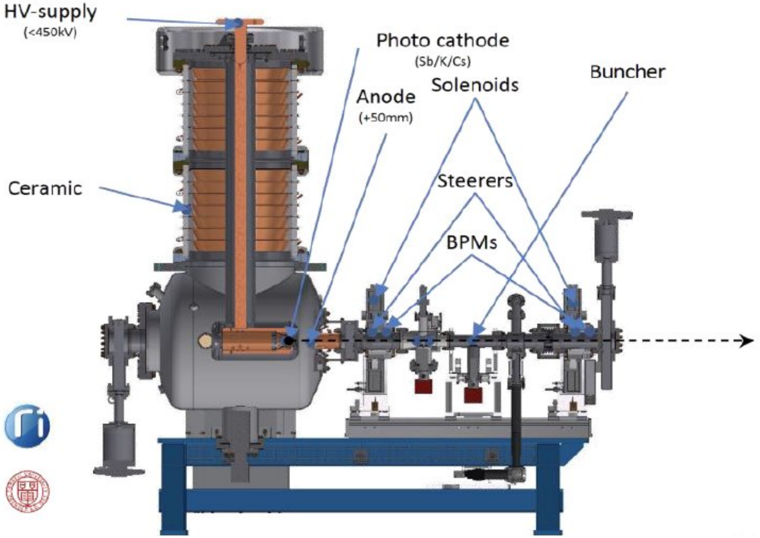


PERLE project @ORSAY



PERLE project @ORSAY

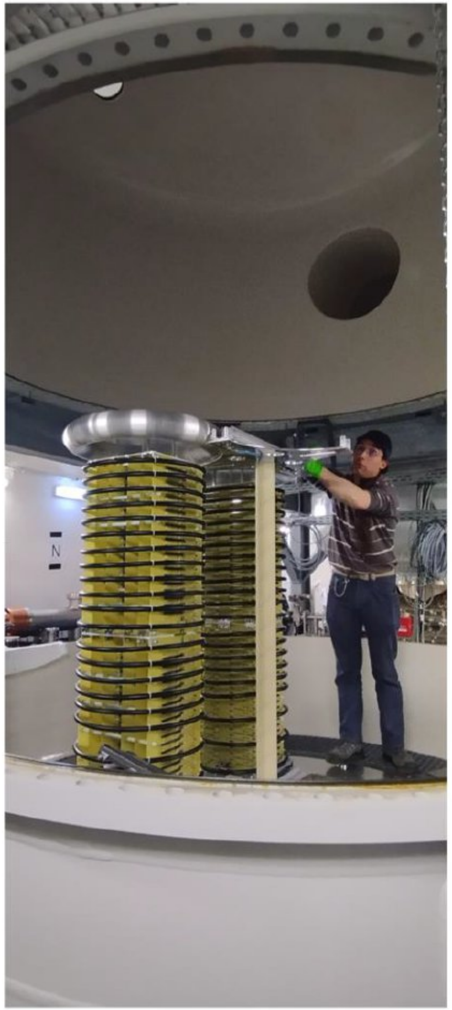


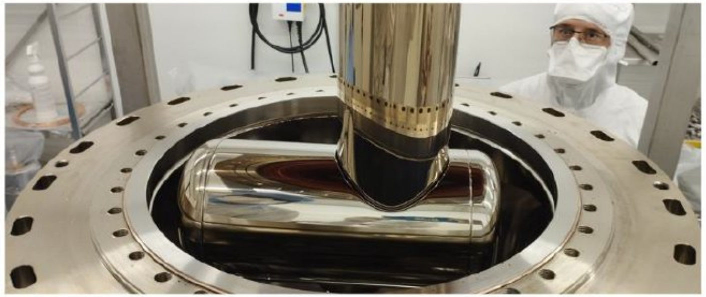


Beam Test Facility

RI develops and manufactures high-performance components and systems, and provides solutions for scientific and industrial applications

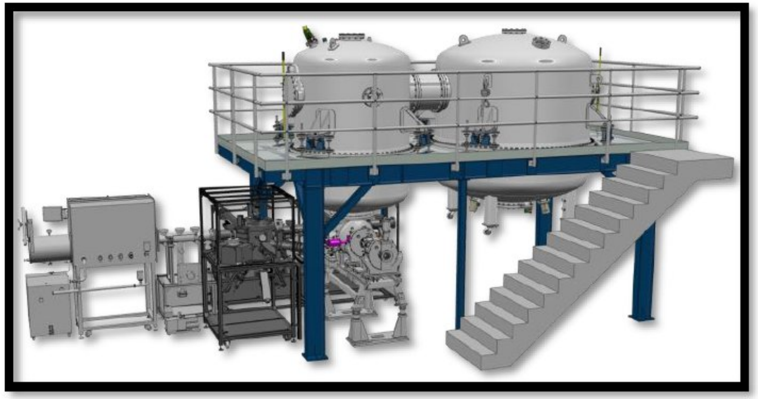
PERLE project @ORSAY



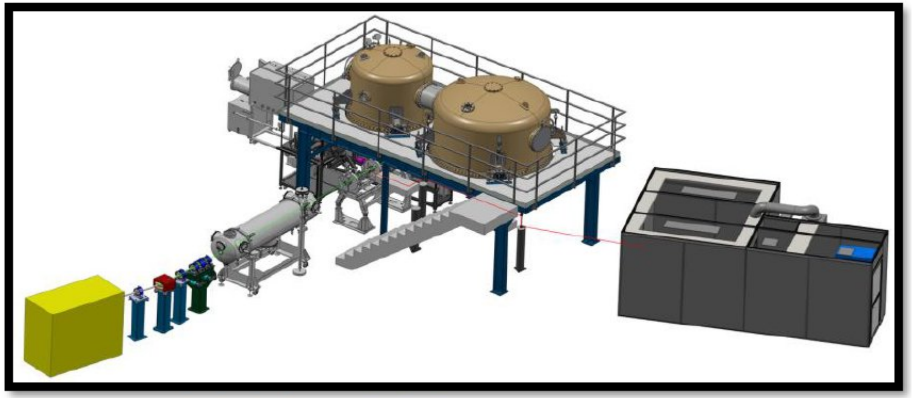


We ensured :
dismantling, packaging and shipping in 3 weeks

PERLE project @ORSAY Time-line

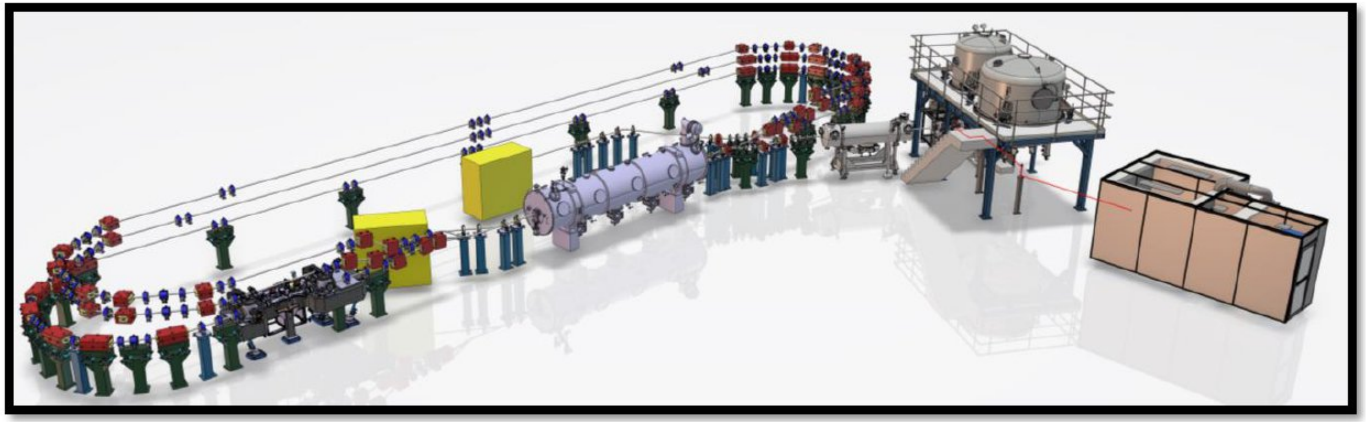


2024 - 2025



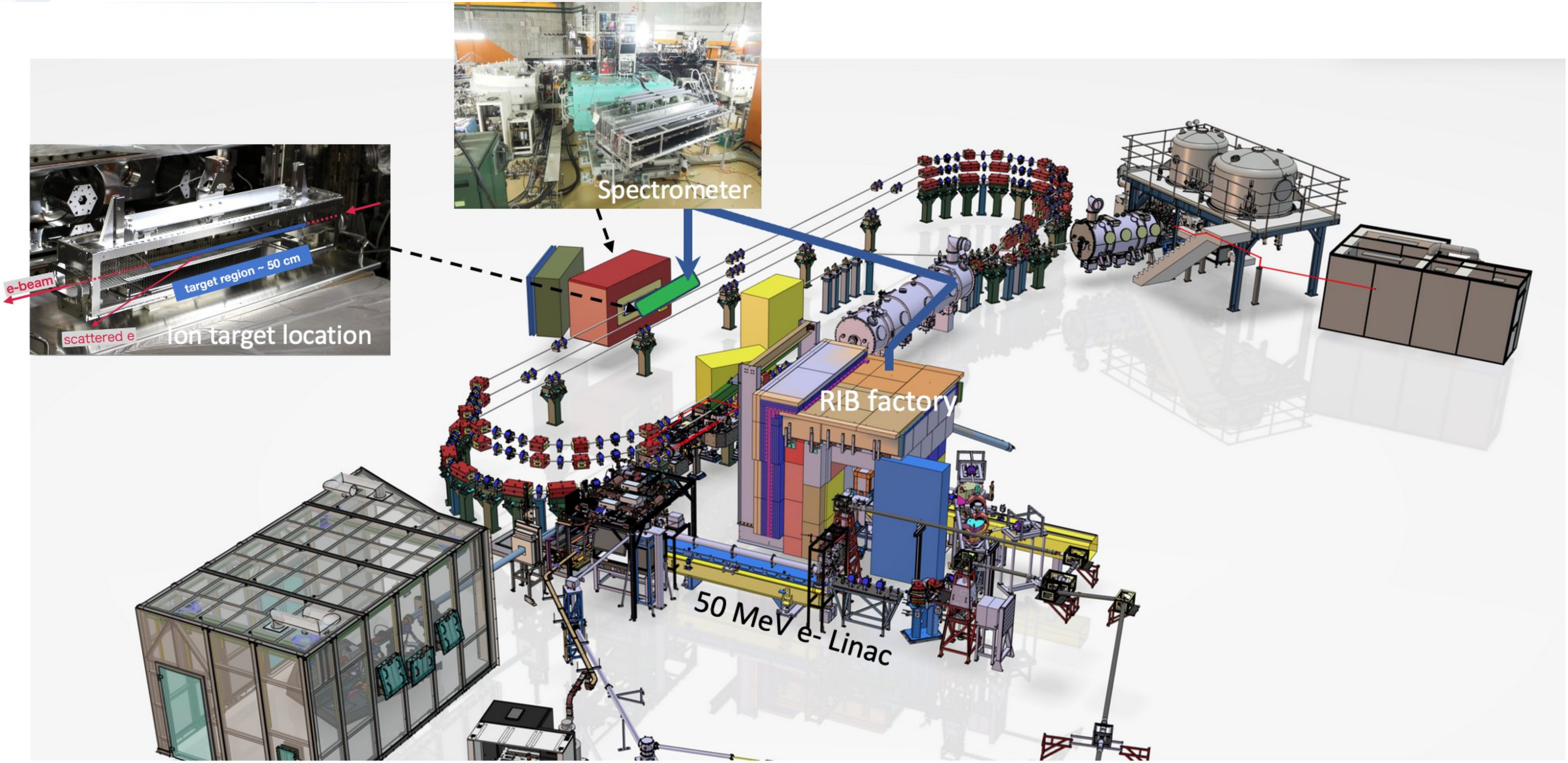
2026 - 2027

2027 - 2028

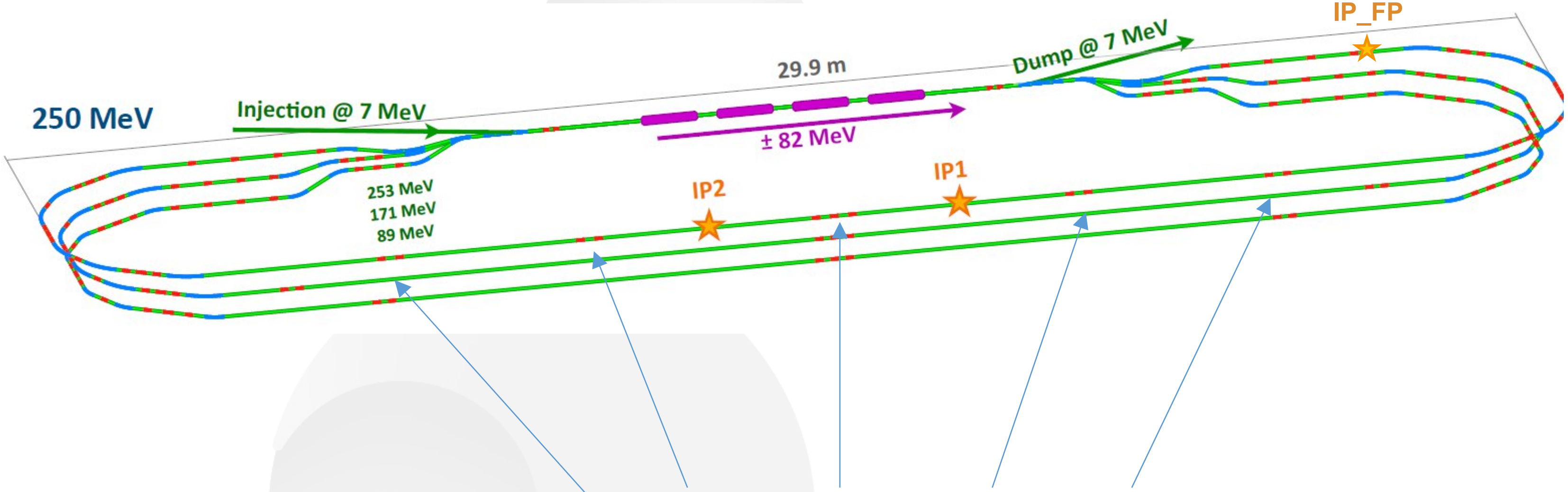


2028 - 2031

DESTIN@PERLE



PERLE 250 MeV : interaction points

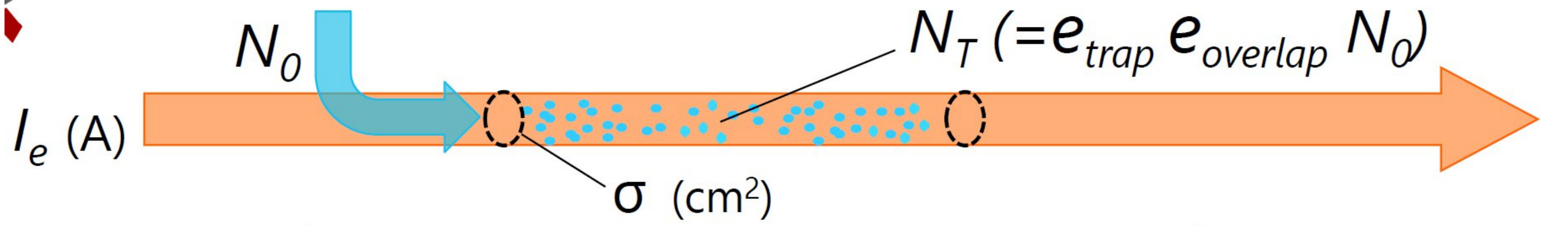


These quads allows beam tuning at IPs

- Control of beam size
- Control of beam angles

X emittance (norm)	Y emittance (norm)	Bunch size (RMS)	Energy spread (RMS)	Charge/Current	Energies
5,6 mm.mrad	5,7 mm.mrad	3mm	0,136%	500pC/20mA	7/89/171/**253** MeV

Achievable luminosity



$$L \sim \frac{I_e/e \quad N_T}{\sigma} \ /(\mathrm{cm}^2\mathrm{s})$$

Current performance (typical)

I_e ~ 175 mA

at σ ~ 3.6 mm^2 ⇨ L ~ **1.4×10^{27} /(cm²s)**

N_0 ~ 2.3×10^8

Number of target ions **N_T ~ 4.6×10^7**

Total efficiency **$e_{trap}\, e_{overlap} = N_T/N_0 \sim 20\ \%$**

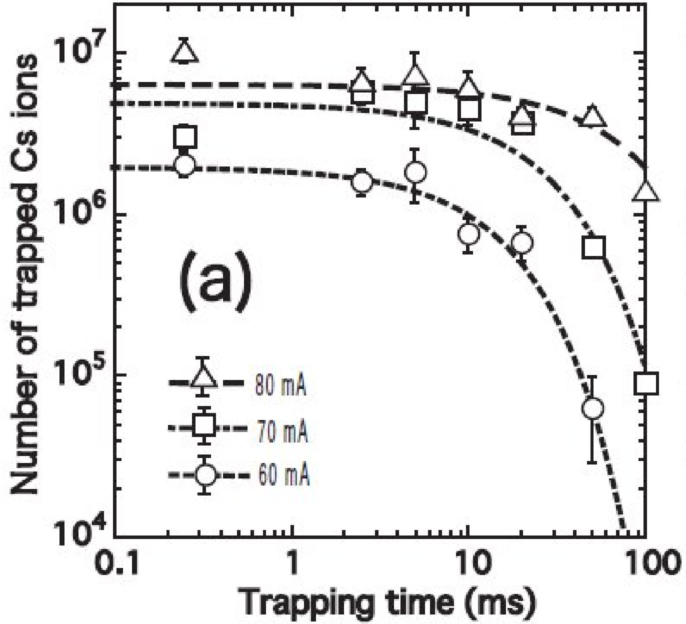
Charges in 500mm

SCRIT (200mA,13mm)

5e12

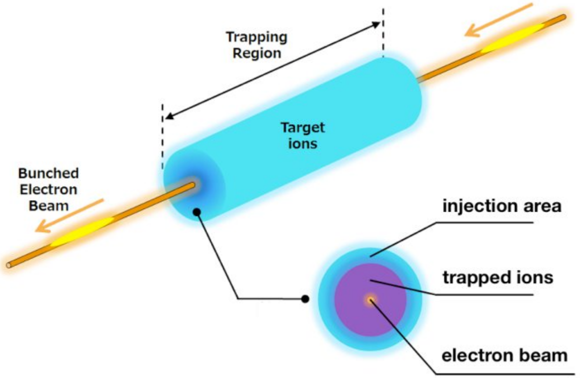
DESTIN (20mA,3mm)

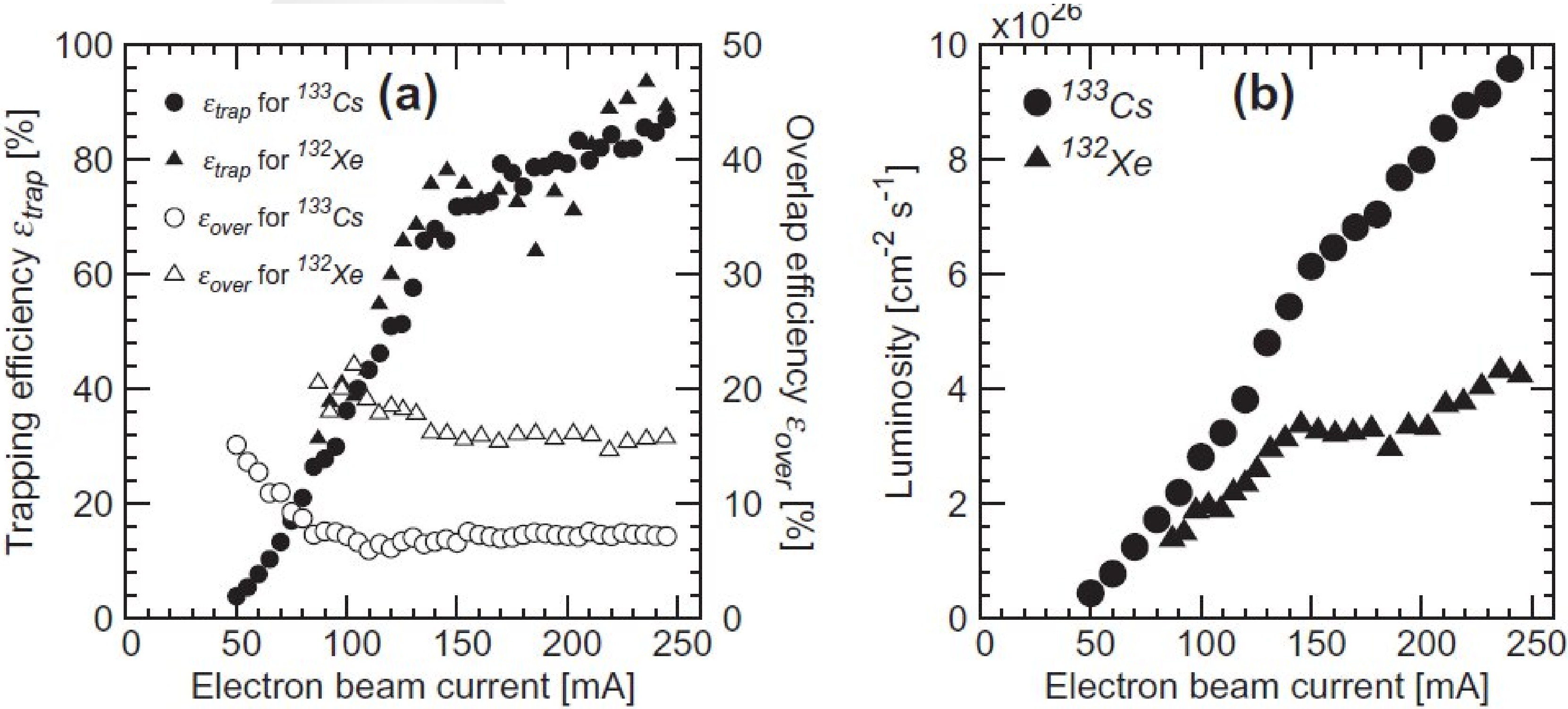
5.2e11



Trapping & Overlap efficiencies

$$\varepsilon_{trap} = N_{trap}/N_{inj}$$
$$\varepsilon_{over} = N_{coll}/N_{trap}$$

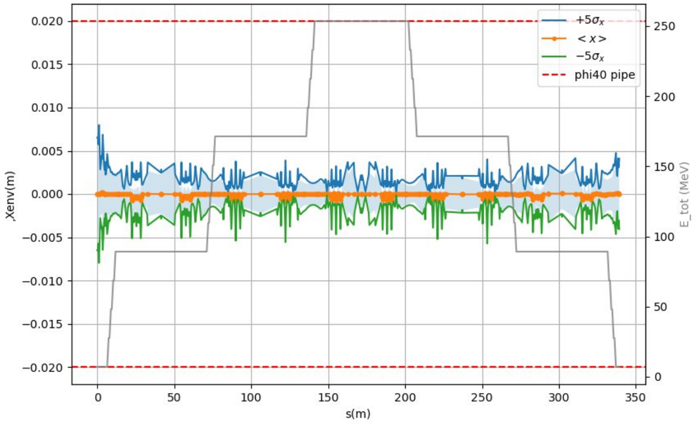


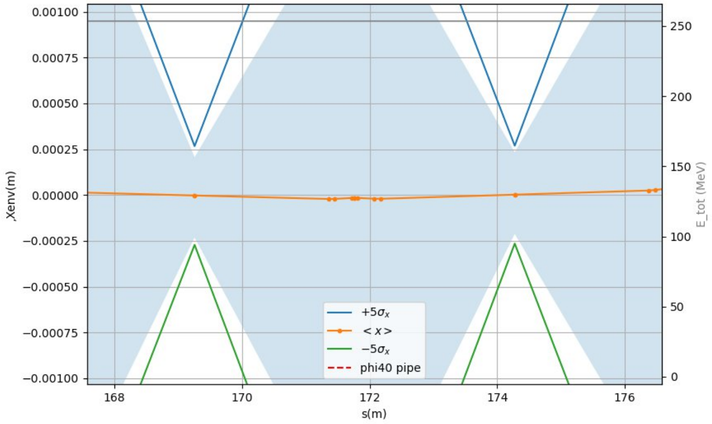


Short trapping time 45ms, 10^8 ^{132}Xe & 4×10^8 ^{133}Cs

Beam envelop

5σ horizontal envelop along PERLE

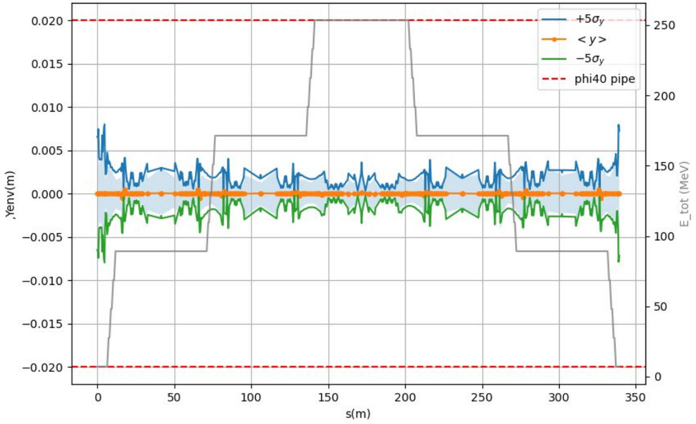


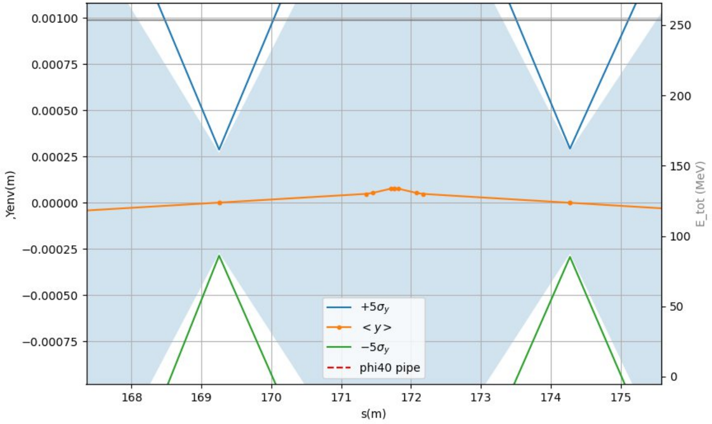


- Blue/green : $\pm 5\sigma$ beam envelop
- Grey : energy (passes)
- Orange : centroid
- Dotted red : beam pipe $\phi 40$

Zoom at IPs

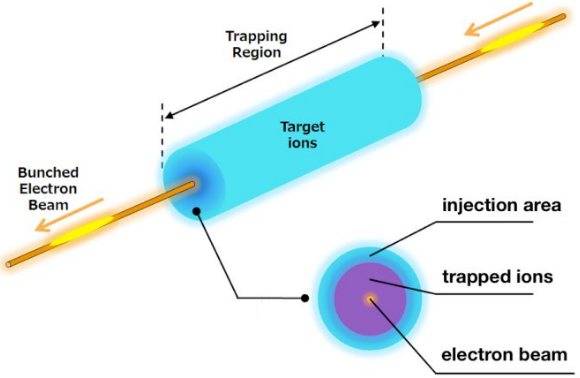
5σ vertical envelop along PERLE

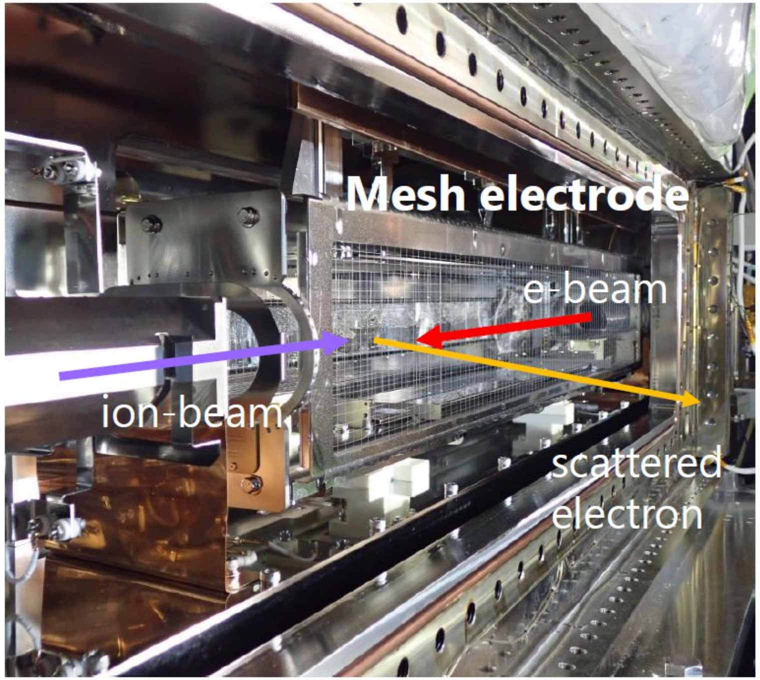




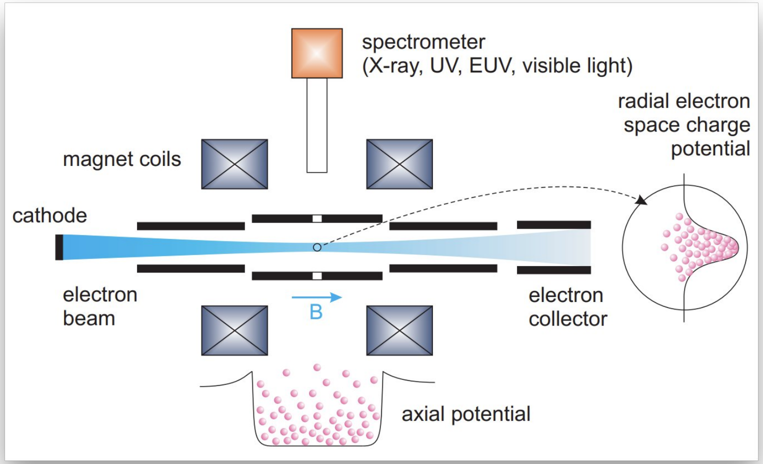
Bunch length and energy spread are normally fixed along the lattice in nominal operation
However, possibility to tune the lattice to minimize either one or the other -> under investigation

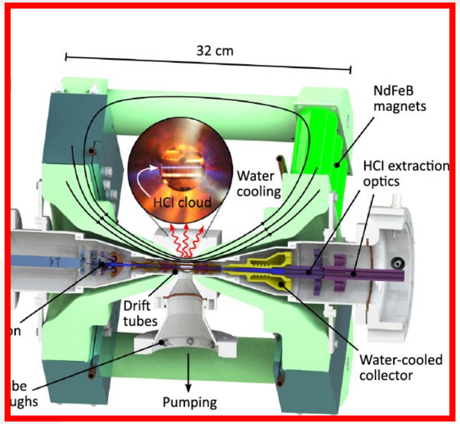
Choice of the trap: important for high luminosity





Alternative: EBIT





Study is ongoing

New PhD position will open soon at Paris-Saclay...

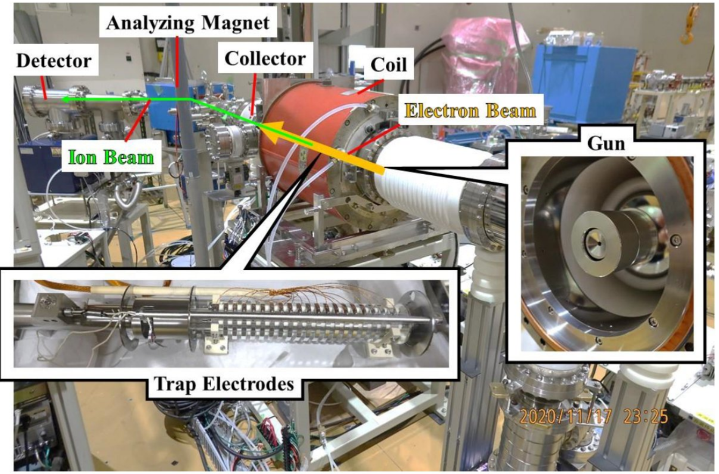
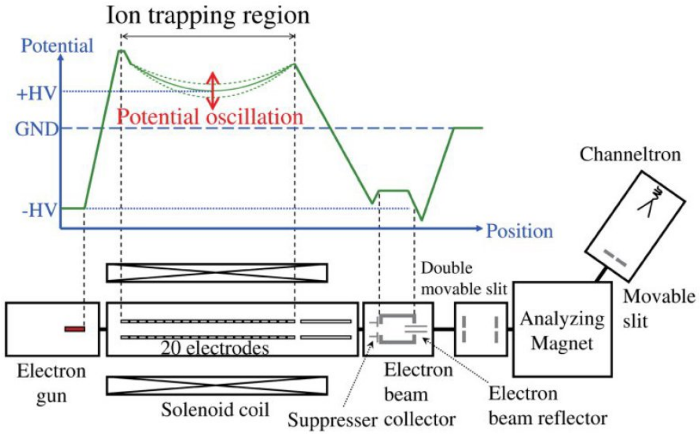


図 2.7：RECB 原理実証実験のためのビームライン写真。

Testing New EBIT Technique

$$V_{\mathrm{trap}}(z,t) = (a + b\sin(\omega t))z^2$$



R. Ogawara et al., Riken Accel. Prog. Rep. 54 (2021)

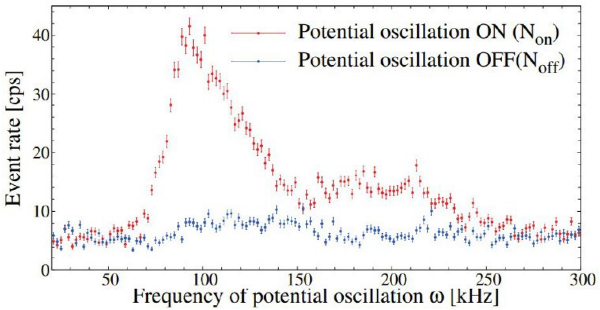


Fig. 2. Spetrum of extracted $^{12}C^{4+}$ ions.

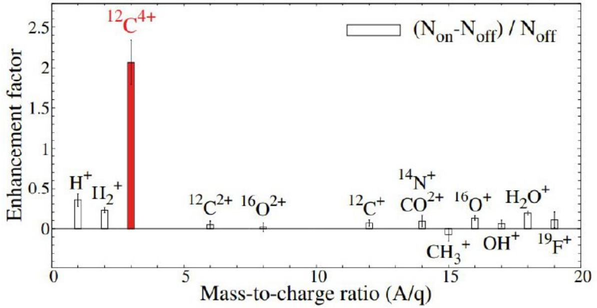


Fig. 3. Enhancement factors of extracted of $^{12}C^{4+}$ ions.

ありがとうございました
Thank you for your Attention
Merci