Projet HINA et développement de l'EBIT (Tancrède)

Michele Sguazzin

25/09/2024

Friends of HINA

Chercheurs


Serge Della Negra


Sarah Naimi


Vladimir Manea

David Lunney


Maroua Benhatchi


Michele Sguazzin

Support technique


Isabelle Ribaud


Denis Reynet


François Daubisse


Alexandre Migayron


Bruno MERCIER


Hervé Lefort


Philippe GAURON

Collaborateurs externes (MPIK)


José Crespo


Klaus Blaum


Manfred Grieser

Stagiaires M1/L3





Sophie, Amelle, Sarah
Damien, Maxime

Main Motivation

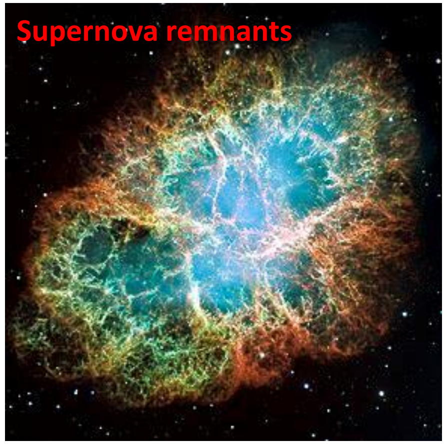
HINA → **H**ighly-charged **I**ons for **N**uclear physics and **A**strophysics

Project goal:

Study nuclear decay in highly charged ions (HCI)

Impact in stellar nucleosynthesis

Where do we find them?



3

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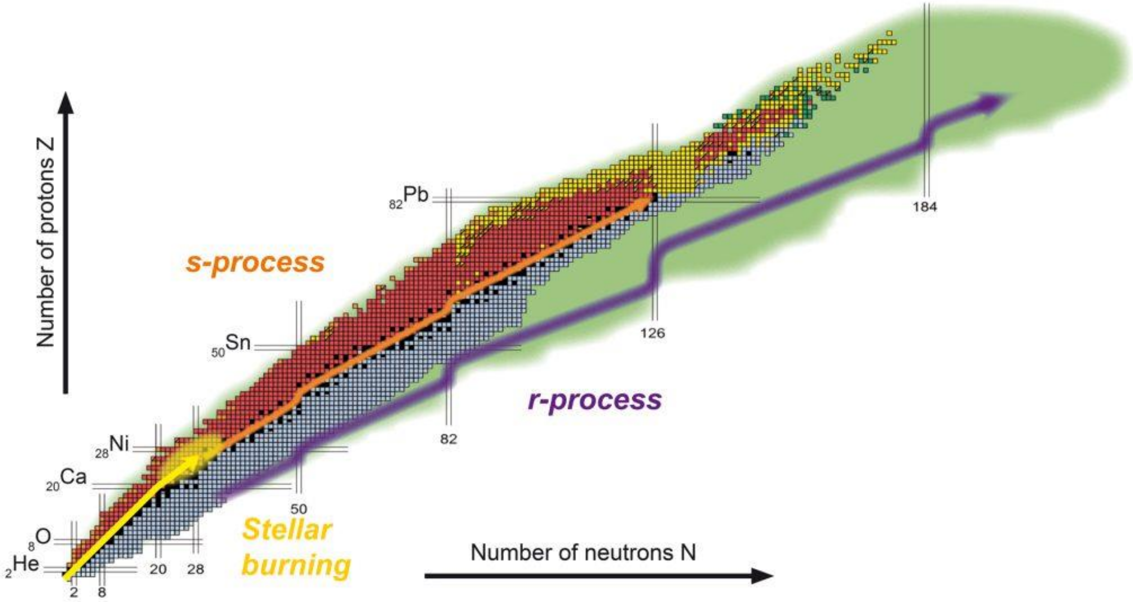
Impact in stellar nucleosynthesis

- Competition between neutron capture and nuclei decay



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Main Motivation

HINA → **H**ighly-charged **I**ons for **N**uclear physics and **A**strophysics

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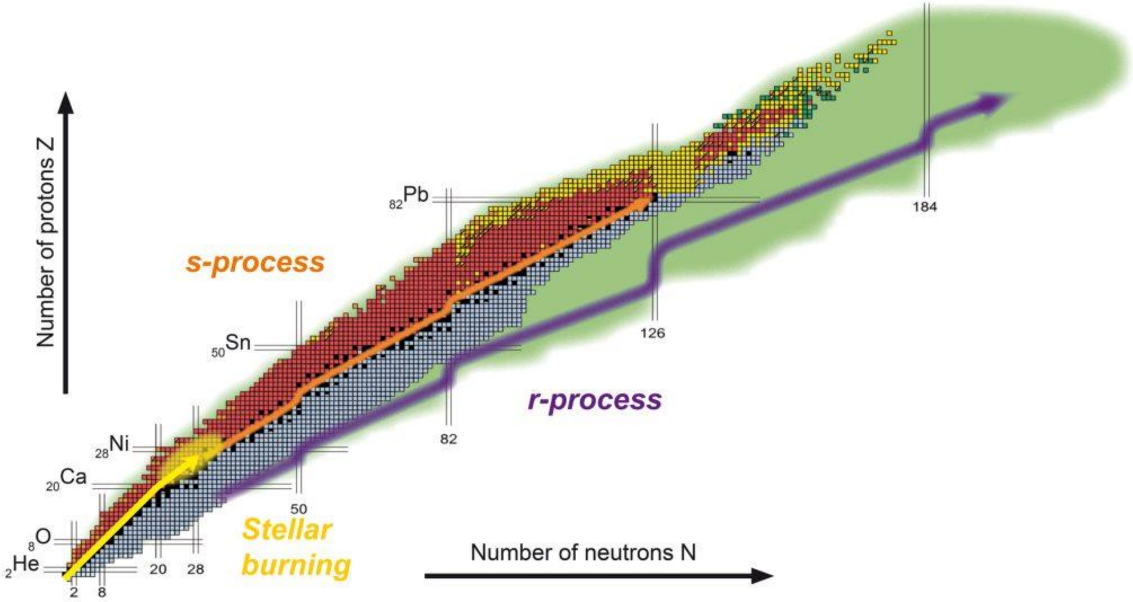
Study nuclear decay in highly charged ions (HCI)

Impact in stellar nucleosynthesis

- Huge densities and temperatures (few keV to hundred keV)

  → in this extreme conditions nuclei are in ionized atoms



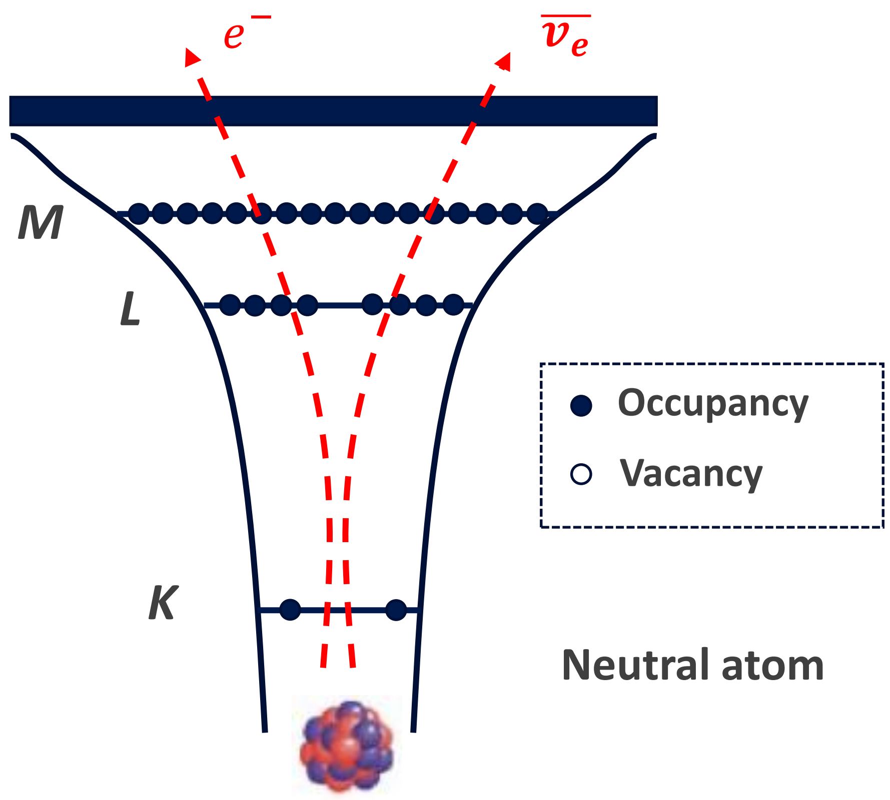
Decay properties can differ from the ones established in neutral atoms

HCI nuclear decay

Since all or most of the bound electrons are lost in HCI → This situation influences the weak decays as electron capture (EC) and beta decay (β^-)

β^- - decay

$n \longrightarrow p + e^- + \bar{\nu}_e$ **continuous state β^- decay**



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β^- - decay

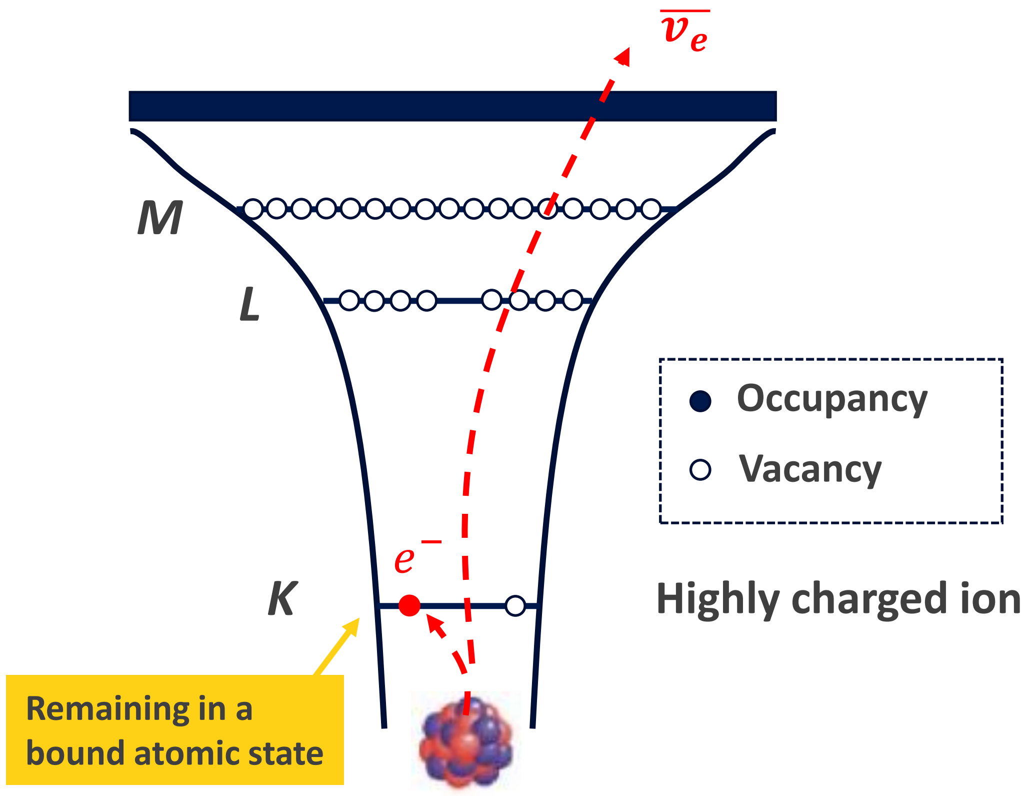
$n \longrightarrow p + e^- + \bar{\nu}_e$ **continuous state β⁻ decay**

$n \longrightarrow p + e_b^- + \bar{\nu}_e$ **bound-state β⁻ decay**

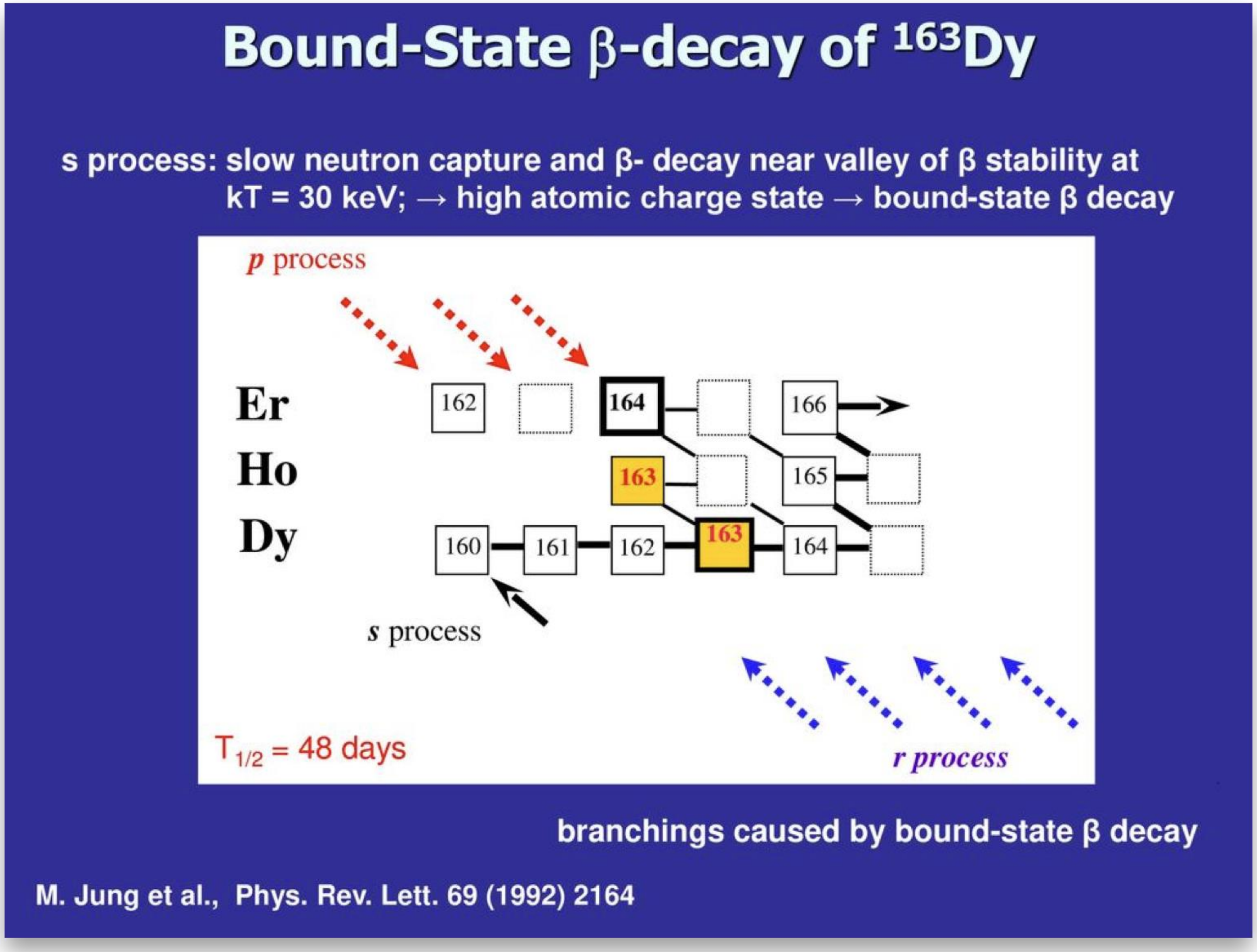
- **Stable nuclei turn in unstable nuclei**

Example:

$^{163}Dy^{0}$ stable ⟶ $^{163}Dy^{66+}$ $T_{1/2}$ = 48 days (β⁻ decay)



Scientific cases



- Dy becomes unstable (and Ho EC is blocked)
- it opens a decay branch
- This can explain the abundance of ^{164}Er.

Where can we study HCI?

The prerequisite for decay studies of heavy HCIs is their production in a (high) atomic charge state of interest

→ **This is a challenging task!!**

Production:

- *In-flight* production and separation of exotic nuclei
- Stripping the bound electrons by sending energetic ions through matter

→ ***Storage rings***

HCI studies timeline

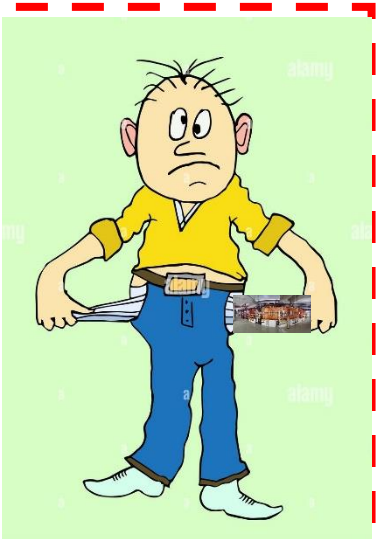
1992 → **Heavy-ion storage ring facilities**

First observation of Bound-state beta decay at ESR

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

HINA project

What can be done if we don't have in our pocket a storage ring with a circumference of 108 m?

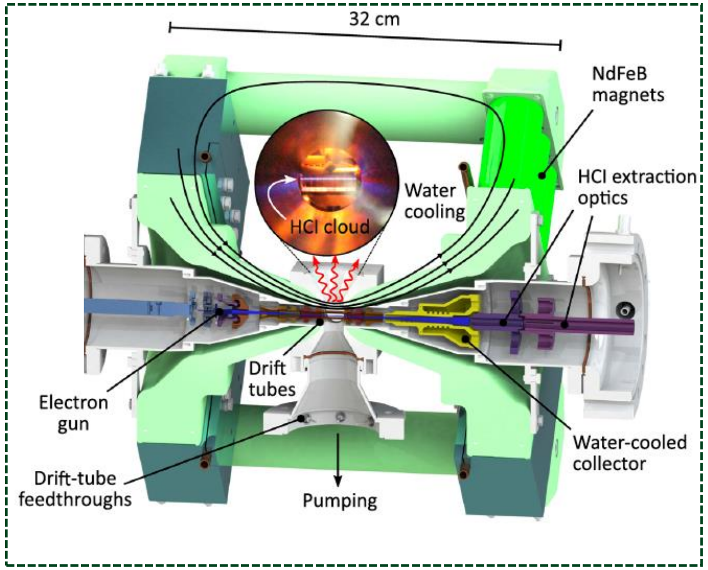


HINA project

External ion source

Low q+

EBIT



Micke et al, Rev. Sc. Inst. 89, 063109 (2018)

Objective

Develop of Heidelberg Compact EBIT (HC-EBIT)

In collaboration with Max-Planck-Institut für Kernphysik Heidelberg

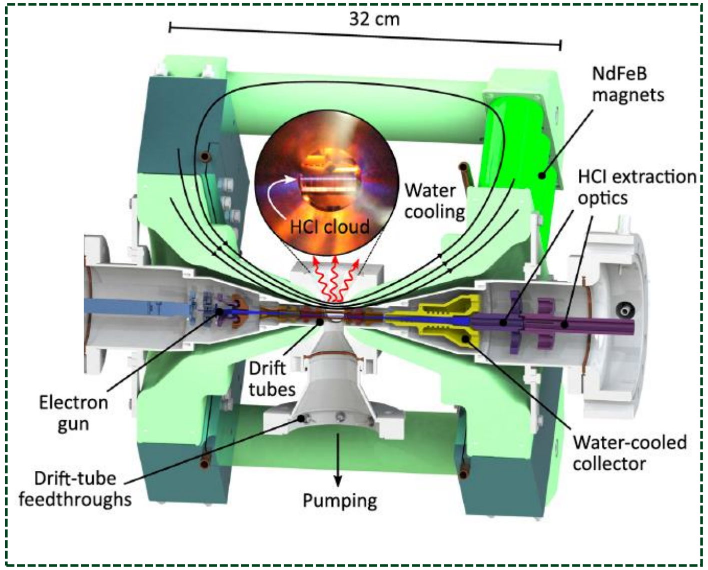
HCI Production & Study

HINA project

External ion source

Low q+

EBIT



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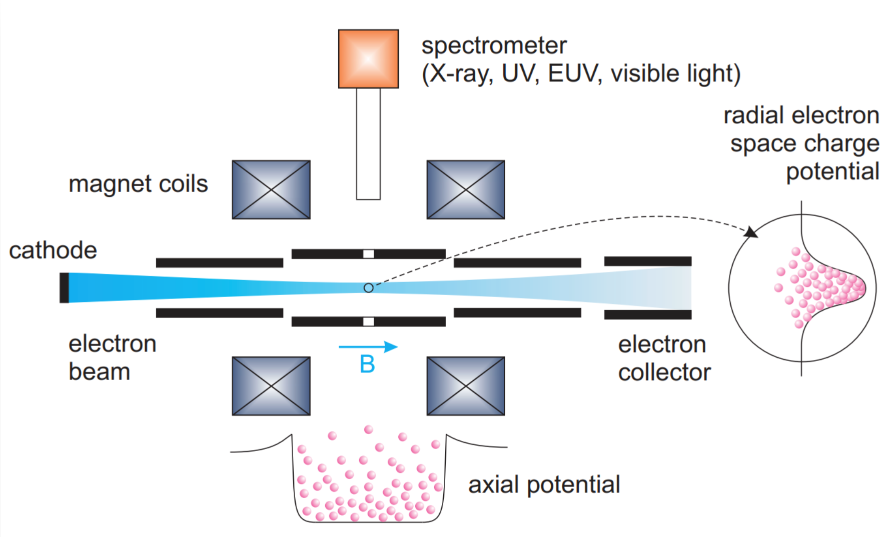

HINA project

External ion source

Low q+

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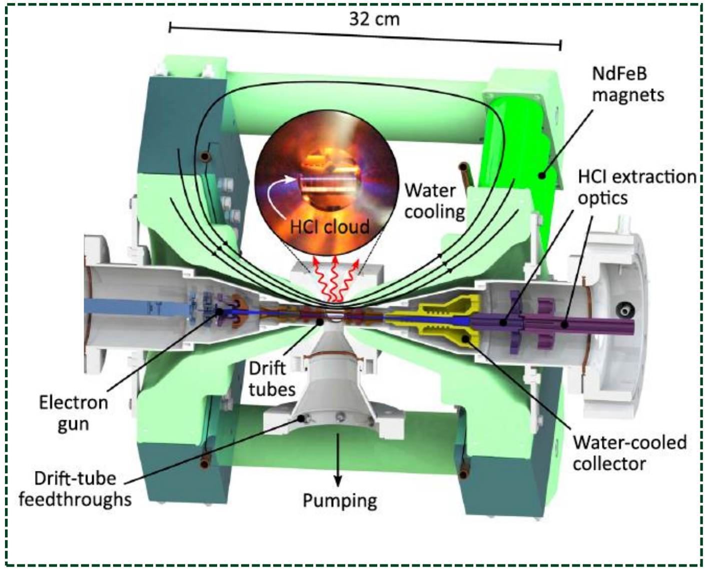

Micke et al, Rev. Sc. Inst. 89, 063109 (2018)

High q+

Zajfman trap

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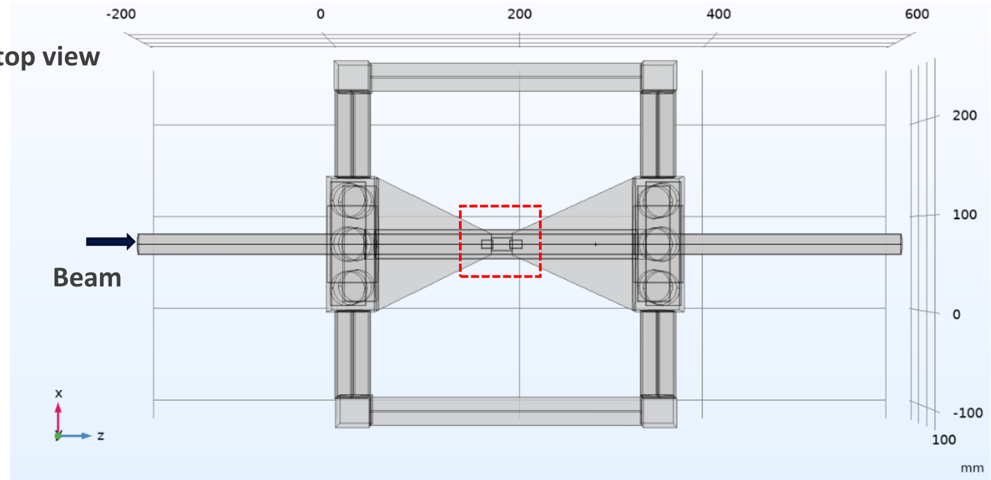
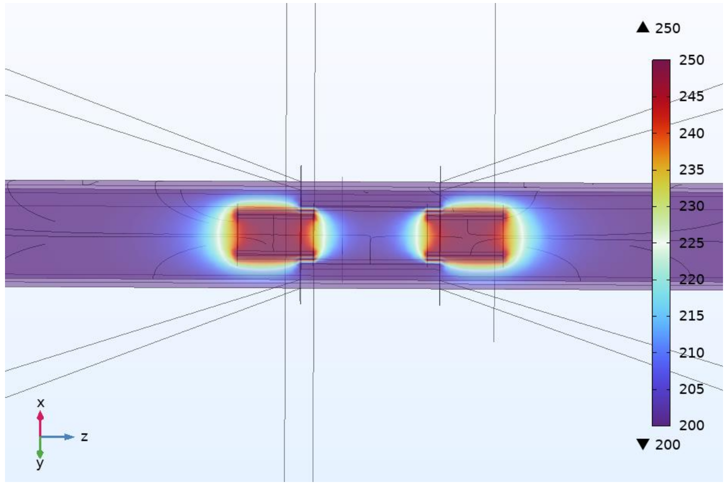
Next talk:
16h50
Piege de Zajfman
Maroua Benhatchi

EBIT development for HINA

Presently we are working on the design of the EBIT and optimization of the injection performing simulations based on:



Trapping region



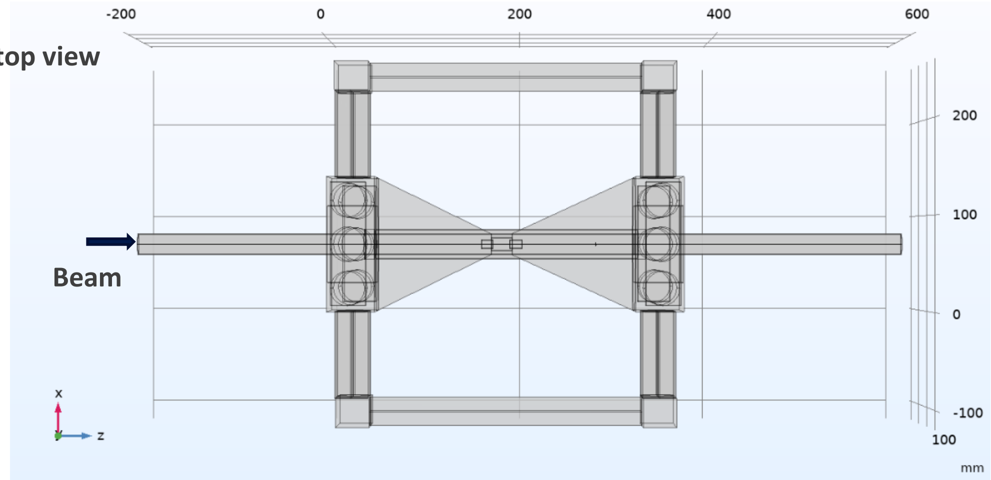
EBIT development for HINA

Presently we are working on the design of the EBIT and optimization of the injection performing simulations based on:

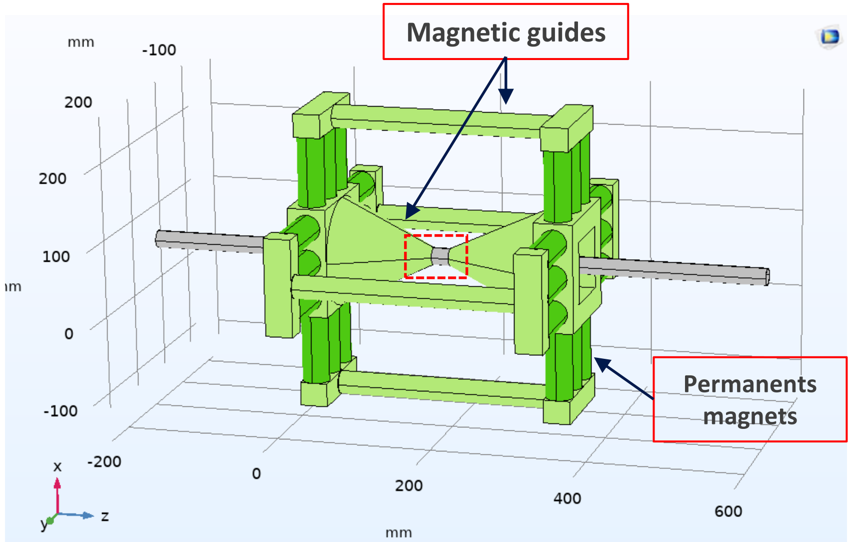
SIMION®

COMSOL

EBIT top view



Magnetic field



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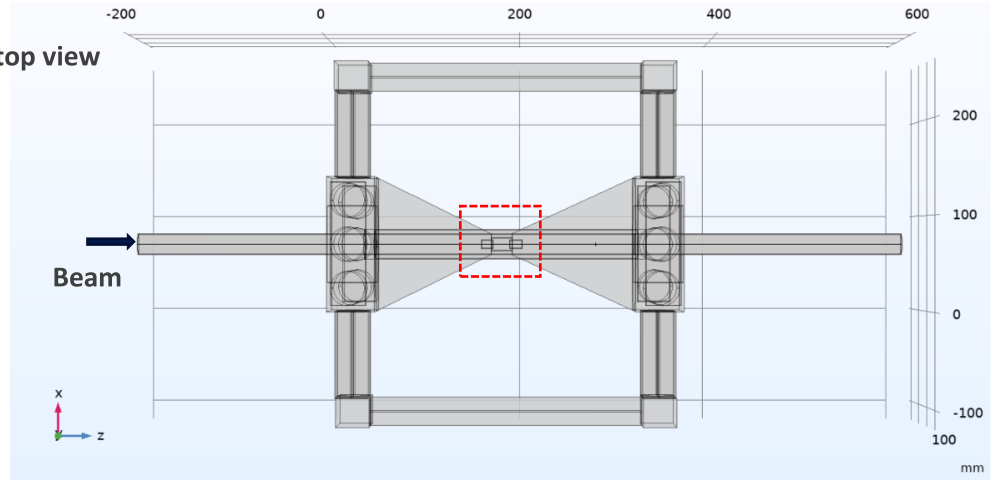
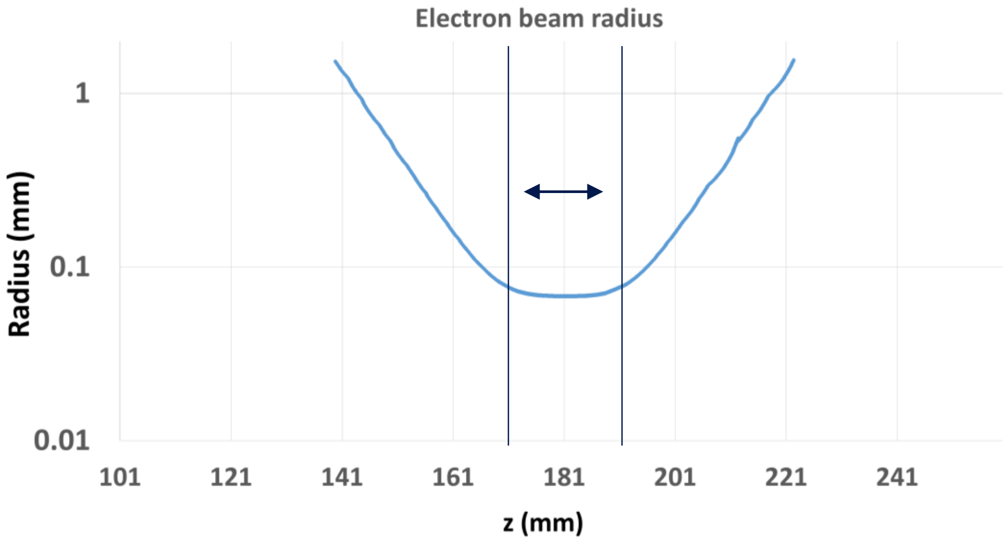
EBIT top view



Magnetic field



Electron beam density

e^- density and speed

$$\tau \propto \frac{1}{n_e \cdot v_e}$$

Charge breeding time

EBIT development for HINA

THIS IS THE CHALLENGING PART OF THE PROJECT!!

Main requirements:

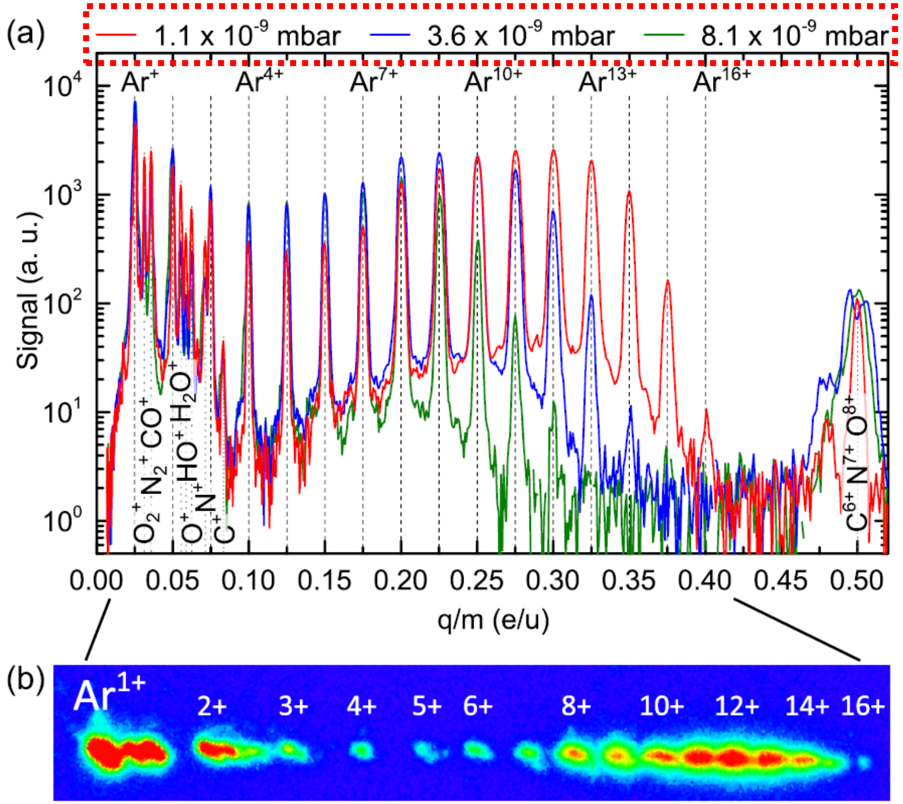
- **High ionization efficiency**

The possibility to reach high charge states (Z) depends on competition between:

1. electron impact ionization ($\sigma_{q \rightarrow q+1}$)
2. recombination processes ($q \rightarrow q-1$)
   - charge exchange with ion and atoms

Impact of vacuum quality to reduce the charge recombination

e- gun: 4mA, 2.8keV



Micke et al, Rev. Sc. Inst. 89, 063109 (2018)

EBIT development for HINA

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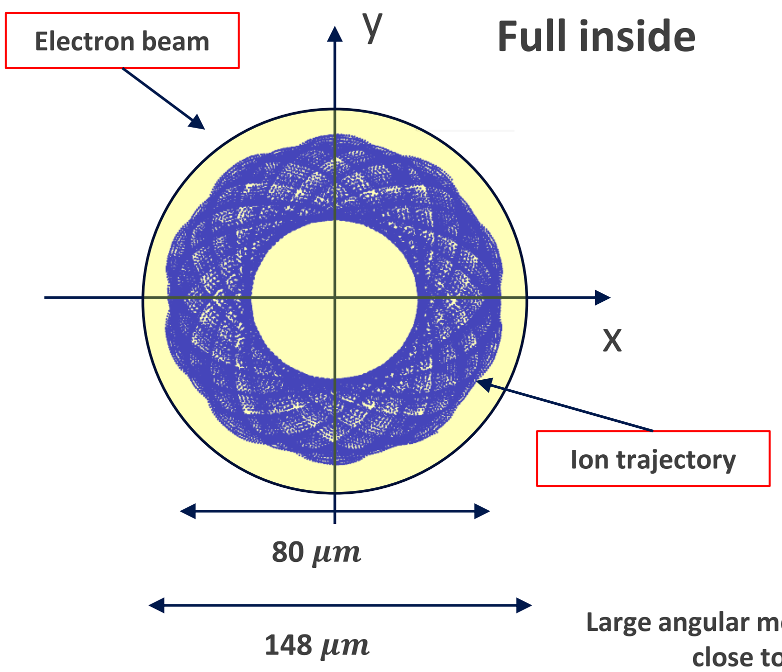
Main requirements:

- **High ionization efficiency**

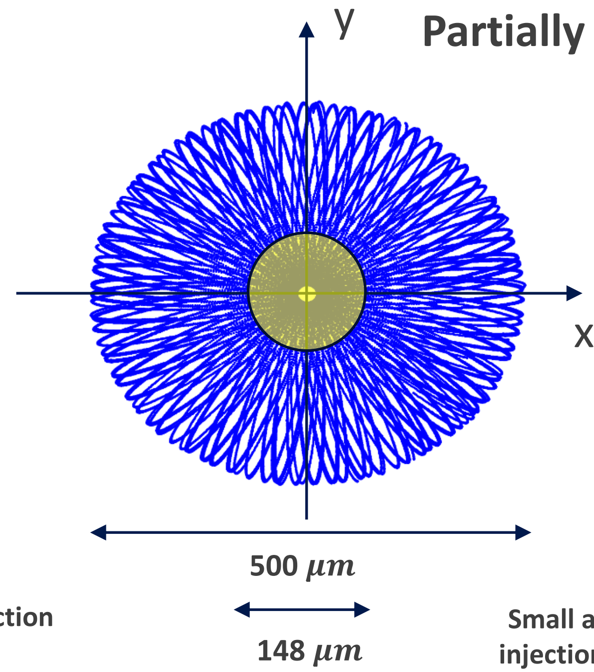
Depending on the way the ions are injected into the EBIT (transverse velocity and position), they can follow different trajectories which bring them to spend more or less time inside the electron beam.

Full inside



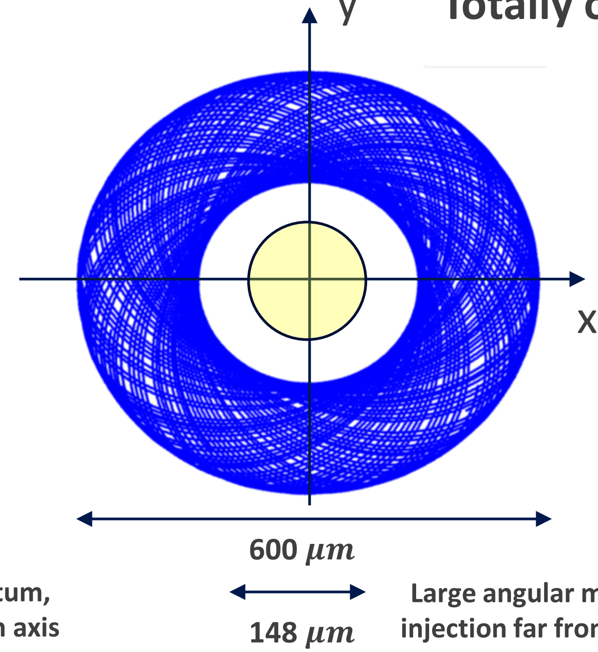
Large angular momentum, injection close to beam axis

Partially outside



Small angular momentum, injection far from beam axis

Totally outside



Large angular momentum, injection far from beam axis

HINA project at MOSAIC

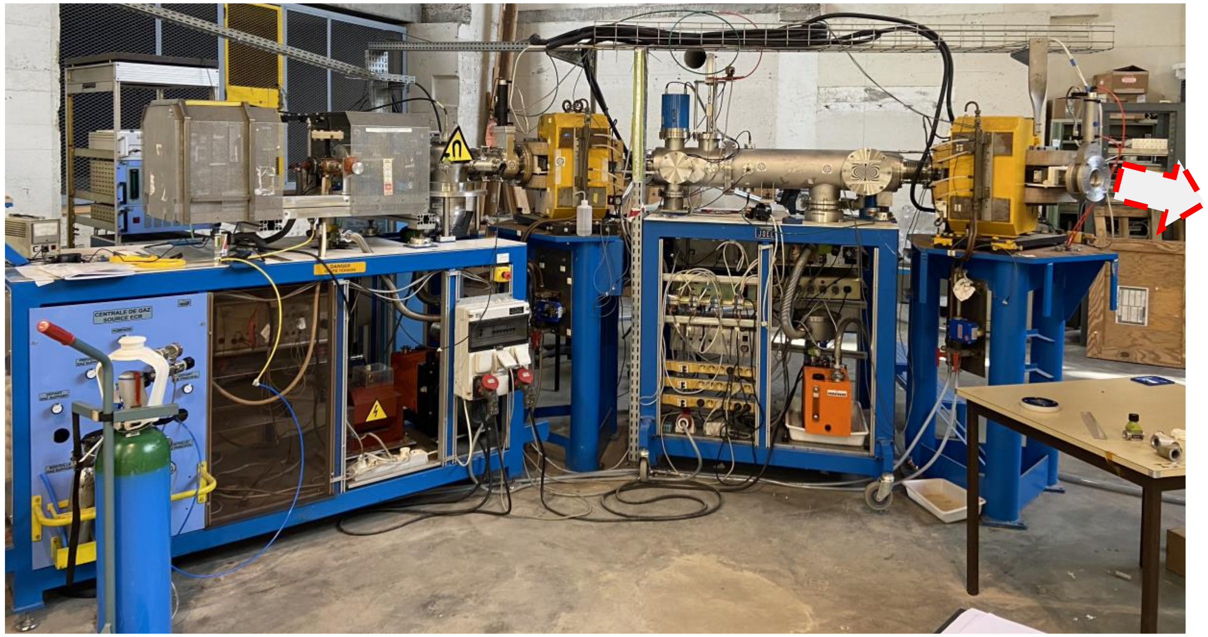
IJCLab Irène Joliot-Curie Laboratoire de Physique des 2 Infinis

mosaic

Tancrède

201- Hall Super ACO

Installation for production of intense beams of multi-charged molecular ions



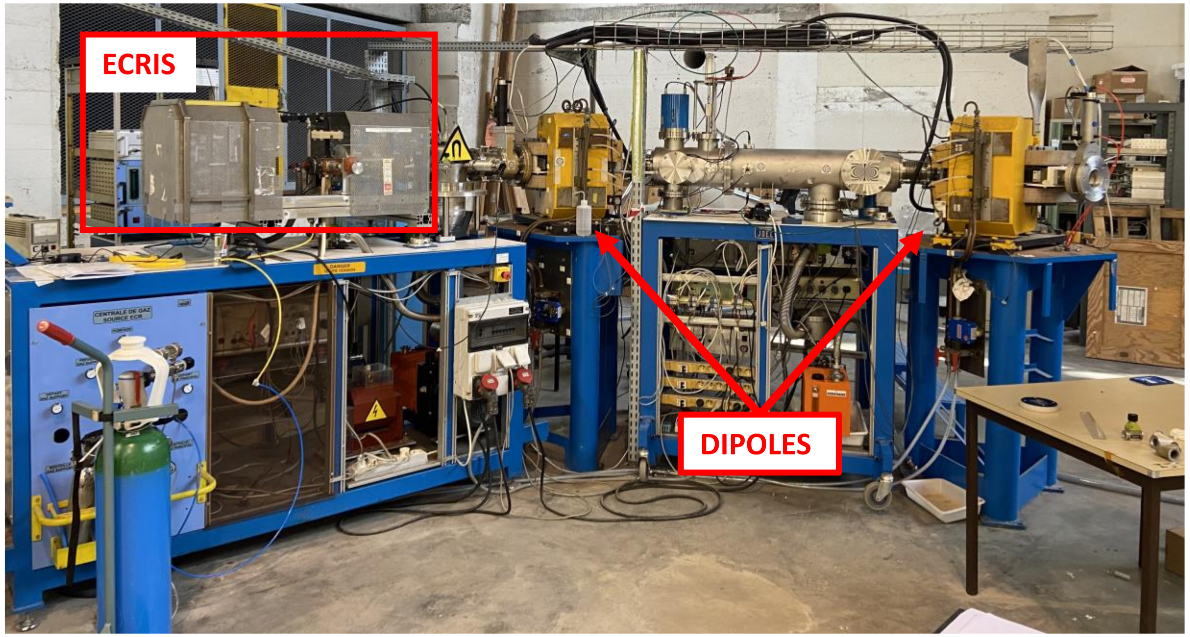
HINA PROJECT Experiments

HINA project at MOSAIC

Tancrède

201- Hall Super ACO

Installation for production of intense beams of multi-charged molecular ions



Available ion Source

- **ECRIS** (*Electron Cyclotron Resonance Source*)

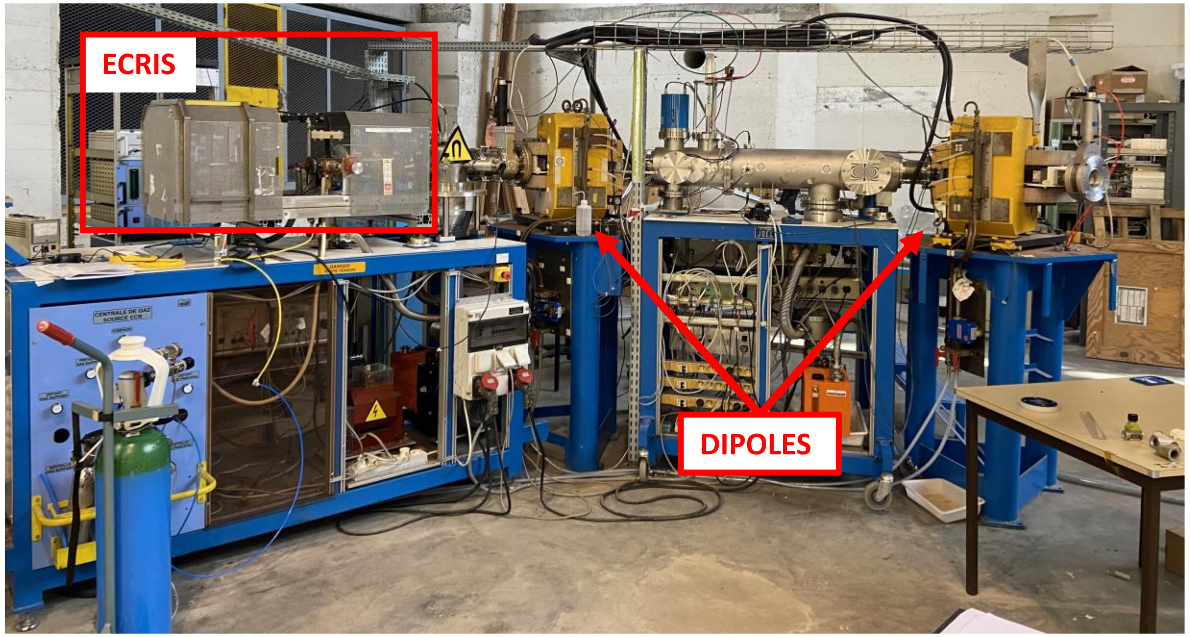
Ar^{1+} beam up to 30 μA
Ar^{8+} beam up to 60 nA

Maximum extraction energy (U_{ext}) of 10 kV

HINA project at MOSAIC

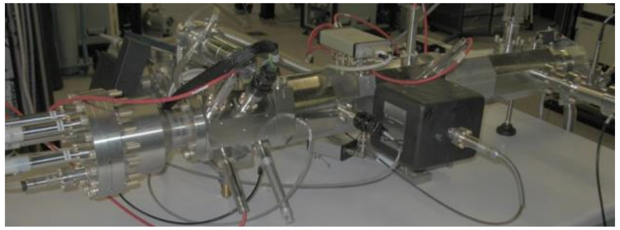
Tancrède → **Installation for production of intense beams of multi-charged molecular ions**

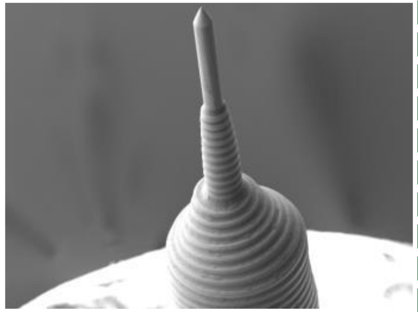
201- Hall Super ACO



Available ion Source

- **LMIS** (*Liquid Metal Ion Source*)





Production of nm ion beams, high current density ion beam and a small energy spread

First measurements at TANCREDE

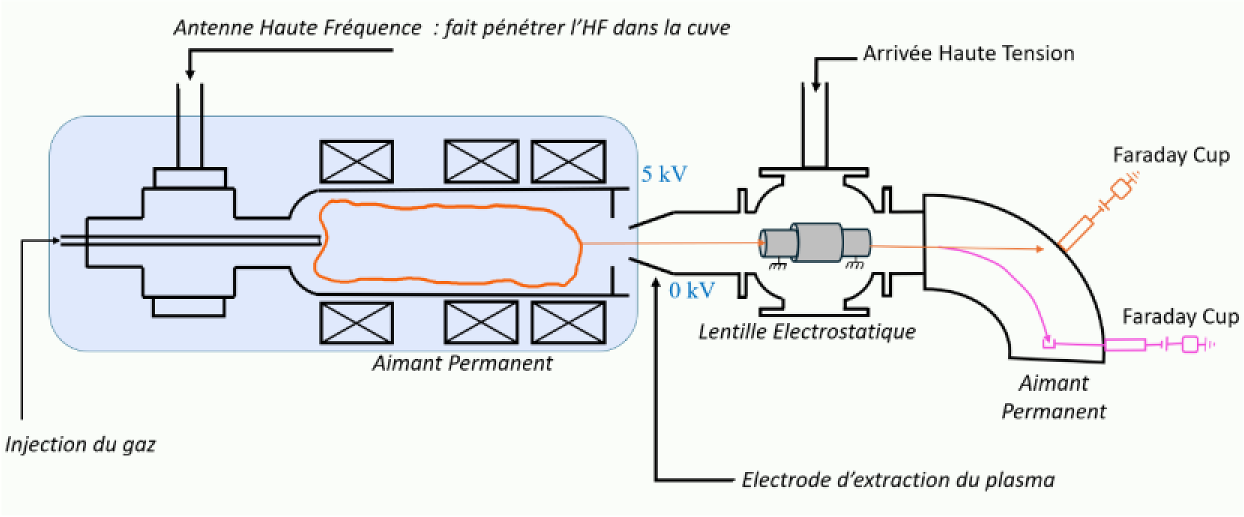
RECOVERY OF TANCREDE FROM April 2024 to August 2024

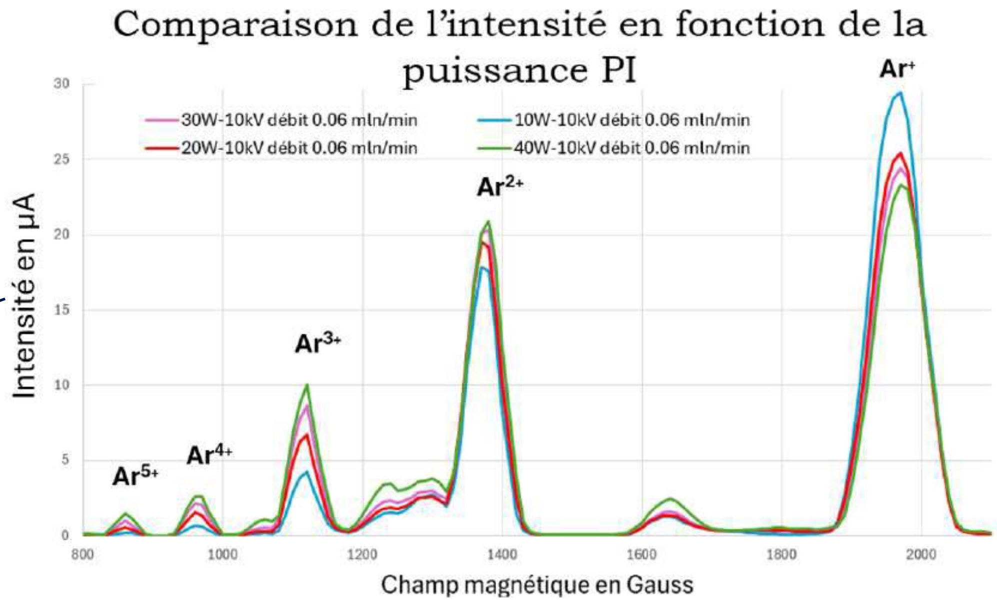
with Tancrede's team

Amelle Khankham (stage M1)

Damien Jaquemin (stage L3)

Characterization of the ECRIS source of Tancrede for HINA and beam transmission





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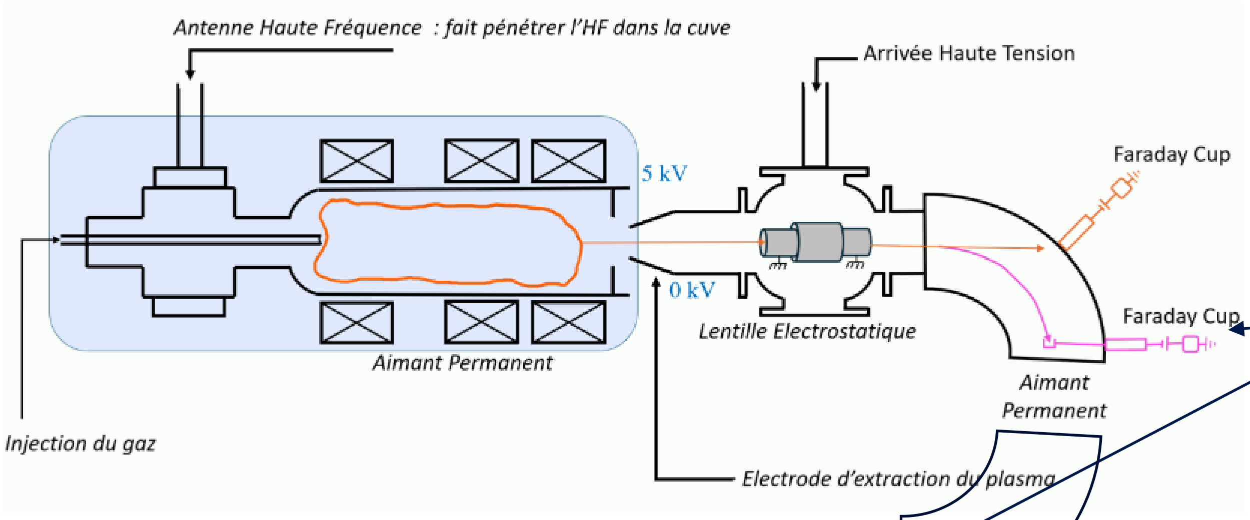
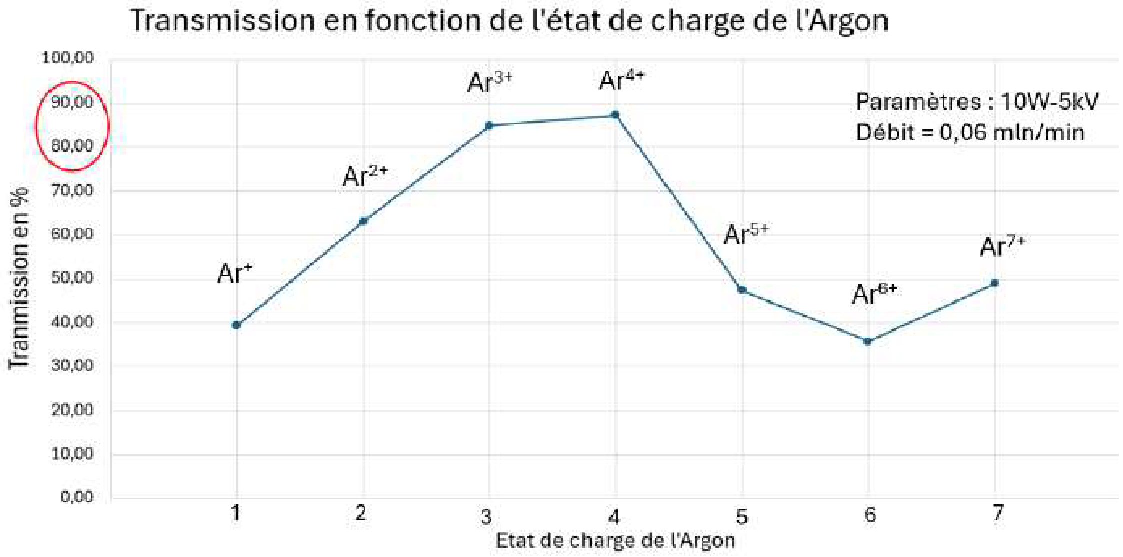
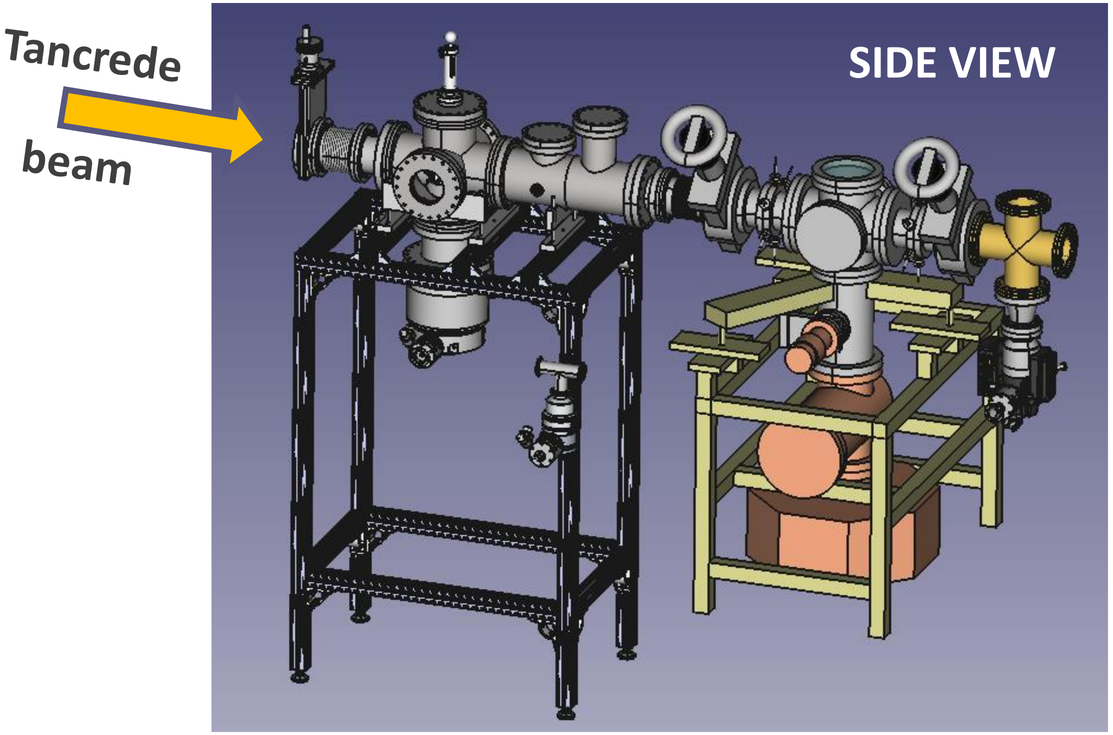
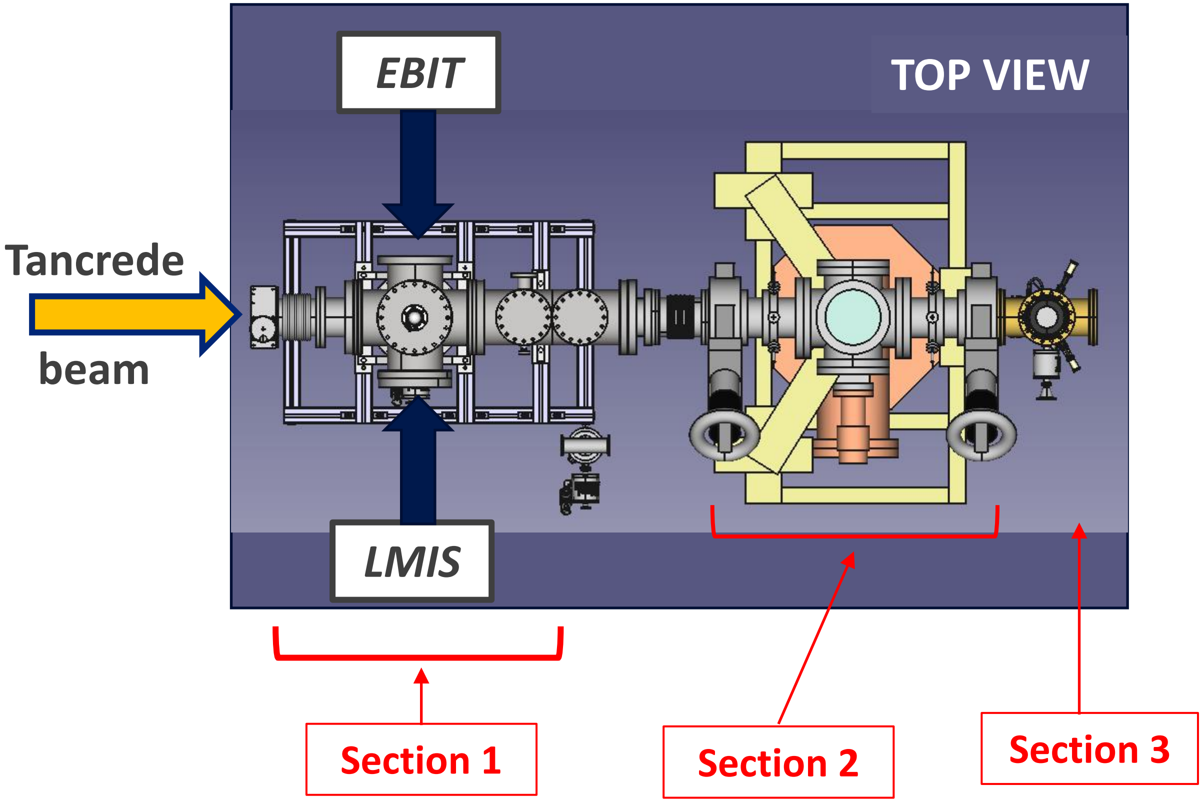


HINA project



Installation of HINA at Tancrede



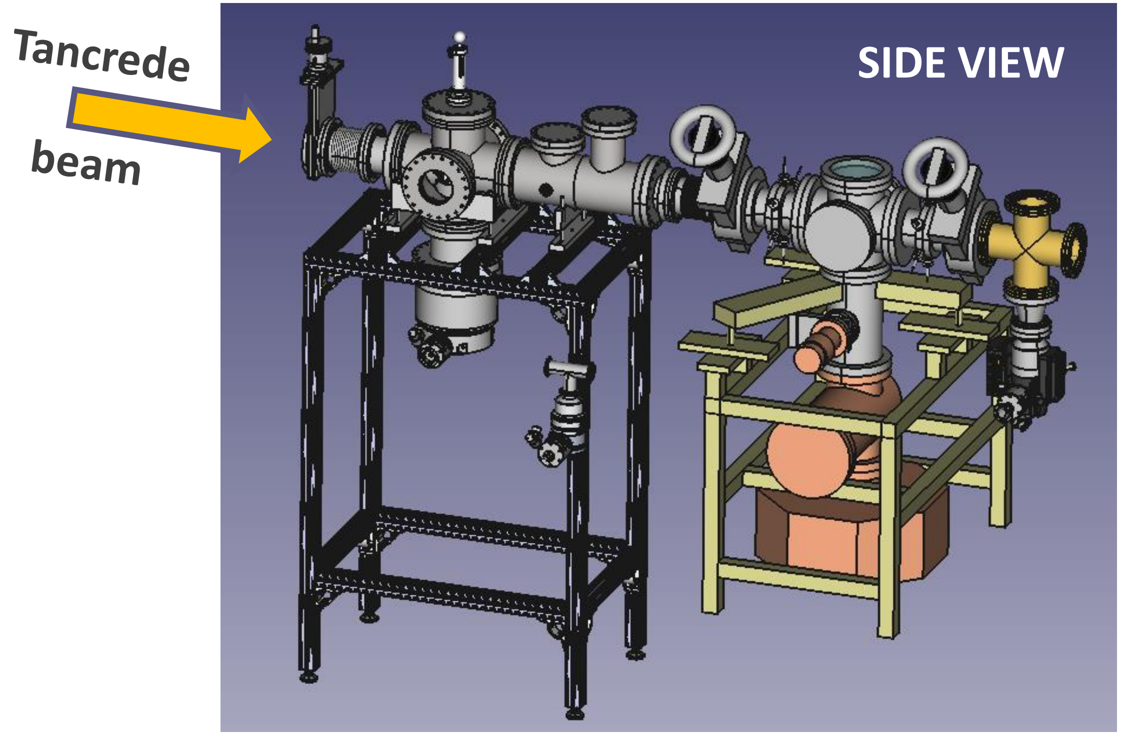


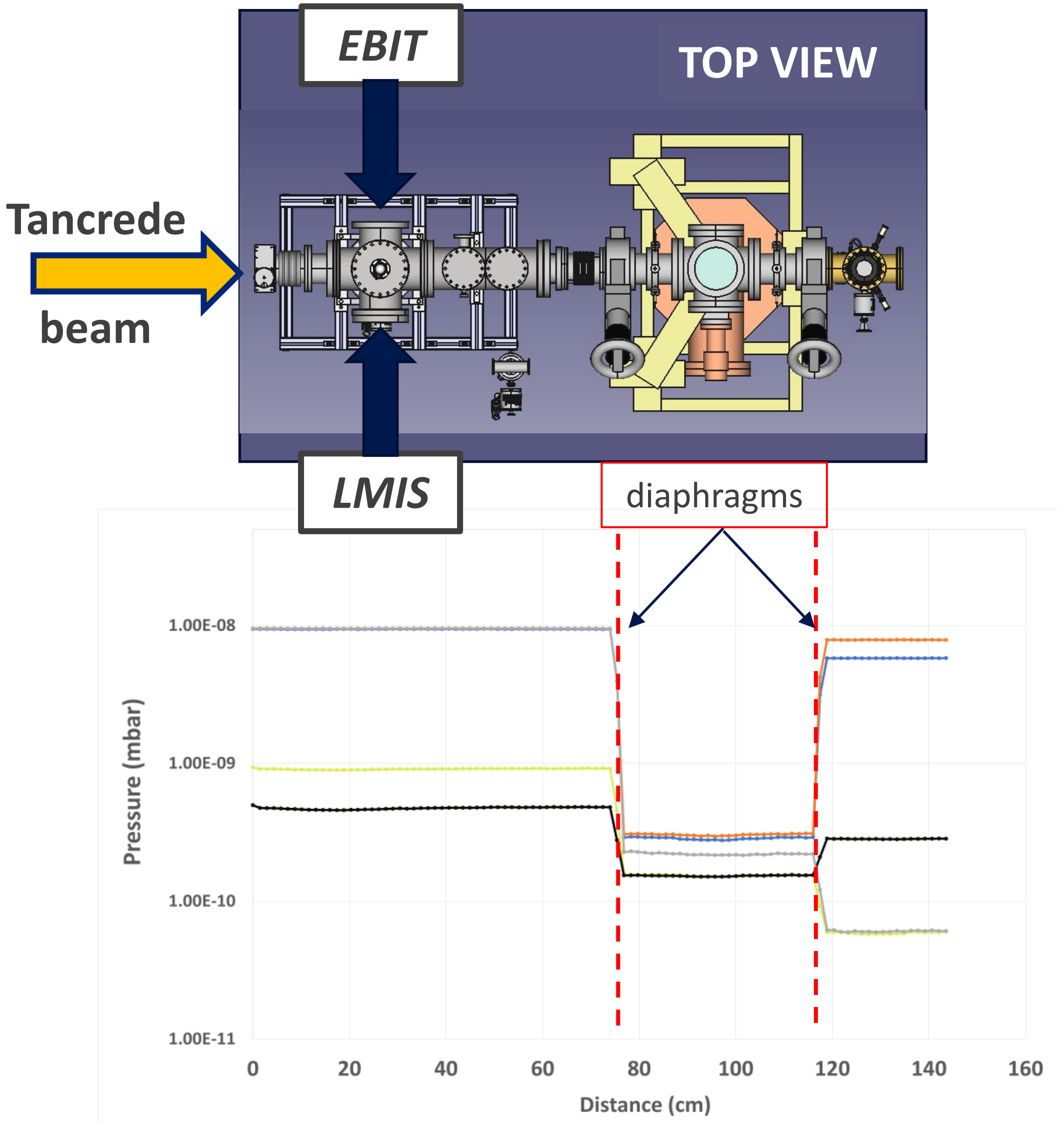
Section 1 → Beam optics elements (quad bender, quadrupoles, etc..)

Section 2 → Zajfman trap

Section 3 → Beam diagnostic (Farady cup and MCP)

Installation of HINA at Tancrede

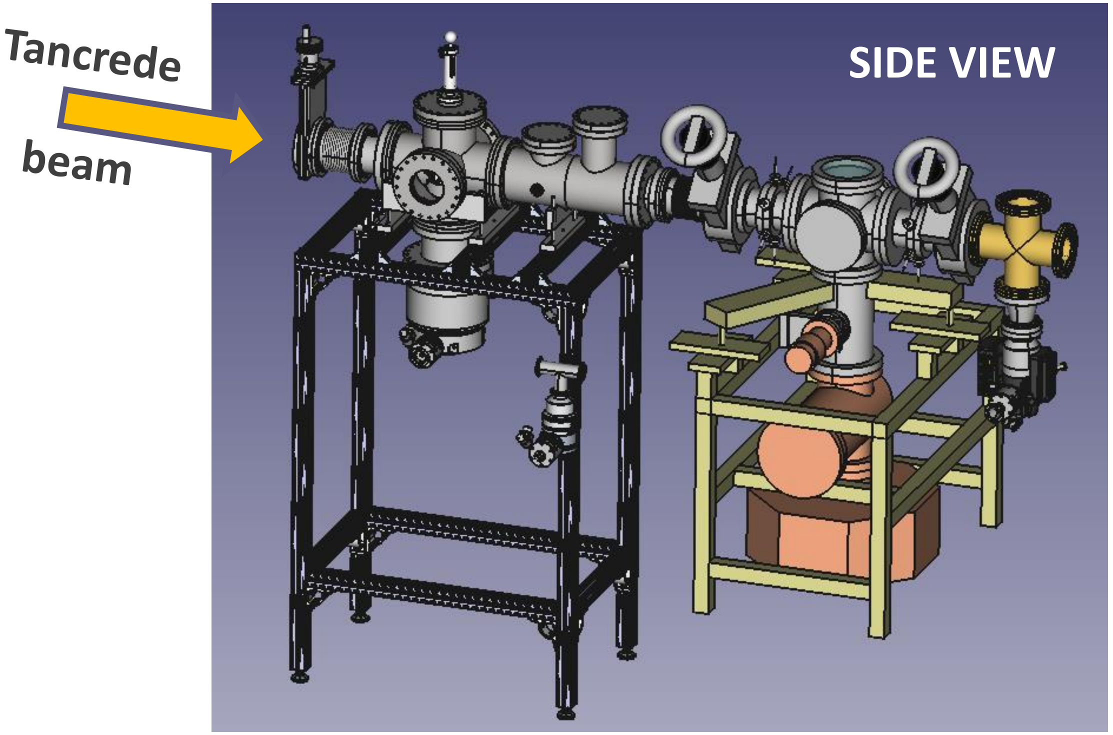


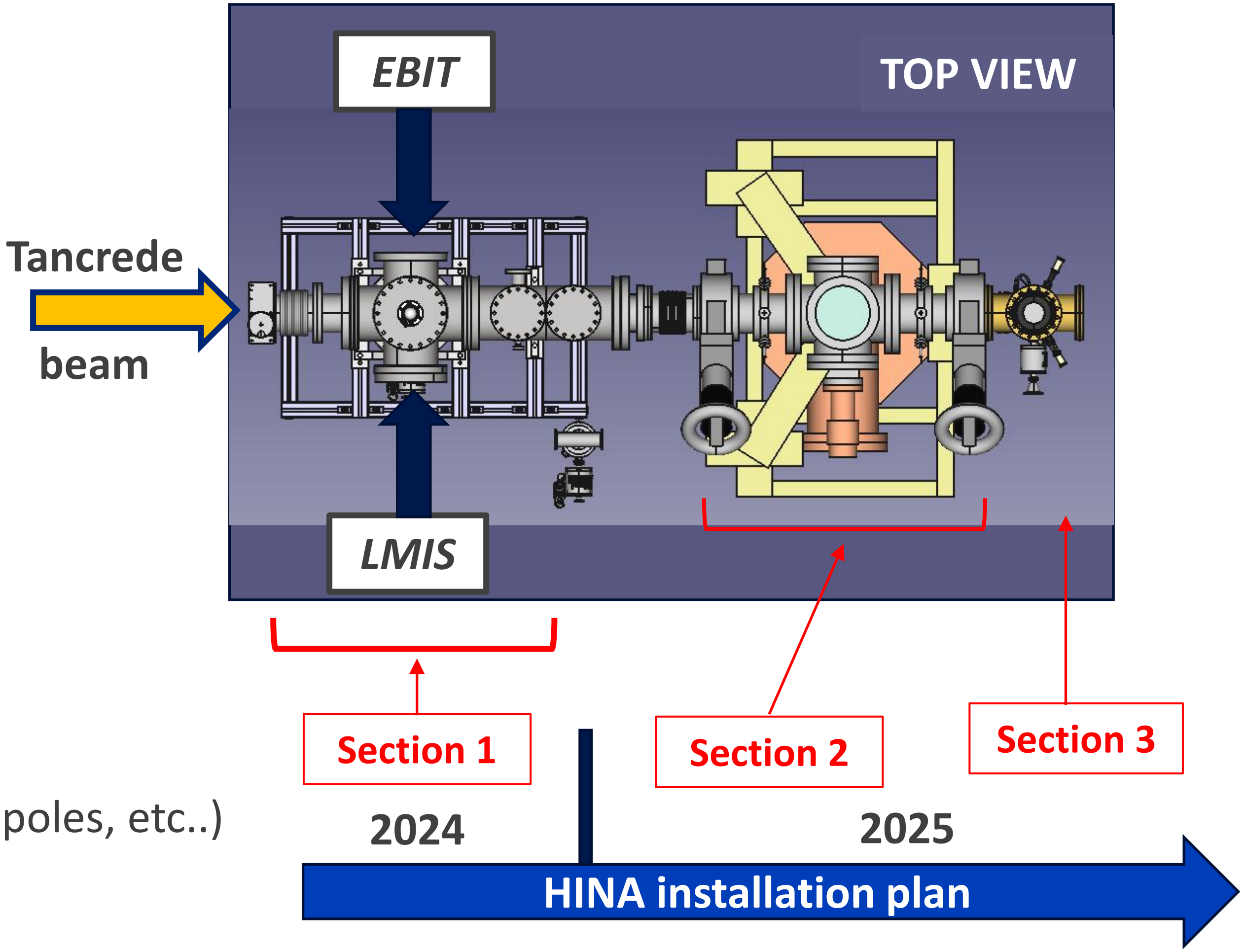


Molflow simulation to estimate Vacuum quality

with the support of the vacuum service

Installation of HINA at Tancrede





Section 1 → Beam optics elements (quad bender, quadrupoles, etc..)

Section 2 → Zajfman trap

Section 3 → Beam diagnostic (Farady cup and MCP)

HINA planning 2024

Experimental planning HINA 2024/2025

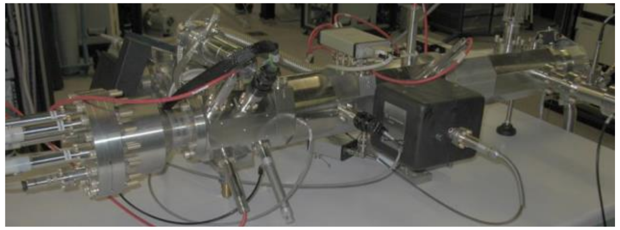
Tancrede beamline test

April 2024 ↔ Aug 2024: **First ECRIS characterization for HINA**

Sep 2024 ↔ Nov 2024: **Section 1 mounting**

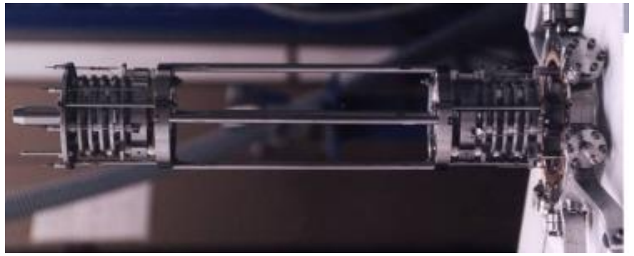
Nov 2024 ↔ Dec 2024: **Commissioning**

LMIS test (Au)



Were supposed to start this summer but postponed to the next year.

Zajfman trap



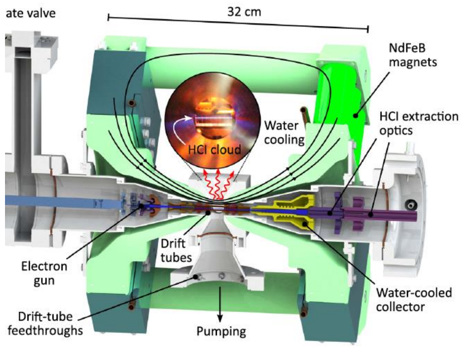
Testing the Ar+ confinement using a discharge ion source. The tests are providing encouraging results and we are scheduling to complete them by the end of the year.

Conclusion

First phase of the project

EBIT development will take place in parallel with the installation of the project at Tancrede!

In the frame of the HINA project we are working on the development of an EBIT for the study of HCI decay!



HC-EBIT

developed in collaboration with

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK HEIDELBERG

Several challenges must be overcame to reach high charge states!

We are working on the optimization of the injection and extraction system to maximize the ionization efficiency and make possible in-trap decay studies!

……Thank you for your attention……

Backup Slide

Scientific cases

BETA-DECAY RATES OF HIGHLY IONIZED HEAVY ATOMS IN STELLAR INTERIORS*

K. TAKAHASHI

University of California, Institute of Geophysics and Planetary Physics
Lawrence Livermore National Laboratory, Livermore, California 94550

and

K. YOKOI†

Kernforschungszentrum Karlsruhe GmbH, Institut für Kernphysik III
D-7500 Karlsruhe, Federal Republic of Germany

Already investigated

instable

Offline NEWGAIN

K. TAKAHASHI and K. YOKOI Beta-Decay Rates

ATOMIC DATA AND NUCLEAR DATA TABLES 36,375-409 (1987)

TABLE V. β^- Rate Enhancement Due to Bound-State Decay

See page 383 for Explanation of Tables

^AZ	n_{26}	T_8 = 1	3	5
^{106}Ru	1	11	17	13
	3	7	16	13
	10	3	15	12
	30	1.8	12	11
^{150}Nd	-	∞	∞	∞
^{157}Gd	-	∞	∞	10^5
^{160}Gd	1	7.3×10^2	14	15
	3	1.1×10^2	13	15
	10	6.2	11	14
	30	1.9	6.8	12
^{163}Dy	1	1.1×10^3	1.7×10^2	61
	3	1.7×10^2	1.6×10^2	59
	10	8.5	1.2×10^2	53
	20	2.3	54	44
^{171}Tm	1	1.9	15	15
	3	1.6	13	14
	10	1.4	9.9	13
	30	1.5	5.2	11
^{179}Hf	1	3.4	34	37
	3	2.2	29	35
	10	1.7	20	32
	30	1.9	8.6	27
^{187}Re	1	5×10^4	66	18
	3	5.9×10^3	55	17
	10	1.3×10^2	34	16
	30	10	12	13
^{194}Os	1	2.3	32	20
	3	2.0	27	19
	10	1.7	16	18
	30	1.8	6.4	14
^{193}Ir	1	1.5×10^3	94	43
	3	1.4×10^2	74	41
	10	25	40	36
	30	13	12	28
^{195}Pt	1	∞	5.7×10^2	55
	3	5×10^4	4.6×10^2	52
	10	3.3×10^3	2.5×10^2	46
	30	3.1×10^3	68	35
^{205}Tl	1	∞	1.4×10^3	77
	3	10^5	1.1×10^3	72
	10	1.1×10^3	4.8×10^2	61
	30	53	105	42
^{210}Pb	1	55	7.1×10^3	8.3×10^3
	3	36	5.0×10^3	8.3×10^3
	10	14	2.0×10^3	6.7×10^3
	30	5.6	4.4×10^2	4.8×10^3

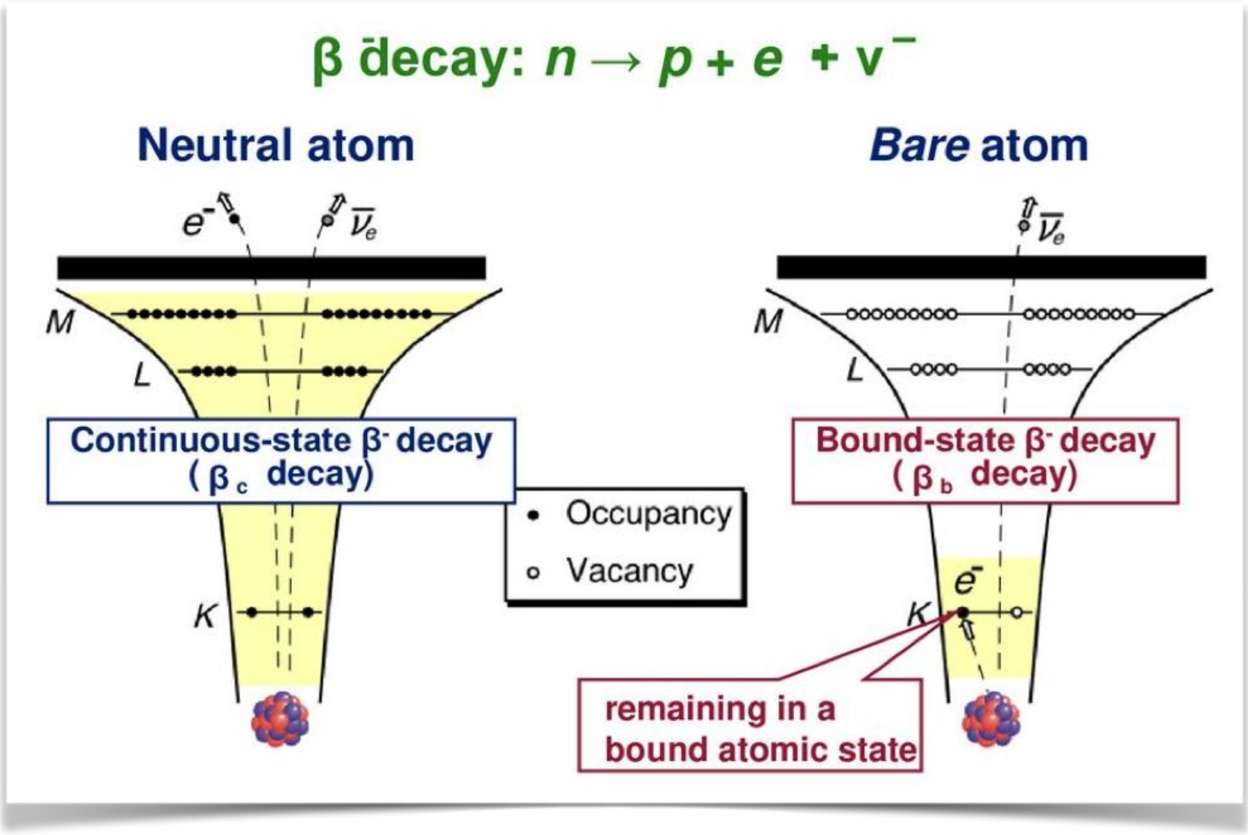
Scientific cases

- EC is disabled in HCIs and clean β+ decay could be studied
- IC (internal conversion) is disabled resulting in longer metastable isomeric states

EC decay of H- and He-like ^{55}Fe

- Half-life 2.756 years
- About 30 events per hour (10^6 ions)
- Proof of principle experiment
  - Try to observe Mn x-ray
  - Mn $K\beta$ should be suppressed for HCIs
  - Observe behavior of Mn $K\alpha$ with charge state

HCI nuclear decay



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

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

HCI nuclear decay

Since all or most of the bound electrons are lost in HCI → This situation influences the weak decays as electron capture (EC) and beta decay (β^-)

β^- - decay

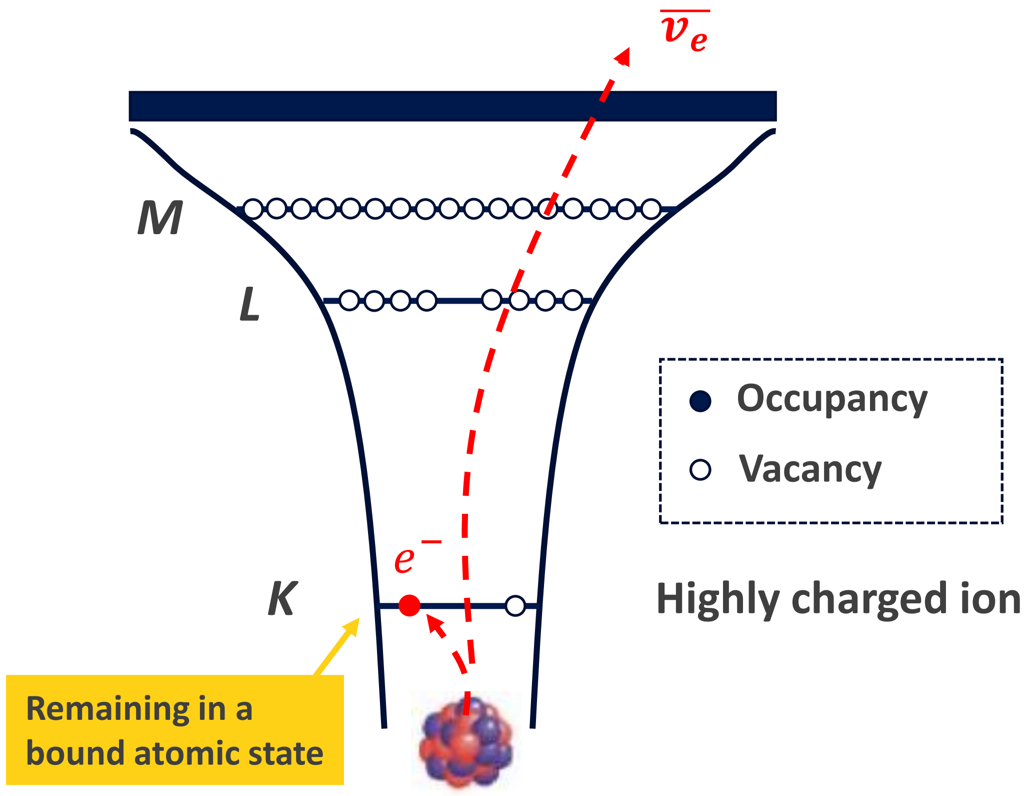
$n \longrightarrow p + e^- + \bar{\nu}_e$ **continuous state β⁻ decay**

$n \longrightarrow p + e_b^- + \bar{\nu}_e$ **bound-state β⁻ decay**

- **Stable nuclei turn in unstable nuclei**

Example:

$^{163}Dy^0$ stable ⟶ $^{163}Dy^{66+}$ $T_{1/2}$ = 48 days (β⁻ decay)



In-Trap Spectroscopy

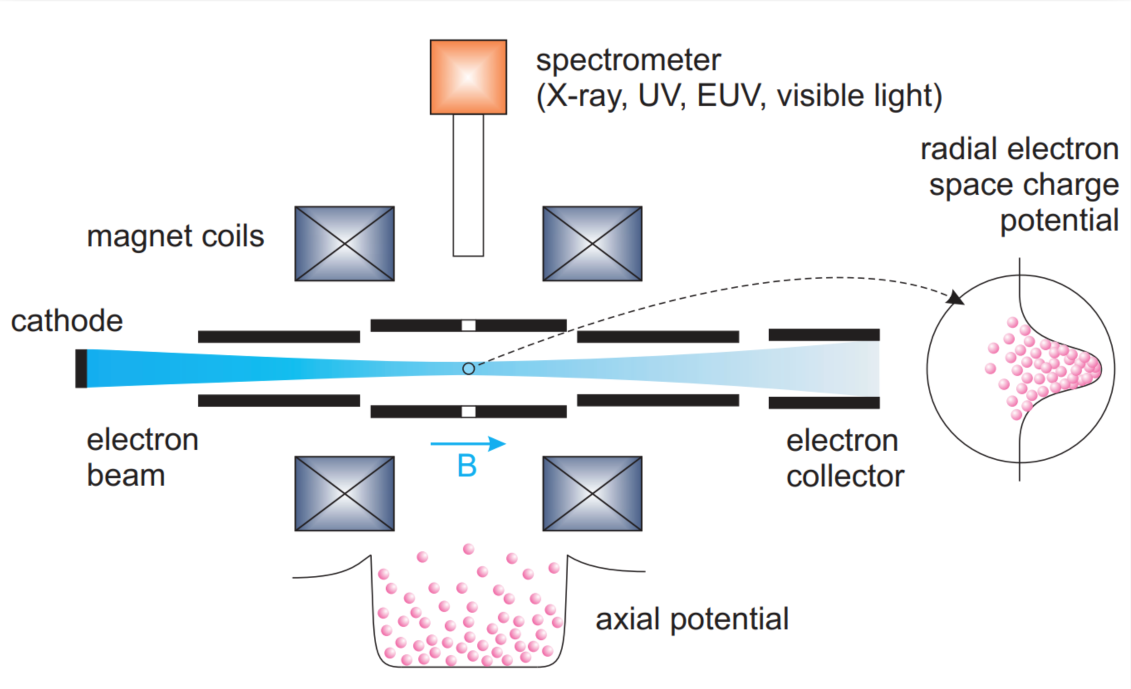
HCI decay studies are carried out in ion traps

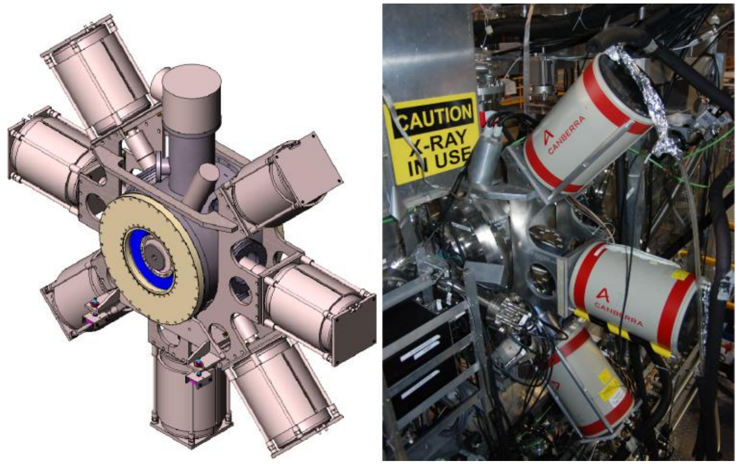
Advantages

- Detection of emitted radiations (unique!!)
- Unlimited beam time (Offline), used online (ALTO, DESIR, etc..)

Disadvantages

- Difficulty to produce bare high Z ions





* K.G. Leach et al., EPJ Web of Conferences

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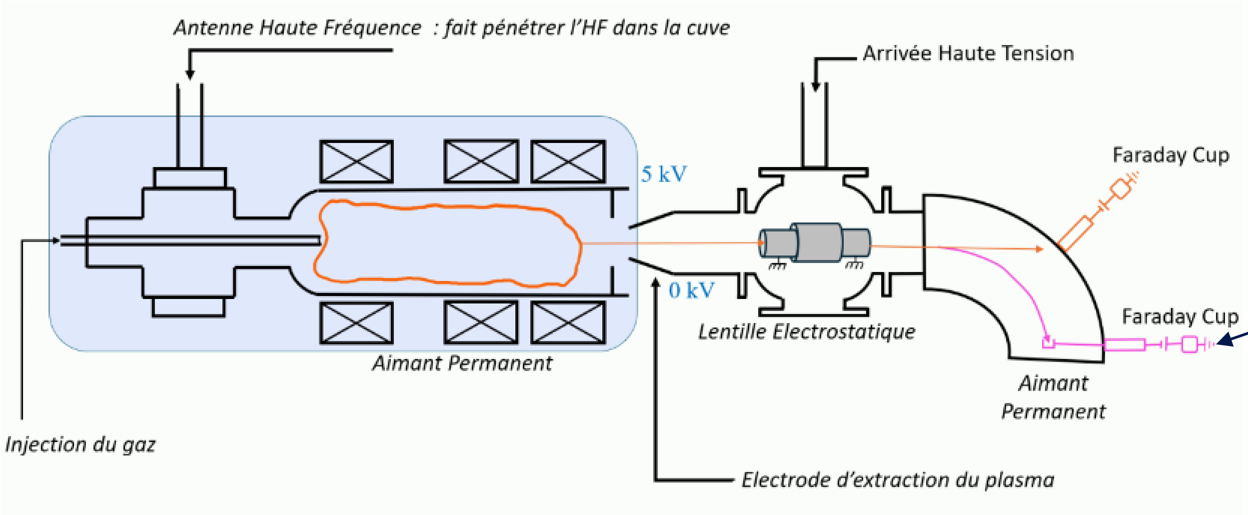
First measurements at TANCREDE

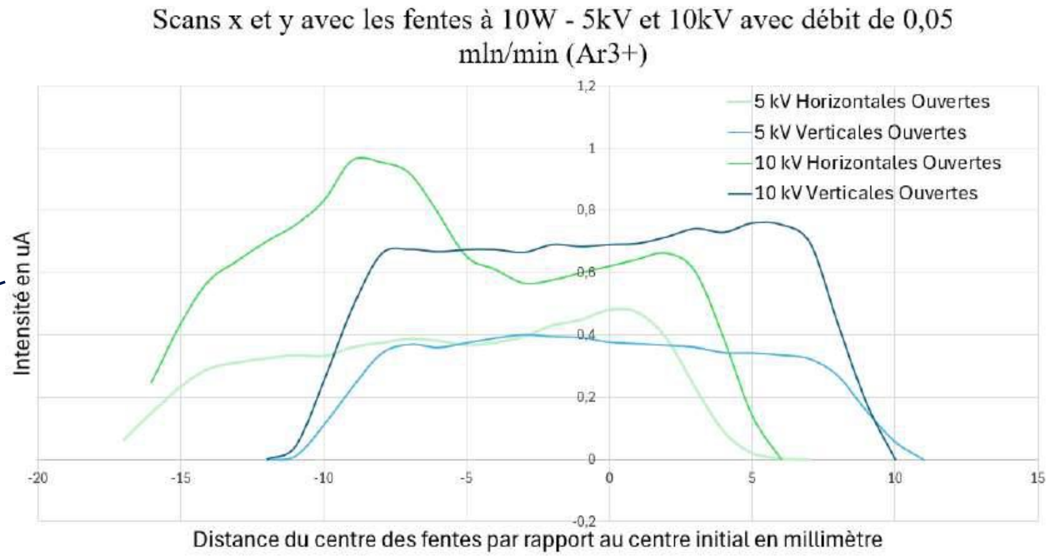
RECOVERY OF TANCREDE FROM
April 2024 to August 2024

Amelle Khankham
(stage M1)

Damien Jaquemin
(stage L3)

Characterization of the ECRIS source of Tancrede for HINA and beam transmission





Where can we study HCI?

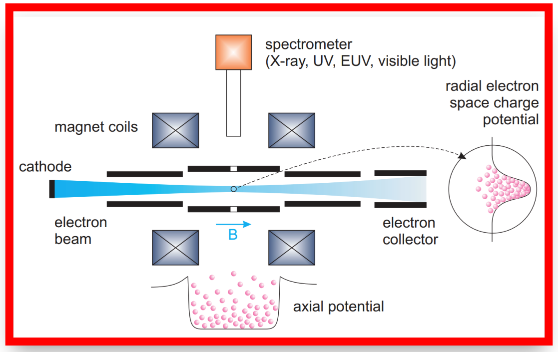
The prerequisite for decay studies of heavy HCIs is their production in a (high) atomic charge state of interest

This is a challenging task!!

Production:

- *Isotope Separation On-Line* (ISOL)
- ***Electron Beam Ion Source/Trap*** **(EBIS/T)**

In-trap decay



HCI studies timeline

1992 → **Heavy-ion storage ring facilities**

2014 → **In-Trap Spectroscopy**

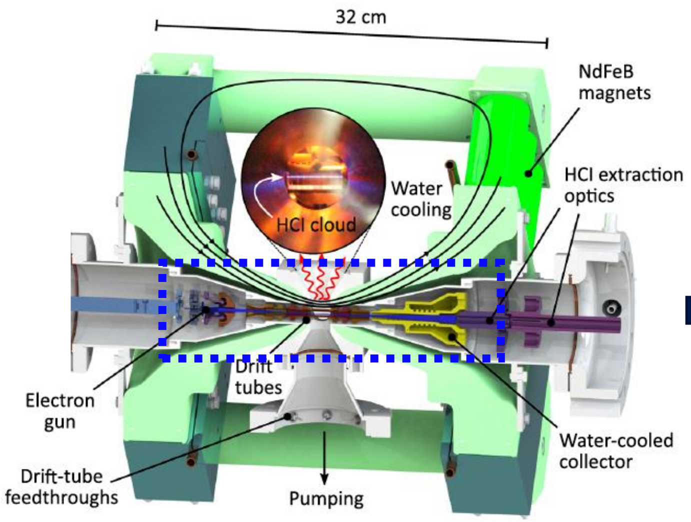
First observation of Bound-state beta decay at ESR

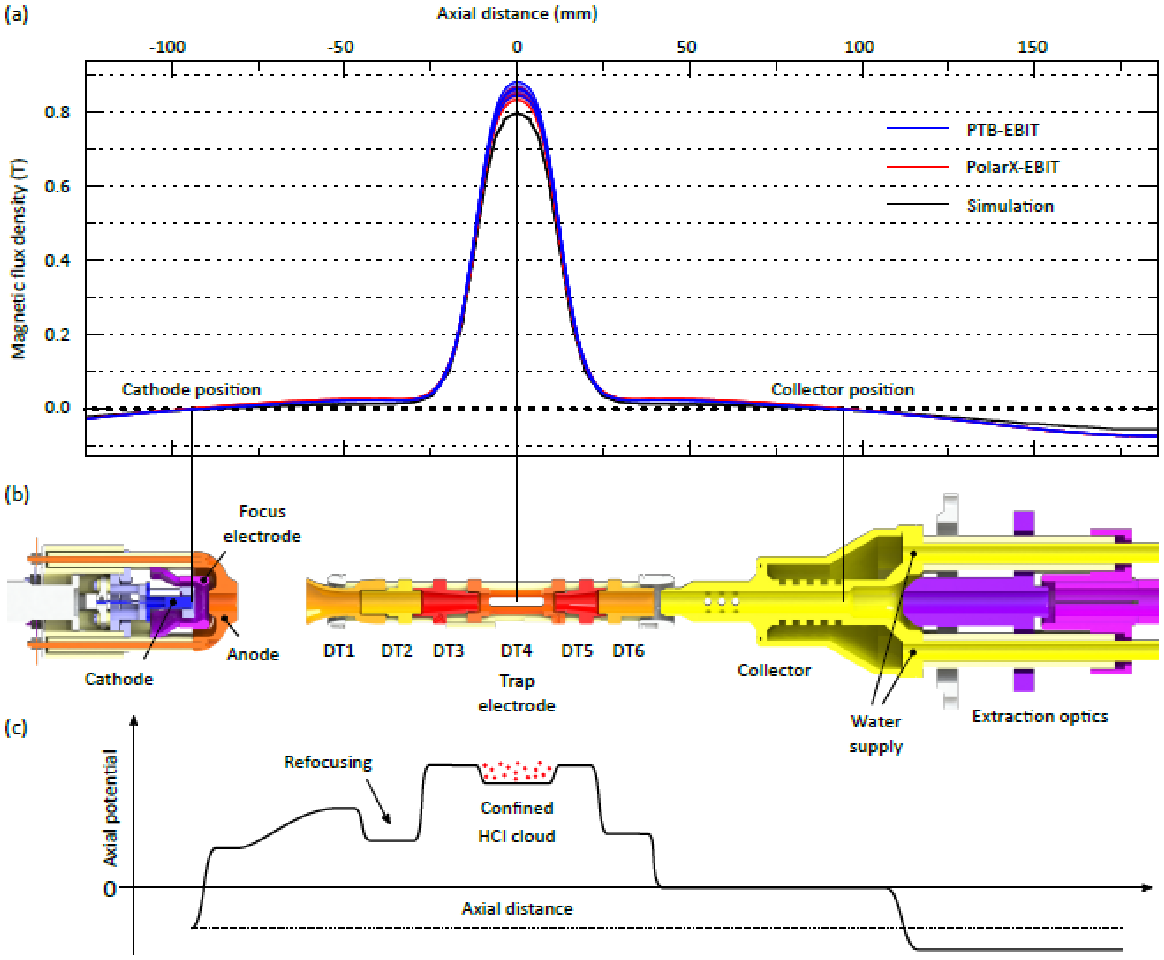
M. Jung et al., Phys. Rev. Lett. 69 (1992), 2164

In-trap spectroscopy of charge-bred radioactive ions

A. Lennarz et al., Phys. Rev. Lett. 113, 082502 (2014)

EBIT simulations

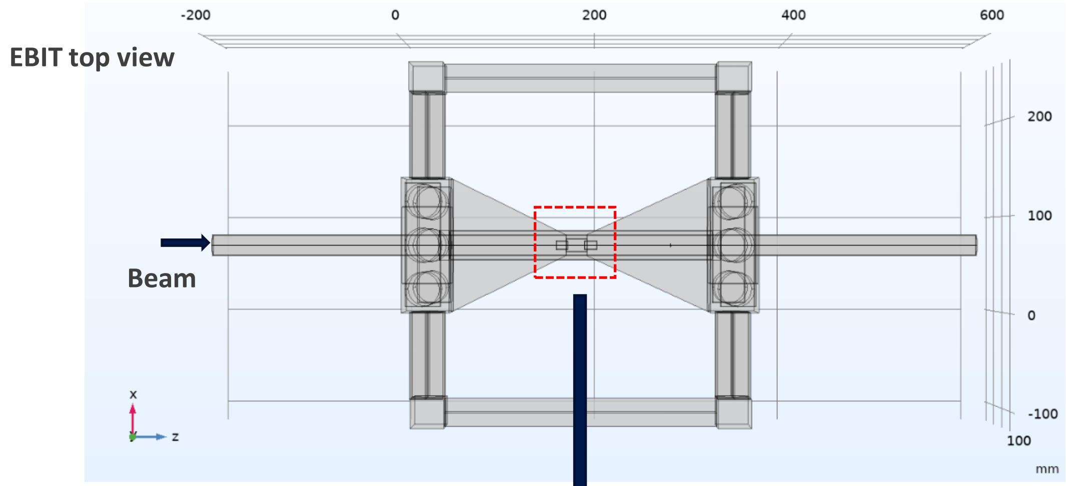


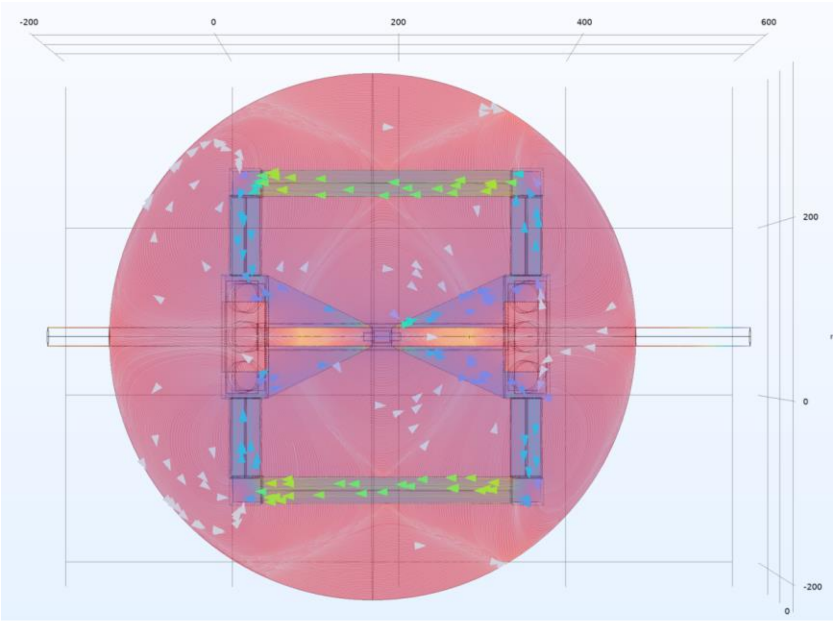


- To optimize the injection we need to simulate the properties of the HC-EBIT
- Fundamental to define the EBIT acceptance

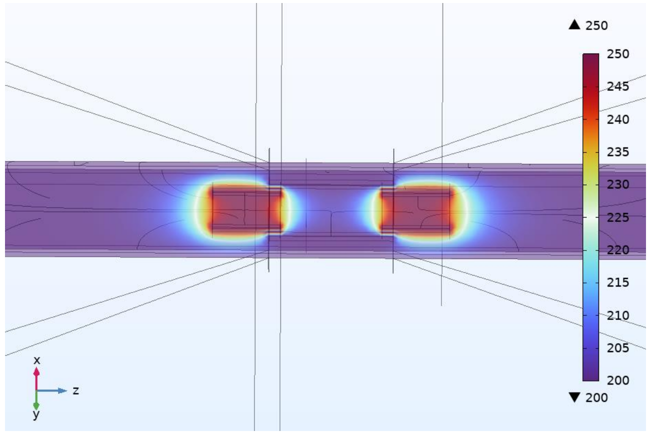
*Micke et al, Rev. Sc. Inst. 89, 063109 (2018)

EBIT simulations (with Comsol)





Trapping region

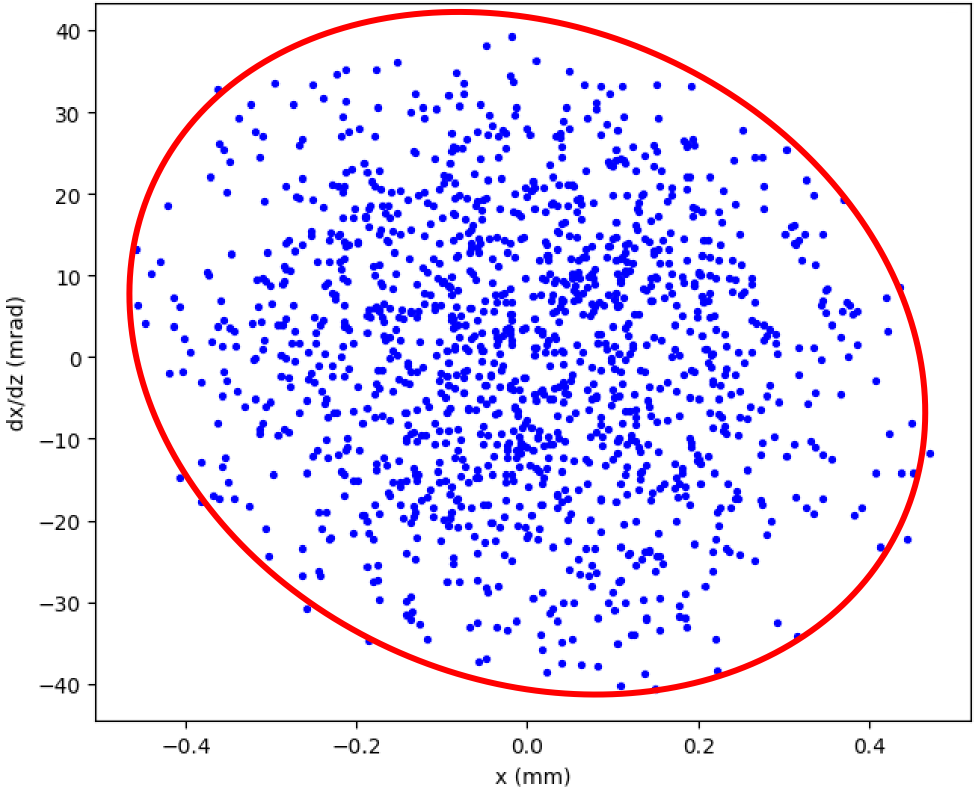


Acceptance

The EBIT acceptance depends on several variables:

- **electron beam and the magnetic field**
- **Energy of the ion beam before injection 20 keV**

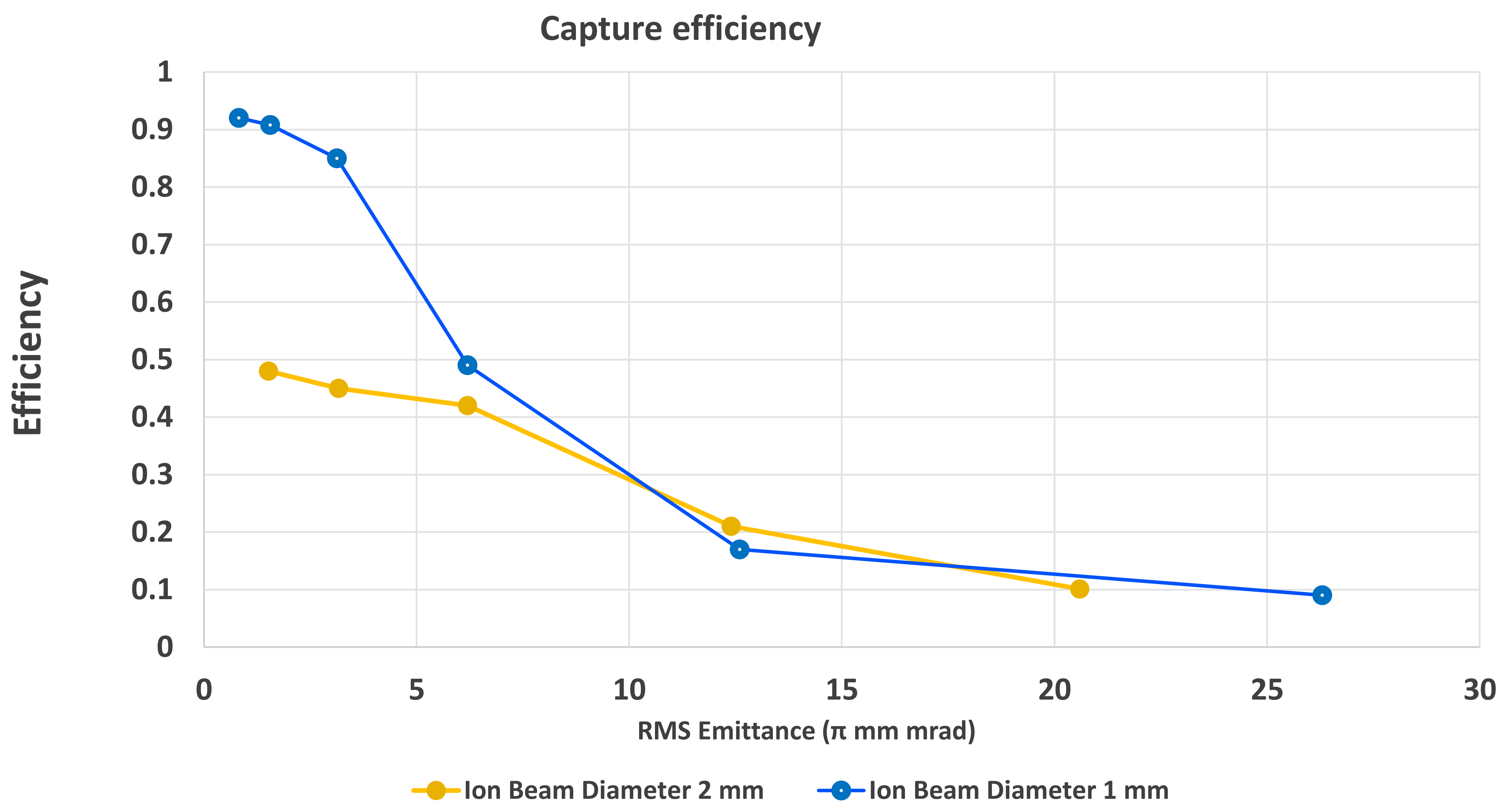
Electron beam: $I_e = 0.08\ A$, $E_e = 10\ keV$
Magnetic field: B = 0.86 T



RMS Emittance (ε_{RMS}) in x & y about 3.7 π mm·mrad

Effective emittance ε_{eff} : $\varepsilon_{eff} = 4 \cdot \varepsilon_{RMS}$ = 14.8 π mm·mrad

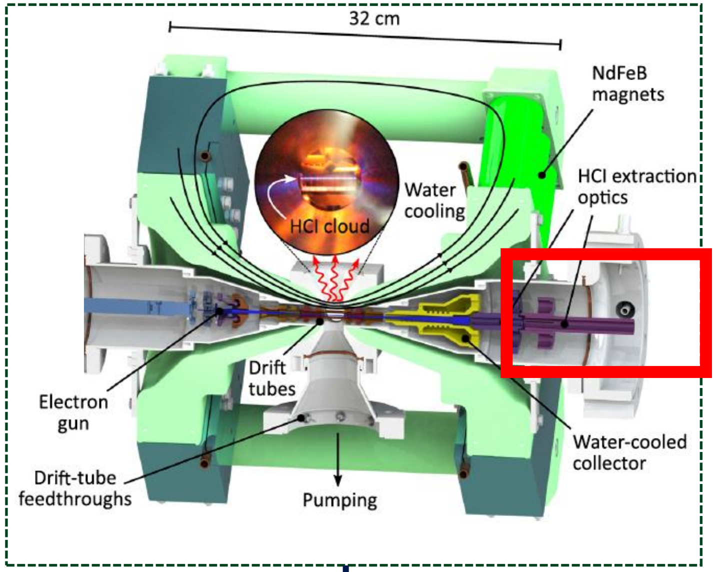
Capture efficiency



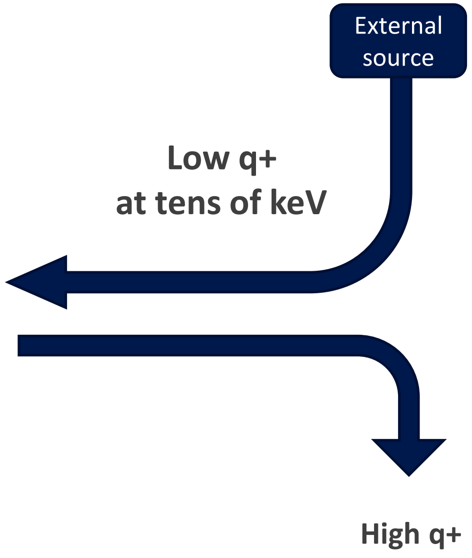
EBIT at Tancrede – Ion beam injection

We are working on the design of the injection and extraction system

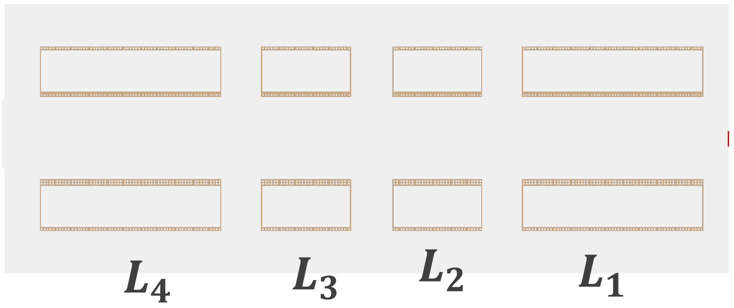
Beams are transported with energies of the order of few tens keV, HV platform is required.



HV platform



Deceleration and extraction optics



Deceleration optics

***previously used for the Napis project**

*This deceleration optics ensured when the LMIS source is used parallel beams with a diameter after deceleration of 1.8 mm and angular spread ± 4 mrad.

Future of EBIT in DESIR

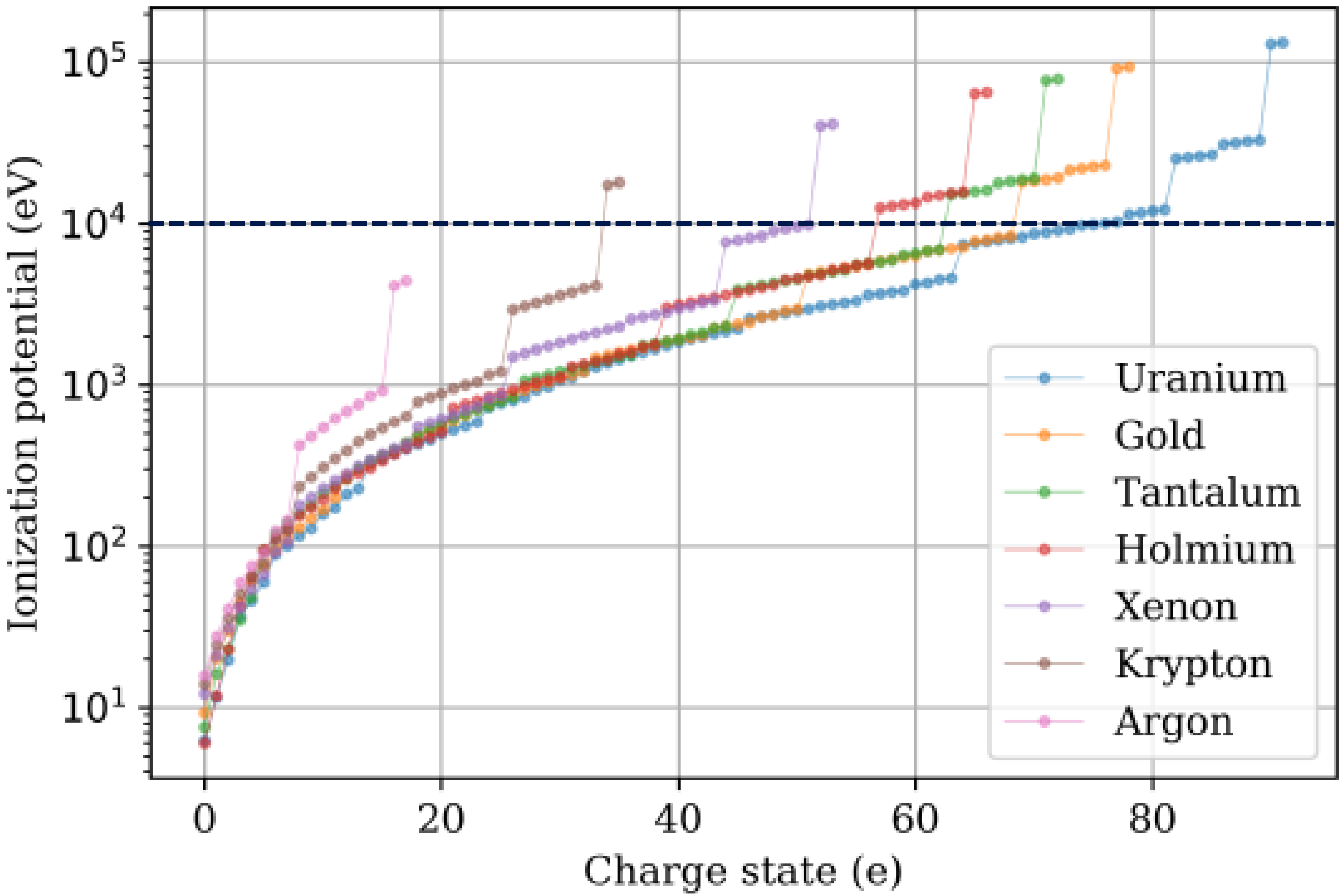
In the frame of DESIR, the development of an EBIT can be provide an important contribution to:

- In-trap decay studies (as done in TITAN EBIT)
- Achieve a higher precision in mass measurements

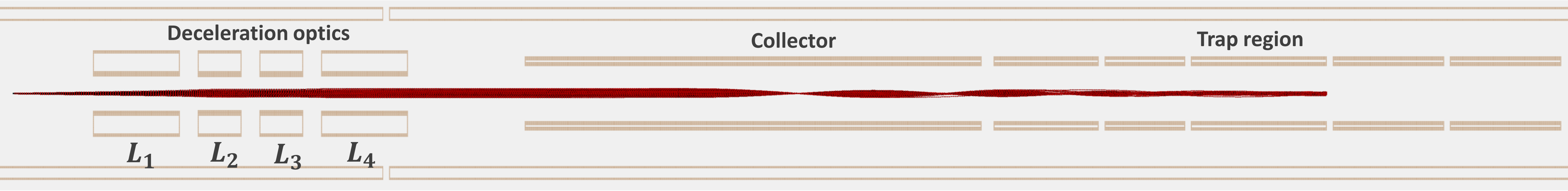
$$\frac{m}{\Delta m} \propto \frac{q \cdot B}{m} \cdot T_{RF}\sqrt{N}$$

- Separation of isomeric states at very low energies
- Laser spectroscopy on 3+ ions at DESIR?
- Or other experiments ?

Scientific cases

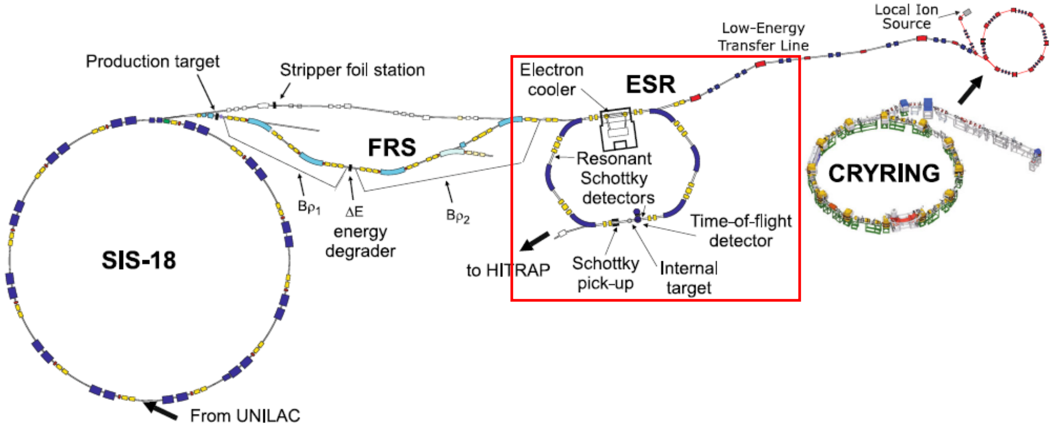


Scientific cases



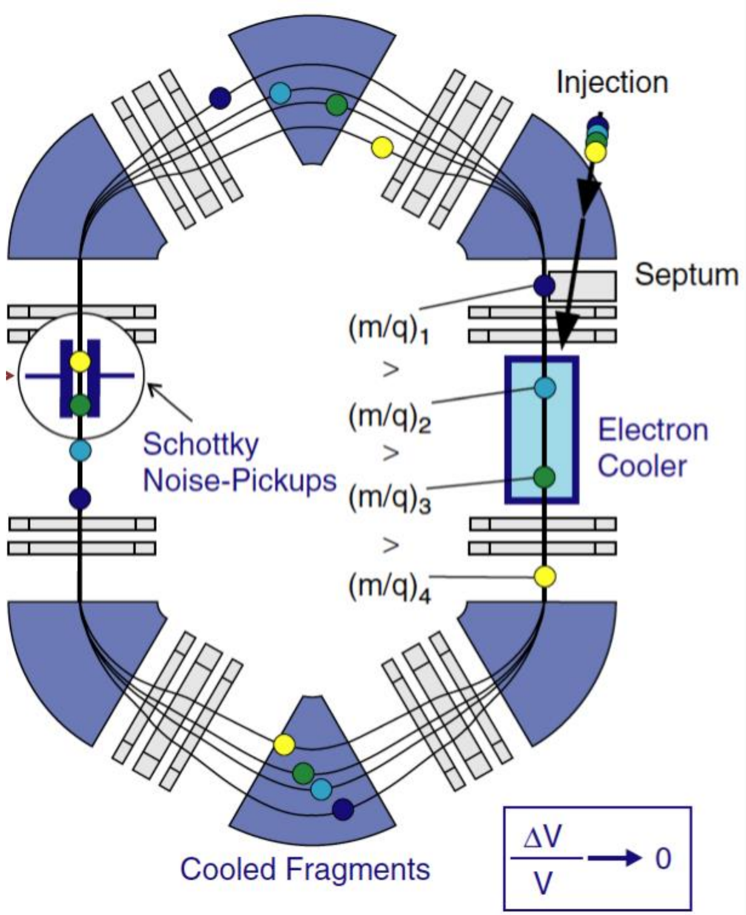
Experiments in storage rings

MAJOR EXAMPLE IS THE GSI/FAIR facility in Germany



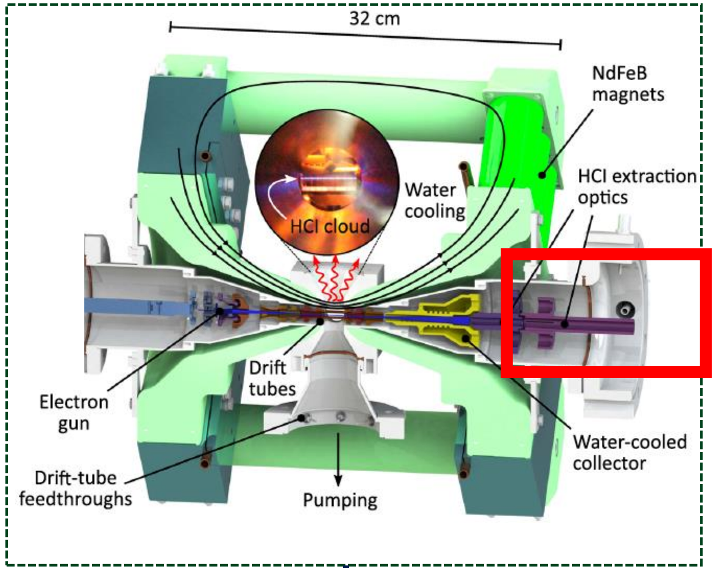
Storage ring mass spectrometry (SRMS)

- m/q of a particle changes in the decay



- **Advantages:**
  - **High charge state (up to bare ions)**
- **Disadvantages:**
  - **Radiation can not be detected**
  - **Beam time availability**

EBIT at Tancrede – Ion beam injection



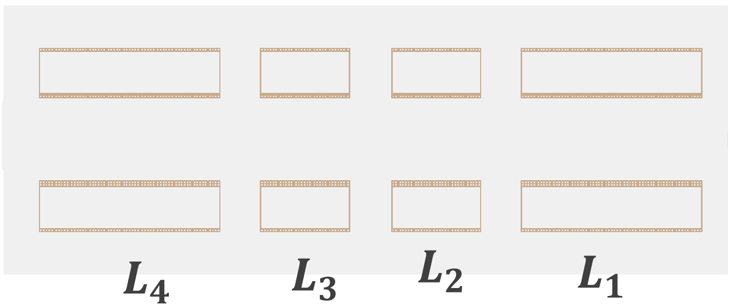
HV platform

External source

Low q+
at tens of keV

High q+

Deceleration and extraction optics



Deceleration optics

*previously used for the Naphis project