IJCLab
Irène Joliot-Curie
Laboratoire de Physique des 2 Infinis

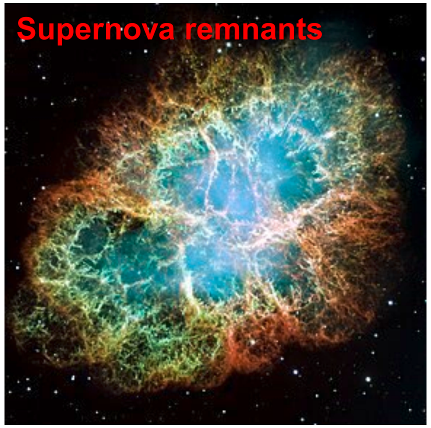
The HINA experiment: Highly charged Ions for Nuclear physics and Astrophysics

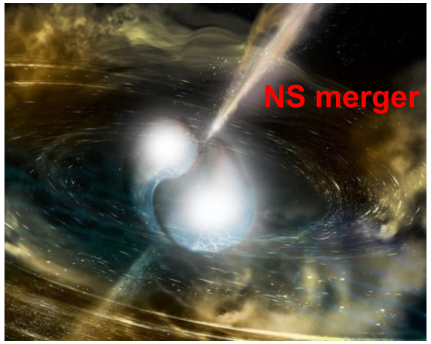
Polynesian Goddess of the Moon and Stars

GANIL Scientific Council
04/02/2025

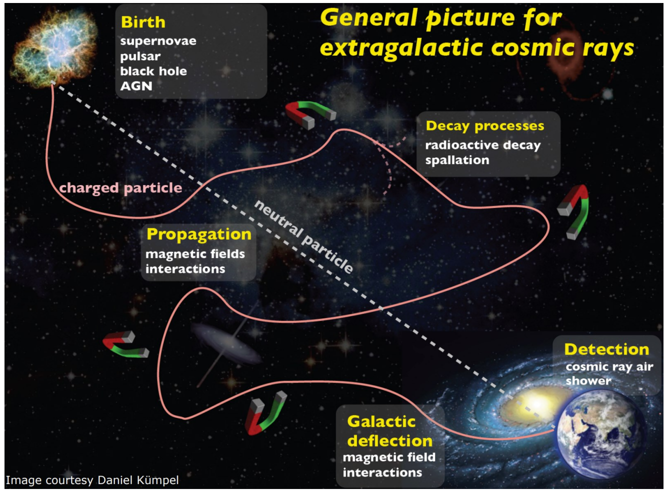
Sarah Naïmi

Where do we find them?

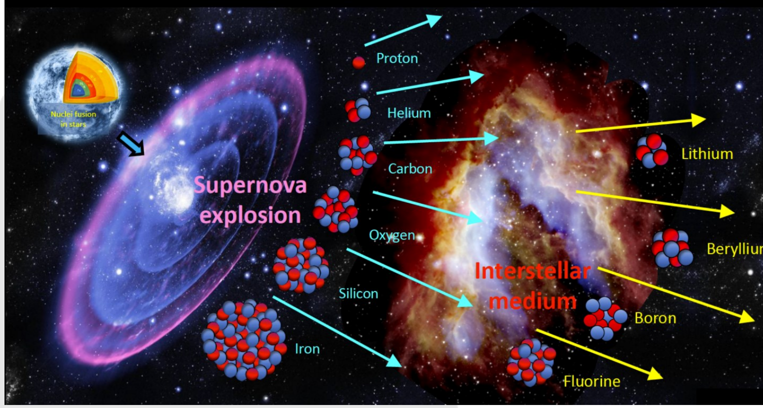




HINA: Nuclear decay of unstable HCIs

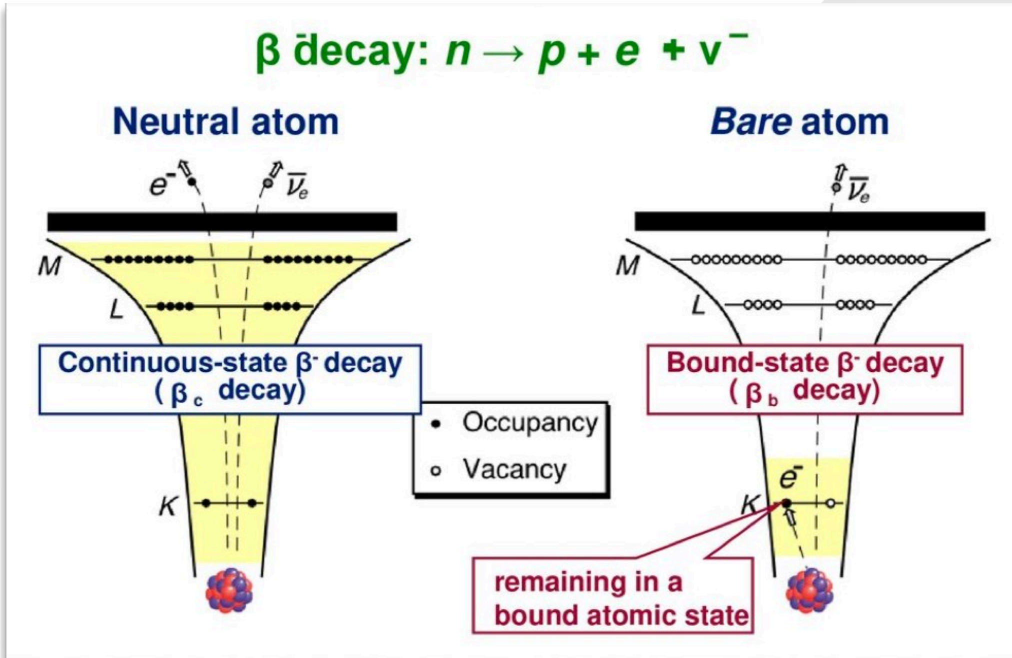


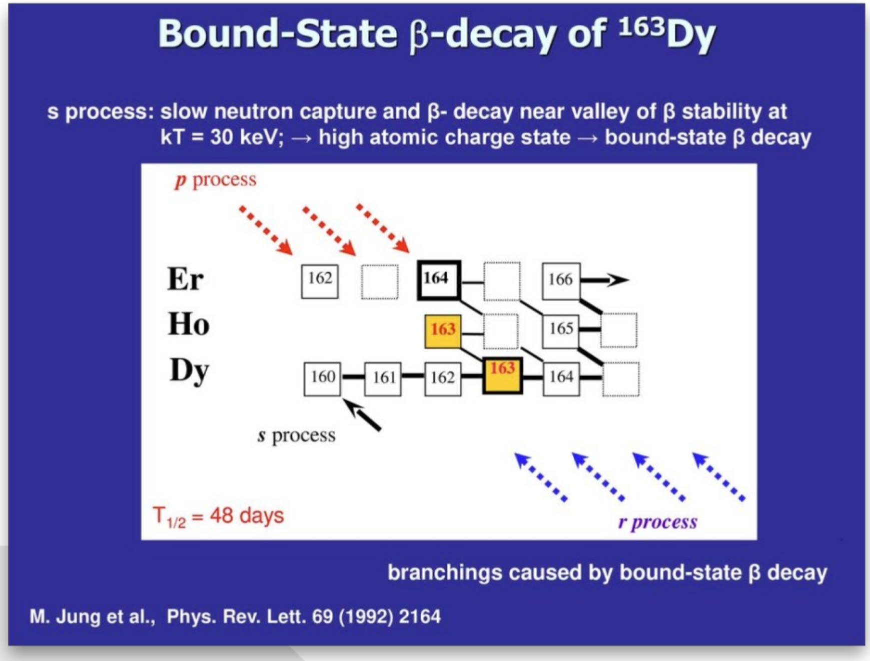
Secondary Li, Be, B, and F nuclei in cosmic rays are produced by the collision of primary cosmic rays, C, O, Ne, Mg, Si, …, Fe, with the interstellar medium.



Measurements of the secondary cosmic ray nuclei fluxes and the secondary to primary flux ratios are important in understanding the propagation of cosmic rays in the Galaxy.

$^{163}Dy^{0}$ **stable** → $^{163}Dy^{66+}$ **unstable**





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

49keV   -2,8keV   13keV   65keV

Nuclear decay is NOT constant!

PHYSICAL REVIEW LETTERS **133**, 232701 (2024)

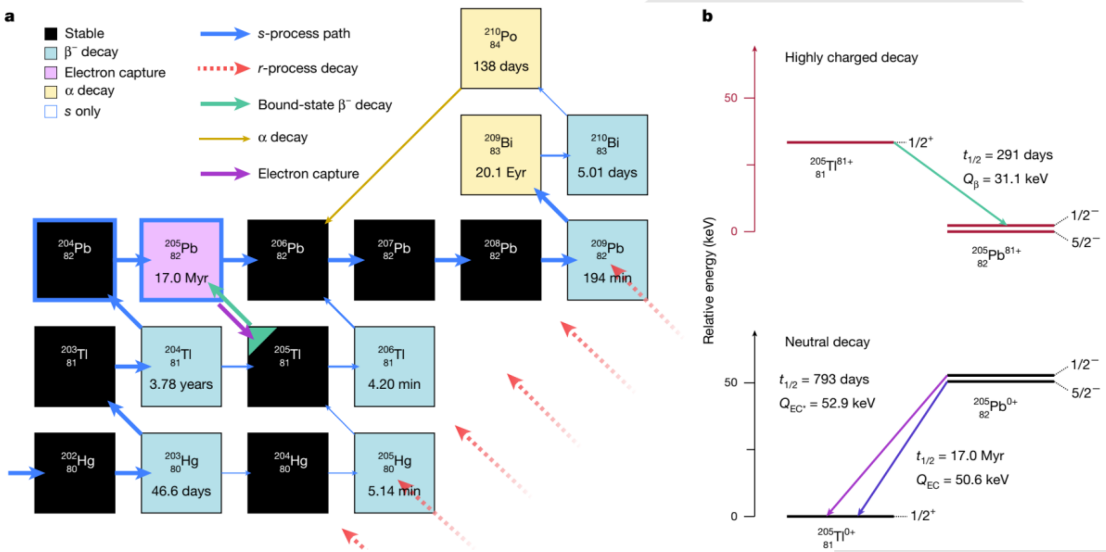
Editors' Suggestion

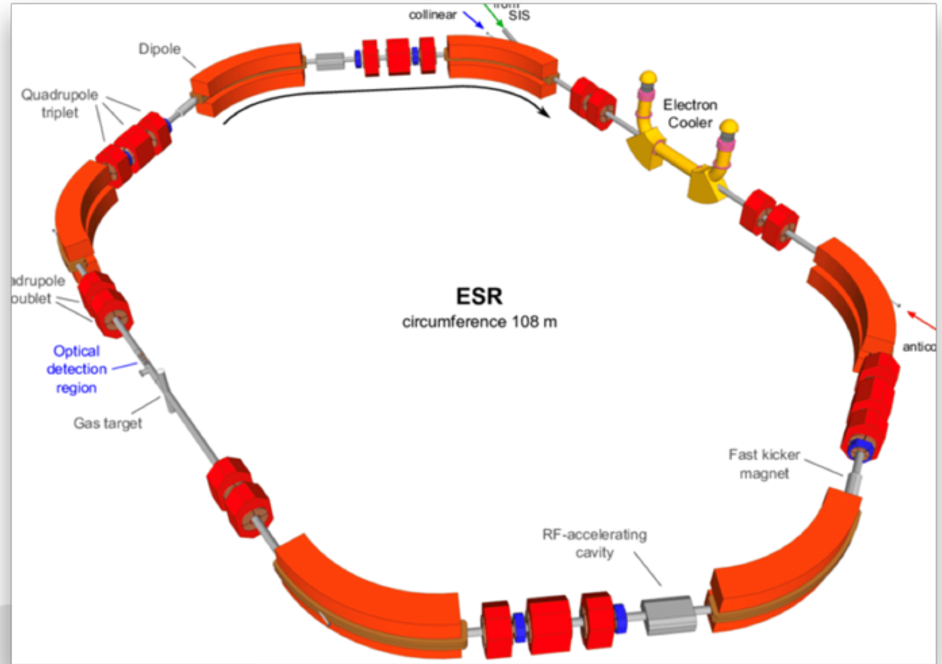
Bound-State Beta Decay of $^{205}Tl^{81+}$ Ions and the LOREX Project

nature > articles > article

Article | Open access | Published: 13 November 2024

High-temperature ^{205}Tl decay clarifies ^{205}Pb dating in early Solar System



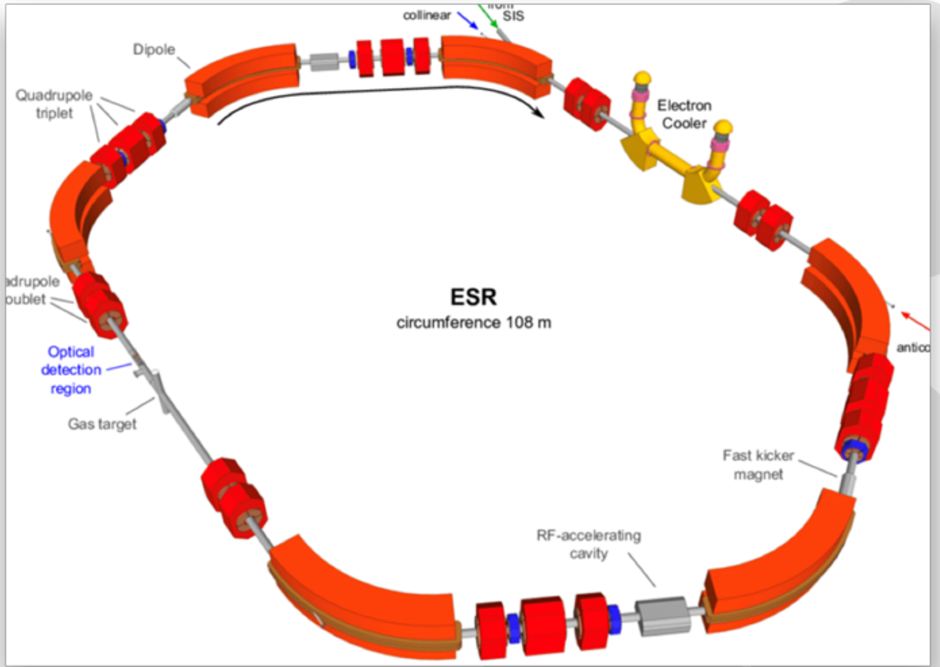


Decay of highly charged ions was mainly studied at storage rings (GSI)

Litvinov Eur. Phys. J. A (2023) 59:102

~40 nuclei were studied in 30 years (Z>26)

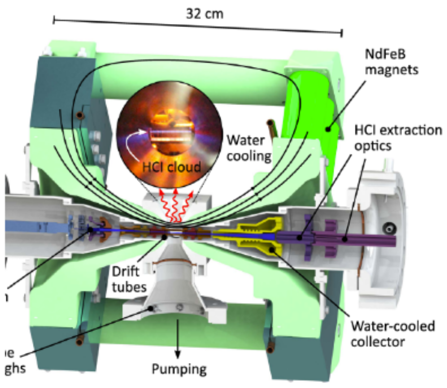
HINA experiment: developing alternative tools

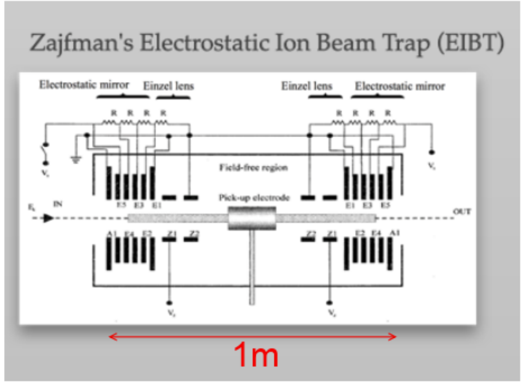


ESR@GSI
Focusing on studying heavy HCIs

Traps as alternative to storage rings
Smaller, cheaper, eco & "outperform"

Focus on light ions



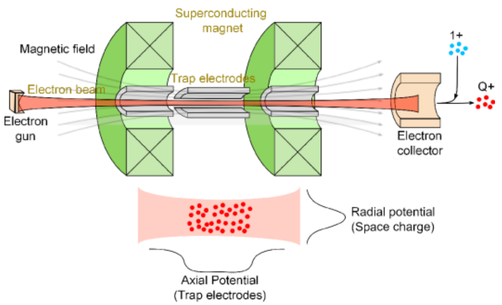


Advantage:
Compact
→ Radiation detection
→ Reduce construction & operation cost

Disadvantage:
Compact
→ Space charge effects

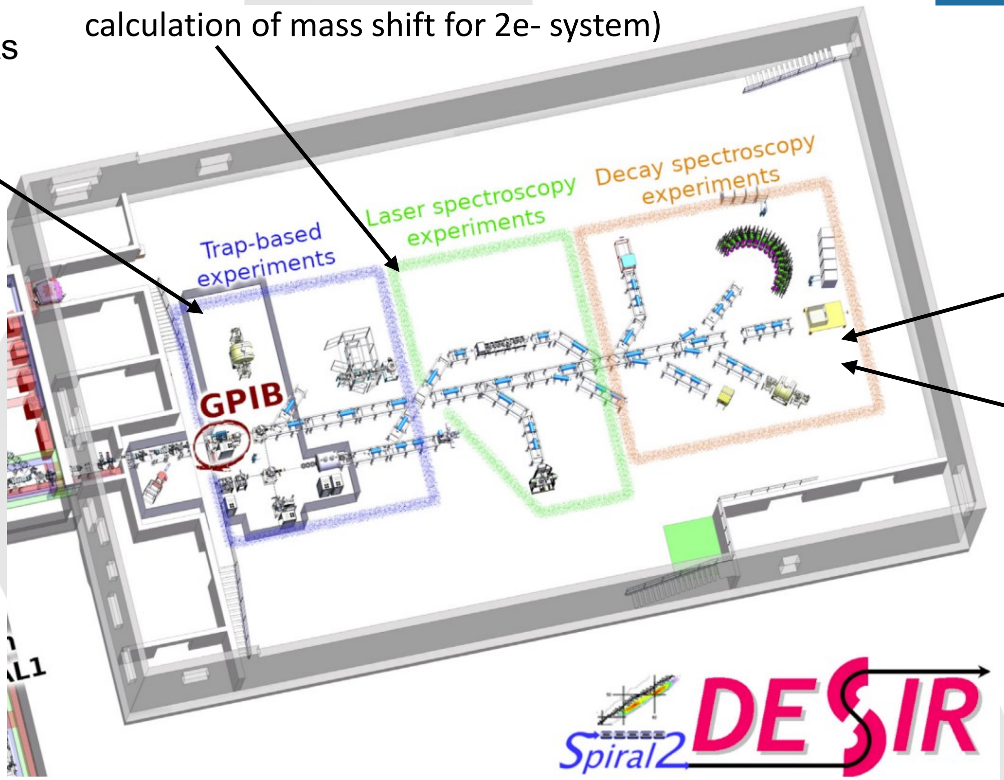
High precision mass measurements

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



High precision collinear laser spectroscopy e.g. Be^{2+}, B^{3+} and C^{4+}

Transition 1s2s $^3S_1 \rightarrow$ 1s2p ^3P_J laser accessible UV (high sensitivity to charge radii & high precision calculation of mass shift for 2e- system)



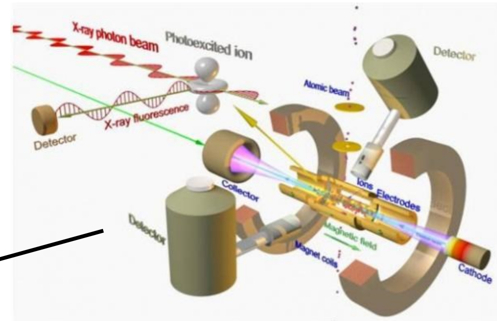
HINA

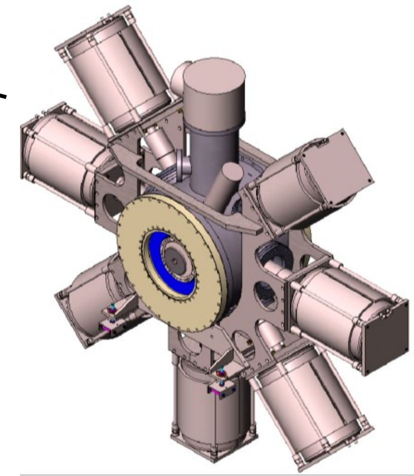
Spectroscopy of HCIs:

Nuclear physics

Astrophysics

Atomic physics, …





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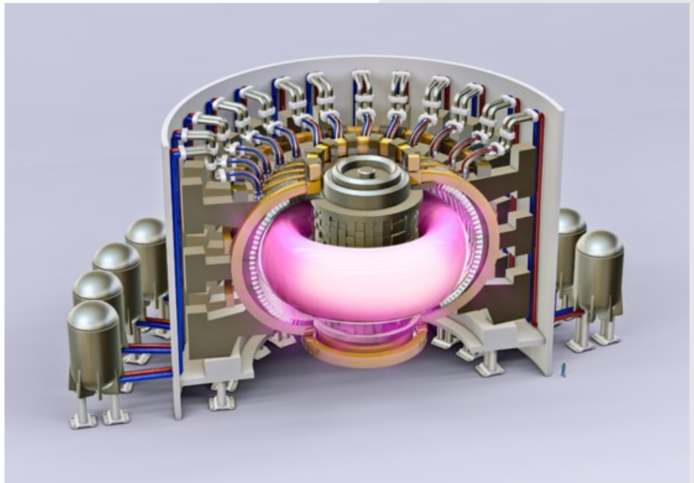
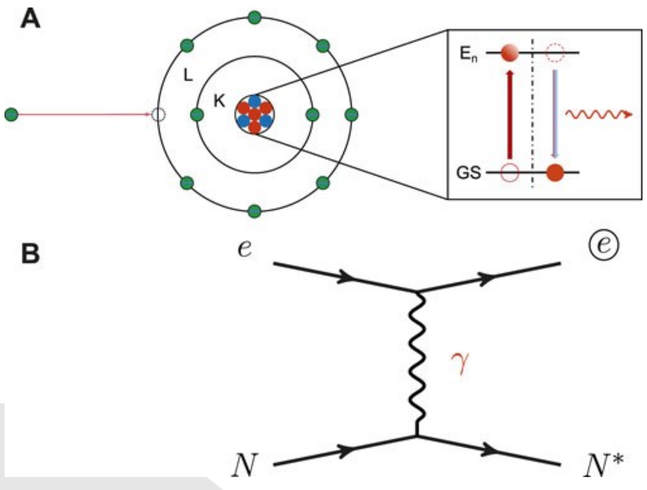


nature > letters > article

Letter | Published: 08 February 2018

Isomer depletion as experimental evidence of nuclear excitation by electron capture



Energy storage: nuclear battery?

HINA

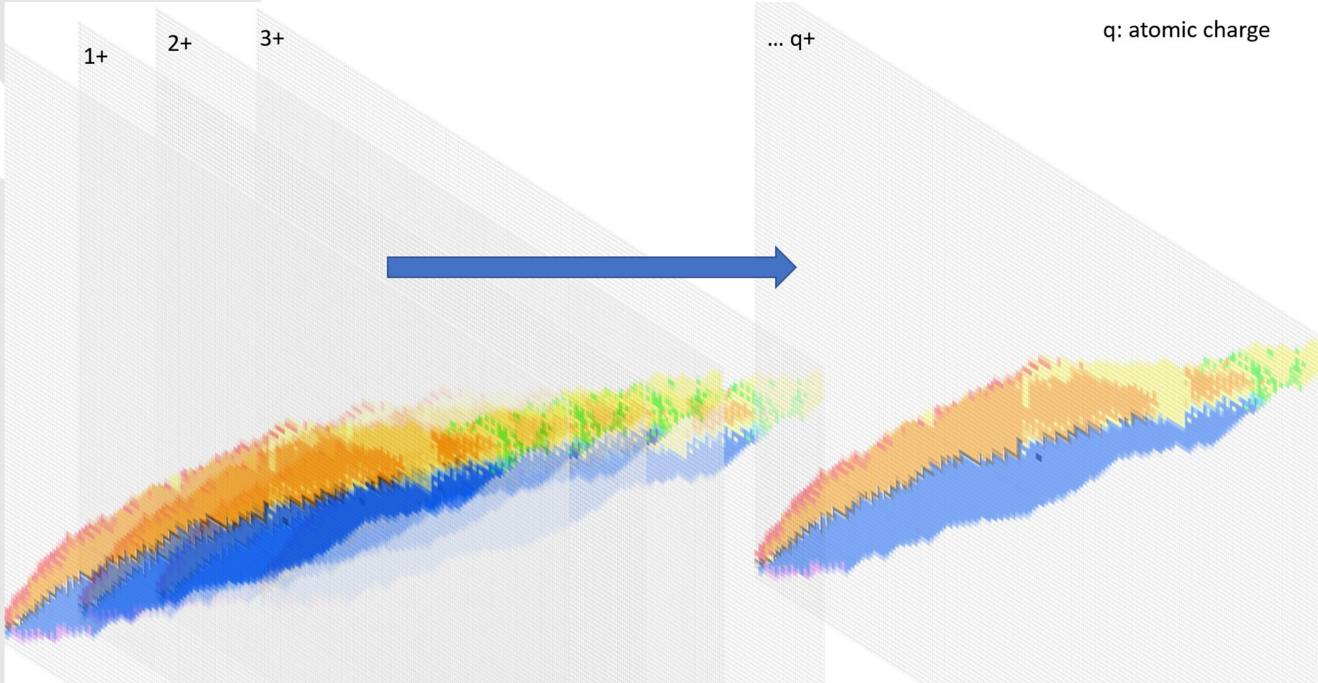
Decay highly charged light ions

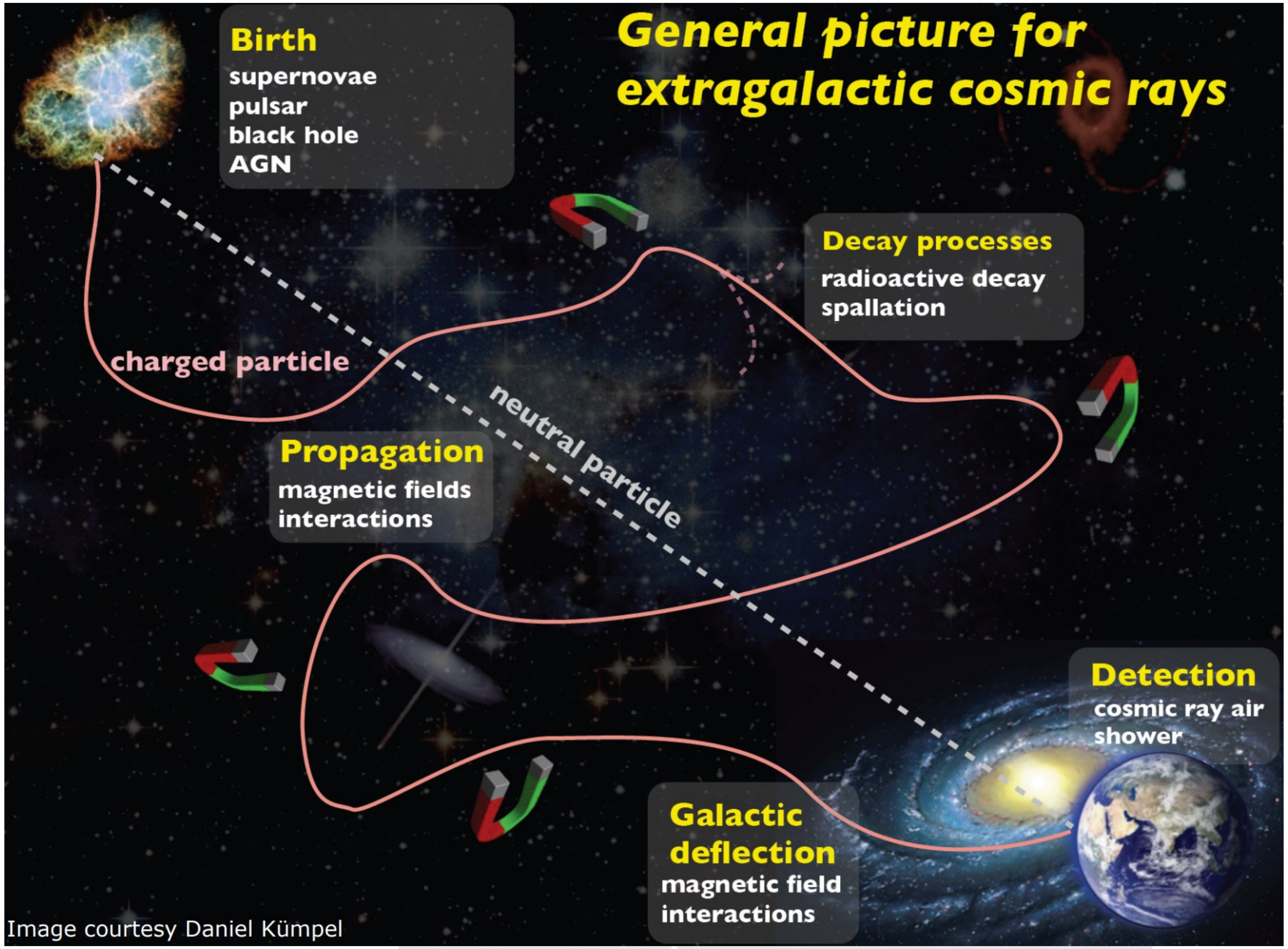
Trap-based setup

Nuclear physics
Astrophysics

High precision
New applications

Adding a new dimension @DESIR for exploring the nuclear chart and increasing scientific impact




Birth
supernovae
pulsar
black hole
AGN
General picture for extragalactic cosmic rays
Decay processes
radioactive decay
spallation
charged particle
neutral particle
Propagation
magnetic fields
interactions
Detection
cosmic ray air shower
Galactic deflection
magnetic field interactions
Image courtesy Daniel Kümpel

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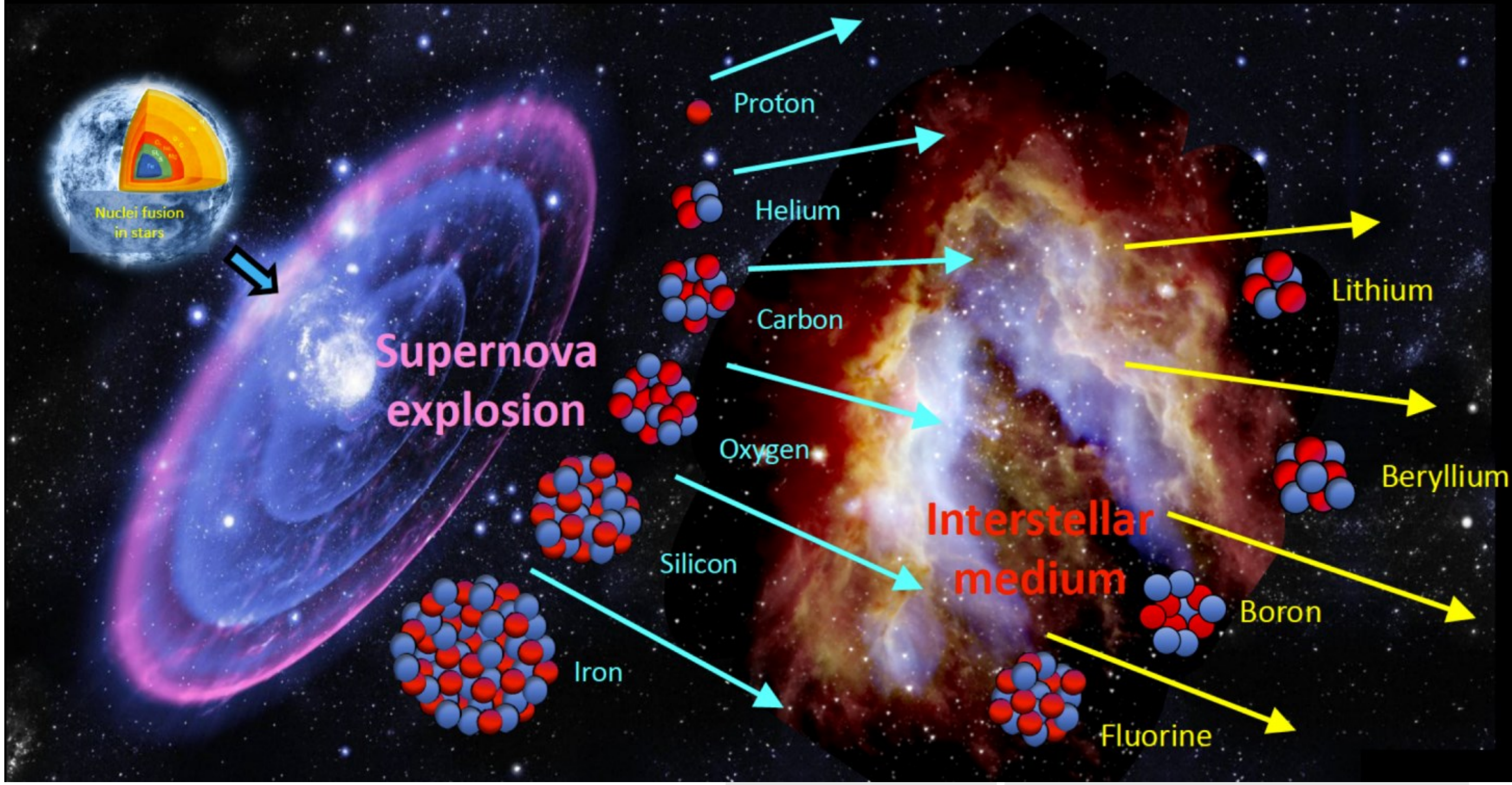

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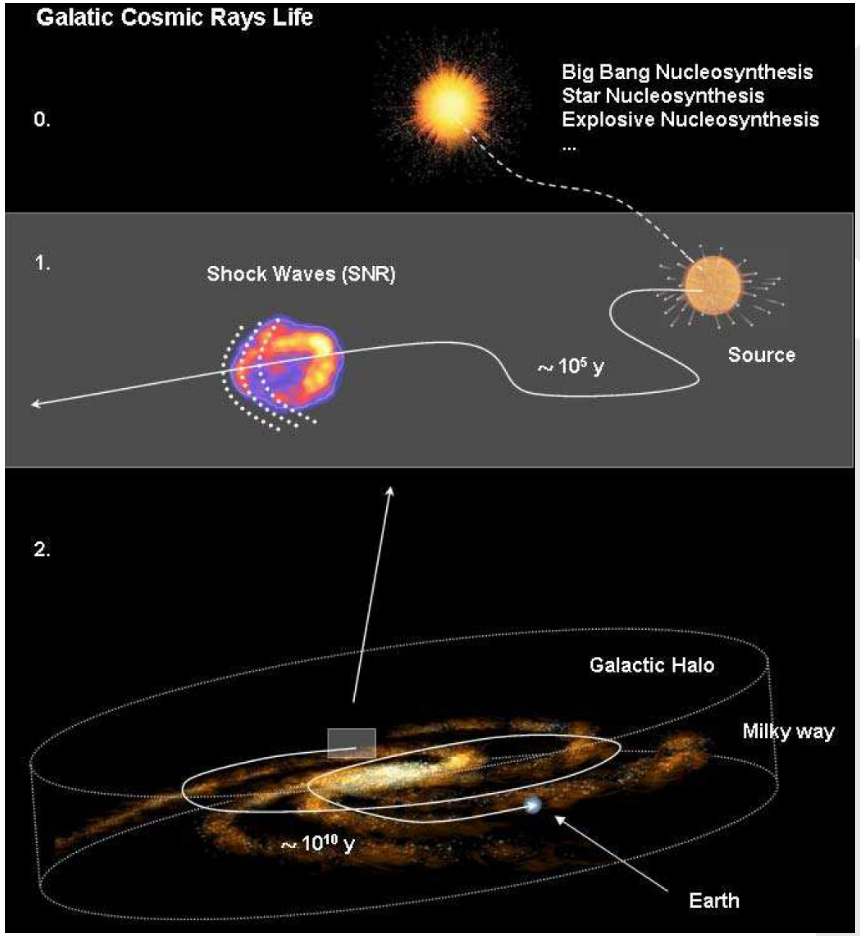


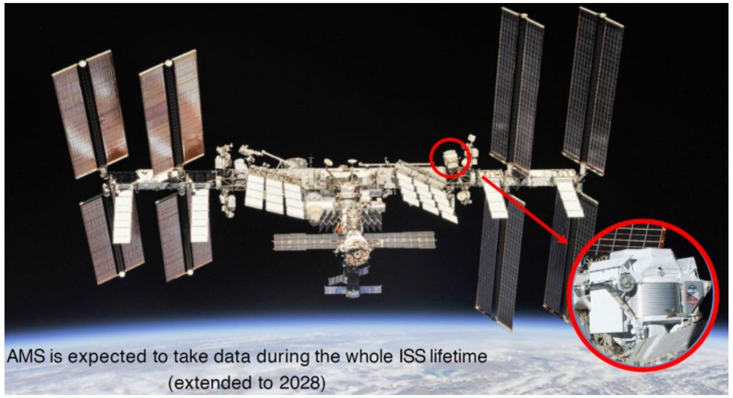
Most interesting GCRs (Astronomic Clocks)

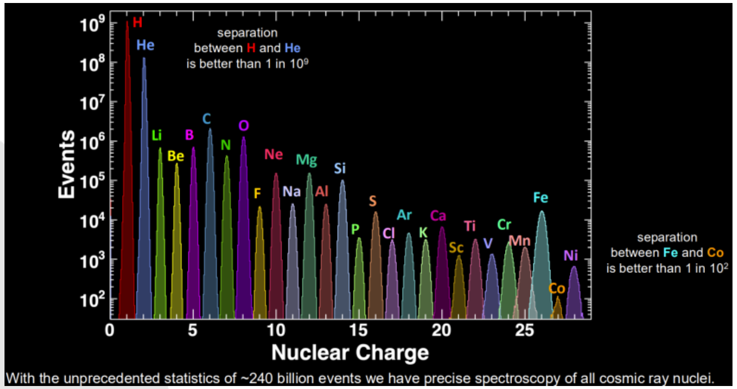
Nuclide	Decay Mode	Half-life
^{7}Be	K-capture	53 days
^{10}Be	β-	1.5 Myr
^{14}C	β-	5730 yr
^{26}Al	β+	0.87 Myr
	K-capture	4.0 Myr
^{36}Cl	β-	0.30 Myr
^{37}Ar	K-capture	35 days
^{41}Ca	K-capture	0.10 Myr
^{44}Ti	K-capture	49 yr
^{49}V	K-capture	330 days
^{51}Cr	K-capture	28 days
^{53}Mn	K-capture	3.7 Myr
^{54}Mn	K-capture	312 days
	β+	400 Myr
	β-	0.8 Myr b
^{55}Fe	K-capture	2.7 yr
^{56}Ni	K-capture	6.1 days
	β+	$\sim$ 1 yr
^{57}Co	K-capture	270 days
^{59}Ni	K-capture	76000 yr

A. Oliva PhD thesis 2007

Measurement is conducted at AMS-02 @ISS since 2011

https://ams02.space/





A.Oliva, talk in CRs and νs in MME conference, 2024

ANNUAL REVIEW OF NUCLEAR AND PARTICLE SCIENCE Volume 57, 2007

Review Article

Cosmic-Ray Propagation and Interactions in the Galaxy

Andrew W. Strong[1], Igor V. Moskalenko[2], and Vladimir S. Ptuskin[3]

Hide Affiliations

Affiliations:

[1]Max-Planck-Institut für extraterrestrische Physik, 85741 Garching, Germany; email: aws@mpe.mpg.de

[2]Hansen Experimental Physics Laboratory and Kavli Institute for Particle Astrophysics and Cosmology, Stanford University, Stanford, California 94305; email: imos@stanford.edu

[3]Institute for Terrestrial Magnetism, Ionosphere and Radiowave Propagation of the Russian Academy of Sciences (IZMIRAN), Troitsk, Moscow region 142190, Russia; email: vptuskin@izmiran.ru

Starting with the heaviest primary nucleus considered (e.g. ^{64}Ni) the propagation solution is used to compute the source term for its spallation products, which are then propagated in turn, and so on down to protons, secondary electrons and positrons, and antiprotons. In this way secondaries, tertiaries etc. are included. (Production of ^{10}B via the ^{10}Be-decay channel is important and requires a second iteration of this procedure.) GALPROP includes K-capture and electron stripping processes, where a nucleus with an electron (H-like) is considered a separate species because of the difference in the lifetime. Since H-like atoms have only one K-shell electron, the K-capture decay half-life has to be increased by a factor of 2 compared to the measured half-life value. Primary electrons are treated

PHYSICAL REVIEW C **77**, 014306 (2008)

Orbital electron capture decay of hydrogen- and helium-like ions

Zygmunt Patyk,[1] Jan Kurcewicz,[2] Fritz Bosch,[3] Hans Geissel,[3] Yuri A. Litvinov,[3] and Marek Pfützner[2]

[1]*Soltan Institute for Nuclear Studies, Hoża 69, PL-00-681 Warsaw, Poland*

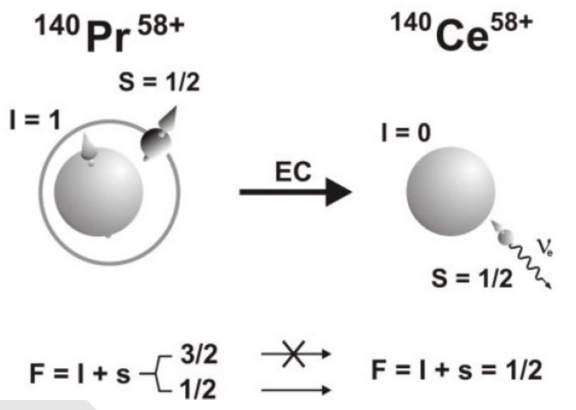
[2]*Institute of Experimental Physics, Warsaw University, Hoża 69, PL-00-681 Warsaw, Poland*

[3]*Gesellschaft für Schwerionenforschung (GSI), Planckstrasse 1, D-64291 Darmstadt, Germany*

(Received 3 August 2007; published 10 January 2008)

Measured H-,He- ^{140}Pr at GSI

Litvinov+, PRL, 2007



Ion	λ_{β^+} (sec^{-1})	λ_{EC} (sec^{-1})
^{140}Pr^{59+}	0.001 58(8)	...
^{140}Pr^{58+}	0.001 61(10)	0.002 19(6)
^{140}Pr^{57+}	0.001 54(11)	0.001 47(7)

Factor 2/3

Orbital EC in H-like & He-like ions

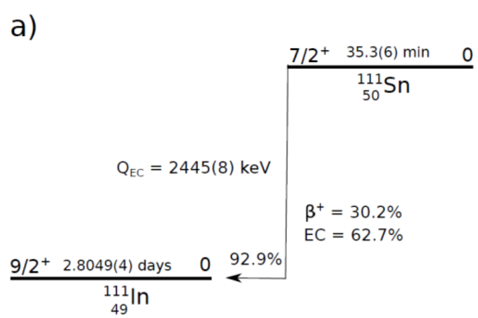
HINA@GANIL

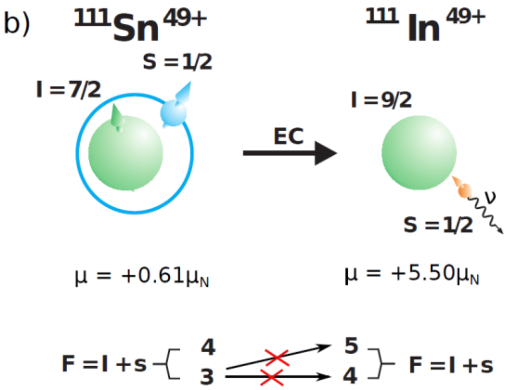
Cosmic Ray

Suggested nuclei to be studied experimentally

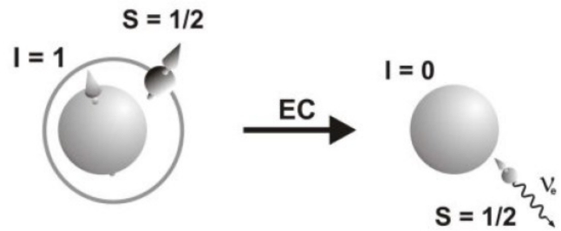
H-like ion	$I_i^{\pi_i} \rightarrow I_f^{\pi_f}$	μ/μ_N	δE (eV)	$\tau_{1/2}$	$T_{1/2}$
^{19}Ne	$\frac{1}{2}^+ \rightarrow \frac{1}{2}^+$	−1.89	0.004	3 d	17.3 s
^{37}Ar	$\frac{3}{2}^+ \rightarrow \frac{3}{2}^+$	+1.15	0.01	10 h	35 d
^{64}Cu	$1^+ \rightarrow 0^+$	−0.22	0.009	7 h	12.7 h
^{68}Ga	$1^+ \rightarrow 0^+$	+0.01	0.001	5 yr	67.7 min
^{71}Ge	$\frac{1}{2}^- \rightarrow \frac{3}{2}^-$	+0.55	0.041	12 min	11.2 d
^{108}Ag	$1^+ \rightarrow 0^+$	+2.69	0.53	0.24 s	2.37 min
^{131}Cs	$\frac{5}{2}^+ \rightarrow \frac{3}{2}^+$	+3.54	0.98	31 ms	9.69 d
^{141}Nd	$\frac{3}{2}^+ \rightarrow \frac{5}{2}^+$	+1.01	0.43	0.4 s	2.5 h
^{178}Ta	$1^+ \rightarrow 0^+$	+2.74	2.87	1.6 ms	9.31 min

Decay by EC is not allowed!





^{64}Cu^{28+} 44%EC ^{64}Ni^{28+}



Standard theory of EC:
overlap of nuclear &
electron wave functions

$F^{\pm} = I \pm ½$

μ>0	μ<0	μ<0
F^+	F^-	1/2
F^-	F^+	3/2 (crossed out)

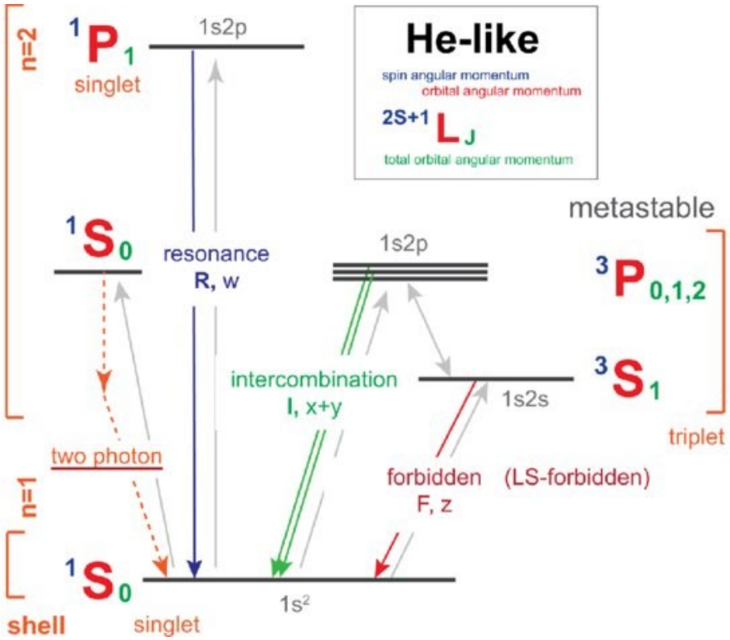
F=1/2

PHYSICAL REVIEW C **84**, 064309 (2011)

Nuclear electron capture in Li-like ions

Katarzyna Siegień-Iwaniuk and Zygmunt Patyk
National Centre for Nuclear Research, Hoża 69, PL-00-681 Warsaw, Poland

Decay of the $^1S_0$ can be very accurately calculated (QED)
--> Suggested for Parity Non-Conservation test



HINA

H-like ion	$I_i^{\pi_i} \rightarrow I_f^{\pi_f}$
^{19}Ne	$\frac{1}{2}^+ \rightarrow \frac{1}{2}^+$
^{37}Ar	$\frac{3}{2}^+ \rightarrow \frac{3}{2}^+$
^{64}Cu	$1^+ \rightarrow 0^+$
^{68}Ga	$1^+ \rightarrow 0^+$

For allowed EC
I→I±1

$$\frac{P_0}{P_1} = \frac{2I+1}{2(I \pm 1)+1}$$

TABLE I. The ratio of probabilities P_0/P_1 that the lithium-like ion decays into the excited states $2\,^1S_0$ and $2\,^3S_1$ of the helium-like ion. The ratio is calculated for two types of EC decays $I \rightarrow I \pm 1$.

I_i	$\frac{P_0}{P_1}$ $I \rightarrow I-1$	$\frac{P_0}{P_1}$ $I \rightarrow I+1$
0		$\frac{1}{3}$
$\frac{1}{2}$		$\frac{1}{2}$
1	3	$\frac{3}{5}$
$\frac{3}{2}$	2	$\frac{2}{3}$
...	...	...
∞	1	1

HINA experiment @DESIR: What? Why? How?

HINA

Decay highly charged light ions

Trap-based setup

Nuclear physics
Astrophysics

High precision
New applications

HINA@GANIL

Cosmic Ray

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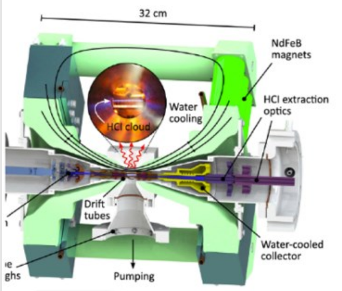
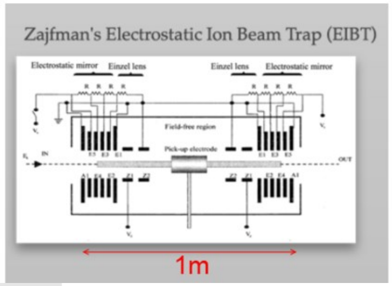
EC on H-,He-&Li-like ions
Nuclear physics, CR & PNC?

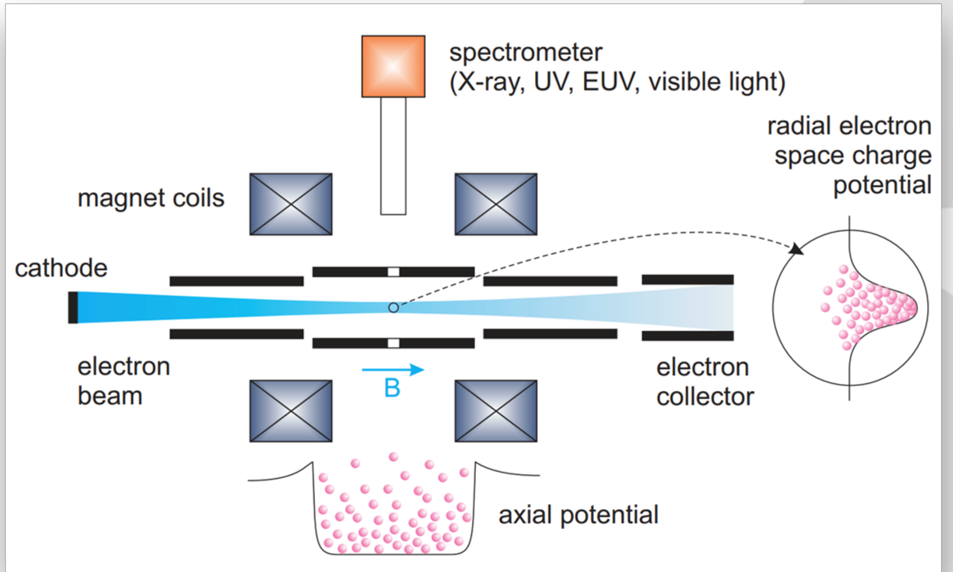
Traps as alternative to storage rings
Smaller, cheaper, eco & "outperform"

Focus on light ions





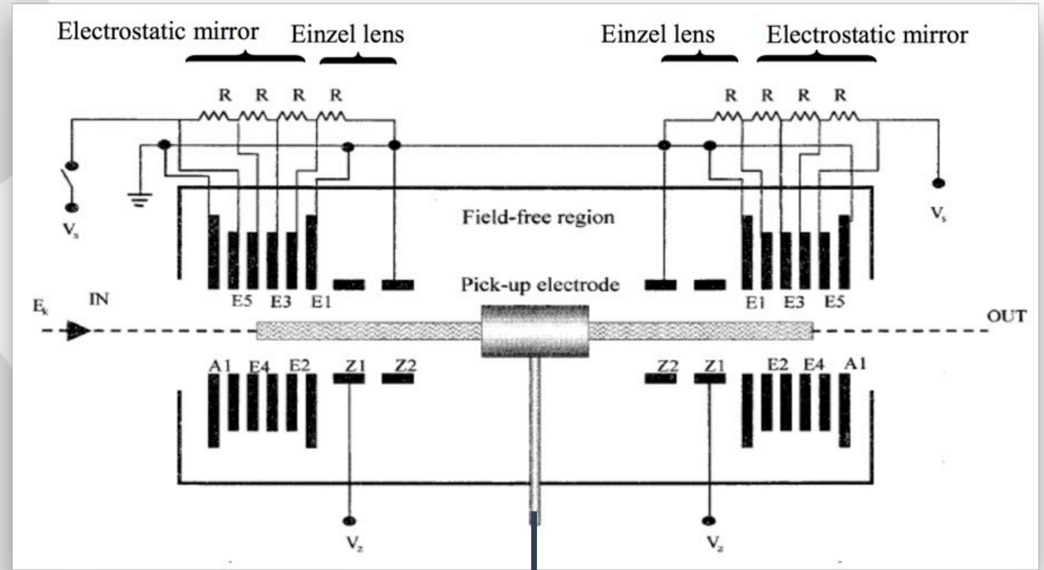
Electron Beam Ion Trap (EBIT)

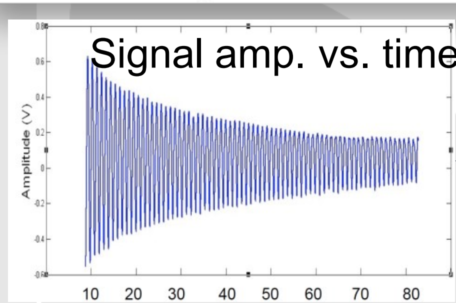


In-situ X-ray spectroscopy

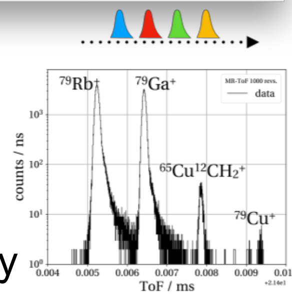
Reference measurement with stable beam

Zajfman's Electrostatic Ion Beam Trap (EIBT)

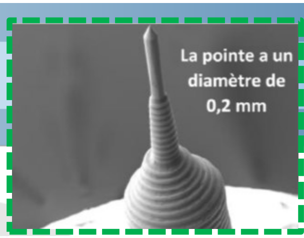


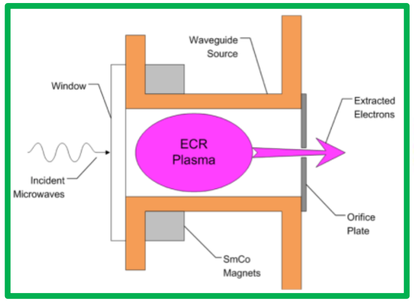


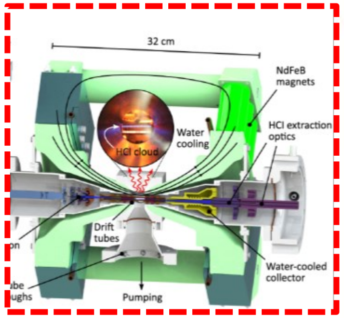
TOF mass
spectrometry

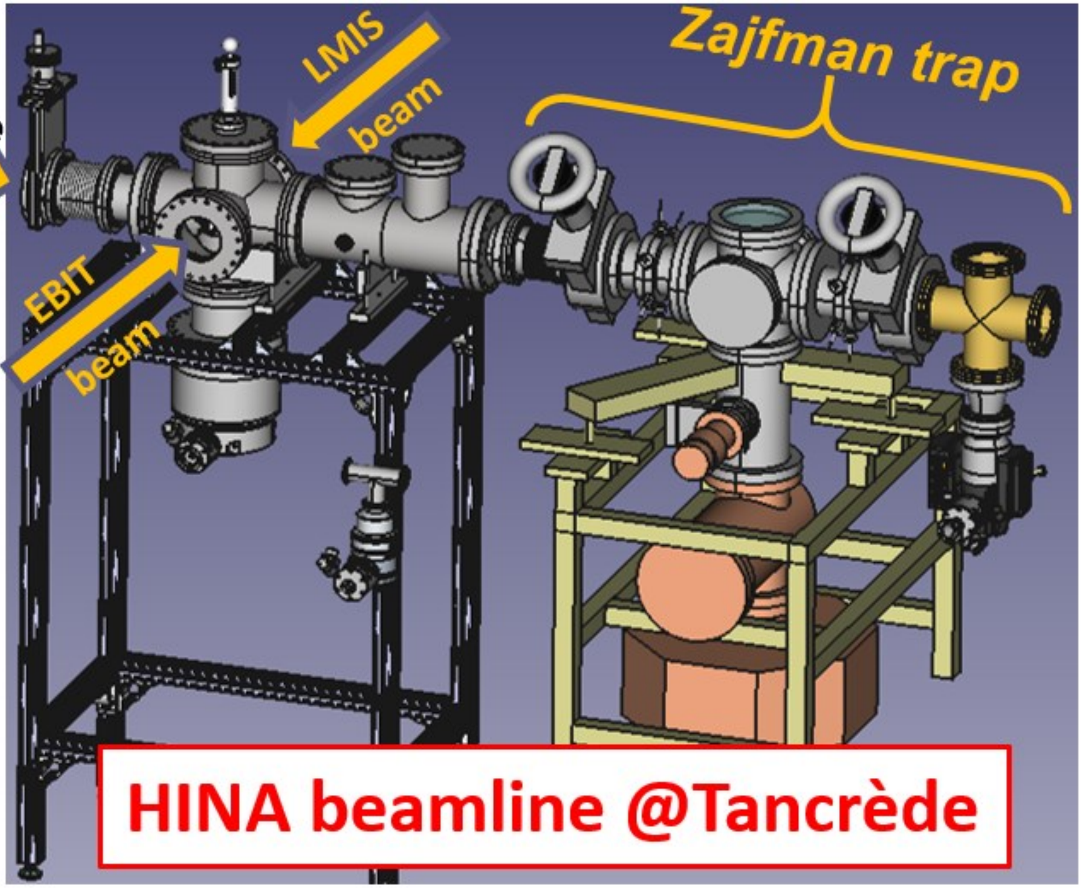


HINA@Tancrède









Experimental setup at IJClab:

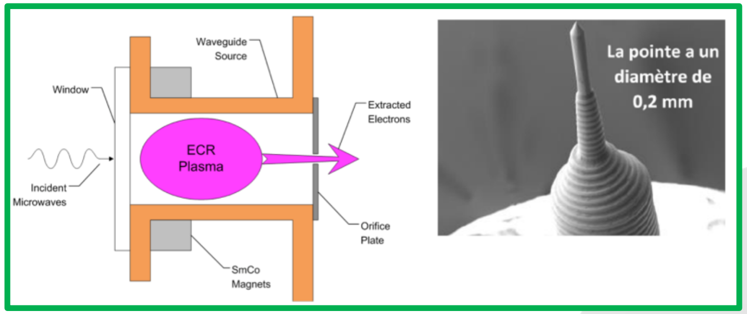
Validation of production and trapping of HCIs

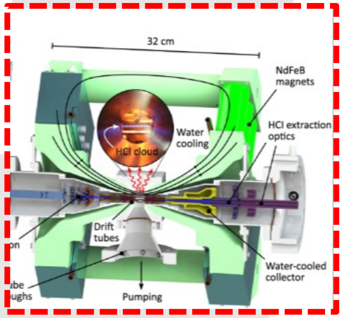
université PARIS-SACLAY

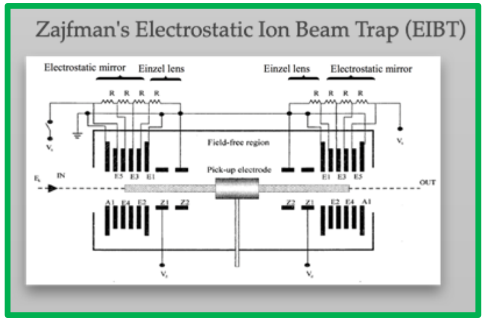
ERM24
IJCLab

Tools under development

Production (ECR/LMIS) → Charge Breeding → Trapping observation







Paul Indelicato

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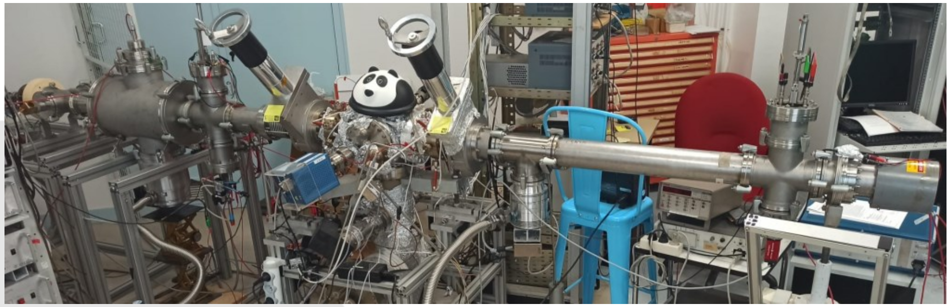
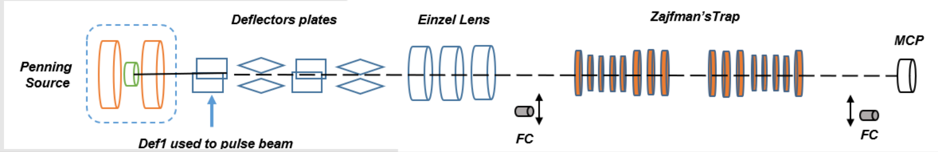
LMIS	^{64}Cu	$1^+ \rightarrow 0^+$
	^{68}Ga	$1^+ \rightarrow 0^+$

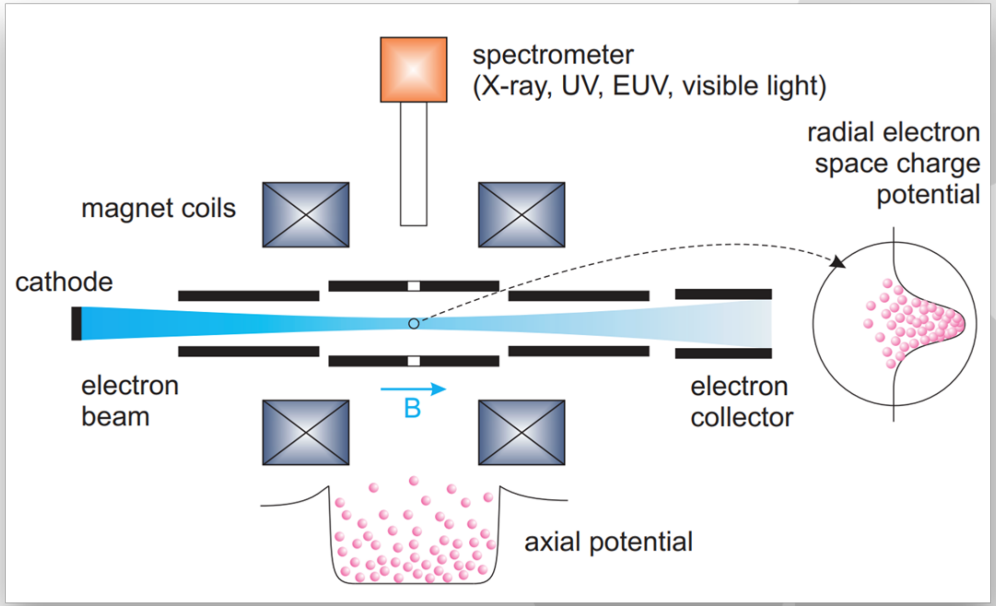
Cu beam is under development

Simulations:
Injection optics
Emittance acceptance
In-trap spectroscopy

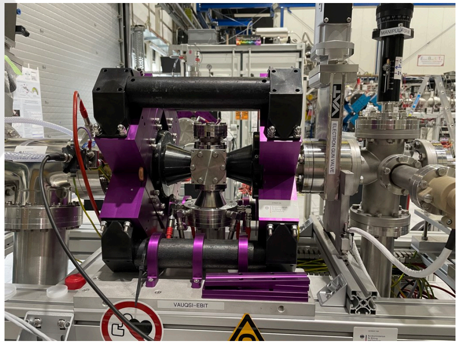




Electron Beam Ion Trap (EBIT)

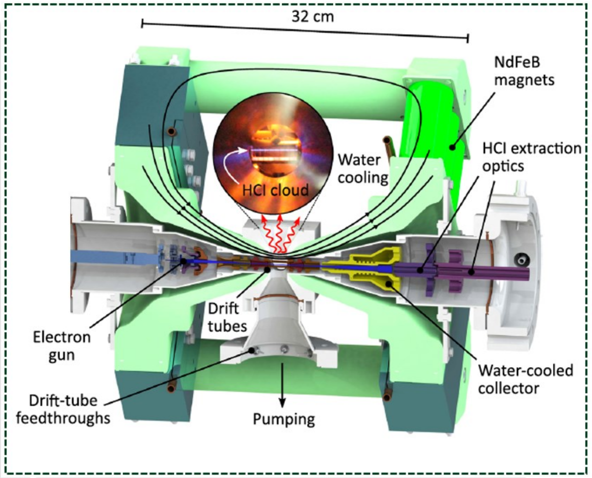


Collaboration with the Max-Planck Institut für Kernphysik (MPIK)

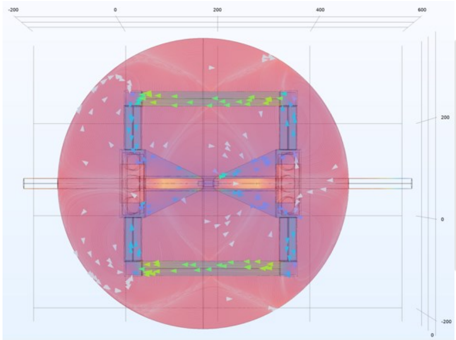


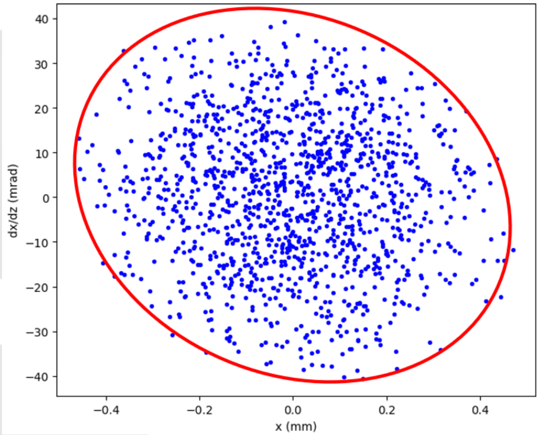

José Crespo

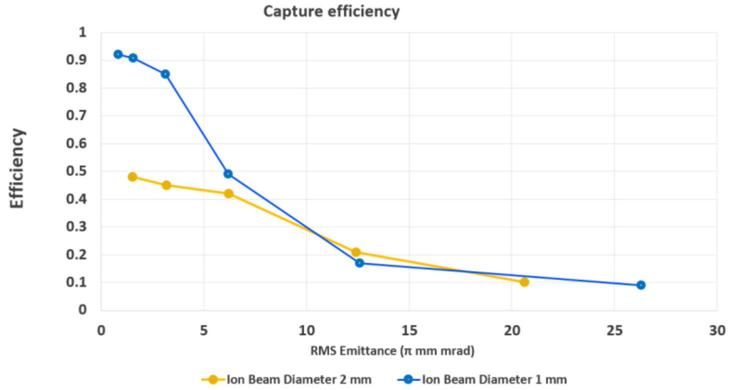

Klaus Blaum

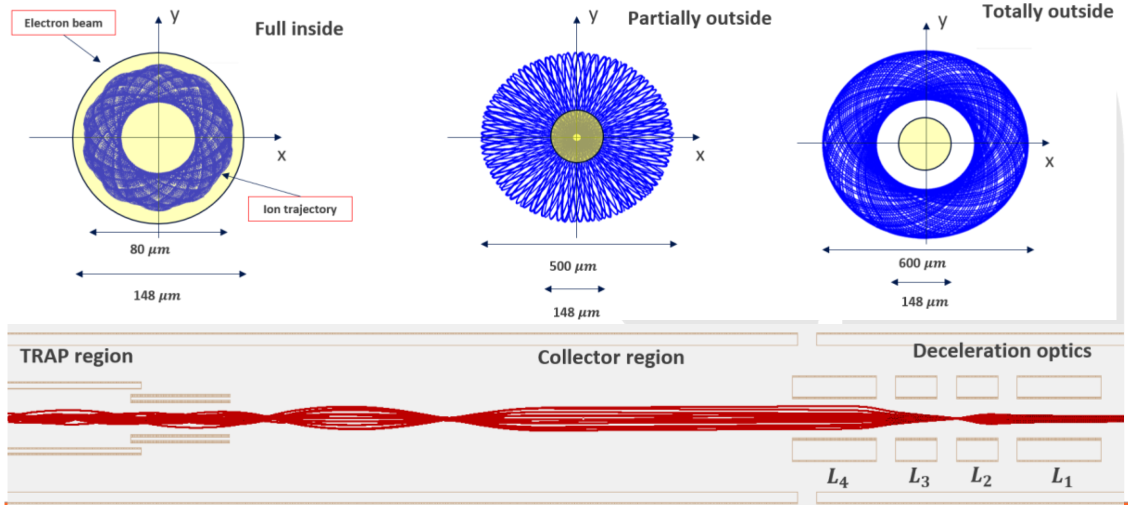


Michele Sguazzin
Postdoc CNRS-in2p3
Oct.2023-present
Mission : Development of highly charged ions physics at DESIR/GANIL









The EBIT acceptance depends on several variables:

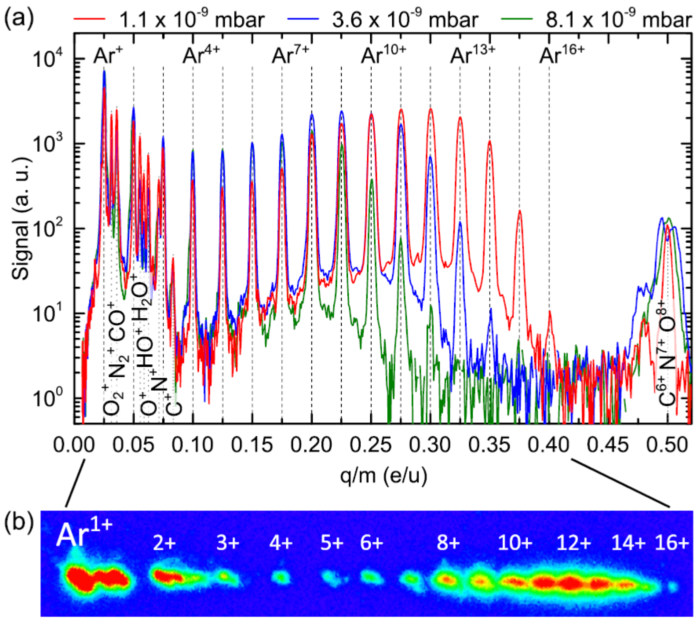
- **electron beam and the magnetic field**
- **Energy of the ion beam before injection 20 keV**

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} : ε_{eff}= 4 · ε_{RMS} = 14.8 π mm·mrad

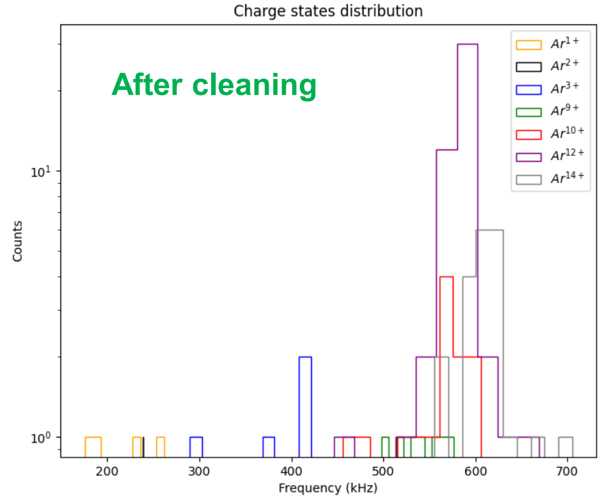
Michele Sguazzin

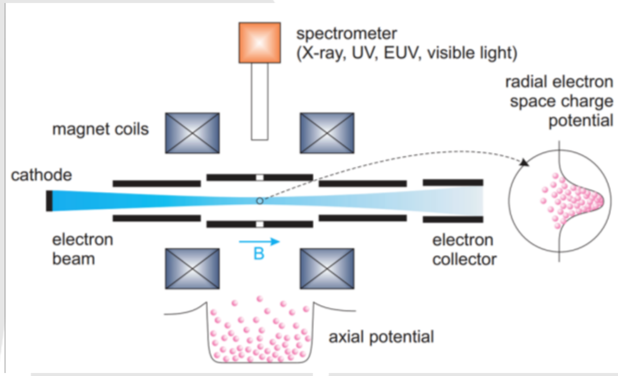
NEW!!



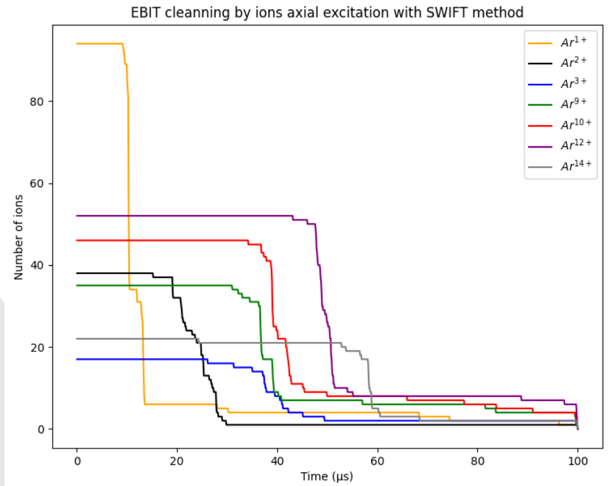
Micke et al, Rev. Sci. Instrum. 89, 063109 (2018):

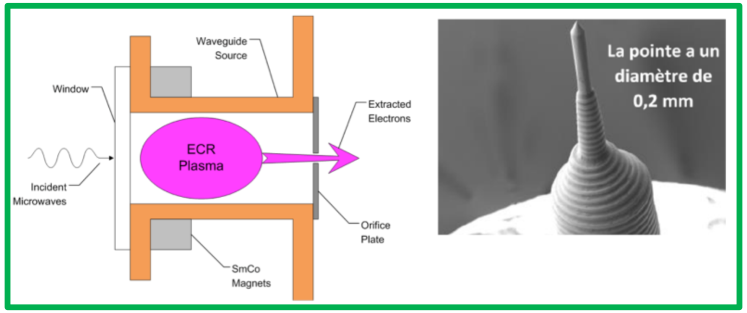
Electron gun operation: 4mA, 2.8keV



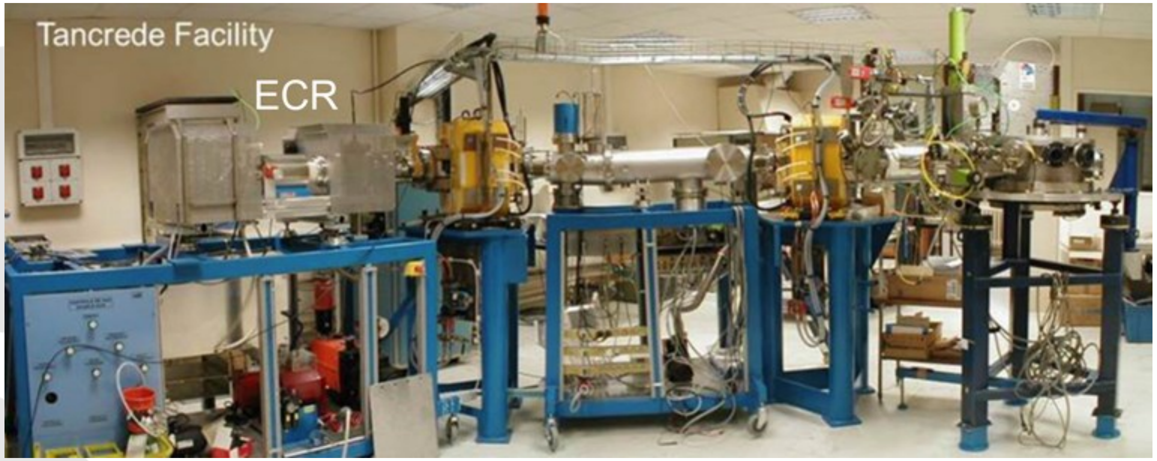


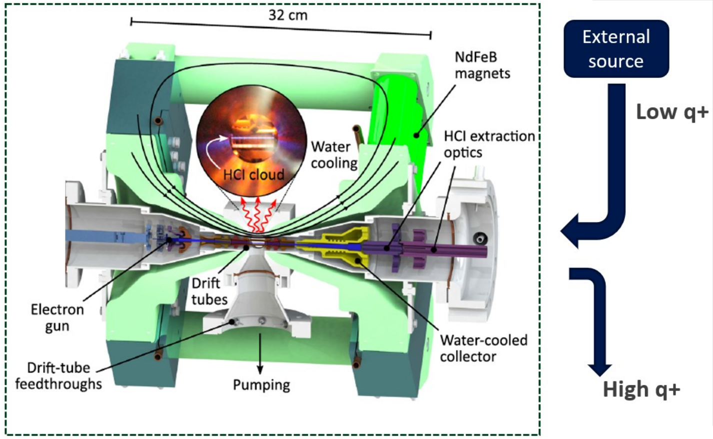
Cleaning: SWIFT method
(Stored Waveform Inverse Fourier Transform)
M. Wiesel, PhD thesis (TUD) 2017

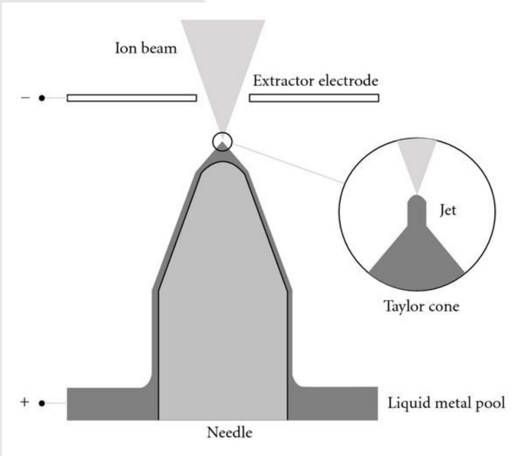




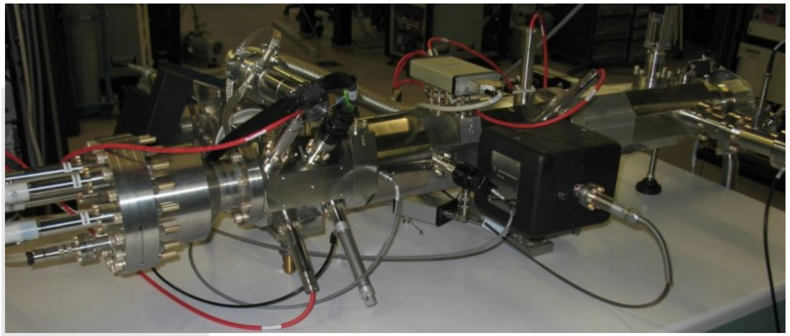
@20keV
ECR ~40 πmm·mrad   LMIS<10 πmm·mrad





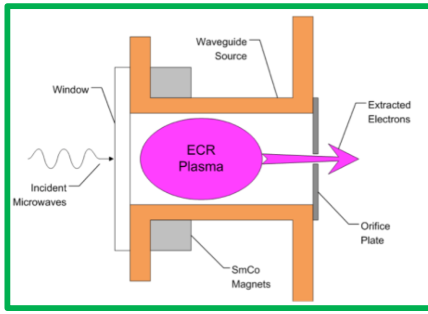


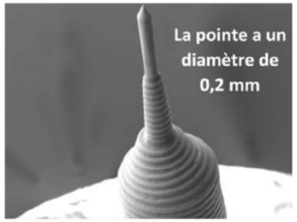
NAPIS (NAParticle Ion Source)
Available at Tancrède/IJCLab



Tools under development

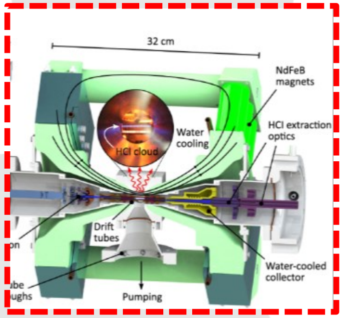
Production (ECR/LMIS) → Charge Breeding → Trapping observation



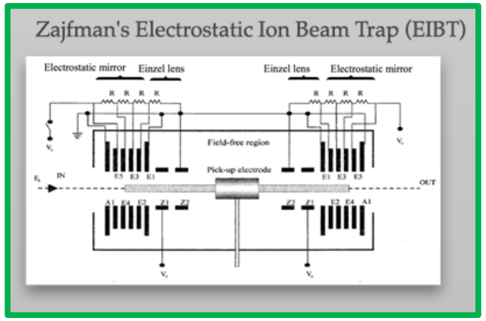


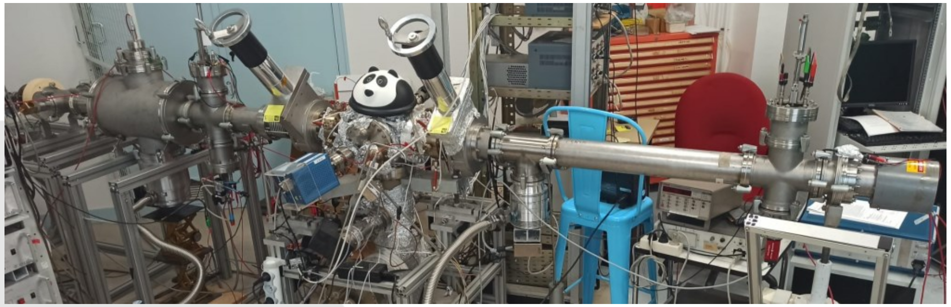
	H-like ion	$I_i^{\pi_i} \to I_f^{\pi_f}$
ECR	^{19}Ne	$\frac{1}{2}^+ \to \frac{1}{2}^+$
	^{37}Ar	$\frac{3}{2}^+ \to \frac{3}{2}^+$
LMIS	^{64}Cu	$1^+ \to 0^+$
	^{68}Ga	$1^+ \to 0^+$

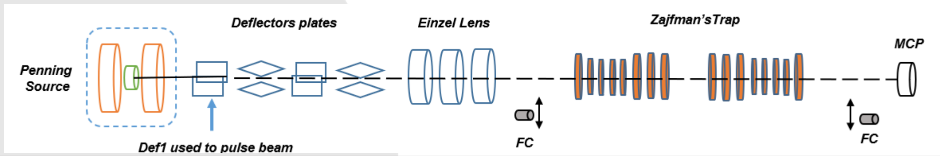
Cu beam is under development



Simulations:
Injection optics
Emittance acceptance
In-trap spectroscopy

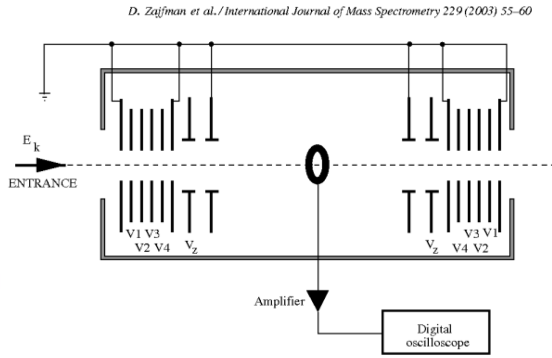






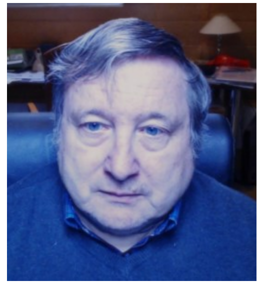
Maroua Benhatchi
PhD student IJCLab/CNRS-in2p3
Dec.2023-present

Mission : Development in-trap decay in Zajfman trap



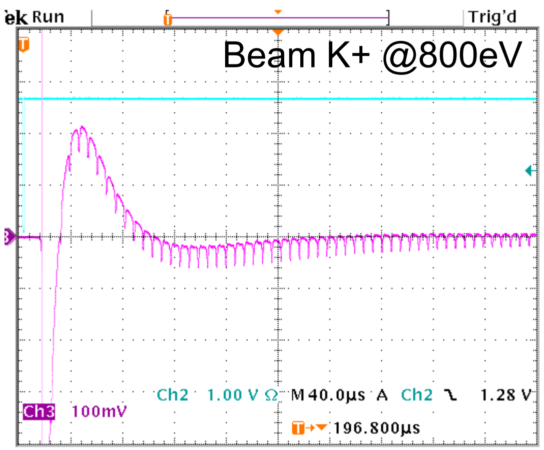
Collaboration with the Max-Planck Institut für Kernphysik (MPIK)

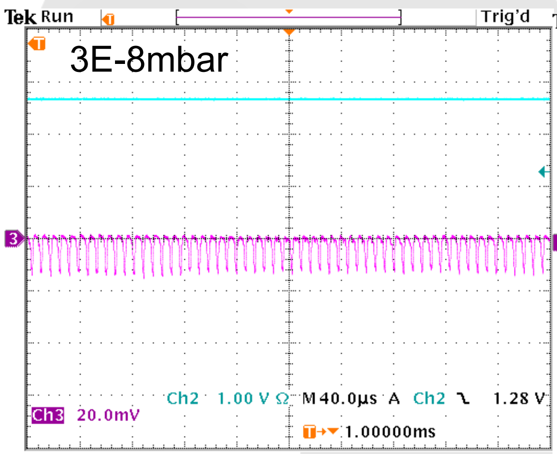
Klaus Blaum

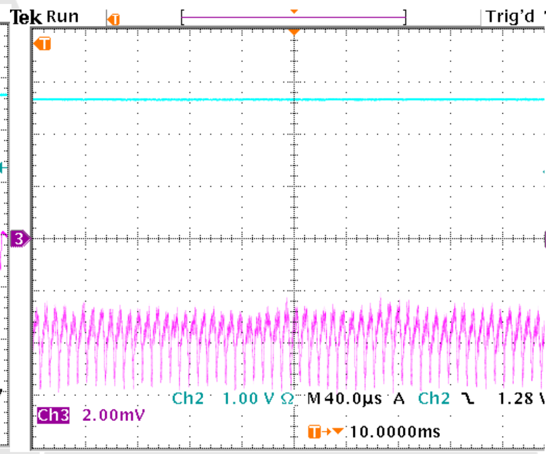


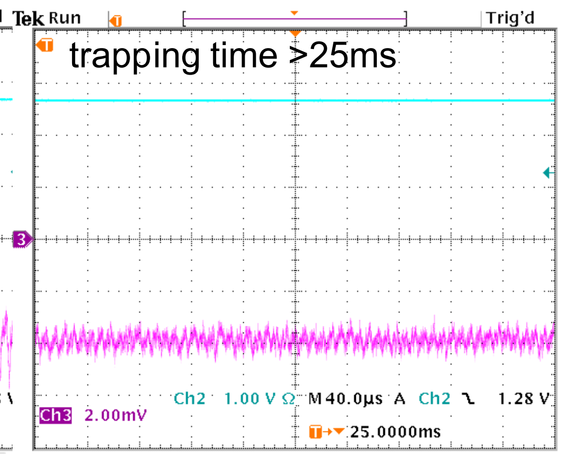
Manfred Grieser

Data analysis ongoing
Electronics DAQ underdevelopment

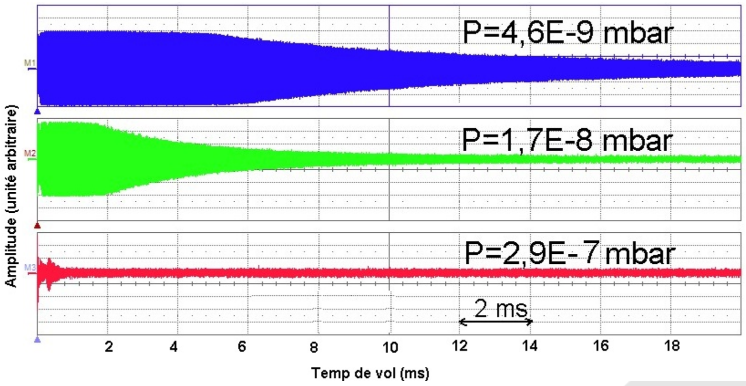


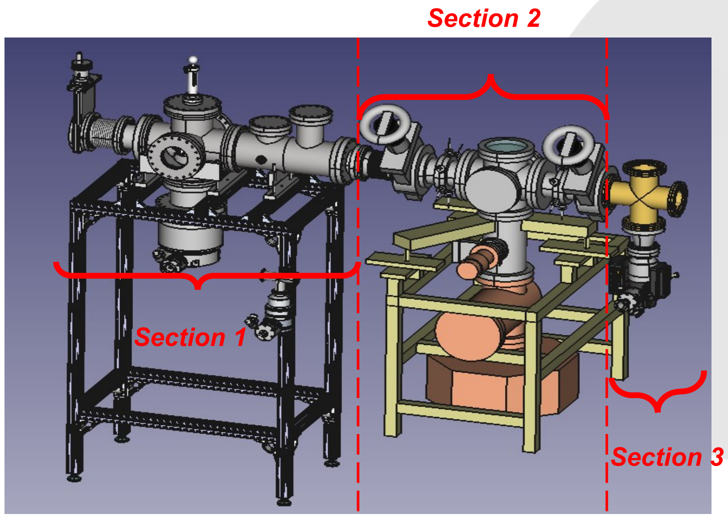


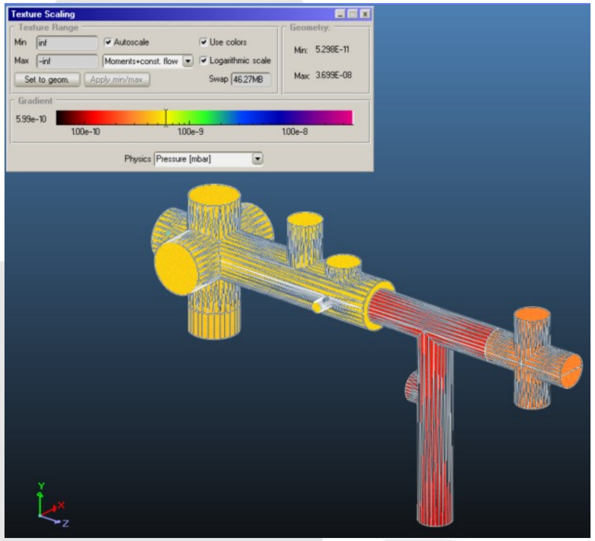




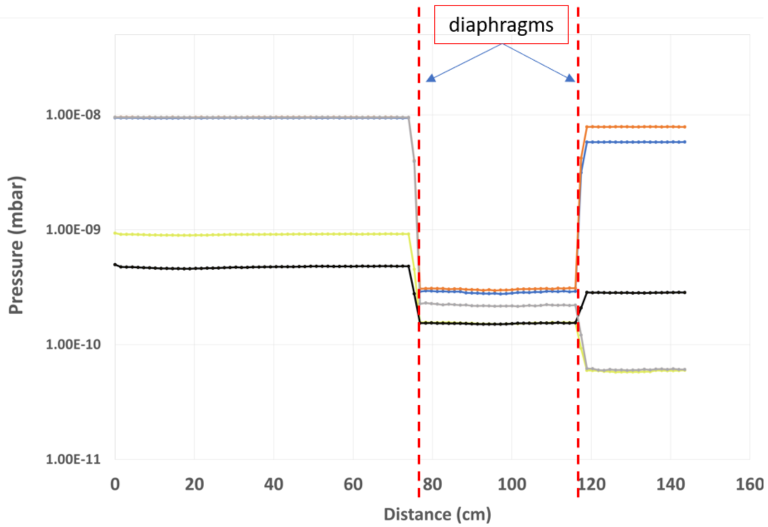
Trapping of A_r^{11+} ions @LKB

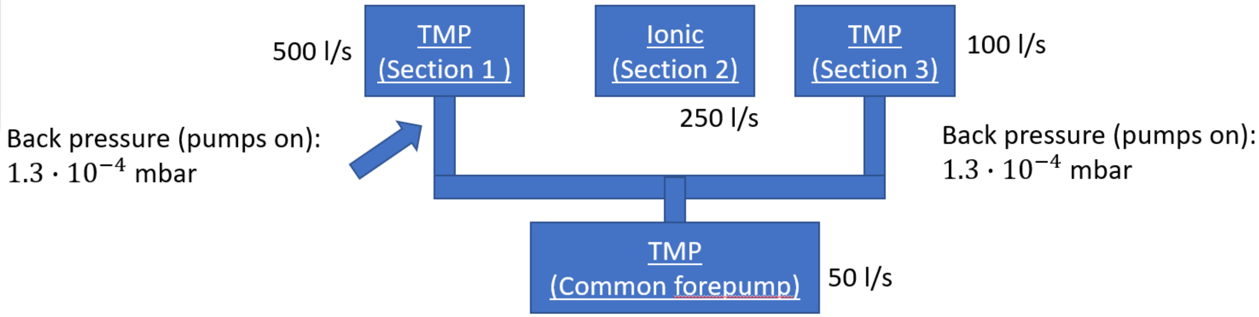


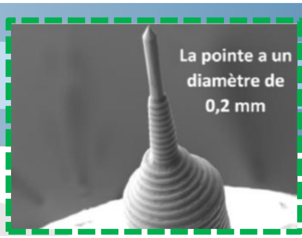


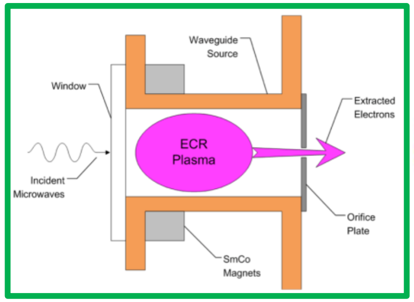


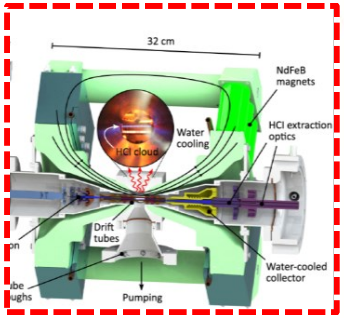
Partial pressure of H_2

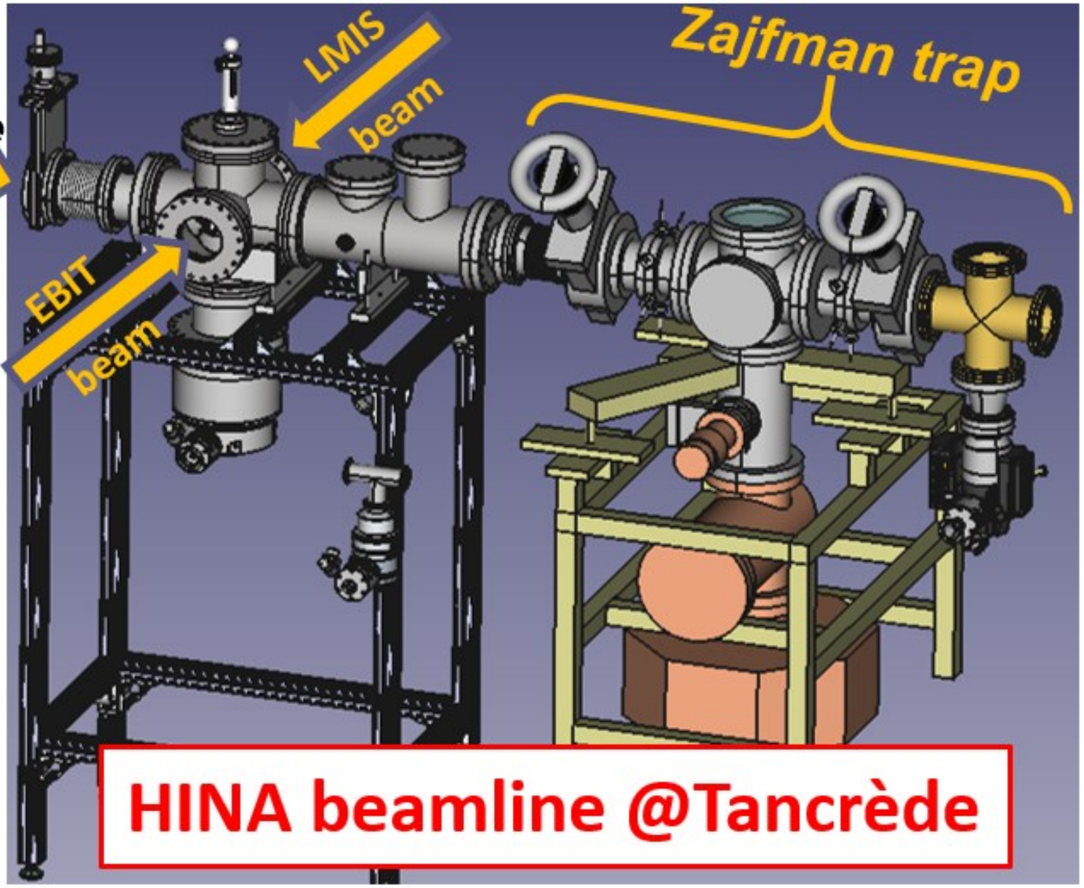












Experimental setup at IJClab:

Validation of production and trapping of HCIs

université PARIS-SACLAY

ERM24
IJCLab

HINA and her followers

Researchers


Serge Della Negra


Sarah Naimi


Vladimir Manea

David Lunney

Karl Hauschild

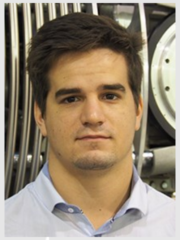

Maroua Benhatchi


Michele Sguazzin

Engineering


Isabelle Ribaud


Denis Reynet


François Daubisse


Alexandre Migayron


Bruno MERCIER


Jihan Maalmi

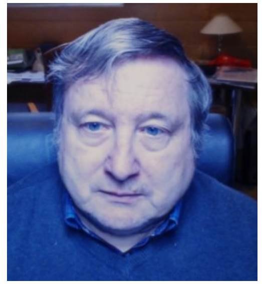
Dominique Breton


Philippe GAURON

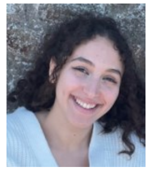
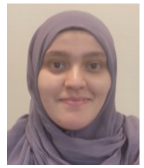
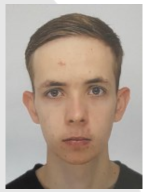
External collaborators (MPIK)


José Crespo


Klaus Blaum

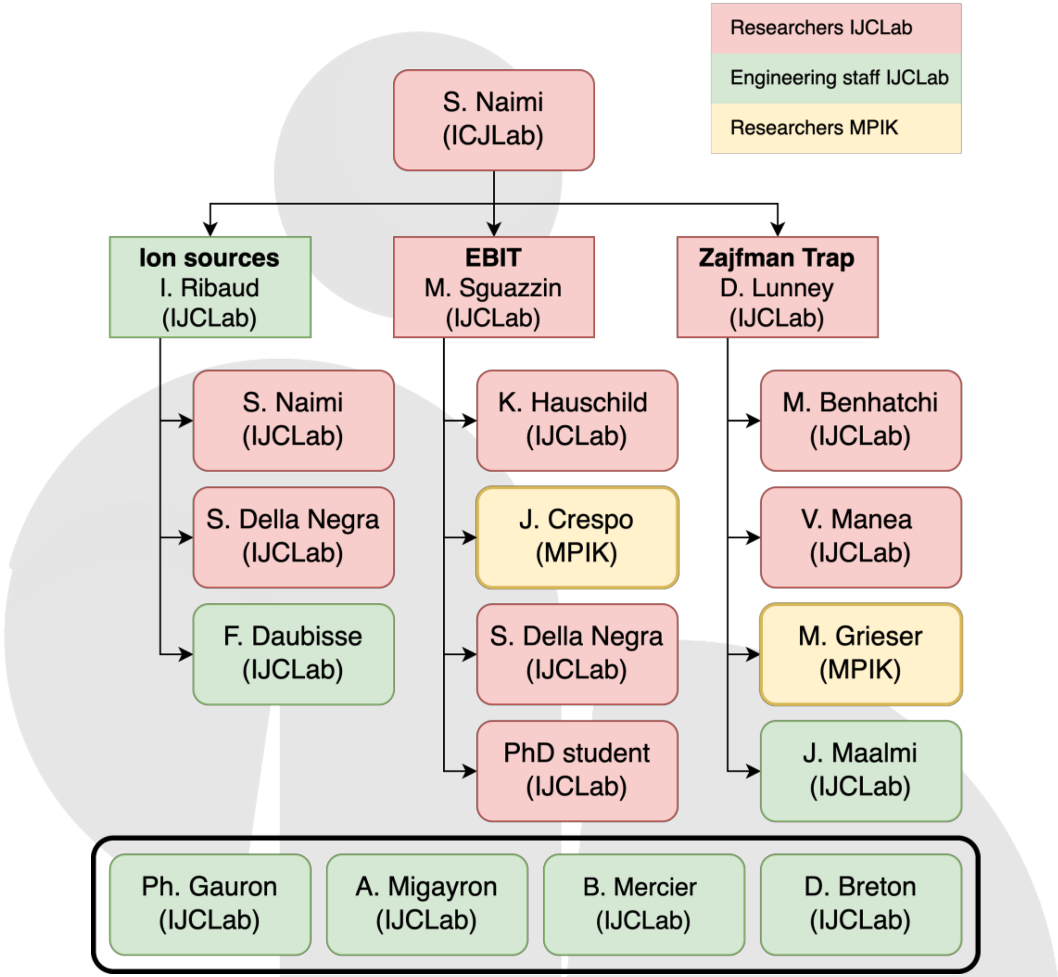

Manfred Grieser

Master/Bachelor students

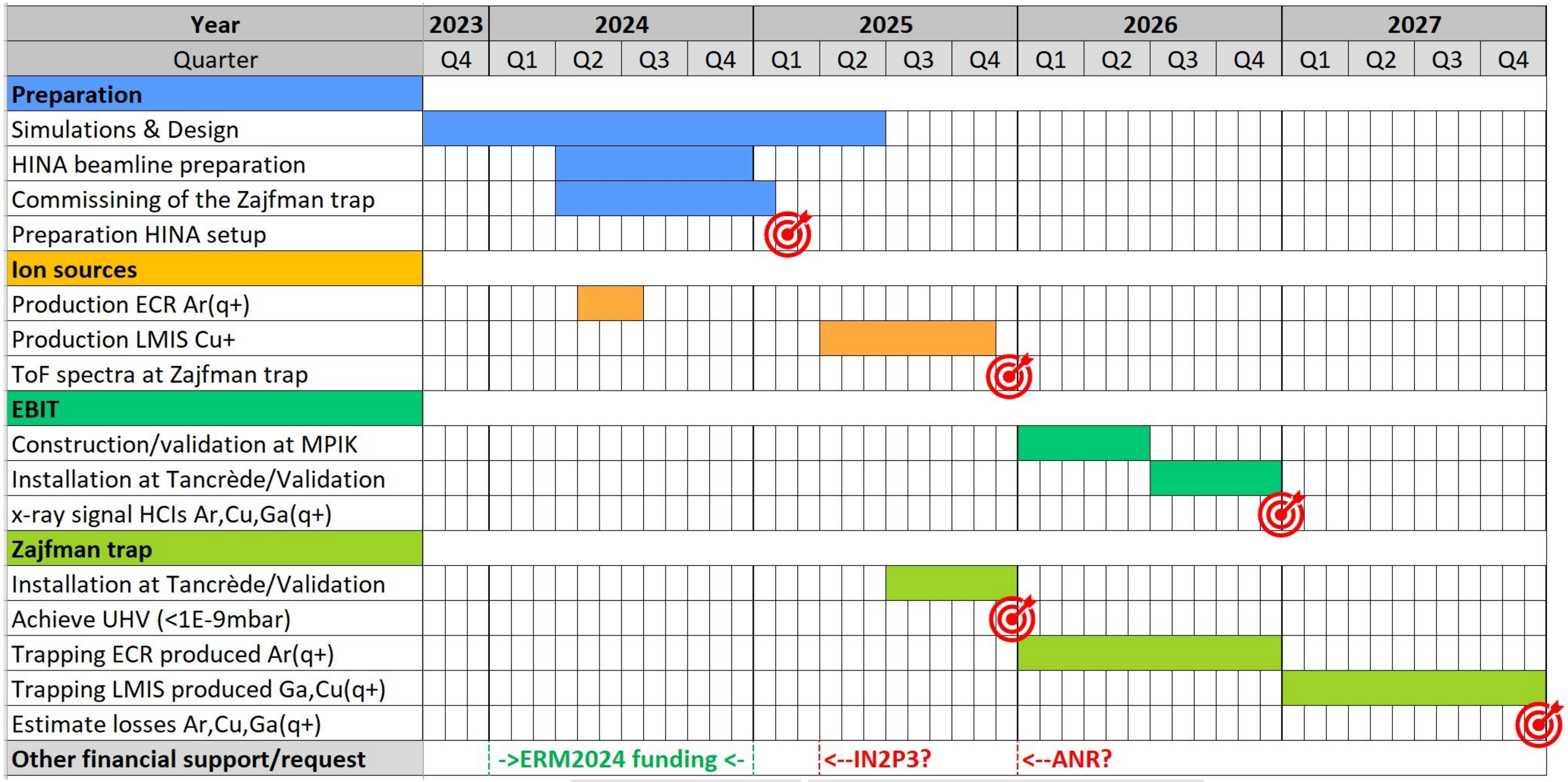






Sophie, Amelle, Sarah
Damien, Maxime

HINA project R&D working groups

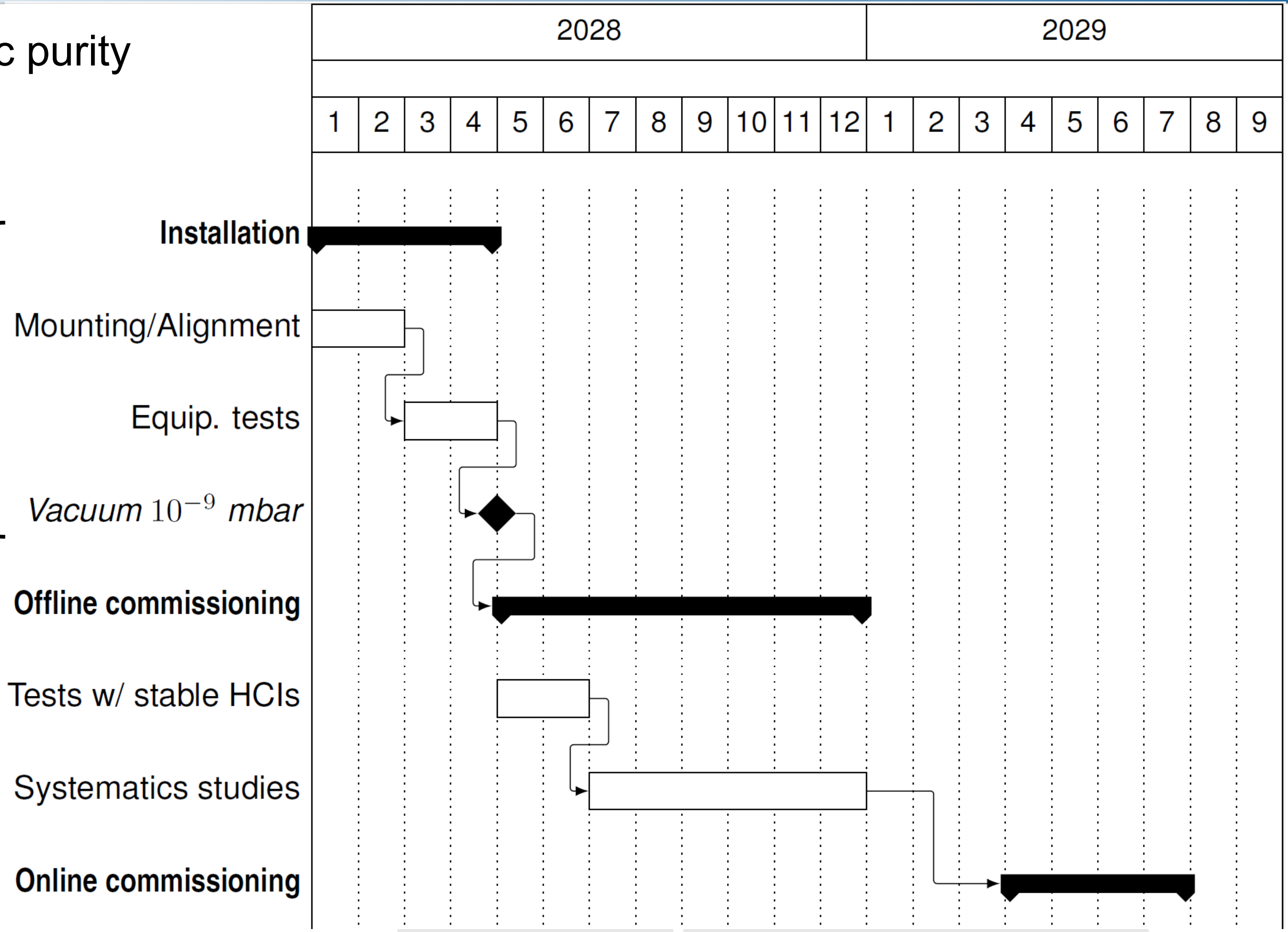


HINA plan @IJCLab



Requirement: isobaric purity

Technical support needed @GANIL (not full time!)



H-like ion	$I_i^{\pi_i} \rightarrow I_f^{\pi_f}$
^{19}Ne	$\frac{1}{2}^+ \rightarrow \frac{1}{2}^+$
^{37}Ar	$\frac{3}{2}^+ \rightarrow \frac{3}{2}^+$
^{64}Cu	$1^+ \rightarrow 0^+$
^{68}Ga	$1^+ \rightarrow 0^+$

Scientific interest

François de oliveira
GANIL

Postdoc & PhD student @GANIL

Some key numbers

Isobaric purification:

$^{19}F\ /^{19}Ne\ ^{\delta m}/_{m} \approx 5{,}000$

$^{37}Ar\ /^{37}Cl\ ^{\delta m}/_{m} \approx 42{,}000$

$^{64}Cu\ /^{64}Ni\ ^{\delta m}/_{m} \approx 35{,}000$

$^{68}Ga\ /^{68}Zn\ ^{\delta m}/_{m} \approx 22{,}000$

Yield:

^{19}Ne production @SPIRAL1 LEB: $1.8 \cdot 10^{8}$pps

^{37}Ar estimate @SPIRAL1 LEB: $9.1 \cdot 10^{7}$ pps

^{64}Cu estimate @SPIRAL1 LEB: $4 \cdot 10^{6}$ pps

^{68}Ga production @SPIRAL1 LEB: $9.4 \cdot 10^{5}$pps

Emittance acceptance HINA @30keV:

HINA exp. $\varepsilon_{RMS} \approx 3\ \pi$ mm·mrad

DESIR-GPIB $\varepsilon_{RMS} \approx 1.2\ \pi$ mm·mrad

Bunched mode:

DESIR-GPIB: 10^5 ions/bunch

Efficiency 0.1 for $^{19}Ne\ (T_{1/2} = 17s)$

--> 10 events in 25ms

-->100 events in 250ms

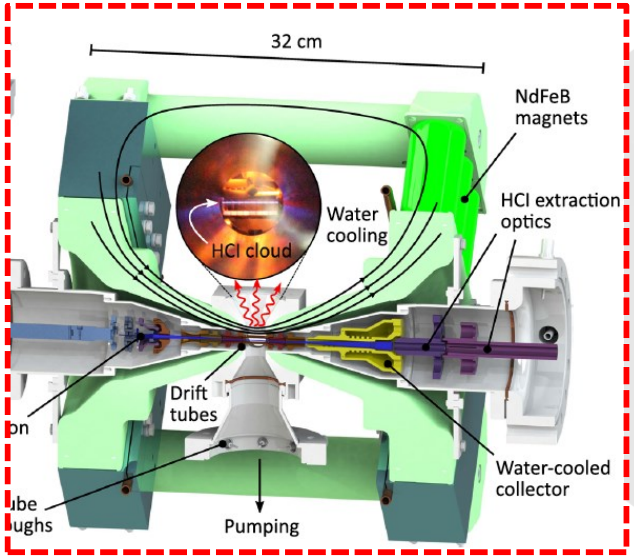
Others:

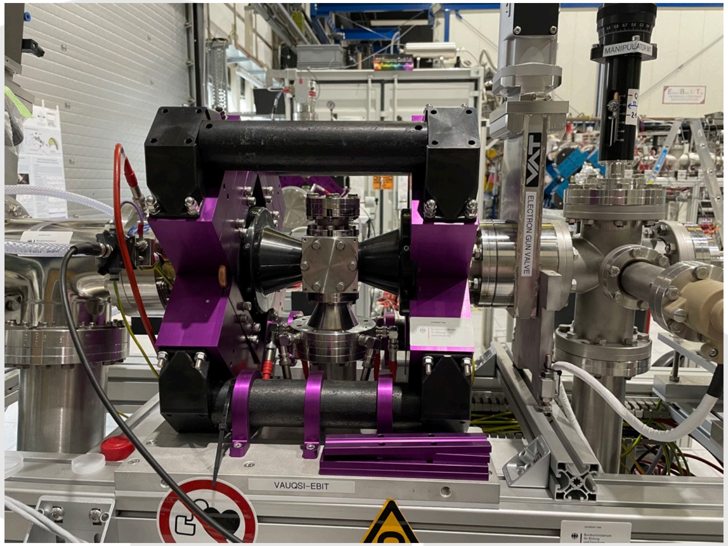
HV platform

Cooling water

Year	2025-2026	2027	2028-2029	Total (k€)
Equipments (k€)	223.5	0	0	223.5
Consumables (k€)	0	8	20	28
Postdoc (k€)	0	0	150	150
Total/an (k€)	223.5	8	170	**401.5**

+travel fees for a researcher from IJCLab





Other financial support:
2024: Paris-Saclay University
2024-2025: IJCLab