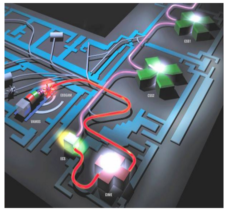
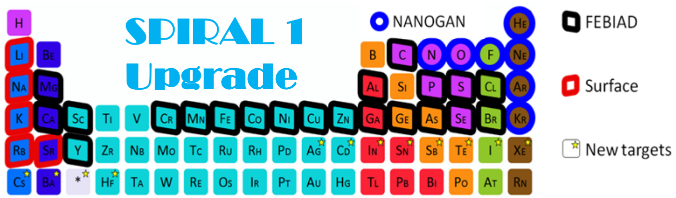
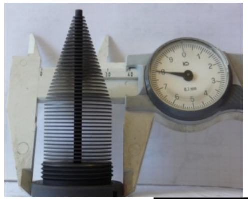
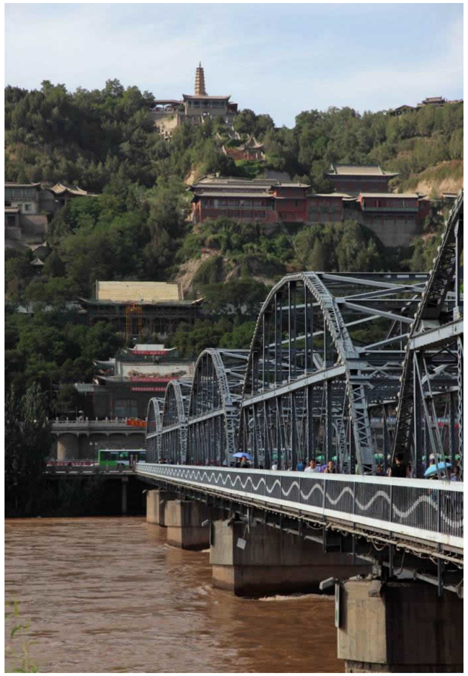






Trends and challenges in Radioactive Ion Beam processes



P. Delahaye, GANIL

HIAT2018
14th International Conference on Heavy Ion Accelerator Technology

GANIL – SPIRAL2 facility

Neutron for Science experimental area
Up to 30 MeV n

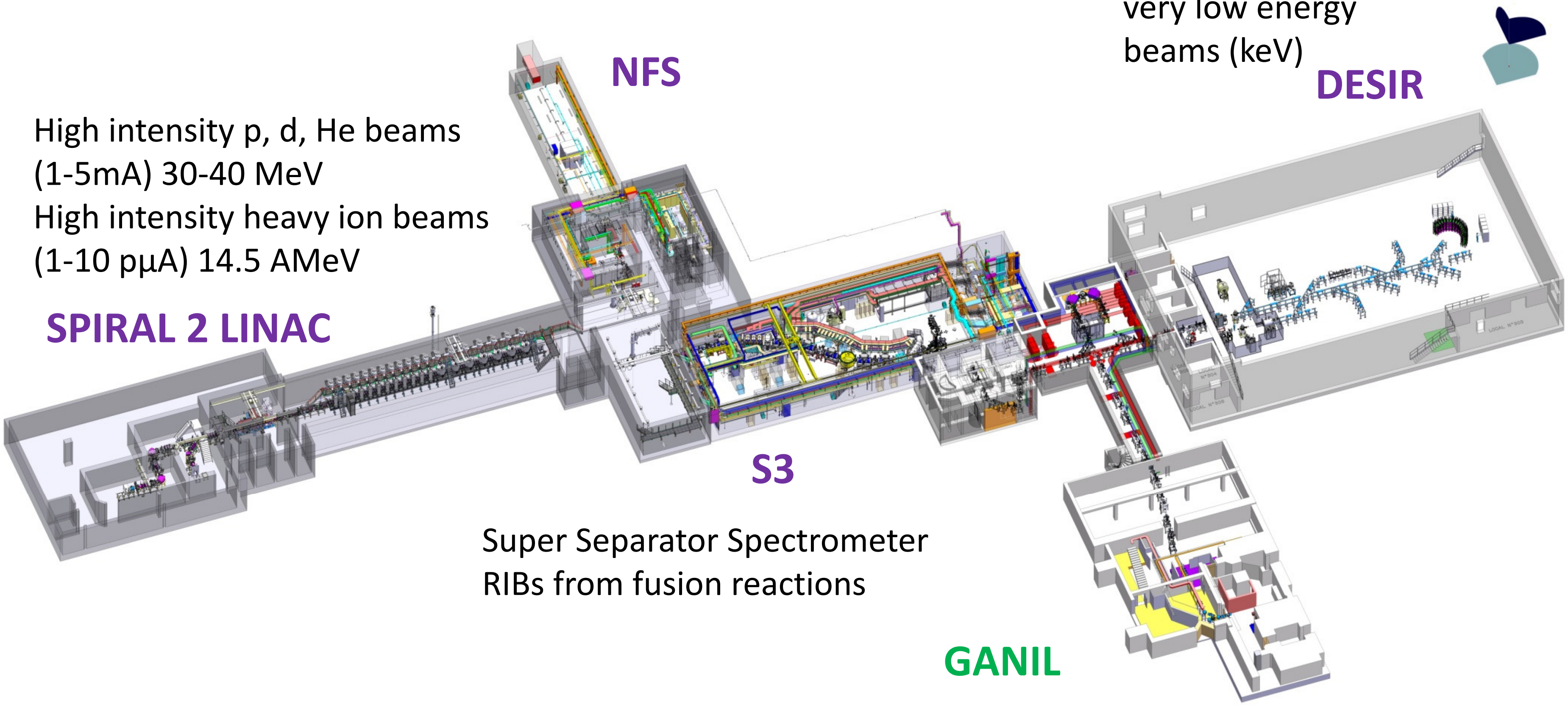
NFS

Experimental hall for
very low energy
beams (keV)

DESIR

High intensity p, d, He beams
(1-5mA) 30-40 MeV
High intensity heavy ion beams
(1-10 pμA) 14.5 AMeV

SPIRAL 2 LINAC



S3

Super Separator Spectrometer
RIBs from fusion reactions

GANIL

Experimental areas and cyclotrons
SPIRAL 1 facility

RIB production mechanisms and processes

- Spectroscopy and reaction with exotic isotopes on both sides of the valley of stability
  - Multiple reaction mechanisms

Fission of actinide targets using
•Photons (ALTO et TRIUMF/ARIEL)
•neutrons (SPIRAL 2 phase 2)
•Protons 1.4 GeV (ISOLDE)
•Protons 600 MeV (TRIUMF)
•Protons 70 MeV (SPES)

Fragmentation
• Heavy ions 70-95 MeV/A (GANIL-SPIRAL 1)

Fusion evaporation
•Heavy ions of a few MeV/A (SPIRAL 2-S3)

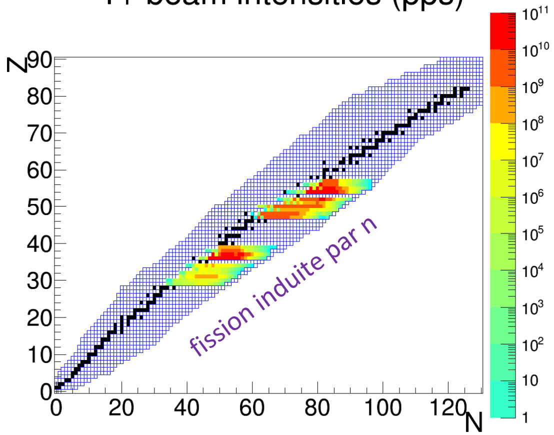
Spallation
•protons à 1.4 GeV à ISOLDE
•Protons à 600 MeV à TRIUMF

Transfer, Capture, Charge exchange reactions with light particules
•ALTO, SPIRAL 2 phase 2
Etc.

Exemples: estimations d'intensités 1+ pour SPIRAL 1 et 2

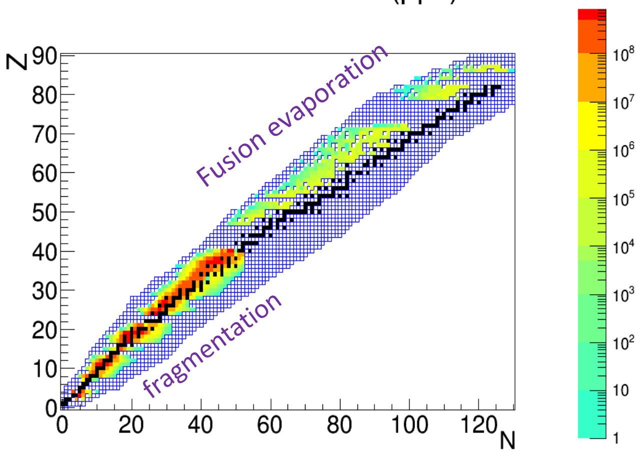
fission @ SPIRAL 2

1+ beam intensities (pps)



fragmentation d'ions lourds et fusion evaporation @ SPIRAL 1

1+ beam intensities (pps)



- Multiples processes
  - Proton, deuton→neutrons, électrons→photons converters
  - Multiple target materials: carbides, oxides, refractory metals, liquid targets…
  - Gas cell technique (ex: S3-LEB)
  - Multiples ionisation techniques: ECRIS, FEBIAD, surface ionisation, Laser resonant ionisation
  - Multiples separation techniques: chemical, laser resonant ionisation, separators etc.

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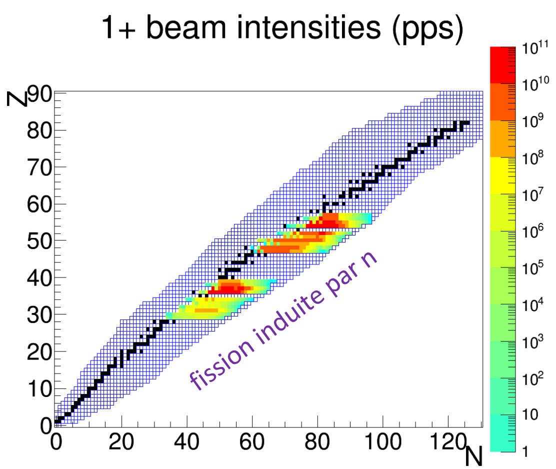
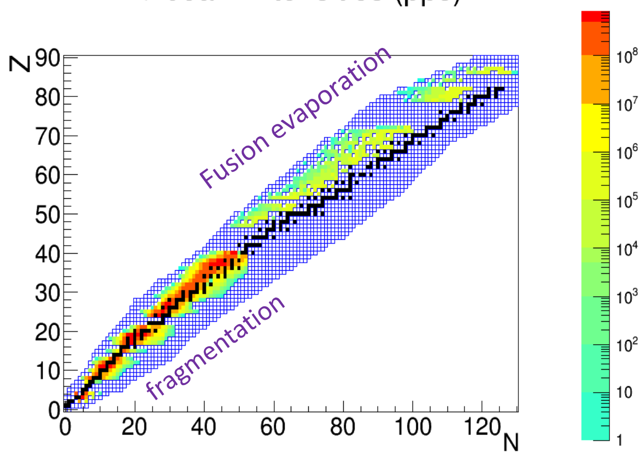


fragmentation d'ions lourds et fusion evaporation @ SPIRAL 1



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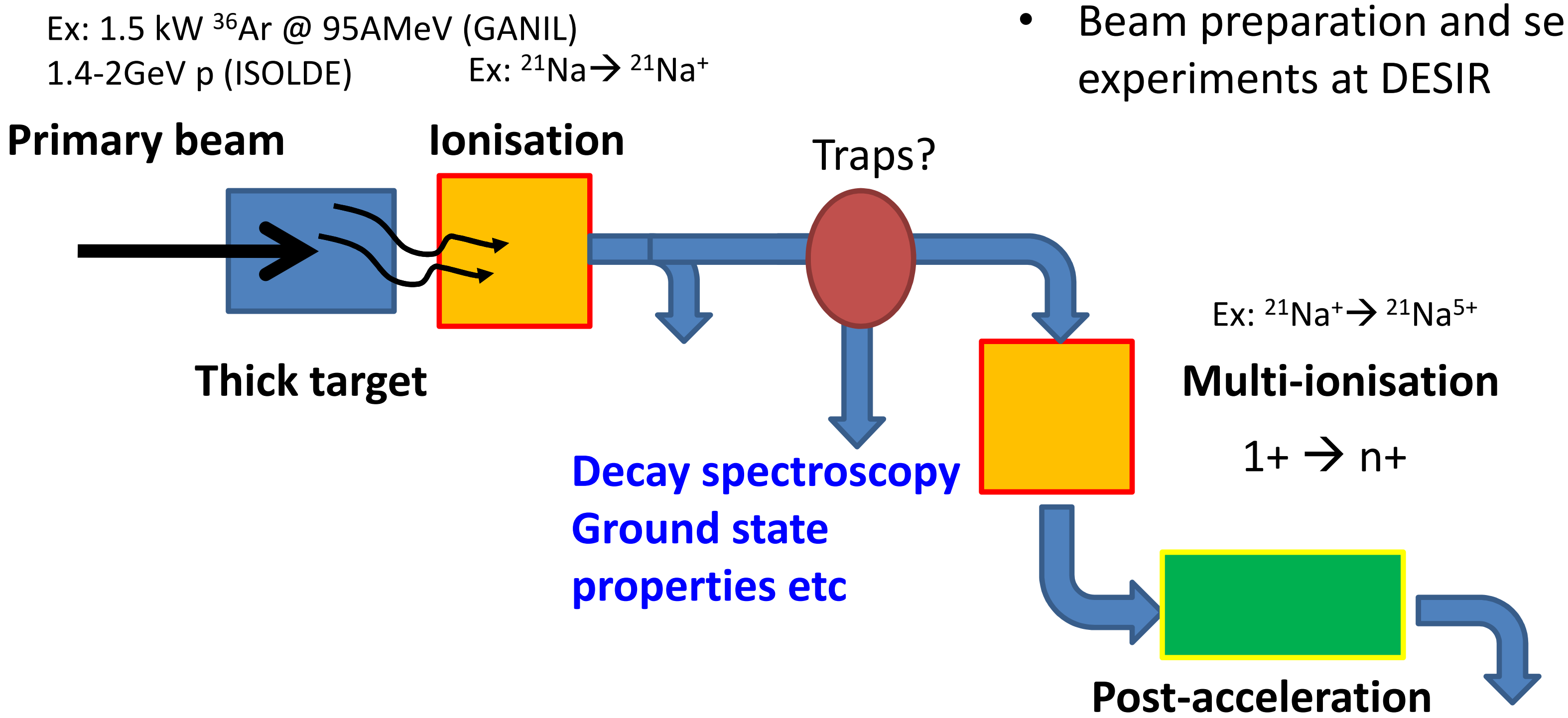

Many places to get contaminated
Many places to be selective and purify the beams!

Excited states, reaction mechanisms, nuclear astrophysics

…

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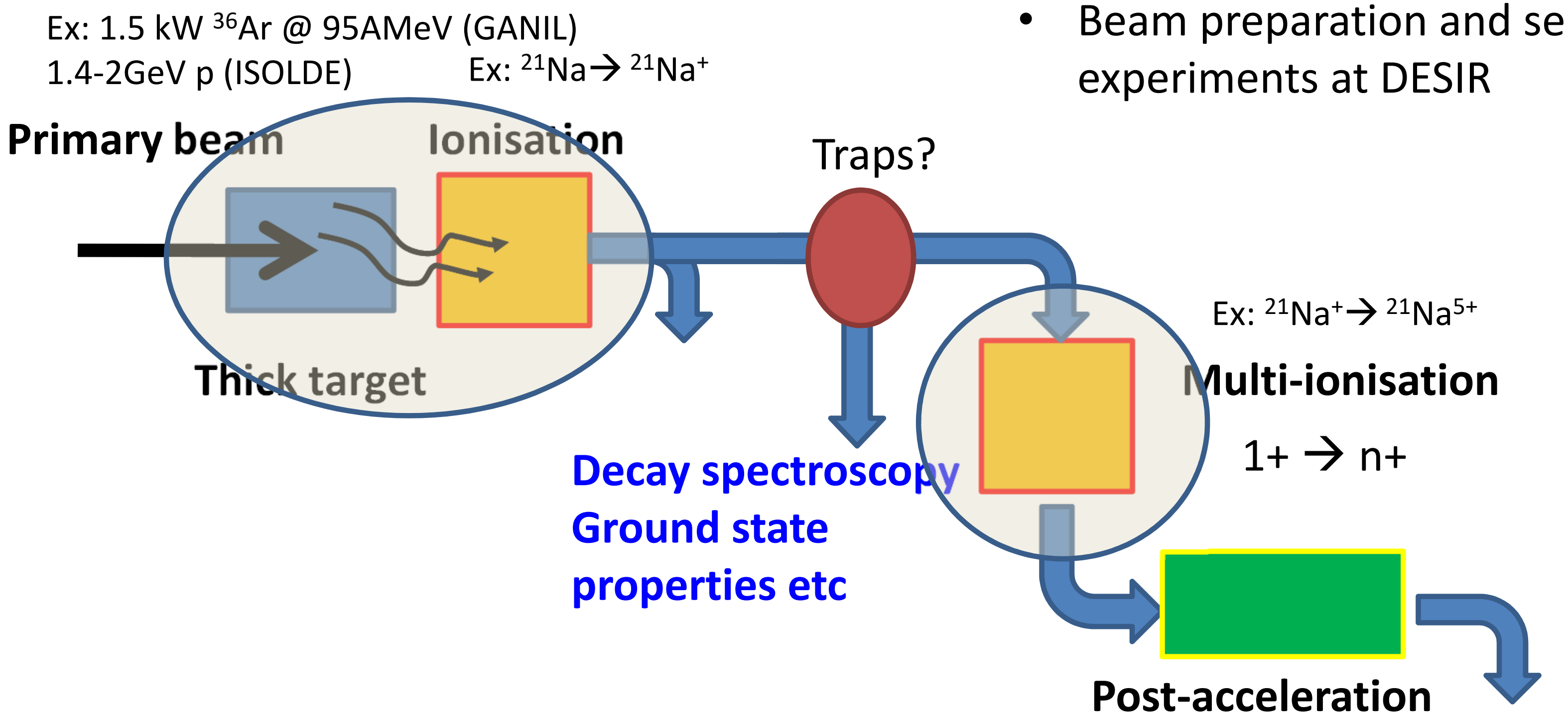

Excited states, reaction mechanisms, nuclear astrophysics

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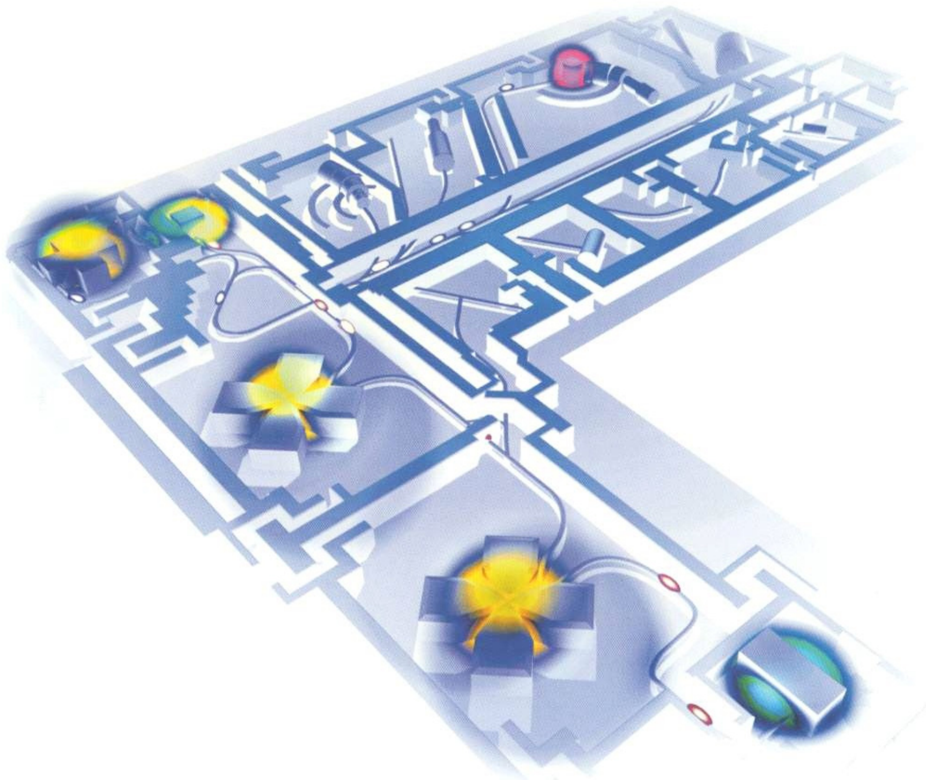
Many places to get contaminated
Many places to be selective and purify the beams!

Reaccelerated radioactive ion beams at SPIRAL 1

Since 2001!

Isotope Separation On Line (ISOL) technique at GANIL

Heavy ion fragmentation on graphite targets



^{12}C to ^{86}Kr up to 95AMeV

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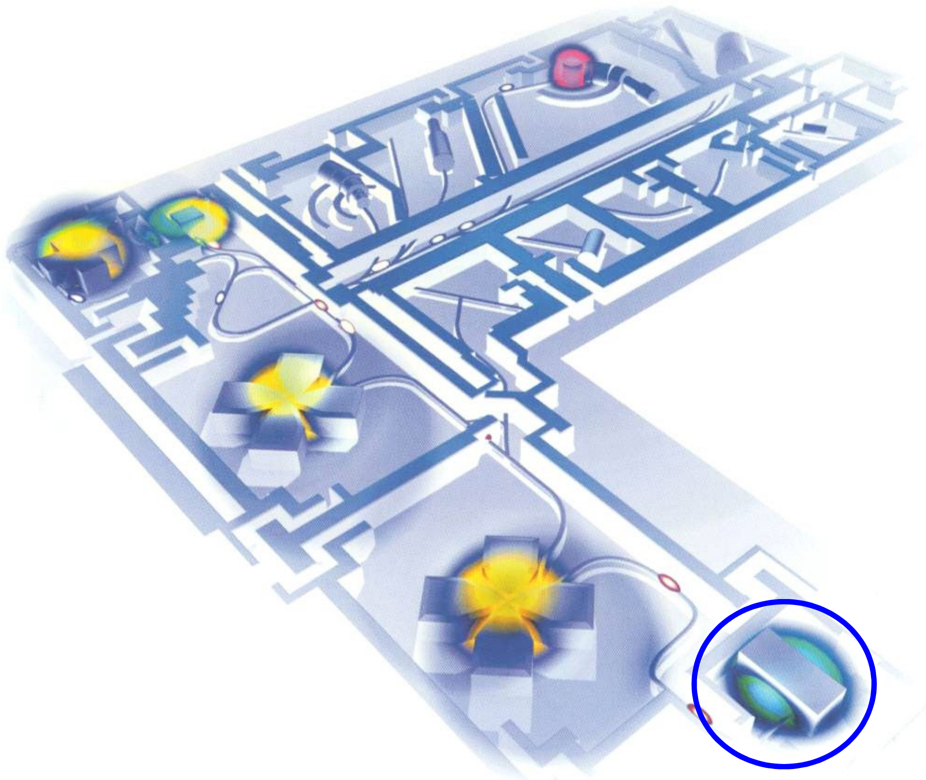

Heavy ion sources

^{12}C to ^{86}Kr up to 95AMeV

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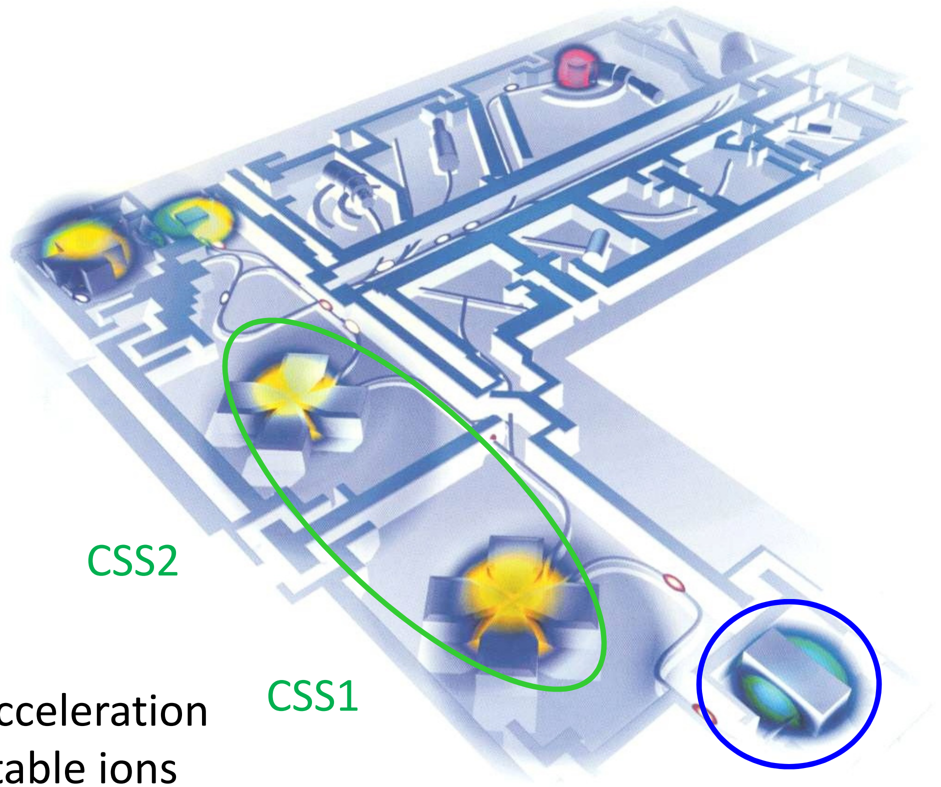

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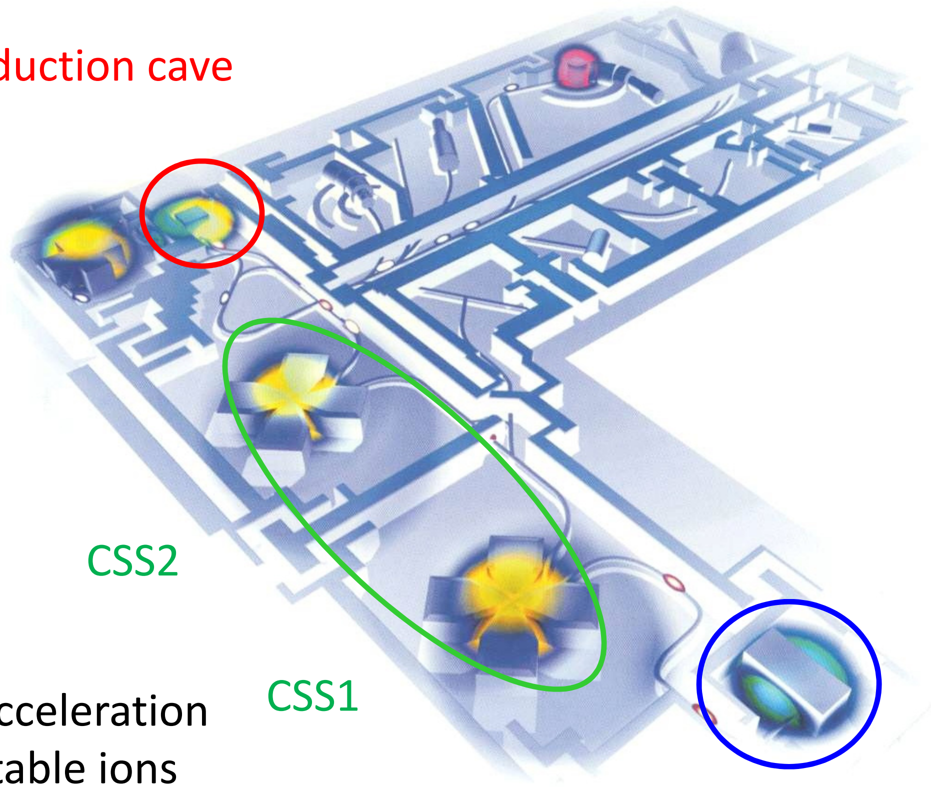

Targets

He

Ne, Ar, Kr, N, O, F

^{12}C to ^{86}Kr up to 95AMeV

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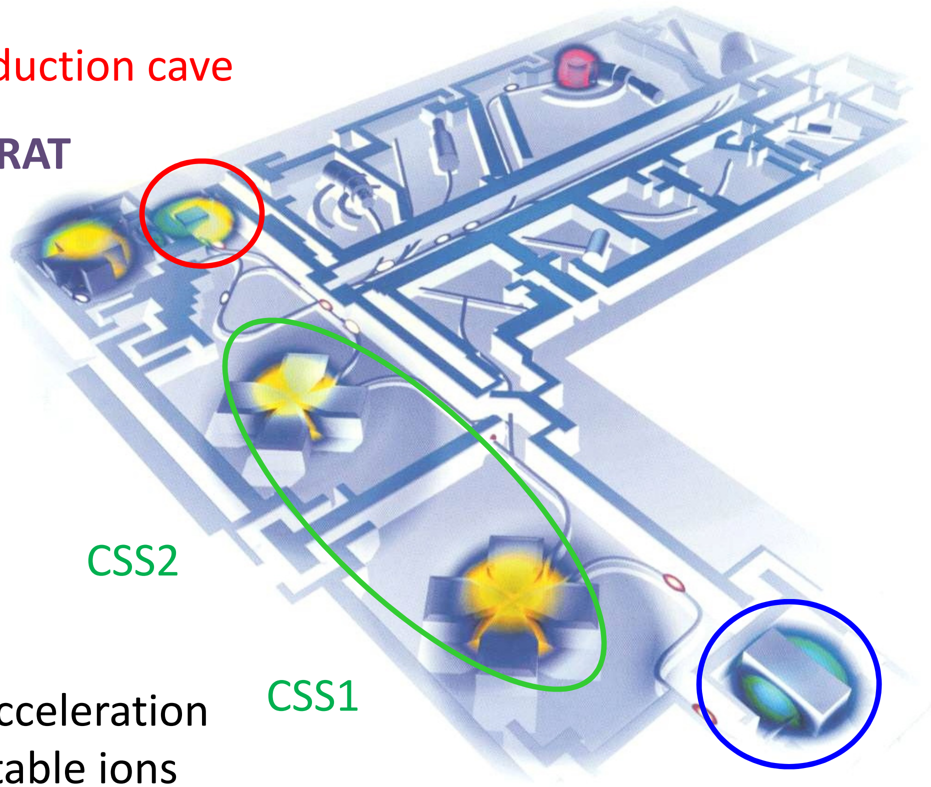

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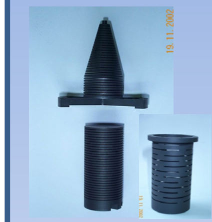

3 kW

He

1,5 kW

Ne, Ar, Kr, N, O, F

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Reaccelerated radioactive ion beams at SPIRAL 1

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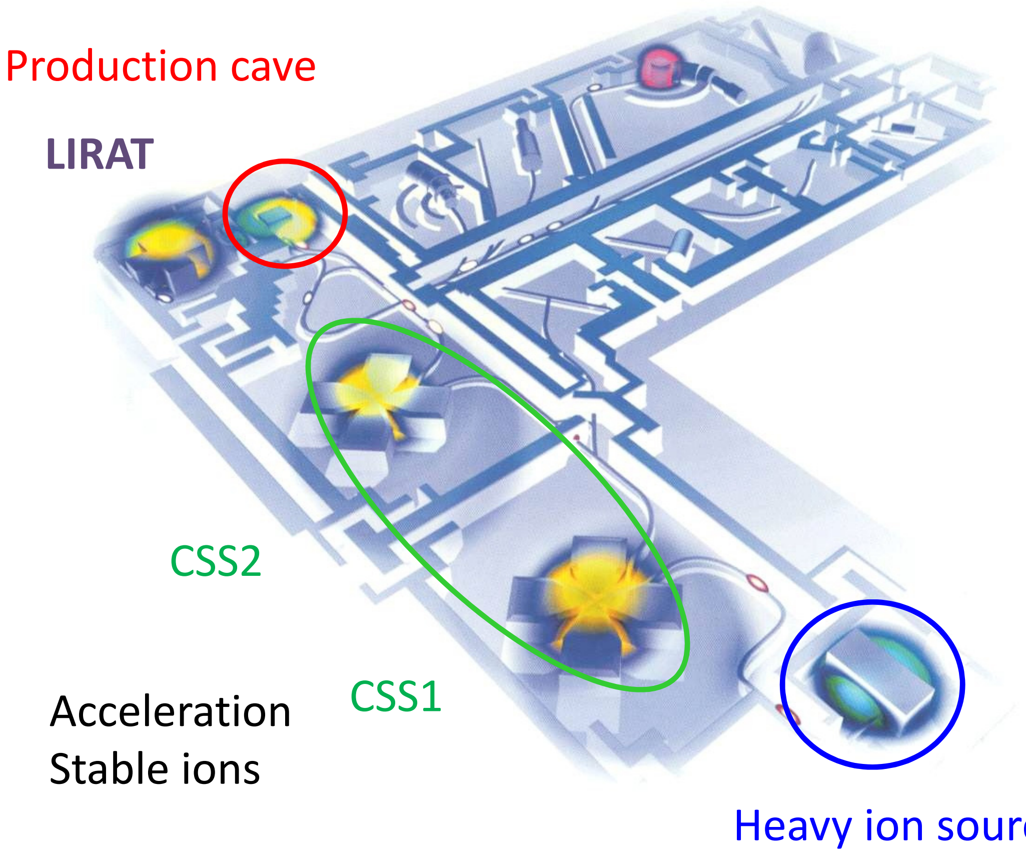

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Reaccelerated radioactive ion beams at SPIRAL 1

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Heavy ion fragmentation on graphite targets

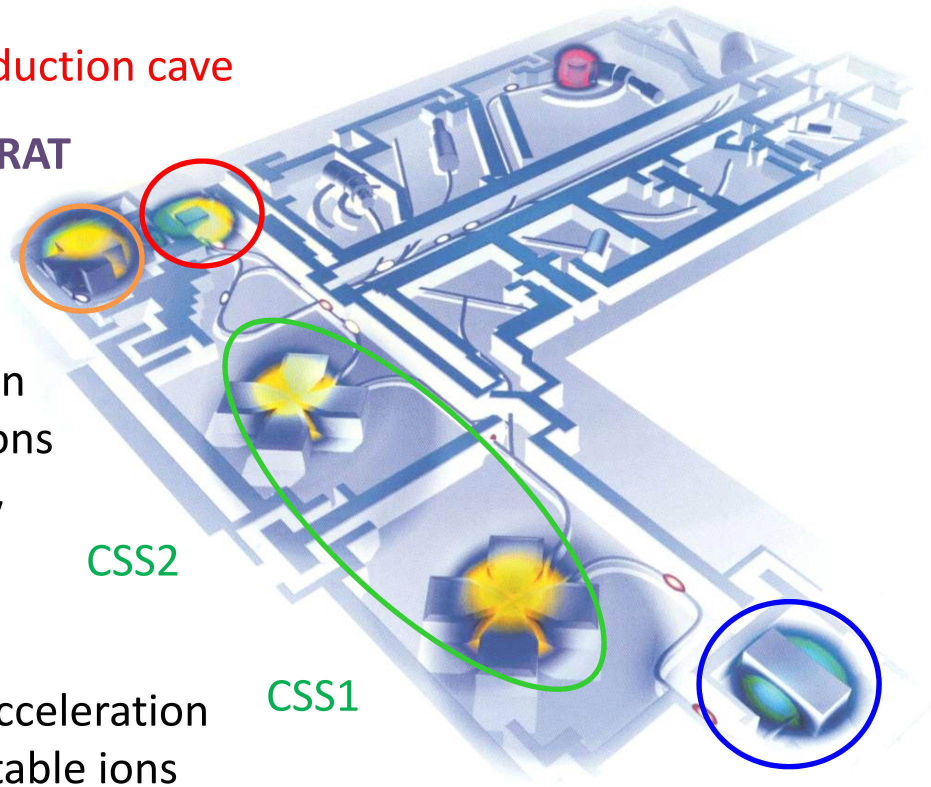
Production cave

LIRAT

CIME

Post-acceleration
Of radioactive ions

Up to 20 AMeV

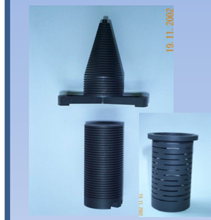


Acceleration
Stable ions

Heavy ion sources

^{12}C to ^{86}Kr up to 95AMeV

Targets



3 kW

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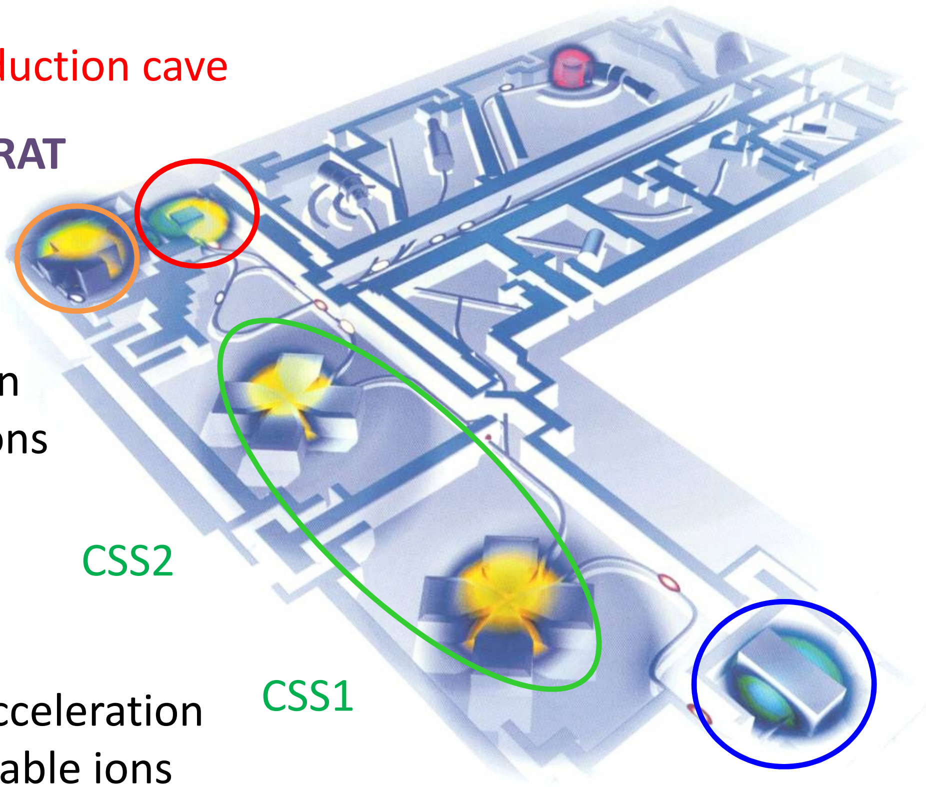


Production cave

LIRAT

CIME

Post-acceleration
Of radioactive ions

Up to 20 AMeV

CSS2

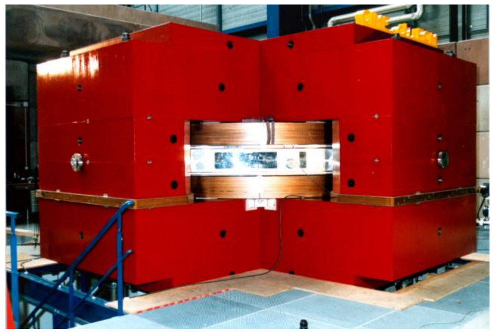
CSS1

Acceleration
Stable ions

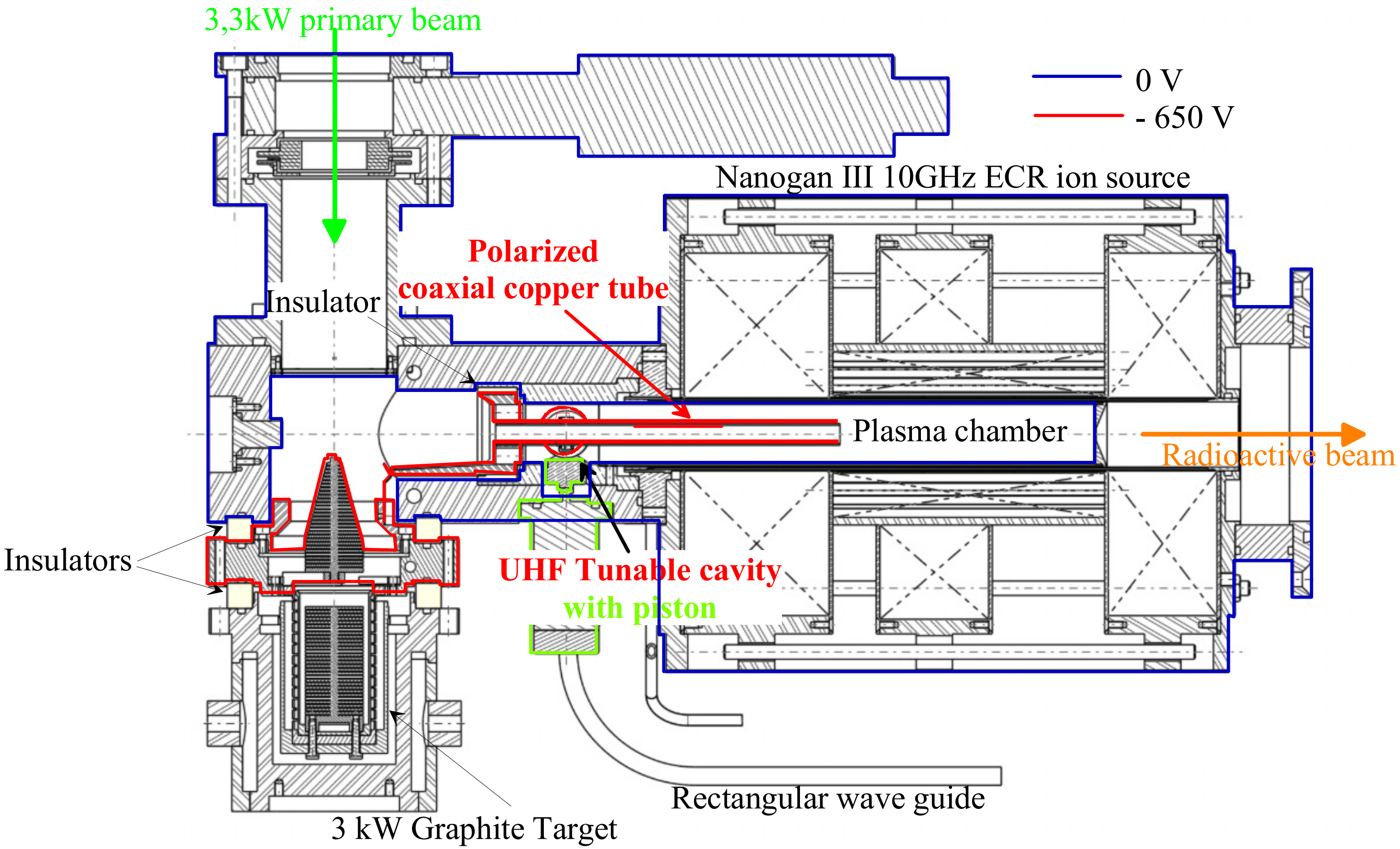
Heavy ion sources

^{12}C to ^{86}Kr up to 95AMeV

CIME:
« Cyclotron d'ions de moyenne énergie »



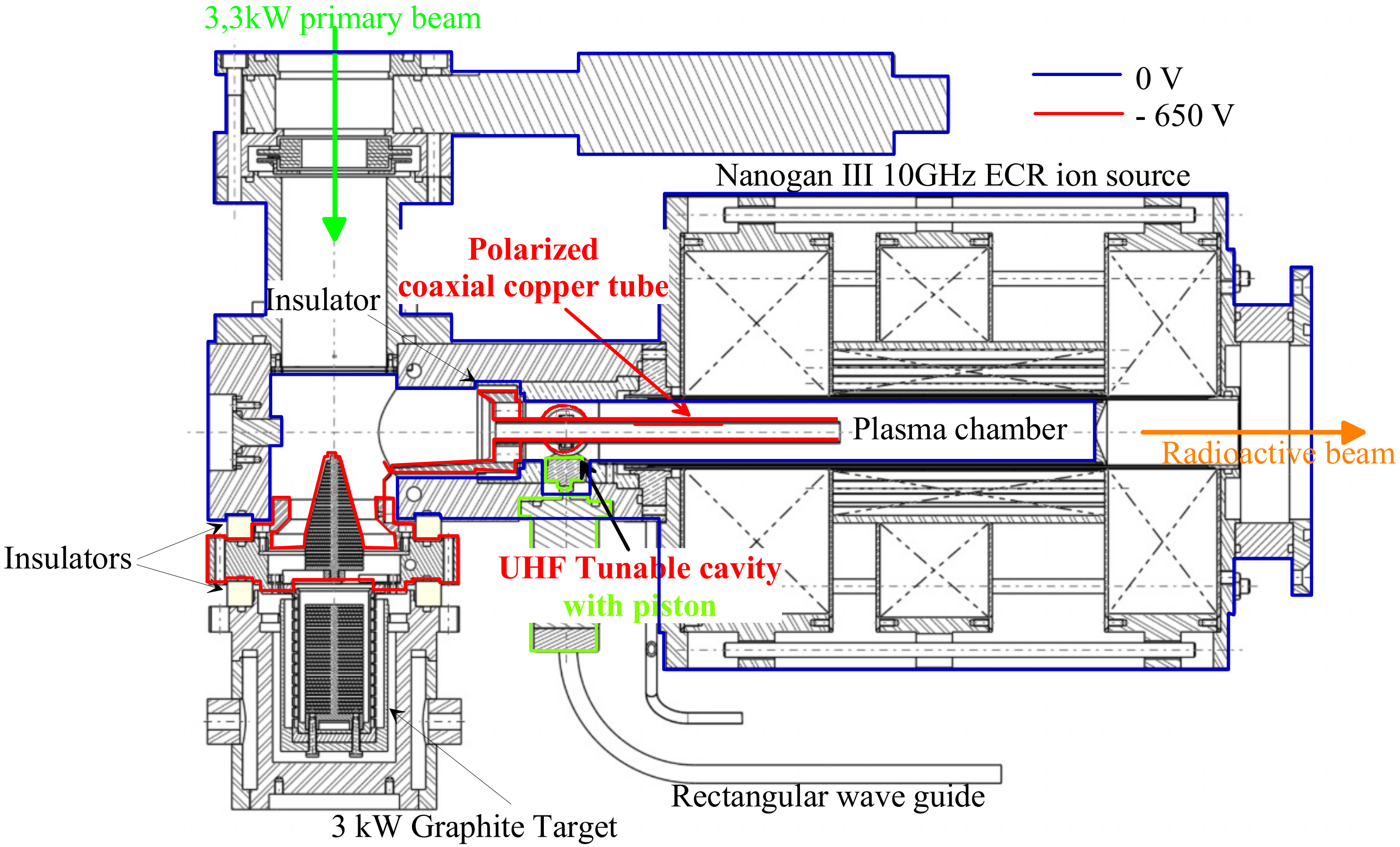
Multi-ionisation of radioactive ion beams



A. C. Villari et al., Nuclear Physics A 787 (2007) 126c–133c

Multi-ionisation of radioactive ion beams

- Best ionisation efficiencies for gases!



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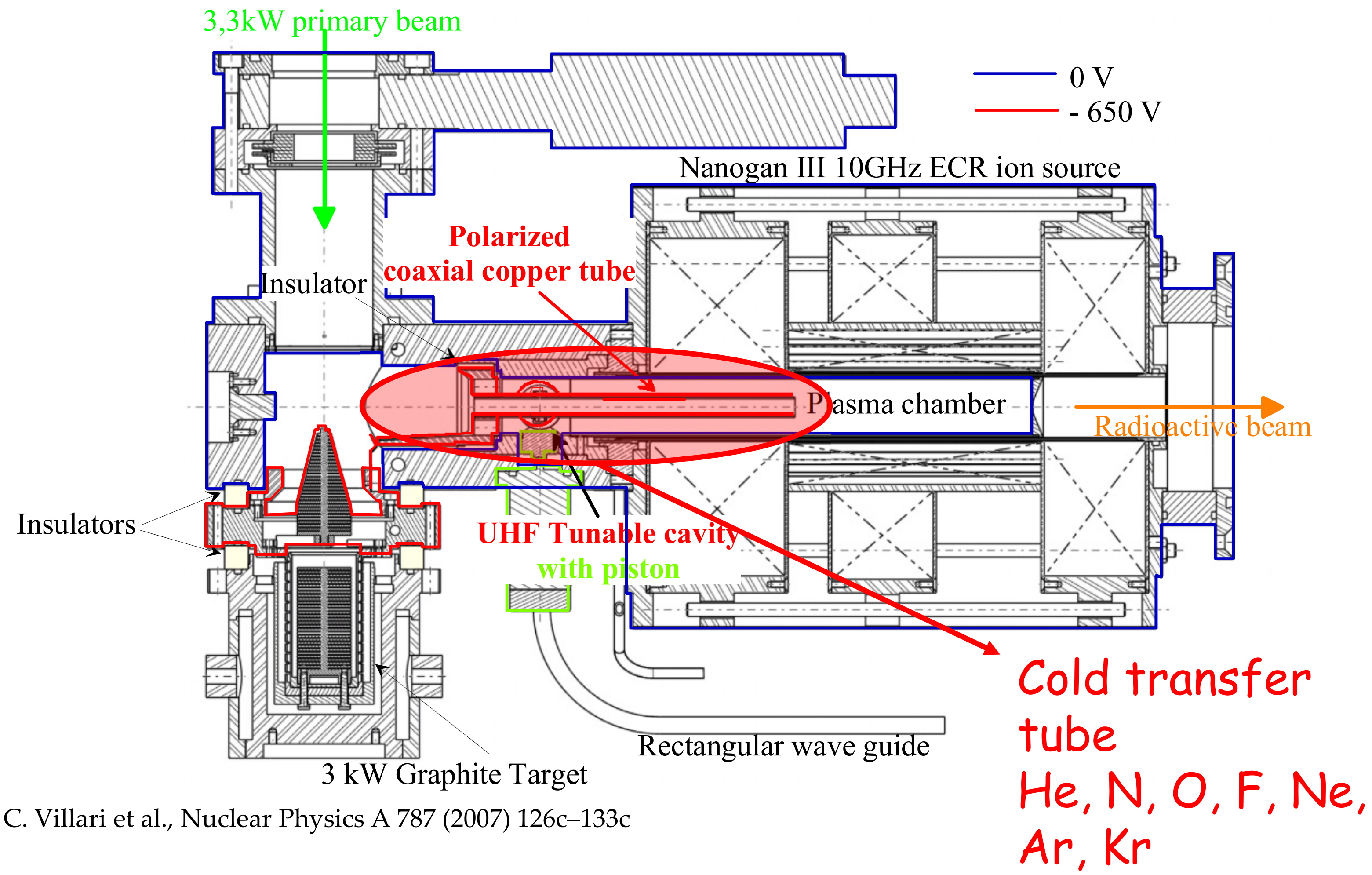

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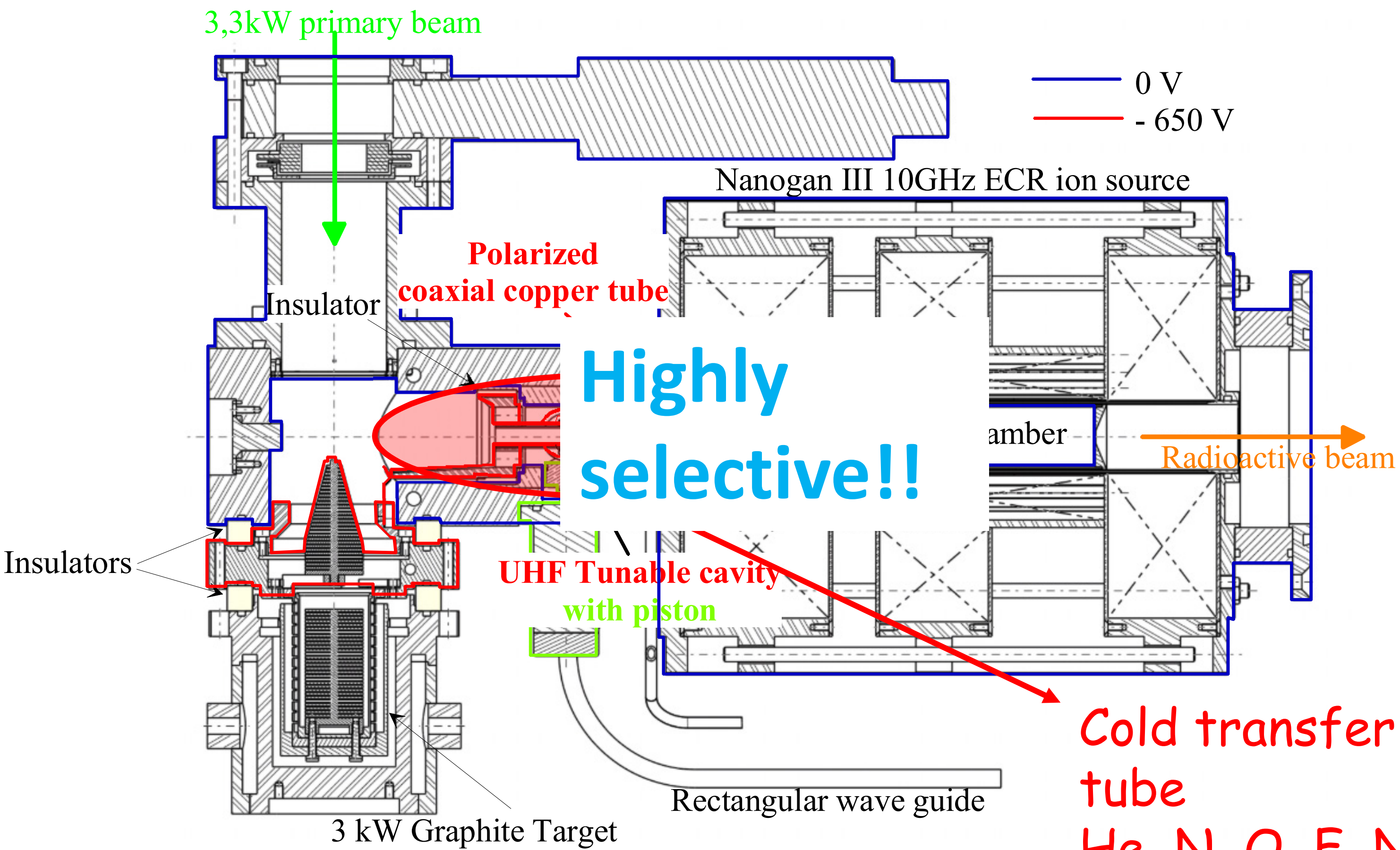

Highly selective!!

Cold transfer tube
He, N, O, F, Ne, Ar, Kr

A. C. Villari et al., Nuclear Physics A 787 (2007) 126c–133c

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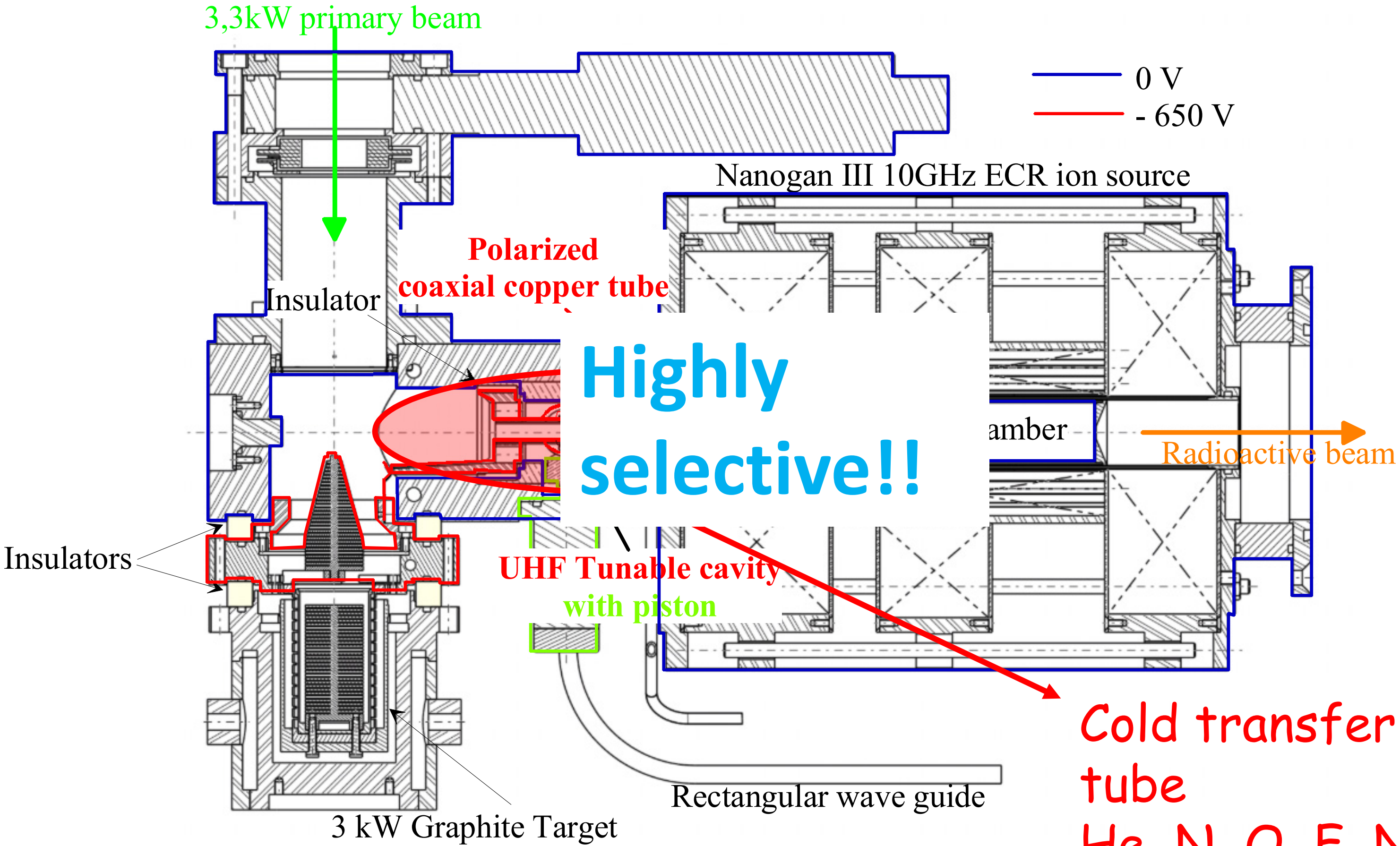

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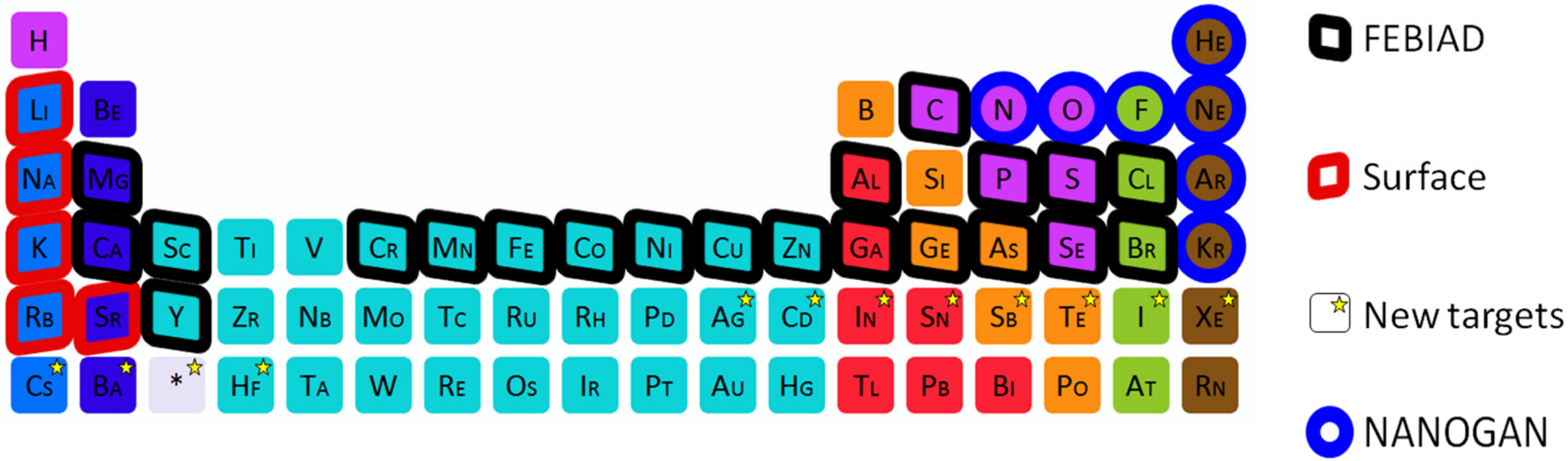
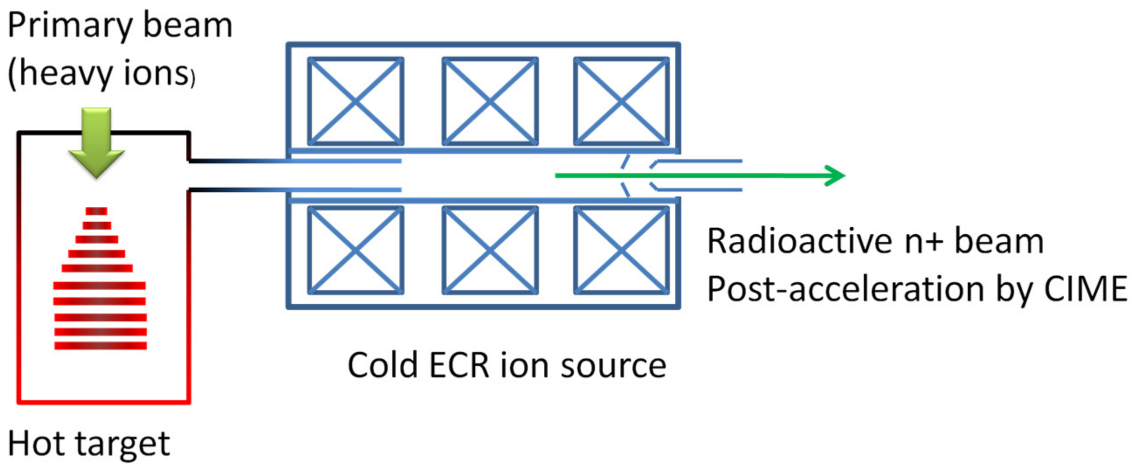
To the cost of universality

SPIRAL 1 upgrade

Extending the number of elements produced by the ISOL method at SPIRAL





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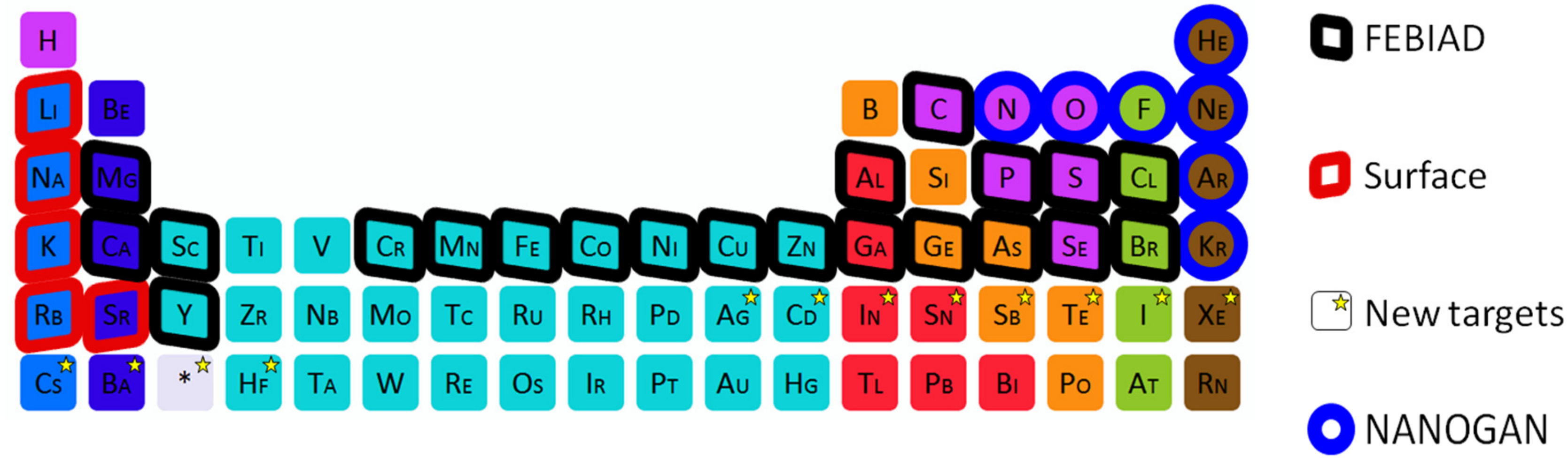
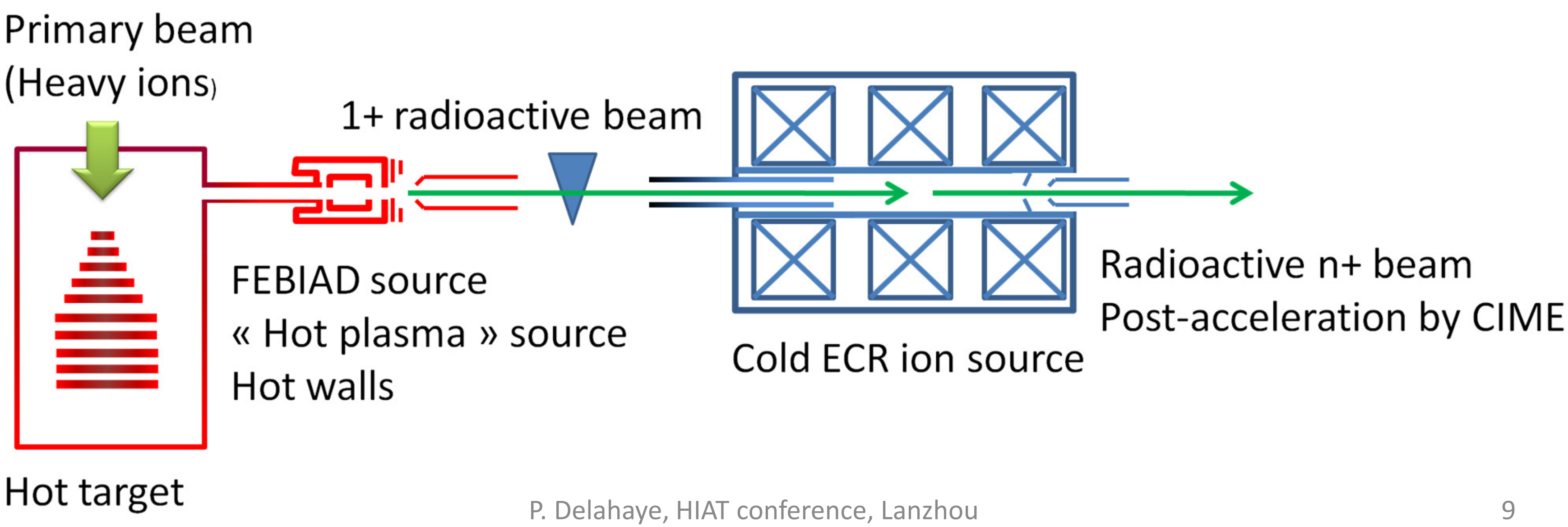
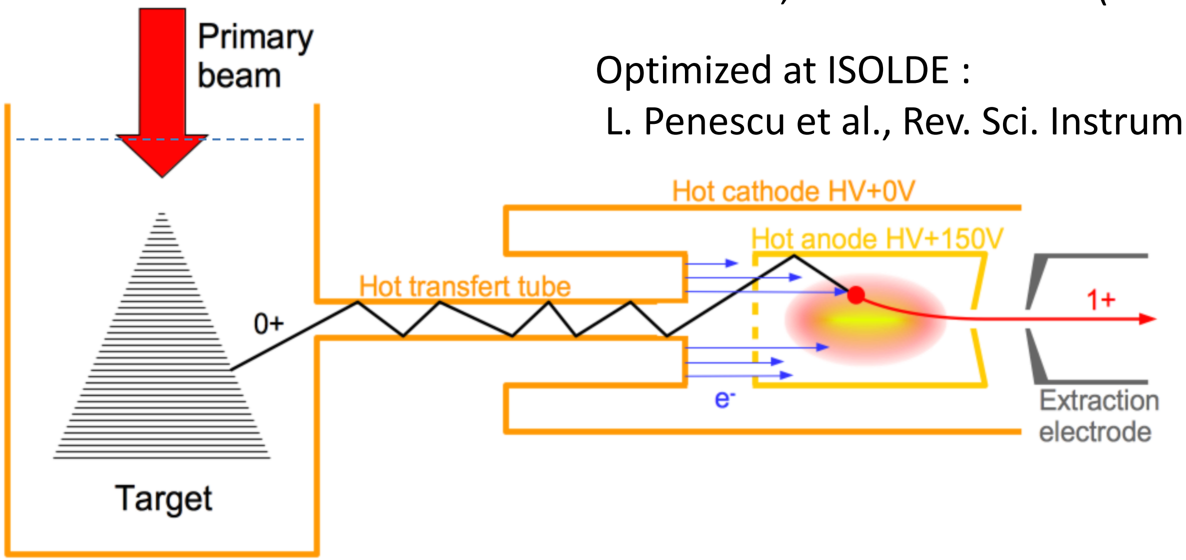




Forced Electron Beam Ion Arc Discharge (FEBIAD) source

Developed in the late 1970's at GSI
R. Kirchner, Rev. Sci. Instr. 67 (1996) 928

Optimized at ISOLDE :
L. Penescu et al., Rev. Sci. Instrum. 81(2010)02A906



- Heated Ta cathode emits electrons
  - Richardson- Dushman law $J_e = A_G T^2 e^{-W/kT}$
- Ionisation via electron impact
  - Target container, transfert tube and cathode temperature >2000°C→ ionisation of non refractory elements with melting point<2000°C

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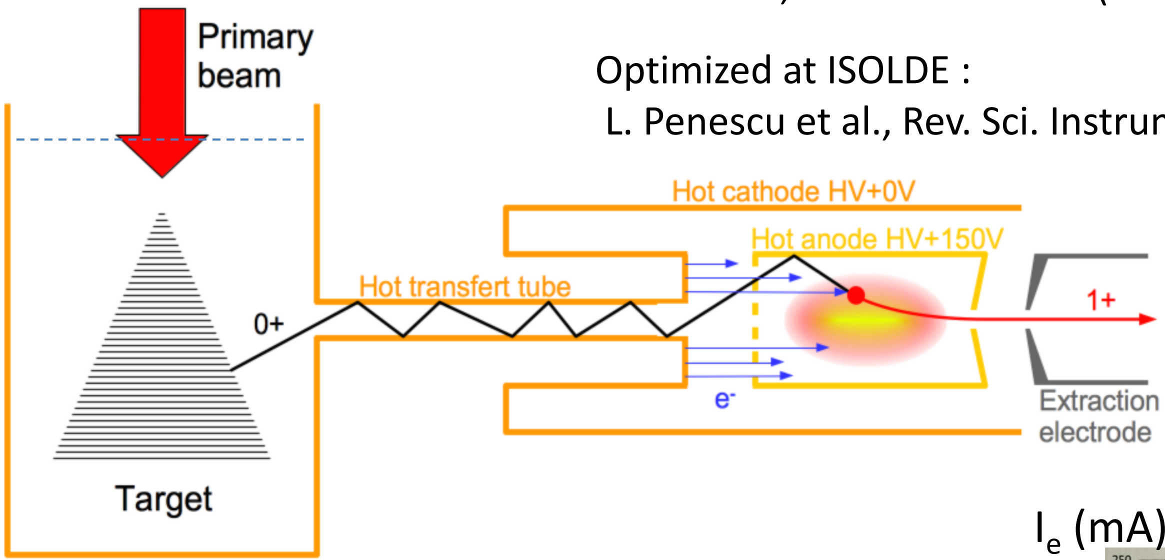

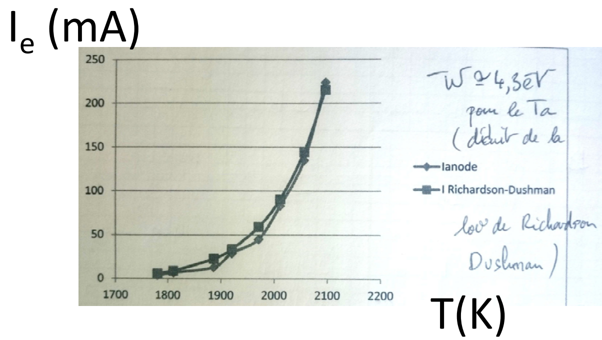

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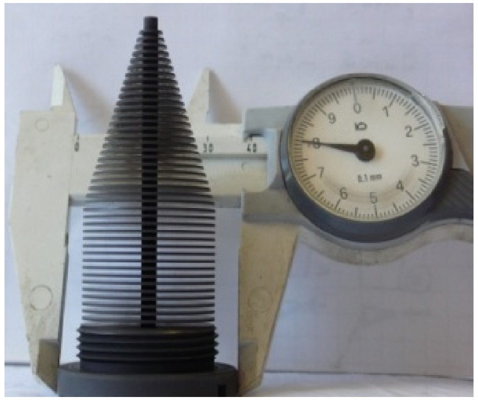
A FEBIAD Target Ion Source system



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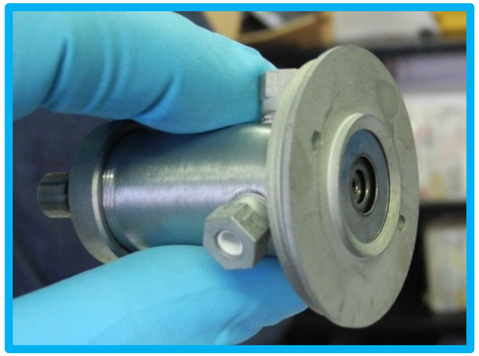

VADIS

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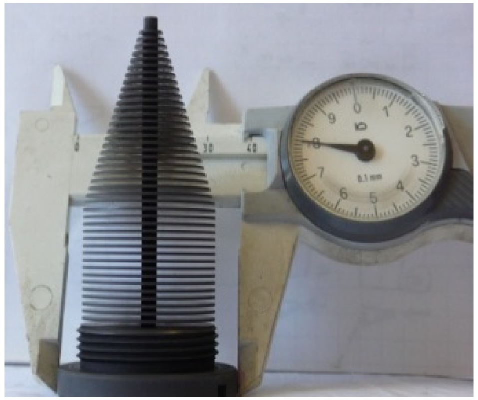

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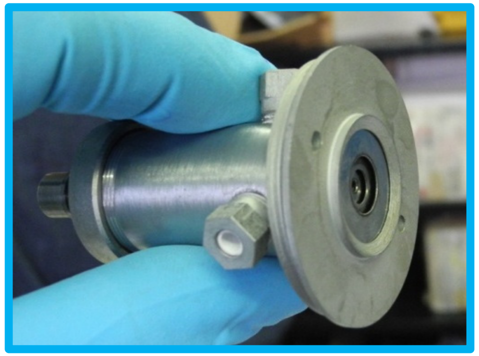

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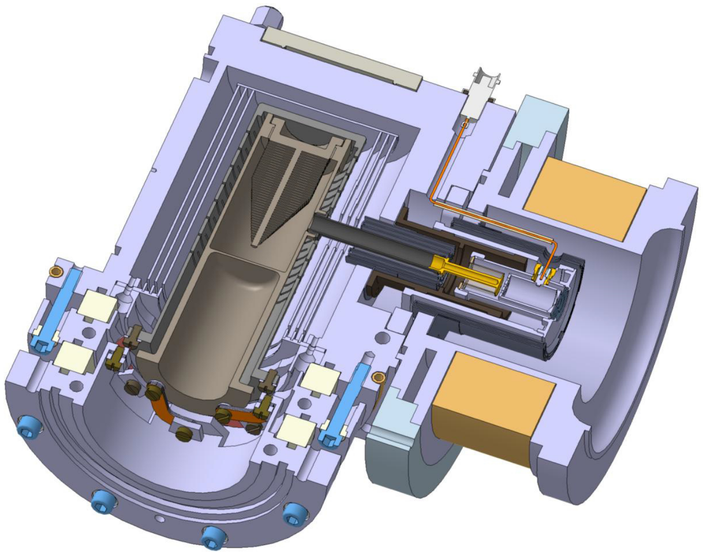

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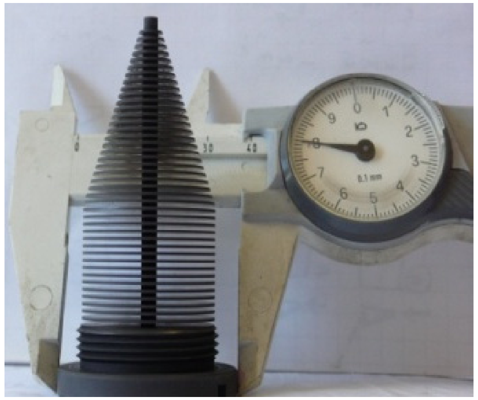

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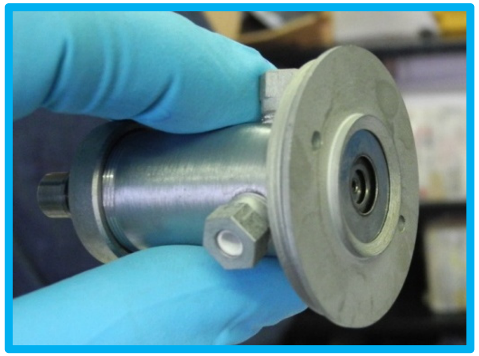

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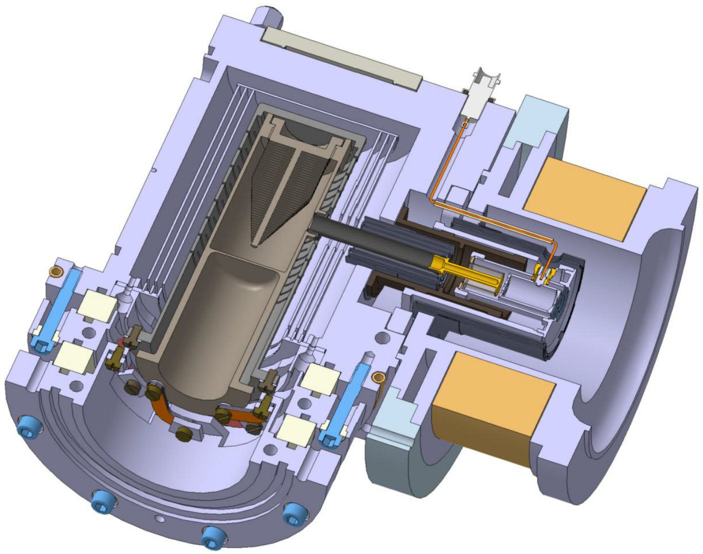

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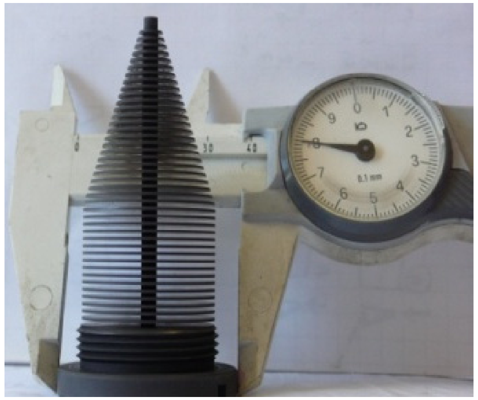

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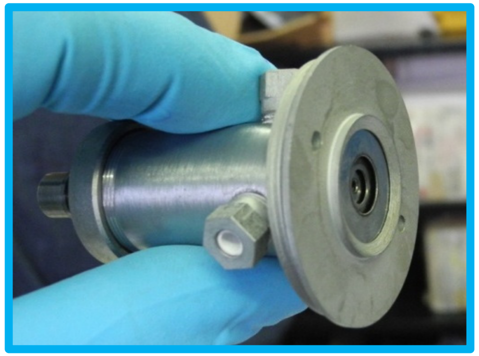
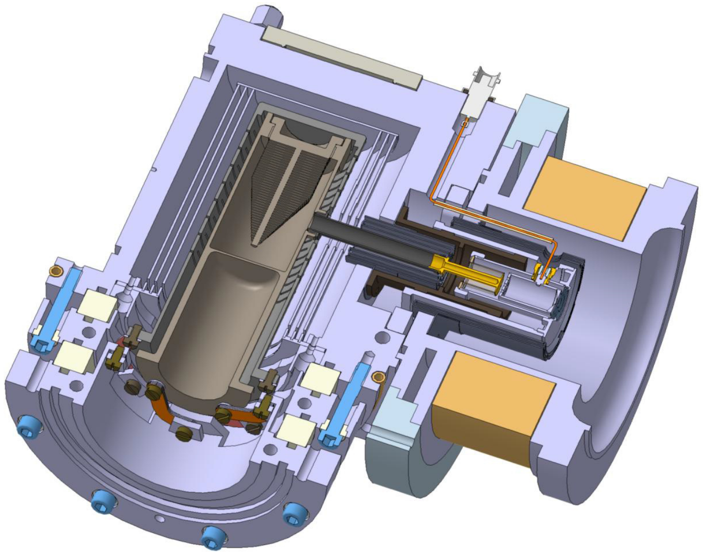
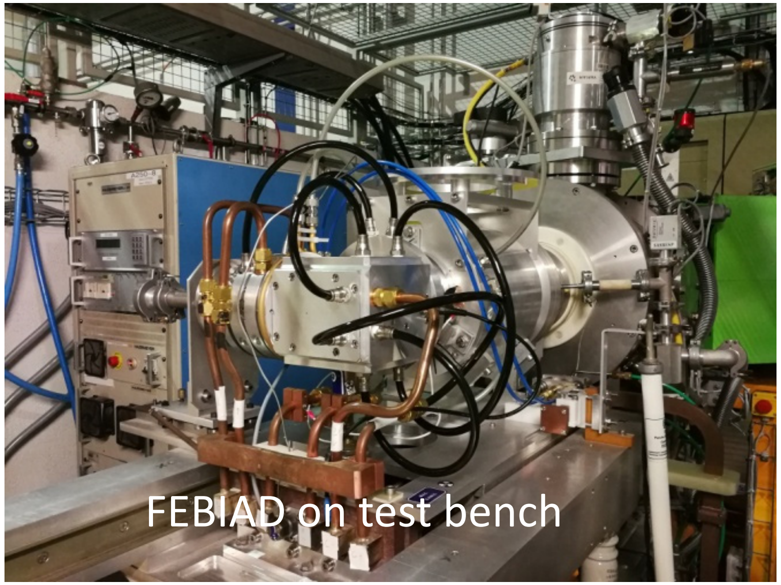


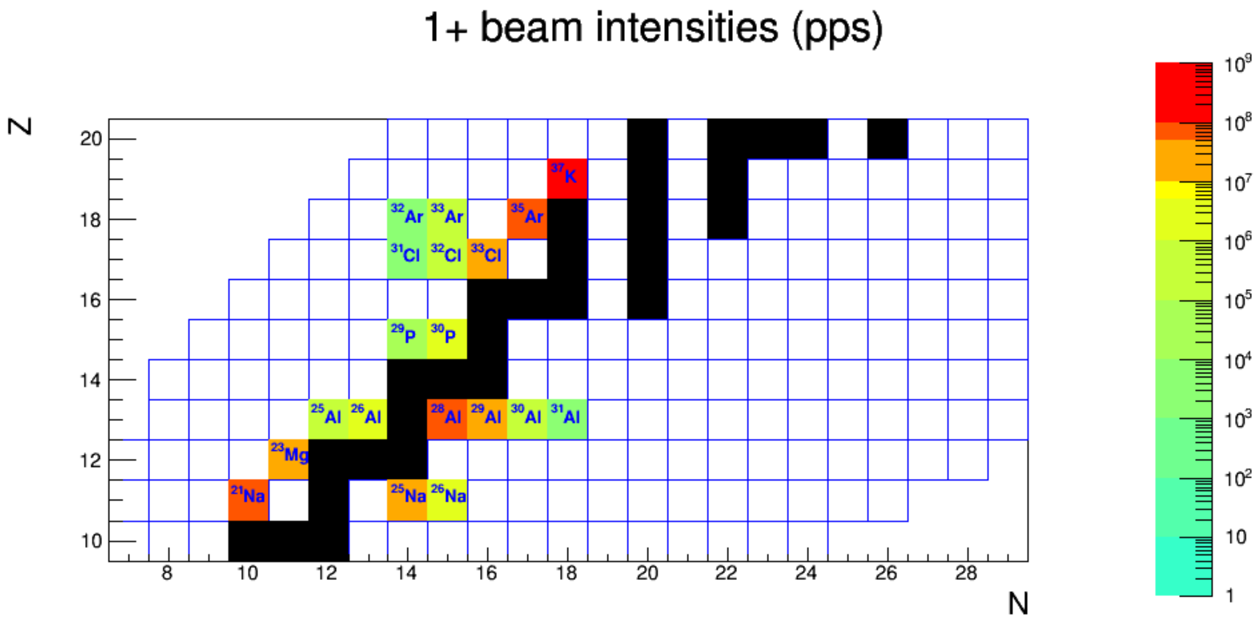
ISOLDE VADIS





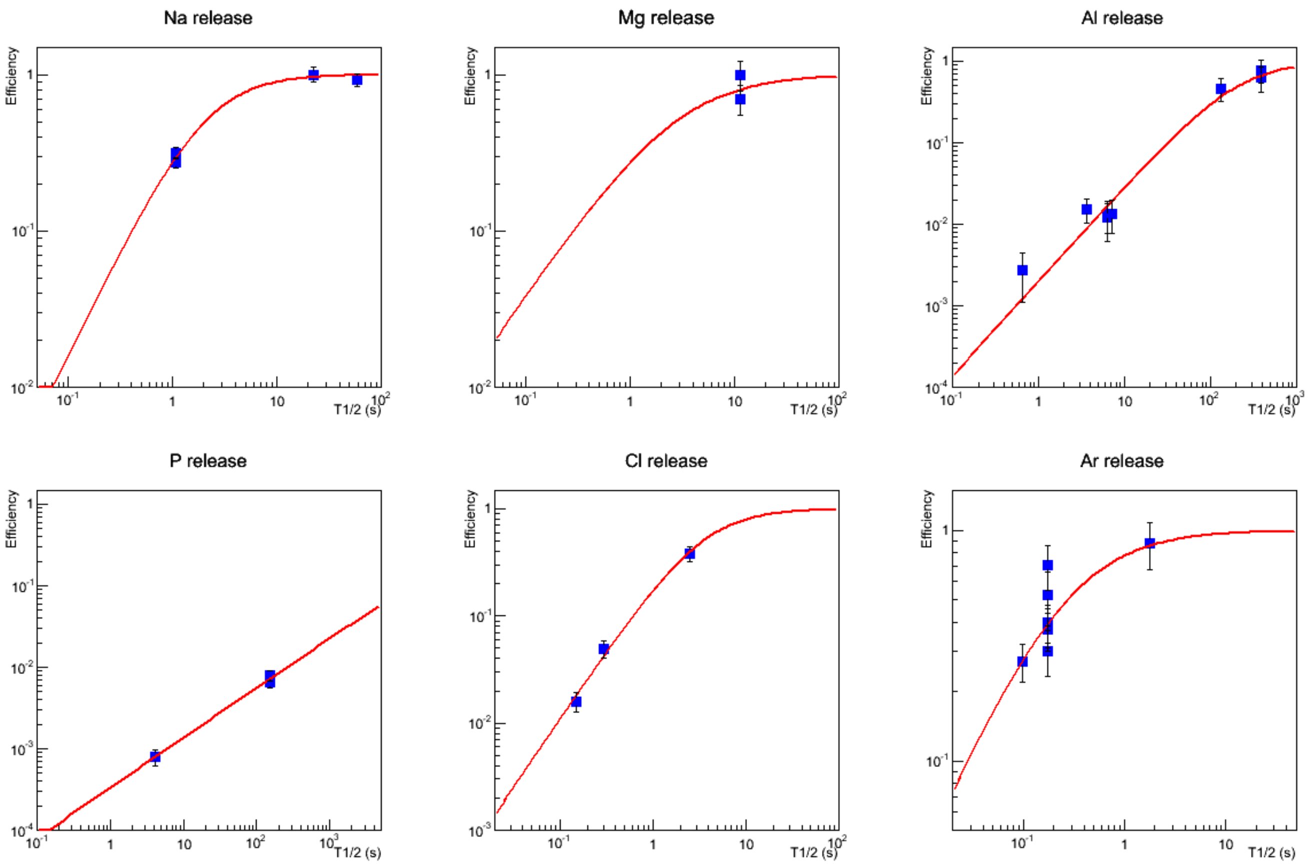
Yield measurements @ SPIRAL 1

- ^{36}Ar @ 95 MeV/n, up to 1300W



Release efficiencies

- Fit of the data with the function $$\frac{1}{1+\left({}^{t_0}/_{T_{1/2}}\right)^{\alpha}}$$



S. Lukic et al., NIM A 565(2006)784

Element	t0 (s)	alpha
Na	2.06	1.36
Mg	2.76	0.97
Al	152	1.16
P	470000	0.61
Cl	3.5	1.27
Ar	0.277	0.97
BeF	9.17	1.50

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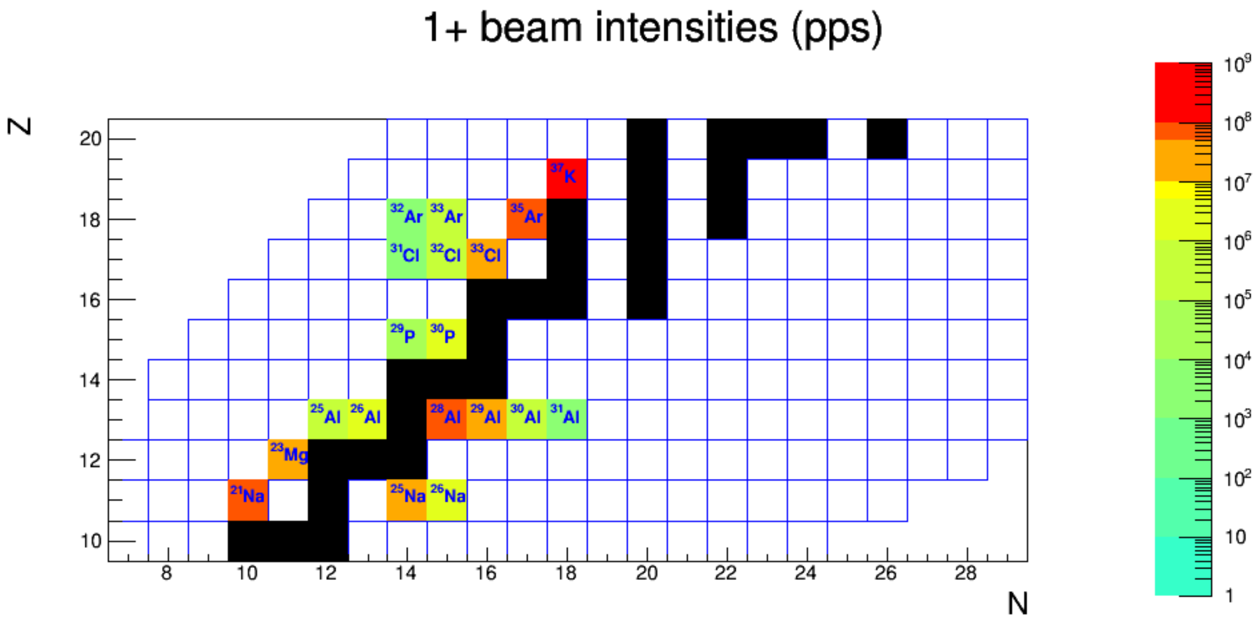
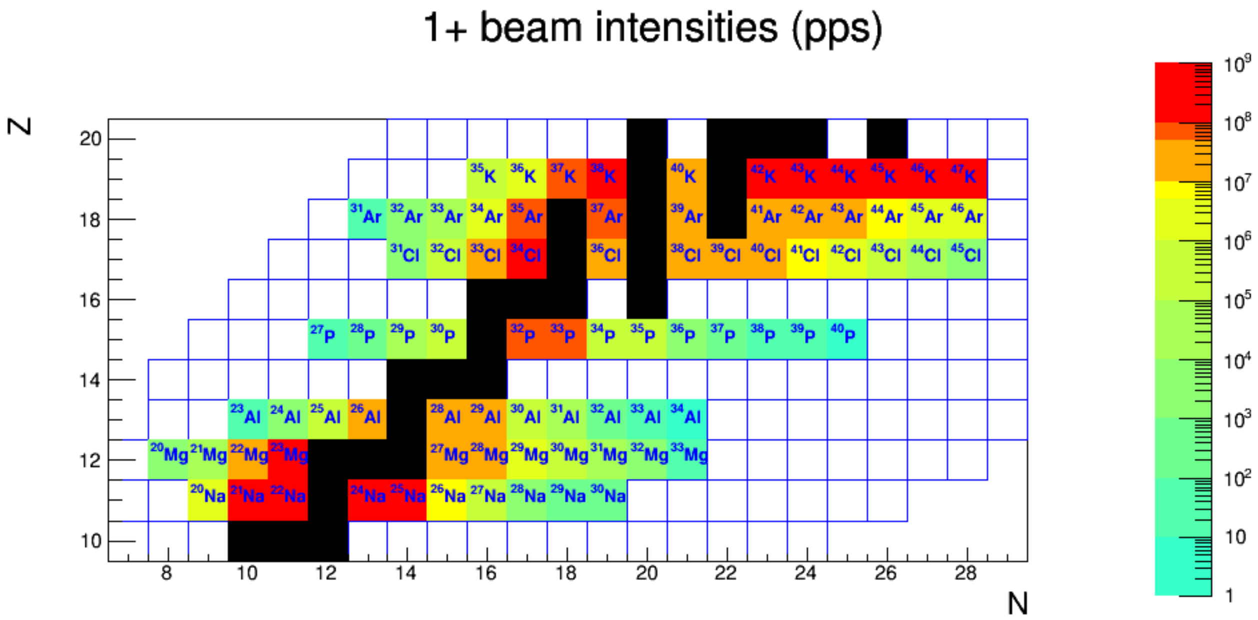


Yield measurements @ SPIRAL 1

- « Safe » predictions for projectile fragmentation



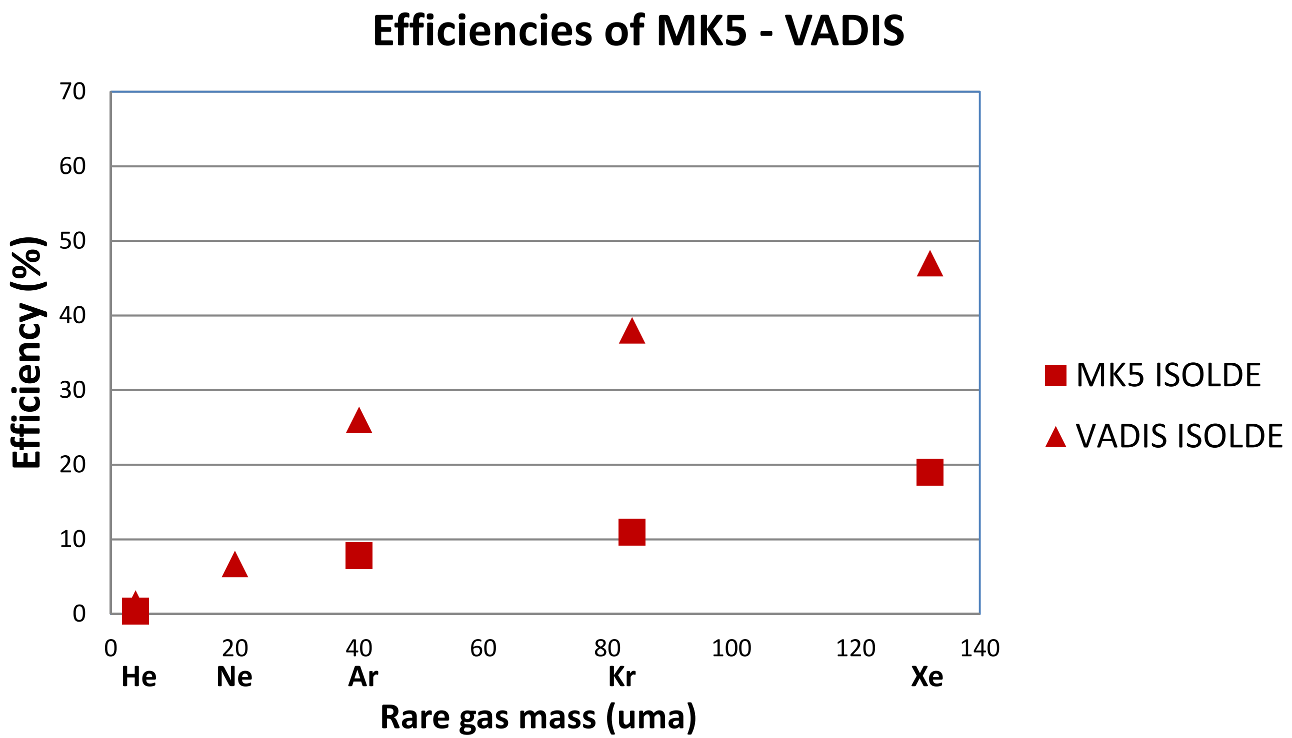
Fragmentation of ^{24,26}Mg, ^{36}S, ^{36}Ar, ^{40,48}Ca at nominal intensities (up to 1.5kW)

Day 1 beams discussed with the community

FEBIAD source latest investigations

EURISOL JRA

Ionisation efficiency measurements



Ref: L. Penescu et al, Rev. Sci. Instrum. 81, *P. Chauveau et al, NIM B 376*, S. Essabaa et al NIM A 317

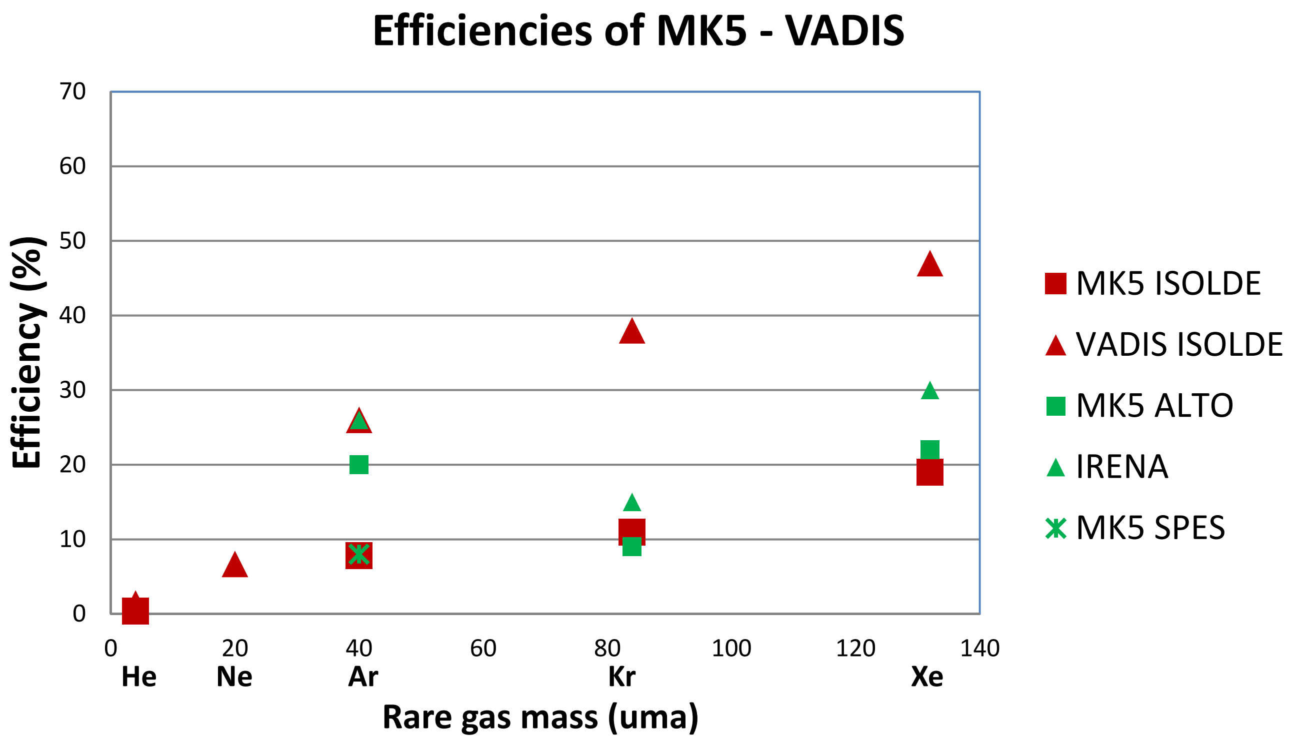
Using a calibrated leak with gas injection: η= I1+/Igaz

FEBIAD source latest investigations

ENSAR2

EURISOL JRA

Ionisation efficiency measurements



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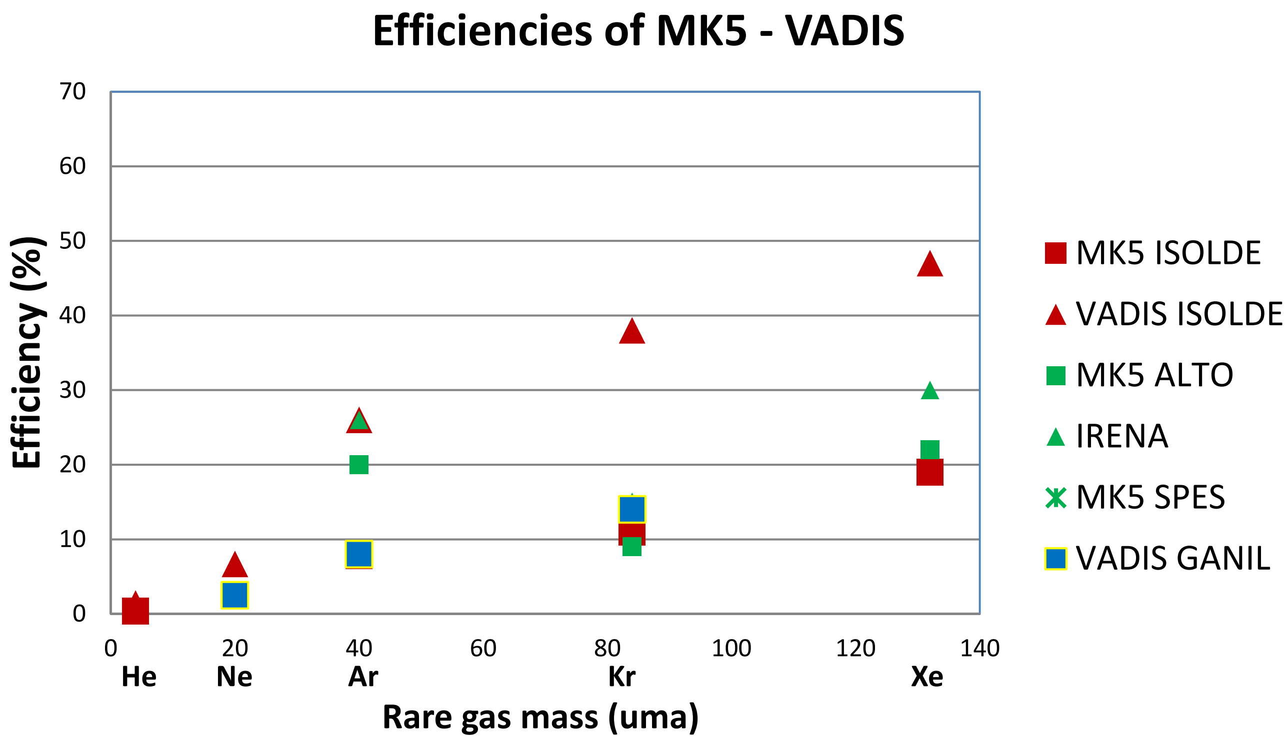

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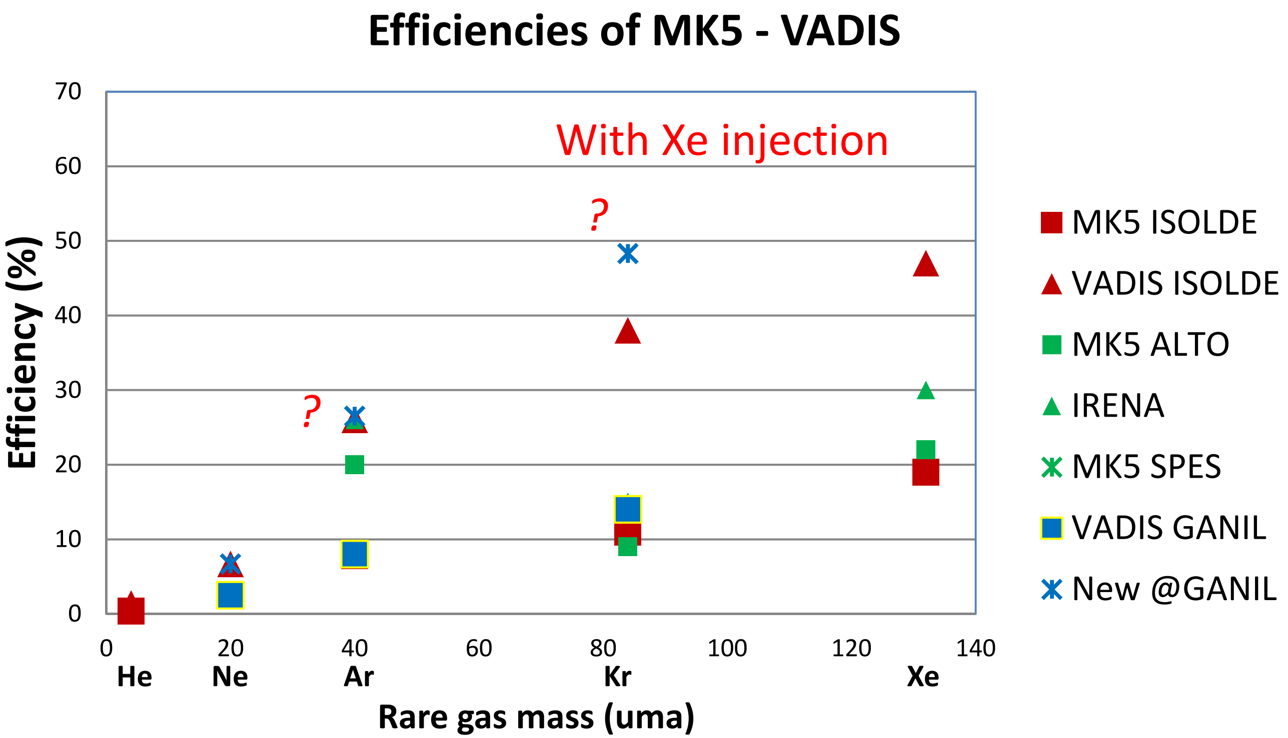

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Intensity increase only obtained for a couple of hours

FEBIAD source latest investigations

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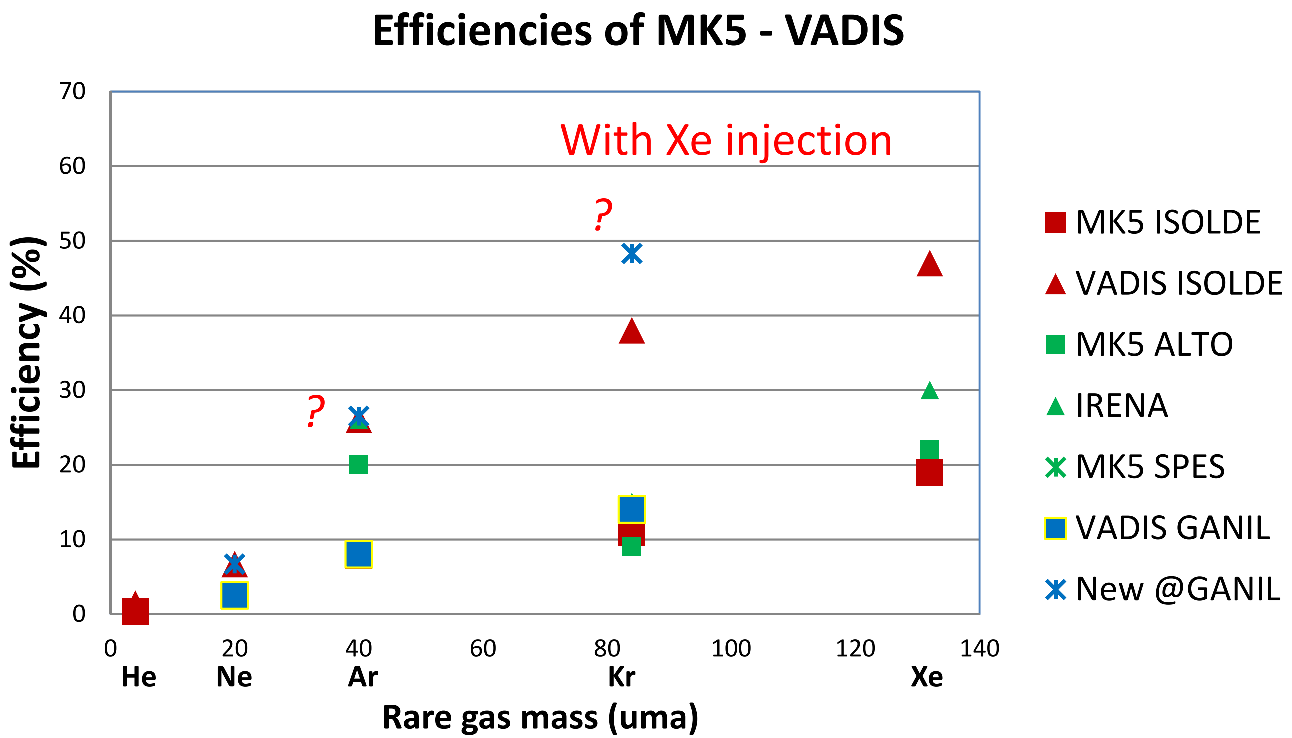

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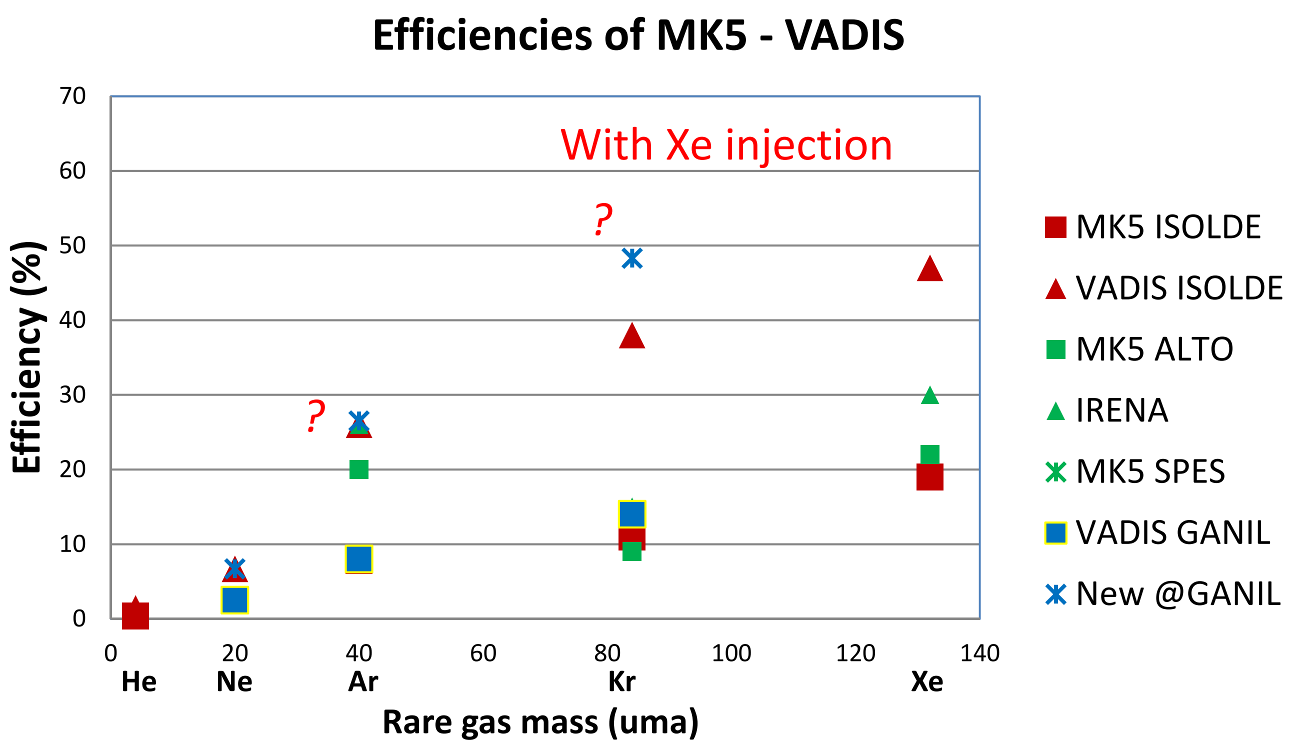

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Using a calibrated leak with gas injection: η= I1+/Igaz

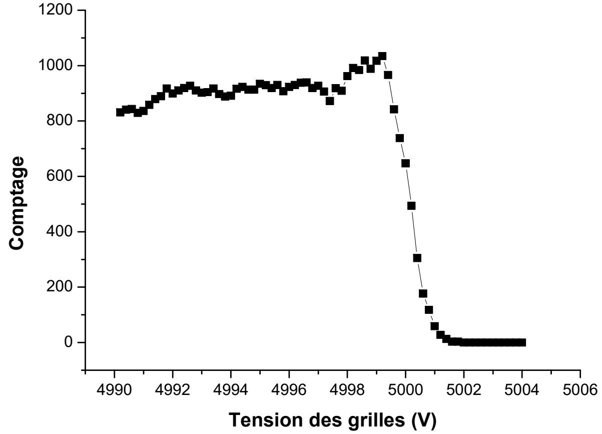
Intensity increase only obtained for a couple of hours

Investigations are being pursued

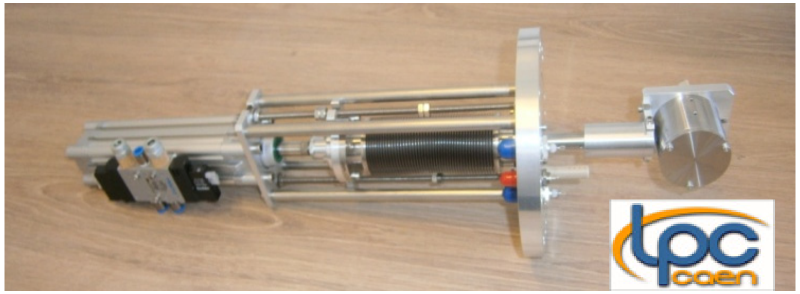
FEBIAD source latest investigations

EURISOL JRA

Energy profile measurement

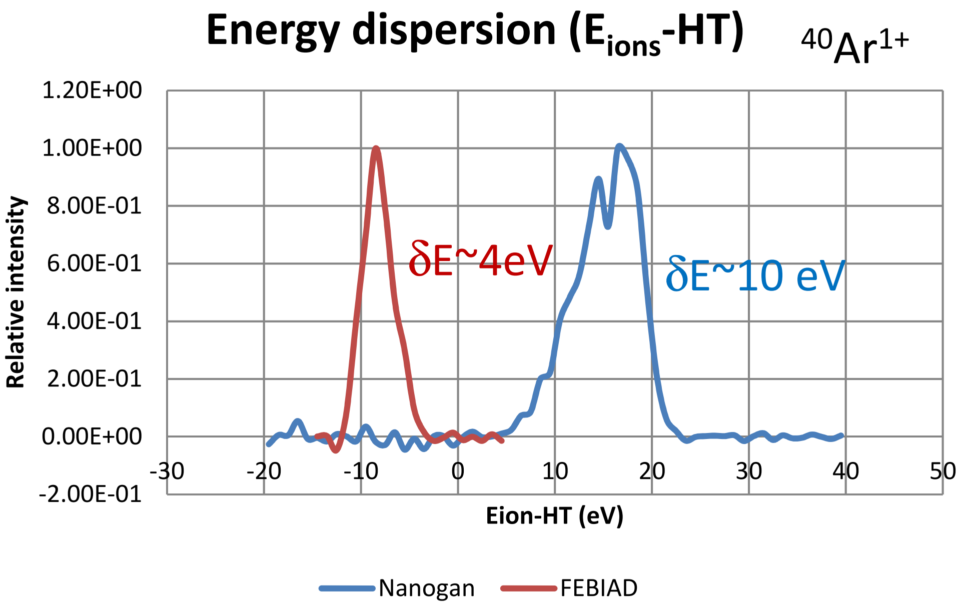


Simulations: M. Herbane, LPC Caen



Charge breeding efficiency depends on δE

σ_E~1.5eV

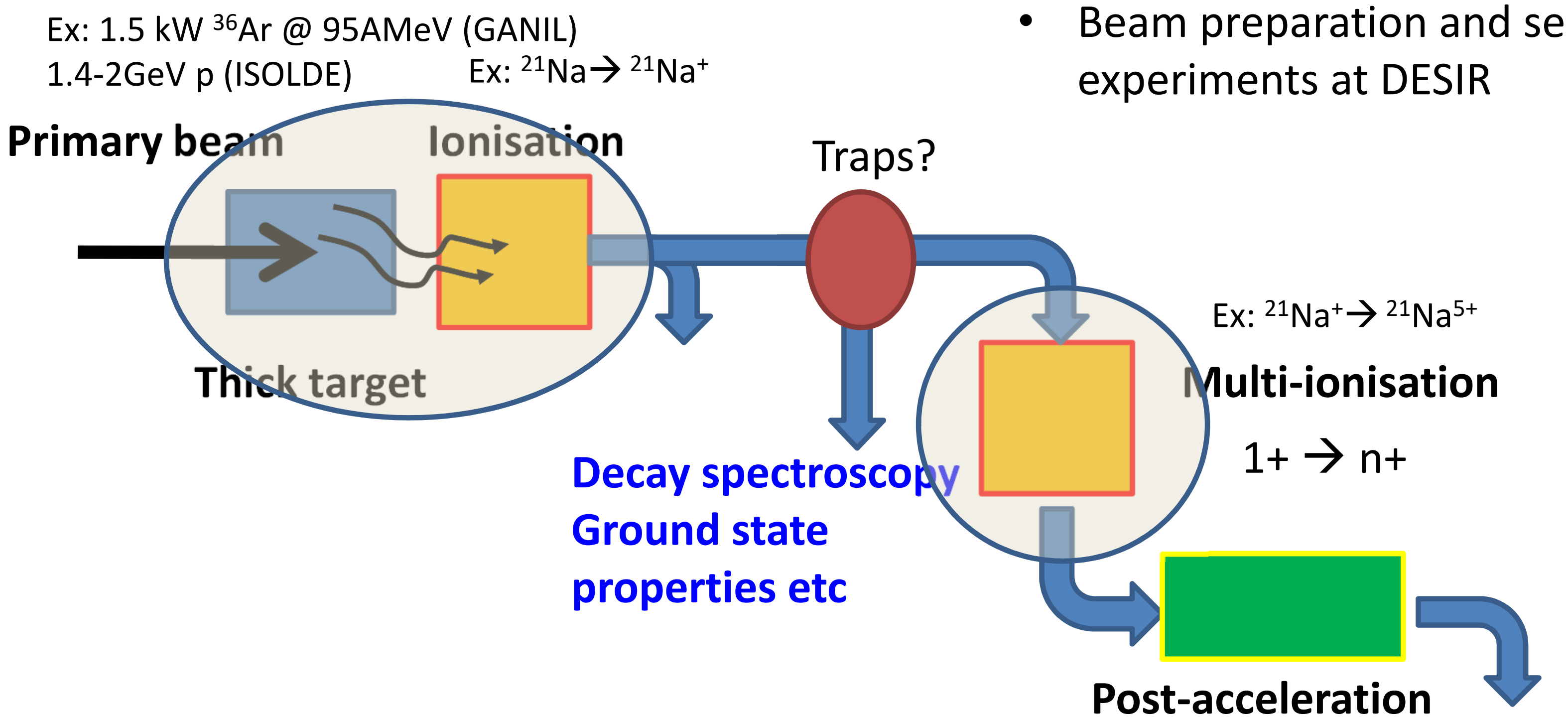


- approximate value HT is taking into account the anode potential

- Plasma sources have a plasma potential that matters for the charge breeding

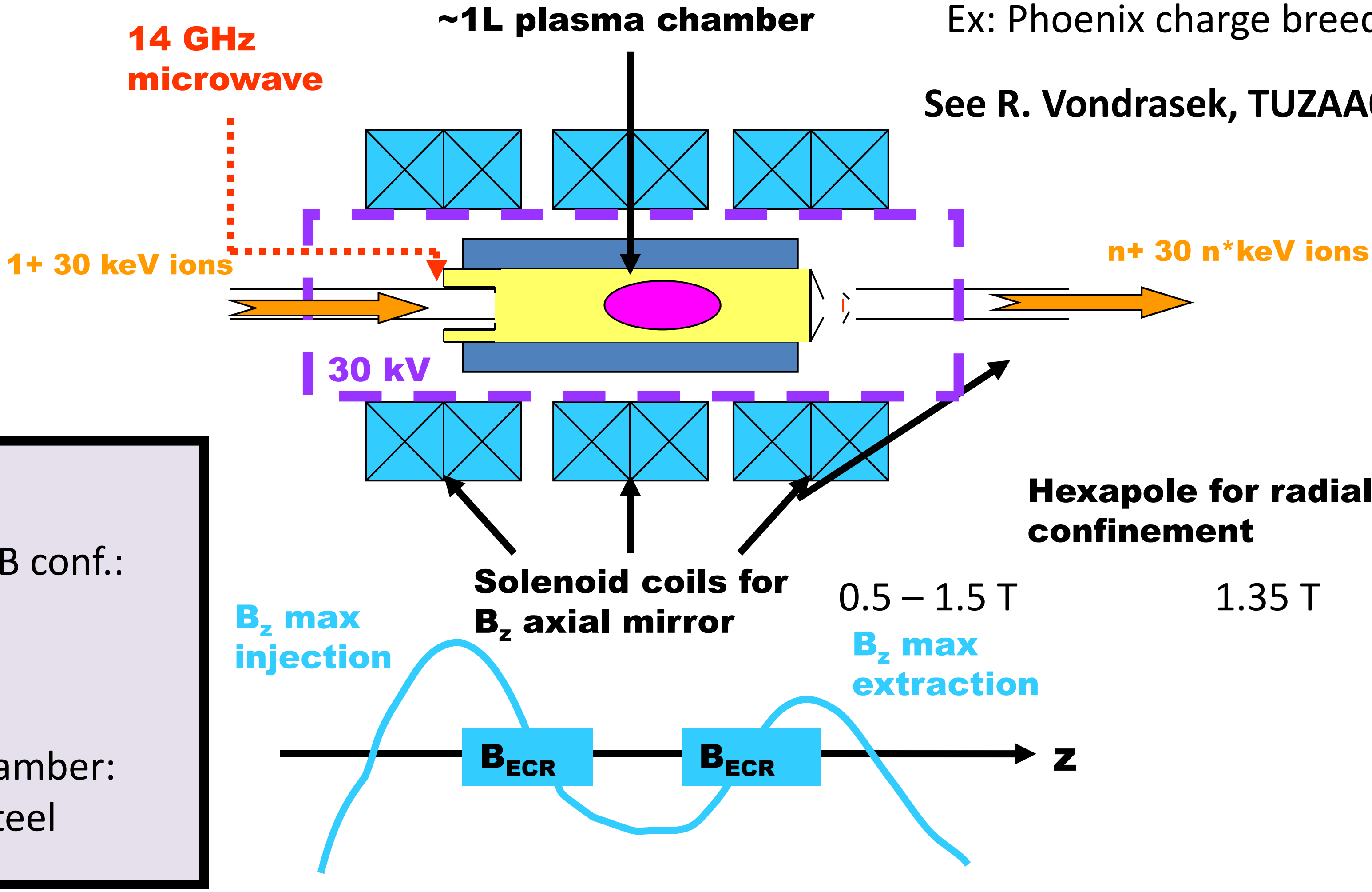
Table of content:
ISOL beam production and processes

- **Enlarging the production at SPIRAL 1**
- Gas cell and trap developments at S3
- Beam preparation and separation for experiments at DESIR



Many places to get contaminated
Many places to be selective and purify the beams!

ECRIS charge breder principle



Ex: Phoenix charge breeder

See R. Vondrasek, TUZAA02

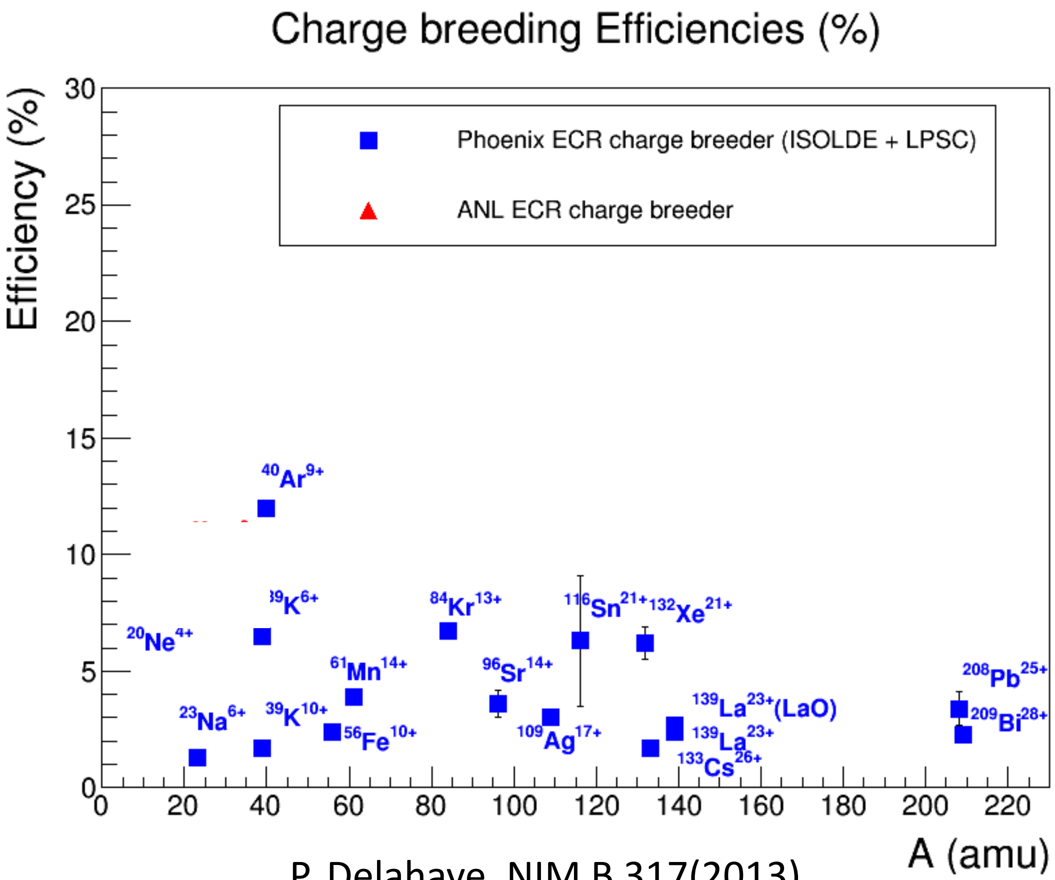
f_{RF}=14GHz
Minimum B conf.:
B_{ecr}=0.52T
B_{min}=0.5T
B_{max}=1.5T
Plasma chamber:
stainless steel

Performances: P. Delahaye et al., Rev. Sci. Instrum. 77, 03B105 (2006), P. Delahaye and M. Marie-Jeanne, NIM B 266 (2008) 4429

Essentially a CW device, but can be pulsed

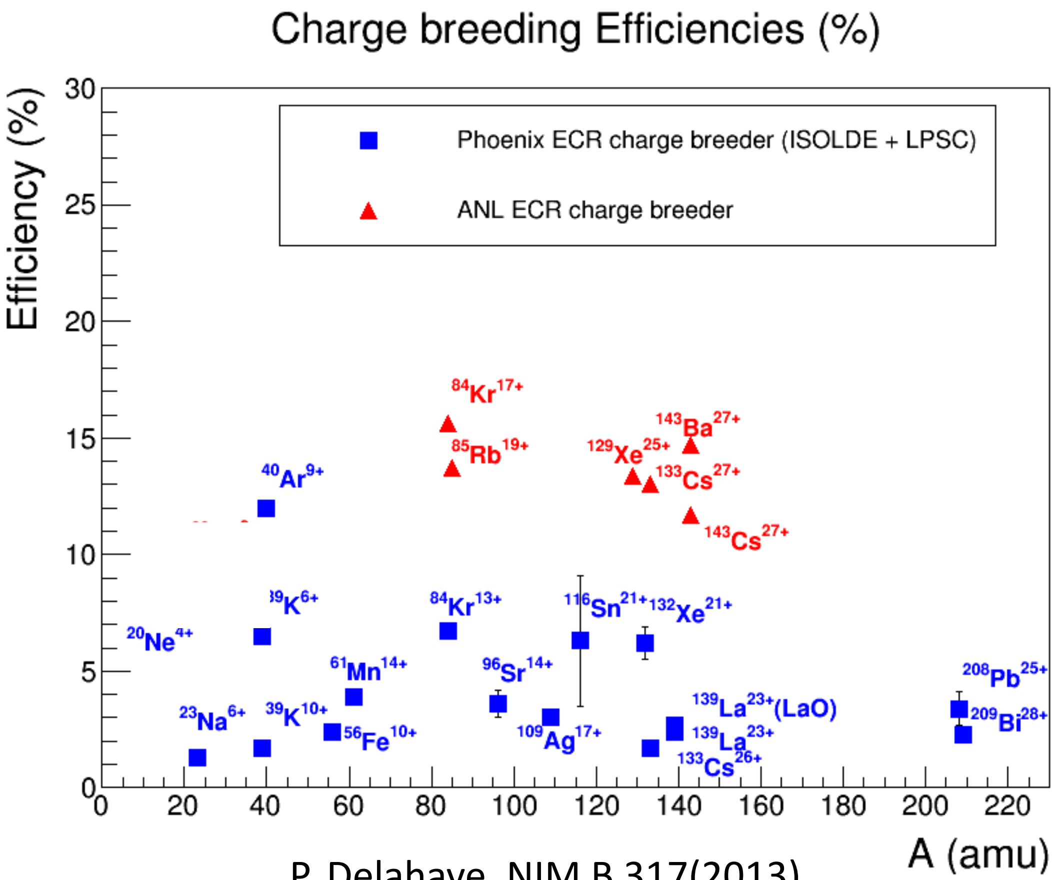
R&D within

Improvement of charge breeding efficiencies



P. Delahaye, NIM B 317(2013) ,
J. Angot et al, ECRIS 2012

Improvement of charge breeding efficiencies



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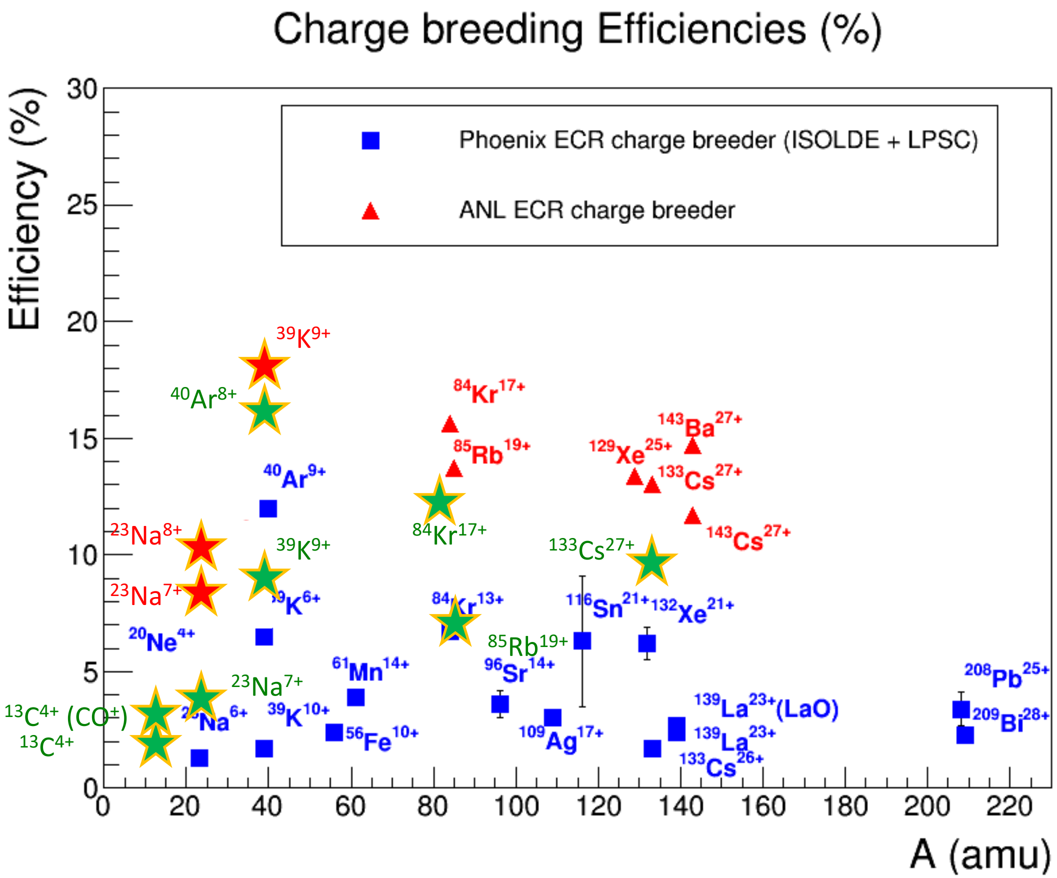


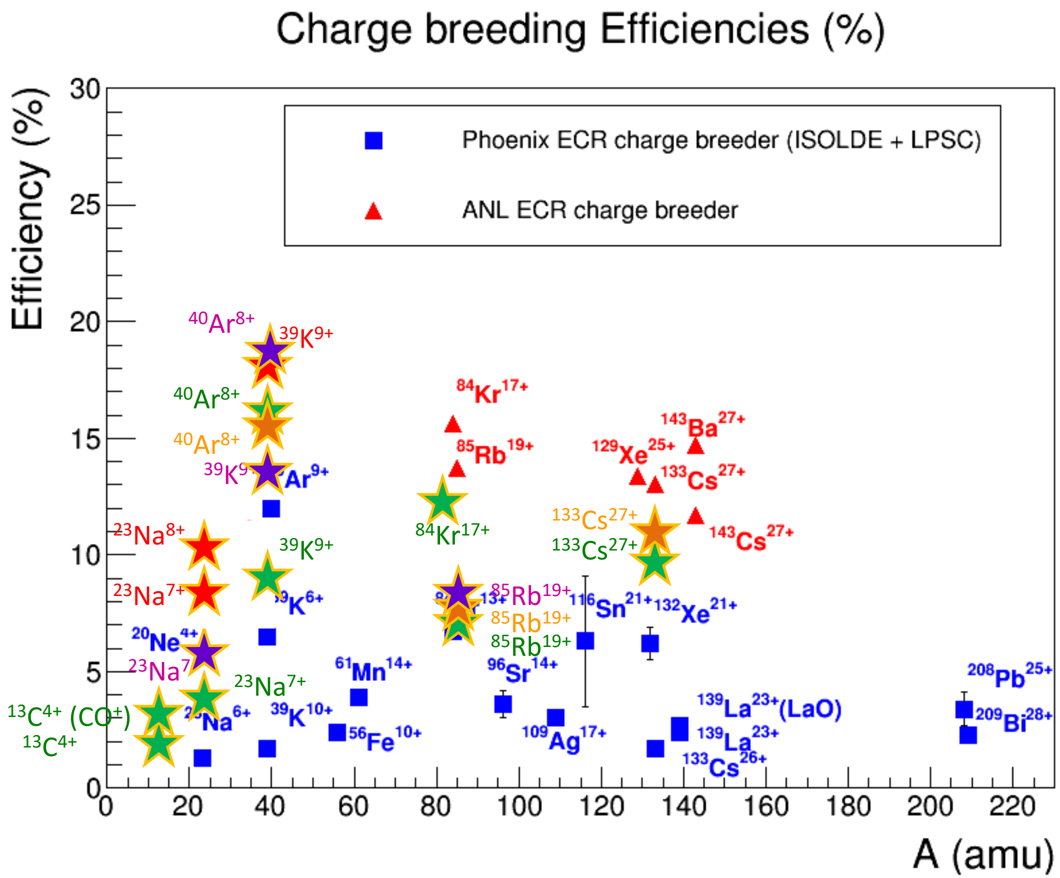
1) Injection of molecules
2) Vaccuum improvement
   - Lower residual pressure
3) Magnetic field improvements:
   - symmetrization at injection
   - axial field optimization
4) Double frequency heating

EMILIE 2012-2014

ANL charge breeder
LPSC charge breeder

H. Koivisto et al, RSI 85 (2014)
L. Maunoury et al, RSI 85 (2014)
T. Lamy et al, ECRIS 2014

Improvement of charge breeding efficiencies



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EMILIE 2012-2014

ANL charge breeder

LPSC charge breeder

EMILIE 2015

SPIRAL charge breeder

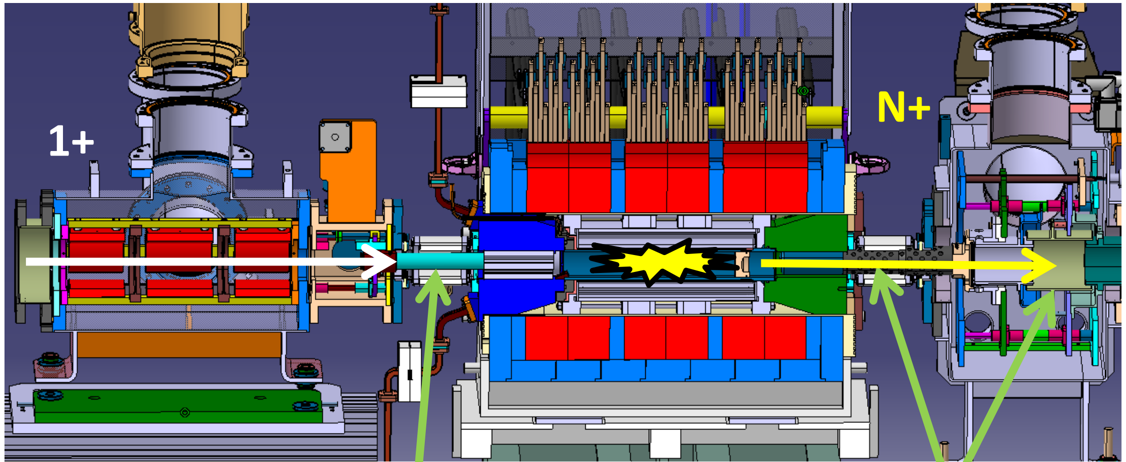
SPES charge breeder

H. Koivisto et al, RSI 85 (2014)
L. Maunoury et al, RSI 85 (2014)
T. Lamy et al, ECRIS 2014

L. Maunoury RSI 87 (2016)
A. Galatà RSI 87 (2016)

SPIRAL 1 charge breeder

R&D in the frame of ENSAR and EMILIE



Electrostatic QPole
Focusing/steering

Mobile
Ground tube

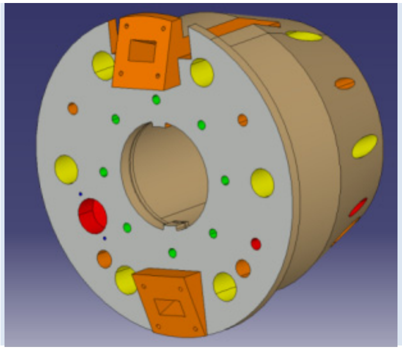
HF : 14,5GHz
+ 8/18GHz

Mobile puller &
electrostatic lens

<u>Several optimizations</u>

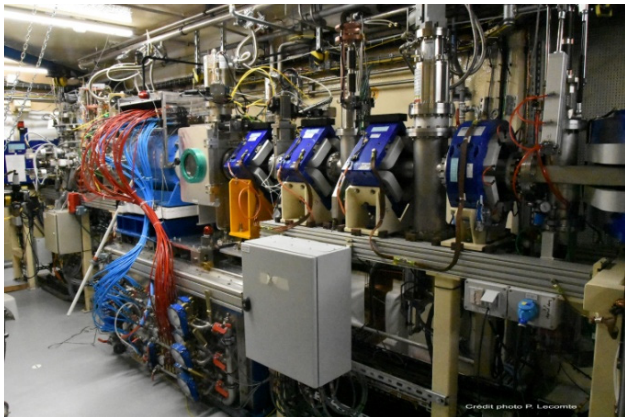
Higher efficiencies & higher beam purity

-Vacuum, materials
- Beam optics
- Gas injection
-2 RF heating capability

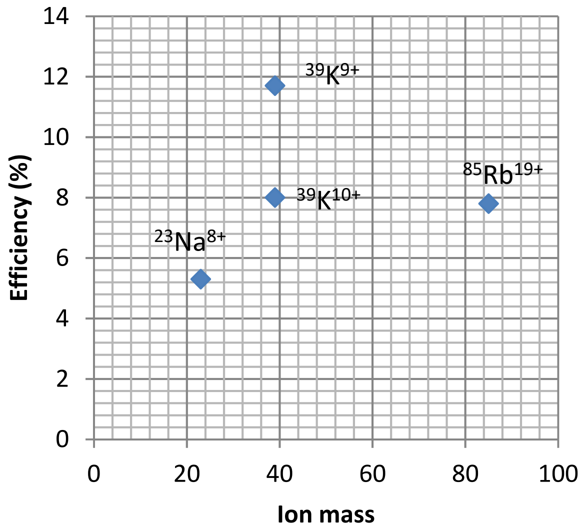


•Design of the injection plug to get a axi-symmetric magnetic field

•Nickel coating on iron plug to reduce the outgasing



Off-line commissioning

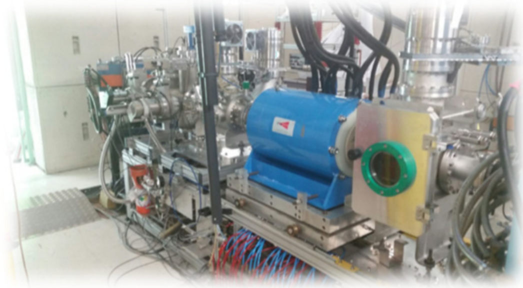


Results with light metallic gases

◆ Booster SPIRAL 1@LPSC

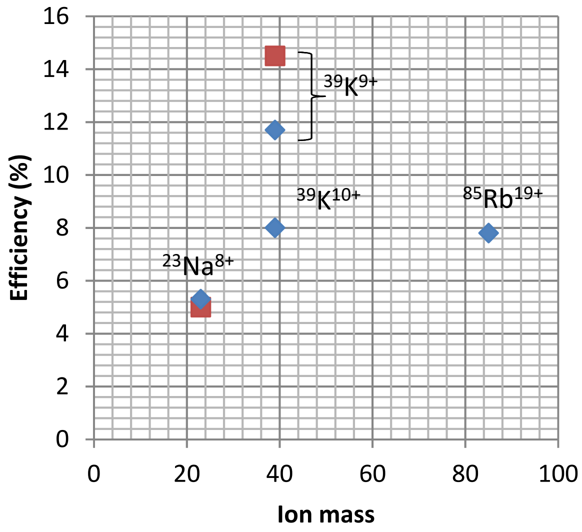
He as support gas

At LPSC 2015



L. Maunoury et al, Rev Sci Instrum. 87(2016)02B508

Off-line commissioning



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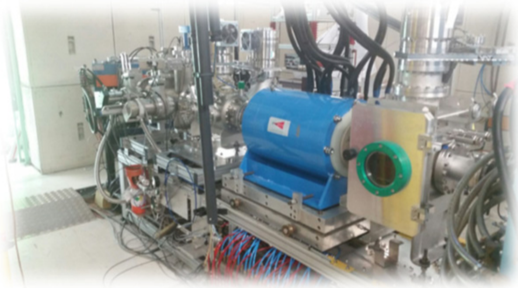
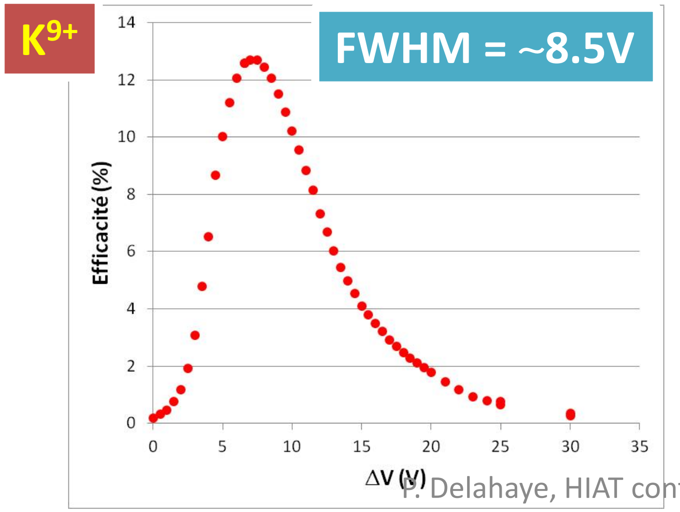
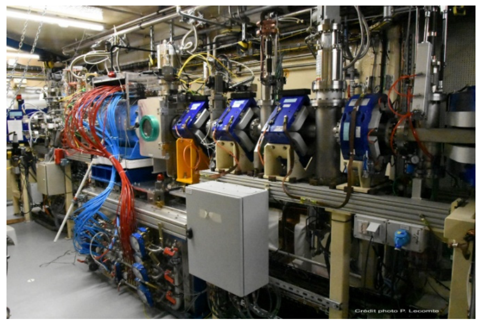


L. Maunoury et al, Rev Sci Instrum. 87(2016)02B508

About 10ms/charge state



In the SPIRAL 1 beam lines 2017-2018



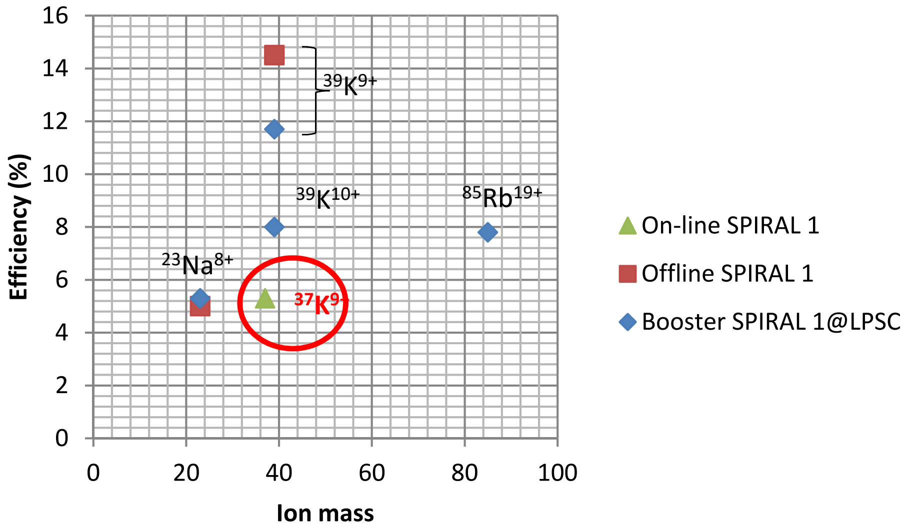
L. Maunoury et al, ECRIS 2018

First on-line charge breeding

$^{37}K^{9+}$ activity monitored on tape station

First on-line charge breeding

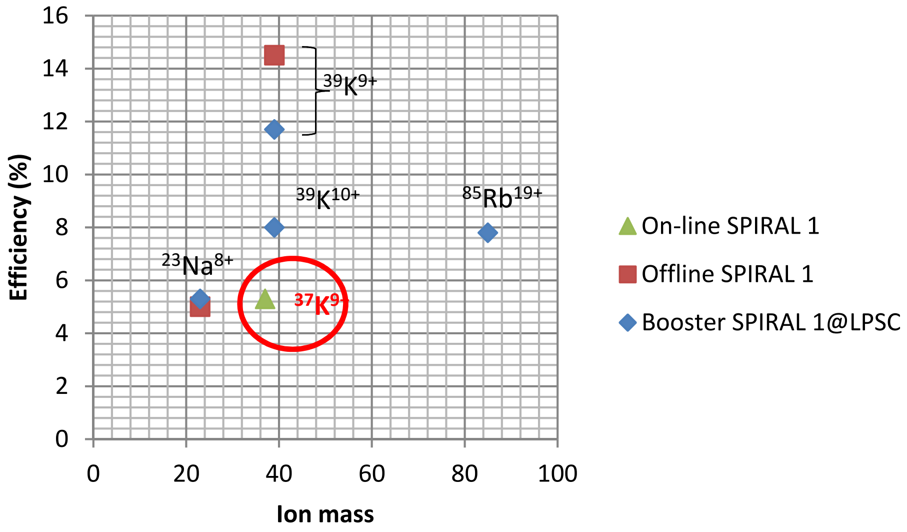
$^{37}K^{9+}$ activity monitored on tape station



5,3% $^{39}K^{1+} \rightarrow {}^{39}K^{9+}$

First on-line charge breeding

$^{37}K^{9+}$ activity monitored on tape station



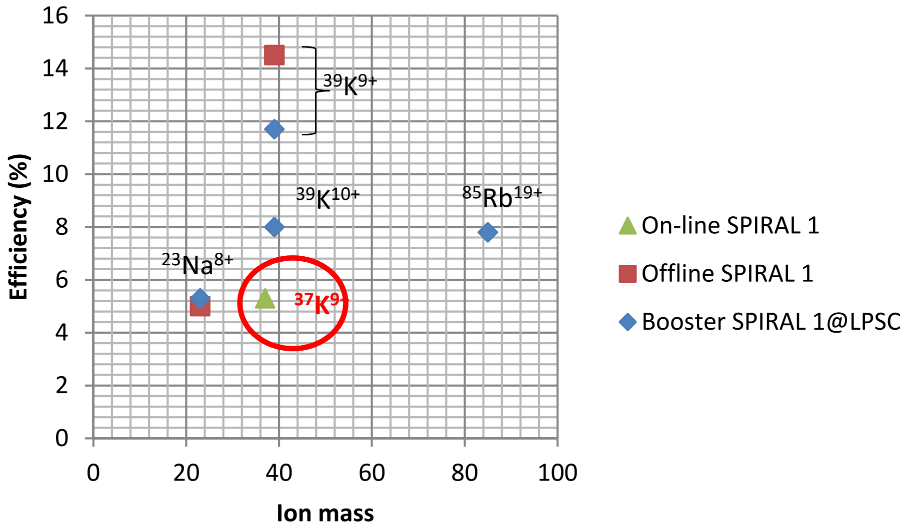
5,3% $^{39}K^{1+} \rightarrow {}^{39}K^{9+}$

Very rapidly obtained! ~2 h

Preliminary number, a factor of 2 within reach

First on-line charge breeding

$^{37}K^{9+}$ activity monitored on tape station



5,3% $^{39}K^{1+} \rightarrow {}^{39}K^{9+}$

Very rapidly obtained! ~2 h

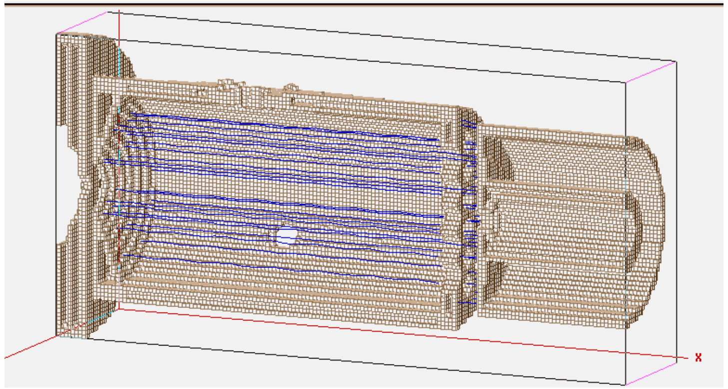
Preliminary number, a factor of 2 within reach

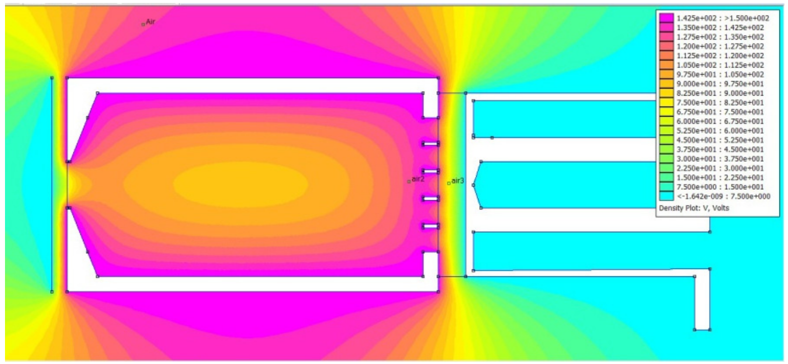
Large ΔV measured :-77V

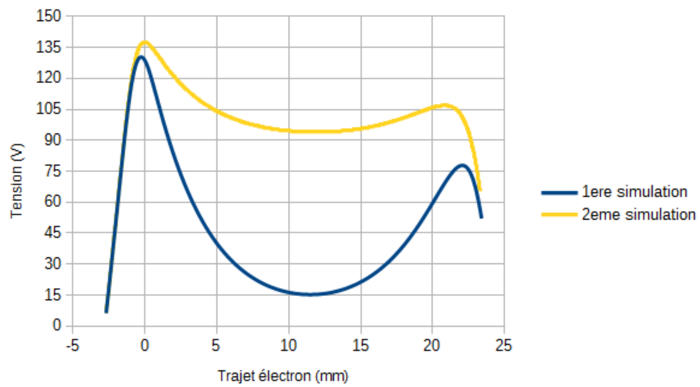
High ebeam current ~300mA
Large decrease of the energy due to the electron beam space charge?

FEBIAD source – investigations after experiments

SIMION 8.1 + FEMM 4.2







High ebeam current ~300mA
Large decrease of the energy due to the electron beam space charge: -55V

B. Pellerin, DUT Mesures physiques

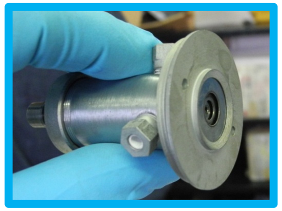
Explaining qualitatively the large energy shift observed on-line with the charge breeder:

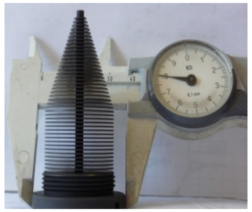
$^{37}K^{+} \rightarrow {}^{37}K^{9+}$

Vplasma ~-70V (exp) compared to ~-55V (theor.) ***Work in progress***

Beam and target R&D

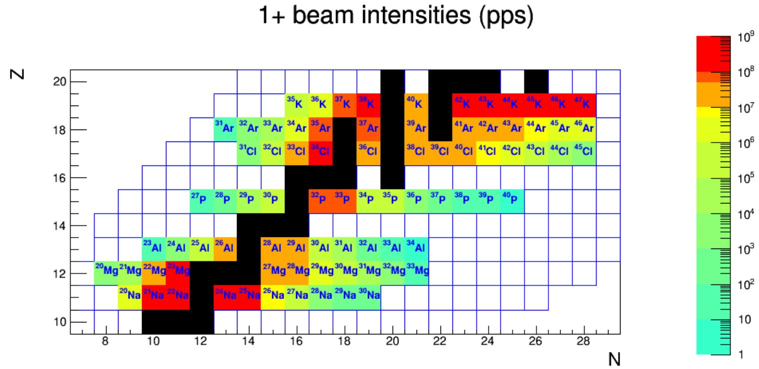
From day 1 beams…





ISOLDE FEBIAD + Graphite targets

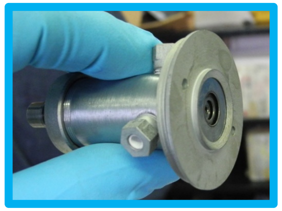
2019-

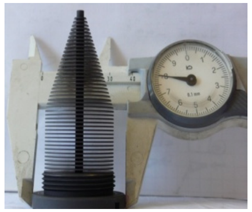


To longer term: 2020-…

Beam and target R&D

From day 1 beams…

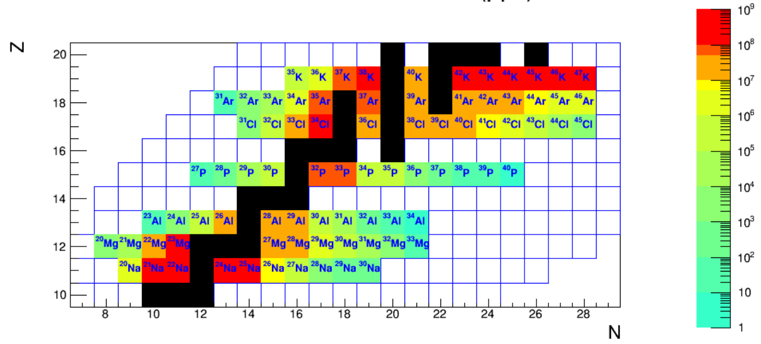




ISOLDE FEBIAD + Graphite targets

2019-

1+ beam intensities (pps)



To longer term: 2020-…

Beam and target R&D

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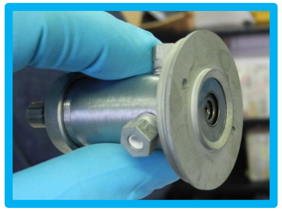

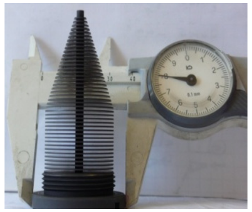

ISOLDE FEBIAD + Graphite targets

2019-

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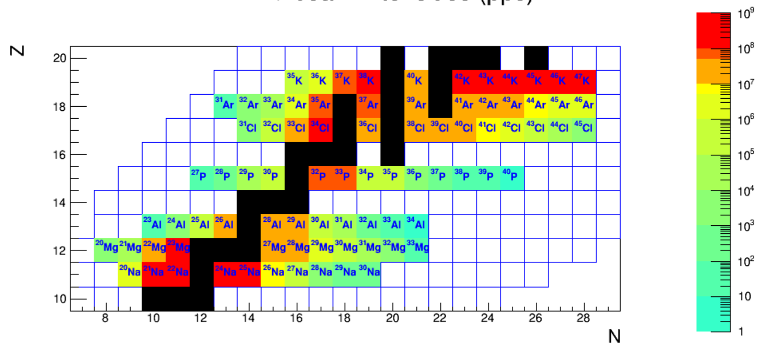

To longer term: 2020-…

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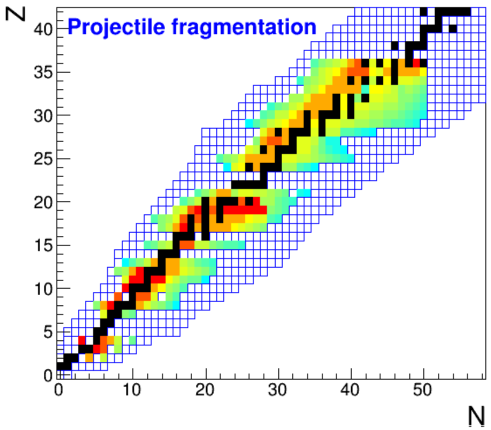

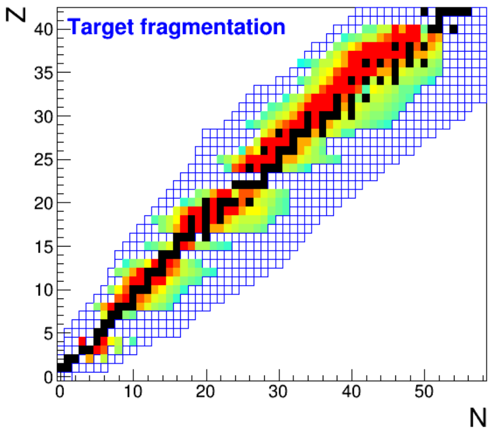

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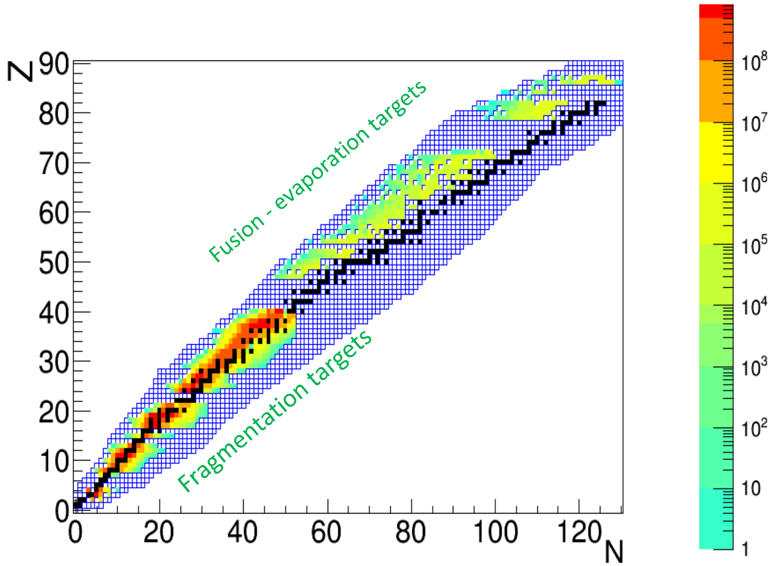

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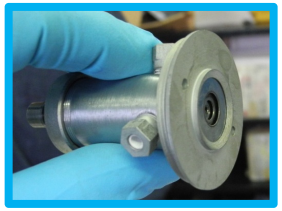
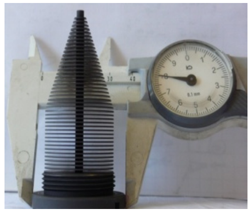
From day 1 beams…

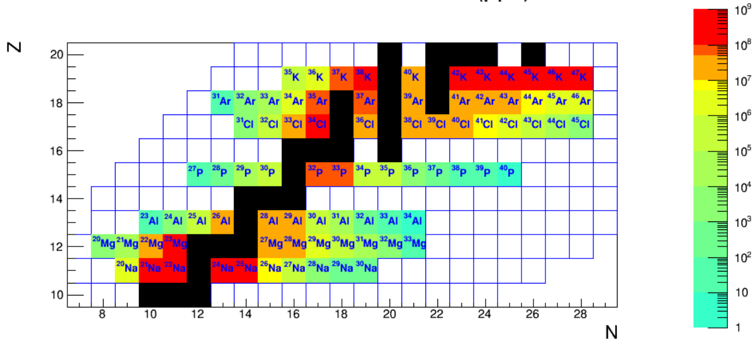




ISOLDE FEBIAD + Graphite targets

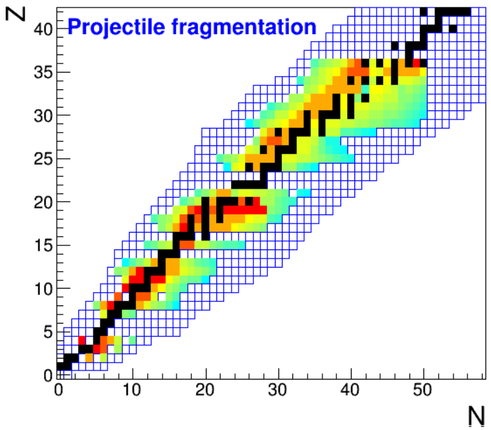
2019-

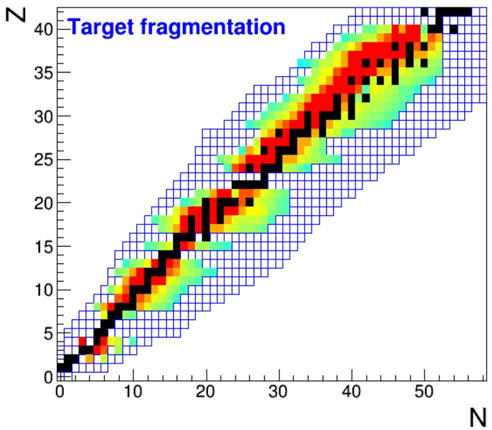
1+ beam intensities (pps)



To longer term: 2020-…

1+ beam intensities (pps)





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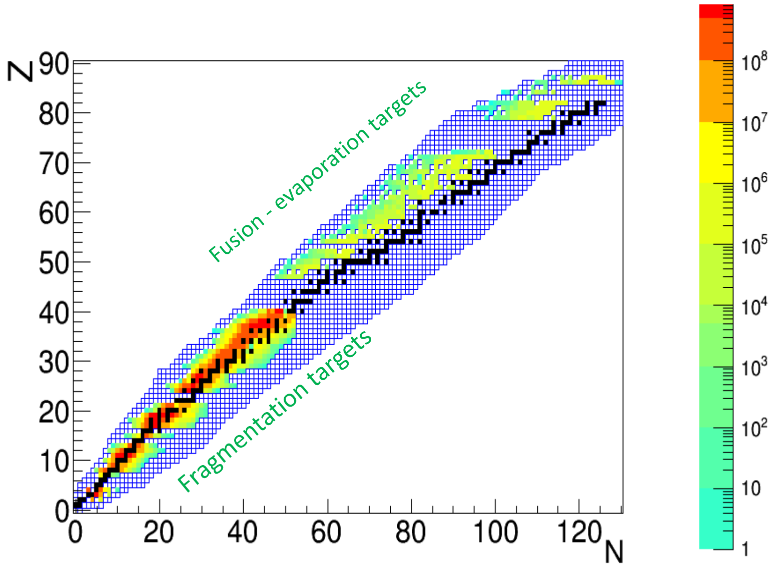

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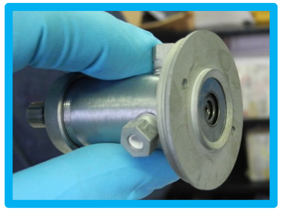

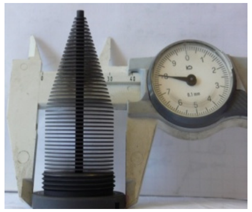

ISOLDE FEBIAD + Graphite targets

2019-

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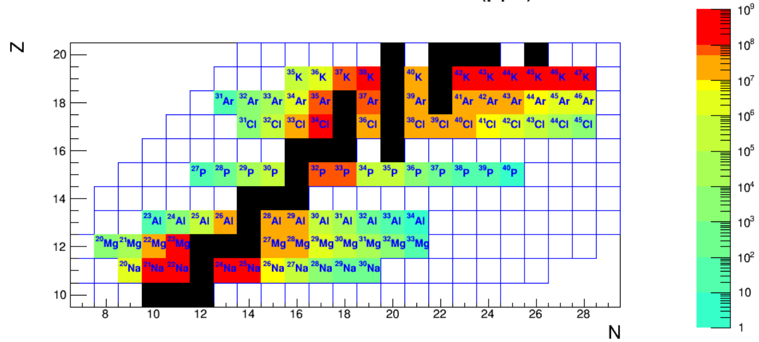
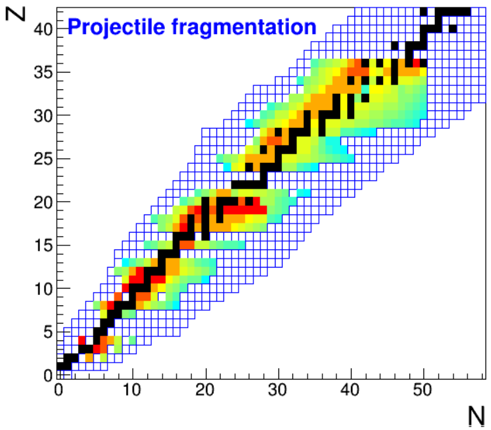
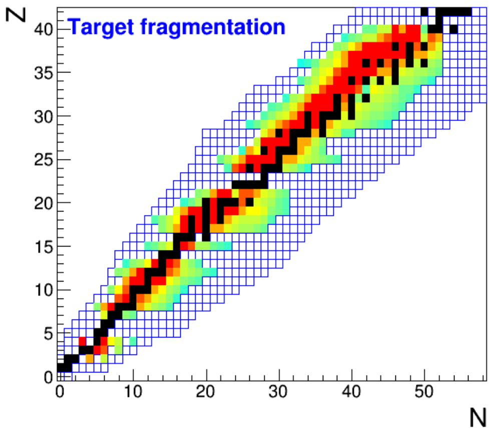


To longer term: 2020-…

1+ beam intensities (pps)





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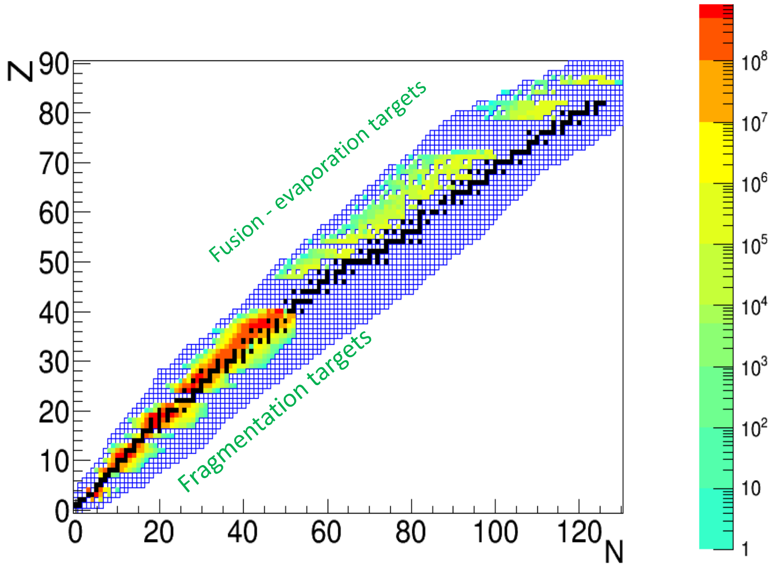
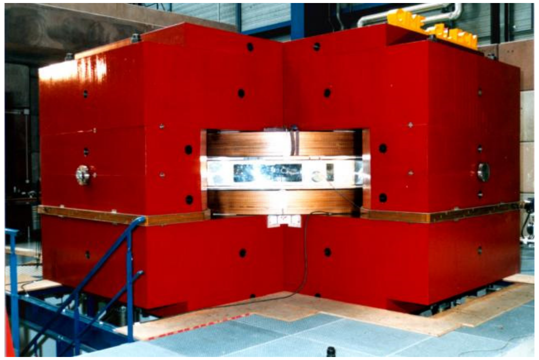


+ ion source developments

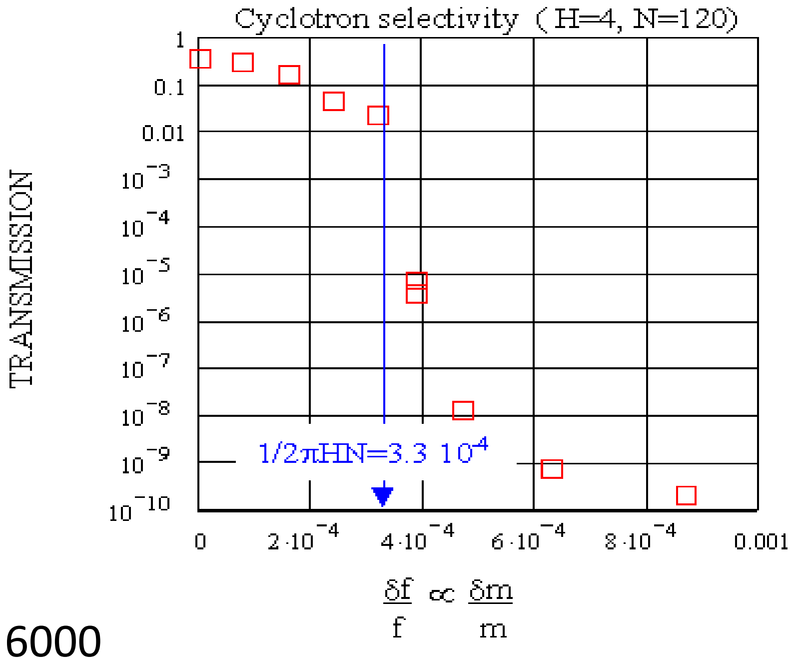
Collaborations within EURISOL/Beamlab within ENSAR2

Beam purity

Known limitation of « universal » ion sources



CIME cyclotron



Suppression ~10 for R=m/δm~1/(2πHN) up to 6000

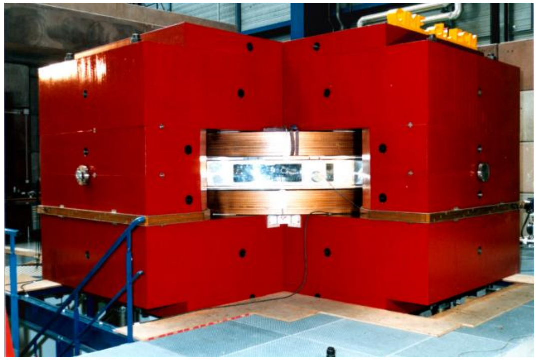
Suppression ~10^6 for R<2000

B. Jacquot et al, *GANIL status report*

http://arxiv.org/ftp/nucl-ex/papers/0502/0502016.pdf

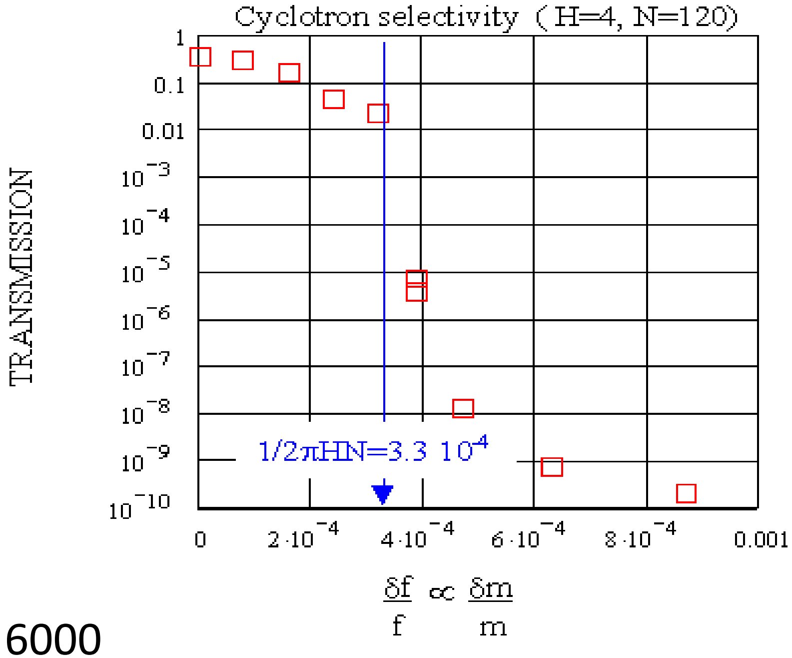
Beam purity

Known limitation of « universal » ion sources



CIME cyclotron

Suppression ~10 for R=m/δm~1/(2πHN) up to 6000
Suppression ~10^6 for R<2000



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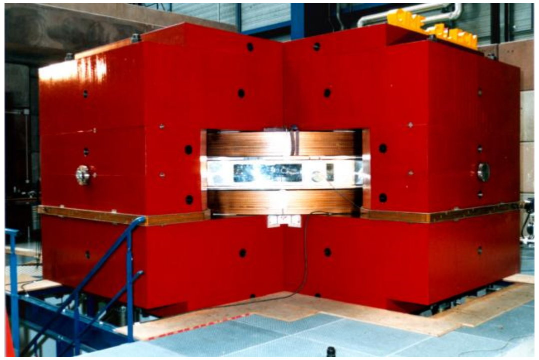

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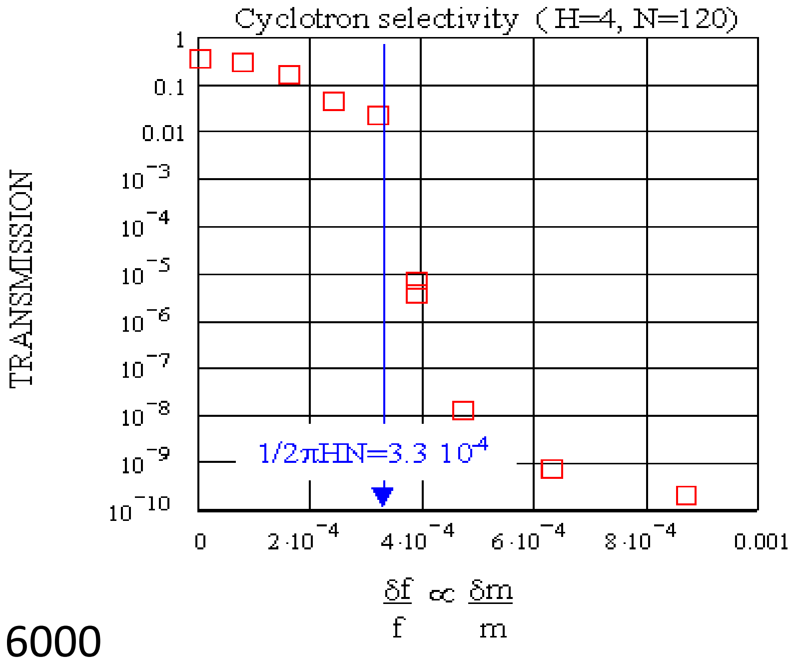

Suppression ~10 for $R=m/\delta m \sim 1/(2\pi HN)$ up to 6000

Suppression ~10^6 for R<2000

B. Jacquot et al, *GANIL status report*

http://arxiv.org/ftp/nucl-ex/papers/0502/0502016.pdf

- Does not apply to non accelerated beams
- Is regularly not sufficient: ex ^{56}Ni vs ^{56}Fe, ^{56}Co, ^{28}Al vs ^{28}Mg, etc
  - Stripping to Q=Z-1, Z when Z is not too high

Beam purity

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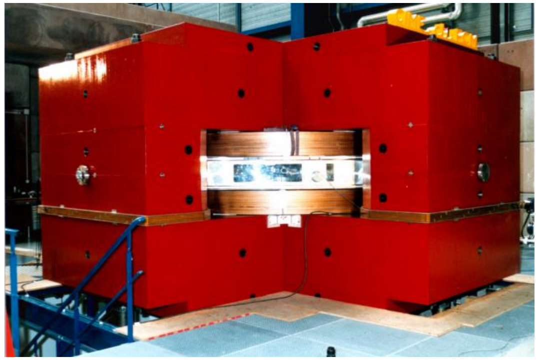

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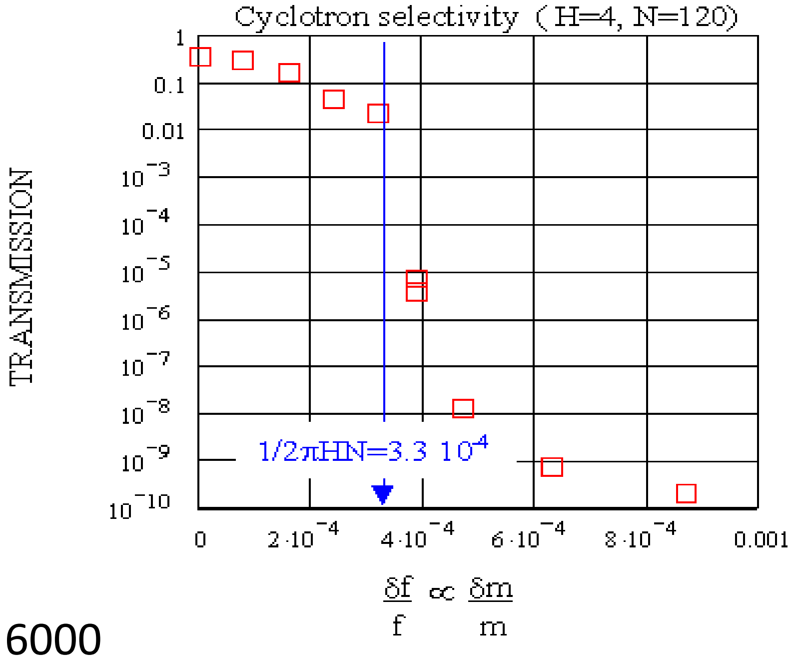

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Need for

* Universal but selective sources

* Other separation techniques

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ISOL beam production and processes

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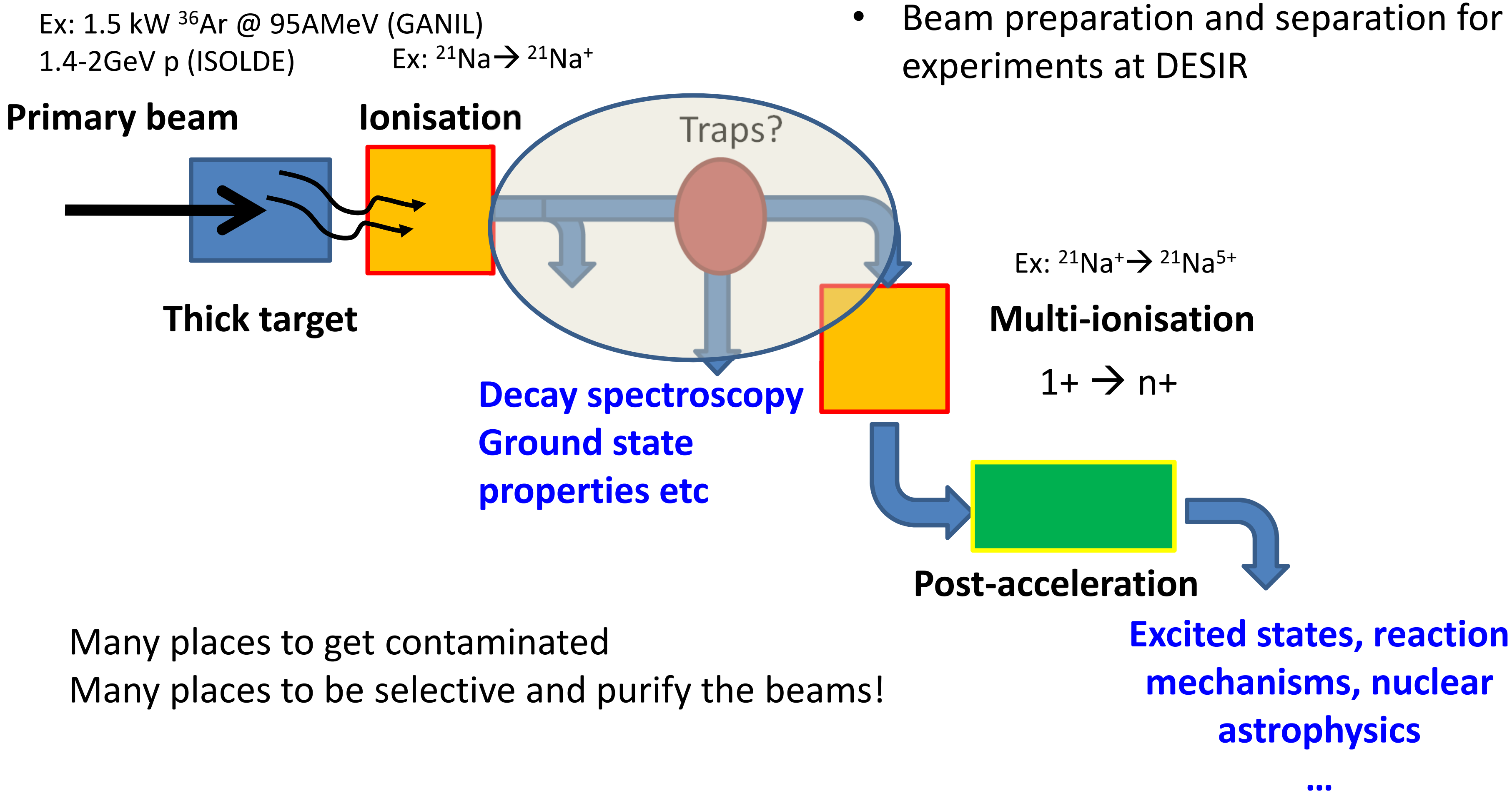
- **Gas cell and trap developments at S3**
- Beam preparation and separation for experiments at DESIR

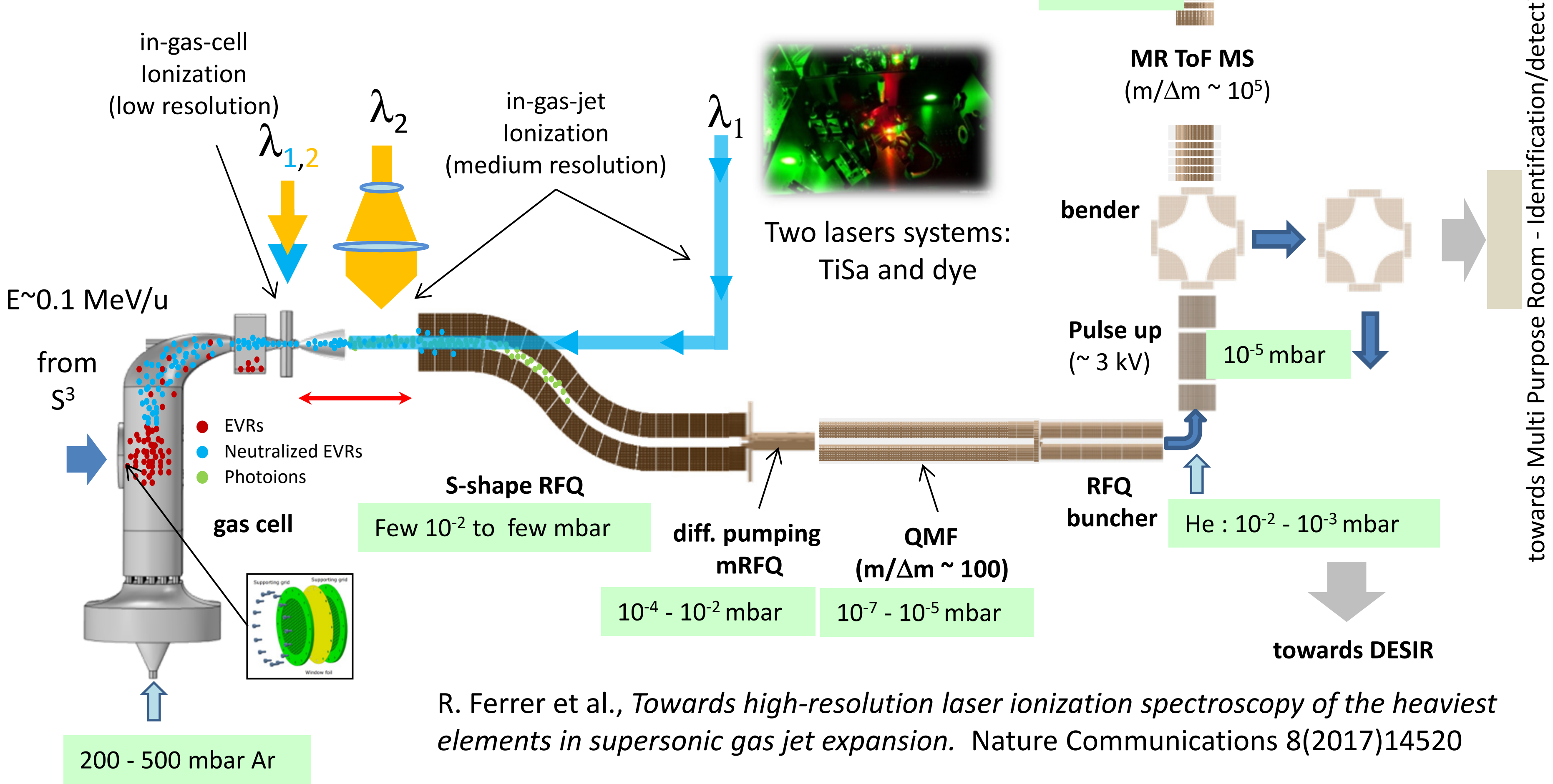


Many places to get contaminated
Many places to be selective and purify the beams!

S³-LEB @ SPIRAL2

KU LEUVEN — (Gas cell studies, laser system)
IPN Institut de Physique Nucléaire Orsay — (Gas cell)
lpc caen Laboratoire de physique corpusculaire — (RFQs)
GANIL spiral2 — (mr-TOF-ms, laser system, infractructure, safety)
LARISSA, JGU Johannes Gutenberg Universität Mainz, University of Jyväskylä — (narrow band-width laser pre-studies at MARA)

Neutralisation and resonant laser ionisation

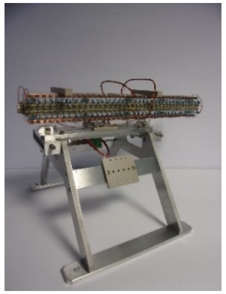


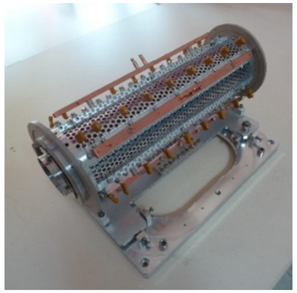
R. Ferrer et al., *Towards high-resolution laser ionization spectroscopy of the heaviest elements in supersonic gas jet expansion.* Nature Communications 8(2017)14520

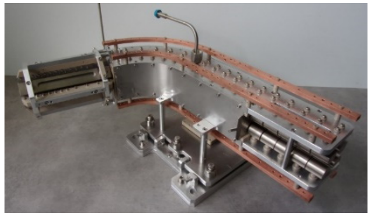
C. Granados et al., *The in–Gas Laser Ionization and Spectroscopy (IGLIS) of actinium isotopes around the N =126 closed shell*, Phys. Rev. C 96(2017)054331

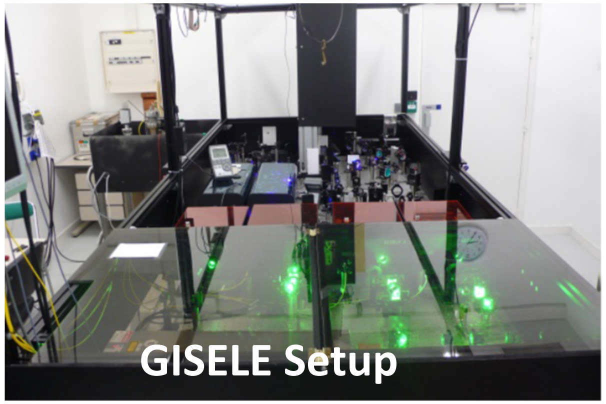
S3-LEB at LPC Caen

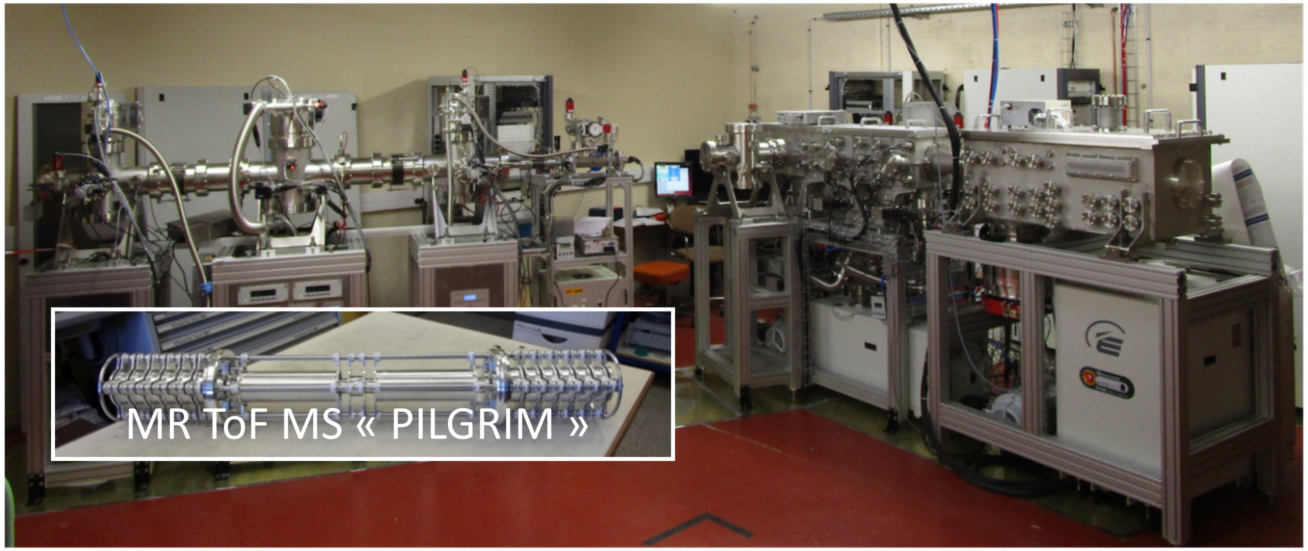
RFQs structures

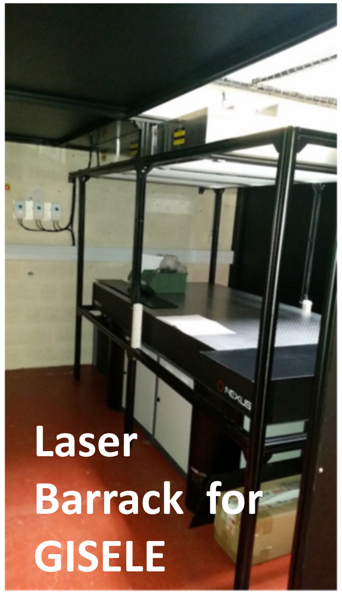












RFQs under commissioning

Gas cell +laser commissioning in the course of 2019

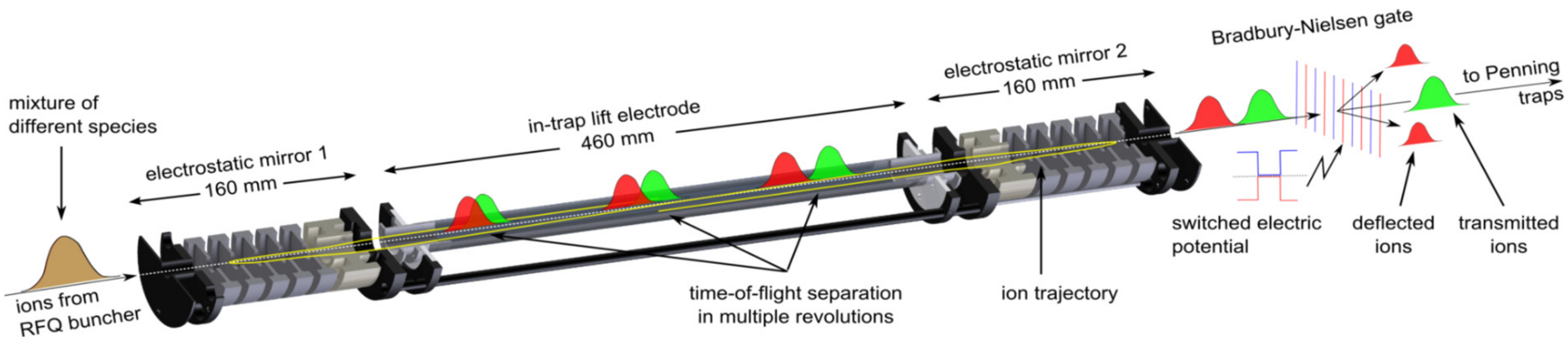
MR-ToF-MS technique

- Typical trapping time: **10-100 ms**
- Resolving power: **up to x·10^5**
- Mass measurement: **δm/m~5·10^{-7}**

for intensities down to **fractions of pps**

ISOLTRAP MR ToF MS:
R. Wolf et al., IJMS 349 (2013)123 and ref therein

$^{53-54}$Ca mass measurements:
F. Wienholtz et al., Nature **498** (2013) 346-349



Photograph Courtesy : R. N. Wolf (University of Greifswald)

Such performances require
- Cooled and bunched beams, with δt <100ns
- High vacuum (<10^{-8} mbar)
- High precision and stability voltage supplies

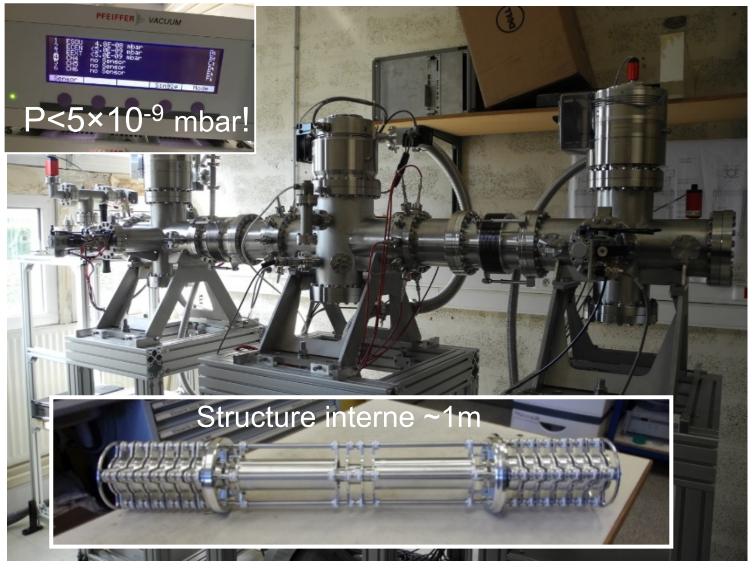
PILGRIM

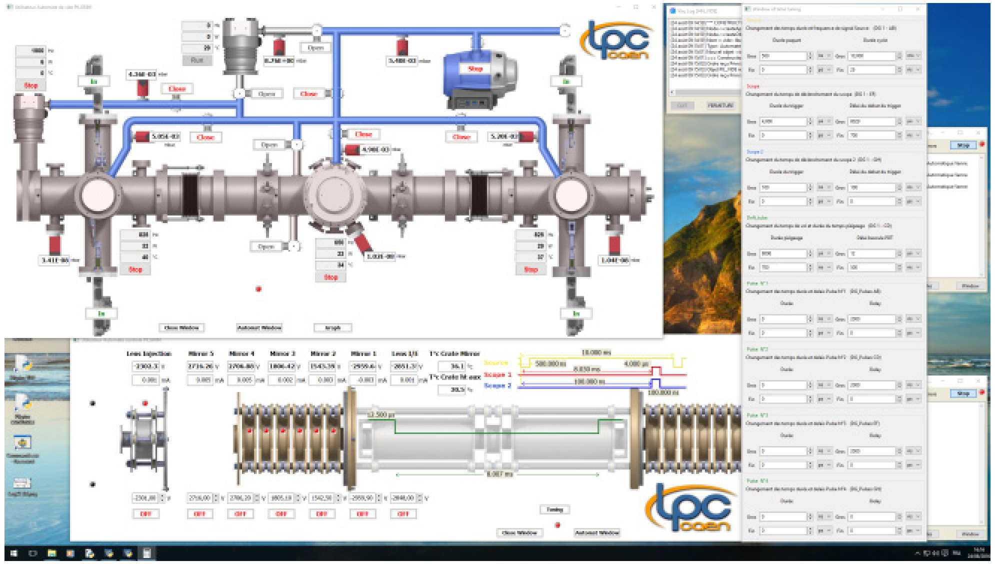
Piège à Ions Linéaire du Ganil pour la Résolution des Isobares et la mesure de Masse

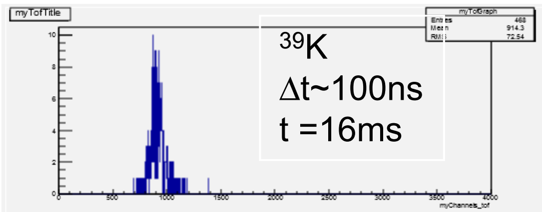
laboratoire commun CEA/DSM CNRS/IN2P3

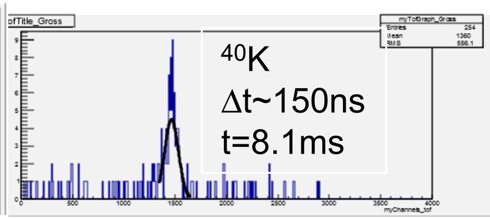
Under commissioning at LPC Caen

PhD thesis B. M. Retailleau









- $R=\Delta t/(2t)$~65,000 in 5 days (!)
- No trapping losses up to t~32ms
- Optimizations going on

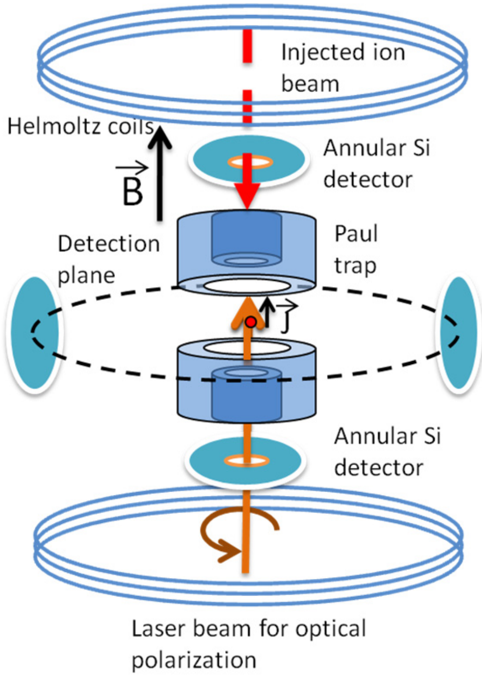
Goals: R>100,000 and $\delta m/m \sim 10^{-6}$

Design, simulation et tests (GANIL)
P. Chauveau, P. Delahaye, Y Liu, A. Shornikov
Collaboration avec uni – Greifswald
R. Wolf, M. Rosenbusch et L. Schweikhard

Design mécanique et fabrication, électronique et slow control (LPC Caen)
Y. Merrer, J. Lory, P. Desrues, J. F. com, C. Vandamme, J. Brégeault et F. Boumard

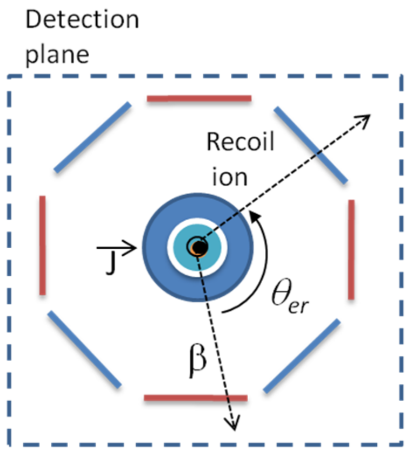
Traps and their limitations…

THE MORA PROJECT
MATTER'S ORIGIN FROM RADIOACTIVITY



In trap optical polarization

Azimuthal plane



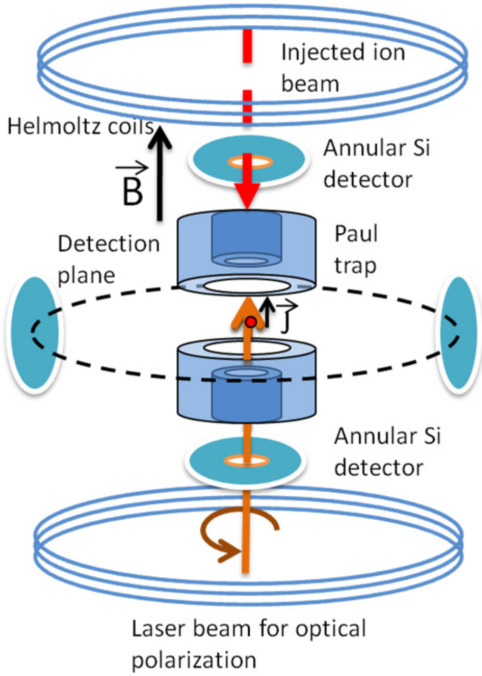
CP violating correlation:

D correlation

RÉGION NORMANDIE

Traps and their limitations…

Goal: accumulate up to $5 \cdot 10^{6}$ ions ($^{23}Mg^{+}$ or $^{39}Ca^{+}$) per bunch
Challenge: Separation from 10^{7}-10^{9} pps of stable $^{23}Na^{+}$ or $^{39}K^{+}$



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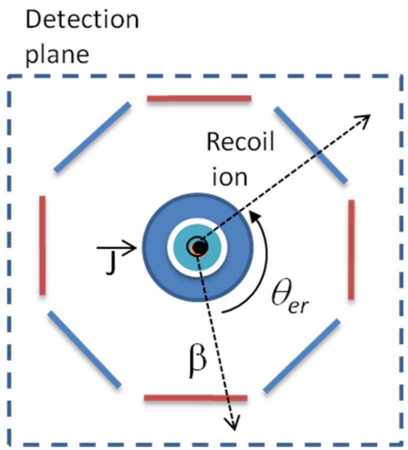

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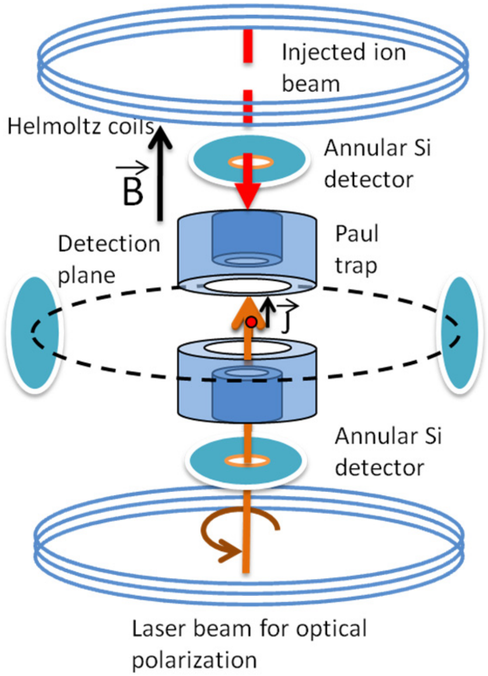

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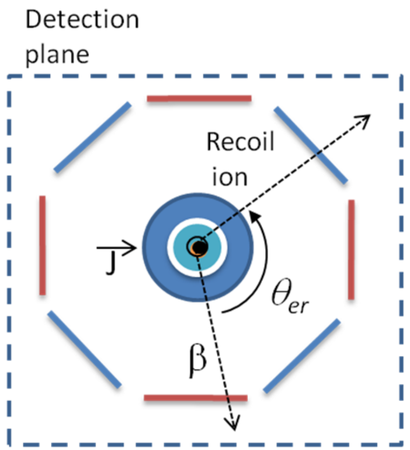

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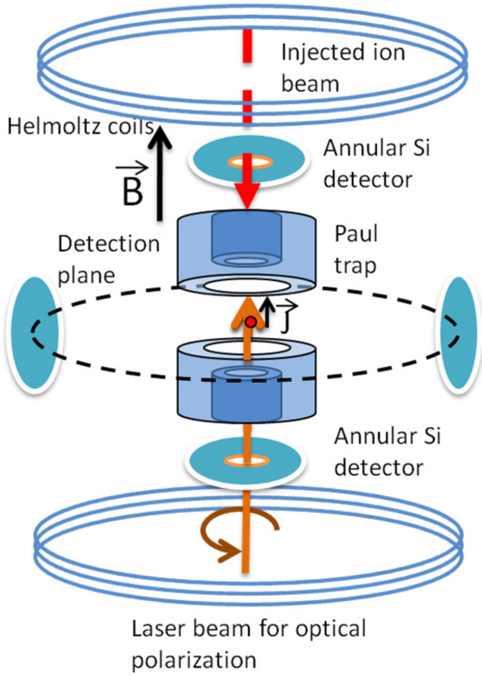

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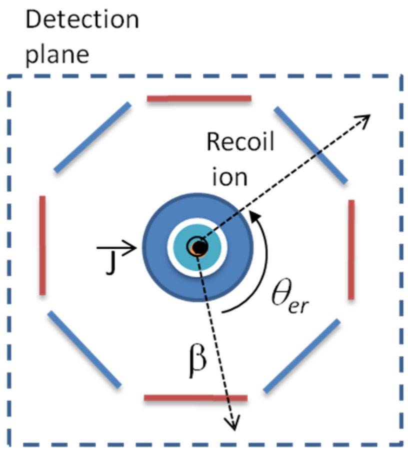

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RÉGION NORMANDIE

Low energy ions
Space charge limits!

RFQ cooler bunchers:
10^6-10^7/bunch
MR-ToF-MS:
separation up to 10^4/bunch!!

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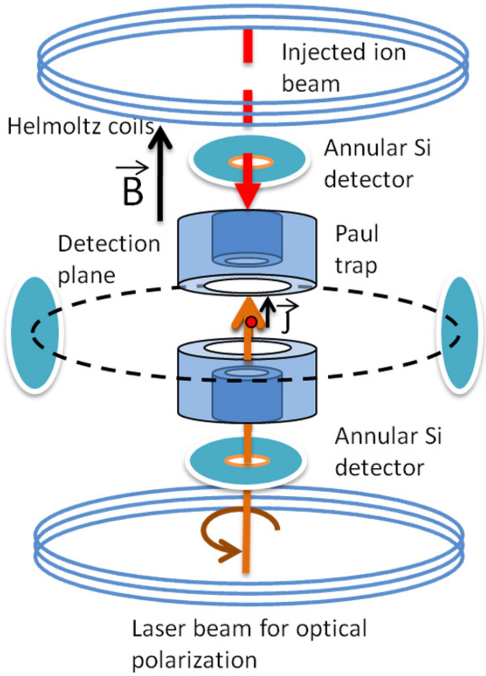

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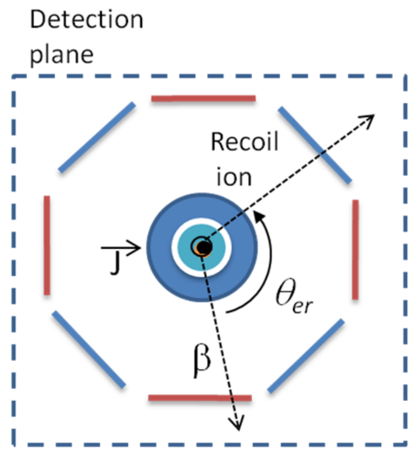

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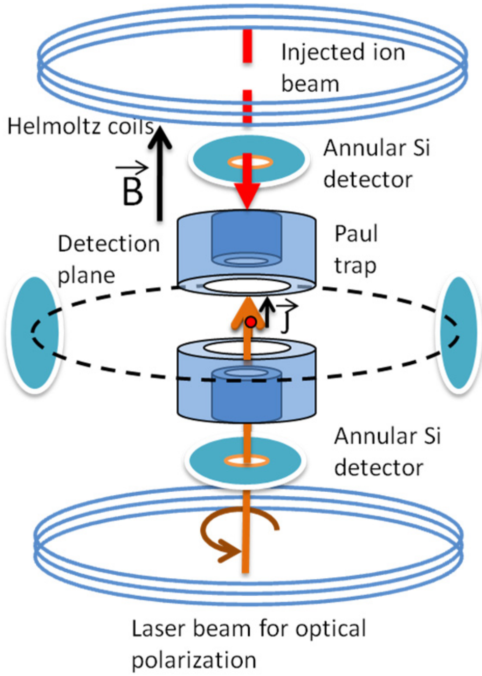

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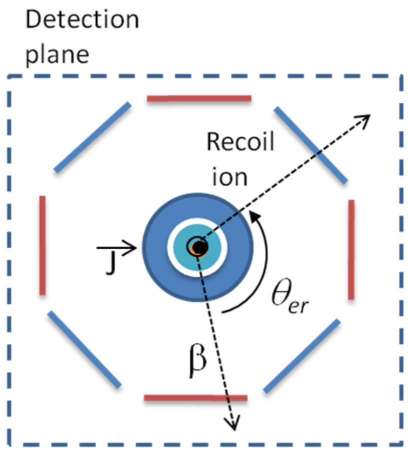

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Need of a stacking trap
OR
A high intensity separator

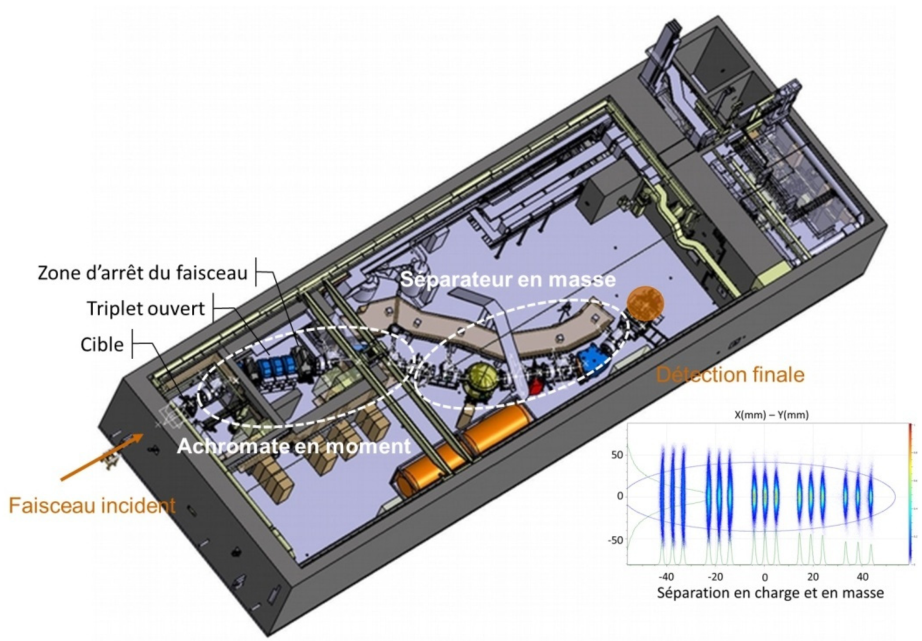
D measurement at GANIL-SPIRAL 2

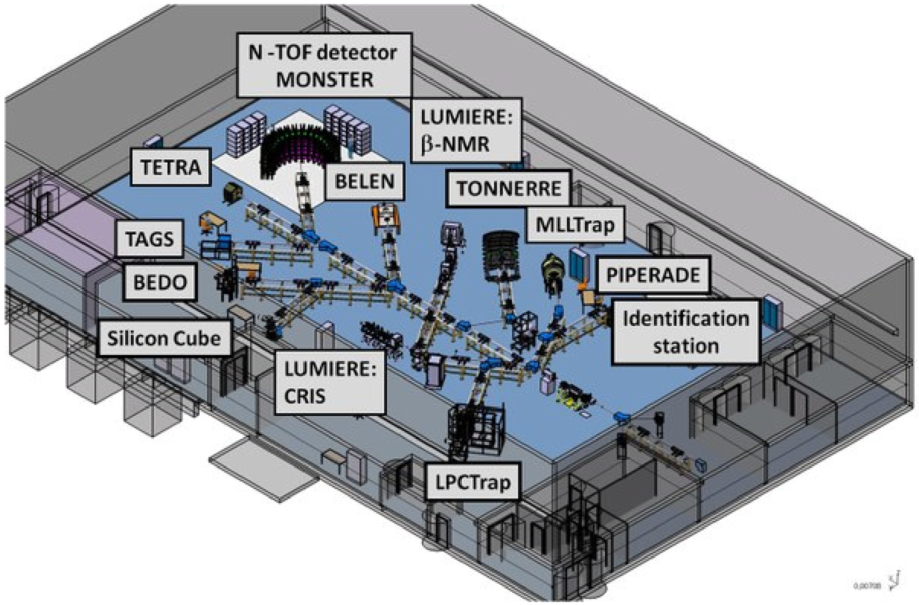
Low Energy Beams :

S3 LEB Traps and laser setups **DESIR**

2022-…

Ground state properties and β-decay of exotic nuclei





Beams from fusion evaporation using the SPIRAL 2 LINAC

Gas cell technique: interesting perspectives for ^{39}Ca: up to 10^7 pps

Beams from S3 – LEB and SPIRAL / GANIL

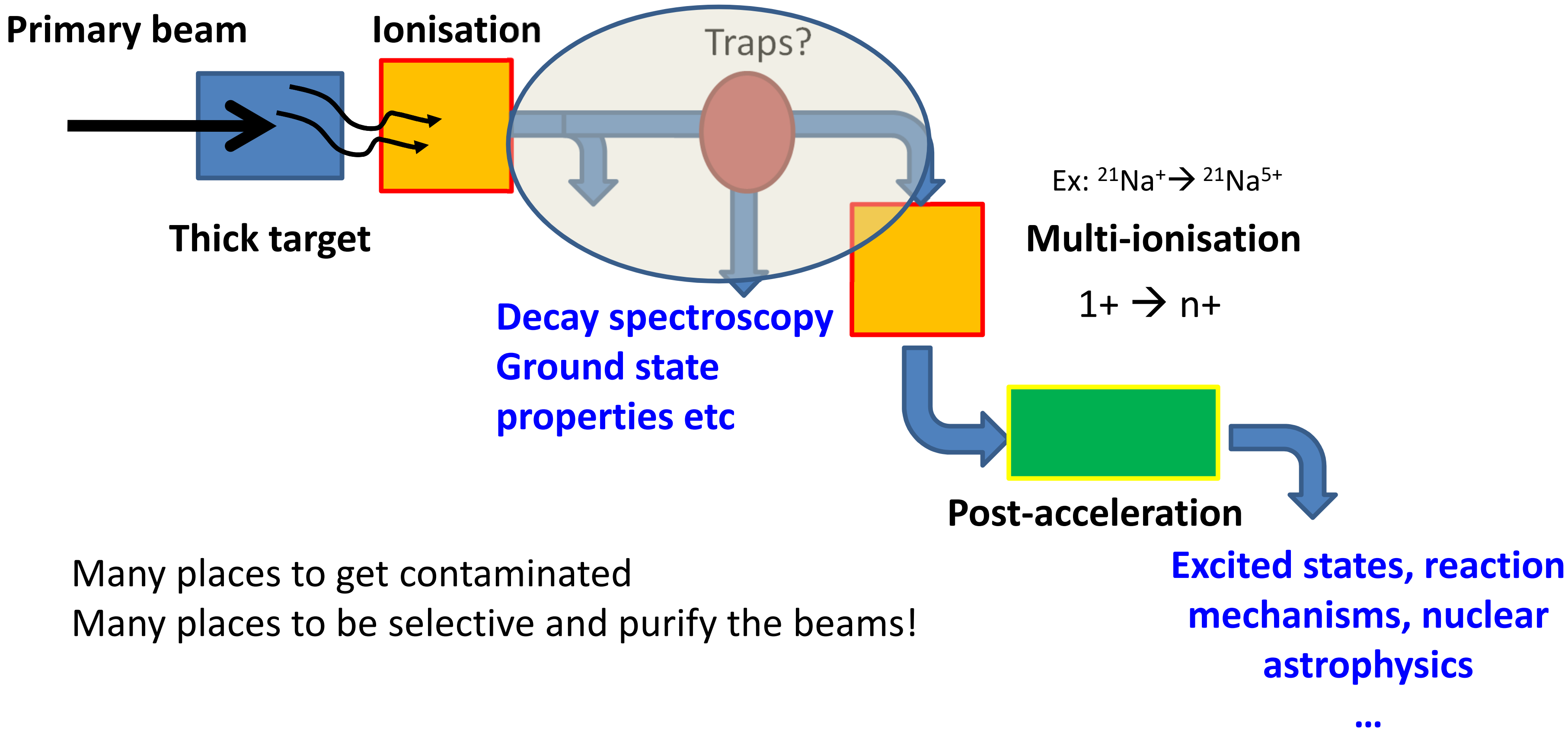
SPIRAL 1: highest yields for ^{23}Mg > 10^8 pps

Table of content:
ISOL beam production and processes

- Enlarging the production at SPIRAL 1
- Gas cell and trap developments at S3
- **Beam preparation and separation for experiments at DESIR**

Ex: 1.5 kW ^{36}Ar @ 95AMeV (GANIL)
1.4-2GeV p (ISOLDE)

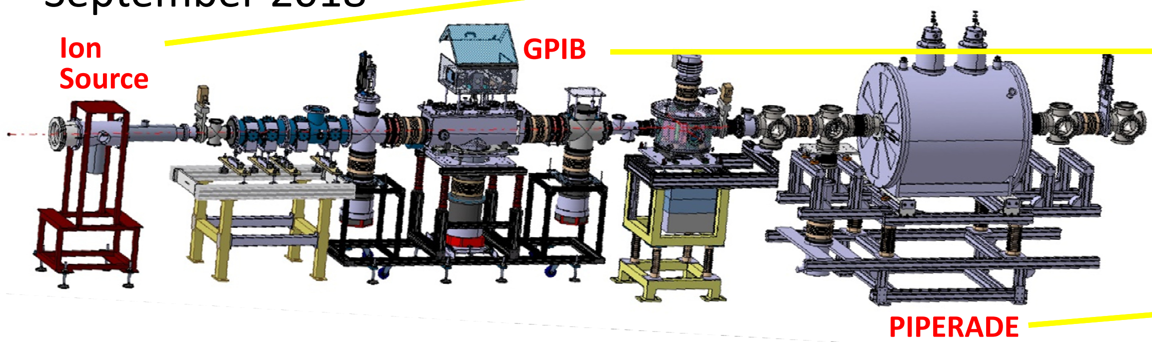
Ex: $^{21}Na \rightarrow {}^{21}Na^{+}$

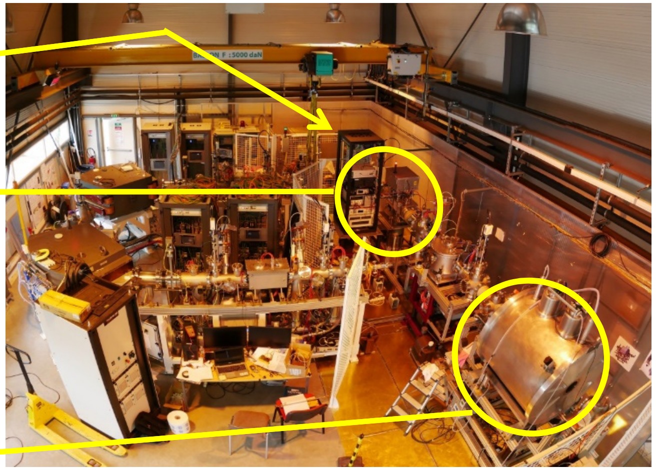


Many places to get contaminated
Many places to be selective and purify the beams!

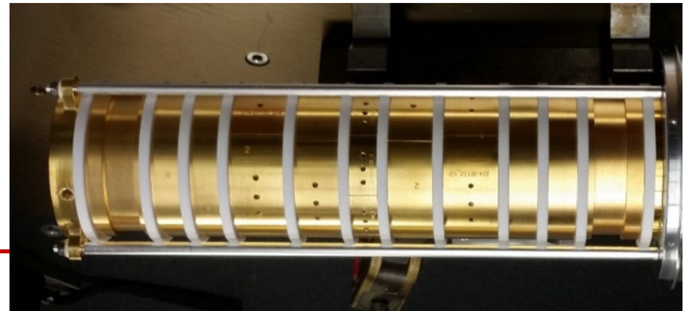
The PIPERADE project!

PIPERADE@ CENBG
September 2018

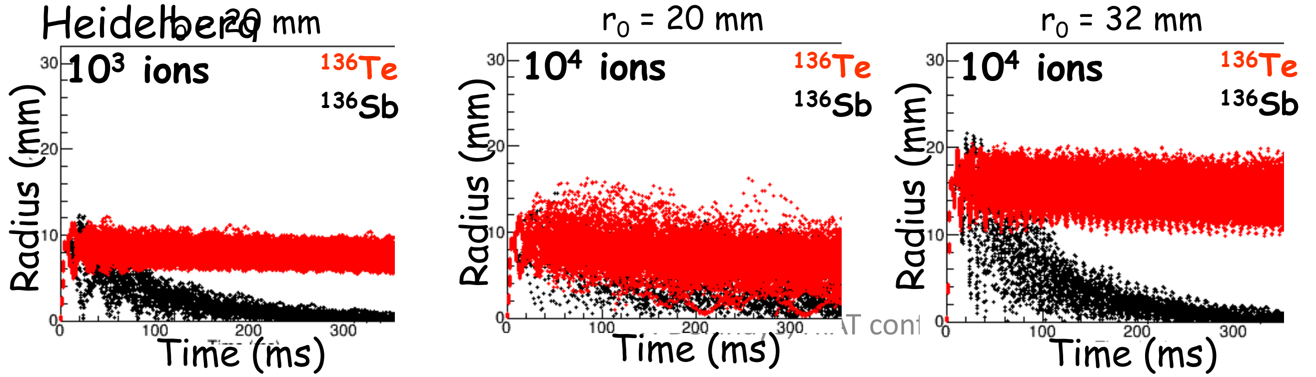


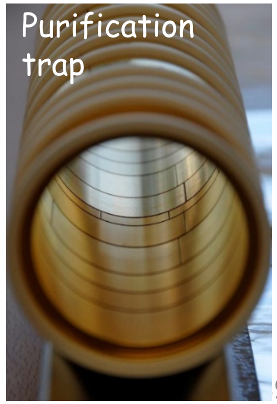


- Double Penning Trap for purification/accumulation
  (Increase statistics of the measurement)
- Large inner radius (Separate larger samples)
- Construction/assembly completed @ MPIK Heidelberg



Simulations of resonant buffer gas cooling

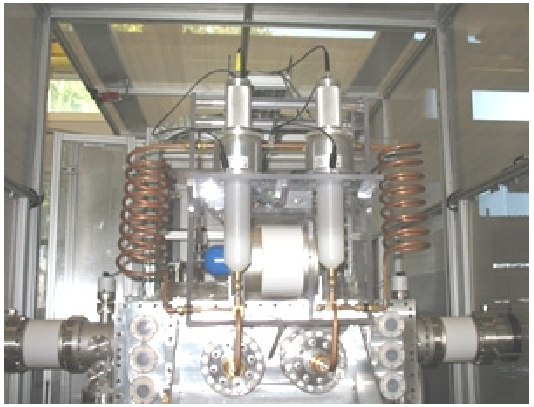




Under commissioning

The DESIR HRS

High intensity cooler

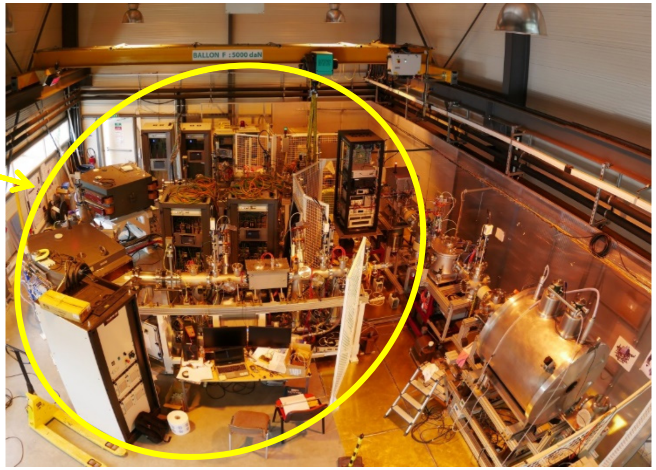


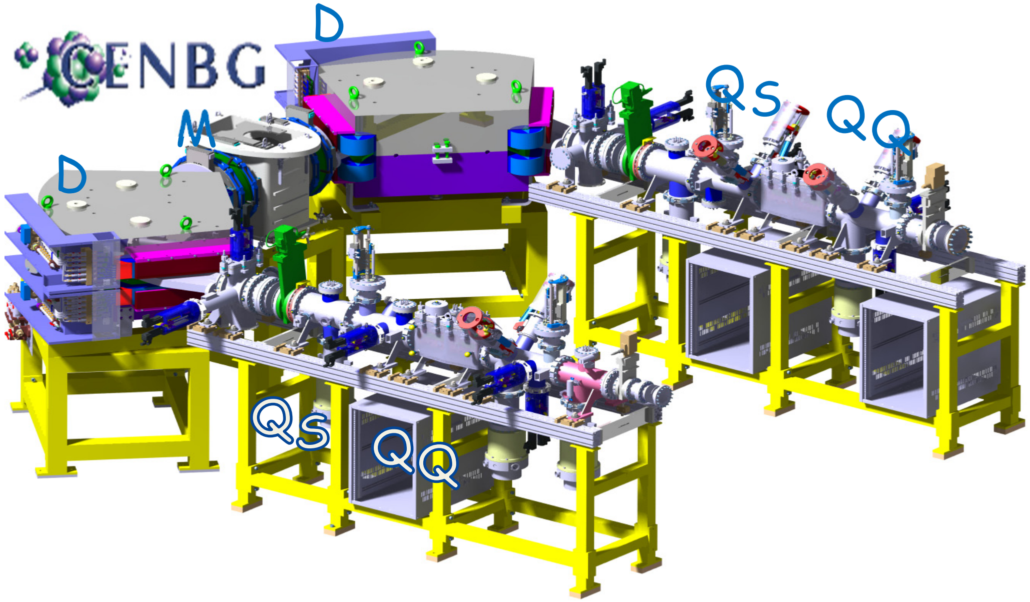
SHIRAC cooler

Space charge →
RF system
2.1 MHz to 4.9 MHz
Vpp: 8kV

J. F. Cam and coworkers

HRS!!





T. Kurtukian – Nieto, L. Serani and coworkers

Under commissioning

Transfer matrix

	(x,)	(a)	(y,)	(b,)
x	−1.0000	−3.6499	0.0	0.0
a	−0.40E−5	−1.0000	0.0	0.0
y	0.0	0.0	1.0000	0.50E−4
b	0.0	0.0	−0.60E−6	1.0000
δ m	−31.32	−57.16	0.0	0.0

- ✓ point-to-point both x and y
- ✓ Mirror symmetric
- ✓ (x|δ) = -31.32 cm/%

With cooled beams: **R~31000**
(Cosy infinity)

Summary

- Some of the R&D hot topics in RIB processes have been illustrated using the commissionning of different facilities for GANIL-SPIRAL 2
    - Plasma 1+ source (FEBIAD)
        - Proven potential for universal RIB ionisation
        - Efficiency is not high but may be improved
        - Physical processes under intense scrutiny from the community
    - ECR Charge breeding
        - Capture efficiencies are improving
        - R&D on reducing the beam contamination is ongoing
    - Ion traps
        - Established techniques for beam preparation (cooling and bunching)
        - Separation of low energy exotic beams is possible ($I<10^6$pps)
        - Space charge limitations have motivated different developments
            - » High capacity RFQ coolers, Penning traps, MR ToF MS

Thanks a lot for your attention!

And thanks a lot to my colleagues!!

CENBG

L. Sérani
T. Kurtukian-Nietao
P. Ascher
S. Grévy

lpc caen

X. Fléchard
J. F. Cam

+N. Lecesne, H. Franberg, S3 team

...