laboratoire commun CEA/DRF CNRS/IN2P3

Radioactive ion beams from SPIRAL1: status, limitations and development

Pierre Chauveau

Outline

Introduction : SPIRAL1

I. Beam production : sources

II. Charge breeding and acceleration

III. Beam purity

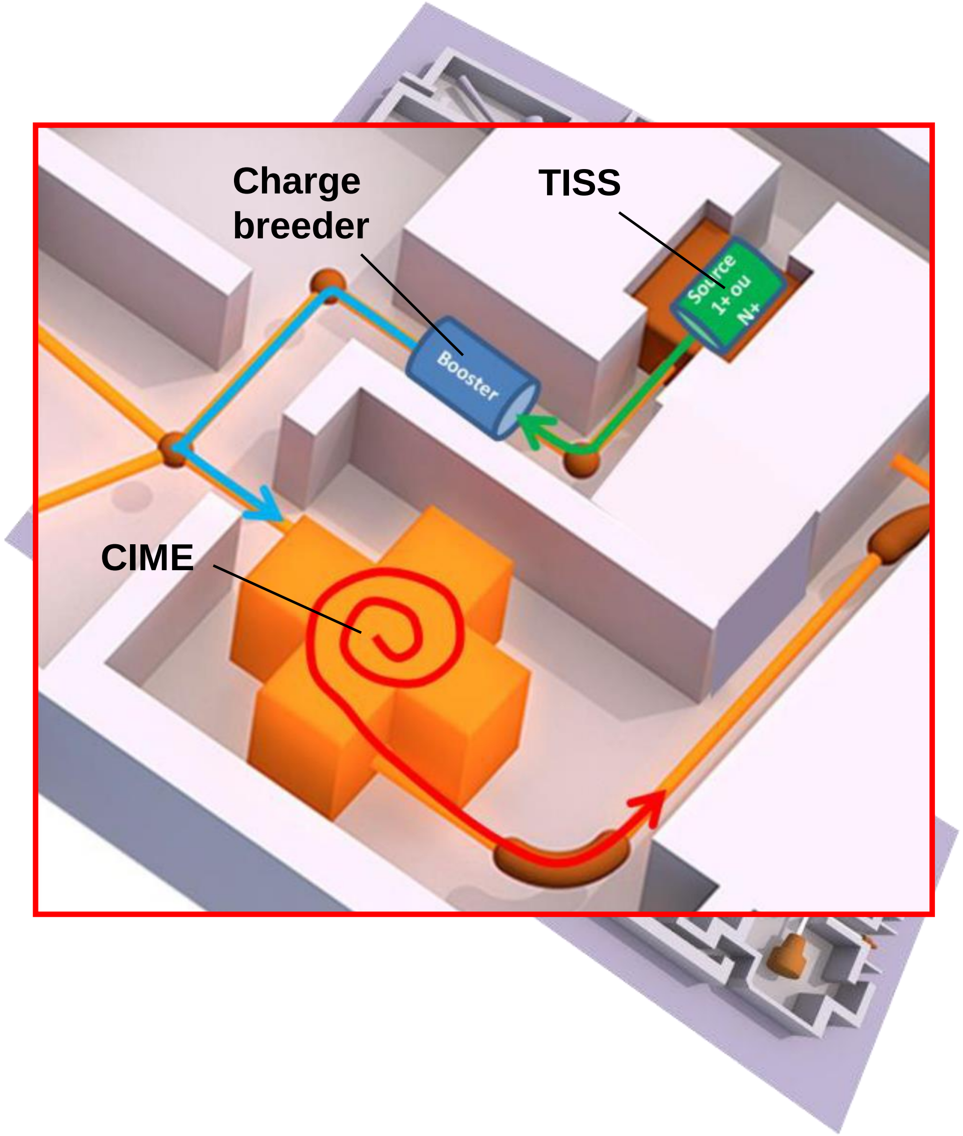
Status

What are the limits ?

How are we improving it / How could we improve it ?

Conclusion

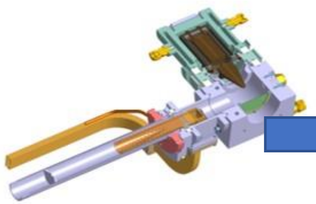
Introduction - SPIRAL



SPIRAL1

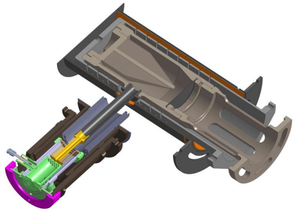
- New target Ion Source Systems (FEBIAD)

New 1+ sources

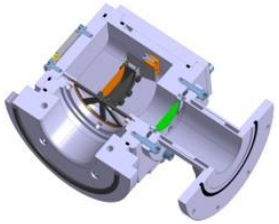


Nanogan
For gaz

MonoNaKe
For alkaline

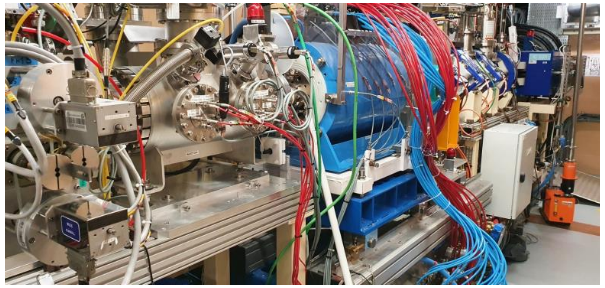


FEBIAD
For condensable



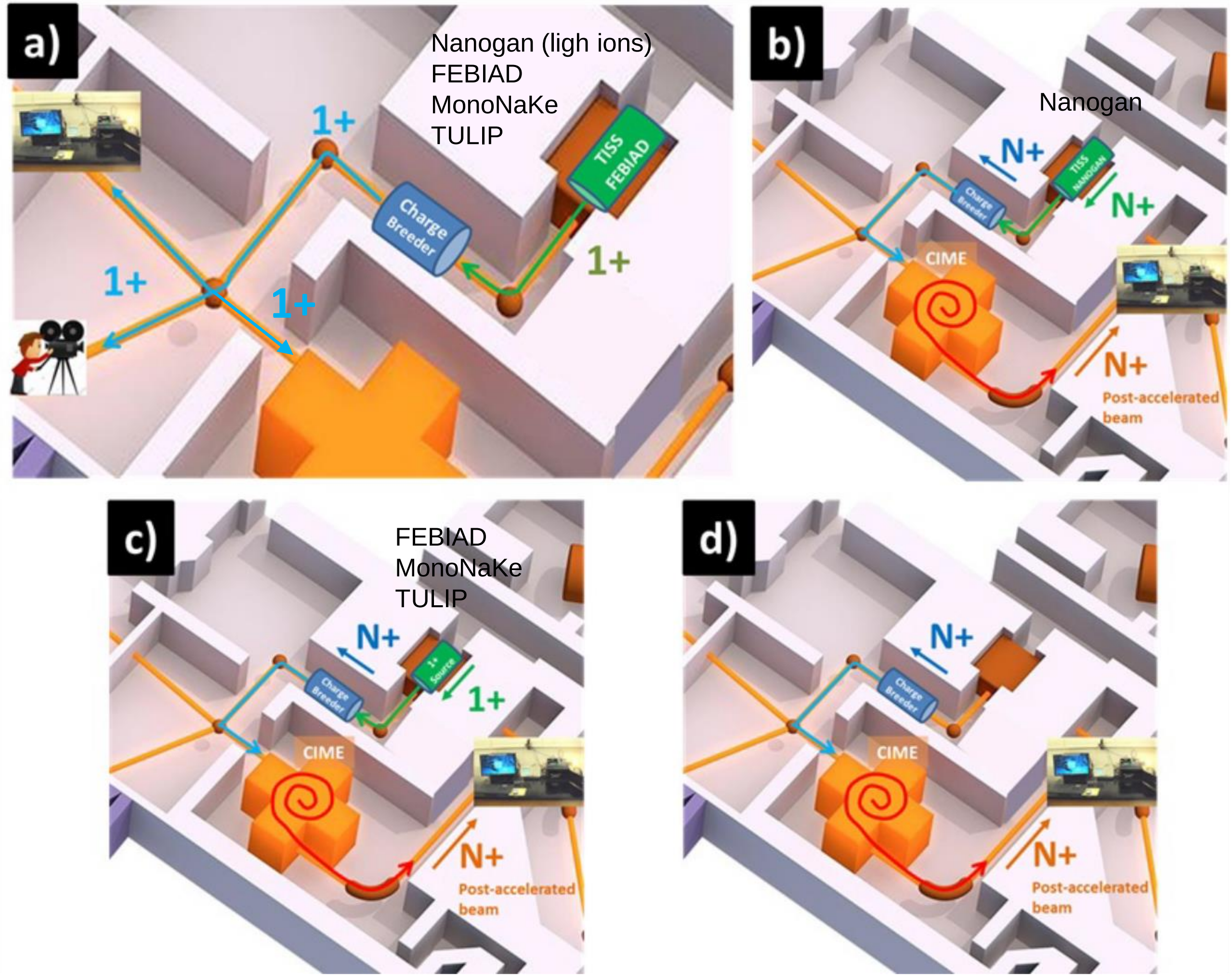
TULIP
For proton rich isotopes

- The charge breeder



- CIME

SPIRAL1 modes



L. Maunoury *et al*, 2018 *JINST* **13** C12022

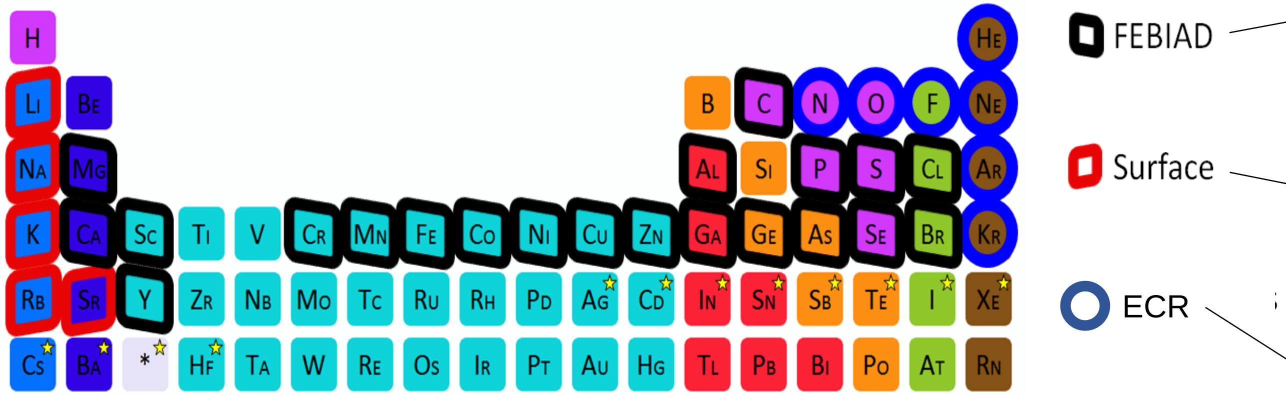
a) 1+ shooting through, for identification, low energy (10-20 keV) physics in LIRAT and soon, low energy (2 MeV/A) post-acceleration of very ligh ions

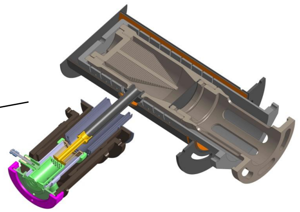
b) N+ shooting through for post-acceleration (up to 24 MeV/A)

c) 1+/N+ for post-acceleration (up to 24 MeV/A)

d) SP1CB as a stable source for post-acceleration (up to 24 MeV/A), for beam tuning or experiments with stable beams

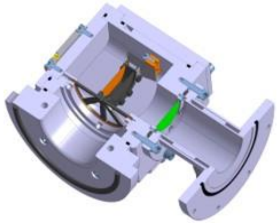
Beam production



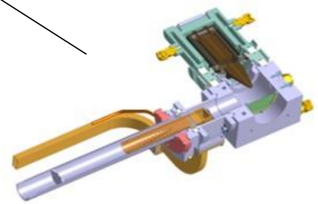


FEBIAD
For condensable

MonoNaKe
For alkaline



TULIP
For proton rich isotopes



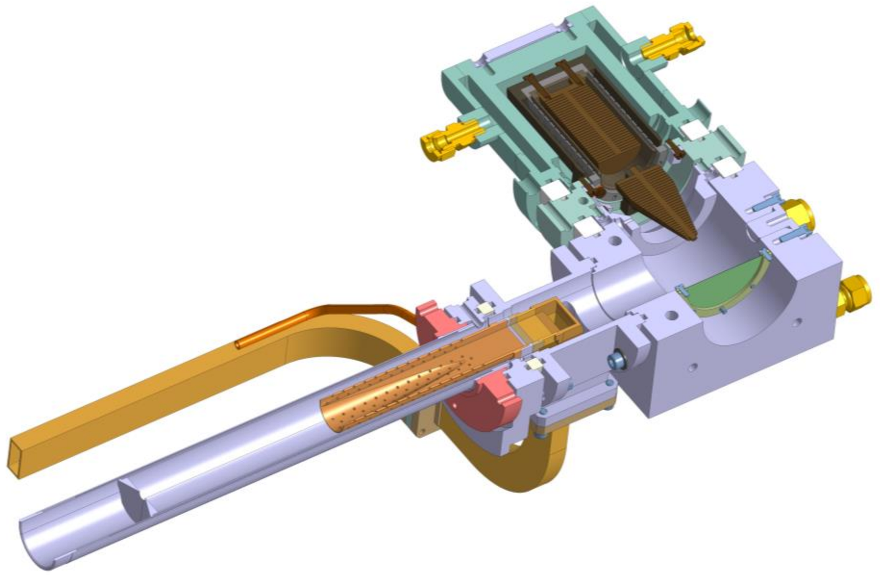
Nanogan
For gaz

Limitations

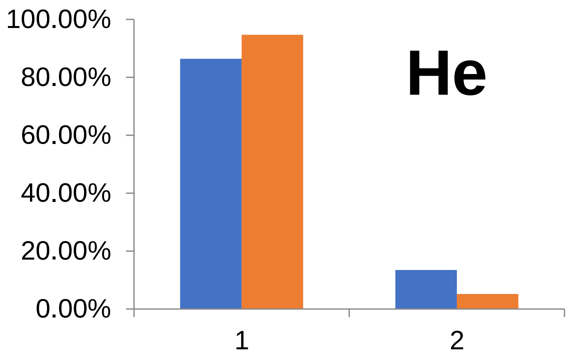
- primary beam power
- fragmentation cross-section
- diffusion/effusion time (refractory materials/short half-lives)
- ionization efficiency
- operational issues (stability, resilience)

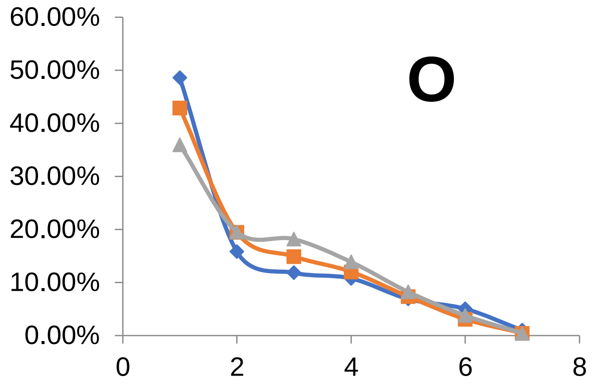
Nanogan III

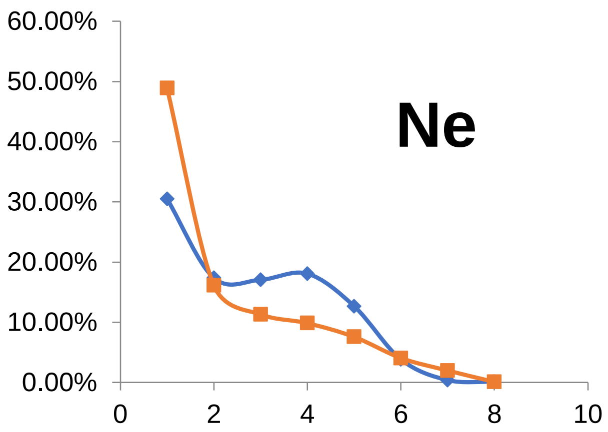
Objective: production of radioactive gaseous ions

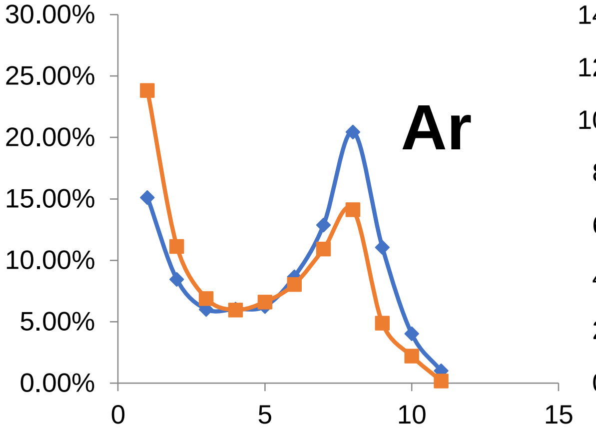


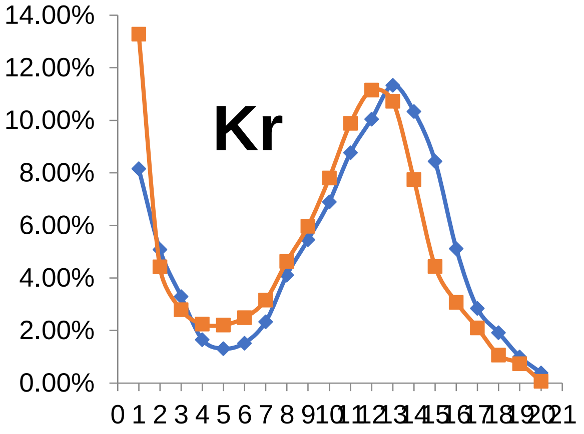
- 87 tests/experiments with radioactive beams since 2001
- Beams of He(6,8), O(14,15,19-21), F(17,18,20,21), Ne(17-19,23-27), Cl(32), Ar(31-35,41,43-46), Kr(71-77,79,81m).

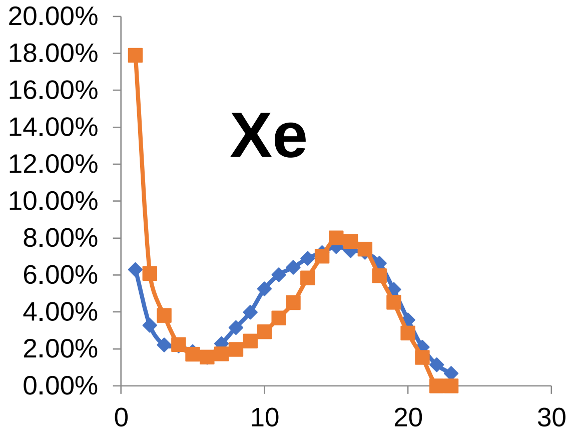






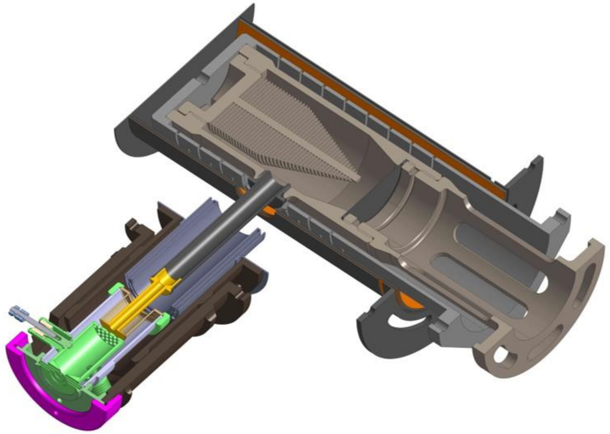




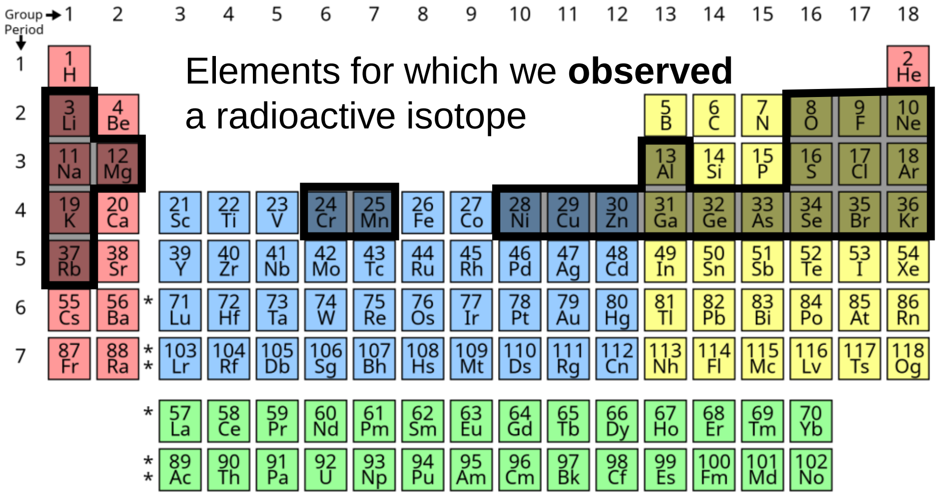


FEBIAD

Objective: production of radioactive metalic ions



- 11 tests/experiments with radioactive beams
- FEBIAD TISSes have received 36Ar (2013,2019,2022), 20Ne (2018), 40Ca (2018,2019), 48Ca (2021), 84Kr (2022) and 50Cr (2023)
- 2 post accelerated beams : ^{38m}K (2019), ^{47}K (2021)
- 90+ radioactive isotopes/isomers **seen**, including around 60 at post-accelerable intensities (>1E5pps).

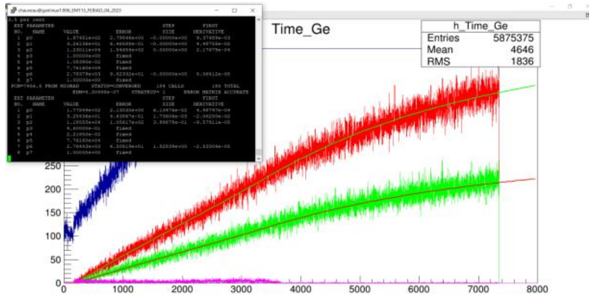


Features

- Efficient: routinely ≈ 20% on Ar
- Resilient: a 15 days endurance test showed no loss in performance
- Repeatable: comparable results and source behavior between 2 TISS

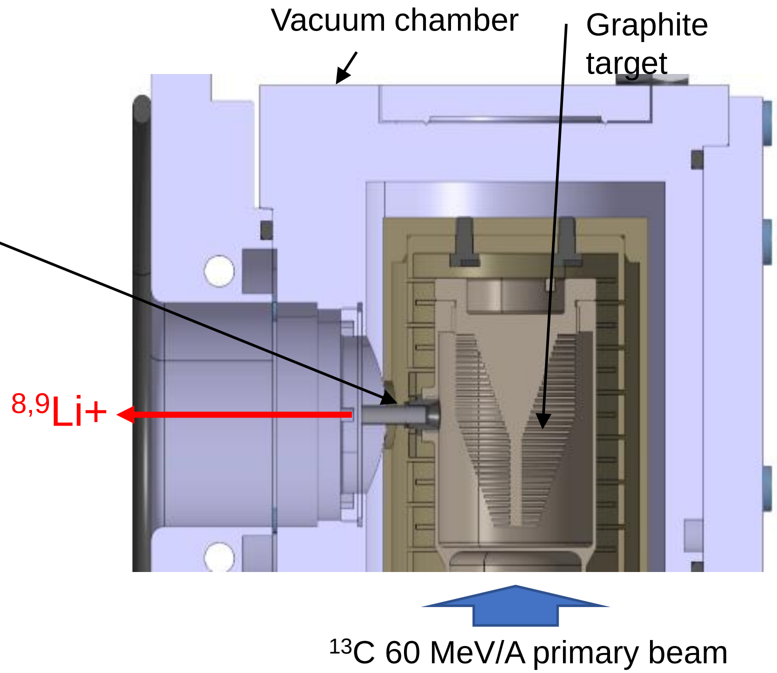
Latest test (^{50}Cr beam)

^{48}Cr rate ok (1.2E4pps/W) but very slow release (46min) at low beam power (30W)

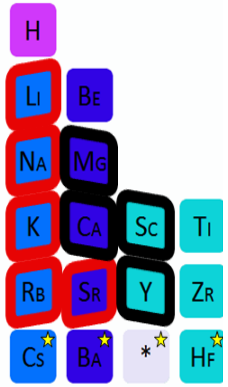


MonoNaKe (slide credit P. Jardin)

Objective: production of radioactive alkali ions



- *In-target production by target and beam fragmentation*
- *Ionization by hot surface*



First on-line test with a Pt ionizer:

$^{8}Li^{+}$ rate = 2,2.10^{4} pps (or AIT efficiency~10^{-5} for 830 W of primary beam), to be compared to AIT efficiency of 0,05 obtained in 2007 with a carbon ionizer.

Two points to analyse :

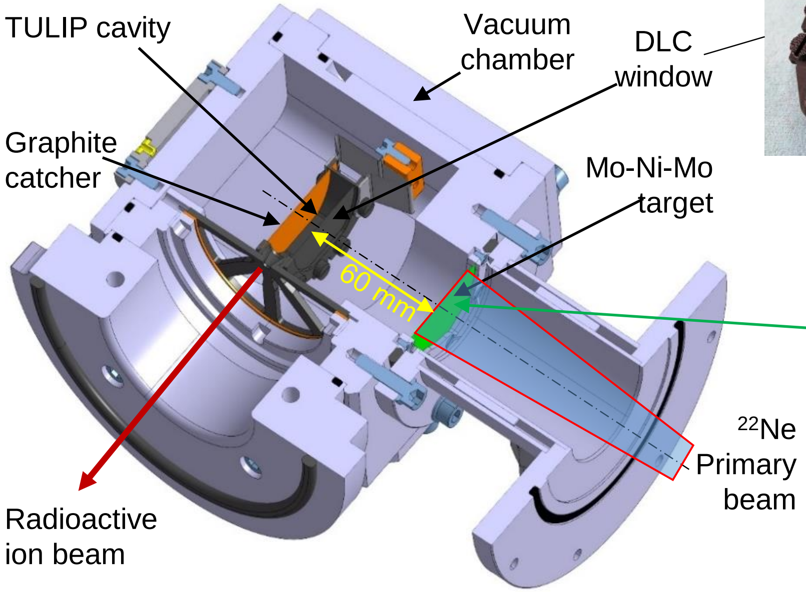
- *Transport in the beam line (results obtained in 20 minutes after the first ion was observed)*
- *Condensation of Li? at the exit of the tube observed during the off-line test*

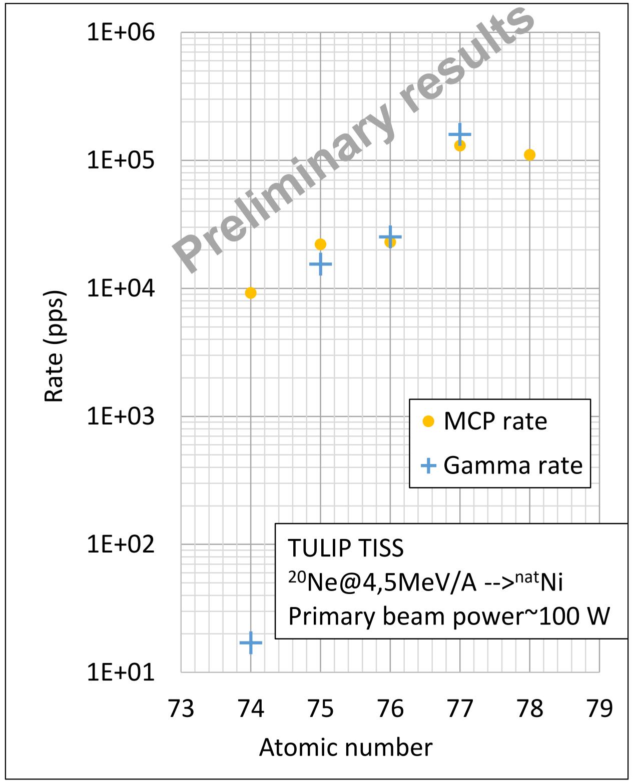
Pt and C ionizer will be compared during an off-line test planned in February and March 2024.

TULIP (slide credit P. Jardin)

Objective: production of neutron deficient short-lived isotopes

Proof of principle: production of $^{74-78}Rb^{+}$ ions





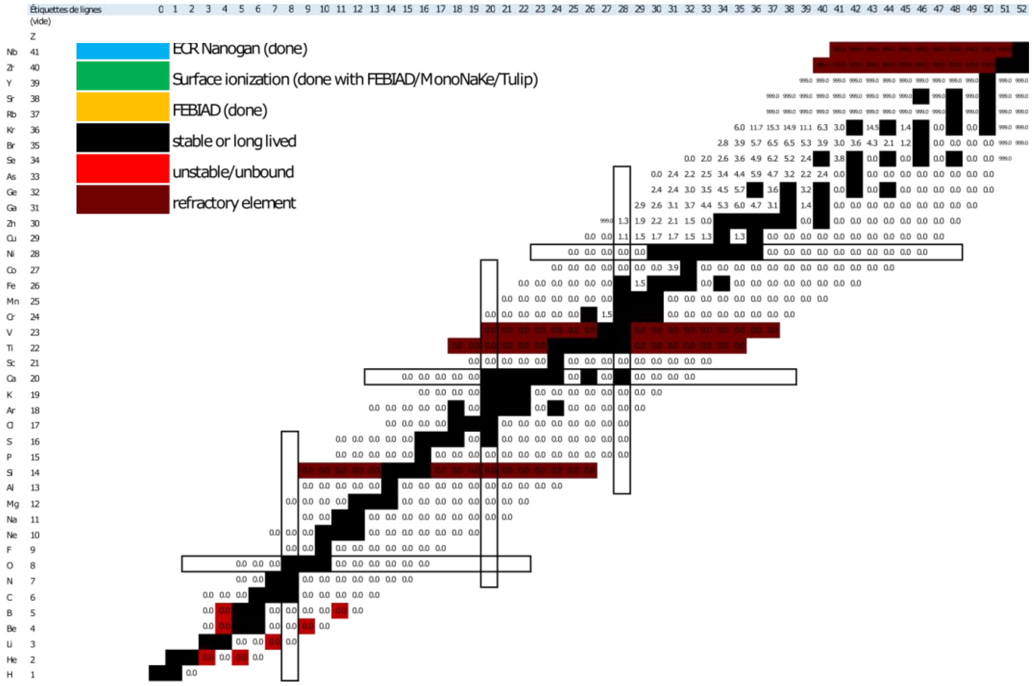
In-target production by fusion-evaporation
Short atom-to-ion transformation time

Final objective: production of metallic ions around ^{100}Sn

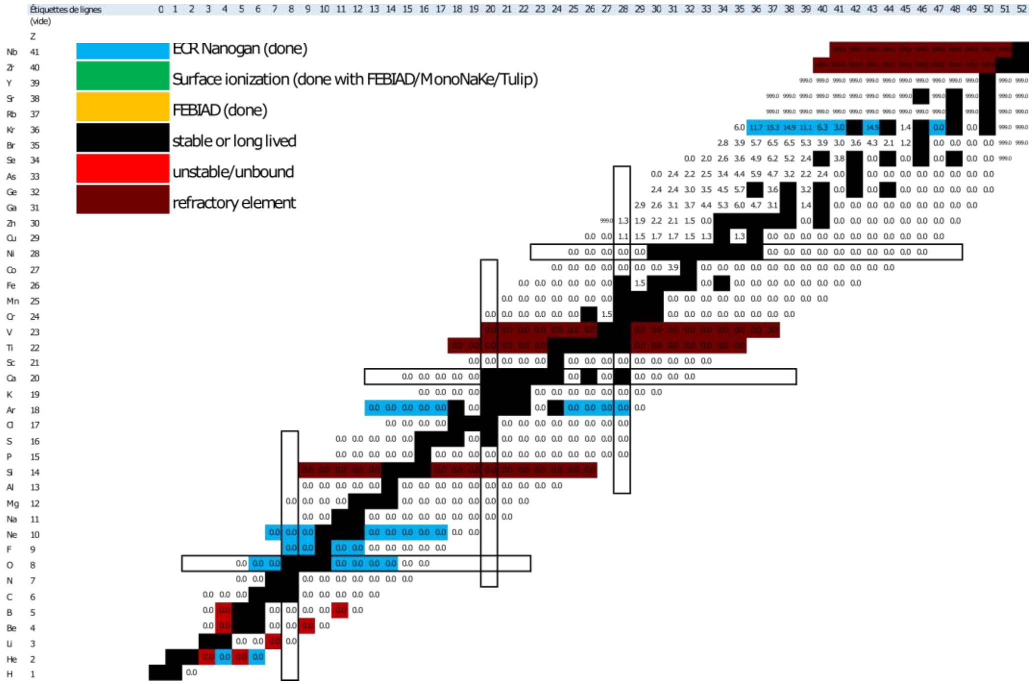
Next steps:

- coupling the TULIP cavity to a FEBIAD ion source. Test planned by end of 2023
- Implementation of a rotating target (production x 7).
- On-line production test of metallic ions around ^{100}Sn
- Application of the principle to the production of other elements

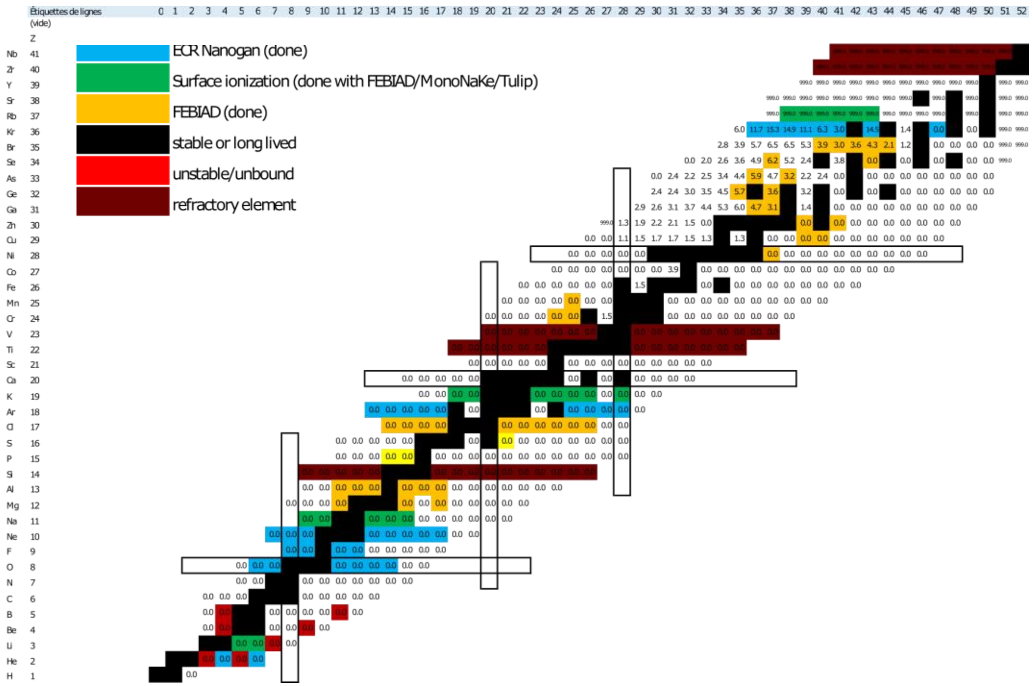
Beam production (status)

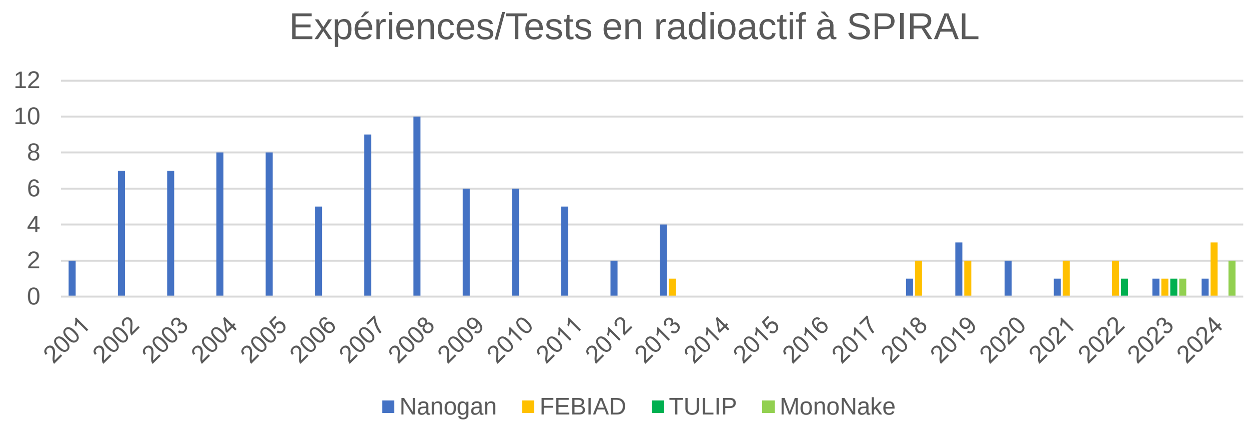


Beam production (status)

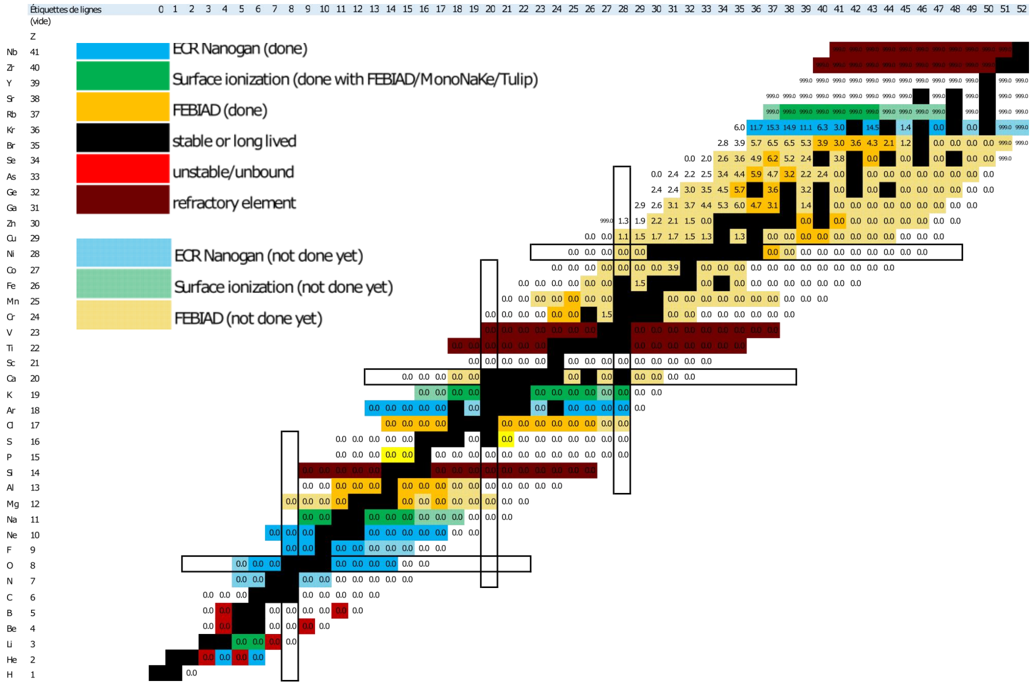


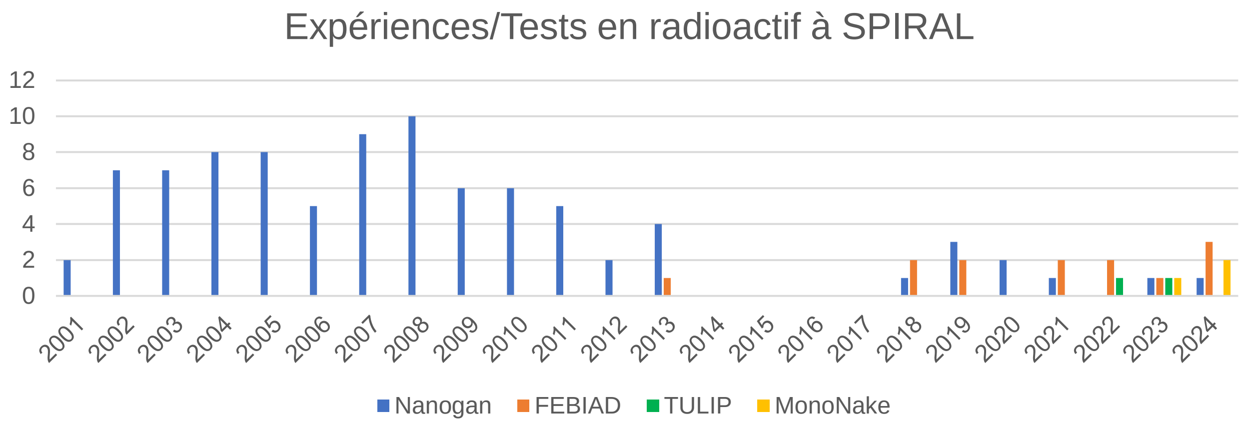
Beam production (status)





Beam production (status)





Developments

- MonoNaKe-Pt
- Fe-Co-Ni beams (hot target)
- New Target(s) + ^{12}C beam
- Molecular extraction
- Tulip-FEBIAD

→ Master Projet Ions radioactifs
1 PhD + 1 Postdoc

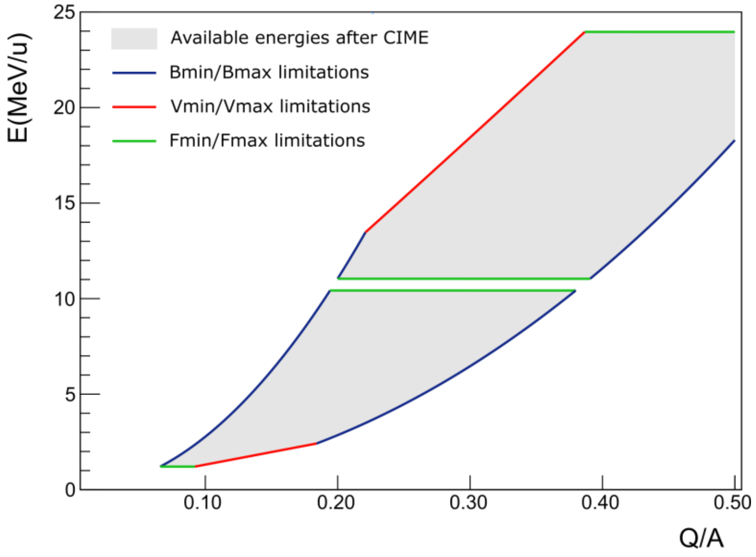
Limitations

- primary beam power
- fragmentation cross-section

^{12}C on new target(s)

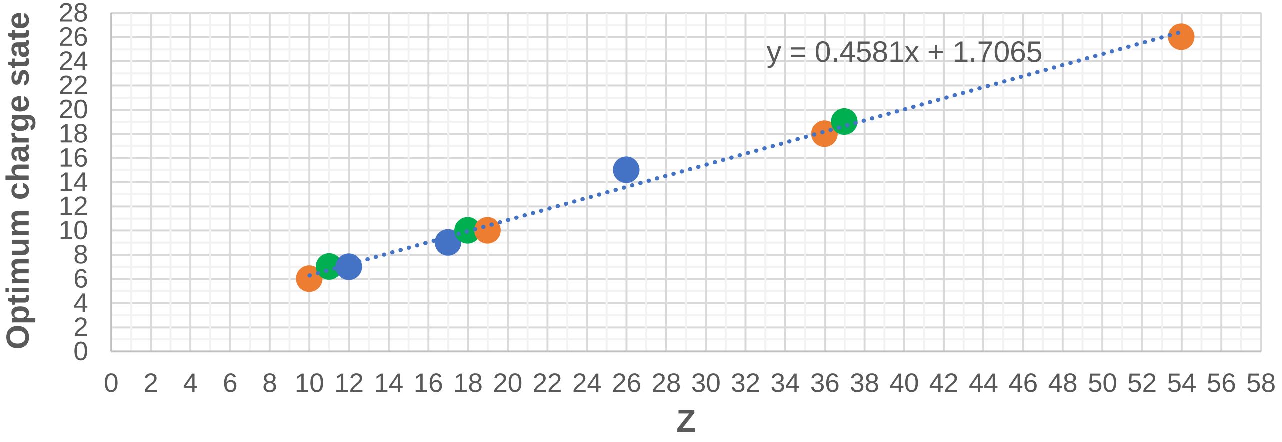
- diffusion/effusion time (refractory materials/short half-lives) -> Target heating, TULIP, Molecular extraction
- ionization efficiency -> MonoNaKe-Pt, FEBIAD source heating, target outgasing
- operational issues (stability, resilience) -> modifications to keep the insulators cold

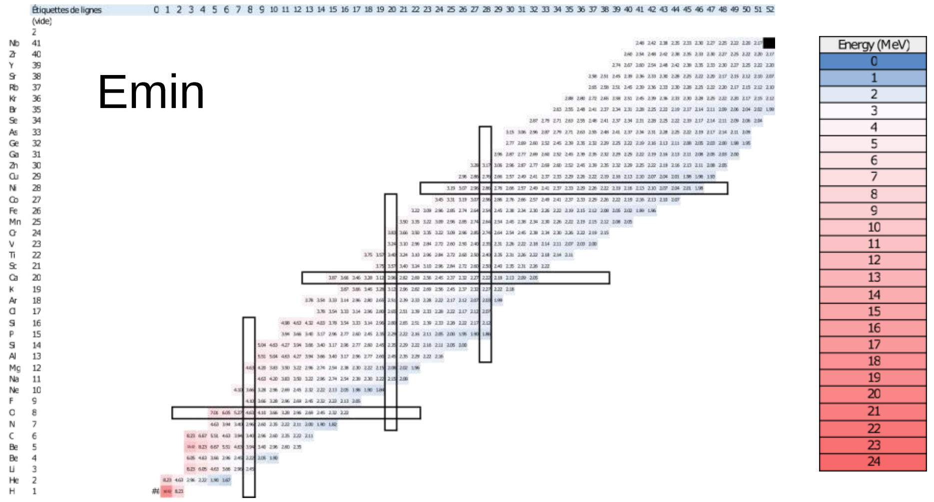
Acceleration

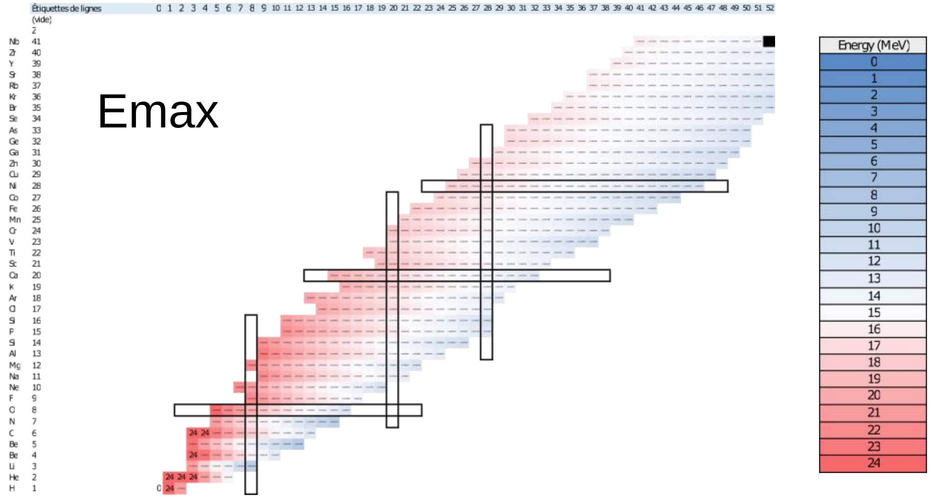


Limited by:

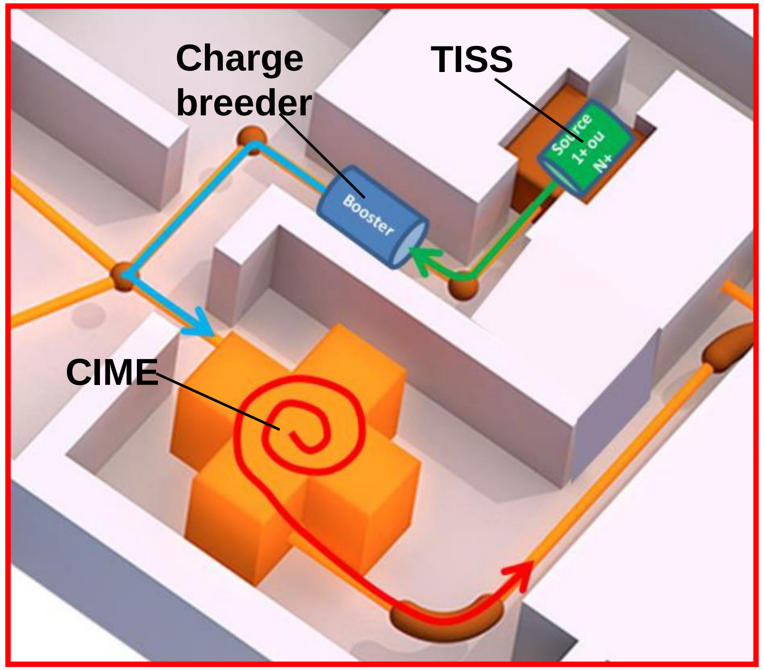
- charge state distribution at the output of the charge breeder
- platform limitations



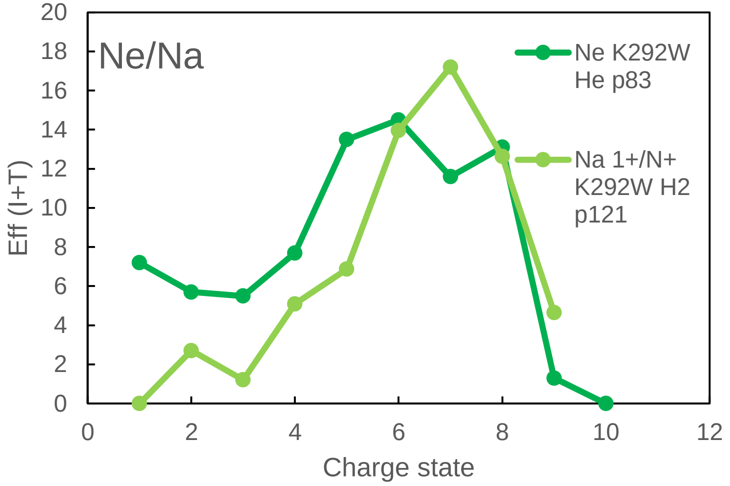




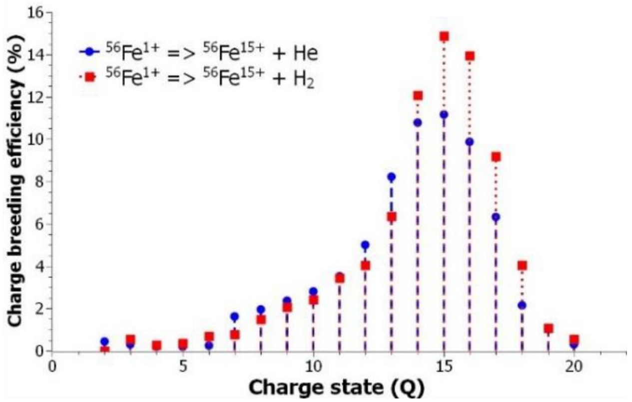
Charge breeding status



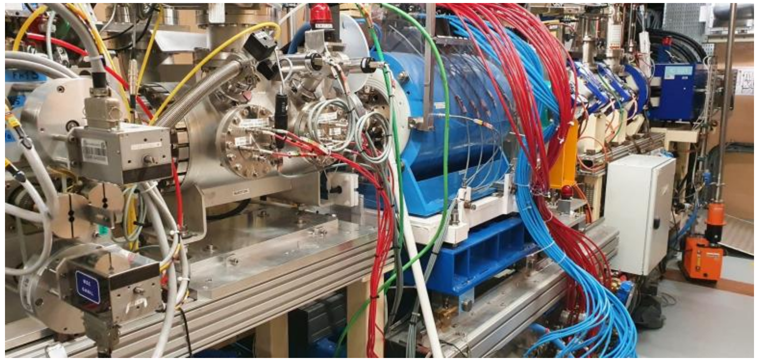
Gaz & Alkali ions



Metallic ions

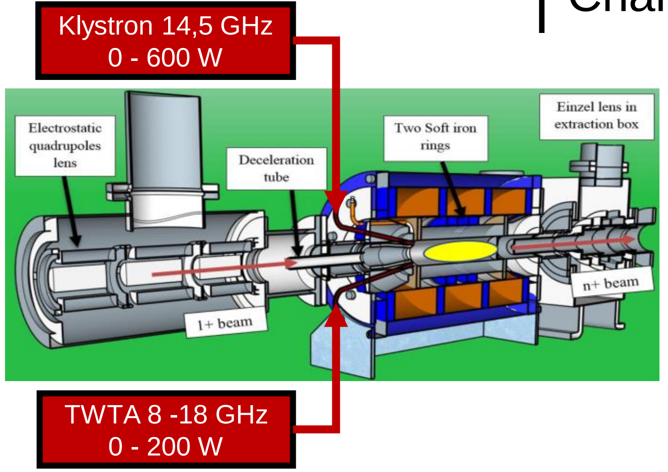


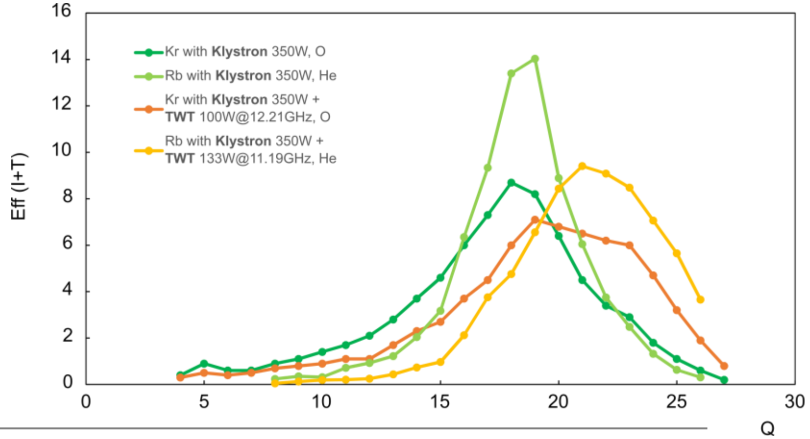
L. Maunoury et al, Journal of Physics: Conference Series 2244 (2022) 012066



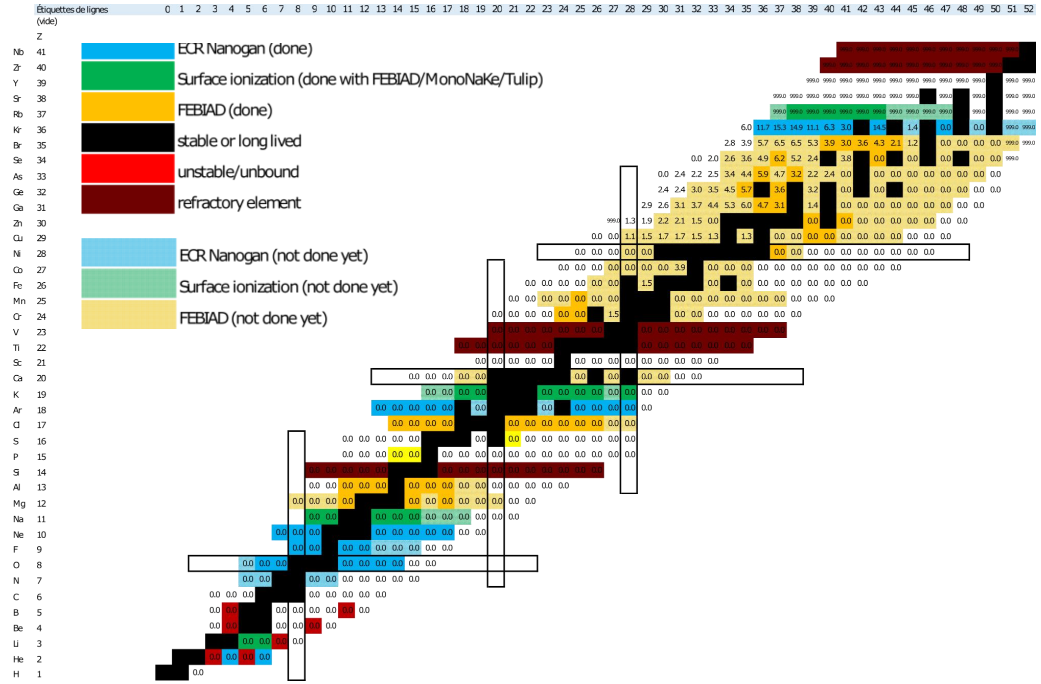
The charge breeder works

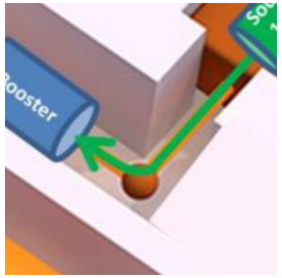
Total efficiency >70%
Charge state efficiency 5-20% depending on Z



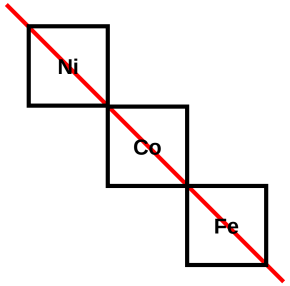


Purity





A selection -> Isobaric contaminants



Purity

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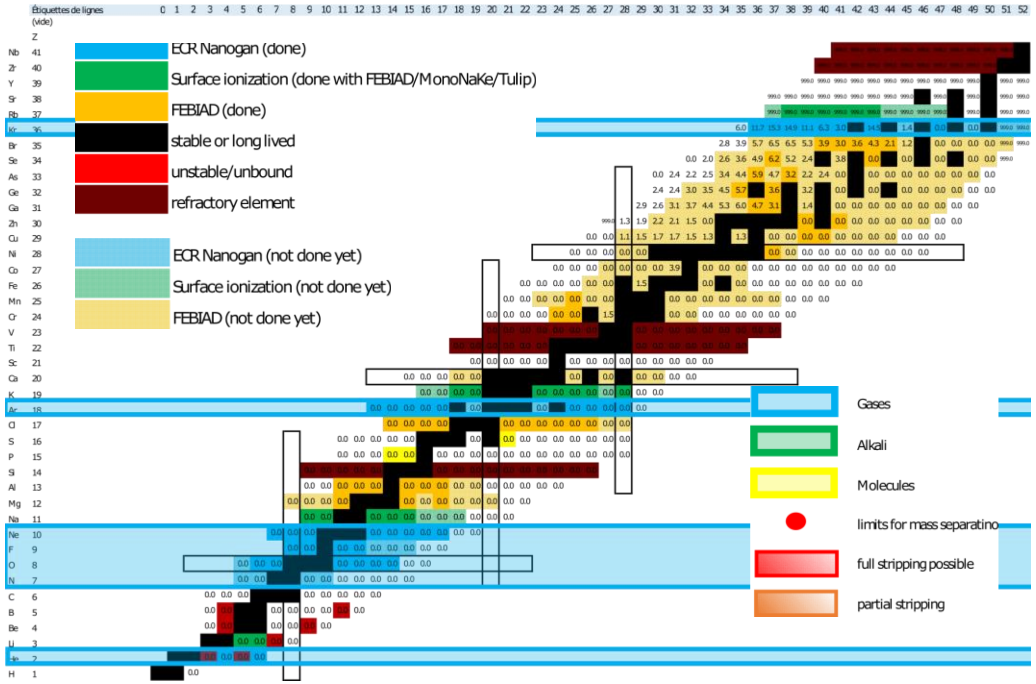
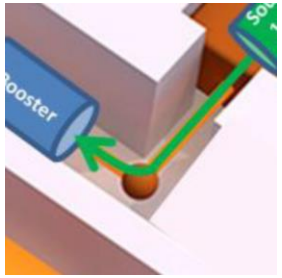
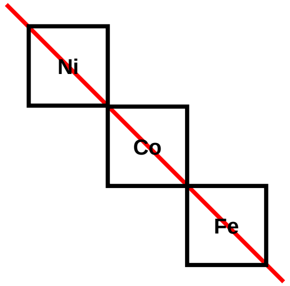


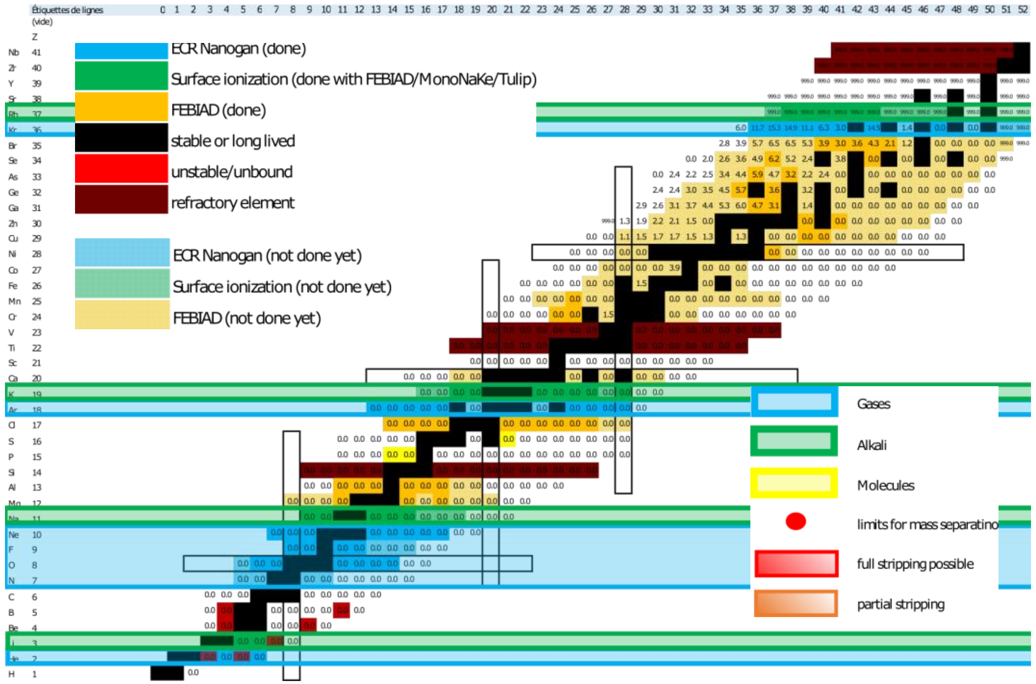


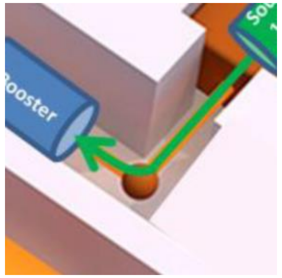


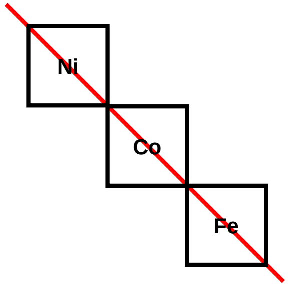
A selection -> Isobaric contaminants

- Z selection – gaz (Nanogan)

Purity



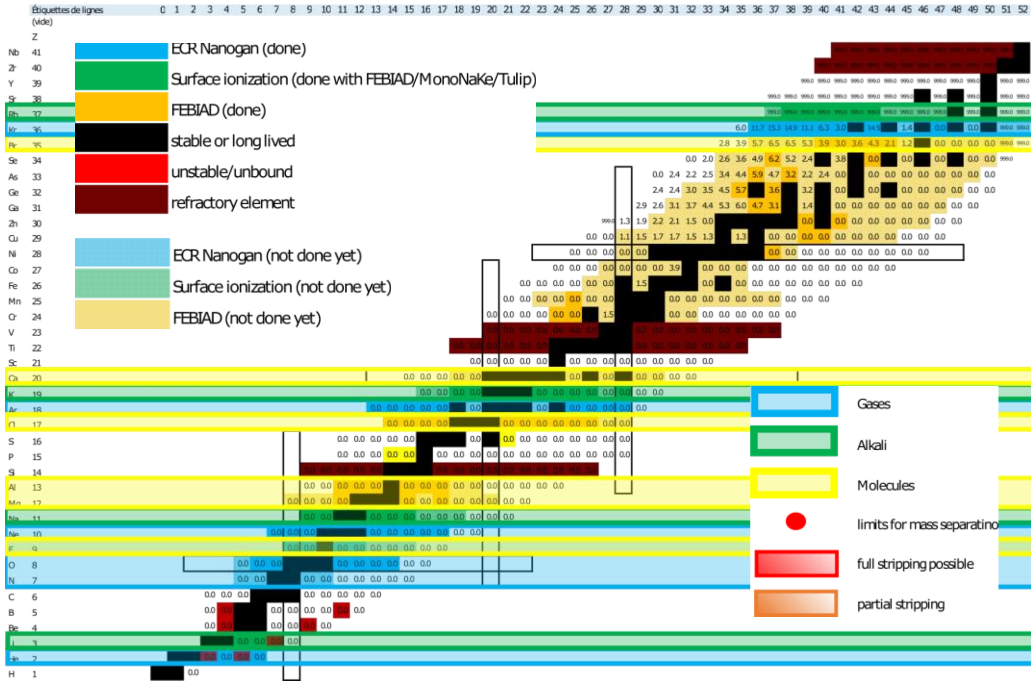


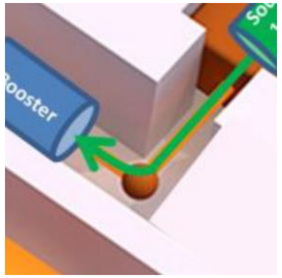


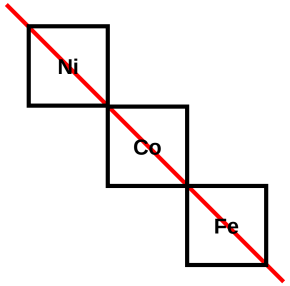
A selection -> Isobaric contaminants

- Z selection – gaz (Nanogan)
- Z selection – alkali (FEBIAD/MonoNaKe)

Purity



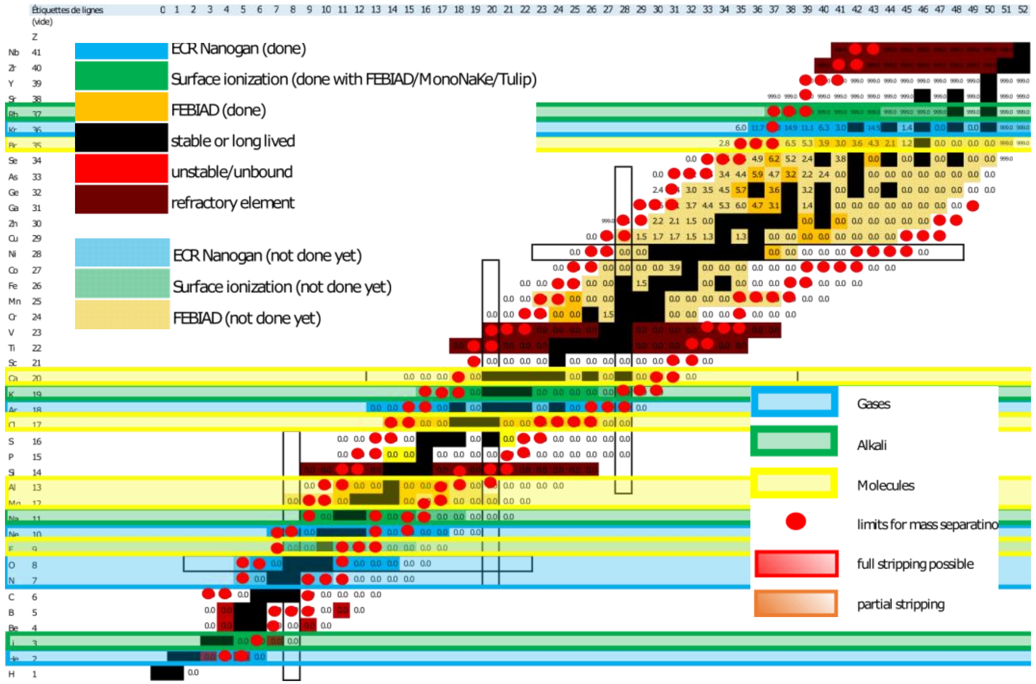


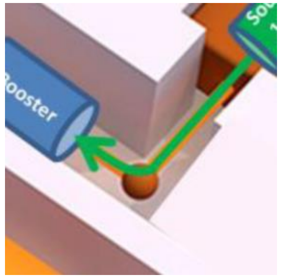


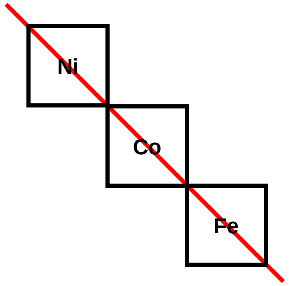
A selection -> Isobaric contaminants

- Z selection – gaz (Nanogan)
- Z selection – alkali (FEBIAD/MonoNaKe)
- Z selection – molecules (reactive gaz injection)

Purity



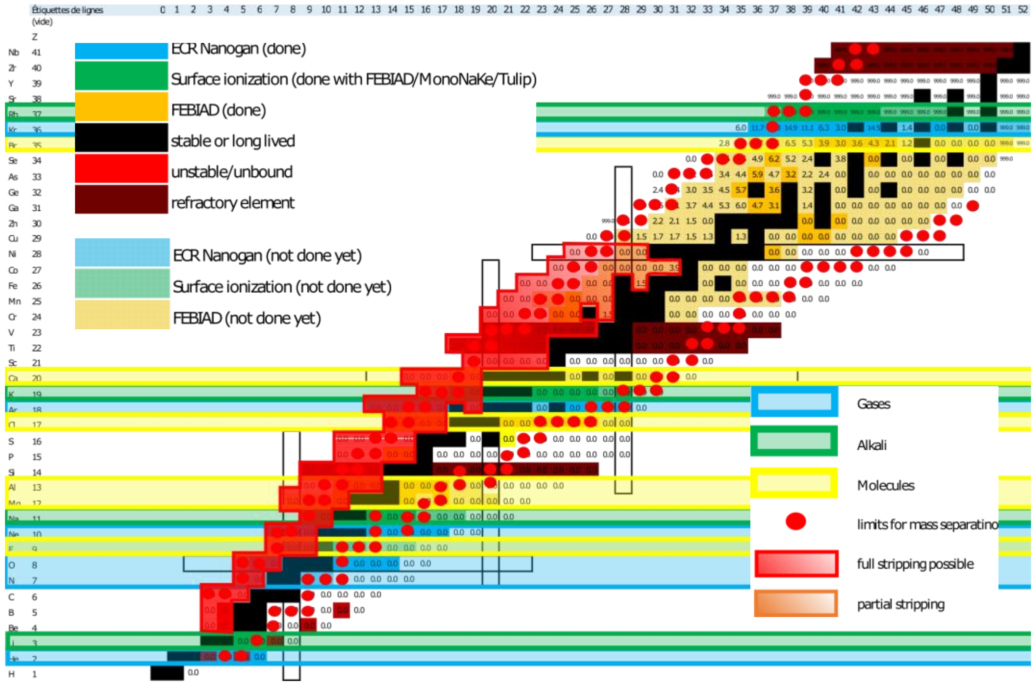


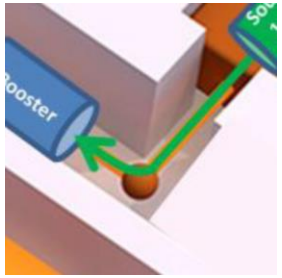


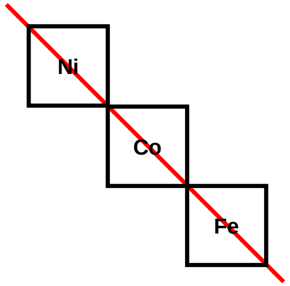
A selection -> Isobaric contaminants

- Z selection – gaz (Nanogan)
- Z selection – alkali (FEBIAD/MonoNaKe)
- Z selection – molecules (reactive gaz injection)
- Isobar separation in CIME (best resolution 2.10^4)

Purity



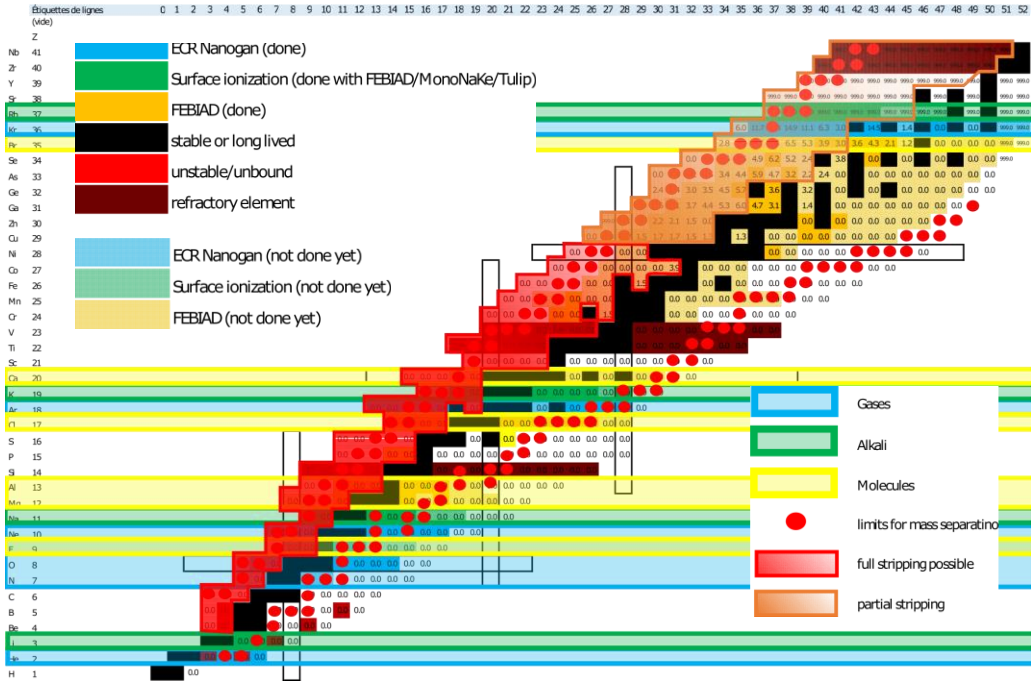


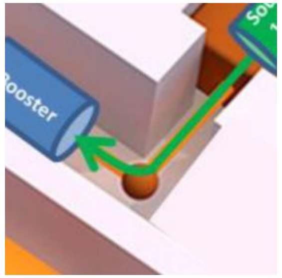


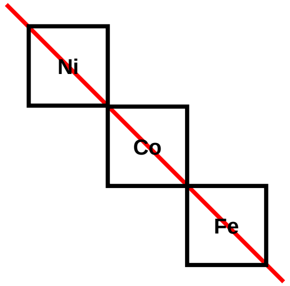
A selection -> Isobaric contaminants

- Z selection – gaz (Nanogan)
- Z selection – alkali (FEBIAD/MonoNaKe)
- Z selection – molecules (reactive gaz injection)
- Isobar separation in CIME (best resolution 2.10^4)
- Full stripping (n-defficient, high energy, Z<28)

Purity



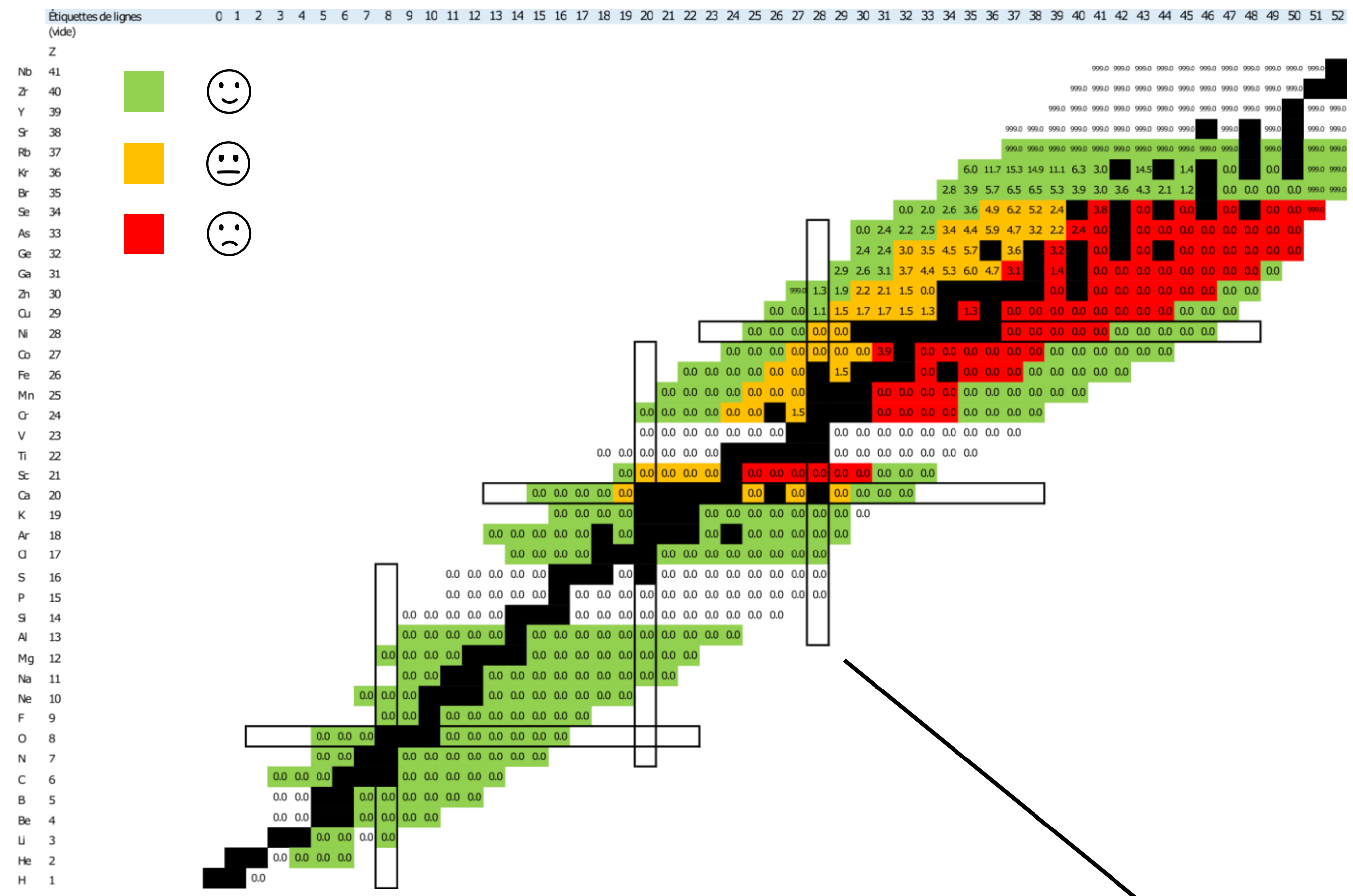




A selection -> Isobaric contaminants

- Z selection – gaz (Nanogan)
- Z selection – alkali (FEBIAD/MonoNaKe)
- Z selection – molecules (reactive gaz injection)
- Isobar separation in CIME (best resolution 2.10^4)
- Full stripping (n-defficient, high energy, Z<28)
- Partial stripping : limited

Purity

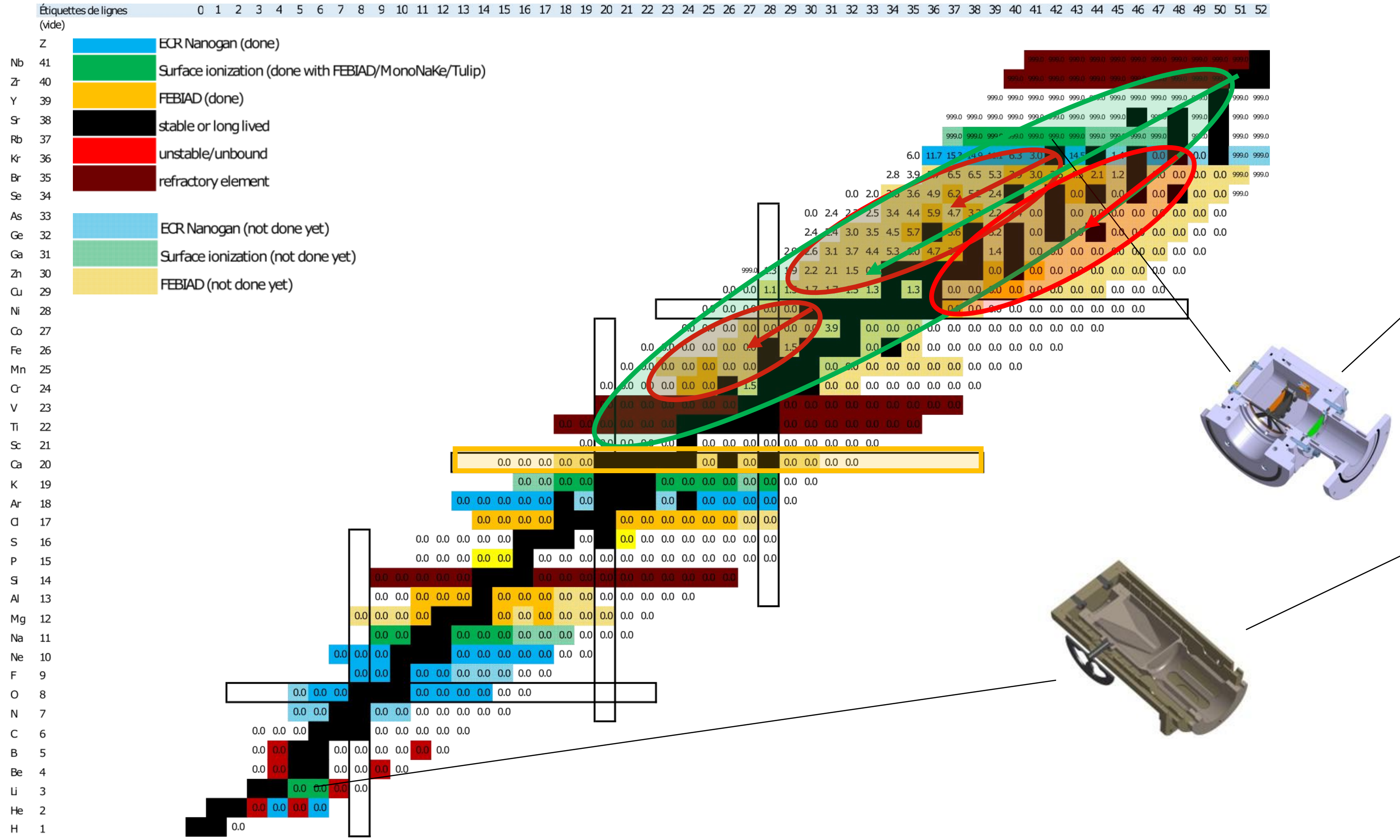


A selection -> Isobaric contaminants

- Z selection – gaz (Nanogan)
- Z selection – alkali (FEBIAD/MonoNaKe)
- Z selection – molecules (reactive gaz injection)
- Isobar separation in CIME (best resolution 2.10^4)
- Full stripping (n-defficient, high energy, Z<28)
- Partial stripping : limited

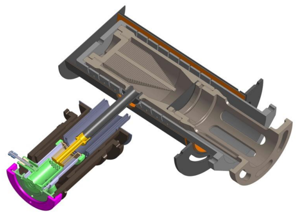
Considers purity only!

Conclusion on beam development



Source development

- New beams (2024)
- New target (2026?)
- Molecular CaF ?



- N-deficient Rb

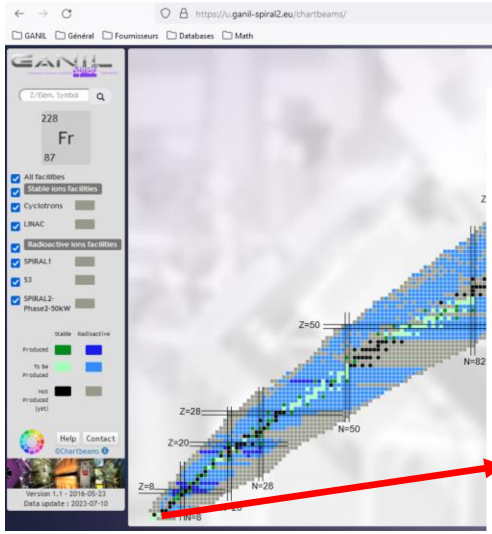
- $^{8\text{-}9}$Li

Main limitations of Spiral1

- Diffusion/effusion time
- Purity

Where to find the informations

https://u.ganil-spiral2.eu/chartbeams/



Measured Beams & immediate extrapolation

Radioactive Beam	halflife	unit	Charge State	Intensity (pps) Low Energy Beamline	Intensity (pps) Post accelerated (on target)	Min Energy (MeV/nucleon)	Max Energy (MeV/nucleon)	Primary Beam (or reaction mechanism)	Primary Beam Power on ECS Target (kW)	Primary Beam Energy (MeV/nucleon)	RIB production target
8Li	840.3	ms	1+	8.3E+04	--	--	--	36Ar	0.85	74	Carbon
8Li	840.3	ms	1+	2.20E+06	1.10E+04	1,6*	4.3**	13C	0.8	60	Carbon

Color code :

2.80E+07 : Measured rates with SPIRAL

2.80E+07 : Extrapolated rates (not measured) with best primary beam at low energy and after acceleration (0.5% at lowest energy, 10% at 2MeV/A)

Specific codes :

* Indicative value which does not include possible optimizations

** for most abundant charge state. Higher energy is a priori possible, but at a cost of reduced intensity

Direct measurement at low energy

Extrapolation at low energy and after post-acceleration with best beam

Estimates requiring beam development (6 months - 2 years)

Radioactive Beam	halflife	unit	Charge State	Intensity (pps) Low Energy Beamline	Intensity (pps) Post accelerated (on target)	Min Energy (MeV/nucleon)	Max Energy (MeV/nucleon)	Primary Beam (or reaction mechanism)	Primary Beam Power on ECS Target (kW)	Primary Beam Energy (MeV/nucleon)	RIB production target
8Li	840.3	ms	2	4.2E+08	1.7E+06	1,6*	16,6**	13C	1.2	75	Carbon
9Li	178.3	ms	2	5.6E+07	2.2E+05	1,6*	13,1**	13C	1.2	75	Carbon
11Li	8.75	ms	2	3.4E+04	8.1E+01	1,6*	8,8**	18O	1.2	75	Carbon

Estimates requiring target development (2-3 years)

Radioactive Beam	halflife	unit	Charge State	Intensity (pps) Low Energy Beamline	Intensity (pps) Post accelerated (on target)	Min Energy (MeV/nucleon)	Max Energy (MeV/nucleon)	Primary Beam (or reaction mechanism)	Primary Beam Power on ECS Target (kW)	Primary Beam Energy (MeV/nucleon)	RIB production target
8Li	840.3	ms	2	8.4E+08	3.3E+06	1,6*	16,6**	12C	3.65	95	SiC
8Li	840.3	ms	2	6.0E+08	2.4E+06	1,6*	16,6**	12C	3.65	95	CaO
8Li	840.3	ms	2	5.1E+08	2.0E+06	1,6*	16,6**	12C	3.65	95	NiO
9Li	178.3	ms	2	9.7E+07	3.7E+05	1,6*	13,1**	12C	3.65	95	SiC
9Li	178.3	ms	2	6.8E+07	2.6E+05	1,6*	13,1**	12C	3.65	95	CaO
9Li	178.3	ms	2	5.8E+07	2.3E+05	1,6*	13,1**	12C	3.65	95	NiO

Color code :

2.80E+07 : Intensity estimates for FEBIAD (VADIS) source (January 2016)

--- : Estimated yields inferior to 5,0E-02

Specific codes :

* Indicative value which does not include possible optimizations

** for cited charge state. Higher energy is a priori possible, but at a cost of reduced intensity

Update : 06/2023

Estimates with good beams on 12C target and best source conditions

Estimates with 12C beam on new targets and best source conditions

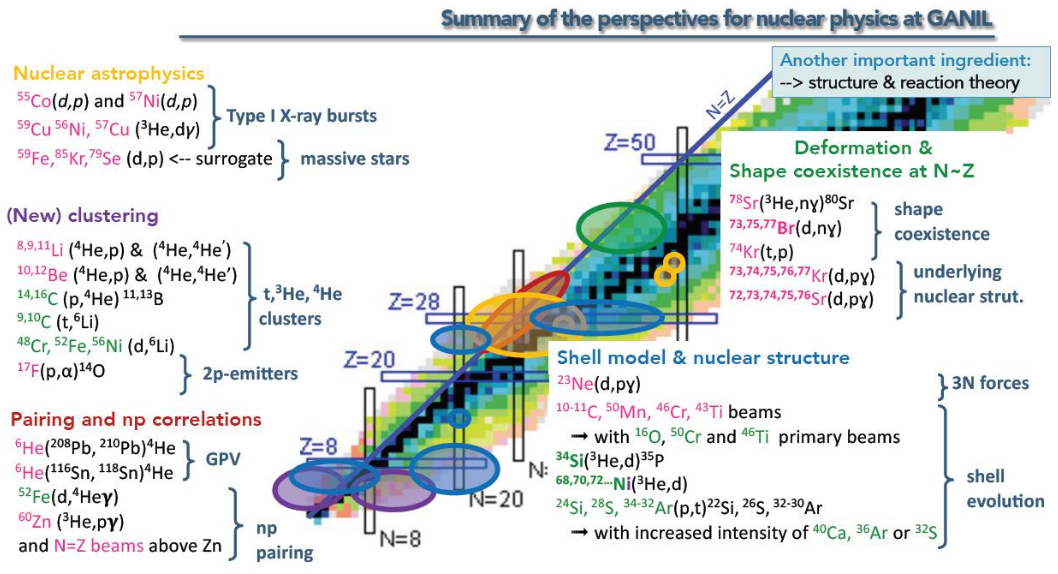
Only displayed if better than best beam extrapolation

Thank you for your attention!

Backup – Beam development

Logic of beams development:

- Accepted proposal/Endorsed LoI → Specific beam development
- Probing the community (LoI WS 2016 / WS 2023 / discussions with physicists / what we know we can do) → Broadband beam development

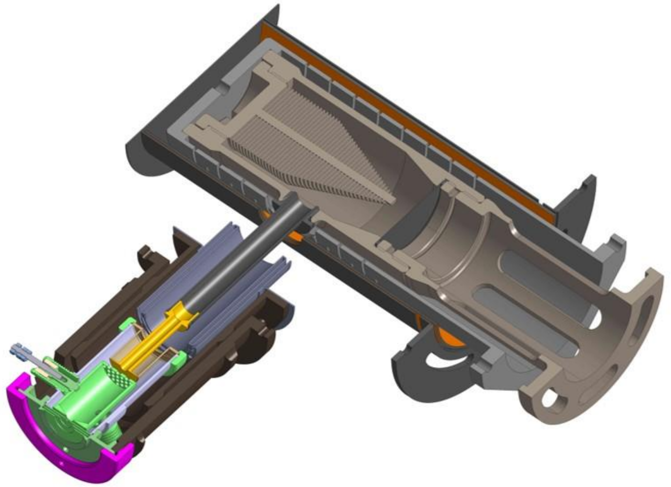


M. Assié, WS Cible-Source, 09/2023

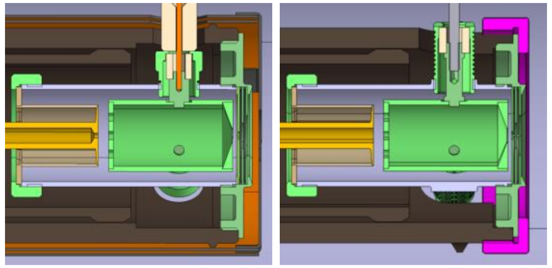
Shopping list SPIRAL1

- ^{6}He
- ^{8,9,11}Li
- ^{10,12}Be
- ^{10,11}C
- ^{17}F
- ^{23}Ne
- ^{43}Ti
- ^{46}Cr
- ^{50}Mn
- ^{59}Fe
- ^{55}Co
- ^{56,57}Ni
- ^{57,59}Cu
- ^{60}Zn
- ^{79}Se
- ^{73,75,77}Br
- ^{73,74,75,76,77}Kr
- ^{72,73,74,75,76}Sr

Backup - The upgrades on the FEBIAD



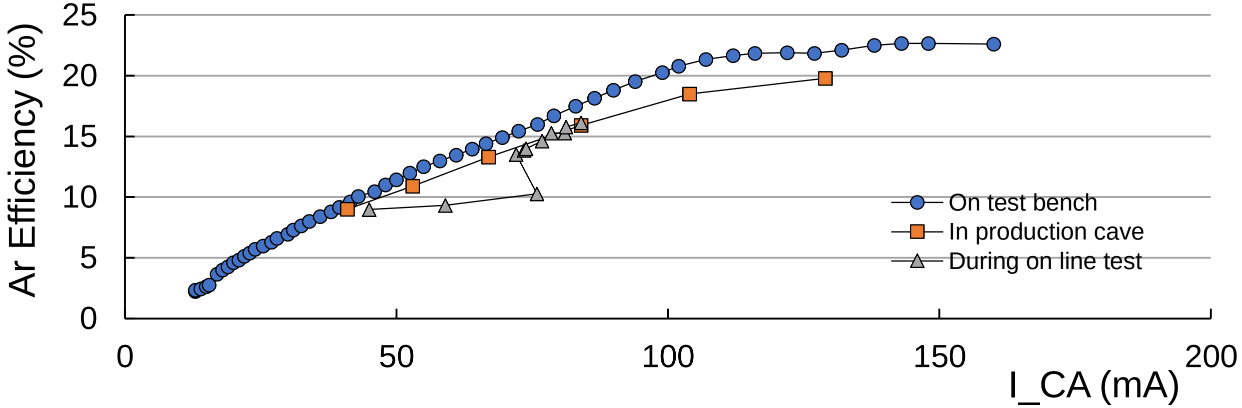
Poster ICIS
V. Bosquet



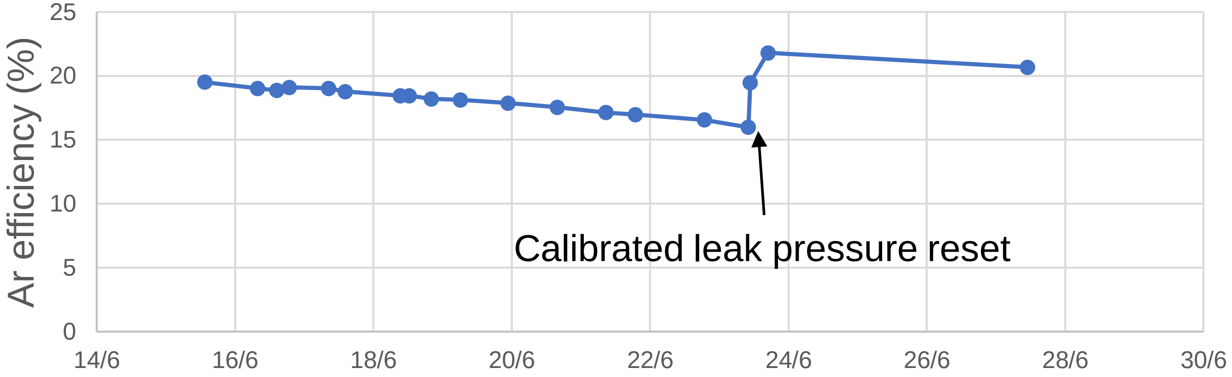
Insulator were the main point of failure.

- Increasing the size of the openings
- Pulling the insulators far from the hot anode

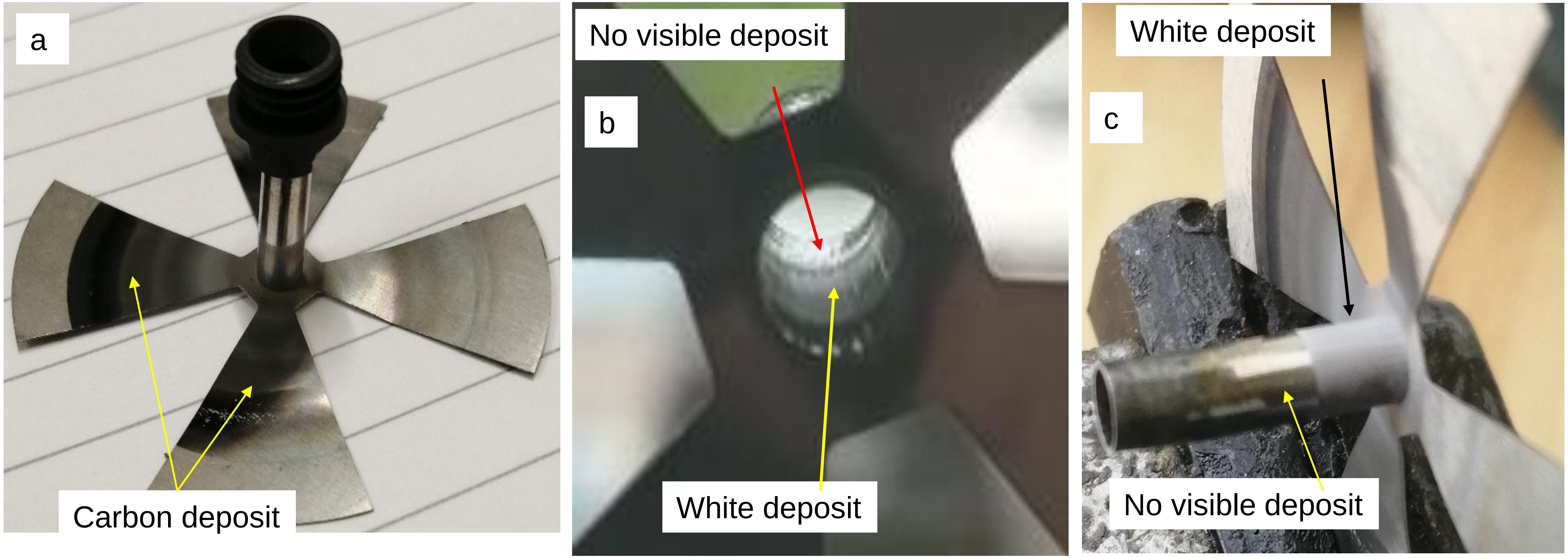
Progress in resilience and reliability



- 3 months in SPIRAL1
- 3 Machine study (2 radioactive + 1 stable)
- 10+ heating cycles
- **Efficient:** ^{40}Ar Efficiency up to 23%
- **Resilient:** 2 days of irradiation, 15 days at 20% ^{40}Ar efficiency and 10+ heating cycles without loss of performance
- **Stable over time :** same results 3 months appart
- Reliable : same results on test bench and SPIRAL and between 2 TISSes



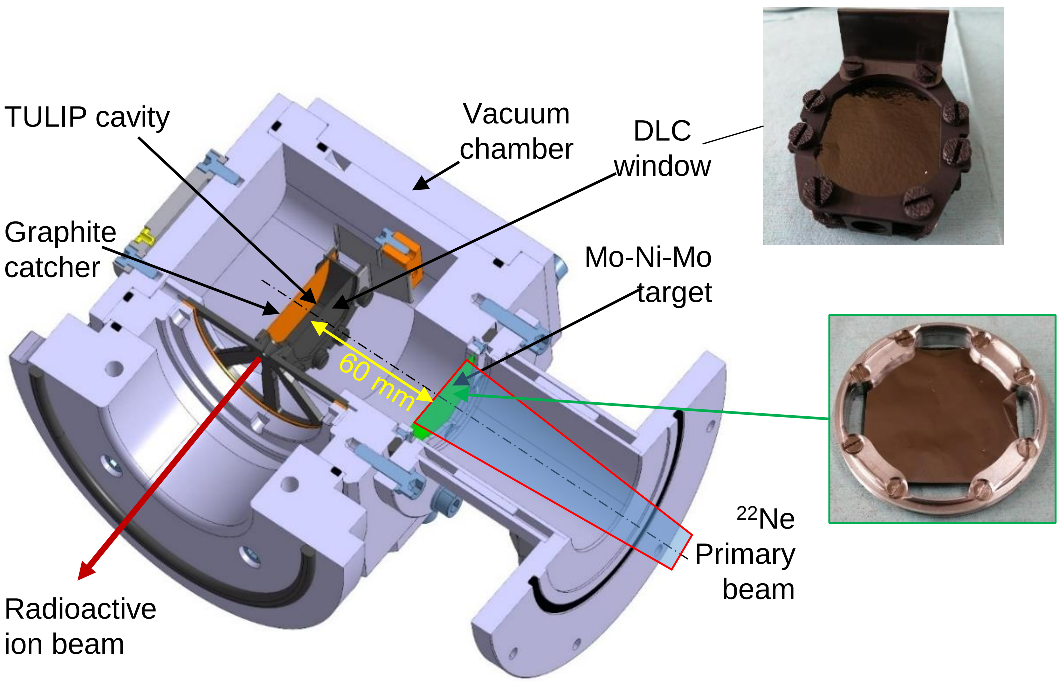
Backup - MonoNaKe
Observations during the off-line test



Backup - TULIP (slide credit P. Jardin)

Objective: production of neutron deficient short-lived isotopes

Proof of principle: production of $^{74\text{-}78}Rb^+$ ions



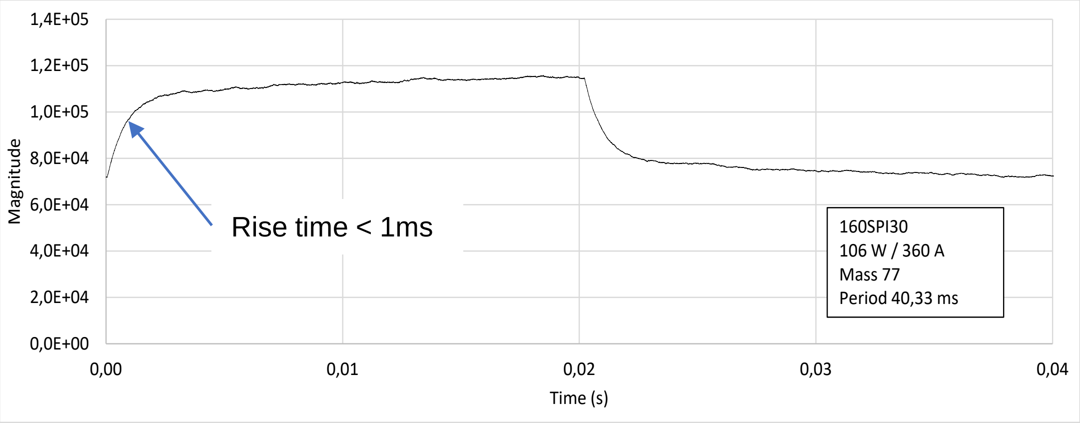
In-target production by fusion-evaporation
Short atom-to-ion transformation time

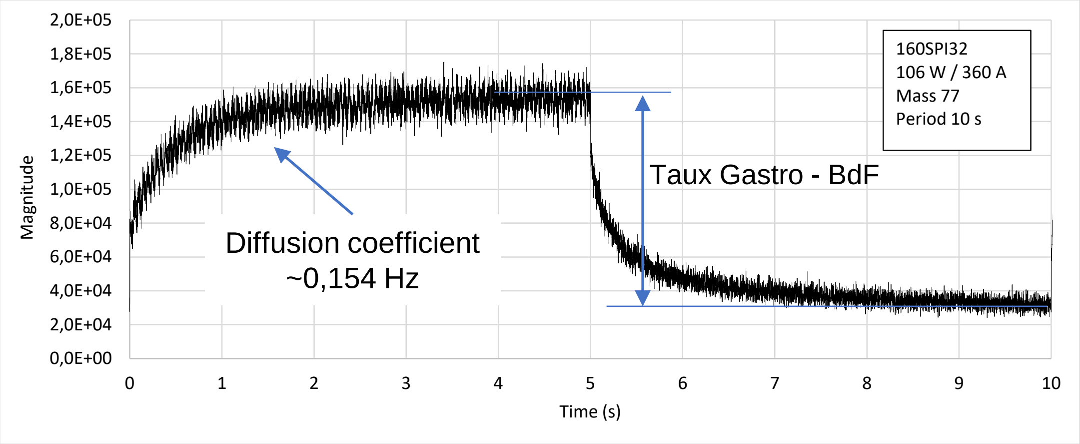
Last On-line test in July 23

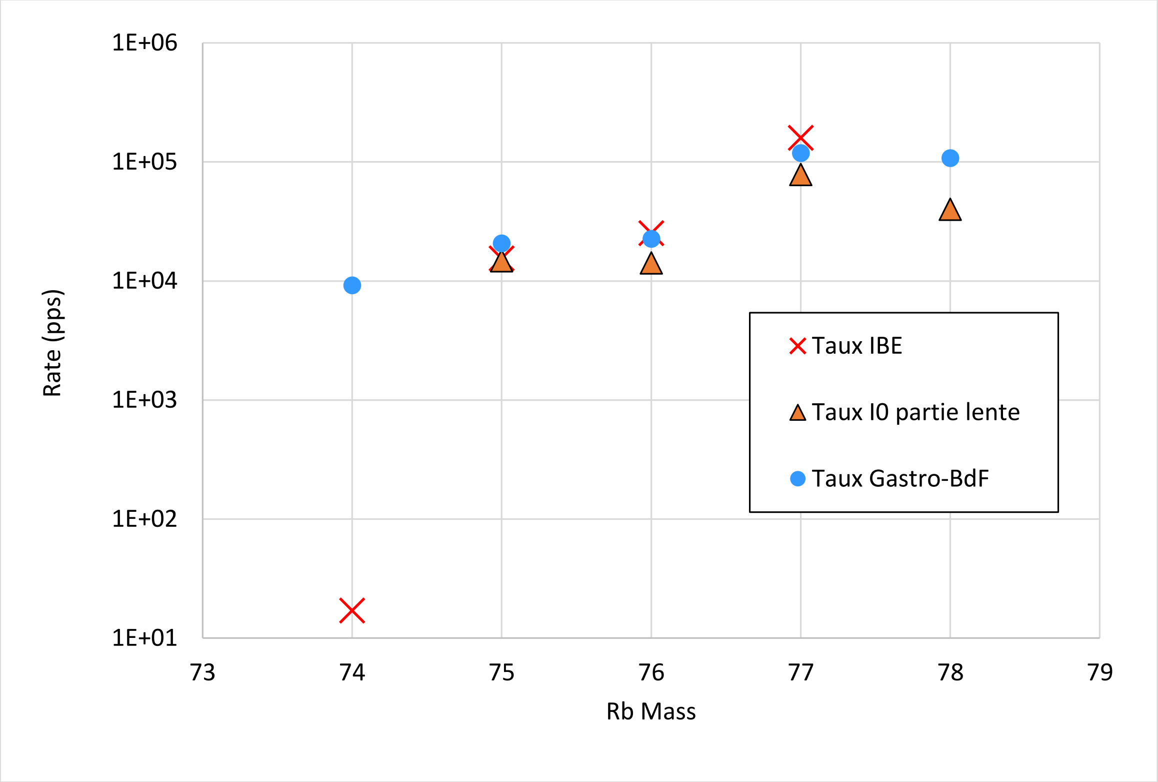
- ^{20}Ne@4,5 MeV/A -> ^{nat}Ni
- $^{74 \text{ to } 78}Rb^+$ observed
- Rates up to few 10^5 pps
- TISS 3 days under irradiation without damage
- Data under analysis

Backup - TULIP

Objective: production of neutron deficient short-lived isotopes



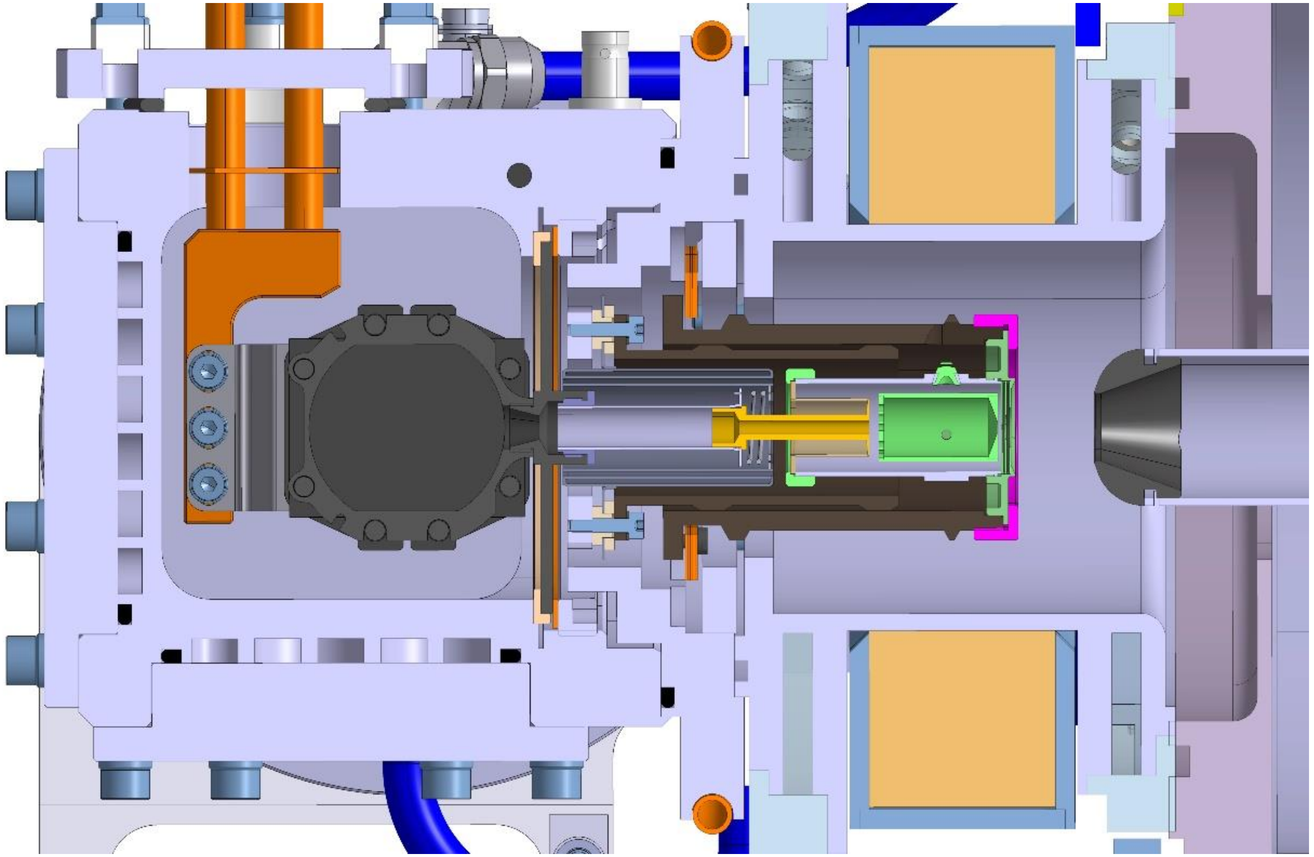




Data currently under analysis

Backup - TULIP

Final objective : production of metallic ions around ^{100}Sn



Next steps:

- coupling the TULIP cavity to a FEBIAD ion source. Test planned by end of 2023
- Implementation of a rotating target (production x 7). Test planned by 2d semester of 2023
- On-line production test of metallic ions around ^{100}Sn. When ^{50}Cr beam available
- Application of the principle to the production of other elements