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PRODUCTION OF "COCKTAIL BEAMS" WITH ECR BOOSTER, POST-ACCELERATED FOR INDUSTRIAL APPLICATIONS

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Abstract

The GANIL (**G**rand **A**ccélérateur **N**ational d'**I**ons **L**ourds) in Caen produces with cyclotrons up to 20 % of the beam times dedicated to industrial applications, such as the irradiation of electronic components. The SAGA project (**S**pace **A**pplication at **GA**NIL **A**ccelerators) aims to increase beam times for these applications in the future in order to meet demand from French and European industries.

INTRODUCTION

In this context, one of the challenges is to be able to switch rapidly from one beam to another in order to optimize the beam time available for irradiation. This project involves technical and organisational developments (on existing GANIL and SPIRAL2 facilities, see Fig. 1) to improve the supply of medium and high energy beams for experimental needs.

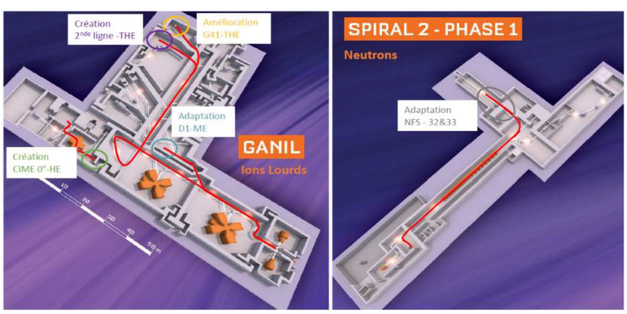
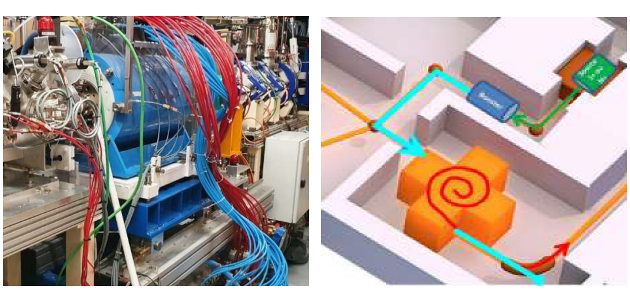


Figure 1: Layout of GANIL/SPIRAL2 accelerators.

The work package *CIME 0°-HE* plans to install a new irradiation station for medium energy beams (up to 20 MeV/u), using the Charge Booster as stable ion source (from SPIRAL1 facility) to provide cocktail beams (Fig. 2).



(a) Phoenix Charge Booster (b) ECR SPIRAL1 Facility

Figure 2: Charge breeder (a) and SPIRAL1 layout (b).

To meet the requirements, this ECR Ion Source has to produce several elements, with very close A/Q, which were separated and post-accelerated by CIME cyclotron.

The Phoenix Booster, usually dedicated to increase the charge state of a monocharged radioactive beams produced by target ion source (FEBIAD, surface ionisation ion source), can also produce gaseous stable beams in ECR source mode. However, the needs for industrial application require a cocktail beam including metallic one. That implies few modifications on Booster to be able to provide this cocktail with acceptable intensities.

Finally, the chosen cocktail beam must be optimised to deliver the highest energy reachable with the CIME cyclotron, and to ensure a reasonable switch time between each beam.

EXISTING SPIRAL1 FACILITY

The SPIRAL1 facility at GANIL (Caen, France) is a RIB factory using the ISOL method [1]. It has been providing post-accelerated RIBs to experimental areas since 2001. Over the last decade, SPIRAL1 has been upgraded to provide beams of condensable elements, by coupling one or several types of TISS emitting 1^+ ions [2] to a charge breeder, to boost the charge state of radioactive ions from 1^+ to n^+ for subsequent post-acceleration.

The charge breeder is a PHOENIX type ECR ion source developed at LPSC and tested at ISOLDE, that was then improved before being installed at SPIRAL1 [3, 4].

Standalone, the Booster device can also produce stable beams of gaseous elements.

A post acceleration of these beams, up to 20 MeV/u, is feasible using the CIME cyclotron [5].

SAGA PROJECT – CIME 0°

Irradiation Station Project

The cyclotron extraction line has to be redesigned to accommodate the SAGA's irradiation station (see Fig. 3).

To allow the use of the beam, from 2026 ideally, some arrangements are necessary for tunings and measurements:

- stripper and collimator to vary the flux and/or the energy,
- diagnostics to measure intensities, alignment, shape and homogeneity of the beam,
- wobbler or high gradient quadrupole to adjust irradiation surface.

The chamber, ending the line, would be equipped with a vacuum-atmospheric pressure window to allow irradiation in both modes: in a vacuum or controlled atmosphere. In consequence, a fast protection valve system has to be developed to ensure the protection of devices and cyclotron in the event of a breakage.

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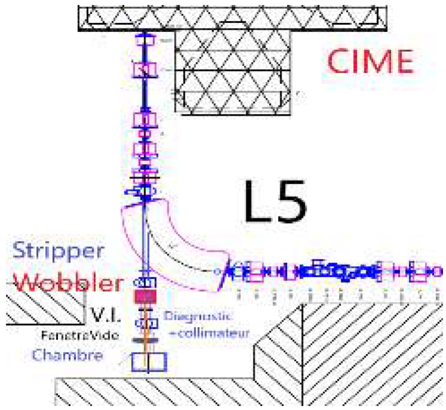

Figure 3: CIME Extraction line and Irradiation station project.

Users Conditions

To meet the requirements for the irradiation of their components, experimenters specified their expectations and the specifications of the beams to be supplied:

- energy beam >12 MeV/u,
- 5 to 10 ions on the largest scale LET,
- intensity $>10^4$ pps,
- fast beam switch.

LET (Linear Energy Transfer) (Fig. 4) is the amount of energy that an ionizing particle transfers to the material being traversed, per unit of distance. It describes the action of radiation on matter. This parameter depends on the energy beam supplied and the ion chosen.

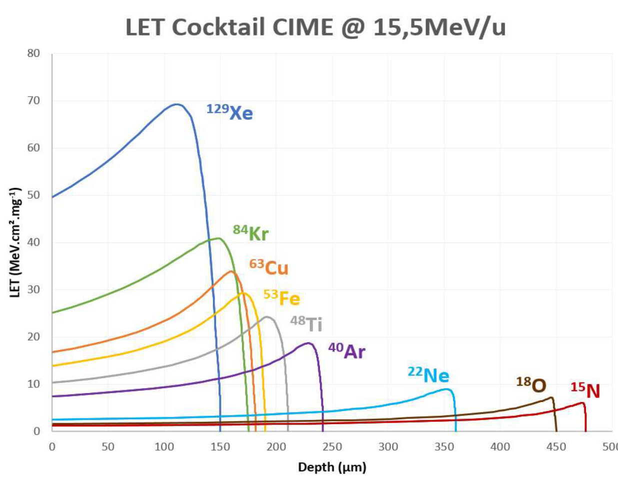

Figure 4: LET for several beams.

Cocktail Beam Proposal

The Accelerators Physic Group and the Target Ion Source Group have jointly established a list of elements that could fulfil the industrials requirements, cyclotron specifications, and Phoenix Booster capacity of production.

This "cocktail beam" combines elements on a large mass scale with a very close A/Q, which avoids repeated adjustments on ion source and extraction line (Figs. 5 and 6). However, the difference of magnetic rigidity between chosen ions is far enough to satisfy the CIME cyclotron resolution.

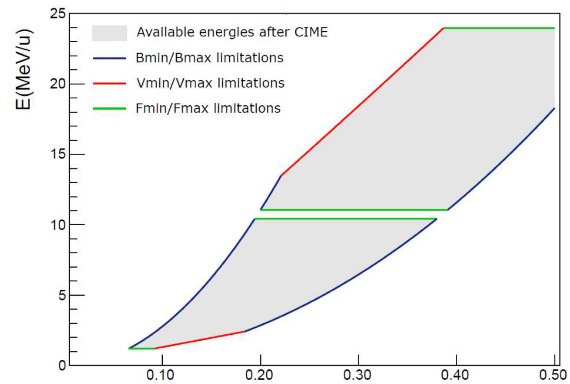

Figure 5: Energies accessible after post-acceleration in CIME as a function of the Q/A ratio. Coloured lines also display the platform limitations in terms of magnetic field, electric field and driving frequency.

Energy = 15,5 MeV

Ions	A/Q	I_{max} Expected *(Post-Acceleration)*
$^{15}N^{4+}$	3,750.	10^6pps
$^{18}O^{5+}$	3,600	$>10^8$pps
$^{22}Ne^{6+}$	3,665	10^7pps
$^{40}Ar^{11+}$	3,632	$>10^8$pps
$^{48}Ti^{13+}$	3,682	10^5pps
$^{56}Fe^{15+}$	3,723	10^6pps
$^{63}Cu^{17+}$	3,738	10^8pps
$^{84}Kr^{23+}$	3,643	>> enA
$^{129}Xe^{35+}$	3,683	10^5pps

Figure 6: Cocktail Beam Proposal for EM 132.

Cyclotron Switch Mode

For the acceleration and extraction of an ion (with q/m ratio), the magnetic field (B) and the HF frequency (F^{RF}) of the cyclotron must be adjusted with great precision, knowing that:

$$q/m = 2\pi[F^{\mathrm{RF}}/H]/B^{\mathrm{cyclo}}, \tag{1}$$

with H as cyclotron harmonics (here $H = 2$ @15.5 MeV/A).

After tuning the ion of reference [q_0/m_0], the switch to an element [q_1/m_1] is therefore obtained by a variation of the RF frequency or of the magnetic field.

The frequency modification requires a scan in position of the HF panels to obtain the resonance. This intervention requires approximately 20-25 minutes and therefore cannot satisfy the switch time requirements.

A variation on cyclotron's magnetic field (B) below 2 % can be considered without much re-tuning line injection and accelerator. This operation, estimated around 5 minutes, also involves adjusting High-Voltage (V) devices, included Ion Source extraction energy.

Therefore, we obtain:

$$\frac{-(B_1 - B_0)}{B_0} = \frac{Q_1/m_1 - Q_0/m_0}{Q_0/m_0} = \frac{(V_1 - V_0)}{V_0}, \tag{2}$$

$$-\Delta B = \Delta Q/m = \Delta V, \tag{3}$$

with $\Delta B < 2$ %.

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COCKTAIL BEAM PRODUCTION

The gaseous elements of the cocktail [Xe, Kr, Ar, Ne, O, N] are produced by injection into the Booster, via the UDV valves and a calibrated leak, or thanks to the residual gases present in the source.

To provide metallic ions, two modifications have been done on the source to allow sputtering method (Fig. 7):

1. The 14 GHz RF Waveguide in Aluminum replaced by a Copper reference. [Cu]
2. A removable rod is install instead of the 8–14 GHz Wave Guide, to fix a sample of the needed metal [Fe, Al, Ag, Ti, …]

Both elements are insulated and connected to a polarization power supply.

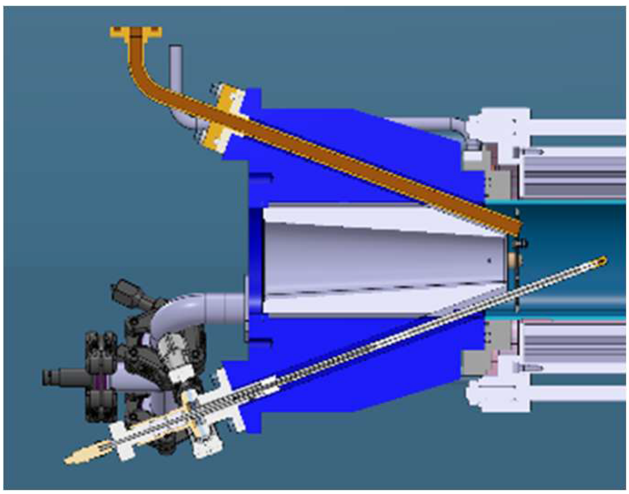

Figure 7: Adaptation of device at injection of charge breeder.

Moreover, some metallic ions are "naturally" produced by sputtering or evaporation of elements located close to the plasma environment (injection nose, plasma electrode, chamber, ...).

Preliminary Tests

Mainly used for charge breeding of 1^+ beams, these preliminary tests consist of checking the functionality of the Booster Phoenix in "ECR Source" mode:

1. after the modifications (waveguide and rod),
2. for the production of cocktail beams (8 to 10 ions) with high extraction voltage (~30 kV),[1]
3. with simultaneous injection of heavy elements [Kr+Xe], to check the respective non-influence on their usual distribution; especially on high charge states.[1]

Concerning point 3, a comparison was carried out between single tuning mode and simultaneous tuning mode.

The respective distributions are shown in Fig. 8 for ^{129}Xe and ^{86}Kr when optimised to a single gas. The results show that the distributions are not significantly affected by the "cocktail" mode (Fig. 9). The maximum charge states for Kr remains around 18^+, while that of Xe is around 26^+.

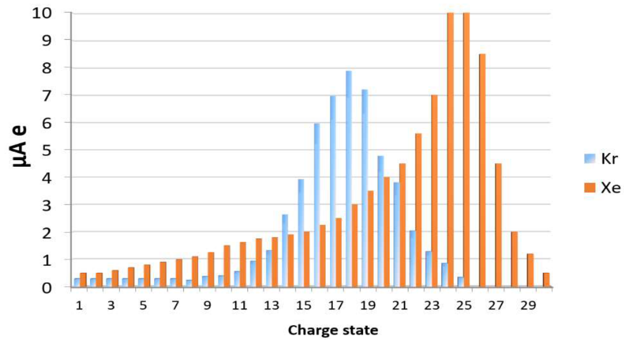

Figure 8: 2018: Booster Phoenix references on ^{129}Xe and ^{86}Kr when it was tuning to optimise single gas.

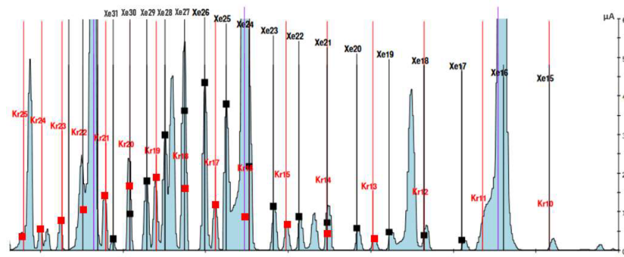

Figure 9: 2024: Distributions of simultaneous ^{129}Xe and ^{86}Kr @31 kV.

The use of the sputtering rod also requires preliminary tests to define the optimal insertion position, relative to the plasma, and the polarization to apply. An incorrect use, which could lead to the contamination of the plasma chamber (deposition on the walls) or even the melting of the sample, would be very critical for the current operation of the Booster with the radioactive beams on SPIRAL1. The 2024 SPIRAL1 planning did not allow to test these points prior to the SAGA experiment. For metallic ions, the strategy is therefore, first, to polarize the waveguide for copper production, and to quantify the rates (post-acceleration) of the elements from the booster parts.

EXPERIMENT RESULTS

Source Settings

Booster parameters for cocktail beam production:

- Gas injection: ^{84}Kr and ^{16}O on UDV valves, ^{129}Xe on calibrated leak,
- High Voltage: 28.37 kV (to reach post-acceleration, a final energy of 15.5 MeV/A),
- RF: 14 GHz (klystron) – power 680 W,
- Magnetic Field (Solenoid coils intensities): Injection 1200 A, Medium 351 A, Extraction 654 A.

The ^{84}Kr^{23+}, predominant in the cocktail, is used as the reference beam for line transport adjustment and cyclotron tuning (Fig. 10).

From these settings, the theoretical variations are applied to the magnetic field of CIME ($\Delta B*$) and to the high voltages (ΔV), including HV source, to shift on the next element of the cocktail.

[1] Conditions required to achieve: post acceleration, energies higher than 12 MeV/A.

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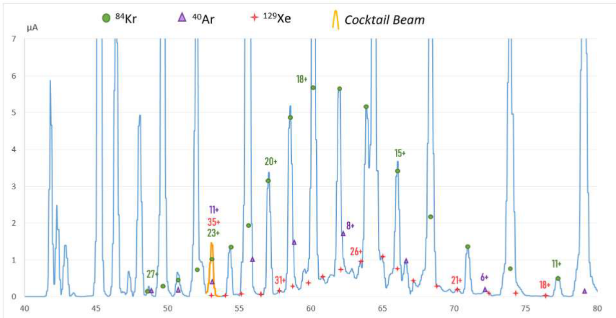

Figure 10: Mass spectra during experiments. In yellow, A/Q used for cocktail beam.

Switch times are recorded and intensities after post-acceleration (Fig. 11) are measured using:

- a faraday cup when I $\geq 10^8$ pps,
- a gas profiler when I $< 10^8$ pps.

	Ions	A/Q	Coeff. for ΔB & ΔV	Switch Time	N_{PPS} (Post-Acceleration)
Energy = 15,5 MeV	$^{84}Kr^{23+}$	*3,643*	*Ref.*		1.10^{10}pps
	$^{40}Ar^{11+}$	3,632	0,997	5 min	2.10^{10}pps
	$^{84}Kr^{23+}$	*3,643*	*Ref.*	5 min	1.10^{10}pps
	$^{22}Ne^{6+}$	1,005	1,005	5 min	2.10^{10}pps
	$^{129}Xe^{35+}$	1,009	1,009	5 min	6.10^{6}pps
	$^{48}Ti^{13+}$	1,011	1,011	5 min	2.10^{5}pps
	$^{63}Cu^{17+}$	1,015	1,015	5 min	2.10^{5}pps
	$^{56}Fe^{15+}$	1,022	1,022	5 min	1.10^{8}pps
	$^{15}N^{4+}$	1,028	1,028	5 min	3.10^{7}pps
	$^{129}Xe^{34+}$	1,039	1,039	10 min	2.10^{6}pps
	$^{27}Al^{7+}$	1,056	1,056	20 min	5.10^{5}pps
	$^{84}Kr^{23+}$	*Ref.*	*Ref.*	25 min	1.10^{6}pps

Figure 11: EM132 SAGA @GANIL – July 2024 : Production rates.

Except for $^{18}O^{5+}$, which is not evaluated regarding its LET proximity with ^{15}N, all elements of the cocktail beam proposal are measured at sufficient rates. Moreover, the switch times between 2 beams, about 5 minutes, are in line with expectations.

Additional test is done to estimate the required delay to switch to an ion whose Q/A implies a greater field variation (Fig. 12). First with $^{129}Xe^{34+}$, needing $\Delta B > 1$ %, intensity is suitable but tuning time doubles. Finally, for $^{27}Al^{7+}$ (metal from the Booster plasma chamber), with $\Delta B \approx 2$ %, the time increases proportionally. These results show that transfer times remain acceptable for industrial applications (~5 min) for magnetic field variations below 1 %.

CONCLUSIONS

GANIL, with its SPIRAL1 facilities (Phoenix Booster + CIME), has the capacity to supply a medium-energy cocktail beam (>12 MeV/A) for industrial applications. The production rates and switching times measured during the EM132 experiment meet initial expectations. The modifications made to the ion source, by replacing the waveguide and installing a sputtering rod, make it possible to produce additional metallic elements.

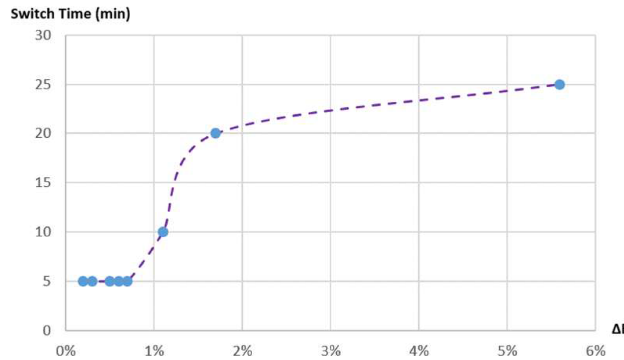

Figure 12: Switch time evolution according to CIME ΔB.

Means of improvement:

- Propose cocktail beams and define the settings for different energies, between 12 and 20 MeV/A),
- Try to produce other elements to extend the coverage of 'missing LET zones', in particular between Kr and Xe (with Ag or Rh, using a sputtering rod).

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