STATUS REPORT ON METALLIC BEAM PRODUCTION AT GANIL/SPIRAL 2

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Abstract

Primary ion beams from metallic elements are routinely produced at GANIL using ECR4 [1] and ECR4M [2] room temperature (RT) ECR ion sources. Ionization efficiency measurements, partially presented in the past, are summarized in this paper together with updated and new results obtained with Cd, Mo and Ta. Preliminary results obtained at Grenoble with the PhoenixV2 [3] ion source for Ni and Ca beam production [4] are also included. These ionization efficiencies are compared according to the ordinary production methods: oven, sputtering, MIVOC, gaseous compounds. The present SPIRAL 2 heavy ion injector designed for ions Q/A=1/3 is of interest to accelerate metallic ions up to the mass ~60. Above this value, the achievable intensities are dramatically limited by the atomic physics processes in the ECR plasma (intensities << 1 pμA). This limitation will be overcome with the future Q/A=1/6,1/7 injector. In order to choose the best ion source for such an injector, best world results have been compiled for different existing RT (Room temperature) and superconducting (SC) ECR ion sources.

ECR4/4M AND PHOENIX V2 ION SOURCES

In this section, the main differences between ECR4/4M (ECR4 or ECR4M) and Phoenix V2ion sources are presented. Although the global magnetic structure of these ion sources is comparable, i.e. superposition of an axial magnetic field created by resistive coils and of a radial field created by permanent magnets, some differences have to be pointed out:

RF Injection

Phoenix V2 is working at 18 GHz (instead of 14 GHz for ECR4/4M) with a direct rectangular RF injection (coaxial RF injection for ECR4/4M) allowing more RF power to be injected into the source.

Magnetic Confinement

Due to its direct RF injection, a massive iron plug can be placed behind the injection flange of Phoenix V2, leading to a much stronger injection magnetic field: 2 T for Phoenix-V2 compared to the 1 T for ECR4/4M. Moreover, Phoenix-V2 is equipped with a third coil located at the middle, helping to get a better shaped axial magnetic field.

Access to the Plasma

The internal diameter of the plasma chamber is about the same for ECR4/4M and Phoenix V2 (~63 mm). Using ECR4/4M, the oven used to evaporate metals can be placed only on axis (in front of the hot plasma) without any bias voltage, unlike Phoenix V2 where the oven is located off axis (beside the hot plasma) while keeping the biased disk functionality.

Beam Extraction

The beam is extracted at 60 kV from Phoenix V2 (2 accelerating gaps) instead of 25 kV for ECR4/4M (1 accelerating gap). The beam line inner diameter is higher for Phoenix V2 than the one of ECR4/4M, resp. 150 mm and ~65 mm. These differences lead to a better beam transmission for Phoenix V2 (~80-90%) than for ECR4/4M (~50%).

For Phoenix V2, the use of high speed turbo molecular pumps (2x1000 L/s) at the extraction leads to a vacuum level one order of magnitude lower than ECR4/4M (10^{-8} mbar for Phoenix V2 and 10^{-7} mbar for ECR4/4M). This is a crucial requirement to reduce the charge exchange process in the source and in the beam line, and therefore to keep alive the high charge states escaping the source.

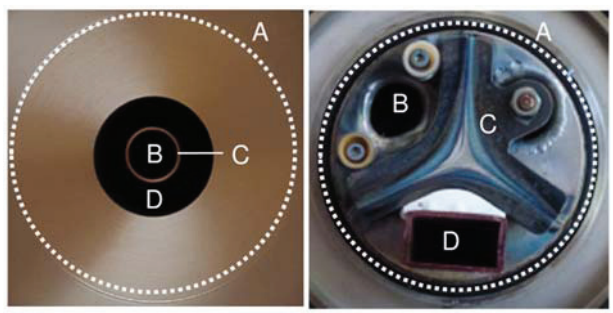

Figure 1: Injection view of ECR4/4M (left side), injection view of Phoenix V2 (right side). (A): inner diameter of the plasma chamber; (B): oven port and gas injection, (C) left side: biased tube, (C) right side: biased disk, (D) left side: 14 GHz coaxial RF injection, (D) right side: 18 GHz rectangular RF injection.

METALLIC BEAM PRODUCTION METHODS

In view of the very high charge states required for SPIRAL 2 (Q/A=1/3 => $^{14}Ca^{14+}$, $^{48}Ca^{16+}$, $^{58}Ni^{19+}$), the choice of the oven method and the use of pure metallic samples seems to be the most relevant alternative: the buffer gas

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flow, required to shift the distribution on high charge state, can be controlled regardless of the metal vapor injected into the source.

Primary beam production at GANIL (ECR4/4M), requiring a smaller Q/A (1/3 → 1/8), the MIVOC (Metal Ions from VOlatile Compound) method can also be used [5]. For very low vapor pressure elements (Ta for example), dismissing the use of an oven for evaporation, the sputtering method can be another alternative [6].

IONISATION EFFICIENCY DEFINITION

The ionization efficiency of a specific atomic species is defined as the ratio of the extracted ion flow over the injected neutral flow.

Extracted Ion Flow

The ion flow extracted from the ion source is deduced from the spectrum obtained downstream in the Faraday cup by summing I/q for all charge states (I being the beam intensity for the charge state q). This value expressed in pμA is corrected by the beam transport from the ion source to the Faraday cup, i.e. the total electrical intensity in the spectrum (sum of I for all charge state and species) divided by the drain current of the high voltage power supply.

Let us keep in mind, that the beam transport is assumed to be the same for all species and charge states, which is probably not the case. Since the spectra contain mainly ions coming from the buffer gas (see Fig. 2,3,6 and 7), the deduced beam transport is mainly the one of the buffer gas.

Because the transport efficiency of the ions coming from the light buffer gas is probably lower than for the heavier metallic ions, the ionization efficiencies given in this paper could be over-estimated. Some errors could come from this transport efficiency correction, especially for low values.

RESULTS FOR LEAD

Extracted Ions

The $^{208}Pb^{28+}$ beam has been produced during 17 days with a mean intensity of 1.4 μA (I_q^{mean}) at faraday cup location. The ^{208}Pb ion flow reaching the faraday cup (over all charge states) can be deduced from the spectrum Fig. 2:

$$\frac{I_q^{mean}}{I_q} \times \sum_q \frac{I_q}{q} = \frac{1.4}{4.5} \times 2.5 \approx 0.78\ \text{p}\mu A$$

Taken into account the beam transport efficiency of 50% (T) - assumed to be the same for all charge state and species - leads to an ion flow extracted from the source of:

$$\frac{1}{T} \times \frac{I_q^{mean}}{I_q} \times \sum_q \frac{I_q}{q} = \frac{1}{0.5} \times \frac{1.4}{4.5} \times 2.5 \approx 1.55\ \text{p}\mu A$$

Injected Neutrals

The material consumption of 38 mg measured by weighting the sample after 17 days, leads to a mass flow of 93 μg/h injected into the source, equivalent to 12.0 pμA.

Therefore, the ionization efficiency of the ion source ε is:

$$\varepsilon = \frac{1.55}{12.0} \approx 0.13 = 13\%$$

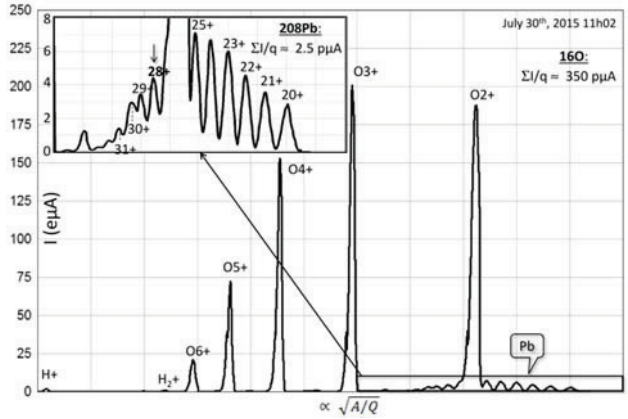

Figure 2: Spectrum obtained with ECR4M and optimized on $^{208}Pb^{28+}$ (4.5 μA). RF power: 380 W (120 W reflected), buffer gas O_2: 8.5×10^{-6} mbar at injection, 2.0×10^{-7} mbar at extraction, 18.5 kV/1.8 mA, axial magnetic coils: 960A/729A, oven power 1.9 W (~200°C off-line), oven position: +6 mm inside the plasma chamber, no bias. Transport efficiency up to the faraday cup: ~50%.

RESULTS FOR MOLYBDENIUM

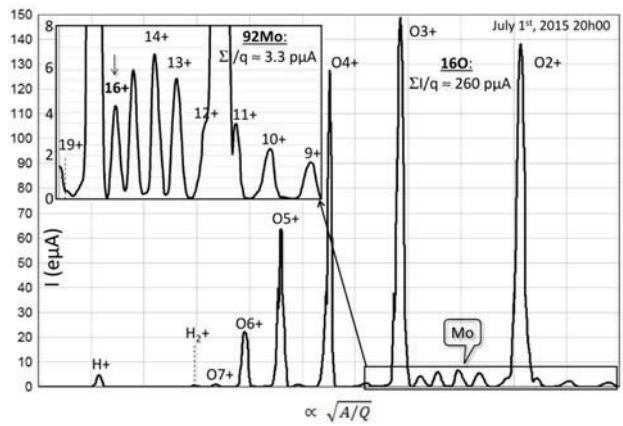

Figure 3: Spectrum obtained with ECR4M and optimized on $^{92}Mo^{16+}$ (4.1 μA). RF power: 140 W (37 W reflected), 18 kV/1.8 mA, buffer gas O_2: 8.5×10^{-6} mbar at injection, 2×10^{-7} mbar at extraction, oven power 3.5 W (~250°C off line), oven position: 0 mm inside the plasma chamber, no bias, coils: 940A/730A. Transport efficiency up to the faraday cup: ~40%.

Extracted Ions

The $^{92}Mo^{16+}$ beam has been produced with a mean intensity of 1.25 μA for 6 days. Following the same calculation method previously detailed, the ion flow extracted from the source is:

$$\frac{1}{0.4} \times \frac{1.25}{4.1} \times 3.3 \approx 2.51\ \text{p}\mu A$$

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Injected Neutrals

The measured consumption for $^{92}MoO_3$ was 1.34 mg/h, i.e. 0.88 mg/h for ^{92}Mo, leading to a neutral flow injected into the source of about 256 pμA.

Therefore, the ionization efficiency ε of the ion source is:

$$\varepsilon = \frac{2.51}{256} \approx 0.0098 \approx 1\%$$

Figure 4: Aspect of the Mo fed oven after the 6 days run.

RESULTS FOR TANTALUM

Extracted Ions

The $^{181}Ta^{24+}$ beam has been produced with a mean intensity of 4.5 μA for 17 days. Following the same calculation method previously detailed, the ion flow extracted from the source is:

$$\frac{1}{0.5} \times \frac{4.5}{5.5} \times 2.0 \approx 3.3\ \text{p}\mu A$$

Injected Neutrals

The measured consumption for ^{181}Ta was 3.0 mg/h, leading to a neutral flow injected into the source of about 444 pμA.

Therefore, the ionization efficiency ε of the ion source is:

$$\varepsilon = \frac{3.3}{444} \approx 0.0074 \approx 0.75\%$$

Figure 5: Aspect of the Ta electrode after the 17 days run.

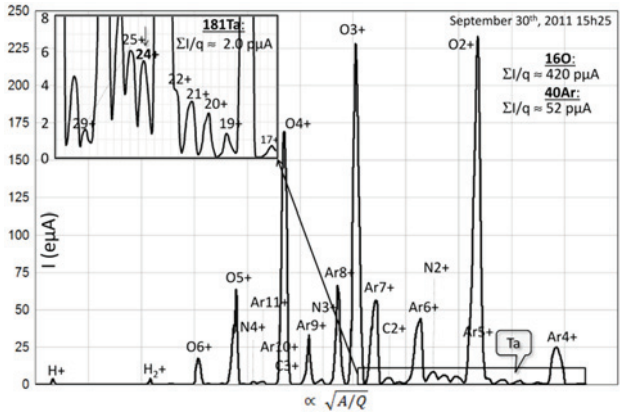

Figure 6: Spectrum obtained with ECR4M and optimized on $^{181}Ta^{24+}$ (5.5 μA). RF power: 371 W (22 W reflected), 19 kV/2.4 mA, buffer gas Ar + O_2: 2×10^{-5} mbar at injection, 2×10^{-7} mbar at extraction, sputtering voltage: –1200 V/1.4 mA, sputtering electrode position: +16 mm inside the plasma chamber, coils 895A/755A. Transport efficiency up to the faraday cup: ~50%.

RESULTS FOR CADMIUM

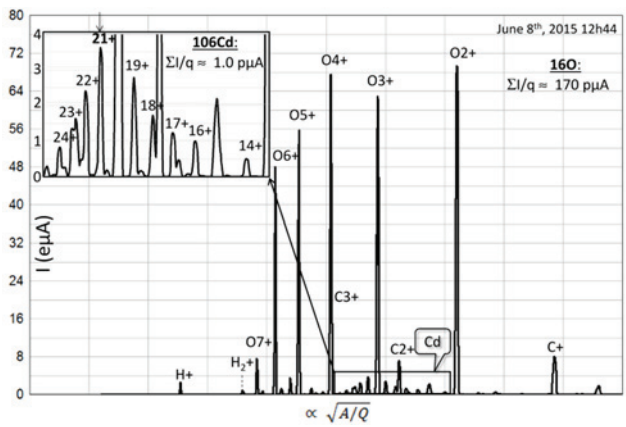

Figure 7: Spectrum obtained with ECR4 and optimized on $^{106}Cd^{21+}$ (3.7 μA). RF power: 139 W (17 W reflected), 25 kV/1.0 mA, buffer gas O_2: 6×10^{-6} mbar at injection, 2.0×10^{-7} mbar at extraction, oven power 0.5 W (~100°C off line), oven position: +6 mm inside the plasma chamber, no bias, coils 1071A/1044A. Transport efficiency up to the faraday cup: ~50%.

Extracted Ions

The $^{106}Cd^{21+}$ beam has been produced with a mean intensity of 1.4 μA for 11 days. Following the same calculation method previously detailed, the ion flow extracted from the source is:

$$\frac{1}{0.5} \times \frac{1.4}{3.7} \times 1.0 \approx 0.75\ \text{p}\mu A$$

Injected Neutrals

The measured consumption for ^{106}CdO was 34 μg/h, i.e. 30 μg/h for ^{106}Cd, leading to a neutrals flow injected into the source of about 7.6 pμA.

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Therefore, the ionization efficiency ε of the ion source is:

$$\varepsilon = \frac{0.75}{7.6} \approx 0.099 \approx 10\%$$

IONISATION EFFICIENCIES COMPILATION

These ionization efficiencies and previously published data obtained with ECR4/4M [7][8][9][10] are graphically represented in Fig. 8, according to the production methods. Some results, published only in GANIL internal reports, and preliminary results obtained with Phoenix V2 at Grenoble for Ca and Ni [4] have also been included.

It is important to keep in mind that the ionization efficiency for a given element may easily vary by a factor of 2, depending on how the ion source is tuned. For example, a too fast tuning could lead to a temporary over-evaporation and significantly decrease the ionization efficiency.

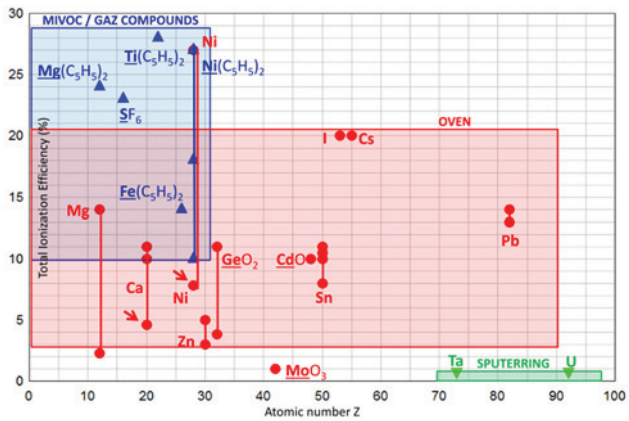

Figure 8: Total ionization efficiencies compilation obtained with ECR4/4M and Phoenix V2 (red arrows).

Therefore, the Fig. 8 must be interpreted from a statistical point of view. It appears that:

- The ionization efficiencies obtained by the (MIVOC/Gas compound) method (~20%) is higher than those obtained by the oven method (~10%). With the sputtering method, the ionization efficiency drastically shuts down by one order of magnitude (~1%).
- Very high ionization efficiency for Ni (~27%) has been measured using the oven method (internal report GPI-2010-138). More tests have to be done to confirm this result.
- Very low ionization efficiency (~1%) has been obtained for Mo using the oven method with the compound MoO_3.
- The ionization efficiencies obtained for Ca and Ni with Phoenix V2, respectively 4.6% and 7.5% (corrected by a beam transport of ~ 80%), are a bit lower than those obtained with ECR4/4M. No clear conclusion could be drawn. More tests over longer periods, should start in the next months coming with Phoenix V2 installed in the SPIRAL 2 Q/A=1/3 injector.

IONISATION EFFICIENCIES INTERPRETATION

In order to be captured by the plasma, the atoms or molecules must be ionized during their first crossing through the plasma, otherwise they remain stuck onto the cold plasma chamber walls.

When using the MIVOC method, the molecules lost on the walls can be re-evaporated into the plasma due to the high vapour pressure of the compound (~10^{-2} mbar at 25°C). This leads to a higher probability to be ionized, and therefore to a better ionization efficiency for the MIVOC method.

Concerning the much lower ionization efficiency obtained with the sputtering method (~1%), the interpretation is much unclear. With the sputtering method, the condensable atoms of the rod are mainly injected into the plasma under a neutral form and with energy in the order of eV [11]. This energy, much higher than the thermal energy of atoms produced by the oven method (1273 K ↔ 0.1 eV), could explain the very low ionization efficiency.

IMPROVEMENT OF THE IONIZATION EFFICIENCY

In addition to the reduction of the material consumption of importance for the use of rare and expensive isotopes, the improvement of the ionization efficiency will reduce the plasma chamber contamination and could result in a better beam stability. As the metal vapor injected into the plasma will be decreased, could we expect a better charge state distribution? This remains an open question.

At least two parameters are not under control when using the oven, MIVOC or sputtering methods:

- The energy of the metallic atoms sent into the plasma (probably not optimum).
- The trajectory of the metallic atoms injected into the plasma (wide angular atom dispersion as they are neutral, hence insensitive to electric and magnetic field).

Injecting 1+ metallic ion into the plasma source, i.e. controlling the energy and trajectory, could be a way of improving the ionization efficiency by targeting the best place to trap and multi-ionize the ions. It has been already proved using charge breeder devices [12] that the injection of low intensity (<1 μA) 1+ metallic ions leads to ionization efficiencies close to those obtained with gaseous ions.

The first question that arises is to estimate by calculations the maximum 1+ intensity that can be injected while keeping good ionization efficiency. To be of interest for stable beam production a mono-charged beam with a threshold intensity of a few tens of μA should be injected.

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FUTURE Q/A=1/6, 1/7 SPIRAL 2 INJECTOR

The SPIRAL 2 LINAC has been designed to accelerate 5 mA deuterons at 40 MeV (Q/A=1/2). This deuteron beam will produce high neutrons flux via a carbon converter that will be used either directly for physics (NFS: Neutrons For Science) or for the delivery of high intensity RIB produced by neutron-induced fission of a uranium target (up to 10^{14} fissions/s).

The RFQ injector of the LINAC has been designed to accelerate also Q/A=1/3 ions that will be used for the in-flight radioactive ion production system named S3 (Super Separator Spectrometer). In order to accelerate beams up to the uranium mass, a separate cave has been built to later host a second injector including a RFQ able to pre-accelerate Q/A=1/6, 1/7 ions (much more easy to produce with an ion source) at the required entrance energy of the LINAC.

The best world results represented in Fig. 9 highlights some rules:

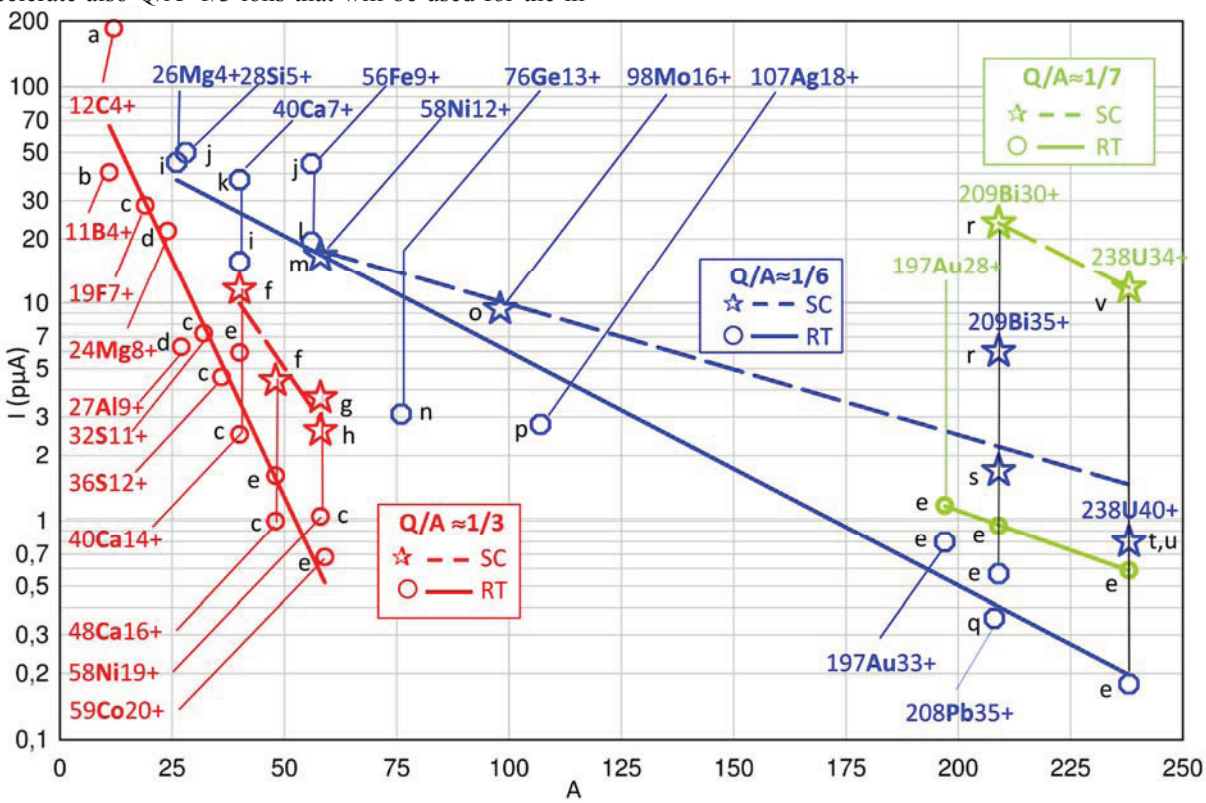

Figure 9: Best world intensities obtained for Q/A=1/3, 1/6 and 1/7 with RT (room temperature) and SC (Superconducting) ion sources. The letters a, b, c...make reference to publications (see references).

The best world results represented in Fig. 9 highlights some rules:

- Above A=60, the intensities fall below 1 pμA, which are comparable to those already obtained with the existing GANIL facility.
- Up to A=25, the choice of Q/A=1/3 is justified. However no data are available for Q/A=1/6, 1/7.
- For A=25, the choice of Q/A=1/6, 1/7 is evident, and the gain in intensity becomes much more important when the mass increases.
- For A between 25 and 60, a RT Q/A=1/6,1/7 ion source seems the most suited and cheapest solution. However, no results from Q/A=1/6, 1/7 SC ion sources are available since they have been developed for heavy ions. Tests should be done.
- For A higher than 60, the choice of a Q/A=1/6,1/7 SC ion source becomes more and more evident when the mass increases.
- For A above 200, the best choice is clearly a Q/A=1/7 SC ion source.

Table 1: Best ion charge state (Q/A=1/3 or 1/6, 1/7) and best ion source (RT: room temperature or SC: Superconducting) to get the maximum intensity for SPIRAL 2.

Ion mass	Best ion source	Comment
A < 25	Q/A=1/3 , RT	
25 < A < 60	Q/A=1/6? 1/7? RT a priori	- No data for Q/A=1/7 - No optimized data with SC ion sources
60 < A < 200	Q/A=1/6-1/7 , SC	- No data for Q/A=1/7 - Too few data
A > 200	Q/A=1/7 , SC	- Bi, U

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Although the choice is clear for A<25 and A>200, the conclusion for intermediate masses would need more data with SC ion sources not build and optimized for such masses. In addition, physics requests have to be taken into account for the final choice.

It is important to keep in mind that the best intensities presented in Fig. 9 are the best never obtained, so that they have to be divided by a factor of 2 to get intensity in operation.

REFERENCES

[1] P. Sortais et al., Rev. Sci. Instrum. 61, 228 (1990). http://dx.doi.org/10.1063/1.1141324

[2] R. Leroy et al., Proceedings of 12th ECRIS Workshop (Riken 1995).

[3] C. Peaucelle et al., Proceedings of 19th ECRIS Workshop (Grenoble 2010). http://accelconf.web.cern.ch/AccelConf/ECRIS2010/papers/tucoak01.pdf

[4] C. Barué et al., Proceedings of the 15th ICIS (Chiba), Rev. Sci. Instrum. 85, 02A946 (2014). http://dx.doi.org/10.1063/1.4847236

[5] H. Koivisto et al., Proceedings of 13th ECRIS Workshop (College Station 1997).

[6] R. Harkewicz et al., Rev. Sci. Instrum. 66, (1995) 2883. http://dx.doi.org/10.1063/1.1146501

[7] P. Lehérissier et al., Proceedings of the 9th ICIS (Oakland 2001). Rev. Sci. Instrum. 73, 558 (2002). http://dx.doi.org/10.1063/1.1429316

[8] P. Lehérissier et al., Proceedings of the 11th ICIS (Caen 2005). Rev. Sci. Instrum. 77, 03A318 (2006). http://dx.doi.org/10.1063/1.2164888

[9] P. Jardin et al., Proceedings of 13th ICIS (Gatlinburg 2009). Rev. Sci. Instrum. 81, 02A909 (2010). http://dx.doi.org/10.1063/1.3267296

[10] F. Lemagnen et al., Proceedings of the 21th ECRIS (Nizhny Novgorod 2014). http://accelconf.web.cern.ch/AccelConf/ECRIS2014/papers/mopph002.pdf

[11] A. Arnau et al., Surface Science Reports 27, 113-239 (1997). http://dx.doi.org/10.1016/S0167-5729(97)00002-2

[12] L. Maunoury et al., Proceedings of the 15th ICIS (Chiba), Rev. Sci. Instrum. 85, 02A504 (2014). http://dx.doi.org/10.1063/1.4828374

REFERENCES IN FIG. 9

[a] M. Muramatsu et al., Proceedings of the 12th ICIS (Seoul), Rev. Sci. Instrum. 79, 02A328 (2008). http://dx.doi.org/10.1063/1.2816706

[b] H. Koivisto et al., Proceedings of the Workshop on the Production of Intense Beams of Highly charged ions, Catania (2000).

[c] C. Barué et al., Proceedings of the 15th ICIS (Chiba), Rev. Sci. Instrum. 85, 02A946 (2014). http://dx.doi.org/10.1063/1.4847236

[d] D. Wutte et al., Proceedings of the 9th ICIS (Oakland), Rev. Sci. Instrum. 73, 521 (2002). http://dx.doi.org/10.1063/1.1425781

[e] Z.Q. Xie et al., Proceedings of the 13th ECRIS workshop (College Station 1997).

[f] H.W. Zhao et al., Proceedings of 18th ECRIS workshop (Chicago 2008) (data in the talk only).

[g] H.W. Zhao et al., Proceedings of 19th ECRIS workshop (Grenoble 2010). http://accelconf.web.cern.ch/AccelConf/ECRIS2010/papers/mocoak01.pdf

[h] L.T. Sun et al., Proceedings of 19th ECRIS workshop (Grenoble 2010). (data in the talk only).

[i] R. Lang et al., Proc. of 15th ECRIS workshop (Jyvaskyla 2002).

[j] A. Kitagawa et al., Proc. of 19th ECRIS workshop (Grenoble 2010). (data in the talk only). http://lpsc.in2p3.fr/Indico/getFile.py/access?resId=11&materialId=slides&confId=467

[k] D. Hitz et al., Proceedings of the 12th ECRIS workshop (Riken 1995).

[l] S.L. Bogomolov, Physics of Particles and Nuclei Letters, Vol. 12, n°7 (2015). https://www.researchgate.net/publication/286522922

[m] L.T. Sun et al., Proceedings of 19th ECRIS workshop (Grenoble 2010). http://accelconf.web.cern.ch/AccelConf/ECRIS2010/papers/mocoak02.pdf

[n] P. Lehérissier et al., Nuclear Instrum. and Methods B211 (2003). http://www.sciencedirect.com/science/article/pii/S0168583X03012138

[o] G. Machicoane et al., Proceedings of the 15th ICIS (Chiba), Rev. Sci. Instrum. 85, 02A957 (2014). http://dx.doi.org/10.1063/1.4858095

[p] R. Scott, Proceedings of 19th ECRIS workshop (Grenoble 2010) (data in the poster only). http://lpsc.in2p3.fr/Indico/getFile.py/access?resId=17&materialId=poster&confId=467

[q] R.C. Vondracek, Proceedings of the 10th ICIS (Dubna), Rev. Sci. Instrum. 75, 5 (2004). http://dx.doi.org/10.1063/1.1691507

[r] L.T. Sun, Proceedings of 21th ECRIS workshop (Nizhny Novgorod 2014). http://accelconf.web.cern.ch/AccelConf/ECRIS2014/papers/tuommh03.pdf

[s] D. Leitner et al., Proceedings of 16th ECRIS workshop (Berkeley 2004).

[t] D. Leitner et al., Proceedings of the 12th ICIS (Seoul), Rev. Sci. Instrum. 79, 02C710 (2008). http://dx.doi.org/10.1063/1.2816790

[u] L.T. Sun, Proceedings of 21th ECRIS workshop (Nizhny Novgorod 2014). http://accelconf.web.cern.ch/AccelConf/ECRIS2014/papers/tuommh03.pdf

[v] J. Benitez et al., Proceedings of 20th ECRIS workshop (Sydney 2012). http://accelconf.web.cern.ch/AccelConf/ECRIS2012/papers/thxo02.pdf

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