STATUS AND DEVELOPMENT OF ECR ION SOURCES

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Abstract

For the production of eV to TeV beams or from pps to hundredth of mAe intensities, the ECR ion source is now the standard device for production of heavy ion beams in CW or pulsed mode. We will try to present the most advance machines dedicated to the accelerator applications. We will start with the sources for the CW applications on cyclotron. We will present also the main characteristics of the permanent magnet sources from the Nanogan family that is very suitable for the high voltage applications. Due to the very good reliability of the ECR devices, a strong effort is also done for the upgrade of the production of intense beams of mono or low charge state ions like H+ or B+. We will also recall the fact that an ECR base on a "Minimum |B|" magnetic structure can be optimized for the pulsed operation using the so-called "Afterglow mode". Due to their good efficiency properties ECR ion sources are also a new field of development for the production of mono or multicharged radioactive ions. From the preliminary monocharged ion production at Louvain-la-Neuve to the latest developments about the beam bunching at Grenoble, we will present the most typical uses of ECR ion sources for RIB production. Finally we will present the latest programs of development that show that the ECR technology is always rich of new applications.

1 INTRODUCTION

The ECR ion sources of the CW multicharged ions (MCI) beam have been initially developed for use on cyclotron injector. But now the ECR sources have very various other applications like RFQ injector, Linac injector, THT platform, Tamdem terminal, high current of monocharged ions, charge accumulator, online production of mono- or multi- charged radioactive ions production or charge breeder. We will try to make a review of the latest devices dedicated to these main fields of applications.

2 CW SOURCES FOR CYCLOTRON

2.1 Current or charge optimization

The production of multicharged ions is based on a fundamental contradiction. At fixed electronic density(n_e) and with high enough electronic energy, the generation of more and more charged ions demands longer and longer ionization time, i.e. if $n_e\tau_i$ is maximum (τ_i confinement time) the average <Z> will be maximum. Unfortunately if the "resident" time of the ion in the plasma is long, the flux of losses is small, so the current is small. For accelerator with stripping that works with fixed charge for final acceleration the ion source development is closed to a race for currents. But for compact accelerator (like compact cyclotron without stripping) it is more close to a race for charge state. We will compare now the most advance devices dedicated to MCI production.

2.2 Compact room temperature devices

A large part of the compact room temperature sources are derived from the Minimafios and CAPRICE sources developed by Richard Geller and Bernard Jacquot. Initially design at 10 GHz now the standard frequency is 14 or 18 GHz. They are generally built around a FeNdB hexapolar system and delivering a transversal field higher than 1 T. Depending of the volume and of the coil geometry, the total electrical consumption can go from 30 to 150 KW.

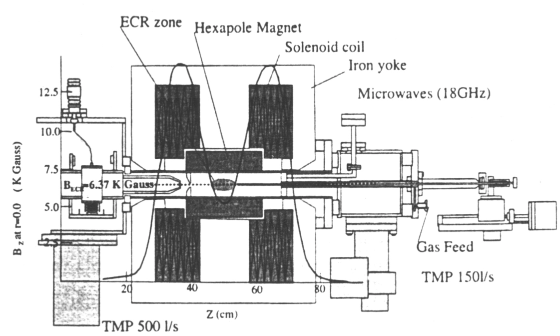

Figure 1: Cross sectional view of RIKEN 18 GHz ECRIS.

The most advanced source of this category is presently the 18 GHz RIKEN source [1] (see Fig. 1). A record current of 1 mAe of Ar^{8+} shows that it is a source very well optimized for high currents of medium charge state. But other optimization shows very good current of Ar^{12+} (200 µAe), Ar^{16+} (16 µAe) or Ar^{17+} (1 µAe). Close results are also observed on very various others devices of the same type ECR4-M (GANIL), AECR (Berkeley), or IMP (Beijing) [2].

This type of ECRIS is widely used for metallic ion beam production. The typical current density (J_i) of extracted current can go from 1 to 5 mA.cm^{-2} and for average Z of Argon ($<Z>_{Ar}$) from 6 to 10.

2.3 Superconducting devices

The room temperature sources work with a typical magnetic field of 1.0 to 1.3 T even for radial or axial system that is close to the limit of classical magnetic technology.

If we want to go on the upgrade of the magnetic field for the upgrade of the confinement, of course we have to switch to superconducting device. But in this case we have also to increase the volume of the source due to the minimum size of coils. SERSE (Catania) is a typical machine of this type (see Fig.2). The maximum radial field is 1.4 T and 2.7 T for the axial field at UHF injection [3].

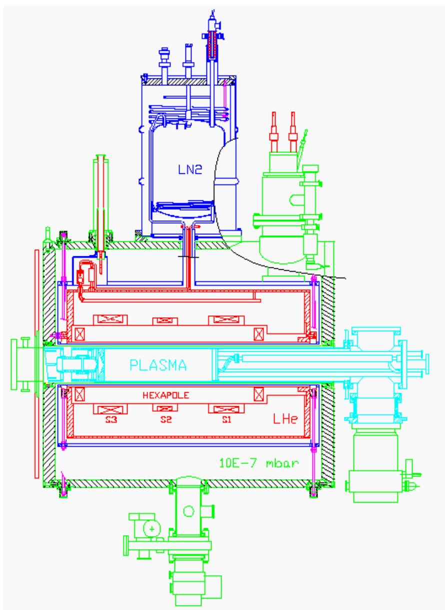

Figure 2: The SERSE source.

Currents which have been observed for Argon ions from 11+ to 16+ are similar to those observed with the RIKEN source. But a very nice beam of Ar^{17+} (2.6 µAe) have been produced.

For large device very good $\langle Z \rangle_{Ar}$ (close to 13) can be produced but for these tuning the total current extracted from the source remain quite low so J_i = 0.3 - 1 mA.cm^{-2}, showing by this way an extreme compromise between confinement and total current extracted from the source.

Two others SC devices are under development : A hybrid device in RIKEN with superconducting axial field and permanent magnet for radial field [4] and VENUS in Berkeley with 2.4 T of radial field and 4 T of axial field (see M.A. Leitner et al. , theses proceeding) [5].

3 SOURCE FOR HIGH VOLTAGE PLATFORM

3.1 ECR source and technical constraints

We have seen that the multicharged ion sources can be large and expensive devices so for special environment (THT platform or RIB system) if the ultimate charge state is not an issue, we can design smaller, simpler and cheaper source.

The main compromise on the performances comes from the limitation of the plasma volume that induces the limitation of the maximum charge state but minimizes the global size of the source.

3.2 Nanogan on a tamdem terminal

Initially dedicated to on line production of multicharged radioactive, Nanogan has been designed as a "throw away" ECRIS [6]. This is an ultra compact with an outer diameter of 12 cm, a 28 mm in diameter plasma chamber and a 90 mm in length minimum |B|. In spite of theses dimensions, it is easy to maintain radial and axial magnetic fields of 0.7 T, so to maintain a reasonable level of confinement.

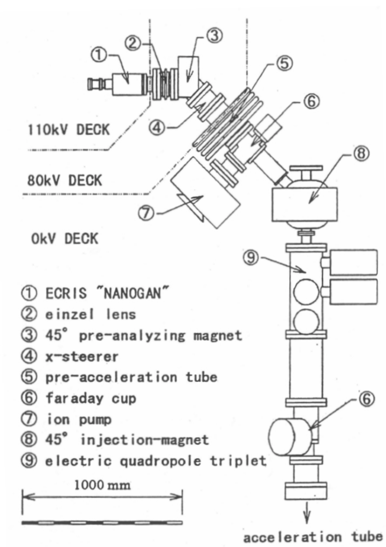

Figure 3: The layout of the in-terminal ECR ion injector.

By this way the current density J_i can go from 1 to 3 mA.cm^{-2} for an $\langle Z \rangle_{Ar}$ from 8 to 1 : Ar^{8+} (50 µAe), Ar^{11+} (1 µAe).

The source is so small that we can include it on the terminal of a tamdem [7] (see Fig.3). In this case the source replaces totally the negative ion accelerator and directly produces better charge states and currents than with a stripper, so the Tamdem comes back to the Van De Graaf geometry.

3.3 SuperNanogan

Using the technology of permanent magnets we can re-optimize the structure for a better multicharged ion production close to the level of room temperature source.

It is what have been done with the SuperNanogan source with an outer diameter of 50 cm, a 45 mm in diameter plasma chamber and a 120 mm in length. The minimum |B| structure has radial and axial magnetic fields of 1.1 T (see Fig.4). By this way we can maintain the J_i to

1-3 mA.cm-2 upgrade the $\langle Z\rangle_{Ar}$: Ar^{8+} (300 µAe), Ar^{14+} (1 µAe).

This source is relatively compact, so it is used as injector on HV platform of the HMI/Berlin RFQ and will be used as Lead injector on a large TAMDEM like at JAERI/Tokai (Japan).

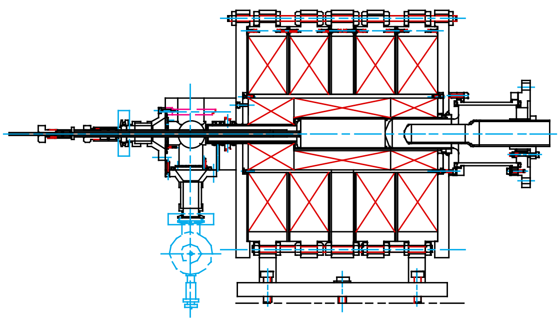

Figure 4: The full permanent magnet SUPERNANOGAN source functioning at 14.5 GHz.

4 SOURCE FOR HIGH CURRENT

4.1 2.45 GHz devices

If we reduce drastically the magnetic field to a quasi uniform field, we collapse totally the possibility to produce MCI but in this case we can extract very high current density of monocharged ions.

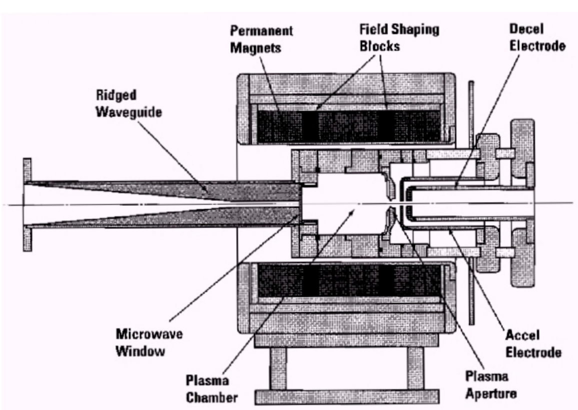

Figure 5: Compact 2.45 GHz ion source.

Generally the resonance surface is very close to the extraction area in order to generate a "rapid" ionization (confinement time of some tenth of microseconds) followed by an immediate extraction after very few collisions between the ions and the electrons. The sources of this type function generally at 2.45 GHz [7] and are dedicated to the CW production of H^+ ions. Of course the <Z> is 1 and the current density can reach more than 100 $mA.cm^{-2}$.

Fig. 5 shows a permanent magnet version developed at Chalk River and producing up to 60 mAe of H^+. Similar machines are operational at Saclay [8] (France) and Los Alamos [9] (USA).

4.2 Microgan 10 GHz

If we look for a compromise between mono and multicharged ion production, for example for industrial purposes, a specific functioning point has been observed with the Microgan source. Here we maintain a minimum |B| structure for the production of the MCI and collapse the confinement with pressure in the source. By this way we can also reach a functioning point with high current density where J_i = 3-30 mA.cm-2 and $\langle Z\rangle_{Ar}$ = 2 corresponding to H+ (12mAe), B^+ (2.9 mAe), B^{2+}(0.3 mAe), B^{3+}(0.06 mAe), Ar^{8+} (32 µAe).

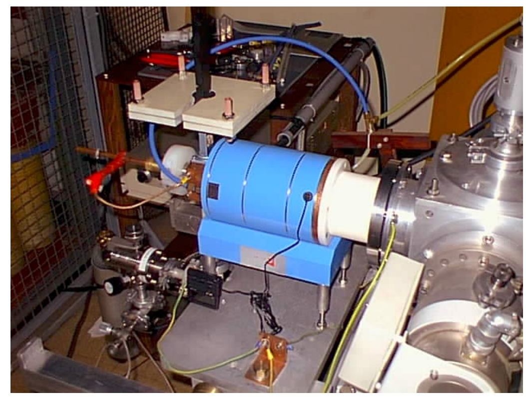

Figure 6: The compact Microgan 10 GHz ion source.

The balance between the two tunings, is just done by the compromise between the pressure and the power. For the high charge state tuning the source works around 10^{-5} mbar and 60 W, for the monocharged ions tuning we reach 10^{-3} mbar and 200 W. It means that the loss of confinement as to be compensated by power in order to maintain the density.

5 SOURCE FOR PULSED OPERATION

5.1 The afterglow pulsed mode

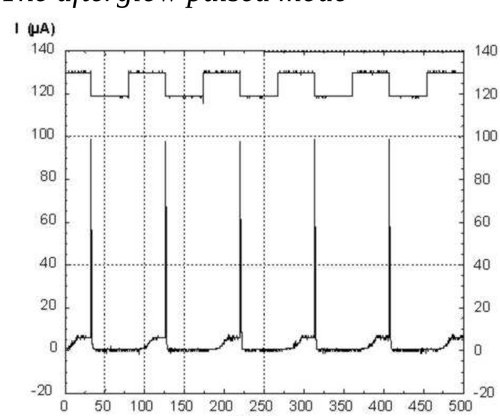

Figure 6: Bunched beam of Lead with ECR4 14.5 GHz at CERN.

If we identify a basic limitation for CW operation, we can find another compromise in playing with the time structure. This way is called the afterglow pulsed mode. In fact, we tune the ECRIS as an EBIS. We accumulate the ions, confine, ionize and then induce a rapid de-confinement of MCI. It means that an electrostatic confinement effect is superposed the magnetic confinement of the minimum |B|.

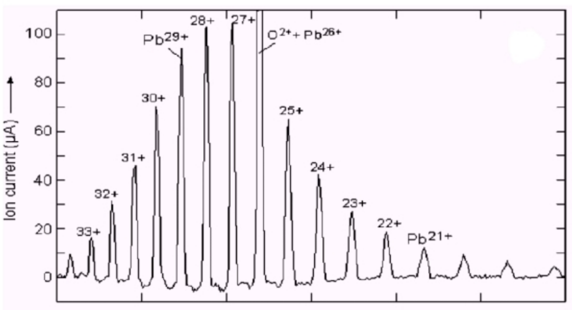

Figure 7: Lead spectrum with ECR4 14.5 GHz at CERN.

This electrostatic trap is a consequence of the ECR heating and can collapse at the end of it [11]. During the steady state operation we can minimize the flux of ions i.e. we can accumulate ions in the plasma afterward we can generate an increase of the current density (see Fig. 6).

5.2 CERN and GSI operations

Since the afterglow effect is an electrostatic effect, it is mainly efficient with highly charged ions like Pb^{27+} used at CERN [12].

The optimum CW current of the source is 30 µAe with Pb^{27+} . During the pulse operation this one is reduced to roughly 10 µAe followed by a 100 µAe afterglow peak. It means that the useful current density during the peak is three time higher than during CW tuning (see Fig.7).

6 RIB PRODUCTION WITH ECRIS

6.1 Mono and Multicharged ion production

We have review the properties of ECR dedicated to the optimization of the number of particle we extract from the source, independently of what we inject inside in order to get the beam.

For the ionization of radioactive ion the key factor is the efficiency of the source i.e. the ratio of the given number of particle we inject by respect to the number of ions contained in the beam of this particle. Even with mono- or multi-charged ions the gaseous efficiency of ECRIS is very good, typically from 20 to 80 % for the global efficiency. The efficiency per charge state will depend of the nature of the charge state distribution.

6.2 Louvain and SPIRAL systems

The first production of radioactive ions with an ECRIS has been done at Louvain-la-Neuve [13] with direct coupling of the target to the source (see Fig. 8).

It is a relatively simple installation where the gaseous radioactive compounds desorb from the heated target and diffusion over some meters up to the plasma chamber of the source.

Depending of pressure in the source (outgassing) production of mono and multicharged ion is possible for post acceleration. Beams of $^{6}He^{+}$, $^{13}N^{+}$, $^{19}Ne^{+}$ are now commonly produced.

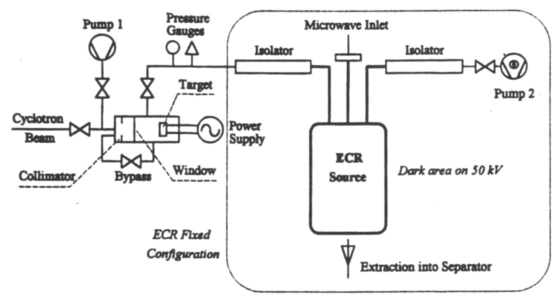

Figure 8: Experimental setup on line gaseous ionization of radioactive ion at Louvain-la-Neuve

Le limitation of this method comes from the diffusion time over the transfer tube, the outgassing from the target, that de-tuned the ECR, and the sticking on the wall for metallic elements.

This technic is also applied at GANIL where multicharged ions are produced for noble gas ions[14]. A beam of $^{31}Ar^{8+}$ (10 ms lifetime of the nucleus) has been produced showing the duration of the ionization process.

6.3 Charge breeding

A powerful technology for production of multicharged radioactive ions (for post-acceleration purpose) is the charge breeding [15]. We make the coupling of two ECRIS so by this way we can separate a first high pressure "producing" unit (1+ source) and a low pressure "charge accumulator" (n+ source) (see Fig.9). If we assume two times an efficiency of 70% for each source, it means that we can maintain a global efficiency of 50% [16].

Breeding times of 25 ms have been observed for the transformation of Ag^{1+} to Ag^{19+}, theses times show that the breeding time is compatible with ionization of short lifetime elements. The use of the source as a pure buncher (ECR Ion Trap) has been also shown but with an efficiency presently reduced by a factor 2 [17].

7 FUTURE DEVELOPMENT AND CONCLUSION

We have seen that a lot of sources function with a frequency around 14 GHz, so with an electronic density around some10^{12} $e^{-}cm^{-3}$. Very various devices optimize the confinement system in order to increase the average charge state extracted from the source.

Now if we want to produce new high current beams of medium charge states, we have to switch to a new level of density around 10^{13} $e^{-}cm^{-3}$ and then to redefine new charge/current optimizations. It is the subject of a large collaboration program between CERN / GSI (Darmstadt) / CEA (Grenoble) / ISN (Grenoble) [17] for LHC application, that looks for 1 mAe of Pb^{27+} in pulsed mode. Preliminary tests will be done on the SERSE in Catania and also a new room temperature source (see Fig. 10) called PHOENIX that is under assembly at ISN for development of high current of medium charge like 5 mAe of Ar8+ at 28 GHz.

It is clear now that the ECR technology can answer to numerous problems of positive ion productions and that we have not yet reached any ultimate physical limitations.

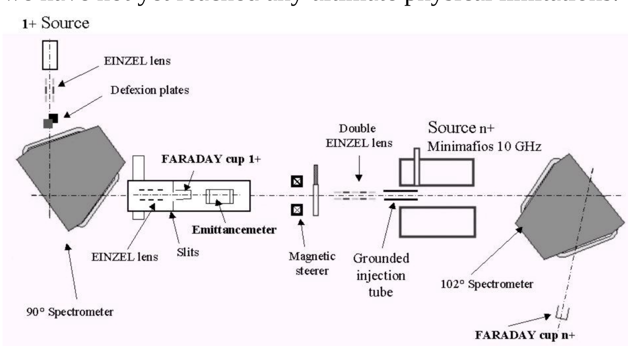

FIG. 9. Experimental setup for charge breeding operation

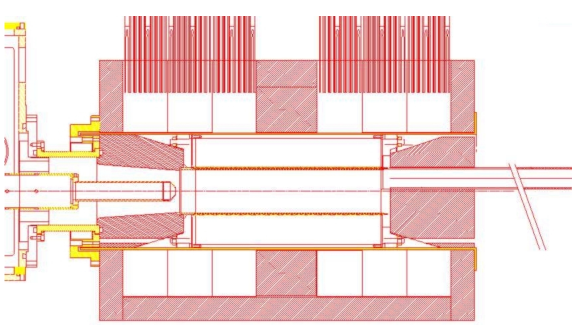

Figure. 10: The room temperature PHOENIX 28 GHz source for high current of medium charge state

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