INTENSE HIGHLY CHARGED HEAVY ION BEAM PRODUCTION

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Abstract

With the increase in applications of heavy ions in various fields, the production of intense beams of highly charged heavy ions from ion sources become more and more important. For example, the ion sources are required to produce intense dc beams of highly charged heavy ions for accelerator facilities for radioisotope beam production, and intense short-pulsed beams for injection into synchrotrons. Additionally, in these applications, the ion sources face several important characteristics that need to be improved to meet these requirements, such as source lifetime, reliability, current stability, and beam emittance. Thus, several high-performance ion sources (including ECR, electron-beam, and laser ion sources), for production of the intense beams (dc and pulsed) of highly charged heavy ions, have been constructed and achieved remarkable breakthrough in the past decade. In this contribution, state-of-the-art ion sources for production of intense highly charged heavy ion beams is reviewed. Future perspective is also discussed.

INTRODUCTION

The demands for high beam intensity and a variety of ion species in heavy ion accelerator facilities have become more important in the past decade. It is obvious that the choice of ion source strongly depends on the requirements of the accelerators. For example, the Relativistic Heavy Ion Collider (RHIC) needs an intense short-pulsed beam produced by an electron beam ion source (EBIS) [1]. In contrast, the electron cyclotron resonance ion source (ECRIS) is one of the best choices for the radio isotope beam factory (RIBF) project [2,3] for production of a radioisotope beam using projectile-like fragmentation. It is obvious that the heavy ions, which have a higher mass to charge ratio from an ion source, gives a lower cost and accelerators that are more compact. Furthermore, the increase in beam intensity will also give a significant impact for the construction of the accelerator complex from the point of view of cost performance. For example, in the case of ^{138}Sn production by an in-flight uranium fission reaction, we obtain only ~5 times the production gain by increasing the energy from 200 MeV/u to 400 MeV/u [4]. Obviously, the construction cost of a new ECRIS that can increase the beam intensity by a factor of five is significantly smaller than the construction cost of the additional accelerators required to increase the energy. In the past decade, the beam intensity of $U^{33+\sim35+}$ ions, which are suitable charge states for the RIBF facility, has been increased by one order of magnitude. The improvement in the performance of ion sources can be attributed mainly to a better understanding of the physics of the ion sources and the use of modern technology such as superconducting magnets. With regard to understanding the physics of ion source, in the past decade we have gradually identified the effect of key components of the ion source on the beam intensity and the main parameters of plasma. Simulation codes have also seen rapid development, with dimensions expanded from zero or one to three dimensions in real space. Comparisons between experimental and calculated results have given us a better understanding of this physics.

In the current paper, I focus on the most recent results for high-performance ion sources in terms of production of multi-charged heavy ions, progress in simulation codes, and experimental results for studying the physics behind them.

ION SOURCES FOR PULSED BEAM PRODUCTION

Electron Beam Ion Source (EBIS)

The EBIS was invented by Donets in 1960's and used as an external ion source for accelerators in the 1970's [5]. Since then, more than 30 EBISs have been constructed for various applications due to their excellent performance as described in past review papers [5-7]. The production of highly charged ions in the EBIS is strongly dependent on the atomic collision processes, i.e., successive ionization, heating of ions by electron impact, cooling of ions by ion-ion collisions, and internal loss of highly charged ions by charge exchange. The ion capacity of the trap of the ion source is determined by $\mathrm{Q} = 3.36 \times 10^{11} ILE^{-1/2}$, where I, E, and L are the electron beam current, electron energy, and the trap length. When the desired charge becomes the peak of the charge state distribution, which is governed by the $j\tau_c$ (j: electron beam current density, τ_c: confinement time in the trap), the electrostatic barrier is dropped at the beam extraction side, and the highly charged heavy ions can exit the trap. They can then be extracted through the aperture on the axis of the collector. The EBIS has the unique feature that the total extracted charge per pulse is almost independent of the ion species or charge state. Additionally, the beam pulse width can be controlled by extraction-barrier voltage manipulation, and therefore short pulses (~10 μs) of high current (several mA) are possible. This makes EBIS suited for single turn synchrotron injection.

The most advanced EBISs use refrigerator-cooled superconducting (SC) magnets, which produce high magnetic fields (typically several T) and several ampere electron beams, thus achieving extremely high electron current densities at high electron beam energies and producing the desired charge state of heavy ions. One of the modern EBIS is the RHIC-EBIS [8]. It was designed to produce milliampere currents of any ion species with a pulse with of ~10 μs, allowing single-turn injection for both the RHIC and National Aeronautics and Space Administration Space Radiation Laboratory (NSRL).

Since it could become necessary to supply heavy ion beams to multiple users simultaneously, it needs to be possible to switch the ion species in 1 second. The species from EBIS can be changed on a pulse-to-pulse basis, by changing the 1+ ion injected into the EBIS trap from the external ion sources. For example, it could produce more than 1.7 mA of Au^{32+}, 10 μs pulse width, at a 5 Hz repetition rate for RHIC [9]. For NSRL, it requires He^{2+}, Si^{13+}, Fe^{20+}, etc. at 2~3 mA, with a pulse width of 10 μs. An electron current of 10 A and trap length of 1.5 m is enough to produce the required total extraction ion charge (${}^{5\cdot}5\times10^{11}$). The extraction energy of 17 keV/u is chosen to minimize the space charge effect in the low energy beam transport line (LEBT). Table 1 shows the main parameters of the RHIC-EBIS. The maximum beam intensities of heavy ions are listed in Table 2. Note that the beam intensity of Au^{32+} is 72% of the designed value for only 5 A electron beam. The pulse-to-pulse fluctuation of the beam current is lower than 1%. The EBIS has been operated with alternating Au^{32+} and Fe^{20+} beam pulses at a 0.5 Hz repetition rate.

Table 1: BNL EBIS Main Parameters [8]

Ions	He to U
Total intensity	$>1.1\times10^{11}$charges
Q/m	>1/6
Pulse width	10~40 eμs
Repetition rate	5 Hz
Beam current	1.7~0.42 mA
Ion energy	17 keV/u
Switching time	1 s
Electron beam current	10 A
Trap length	1.5 m
Trap mag. field	5 T

Table 2: Intensity of Highly Charged Heavy Ions

Ions	Ion/pulse (10^9)
He^{1+}	67
Ne^{5+}	5.5
Fe^{20+}	1.7
Au^{32+}	0.92

Recently Donets proposed the so-called reflex mode of EBIS. This ion source has a specially designed electron gun and electron reflector, which allows multiple uses of the electron beam. At some conditions, the electron can be reflected a hundred times. The main feature is that to produce the same beam intensity of highly charged heavy ions, the electron beam energy can be decreased by factor of 100 [10]. It is a great advantage to maximize the electron current in the trap by using a very weak electron beam form the electron gun.

Despite the success using an EBIS in the application described above, it has been reported that it has some limitation on the behavior. In the 1990's, Donets reported an anomalous behavior that might limit EBIS performance [5]. One of the explanations is the existence of plasma instabilities. The instabilities associated with the beam current, electron beam, and trapped ions were intensively studied in the 1980's [11]. It was found that the effective ionization rate was reduced and the radial ion current was increased with the instabilities. It should also affect the stability of the beam. To improve the performance of the EBIS further with an intense electron beam, it is important to study the instabilities experimentally and theoretically. Especially, the development of the simulation code to calculate the dynamical effect may be one of the key issues.

Laser Ion Source (LIS)

The main energy transfer from the laser to the plasma is inverse bremsstrahlung for the laser power density up to 10^{13} W/cm^2 [12]. The transfer efficiency is strongly dependent on the electron-ion collision frequency governed by the critical density of plasma, electron temperature, and atomic number of the material. an detailed analysis of the absorption process indicated that the efficiency decreases with increasing laser power and wavelength. Therefore, for laser ion source design, lasers which have power densities of 10^{10}~10^{13} W/cm^2, wavelengths >1000 nm and pulse widths of 1~100 ns are being used in many laboratories. In that case, the experimental results and theoretical calculations show that the absorption efficiency ranges from 70 to 90% [12]. In the laser plasma, the successive ionization by electron impact is the dominant process. For this reason, electron temperature, density, and the exposure time of ions in the plasma are the key parameters to produce highly charged heavy ions. The electron temperature increases with increasing laser power and decreases with increasing critical plasma density (wavelength of laser). The mean charge state increases with increasing power density.

In the early stage of the free expansion of the laser plasma, the recombination processes are the dominant process for reducing the mean charge state of the heavy ions in the plasma. This is written as $R_{3B} \propto Z_{ion}^{3}N_e/T_e^{9/2}$,where Z_{ion}, N_e, and T_e are the atomic number of the ions and the density and temperature of electrons. To maximize the intensity of the highly charged ions, it should be made into a high-temperature low-density plasma. [13]

The laser ion source was proposed in the 1960's for production of highly charged heavy ions. In the 1980~1990's, LISs were used to inject heavy ions into synchrotrons. For injecting intense beam into the synchrotron, a 100 J, CO_2 laser (1Hz repetition) has been used in the most advanced laser ion source [14]. With this laser, an intense pulsed Pb^{27+} ion beam (peak current of a few mA) has been successfully produced.

The laser ablation plasma has a very high density and initial expanding velocity. Therefore, we can transport the intense ion beam in the plasma condition (neutralization) into the first stage accelerator. Taking into account the advantages of the laser plasma, the direct plasma injection scheme (DPIS) was proposed [15]. The obtained peak current at the extraction side of the RFQ was more than 9 mA from a carbon graphite target using a 4 J CO_2 laser already in the early stage of the test experiment. After the test experiments, a new RFQ linac was fabricated to accelerate high intensity heavy ion beams (~100 mA). A

400-mJ Nd-YAG laser was tested to produce a fully stripped carbon beam and the accelerated peak current reached up to 17 mA [16]. In 2005, intense C beams (>60 mA) were accelerated, when using the 4 J CO_2 laser [17]. They also obtained 70 mA of Al ions with a 2.3 J commercial Nd-YAG laser. The stabilities of the beam intensity and pulse width were demonstrated in 2006 [18]. It was reported that the fluctuation of the RFQ output current and pulse duration were ±6 and ±11% respectively. Although the peak current is high enough, the pulse width of the beam is sometimes too short. The pulse width (τ) and beam intensity (I) are defined as, $\tau \propto L$, $I \propto L^{-3}$ [18], where L is the distance from the target to the extraction system. It is easy to increase the pulse width by increasing the drift distance between ion source and RFQ. However, the injected current to the RFQ becomes very small, since the intensity is proportional to L^{-3} as shown in the formula. Recently, to minimize the reduction of the current, a solenoid magnet was successfully used for focusing the beam [19]. As an example of the applications, a research and development program was initiated, using the DPIS as an injector for compact carbon-ion cancer therapy and intense heavy-ion beam injection for the Cooler-Storage-Ring of the Heavy Ion Research Facility in Lanzhou [20].

ION SOURCES FOR DC BEAM PRODUCTION

Electron Cyclotron Resonance Ion Source (ECRIS)

In the past three decades, the beam intensities of highly charged heavy ions from high performance ECRISs have increased dramatically, as shown in Fig. 1. Such improvement is mainly due to a better understanding of the ECR plasma and the use of modern technology, i.e., superconducting magnets and permanent magnet technologies.

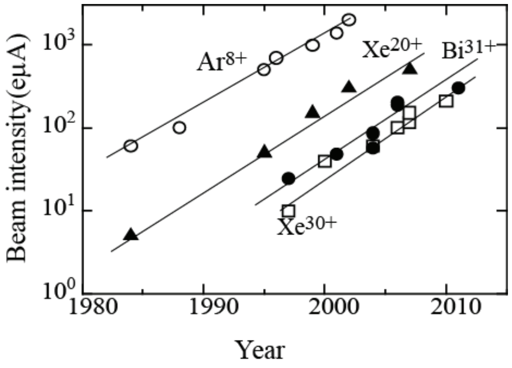

Figure 1: Time evolution of the beam intensity of highly charged heavy ions provided by high performance ECRISs.

The ion confinement time (τ_c), electron density (n_e), and electron temperature (T_e) of the ECRIS are critical to produce intense beams of highly charged heavy ions. The systematic ionization is the most efficient way of producing highly charged heavy ions. For example, to produce Xe^{20+}, we need $n_e\tau_c \approx 10^9$ cm^{-3} s. However, to produce higher charge state Xe ions, e.g., Xe^{27+}, $n_e\tau_c$ should be 10^{10} cm^{-3} s [21]. On the other hand, the beam intensity can be written as $I_q = (n_q qV/\tau_c) f_{ext}$, where f_{ext} and V are the efficiency of the plasma flow to the extraction hole from the main plasma and the volume of the plasma, respectively. To maximize the beam intensity, we have to minimize τ_c and maximize n_e, while simultaneously keeping $n_e\tau_c$ constant. Further, we have to maximize f_{ext}. To achieve these conditions, we have to control the ECR plasma by changing several key parameters such as the magnetic field distribution, RF power and frequency, gas pressure, and the chamber size of the ECR ion source.

The criterion for manipulating the ion confinement time is satisfied by using magnetic mirror confinement techniques. It is well known that the magnetic field strength and shape at both the beam extraction side (B_{ext}) and the injection side (B_{inj}), as well as the radial magnetic field strength on the inner surface of the plasma chamber (B_r), strongly influence the charge distribution and the beam intensity. The beam intensity increases with an increase in B_{inj}, B_{ext}, and B_r and then becomes saturated above certain values ($B_{inj} > 4B_{ecr}$, $B_r > 2B_{ecr}$, and $B_r > B_{ext} > 2B_{ecr}$) (high B-mode operation) [22]. Furthermore, it is natural to think that the minimum strength of the mirror magnetic field (B_{min}) should influence the beam intensity of heavy ions because the magnetic field configuration (or the gradient of the magnetic field) affects the plasma confinement and the effectiveness of electron heating in the resonance zone [23, 24].

Simulation codes based on the Fokker-Planck equation have developed rapidly in the past decade. Since 2000, the code proposed by A. Girard has provided information about the effects that parameters such as RF power, mirror ratio, and gas pressure have both on the key parameters (n_e, T_e, and τ_c) of the ECR plasma and the beam intensity [25]. The simulation code also shows the frequency effect, implying that higher frequencies enable longer electron confinement time in the plasma. We obtained several sets of results with SERSE (14 and 18 GHz) [26] and SECRAL (18 and 24 GHz) [27]. The RF power is an important factor for increasing the beam intensity. Obviously, there are limitations on the beam intensity at high RF power. Very recently, the effect of the RF power on the plasma parameters (electron density, temperature, and current) and high RF-power instability were demonstrated using FAR-TECH's generalized ECRIS model (GEM) [28]. They showed that the instability threshold of the RF power increased with an increase in gas pressure. The origin of the instability was pitch-angle scattering of the electrons by the ECR heating process. Despite this important information, we have few experimental results for beam intensity saturation at present. The beam intensity of a high-performance superconducting (SC)-ECRIS that has a larger plasma chamber volume increases linearly and does not saturate at high power [27]. To clarify this phenomenon, we need to carry out further investigation under various conditions.

All the results that presented thus far have been described as either dimensionless or one-dimensional in real space. In fact, it is well known that the geometry of the ion source strongly affects the ECR plasma or the beam intensity. We have seen several studies on the effect of the size of the ECR zone on the beam intensity in the past decade [29-31]. At present, we can obtain such information using two new ECRIS, the RIKEN SC-ECR at RIKEN [32] and SuSI at MSU [33], which can produce flexible magnetic field distributions. These ion sources can change the magnetic field gradient and ECR zone size independently. Figure 2 shows a plot of the beam intensity of highly charged heavy ions as a function of the surface size and magnetic field gradient. These results show that gentler field gradient and larger zone size give higher beam intensity.

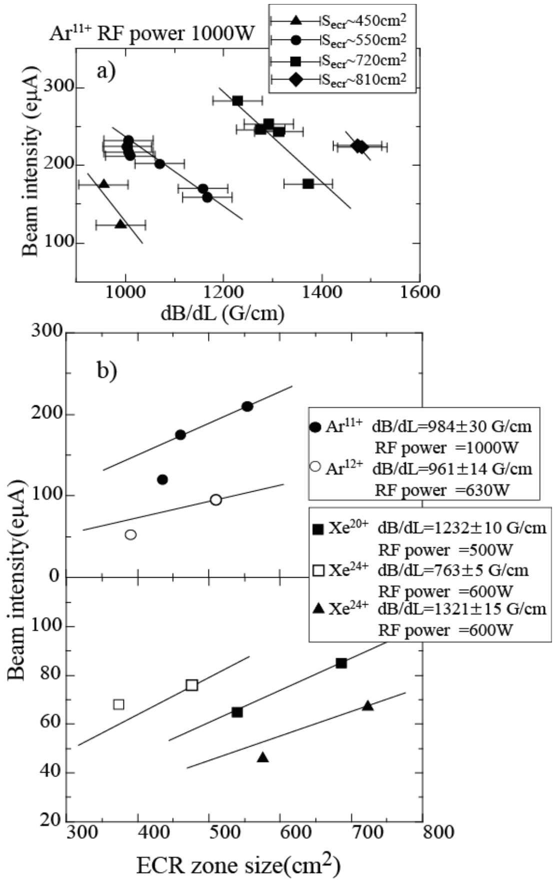

Figure 2: Beam intensity of highly charged heavy ions as a function of the average magnetic field gradient (dB/dL) (a) and the size of the ECR zone (b).

Recently, changes in the ECRIS performances have been obtained by slightly varying the microwave feed frequency ("frequency tuning") [34], which produce strong fluctuations in the beam intensities even for frequency variations in the MHz range. Simulations have shown that the ECR heating efficiency depends on the electromagnetic field distribution in the plasma chamber and on the electric field distribution on the resonance surface. In the case of strongly corrugated plasma surfaces, the scattering effect shortens the ion lifetime. In this case, the beam brightness decreases and is mostly populated by ions at low charge states. If we have "good" matching between the microwave frequency and the geometry of the plasma chamber and ECR zone, a smooth plasma surface can be created. In this case, the ion confinement time and brightness of the extracted beam will be increased. These experimental and theoretical results indicate that frequency tuning affects not only the heating process but also the efficiency of beam extraction (f_{ext}).

The fully superconducting ECR ion source has been one of the main developments in producing intense, highly charged ion beams in the past few years. The design, construction, and development of high magnetic field SC-ECRISs, such as SERSE, VENUS [35], and SECRAL have addressed many of the technological challenges and opened new avenues for further development of new ECRIS.

VENUS was the first high magnetic field SC-ECRIS developed for operating at 28 GHz. A number of modifications were carried out during its development, e.g., the special cramping technique of the hexapole magnet to increase the radial magnetic field. The modifications of the VENUS were then incorporated into the design of the new SC-ECRIS.

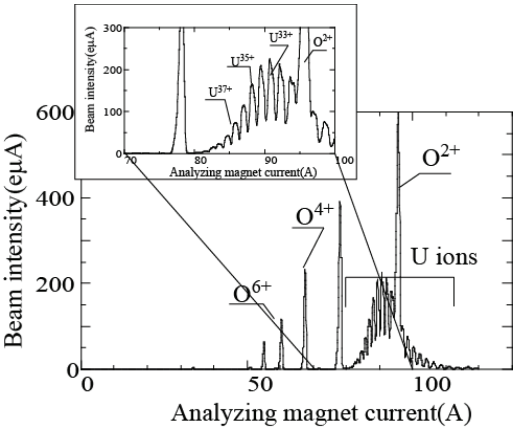

Figure 3: Charge state distribution of the highly charged U ion beam from the RIKEN 28 GHz SC-ECRIS.

SECRAL is a compact SC-ECRIS designed to operate at microwave frequencies of 18−28 GHz. The unique feature of the SECRAL source is its unconventional magnetic structure, in which superconducting solenoid coils are placed inside the superconducting sextupole. One of the advantages of this structure is that the magnet assembly can be compact in size compared to similar high-magnetic field ECRISs with conventional magnetic structures. A compact source results in higher RF power density and more efficient beam transport due to the short distance between the extraction hole and the analyzing magnet. The RIKEN SC-ECRIS can be operated at flexible axial field distributions from the so-called "classical B_{min}" to the "flat B_{min}" [30]. The RIKEN SC-ECRIS enables researchers to change the gradient of the magnetic field strength and the surface size of the ECR zone. Using these superconducting ECRISs, intense beams of highly charged heavy ions were successfully produced. One of the examples is shown in Fig. 3. The RIKEN 28 GHz SC ECRIS produced ~180 μA of U^{35+}, and 225 μA of U^{33+} with the sputtering method at an injected RF power of ~4 kW (28 GHz). SECRAL produced 50 μA of Bi^{40+} at an RF power <4 kW (24+18 GHz) [36]. Very recently, VENUS produced 440 μA of U^{33+} at ~8 kW (18+28 GHz) using a high temperature oven [37].

The most critical technology for developing an ion source is a high-field superconducting magnet system capable of confining the plasma at high frequencies (>18 GHz). The maximum field produced in a superconducting magnet is generally limited by quenching. To avoid quenching, the magnet design must keep the current densities and the local magnetic fields at the coils below the short-sample critical current in the superconducting wire. All the current ECR ion sources utilize NbTi. However, the performance of NbTi is limited by its upper critical field of about 10 T at 4.2 K. The maximum magnetic field for the RIKEN 28-GHz ECRIS at the coils is required to be ~7 T to produce the designed magnetic field. In this case, the operational current (I_{op}) is ~80% of the critical current (I_{c}), which is almost limited value for long-term operation. Therefore, to use a frequency higher than 28 GHz, we may need a new magnet structure and the use of advanced superconducting magnet technology. For example, at an operating frequency of ~50 GHz, reasonable estimates for the axial and radial fields are ~7 and ~4 T, respectively. When using higher microwave frequencies (>18 GHz), we face another technical problem, which is the large heat-load of highly energetic X-rays emitted from the plasma. For this reason, we have to solve the heat-load problem to further increase the beam intensity of highly charged heavy ions. In the past few years, SC-ECR ion sources operating at high microwave frequencies (>18 GHz) are being considered for practical use in various fields, and the beam intensity of highly charged heavy ions continues to increase owing to the optimization of the ion source performance. On the other hand, we are faced with several technical problems at frequencies higher than 28 GHz. At these frequencies, we may need a new ECR ion source structure and new superconducting magnet technology, as described above. Fortunately, there are several proposals for new SC-ECR ion sources [38,39].

We observed that the beam intensity increased linearly with an increase in the RF power and it was not saturated at high RF power. Thus, it may still be possible to increase the beam intensity even with the present ECRIS. The simulation code based on the Fokker-Planck equation can reproduce the experimental results and reveals the effect the key components have on the main parameters of the ECR plasma and beam intensity. Furthermore, it predicts phenomena under extreme conditions such as very high RF power. Investigation of these effects is important for optimizing the ion source structure and minimizing the construction cost of the ion source for production of the desired intensity and charge state of heavy ions. Studies on the size and shape of the ECR zone surface have just begun, and we have already obtained some new information. Theoretically, the three-dimensional particle-in-cell (PIC) code has shown that the matching between the microwave frequency and the geometry of the plasma chamber plays an important role, not only in increasing the heating efficiency, but also in increasing the beam intensity.

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