INTENSE HIGH CHARGE STATE HEAVY ION BEAM PRODUCTION FOR THE ADVANCED ACCELERATORS[#]

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Abstract

Modern advanced heavy ion beam accelerators have strong needs for either dc or pulsed intense high charge state heavy ion beams, such as dc beams for FRIB project, SPIRAL2 project, HIRFL/IMP facility, RIBF/RIKEN facility etc., and pulsed beams for RHIC, LHC, FAIR project. After decades' development, only several typical ion sources have found their applications in these accelerators, i.e. Electron Beam Ion Source (EBIS), Laser Ion Source (LIS) and Electron Cyclotron Resonance Ion Source (ECRIS). This paper gives a general review of the advantages and limitations of these three types of ion source with their latest development and performance.

INTRODUCTION

Modern particle physics, nuclear physics and high energy physics and medical and industrial applications as well are the driving force for the fast development of heavy ion accelerators, such as FRIB project, SPIRAL2 project, HIRFL facility, RIBF project, RHIC, LHC, FAIR and etc. The preinjectors for those accelerator facilities are essentially important. Higher Q/M or charge state Q from an ion source makes the downstream accelerators more compact and less costly. High Charge state Ion (HCI) beam at the preinjector is delivered from a HCI source. But because of the capacity and characteristics of an ion source is inherent, the choice of ion beam charge state is a trade-off between ion beam intensity and charge state. Therefore, the choice of the ion source is also strongly depending on the accelerator needs, for instance, EBIS is the ion source solution to RHIC preinjector [1], and ECRIS is the only choice for FRIB project [2]. Before any discussion on ion source technology, let us recall the physics behind the HCI production with an ion source. Ions production in an ion source is realized by energetic electron impact with neutrals. Atomics physics reveals that the probability of the producing multiply charged ions by a single electron impact falls off rapidly with increasing ion charge state Q. Therefore the only efficient way for the production of HCIs is by means of successive ionization or step by step striping. Then we have to increase τ the exposure time of the ions to a cloud of energetic electrons so as to ionize the ions to the desired charge sate before they are lost. For HCIs production the optimum electrons' energy (T_e^{opt}) must be in the range of keVs, which should be generally 3~5 times the threshold energy of the incident subshell electron that should be removed to obtain the desired charge state. Actually, there is a strong correlation between the product of ($n_e\tau$) and Teopt. For certain T_e^{opt}, a corresponding minimum value of ($n_e\tau$) for the transition of any ion Q-1 to the next charge state Q is mandatory. In Figure 1, Golovanivsky's diagram of the ($n_e\tau$) Teopt criteria gives the typical values of ($n_e\tau$) and T_e^{opt} for the ionization of hydrogen-like ions to become fully stripped nuclei and also some other partially stripped ions that can be produced with the same ($n_e\tau$) T_e^{opt} values [3]. For HCI production, the vacuum condition is also essential. The residual neutral density n0 must be low enough to minimize the charge exchange process. The critical neutral density to produce certain charge state Q is correlated with the electron density, the ion species and the T_e^{opt} value as well [4].

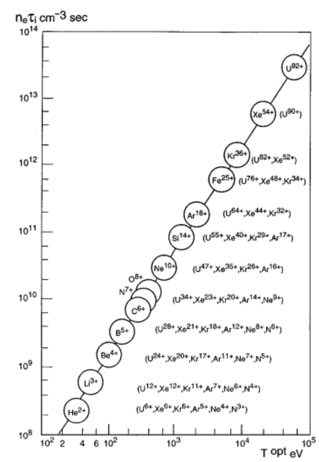

Figure 1: Golovanivsky's diagram of the $(n_e\tau)T_e$ criteria.

With the knowledge as discussed above, an ion source that can produce intense HCI beam must be able to provide necessary control of ($n_e\tau$) T_e^{opt} values. Taking three types of HCI beam sources EBIS, LIS and ECRIS that are most popularly studied HCI machines today for example, in EBIS, one can have precise and independent control of the parameters, while in ECRIS these parameters are coupled , and in LIS, one can have the least independent control over all the parameters [5].

EBIS

EBIS or Electron Beam Ion Source was first proposed in 1967 and lately demonstrated in 1968 by Dr. Donets in Dubna. In an EBIS, an electron gun produces high current electron beam on one end which is then compressed to high current density as it passes through a long solenoid field. The electron beam is decelerated and stopped in an electron collector on the other end of the device. During a definite period of time, gas or singly charged ions from external ion source of working substance is injected into trap. Electrostatic potentials are applied to cylindrical electrodes in the solenoid bore to trap ions axially, and the radial trapping of ions are established by space charge of the electron beam. Since the HCIs are produced through stepwise ionization by the energetic electrons, the longer

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the ions are kept in the trap, the higher the achievable charge state. Once the desired charge is at the peak of the Charge State Distribution or CSD, the electrostatic barrier is dropped from the collector side, and then the HCI can exit the trap and be extracted through the aperture on the axis of the collector. The ion capacity of the trap is determined by the electron beam current I_e, current energy E_e (or electron beam velocity) and the trap length L. And the extractable ion charge can be 50~80% of the total trapped charge of the device. Therefore, the performance of an EBIS can be precisely predicted at the design phase

Unique features of an EBIS are (1) the total extracted charge per pulse is nearly independent of ion species or charge state, (2) beam pulse width is controllable by means of barrier voltage manipulation, (3) any ion species of very intense pulsed HCI beam (several emA) with short pulse length of ~10 µs, and (4) very fast beam species switching time, i.e. 1 second. These features make EBIS the only choice of ion sources for RHIC heavy ion preinjector. At BNL, for the RHIC heavy ion program, for example, 1.7 emA Au^{32+} with the pulse length of ~10 µs is required from the ion source in order to deliver 3×10^9 ions/pulse to the Booster at a repetition rate of 5 Hz. To meet the requirements, a powerful RHIC-EBIS (as shown in Figure 2) has been built based on the R&D prototype device that has already demonstrated its design performance [1]. The typical design parameters of RHIC-EBIS are given in Table 1. Recent operation of this ion source with 10 A EBIS electron beam has produced very intense HCI beams at the Booster input , such as 6.1×10^9 $^{63}Cu^{11+}$ ions/pulse, 1.5×10^9 $^{197}Au^{32+}$ ions/pulse and 1.1×10^9 $^{238}U^{39+}$ ions/pulse. Rough estimation of the ion beam transmission efficiency from the ion source to the Booster input is ~56% that will double the actual source output to the Booster input numbers, which means the design goal of the RHIC-EBIS has been met [6].

Figure 2: Picture of RHIC-EBIS at BNL.

EBIS and EBIT are very closely related devices. EBIT devices have popular application in atomic physics research which can produce very high charge state ions inside the trap, such as the SuperEBIT built in LLNL that had provided the extraction of ~100 $^{238}U^{90+}$ ions/s [7]. Besides that EBIS/T devices have found the application in accelerators as charge breeders, such as the ReA3-EBIS/T at MSU [8], CARIBU EBIS at ANL [9], and etc.

Electron String Ion Source or ESIS is another working mode for EBIS device. It was also proposed and first tested in Dubna by Dr. Donets. Rather than dumping the electron beam after a single pass through the trap, with a negatively biased electrode, the electrons reflect /oscillate repeatedly though the trap which increases the electron current in the trap. This mode can greatly reduce the needs for high current electron gun and also decrease the power dissipation of the collected beam. The Reflex EBIS in Dubna has produced 200 eµA Ar^{16+} and 150 eµA Fe^{24+} with only 5-6.5 mA electron current [10].

Table 1: Design Parameters of RHIC-EBIS

Design Parameters	RHIC EBIS
Max. electron current	I_e = 10A (12A max.)
Electron energy	E_e = 20 keV
Electron density in trap	J_e = 575 A/cm^2
Length of ion trap	l_{trap} = 1.5 m
Ion trap capacity	$Q_e = 1.1\times10^{12}$
Ion yield (charges)	$Q_{ion} = 8.1\times10^{11}$ (@Ie=9.6A)
Yield of ions Au^{32+}	$N_{Au}{}^{32+} = 3.4\times10^9$/pulse

LIS

LIS or Laser Ion Source was proposed based on laser induced plasma as an ion source for accelerator injection firstly in1969 by two groups. And the application of an LIS to inject ions to the JINR synchrotron for operation was completed in 1977. The development of new LIS devices has never been stopped since then. The general physics picture of a LIS is very simple. A short pulse, high power laser beam is focused by an optical lens or optical system onto a solid target. The target material will be evaporated and the electrons are heated by the intense laser radiation to the temperature up to several hundred eV. The energy absorption is done by the inverse Bremsstrahlung mechanism. Plasma ions are stepwise ionized to high charge state due to electron-ion collisions in the high temperature dense plasma. The temperature of the plasma Te and final CSD depend strongly on the laser power density P_L (W/cm^2) at the target. The formed plasma expands longitudinally normal to the target with a conical angle of 20˚~30˚. The plasma pulse duration is much longer than the laser pulse which is normally in the order of 10 ns. The length L of the drift space between the target and the extraction system determines the ion pulse length τ_L. Generally, (1) the beam pulse length $\tau_L \propto L$, and (2) the ion beam current density $j \propto L^{-3}$.

The collaboration work between CERN, ITEP-Moscow and TRINITI-Troitsk on the development of a LIS for LHC is a very nice approach to a very high charge state intense pulsed beam ion source. A 100 J, ~25 ns CO2 laser operating in the maser oscillator power amplifier configuration was developed for the project. The schematic experimental setup of the LIS test bench is given in Figure 3. It consists of a number of individual subsystems: (1) A good reliability CO2 laser machine of 5-100 J output energy, (2) A Target illumination system (includes the optical system), (3) A target manipulation system that can precisely control the target movement and is capable of delivering 105-106 pulses without any

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maintenance, (4) A beam extraction system to accelerate the ions from the expanding laser-produced plasma to a energy of 10-30 keV/u, and (5) a low energy beam transport line or LEBT to match the beam from the LIS to the successive accelerator, i.e. a RFQ. With the high power CO2 laser amplifier, the team produced 1-2×1010 Pb27+/pulse in a pulse of 3.5 μs with the LIS device and the total extracted current was ~20 emA with the HV potential of 105 kV [11]. Unfortunately, the lifetime of the source at 1 Hz operation is only on the order of hours and more further improvement and R&D work needs to be done to achieve the minimum acceptable lifetime of ~ 2 weeks (>106 cycles). Since the baseline for LHC is using an ECRIS as the ion beam preinjector, the LIS project was then stopped in CERN around 2003 and redirected to the application in ITEP TWAC project [12].

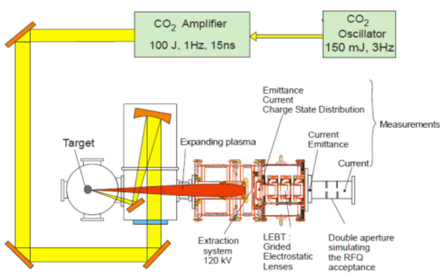

Figure 3: CERN high current LIS setup sketch plot.

As discussed above, in the LHC-LIS project, intense beam from the LIS is matched to the subsequent accelerator through a LEBT. Although the source could be biased to maximum 120 kV for intense LIS beam extraction and transmission, the strong space charge therein will obviously deteriorate the beam quality and transmission efficiency and the matching system is very complicated and costly. A more straightforward solution is the so-called Direct Plasma Injection Scheme or DPIS which was proposed firstly by Dr. Okamura in RIKEN as is shown in Figure 4 [13]. Literally, the LIS device is directly connected to a RFQ without any LEBT section to match beam injection. Since the ions fly from the target to the entrance of the RFQ at a neutralized plasma state, the space charge effect can be neglected during the transport from the source to the RFQ entrance. The ion species selection will be performed inside the RFQ. By proper setting of the ion beam extraction HV to the value for desired ion beam bunching, unwanted ions will be mostly de-bunched and lost before the exit of the RFQ. Compared to traditional LEBT matching to RFQ, this solution is more compact one and almost trouble free of strong space charge effect impact. But since the ions from the LIS injector are directly fed into the RFQ entrance by applying desired HV potential, the phase space matching of the beam is not possible. A strong mismatching problem can lower the efficiency of this DPIS combination. Nevertheless, ~30emA C^{6+} beam bunch has been obtained after the RFQ acceleration with this scheme.

LIS has already been successfully put into accelerator application for tens of years, and some new projects are still going on such as the work of matching of a LIS with the RHIC-EBIS as a primary ion provider [14], however there are still many obstacles that limit the popular application as intense pulsed HCI beam preinjector. The typical questions are (1) the beam quality, especially the pulse to pulse beam quality consistency mostly due to target homogeneity, (2) beam energy spread, especially the energy spread issues at high laser power density, (3) pulse to pulse beam intensity fluctuation, (4) beam repetitiveness, and (5) source life time. Several groups, for instance Okamura's team in BNL, Hattori's team in NIRS and Zhao's team in IMP, are now involved in the studies to improve LIS performance. For future advanced accelerator that needs 100μs pulse length ~10^{11} ions/pulse intense HCI beams, a very powerful next generation LIS might be the most possible ion source choice.

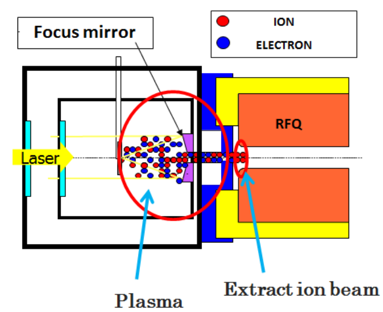

Figure 4: Schematic plot of a DPIS setup.

ECRIS

ECRIS or Electron Cyclotron Resonance Ion Source concept was proposed by Geller in late 1960s and the first machine using the ECR heating to produce multiple charge state ions was reported by Okamoto and Tamagawa in 1972 [15]. A major step forward was made when the first actual ECRIS SuperMAFIOS ion source was successfully built in 1974 by the Grenoble group who had the idea to design a machine having a closed resonance surface. ECRIS was actually developed from plasma fusion device. Plasma electrons are heated through ECR heating to high energy by coupled microwave power with the frequency in the range of 2.45 GHz to 28 GHz. The plasma is confined by a strong nested so-called mini-B magnetic field configuration, which is the superposition of an axial mirror field and a radial multiple field (normally a hexapole field). Hot electrons are confined at the centre of the nested field and the HCIs, which are produced by stepwise ionization while they are staying in the plasma, are trapped by the space charge established by the electrons inside the plasma. The lost ions that enter the extraction region will be accelerated by the applied HV potential to form intense mixed ion beams. HCI beams can be selected from the mixing beams with an analyser magnet.

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ECRIS is the best machine to produce intense HCI beam of CW or long pulse (> ~1 ms). CW mode is the normal operation condition for an ECRIS and the so-called AG or AfterGlow mode is the solution for pulsed beam production, normally by means of pulsed microwave power. In recent 15 years, ECRIS performance has been boosted enormously, for instance CW Xe^{30+} beam was only 10-15 eμA from a state-of-the-art ECRIS about 14 years ago, and this number has been multiplied by a factor of at least 15 with one of the 3rd generation ECRISs SECRAL [16]. The tremendous improvement is driven by the strong needs from modern advanced heavy ion accelerator projects or facilities, such as FRIB, SPIRAL2, FAIR, HIRFL/IMP and RIBF/RIKEN. For example, FRIB accelerator needs for uranium HCI beams can only be met by merging 2 charge states, i.e. U^{33+} and U^{34+} [17], but with ECR source researchers' continuous effort, this stringent condition can be achieved with one single charge state U^{33+} beam of ~450eμA. However, it is still the scaling laws firstly raised by Geller more than 20 years ago governs the development of ECRISs [18]. According to the scaling laws, one must build a high enough magnetic field min-B device to confine the much denser plasma that are induced by higher frequency microwave heating, so as to produce intense HCI beams since $\Sigma n_q = n_e$ and $n_e \propto \omega^2$, where n_q is the ion density of charge state q and ω is the microwave frequency. For 3rd generation ECRIS, the microwave frequency is in the range of 18-28 GHz. Therefore, to satisfy the optimum magnetic field confinement criteria, i.e. maximum axial magnetic field peak ~ 4 B_{ecr}, radial magnetic field at plasma chamber ~2 B_{ecr} and the last closed magnetic field contour inside the plasma chamber should be ~ 2 B_{ecr} (B_{ecr} is the ECR magnetic field corresponding to microwave frequency ω, $\omega=2\pi.eB_{ecr}/m_e$, *for 28GHz,* B_{ecr} *= 1.0 T*), the magnet based on room temperature conductor is no way to meet the requirements and superconducting magnets are therefore incorporated. In recent 15 years, several fully superconducting ECRIS have been successively built in different labs, such as SERSE in INFN/Catania [19], VENUS in LBNL [20], SECRAL in IMP [16], SuSI in MSU [21], and SC-ECRIS in RIKEN [22]. The latest advancement in ECRIS techniques owes much to the contributions from these ion sources. For reference, the results of xenon HCI beam production with several typical 3rd generation ECRISs are given in Figure 5 in comparison with one of the best room temperature ECRIS GTS from Grenoble [23].

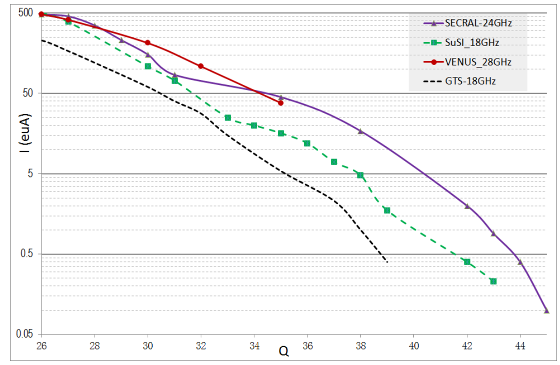

Figure 5: Xenon HCI beam production with several high performance ECRISs.

To further satisfy the needs of the advanced heavy ion accelerators already built or to be built, so called 4th generation ECRIS concept has been put forward for years. The 3rd generation ECRIS magnet has already employed the cutting edge techniques of NbTi superconducting wire. Therefore, the utilization of Nb_3Sn wire in the next generation ECRIS design and fabrication has been considered to be a must. Two structure options have been discussed, i.e. the VENUS configuration that features larger plasma chamber and higher radial field but bulky magnet body size and more costly, and the SECRAL configuration which is a reversed structure of a conventional one that features compact size and simpler structure but lower radial field and smaller plasma chamber. And obviously, both of the two structures have to face the big challenges of complicated Nb_3Sn wire treatment, especially in sextupole coil fabrication. Having this in mind, a mixed structure ion source called MK-I was recently invented by Dr. Xie [24]. This structure adopts a close-loop coil with rectangular Ioffe Bars structure for the sextupole magnet design, and axial magnetic field is provided by both the sextupole coil end turns and the three axial solenoid coils. The biggest advantage of this design is the much simpler interaction forces between the sextupole coils and the solenoids, and the avoiding of using Nb_3Sn wire in the sextupole fabrication. But the complicated structure makes the winding of the sextupole coil very difficult, even with NbTi wire. This might be the strongest obstacle. Other issues like partial hexagonal warmbore and plasma chamber design are also problematic when it comes to source fabrication. The schematic picture of this magnet design is given in Figure 6.

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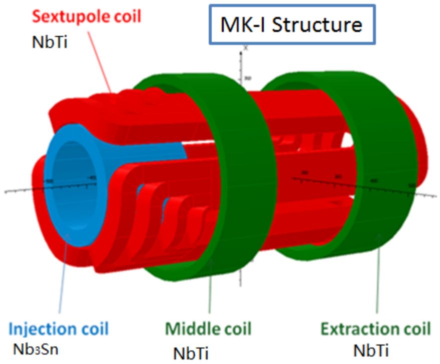

Figure 6: A new conceptual structure MK-I for next generation ECRIS magnet.

While the race for more performing ECRIS is following the guideline of higher frequency, higher microwave power, one must think about whether this is the only way out. Several issues have been raised for years about the techniques that could be applied with ECRISs to make performance improvement other than just building a high frequency costly ECRIS heated with tens of kW microwave power: (1) microwave power coupling mode and method, Gaussian beam distribution power centred HE11 mode [25] coupled with optical system may improve the coupling and ECR heating efficiency, (2) manipulation of EDF inside the ECR plasma, external mA electron beam donor with the energy of several keV could possibly narrower the CSD and help to produce more intense HCI beams, (3) reducing the high energy electron population which is useless for HCI production [26], (4) corrugated plasma chamber structure that fits the plasma flux can minimize the microwave power needs to obtain high enough power density, and (5) refined AG mode with certain tricks to dump more lost HCI ions toward ion source extraction to enhance pulsed beam intensity enormously. Additionally, to meet modern heavy ion accelerator needs, ECRIS researchers still have many technical challenges, such as (1) continuous massive metallic vapour feeding for weeks, (2) high cryogenic heat load caused by strong bremsstrahlung radiation at high power, and (3) high efficiency, good quality transmission of high intensity HCI beam of ~20 emA from the ion source to the subsequent accelerator.

CONCLUSION

HCI sources are widely adopted by heavy ion accelerators. Based on the accelerator needs and properties, the choice of ion source is critical. The mostly recommend HCI sources are EBIS, LIS and ECRIS, which have made tremendous improvement in the last 40 years. ECRIS is still the best option for CW or long pulse length HCI beam preinjector, while EBIS is so far the best choice for ~10μs pulse length intense HCI beam producer. The development of LIS makes this device provide alternative option for pulsed intense HCI source choice.

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