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PERSPECTIVES IN HIGH INTENSITY HEAVY ION SOURCES FOR FUTURE HEAVY ION ACCELERATORS

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Abstract

Driven by the development of next generation heavy ion accelerators such as IMP-HIAF, GSI-FAIR, RIKEN-RIBF, SPIRAL 2, JLEIC and so on that need very intense highly charged heavy ion beam injectors working at either pulsed or CW modes, intense research and development work towards more powerful ion sources have been made in different laboratories, which likewise has stimulated obvious advancement of the performances in recent years. However, even the best performing ion sources can't meet all the requirements. While the ion source researchers are tackling the next generation ion sources development, it is worth investigating the possibilities of other solutions, especially when very intense heavy ion beams are needed for the more intense and powerful heavy ion accelerators, for instance the driver accelerator to study inertial confinement fusion with heavy ion. This invited talk presents recent advancements of highly charged heavy ion sources, and discusses the other possible approaches for intense highly charged heavy ion beams for future heavy ion accelerators.

INTRODUCTION

Heavy ion accelerators have played important role in the past century in human cognation of the world from nuclear structure to the resources of the universe. Presently, there are three major areas drives the scientific projects with the so called next generation heavy ion accelerator facilities, i.e. Rare Isotopes (RI) facilities in the field of nuclear structure physics, high luminosity Electron Ion Colliders as next generation Quantum ChromoDynamics (QCD) facilities in the field of hadron physics [1], and High Energy Density Physics (HEDP) with the heavy ions from accelerators to investigate the physics in the so called "warm dense matter regime" [2]. The next generation RI accelerators will provide very high intensity heavy ion beams on target to produce radioactive isotopes through fragmentation, for instance FRIB at MSU [3], FAIR at GSI [4] and HIAF at IMP [5]. In an EIC machine, heavy ion beams are needed for electrons' collision with heavy ions for high-resolution imaging of gluon-dominated matter measurement. To make efficient collisions with electron beam, high luminosity beam bunch should be made that needs intense ion beam injection, electron beam cooling and compression in the storage ring, for instance JLEIC proposed by JLab [6], and eRHIC proposed by BNL [7]. HEDP research deserves high energy deposition per gram of matter, i.e. J/g, and the most favourable beam ion is uranium due to its high nuclear charge. Therefore, very intense high energy (>1 GeV/u) ion beams with a very short beam bunch length (~100 ns) is requested. The FAIR project at GSI and the HIAF project at IMP are expected to provide the energy density up to 120 kJ/g and 300 kJ/g respectively [2], which will possibly promote the HEDP research to enter the "radiation dominated regime". In conclusion, next generation heavy ion accelerators need high intensity beams, mostly very heavy ones, for instance U, Pb, Au and so on. For simplicity, and also for easy comparison, in the following contents about accelerator design needs on heavy ion beam intensities, they are all unified as U high charge state ion beams, since U^{3n+} is one of the mostly interested ion within the community. Other interested ion beams, such as Pb^{30+}, Au^{32+}, are also unified as U^{3n+} beams based on the ion source's capacity, the ionization potential of the incident ion, and so on. If not specified, 1 Hz is the typical repetition rate.

HIGH INTENSITY HEAVY ION SOURCES

Since heavy ion beam will be eventually accelerated to the needed energies for scientific goals, for instance, 200 MeV/u for FRIB and 30 GeV/u for FAIR with SIS100. For efficient acceleration and budget issues, highly charged ion beams are favoured, for instance $U^{33+, 34+}$ is FRIB's baseline design of ion source requirement, and U^{35+} is desired for HIAF BRing injection. However, the production of intense stable heavy ion beams is more complicated compared to that of mono-charge or low charge ion beams. Highly charge ion production should take into account of several critical aspects, such as high density energetic electrons (n_e, T_e), long enough ion confinement for ionization (τ_i), and ion losses due to charge exchange and confinement. A powerful high charge state ion source should have a very good compromise among those parameters. Alternatively, charge stripping strategy is one straightforward solution to intense highly charged ion beam production. Worldwide heavy ion accelerators are mostly using the following ion sources as the injectors for intense highly charged ion beams:

ECR Ion Source

ECRIS or Electron Cyclotron Resonance Ion Source concept was proposed by Geller in late 1960s is the best machine to produce intense HCI (Highly Charged Ion) beam of CW or long pulse (> ~1 ms) [8]. HCIs are produced in ECRIS through stepwise ionization of ions by hot electrons energized by incident microwave power through ECR process. 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

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20 years, ECRIS performance has been boosted enormously, for instance CW Bi^{31+} beam was only 29 eμA from a state-of-the-art ECRIS about 14 years ago [9], and this number has been multiplied by a factor of at least 23 with one of the 3rd generation ECRISs SECRAL (Fig. 1) [10], and U^{34+} beam intensity has also been increased by a factor of 20 in 2011 when 400 eμA was produced with VENUS [11]. Provided that sufficient uranium vapour is available to the plasma, modern superconducting ECR ion source could produce ~1 emA U^{34+} based on the records with Bi beams.

Figure 1: 3rd generation ECRIS SECRAL.

EBIS

EBIS or Electron Beam Ion Source was first proposed in 1967 and lately demonstrated in 1968 by Dr. Donets in Dubna [12]. HCIs are also produced via stepwise ionization by the energetic electrons injected from an external electron gun. 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. Pulsed HCI beam up to several emA with pulse length of ~10 μs of any ion species is achievable with EBIS through fast extraction, and in a slow extraction, pulse length could be longer up to ~ms, but pulsed beam intensity will be lower that is limited by the total charge capacity in the trap. EBIS is the most powerful machine to produce short pulse ion beams of very high charge states. RHIC-EBIS is one of the state of the art EBISs in service (Fig. 2). It has been built with the maximum trap charge capacity of 1.1×10^{12}, which allows a maximum ion yield of 5.5×10^{11} per pulse with the electron gun operating at 10 A. The typical performance of the RHIC-EBIS is ~3.4×10^{9} Au^{32+} ions/pulse [13].

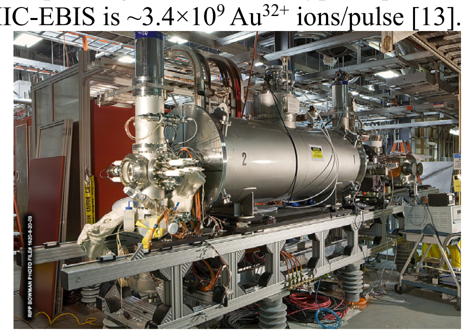

Figure 2: RHIC-EBIS at BNL.

LIS

LIS or Laser Ion Source was proposed based on laser induced plasma as an ion source for accelerator injection firstly by two different groups in 1969 [14, 15]. LIS is based on plasma generation by a high power laser beam focused by a mirror or lens system onto a solid target. Typically, a 1×10^{8}~1×10^{14} W/cm^2 laser power density on the target is needed to make a LIS work. Once radiated by laser power, target material will be evaporated and the electrons are heated by the intense laser radiation to the temperature up to several hundred eV via 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 collaboration work between CERN, ITEP-Moscow and TRINITI-Troitsk on the development of a LIS for LHC was a very nice approach to a high charge state intense pulsed beam ion source for heavy ions [16]. A 100 J, ~27 ns pulse length CO_2 laser system was utilized for LIS (Fig. 3) and demonstrated a very impressive results of high charge state ion beams production in 2003, i.e. 2.3×10^{10} Pb^{27+} ions at a pulse length of 3.6 μs. LIS was once regarded as an intense high intensity HCI beam machine of poor beam emittance, bad reproducibility. Recent years' work in different labs such as BNL [17] and IMP [18], has greatly improved the source performance, reliability as well as reproducibility. Very high intense high charge ion beams up to Sn^{24+} could be produced [18]. Typical ion beam intensity is in the range of 10^{8}~10^{11} ions/pulse with a pulse length of 1~10 μs (weak solenoid confinement during the plasma drift is a very flexible knob to get higher beam intensity and manipulate beam pulse length [19]). To produce more intense high charge state heavier ion beams definitely needs higher power laser system.

Figure 3: 100 J/1 Hz MO-PA CO_2 laser system for LIS.

Charge Stripping

Charge stripping is one irreplaceable scheme to get unrivalled intense pulsed beams of highly charged ions. This unique scheme to have very intense highly charged heavy ion beams has been utilized in the HSI (High current injector) at GSI by accelerating of ion beams from mono-charge state or low charge state ion sources successively with a 36 MHz IH-RFQ and two IH-DTL sections (Fig. 4) to 1.4 MeV/u, and then stripping via a gas stripper to high charge states [20]. Typically, two types of intense ion sources have been put in operation at GSI for this scheme, i.e. filament type multi-cusp ion source MUCIS and MEVVA type ion source VARIS [21]. MUCIS is used to produce low charge state gaseous ion beams while VARIS is to get low charge state metallic ion beams, for instance, ~100 emA U^{4+} extraction via a multi-aperture extraction system from VARIS. However, due to high divergence

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and relatively big transverse emittance, most of the beam is lost in the LEBT. For FAIR project, 18 emA U^{4+} in front of the gas stripper or 15 emA U^{28+} after the gas stripper is required [22]. Recently, with the upgrades in the front end part of UNILAC, especially the recently developed H_2-gas stripper, 11.1 emA U^{28+} has been produced after the stripper section, which amounts to 74% of the FAIR intensity requirements [23]. The typical beam repetition rate of 11.1 emA U^{28+} is 1 Hz with a pulse length of 100 μs, which demonstrates ~2.48×10^{11} U^{28+} particles per pulse. Longer pulse duration can make more particles per pulse available. Theoretically, it is possible to produce CW high charge state ion beams with this strategy, but practically it is very challengeable. To accelerate such high M/Q (~60 for U^{4+}) ion beam from 2.2 keV/u to 1.4 MeV/u is very difficult, especially in terms of linac driver's cost, CW operation cost, ion source CW operation life span, machine protection and so on. Nevertheless, Charge Stripping scheme is the most powerful HCI source with regard to beam intensity.

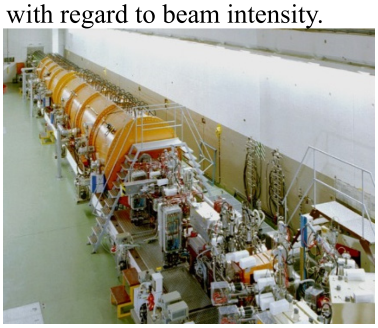

Figure 4: High Current Injector (HSI) at GSI.

ION SOURCE CHOICE FOR HEAVY ION ACCELERATORS

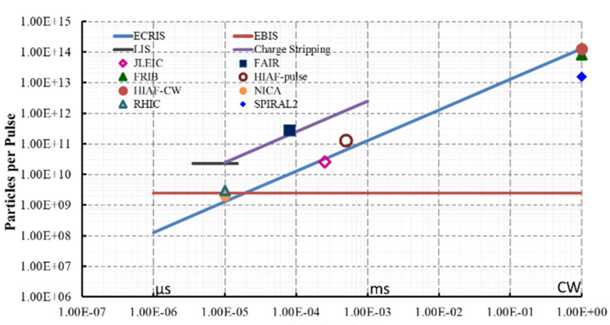

Figure 5: Performances of state of the art HCI sources and the requirements of heavy ion accelerators.

As is the well-known Chinese wisdom, the longest journey starts with the first step. An efficient ion accelerator should start with a powerful and optimal ion source. For high intensity heavy ion accelerators, especially the next generation complex, choice of a suitable high charge state ion source is essential. Fig. 5 gives the high charge state ion beam production capacities with the state of the art ion sources discussed in former section. For direct comparison, ion beam species are all unified as U beams. Due to their operation modes are different, the presented particles per pulse in the picture does not necessarily cover the whole pulse length range from 1 μs to 1 s (CW for 1 Hz operation). In Fig. 5, several typical heavy ion accelerator facilities' requirements on highly charged ion beam as unified as U^{28+} or U^{3n+} are also illustrated [3-7, 24, 25]. Based on this picture, optimal ion source selection based on accelerator operation mode and beam requirements will be briefly discussed in the following contents.

CW Operation

CW operation are typically requested by cyclotrons or SRF linacs that can provide the maximum heavy ion beam power onto the segmentation target so as to maximize the produce of rare isotopes. RIBF in RIKEN is a typical one using a combination of linac and cyclotron accelerators aiming to achieve 6×10^{12} particles/s U beam with energy of 345 MeV/u ultimately [26]. FRIB at MSU is using the cutting edge technology heavy ion SRF linac to accelerate CW uranium ion beams to 200 MeV/u with a 400 kW beam power onto the target in Phase I. ~14 puA $U^{33+,34+}$ beam, or 8×10^{13} particles/s U beam is needed [27]. According to Fig. 5, it is obvious that ECR ion source is the most powerful machine to produce CW or dc high intensity HCI beams, and undoubtedly the best option for high intensity CW heavy ion accelerators.

Operation with 100 μs~1 ms Beam Pulse

This operation mode is typically for those accelerator facilities composed of heavy ion linac injector and storage ring that use multi-turn injection to accumulate high enough ion beam intensity. For instance, the UNILAC serves as a 11.4 MeV/u injector with ~2.75×10^{11}/pulse U ions for SIS18 (FAIR/GSI), the iLINAC (a ~60 m long CW SRF linac) drives ~1.0×10^{11}/pulse uranium ions to 17 MeV/u to inject into BRing (HIAF/IMP), JLEIC uses a combination of room temperature linac for low β section and SRF linac for high β section to accelerate ~2.6×10^{10}/pulse Pb ions to 42 MeV/u as heavy ion beam injector for the Booster ring [28]. As given Fig. 5, the best performing 3rd generation ECR ion source operating at 28 GHz can meet the requirement of JLEIC, but still barely make it for HIAF pulse mode for BRing injection. Beam intensity with Charge stripping scheme is still ~25% lower than FAIR requirement, nevertheless much more than the project needs of both HIAF and JLEIC. EBIS can barely make 1×10^{10}/pulse ion beam intensity, and LIS' extracted ion beam pulse length is much shorter than 100 μs, so they are both not very recommended for this operation mode.

Operation with ~10 μs Short Beam Pulse

This operation mode is typically for single turn or very few turns injection to a booster ring, so as to reduce the sensitivity to small beam loses at injection that may cause a pressure bump resulting in further beam loss and the consequent radiation issues, and also a much simpler injection structure design compared to a multi-turn injection one. An EBIS operates best as a pulsed device, since the total charge per pulse is essentially independent of the

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extracted pulse width, short pulses (typically 10~40 μs) can be extracted for efficient single turn or very few turns injection into a synchrotron through a linac preinjector. With RHIC-EBIS, the AGS Booster can operate with 1~4 turn injection mode [29]. The similar operation mode is also adopted for NICA at JINR with an EBIS type machine named Krion-6T [30]. As given in Fig. 5, RHIC-EBIS can meet the beam intensity requirement of the synchrotron boosters' preinjectors. LIS with ~100 J laser irradiation onto the target and Charge Stripping scheme are both able to provide HCI beam intensities well beyond the requirements of the preinjectors by a factor of ~10 times higher. Nevertheless, EBIS can produce higher charge states and better quality beams over LIS. While Charge Stripping scheme is a more costly and complicated solution compared to an EBIS. Operating at such a short pulse length, ECRIS loses the advantage in beam intensity of HCIs as shown in Fig. 5. Therefore, it is not recommended to use ECRIS as injector ion source for such operation mode. Overall, EBIS is the best option for this operation mode, while LIS could be an alternative option, especially for the application in a heavy ion treatment accelerator with intense C^{6+} beam.

FUTURE DEVELOPEMNT AND POSSIBILITIES

Driven by the increasing demands from the future heavy ion accelerators, presently there are many research activities to develop more powerful HCI sources beyond the success of the state of the art ion sources as shown in Fig. 5, for instance the 4th generation ECRIS, the Tandem EBIS, and a HCI scheme based on a gasdynamic ECRIS.

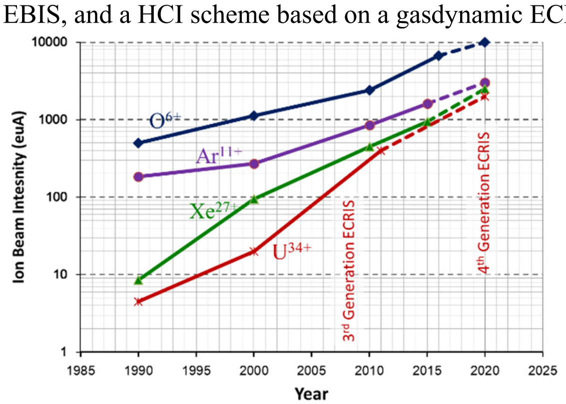

Figure 6: Evolution of ECRIS ion beam intensities.

Based on the success of the 3rd generation ECRIS, a 4th generation ECRIS operating at a frequency of 45 GHz can increase the beam intensity of U^{34+} by a factor of ~2.6 or more according to the frequency scaling laws, i.e. $I_q \propto \omega_{ecr}^2$, where I_q is the beam intensity of high charge state ion, and ω_{ecr} is the microwave frequency. Therefore, 1~2 emA highly charged U^{3n+} beam could be produced. Fig. 6 gives the evolution of ECRIS performances vs. the different generations. A 45 GHz ECRIS called FECR is now under development at IMP [31], aiming to build the prototyping machine for HIAF project FECR features a fully Nb_3Sn superconducting magnet, a quasi-optical 45 GHz microwave transmission and coupling system, a 50 kV/50 emA multi-electrode extraction system and a totally ~13 W@4.2 K cooling capacity GM cooler system.

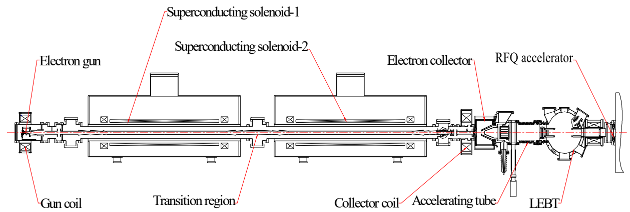

Figure 7: A schematic plot of the Tandem EBIS concept.

For an EBIS, the desired HCI beam intensity or particles/pulse $N_i \propto k \cdot I_e \cdot L_{trap} \cdot E_e^{-0.5}$, where I_e is the electron beam current, L_{trap} is the trap length, E_e is the electron beam energy k is the factor determined by the neutralization factor in the trap and the fraction of desired charge state i. One way to increase the intensity of the extracted ion beam from EBIS is an axial extension of the ion trap, making it longer. The capacity of the ion trap is proportional to the length of the trap if the radial depth of the potential well remains the same in any axial position of the trap. A tandem EBIS based on RHIC-EBIS with 1.5 m long trap has been proposed [32]. With two extended RHIC-EBISs of ~1.8 m long trap each (Fig. 7), >2 times beam intensity yield increase is expected by fast extraction. There is also possibilities to increase the electron current and optimize for narrow EBIS charge state distribution to have potentially >50% extra gain on the interested ions [33]. Thus, based on the existing RHIC-EBIS performance, production of 1×10[10] U^{3n+}/pulse with 10~40 μs pulse length is possible.

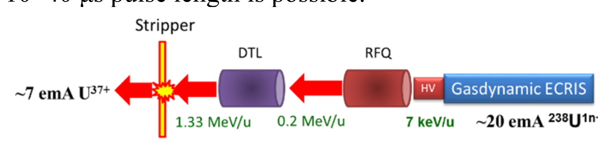

Figure 8: Charge Stripping scheme based on a Gasdynamic ECRIS concept.

When utilization of microwave radiation with the frequency ⩾28 GHz , it is possible to build up a plasma density of 10^{13}~10^{14} cm^{-3}. Significant increase of the plasma density leads to a change of the confinement mode, i.e. so-called quasi-gasdynamic confinement, instead of collisionless confinement in traditional ECRIS. Demonstrated by IAP/RAS, this type of ion source (or Gasdynamic ECRIS) can produce unprecedented ion current densities up to 800 emA/cm^2 [34]. Irradiated with a 1 ms pulse duration 75 GHz microwave power of 200 kW, very intense pulsed heavy ion beams have been produced from a simple mirror trap, such as a total current of 300 emA Pt ion beams with an average charge of 7+, including 14 emA Pt^{10+} [35]. It has been foreseen that by increase of the microwave frequency, higher microwave repetition rate, a better magnetic field confinement with improved MHD stability, it is possible to produce very dense heavy ion beams of higher charge states, such as U^{1n+} with the pulse beam intensity of ~20 emA [36]. As

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illustrated in Fig. 8, with a combination of RFQ and 2 DTL tanks, it is possible to accelerate U^{1n+} up to 1.33 MeV/u. Successively with a ~20 μg/cm^2 carbon stripper [37], uranium charge state can be easily boosted to 35+~38+ with a beam intensity of ~7 emA. Compared to the Charge Striping scheme for FAIR, this solution has higher efficiency of ion acceleration as a result of higher ion charge state from the ion source and therefore lower driver linac cost, better flexibility in ion beam switch (gaseous or metallic ion beams from the same source), and much better beam quality [38].

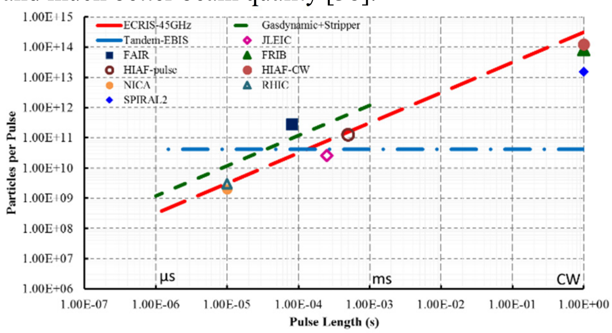

Figure 9: Perspectives in future HCI sources.

Fig. 9 gives the potentials in producing intense HCIs with the three developments as discussed above, in comparison with the requirements of several typical heavy ion accelerators. Obviously, the current needs of FAIR could only be met with the existing Charge Stripping scheme. The recently proposed Gasdynamic+Stripping scheme can provide sufficient pulsed beams for all the other facilities. It is worth mentioning that a 4th generation 45 GHz ECRIS can produce the needed beam intensities with either pulse or CW mode for all the facilities except FAIR.

CONCLUSION

Physics is driving the development of more intense, more powerful and higher brightness future heavy ion accelerators that need intense highly charged ion beams. This paper has reviewed the existing high current HCI beam sources developed for modern heavy ion accelerators. By comparing the already demonstrated performance with the accelerators' requirements, recommendations on HCI beam injector source have been made. Discussion on more powerful HCI sources as primary ion beam injector is also presented, which might pave the way for the development of more powerful heavy ion accelerators in the future.

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