BNL-73247-2004-CP

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High-Intensity, High Charge-State Heavy Ion Sources

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Presented at the XXII International Linac Conference
Lübeck, Germany
August 16-20, 2004

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Contract No. DE-AC02-98CH10886

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HIGH-INTENSITY, HIGH CHARGE-STATE HEAVY ION SOURCES*

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Abstract

There are many accelerator applications for high intensity heavy ion sources, with recent needs including dc beams for RIA, and pulsed beams for injection into synchrotrons such as RHIC and LHC. The present status of sources producing high currents of high charge state heavy ions is reviewed. These sources include ECR, EBIS, and Laser ion sources. Benefits and limitations for these type sources are described. Possible future improvements in these sources are also mentioned.

INTRODUCTION

In heavy ion preinjectors, the choice of charge state, (or minimum charge-to-mass ratio), to be designed for, is an important consideration. Higher Q/M from an ion source makes the downstream accelerators more compact and less costly, but generally there is a tradeoff between intensity and charge state from a source, which may or may not be acceptable. If one can select a charge state high enough to eliminate one or more subsequent stripping stages, however, this lower initial intensity may result in equal or higher final intensities.

Examples of future applications which are pushing requirements for high intensity, high charge state heavy ion sources include the following:

- At Brookhaven, a new heavy ion preinjector is planned as a simpler, more modern replacement for the two Tandem Van de Graaff accelerators which are presently used for the heavy ion program at RHIC. As an example, ion source requirements for Au ions include the following a.) charge state 32+, to eliminate the need for stripping before injection into the Booster synchrotron; b.) pulse width ~ 10 μs, to allow simple single turn injection into the Booster; c.) Au^{32+} current from the source of 1.7 emA, in order to deliver the required intensity of 3 x 10^9 ions/pulse to the Booster; d.) 5 Hz repetition rate. In addition, in order to support simultaneously the beam requirements for the NASA Space Radiation Laboratory (NSRL), the ion source must be able to deliver to Booster a second beam species, with pulses interleaved with the RHIC beam pulses, *switching species at the 5 Hz repetition rate.* Examples of the beams required for NSRL include He^{2+}, C^{6+}, O^{8+}, Si^{14+}, Ti^{18+}, Fe^{21+}, and Cu^{22+}, all at currents of 2-3 emA, and pulse widths of ~ 10 μs. As will be discussed below, an Electron Beam Ion Source (EBIS), similar to that which has been developed at Brookhaven [1], can meet these requirements.
- Driver accelerators for rare ion production, such as the Rare Ion Accelerator (RIA), require dc beams of essentially any ion species. Examples of required beams and intensities for RIA are 230 eμA of $U^{28+,29+}$, 280 eμA of $Pb^{25+,26+}$, 220 eμA of Xe^{18+}, 350 eμA of Ni^{12+}, 230 eμA of Ar^{8+} [2]. In applications such as this, which require high current dc beams, the ECR ion source is essentially the only option. Present state-of-the-art ECRs can exceed RIA requirements for gaseous beams, and are close to meeting the requirements for the more difficult beams produced from solids.
- At CERN, LHC requirements for heavy ions depend on the acceleration scheme used. While initial operation is with Pb ions, ions such as He, O, Ar, Kr, and In have also been requested [3]. The baseline plan for Pb ions requires an upgraded ECR producing > 200 eμA of Pb^{27+}, in 200 μs pulses, at 5 Hz. This scheme also requires the use of LEIR for ion storage and cooling. In an alternative scheme, one could avoid the use of LEIR if one would produce directly from the source ~ 5 emA of Pb^{25+}, in 5.5 μs pulses, at 1 Hz. A laser ion source (LIS) was being developed for this option [4], and an EBIS with a reasonable scaling from Brookhaven parameters could also be considered. A third option, also not needing LEIR, would be to produce ions in a charge state which would also eliminate a stripping stage. In this case, one would need 2-3 emA of Pb^{54+} ions, in 5.5 μs pulses at 1 Hz. Parameters for an EBIS meeting these requirements were presented in [5].

ION SOURCE CONSIDERATIONS

As seen from the above examples, source requirements can depend strongly on the application. Some important considerations are common to almost all accelerator applications, such as source lifetime, reliability, stability (both pulse-to-pulse and long term), magnitude of current fluctuations (noise), and beam emittance. Other aspects have varying importance depending on the application. For instance, the ease and speed of changing species is important for RHIC, but nearly irrelevant for the other applications. Some applications have less flexibility than others regarding the choice of beam species, so sources favoring ions coming either from gases (ECR) or solids (LIS), may be at a disadvantage. Finally, for these high current applications, the charge state distribution of ions coming from the source can be an important

*Work performed under Contract Number DE-AC02-98CH10886 with the auspices of the US Department of Energy.

consideration, because the extraction and initial transport has to be designed to handle space charge from the total extracted current, which can be anywhere from a few times to a hundred times larger than the current in the desired charge state, depending on the ion source, charge state, etc.

The sources described in the following sections have characteristics which are favorable for the production of high charge state ions. To produce high charge state ions, one needs high energy electrons in the source. A high density of these high energy electrons is required to produce the desired intensity and charge state. The ions must stay in the electron beam or plasma long enough to reach the desired charge state through stepwise ionization. Also, it is desirable to keep the background pressure as low as possible to minimize the recombination of ions. In the EBIS, one can control precisely and independently these parameters, while in ECR sources these parameters are coupled quite a bit, and the LIS offers the least control over them independently.

EBIS SOURCE

Principle of operation

In an EBIS source, a high current electron beam is produced on one end, compressed to high current density as it passes through a long magnetic solenoid, and is then decelerated and stopped in an electron collector on the other end of the solenoid. Gas can be fed into the solenoid region, or singly charged ions injected into the solenoid from an external source through the collector end, to feed the trap with the desired beam species. Electrostatic potentials are applied to cylindrical electrodes in the solenoid bore to trap ions axially, while the space charge of the electron beam provides radial trapping of the ions. These trapped ions undergo stepwise ionization by the electron beam; the longer they are held in the trap, the higher the charge state of the ions. When the desired charge state is at the peak of the charge state distribution, the electrostatic barrier is dropped from the collector end, and ions exit the trap and are extracted through an aperture on the axis of the electron collector. The total number of charges extracted is limited by the loss of radial confinement when the space charge of the electron beam is fully neutralized, and this extracted ion charge can be 50-75% of the total electron charge in the trap. Therefore, the extracted ion current can be accurately predicted for an EBIS, based on the easily calculable electron charge in the trap region – determined by the electron current, electron beam velocity, and trap length.

As a result of this ion production process, the EBIS has the unique feature that the total extracted charge per pulse is nearly independent of ion species or charge state (except at the very high charge states)! In addition, because one can control how one drops the barrier voltage (or puts a small accelerating gradient within the trap electrodes), one can control the pulse width of the extracted ion beam, and therefore short pulses of high current are possible, making it well suited for few-turn synchrotron injection.

Performance

Recent advances in the standard EBIS have been achieved at Brookhaven, where a prototype of the EBIS required for RHIC has been developed [1]. This EBIS has been operated with a 10 A electron beam current, and a 0.7 m long trap. Experiments have mainly concentrated on performance with Au beams, with > 50nC of charge per pulse being extracted. A current of ~550 μA of Au^{32+} has been produced in ~ 15 μs pulses. A scaling up of the trap length to 1.5 m is planned to get a factor of 2 increase in ion current, thus meeting the RHIC requirements.

Features; Advantages

- Easily produces the highest charge states of the three type sources
- Produces a narrow charge state distribution; typically 20% of the total current is in the desired charge state
- Produces beams of any species; intensity is independent of species; can switch species pulse-to-pulse
- One can control the pulse width (produces a fixed charge/pulse)

Technological aspects of the source

- Electron gun (BNL EBIS uses 10A electron beam)
- Electron collector (BNL design for 15A * 15 kV = 225 kW)
- Superconducting solenoid (5T, 8" bore, 2 m long will be required for the RHIC EBIS)
- Auxiliary ion sources used for external injection of 10's of μA of singly charged ions; multiple sources feeding the trap for fast switching of species.
- Ultrahigh vacuum (10^{-9} to 10^{-10} Torr)
- Modern control system makes operation stable, reproducible, and increases flexibility. Makes control of many EBIS parameters in a complex cycle easy.

Potential issues

- Possibility of instabilities at high electron beam currents. (Not observed at BNL, up to 10A).
- Not much operating experience at high currents.
- Energy spread of fast-extracted ions

ECR SOURCE

Principle of operation

The ECR plasma chamber is placed in an axial magnetic mirror field configuration, produced by two solenoid coils, and a radial cusp magnetic field produced by a sextupole magnet. The superposition of these fields produces a minimum-B configuration in the center. Gas for the species of interest, or alternatively a buffer gas, is fed in to the chamber. Plasma is produced via the injection of microwave power into the chamber, and is confined due to the confinement of plasma electrons in the magnetic field configuration. For a given microwave frequency, the magnetic fields are chosen such that there is a surface within the chamber where the electron-cyclotron resonance condition is satisfied. Electrons in this region are resonantly heated to high electron temperatures, necessary for the high charge state ion production in the plasma, which then occurs predominantly via stepwise ionization. Ion current can be increased with increasing rf power, and by increasing the rf frequency/magnetic field combination. When the beam of interest can not be produced from a gas, the options are the heating/sputtering of solid material inserted into the plasma, using metal in vapor released from volatile compounds, or the use of a very high temperature oven.

In pulsed operation, one sometimes measures an enhanced intensity of extracted high charge state ions right after the rf power is turned off, called the "afterglow" mode. This enhancement is explained by the increase in the rate of electron loss when rf power is turned off, causing ions, confined by the electron space charge, to exit the plasma more quickly as well.

A recent review of the physics of ECR's has been presented in [6].

Performance

The superconducting ECR VENUS is being developed at LBL as a demonstration of a source which will meet RIA requirements, and there are also very active developments at many other labs worldwide. Only a few examples of high current ECR performance, pulsed and dc, are given in Table 1. Further details for various sources can be found in [7].

Table 1: Some examples of ECR performance

	Ion	Q	I (eμA)	Width (μs)
CERN, 14.5 GHz [3]	Pb	27	120	~200
PHOENIX, 28 GHz [8]	Pb	27	~550	~200
SERSE, 28 GHz [9]	Xe	25	500	>200
SERSE, 28 GHz [9]	Xe	27	~100	dc
LBL VENUS 28 GHz [10, 11]	Xe	27	120	dc
CEA-GTS 18 GHz [12]	Xe	27	168	dc
LBL VENUS 28 GHz [10, 11]	Bi	27	220	dc
RIKEN 18 GHz [13]	Xe	20	300	dc

While, as mentioned above, for EBIS the output current is almost independent of species or charge state, for the ECR there are strong dependencies on both, and

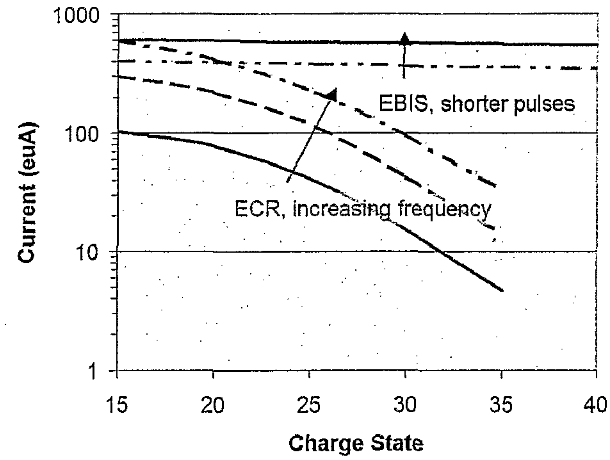

Figure 1: Illustration of approximate charge state dependence for ECR and EBIS, for species such as Xe.

going up by one or two charge states can sometime result in a factor of 2 drop in intensity. A schematic representation of the charge state dependence for both type sources is illustrated in Fig. 1.

Features; Advantages

- Essentially the only choice for high current, high charge state, dc applications
- Reliable; many operating ECRs, a lot of experience

Technological aspects of the source

- Superconducting magnets (both solenoids and hexapoles). VENUS, operating at LBL at 28 GHz, has 4 T injection field and 2 T hexapole at plasma chamber.
- RF power source – for example, 28 GHz gyrotron, at 10-15 kW; plus sometimes multiple frequencies used, requiring multiple rf sources.
- High temperature oven may be used for metal ion production.

Potential issues

- Broad charge state distribution, so one has to extract & transport a high total current
- Performance depends on species, favoring gases and low melting point solids
- "Memory" effects in the plasma chamber can lead to slow ion species switching times.

LASER ION SOURCE

Principle of operation

A simplified picture of the process of high charge state ion production in a laser ion source is the following. A short pulsed, high power laser beam is focused to a small spot on a solid target containing the desired beam species. Evaporation of target material occurs, and electrons in the gas absorb laser energy via inverse Bremstrahlung, causing their energy to increase. A plasma forms, and rapidly expands normal to the target. Plasma ions are stepwise ionized to high charge states.

The electron temperature increases with laser power density and wavelength, which is advantageous for the production of high charge states. More details on the design choices for a LIS can be found in [14]. Results of an experimental comparison of several different laser types was presented in [15]. A CO_2 laser is still the best choice for the production of highly charged ions.

Performance

There has been an ongoing collaboration between CERN, ITEP-Moscow, and TRINITI-Troitsk on the development of the LIS for LHC, an application mentioned in the introduction. The most recent step has been the development of a 100 J, 15-30 ns CO_2 laser operating in the master oscillator-power amplifier configuration, and the testing of a source using this laser. The laser is designed to operate at the required repetition rate of 1 Hz. With this laser, they have produced a few emA's peak current of Pb^{27+}, with a pulse width of several microseconds, and extracted these ions at 105 kV [4]. The total extracted current was ~ 20 emA, and the charge state distribution was quite a bit narrower than previous results for Ta using a 30 J laser. Since the LIS produces higher currents and shorter pulses than the ECR, if it were included in Fig. 1, it would be at higher current but with a falloff with charge state similar to the ECR.

Unfortunately, the lifetime of the source at 1 Hz operation is so far only on the order of hours, and improvements are needed in several areas in order to achieve at least a minimum acceptable lifetime of ~ 2 weeks. Since the baseline for LHC is now an ECR, the first use of this LIS is now redirected to a new high current injector for the ITEP Terawatt Accumulator (TWAC) project.

Features; Advantages

- Produces high currents, short pulses

Technological aspects of the source

- High power laser – 100 J, CO_2, 15-30 ns pulse
- Laser beam optics
- Targets – 3×10^{13} W/cm^2 on the target

Potential issues

- Laser reliability
- Achieving the desired repetition rate of the laser
- Pulse-to-pulse beam current fluctuations
- Target erosion; coating of optics by evaporated target material
- Species approximately limited to solid targets (high melting point solids are best).

FUTURE DEVELOPMENTS

Improvements continue to be made in all three type sources. EBISs are going to higher intensities via higher electron beam currents and longer trap lengths. ECRs continue to move to higher frequencies and higher magnetic fields. For the LIS, developments are aimed more at reliability and lifetime. However, there are more extreme variations on these type sources which are also being developed.

At Dubna, rather than dumping the electron beam after a single pass through the trap region of an EBIS, the electron collector was replaced with a repeller electrode, using a geometry which was very symmetric to the electron gun side. With this negatively biased electrode, electrons reflect/oscillate repeatedly through the trap, raising the effective electron current in the trap by forming what is called a "string" [16]. This Reflex EBIS was used at JINR on the Nucleotron in June '02 and June '03 runs to produce N^{6+} (300 eμA), N^{7+} (350 eμA), Ar^{16+} (200 eμA), and Fe^{24+} (150 eμA) [17]. Beam pulse width was ~8 μs, for single turn injection into the ring. The outstanding feature here was that this was achieved with *only 5-6.5 mA electron current*! This represented an effective 50-times reflection of electrons through the trap, and therefore an electron beam with only 2% of the beam power that would have been required in the normal EBIS mode. The effective electron current density in the trap was 150-200 A/cm^2. They report good stability over the 4 weeks of running for this Reflex EBIS. A step even beyond this is the Tubular EBIS, also being developed at Dubna [18]. Here, the attempt is being made to increase the effective electron beam current even further by establishing a reflex mode of operation of an electron beam in a somewhat complicated geometry, but which essentially fills the space between two coaxial cylinders running the length of the trap (a "tubular" geometry).

The ECLISSE project is a coupling of a LIS and an ECR, where one hopes to enhance with the ECR the charge states coming from the LIS [19].

CONCLUSION

While all performance goals have not yet been demonstrated for high charge state heavy ion sources which would fulfill RHIC, LHC and RIA requirements, solutions for all three applications seem to be well within reach. One important aspect not covered in this paper is the fact that as intensity from these sources steadily increases, the transport of these beams, for matching into an RFQ, for example, is becoming more difficult, due to space charge.

The sources described above have differing characteristics, so depending on the application, frequently one will be a better fit than another. The ECR is clearly the choice for RIA, which requires dc beams. However, for RHIC, where one requires high currents in short pulses, plus any ions species and fast switching, the EBIS is an excellent match. For LHC, all 3 source types would seem to be candidates, but constraints in the schedule result in the ECR being the best choice at present.

REFERENCES

[1] J.G. Alessi, E. Beebe, D. Graham, A. Kponou, A. Pikin, K. Prelec, J. Ritter, V. Zajic, Proc. PAC 2003, p. 89.

[2] J.A. Nolen, Proc. Linac 2002, p. 29.

[3] C.E. Hill, D. Küchler, H. Kugler, R. Scrivens, Proc. Linac 2002, p. 148.

[4] A. Balabaev, S. Kondrashev, K. Konukov, A. Lozhkin, B. Sharkov, A. Shumshurov, A. Charushin, K. Makarov, Yu. Satov, Yu. Smakovskii O. Camut, J. Chamings, H. Kugler, and R. Scrivens, Rev. Sci. Instrum. 75 (2004) 1572.

[5] E. Beebe, J. Alessi, A. Kponou, A. Pikin, K. Prelec, Proc. EPAC 2003, p. 281.

[6] A. Girard, D. Hitz, G. Melin, K. Serebrennikov, Rev. Sci. Instrum. 75 (2004) 1381.

[7] S. Gammino, G. Ciavola, L. Celona, L. Andò, D. Hitz, A. Girard, G. Melin, Proc. PAC 2003, p. 81.

[8] P. Sortais, J.-L. Bouly, J.-C. Curdy, T. Lamy, P. Sole, T. Thuillier, J.-L. Vieux-Rochaz, D. Voulot, Rev. Sci. Instrum. 75 (2004) 1610.

[9] S. Gammino, G. Ciavola, L. Celona, D. Hitz, A. Girard, G. Melin, Rev. Sci. Instrum. 72 (2001) 4090.

[10] C.M. Lyneis, D. Leitner, S.R. Abbott, R.D. Dwinell, M. Leitner, C.S. Silver, C. Taylor, Rev. Sci. Instrum. 75 (2004) 1389.

[11] D. Leitner, private communication.

[12] D. Hitz, A. Girard, K. Serebrennikov, G. Melin, D. Cormier, J.M. Mathonnet, J. Chartier, L. Sun, J. P. Briand, M. Benhachoum, Rev. Sci. Instrum. 75 (2004) 1403.

[13] T. Nakagawa, T. Aihara, Y. Higurashi, M. Kidera, M. Kase, Y. Yano, I. Arai, H. Arai, M. Imanaka, S. M. Lee, G. Arzumanyan, G. Shirkov, Rev. Sci. Instrum. 75 (2004) 1394.

[14] B. Yu. Sharkov, S. A. Kondrashev, Proc. EPAC 1996, p. 1550.

[15] P. Fournier, H. Haseroth, H. Kugler, N. Lisi, R. Scrivens, F. Varela Rodriguez, P. Di Lazzaro, F. Flora, S. Duesterer, R. Sauerbrey, H. Schillinger, W. Theobald, L. Veisz, J. W. G. Tisch and R. A. Smith, Rev. Sci. Instrum. 71 (2000) 1405.

[16] E. D. Donets, Rev. Sci. Instrum. 71 (2000) 810.

[17] E.D. Donets, D.E. Donets, E.E. Donets, V.V. Salnikov, V.B. Shutov, S.V. Gudkov, Yu.A. Tumanova, and V.P. Vadeev, Rev. Sci. Instrum. 75 (2004) 1543.

[18] E.D. Donets, E.E. Donets, R. Becker, L. Liljeby, K.-G. Rensfelt, E.N. Beebe, and A.I. Pikin, Rev. Sci. Instrum. 75 (2004) 1566.

[19] S. Gammino, L. Andò, L. Celona, G. Ciavola, L. Torrisi, J. Krasa, L. Laska, M. Pfeifer, K. Rohlena, B. Badziak, P. Parys, J. Wolowski, E. Woryna, G. Shirkov, Proc. EPAC 2002, p. 1709.