Multi-Charged Ion Sources for Pulsed Accelerators

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The relatively low duty cycle of pulsed accelerators can give rise to problems in matching the characteristics of multi-charged ion sources to the beam intensity required by the user. Heavy ion physics interests, especially in the heavy ion colliders, demand more and more intensity whilst the accelerator designers require higher charge states to ease their machine problems. Various options for ion sources for present and future heavy ion accelerators are presented.

I. INTRODUCTION

With the interest growing in high energy heavy ion physics to use existing accelerator facilities, the demands for beam intensity to the user become ever more important. As these beams are often accelerated in existing proton accelerator chains, severe restrictions are imposed on the charge states permitted from the ion source, especially in the early part of the system where the particles are sub-relativistic. For light ions it has not proved too difficult to adapt proton linacs to accelerate either fully stripped or He-like (i.e. two electrons remaining) ions, although this has required running the machines at the limit of their performance [1]. As the Z of the projectile increases, it becomes more difficult to stay within these limits without compromising the intensity delivered by the source. A solution is, then, to build a special injector (often a linac) for the highest possible Z, adapted, in energy and charge state, to the requirements of the next accelerator in the chain. The highest possible charge state at an acceptable intensity is required from the source to keep the cost, and size, of this injector to a reasonable level. For most injectors, intermediate stripping, an inefficient process, is generally needed to attain the required charge state, thus increasing the intensity requirements. However, if developments in source technology are able to improve performance in relation to charge and intensity the injector may still be able to cope. Equally, the acceleration of lighter ions is eased. It should not be forgotten that it is the number of ions on target that is of interest to the experiment. In the future, the requirements of planned heavy ion colliders, especially with respect to filling times, will increase the intensity requirements.

At the last conference, there was a review of intense high charge state ion sources [2]. Figure 1, based on data given in that paper, compares the charge states from various sources for different ions. This paper will look specifically at the problems and progress made in the production of high charge state heavy ions (Z in the range 80 - 92) for injection into synchrotrons where the inherent duty cycle imposes additional difficulties. However, any progress in source performance could have benefits for the subsequent machines.

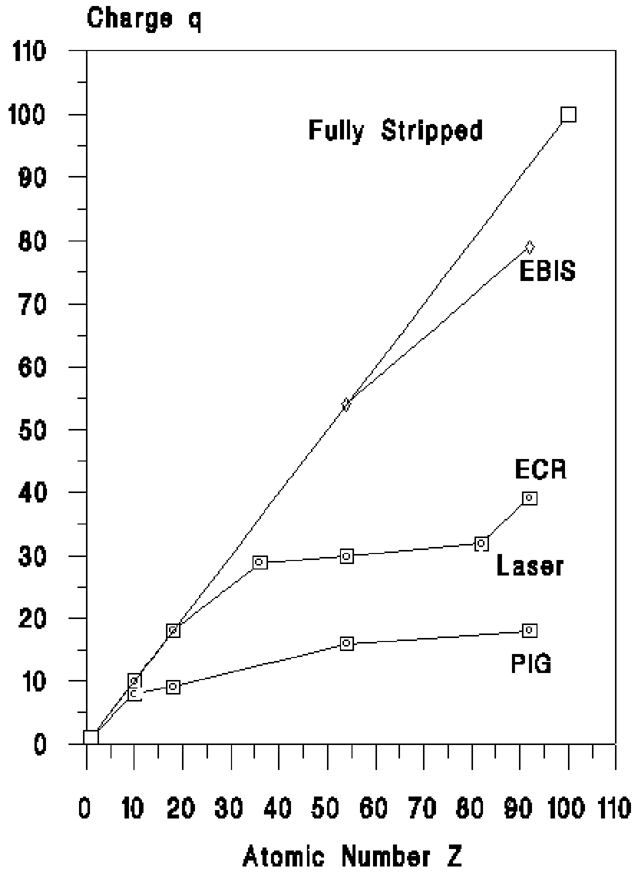

FIG. 1 Charge states from EBIS, ECR, Laser and PIG sources.

II. EXISTING SOURCES

At the present time, there are only two types of source which can provide reasonable beams (i.e. >10 eμA or >10^9 ions per pulse) of highly charged heavy ions, the ECR (Electron Cyclotron Resonance) [3] and the EBIS (Electron Beam Ion Source) [4]. The inherent low duty cycle of synchrotrons can be put to good use in that the dead time between beam pulses can be used to increase either the source output or the charge state. Development of the LIS (Laser Ion Source) [5] is indicating that the potential could exist for high currents of highly charged heavy ions. This is not to say that there are not other types of source which can produce heavy ions but in these devices, the mean charge state tends to be low.

The production of highly charged or fully stripped light ions is starting to become popular both for ion physics and medical applications [6], and interesting beam intensities are becoming available. However, the step from He like ions to fully stripped is normally the most difficult and leads to a considerable loss of intensity. Even with He-like ions their charge/mass ratio is generally high, thus facilitating the design of the next accelerator. An additional advantage of these ions is that they are generally available as elements or simple compounds in gaseous form and thus are easy to inject into the source.

As the mass of the ion increases the charge/mass ratio falls and it becomes important to produce the highest charge state possible to keep costs down. Ion physicists are now interested in having the heaviest ions possible (with certain restrictions) and with the highest possible number of ions on target [7]. Unfortunately, beam intensity falls with increasing charge state and accelerator problems increase with lower charge/mass ratios. In addition heavy elements tend to be metallic, refractory and in their natural state, mixtures of isotopes. The injection of the sample into the source in a controlled manner can present various difficulties. Hence, the major scientific and technical problems in producing the required beam usually fall onto the ion source.

A. ECR

The ECR source has become established as a major provider of multiply-charged ion beams for a great number of applications. Some of this popularity can be attributed to the simplicity of the source and to its adaptability. For lighter ions in low charge states, and where gaseous injection can be used, this source has shown that it can be adapted to industrial and research environments using relatively cheap consumer technologies.

Although the ECR, at first sight, is not well adapted to pulsed accelerator injection in that it was conceived as a continuous source, it has successfully been used for injection into linacs [8]. The operation of the source in pulsed mode already gives a useful increase in intensity (and mean charge state) over CW operation and the afterglow operation has led to a dramatic increase in heavy ion intensity. ECRs in afterglow mode are now in regular operation at GSI [9] and CERN [10]. In the latter case, a 14.5 GHz ECR4 type source has been used in regular operation at the CERN PS complex giving over 600 μs pulses of 120 eμA of Pb^{27+} at 2.5 keV/u [11]. A schematic diagram of this source is shown in figure 2. For reasons of stability the source operates at 10 Hz repetition rate and is required to maintain the short term intensity to better than 10% from pulse to pulse. This performance was maintained not only during the eight week physics period, but also during the 3 month accelerator commissioning period.

An unfortunate consequence of the demands for the highest possible intensity, is that isotopically pure or highly enriched materials must be used as samples. For low melting point materials, such as lead, evaporation into the plasma from a small oven is an easy and highly controllable way of optimising source performance. Even with continuous operation of the oven, sample consumption is small (4 - 7 mg of lead per day). Refractory materials can present problems. Sample heating of rod samples at, or near, the ECR surface has been used but does present problems in maintaining source stability. Laser ablation has also been tried [12].

B. EBIS

The EBIS [13] would seem ideally suited to synchrotron operation. In low duty cycle applications there is time between pulses to store and ionise the sample and the extracted pulse length can easily be adapted to the next machine in the chain.

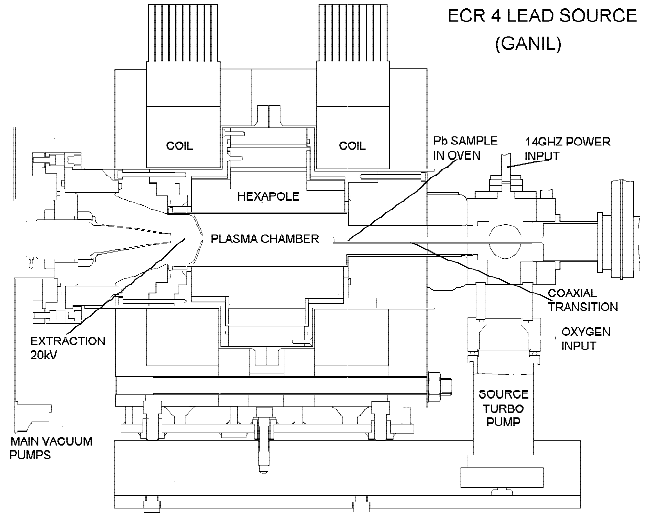

FIG.2 The ECR4 source used for lead ions.

Theoretically, the maximum possible charge extractable from the source is give by its length and the electron beam current as long as the electron beam energy is matched to the desired charge state. In reality, the electron beam, whose space charge potential well provides radial confinement for the ions, cannot be totally neutralised and a figure of around 50% seems to be practical. A second limitation to the source output relates to the duty cycle. The width and peak of the charge state distribution is related to the length of time the ions are held in the trap and, depending on the duty cycle, the yield of a given species will be somewhat less than the maximum. Figure 3 shows an outline of a theoretical EBIS.

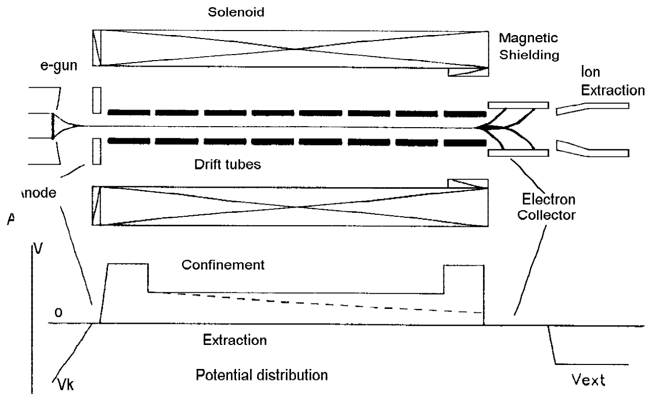

FIG.3 Schematic confined flow EBIS

Although the EBIS has a reputation for being a difficult source to operate, a number have been used on accelerators. Most of the problems arise from the need to maintain the dense electron beam stable within the magnetic field over the operating range. Cathodes are normally unable to provide sufficient current density and some form of beam compression is needed. In magnetic compression, errors in the fields in the transition from compression to laminar flow can give rise to instabilities which can prove difficult to overcome. Efficient collection of the electron beam at the end of the source is needed either for energy recovery or to reduce the effects of thermal outgassing from the beam dump. Gaseous ions can be easily produced either from the rest gas or from controlled injection from outside. Refractory materials do give rise to problems but it has proved possible to overcome this by the injection of low charge ions from an external source such as a MEVVA.

Accelerator use of the EBIS seems to have been limited to SATURNE source, CRYSIS [14] and KRION-C [15]. All of these three sources use superconducting magnetic field configurations.

C. The Laser Source

The ECR requires a hot dense plasma to ionise the sample. In view of the limitations in plasma density obtainable by microwave heating, plasma confinement becomes crucial to the formation of high charge states. Laser induced plasmas from solid targets can have the required characteristics of plasma density and temperature. The key element of a laser source is a powerful laser producing a short beam in the nanosecond range well focused onto the surface of the target (power densities of the order of 10^{13} W.cm $^{-2}$). The enormous heating in the layers near the focus result in the production of a rapidly expanding highly ionised plasma. Ions in this plasma have a mixture of charge states and energies and the major problem in the LIS is the extraction of the desired species as a beam of reasonable optical characteristics. A review of LIS was presented at an earlier conference [16]. Figure 4 shows the basic layout of a laser driven ion injector.

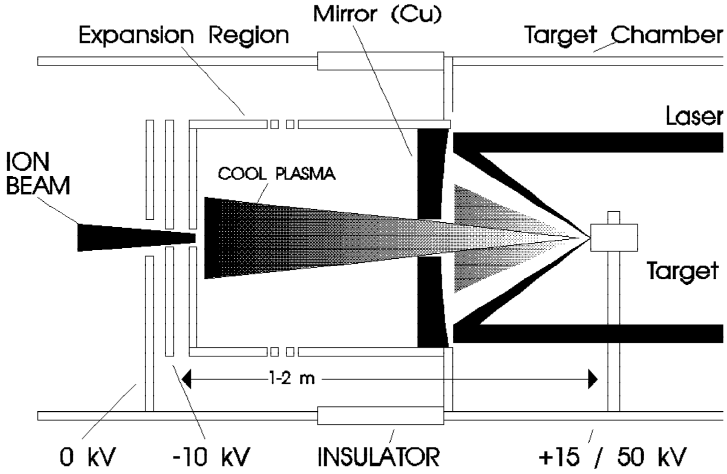

FIG. 4 Beam formation in a laser source

At the moment there seems to be only one laser driven ion source in operation and that is in Dubna [17]. This source, using a 10 J/pulse CO_2 laser delivering about 10^{10} W.cm^{-2} on target, is mainly used for light ion production up to Si^{14+}. However, ions both of copper (Cu^{14+}) and tungsten (W^{11+}) have been produced. CERN, in collaboration with a number of other institutes [18] is investigating a laser ion source and extraction systems for heavy ions. Working with tantalum, charge states up to 20+ have been produced . The first demonstration of a "useful" beam has been made last year when an Al target was used. To confirm its high quality this beam has been accelerated with a RFQ (built by LBL for the oxygen ion acceleration in Linac 1 in 1986 [1]). 3 emA of Al^{9+} and Al^{10+} were accelerated with good transmission from 5.6 keV/u to 127 keV/u [19]. It should be noted that, due to the inherently short pulse produced with a Laser Ion Source, space charge problems are severe and special attention must be paid to them. It can be easy to produce and extract these ions, but their capture and further acceleration in a RF structure is not necessarily so straightforward. In general this will mean higher extraction voltages to overcome these difficulties.

D. Other Possibilities

It is appreciated that the types of source mentioned above may not represent the totality of high charge state or heavy ion sources. The metal vapor or arc sources are regularly used for refractory elements but are limited in the maximum charge state available. PIGs have for a long time been the mainstay of the low charge state regime but are unable to reach the types of performance that the power sources discussed above can attain. This is not to say that PIGs or arc sources should be disregarded; their relative simplicity and low cost could make them of use where high charge states are not too important or as a low charged particle source for injection of difficult materials into the stripper type sources such as ECR or EBIS.

An elegant solution to the problem though somewhat cumbersome in equipment was found at BNL for injection into the AGS booster. Taking advantage of a tandem, they are able to use negative ions with stripping in the terminal and optionally after the tandem, and this is presently being use to produce Au^{13+} (Au^{33+} with the second stripping). The disadvantage is the need of a tandem and its infrastructure.

III. DEVELOPMENTS

At this conference, progress in the development of ion sources will be presented by many authors and in all probability much of what has been written above will be already out of date. However, it would be instructive to see along which lines the development and improvements of high charge state heavy ion sources might go. In the absence of commercial, governmental or strategic pressures, development will have to be guided by anticipated accelerator requirements in the present academically orientated environment.

A. ECR

Study of the processes involved in the ECR plasma [20] will help source operators develop strategies for optimising source output. Already the afterglow is being exploited with considerable success in heavy ion accelerator operation. A big step in intensity was obtained in passing from 10 GHz to 14 GHz thus seeming to confirm the empirical f^2 scaling of plasma density with frequency. On this basis, additional improvements could be expected from further frequency increases. However, this requires that microwave power plant technology follows these demands. Not only does one require kilowatt level transmitters for these sources, the power feed technology must also be capable of delivering power reliably and efficiently to the plasma. The gyrotron would seem to be a suitable source of high power microwave energy if the problems associated with power control can be resolved. Fine control of the power injected into the source has been found to be important for stability.

Any increase in frequency brings about an increase in magnetic field, and it must be asked when a change to superconducting field configurations will become necessary. Problems in producing strong gradients in the multipole radial confinement field may limit supra source performance. These same strong gradients may be more important for performance than other parameters. There is evidence of plasma densities far in excess of the plasma frequency limit in sources with high longitudinal gradients [21] and at lower frequencies than traditional sources. With some of the existing sources, high field operating modes can be observed with high extracted currents but these modes tend not to have acceptable stability for modern high energy physics applications. The understanding and mastering of these instabilities should be one of the objectives of research and development into ECR sources for heavy ion, high charge applications.

Further investigations should show if any of the following techniques can be used to improve ECR performance:- biased electrodes in plasma; plasma chamber wall materials or coatings; multi-frequency operation; plasma (pilot) gas composition; alternative chemical composition of samples; pulsed magnetic fields [22].

B. EBIS

Unlike the ECR, the EBIS is somewhat neglected. In many cases this source and the related EBIT have remained a device for use in atomic physics experiments. In view of the extensive interest in ECR and laser sources, BNL have decided to investigate the feasibility of using EBIS for injection into a synchrotron [23]. This would eliminate many of the problems associated with the present, tandem based, injection scheme and increase the range of ions available. An EBIS would have the advantages of smaller inherent emittance, more easily adjustable pulse length, more control of peak charge state and more easily applicable scaling rules. The availability of an experimental source originally conceived for atomic physics studies also helped in this choice [24].

The main problems to be overcome are related to the attainment of a stable high density electron beam of adequate intensity to obtain the required number of particle. Studies of the emitter and beam compression, especially at high currents and current densities are crucial to this objective. It will also be necessary to investigate the neutralisation problem. Although it is theoretically possible to fully neutralise the electron beam, 50% is about the maximum that can be achieved experimentally and probably lower in the synchrotron injector environment. Also of interest for heavy ions will be ion cooling within the trap where large gains can be hoped for in maximum charge state.

C. The Laser Source

At the present moment it seems the LIS is limited mainly by the available laser power and of course by the repetition rate of the laser. The use of CO_2 lasers seems for the time being the optimum choice. Theoretical considerations were favoring anyhow long wave lengths. However the possible power density can be higher with smaller wave lengths. Tests at the Institute of Physics at the Czech Academy of Science have shown that even higher charge states (Ta at 45+) [25] can be obtained with iodine lasers having roughly a ten times shorter wave length even with smaller pulse lengths provided the total energy is the same. The dimensions and repetition rates of such lasers are, however, problematic. Future developments in the laser field may overcome this problem. The CO_2 laser used at CERN has a repetition frequency of 0.1 Hz. It seems the know-how exists to build CO_2 lasers with 1 Hz and a somewhat higher energy (100 J / pulse). Such a laser should be able to comply with the present CERN installation i.e. be able to deliver several milliamps of e.g. Pb^{27+}. Technical problems concern not only the construction of such a laser but also the target chamber, pulse to pulse reproducibility and the lifetime of the optics. but also the handling of the highly space charge influenced beams. High extraction voltages will be required which make the subsequent bunching section in the RFQ more difficult.

IV. THE COLLIDER PROBLEM

The key element in multistage injector complexes for heavy ion collider facilities such as CERN's LHC or BNL's RHIC is finally the ion source. Its performance defines the final luminosity that can be obtained for physics with reasonable efficiency. In the case of CERN, the recently commissioned Heavy Ion Accelerating Facility [26] for fixed target physics whose layout is shown in figure 5 and which required a purpose built injector linac using an ECR source for ion production, compatible with injection into the PS booster. The anticipated performance of this scheme was used to set up a collider scenario. With the anticipated performance of the source of 80 eμA of Pb^{27+}, stripped to Pb^{53+} at 4.2 MeV/u and accelerated in the PS Booster, 4 x 4 bunches would be accelerated in the PS. After final stripping to Pb $^{82+}$ between PS and SPS, nine PS cycles would be accumulated in the SPS, accelerated and injected into LHC. Four SPS cycles would then be needed to fill each ring and even with optimisation of the number of ions per bunch, the luminosity would be limited to

3.6×10^{24} cm^{-2} s^{-1} which is well below the desired figure of 10^{27}. To achieve the desired luminosity with the present ECR source a special scheme has been elaborated [27]. The Linac with its source would operate with a repetition rate of 10 Hz and inject into the LEAR (Low Energy Antiproton Ring) machine. Electron cooling would be used to accumulate sufficient intensity within a small emittance.

First electron cooling tests with Pb^{53+} ions were performed in LEAR in December 1994 [28]. The test showed, that cooling time constants (1/e) of 50 ms for the momentum and of 300 ms for the transverse emittances can already be reached with the present state of the cooler. However the lifetime of the ion beam decreased to values of 2 s in the presence of an electron beam of 0.4 A. Further studies were made this year with Pb^{52+} and Pb^{54+} and gave very encouraging results. They revealed that the recombination of these charge states with the electron beam is much weaker and hence the cooling lifetimes are much longer than for $Pb^{53+.}$

In the case of RHIC they propose to inject four pulses of 3 x 109 Au 35+ from an EBIS via a RFQ and a purpose built linac of 2 MeV/u into the AGS booster. Once accumulated, these particles would be accelerated as three bunches, fully stripped before acceleration and transfer to RHIC. Nineteen AGS cycles would then be needed to fill each ring.

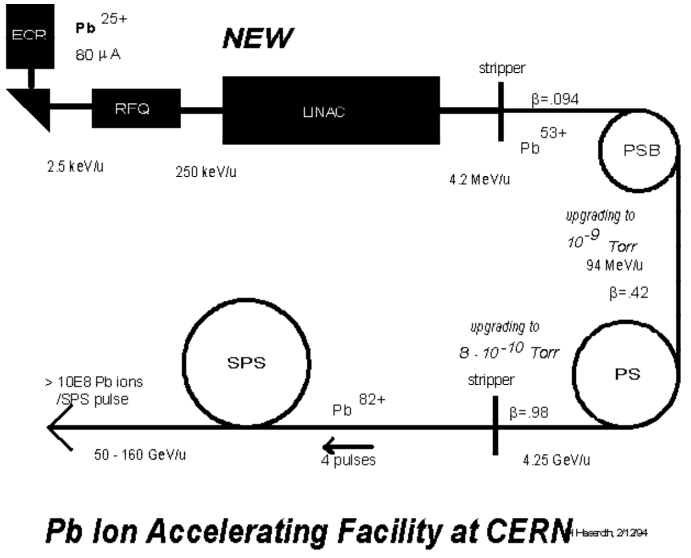

FIG.5 Layout of the Lead Ion Accelerator Facility

V. CONCLUSIONS

The interest in high energy heavy ion physics is growing steadily as is shown by the inclusion of heavy ions in the options for new hadron collider proposals. Unfortunately, these options require more performance from the ion source, most especially in terms of intensity. Not many options lie open to achieve this goal without development effort. The ECR source is well developed but further work is be afterglow. EBIS is interesting for future synchrotron applications and BNL experience on an experimental setup indicates that its reputation as a difficult source may not be founded. The Laser source holds the most promise for high intensities and high charge states but the technological problems of converting the laboratory techniques into a reliable operational device suited to modern high energy accelerators mean that it will be a few years before this device becomes a standard injector.

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