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Design proposal for an EBIS as lead ion source for the LHC

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Abstract

In this note a possible design for an Electron Beam Ion Source (EBIS) for the ion preinjector for LHC is presented. It will produce lead ions that are injected into and further accelerated in an RFQ/LINAC arrangement. The source is based on the REXEBIS, a charge breeder under construction for the REX-ISOLDE project, and unlike previously proposed EBISs for heavy ion injectors, the design parameters for the LHCEBIS are fairly modest which means there is no need for the development of a new high-current device.

The LHCEBIS is based on a 1.5 A electron beam with 5 keV energy. The electron beam is produced in a magnetic field of 0.2 T, and compressed by a 3 T solenoidal field to a current density of >400 A/cm^2. The magnetic field is provided by a warm-bore superconducting solenoid. The source will operate with a repetition rate of 1 Hz, and the yield will be $1.5 \cdot 10^9$ Pb^{54+} per pulse. Using slow extraction, the extracted pulse length will be between 50 and 100 μs and the energy spread <25 eV/u. The transverse emittance is calculated to be <110 π mm mrad at an extraction voltage of 10 kV. The lead is introduced into the EBIS as 1$^+$ ions from an external ion source by so-called ion injection. To be able to control the introduction of light evaporative cooling ions precisely, they (preferably H$^+$ or He^{2+}) are injected by ion injection. Apart from lead, the source could, for instance, deliver O, Ca and Nb with intensities of $2 \cdot 10^{10}$, $1 \cdot 10^{10}$, and $3 \cdot 10^9$ ions per pulse, respectively.

It should be pointed out that the radiative recombination rate for the highly charged ions can be restrictive for the performances of the LHCEBIS, and that the data presented within this report are based on theoretical estimations of the radiative recombination and ionisation cross-sections.

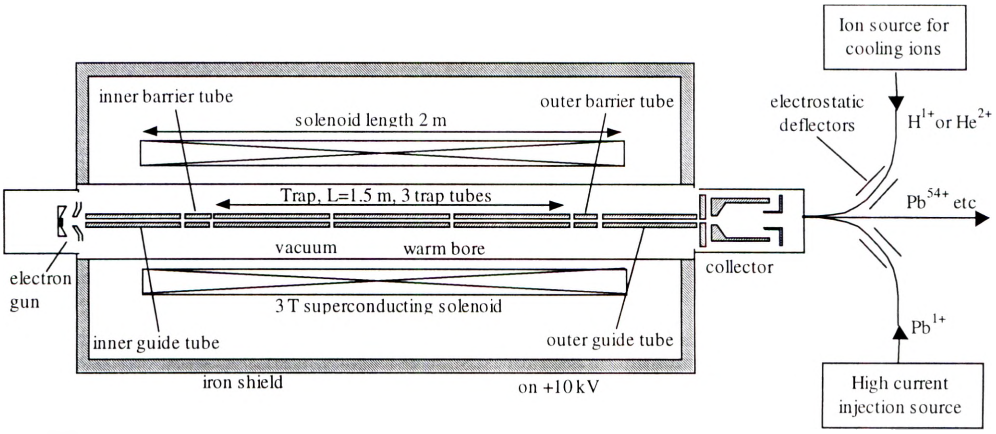

Figure 1. *Schematic drawing of the LHCEBIS showing the most important elements described within this proposal. (Not to scale.)*

1. Introduction

When using an EBIS [1] instead of an ECR ion source [2], which is the main ion source candidate for the LHC for the moment, the first stripper stage after the LINAC at 4.2 MeV/u becomes obsolete. The use of an EBIS as ion source for large heavy ion collider projects such as LHC or RHIC is by no means new; in fact the RHIC project is investigating the possibility [3]. However, this proposal has a different design approach. Instead of the development of a new EBIS generation with a high electron current, a moderate concept is proposed which is almost completely based on already existing EBIS techniques.

The main challenge when using an EBIS as an ion source for a large heavy ion injector is to create sufficient negative space charge to confine the large positively charged ion-cloud. So far, the suggested solution to the space charge problem has been to increase the electron beam current by one order of magnitude from present state-of-the-art of about 1 A to 10 A. That requires the development of a new generation EBIS, with some difficult obstacles. Instead let us inspect the expression for the electron charge C inside an EBIS:

$$C = \frac{1.05 \cdot 10^{13} \cdot I_e L}{\sqrt{E}} \text{ elementary charges}$$

where L (m) is the trap length, I_e (A) and E (eV) the electron current and energy, respectively. One notices from the formula that an alternative way to increase the negative charge is to decrease the electron beam energy E. A low electron beam energy is possible in the proposed EBIS since the lead ions have not to be fully stripped. Furthermore, by making use of a moderate electron beam energy the charge state distribution can be distorted in favour for one desired charge state (in our case Pb^{54+}), boosting the fraction of ions in that charge state from about 20% to at least 50% (see sec. 2.1 below). The principal charge state has an ionisation energy just above the chosen electron beam energy, i.e. the sequential ionisation feeds ions into this charge state but can not further ionise them, thus increasing the relative abundance for that charge state with breeding time.

Operation with a boosted charged state leads to a more effective use of the confining negative space charge (i.e. the electron current), which can therefore be decreased by a factor of two to three. Keeping the electron beam current low has several advantages, such as:

- Straightforward electron beam formation.
- The need for heavy cooling of the electron collector disappears.
- Fewer problems with electron reflection from the collector into the trap region.
- Electron beam losses at the anode constitute a less serious problem from a vacuum point of view.
- No need to protect the drift tubes and other electrodes in the event of an accidental electron beam loss.
- The risk for RF generation by the electron beam is reduced.

The main disadvantage – a relatively high radiative recombination rate – will be discussed in sec. 2.1.

The proposed EBIS has a design very similar to the REXEBIS [4,5] which will be used in the REX-ISOLDE project. The constructional changes that are needed to adapt an REXEBIS to LHCEBIS performances concern mainly the electron gun, which will have to deliver 1.5 A instead of 0.5 A, and the collector design. Even if the LHCEBIS is to be used for a completely different purpose (the REXEBIS charge breeds few ions to a moderate Q/A with a very high efficiency), one can benefit from the experience gained from the construction of the REXEBIS.

2. General design aspects

The design parameters for the EBIS are determined by the goals of the physics carried out at the heavy ion collider LHC. By using the concept outlined in ref. [6], the EBIS has to deliver $1.24 \cdot 10^9$ ppp (pulse rate ~0.8 Hz) to the PSB and the PS for the LHC luminosity requirement to be fulfilled, and with a certain safety marginal that would mean $1.5 \cdot 10^9$ ppp. Expected good emittance properties of the extracted beam and a high beam transport efficiency (see sec. 5) allow a low safety margin, and the long experience of EBIS development has showed that their performances are quite predictable. The main performance limiting uncertainty is the radiative recombination rate.

2.1 Charge state

The proposed EBIS will deliver lead ions with charge state 54^+, which can be achieved with moderate EBIS parameters. To breed lead ions to charge state 82^+ within the EBIS, and in that way avoid the final stripper is not realistic, since it would require an extreme $j_e\tau$-value (with ion cooling problems etc as consequences) and an electron beam energy exceeding 90 keV.

For lead ions 53^+ and 54^+ the ionisation potential to attain the next higher charge state increases dramatically from about 3.3 keV to 5.4 keV (multiconfiguration Dirac-Fock calculated [7]). By choosing the electron beam energy in between these values, after some time all ions will end up in charge state 54^+. A large difference in ionisation potential between the two charge states is necessary for this concept to work, since all beam electrons do not propagate with the same velocity (the radial potential causes kinetic energy variations). If the ionisation potentials were close, the spread of the electron beam velocity would cause a distribution between two or more charge states instead of a single one.

The charge state development for lead ions bombarded with 5 keV electrons is shown below. Note that the first graph (Figure 2) does not include any recombination processes, neither ion loss effects due to ion heating by electron Coulomb scattering. The dielectronic recombination with the electron beam will be negligible (the recombination rate with secondary electrons is not fully clear) in the LHCEBIS, and the charge exchange probability between a neutral gas (residual gas pressure 10^{-11} torr) and a Pb^{54+} ion is less than 2% according to Muller and Salzborn's formula for electron transfer from atoms or molecules to highly charged ions [8]. It will later be shown that the ion losses due to heating and subsequent radial escape can also be kept small. Nevertheless, the radiative recombination seems to be non-negligible, and the theoretical prediction from Kim and Pratt [9] indicates radiative recombination cross-sections of the same order as the ionisation cross-section for the highest charge states. When taking the radiative recombination into account, the charge state evolution is modified as shown in Figure 3. The result is a slightly slower breeding (which can be compensated by increasing the electron beam current density) and a smaller fraction of ions in the desired charge state (not possible to enhance). One has to keep in mind that both the ionisation and recombination cross-sections are based on theoretical calculations, and therefore the real number of obtained Pb^{54+} ions in the LHCEBIS may be larger or smaller.

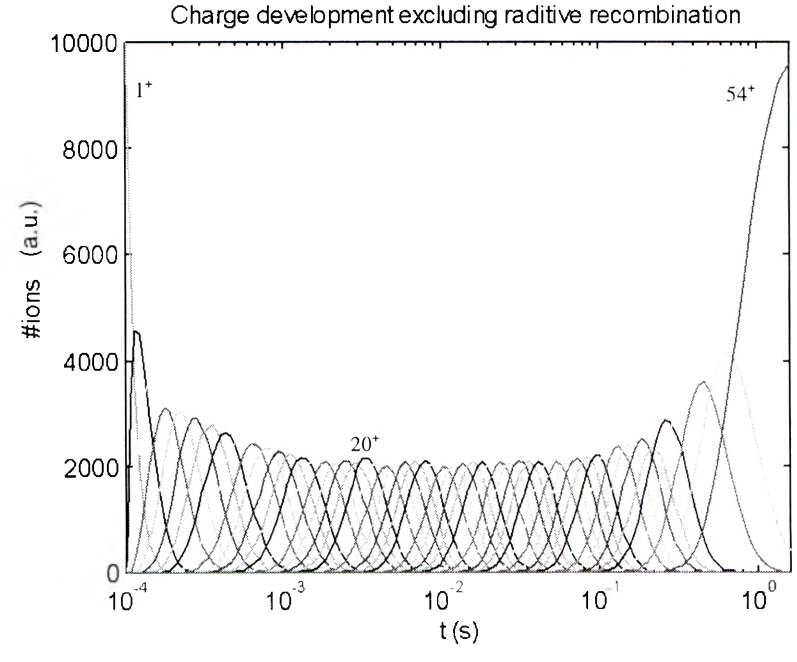

Figure 2. *Relative charge state abundance for Pb stepwise ionised by a 5 keV electron beam (radiative recombination excluded).*

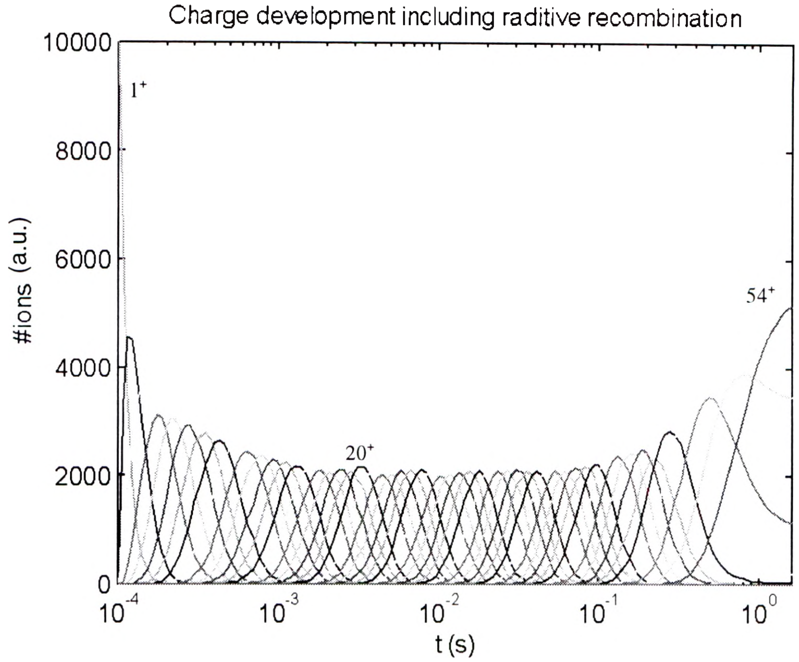

Figure 3. *Relative charge state abundance for Pb stepwise ionised by a 5 keV electron beam (radiative recombination included).*

2.2 Space charge effect

The negative space charge, constituted by the electrons, will be provided by the single pass electron beam. The proposed LHCEBIS has a total trap capacity of 53 nC, and assuming a maximal trap compensation of 50% [10,11], the useful space charge will be ~25 nC. From the charge evolution graphs in Figure 2 and Figure 3 it is clear that the relative abundance of Pb^{54+} ions can be at least 50%, which equals an effective trap capacity of $\sim 1.5 \cdot 10^9$ Pb^{54+} ions.

If cooling ions have to be added H^+ or He^{2+} are suggested. Even if the evaporative cooling effect increases with the charge state of the evaporative ions, they should have a low atomic number to keep the undesirable occupation of negative space charge as low as possible. Moreover, the momentum transfer, and therefore the cooling effect, is more effective for light ions, and the optimal solution is probably to inject H^+ or He^{2+} ions [12] from an external ion source, since the possible charge exchange process between the lead and not fully ionised cooling ions is then eliminated. The quantity of cooling ions, and therefore the amount of occupied negative space charge, is not known and has to be investigated experimentally.

Residual gases are also ionised and trapped within the electron beam. A total residual gas pressure of 10^{-11} torr is achievable inside the trap region, and that yields a space charge compensation of only some percent for a 1 s breeding period. A positive side effect of the residual gases is the evaporative cooling of the hot lead ions.

An EBIS is virtually indifferent to the ion species that are injected for breeding. Thus, the EBIS is also capable of breeding for example O, Ca and Nb as shown in Table 1.

Ion	Peak charge	Breeding time	# ions per pulse
Lead (Pb)	54^+	1 s	$1.5 \cdot 10^9$
Oxygen (O)	8^+	0.1 s	$2 \cdot 10^{10}$
Calcium (Ca)	18^+	0.5 s	$1 \cdot 10^{10}$
Neobium (Nb)	31^+	0.5 s	$3 \cdot 10^9$

Table 1. *Ion yield parameters for the proposed LHCEBIS assuming 50% compensation and 50% of the ions in the desired charge state.*

3. Description of a breeding cycle

3.1 Injection

The lead is introduced into the trap region by external ion injection, i.e. 1^+ Pb ions are produced in a high-current external ion source (for example a RF-source [13]) and then injected into the EBIS. This type of injection scheme is, for instance, used at CRYSIS in Stockholm, and the same principle is planned to be used at the RHIC-EBIS. At CRYSIS Pb, O, Ca and Nb amongst other elements have been successfully injected [14].

In principle, two different injection scenarios are possible. The first implies the injection of 5 μA for 50 μs, corresponding to a total number of $1.5 \cdot 10^9$ 1^+ Pb ions. This method is called pulsed injection, and since the exact amount of lead ions needed for LHC is injected, no boiling-off during the breeding phase is allowed. After the ion bunch has entered the trap region, the outer barrier voltage is raised to confine the ions longitudinally. To ensure a minimal degree of boiling-off and radial heating, evaporative ion cooling can be used. In addition, the 1^+ ions should be injected into the very bottom of the electron beam potential[1]. It then follows that the ions are completely trapped inside the electron beam, and they have a low initial temperature.

An alternative method is to completely fill the trap with 1^+ Pb ions, i.e. to compensate it already at injection. Since the external ion sources are limited in current, slow injection has to be used, that means a 2.5 μA beam is injected over an already raised outer barrier for some ten milliseconds[2]. The temperature of these ions inside the trap is higher than in the previous alternative, and during breeding most of the Pb ions are boiled-off, so only a fraction (about 1/54) of the initial number of ions (which corresponds to $1.5 \cdot 10^9$ ions) remains when the Pb^{54+} ions are extracted. Experimental tests have to decide which of the methods (or a mixture of both) provides the highest number of Pb^{54+} after the breeding has finished.

It is essential that the ions pass the outer guide tube with a high velocity during injection and therefore not have time to be ionised, since an ionisation outside of the trap results in ion rejection at the trap entrance and thereby a low injection efficiency. Hence, the injection energy is such that the ions pass the outer guide tube with ~2000 eV, and the trap tube potential is raised during injection to allow the ions to be trapped within the electron-beam potential well. Directly after injection, the trap tube potential is decreased so an electron beam energy of 5 keV is obtained inside the trap.

3.2 Breeding

When the ions have entered the trap region, they are ionised to higher charge states. As was shown in Figure 2 and Figure 3, a breeding time of ~1 s is needed to reach Pb^{54+} with a current density of 400 A/cm^2. Thus, the EBIS can work with a repetition rate of almost 1 Hz since the extra time required for injection, extraction and cleaning is negligible.

While the ions are trapped inside the confinement region they are heated (mainly in radial direction) by the electron beam. Heat is transferred from the electrons to the ion population by elastic small-angle Coulomb scattering, and may cause radial boil-off of the highly charged lead ions. According to ref. [15] the radial holding voltage, i.e. the radial voltage needed to prevent the Pb^{54+} lead ions from escaping, is in the order of 20 V, which is much less than the radial voltage from the electron beam well. Thus, there is little danger from an ion loss perspective. However, if the ions are heated so they leave the electron beam for certain fraction of the breeding time, this has to be compensated for by an increase in confinement time or electron current density. In fact, the 1 s confinement requirement is based on an electron density of 400 A/cm^2, but in reality one can expect a density of 450 A/cm^2 from the design, and that would to a certain extent compensate for the decreased time the ions spend within the electron beam.

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[1] Due to the small acceptance for ion injection at the bottom of the electron beam potential [5], the injection current might have to be larger than 5 μA if the emittance of the external ion source is poor.

[2] With an injection time of 10 ms, the needed injection current has to be 2.5 μA to fill the trap to 50% (25 nC), however, due to a low efficiency for continuous injection, the injection current may have to be an order of magnitude larger.

To reduce the heating of the lead ions the use of evaporative ion cooling is suggested. Light cold ions, with a limited maximum charge state, are injected as coolant from an external ion source. The cooling ions have to be slowly injected over the outer barrier to attain a controlled cooling process, both in time and in the quantity of injected coolant. The low electron beam energy is a disadvantage from a heating point of view since the heating is proportional to the inverse square root of the beam energy, but, due to the boosted charge state mode one can not increase the beam energy.

Depending on which injection scenario is used, the trap potential has to be adjusted differently during the breeding period. If a pulsed injection with few ions is utilised, the trap tube potential has to be decreased slowly while the trap compensation (and therefore the beam potential) increases in order to keep the electron beam energy at 5 keV. On the other hand, if the trap is fully compensated at the injection, the trap tube voltage should be fixed during breeding.

3.3 Extraction

After breeding, the ions are extracted from the trap region by so-called slow extraction. That means the outer barrier is lowered so the ions are free to leave the trap and the EBIS by their inherent kinetic energy – a process that takes approximately 50 to 100 μs (that means multiturn injection into the Booster). Immediately before the opening of outer barrier, the trap and barrier potentials are simultaneously elevated ~1000 V. By doing so, the ions will have enough energy to overcome the energy threshold caused by the expanding electron beam in the outer guide tube. The consequence of an increased trap potential is a higher electron beam energy, and therefore the risk for ionisation to a higher charge state, however, since the trap potential is elevated for only some 10 μs, there is no time for a significant amount of ionisation to a higher charge state than 54^+. Since the complete trap potential is raised, the process does not introduce any energy spread to the ions.

Nevertheless, the extracted beam has a finite energy spread, partly caused by the fact that the ions are extracted from the trap at times with different level of compensation. At the beginning of the extraction period, the trap may have 50% compensation, giving the extracted ions an extra energy of +1000*Q eV (⇔ 260 eV/u) compared to the last ions that are extracted from a nearly empty (non-compensated) trap. This large energy spread can however be compensated for, so a much lower effective energy spread is reached, by increasing the trap potential during the extraction phase so the potential drop is exactly matched (active trap potential compensation).

If single-turn injection into the Booster is desired, the extraction time has to be as short as 5 μs [16]. To reach this goal an accelerated extraction technique must be used, but using a simple longitudinal voltage gradient at the extraction phase would introduce an extracted ion energy spread of about 2000*Q eV (⇔ 500 eV/u). That is why multiturn injection would be preferred.

4. Mechanical design

4.1 Solenoid

For electron beam focusing and ion confinement in the trap region, a solenoidal magnetic field is used. The field is produced by a superconducting magnet with an axial full field of 3 T. The solenoid is shielded, and it has a "warm bore", i.e. the inner cylinder is at room temperature. A warm bore design has several advantages, for instance it is easy to open up since the solenoid has not to be warmed up to room temperature. Furthermore, with drift tubes at room temperature, the out-gassing caused by spurious electron beam load is low. Finally, the drift tubes do not condense gases and thus do not have a "memory effect". However, this is only of importance if different ion species are used consecutively in a run.

4.2 Electron gun

The electron beam is generated in a semi-immersed gun, i.e. a gun configuration with a flat cathode that is immersed in the fringe field (~0.2 T) of the solenoid. The cathode, a LaB_6 with 310-crystal orientation, can have a high emission density (~30 A/cm^2) with a lifetime of approximately 1 year. With an anode voltage of 10 000 V the gun perveance becomes a moderate 1.5 microperv for a 1.5 A electron beam. After the emission from the electron gun, the beam is compressed by the increasing magnetic field strength (approximately linearly to B) when entering the solenoid, resulting in an electron current density of >400 A/cm^2 in full magnetic field. In the axial position corresponding to a field strength of about 1 T, the electron beam energy is decreased from 10 keV to 5 keV, and thereby the perveance increased to a relatively high, but still feasible value of 4.2 microperv. It is easier to design and construct a low perveance gun with a high anode voltage and thereafter decelerate the electron beam inside the drift tubes, than it is to produce a 4.2 microperv electron gun. The ratio of the electron beam to the drift tube radius is such that virtual cathodes do not occur.

4.3 Drift structure

The drift tube structure will be mounted in vacuum inside the room temperature bore of the solenoid. To reach the high vacuum (10^{-11} torr) inside the EBIS, one turbopump on each side of the solenoid, and NEG strips inside the trapping region are necessary. The system of drift tubes defines the extension of the trap in longitudinal direction, and the potential determines the electron beam energy. The drift tubes can be divided into three types: guide, barrier and trap tubes (Figure 1).

The drift tube radius, or more correctly the tube to electron beam radius ratio, is an important parameter since it determines the total radial potential well (tube to beam axis potential difference) and affects the ion losses. A large tube radius keeps the ion losses low since the radial potential well is large. When the electron beam becomes compensated by the ions and the radial potential decreases, the ions may have sufficient energy to leave the electron beam radially, and oscillate with a large radius. If the trajectory radius is larger than the drift tube radius, the ions are lost at the walls. To keep this radial ion loss as low as possible it is desirable to have a large tube radius. On the other hand, the large potential well yields significant extracted ion energy spread, and makes the electron beam transport more difficult. A non-compensated electron beam of 1.5 A has a potential well (electron beam edge to beam axis potential difference) of 320 V, and a total potential well of 2250 V for a 0.25 mm and 5 mm electron beam and tube radius, respectively. Even with a 50% trap compensation, the radial holding voltage is ~1000 V, which exceeds the radial heating by far (in the order of 20 eV/Q). Thus, the ion losses in radial direction are expected to be low, and can be made very small in longitudinal direction if the barrier potentials are high enough. The drift tube to electron-beam radius-ratio can be decreased if the design should be impaired be electron beam perveance problems.

The total number of drift tubes is only 7 (two guide; two barrier; three trap tubes to allow cleaning of the trap after extraction) and with such a low number of tubes unnecessary risks of self-induced RF generation are avoided. If fast extraction were to be used, the number of trap tubes had to be increased so that a longitudinal electrical field gradient along the trap could be created by applying different voltages to the trap tubes. The need for very high field gradient results in a large extracted energy beam spread, which makes the technique unattractive.

The tube potential is set so the electron beam is decelerated from 10 keV to 5 keV in a high magnetic field, typically 1 T.

4.4 Electron collector

At the electron collector the electron beam is separated from the ion extracted ions, and the electrons are absorbed at the collector surface. With a collector potential of +3 kV relative to the cathode, the deposited effect on the collector surface, which has to be cooled away by water, is 4.5 kW. Compared to many other EBISs, the collector end has an open design with a large diameter extractor looking into the collector, see Figure 4. An open end ensures that the ion beam aberrations are kept small.

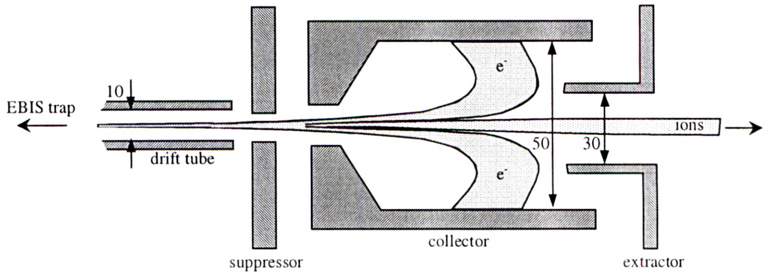

Figure 4. *Schematic drawing of the electron collector. Note the open collector end and the large extractor diameter. (Not to scale. Typical dimensions and beams shapes indicated.)*

Given that the collector is bakeable, and the design has an open end, a good vacuum inside the collector is obtained. No extra bucking or transverse magnet correcting coils are foreseen, however, the collector is surrounded by an iron cylinder to decrease the magnetic field inside the collector region, and thereby improve the electron beam expansion and absorption.

5. Beam properties

The transverse emittance at an extraction voltage of 10 kV is estimated to <110 π mm mrad [5]. The extracted beam has a finite energy spread caused by: finite injection energy; ion heating due to elastic electron-ion collisions; ion heating due to ionisation at different radii (i.e. different electrostatic potentials); trap potential decrease during the extraction phase due a fall in electron beam compensation as the trap is emptied (see sec. 3.3). The first contribution is negligible compared to the ion heating, which should be limited to 20 eV/Q (⇔ 5 eV/u). Simulations show that the third contribution could be kept below 50 eV/Q (⇔ 13 eV/u). [5]. By balancing the trap potential decrease during the extraction phase, also the last contribution to the energy spread can be considerably diminished. The exact total energy spread is difficult to estimate, but it should be <100 eV/Q (⇔ 25 eV/u). with a correctly applied balancing voltage. The design assumes very high extraction efficiency, which should be obtainable with beam emittance matching and if no aberration are introduced [5]. The existing LEBT system between the ECR4 and the RFQ is believed to have a transport efficiency of nearly 100% for a 120 eμA lead beam on which a ~3 mA oxygen beam is superimposed all the way to the analysing magnets [17]. Thus, the extraction of $1.5 \cdot 10^9$ 54^+ lead ions within 100 μs, corresponding to 130 eμA, should also result in a very high transport efficiency. The recombination due to charge-exchanges during the time of transport is negligible with a LEBT residual gas pressure of 10^{-9} mbar, which is necessary to reach the intended good vacuum inside the EBIS.

6. Conclusions

This proposal has shown that it is possible to design an EBIS that meets the LHC specifications for lead ion production without having to develop and exploit a high current and high energy EBIS. Instead, an alternative route can be taken which makes use of an electron beam with relatively low current and energy, and utilises the effect of boosted charge state.

The main advantage of the LHCEBIS compared to a high current EBIS is that its function is founded on performances not far away from those already obtained in existing EBISs. By avoiding an electron beam with high current and energy, several of the unexplored, but probable, difficulties associated therewith are circumvented. Compared to a high performance ECR ion source, the LHCEBIS will provide a faster ion expulsion from the source, and the need for the first stripper foil is avoided. In addition, the need for tuning when changing between different elements is minimal for an EBIS compared to an ECR ion source.

Nevertheless, the LHCEBIS design has a few uncertainties. The electron beam has a quite high perveance that can make it difficult to propagate through the drift tubes. Besides, the need for cooling ions reduces the effective negative space charge that can be used to confine the lead ions. The main limitation is probably the radiative recombination, which may be high and in that case broaden the charge state distribution. To determine the effect of the latter, measurements of the radiative recombination rate should be carried out, as well as an experimental investigation of the ionisation cross-sections for lead for the higher charge states. The REXEBIS twin source at the Manne Siegbahn Laboratory in Stockholm could serve as a possible set-up for the preliminary tests.

If the efficiency should turn out to be worse than predicted, the electron current has to be increased or a longer trap utilised. It is however difficult to increase the electron current much higher than 2 A for a 5 keV electron energy due to the perveance limit, and the practical upper trap length is around 2 m (set by superconducting solenoid limitations). If a shorter breeding time is requested, either the current density extracted from the cathode or the magnetic compression has to be increased.

Without having performed a detailed price study, the LHCEBIS including injection sources would have an estimated price of 500 000 CHF (based on price figures from the REXEBIS).

Electron voltage (gun)	10 keV
(trap)	5 keV
Electron current	1.5 A
Electron current density	>400 A/cm^2
Extracted ion energy spread	<25 eV/u
Trap length	1.5 m
Full magnetic field	3 T
Total charge capacity	$3.3\cdot10^{11}$ elementary charges
Yield Pb^{54+}	$1.5\cdot10^{9}$ ions
Transverse emittance at 10 kV extraction voltage	<100 π mm mrad

Table 2. *Design parameters for the proposed EBIS for the LHC lead ion preinjector.*

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