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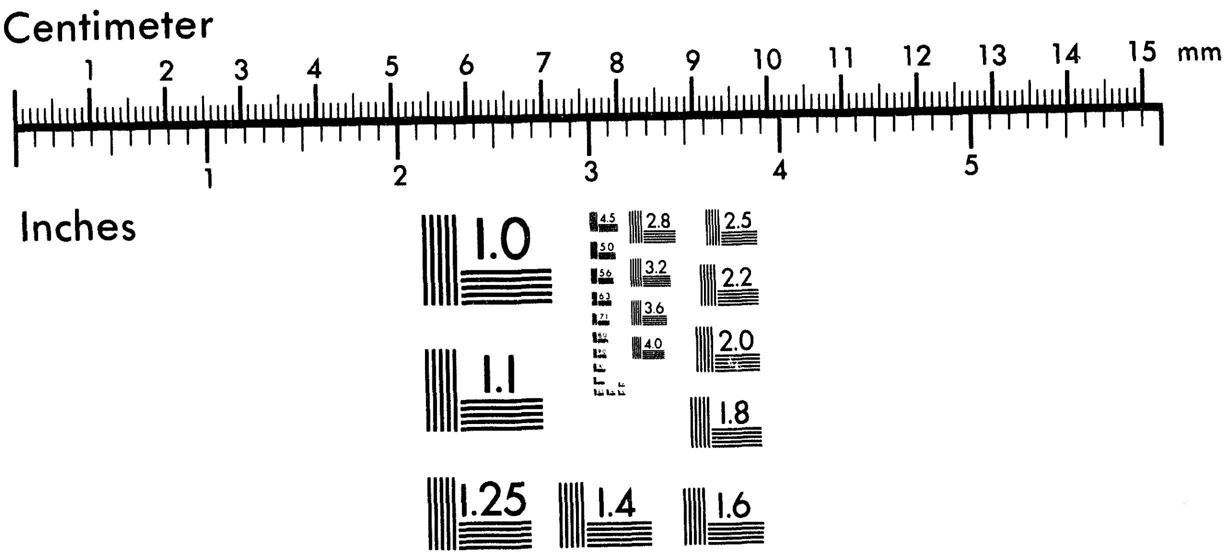

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Possible Application of an EBIS in Preinjectors for Large Heavy Ion Colliders*

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Abstract

High energy, heavy ion nuclear physics has so far been limited to experiments with a fixed target. Presently there are two projects that would greatly extend the available collision energy: the Relativistic Heavy Ion Collider (RHIC) under construction at Brookhaven National Laboratory (BNL), and the Large Hadron Collider (LHC) planned at CERN. While RHIC was from the very beginning designed for collisions of all heavy ions up to gold, LHC was initially considered as a p-p and, perhaps eventually, an e-p collider, with the heavy ion option added at a later stage; this option is now included in the planning right from the beginning. The present RHIC scenario for acceleration of gold ions starts with the BNL Tandem injecting Au^{14+} ions into the Booster; after acceleration ions are stripped to a charge state of 77+, injected into the AGS, stripped again to 79+ and injected into RHIC, with three bunches per cycle. The LHC scenario for acceleration of lead ions will use as the injector the

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CERN Heavy Ion Facility: production of ions in a charge state around 27+ in an ECR ion source, followed by an RFQ/linac combination, stripping to Pb^{53+} at 4.2 MeV/u, acceleration in the PSB and PS, stripping to the state 82+, and acceleration in the SPS. There would be 144 bunches injected into the LHC per SPS cycle. However, the resulting luminosity would be rather low and several accumulating schemes are being considered as well. In this paper we are considering a next-generation EBIS device as a possible substitution for ion sources in the preinjector stages of the two colliders with the objective of achieving an improved performance.

1. Introduction

The acceleration scenario in a multistage accelerator facility, such as BNLs RHIC or CERNs LHC, depends on the characteristics and performance of the first stages. At BNL, it was a fortunate situation that a Tandem Van de Graaff existed on site and that the RHIC design could be matched to the Tandem performance. The original scenario for acceleration of gold ions envisaged a stripping of the Tandem beam to a charge state 33+ before injection into the Booster and capture into one bunch per cycle [1]; a second stripper would produce fully stripped ions for injection into the AGS. This scenario was revised when it was realized that helium-like heavy ions could also be accelerated in the AGS, with the result that there was no need for stripping after the Tandem [2]. In this scenario (Fig.1A), gold ions in the charge state 14+ will be directly injected into the Booster, with the first stripper producing Au^{77+} for injection into the AGS and with the second one for a full stripping in the RHIC injection line. Because of a much higher stripping efficiency in the latter case, an overall intensity gain of 3 is expected, allowing formation of three bunches per cycle and requiring only 19 AGS cycles to fill one RHIC ring with 57 bunches; RHIC filling time will be shortened by the same factor of 3. The expected performance of the Tandem and the rest of the system should be sufficient to reach the design value of the luminosity of 2×10^{26} $cm^{-2}s^{-1}$.

CERNs facility for acceleration of lead ions in the SPS [3,4] is being commissioned right now, but even before it was approved, it was investigated [5] how it could be upgraded for future use by the LHC [6]. In the present scenario (Fig.2A) lead ions are produced in an ECR source, operating in the "after-glow" mode, accelerated in an RFQ and an IH linac to an energy of 4.2 MeV/u and stripped to the charge state 53+. Four PS Booster rings will be filled with one source pulse. For the LHC, 4 x 4 bunches (using two different rf systems in the Booster) would be transferred into the PS ring. The bunches will be further accelerated with h = 16, and after a full stripping injected into the SPS. Then 9 PS pulses could be accumulated in the SPS and accelerated to the full energy for injection into the LHC. Four SPS cycles would be required to fill each ring with 560 bunches in 660 available buckets [7]. Assuming the present performance of the ECR source (80 μA of Pb^{27+}), this scenario would result in a luminosity of 2.5×10^{24} $cm^{-2}s^{-1}$ which is way below the desired and possible range of about 10^{27}. In several studies different parameters were varied, the favored scenario still using a bunch spacing of 135 ns in the LHC. To reach the minimum of 25 ns, with the corresponding increase in luminosity, seems at the moment very difficult. Several schemes have been considered to increase the luminosity through an increase in the number of ions per bunch to the maximum which is feasible. This value is

3.6×10^{24} $cm^{-2}s^{-1}$ per bunch imposing a luminosity half-life (limited by nuclear effects) of 10 hours and assuming the same transverse physical emittances as for proton operation [8]. An obvious solution is to try to increase the yield of the ECR source by more than an order of magnitude; it may be possible to achieve a substantial improvement by introducing some new approaches in the source design (superconducting magnets, higher radio frequency and/or power), but this is not certain. The most promising, or perhaps most "conventional" scheme seems to be ion stacking and cooling in the LEAR ring [9]. The sequence would be as follows: The linac is running at 10 Hz and LEAR takes 20 linac ion pulses of Pb^{53+} with multiturn injection during 60 μs. The accumulated beam is then cooled during 0.1 s, using electron cooling, until a new linac pulse can be accepted. After 20 such cycles the beam is captured and accelerated, at h = 4, to 14.8 MeV/u and transferred to the PS. After some rf manipulation necessary to achieve a correct bunch spacing, four bunches are accelerated to 3.1 GeV/u. The SPS receives four bunches with 1.6×10^8 particles per bunch. Full stripping is achieved in the transfer channel to the SPS. Thirty-two such batches are successively transferred into the SPS and stored until acceleration using a fixed frequency rf system. Three of such SPS batches and a fourth one containing only 28 PS batches are fed to the LHC. Due to different kicker rise times only 496 of the maximum possible 660 buckets can be filled. The luminosity with this scheme would be about 2 x 10^{27} $cm^{-2}s^{-1}$, and it would take 124 PS cycles or 8 minutes to fill one ring.

Another interesting scenario is the possible use of a laser ion source that could deliver 6.4 mA of lead 25+ during a 5 μs pulse (corresponding to 8 x 10^9 lead ions), to fill one Booster ring only. With this performance, using 32 PS batches to the SPS and 4 SPS batches to the LHC one could achieve a luminosity of 1.1 x 10^{27} $cm^{-2}s^{-1}$, with again 496 bunches in the LHC and a filling time of around 3 min [7]. In this scheme no transverse cooling is needed and it is believed that also for the longitudinal phase space there would be no problems.

The reasons to consider improvements of preinjectors for the two colliders are different: while for RHIC a new source and preinjector, consisting of a combination RFQ/linac [10], would eliminate the 840 m long transfer line between the Tandem and Booster, extend the range of available ion species up to uranium, and make the operation more reliable and efficient, for LHC the main reason would be to increase the intensity so that the collider may reach the desired value of the luminosity, without sacrificing too much in the duration of the LHC filling time. In either case, there are presently no ion sources that would fully satisfy those requirements. There are three candidates for a high charge state, heavy ion source that may be developed for collider needs. They are:

Electron Cyclotron Resonance (ECR) ion source, Electron Beam Ion Source (EBIS), and a laser driven ion source. A laser ion source has already been considered at CERN and an experimental program is underway; however, we feel that the other two approaches seem to be more promising and able to deliver a broader spectrum of ion species. Of those two, ECR sources are much further in their development and applications, and there are strong programs in several laboratories to further improve their performance. On the other hand, most EBIS devices have been custom designed for atomic physics studies, where extremely high charge states, but low ion beam intensities were needed. Still, an EBIS may have several advantages: a smaller emittance, an adjustable pulse length, freedom in selecting an optimum charge state, and last but not least, scaling rules which are simpler than for ECR sources, requiring in principle a higher electron beam current only. This is the reason that we are, in this paper, considering a possible EBIS development for applications at large colliders, as an alternative to the Tandem and to the ECR source, respectively.

2. State-of-the-art of EBIS Devices

In an EBIS, multiply charged ions are produced by electron impact in a magnetically confined electron beam of proper energy. The ions are confined radially by the space charge of the electron beam and axially by potentials on trap electrodes. The duration of the ion pulse can be adjusted in a wide range and this is one of the advantages of an EBIS because the source pulse length can be matched to the injection interval into a synchrotron. The available number of ions in the desired charge state q, N(q), will be

$$N(q) = k \times k(q) \times \frac{1.05 \times 10^{13} IL}{q\sqrt{V(e)}}$$

where I(e) and V(e) are electron beam current and voltage, resp., L is the length of the trap, k is the neutralization degree and k(q) the relative charge abundance. Values for k up to and above 0.5 are routinely achieved, while the relative charge abundance for heavy ions in charge states of interest is usually between 0.1 and 0.2.

There are a number of EBIS (and its close relative, EBIT) devices in operation, but except for a few they all have been built for atomic physics studies of ions in high charge states. For such an application the source has to produce a relatively small number of ions, but in charge states that go to fully stripped xenon and helium-like uranium. There are two operating synchrotrons where an EBIS serves as the source of ions in the injector: SATURNE at Saclay, France and CRYRING in Stockholm, Sweden. Unfortunately, SATURNE will be shut down in the near future and there will be no further experiments performed either on its present EBIS, DIONÉ, or on the upgrade, RHEA. The synchrotron requirements for fixed target nuclear physics experiments (SATURNE) or for atomic physics studies (CRYRING) are modest and, with the exception of RHEA, no special efforts have been devoted to develop a device with more than an order of magnitude higher yield that would be needed for a collider. Still, for the purpose of establishing an experimental reference for scaling-up, we shall quote the most recent performance of the two sources.

DIONÉ is the only one of them where production of heavy metallic ions has been tried; however, until very recently there was no possibility to further accelerate heavy ions at SATURNE and the tests were very limited. Table I shows the source yield when running with gold ions [11]; the total amounts of positive charges extracted from the source when operated with lead and uranium were similar, but charge state distributions were not measured. The source charge state distribution shows an optimum around Au^{48+}, with a yield of about 3.5×10^7 particles in this charge state, which is about 11% of the total beam. The evaporative ion cooling was not used; it probably would make the distribution narrower and the yield higher. As this was just the first and only test with high intensity gold ions, the result is very encouraging. The peak for lead ions was around Pb^{52+} and for uranium around U^{55+}.

The Stockholm EBIS was tested mostly with argon and xenon, and neutralization degree values above 60% were observed [12]. Their experience has been that a longer confinement time, with evaporative ion cooling, leads to narrower charge state distributions, without loss of intensity. Some Stockholm results are also shown in Table I; in the test quoted there, the optimum charge state was Xe^{23+} ($q/m = 0.176$; 1.3×10^8 particles per pulse and a 20% abundance). Higher optimum charge states of xenon were achieved by extending the confinement time, e.g., Xe^{45+} was the optimum after 2 seconds and with 23% abundancy; however, only a very low electron beam current was used in that test.

Experiments with these two EBIS devices indicate, that in the explored range of parameters the yield of positive charges is proportional to the electron beam current, that the electron beam can be more than 50% neutralized and that up to 20% of the extracted beam can be in the optimum charge state.

3. Collider Requirements

3.1 RHIC

The RHIC design calls for 57 bunches injected per ring, with a filling time not longer than one minute per ring to avoid intrabeam scattering losses during the injection. The present scenario envisages acceleration of three bunches per AGS cycle, each with 10^9 particles, requiring a filling time of about 38 s per ring.

At this stage of ion source development, selection of the best charge state from an EBIS is still a free parameter (which was not the case for the Tandem beam). To select a charge state as high as possible would make the preinjector less expensive and more compact, as well as increase the output energy of the Booster and, therefore, the stripping efficiency in the AGS injection line. But, on the other hand, the yield of an EBIS is to the first approximation inversely proportional to the charge state and a compromise has to be found to satisfy these conflicting requirements. After considering these basic relationships, it seems that for the best final intensity the source should produce gold ions in a charge state around 35+ or uranium ions around 45+.

In order to reduce the parameters and size of an EBIS for RHIC, we propose to inject four EBIS pulses in a fast sequence into the AGS Booster. The pulses will have to be short enough so that each occupies a single turn; the Booster acceptance is large enough to allow for such a stacking. The overall efficiency for acceleration, one stripping stage, and transfer has been estimated to be about 25% (on the basis of Booster-AGS proton operation and measured values for stripping efficiency); this means that the source should deliver 3×10^9 gold particles per pulse in order to fill three RHIC bunches per cycle. With a confinement time of 100 ms, the total injection time into the Booster would be 300 ms, for four pulses. Figure 1B shows the acceleration scheme based on an EBIS.

3.2 LHC Requirements

Although the present LHC scheme calls for an initial lead beam in a charge state near 27+ to be accelerated in the RFQ/linac combination, this is not necessarily the best choice if an EBIS is considered as the ion source. It is true that the output beam intensity will be reduced if a higher charge state is selected, but the gain (about a factor of 6) by avoiding the need for the first stripper may more than outweigh any loss. Therefore, we should start our consideration assuming a beam of Pb^{53+} obtained directly from the source. The overall acceleration efficiency between the ion source and the LHC collider becomes now close to 20% because the first stripper has been eliminated and a short source pulse will make single turn injection into the PSB possible.

In order to reach a luminosity of 10^{27} $cm^{-2}s^{-1}$, and accepting that the LHC rings would be filled with 496 bunches each, they should contain 6.2×10^{7} particles per bunch [5] (typically 8.9×10^{26} $cm^{-2}s^{-1}$ for a bunch distance of 135 ns and one experiment). By using the concept as described above (for the laser ion source), an EBIS should deliver

$$N(53+) = \frac{4\times 6.2\times 10^{7}}{0.2} = 1.24\times 10^{9} ppp$$

which may well be a realistic assumption for scaling-up of present EBIS devices. The source considered for RHIC, that should deliver 3 x 10^9 gold ions in the charge state 35+ (which corresponds to 2 x 10^9 Pb^{53+} ions) and which probably represents the present technological limit of EBIS devices, would achieve the required luminosity with a certain safety margin. Fig.2B shows the LHC acceleration scheme using an EBIS in the preinjector.

4. A Possible Design of an EBIS for Large Colliders

From considerations so far it became clear that the yield of existing EBIS devices is not satisfactory for use on a large hadron collider. In order to reach yields of several times 10^9 heavy particles per pulse in the desired charge state it will be necessary not only to increase the electron beam current by a good order of magnitude, but optimize other parameters as well. At present there is still not enough information available to proceed to the design of the final EBIS for a collider and it is therefore preferable to first study an intermediate device. There was a program at Saclay [13] to develop RHEA, an EBIS with an electron beam current of 5 A, that could have been within a factor of 2 to 3 from the source needed for our purpose, but unfortunately this project was terminated with the demise of SATURNE. About a year ago a program was initiated at BNL, to study an EBIS with an electron beam current of 1-2 A, as a feasibility test for an upgrade to the size needed for RHIC [14]. However, even before we have the results from this test, we can establish several guidelines for the final design and determine its tentative parameters.

Assuming now that this source has to deliver about 3 x 10^9 gold ions in the charge state 35+ or about 2 x 10^9 lead ions in the charge state 53+, in either case the corresponding number of positive charges is about 1.05 x 10^{11}. With evaporative ion cooling one can expect that the output beam will have about 20% in this charge state, so that the total number of positive charges extracted would be 5.25 x 10^{11}. This is by a factor of about 25 higher than the best result achieved so far on DIONÉ; most of this increase will have to be achieved by increasing the electron beam current. Neutralization efficiencies above 50% have been achieved, which means that the capacity of the trap should be at least 1.1 x 10^{12}. This value can in principle be achieved with many combinations of source parameters, but there are some practical limits. First, we feel that the length of the trap should not be more than L = 1.5 m (this is 50% longer than the trap on DIONÉ). The electron beam current is one of the most important parameters to determine the capacity of the trap; we have selected a value of I(e) = 10 A as a realistic limit. The electron gun voltage of 20 kV is needed to reach a perveance value of 3.5 x 10^{-6} $AV^{-3/2}$, which is high but achievable. Such a voltage is not needed to reach required charge states of gold and lead ions so that the electrons may be decelerated to a lower value in the trap itself, raising with this the trap capacity as well. The drop in potential between the trap wall and the axis of the beam will depend on the ratio of the radius of trap electrodes to the beam radius; it could range from 2 to 5 kV, without space charge neutralization. The resulting design would have a capacity well above the required value, leaving a margin for the estimated value of 20% in the optimum charge state.

The next parameter to be estimated is the necessary electron beam current density. If we use values of the product of the electron beam current density J and confinement time τ, calculated by Donets [15], we get an estimate for J. τ of about 20 As/cm^2 for gold ions in the state 35+ and about 100 As/cm^2 for lead in the state 53+. The latter case is more demanding, but on DIONÉ [11] similar charge states have been achieved after a confinement time of 160 ms, which means that a current density of 500 A/cm^2 should be sufficient. Table II shows parameters of this EBIS.

5. Conclusions

It has been shown that an EBIS source is an interesting possibility to achieve the intensities as required for heavy ion colliders. Although a substantial development effort will be needed, especially in raising the electron beam current by an order of magnitude, the outcome looks feasible and promising.

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Table I

Au[a]	CHARGE STATE	41	42	43	44	45	46	47	48	49	50	51	52	53	54
[5]	YIELD, $x10^7$ppp	1.3	1.4	1.7	2.3	3.3	3.3	3.5	3.5	3.3	2.7	2.5	1.7	1.0	0.4
	%	3.6	3.9	4.8	6.6	9.4	9.7	10.9	10.8	10.8	9	8.3	5.9	3.3	1.5
Xe[b]	CHARGE STATE	20	21	22	23	24	25	26							
[6]	YIELD, $x10^7$	5.3	7.3	10.4	13.3	12.7	8.5	3.5							
	%	7	10	15	20	19	14	6							

a TOTAL POSITIVE CHARGE: $1.5x10^{10}$; CONFINEMENT TIME: 0.16 s

b TOTAL POSITIVE CHARGE: $1.5x10^{10}$; CONFINEMENT TIME: 0.04 s

Table II

Electron beam current	10 A
Electron beam voltage	20 kV
Length	1.5 m
Trap capacity	1.1×10^{12}
Yield, positive charges	5.25×10^{11}
Yield, Au^{35+}, design value	3×10^{9}
Yield, Pb^{53+}, design value	2×10^{9}

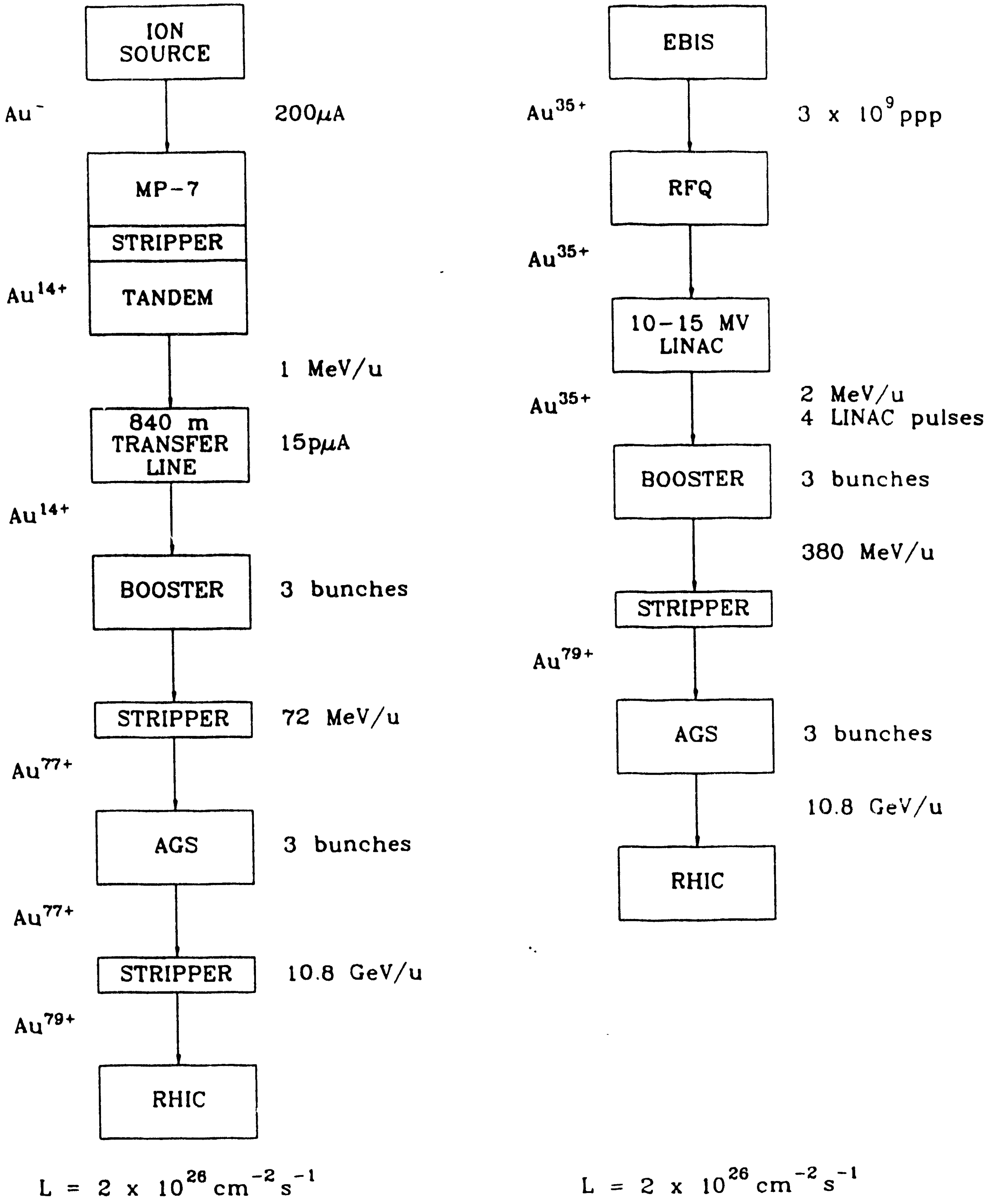
Figure Captions

Fig. 1 Block diagram of the RHIC facility at BNL.

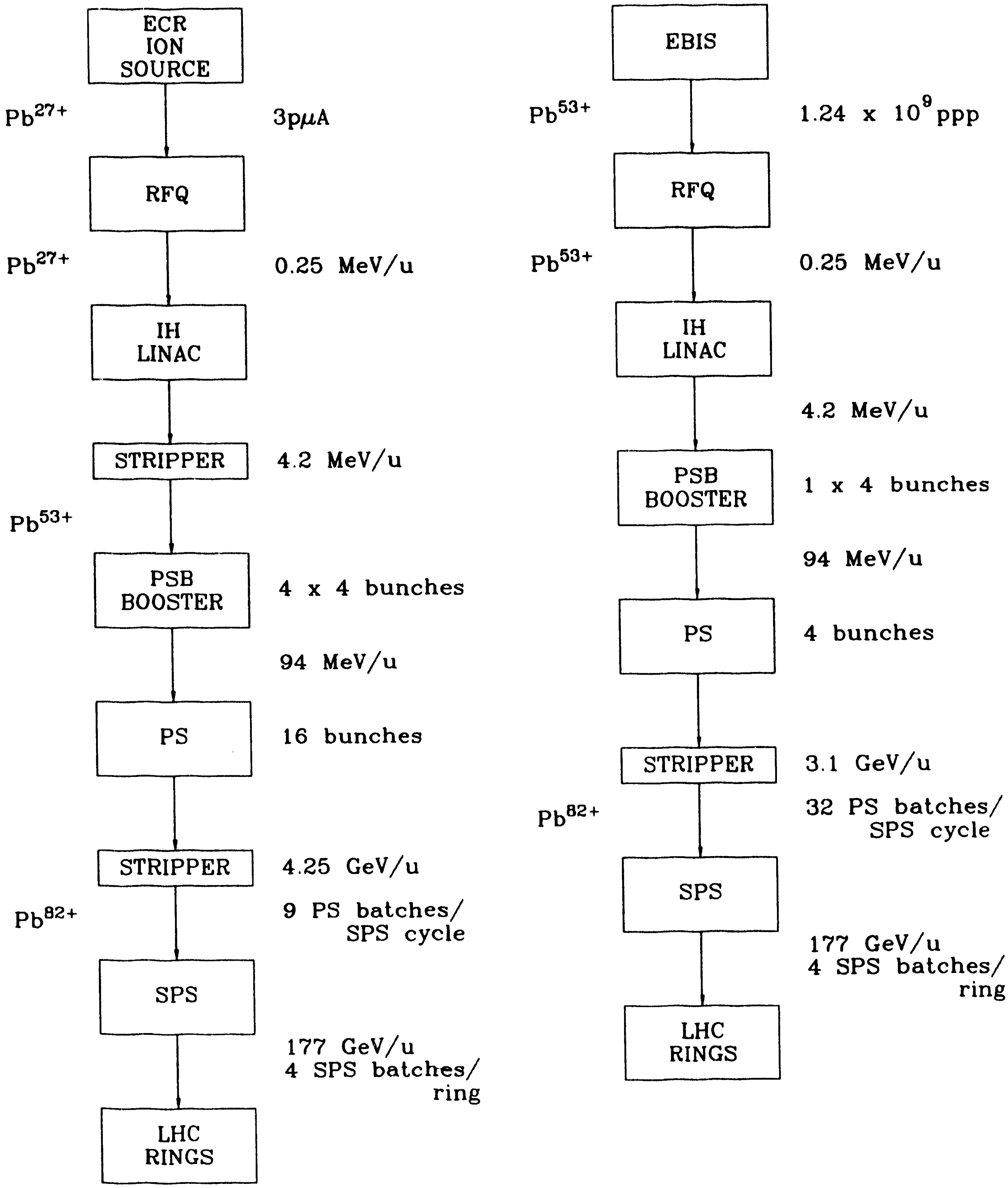
A - present scenario; B - scenario with an EBIS in the preinjector.

Fig. 2 Block diagram of the heavy ion facility at CERN.

A - present scenario; B - scenario with an EBIS in the preinjector.


ION SOURCE
Au⁻
200μA
MP-7
STRIPPER
Au14+
TANDEM
1 MeV/u
840 m TRANSFER LINE
15pμA
Au14+
BOOSTER
3 bunches
STRIPPER
72 MeV/u
Au77+
AGS
3 bunches
Au77+
STRIPPER
10.8 GeV/u
Au79+
RHIC
L = 2 x 10^26 cm^-2 s^-1
EBIS
Au35+
3 x 10^9 ppp
RFQ
Au35+
10-15 MV LINAC
Au35+
2 MeV/u
4 LINAC pulses
BOOSTER
3 bunches
380 MeV/u
STRIPPER
Au79+
AGS
3 bunches
10.8 GeV/u
RHIC
L = 2 x 10^26 cm^-2 s^-1

(A) (B)



$L = 2.5 \times 10^{24}\ cm^{-2}\ s^{-1}$

(A)

$L = 1 \times 10^{27}\ cm^{-2}\ s^{-1}$

(B)

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