EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN - PS DIVISION

CERN/PS 99-042 (BD)

THE PRODUCTION OF DENSE LEAD-ION BEAMS FOR THE CERN LHC

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To reach the design luminosity for lead-ions in the LHC, the present Low Energy Antiproton Ring (LEAR) has to be converted into a Low Energy Ion Ring (LEIR). Since the present ECR lead-ion source does not provide sufficient intensity, the main goal of LEIR is to act as a low-energy (4.2 MeV/u) accumulator where the ion beam is stacked and cooled (with the help of an electron-cooler) to reach the required intensity and emittances. An experimental program has been carried out at LEAR in recent years in order to test the cooling and stacking process with the present electron-cooler. A variety of results have been reported at previous conferences. This paper will focus on the electron cooling aspects resulting from the afore mentioned experiments. Taking into account the experience gained, some guidelines will be given concerning the future LEIR machine and the electron cooling device(s) that will be needed to produce cold dense electron beams.

Invited paper presented at ECOOL99, Uppsala (Sweden), May 19th-22nd, 1999
To be published in Nuclear Instruments and Methods in Physics Research, Sect. A

Geneva, Switzerland
1 June 1999

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Abstract

To reach the design luminosity for lead-ions in the LHC, the present Low Energy Antiproton Ring (LEAR) has to be converted into a Low Energy Ion Ring (LEIR). Since the present ECR lead-ion source does not provide sufficient intensity, the main goal of LEIR is to act as a low-energy (4.2MeV/u) accumulator where the ion beam is stacked and cooled (with the help of an electron-cooler) to reach the required intensity and emittances. An experimental program has been carried out at LEAR in recent years in order to test the cooling and stacking process with the present electron-cooler. A variety of results have been reported at previous conferences. This paper will focus on the electron cooling aspects resulting from the afore mentioned experiments. Taking into account the experience gained, some guidelines will be given concerning the future LEIR machine and the electron cooling device(s) that will be needed to produce cold dense electron beams.

PACS Numbers: 29.20Dh, 29, 27 Ac.

1. Introduction

To reach the design luminosity for the lead experiments in LHC the required number of ions is 10^8/ bunch at 2.7 TeV/nucleon. The present lead-ion injection complex (Fig.1), comprising the ECR source, the RFQ and the LINAC with stripper (from Pb^{27+} to Pb^{54+}) is able to produce 25 µAe (≅ $3.2 \cdot 10^6$ ions/µs) $Pb54^+$ ions at a repetition rate of 10 Hz. This is not sufficient to fulfil the desired luminosity for the lead ions in LHC [1]. A gain of the order of 150 has to be found by some means. It has been proposed therefore to transform the LEAR machine into a low energy accumulator ring to increase the number of ions per bunch [2]. The final goal is to accumulate 1.2 10^9 ions per cycle, of 3.6 s duration, at 4.2 MeV/nucleon. After having accumulated and cooled the beam down to the requested emittances the ion beam is bunched, accelerated to 14.8 MeV/nucleon and transferred to the PS. The beam is accelerated in the PS and fully stripped prior to transfer to the SPS.

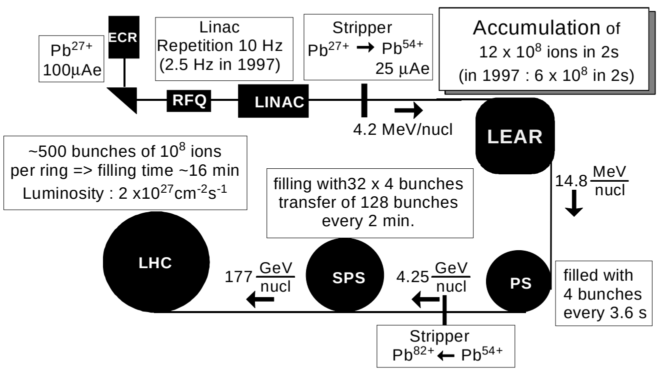

Fig. 1: The lead-ion injection scheme for LHC

Within this framework some modifications and tests have been carried out on LEAR in order to check the feasibility of such a storage ring. The results obtained, which have been the subject of many publications [Ref.3, including an exhaustive reference list] will be summarised hereafter as an introduction to the future LEIR machine that is intended to increase the number of stacked ions by a factor 10.

2. Main issues from recent LEAR experiments

In order to check the feasibility of the future LEIR machine, experiments have been carried out using LEAR. Within this context some changes and improvements have been made on the injector and on the LEAR ring itself. The physical changes are illustrated in Figure 2.

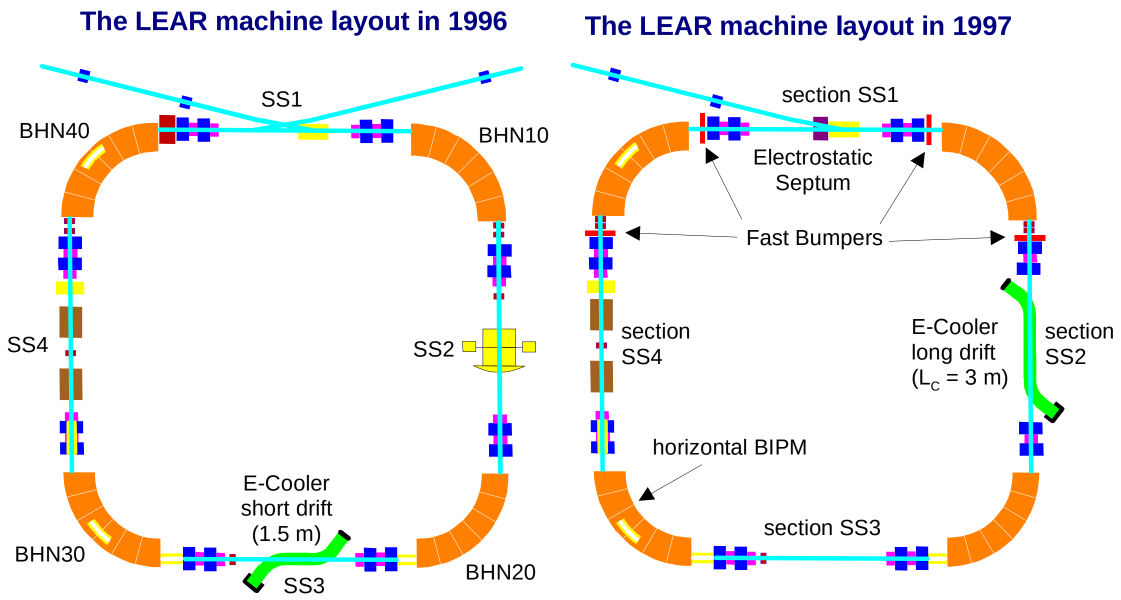

Fig. 2 : Old configuration of LEAR and modifications reported for these experiments. A thin septum and four fast bumper magnets have been installed to test multiturn injection. The electron cooling has been moved to straight section 2 to have different Twiss functions in the cooling and the injection section whilst keeping the symmetry of two in the lattice.

First the electrostatic septum was moved and fast bumpers installed for testing multiturn injection in the following way: the injected ion energy is increased by about 4.10^{-3} while the bumper currents are decreased, within 200 µs, so as to keep the injected orbit constant (Fig.3). This procedure (involving longitudinal and transverse injection) should allow a 35-turn injection with a final 50π transverse emittance and 4.10^{-3} momentum spread. The repetition frequency in the experiments is 2.5 Hz instead of the foreseen 10 Hz.

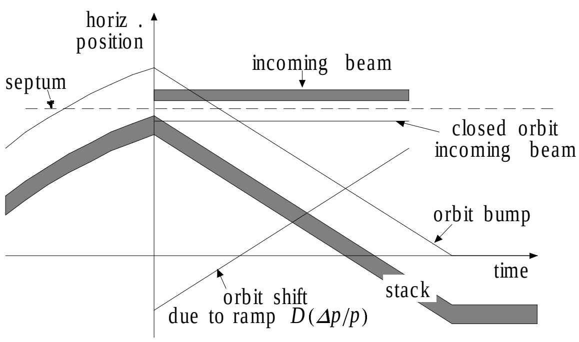

Fig. 3 : Principle of multiturn injection with combined stacking in transverse and longitudinal phase spaces.

The LEAR electron-cooler has been displaced and lengthened from 1.5 to 3m (Fig. 2) and its energy made variable, over a small dynamic range, by superimposing a sawtooth voltage on the high voltage generator. It is thus possible to drag, and cool, the injected batch from its initial energy to the stack energy. The electron current intensity is adjustable from 50 to 300 mA (above 400 mA the e-beam exhibits instabilities).

Figure 4 shows an example of the longitudinal distribution, versus time, obtained from a Schottky pickup. From Figure 4 it appears that, while the beam is cooled the longitudinal cooling force is strong enough to move the stacked ion beam away from its nominal energy in correlation with the sawtooth generator.

It was possible to modify, in some parts of LEAR and in a rather flexible way, the machine lattice parameters, namely, the betatron amplitude β_h and the dispersion *D*. The corresponding experiments and results have been reported in several papers, one of which is presented at this workshop [4]. The measurements show a dependence of the transverse cooling time on the beta function and also, owing to the space charge effects, on the dispersion at the level of the cooler.

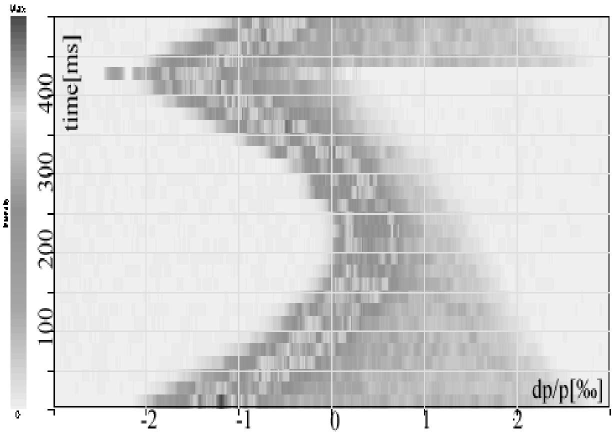

Fig.4:Longitudinal cooling using the dragging method. The picture represents successive longitudinal Schottky spectra taken every 16 ms and seen from the top. The darker, the denser the beam is. Immediately after injection (bottom), in presence of the stack, the electron beam energy is suddenly changed and then after 150 ms, slowly decreased to the stack energy. The injected beam is cooled to the stack but, in the meantime, the stack has been dragged by the electrons. Finally the whole beam is decelerated to the stack energy leaving space for a new injection (top) .

Lead-ion lifetime measurements have been made. Lifetime depends on the recombination of the incompletely stripped ions with a) the residual gas molecules in which density is proportional to the partial pressures and b) the cooler electrons in which density is proportional to the current intensity. Experiments show that Pb^{53+} have a very short lifetime and should be avoided. This is the reason why Pb^{54+} is the candidate retained for the future. Figure 5 represents the recombination effects (obtained with Pb^{54+}). It appears that the overall lifetime is of the order of 6 seconds so that the total stacked intensity saturates at about $6{\cdot}10^8$ ions. A reduction of the residual gas pressure is therefore mandatory.

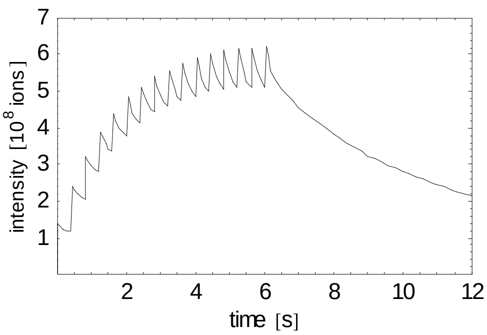

Fig. 5 : Accumulation of lead ions for 16 injections. The increased losses after each injection are clearly visible.

Concerning the recombination with the electron beam, increasing the current intensity decreases the lifetime. The problem is however more complex since some resonant (or di-electronic) recombination processes do occur depending on the relative velocities between the cooled ions and the electrons.

3. Proposals for the LEIR machine

As seen in Figure 5, a factor of 2 is missing in intensity and a second factor of 2 in the stacking speed in order to satisfy the LHC. This is due to the fact that the ion lifetime is too short. One way to overcome this problem is to increase the cooling forces, and therefore the cooler intensity, so as to cool faster, however this would result in decreasing the ion lifetime.

The main goal is therefore to increase the number of injected and stacked ions. There are several possibilities that could provide an increase of the stacked intensity, most of them presently under investigation.

Firstly, it would be useful to increase the ion production. Next it is essential to focus our efforts on the multiturn efficiency, since electron cooling does not depend, to the first order, on the number of circulating ions. Within this framework, a possible improvement could be based on the use of a corner- or inclined septum. Also multiturn injection associated with fast cooling must be made at a rate of 10 Hz instead of the present 2.5 Hz.

Residual gas pressure should be reduced to decrease the recombination rate and therefore increase the final stacked intensity. A reduction by a factor 3 to 5 would be welcome. The methods to obtain such an improvement are beyond the scope of this paper.

On the electron-cooling side, studies are underway and are summarised hereafter.

3.1 Increasing ion production

At the level of the ECR source, one might expect to gain a factor 3, maybe 5, in the number of ions produced, with hopefully no final emittance increase.

In order to avoid the losses inherent to a septum, the stripping foil (designed for charge exchange from Pb^{27+} to Pb^{54+}) could be put at the machine entrance and made “corner” shaped (Fig.6). This would imply moving the LINAC nearer to LEIR, since the present transfer line does not allow the transport of Pb^{27+}. The former LEAR multi-turn transverse and longitudinal injection simulations (Fig.6) show that 85% of the produced Pb^{54+} are collected. This is a factor 2 better than resulted from the previously mentioned technique and is comparable to the injection with an inclined septum (see 3.2). More studies are underway, but attention must be paid to the local vacuum degradation, since the other species, produced by the foil, are lost in the vicinity of the injection point.

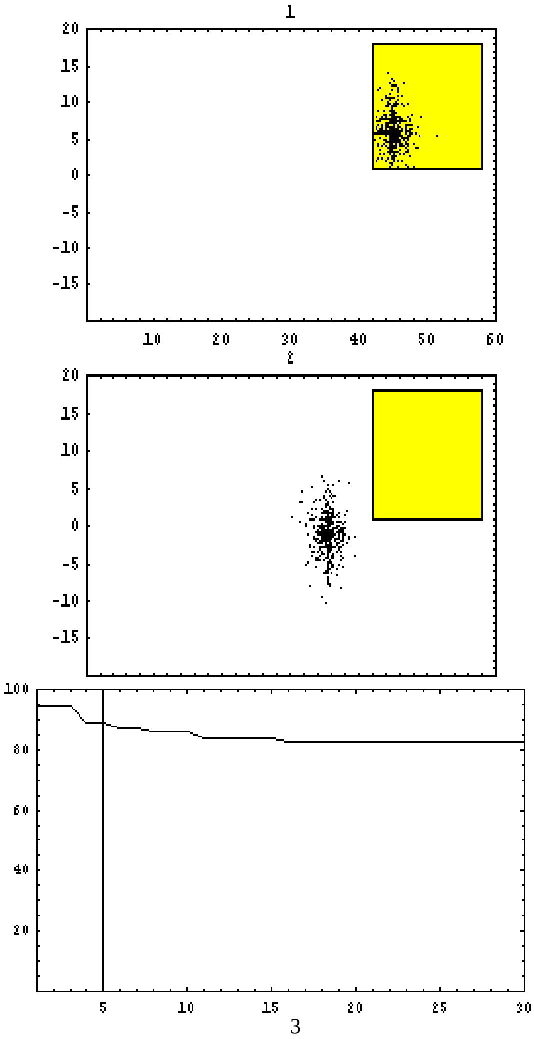

Fig 6: Simulation of the stripping foil placed at the LEIR entrance.

1) Particles passing the foil at t = 0s.
2) Particles after 1 turn. The orbit is moved horizontally by 0,4 mm/turn and momentum increased by $\Delta p / p = 10^{-4}$ per turn
3) Efficiency (vertical axis) versus the number of turns (horizontal axis)

When passing through the stripping foil, the particles will produce 16% of the required ion state, Pb^{54+} for example. It would be worth foreseeing a way to make the other particles of different charge levels recirculate through the foil until all of them are stripped to the same state. Such a specialised machine (or recycler, built around the ring or some other new idea), giving thus a large theoretical gain in ion production, is being studied.

3.2 Improvement of the multiturn injection

A multiturn injection scheme combining stacking in horizontal momentum space [2] was used for the experiments in 1997. With a normalised dispersion (i.e. the dispersion divided by the square root of the betatron function) of about $5m^{1/2}$ and a momentum ramp reduced to $4\cdot10^{-3}$, due to acceptance limitations, a linac pulse could be injected over 70 revolutions with an efficiency of about 40%. When improving the injection efficiency, care has to be taken not to increase the cooling times. Indeed, injection into larger horizontal acceptances would increase the injection efficiency but not necessarily the stacking rate due to the increase of the cooling time. The aim is therefore to increase the injection efficiency without changing the acceptances. Two ways for improvement are considered :

- Optimisation of the normalised dispersion. During the accumulation experiments in LEAR, a lattice with increased dispersion was set up and the increase of the injection efficiency was confirmed by simulations and experiments. However no exhaustive study to optimise dispersion for combined multiturn injection, in conjunction with electron cooling, was done.
- Stacking also in the vertical phase space. This can be achieved with an inclined electrostatic septum [5,6](Fig.7) which can be constructed without major mechanical problems.

For a fair comparison, the pulse length which can be injected with a given efficiency, should be considered. The injection of a linac beam of emittance 50π mm mrad (2σ) and intrinsic momentum spread $0.2\ 10^{-3}$ into acceptances $A = 50\pi$ mm mrad with a momentum ramp of $6\ 10^{-3}$ is optimised. The following number of turns could be injected with an efficiency of about 50% :

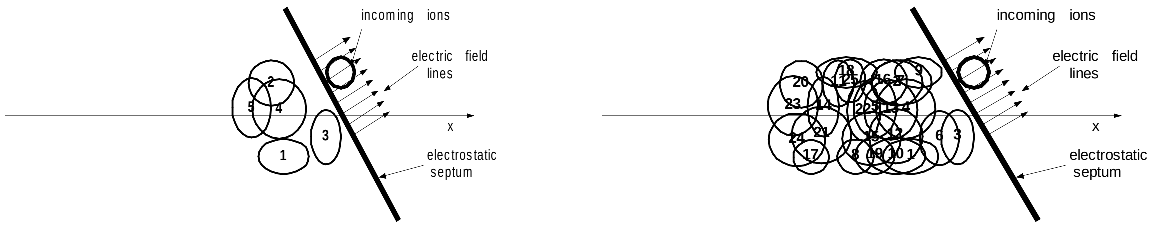

Fig. 7 : Combined stacking in horizontal and vertical phase space and in momentum using an inclined septum

- Stacking in horizontal phase space and in momentum. About 75 turns can be injected with an optimised normalised dispersion of about 10 $m^{1/2}$. Only a small improvement can be expected by further optimisation of the dispersion.
- Stacking into all three phase planes. In simulations, more than 150 turns could be injected with an efficiency of 50%. The normalised dispersion is about 7 $m^{1/2}$. However, as the vertical phase space is also exploited for stacking, the injected ions have large oscillation amplitudes in both transverse phase spaces. Thus one would expect an increase in the cooling times.
- Stacking into all three phase planes with correlated acceptances. To avoid that the ions are injected with simultaneously large betatron oscillation amplitudes in both transverse phase spaces, the sum of the emittances is limited to a value of 50π mm mrad. According to simulations, 120 turns can be injected with an efficiency of 50% again with a normalised dispersion of about 7 $m^{1/2}$.

3.3 Electron-Cooling

One could foresee the use of two coolers, named hereafter Cooler1 and Cooler2, operating each at low energy (≅ 3 keV). The principle is described by Figure 8a for $D = 0$.

- Cooler 1 is supposed to use a large perveance gun, of the order of 3 μ-Perv. Its active length will be about 3 m. With an electron current of the order of 0.5A the cooler is expected to cool the ion beam transversely from 40π to 4π in less than 100 ms. Large magnetic solenoidal fields (B>0.1T) are foreseen so as to operate with magnetised electrons. The cooler's, high voltage, and therefore electron energy, will be ramped, so as to drag the injected batch from its injection energy to the stack energy. Electron beam expansion and/or compression will be investigated mainly in view to change the e-beam diameter. As for the present cooler, neutralisation electrodes will be installed, but their use will depend on their effects on the cooled ion beam lifetime, since the stored ions together with the high intensity electron beam would decrease the Pb^{54+} lifetime.
- Cooler 2 is expected to use a lower perveance gun (≅0.6 – 1μPerv). It is intended to maintain the stack cooled, above all transversely. It will operate at fixed energy. Due to Cooler1, the dragging process, induced by the sawtooth voltage generator (see Fig. 4 and 8), will of course, despite Cooler2, change the stacked beam energy with time. If not too large, this effect is welcome since it is expected to reduce the recombination rate of the ions with the cooler electron beam. Even a gain by a factor two in lifetime, and therefore of the stacked intensity, is welcome. At the end of the stacking process, Cooler1 will stay for about 200 ms at the same energy as Cooler2 so as to obtain small emittances prior to bunching and acceleration of the ions.

An option could consist of the use, for Cooler2, of a hollow electron beam [7]. If the hole diameter is made larger than the one in the cooled stacked ion beam, no recombinations should, occur. The already mentioned effects of Cooler 1 on the stack's longitudinal velocity will be more pronounced but should again reduce the recombination rate and therefore allow an increase of the stacked intensity. Open collectors are also considered, since they could avoid the use of toroids and therefore simplify the necessary closed orbit corrections.

The process described by Fig. 8a can be refined by using the idea that, in the case of electron beams with relatively large space potentials, the cooling times are reduced when the coolers are placed at a location where the dispersion $D \neq 0$ [4]. Fig. 8b illustrates the cooling process where, for both coolers $D > 0$. As for the previous case (Fig. 8a, $D = 0$) Cooler1 energy is ramped down to that of Cooler2 (where the stack is sitting). As a consequence the Cooler1 electron beam position has to be moved in correspondence with energy since $r_o(t) = D.\Delta p(t)/p_o$. Cooler1 forces are thus kept optimal so that, with respect to the previous case, one could foresee even reducing the electron beam intensity and by consequence reducing the recombination rate.

A horizontal displacement of the e-beam can be obtained with electric or magnetic dipoles located between the gun output and the toroid entrance. Conversely one could foresee displacing the ion beam trajectory with time at the cooler level. Care must be given to unforeseen increases of the electron or ion transverse temperature.

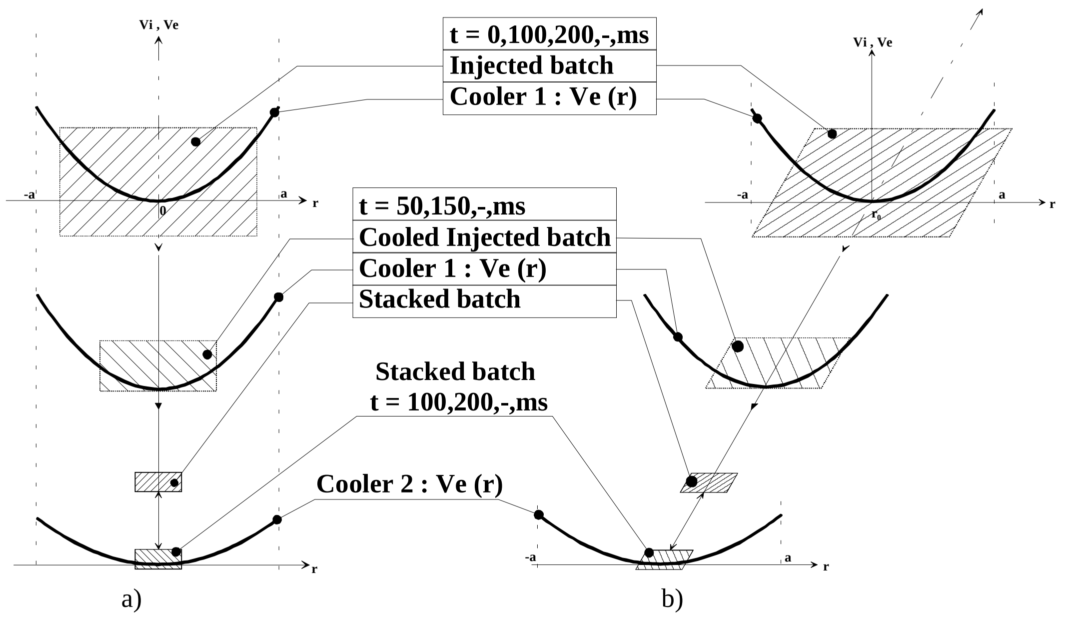

Fig. 8 : Principle of cooling and stacking techniques with 2 coolers:a) $D = 0$[m], b) $D>0$[m]. a : electron beam radius, v_i v_e : ion and electron velocities.

4. Conclusions

In view of the proposed use of Lead-ions in the LHC, some modifications have been implemented on the former LEAR machine and on the LINAC. The experimental results obtained show the necessity to increase the stacked intensity by a factor 10. However, the experiments have demonstrated the validity of some techniques and theories, so that we are now in position to propose the necessary improvements to be implemented on a dedicated LEIR machine. Within this framework, some ideas concerning mainly the ion production, injection and cooling processes, are proposed as a preliminary to more detailed studies.

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