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ELECTRON COOLING WITH NEUTRALISED ELECTRON BEAMS

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The drift velocity induced by the space charge of the dense electron beams used for electron cooling are detrimental on the cooling process as it limits the equilibrium emittances that one can obtain. At the Low Energy Antiproton Ring (LEAR), an electron beam neutralisation system has been implemented in order to reduce this effect and to obtain ultra cold anti(proton) beams. In this paper we will briefly discuss the physics of the neutralisation process and give the main characteristics of the system installed at LEAR. The preliminary results of electron beam neutralisation and electron cooling of protons with neutralised beams will be presented as well as the results of the experiments made on the linear test bench.

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The drift velocity induced by the space charge of the dense electron beams used for electron cooling are detrimental on the cooling process as it limits the equilibrium emittances that one can obtain. At the Low Energy Antiproton Ring (LEAR), an electron beam neutralisation system has been implemented in order to reduce this effect and to obtain ultra cold anti-(proton) beams. In this paper we will briefly discuss the physics of the neutralisation process and give the main characteristics of the system installed at LEAR. The preliminary results of electron beam neutralisation and electron cooling of protons with neutralised beams will be presented as well as the results of the experiments made on the linear test bench.

1. INTRODUCTION

The generation of very intense electron beams with currents of up to 2.5A at energies below 20keV [1] opens up the possibility to improve the performance of the electron cooling device for cooling and accumulation of protons and antiprotons at LEAR. The use of an intense electron beam in the future will also enable Pb^{53+} ions at an energy of 4.2 MeV/u to be rapidly cooled prior to their transfer to the LHC.

However, the electron azimuthal drift velocity induced by the space charge of the dense electron beams is essentially larger than the transverse velocity introduced by the cathode temperature and by the gun optics. It restricts the possibility of using intense electron beams effectively for electron cooling. One way to reduce this effect is the use of an electron beam neutralisation system [2].

The electron beam ionises the residual gas molecules during its passage from the cathode to the collector. The positive low energy ions of residual gas are accumulated between electrostatic traps [2,3] placed on either side of the drift space. Each trap consists of two metallic half-cylinders, separated by a conductive glass insulator (Fig. 1). Positive voltages U_{tr1}, U_{tr2} of different values up to 6 kV are applied to all the metallic cylinders. The transverse electrical field between this electrodes leads to the accumulation of ions and the drift of the secondary electrons to the conductive glass insulators. In this manner the unwanted secondary electrons are removed from the electron cooling system.

The generation of an intense neutralised electron beam is not a very simple task due to development of beam-drift coherent instabilities of the secondary ions and primary electrons. The upper current density limit [3,4,6] is given by :

$$J_{max} = \frac{v^2 B}{8Lc} \tag{1}$$

where L is the neutralised beam length, B the longitudinal magnetic field of the electron cooler, and v and c are the velocity of the electrons and light, respectively.

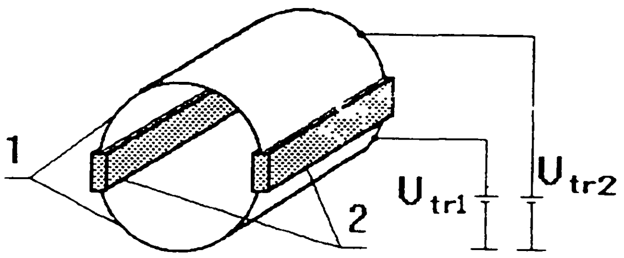

Fig. 1 - The schematics of the electrostatic trap.
1-metallic electrodes, 2-conductive glass plates.

The lower current density limit [3,4] follows from the suppression of Landau damping of the ion cloud due to the lower density. It is given by

$$J_{min} = \frac{veZB^2}{4\pi Mc^2} \tag{2}$$

where M is the ionised ion atomic mass, and eZ the ion charge.

However the dependence of J_{max} represented by formula (1) does not give a complete description of the many parameters that influence the development of the instabilities. One point of concern is the influence of the density of secondary electrons on pressure. This point will be developed in the next paragraphs.

2. TEST-BENCH MEASUREMENTS

On the linear test bench a number of experiments were performed to neutralise electron beams of 30 mm diameter, with currents up to 2 A and an energy of 12 keV. The distance between the ion traps was 2.5 m, the diameter of vacuum chamber 30 cm, and the pressure in the system between 10^{-6} + 3×10^{-9} Torr. The magnetic field was 300-400 Gauss.

The measurement of the neutralisation factor on the test bench was made with a diagnostic pencil beam [4]. The pencil beam is deflected due to the change in the radial electrical field of the electron beam which is being neutralised.

The dependence of the upper beam current limit on the accelerating voltage $U_0 \cong mv^2/2$ is shown in Fig. 2 for different values of the pressure. The upper limit on the beam current has a linear increase with accelerating voltage (see (1)) (Fig. 2) but decreases with better vacuum conditions (Fig. 3).

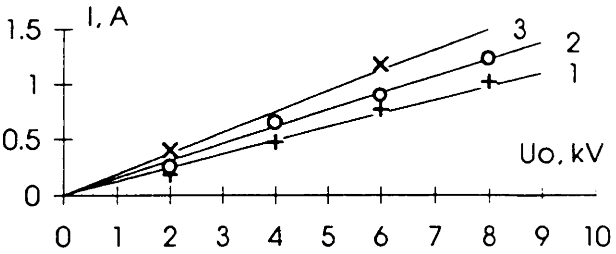

Fig. 2 - The dependence of the upper current limit on the accelerating voltage. 1) $P = 3 \times 10^{-9}$ Torr, 2) $P = 6 \div 8{\times}10^{-8}$ Torr, 3) $P = 1.5 \div 4{\times}10^{-7}$ Torr.

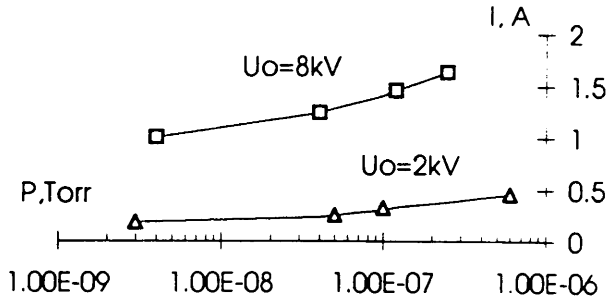

Fig. 3 - The dependence of the upper critical current limit on the pressure

The stability of the neutralised electron beam is determined by the current losses of the primary beam, $\Delta I/I$, or by the density of the secondary electrons oscillating in the electron cooling system. The secondary electrons produce feedback for the beam drift instability. For a fixed pressure the upper current limit I_{max} for stable conditions was achieved when the current losses were lower than $\Delta I/I < 4 \times 10^{-4}$. The degree of neutralisation $\eta = n_i/n_e$ was found to be equal to 0.7-0.95 (n_i: the ion density, and n_e: the density of the electron beam). The instability appears as an abrupt jump to the de-neutralised state and its repetition rate was also found to depend on the current losses. When the collector potential was positive with respect to the vacuum chamber, the upper current limit increased and the losses from the collector were reduced. In this regime, the degree of neutralisation was equal to 85-95% for beams having an energy of 6-12 keV and current losses $\Delta I/I < 4 \times 10^{-4}$. For stable conditions and energies between 2-4 keV, the degree of neutralisation was between 50-95%, depending on the beam current. The degree of neutralisation increased when the beam current decreased.

3. NEUTRALISATION OF THE ELECTRON BEAM ON LEAR

There are two ways to measure the degree of neutralisation η with or without the cooled ion beams. In experiments with cooled proton beams the revolution proton frequency was monitored from a longitudinal Schottky pick-up signal display on the spectrum analyser [2] for both neutralised and charged electron beams. The measure of the frequency difference between the two situations gives a direct measurement of the change in the electron beam space charge. The time of flight method [2-4] was used for measurements of the degree of neutralisation without cooled ion beams. In this method, the response of the electron beam to an external excitation is measured on a network analyser and the change in phase of the signal gives the degree of neutralisation. Both methods give fairly good agreement in the estimation of the neutralisation factor.

On the experiments made at LEAR, the upper limit on the current for stable regimes was found to be lower due to the ultra-high vacuum, $10^{-11} \div 5{\times}10^{-11}$ Torr, in the machine. For a fixed electron energy, the pressure is the main parameter which determines the magnitude of the upper current limit for stable regimes. Lower current limits also exist and are observed in the form of instabilities. The dependence of the upper and lower current limits on the accelerating voltage is presented in Fig. 4. The degree of neutralisation of the space charge between lower and upper limits is equal to 80-95%.

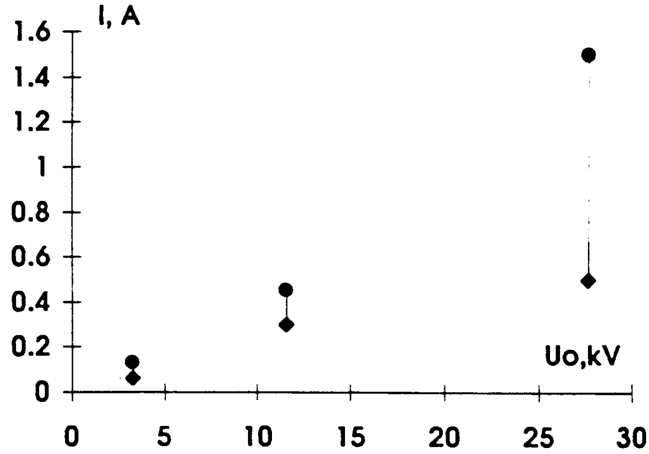

Fig. 4 - The dependence of the upper (•) and lower (♦) current limits on the accelerating voltage. $B = 600$ Gauss.

The cooling of protons with neutralised electron beam was performed at various energies and the possibility of adjusting the electron cooling parameters during the neutralisation process was also demonstrated. Due to high level of neutralis tion, the change in the beam space charge leads to an energy shift of the cooled protons. This shift is compensated for by a servo-system [2] which corrects the accelerating voltage as the beam energy changes. The vertical and horizontal emittances of the cooled proton beam were measured using the H^0 beam profile monitor [1] and were $\varepsilon_v \approx 2\pi$ mm·mrad, $\varepsilon_h \approx 4\pi$ mm·mrad.

5. DISCUSSION OF RESULTS AND FURTHER STUDIES

In the experiments both on LEAR and on the test bench, the upper current limit reduced and lower limit increased when the vacuum in the systems was improved. The upper current limit on LEAR was 3-4 times less than one would expect from Eq. (1) due to the ultra-high vacuum $10^{-11} \div 2{\times}10^{-11}$ Torr. When the pressure increased up to $4 \div 6{\times}10^{-11}$ Torr the upper limits of the stable regime were 1.5-2 times greater compared with data represented in Fig. 4 for the low energies,i.e. 3-11 keV. The value of the low limit current is determined by the mass M and charge Z of the secondary ions that compensate the space charge of the electron beam. The results of the measurements of the lower limit can be explained by formula (2) if one assumes that the average ion mass spectrum is equal to $M/Z \cong 1.2$ for an electron beam in the energy range 11-27 keV and $M/Z \cong 2$ for an electron beam with an energy of 3.3 keV.

The generation of intense neutralised electron beams is an important issue for the rapid cooling of Pb^{53+} ions in LEAR [5]. In order to obtain fast cooling times, an intense electron beam with a perveance up to 5 $\mu A/V^{3/2}$ at 2.6 keV will need to be generated. The goal of the next experiments on LEAR is to increase the upper current limit for the stable conditions. One way to solve this problem may be to obtain a regime with a minimal escape current of secondary electrons from the collector. The use of additional clearing electrodes with a transversal electrical fields $E_\perp$ is probably one of the ways of resolving this problem. The electrodes should be placed near to the collector and must completely eliminate the secondary electrons as they pass through them. In order not to change the trajectories of the primary electrons, coils producing a transverse magnetic field with $H_\perp = (v/c)E_\perp$ must be placed on the vacuum chamber of the clearing electrodes.

6. CONCLUSIONS

Neutralised electron beams have been used for the low-energy proton cooling on LEAR. A neutralisation factor of about 0.8-0.95 has been reached for stable neutralised electron beams with beam perveances between 0.1 + 0.7 $\mu A/V^{3/2}$ and energies in the range 3-27 keV. The beam-drift instability restricts the use of more intense electron beams. The next investigation will be directed to increasing the upper current limit of the beam-drift instability.

7. REFERENCES

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