MEASUREMENTS OF ELECTRON COOLING AND "ELECTRON HEATING" AT CELSIUS

D. Reistad, L. Hermansson, T. Bergmark, O. Johansson, A. Simonsson
The Svedberg Laboratory, Box 533, 751 21 Uppsala, Sweden

A.V. Burov
Budker Institute of Nuclear Physics, 630090 Novosibirsk, Russia

ABSTRACT

The drag rates of the CELSIUS electron cooler are similar to those of other electron coolers. On the other hand, when the stored beam is exposed to the electron beam at the injection energy at CELSIUS, a large fraction of the stored beam is rapidly lost. This is true whether the electron beam energy is tuned for cooling or whether the energy is shifted from the value, which is appropriate for cooling. One possible explanation for this phenomenon is non-linear effects due to the finite diameter of the electron beam, which is smaller than the maximum beam size.

1. INTRODUCTION

CELSIUS [1] is supplied with ions from the Gustaf Werner Cyclotron with stripping injection or multi-turn injection without stripping. These injection methods [2] make use of a vanishing orbit bump, in order to utilize the whole available horizontal acceptance of the ring. The injection energy while stripping injecting protons (starting with H_2^+ molecular ions) is 48 MeV.

An electron cooling system [3] is used to improve the momentum spread and size of beams, which travel with velocities within the velocity range of the electrons (up to 550 MeV/u). The electron cooling system will also be used to accumulate ions, which are only available with small intensity from the cyclotron.

The nominal acceptance of CELSIUS is 120 π mrad×mm in both planes, and the β-values in the electron cooler are 10 m horizontally and 7 m vertically. Thus, the nominal acceptance corresponds to a beam size of 70 mm in the horizontal plane and 58 mm in the vertical plane. The diameter of the electron beam is only 20 mm. At the design stage, it was not thought that beam-beam effects between the electron beam and the stored ion beam would be significant, because the beam-beam tune shifts are typically not more than 5×10^{-3}.

2. DRAG RATE MEASUREMENTS

The longitudinal drag rate has been measured with coasting beams of protons, deuterons, and oxygen ions with several energies. The measurement technique has been to step the output voltage from the electron cooler high voltage power supply, and to observe with a spectrum analyzer how the revolution frequency of the ions changes as a function of time after the step. Fig. 1 shows comparisons between the drag rate measured at CELSIUS with drag rates measured at other laboratories [4,5]. These measurements show, that the influence of the cooling electrons on the *cooled* ions in CELSIUS is similar to that in other electron cooling systems.

3. "ELECTRON HEATING"

When turning on the electron beam in the presence of a 48 MeV stored and bunched proton beam for the first time in 1988, the accelerator staff at Uppsala were disturbed to find that the stored beam lifetime became much shorter than before it was exposed to the electron beam. This phenomenon, which we have nick-named "electron heating," has been the subject of study for some time, however without obtaining a complete understanding.

Similar effects (although less pronounced than at CELSIUS and probably with different explanations) have been observed at NAP-M [6], Fermilab [7], Indiana [8], and TARN II [5,9]. On the other hand, they seem to be completely absent at LEAR [10], ESR and TSR [11], ASTRID [12], and CRYRING [13].

In order to separate the effects of electron heating and electron cooling, the electron heating phenomenon has often been studied with the electron beam energy offset from the value, which is appropriate for cooling (26 keV for cooling of 48 MeV protons) by one or several keV. Figure 2 shows three examples of measured intensity vs. time for a bunched proton beam with an injected intensity of about 25 mA. The three cases are: without electrons, with an electron beam of 50 mA, with energy that is tuned for cooling, and with an electron beam of the same current, which has an energy which is 1 keV too high for electron cooling to take place.

The initial lifetime of a bunched 48 MeV proton beam typically changes from 50-100 s without electrons to 0.5-1 s when it is exposed to 100 mA of electrons, and a 280 MeV bunched proton beam changed its lifetime from about 7000 s without electrons to 50 s when exposed to 500 mA of electrons.

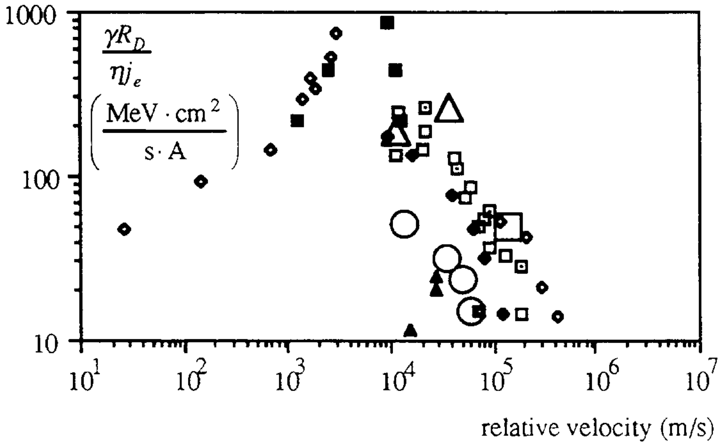

Fig. 1. Comparison between measured drag rates at LEAR (49 MeV protons, ⊡), NAP-M (65 MeV protons, ◆), FNAL (203 MeV protons, ■), IUCF (45 MeV protons, ◈), Novosibirsk (850 keV protons, ■), INS (20 MeV protons, ◻), ICE (47 MeV protons, ▲), CELSIUS (783 MeV deuterons, ○, 296 MeV ^{16}O-ions, □, and 180 MeV protons, △).

Other observations are, that the electron heating is much worse for a bunched beam (with rf.) than for a coasting beam, and that it does not make any difference if the electron energy is detuned one or several keV or if it is increased or decreased.

The initial (just after injection) proton beam lifetime is roughly inversely proportional to the electron beam current.

A change of vacuum in the electron cooling region of nearly two orders of magnitude (from 10^{-6} Pa to a few times 10^{-8} Pa) had almost no effect on the stored beam lifetime in presence of detuned electrons.

Turning on and off the clearing electrodes, which are intended to remove low energy electrons and ions, which are trapped in the electron beam, had no effect on the stored beam lifetime in presence of detuned electrons.

When making the electron beam losses much higher than normal, by increasing the collector anode voltage or decreasing the collector voltage, then the stored beam lifetime became even shorter. For example, changing the losses of a 250 mA electron beam from 32 μA to 240 μA by increasing the collector anode voltage from 400 V to 1 kV, changed the initial 48 MeV proton beam lifetime from 0.6 s to 0.4 s.

In order to answer the question whether the electron heating effect is a coherent effect or a single particle one, the stored beam lifetime has been measured with different stored proton beam intensities. Two different methods were used to reduce the stored beam intensity from its normal value, which is about 25 mA for protons. One method was to reduce the pulse length from the cyclotron from its normal value of 8 ms. The other method was to detune the injection septum magnet in CELSIUS, in order to hit the area in horizontal phase space which is accepted by the injection process with a lower intensity.

With the first method the stored beam emittance becomes smaller at the same time as the intensity is reduced, because injection takes place only during a small part of the time during which the orbit bump is shrinking. When the proton beam intensity had been reduced with this method, the electron heating phenomenon became less pronounced than with full intensity, and completely absent if the intensity was reduced enough and the rf. was off.

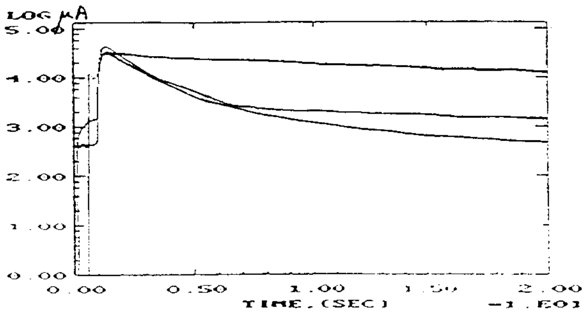

Fig. 2. Measured intensity vs. time for a bunched proton beam with an injected intensity of about 25 mA. The three cases are: without electrons (upper curve), with an electron beam of 50 mA, with energy that is tuned for cooling, and with an electron beam of the same current, which has an energy which is 1 keV too high for electron cooling to take place (lower curve).

With the other method on the other hand, it is thought that the emittance of the stored beam is roughly the same for different intensities. There was no significant difference in lifetime while changing the stored proton current from 25 mA to 4 mA.

This indicates, that the electron heating is not a coherent effect, but a single-particle instability, caused by the electron beam.

The instability may be due to excitation of resonances by non-linear electrical fields from the electron beam. These may be due to:

a. The electrical field increases as r inside of the electron beam, but decreases as $1/r$ outside it.

b. Non-linear electrical fields from the electron beam are seen by the ions in the toroids, where the electron beam is bent into and away from the stored beam.

c. The vacuum chamber of the electron cooler is not perfectly cylindrical. An approximately cylindrical environment for the electron beam, with 100 mm diameter, is created with 8 longitudinal wires, which are placed inside the drift tube.

d. The electron beam may be displaced from the axis of the vacuum chamber.

e. The electron beam may have an uneven effective charge density, due to inhomogeneity or asymmetry of emitter and gun, or due to an inhomogeneous distribution of secondary particles inside the electron beam.

For ions with displacement larger than the electron beam radius, the amplitude of the exciting force from the finite diameter of the electron beam itself (case a) is much larger than those from cases b and c.

This means, that we should expect the lifetime to be sensitive to changes of the electron beam radius. With a larger radius, a smaller fraction of the stored ion beam is outside the electron beam. Ions with large amplitudes should get a better lifetime. On the other hand, if the electron current density is kept constant, the ions with displacements, that are smaller than the electron beam radius will be more disturbed by the other exciting forces (b, c, d, e...) due to the higher electron current.

Measurements of such dependence have been done. The electron beam diameter in the drift tube was increased from 2 cm to 3.6, 4 and 5 cm by running the electron cooler with a smaller magnetic field in the drift tube solenoid, than in the toroids and the gun and collector solenoids. The electron current was 100 mA, 314 mA, 400 mA and 625 mA respectively in order to maintain a constant current density. The best lifetime was observed when the electron beam diameter was 4 cm and the electron current was 400 mA. In figures 3 and 4 the lifetime of 48 MeV protons in presence of detuned electron beams of 100 mA, 2 cm diameter, and 400 mA, 4 cm diameter are compared with the lifetime without electrons present.

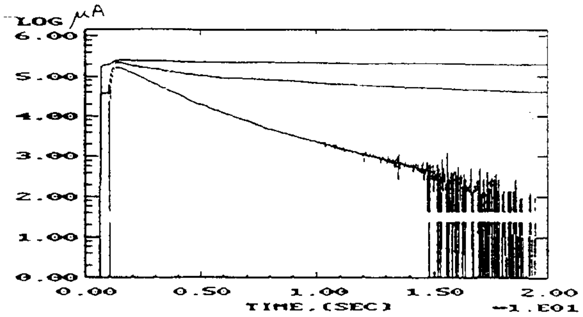

Fig. 3. Measurement of intensity (shown as ^{10}log of μA) vs. time (from zero to 20 s) for a bunched beam of 48 MeV protons (rf. voltage about 200 V), without electrons (best lifetime), with 400 mA electron beam with 4 cm diameter, and with 100 mA of electron beam with 2 cm diameter (worst lifetime).

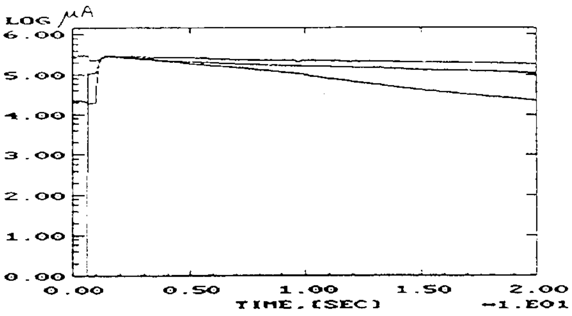

Fig. 4. As fig. 3 but for coasting beam of 48 MeV protons. The best lifetime is without electrons. The next curve is with 400 mA electron beam with 4 cm diameter. The worst lifetime is with 100 mA electron beam with 2 cm diameter.

We tested the hypothesis that the electron heating would only be due to the fact that the electron beam diameter is smaller than the ion beam size by first cooling the ion beam, then turning the electron current to zero, increasing the voltage of the high voltage power supply by 1 kV, and turning the electron current on again. The result was that beam losses do appear, with a delay after that the detuned electrons are applied, which varies with the electron current, and is a few seconds with 400 mA electron current, about 5 s with 200 mA, and 20 s with 50 mA. Thus, we have to conclude, that electron heating is present also for a beam which fits inside the electron beam, and that also other non-linear fields from the electron beam or other effects are important.

4. OTHER EXPLANATIONS

Another hypothesis to explain the electron heating phenomenon for intense stored beams has been proposed by Parkhomchuk and Pestrikov [14]. They suggest that the electron heating is also due to that the stored beam sees an additional impedance from the interaction with the electron beam. We have to conclude that several effects may play a role at the same time.

5. STUDIES OF LONGITUDINAL SCHOTTKY SPECTRA

Longitudinal Schottky noise spectra from coasting beams have been observed to see how these are influenced by the presence of a "detuned" electron beam.

The pickup which is used for these measurements is resonant at 68 MHz, which corresponds to the 60th harmonic of the revolution frequency for 48 MeV protons.

When the electron beam is present, there are dips in the measured spectra. These are absent without electrons. The density of these dips is so high, that one can usually see 3-6 of them at the same time. An example of such a measurement is shown in fig. 5. It is possible to identify resonances, which correspond to the observed peaks. These are of 6th and 7th order, see fig. 6 (Since the chromaticity is not corrected in CELSIUS, the momentum spread causes tune spread. Instead of a working point there is a "working line," as shown in fig. 6).

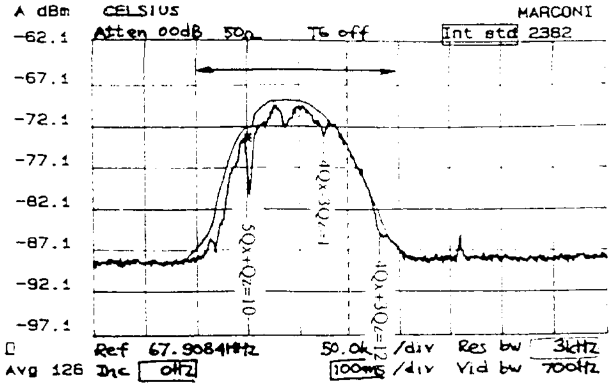

Fig. 5. Longitudinal Schottky spectra of coasting beam of 48 MeV protons with and without presence of 50 mA of "detuned" electron beam.

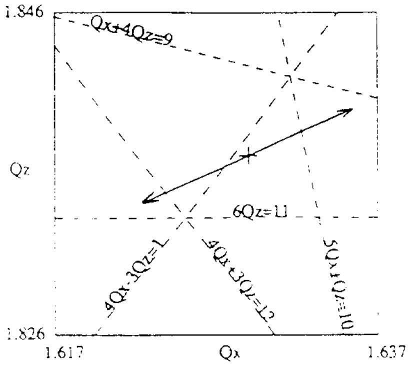

Fig. 6. Identification of resonances in tune diagram corresponding to several dips seen in the Schottky spectrum in fig. 5.

6. TRACKING CALCULATIONS

The electron heating phenomenon has been simulated in tracking calculations with SIXTRACK [15]. New subroutines have been added to represent the effects of the finite diameter electron beam, the solenoid, the electron beam in the toroid region, and our eight rods in the drift tube [16]. It was pointed out by Parkhomchuk, that it is necessary to evaluate the effect of the finite diameter electron beam by splitting the length of the interaction region into several pieces, and to calculate the kick from the displacement of the ion at each of these. Otherwise, the sharpness of the electron beam edge becomes exaggerated. We have chosen to split it in 10 pieces. With an electron beam of 0.5 A the results of the simulations seems chaotic after 10^4 - 10^5 turns of tracking of a 48 MeV proton, which starts at an amplitude just outside of the electron beam. The presence of rf. dramatically increases the chaotic behavior. The presence of a 0.1 A electron current and rf. causes a behavior which seems chaotic after about 10^6 turns. The non-linear electrical fields from the electron beam in the toroid regions, and the nonlinear electrical field from the eight rods, which surround the electron beam in CELSIUS at 100 mm diameter, seem to give rise to heating which is weaker than the electron cooling.

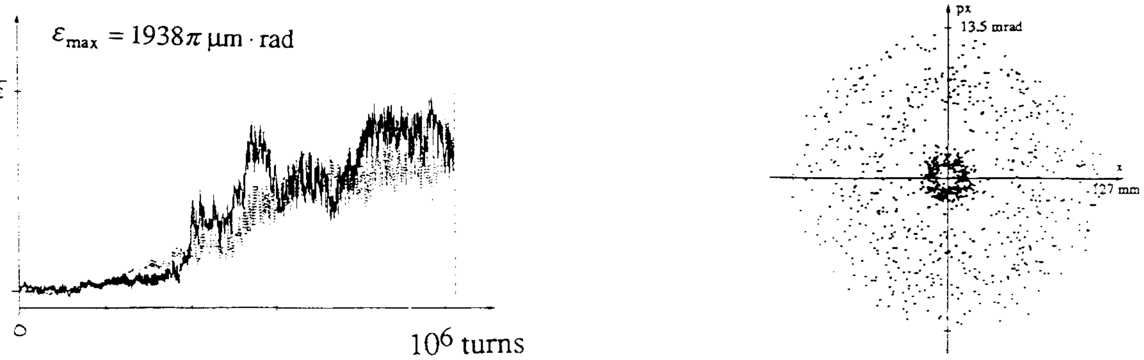

Fig. 7. Some results of tracking computation of 10^6 turns of a 48 MeV proton in presence of 0.5 A electron beam, 190 V rf., and 0.1 T solenoid field. The left figure shows how the $\sqrt{\varepsilon_x}$ (black) and $\sqrt{\varepsilon_z}$ (gray) vary as a function of turn number from 0 to 10^6, and the right figure shows the position of the proton in horizontal phase space plotted once every 10^3 turns.

As an example of the output of the tracking computations, fig. 7 shows some results of a computation of 10^6 turns of a 48 MeV proton, which starts just outside of a 0.5 A electron beam in CELSIUS. This computation is made for an rf. voltage of 190 V and a solenoid field of 0.1 T.

7. CONCLUSIONS AND PLANS

So far, we have not made any observation that contradicts our hypothesis that the electron heating is mainly due to high-order resonances, driven by the non-linear electrical fields from the electron beam. In CELSIUS, these are especially due to the fact that the diameter of the electron beam is smaller than the diameter of the injected ion beam; in fact, this seems to be the only effect, which gives rise to electron heating which is stronger than electron cooling at the injection energy.

If we gain further confidence in our hypothesis presented here, we will consider to equip our electron cooler with new solenoids for the electron gun and the collector with stronger and variable magnetic field, in order to get a variable diameter electron beam.

8. ACKNOWLEDGMENTS

Stimulating discussions and participation in experiments by Håkan Danared, Tim Ellison, Johan Jeansson, Arne Johansson, S.Y. Lee, Søren Pape Møller, Vasily Parkhomchuk, Miroslav Sedlacek, Anatoly Sharapa, Markus Steck, Tetsumi Tanabe, Gerard Tranquille, and many TSL staff members are gratefully acknowledged. Acknowledgments are also due to Frank Schmidt, who has generously provided us with SIXTRACK.

REFERENCES

[1] D. Reistad et al., *Recent Commissioning Results at CELSIUS*, Proc. 13th Int. Conf. on Cyclotrons and their Applications, Vancouver, Canada, July 6-10, 1992, 266.
[2] K. Hedblom et al., *Calculations on Multiturn and Stripping Injection in CELSIUS*, Proc. 3rd European Particle Accelerator Conference, Berlin, Germany, 24-28 March, 1992, 462.
[3] M. Sedlacek et al., *Design and Construction of the CELSIUS Electron Cooler*, these proceedings.
[4] T.J.P. Ellison, *Electron Cooling at IUCF — 0.3 MeV in 1988, 9 MeV in 1998?* Proc. Workshop on Electron Cooling and New Cooling Techniques, Legnaro, Italy, 15-17 May, 1990, 29.
[5] T. Tanabe et al., *Electron Cooling Experiments at INS*, Nucl. Instr. and Meth. in Phys. Res. **A307** (1991) 7.
[6] G.I. Budker et al., *Experimental Studies of Electron Cooling*, Particle Accelerators **7** (1976) 197.
[7] T. Ellison et al., *Fermilab 120 keV Electron Cooling System*, FNAL TM 1156.
[8] T. Ellison, private communication (1992).
[9] T. Tanabe et al., *Status of Electron Cooling at TARN II*, these proceedings.
[10] G. Tranquille, private communication (1992).
[11] M. Steck, private communication (1992).
[12] S. Pape Møller, private communication (1992).
[13] H. Danared, private communication (1992).
[14] V.V. Parkhomchuk, D.V. Pestrikov, *Coherent Instabilities at Electron Cooling*, these proceedings.
[15] F. Schmidt, *SIXTRACK version 1.1*, CERN/SL/91-52.
[16] A. Simonsson, *Simulations of Electron Heating*, TSL-Note 93-06.