REPORT OF THE WORKING SESSION ON HEAVY IONS AND HIGH-ENERGY COOLING

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ABSTRACT
A report is presented of the Working Session on Heavy Ions and High Energy Cooling.

1. INTRODUCTION

The Working Session on Heavy Ions and High-Energy Cooling met on Wednesday morning, October 6. Presentations were made by Robert Pollock, Tim Ellison, Markus Steck, Michael Seurer, Pierre Lefevre, Andreas Wolf, and Guregen Ter-Akopian.

The contributions of this session can be divided into three groups:
- a. new projects with electron cooling,
- b. new applications of the electron cooling,
- c. experimental and theoretical investigations of the electron cooling physics.

2. NEW PROJECTS WITH ELECTRON COOLING

2.1 LHC Project

In this group the possibility is examined of using electron cooling for the storage of more intense heavy ion beams in order to enhance a luminosity.

The one proposed for the LHC scheme is based on the accumulation of Pb$^{3+}$ at 4.2 MeV/n in the cooling ring with a stack of up to $1.2 \times 10^9$ ions per bunch. When, with about 500 bunches per LHC ring, the total luminosity is close to the desired $2 \times 10^{37}$ cm$^{-2}$s$^{-1}$, a solution based on the performances achieved with an ECR source is the conversion of LEAR into a Low-Energy Accumulator Ring. The beam lifetime limitation in LEAR is carefully estimated taking into account the intra-beam scattering ion recombination with cooling electrons, charge exchange on the residual gas, microwave instability, and space-charge tune shift.

2.2 K4-K10 Project TREBLé

The aim of the Dubna project of heavy ion storage rings complex is to provide high precision beams of exotic nuclei with a mass number ≤50 in the energy range from a few MeV to about 200 MeV/µ. The first ring, K4, is intended to accumulate the primary ion beam from the JINR sector focusing cyclotron U400M, to cool this beam and to increase the energy up to 170 MeV/µ. After cooling the beam is ejected and used to produce the exotic nuclei which are injected into the second ring. The nuclei with a lifetime ≥1 s can be cooled and accumulated in the ring and their energy can be optimized. For the short-lived nuclei (lifetime <1 s), a target illumination will be preferable immediately after cooling.

At the first stage of the project only one ring (K4) will use the exotic nuclei for injection and cooling. Then the luminosity will be of 2 or 3 orders of magnitude less.

3. NEW APPLICATIONS OF THE ELECTRON COOLING

3.1 New Applications at the IUCF

Some new applications of the electron cooling have been developed in the cooling-ring synchrotron, at the Indiana University Cyclotron Facility (IUCF).
Methods have been developed to use electron cooling to help in beam accumulation, both for stripping injection of unpolarized beams and rf stacking of polarized beams.

Typical cyclotron beam current is about 0.5 μA. The beam normalized emittance is about 1 μm and the momentum spread of about 0.03%. After a few seconds of injection a stored proton current up to 1 μA at 45 MeV can be obtained. Multiplication of an observed rate of 12 mA/min with a best observed lifetime while kicking of 1 hour would give 7 mA. However, the best stored current to-date with this mode is lower by an order of magnitude. There is evidence for a stored current-dependent loss of transfer efficiency with a threshold near 0.4 mA. Longitudinal space-charge effects may play a role by limiting the time contraction. Other physics also cannot be excluded. The present performance of the stacking mode is critically dependent on a good cooling.

IUCF is also studying a new project: the development of the technology for electron cooling in the 2-20 GeV/n energy range.

3.2 The Development of the Technology for Electron Cooling in the 2-20 GeV/n Range

Two principal goals are defined:

1. to determine the feasibility of the electron cooling the 12 GeV/c beams in the SSC Meadl Energy Booster

2. to develop and demonstrate the necessary technology, based on High-Voltage Pelletron Accelerator, leading to its commercial availability.

Above electron energies of about 500 keV the traditional approach of using a Cockcroft-Walton power supply and a magnetically-confined electron beam becomes unpractical. A non-magnetically confined electron beam generated and collected in the terminal of a Pelletron accelerator seems ideally suited for these higher energy systems.

The first goal has been completed. Remains the last main problem-collection δ (δ is the inefficiency) which must be in the range 10^-5-10^-4. (δ = J_{loss}/J_{in})

The following improvements may be useful:

a) Improved diagnostics systems

The previous system did not work for beam currents exceeding 10^4. The present system design might allow measurements of the beam position and profile for currents in the range 10^4-10^6 A.

b) Improved electron gun

The present gun design will produce a much smaller beam emittance and has true Pierce geometry in the gun region.

c) Improved electron collector

IUCF is building a collector which includes a dipole suppressor which may allow δ ≤ 10^-6.

d) Ion clearing electrodes

The system pressure will be improved using non-evaporable getter pumps, and ion clearing electrodes will be employed to prevent space-charge neutralization.

The author expects that collection inefficiencies will be in the range 10^-5-10^-4 for the higher energy systems for manageable power dissipation.

4. THE EXPERIMENTAL AND THEORETICAL INVESTIGATIONS OF THE ELECTRON COOLING PHYSICS

Experimental and theoretical investigations on the beam cooling parameters have been made at IUCF. Assuming that the longitudinal coupling impedance is almost completely space-charge dominated, one can find the relative momentum spread of the electron-cooled proton beam and the longitudinal space-charge impedance.

Two independent methods have been used:

- fitting the measured longitudinal bunch shape to the theoretical one found from equilibrium the solution of the Fokker-Planck equation for the electron-cooled case.
- analyzing the frequencies of the dipole and quadrupole longitudinal bunch modes.

The results of both methods coincide with a satisfactory accuracy and show the presence of the significant space-charge forces.

Both methods may be useful, but the first one seems to be not very reliable because of difficulties to measure exactly the tails of the bunch longitudinal density.
The last two papers are devoted to a detailed examination of the physics of electron cooling for heavy ions (up to Au$^{79+}$).

At GSI, in Darmstadt (Germany), the temperature of heavy ion beams in equilibrium between electron cooling and heating by intra-beam scattering has been measured over a large range of ion and electron beam intensities. A comparison of cooling forces at small relative velocity for ions Cs$^{6+}$, Tl$^{22+}$ and Au$^{79+}$ shows a strong increase with the ion charge which, however, favours a proportionality to $Z^{1.5}$ than $Z^2$. In all experiments by now a $N^{1.5}$-dependence of the momentum spread versus the number (N) of stored particles has been observed. For the transverse emittance results varied in the range $N^{1.5}$ to $N^{2.5}$ note that the observed lower limit for the detectable beam momentum spread $7 \times 10^{-7}$ is likely to be caused either by the power supply ripple of the main ring magnets or by the energy instability of the electron gun.

Moreover, the cooling force of the electron beam and the intra-beam scattering rate of the dense ion beam were investigated in separate experiments. Because of lack of adequate diagnostics for the transverse degree of freedom the experiments were concentrated on longitudinal cooling force, cooling rate and longitudinal heating rate. For measurements of the longitudinal cooling force at small relative velocities between electrons and ions the cooled beam was heated by white noise and the cooling force of the electron beam was determined according to

$$ F = D \cdot \psi^{-1} \frac{\partial \psi(E)}{\partial E} $$

where $D$ is the diffusion coefficient and $\psi$ the energy-dependent distribution function.

For three ion charges, 6+, 22+ and 79+ increasing of the longitudinal cooling forces can be described by a proportionality $\equiv Z^{1.5}$. Note that this law can be determined without knowing the absolute value of the diffusion coefficient $D$, and that the same charge dependence of the electron cooling force was measured at the TSR ring in Heidelberg for D$^+$, Li$^{3+}$, C$^{6+}$, O$^{8+}$ and S$^{16+}$ ions.

5. CONCLUSIONS

1. The new heavy ion projects (CERN, Dubna) show that it is practically impossible to obtain the designed high luminosity without electron cooling.

2. The technology of electron cooling of high energy ions has been developed. It will open new feasibility in very high-energy project.

3. As a result of new experimental investigations (GSI, Heidelberg, IUCF) the electron cooling physics for heavy ions has been understood in more details.