PRELIMINARY STUDY OF ELECTRON COOLING POSSIBILITY OF HADRONIC BEAMS AT PETRA

K. Balewski, R. Brinkmann, Ya. Derbenev, K. Floettmann, N. Holtkamp,
M. Schmitz, G.-A. Voss, P. Wesolowski, DESY, Hamburg, Germany
D. Yeremian, SLAC, Stanford, CA, USA

Abstract

One way to increase the electron-hadron collision luminosity in HERA is the diminution of the phase-space volume of the circulating hadron beam, which could be achieved via electron cooling in the PETRA-preaccelerator. In this method hadron and electron beams with equal Lorentz factors are brought together in an interaction section of about 40 m length. The electron cooling technique at high energies in PETRA-p (7.5-40 GeV) requires electron beam energies of about some 10 MeV and beam currents of Amperes for cooling times of protons of about 10 minutes. One of the technical obstacles might be the excessive electron beam power, which motivated the investigation af a linac-based scheme to produce bunches that match the bunch length of the hadron beam. A further possibility is reuse of recirculated cold electron bunches, to which end a short-time storage ring is being considered. This paper presents preliminary studies of an electron linac as well as recycler ring at 10 MeV energy for cooling of proton and ion beams in PETRA.

1 INTRODUCTION

According to the Liouville theorem the phase space density of a particle beam can not be reduced by means of beam optics. This theorem, which reflects directly the entropy considerations, expresses that the transverse and longitudinal beam emittance (temperature) might only be reduced if the beam interacts with an external system, e.g. a beam of cold electrons. The method of electron cooling, based on this phenomenon, is an attractive possibility to improve the emittance. In this method the hadron beam and cold electron beam travel together with the same Lorentz factors in a cooling section. After passing the cooling section the beams are separated. A number of operating electron coolers at moderate energies (up to $\simeq$1 GeV per nucleon) confirm the applicability of this method, so far restricted to low hadron energy.

1.1 Motivation of Beam Cooling at DESY

The proton beam from the PETRA preaccelerator is used for injection at 40 GeV into the HERA synchrotron ring at DESY. A reduction of emittance of the injected beam can contribute to the peak luminosity at the intersection of the colliding electron and proton beams at top proton energy of 820 GeV. The electron cooling will be particularly interesting for more distant future projects at HERA, possibly with polarized protons and heavy ion beams. Moreover, the cooling in PETRA supports a complementary project of cooling in HERA at top energy of 820 GeV in the luminosity operation mode.

1.2 Electron Cooling of Hadronic Beam in PETRA

The cooling rate drops rapidly with hadron energy as $\gamma^{5/2}$. This requires, particularly for protons, high electron beam currents. For electron cooling in PETRA[1] an intermediate energy of 15-20 GeV is chosen as a balance between parasitic intrabeam scattering in a proton beam at lower energies and unacceptably long cooling times at higher energies. For the equality of the Lorentz factors the respective electron energy of 7.2-9.7 MeV is required. Table 1 summarizes the proton and electron beam parameters for cooling in PETRA.

	protons		electrons	
	PETRA γ = 20	PETRA γ = 15	Injector γ = 20	Injector γ = 15
$\epsilon_{\rm N}$ [π mm mrad]	4.0	4.0	4.0	4.0
$\frac{\Delta E}{E}$ [10^{-4}]	5.0	5.0	5.0	5.0
σ_z [m]	0.5	0.5	0.5	0.5
$\theta_{\rm trans}$ [10^{-5}]	3.1	3.7	3.1	3.7
$\theta_{\rm long}$ [10^{-6}]	1.3	2.2	1.3	2.2

Table 1: Parameters for electron cooling

Since for appropriate cooling times excessive virtual electron beam power is required, the idea arose[2] to reduce the beam power using the bunched electron beam, matched in size to the hadron bunches (Fig. 1).

Such an electron beam can be generated by means of a superconducting linac. The further reduction of the electron beam power might be achieved by reusing cold electrons by means of a recirculator. In this scheme the same electron bunches, circulating in a short-time storage ring, are used several thousand times. However, the ring design constrains the magnetic focusing, hence the magnetic field in the cooling section becomes – at high currents for proton cooling – hardly to avoid. Nevertheless, preliminary estimates have shown that the design of a magnetized ring is realistic. In this case the injector operates with low duty cycle and a repetition frequency in kHz–range. It becomes substantially easier to achieve higher accelerating

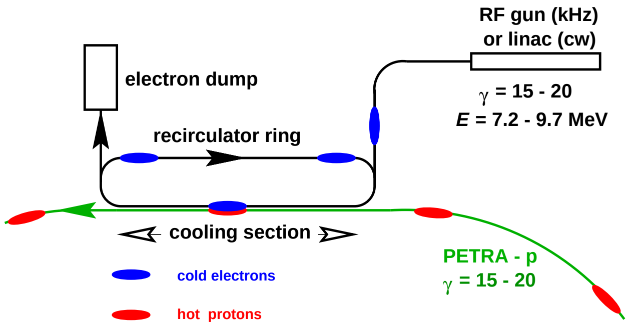

Figure 1: Basic idea of electron cooling by bunched electron beam. The electron bunches match in space the hadron bunches, hence the virtual electron beam power is substantially reduced. Further power reduction might be achieved using recirculator

gradients than in cw-mode, what suppresses the emittance growth in the initial part of the injector. In fact, our requirements for emittance and beam current are fulfilled by the succesfuly operating ELSA rf–gun[4], which has a repetition frequency of 10 Hz. The question remains open, whether the repetition rate enhancement to kHz could be achieved. The collective beam–beam effects in the recirculator require separate studies. Some basic ideas concerning the recirculator are presented in Section 4.

2 COOLING TIME IN PETRA

Due to analytical formulas for transverse and longitudinal electron cooling rates[3] the cooling time can be expressed as:

$$\tau_{\rm long} = \frac{\beta^4\gamma^6 J_{\rm A}\theta_{\rm trans}{}^2\theta_{\rm long}}{6\pi\, cr_{\rm p}\, L_{\rm C}\,\eta\, j_{\rm e}}\,\frac{A}{Z^2},$$

$$\tau_{\rm trans} = \frac{\beta^4\gamma^5 J_{\rm A}\theta_{\rm trans}{}^3}{6\pi\, cr_{\rm p}\, L_{\rm C}\,\eta\, j_{\rm e}}\,\frac{A}{Z^2},$$

with:

$$J_{\rm A} = \frac{mc^3}{e} = 17\ \text{kA},$$

$$j_{\rm e} = \frac{ecN_{\rm e}}{(2\pi)^{3/2}\sigma_{\rm x}\sigma_{\rm y}\sigma_{\rm z}},$$

$$\theta_{\rm trans} = \sqrt{\frac{2\epsilon_{\rm N}}{\beta_{\rm cool}\gamma}},$$

$$\theta_{\rm long} = \sqrt{2}\frac{\sigma_{\rm E}}{\gamma^2}.$$

Here $\eta = L_{\rm cool}/L_{\rm ring}$ is the cooling section length normalized by the ring circumference, A–atomic number, Z–mass number, $r_{\rm p}$–classical proton radius, $L_{\rm C}$–Coulomb logarithm, $\beta_{\rm cool}$–beta function in the cooling section. For optimum cooling rates $\beta_{\rm cool}$ for hadrons and electrons (in the case of comparable emittances) should be equal. Inserting proper values from Table 1 and $eN_{\rm e}$ = 5 nC/bunch, $L_{\rm C}$ = 10, $\beta_{\rm cool}$ = 200 m, $\eta = \frac{50}{2304}$ one obtains:

	protons		gold, A=197, Z=76	
γ	15	20	15	20
$\tau_{\rm long}$	4.0 min.	7.1 min.	8.2 s	14.6 s
$\tau_{\rm trans}$	4.4 min.	9.0 min.	9.0 s	18.4 s

3 INJECTOR LINAC

3.1 Fundamental Concept

The preliminary design of the cw-injector linac (Fig. 2) consists of a 120 keV Pierce thermionic electron gun, a buncher, a combined normal- and superconducting accelerating structure and a debuncher section for final longitudinal bunch expansion. The electron gun delivers the pulses of 1.3 ns length. The bunches are longitudinaly compressed using a gap cavity, operating at 83.33 MHz to $\sigma_{\rm z}$ = 17 mm. The beam with β = .59, driven in solenoidal field enters subsequently the preaccelerating normal-conducting two-cell structure, operating with high gradient at 352 MHz. The cavity lengths are matched on the time of flight in the cell (β-matching). The preaccelerated relativistic beam – which is not anymore strongly influenced by space charge forces – is injected at 2 MeV into the superconducting 8-cell 352 MHz structure. At the operation energy of 7.2-9.7 MeV the bunches are expanded to the appropriate length, thus matching the hadron bunches in PETRA. The next subsection presents the simulations of particle tracking in the described structure.

3.2 Computer Simulations

The preliminary simulations of the high current electron gun as well the accelerating structure were provided. The gun was developed using the code EGUN[5]. The normalized emittance $\epsilon_{\rm N}$ of 6.4 π mm mrad for the current of 2.5 A, which corresponds to a bunch charge of 5 nC, was achieved.

The results of PARMELA[6] tracking simulations in the buncher and accelerator are shown in Table 3.

		A	B	C
$\epsilon_{\rm N}$	π mm mrad	6.4	9.0	9.5
ΔE	keV	0.55	4.3	62.0
$\sigma_{\rm z}$	mm	235(FW)	17.0	14.7

Table 3: Results of PARMELA simulations of the injector with 3 nC bunch charge at points A, B and C (see Fig. 2)

The simulations show an emittance growth which is due to the space charge forces in the bunching section. At the moment the efforts are focused on the reduction of this emittance growth. For cooling of heavy ions much lower current is required, which corresponds to 0.2 nC bunch charge. For the beam, which is not space charge dominated, it is a reasonable assumption, that the emittance in electron

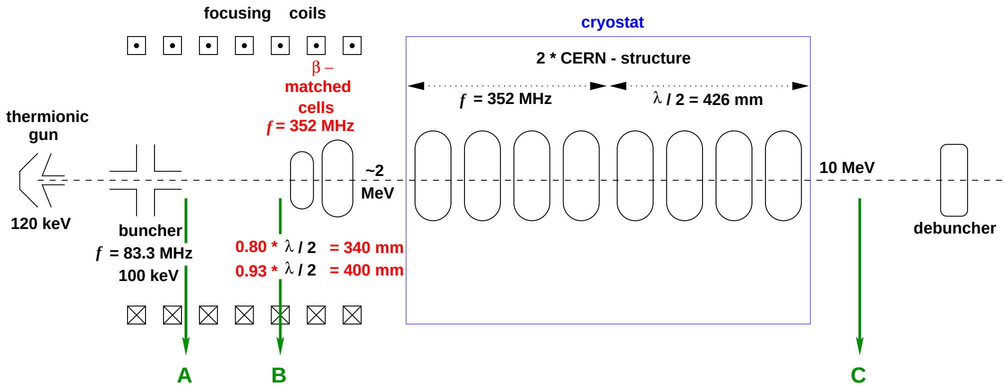

Figure 2: Basic design scheme of the injector linac

gun does not change substantially between cathode and anode and remains on the thermal level of $\simeq 2\ \pi$ mm mrad. In this case the normalized emittance does not grow in the injector, which becomes sufficient for ion cooling.

4 PROSPECTS FOR ADVANCED ELECTRON TRANSPORT

To cool a proton beam at PETRA electron bunches of 5-10 nC at normalized emittance of 2–4 π mm mrad are required. A 'classical' transport of electrons in a continuous solenoid of 0.5–2 kGs at emersed cathode would be sufficient, in principle, to suppress the space charge disruptive effect. However, magnetic field is not compatible with rf-superconductivity. This constrain can be resolved by admission of gaps and by optical matching between solenoids. The matching is expressed in resulting conservation of magnetic flux in the electron beam between cathode and solenoid of cooling section. Preliminary analysis showed that the precession demands can be satisfied with respect to the linear optic problem as well as to the disperse effects due to inhomogenious space charge, solenoidal nonlinearities, and rf-induced energy gradients.

The efficiency of the injector, as above mentioned, can be drastically enhanced at incorporation of electron recirculator. At electron current required for cooling of ion beam (non-magnetized transport), the Coulomb tune shift will not exceed 0.1. This value seems sufficiently small to maintain the injected emittance during $\simeq 10^3$ beam revolutions. At use of a magnetized injector for cooling of proton beam (high electron current) the injector also can be matched with the recirculator; then, the solenoid of cooling section becomes a part of the electron ring, matched with the rest of the recirculator focussing lattice (axially symmetric, including arcs). The Coulomb tune shift becomes reduced to a value of about $2-4\cdot 10^{-3}$. This scheme seems capable to provide a sufficiently tranquil electron beam in the cooling section, together with beam stability during the injector cycle.

5 CONCLUSIONS

The presented scheme for electron cooling of hadronic beam in PETRA is an attractive alternative to 'classical' cooling by a DC electron beam. The cooling of heavy ions is believed to work in the single pass mode, while the cooling of protons requires further progress on the injector or/and recirculator. The collective effects in the electron ring for the cooling option with a recirculator demand separate consideration.

Allthough the magnetized injector and recirculator ideas seem clear in the fundamental features, the extended analysis and simulations must be performed to justify these concepts and related technical effords.

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