ELECTRON COOLING AT PETRA USING A BUNCHED BEAM

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Abstract

An increase in the luminosity of the circular hadron - lepton collider HERA may be achieved via electron cooling of hadrons in the PETRA-preaccelerator. The cooling of high energy ($\simeq$ 15-20 GeV) protons requires a high electron beam current ($\simeq$ few amperes) with low emittances ($< 4\,\pi$ mm mrad normalized) to reach reasonable cooling times of < 10 min. For this purpose a linac-based scheme including recirculator and magnetized cooling section has been considered. In this scheme short electron bunches are accelerated in rf-fields. After longitudinal extension to match the bunch length in PETRA their correlated energy spread is removed. Matching is provided for the technically unavoidable gaps in the solenoidal field. This paper presents the status of the development of the proposed scheme for electron cooling.

1 INTRODUCTION

The electron cooling method of reducing emittance, which is based on the interaction of hot particles with a cold electron beam, has been succesfully applied in a number of machines. So far applications have been restricted to low hadron energy (up to $\simeq$0.5 GeV per nucleon). For acceptable cooling times, particularly for protons in PETRA[1] at higher energies ($\simeq$ 18 GeV), a low emittance beam current in the range of Amperes is required. The resulting excessive virtual DC electron beam power may be recovered using a bunched electron beam matched in size to the hadron bunches[1, 2]. The quality of such a beam is crucial for cooling and can be delivered by an injector, the basic scheme of which is described in section 3.

Further electron beam power reduction can be achieved by reusing the electrons $\simeq 10^3$ times. For this purpose a recirculator ring for electrons is proposed [3].

2 BASIC FEATURES OF COOLING PROTONS BY A BUNCHED BEAM

Since electron beam quality is essential for cooling particular attention has been paid to the electron transport from their birth, through the accelerating section, recirculator, up to the cooling section (see Figure (1)).

The cooling of $\simeq$ 18 GeV protons demands electron peak currents in the range of 1-2 A driven in a cooling section of 50 m length. In this regime the suppression of space charge forces in the cooling section (CS) is necessary. This can be achieved using longitudinal magnetic fields in the CS, as well as on the cathode. The field strength need not be maintained constant over the whole electron transport channel. The use of single coils instead of a continuous solenoid simplifies the technical layout of this transport line. However, in this case a magnetic matching[4, 5] between single elements should be provided. The conservation of transverse canonical electron momenta in the electron transport channel leads to a condition

$$r_{\mathrm{cath}}{}^2\, B_{\mathrm{cath}} \;=\; r_{\mathrm{CS}}{}^2\, B_{\mathrm{CS}}, \tag{1}$$

which must be fulfilled for the tranquility of the beam at least in the CS. This condition is non-restrictive besides the CS, where transverse beam excitation may be accepted.

3 INJECTOR SETUP

An injector completely immersed in a constant magnetic field of 3 kG strength and using a TRW (traveling wave) accelerating structure has been proposed elsewhere [6]. Its rf accelerating section operates at an intermediate frequency (208 MHz) with short electron bunches. These are generated by a thermionic electron gun and buncher. The short bunches are subsequently expanded longitudinally to reduce the energy spread and to match to the size of the hadron bunches.

Although this structure defines a physical solution for the injector, its realization may encounter some technical problems, since in this solution a 3 kG magnetic field has to surround large rf-cavities. A substantial modification has been done in the accelerating section. The continuous solenoid is replaced by thin lenses. At the same time, the TRW structure is substituted by normal conducting standing wave 208 MHz single cavities, which are part of existing rf-hardware at DESY.

The electron gun, as well as the bunching section is immersed in a constant solenoidal field. In this low energy region the longitudinal variations of the solenoidal and rf fields are smooth compared to the step of Larmor oscillations $L_{\mathrm{L}} = 2\pi\frac{p}{eB}$ (see Table 1). In this case the transverse

		gun	acc. structure	
E	[MeV]	0.120	2.0	9.0
B	[G]	3000	2000	1000
L_{L}	[mm]	26	258	2000

Table 1: Step of Larmor oscillations L_{L}.

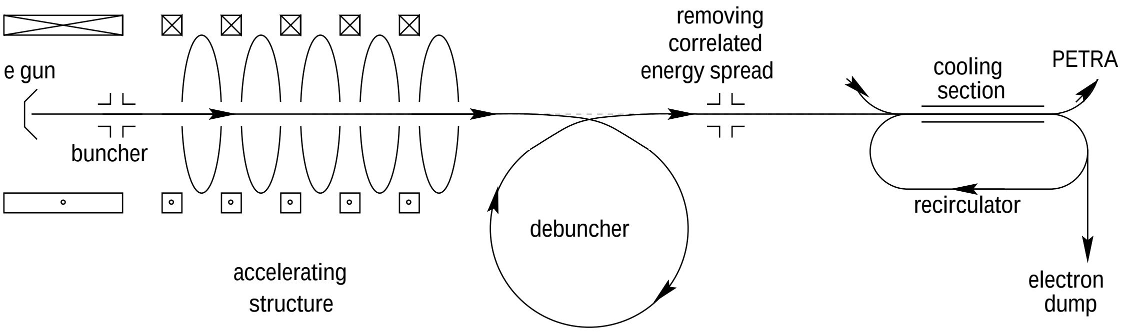

Figure 1: Schematic layout of electron cooling by a bunched beam.

excitations originating from field gradients average over the phases of Larmor oscillation (adiabatic regime).

At higher energy the transverse kicks from rf and solenoidal edge fields can be alternately compensated using Larmor phase matching. This is provided if the phase advance of Larmor oscillation between subsequent cavities is π. In this way a semi-periodic accelerating structure can be defined, in which a condition

$$\int_{\mathrm{I}}^{\mathrm{II}} \frac{dz}{L_{\mathrm{L}}(p,B)} = \pi \tag{2}$$

is fulfilled for two neighbouring cavities (the integration limits are the centers of both cavities; momentum and field are functions of z). In such way a compensating structure has been defined at the ends of which the beam excitations are canceled (see Figure (2)).

In the transition between both regimes (1-3 MeV) an expansion of the transverse beam size occurs in decreasing magnetic field. This intermediate region is most critical for emittance conservation.

4 RECIRCULATOR AND DEBUNCHER

A weakly focusing storage ring for electrons fitting the PETRA tunnel and including the cooling section is proposed elsewhere[3]. This machine consists of two long straight sections, two very short sections immersed in solenoids, and four combined function bending magnets. The transverse focusing is provided by solenoids and one quadrupole triplet. The length of this machine is chosen such that three electron bunches circulate simultaneously. An isochronous lattice has been found[3], which aviods debunching of electrons.

Preliminary solutions for the debuncher have been proposed elsewhere[6]. Its scheme is based on a long paraxial dispersive section, in which particles travel in a dipole field perpendicular to the flight direction. As an alternative, a small storage ring for several turns has also been presented, the basic idea of which is analogous to the idea of the recirculator. Although both schemes are potentially applicable for debunching at relativistic energies, the final layouts demand intensive studies.

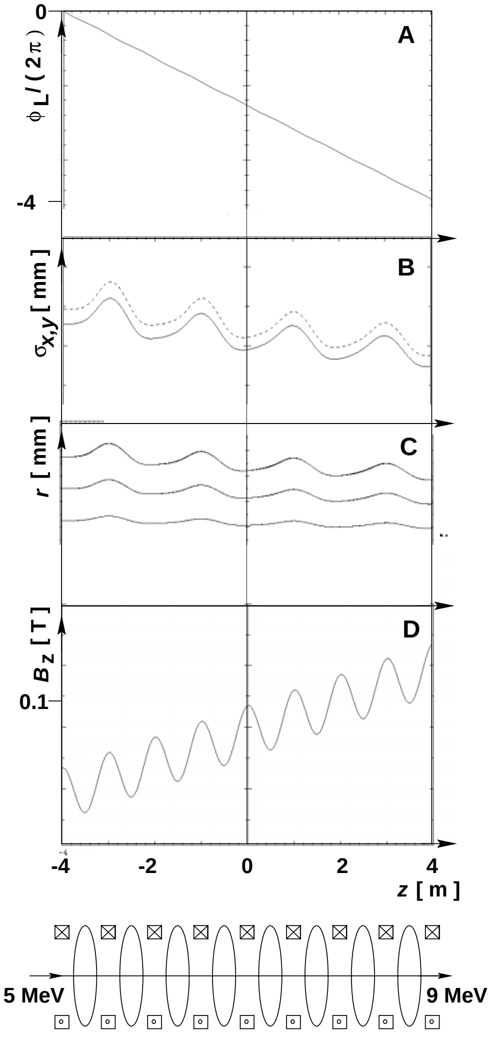

Figure 2: Beam driven in discontinous solenoidal field. Below: The alternating setup of cavities and lenses. D: solenoidal field in the acceleration section. The field fulfills the requirement (2). C and B: Trajectories of representative particles and beam size. The electron beam leaving the section is tranquil. The size of the beam scales according to Equation (1). A: Number of full Larmor steps (Larmor phase over 2π.)

		electrons gun	electrons CS	protons 18 GeV
B	[G]	3000	600	600
ϵ_{N}	[m]	$2 \cdot 10^{-6}$	$2 \cdot 10^{-6}$	$4 \cdot 10^{-6}$
β_{F}	[m]			200
σ_{x}	[mm]	3.0	6.7	6.7
σ_E	[keV]	25	0.85	
σ_E/E		$3 \cdot 10^{-3}$	$1 \cdot 10^{-4}$	$4 \cdot 10^{-4}$
σ_z	[mm]	17	500	500

Table 2: Parameters of the electron beam after acceleration and in the cooling section (CS).

5 COOLING TIMES FOR PROTONS

The parameters of the electron beam leaving the accelerating structure together with the beam features in the cooling section are summarized in Table 2. Simulations of the injector have been done with the tracking algorithm Astra [7]. The transversal and longitudinal emittances of both beams have similar values. In this case analytical formulas for transverse and longitudinal cooling rates for protons [8] may be applied:

$$\tau_{\mathrm{long}} = \frac{\gamma^6 J_{\mathrm{A}} {\theta_{\mathrm{trans}}}^2 \theta_{\mathrm{long}}}{6\pi\, c r_{\mathrm{p}}\, L_{\mathrm{C}}\, \eta\, J_{\mathrm{e}}}$$

$$\tau_{\mathrm{trans}} = \frac{\gamma^5 J_{\mathrm{A}} {\theta_{\mathrm{trans}}}^3}{6\pi\, c r_{\mathrm{p}}\, L_{\mathrm{C}}\, \eta\, J_{\mathrm{e}}},$$

with:

$$J_{\mathrm{e}} = \frac{ce}{(2\pi)^{3/2} \sigma_{\mathrm{x}} \sigma_{\mathrm{y}} \sigma_{\mathrm{z}}}$$

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

$$\theta_{\mathrm{long}} = \sqrt{2}\frac{\sigma_E}{\gamma^2}.$$

Here, $r_{\mathrm{p}} = \frac{mc^3}{e} = 1.5 \cdot 10^{-18}$ m is the classical proton radius, $J_{\mathrm{A}} = 17$ kA the Alfven current and L_{C} the Coulomb logarithm (which is the logarithm of the ratio of maximum to minimum effective impact parameters, and which is of the order of 10). The fraction of the hadron ring length occupied by the cooling section is denoted by η. This gives an estimation of cooling times for protons in PETRA and has been calculated to be 5.3 min for longitudinal and 7.9 min for transversal cooling time.

6 CONCLUSIONS AND OUTLOOK

It has been demonstrated that there are no fundamental problems associated with the schemes presented above. The cooling times in PETRA, achievable using the presented injector, are in the range of several minutes when both beams are matched in size and bunch length. Furthermore, a solution for a recirculator, which is given elsewhere[3] allows the substantial reduction of DC beam power and repetition frequency of the gun.

The electron beam size optimization for fastest cooling rate demands further study. An extended analysis and further simulations must be performed to justify the complete electron track.

The given physical solution of the injector, may serve as a basis towards the goal of medium energy electron cooling.

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