Electron Cooling Possibilities for HERA

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Abstract

Electron Cooling of the hadron beam in HERA could be a way to upgrade the luminosity for electron-proton and electron-heavy ion collisions. Because of the necessary electron energy of 450 MeV for cooling protons and about 180 MeV for cooling heavy ions the conventional approach using electrostatic DC sources is not possible. Instead an electron storage ring could be used. For this ring there are special requirements like small damping times, small emittances, bunch sizes matched to the hadron beam and a long straight section for interaction with the ion beam. The feasibility of such an electron storage ring has been studied, and the results with a possible solution are presented in this paper. In the case of heavy ion operation the luminosity gain can be significant.

1 HEAVY IONS IN HERA

To access a new field of physics experiments it is under discussion to operate HERA with heavy ions instead of protons [1]. The heavy ion beam energy would be the proton energy of 820 GeV multiplied by Z/A, for example for $^{197}\mathrm{Au}^{79+}$ ions it would be 330 GeV/nucleon. One obstacle against reaching acceptable luminosities with heavy ions is the seriously enhanced intra-beam scattering (IBS) compared to protons. Even with small bunch charges the beam emittance would deteriorate within few hours.

Thus it is necessary to constantly cool the beam against IBS during the luminosity runs. It has been studied what performance can be reached with electron cooling: In a specific section of the ring the heavy ion beam is brought into overlap with an electron beam of same velocity, so that heat energy is transfered from the heavy ions to the electrons.

This method of cooling is successfully used at several low energy rings, where the cooling devices are conceived as electrostatic DC sources. In the case of heavy ion operation at HERA the beam energy of the cooling electrons has to be about 180 MeV. Thus an electrostatic source cannot be used, but an electron storage ring could be used instead, as first considered by Budker and re-investigated in the late 1970s [2][3].

Using a storage ring as electron cooler is in a way elegant, because the electrons, which absorb the heat energy of the ions, themselves loose this heat energy by emitting synchrotron radiation in bending magnets (radiation damping). This is in contrast to DC sources and LINAC based cooling devices, where the heated electron beam has to be dumped.

2 DEMANDS ON ELECTRON BEAM

For these studies the $^{197}\mathrm{Au}^{79+}$ ion was taken as an example. Under the assumption that the heavy ions are injected with the same normalized emittance as presently the protons, for a bunch charge of $N_I = 5 \cdot 10^8$ the IBS growth times are $\tau_{IBS,\perp} \approx$ 14 h, $\tau_{IBS,\parallel} \approx$ 1.2 h. The cooling times which can be achieved with electron cooling are [4] [5]

$$\tau_{c,\perp} \approx \frac{\gamma^5 I_A \theta_\perp^3}{6\pi c r_p L_C \eta J_e} \cdot \frac{A}{Z^2} \quad , \tag{1}$$

$$\tau_{c,\parallel} \approx \frac{\gamma^6 I_A \theta_\perp^2 \theta_\parallel}{6\pi c r_p L_C \eta J_e} \cdot \frac{A}{Z^2} \quad , \tag{2}$$

with I_A = 17 kA the Alfven current, $r_p = 1.5 \cdot 10^{-18}$ m the classical proton radius, J_e the electron current density, $L_C \approx 10$ the Coulomb logarithm and η the ratio of cooling section length to heavy ion ring length. If the cooling section is designed as an insertion with constant β functions, the beam divergences $\theta_\perp, \theta_\parallel$ are

$$\theta_\perp = \sqrt{\epsilon_e/\beta_e + \epsilon_I/\beta_I} \quad , \tag{3}$$

$$\theta_\parallel = \gamma^{-2}\sqrt{\sigma_{E,e}^2 + \sigma_{E,I}^2} \quad . \tag{4}$$

Thus to obtain small cooling times one has to aim for small electron emittances and energy spreads, large β functions and high currents. The damping times of the electron beam have to be small, otherwise the heat transfer from the ions to the electrons (subsequently called beam-beam scattering, or BBS) would cause an untolerable emittance growth of the electron beam. Also, small damping times help against the IBS of the electron beam, which is the main limiting factor for the achievable electron emittance.

The bunch spacing in the cooler ring has to be equal to (or an integer part of) the bunch spacing in the HERA ion ring, which is 96 ns (10 MHz). Also, the bunch dimensions should be equal or smaller than that of the ion bunches (they can be smaller because the protons perform betatron and synchrotron oscillations).

3 COOLER RING

The cooler ring under consideration has a circumference of 330 m and consists of a long cooling section with a length

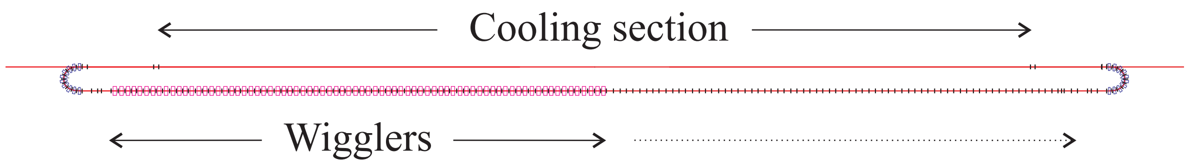

Figure 1: Cooler ring schematic layout

of 120 m, an opposite straight section with wigglers for increasing the damping decrements, and small arcs which fit into the existing HERA tunnel. A high-β insertion with β_x = 500-2000 m has been taken as cooling section. This type of insertion has the advantage of simplicity, since beside some matching quadrupoles there are no elements necessary within the cooling section. A schematic layout is shown in figure 1.

It has been studied what emittances and damping times can be achieved with reasonable efforts. In calculating the equilibrium emittance the synchrotron radiation, transverse coupling, IBS and BBS have been included. At the relatively low electron energy of 180 MeV IBS gives the main contribution to the equilibrium emittance.

For small emittances small damping times are necessary, and to achieve this there are foreseen wigglers. In principle nearly the whole straight section opposite the cooling section can be filled with wigglers. For the wiggler field strength it has been chosen 1 T, which can be reached with permanent magnets. Using wigglers with higher field strength is discussed below.

The beam parameters of the ring are given in table 1, in equilibrium with the proton beam being cooled. The transverse damping times are in the order of 200 ms. For the transverse heavy ion IBS growth time it has been assumed equal distribution between horizontal and vertical planes.

	HERA	cooler ring
beam energies	330 GeV/n.	180 MeV
N$_I$, N$_e$ per bunch [10^{10}]	0.05	5
ϵ_x, ϵ_y [nm rad]	1.9, 0.5	12.0, 2.9
β_x, β_y in cooling sect. [m]	2000, 500	500, 125
bunch length σ_z [m]	0.37	0.39
σ_E/E [10^{-4}]	2.5	8.9
$\tau_{c,\parallel} \approx \tau_{IBS,\parallel}$ [h]	0.14	
$\tau_{c,\perp} \approx \tau_{IBS,\perp}$ [h]	0.19	

Table 1: Beam parameters for HERA-p filled with heavy ions ^{197}Au^{79+} and for cooler ring

Obviously it would be best if the injected beam coming from the pre-accelerators already has the parameters of the cooling equilibrium. Nevertheless, if the beam is injected with the same normalized beam parameters as the present proton beam, it would take about three hours to cool down the beam to equilibrium, which seems a tolerable time span. The time evolution of specific luminosity with and without electron cooling is shown in Fig. 2.

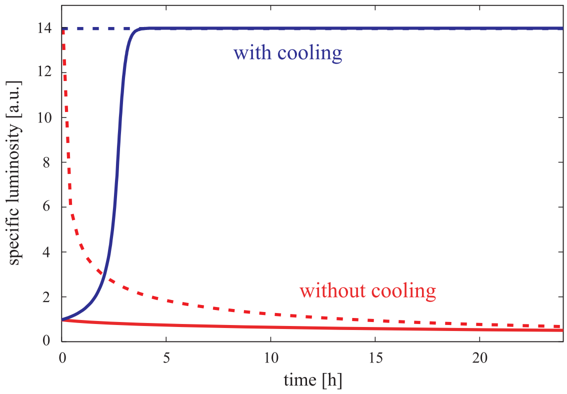

Figure 2: Luminosity evolution with and without cooling

4 COOLING PROTONS

It would also be possible to use the same ring for cooling the HERA protons, by setting the electron beam energy to 450 MeV and increasing the electron bunch charge, but the resulting cooling times and the beam parameters at equilibrium are rather modest. To enhance the cooling effect it would be necessary to build a cooler ring with larger arcs, which significantly increases the civil construction efforts.

Even then the achievable cooling times lie in the region of some ten hours, and it would take about 150 h to reach the equilibrium state. This implies that cooling protons in HERA only makes sense when they are already injected near the equilibrium beam parameters. It is under study if the proper injection parameters can be reached with the help of beam cooling in the pre-accelerator PETRA.

The beam parameters of the cooled proton beam and the cooling electron beam are given in table 2. The gain in luminosity would be about a factor of two, but the equilibrium energy spread and bunch length are about twice as presently at start of luminosity runs, because the longitudinal plane is not cooled effectively enough.

Table 3 gives a comparison of the HERA colliding beam parameters presently, after the scheduled luminosity upgrade (which mainly consists of minimizing the β functions at the interaction points) [6][7], and after the luminosity upgrade in combination with electron cooling.

5 ALTERNATIVE RING DESIGNS

Since the aforementioned approach for the electron beam optics the beam divergence and thus the achievable cooling times are limited by the electron emittance, another approach for an optics for the cooling section has been

	average in 1997		after upgrade 2000		with cooling	
	e-beam	p-beam	e-beam	p-beam	e-beam	p-beam
energy [GeV]	27.5	820	27.5	820	27.5	820
# of colliding bunches	174	174	174	174	174	174
part. per bunch [10^{10}]	2.8	4.8	4.18	10	4.18	10
ϵ_x, ϵ_y [nm rad]	49, 7.0	5.7, 5.7	22, 4.0	5.7, 5.7	22, 2.2	3.8, 0.9
β_x^*, β_y^* [m]	1.0, 0.7	7.0, 0.5	0.63, 0.26	2.45, 0.18	0.6, 0.10	3.5, 0.25
beam-beam tune shift / IP	0.0078, 0.020	0.001, 0.0003	0.027, 0.041	0.0017, 0.0005	0.031, 0.039	0.0030, 0.0018
peak luminosity [$\mathrm{cm}^{-2}\mathrm{s}^{-1}$]	$8.31 \cdot 10^{30}$		$7.4 \cdot 10^{31}$		$1.3 \cdot 10^{32}$	

Table 3: Beam parameters currently / after upgrade / with cooling

	HERA	cooler ring
beam energies	820 GeV	450 MeV
N_p, N_e per bunch [10^{11}]	1	2
ϵ_x, ϵ_y [nm rad]	3.8, 0.9	8.0, 2.0
β_x, β_y in cooling sect. [m]	1000, 250	1000, 250
bunch length σ_z [m]	0.31	0.22
σ_E/E [10^{-4}]	2.1	4.4
$\tau_{c,\|} \approx \tau_{IBS,\|}$ [h]	9.0	
$\tau_{c,\perp} \approx \tau_{IBS,\perp}$ [h]	34.2	

Table 2: Beam parameters for HERA-p and for cooler

studied. In combination with a skew quadrupole block the edge focusing of a solenoid can be used to transform a flat beam (i.e. no vertical emittance) into a divergence-free round beam [8][9].

The limitation of this scheme is given by the achievable vertical emittance, since it defines the beam divergence within the solenoid. Depending on the vertical emittance the resulting beam divergence within the cooling section can still be significant. Also, with a flat beam the IBS effect grows considerably, so that the resulting cooling performance is not necessarily improved compared to the high-β approach.

To further reduce the damping times (and thus the influences of IBS and BBS) the radiated power could be increased by using stronger wiggler fields. In principle it is possible to foresee superconducting high-field wigglers, but then the beam energy spread is increased. The energy spread in the cooling section can be reduced to an appropriate level with the help of an energy compressor system in front and a symmetric anti-compressor behind. With such a system the energy spread in the cooling section would be smaller and the bunch length larger than within the rest of the ring.

To justify the additional technical efforts described above, further analysis and simulations have to be carried out.

6 SUMMARY

It has been studied what can be achieved with electron cooling in the case of HERA. For operation of HERA as electron - heavy ion collider, beam cooling allows significantly higher luminosities than without cooling. A storage ring based cooler can deliver more than sufficient beam parameters, and could be constructed small enough to fit into the existing HERA tunnel.

For the case of cooling the HERA protons the beam parameters achievable with a storage ring are roughly sufficient to counteract emittance dilution during a luminosity run caused by IBS, but only at larger longitudinal emittance. It is also necessary to inject a beam already precooled in the pre-accelerators. The gain in specific luminosity can be near a factor of two.

7 REFERENCES

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