# PROSPECTS OF HIGH ENERGY ELECTRON COOLING

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*Abstract*

Recent years' studies of possibilities to build the efficient relativistic electron cooling devices led to innovative concepts of electron beam transport and acceleration as well as to the new approaches to organization of cooling process and colliding beams regime. The new optical solutions, conceptual designs, current R&D, and tentative proposals to upgrade the luminosity of colliders will be discussed and illustrated in this report.

## 1 INTRODUCTION

The modern hadron colliders have been operated or designed near the limits of luminosity determined by their optical strength. Next luminosity upgrades of colliding beams refer to decrease of beam emittances or maintaining them using a suitable cooling technique. Electron cooling method invented by G.Budker in 1966 [1] and realized in Novosibirsk in 1974 [2,3] can be considered today as a perspective candidate for such services, in view of following reasons: 1) this method does not meet a limit - in principle of cooling rate due to beam intensity; 2) it possesses a high credibility based on quite a long history of its successful development and employment at low energies [4,5]; 3) accumulated experience and recent progress in development of electron injectors and accelerators allow to consider the existing technology sufficient to produce intense high quality electron beams required for electron cooling; 4) recent establishments and ideas in the area of optical transformations and transport of charge particle beams [5-8] promote substantially the electron cooling capabilities.

The new concepts, tentative proposals, and current R&D are the subject of this report. The contents are based on contributions to recent workshops on electron cooling [5], reports to this conference [9-11], and on some new proposals and ideas.

## 2 ELECTRON COOLING AND LUMINOSITY

Cooling effect on luminosity is expressed in two factors: 1) increase the start-up the luminosity by emittance decrease to a limit determined by admittable tune shift; 2) prevention of beams blow-up due to IBS, noise, and beam-beam stochastic influence. There are the important observations that the tune shift limit and non-linear stochastic effects depend on beam structure in phase space. Electron cooling is also effected by beams disclosure in phase space. On the other hand, there are the certain possibilities to control these links in order to maximize the cooling effect and luminosity.

### *2.1 Equalization of cooling decrements*

Transverse temperature of relativistic beams usually is large with respect to the longitudinal one ($\gamma\theta >> \Delta\gamma/\gamma$, where $\theta$ is for angle spread). It results in a correspondent ratio between cooling times: $\tau_\perp \sim \tau_\parallel \cdot (\gamma^2\theta/\Delta\gamma)$. Transverse extension of beams is usually considered as a measure to raise the transverse cooling rate; however, it requires a very large beam defocusing in cooling section that makes it difficult the beam alignment. Instead, one can redistribute cooling decrements organizing the <u>dispersive cooling</u>. The arrangement consists in introduction of dispersion for hadron beam in cooling section, and offset in $\gamma$ and transverse positions between electron and hadron beam. An alternative to beam offset is introduction of electron dispersion if suitable [6,12,26].

The equalized cooling rates can be expressed by formula

$$\tau_c^{-1} \sim \frac{Z^2}{A}\frac{r_e r_p c}{\gamma\varepsilon_6}\eta N_e \frac{log_c}{\sqrt{1+(\Delta\gamma_e/\Delta\gamma)^2}}, \qquad (1)$$

where $\varepsilon_6 = \varepsilon_x\varepsilon_y\varepsilon_\parallel, \quad \varepsilon_\alpha = \sigma_\alpha\Delta p_\alpha/mc, \quad log_c \le 12$, $r_e$ and $r_p$ are for the classical radii of electron and proton, $Z$ and $A$ are for the hadron atomic number and weight, $N_e$ is for number of particles in electron bunch, $\eta$ is the cooling section length respectively to hadron beam orbit circumference, and $\varepsilon_\alpha$ are for hadron normalized emittances. The <u>Coulomb</u> logarithm of electron cooling, $log_c$, is determined by ratio between effective maximum and minimum impact parameters; it varies from a maximum value of about $\sim$12 at $\theta >> \theta_e$ to a minimum of about 4-2 at $\theta << \theta_e$, when contribution of collisions with electron <u>Larmor circles</u> prevaluate in cooling effect. Expression in (1) is obtained by averaging the instantaneous cooling rates over hadron particles 3-dimensional oscillations under conditions that the beams' transverse sizes are matched, while the electron bunch length is shorter than that of hadron beam.

### *2.2 Electron cooling against IBS*

In the area $\gamma >> Q$, where $Q$ is for characteristic "betatron tune", the IBS rates can be estimated as

$$\tau_\parallel^{-1} = \frac{Z^4}{A^2}N\frac{r_p^2 c}{\gamma\varepsilon_6}\frac{\gamma^2\theta_y}{\Delta\gamma}\cdot log_h, \qquad log_h \approx 20-15 \quad (2)$$

$$\tau_{\parallel} : \tau_x : \tau_y = \left(\frac{\Delta\gamma}{\gamma}\right)^2 : Q^2\theta_x^2 : \left\{\gamma^2\theta_y^2/[1+(\frac{\gamma\kappa}{Q})^2]\right\}, \quad (3)$$

where $\kappa$ is for $x-y$ coupling.

IBS cooling criterium can be found from equation $\tau_c = (\tau_\alpha)_{min}$; usually $\tau_{||}$ is a minimum of three cooling rates as result of beam acceleration before cooling. Equilibrium criterium can be found at $\tau_{||} = \tau_x = \tau_y$:

$$N_e > N_{cr} \sim \frac{N}{\eta}\frac{Z^2}{A}\frac{m_e}{m_p}\sqrt{1+\left(\frac{\gamma\kappa}{Q}\right)^2}\frac{log_h}{log_c}, \quad (4)$$

then $\Delta\gamma = (N_{cr}/N_e)\Delta\gamma_e$, at

$$\frac{\gamma\theta_x}{\Delta\gamma/\gamma} = \frac{\gamma}{Q}; \qquad \frac{\theta_y}{\theta_x} = \sqrt{\kappa^2 + (Q/\gamma)^2}\,. \quad (5)$$

Thus, a minimum (possibly small ) $\kappa$ leads to a flat equilibrium, minimum $\varepsilon_6$, and maximum cooling rate.

### 2.3 Equilibrium cooling with electron fringe

The dispersive cooling with flat beams being employed at very high energies allows to substantially reduce the critical number of electrons required to fight the IBS. However, considering cooling at equilibrium, one has to remember that the longitudinal drag force (hence, the cooling rates) jumps down for particles of transverse amplitudes exceeding the electron beam size. A possible measure to extend the beam core life time might be to compliment the electron beam by a ”fringe” of density behaviour

$$n(r_\perp) = n_o\frac{a^2}{r_\perp^2}$$

from electron core radius $a$ to fringe radius $b >> a$. Then the particles scattered out of beam core could be returned during a desirable time, while the critical (total) number of electrons will be increased by a factor $\sim 2\ln(b/a)$, instead of $(b/a)^2$.

### 2.4 Beam-beam reduction with round star-focus using beam adapters

Very flat, deeply cooled beams could not be suitable for hadron colliders, because of too strong beam-beam interaction. To moderate it, the flat beams can be transformed to round ones at collision area applying adapting optics, or plane-vortex transformers [6,13,14]. Then, the star tune shift and luminosity will be controlled by the large of two emittances, $\varepsilon_x$ ($\Delta\nu_y = \Delta\nu_x$). Since the colliding beams are round and particle tracks in partner beam area are also close to circles, the beam-beam interaction becomes essentially regularized. Therefore, one can expect a strong reduction of stochastic effects and increase of $\Delta Q$ beam-beam limit. At the same time, one has a strongest cooling that also stabilizes the beams.

## 3 OPTICAL PRINCIPLES OF BEAM TRANSPORT FOR RELATIVISTIC ELECTRON COOLING

### 3.1 Cooling in solenoid

Electron beam transport in a solenoid (with immersed gun cathode) is a traditional optical solution for electron cooling at non-relativistic energies . It also can be considered as a favorable solution for all energies, in view of two important reasons: 1) solenoidal transport resolves a contradiction between the requirements of a strong focusing and low transverse temperature of electron beam along an extensive cooling section; 2) cooling efficiency with magnetized electron beam is limited only by electron longitudinal temperature which is very small comparatively to the transverse one [6,7,12,27].

But it would be difficult and impractical to combine a continuous solenoid with an efficient accelerator line and/or an electron cooler ring.

However, does the solenoid necessarily have to be continuous?

### 3.2 Magnetized beam acceleration and transport with discontinuous solenoid

Recent years’ investigations led to establishment of new optical solutions for electron cooling accelerator lines as well as for recirculators or storage rings [6-8].

In case of electron line, an extended solenoid could be used only in electron gun (injector) and cooling section, while a lumped focusing (axial, quadrupole, including bends, etc.) can be applied along the rest of transport line. In other words, a calm beam state can be ejected from magnetized electron source, transported through all the acceleration line, and injected in solenoid of cooling section. Matching conditions (including compensation for various aberrations) have been formulated, proved on general base of Hamilton’s dynamics [8], and confirmed in simulations [9-11]. Matching conditions are expressed, in general, in resulting conservation of cyclotron adiabatic invariant $p_\perp^2/B$. Magnetized, or calm beam state is referred to a typical situation $p_\perp^2/meB << \frac{SeB}{\pi mc^2}$, where $S$ is beam area.

When $p_\perp^2/B$ is conserved, this automatically leads to conservation of magnetic flux across the beam [8]. Thus, a matched transition between two solenoids is equivalent to adiabatic transition in a continuous slowly varying solenoid.

Matching demands leave a wide freedom to design a suitable focussing channel of electron linacs.

Transport concepts with magnetized beam in solenoid have been extended to recirculator rings. Here the cooling section solenoid becomes a part of focusing lattice of electron ring (optically conjugated with electron accelerator at injection)[6,11].

### 3.3 Electron recirculators and storage rings with adapting optics

Beam adapters being introduced in high energy electron rings transform beam area in solenoid into the (large) horizontal emittance in arcs: $\varepsilon_d = (eBS/\pi mc^2) = \varepsilon_x$, while the cyclotron emittance becomes transformed into a small vertical emittance: $(< r_c^2 > eB/mc^2) = T_\perp/eB = \varepsilon_y$ [6,15-18].[1] Such adaptation extends the life time of electron temperature in solenoid against IBS and radiation effects outside the solenoid.

Note that non-magnetized electron guns with flat cathodes can be used, in principle, to obtain magnetized beam in solenoid with help of adapters, although such a way seems not practical in view of very large required ratio between cathode sizes $(\sigma_x/\sigma_y = \frac{\varepsilon_d}{\varepsilon_c})$ [8].

Finally, it follows from the above discussion that there is no way to inject a round electron beam from a non-magnetized gun into a solenoid avoiding a large cyclotron beam excitation $(r_c \sim \sqrt{S/2\pi})$ [8].

## 4 MAGNETIZED INJECTORS WITH RING CATHODE AND HOLLOW BEAM CONCENTRATOR

Space charge destructive effects on beam emittance in electron sources can be reduced or maximum current increased at use of ring-shaped magnetized cathodes that generate the hollow beams. After acceleration to a properly high energy the beam can be concentrated applying alternating dipole magnets in resonance with particle tune in focusing field along the beam line [6]. The concentration principle is similar to that has been used for bunching of coasting beams.

## 5 MEDIUM ENERGY ELECTRON COOLING PROJECTS

Currently, there are two relativistic energy range electron cooling projects being developed at existing colliders: at Fermilab, for 8.9 GeV/c antiprotons in the Recycler ring [9], and at DESY, for a 15-20 GeV bunched proton beam in PETRA ring [10].

The goal of cooling in Recycler is to attain the luminosity $10^{33}/cm^2 \cdot s$ for $p\bar{p}$ beams in Tevatron, by recycling and refilling the $\bar{p}$ beam. The basic element of cooling device is electrostatic accelerator 4.5 MeV (Pelletron) of current 0.5-1 A (under commissioning). Solenoid covers cooling section (20 m), electron gun, and collector, at lumped focusing between them over bends, e.t.c. The design of matched beam transport has been confirmed in simulations [9]. The estimated cooling time at refilling is 15 min.

Increase the start-up the luminosity (by a factor 2-3, at least) of $pe^\pm$ colliding beams in HERA ring is a goal of electron cooling in PETRA. The proton beam can be cooled vertically, since the IBS is relatively week in this plane; the cooled $p$-beam should match the $e^-$ or $e^+$ partner colliding beam [10].

The basic element of cooling device (under conceptual development since 1997) is an RF electron linac 10 MeV, with magnetized pulse injector (grid-operated cathode or RF-gun laser-stimulated). Lumped focusing (after 2-4 MeV) is designed to cooperate with RF structure and transmit the $e$-beam to magnetized cooling section (50 m). Optical matching has been tentatively designed and confirmed in simulations [10].

Electron recirculator ring 10 MeV is an essential complementary to electron linac in DESY project: it will allow to reduce the injector (and warm linac) repetition rate to 30-10 kHz ( instead of 10 MHz). The high beam quality life time (hence, repetition rate) is limited by $e-e$ and $p-e$ intrabeam scattering [11].

The estimated cooling time for 95 % p-beam emittance is 5 min.

Table 1: Electron storage ring-cooler for RHIC (heavy ions)

| | |
|---|---|
| $\gamma$ | 108.4 |
| $N_e$ | $1.5 \times 10^{10}$ |
| $\ell_b$ cm | 15 |
| Circumference, m | 200 |
| Number of bunches | 60 |
| Solenoid, m×G | 40×390 |
| Wiggler, m×T | 40×3.6 |
| Life time, min | 0.6 |
| $(\tau_c)_{\|\|}$, min | 8 |
| $(\tau_c)_\perp$ | 28 |

## 6 COOLING WITH ELECTRON STORAGE RINGS

Before recent years, electron cooling with storage rings, where the electron beam itself is cooled by the radiation, was not considered as a promising possibility, because of a large electron emittances due to quantum fluctuations of radiation in wigglers (high energies) and $e-e$ IBS (lower energies). Introduction of beam adapters [6,15-18] to transform a flat beam (large $\varepsilon_x$ emittance) to a round beam in solenoid (with a low temperature due to only the vertical emittance in arcs, at a maximally reduced coupling) remove this deficiency. Tentative conceptual designs are illustrated in Table 1 [19] and 2 [6,20].

[1] It should be noted that this factorization is not voluntary, but reflects a true disclosure of a magnetized beam statistical state ($r_c^2 << S/\pi$) in canonical phase space of solenoid [8].

Table 2: Storage Ring-Cooler at $\gamma = 10^3$ (Tevatron/HERA)

| | |
|---|---|
| Circumference, m | 140 |
| $N_e$ | $10^{12}$ |
| Wiggler, m×T | 40× 6 |
| Solenoid, m×T | 60× 1 |
| Adapter length, m | 2 |
| $\sigma_\parallel$ in wiggler, cm | 3 |
| $\sigma_\parallel$ in solenoid, cm | 25 |
| $\Delta\gamma/\gamma$ in solenoid | $10^{-4}$ |
| $(\varepsilon_\perp)_p$, norm, mm×mrad | $\pi$×2.5 |
| cooling time | 2h |

## 7 LINAC-BASED COOLING IN COLLIDER RINGS

The established possibility to transport high quality electron beams from magnetized guns to solenoid of cooling section using a convential lumped focusing allows to extend the linear electron cooling to high energies of collider rings.

After $e$-beam forming and pre-acceleration in injector (as above described), the beam could be accelerated to tens, hundreds, and even thousands of MeV ($\gamma = 7 \times 10^3$ - the LHC case !). A superconducting linac with energy recovery would be the most suitable to be used for this goal; recently, the recuperation has been successfully realized at Jefferson Laboratory in e-linac 48 MeV [21].

The loading of electron injector and linac can be essentially reduced at incorporation with recirculator ring.

The cooling agenda for a main ring might consist of two stages: precooling at injection energy, and cooling at top energy of the ring; here, the equilibrium emittances can be limited by the beam-beam interaction. At a slow acceleration (HERA case), the e-beam could continuously accompany the hadron beam, to maintain the hadron emittances against IBS.

At a proper reduction of betatron coupling outside the cooling section (for both of beams), the beams could match the flatten areas in solenoid, to maximize the cooling rate; and, as described in Section 2, plane-vortex adapters can be employed to transform the flat colliding beams to round ones at collision area, in order to reduce the beam-bean tune shift to (an increased) admissible level. As result, the luminosity could rise significantly.

Table 3 and 4 illustrate the estimated beam parameters and cooling rates.

It should be noted, that the necessary electron bunch charge is determined not as much by a requested cooling rate as by the cooling criterium due to IBS (see relationship in (4)).

In the reality, equilibrium cooling rates and emittances at top energies cam be limited by beam misalignments. In this connection, again, the dispersive cooling looks a favorable option comparatively to the beams extension.

Table 3: Linac-based cooling in collider rings (low energy stage)

| | RHIC | HERA$^{1)}$ | Tevatron$^{2)}$ | LHC$^{3)}$ |
|---|---|---|---|---|
| | $Au/p$ | $p$ | $p,\bar{p}$ | $p$ |
| $\gamma$ | 25 | 40 | 150 | 450 |
| $\kappa, \%$ | 10 | 10 | 5 | 5 |
| $\eta, \%$ | 1 | 2 | 1 | 1 |
| $N$, $10^{11}$ | $10^{-2}/1$ | 1 | 1 | 1 |
| $\Delta\gamma/\gamma$, $10^{-4}$ | 3 | 1.5 | 1 | 1 |
| $\sigma_\parallel$, $cm$ | 30 | 30 | 30 | 15 |
| $\varepsilon_x$ $^{4)}$ | 8/4 | 1.2 | 1.6 | 1 |
| $\varepsilon_y$ | 4 | 0.2 | 1.6 | 0.01 |
| $N_e$, $10^{11}$ | 0.5 | 0.5 | 1.5 | 4 |
| $\tau_c$, min $^{5)}$ | 0.3/5 | 0.5 | 5 | 0.5 |

$^{1)}$after cooling in PETRA
$^{2)}$after cooling in Recycler
$^{3)}$after cooling in SPS
$^{4)}$ $\pi \cdot mm \cdot mrad$, r.m.s. value
$^{5)}$ for 95% beam population

Table 4: Linac-based cooling of colliding beams

| | RHIC | HERA | Tevatron | LHC |
|---|---|---|---|---|
| | $Au/p$ | $p$ | $p,\bar{p}$ | $p$ |
| $\gamma$ | 108/250 | $10^3$ | $10^3$ | $7{\times}10^3$ |
| $\Delta\gamma/\gamma$, $10^{-4}$ | 1 | 1 | 0.5 | 0.5 |
| $\sigma_\parallel$, $cm$ | 5 | 15 | 7.5 | 3.7 |
| $\varepsilon_x$ | 0.1/0.25 | 1 | 0.5 | 0.5 |
| $\varepsilon_y$, $10^{-3}$ | 7/5 | 10 | 1 | 1 |
| $\tau_c$,min$^{1)}$ | 0.1/5 | 10 | 0.5 | 5 |

$^{1)}$estimated for r.m.s. emittances

## 8 CONCLUSION AND OUTLOOK

Recent developments in the area of electron and hadron beams optics taken together with accumulated experience and progress in beams transport, acceleration, and diagnostics, compose a sufficient conceptual and technological base for design and construction of efficient relativistic electron cooling devices for hadron colliders. As a critical issue of high energy electron cooling, the beam alignment possibilities should be investigated extensively, basing on the existing methods and technology.

Increase of luminosity of hadron colliders will not be the only benefit of high energy electron cooling. Today, there is a growing interest and quests to spin-polarized colliding beams, $pe$ [28], $pp$ [29], and $p\bar{p}$ [30]. A strong reduction of beam emittances will make it much easier the acceleration and maintenance of polarized beams in hadron rings arranged with Siberian Snakes [28,31,32]. One can also mark the Stern-Gerlach beam splitting [33-35] as a special possibility to obtain polarized $\bar{p}$ and $p$ beams that might become real with electron cooling at top energies of hadron rings.

Looking for more cooling potential one could recall the electron cooling of positrons [22-25]. This is a very intense process, thank to a small value of $e^+$ mass, magnetization [22,23], and possibility to employ the sweeping and dispersive cooling tricks [12]. Creation of a positron storage ring cooled by a linear electron beam might bring new possibilities for effective cooling of hadron beams; in particular, recombination of heavy ion beams could be removed.

Finaly, electron-positron cooling should be investigated also as a way to obtain low emittance $e^+$ and $e^-$ beams for effective $e^{\pm},\ e\gamma$, and $\gamma\gamma$ colliders.

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