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Section A

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Advanced optical concepts for electron cooling☆

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Abstract

The results of explorations of non-traditional solutions of beam transport which could raise the electron cooling rates and efficiency are presented. The proposed optical elements, methods, and conceptual designs are summarized in the following. (1) Magnetized electron beam acceleration and transport with discontinuous solenoid to provide matching between the electron gun and solenoid of the cooling section. These concepts allow the possibility to design and build economical, high beam quality accelerators for electron cooling over a wide energy range, up to that suited for hadron colliders. (2) A special beam adapter (skew quadrupole block) to transform between a magnetized and a flat beam state. This element meets a variety of uses in electron cooling trends. (3) Injectors with ring-shaped cathodes and resonance concentrators of hollow beams involving (optionally) beam adapters. (4) An isochronous (at no RF) electron recirculator ring with a solenoid in the cooling section and beam adapters. (5) Electron storage rings incorporating strong wigglers, solenoid in cooling section with beam adapters, non-coupled focusing outside the cooling section, and (optionally) a strong longitudinal optics for beam compression in wigglers. (6) Hadron beam optics in the cooling section with non-extended beams and dispersion introduced in order to maximize the transverse cooling rate. (7) Low-energy cooling with matched electron and hadron beams. (8) Low-energy cooling with hollow beams. © 2000 Elsevier Science B.V. All rights reserved.

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1. Introduction

Electron cooling was proposed by G. Budker in 1966 [1] as a method to cool heavy particle beams; since its realization in Novosibirsk in 1974, the idea to employ this method to cool hadron beams in colliders continues to excite the minds of the high-energy physics community. The attractiveness of electron cooling can be explained by the consideration that it is capable of cooling intense beams, while the efficiency of its companion, stochastic cooling proposed by Van der Meer in 1968 and employed to accumulate the antiprotons with great success (1984), drops with beam current, especially in case of bunched beams. This respect could change with the realization of microwave feedbacks; ultimately, it could be the optical stochastic [2]

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or earlier proposed electron-stochastic cooling [3,4]. So far, however, the "ordinary" electron cooling has another important advantage: high credibility based on quite a long history of its successful development and employment at low energies [5,6]

According to electron cooling principle, an electron beam has to accompany a hadron beam in a straight in order to serve as a thermostate. There are, in general, two possible ways to obtain multi- and high MeV electron beams for cooling of multi- and high GeV hadron beams: electron linacs and electron storage rings. A linac (with or without energy recovery) can be complemented by a recirculator ring, in order to decrease the repetition rate [23]. Also, the optimum approach would be to combine a linac-based medium energy cooler with an electron storage ring-cooler at the top energy of a hadron facility.

Electron cooling in a synchrotron was proposed and treated earlier as a method to cool high-energy proton and anti-proton colliding beams at energies $\sim 2000\,\text{GeV}$ [7,8]. Recently, studies of physics and the capabilities of high- and medium-energy electron cooling were revived in connection with the quest to raise the luminosity of hadron colliders in the energy range 0.25–1 TeV [9–13]. The difficult and controversial issues related to demands on electron beam energy, current, and quality, do not allow an efficient technical concept of high- or medium-energy electron cooling devices, if to be developed based on traditional solutions of beam transport and acceleration. For a storage ring, the main obstacle is a large transverse temperature of electrons caused by the synchrotron radiation and intrabeam scattering in the arcs. The linac-based case (medium or high energies) challenges one with a need to combine the efficient acceleration (either potential or RF) with beam transport suitable for the electron beam as a cooler.

Below we will discuss some new ideas which seem helpful to resolve the principal issues of relativistic electron cooling (Sections 2–7).

Some of the proposed improvements seem to be of interest to low-energy cooling as possible ways to reduce the limitations due to the space charge (Sections 8 and 9).

2. Magnetized electron beam acceleration and transport with discontinuous solenoid

Electron beam transport with the beam immersed in a solenoid (starting at the gun cathode) is a traditional optical solution for electron cooling at low energies (below 1 MeV). It could also be considered as a favourable principal solution for all energies, since it resolves a contradiction between the requirements of strong focusing and low transverse temperature of the electrons along the cooling section. It also helps to preserve the electron emittances against the destructive Coulomb forces, etc.

But it is technically difficult and cumbersome to combine a continuous solenoid with effective acceleration to a multi-MeV energy range. However, does the solenoid necessarily have to be continuous? Or, more generally, is there a law or a rule that one can avoid beam excitation only by adiabatically slow variation of the solenoid strength? The answer is: no, the adiabatic conditions are not necessary; in fact, there is a continuum of non-adiabatic transparent transitions between two solenoids, either with equal or different field values. An extended proof of principle analysis of this issue has been undertaken during our studies of electron beam transport, options for electron cooling in Recycler of Fermilab [14], LISS project of IUCF, and PETRA at DESY. The outlines are presented below.

2.1. Linear matching

Considerations based on a linear theory can be summarized in the following points:

1. State of particle motion in a solenoid is a superposition of Larmor oscillator and drift component (i.e. Larmor center position):

$$\boldsymbol{\rho} = \boldsymbol{\rho}_{\mathrm{d}} + \boldsymbol{\rho}_{\mathrm{L}}.$$

2. Matching between two solenoids (1 and 2), or conditions of the optical transparency, are expressed in resulting conservation of the "magnetic flux".

$$(B\rho_{\mathrm{d}}^2)_1 = (B\rho_{\mathrm{d}}^2)_2$$

$$(B\rho_{\mathrm{L}}^2)_1 = (B\rho_{\mathrm{L}}^2)_2 \tag{1}$$

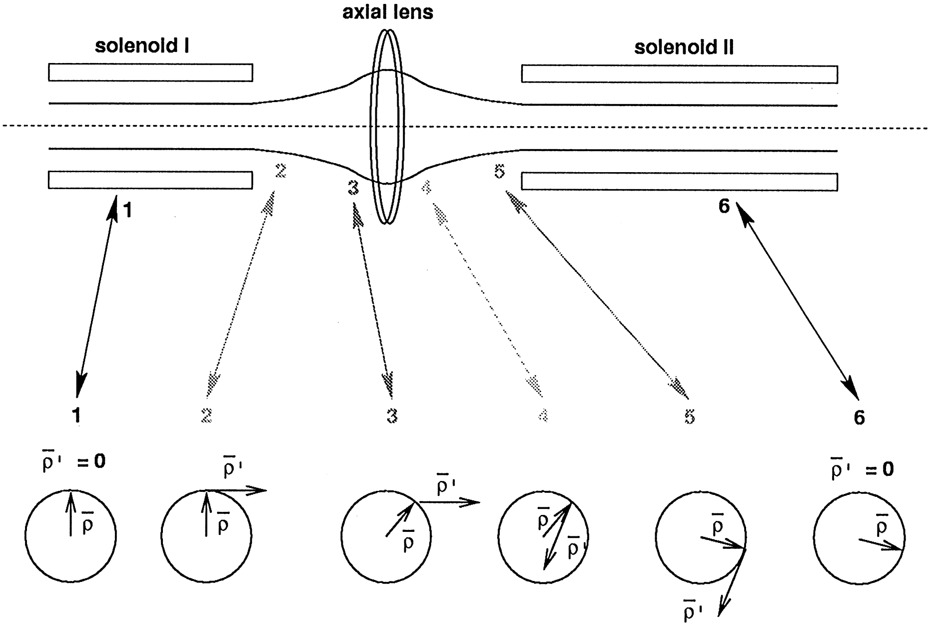

Fig. 1. Principle of axial matching.

which is a reflection of conservation of the generalized axial momentum.

3. There is a continuum of different magnetic lattices for a transparent transition between two solenoids.
4. Not only axially symmetric magnets can be used for a transparent beam transport between solenoids, but also quadrupoles and dipoles (i.e. bends).
5. Matching conditions in Eqs. (1) are not changed by acceleration and can be satisfied without a principal restriction on acceleration rate and energy change. Fig. 1 illustrates the principles of axial matching. Possibilities of matching are confirmed in the simulation search for transparent transitions between solenoids, with and without acceleration [15–17].

2.2. *Compensation for dispersive effects*

Since the Larmor parameters ρ_L related to the cathode temperature are very small ($\sim 10\ \mu\text{m}$ at $B = 1$ kG), a mismatch related to different perturbative forces is a significant issue of magnetized electron beam transport (in general, not only at a discontinuous solenoid!). The perturbations are even more challenging when they possess a dispersion across the beam, and there are several such factors as follows.

1. Non-linearity of the alternating axial field. In the lowest approximation, the longitudinal magnetic field behaves as

   $$B(z, \rho) = B(z) - \tfrac{1}{4}B''(z) \cdot \rho^2$$

2. Chromatic effect related to the RF-introduced energy gradients along the bunch.
3. RF induced transverse kicks.
4. Coulomb force (transverse acceleration):

   $$(\rho'')c = gk(z)/p^3(z)\xi(z)$$

   where k and p are the bunch compression factor and particle momentum, function $\xi(z)$ describes the evolution of beam transverse size, while the constant parameter g ($g' = 0$) describes the transverse and longitudinal behavior of the Coulomb force.

Each of these dispersive factors, in general, excites a Larmor oscillator, $(\rho_L)_{\text{exc}}$ near a given (drift) electron position in the cooling section which can exceed the thermal level:

$$\rho_{\rm d} \gg (\rho_{\rm L})_{\rm exc} \geq (\rho_{\rm L})_{\rm T}.$$

The compensation challenge consists in a specific design for electron transport, where the interference between different sections results in vanishing of the Larmor excitation in the cooling section [13]. This can be achieved by adjusting the Larmor phase advances. Also, special correction magnets (coils, etc.) can be introduced for a final beam adjustment in the cooling section.

3. Vortex-plane beam adapter

The described approach is also extendable to beam transport which involves non-axial magnets. The so-called beam adapter [18–20] is an ultimate example of a non-axial beam transformer.

A beam adapter is a quadrupole block which transforms a cold (zero temperature) beam, ejected from a solenoid, into a flat beam of emittance (normalized)

$$\varepsilon_d = \pi \langle \rho_{\rm d} \rangle^2 eB/mc^2, \tag{2}$$

if the beam possesses a non-zero transverse temperature in the solenoid, it becomes transferred to the other plane, orthogonal to the first, with emittance

$$\varepsilon_{\rm L} = \pi \langle \rho_{\rm L}^2 \rangle eB/mc^2 = T_\perp / eB. \tag{3}$$

The mechanism is as follows. After a beam has passed the solenoid, its fringe field transforms the drift degree of freedom in a vortex (at some point), while the Larmor component becomes transformed into the opposite vortex (with linear accuracy). The adapter's 4×4 matrix is diagonal with respect to its own planes:

$$C_{\rm o} = \begin{array}{c|c} M & O \\ \hline O & N \end{array} \tag{4}$$

with an arbitrary 2×2 quadrupole matrix M, but under condition $N = F \cdot M$, with

$$F \equiv \begin{pmatrix} O, & 2\beta_{\rm s} \\ -1/2\beta_{\rm s}, & O \end{pmatrix}, \quad \beta_{\rm s} = \frac{pc}{eB_{\rm s}}. \tag{5}$$

The adapter transforms the two vortices into the two planes (x, x') and (y, y') oriented 45°, with respect to the quadrupoles' normal planes. Thus, in order to transform the drift component in the solenoid into horizontal motion, the adapter has to be rotated by 45°; then, the Larmor motion will be transformed into vertical motion (Fig. 2). A reverse transformation is obvious.

Adapters can be used in conjunction with solenoids, in order to improve electron beam quality and cooling features; examples will be shown.

4. Electron injectors with ring cathode and resonance concentrator of a hollow beam

The space charge forces effects on beam emittances in electron sources can be reduced (at a given current value and beam cross-section area) by the use of ring cathodes, which produce a hollow beam or halo bunches. The gains of ring (magnetized) cathodes are obvious:

1. Reduction of space charge impact on Larmor emittance by factor $d/2a$ (or, even stronger- at very short bunches available in RF guns), with a and d as the ring radius and width, respectively.
2. Reduction of Coulomb energy spread by the same factor (note, that a flat cathode does not give this reduction).

In addition, there is an increase of the perveance by a factor of $(2a/d)^{1/4}$.

However, after the gun one has to deal with a hollow beam. For some use the hollow shape might be neutral, for some specific ones even useful, and for some destructive.

It is possible and practical to introduce a special technique for effective and fast concentration of a hollow beam without a substantial increase of beam phase space area. The idea is very similar to that which is used to bunch a coasting beam: apply an alternating field resonant with the particles' circulation in the phase space. In order to introduce these principles to the transverse dynamics, one has to magnetize the beam (i.e. cathode): then, the ring-shaped beam area plays the role of a coasting beam (thermal Larmor radius must be smaller than the

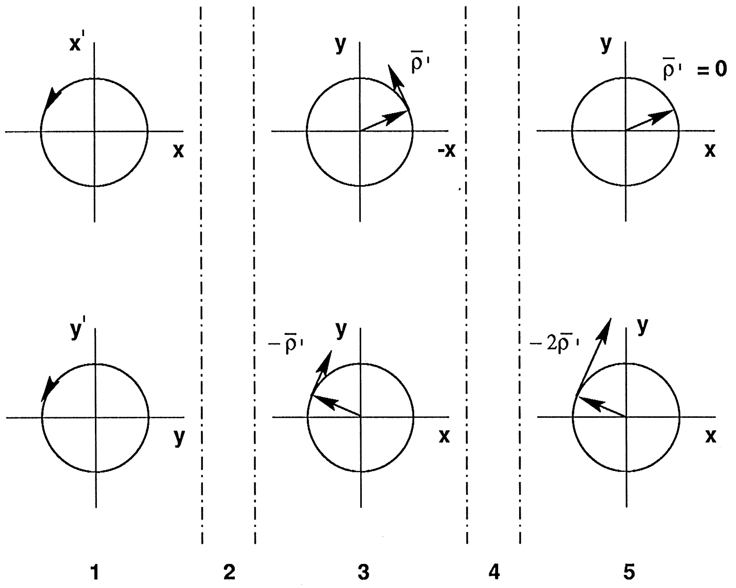

Fig. 2. Matching between a conventional optical channel and solenoid. 1: channel with separated phase planes; 2: beam adapter (skew quadrupole block turned 45°); 3: circular modes created by beam adapter; 4: solenoid's fringe field stops one of two vortices and doubles the other one; 5: drift and Larmor modes in solenoid.

ring width). After pre-acceleration of the hollow beam (with or without extraction from solenoid) to a relatively high energy such that the space charge effect on emittance becomes negligible, resonance dipole magnets and a sufficient non-linearity have to be introduced to perform the concentration procedure along the beam line. It can be arranged in three possible ways: (a) in solenoid, manipulating the drift beam motion by long-wave resonance dipole magnets; (b) in an axial channel (reversing solenoids) after beam extraction from solenoid, applying dipole magnets resonant with the beam rotation; (c) after transformation from a round to a plane state (by beam adapter), manipulating the beam resonantly by dipoles transverse to the beam plane. Let us illustrate the concentration process in case (c), which is the most simple for analytical modeling. Particle dynamics can be followed according to equations for amplitude a and relative phase $\varphi = \psi - kz$ $(x = a\cos\psi, x' = (a/\beta_o \sin\psi)$:

$$a' = -\frac{1}{a}\frac{\partial H}{\partial \varphi}, \quad \varphi' = \frac{1}{a}\frac{\partial H}{\partial a}, \quad \left(\psi' = \frac{1}{\beta_o} + \varphi'\right)$$

with Hamiltonian

$$H(a, \varphi) = \frac{g}{4}(a^2 - a_o^2)^2 - \frac{\beta_o}{2R_o} a \cos\varphi$$

where g is an octupole constant, $R_o = pc/eB_o$, $B(z) = B_o \cos kz$ is the resonance harmonic of the dipole field, and a_o is the resonance amplitude at $B_o = 0$.

The phase concentration process will be driven by the beam confinement in the resonance island of the width

$$\frac{\Delta a_r}{a} \approx 2(R_o\beta_o/ga^3)^{1/2}$$

and beat frequency (at the bottom of the separatrix)

$$\Omega_r \approx (ga\beta_o/R_o)^{1/2} \ll k.$$

The adiabatic process ($\Omega_r = \text{const}, 0 < B_o' \ll \Omega_r B_o$) should start under the condition $\Delta a \ll d$, to avoid a significant filamentation. Ramp of resonance dipole field along the beam line will lead to trapping of particles into the resonance island and phase compression at $\Delta\varphi\Delta a = \text{const}$. The compression should be stopped at a moment $a\Delta\varphi = \Delta a$, i.e. the beam becomes round in the phase space $(x, \beta_o x')$. The kick magnets will set the beam down to the equilibrium orbit. Finally, a beam adapter will return the beam to a round magnetized state in the solenoid of cooling section.

5. Electron recirculators

5.1. Medium-energy recirculators

We consider the involvement of an electron ring as an option (which might become a solution) after acceleration of electrons in RF linac to a multi-MeV energy range.

In context of the above treated magnetized electron transport, the cooling section solenoid becomes a part of the electron ring focusing lattice (Fig. 3a). The outer matching between edges of the solenoid leads to a requirement of a circular optical transformation, which does not present a problem. Note, that at medium energies (below ~ 20 MeV), to keep the electron beam round (rotating) outside the solenoid is useful (if not necessary) in view of the space charge effect.

Since the electron beam is not supposed to be accelerated in the recirculator ring, there is no need for RF in this ring. To avoid beam debunching, the ring must be designed isochronous. Then, the negative mass and head–tail instabilities will be eliminated (or at least decreased substantially), in order for the beam to survive during a time as long as a few hundred (or thousand) turns, before it will be overheated by the IBS or by a beam under cooling. Table 1 illustrates a recirculator design scheme.

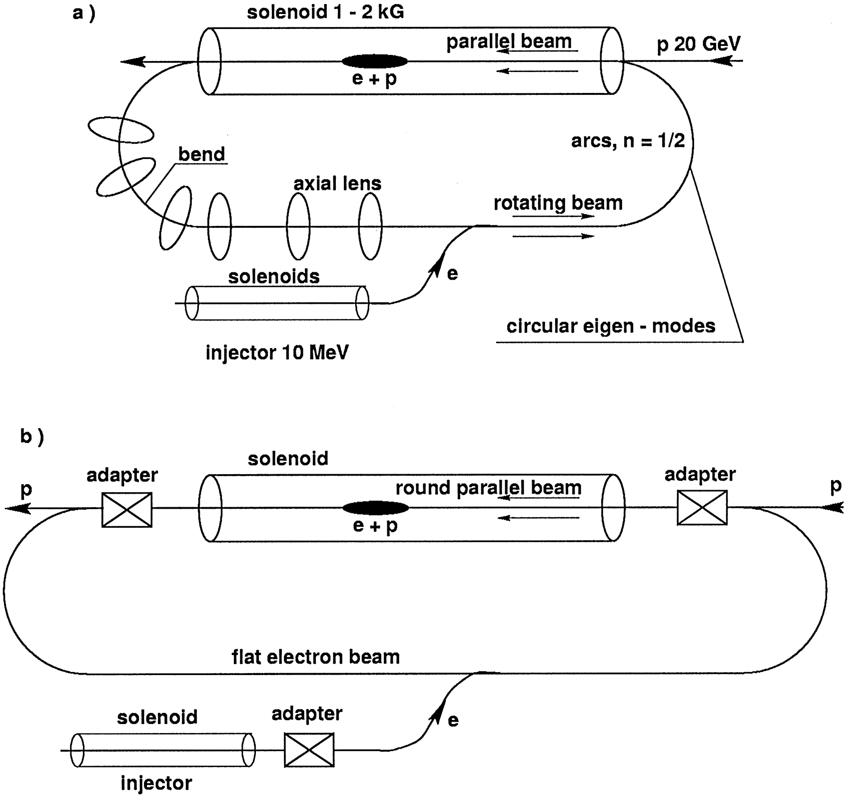

Fig. 3. Electron recirculator rings: (a) medium energy; (b) high energy.

Table 1
Parameters of electron recirculator ring

Energy, MeV	10
Circumference, m	90
Solenoid length, m	36
Arcs, m (total)	10
Solenoid field, kG	1
Larmor phase advance/2π	16
Average compaction factor	0
Peak electron current, A	2
Bunch charge, nC	3
Outer tune	10.3
Bunch length, m	0.5
Transverse normalized RMS emittance, π mm mrad	2
Beam radius, cm	0.7
Space charge tune shift	4×10^{-3}

5.2. *High-energy recirculators*

Concepts for electron beam transport and RF acceleration with discontinuous solenoids gives one a regular base to approach a design of high-energy electron linacs (tens and hundreds of MeV, and even more) for cooling goals. Obviously, the issue of the efficiency of electron beam rises with beam energy. Electron linacs with energy recovery could be developed; but it seems always useful to incorporate an electron recirculator ring with a linac, with or without energy recovery. Note is this connection, that not only the power might become a critical issue of a high-energy linac, but also the current limits related to beam stability in a low-energy part of the beam line.

At high energies, the Coulomb demands become negligible (at least for not very short electron bunches), while it becomes sensible to extend the beam circulation time. Then, the intrabeam scattering (and also radiation) in the arcs will limit the beam high-quality lifetime. From this point of view, it is suitable to have the e-beam flat (i.e. with no coupling) rather than round. However, the cooling section solenoid does introduce a strong coupling.

This contradiction can be easily resolved by the introduction of vortex-plane beam adapters described in the previous section (Fig. 3b). Then the Larmor emittance of the beam in the cooling section turns into vertical emittance in the arcs, being non-coupled with energy and horizontal emittance (large one, related to the beam area in solenoid). Thus, the beam adapter extends the low Larmor temperature lifetime.

6. Electron storage rings for high-energy electron cooling

The main obstacle to high efficiency of electron storage rings as coolers is a large transverse horizontal temperature of electrons due to quantum fluctuations of synchrotron radiation and intrabeam scattering in arcs. Now, this obstacle can be removed by the introduction of a solenoid to the cooling section and beam adapters described above (Fig. 4). Then the outside horizontal emittance is transformed inside of the solenoid into the beam area while the vertical one (small) becomes responsible for the Larmor electron temperature in solenoid. The four dimensional transverse emittance in the solenoid will be equal to the product of the two outside emittances. This makes it sensible to reduce the parasitic coupling between vertical and

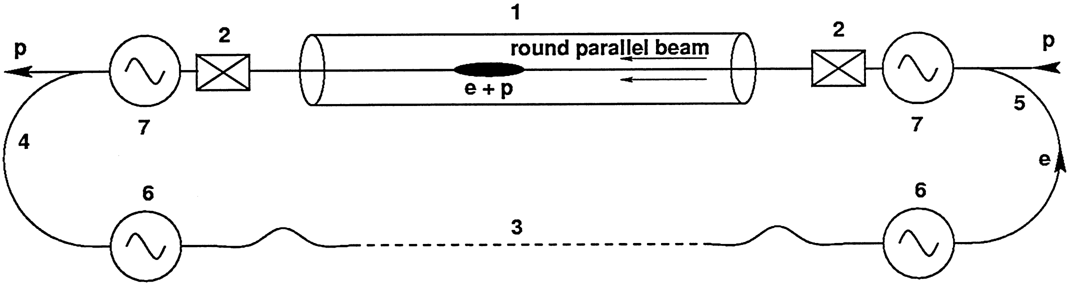

Fig. 4. Electron storage ring for high energy cooling. 1: solenoid; 2: beam adapters; 3: wiggler; 4: arc with bunch expander; 5: arc with bunch compressor; 6: power RF stations; 7: chirping RF stations.

Table 2
Electron storage ring for high-energy cooling

Energy, MeV	500
Circumference, m	140
Number of electrons/bunch	10^{12}
Wiggler field, T × m	6 × 40
Radiation damping time, ms	0.5
Solenoid field, T × m	1 × 60
Adapter length, m	2
Bunch length in wiggler, cm	3
Bunch length in solenoid, cm	25
Relative energy spread in solenoid	10^{-4}
Normalized 95% p,$\bar{\text{p}}$ emittance, π mm mrad	2.5
Cooling time, h	2

horizontal oscillations (outside of cooling section) to as low a level as possible.

Introduction of strong wigglers leads to an increase of electron the energy spread. To decrease this effect, i.e. to obtain a smaller longitudinal emittance, one can introduce a strong longitudinal beam gymnastics around the ring: beam compression from cooling section to wigglers, and reverse. Wigglers also introduce the large "betatron" tunes, hence, large chromatic effects. Therefore, the wigglers have to be accompanied by sextupole fields to compensate for chromaticity.

Table 2 illustrates a conceptual design of electron storage ring-cooler for p$\bar{\text{p}}$ colliding beam in the Tevatron [21]. An electron storage ring with solenoid and beam adapters is also proposed as cooler for heavy ion colliding beams [22].

7. Dispersive electron cooling

In addition to all possible improving measures related to an electron beam, the cooling process can also be optimized by manipulating the optics of the beam undergoing cooling. A characteristic property of ultra-relavtivistic beams (electron as well as hadron) is that their transverse temperature is large compared to the longitudinal one, $\gamma\theta \gg \Delta\gamma/\gamma$. As a result, the transverse cooling rate is reduced by a factor of $\gamma^2\theta/\Delta\gamma$, respectively, to the longitudinal one. This unfair distribution of cooling rates can be corrected by the optical extension of beams in the cooling section, maintaining the equality of beam areas. However, a strong transverse extension requires rather hard efforts on realization of a necessary long focus of a hadron beam around cooling section. It also delivers some disadvantages: a weak focusing makes the beams less stable, and, decrease of anglular spread makes the alignment control between two beams more difficult.

Instead of beam extensions, a completely different way to increase the transverse cooling rate can be used: introduce the transverse gradient of the longitudinal electron cooling drag force, together with the energy–orbit dispersion of a beam under cooling [8]. The decrements redistribution principle is similar to that of the radiative cooling. It should be noted, that the sum of the partial cooling decrements is not affected by the drag force space gradients [8]. And, there is one more important property of this value: it is insensitive to the (common) extension of beams (as well as the longitudinal decrement at $\gamma\theta \gg \Delta\gamma/\gamma$), being dependent, mainly, on the emittance values. Thus, it is reasonable to design the hadron focusing parameter equal to a value of about the length of the cooling section (while the e-beam is magnetized).

A transverse gradient of the drag force may be produced by the introduction of electron dispersion in the cooling section. Electron dispersion, however, might not be welcome in the cooling section of a recirculator or storage ring, because of intrabeam scattering heating effect on transverse emittance. Instead of introduction of electron dispersion, a different technique can be used: introduce the velocity and orbit splits between the two beams to the values of about the respective widths. Whatever in any method a suitable value of hadron beam dispersion to be introduced in the cooling section is about of the order of

$$p\frac{\partial x}{\partial p} \sim \sigma_{\perp}\frac{p}{\Delta p},$$

where $\sigma_{\perp}$ is the beam transverse size.

8. Low-energy cooling in a ring with circular optics

The equilibrium emittances of a beam under cooling can be limited by the Coulomb repulsion when cooling intense low-energy beams. The concept of the recirculator ring (Fig. 3a) with optics matched with solenoid of cooling section prompts a possible way to reduce the space charge effect on 2×2 transverse emittance.

Assume that this type of ring with parameters suitable for a low-energy hadron beam is used as a hadron cooler (solenoid is continuous for e-beam; asymmetry effect on hadron optics should be compensated). The principal optical feature of such a ring is that the drift and Larmor components of the particle state in the solenoid are not mixed by the outside optical channel. Then, if there is no organized redistribution of cooling decrements, only the Larmor mode will experience the cooling, while the drift mode will not. Thus, space charge cannot stop cooling of the Larmor mode since the beam radius will not shrink, being related to the drift mode. Therefore, one of the two emittances can be cooled to a very low equilibrium, especially taking into account the magnetization effect on cooling process [8]:

$$T_\perp = T_\| \to T_{e\|} \sim 10^{-4}\,\mathrm{eV}.$$

At such a low temperature, assuming the solenoid field 1 T, we obtain

$$\frac{\varepsilon_\perp}{\pi} = T_\perp / eB_s = 4 \times 10^{-7}\,\mathrm{mm\ mrad} \quad (!).$$

Note that in a straight utilization with a strong solenoid (with no electron beam) one can obtain a tranquil, very cold beam, perhaps, in a crystalline state.

The drift emittance can be cooled (to the space charge limited size) using the dispersive mechanisms as described in Section 7. Since the Larmor motion and momentum spread will already be cooled, the beam will shrink quickly.

A minimum area of a cooled beam can be obtained after flattening the beam using a beam adapter (Section 3) in the straight utilization or after beam ejection (Fig. 5).

9. Low-energy cooling with hollow beams

The circular optics also allows to realize cooling with hollow beams. The benefits of a hollow electron beam have been discussed in Section 4; a strong reduction of the space charge-related gradient of electron velocities is the most significant improvement in the case of low-energy cooling. The repulsive forces in a beam under cooling also become reduced, although the microwave beam stability should be a subject of the further analysis.

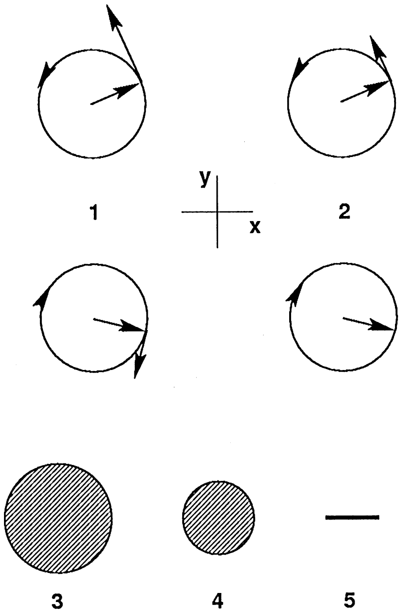

Fig. 5. Electron cooling in a ring with circular optics. 1: circular focusing modes outside solenoid; 2: beam transverse oscillators in the solenoid: one of the two circular modes is transformed into Larmor oscillator, while the other one becomes particle's drift position; 3: beam in the solenoid after the Larmor cooling; 4: beam in the solenoid after cooling of the drift mode; 5: beam flattened after adapter.

A hollow hadron beam can be created in a line (before injection) using the reverse beam gymnastics to those for concentration of a (magnetized) hollow beam, if not already produced by a ring-shaped source. Alternatively, the hollow state (of a bunched beam) can be built-up in the circulation regime, making the same kind of gymnastics with the drift mode, if to apply dipole RF magnets resonance with circulation of this mode outside the solenoid. In the rest, the cooling process can be organized in a manner described in the previous section, although the ring shape can introduce

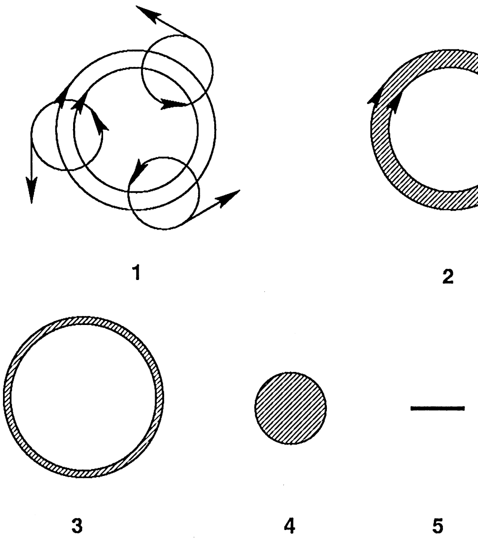

Fig. 6. Electron cooling with hollow beams. 1: ring-shaped drift mode and Larmor oscillators of ion beam in the solenoid; 2: beam in the solenoid after Larmor cooling; 3: beam in the solenoid after cooling of the drift mode; 4: cooled beam after concentration; 5: beam after flattening.

some peculiarities such as a reduction of the initial cooling rate and cooled beam accumulation at the edges of the electron beam. After cooling, the beam can be concentrated, if needed, in the ring or after ejection and acceleration (Fig. 6).

10. Conclusions

Our considerations can be summarized in the following.

1. A solenoid along the cooling section matched with the rest of electron track seems to be a favourable optical solution of electron beam transport for medium and high-energy electron cooling. It resolves the contradiction between a strong focusing and low temperature of electrons in the cooling section.
2. As a spinoff, the solenoid does introduce the magnetization effect to the cooling kinetics [8], allowing one to reach higher cooling rates and lower equilibriums of a beam under cooling.
3. Concepts for magnetized beam transport with discontinuous solenoids seem to open perspectives to create efficient high beam quality electron lines for cooling purposes, with no principal limitation on maximum electron energy.
4. Space charge restrictions on beam quality in electron guns can be reduced by the use of ring cathodes and proposed beam concentration technique.
5. Recirculator rings with a solenoid in the cooling section can be incorporated with the electron line to enhance the efficiency of an electron cooling facility.
6. Vortex-plane beam adapters being used in electron rings will minimize beam dilution in the arcs. This measure substantially raises the efficiency of electron recirculators and promotes the development of storage ring concepts for high-energy electron cooling.
7. Introduction of energy–orbit dispersion for the hadron beam and a space gradient of the electron cooling drag force will allow the transverse cooling rate to be maximized avoiding beam extension.
8. Concepts of low-energy cooling with matched beams and hollow beams seem helpful with the reduction of space charge restrictions of electron cooling efficiency.

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