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Continuous electron cooling for high-luminosity colliders

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Abstract

The prospects to use continuous electron cooling for increasing luminosity and quality of collider experiments, involving nuclei/nucleons, are discussed briefly. Possible sets of collider parameters are presented. © 2000 Elsevier Science B.V. All rights reserved.

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Now, the Electron Cooling (EC), proposed and developed at Novosibirsk [1–9], is accepted as an important working tool at many laboratories throughout the world [10].

There are different types of experiments and problems to apply EC:

- storing of secondary stable and long enough living hadrons, nuclei and ions (maybe in combination with stochastic cooling – to raise effective acceptance);
- achieving of very low "temperature" of stored particles;
- suppression of beam blow-up due to diffusive effects of different natures (multiple scattering by internal targets, external noise, multiple intra-beam scattering, beam–beam effects, etc.

This talk is devoted to the reaching of highest luminosity at the collision stage in colliders, when collisions involve hadrons and (stripped) nuclei. I intend to consider *colliders*, specifically – not "mergers" or "crossers" with their specificity. Consequently, we have in mind $e^{+/-}p^{+/-}$; $e^{+/-}Z$; $p^{+/-}p^{+/-}$; $p^{+/-}Z$; Z_1Z_2, etc., colliders (where Z is the nuclear charge number; we consider the case of fully stripped ions only, since the loss cross-section for non-stripped ion at collisions is overwhelmingly high). We have in mind colliders of relativistic particles ($v \sim c$) with double ring and single head-on interaction region. All four transversal (geometrical) emittances are considered equal to ε (geometrical, without π), all four beta functions equal to β_0, and equal to bunch rms length σ_{long}, equal for both beams. Distance between bunches is equal to D_{bb} – the same for both beams. Transversal space charge effect for ions is considered as limited by the maximal sustainable betatron tune shift $\Delta\nu$, beam–beam effects are considered limited by maximal tune shifts ξ_e and ξ_z.

(The stochastic cooling being quite useful in the collection of secondary heavy particles, is not useful in reaching high luminosity collisions, where high density of particles is needed.)

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Let us look, for example, at the simple formulae for an electron–nuclei (Z, A) collider, presenting ultimate luminosity for different cases.

If the number of electrons per bunch N_{be} is limited "externally" and ion longitudinal density is limited by space-charge tune shift $\Delta\nu$, the ultimate luminosity will be

$$L_{\mathrm{e}Z1} = \frac{c}{2\pi r_{\mathrm{p}}} \frac{A}{Z^2} \gamma_Z^3 \frac{\Delta\nu}{R_{Z\mathrm{av}} D_{\mathrm{bb}}} N_{\mathrm{be}}$$

where $R_{Z\mathrm{av}}$ is average ion storage ring radius, and γ_Z is ion relativistic factor (ion velocity is assumed to be close to velocity of light c).

If the limiting factor is the beam emittance (it could be either the fraction of collider acceptance, small enough to ensure good lifetime, or ion beam emittance affordable for effective electron cooling), number of ions per unit length is limited by space charge, and number of electrons per bunch is limited by ion beam–beam tune shift ξ_Z, the ultimate luminosity will be

$$L_{\mathrm{e}Z2} = \frac{2c}{r_{\mathrm{p}}^2} \frac{A^2}{Z^3} \gamma_Z^4 \frac{\xi_Z \Delta\nu}{R_{Z\mathrm{av}} D_{\mathrm{bb}}} \varepsilon$$

in both previous cases independently of IP beta-function.

If the limiting factors are beam emittance and beam–beam tune shifts, the ultimate luminosity will depend on IP beta-function

$$L_{\mathrm{e}Z\mathrm{bb}} = \frac{4\pi c}{r_{\mathrm{e}} r_{\mathrm{p}}} \frac{A}{Z^2} \gamma_{\mathrm{e}} \gamma_Z \frac{\xi_{\mathrm{e}} \xi_Z}{\beta_0 D_{\mathrm{bb}}} \varepsilon$$

where r_{e}, r_{p} are the classical radii of electron and proton, respectively.

In this case, the proper value of beam emittances should be produced not by beam–beam interaction itself, but "externally" – to prevent the flip–flop instability (when the diminishing of the transversal size of one beam makes beam–beam tune shift for the other one higher than the critical value and its size grows up; this change produces further diminishing of the first beam size, etc.). The solution for electrons (positrons) is the formation of beam emittances needed by quantum fluctuations. For particle beams under EC, it is worth arranging proper emittances by the relative inclination in the cooling section of particle equilibrium orbit and the guiding longitudinal field by the angle corresponding to its emittance angle (using the so-called "monochromatic instability" [2]). In this case, the cooling rate for rms and higher amplitudes is not slowed down, but for smaller amplitude it becomes negative.

The maximal values of tune shifts $\Delta\nu$ and ξ depend on whether strong cooling for the particles involved does exist. Very rough estimations (for optimal operating conditions), based on the "world experience", are

ξ_Z, $\Delta\nu = 0.005$ – if there is no cooling

and

ξ_Z, $\Delta\nu = 0.05$ – if cooling is "good".

And "good cooling" means that number of collisions (or number of turns for space-charge limitation) per cooling time $N_{\mathrm{coll/cool}}$ is

$$N_{\mathrm{coll/cool}} \leq 3 \times 10^6.$$

(It is necessary to be cautious with this estimation, since it is based on the experience with radiation cooling, for which the cooling power grows with oscillation amplitude; for ECooling at collider parameters of interest the dependence is just the opposite. The subject needs careful simulation and experimental study.)

The "good cooling" prevents diffusion, and hence beam emittance and luminosity degradation, due to "non-linearities" in beam–beam interaction or in particle motion under combined action of space-charge and machine imperfections, or due to multiple intra-beam scattering. The latter diffusion is active for ions if

$$\gamma_Z > \frac{\beta_{\mathrm{R}}}{D_{\mathrm{R}}}$$

for a quasi-symmetric collider this condition transforms into operation "above critical energy", or into

$$\gamma_Z > Q_R.$$

For even higher energies – depending on beam emittance and linear density – the multiple intra-beam scattering heating becomes too slow to be taken into account.

In many cases, the same high- and long-living luminosity can be reached without cooling, but would require much higher intensities and emittances. These smaller emittances under good cooling lead to much smaller transversal spot size at collision and allow one to observe the lifetime of reaction products much more efficiently. The correspondingly smaller angular spread at collision gives possibility to study much smaller momentum transfers. In some cases, the much better monochromaticity under cooling is also important for physics.

Discussing future EC-based colliders, we need not forget – up to now, the highest electron energy used for cooling was not higher than 300 keV, hence for ion energies below 600 MeV/A, the most recent and perfectly operating ECooling device was developed and constructed by INP for SIS Heavy Ions Synchrotron at GSI [11], the scheme is presented in Fig. 1. But we see clear prospects for much higher energies.

For electron energies up to, say, 5 MeV ($E_Z < 10$ GeV/A) technically it is quite possible to

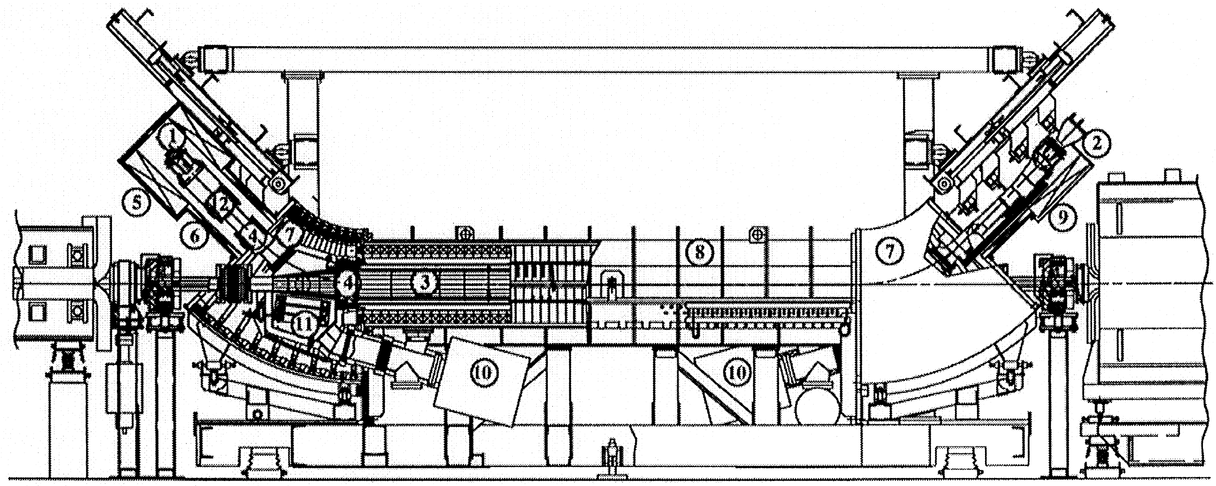

Fig. 1. Electron cooling system for the SIS synchrotron at GSI, Darmstadt. (1) Electron gun; (2) Electron collector; (5,6) gun solenoids; (7) bending magnets with toroidal solenoids; (8) the main high-precision solenoid.

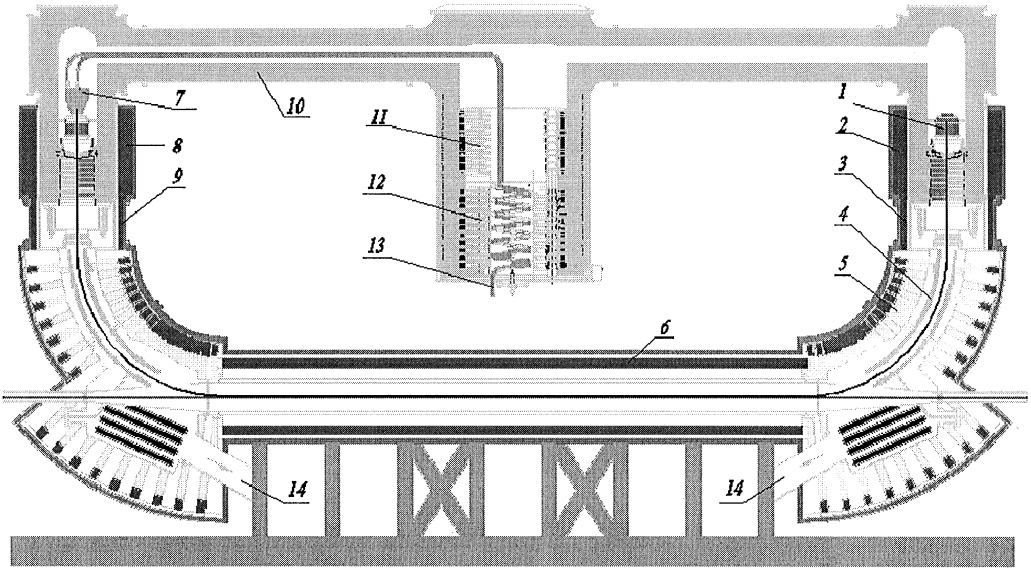

Fig. 2. Scheme for electron cooling system for electron energy up to 5 MeV. (1) Electron gun; (2),(3) gun solenoids; (4) Electrostatic bend; (5) toroidal coil; (6) main solenoid; (7) collector; (8,9) collector solenoids; (10) SF6 feeder; (11) recovery rectifier; (12) main rectifier; (13) collector colling input.

use conventional rectifier-based accelerator–recuperator (the option presented in Fig. 2), similar to INP high-power electron accelerators used for industrial applications [12–14]. In a special installation of 1 MeV, 1 A (presented in Fig. 3) continuous operation was achieved [15], with the whole beam path from the gun to the collector immersed in 500 Gs longitudinal magnetic field. The main improvement needed is to diminish rectifier ripples (by switching, probably, to the higher power supply frequency – from 400 Hz to few kHz) and to stabilize better the average electron energy. The Van de Graaff-type electrostatic accelerators, also considered as potential candidates for this energy range, have excellent energy stability, but provide much smaller ("active") currents. Thus, the long-term reliability of operation could be more difficult to achieve, due to higher sensitivity to the sudden current losses (caused by ion and secondary electrons processes in high-current electron beam under recuperation).

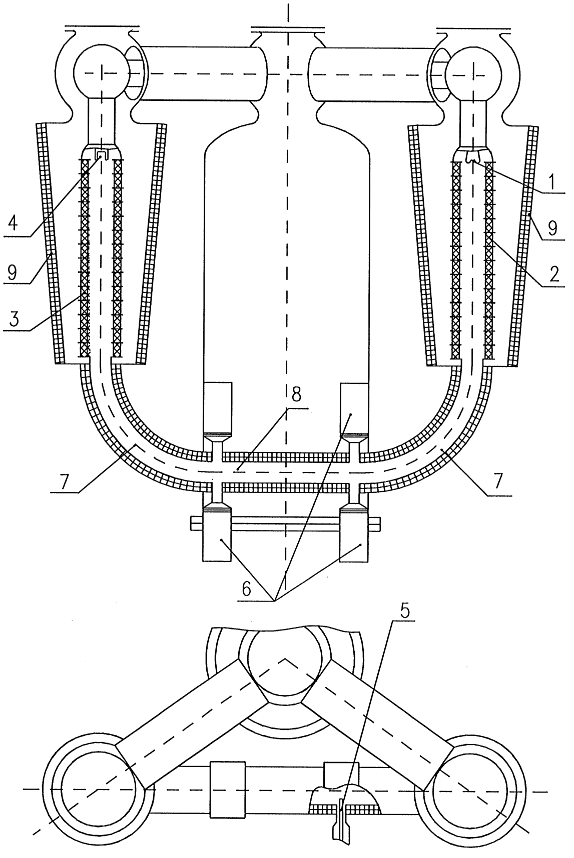

Fig. 3. Experimental installation for 1 MeV, 1 A electron beam acceleration–recuperation studies. (1) Electron gun; (2) accelerator tube; (3) decelerator tube; (4) electron collector; (7)–(9) solenoids.

For higher energies (starting from few MeV to hundreds of MeV electrons, up to hundreds of GeV/A ion energy) the most promising approach, at least, in my view, is the use of RF accelerators–recuperators, of the type now under construction at INP for Free Electron Laser [16], the scheme is presented in Fig. 4. The operation of such a device, yet never tested, does not raise doubts in principle.

For even higher energies (if EC happens to be useful) the electron storage ring under strong enough synchrotron radiation cooling can be of interest.

The important step – very much desirable from technical and economic points of view – is the switching from continuous guiding longitudinal magnetic field, in use in all the EC devices up to now, to the "interrupted field" approach: to immerse in longitudinal field the gun and the cooling section, only. To keep electrons properly transversally magnetized in cooling section, the radial phase advance between the exit from the gun section magnetic field and the entrance to the cooling section magnetic field should be strictly $2\pi n$ (for the same field directions) and the radial magnification should be inversely proportional to the magnitudes of magnetic field – for proper compensation of coming-out and coming-in rotation kicks (any rotation around the beam axis is not important, of course). Special care should be taken to correct chromatic and other aberrations.

But, in addition to the high-intensity effects mentioned and other familiar ones, there is also an important phenomenon, which appears in some cases at high intensities of cooling electrons and ions, called "electron heating" [17], the studies of which started just recently. The suppression of effects of this origin might require additional sectioning of the cooling section, fast feedbacks, and/or proper radius of beams merging, etc. The preliminary estimations show that this kind of instability should not hamper the collider options presented below.

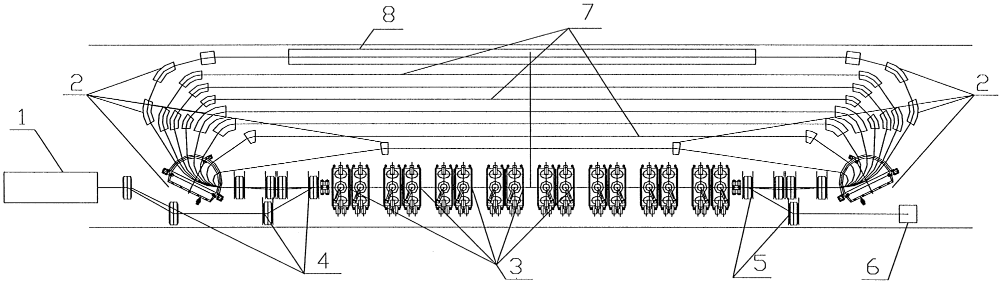

Fig. 4. Microtron–recuperator. (1) Electron gun and pre-accelerator; (2,4,5) bending magnets; (3) RF CW accelerator cavities; (6) beam dumper; (8) cooling section (appropriate positioning).

Prior to giving the sets of parameters for potential colliders, let us present the simplest formulae for EC, multiple intra-beam scattering, recombination rate, and lifetimes as a background for these rough sketches.

The cooling time for reasonably high beam energy ($\gamma_Z \gg 1$) and the longitudinal magnetic field of finite value H_{long} is given by the familiar formula [2,6]

$$\tau_{\mathrm{cool}} = \frac{1}{2\pi r_{\mathrm{e}} r_{\mathrm{p}} c^4} \frac{A}{Z^2} \frac{1}{L_{\mathrm{Ccool}}} \frac{\gamma_Z^2}{n_{\mathrm{e}}\eta} \left(\sum_n v_n \right)^{3/2}$$

where n_{e} is the cooling electron density (in lab system) η the fraction of the collider perimeter occupied by the cooling section, v_n the relative electron–ion velocities of different natures (in their rest frame) and L_{Ccool} the effective Coulomb logarithm for "magnetized" collisions [6,18,19]:

$$L_{\mathrm{Ccool}} = \ln\left[\frac{[\sqrt{2\pi r_{\mathrm{e}} n_{\mathrm{e}}/\gamma_Z^3} + 1/\sqrt{2}L_{\mathrm{cool}}]^{-1}\sqrt{\varepsilon/\beta_{\mathrm{Zcool}}} + (m_{\mathrm{e}}c/e)\,(v_{\mathrm{etr}}/H_{\mathrm{long}})}{(m_{\mathrm{e}}c/e)\,(v_{\mathrm{etr}}/H_{\mathrm{long}}) + (r_{\mathrm{e}}/2)(\beta_{\mathrm{Zcool}}/\gamma_Z^2\varepsilon)} \right].$$

If L_{Ccool} is one unit or more (this requires high enough longitudinal magnetic field in the cooling section), the transverse electron velocities enter the cooling rate via this logarithm, only. Hence, the expansion of electron beam by diminishing longitudinal magnetic field in the cooling section relative to the field at the electron gun makes cooling slower – because the influence of the electron density decrease is much stronger.

For high-energy colliders, the main contribution to velocities in the cooling section v_n are: ion transverse velocities corresponding to the ion beam emittance ε

$$v_{\varepsilon} = \sqrt{2c^2 \frac{\varepsilon\gamma_Z^2}{\beta_{\mathrm{Zcool}}}}$$

and longitudinal electron velocities induced by relative energy spread Δ_{eE} (for example, due to energy modulation along the electron bunch appearing at RF acceleration)

$$v_{\mathrm{elong}} = c\Delta_{\mathrm{eE}}.$$

The latter velocity should be smaller than v_{ε} for not slowing the cooling.

The Multiple Intra-Ion-Beam Scattering (MIBS) can blow-up the beam emittance and kill the collider luminosity. To prevent the degradation, the increase due to MIBS in transversal ion velocities v_{MIBS} collected during τ_{cool} should be smaller than v_{ε}, where

$$v_{\mathrm{MIBS}} = \sqrt{\frac{r_{\mathrm{p}}^2 c^3}{\pi} \frac{Z^4}{A^2} \Lambda \frac{\beta_{\mathrm{Zav}}^{5/2}}{\gamma_Z R_{\mathrm{Zav}}^2 \beta_{\mathrm{Zcool}} \beta_0} \frac{N_{\mathrm{bZ}}}{\varepsilon^{3/2}} \tau_{\mathrm{cool}}}$$

and

$$\Lambda = \frac{\pi}{2} \ln\left(\gamma_Z \sqrt{\frac{\pi\varepsilon^{3/2} A}{2 r_{\mathrm{p}} Z^2}} \right).$$

here $\beta_{Z\mathrm{av}}$ is the average beta-function in ion ring, $\beta_{Z\mathrm{cool}}$ the ion beta-function at the cooling section, and $N_{\mathrm{b}Z}$ the number of ions per bunch.

If we prevented beams blow-up, the luminosity would decrease with time due to losses of particles. The electron beam losses are caused in most cases by single bremsstrahlung at ions in collision; cross-section of the process grows fast with ion charge. As a result, electron beam lifetime is

$$\tau_{\mathrm{elife}} = \frac{N_{\Sigma\mathrm{e}}}{L_{\mathrm{e}Z}\sigma_{\gamma 0}Z^2}$$

where $N_{\Sigma\mathrm{e}}$ is the total number of electrons, and $\sigma_{\gamma 0} = 4\times 10^{-25}$ the single bremsstrahlung cross-section of electron at unit charge.

The ion lifetime, in addition to the usual processes in collisions, is limited by (radiative for our cases) recombination events with cooling electrons. The lifetime due to this process is

$$\tau_{Z\mathrm{rec}} = \frac{1}{30\alpha r_{\mathrm{e}}^2 c^2}\,\frac{\gamma_Z^2}{Z^2 n_{\mathrm{e}}\eta\ln(Z\alpha c/v_{\mathrm{etr}})}\,v_{\mathrm{etr}}$$

(α is the fine structure constant).

Here, I want to underline especially the proportionality of the recombination life-time to v_{etr}: for high Z ions this lifetime could become uncomfortably short, but we have a possibility to increase it

Table 1
Nominal collider parameters

E_{e}	4 GeV
Π_{coll}	270 m
$H_{\mathrm{coll}\ Z\mathrm{av}}$	3.5 T
D_{bb}	5 m

Table 2
Electron–proton collisions (with ECooling/without ECooling)

E_{p}	40 GeV
$s^{0.5}$	25 GeV
N_{pb}	$0.4\times 10^{10}/2\times 10^{11}$
N_{eb}	$4\times 10^{10}/2\times 10^{11}$
β_{coll}	3 cm
$\epsilon_{\mathrm{beams}}$	$1.4\times 10^{-7}/1\times 10^{-4}$ cm (geom., without π)
σ_{rcoll}	10 mcm/0.16 mm
θ_{coll}	$3\times 10^{-4}/5\times 10^{-3}$
L_{cool}	13 m
H_{cool}	0.5 T
I_{coolpeak}	1.0 A
I_{coolmean}	0.1 A
$N_{\mathrm{col/cool}}$	2×10^6
T_{elife}	3×10^3 s/3×10^4 s
T_{recomb}	3×10^5 s
MIBS	Suppresses!/no need
L_{ep}	1×10^{33} cm^{-2} s^{-1}

Table 3
Electron–^{3}He collisions (with ECooling/without ECooling)

E_{HE3}	27 GeV/u
$s^{0.5}$	36 GeV
N_{He3b}	0.5×10^{10}
N_{eb}	$1\times 10^{11}/1\times 10^{12}$
β_{coll}	3 cm
$\epsilon_{\mathrm{beams}}$	$7\times 10^{-7}/6\times 10^{-5}$ cm (geom.)
σ_{rcoll}	15 mcm/0.13 mm
θ_{coll}	$5\times 10^{-4}/4\times 10^{-3}$
L_{cool}	13 m
H_{cool}	0.5 T
I_{coolpeak}	15 A
I_{coolmean}	0.15 A
$N_{\mathrm{coll/cool}}$	3×10^6
T_{elife}	3×10^3 s/3×10^4 s
T_{recomb}	1×10^5 s
MIBS	Suppresses/no need
L_{eHe3}	1×10^{33} cm^{-2} s^{-1}

Table 4
Electron–uranium collisions (with ECooling/without ECooling)

E_{U}	15.5 GeV/u
$s^{0.5}$	243 GeV
N_{ub}	$1\times 10^{8}/1\times 10^{9}$
N_{eb}	$1\times 10^{11}/1\times 10^{12}$
β_{coll}	7 cm
$\epsilon_{\mathrm{beams}}$	$1\times 10^{-6}/1\times 10^{-4}$ cm (geom.)
σ_{rcoll}	25 mcm/0.25 mm
θ_{coll}	$3.5\times 10^{-4}/3.5\times 10^{-3}$
L_{cool}	13 m
H_{cool}	0.5 T
I_{coolpeak}	1.0 A
I_{coolmean}	3 mA
$N_{\mathrm{coll/cool}}$	1×10^6
T_{elife}	200 s/2000 s
T_{recomb}	4000 s
MIBS	Suppresses/no need
L_{eU}	1×10^{31} cm^{-2} s^{-1}

very substantially almost without damaging the cooling rate (keeping the L_{Ccool} bigger than 1).

Let us present now sets of parameters for a "medium energy" collider (the general parameters of the collider in Table 1); the cases for specific collisions are presented in Tables 2–6 .

The previous discussion and evaluation in the tables confirm, in my understanding, a great interest in further development and active use of Electron Cooling for elementary particle physics, as well as for nuclear and atomic studies.

Table 5
Proton–antiproton collisions ($\xi, \Delta\nu = 0.03$! $D_{\mathrm{bb}} = 13$ m!) (with ECooling/without ECooling)

$E_{\mathrm{p,pbar}}$	40 GeV/u
$s^{0.5}$	80 GeV
N_{pb}	$3\times10^{10}/2\times10^{11}$
N_{pbarb}	$3\times10^{10}/2\times10^{11}$
β_{coll}	3 cm
$\epsilon_{\mathrm{beams}}$	$1.6\times10^{-6}/7\times10^{-5}$ cm (geom.)
σ_{rcoll}	20 mcm/0.14 mm
θ_{coll}	$7\times10^{-4}/5\times10^{-3}$
L_{cool}	13 m
H_{cool}	0.5 T
I_{coolpeak}	60 A
I_{coolmean}	0.3 A
$N_{\mathrm{coll/cool}}$	4×10^{7}
MIBS	Suppresses/no need
L_{ppbar}	3×10^{32} cm^{-2} s^{-1}

Table 6
Uranium–uranium collisions ($D_{\mathrm{bb}} = 13$ m!) (with ECooling/without ECooling). (But what for?!)

E_{U}	15 GeV/u
$s^{0.5}$	477 GeV
N_{Ub}	$3\times10^{8}/3\times10^{9}$
β_{coll}	10 cm
$\epsilon_{\mathrm{beams}}$	$1.8\times10^{-6}/7\times10^{-4}$ cm (geom.)
σ_{rcoll}	40 mcm/0.4 mm
θ_{coll}	$4\times10^{-4}/4\times10^{-3}$
L_{cool}	13 m
H_{cool}	0.5 T
I_{coolpeak}	0.3 A
I_{coolmean}	4 mA
$N_{\mathrm{coll/cool}}$	3×10^{6}
T_{recomb}	1500 s
MIBS	Suppresses/no need
L_{UU}	1×10^{28} cm^{-2} s^{-1}

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Note: I need to apologize since the referencing is very incomplete; I hope that the many other references on this subject, especially related to non-Novosibirsk papers, can be found in the references below:

References

[1] G. Budker, At. Energ. 22 (1967) 346; Proceedings of the International Symposium Electron and position Storage Rings, Saclay, 1966, p. II-I-I.

[2] Ya. Derbenev, A. Skrinsky, preprint No 225, INP, Novosibirsk, 1968, Particle Accelerators 8 (1977) 1.

[3] G. Budker, N. Dikansky, V. Kudelainen, I. Meshkov, V. Parkhomchuk, D. Pestrikov, A. Skrinsky, B. Sukhina, IEEE Trans. Nucl. Sci. NS-22 (5) (1975) 2093.

[4] G. Budker, N. Dikansky, V. Kudelainen, I. Meshkov, V. Parkhomchuk, D. Pestrikov, A. Skrinsky, B. Sukhina, Particle Accelerators V 7(4) (1976).

[5] G. Budker, A. Skrinsky, Soviet Uspekhi Fiz. Nauk 124 (4) (1978) 561.

[6] Ya. Derbenev, A. Skrinsky, Sov. Phizika Plazmy 4 (1978) 492.

[7] V. Parkhomchuk, A. Skrinsky, Particle and Nuclear Physics, Vol. 12(3), JINR, Dubna, 1981, pp. 557–613.

[8] V. Parkhomchuk, A. Skrinsky, Rep Progr. Phys. IPJ-EPS 54(7) 919.

[9] N. Dikansky, V. Kudelainen, V. Lebedev, I. Meshkov, V. Parkhomchuk, A. Sery, A. Skrinsky, B. Sukhina, preprint No. 88-81, INP, Novosibirsk, 1988.

[10] I. Meshkov, Electron cooling with circulating electron beams in GeV energy range, Workshop on Electron Cooling and Related Topics, Incorporating the fifth Workshop on Medium Energy Electron Cooling, Uppsala, Sweden, May 19–22, 1999.

[11] M. Steck et al., Workshop on Electron Cooling and Related Topics, Incorporating the Fifth Workshop on Medium Energy Electron Cooling, Uppsala, Sweden, May 19–22, 1999.

[12] R. Salimov, N. Kuksanov et al., Environmental Applications of Ionizing Radiation, Wiley, New York, 1998, pp. 47–63 (Chapter 3).

[13] N. Kuksanov, R. Salimov et al., Rad. Phys. Chem. 35(4–6) (1990).

[14] R. Salimov, N. Kuksanov et al., Rad. Phys. Chem. 46 (1995).

[15] M. Veis, B. Korabelnikov, N. Kuksanov, R. Salimov, EPAC'98, Rome, 1988.
[16] N.A. Vinokurov et al., Second Asian Simposium on Free Electron Laser, 1995, Novosibirsk, Russia.
[17] V. Parkhomchuk, Workshop on Electron Cooling and Related Topics, Incorporating the Fifth Workshop on Medium Energy Electron Cooling, Uppsala, Sweden, May 19–22, 1999.
[18] V. Parkhomchuk, private communication.
[19] Conceptual Design Study of the GSI Electron-Nucleon Collider, INP Report 97-51. Novosibirsk; GSI Report 97-07, Darmstadt.