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Electron cooling application for luminosity preservation in an experiment with internal targets at COSY

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Contents

Abstract

This report is dedicated to investigation of the beam parameter evolution in the experiments with internal target. In calculations of the proton and deuteron beams we concentrated on cluster, atomic beam, storage cell and pellet targets at ANKE experiment mainly. In these calculations electron and stochastic cooling, intrabeam scattering, scattering on the target and residual gas atoms are taken into account. Beam parameter evolution is investigated in the long-term time scale, up to one hour, at different beam energies in the range from 1.0 to 2.7 GeV for proton beam and from 1 to 2.11 GeV for deuteron beam. The results of numerical simulations of the proton and deuteron beam parameters at different energies obtained using new version of BETACOOL program (elaborated at the first stage of this work [1]) are presented.

Optimum parameters of the electron cooling system are estimated. The COSY experiment requirements can be satisfied even when electron cooling time is rather long. That allows to apply an electron cooling system with circulating electron beam [2]. Such a system has potentially low cost in comparison with other possibilities. At the energy range from 500 keV to 1.5 MeV only longitudinal magnetic field can provide an effective focusing of an intensive electron beam. The electron beam acceleration can be produced both by induction acceleration of electrons or using an RF electron LINAC. Specific limitations of such a cooling system are discussed. Preliminary design of the electron cooling system with circulating electron beam is described in the report.

This report contains also preliminary program of experiments at LEPTA (Low Energy Particle Toroidal Accumulator), which are aimed to study the problems of electron cooling system with circulating electron beam. Presently the construction of LEPTA ring is in the final stage at JINR and experiments with circulating beam will be started the next year.

Introduction

The existing stochastic cooling system or an electron cooling system, which cover total energy range of the proton or deuteron beam at COSY, can be used for the following applications:

- at injection energy to increase the intensity of the polarized proton beam with a combined cooling/stacking injection,
- at energy range from about 1 GeV to top energy of 2.7 GeV (2.11 GeV for deuteron beam) for luminosity preservation in an experiment with internal targets,
- for preparation of the proton beam parameters for fast extraction in an experiment with external target.

The ultimate possible efficiency of the beam cooling application at ANKE experiments is investigated in the beginning of this report.

The existing COSY stochastic cooling system is successfully used now for luminosity preservation in the COSY-11 experiment with cluster beam apparatus at relatively low proton beam intensity. Expected target density in ANKE experiment is about one order of magnitude higher and one plans to increase the beam intensity by upgrade the COSY injection system. The investigation of the efficiency of the stochastic cooling system at these parameters is one of the goals of this report. Efficiency of an electron cooling system in difference with stochastic one does not depend on beam intensity but depends very strongly on beam energy. Comparison between two cooling methods is the next goal of this work.

The optimum choice of the electron cooling system parameters and preliminary design of the cooling system with circulating electron beam are also the topics of the report.

Further development of this work is experimental investigations of the electron cooling system with circulating electron beam. We plan to investigate its problems at LEPTA (Low Energy Particle Toroidal Accumulator) ring, which is under construction in JINR now. LEPTA parameters are closed to estimated parameters of COSY electron cooling system. This report contains preliminary program of experiments at LEPTA, which are aimed to study an electron cooling system with circulating electron beam. Electron beam parameters after injection and adjustment of the septum and kicker coils will be measured at special test bench using optic method of the electron beam diagnostics, developed in JINR [3]. Dynamics of circulating electron beam will be investigated when LEPTA assembling is finished. Resonance behaviour and beam stability at injection energy will be studied using RF acceleration of the electron beam. And final test of the cooling system will be performed after installation of the betatron yoke. It will include the injection of electron beam, its acceleration to maximum energy and extraction for diagnostic of the electron temperature.

Presently the construction of the general elements of LEPTA magnetic system is in the final stage and we plan to start assembling of the ring and first experiments with electron beam in the next year. Expected term of the experimental program completion is two years.

1. Target and beam parameters

The internal targets used in COSY are listed in the Table 1.1.

Table 1.1. Experiments with internal targets

Target	EDDA	COSY 11	ANKE
1. Strip or filament	filament		strip
2. Cluster		x	x
3. Pellet			x
4. Atomic beam	x		x
5. Storage cell	x		x

The beam life time in the experiments with solid targets is so short that luminosity preservation using the beam cooling seems to be unrealistic. All the other types of the target will be used in the ANKE experiment and the results of the calculations for them can be extended to other experiments with corresponding corrections the lattice functions in the target position. Therefore in this report general attention was directed to the ANKE experiment.

The cluster beam apparatus of ANKE experiment is very similar to COSY 11 one and maximum designed value of target areal density was equal to 5 x 10^{13} atoms/ cm^2. However, the value really achieved now is substantially higher and can be estimated from of the particle energy loss due to interaction with target using the experiment parameters (Table 1.2.). The formula for relation between relative energy loss of the proton beam and proton revolution frequency, one can calculate the ΔE value:

$$\frac{\Delta E}{E} = \frac{1+\gamma}{\gamma}\frac{1}{\eta}\frac{\Delta f}{f}, \tag{1.1}$$

here η is off-momentum factor, γ is Lorenz factor.

Table 1.2. ANKE experiment with hydrogen cluster beam target at January/February 2001.

Proton beam kinetic energy, GeV	2.65
Revolution frequency, MHz	1.5
Off momentum factor, η	-0.13
Frequency shift during 300 seconds, Hz	192

Theoretical value of the mean energy loss during single cross the target is [4]:

$$\Delta E = 2\xi\, ln\left(\frac{E_{max}}{I} - \beta^2\right), \tag{1.2}$$

here E_{max} is the maximum energy loss in a head-on collision of the projectile with a target electron:

$$E_{\max} = \frac{2m_e c^2 \beta^2 \gamma^2}{1 + 2\gamma \frac{m_e}{M} + \left(\frac{m_e}{M}\right)^2}, \quad (1.3)$$

m_e is the electron mass and M - the projectile mass, ξ is a quantity which is proportional to the areal density ρx of the target (ρ – target density in g/cm^3):

$$\xi = 0.1535 \frac{MeV\, cm^2}{g} \frac{Z_1^2}{\beta^2} \frac{Z_2}{A_2} \rho x, \quad (1.4)$$

where, Z_P and Z_T are the charge number of projectile and target atoms, I is ionisation potential: $I = Z_T^{0.9} \times 16 eV$

Experimental value of the energy losses follows from Formula (1.1):

$$\Delta E_{str,\exp} = \frac{1+\gamma}{\gamma} \frac{E}{\eta} \frac{\Delta f}{f} \frac{T_0}{\tau_{\exp}}, \quad (1.5)$$

T_0 – revolution period, $\tau_{\exp}$ = 300 sec is the experiment duration.

Experimental value of the energy loss during one revolution in the ring is 7.3 meV, which gives the target areal density of $1.3 \cdot 10^{15}$ Atoms/cm^2.

The maximum designed areal density of the storage cell is expected to be of 10^{14} atoms/cm^2.

The frozen pellet target provides a total number of atoms per pellet of $1.8 \cdot 10^{14}$ – $1.1 \cdot 10^{16}$. Influence of the target on the beam parameters can be estimated by introducing the "effective areal density" which is proportional to ratio of the atom number per the pellet to the beam cross section. We assume that in each moment of time one pellet is inside the beam. At the beam emittance of 1π·mm·mrad the effective target density lies between $3 \cdot 10^{14}$ and $2 \cdot 10^{16}$ Atoms/cm^2.

Maximum achieved intensity of the proton beam is $7 \cdot 10^{10}$. In the future one can expect improvement of the intensity to 10^{11} or even more by upgrade of the injection system. Now the maximum beam energy is 2.65 GeV, but it is possible in the future to increase this value to 2.7 GeV. At the same magnetic rigidity the maximum deuteron beam energy is 2.11 GeV.

Thus, in this report the calculations of the beam parameters were fulfilled at target density from 10^{15} to 10^{16} Atoms/cm^2 (at lower value the experiment can be performed during long time duration without cooling), at the beam intensity up to 10^{11} particles and in the beam energy range from 1 GeV to 2.7 GeV for protons and to 2.11 GeV for deuterons. The ring acceptance was taken of 10^{-5} π·m·rad in the both planes, which is corresponds to expected aperture of the gas storage sell. The initial beam parameters were taken approximately corresponded to these ones after acceleration: emittances of 10^{-6} π·m·rad in the both planes and momentum spread of 10^{-4}.

2. ANKE experiment without cooling

Efficiency of the cooling application at experiment with internal target is determined by relation between different sources of the particle losses. Generals of them are the following:
- single scattering on the target atoms on a large angle,
- the same for residual gas atoms,
- emittance growth and aperture limitation,
- momentum spread growth and limitation of longitudinal acceptance.

The particle losses due to single scattering on the target atoms restricts the experiment duration and can not be effected by the beam cooling. Emittance and momentum growth can be compensated by stochastic or electron cooling. In this case luminosity life time is determined only by single scattering process. The sources of the beam phase volume growth are the multiple scattering on residual gas and the target atoms, intrabeam scattering.

First of all influence of residual gas on the beam life time was investigated under assumption that average pressure in COSY vacuum chamber is $5\cdot10^{-9}$ Torr and gas composition is 95% of hydrogen and 5% of nitrogen. At these conditions the particle life time is about 10^{6} seconds and emittance growth rate at minimum beam energy of 1 GeV is about $3\cdot10^{-10}$ $\pi\cdot$m$\cdot$rad/sec. Thus the interaction with the residual gas does not restrict particle life time and slightly influences on the particle losses due to emittance growth.

2.1. Interaction with the target

Ultimate efficiency of the beam cooling can be estimated in the case of high target density and low intensity of the ion beam – in this case beam parameters are determined only by interaction with the target. Multiple scattering on the target atoms leads to the linear in time growth of the beam emittance and particle losses takes place when the beam emittance increases up to 0.3 of the ring acceptance [4]. The period of time when the emittance growth does not lead to the particle losses can be estimated by the following formula:

$$\tau = \frac{A\tau_{\varepsilon}}{3\varepsilon}, \qquad (2.1)$$

which gives the time of emittance growth from zero value to acceptance limit. Here A is the ring acceptance, τ_{ε} is the characteristic time of the emittance growth calculated at certain value of the beam emittance ε.

Fig. 2.1, 2.2 show the characteristic times of the single scattering process and emittance growth up to acceptance limit in both planes for proton and deuteron beam. The ring acceptance was taken of 10^{-5} $\pi\cdot$m$\cdot$rad in the both planes. The beta functions of the ring at the target position were taken of 2 meters in the horizontal plane and of 3 meters in the vertical one. The presented values correspond to the hydrogen target at the areal density of 10^{16}Atoms/cm^2 and beam emittances of 10^{-6} $\pi\cdot$m$\cdot$rad in the both planes. All the characteristic times are linearly scaled with the target density and can be simply recalculated to each required value. The difference in the energy dependence of the single and multiple scattering life times appears because of in the single scattering life time calculation the particle losses due to nuclear scattering are taken into account. The difference between horizontal and vertical degrees of freedom is explained by the difference in the beta functions in the target position.

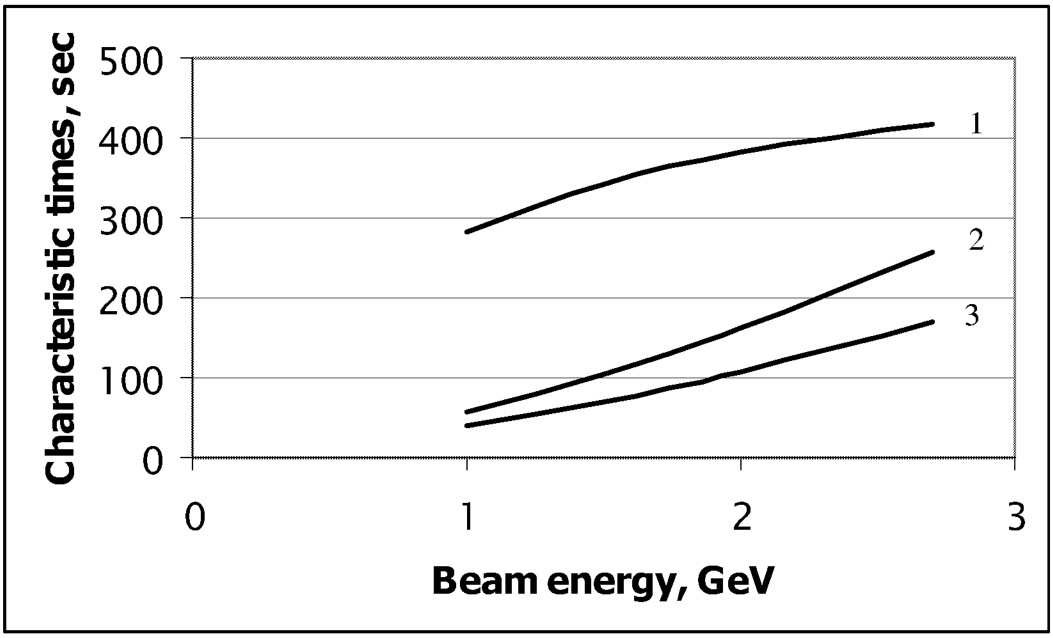


Fig. 2.1. The *proton beam* life time due to single scattering on the target atoms (1) and the times of emittance growth up to the acceptance limit in horizontal (2) and in vertical (3) planes.

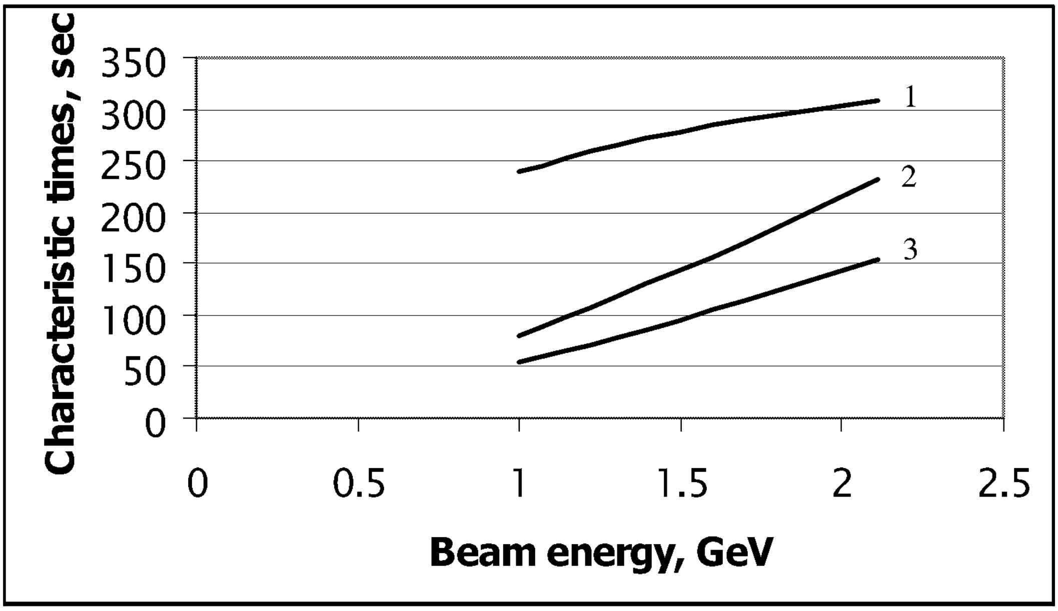


Fig. 2.2. The *deuteron beam* life time due to single scattering on the target atoms (1) and the times of emittance growth up to the acceptance limit in horizontal (2) and in vertical (3) planes.

For both kinds of particles (protons and deuterons) the experiment duration is limited by about 5 minutes at the target density of the order of a few 10^{16} Atoms/cm^2 and by about 1 hour at the target density of about 10^{15} Atoms/cm^2. Correspondingly in the following calculations we will investigate two cases: short term beam parameter evolution at high target density and long term evolution at low target density.

For both beams in the total energy range the particle losses due to aperture limitation play a significant role and suppression of the emittance growth by the beam cooling can increase the integral luminosity of the experiment by several times. Ultimate possible efficiency of the cooling decreases with the increase of the beam energy, and for deuteron beam at maximum energy the maximum gain in the luminosity is less than two times.

More accurate estimations of the possible cooling efficiency at high beam intensity have to include consideration of the intrabeam scattering process.

2.2. Calculations in presence of intrabeam scattering

The intrabeam scattering calculations are performed for the lattice parameters given in Fig. 2.3. Initial beam parameters in the numerical investigations were chosen the following: beam emittance in the both planes is equal to 10^{-6} π·m·rad, momentum spread is equal to 10^{-4}.

Calculations were performed taking into account the beam interaction with residual gas and target atoms and intrabeam scattering in the ion beam. The initial beam intensity was chosen to be equal maximum expected value of 10^{11} particles. An example of the calculations of short term variation of the beam parameters at the target areal density of 10^{16} Atoms/cm^2 is presented in the Fig. 2.4 for proton beam at energy of 2.7 GeV.

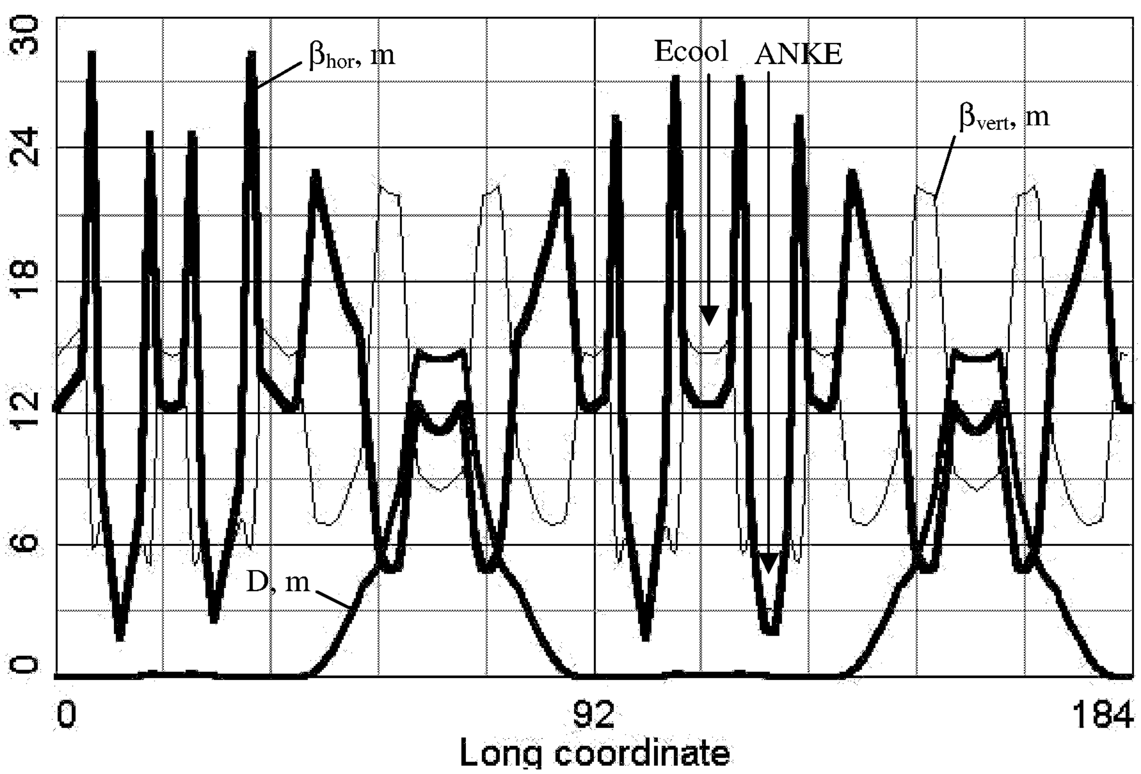


Fig 2.3. Lattice parameters at ANKE experiment, Q = 3.571, γ_{tr} = 2.243.
In the cooling section: Beta-functions = 13/15 m, Dispersion = 0,
in ANKE: Beta-functions = 2/3 m, Dispersion = 0

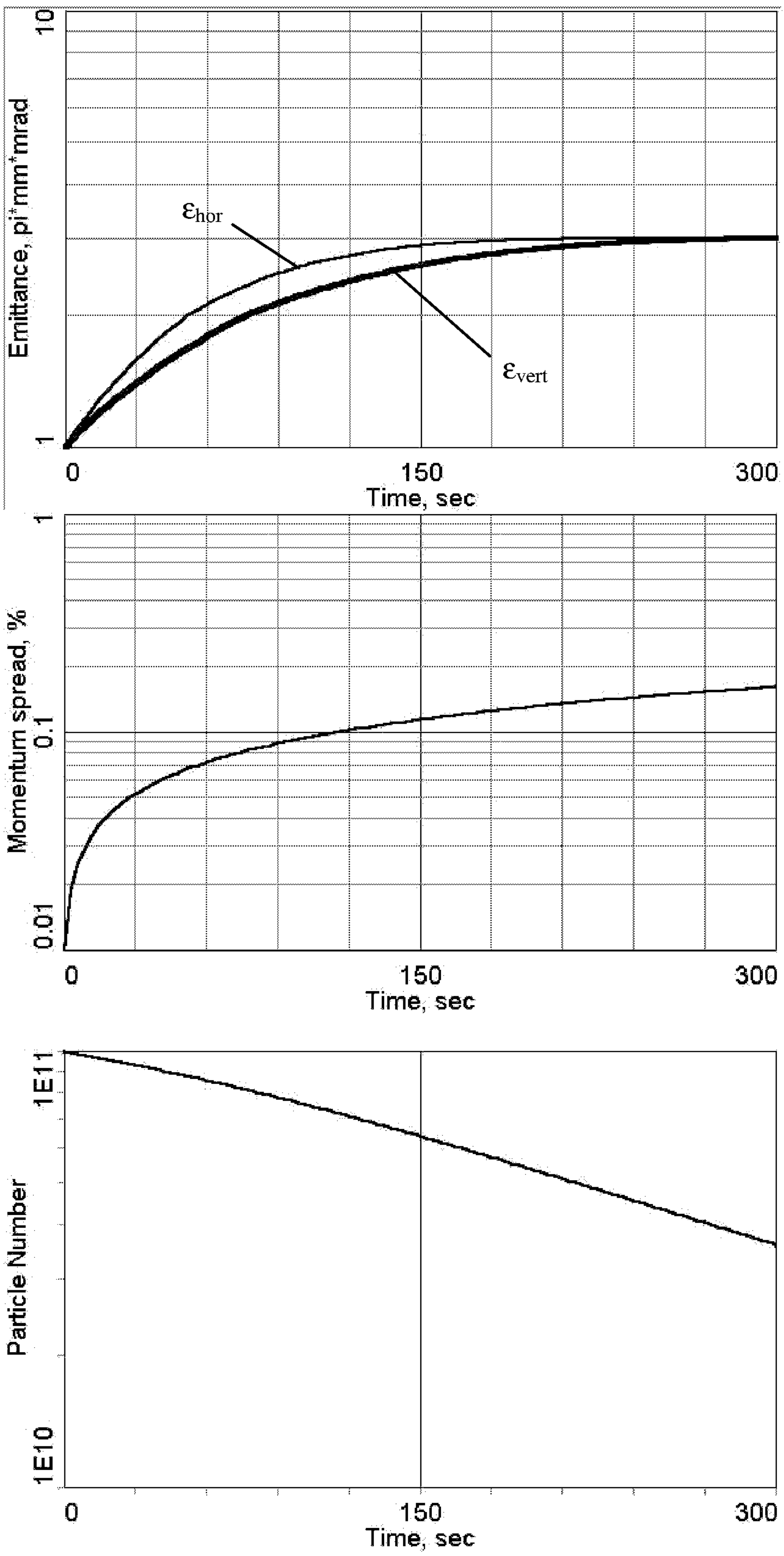


Fig. 2.4. The dependencies of the proton beam emittance (a), momentum spread (b) particle number (c) on time, target density is 10^{16} Atoms/cm^2.

One can see that after five minutes of experiment the beam emittance is limited by the ring acceptance, and the particle number decreases from 10^{11} to $3.6 \cdot 10^{10}$. The particle number after five minutes of experiment calculated without taking into account aperture limitation is equal to $4.85 \cdot 10^{10}$. The ratio between final particle number calculated without and with the aperture limitation can be used as a parameter, which characterises the gain in the experiment luminosity when the cooling completely suppresses the emittance growth. The ultimate possible cooling effect on the experiment (ratio of the beam intensity with cooling to that one without cooling) at high target density is presented in the Fig. 2.5. The possible gain in the particle number after one hour of experiment at the target density of 10^{15} Atoms/cm^2 is presented in the Fig 2.6.

One can see that the beam cooling can provide maximum gain in the beam intensity at minimum beam energy and for the proton beam, where this value is up to ten times. The gain for deuteron beam is about two times less due to intrabeam scattering dependence on the particle mass. At maximum energy the gain decreases to the value of about 50%. It is explained by the strong dependence of the intrabeam scattering on energy (as $\beta^3\gamma^4$). As result at maximum beam energy the emittance growth due to this process does not play a significant role. The difference between hydrogen and deuterium targets is negligible because of the main processes are determined by the interaction of the beam with electrons of the target atoms.

In the presented version of the numerical program the particle losses due to longitudinal acceptance limitation are not taken into account, correspondingly presented calculations can underestimate the particle losses due to growth of the momentum spread.

The next chapters of the report are dedicated to calculations of the beam parameter evolution in the presence of stochastic or electron cooling.

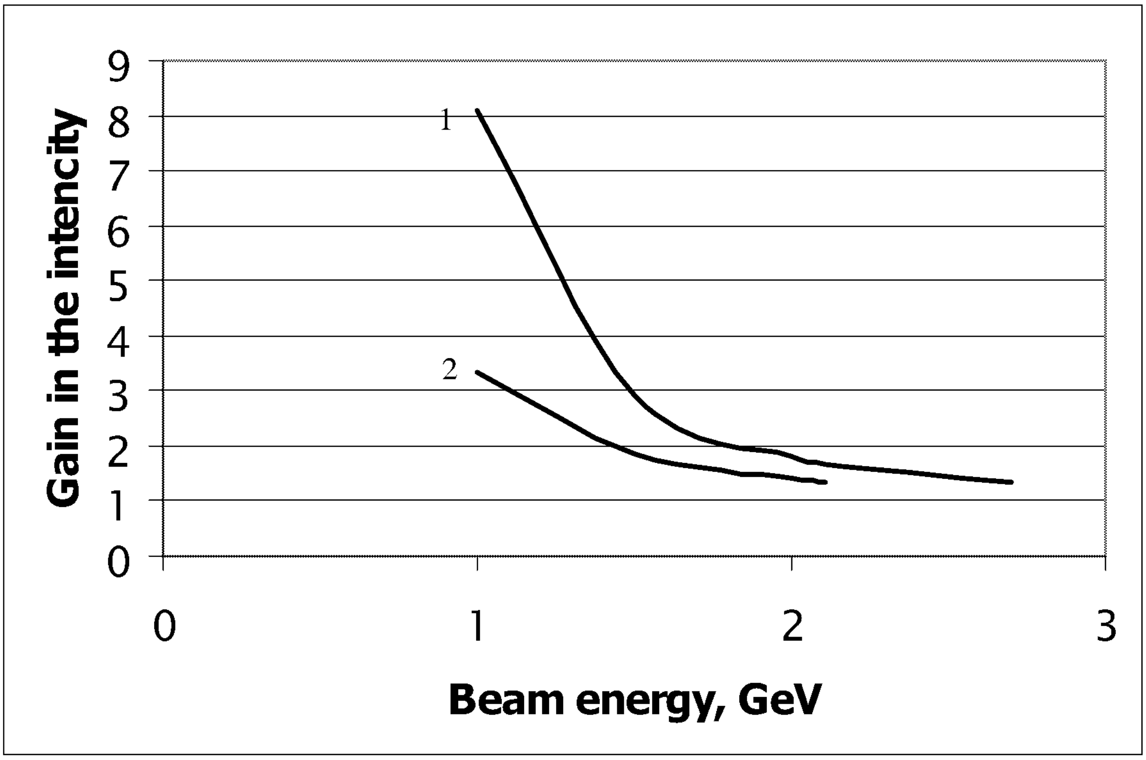


Fig. 2.5. Ultimate gain in the beam intensity which can be obtained using cooling at the experiment duration of *5 minutes*: 1 – proton beam, 2 – deuteron beam. The hydrogen target density is 10^{16} *Atoms/cm*^{2}, initial beam intensity is 10^{11} particles.

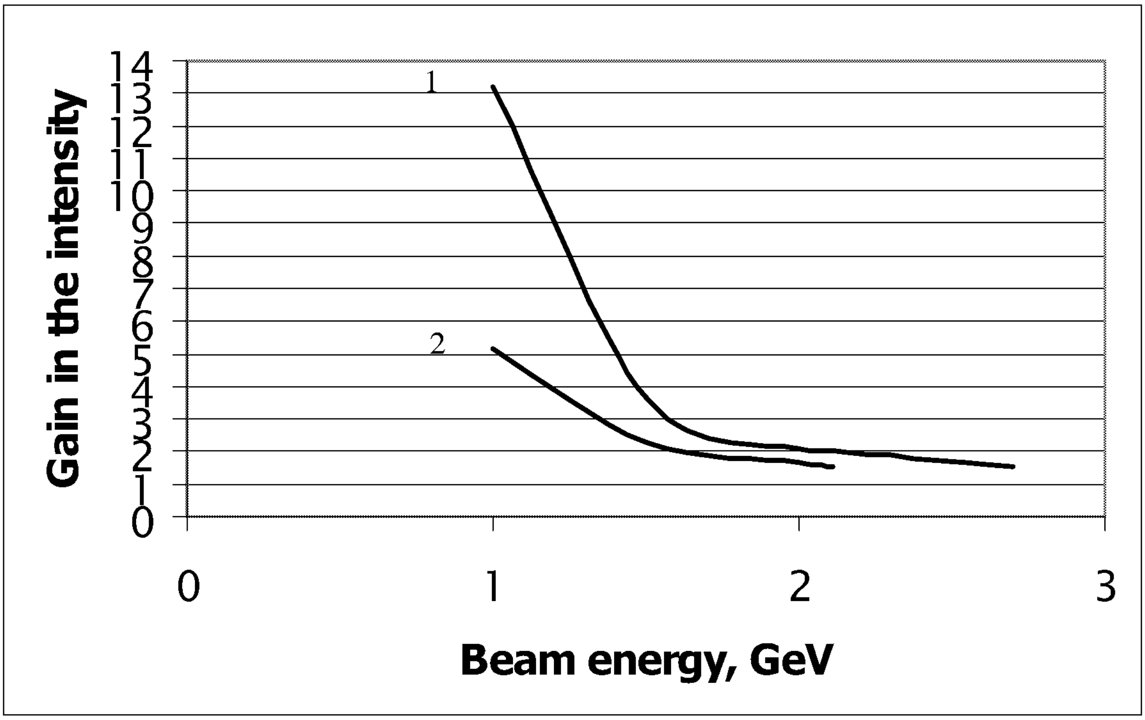


Fig. 2.6. Ultimate gain in the beam intensity which can be obtained using cooling at the experiment duration of *1 hour*: 1 – proton beam, 2 – deuteron beam. The hydrogen target density is 10^{15} *Atoms/cm*^{2}, initial beam intensity is 10^{11} particles.

3. Beam parameter evolution with existing stochastic cooling system

The parameters of the stochastic cooling system used in the following calculations are presented in the Table 3.1. Total frequency range divided into two bands. Cooling in all planes independently is possible. Band I is used for longitudinal cooling (filter method), Band II for horizontal cooling. Both bands together can be used for vertical cooling.

Table 3.1. Parameters of stochastic cooling system

	Band I	Band II
Lower frequency, GHz	1.0	1.8
Upper frequency, GHz	1.8	3.0
Bandwidth, GHz	0.8	1.2

Fig. 3.1. shows the emittance and momentum spread evolution of the proton beam at energy of 1 GeV and initial particle number of 10^{11} under common action of the hydrogen target of 10^{16}Atoms/cm^2 areal density, residual gas, intrabeam scattering and stochastic cooling. During the first 50 seconds the emittances in both plane increase to the acceptance limit. After that cooling has no more influence on this value. Momentum spread monotonically increases with tendency to saturation due to decrease of the particle number. After 5 minutes of the experiment the particle number decrease down to about $9.4\cdot 10^9$. At the same conditions without stochastic cooling the particle number decreases down to about $6.7\cdot 10^9$ it means that the stochastic cooling decreases the particle losses by about 20%.

At target density of 10^{16} Atoms/cm^2 the similar situation takes a place at maximum proton beam energy of 2.7 GeV and initial beam intensity of 10^{11} particles: stochastic cooling does not compensate emittance growth, and the gain in the particle number after 5 minutes of experiment accompanied with cooling is about 15%.

In order to estimate a range of the beam parameters in which the stochastic cooling can be effective in the experiment with internal target the particle number corresponding to an equilibrium between heating due to interaction with the target, residual gas, intrabeam scattering and stochastic cooling (in horizontal plane – in this case in vertical plane all the heating effects are suppressed by cooling) was calculated (Fig. 3.2, 3.3).

Maximum efficiency of the stochastic cooling corresponds to the maximum beam energy due to dependence of the mixing factor on off momentum factor. When the particle number is higher than about 10^{10} the intrabeam scattering (IBS) begins to play a significant role, that one can see from the change of the curve derivatives in the Fig. 3.2, 3.3.

More attractive region of parameters for the existing stochastic cooling system application is the target density below 10^{15} Atoms/cm^2 and particle number of a few units of 10^{10}. This region corresponds to long term experiment and the Fig. 3.4 presents the emittance and momentum spread evolution during one hour under common action of IBS, target, residual gas and stochastic cooling. (Beam energy is 2.7 GeV, initial intensity is $2\cdot 10^{10}$ particles, target density is 10^{15} Atoms/cm^2.) After the beam relaxation the stochastic cooling stabilises the horizontal and vertical emittance at the level of about 0.2 – 0.3 $\pi\cdot$mm$\cdot$mrad and momentum spread at the level of $5\cdot 10^{-5}$. The computer simulation shows that the particle number decreases during 1 hour of experiment to the value of $8.4\cdot 10^9$. Without cooling the final particle number is about $5.6 \cdot 10^9$. Thus the stochastic cooling application gives the gain in the experiment luminosity of about 50%.

As a conclusion from this analysis one can expect effective application of existing stochastic cooling in the experiment with internal target when the beam intensity is about or below of $2 \cdot 10^{10}$ particles, and the target density does not exceed 10^{15} Atoms/cm^2.

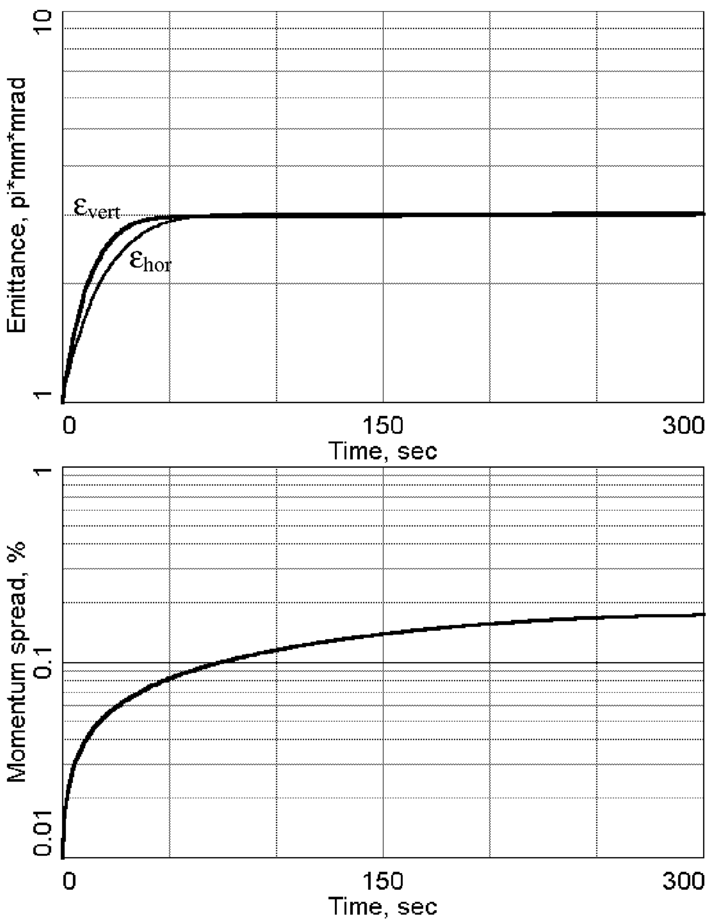


Fig. 3.1. Emittance and momentum spread evolution at stochastic cooling. Target density is 10^{16} Atoms/cm^2, beam energy 1 GeV, the beam intensity is 10^{11} protons.

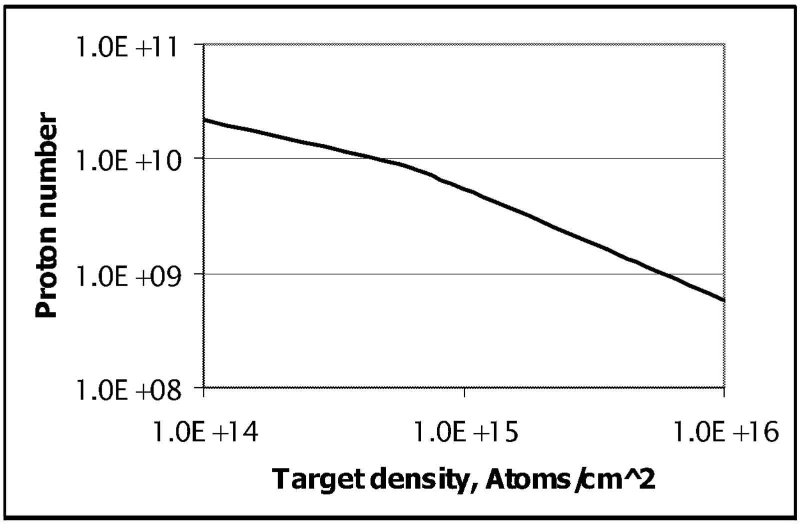


Fig. 3.2. Proton number corresponding to equilibrium between heating effects and stochastic cooling in the horizontal degree of freedom. Beam energy is 2.0 GeV.

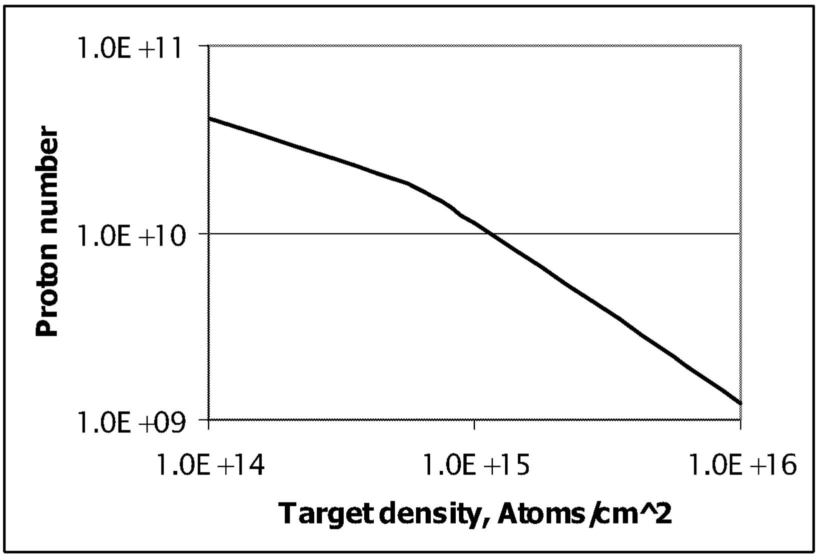


Fig. 3.3. Proton number corresponding to equilibrium between heating effects and stochastic cooling in the horizontal degree of freedom. Beam energy is 2.7 GeV.

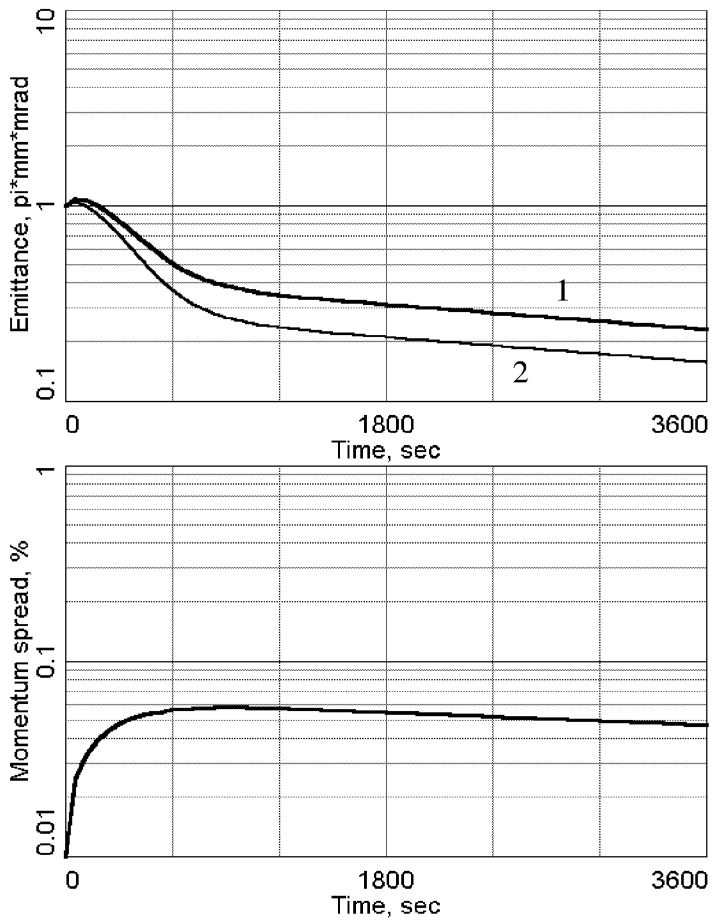


Fig. 3.4. Emittance (1 - horizontal, 2 - vertical) and momentum spread evolution. Target density is 10^{15} Atoms/cm^2, beam energy 2.7 GeV, initial beam intensity is $2 \cdot 10^{10}$ protons.

4. Electron cooling application

4.1. Beam parameter evolution with an electron cooling

The calculations in this chapter were performed at the electron beam and solenoid parameters corresponding to the existing COSY electron cooling system (Table 4.1). Longitudinal and transverse temperature were chosen using the results of the friction force measurements performed at COSY in May 2001. Only the maximum electron beam energy is varied in accordance with the proton energy.

Table 4.1. Electron cooling system parameters.

Effective length of the cooling section, m	1.4
Maximum magnetic field value, kG	1.2
Maximum value of electron beam current, A	3
Electron beam radius, cm	1.26
Transverse electron temperature, meV	300
Longitudinal electron temperature, meV	10
Neutralisation factor, %	30
Beta functions in the cooling section, m	13/15

The beam parameter evolution is calculated taking into account all general heating effects: interaction with residual gas, internal target and intrabeam scattering.

At minimum proton energy of 1 GeV and target density of 10^{16} Atoms/cm^2 the value of the electron beam current required for compensation of the beam heating in all degrees of freedom is of the order of a few Amperes. Fig. 4.1 presents the emittance and momentum spread evolution during 5 minutes of experiment at electron beam current of 1.5 A. After the relaxation of the beam parameters at initial stage the emittances and momentum spread keep to be the constant values during long time and the particle losses are determined only by the single scattering on the target atoms. In this range of parameters electron cooling application have a maximum efficiency and after five minutes of experiment it allows to have proton beam of 10 times higher intensity than without cooling.

At maximum proton energy (2.7 GeV) even maximum electron beam current can not provide the stabilisation of the emittance and momentum growth. However at electron beam current of 3 A (Fig. 4.2) the heating processes are substantially suppressed and gain in the particle number after five minutes of experiment is about 20% which is close to maximum achievable value (see Fig. 2.5). The experiment at high target density will be considered in more detail in the next chapter.

At lower target density the electron cooling stabilises the proton beam parameters in the total energy range. In the Fig. 4.3 the equilibrium beam parameters as a function of beam energy are presented. The electron beam current was chosen to obtain equilibrium proton beam emittance of about 10^{-6} $\pi\cdot$m$\cdot$rad. The equilibrium is reached during about 10 minutes and after that emittance and momentum spread slowly decrease with decrease of the particle number due to losses in the target.

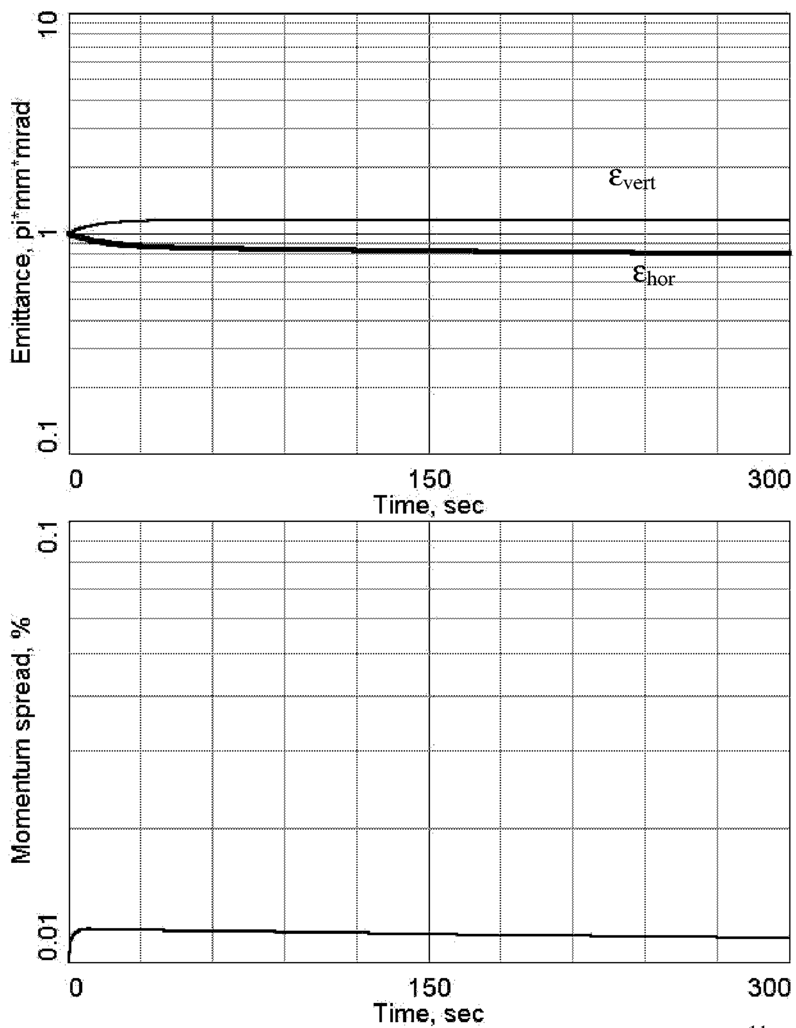


Fig. 4.1. Proton beam parameter time dependencies. Proton number is 10^{11}, energy is 1 GeV, target density is 10^{16} Atoms/cm^2. Electron beam current is 1.5 A.

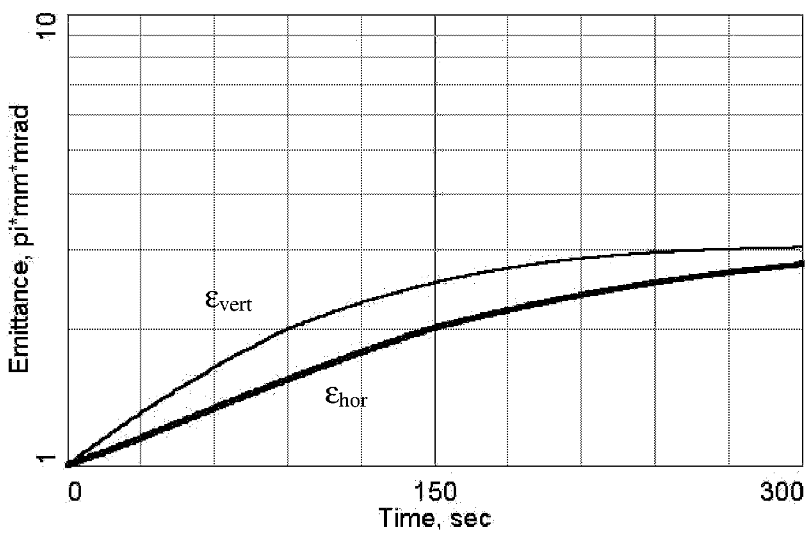


Fig. 4.2, a. Proton beam emittance time dependencies. Proton number is 10^{11}, energy is 2.7 GeV, target density is 10^{16} Atoms/cm^2. Electron beam current is 3 A.

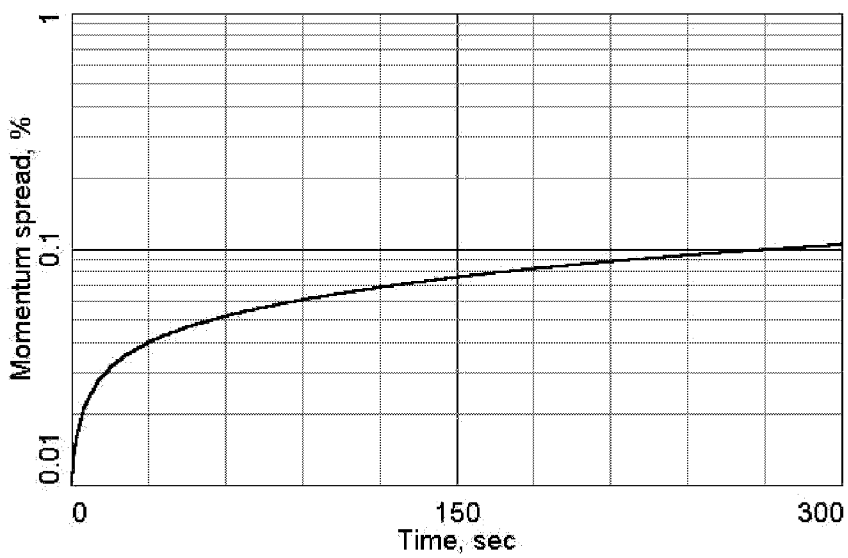


Fig. 4.2, b. Proton beam momentum spread time dependencies. Proton number is 10^{11}, energy is 2.7 GeV, target density is 10^{16} Atoms/cm^2. Electron beam current is 3 A.

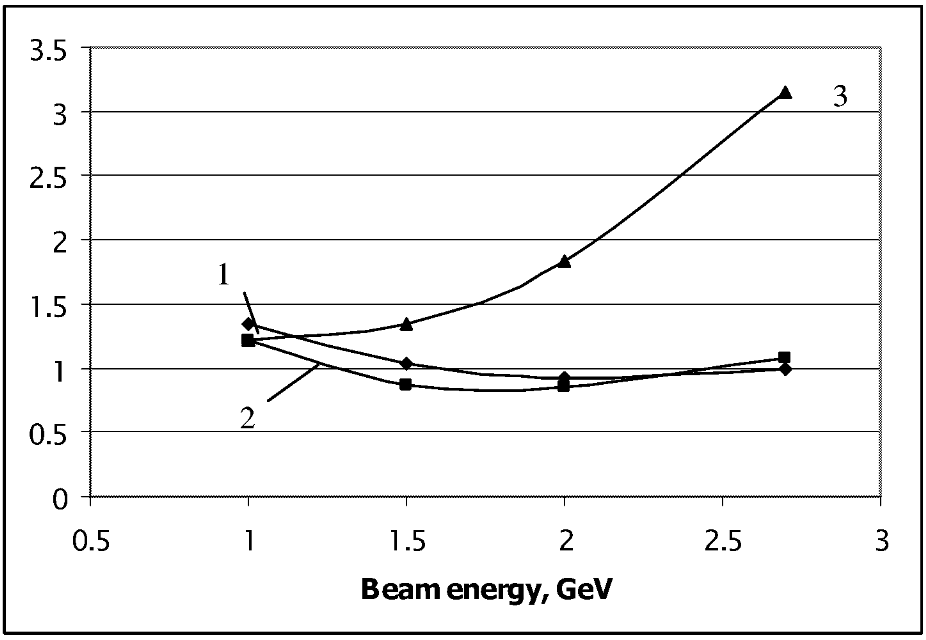


Fig 4.3. Equilibrium proton beam parameters as a function of the beam energy.
1 –horizontal emittance in 10^{-6} π·m·rad, 2 – vertical emittance in 10^{-6} π·m·rad, 3 – momentum spread in 10^{-4}. Proton number is 10^{11}, target density 10^{15} Atoms/cm^2.

Analogous dependencies for deuteron beam are presented in the Fig. 4.4. In the first approximation the cooling time for deuterons is two times longer than for protons, but characteristic time of the emittance growth due to multiple scattering with the target atoms is longer by four times. As result the electron beam current required to obtain the equilibrium is about two times lower. The values of the electron beam current used in the calculations of the Fig 4.3 – 4.4 are presented in the Fig. 4.5. The equilibrium is reached in the case of deuteron beam during 20 – 30 minutes and this time is comparable with the particle life time due to single scattering on the target atoms.

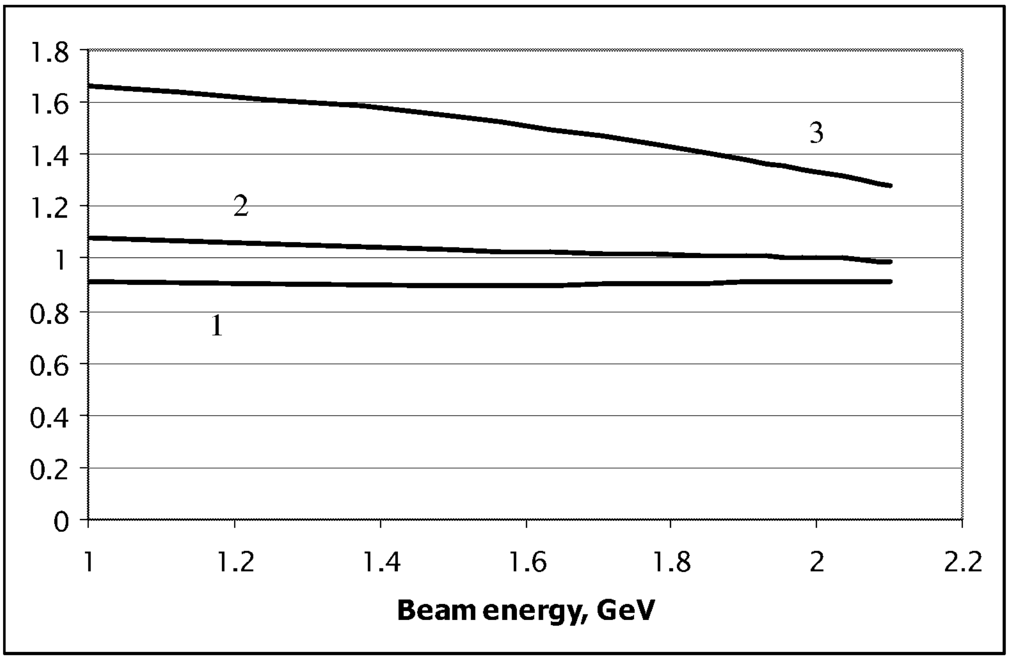


Fig 4.4. Equilibrium *deuteron beam* parameters as a function of the beam energy.
1 – horizontal emittance in 10^{-6} π·m·rad, 2 – vertical emittance in 10^{-6} π·m·rad, 3 – momentum spread in 10^{-4}. Deuteron number is 10^{11}, target density 10^{15} Atoms/cm^2.

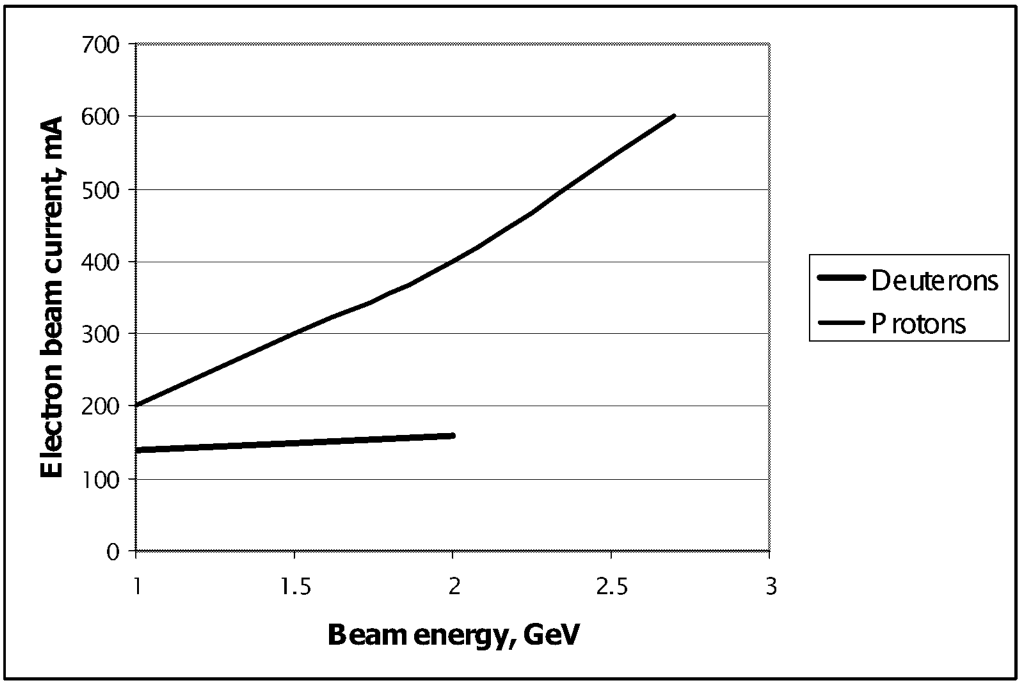


Fig. 4.5. The electron beam current required to reach the equilibrium emittance in both planes of about 10^{-6} π·m·rad.

The stabilization of the ion beam parameters is important in the experiment with cluster beam target. The target dimension in the horizontal plane is less than the ion beam dimension corresponding to the acceptance limit. The numerical model used in these calculations does not permit to solve the problem correctly in the case, when the horizontal emittance is varied during the experiment. However one can estimate possible gain in the experiment luminosity due to horizontal emittance stabilization as a ratio between maximum beam dimension and target dimension. This ratio is about 1.5 – 2 and taking into account that the characteristic time of emittance growth without cooling is about 10 minutes the gain in the luminosity can be estimated by the value 1.5.

The electron beam radius of 1.26 cm required for electron cooling at injection energy is more than two times bigger than ion beam one at experiment with internal target. Decrease of the electron beam radius permits to decrease the beam current. In the experiments with gas jet and cluster targets this fact does not play a significant role due to small value of the electron beam current density required for effective cooling. In the experiment with higher target density and at maximum beam energy the electron beam current density has to be as high as possible and an accurate choice of the electron beam radius is necessary to minimize the electron beam current. The optimum electron beam parameters will be discussed below.

4.2. Electron cooling in experiments with the pellet target

In the experiment with the pellet target the effective target density depends on the beam cross section and as a result its value is changed when the beam emittance is varied. Correspondingly the efficiency of electron cooling system can be substantially higher in the case, when the cooling suppresses the heating effects. In the previous chapter the electron cooling efficiency in the experiment with high target density was considered only from the side of the suppression the particle losses due to acceptance limitation and effective target density was assumed to be constant. In this chapter we investigate the experiment with the pellet target taking into account variation of the effective target density.

In this chapter the parameters of the electron cooling system presented in the Table 5 (chapter 5) are used in the simulations. The proton beam intensity is 10^{11} particles, which corresponds to the expected value after installation of new injection system.

The luminosity of the experiment with pellet target is determined by the expression:

$$L = \frac{N_b N_t}{S_t T_{rev}} P, \qquad (4.1)$$

where N_b is the particle number in the beam, T_{rev} – revolution period, N_t is particle number in the target, S_t – target cross-section, P – probability of the particle cross the target.

Assuming that the pellets cross the beam one by one with the period equal to the time duration of the beam crossing by a pellet, one can estimate the probability as the following:

$$P = \frac{S_t}{S_b} \approx \frac{S_t}{\pi\sqrt{\beta_x \varepsilon_x \beta_y \varepsilon_y}} \qquad (4.2)$$

where $\beta_{x,y}$ –horizontal and vertical beta functions in the target position (dispersion in the target position is closed to zero), $\varepsilon_{x,y}$ – corresponding two-sigma emittances. As a result we have:

$$L = \frac{N_b N_t}{\pi T_{rev}\sqrt{\beta_x \varepsilon_x \beta_y \varepsilon_y}} \qquad (4.3)$$

The pellet diameter lies in the range from 20 to 80 μm, the target density is about $1.4 \cdot 10^{22}$ Atoms/cm^3. Target parameters and luminosity of the experiment are presented in the Table 4.2. The luminosity is calculated under assumption that one pellet is in the beam, beam emittance is 1 π·mm·mrad in the both transverse planes, the proton beam intensity is 10^{11} particles and beam energy is 2.7 GeV.

The luminosity life time is equal to:

$$\frac{1}{L}\frac{dL}{dt} = \frac{1}{N_b}\frac{dN_b}{dt} - \frac{1}{\varepsilon_x}\frac{d\varepsilon_x}{dt} - \frac{1}{\varepsilon_y}\frac{d\varepsilon_y}{dt}. \tag{4.4}$$

Thus, in difference with the case of gas storage cell target the luminosity life time depends not only on the particle life time, but also on the emittance variation. At optimum experiment conditions the electron cooling can provide practically constant luminosity during long period of time by corresponding choice of the electron beam current. In the Fig. 4.6 the luminosity of the experiment at maximum beam energy is presented for pellet diameter of 40 μm and 50 μm.

Table 4.2. The pellet target parameters

Pellet diameter, μm	Number of particles	Target cross-section, cm2	Target length, cm	Luminosity, cm-2*sec-1
20	$1.8 \cdot 10^{14}$	$3.14 \cdot 10^{-6}$	0.00157	$3.66 \cdot 10^{32}$
30	$5.94 \cdot 10^{14}$	$7.07 \cdot 10^{-6}$	0.00236	$1.21 \cdot 10^{33}$
40	$1.43 \cdot 10^{15}$	$1.26 \cdot 10^{-5}$	0.00314	$2.91 \cdot 10^{33}$
50	$2.75 \cdot 10^{15}$	$1.96 \cdot 10^{-5}$	0.00393	$5.6 \cdot 10^{33}$
60	$4.84 \cdot 10^{15}$	$2.83 \cdot 10^{-5}$	0.00471	$9.85 \cdot 10^{33}$
70	$7.54 \cdot 10^{15}$	$3.85 \cdot 10^{-5}$	0.0055	$1.54 \cdot 10^{34}$
80	$1.1 \cdot 10^{16}$	$5.03 \cdot 10^{-5}$	0.00628	$2.32 \cdot 10^{34}$

At pellet diameter of 40 μm electron cooling compensate the particle losses by corresponding decrease of the beam emittance and the experiment luminosity variation during first five minutes is negligible. At the same conditions without electron cooling the luminosity decreases by about 3 times. At bigger pellet diameter the power of electron cooling is not high enough to suppress the beam heating due to interaction with target and the cooling application leads only to some increase of the luminosity life time.

The effectiveness of the cooling application can be estimated by comparison of an integral luminosity after certain period of experiment with and without the cooling. The integral luminosity for some period of experiment can be calculated:

$$L_{\text{int}} = \frac{N_t}{\pi T_{rev}\sqrt{\beta_x \beta_y}} \int_0^{T_{\exp}} \frac{N_b}{\sqrt{\varepsilon_x \varepsilon_y}} dt. \tag{4.5}$$

Or in the case of numerical integration of the beam dynamics

$$L_{\text{int}} = \frac{N_t}{\pi\sqrt{\beta_x\beta_y}}\frac{\Delta t}{T_{rev}}\sum_{i=1}^{n}\frac{N_b}{\sqrt{\varepsilon_x\varepsilon_y}}, \quad (4.6)$$

where Δt is integration step over time, n is the number of the integration steps.

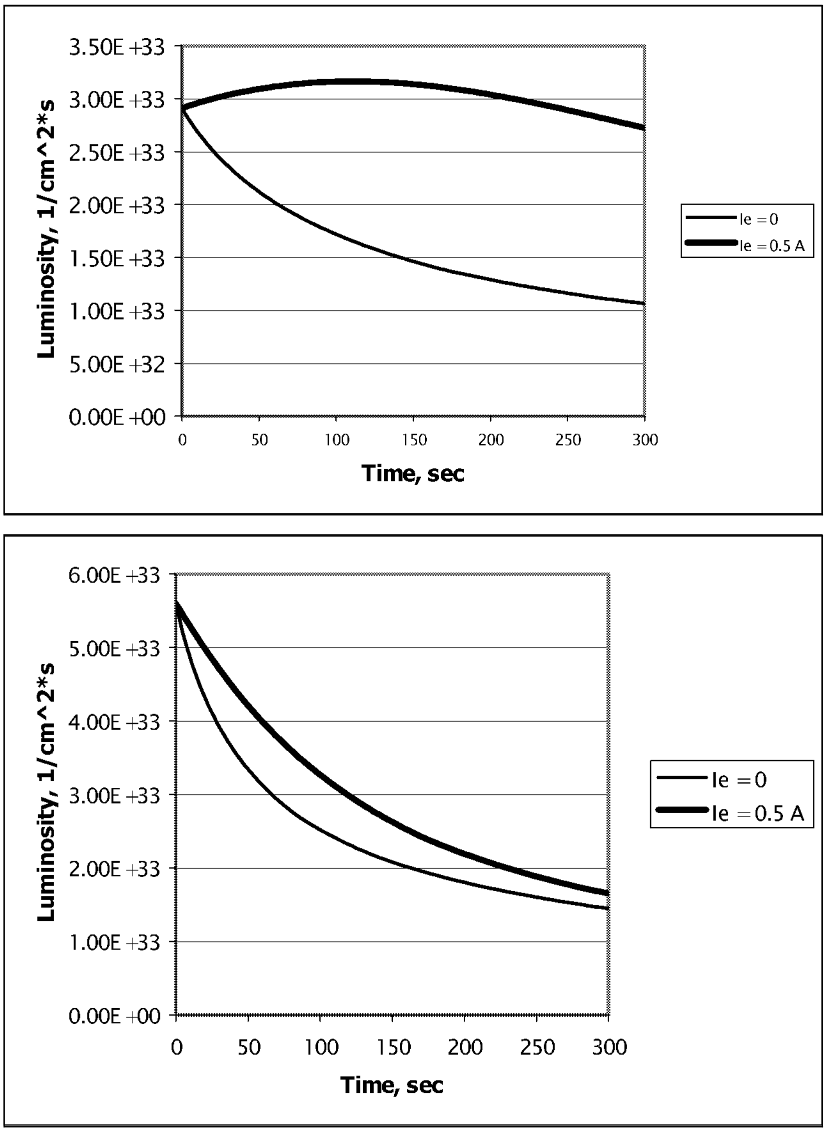


Fig. 4.6. Luminosity time dependence at pellet diameter of 40 μm (upper plot) and 50 μm (bottom plot), proton beam energy is 2.7 GeV.

The gain in the integral luminosity after five minutes of the experiment provided by the cooling application (Fig. 4.7, 4.8) is several times at pellet diameter less than 50 μm, and decreases to about 10% at bigger pellet diameter. At the pellet diameter less than 40 μm the electron beam current of 500 mA is not optimal to obtain maximum luminosity that explains peculiarity of the curve in the Fig. 4.7. The dependence of the luminosity on the electron beam current will be discussed more detail below.

At big target density, when the cooling only slightly influences on the beam parameters during experiment, the cooling system can be used also for preliminary preparation the beam parameters before the target switching on. All the previous estimations were performed at the following initial beam parameters: emittances in both planes are 1 π·mm·mrad and momentum spread is 10^{-4}. The beam parameters corresponding to the equilibrium between electron cooling and intrabeam scattering are the following: horizontal emittance is about 0.3 π·mm·mrad, vertical emittance - 0.1 π·mm·mrad and momentum spread is about $8 \cdot 10^{-5}$. The equilibrium is reached during 30 – 60 sec depending on initial beam parameters. Without the target the beam life is higher than 10^5 sec and permits to perform all required manipulations of the beam parameters.

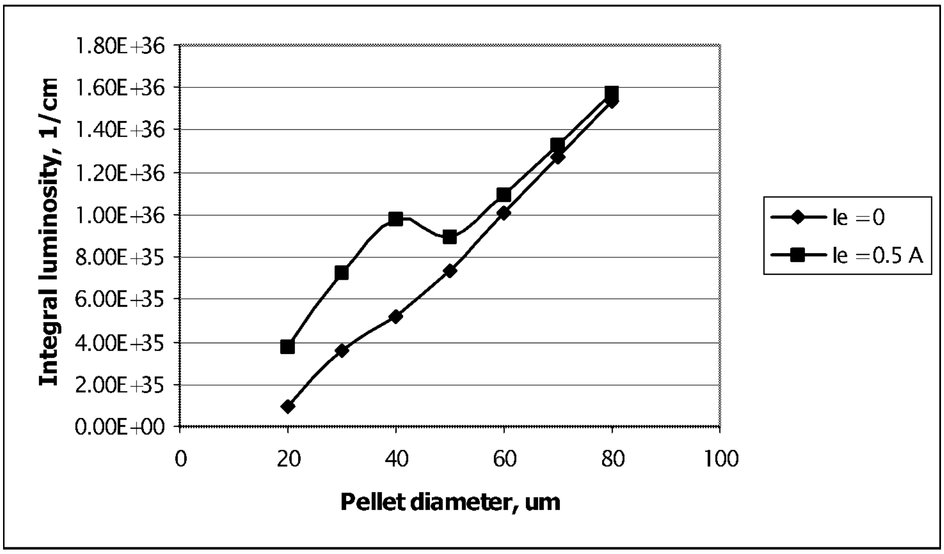


Fig. 4.7. Integral luminosity after five minutes of experiment as a function of the pellet diameter, beam energy is 2.7 GeV.

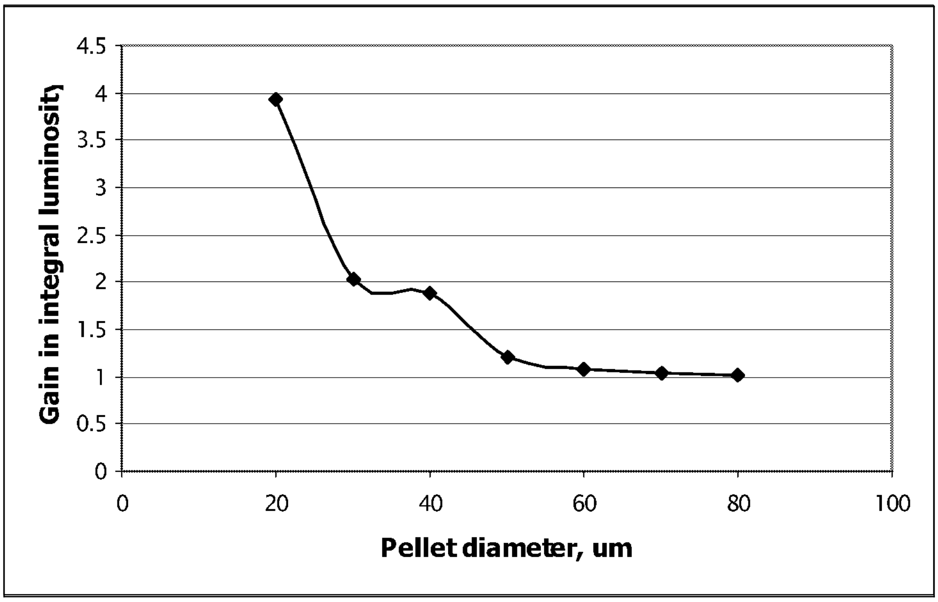


Fig. 4.8. Gain in the integral luminosity after five minutes of the experiment at electron beam current of 0.5 A, proton beam energy is 2.7 GeV.

In the Fig. 4.9 the integral luminosity was calculated under assumption that emittances in the both planes are the same and momentum spread is 10^{-4}. The integral luminosity monotonically increases with the decrease of the initial beam emittance and expected gain after five minutes of experiment due to initial preparation the beam before experiment is about 10%.

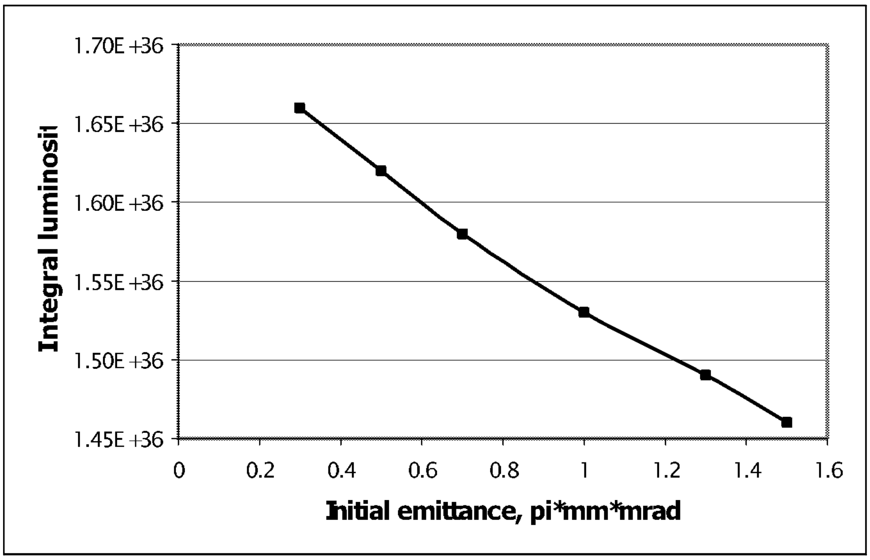


Fig. 4.9. Integral luminosity in 1/cm^2 after five minutes of experiment without cooling as function of initial beam emittance, beam energy is 2.7 GeV, pellet diameter is 80 μm.

In order to obtain maximum integral luminosity one can to optimise the experiment duration also. The integral luminosity increases approximately as a square root from the experiment duration (Fig. 4.10). Maximum gain in the luminosity obtained due to beam cooling before experiment corresponds to short term of the experiment, and it decreases with increase of the experiment duration (Fig. 4.11).

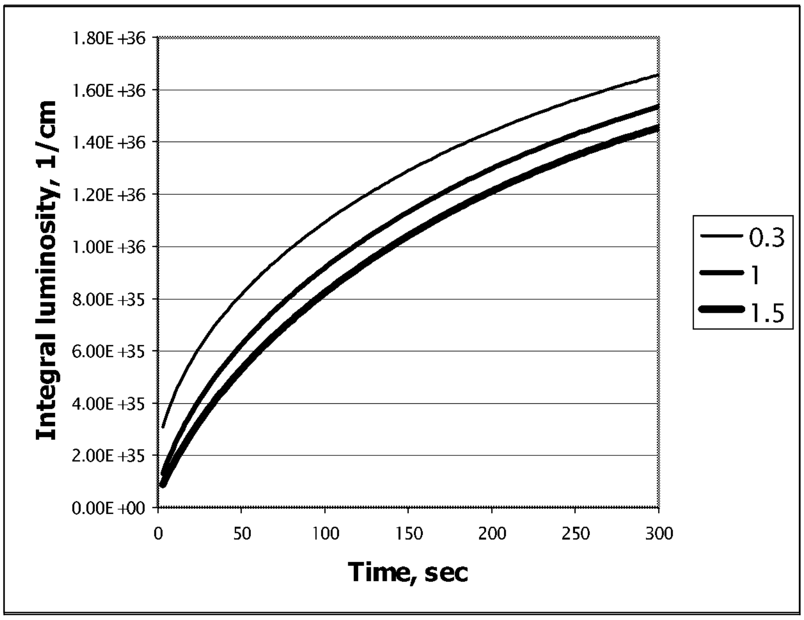


Fig. 4.10. Integral Luminosity as function of the experiment duration depending on initial beam emittance in π·mm·mrad, beam energy is 2.7 GeV, pellet diameter is 80 μm, cooling is off.

Thus, even at big target density, when the cooling power is not enough to suppress the heating due to interaction with the target, the experiment luminosity can be improved by preparation the beam parameters before the target switching on and by optimization of the experiment scenario.

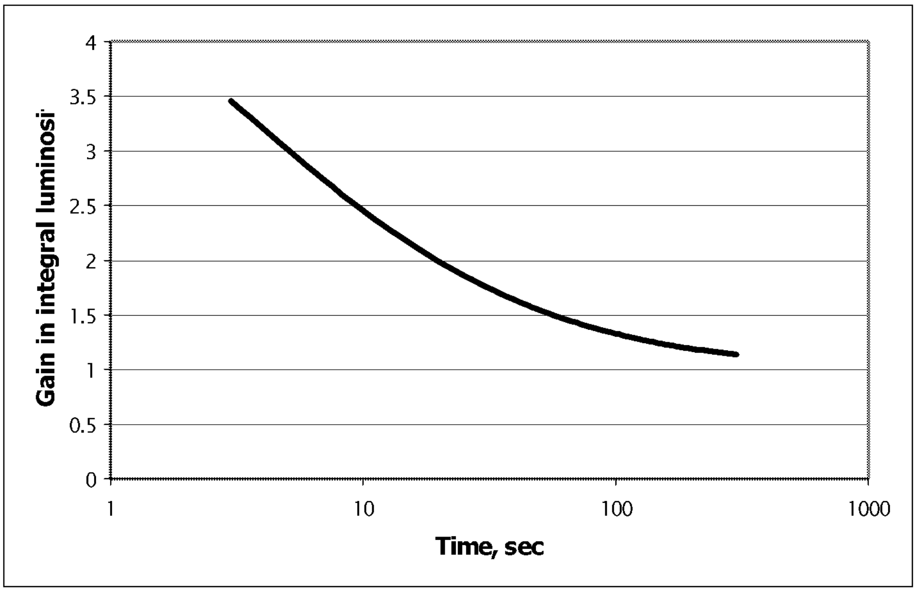


Fig. 4.11. The ratio between the integral luminosity at initial emittance of 0.3 π·mm·mrad and 1.5 π·mm·mrad versus experiment duration, beam energy is 2.7 GeV, pellet diameter is 80 μm, cooling is off.

At maximum experiment energy the luminosity increases with the electron beam current and maximum luminosity corresponds to maximum electron beam current. The electron cooling efficiency increases with decrease of the experiment energy (Fig. 4.12). And at minimum experiment energy it is not necessary to have maximum electron beam current to obtain the maximum luminosity – the luminosity dependence on the current has a saturation in the region of 400 mA (Fig. 4.13). The reason of the saturation can be explained by analysis of the luminosity time dependence (Fig. 4.14).

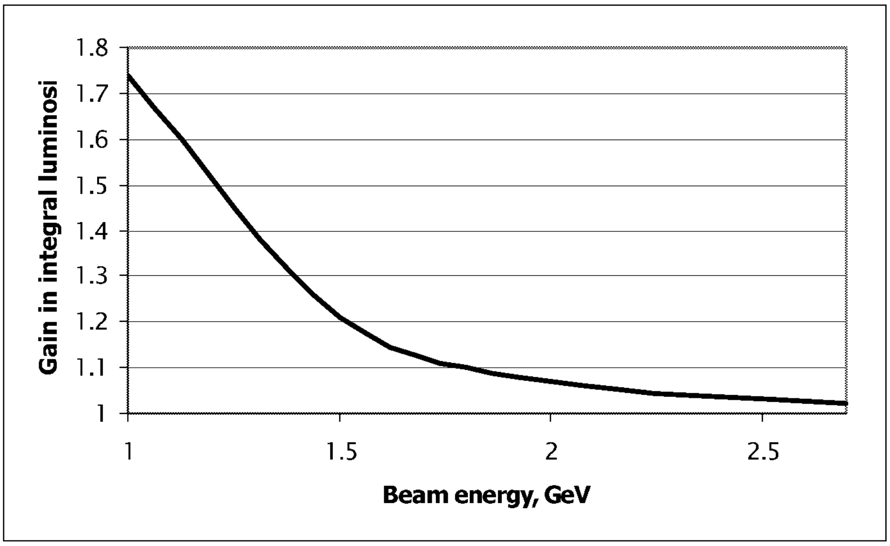


Fig. 4.12. Gain in integral luminosity after five minutes of experiment at electron beam current of 0.5 A, pellet diameter is 80 μm.

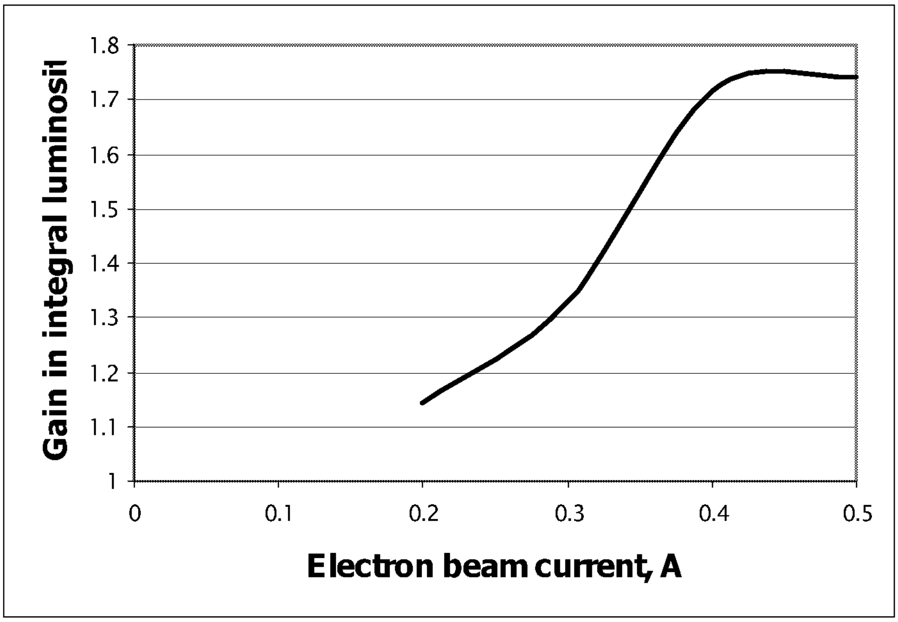


Fig. 4.13. The gain in integral luminosity after five minutes of experiment as function of electron beam current, beam energy is 1 GeV, pellet diameter is 80 μm.

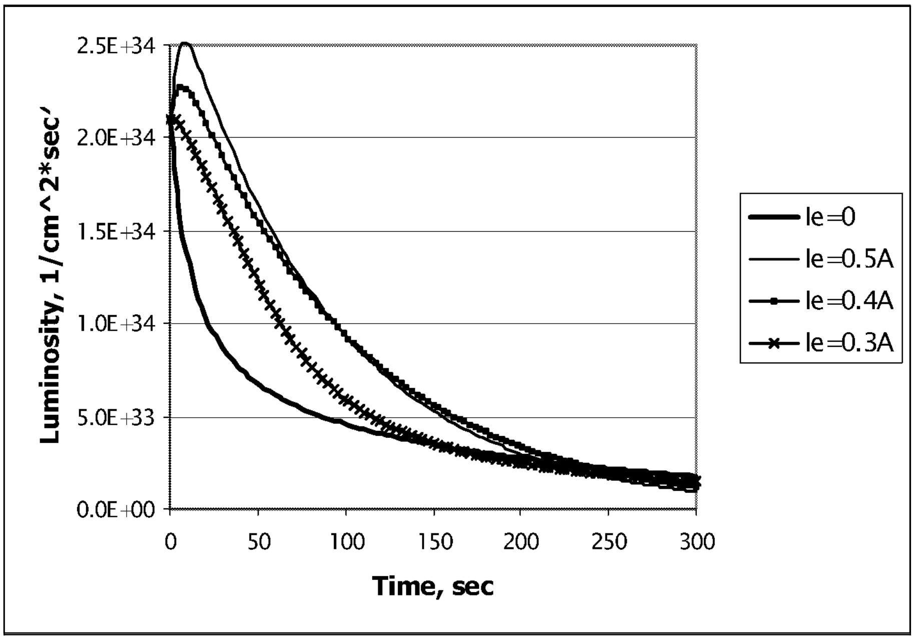


Fig. 4.14. Luminosity time dependencies at different electron beam current, beam energy is 1 GeV, pellet diameter is 80 μm.

At the electron beam current of 0.3 A the beam heating due to interaction with the target prevails on the cooling and beam emittance increases during experiment, but not so fast as without cooling. This "deceleration" of the emittance growth gives some gain in the luminosity life time in accordance with formula 4.4. At the electron beam current of 0.4 and 0.5 A the electron cooling completely suppresses the emittance growth and at the first stage of experiment (about 20 sec) the beam emittance decreases to the equilibrium value. The equilibrium is determined by the electron beam current and at 0.5 A it corresponds to about 0.62 π·mm·mrad in the horizontal plane and 0.88 π·mm·mrad in the vertical one. At the electron beam current of 0.4 A equilibrium emittances have some higher values: 0.7

π·mm·mrad - horizontal and 0.98 π·mm·mrad - vertical. After reaching the equilibrium luminosity decreases with the life time determined only by single scattering losses in the target. These losses is proportional to the probability of the particle cross the target, and, therefore, inversely proportional to the beam emittance. Thus, the initial gain in the luminosity, when the beam emittance decreases, is compensated by the shorter luminosity life time after reaching the equilibrium. It means that at the elevated beam energy and (or) relatively small target density the electron beam current has to be optimised to obtain maximum integral luminosity at each given experiment duration.

The possibility to vary the beam emittance during experiment can be investigated by comparison between the electron cooling rate and heating rate due to interaction with the target. In the Fig. 4.15 the dependencies of cooling and heating rate on the beam emittance at the beam energy of 2.7 GeV are presented.

At the pellet diameter of 80 μm (curve 4 in the Fig. 4.15) the heating always prevails on the cooling (curve 1), equilibrium is impossible and emittance of the beam increases to acceptance of the ring. The cooling application can decrease the speed of the emittance growth only.

At the pellet diameter of 40 μm one can see the stable equilibrium point (point 1 in the Fig. 4.15) and unstable one (point 2). When the beam emittance value is less than certain value corresponded to the unstable equilibrium the emittance of the beam decreases under common action of the cooling and target to the stable equilibrium point. When the beam emittance is less than its value in the stable equilibrium, it increases, but the emittance increase is limited by the value corresponded to the stable equilibrium point.

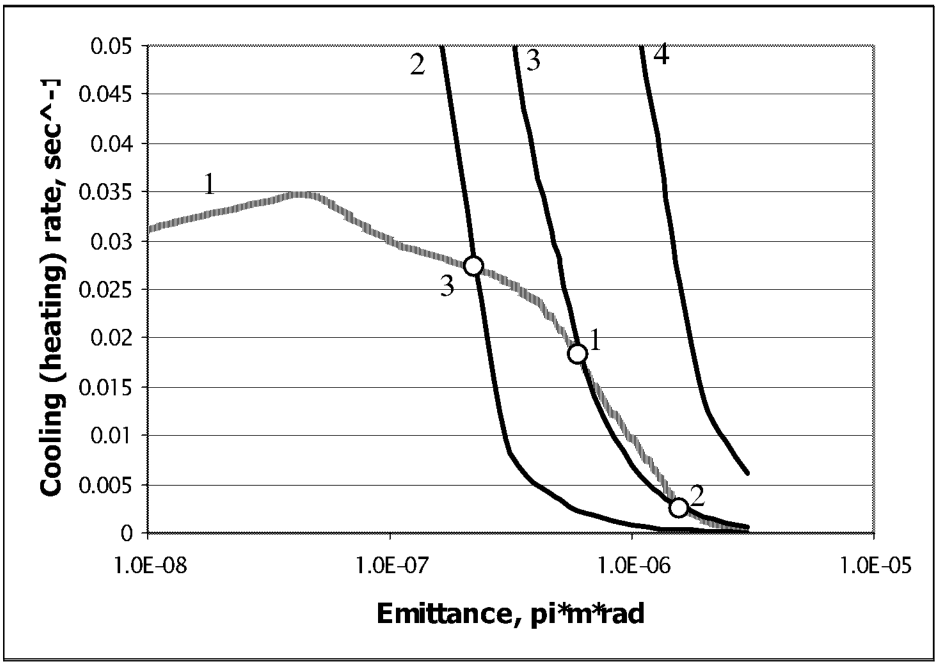


Fig. 4.15. Cooling rate at electron beam current of 0.5 A (1) and heating rate at pellet diameter of 20 μm (2), 40μm (3) and 80μm (4) as functions of the beam emittance, beam energy is 2.7 GeV.

At the pellet diameter of 20 μm the emittance value corresponded to the stable equilibrium (point 3 in the Fig 4.15) is less than in the previous case and unstable equilibrium lies outside the ring acceptance.

At low beam energy the maximum of the cooling rate is displaced to the region of higher emittances (this is a kinematic effect – the same emittance at low energy corresponds to low particle transverse velocity in the particle rest frame) and the maximum value increases due to strong dependence of the cooling time on the particle energy in the laboratory frame.

At the beam energy of 1 GeV the stable equilibrium points exist and unstable ones are outside the acceptance at all pellet diameters (Fig. 4.16). In this case the equilibrium beam emittance value can be varied by corresponding variation of the electron beam current. The range of the emittance variation is illustrated by the Fig. 4.17. At electron beam current of 150 mA the stable equilibrium is reached at the emittance value of about 1.5 π·mm·mrad and the equilibrium displaces to the value of about 0.8 π·mm·mrad at the electron beam current of 500 mA. Thus, one can obtains the regime with permanent luminosity during the experiment compensating of the particle losses by corresponding increase of the electron beam current (and decrease of the beam emittance) (see formula 4.4).

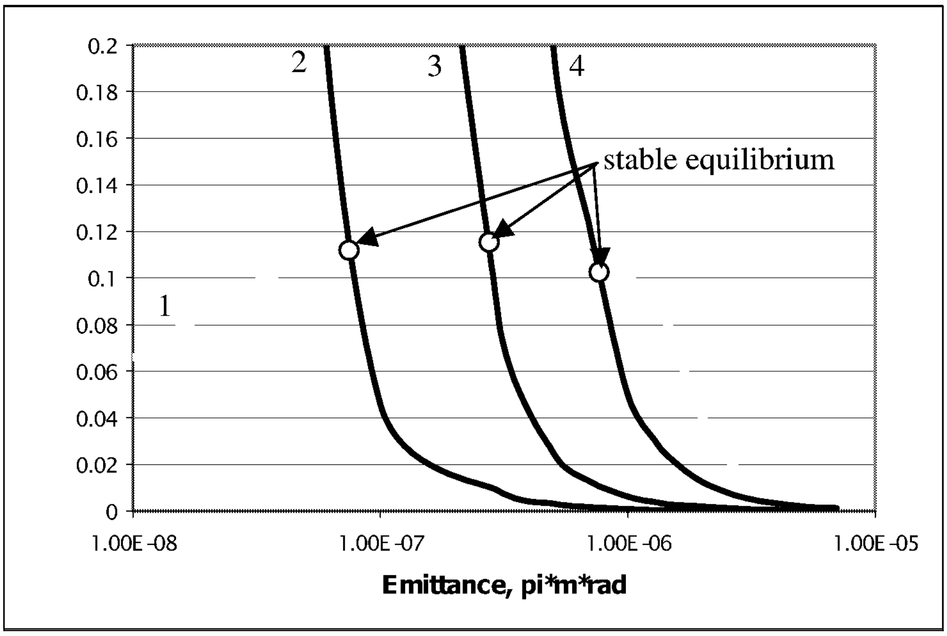


Fig. 4.16. Cooling rate at electron beam current of 0.5 A (1) and heating rate at pellet diameter of 20 μm (2), 40μm (3) and 80μm (4) as functions of the beam emittance, beam energy is 1 GeV.

The Fig. 4.15 – 4.17 are plotted without taking into account intrabeam scattering in the proton beam. However, the intrabeam scattering at the beam intensity up to 10^{11} particles slightly displaces the equilibrium position only.

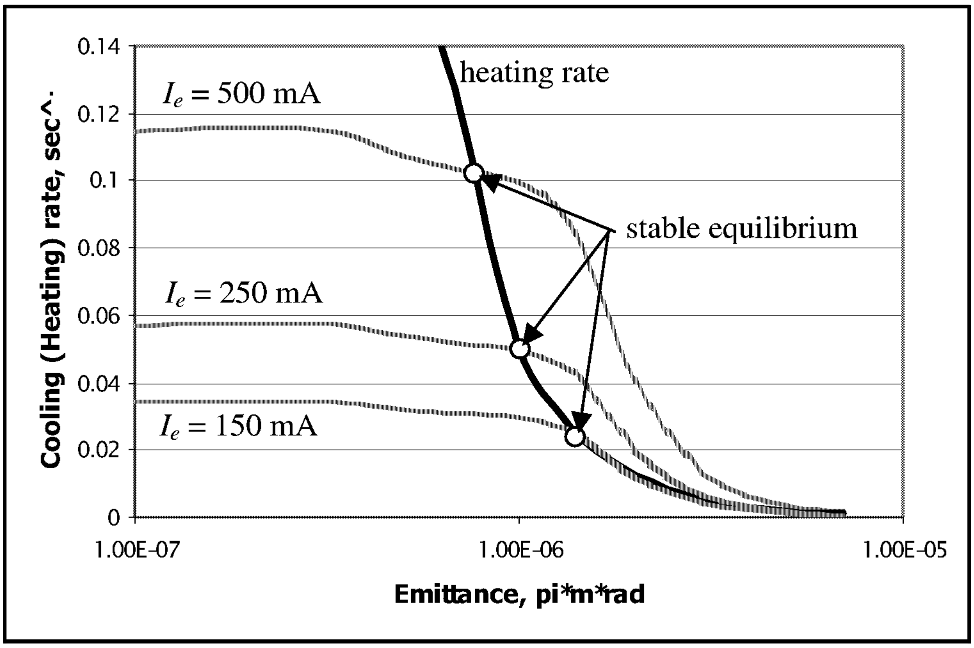


Fig. 4.17. The equilibrium position depending on the electron beam current. Pellet diameter is 80 μm, the beam energy is 1 GeV.

In the experiments with the deuteron beam the electron cooling gives a substantial gain in the luminosity even at big pellet diameter, due to small deuteron energy. But at deuteron beam energy of 2.11 GeV (Fig. 4.18) the electron cooling completely suppresses the beam heating only at maximum electron beam current of 500 mA and gain in the integral luminosity after five minutes of the experiment is about 50% (Fig. 4.18).

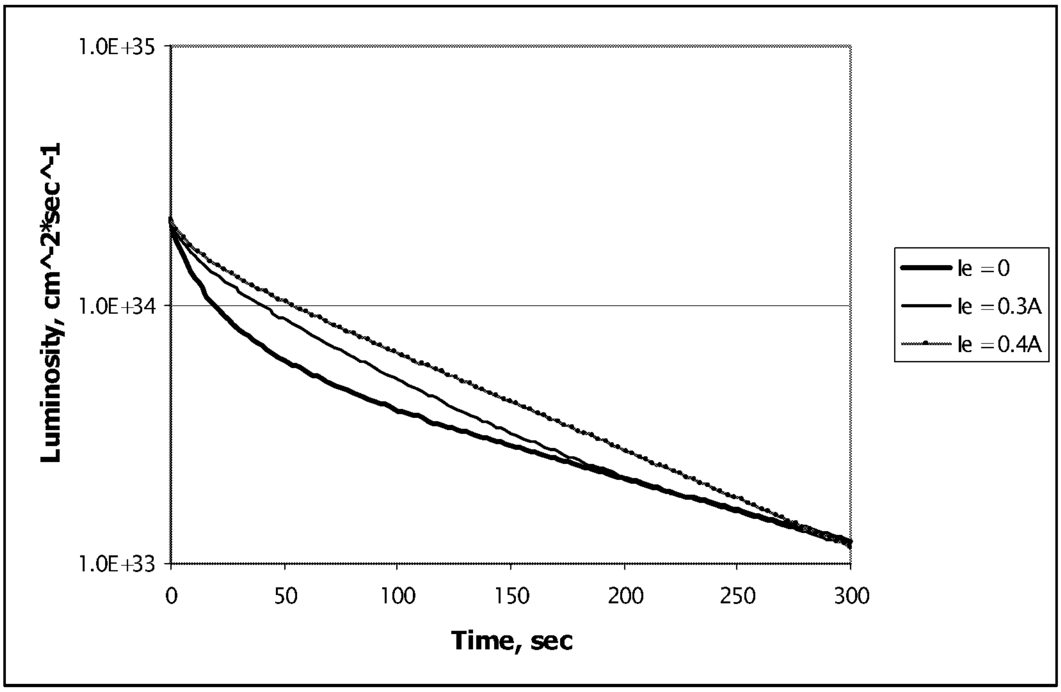


Fig. 4.18. Luminosity time dependence at different electron beam current. Deuteron beam energy is 2.11 GeV, the pellet diameter is 80 μm.

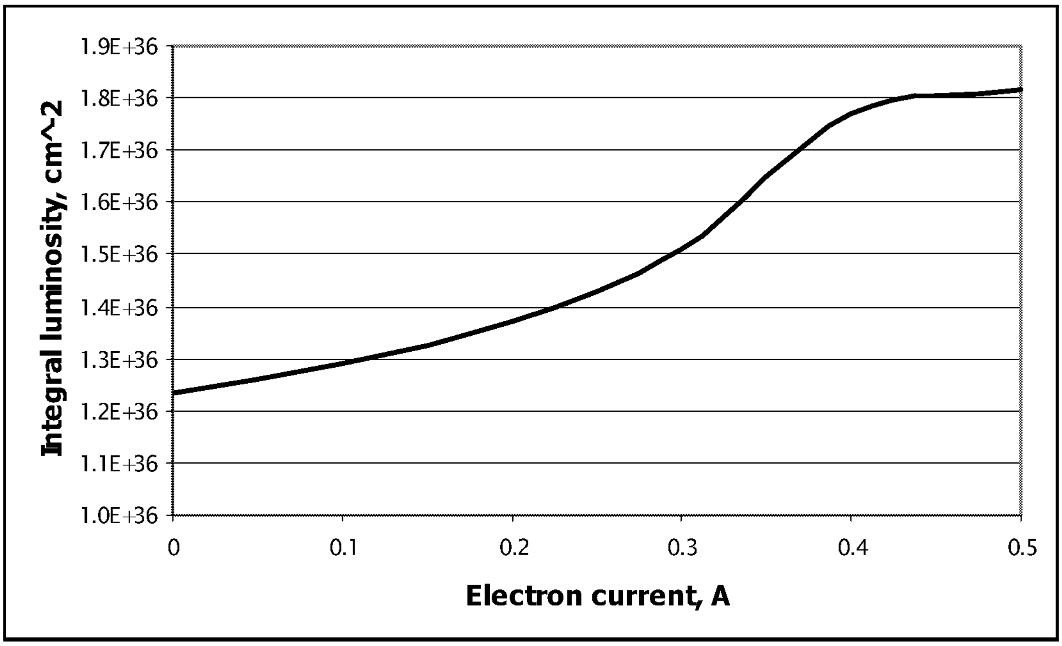


Fig. 4.19. Integral luminosity after five minutes of experiment as function of electron beam current. Deuteron beam energy is 2.11 GeV, the pellet diameter is 80 μm.

At less deuteron beam energy or at less pellet diameter the maximum gain in the integral luminosity can be achieved at less electron beam current and, as in the case with the proton beam, maximum expected gain in the luminosity can be 3 – 4 times.

4.3. Possible development of the existing electron cooling system

There are two possible design of the new cooling system:
- Traditional configuration of cooling system + HV accelerator,
- Cooling system with circulating electron beam.

Traditional configuration of the cooling system can provide electron beam at low transverse and longitudinal temperature, and the presented numerical results demonstrate its ability for ion beam parameters stabilization.

Electron cooling system with circulating electron beam has substantially low cost, but in such a system the electron beam quality is determined by a method of the beam acceleration, stability of electron motion in the electron storage ring, number of electrons and the ring circumference.

The required electron beam energy lies in the range from 0.5 to 1.5 MeV. Stable motion of the intensive electron beam at such relatively small energies can be provided only in the storage ring with longitudinal magnetic field. Electron beam acceleration can be provided using linear RF accelerator which periodically fills up the ring with new portion of electrons, or directly in the electron storage ring using induction acceleration.

In the first case longitudinal temperature of the electron beam can be even higher than transverse one, and one of the general problems of this method is to adjust the momentum spread of the electron beam with the ring dynamic aperture on momentum deviation.

Induction acceleration of the electron beam permits to keep the flattened velocity distribution of the electrons and in principle provides the same longitudinal temperature as HV accelerator. However at constant value of the guiding magnetic field the working point crosses resonance regions of the Larmor oscillations. Due to this fact the transverse temperature of the electron beam can be higher than one in traditional cooling system by several orders of magnitude.

The design of the electron cooling system of traditional configuration was performed at COSY earlier [5]. The following chapters of this report are dedicated to investigation of cooling efficiency at relatively pure electron beam quality. The brief description of the cooling method with circulating electron beam and preliminary design of the installation are given.

5. Electron cooling system with circulating electron beam

The choice of the electron cooling system parameters is restricted by number of limitations. Part of them is common for both systems: with single pass and with circulating electron beam. First of all it is requirement of the beam magnetisation, which limits the minimum value of the longitudinal magnetic field and maximum value of electron beam current.
Other limitations are related only to the system with circulating electron beam and particle dynamics in the storage ring with longitudinal magnetic field. Generals of them are the following:
- upper limit of the electron beam circulation period determined by increase of electron temperature during cooling process,
- upper limit of the electron beam momentum spread determined by dynamic aperture of the ring,
- upper limit of the electron beam current determined by threshold of microwave instability,
- limitations of the magnetic field and electron beam current due to longitudinal-transverse relaxation of the electron beam.

5.1. Magnetic field limitations

Electron beam magnetization is an efficient way of electron cooling rate increase using of longitudinal magnetic field [6] for transportation of the electron beam from the gun cathode to the collector through drift chambers including cooling section. The criterion of electron beam magnetization has a clear physics meaning: radius of electron Larmor spiral in magnetic field has to be smaller of the mean distance between electrons [6]:

$$\rho \le (n_e)^{-1/3} \; when B > B_{\min 1} \equiv \frac{m}{e}\sqrt{T_{\perp} mc^2}\left(\frac{I_e}{\beta\gamma\pi a^2 ec}\right)^{1/3}. \tag{5.1}$$

Here n_e is electron density in the electron rest frame, I_e – electron beam current, e, m – electron charge and mass, βc – electron velocity, $\gamma = \left(1-\beta^2\right)^{-1/2}$. Computer simulations with single pass electron beam show significant, up to several times, growth of cooling rate when $B \Rightarrow B_{min1}$ and its saturation *at* $B > B_{min1}$.

When electron beam is magnetized, electron drift caused by its own electric and guiding magnetic fields is sufficiently suppressed and does not exceed electron thermal velocity if

$$B > B_{\min 2} \equiv \frac{2I_e}{\beta\gamma a}\cdot\sqrt{\frac{m}{T_{\perp}}}. \tag{5.2}$$

Comparing the criteria (5.1) and (5.2) one can see, that $B_{min1} > B_{min2}$, when

$$I < \frac{\beta\gamma c e}{\sqrt{\pi}\, r_e^{3/2}}\cdot\sqrt{a}\left(\frac{T_{\perp}}{2mc^2}\right)^{3/2} \approx 17.7\beta\gamma\sqrt{a_{[cm]}}\cdot\left(T_{\perp}\right)_{[eV]}^{3/2}, \tag{5.3}$$

where r_e is electron classic radius. For COSY electron cooling system this condition is satisfied in the total range of the electron beam current required for effective cooling at minimum beam energy and minimum beam temperature. At reasonable electron beam transverse temperature (0.5 – 1 eV) the magnetic field value of 1 – 1.5 kG is big enough to provide beam magnetisation. More strong limitation of the magnetic field value follows from the requirement of suppression of the transverse-longitudinal relaxation in the electron beam during long circulation period. This process will be discussed below.

5.2. Principles of electron cooling with circulating electron beam.

The limitations of the electron beam circulating period are determined by the energy exchange between proton and electron beam due to the cooling process. The principle scheme [7] of the cooler with circulating electron beam (Fig. 5.1) includes an injector ("electron gun"), storage ring and electron collector ("electron dump"). The ring has straight section inserted in the structure of a hadron storage ring, where electron beam merges with proton one and cools it.
Due to interaction between the particles (antiprotons, ions) and electrons the particle temperature decreases when the electron one increases. The variation of both temperatures in Maxwellian plasma is described by the equations [7]:

$$\frac{dT_p}{dt} = \frac{4\sqrt{2\pi}\eta n_e z^2 e^4 L_C}{\gamma^2 mM} \cdot \frac{T_p - T_e}{\left(\frac{T_p}{M} + \frac{T_e}{m}\right)^{3/2}}; \qquad (5.4)$$

$$N_p \frac{dT_p}{dt} = -N_e \frac{dT_e}{dt}, \qquad (5.5)$$

where T_p, T_e are the particle and electron temperatures in the particle rest frame, m and M – their masses, N_p, N_e – the particle numbers in the rings, η is the ratio of the cooling section length to the circumference of the particle ring, L_C – Coulomb logarithm, n_e – the electron density, t – current time in Laboratory reference frame. The particle temperature in a cooler with single pass electron beam (and with Maxwellian velocity distribution!) decreases in accordance with the 1st equation, where $T_e = const.$
Therefore electron temperature in cooling process increase very fast and electron beam is to be renewed after electrons have got a significant temperature.
For typical parameters of the cooler the number of circulating electrons N_e is comparable with that one of the particles N_p circulating in COSY.

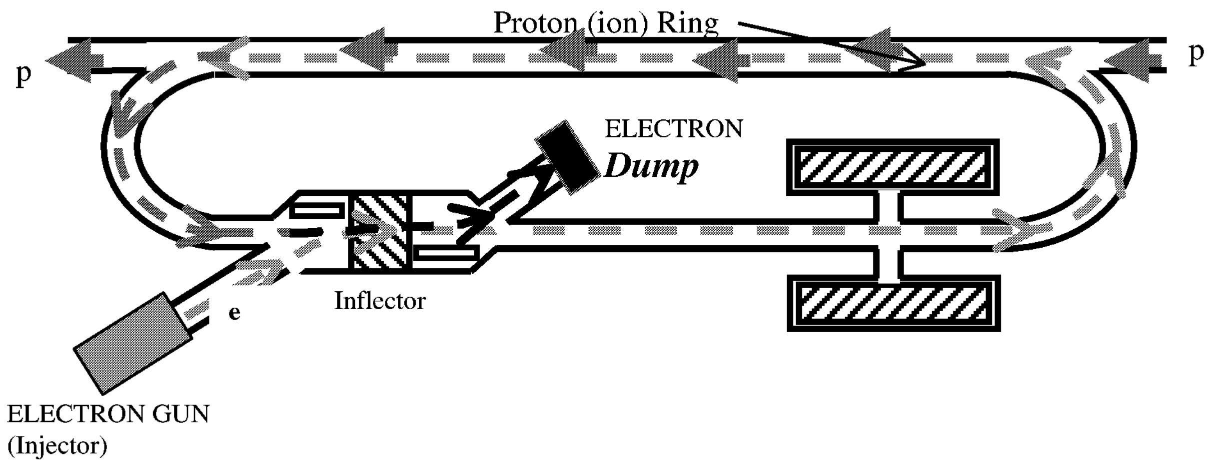


Fig. 5.1. Principle Scheme of Electron Cooler with Circulating Electron Beam

For electron beam with flattened velocity distribution electron beam parameter evolution during cooling process can be calculated as described in [1]. An example of the electron temperature variation during circulation is presented for COSY parameters in the Fig. 5.2.

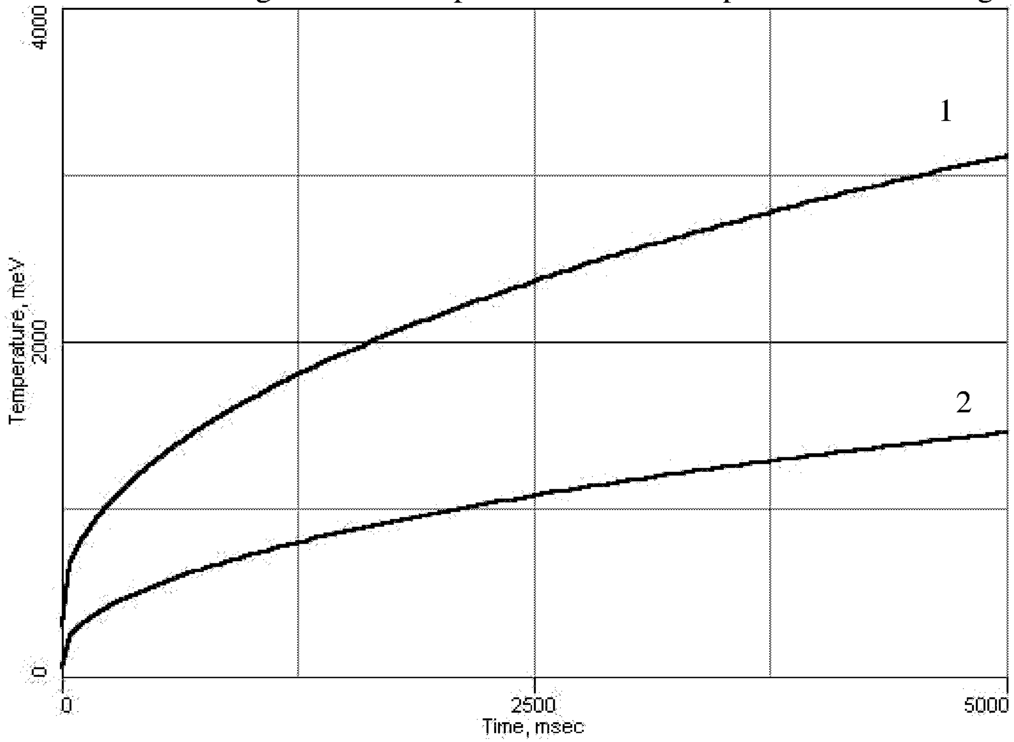


Fig. 5.2. Evolution of the transverse (1) and longitudinal (2) electron beam temperature during circulation. Proton beam energy is 1 GeV, proton number is 10^{11}, initial transverse electron temperature is 300 meV, longitudinal – 50 meV, electron beam radius is 0.5 cm, current – 0.5 A, electron ring circumference is 20 m, magnetic field is 1.2 kG, cooling section length – 1.4 m.

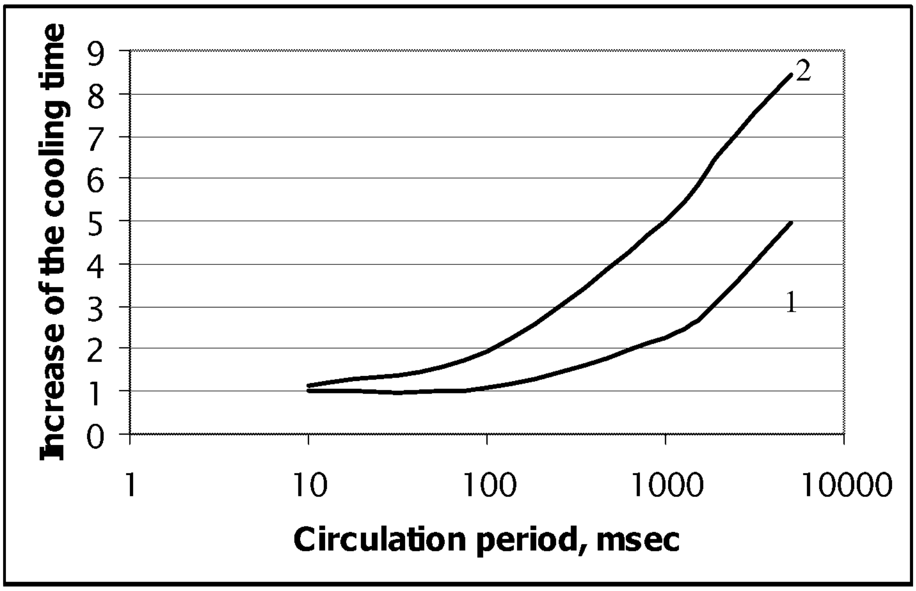


Fig. 5.3. Ratio of the characteristic cooling time of transverse degree of freedom providing by the cooling system with circulating electron beam to single pass one. Proton beam energy is 2.7 GeV (1) and 1 GeV (2), proton number is 10^{11}, initial transverse electron temperature is 300 meV, longitudinal – 50 meV, electron beam radius is 0.5 cm, current – 0.5 A, electron ring circumference is 20 m, magnetic field is 1.2 kG, cooling section length – 1.4 m.

The limitation of the circulation period is stronger at low beam energy. In the Fig. 5.3 the dependence of the cooling time on circulating period is presented at proton beam energy of 1 GeV and 2.7 GeV.

At circulation period shorter than 100 msec efficiency of the cooling system with circulating beam is practically the same as the single pass one (at minimum energy increase of the cooling time is less than two times). The cooling efficiency decreases during the circulation and after the period of time longer than approximately a few seconds further circulation of electrons does not influence practically on the proton beam parameters.

The circumference of the electron ring determines the total number of electrons and as a result the thermal capacity of the electron beam. In principle the electron beam circumference is to be as long as possible. The ring circumference of 20 meters is the minimum value, which permits to install in the ring injection and extraction systems, helical quadrupole lens for electron focusing and betatron yoke (if it is necessary).

The electron cooling system parameters determined by the requirements of beam magnetization and cooling efficiency are listed in the Table 5.1 and further calculations are performed at these parameters.

Table 5.1. General parameters of the electron cooling system with circulating electron beam

Electron ring circumference, m	20
Magnetic field, kG	1 – 1.5
Electron beam radius, cm	0.5
Maximum electron current, A	0.5
Effective length of the cooling section, m	1.4
Circulation period, msec	100 – 1000
Transverse electron temperature, meV	300 – 1000
Longitudinal electron temperature, meV	50 – 100

5.3. Storage ring with longitudinal magnetic field.

At electron energy of 10 MeV and higher usual strong focusing ring can be used for storage of electrons. In the case of low electron energy the storage ring with longitudinal magnetic field has some advantage (like electron magnetization) and provides a stable motion of circulating electrons. Such electron ring can be used simultaneously for preliminary acceleration of electrons. Then the injector delivers electrons of rather low energy. So called "modified betatron" is one of possible schemes of the storage ring with cooling electron beam. Combination of the ring with an injector provides an added bonus.

5.3.1 Particle dynamics in the ring with longitudinal magnetic field

Focusing system of the ring consists of straight and toroidal solenoids connected together as a racetrack. To form a closed orbit for a circulating particle the helical quadrupole winding is used. In the cooling section the quadrupole field is absent to avoid distortion of the cooling process. The helical winding can be placed in the straight section opposite to the cooling one.

Due to presence of the longitudinal and helical quadrupole magnetic fields the particle motion in the horizontal and vertical plane are strongly coupled. When the number of the spiral winding steps in the focusing section is integer the particle motion in the first approximation consists of two independent modes [8]:

a) fast Larmor rotation of every particle around "own" magnetic field line, which tune is equal to:

$$Q_{fast} \approx \frac{C}{2\pi\rho}, \tag{5.6}$$

$\rho = v/\omega_B, \omega_B = eB/\gamma mc$ is the electron cyclotron frequency, ρ is the electron Larmor radius, B is the longitudinal magnetic field averaged over the closed orbit, C is the ring circumference;

b) slow rotation of the beam as a whole around the axis of the helical quadrupole winding with the tune

$$Q_{slow} \approx \left(\frac{G}{B}\right)^2 \frac{L}{2k}, \tag{5.7}$$

L is the length of the sections with quadrupole field, G is the gradient of the quadrupole field, $k = 2\pi/h$, h is the step of the spiral winding.

For instance at typical parameters of the focusing system B = 1000 G, G = 20 G/cm, h = 60 cm, L = 120 cm, C = 20 m and at electron energy of 500 keV the working point corresponds to Q_{fast} = 109.4 (at maximum beam energy of 1.5 MeV Q_{fast} = 49.1), Q_{slow} = 0.24. In this case dispersion in the cooling section is relatively small: D_x = 10 cm, ellipticity of the electron beam cross section in the cooling section is less than 1%, i.e. circulating beam in the cooling section has round shape. Angular spread of the electron beam due to action of the helical quadrupole field can be reduced to the value less than 1 mrad by adiabatic variation of the gradient value at the entrance and at the exit of the quadrupole field region. Calculation of the ring lattice functions and beam parameters in the cooling section are provided numerically and the algorithm and computer code elaborated in JINR for this aim are described in [9]. Detailed design of the electron ring optics and accurate choice of the working point in the total range of electron energy can be a topic of further steps of the cooling system design and are not included in this report.

The motion stability conditions can be written as the following:

$$Q_{fast} \neq \frac{n}{2},\ Q_{slow} \neq \frac{k}{2},\ Q_{fast} \pm Q_{slow} \neq l \tag{5.8}$$

n, k, l are integer.

The resonant condition for the fast mode of oscillation (due to large value of its chromaticity) limits a dynamic aperture of the ring on momentum deviation. The particle momentum spread can not exceed the distance between nearest integer and half integer resonances. This value can be estimated by the following expressions:

$$\frac{\Delta Q_{fast}}{Q_{fast}} = -\frac{\Delta \rho}{\rho} = -\left(\frac{\Delta p}{p}\right)_{\max}, \ \left|\Delta Q_{fast}\right| \le \frac{1}{4}, \tag{5.9}$$

which gives us

$$\sigma_0 = \left(\frac{\Delta p}{p}\right)_{\max} \sim \frac{1}{4Q_{fast}} \ . \tag{5.10}$$

Fig. 5.4 presents the dynamic aperture value at the ring circumference of 20 m. Width and power of resonances are determined by the errors of the focusing fields. Fast crossing of high order resonance leads to increase of the beam transverse temperature only. However, during a long circulation period the stability conditions (5.8) have to be satisfied to keep a good beam quality even at small instability increment.

At minimum electron beam energy and magnetic field of 1 – 1.5 kG the value of the ring dynamic aperture (Fig. 5.4.) is approximately equal to $2\cdot 10^{-3}$ and such a value of the electron beam momentum spread has to be provided by the system of the electron beam acceleration. At maximum electron beam energy this limitation is not so strong.

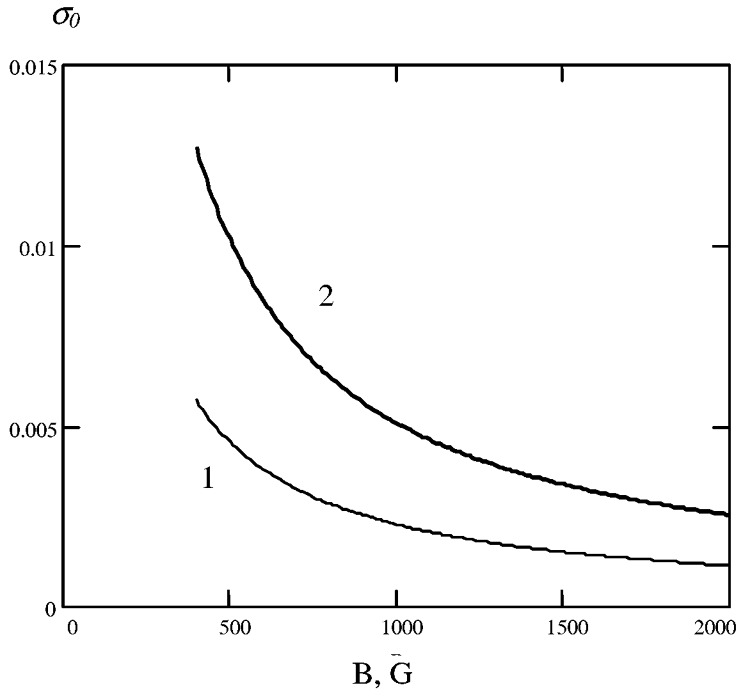


Fig. 5.4. Dynamic aperture on momentum deviation as function of longitudinal magnetic field, 1 – beam energy is 500 keV, 2 – beam energy is 1.5 MeV.

In principle, the maximum permitted value of momentum spread limits the circulating beam current because the momentum shift between particles at the axis and at the beam radius produced by the beam space charge has not to exceed $(\Delta p/p)_{\max}$. The shift in electron momentum due to electron beam space charge is equal to

$$\frac{\Delta p}{p} = (1-\eta_n)\frac{eI}{\beta^3 \gamma m_e c^3}, \tag{5.11}$$

where η_n is neutralisation factor. Correspondingly, the maximum current of electron beam is limited by the value

$$I \le \frac{\beta^3 \gamma m_e c^2 \sigma_0}{(1-\eta_n)e} . \tag{5.12}$$

However, even at zero neutralisation factor this condition practically does not limit a possible value of the beam current up to magnetic field value of several kG (Fig. 5.5).

More serious limitation of the circulating beam current is determined by the threshold of the microwave instability and it is discussed in the next chapter.

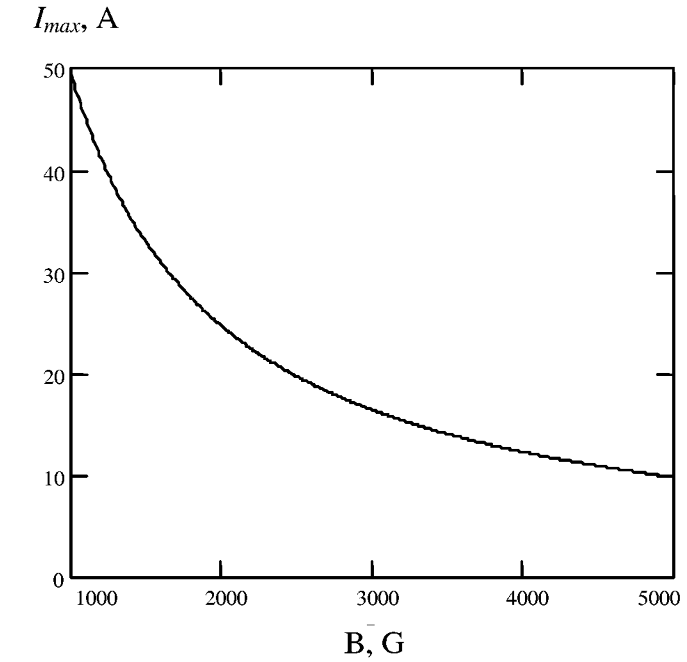


Fig. 5.5. Upper limit of the circulating beam current determined by momentum shift due to its space charge. Beam energy is 500 keV, neutralisation factor is equal to zero.

5.3.2 Current limitation due to microwave instability

At given maximum value of the momentum spread the longitudinal microwave instability limits the intensity of the circulating beam. Dynamics of longitudinal motion in the LEPTA is the same as in a standard strong focusing ring, and therefore we can use the usual criterion for longitudinal stability of the electron beam, which can be written as follows [10]:

$$I \le 4F_{long} \frac{mc^2 \beta^2 \gamma |\eta|}{e|Z_n / n|} \sigma_f^2 , \tag{5.13}$$

σ_f is a spread in momentum deviation (half width on half height). Z_n is a longitudinal coupling impedance of the beam for a mode with number n. Factor F_{long} takes into account the real shape of the stability diagram. In standard Keil-Schnell criterion F_{long} = 1. However, when beam energy is less than critical one and momentum distribution function has a long "tails"

F_{long} value can be significantly larger than unit. In this case with a good accuracy we can write:

$$F_{long} \cong \sigma_0^2 / 2\sigma_f^2, \tag{5.14}$$

where σ_0 is a dynamical aperture of the machine on momentum deviation. If the crossing of the half-integer resonance is impossible σ_0 is limited by the condition (5.10). The impedance for cylindrical beam and vacuum chamber is described with the formula:

$$\left|\frac{Z_n}{n}\right| = \frac{377}{2\beta\gamma^2}\left(1 + 2\ln\frac{b}{a}\right), \tag{5.15}$$

where b and a are the radii of vacuum chamber and electron beam. This formula gives us about 250 Ohms at minimum beam energy.

For described focusing structure the transition energy of the ring can be estimated as $\gamma_{tr}^2 \cong \pm Q_{fast}\, Q_{slow}$ [8]. The sign of γ_{tr}^2 is determined by the directions of the longitudinal magnetic field and the quadrupole helical winding rotation, what permits to us choose the regime with $\eta > 0$ (no negative mass instability) in the total energy range. In this case the instability takes place due to finite conductivity of the vacuum chamber walls.

The threshold current (5.13) as a function of beam energy and longitudinal magnetic field is presented in the Fig. 5.6, the tune value of the slow mode of oscillations was chosen to be equal 0.2 in the total energy range. The threshold current decreases with the increase of magnetic field value due to dependence of σ_0 on the magnetic field (see Fig. 5.4).

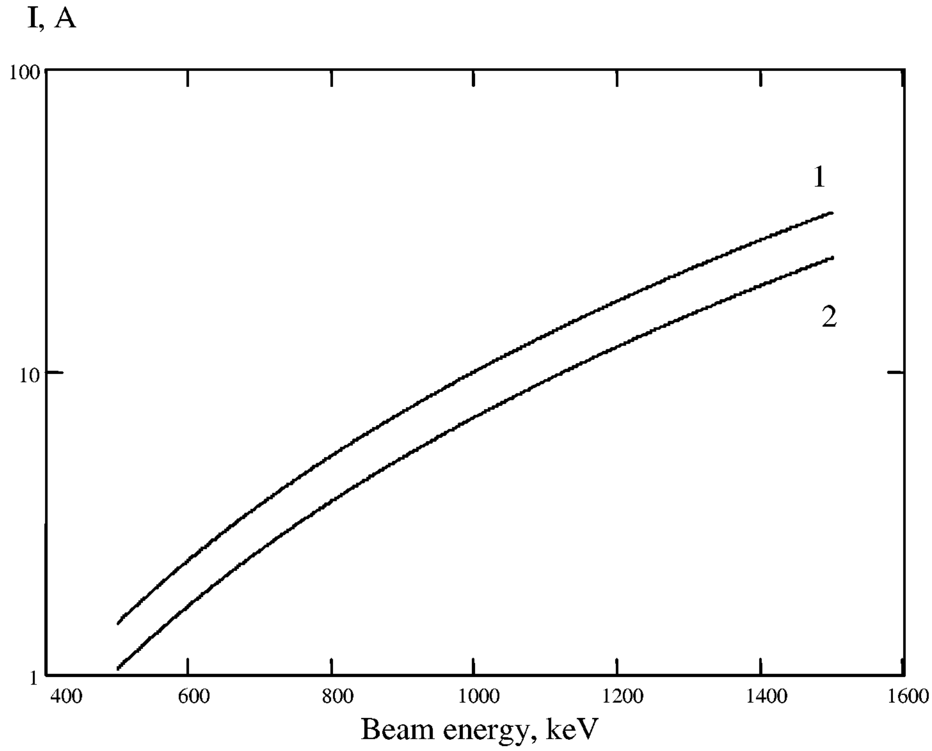


Fig 5.6. Threshold electron beam current of microwave instability: 1 – magnetic field is 1 kG, 2 – magnetic field is 2 kG.

At minimum electron beam energy the threshold beam current is higher than maximum designed value only by two times, however, even taking into account decrease of the cooling efficiency for the system with circulating electron beam, required value of electron beam current at minimum energy does not exceed 0.3 A.

5.3.3. Transverse-longitudinal relaxation of electron beam

In the magnetised electron beam intrabeam scattering is substantially suppressed by longitudinal magnetic field. Characteristic time of the temperature growth rate can be estimated by the following empirical expression [11]:

$$\frac{1}{\tau_{relax}} = \frac{1}{T_{||}}\frac{dT_{||}}{dt} \approx \frac{2\pi r_e^2 n_e mc^3 L_C}{T_{||}}\sqrt{\frac{mc^2}{T_\perp}} e^{-2.8/\rho n_e^{1/3}}, \tag{5.16}$$

where r_e is the electron classical electron radius, $L_c \sim 10$ is the Coulomb logarithm, n_e is the beam density, $\rho = \sqrt{2mc^2 T_\perp}/eB$ is the particle Larmor radius in the longitudinal magnetic field B. Exponential term in (5.16) leads to strong dependence of the relaxation characteristic time on the temperature of transverse degree of freedom and on the beam current (Fig. 5.7).

At electron beam current of 0.1 A the magnetic field value of 1.5 kG seems to be big enough to suppress intrabeam scattering of the electron beam during the period required for beam circulation. At maximum electron beam current the relaxation time is less than circulation period by about three orders of magnitude. It means that this process has to be taken into account in estimations of the cooling system efficiency.

The formula (5.16) describing the electron beam relaxation is half-empirical one and due to importance of this process for cooling system with circulating electron beam has to be carefully tested with the real installation. The process of the transverse – longitudinal relaxation in the cooling system with circulating electron beam will be experimentally investigated at LEPTA ring (see chapter 7).

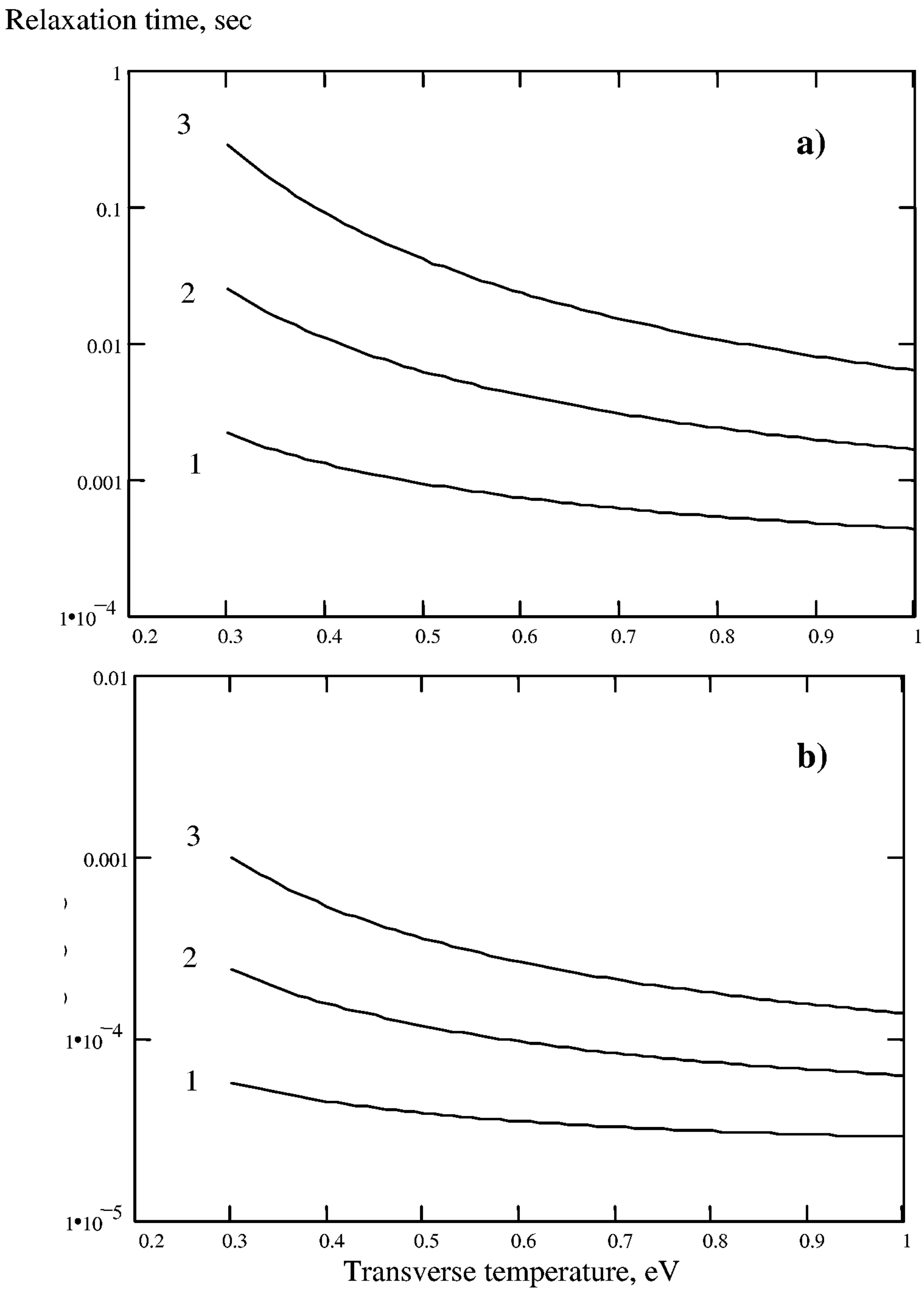


Fig. 5.7. Characteristic time of the transverse-longitudinal relaxation of the electron beam, magnetic field is 1 kG (1), 1.5 kG (2), 2 kG (3), longitudinal temperature is 50 meV, electron beam current is 0.1 (a) and 0.5 A (b).

5.4. Electron cooling with circulating electron beam in experiments with internal target

In experiments with internal target additional limit appears for the electron beam circulation period. It is connected with the coherent energy losses of the ion beam due to interaction with the target. Due to energy exchange between the ion beam and circulating electron one the beam velocities in the cooling section are the same. Correspondingly, the coherent energy variation of the electron and ion beams during the circulation period are connected in accordance with the relation:

$$\left(\frac{\Delta E}{E}\right)_e = \left(\frac{\Delta E}{E}\right)_i . \tag{5.17}$$

During the circulation period the energies of the ion and electron beams have to be inside the dynamic apertures on momentum deviation of corresponding ring. The dynamic aperture on momentum deviation of the electron ring with longitudinal magnetic field (σ_0 formula 5.10) is less than that one of the ion ring. Coherent momentum shift of the electron beam can be calculated as the following:

$$\frac{\delta p}{p} = \frac{1}{2}\frac{\Delta E}{E}\frac{T_{circ}}{T_{rev}} , \tag{5.18}$$

where ΔE is the ion energy loss after crossing the target (formula 1.2), E is the ion energy and T_{circ} is the electron beam circulation period. From the condition $\delta p/p \le \sigma_0$ one can write the condition for upper limit of the circulation period:

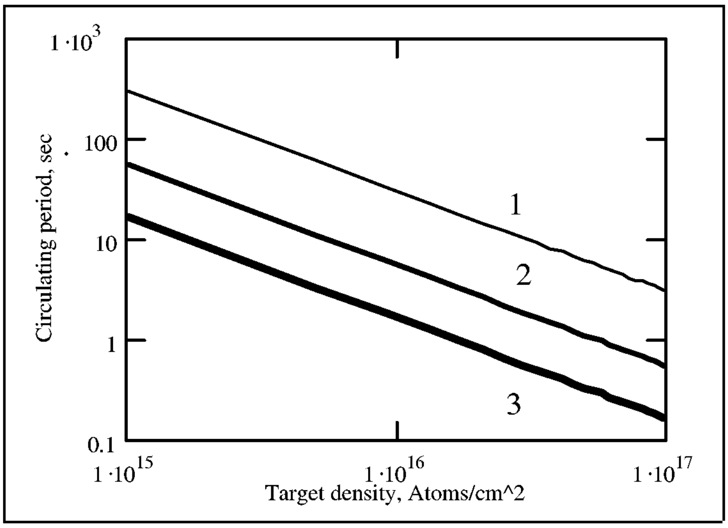
$$T_{circ} \le T_{\max 1} = \frac{T_{rev} E \rho_L}{2\Delta E C} , \tag{5.19}$$

where C is the electron ring circumference, ρ_L is the electron Larmor radius in the longitudinal magnetic field, T_{rev} is the ion revolution period. The dependencies of the maximum circulation period of the electron beam on the particle energy and the target density are presented in the Fig. 5.8. In the total range of the COSY experiment parameters the circulation period has to be less than about 1 second to avoid a resonance of the electron beam.

Other limitation connected with this effect is related to distortion of the cooling process after refresh the electron beam: the coherent momentum shift of the ion beam after circulation period has to be substantially less than its momentum spread. Only in this case the model using for cooling process simulation gives correct results for the system with circulating electron beam. The condition, when the used numerical model is valid for calculation of the cooling time for the system with circulating electron beam, can be expressed in the following form:

$$T_{circ} << T_{\max 2} = \frac{2 T_{rev} E (\Delta p / p)_i}{\Delta E} . \tag{5.20}$$

The momentum spread of the ion beam $(\Delta p/p)_i$ depends on many parameters and can be varied by about one order of magnitude depending on experiment conditions. In the Fig. 5.9 the coherent energy shift of the proton beam as a function of the circulation period and beam energy is presented. One can see that at circulation period of about several hundreds of msec this effect can be ignored at all reasonable ion beam parameters.



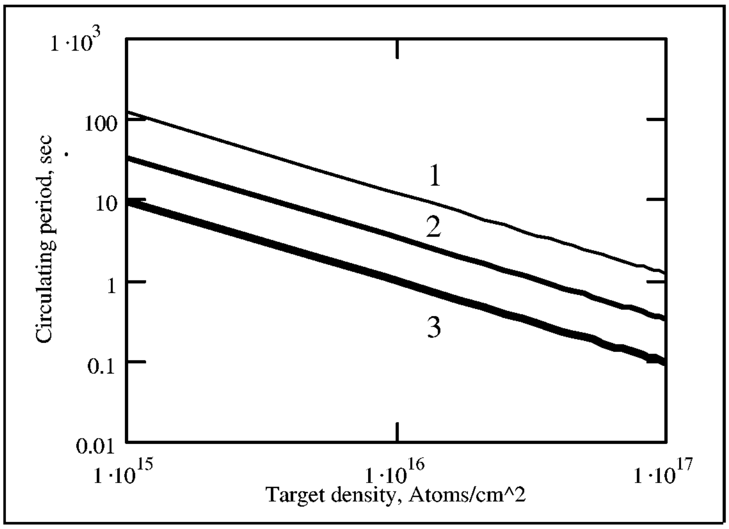


Fig. 5.8. Maximum circulating period of the electron beam as function of the target density:

a) proton beam at energy 2700 MeV (1), 1000 MeV (2), 500 MeV (3);
b) deuteron beam at energy 2100 MeV (1), 1000 MeV (2), 500 MeV(3).

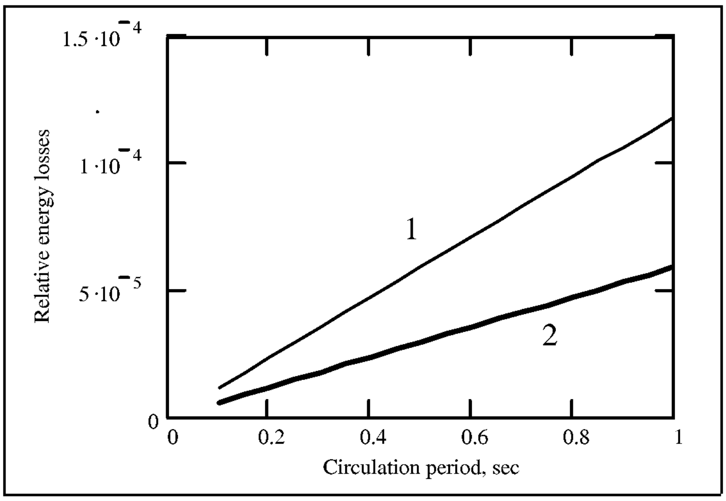


Fig. 5.9. Relative energy losses of the proton beam at target density of 10^{16} Atoms/cm^2, at energy 1000 MeV (1) and 2000 MeV (2).

5.5. Induction acceleration of the electron beam.

The electron acceleration can be provided using RF linac with further injection into electron ring or inside the electron ring using low frequency betatron acceleration. In the second case the energy spread of the accelerated electron beam caused by variations of the acceleration voltage during revolution period, is equal to [12]:

$$\Delta\varepsilon = e\left(\frac{\partial V}{\partial t}\tau_{rev}\right)_{inj} - e\left(\frac{\partial V}{\partial t}\tau_{rev}\right)_{fin}, \qquad (5.21)$$

where V is the accelerating voltage, τ_{rev} is the electron revolution period. When $V=V_0 \sin(\omega t)$ and initial and final phases of acceleration are symmetrically disposed around the voltage maximum, this formula gives us

$$\frac{\Delta\varepsilon}{\varepsilon} \approx \left(\frac{C\omega}{c}\right)^2 \frac{1-\beta_{inj}}{\beta_{inj}\bar{\beta}}. \qquad (5.22)$$

In this case the acceleration voltage amplitude can be obtained by integration of the motion equation:

$$eV_0 = \frac{C\omega}{c}\frac{\varepsilon}{2\bar{\beta}\cos\omega t_{inj}}, \qquad (5.23)$$

where C is the electron ring circumference, β_{inj}, $\bar{\beta}$ - initial and average electron velocity in the units of the speed of light.

Using the existing COSY high voltage power supply for injection one can accelerate electrons 0.5 msec from ε = 100 keV (injection) up to 1.5 MeV. The estimated momentum spread value caused by the voltage variation is negligible (Table 5.2).

Table 5.2. Parameters of the induction acceleration system

Injection energy, keV	100
Maximum energy, keV	1500
Electron ring circumference, m	20
Frequency of the acceleration voltage variation, kHz	1
Required amplitude of the acceleration voltage, V	500
Beam momentum spread caused by voltage variation	$2\cdot10^{-7}$

During the electron beam acceleration inside the ring with constant value of the longitudinal magnetic field the working point crosses series of the resonances of the fast mode of oscillation. The experiments at Modified Betatron Accelerator in NRL (USA) [13] have shown that the crossing of the high order resonances does not lead to the particle losses. An increase of the beam transverse temperature in these experiments was not investigated and we plan to perform such investigations at LEPTA ring (see chapter 7).

6. Principles of the electron cooling system design

All general elements of electron cooling system with circulating electron beam are presented in the Fig. 6.1. If the electron acceleration is performed with RF electron linac, the betatron yoke is not necessary and instead of electron gun one needs to install the RF cavity and debunching system, if necessary to reduce Δp/p (see [14]).

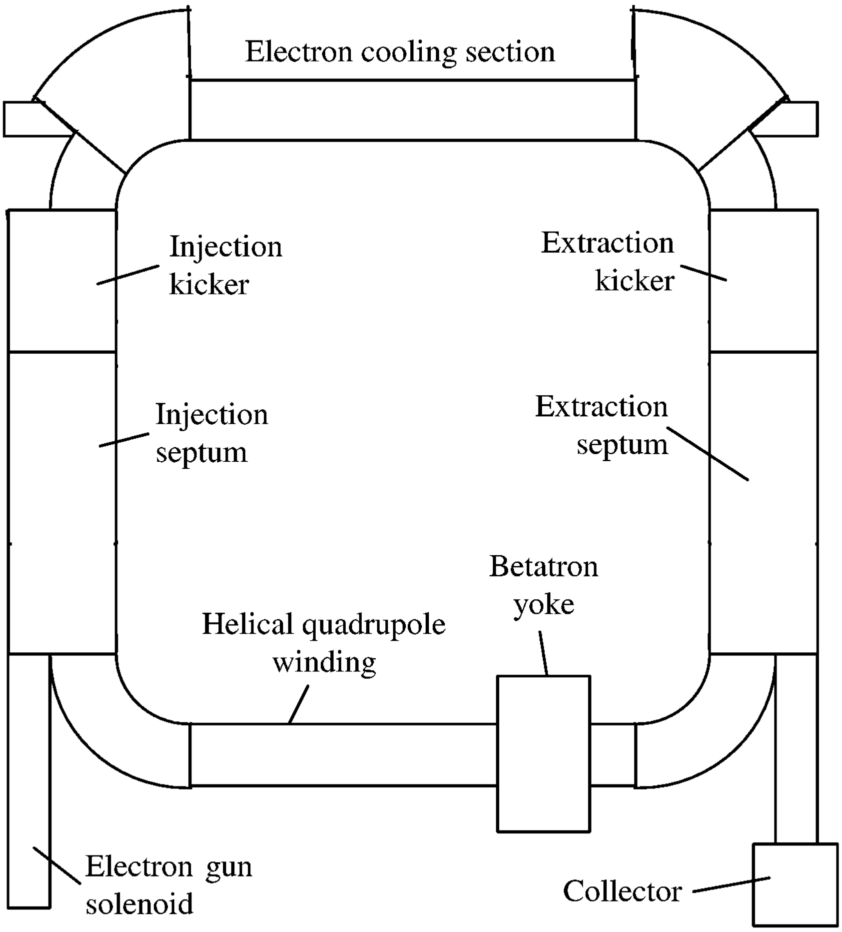


Fig. 6.1. Layout of the electron cooling system with circulating electron beam.

The electron beam injection into the ring is provided along the longitudinal magnetic field with transverse field of septum coils, which displace the electron beam to the vicinity of the equilibrium orbit at the distance of about diameter of the gun solenoid. Then the kicker plates displace the beam to the equilibrium orbit.

Inside the septum coil the electron beam drifts in the longitudinal magnetic field of the septum solenoid and transverse magnetic field of the septum coil. The field of the septum coil has a zero value at the orbit of circulating beam due to special coil design. Possible design of the septum coil is presented in the next chapter. The septum coils are operated in the DC mode.

The field of the kicker displaces the electron beam to the equilibrium orbit and after the beam occupies the total ring circumference the field of the kicker has to be switched off during the time substantially shorter than revolution period. Drift of the electrons inside the kicker can be performed by transverse magnetic field or by electric field. When electrostatic kicker is applied the cooling system can be used also in the single pass mode of operation. In this case both kickers – injection and extraction are used in the DC mode and electron beam is displaced by injection kicker to the orbit inside the cooling section and after moving through the cooling section is displaced to extraction septum and to the collector by extraction kicker. Such a possibility looks like very attractive for COSY – it permits to use electron cooling system at injection energy in the single pass regime with existing electron gun and its power supply system. The example of the electrostatic kicker design is presented in the next chapter.

In the case of induction acceleration of the electron beam the existing COSY electron cooling system can be upgraded to medium energy electron cooling system by installation of several new solenoids and betatron yoke for electron acceleration. Two of the new solenoids (septum solenoids) are to be placed vertically above the existing toroidal solenoids. In each of these solenoids the coils of magnetic septum and electrostatic kicker are placed. Existing electron gun and collector with their solenoids are placed above these two new septum solenoids. To form a closed orbit for electron beam two toroidal and straight solenoids are connected with the septum solenoids. In the straight solenoid (which is placed opposite to the cooling section) the betatron yoke and helical quadrupole windings are placed.

In the regime with circulating electron beam the beam from the gun is directed to the closed orbit by injection septum and kicker plates. When the beam fills total circumference of the electron ring kicker voltage is switched off. After that beam is accelerated to required energy with the betatron yoke. Next current pulse applied to the betatron yoke coil decelerates the circulating electron beam and after deceleration the electron beam is extracted to the collector by the pulse applied to the extraction kicker.

The cooling system with induction acceleration has a lower cost in comparison with RF acceleration, but general problem of this system is beam quality degradation after crossing of number of resonances. This problem as well as optimisation of injection system can be experimentally investigated at LEPTA ring.

7. Program of experiments at LEPTA

7.1. LEPTA parameters

The general aim of the LEPTA ring construction (Fig. 7.1) is to provide storing low energy positrons, electron cooling of positrons and generation of the directed flux of positronium atoms. However at design study of the ring all the parameters were chosen such that we have a possibility to test beam parameters required for electron cooling system with circulating electron beam. The parameters of the ring in the mode with circulating electron beam (Table 7.1) are closed to the parameters of COSY cooling system and designed parameters of the betatron yoke cover the total energy range of the circulating beam required for COSY.

Adjustment of the injection and extraction system, investigations of an influence of the helical quadrupole winding will be performed during ring commissioning using optic method of the beam temperature measurement [3].

At the first stage of the LEPTA operation the study of the beam dynamics will be performed at the beam energy of 10 keV and variation of the beam energy will be provided using small RF cavity. Final test of the system will be performed after installation of the betatron yoke and it presumes the electron beam acceleration and test of the beam temperature at maximum required energy.

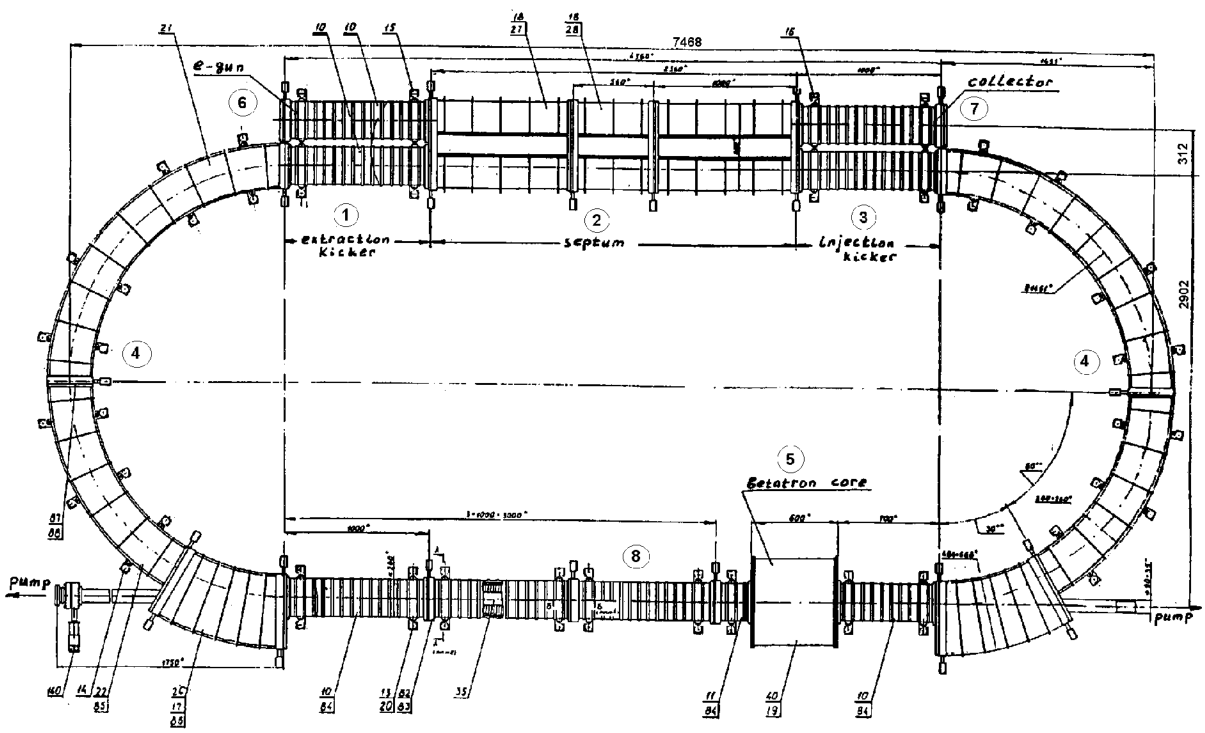


Fig 7.1. The assembly drawing of the LEPTA: 1 - extraction kicker, 2 - septum, 3 - injection kicker, 4 - toroidal sections, 5 - betatron core, 6 - electron gun, 7 - electron collector, 8 - cooling section.

Table 7.1. General parameters of the LEPTA.

Ring parameters		
Circumference, m	18.28	
Longitudinal magnetic field, G	1000	
Major radius of the toroids, m	1.45	
Bending magnetic field, G	1.75 – 124	
Gradient of the quadrupole magnetic field, G/cm	10 – 15	
Electron beam radius, cm	1.0	
Residual gas pressure, Torr	10^{-10}	
Electron beam parameters		
	At injection	After acceleration
Energy, keV	10	4360
Current, A	0.1	0.5
Revolution period, nsec	300	60
Acceleration cycle		
Induction voltage amplitude, V	50	
Repetition frequency, Hz	1	
Cycle duration, msec	10	

7.2. Preliminary program of the experiments.

General problems which have to be experimentally investigated before design of the full scale electron cooling system with circulating electron beam are the following:
- beam parameter distortion during injection,
- variation of the longitudinal beam temperature due to transverse-longitudinal relaxation,
- beam parameter distortion after crossing the resonances of the fast mode of oscillation.

The aim of the investigations is the final choice of the magnetic field value and the optimal position of the working point of circulating beam in the total range of the beam energy, accurate measurements of the maximum beam current which can circulate in the ring without loss the quality during required period of time. These experiments will be performed at the special test bench during the LEPTA assembling and with circulating electron beam during the ring commissioning.

7.2.1. Tuning of injection system and helical quadrupole winding

Injection system of the ring consists of magnetic septum (Fig. 7.2, Table 7.2) and electrostatic kicker (Fig. 7.3). Variation of the angle of the electron beam trajectory at the entrance and at the exit of the septum and kicker is about 15 mrad and only a resonance optics of these elements permits to keep electron beam quality after injection. In this case the integer number of the electron Larmor rotations has to take place at the length of the kicker and septum. Calculate of the effective length of the septum and kicker coils accurately is a complicated numerical problem and these values will be measured experimentally using optic method of the electron transverse temperature measurements.

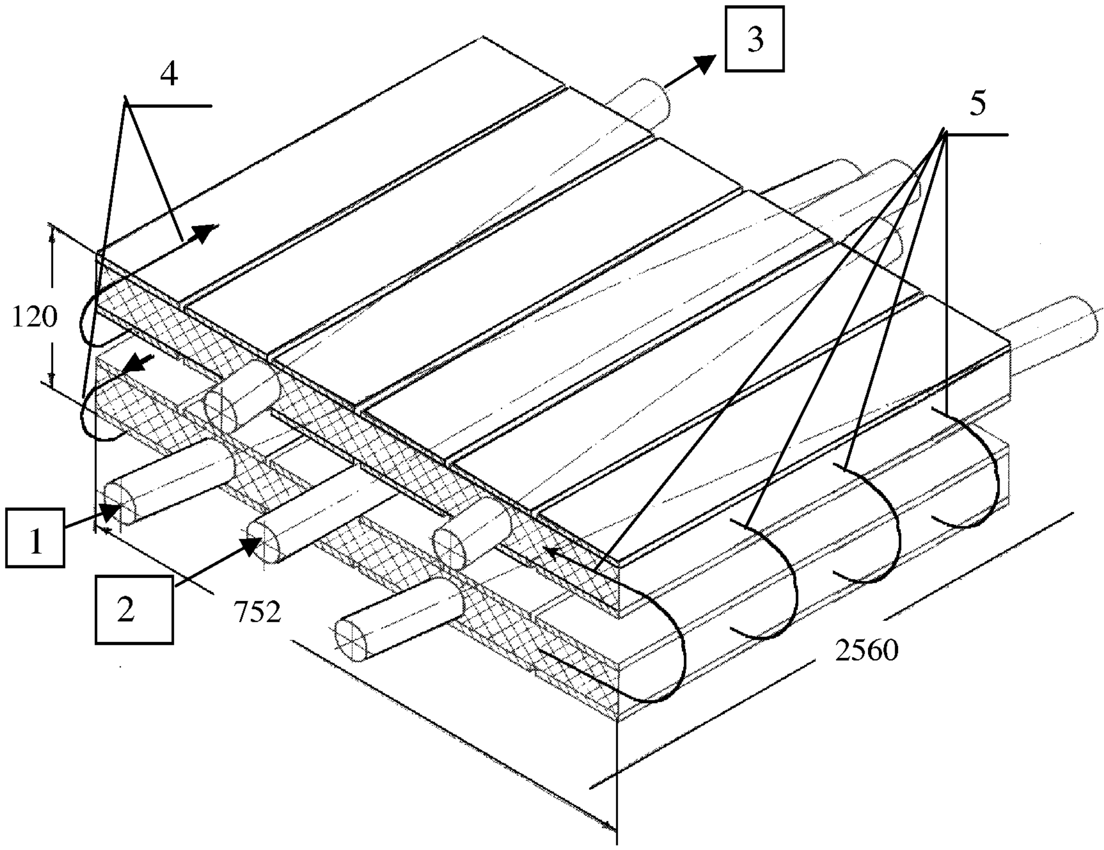


Fig.7.2. Septum design.1 -Beam from the gun, 2 - Circulating beam, 3 - Extracted beam, 4 -Current lines, 5 - Magnetic field lines.

Table 7.2. General parameters of the septum coils.

Magnetic field value, G	120
Current, A	1600
Number of turns	6
Conductor cross-section, mm	4 x 12
Beam displacement, mm	300

Initially the effective lengths of both coil fields will be measured independently by measurement of the magnetic field value corresponding to minimum distortion of the beam parameters after crossing the coil. After that the length of the kicker coil will be corrected to have an integer ratio between septum and kicker coil lengths.

The distortion of the angular spread of the circulating electron beam after crossing the helical quadrupole winding is minimised by adiabatic variation of the quadrupole field gradient at the entrance and at the exit of the coil. The designed and constructed helical quadrupole coil (Fig. 7.4) has in each cross-section a geometry of "Panofsky lens" which provides a maximum linearity of the field. The gradient variation at the entrance and exit of the coil is provided by corresponding variation of the number of winding turns. Accurate calculation of the particle dynamics in the coil is practically impossible due to difficulties in measurements of the fringe fields, and test of the coil and (if it would be necessary) correction of its design will be performed also using optic method of beam diagnostics. All these investigations will be performed at special test bench, which is under construction now.

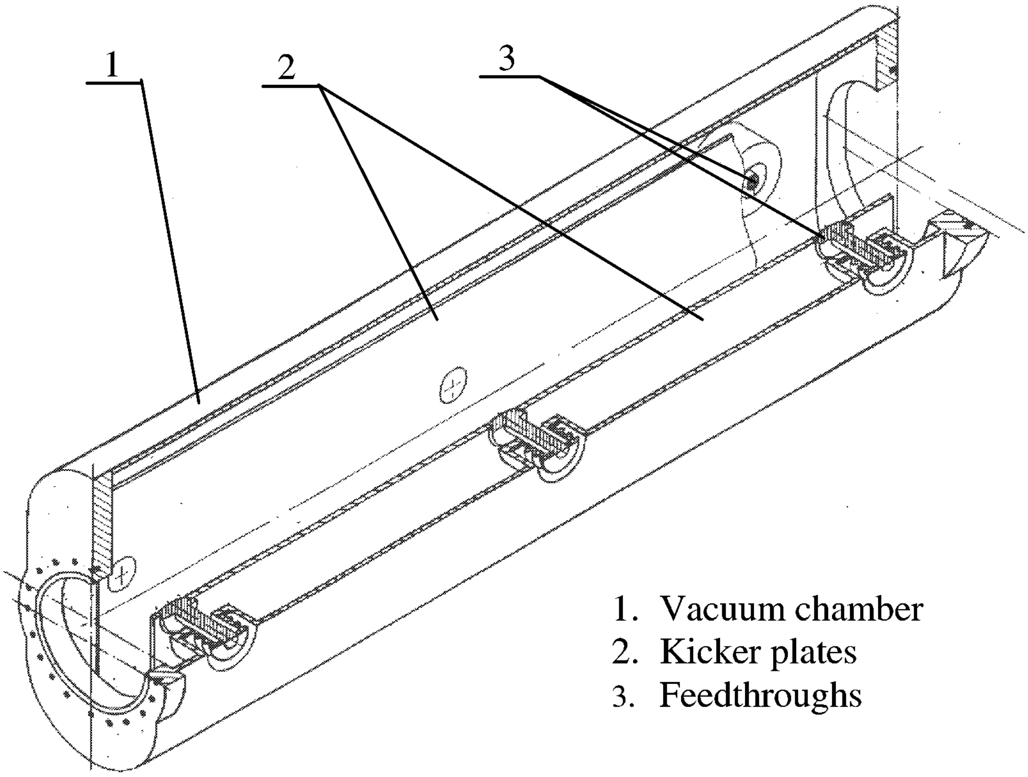


Fig. 7.3. Schematics of the kicker. Kicker length is about 90 cm, beam displacement is 6 cm.

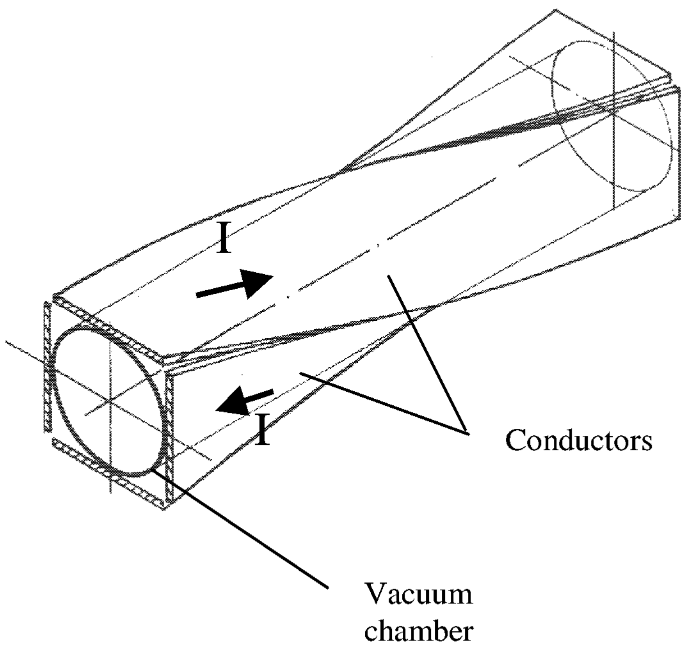


Fig. 7.4. Schematics of the helical quadrupole winding.

7.2.2. Study of the circulating beam dynamics

Stability diagram in the vicinity of the working point at injection energy of 10 keV is presented schematically in Fig 7.5. The most dangerous resonances are the integer (342 and 343) and half integer (342.5) ones of the fast mode of oscillations, the half integer and 1/3 nonlinear of slow mode of oscillations and the coupling resonance of the modes $Q_{fast} + Q_{slow} = 342$. Nonlinear resonances of the fast mode of oscillations have very high order and estimations show that they practically do not influence on beam parameters.

An accurate calculations of the position of the resonances and increments in their centre were performed using especially elaborated computer code BETATRON. Power of nonlinear resonance of slow mode of oscillations was calculated using averaging method. The nonlinear resonance appears due to sextupole component of the longitudinal magnetic field in the toroidal sections and leads to variation in time of the motion invariant corresponding to the slow mode of oscillation. Due to coupling between horizontal and vertical degrees of freedom the variation of slow invariant produces variation in time of the beam cross-section. In experiment the power of the resonance can be estimated by measurements of the frequency of beam cross-section variation.

Real width of the linear and coupling resonance is determined by the errors of the focusing fields. In the case of focusing by longitudinal magnetic field the errors can not to be calculated through the errors in the position of the focusing elements. The errors of the focusing field appear due to those in the solenoid winding and can be evaluated only by measurements of the real field distribution in each section of the solenoid. However the field measurements has to be performed in the position of the closed orbit which is known with accuracy of about a few millimetres.

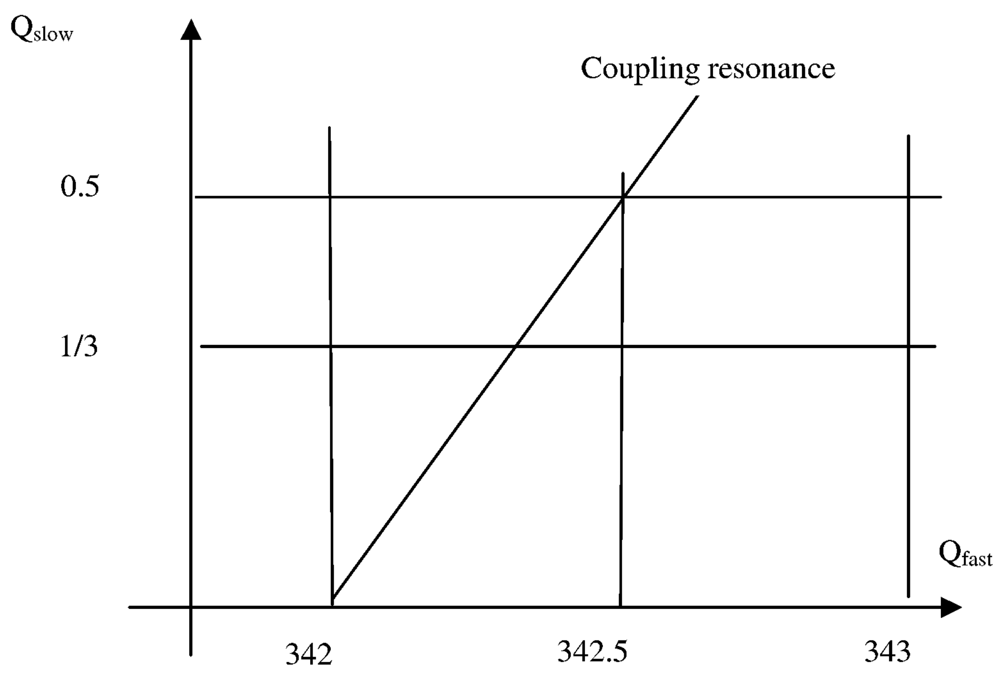


Fig 7.5. Stability diagram in the vicinity of the working point at beam energy of 10 keV and magnetic field value of 400 G.

Thus the dynamic behaviour of the ring can be investigated only experimentally. And such an investigation is of great importance for proposed cooling system. The width and power of the fast mode resonances in real structure are the key parameters in the problem of betatron acceleration of circulating beam. A possibility of the resonance crossing and beam parameters distortion in the resonance vicinity will determine the choice of acceleration regime. In the case of electron beam acceleration with RF accelerator the dynamics investigation will determine the requirements to the momentum spread of injected electron beam.

The tune of the slow mode of oscillation can be measured using pick up electrodes. The frequency of the slow oscillations at beam energy of 10 keV is about 700 kHz and corresponds to coherent oscillations of circulating beam. The tune of the fast mode of oscillations can not to be measured directly (characteristic value of the frequency of the fast mode of the betatron oscillations is about 1 GHz, and the signals produced by each particle on pick-up electrodes are incoherent.) Its measurements we plan to perform by displacement of the beam energy to the region of the coupling resonance which leads to increase of the amplitude of the slow mode. For this aim small RF cavity will be installed in the ring.

In order to test beam parameters variation after the resonance crossing the beam will be extracted from the ring and directed to the optic diagnostics for the beam temperature measurement.

The longitudinal temperature of the circulating electron beam will be measured using Schottky diagnostics. This permits to measure growth rate of the longitudinal temperature due to transverse-longitudinal relaxation, which is impossible in the case of single pass electron beam of a traditional electron cooling system. Experimental study of the relaxation process allows finding the limit of the maximum value of the electron beam current in the electron cooling devices with circulating electron beam.

Summary

1. Role of the cooling in experiments with internal targets

The beam energy and required target density in experiments with internal targets is determined by physical problem to be investigated. Investigations of nature of a_0-mesons are to be performed at maximum proton beam energy, required level of the luminosity is 10^{33} cm^{-2}·sec^{-1} and higher. This experiment can be provide using a pellet target. Measurements of the deuteron break-up, ω, η, K mesons production are performed in the wide energy range from 1 GeV to about 2 GeV, and with all the types of the ANKE targets. The effective density of the hydrogen cluster beam target, achieved in the experiment at January/February 2001, is about $2\cdot10^{15}$ Atoms/cm^2. Expected areal density of the gas storage cell is 10^{14} - 10^{15} Atoms/cm^2. Effective density of the frozen pellet target is expected to be between $3\cdot10^{14}$ and $2\cdot10^{16}$ Atoms/cm^2 at beam emittance of 1 π·mm·mrad.

In the experiments with the internal target the upper limit of the circulating beam life time (and, as a result, the experiment duration) is determined by single scattering on large angles with the target atoms. At the target density below 10^{15} Atoms/cm^2 the beam life time and characteristic times of the emittance growth due to interaction with the target are longer than one hour and experiment can be performed without cooling. At the effective target density over than approximately $2\cdot10^{16}$ Atoms/cm^2 the beam life time is shorter than expected cooling times at realistic parameters of the cooling system. In this case cooling cannot effect on the beam parameters effectively.

The range of the target density from 10^{15} to $2\cdot10^{16}$ Atoms/cm^2, in which cooling can be used for luminosity preservation, covers parameters of all types of the ANKE target practically. Only in the experiments with solid target the beam life time is so short that luminosity preservation using cooling seems to be unrealistic. The difference between the hydrogen and deuterium targets is not substantial because of the general processes which influences on the beam parameters are determined by interaction with the electrons of the target atoms.

In this report the possibility of the cooling application was investigated in two ranges of the target density: long term experiment (up to 1 hour) at the target density of 10^{15} Atoms/cm^2 and short term experiment (about 5 minutes) at the target density of 10^{16} Atoms/cm^2.

In the experiment with gas storage cell target, when the target dimensions coincide with the aperture of the vacuum chamber, the role of the beam cooling is to reduce the particle losses due to aperture limitation by suppression of the emittance growth. Maximum achievable gain in the experiment luminosity is determined by the relation between the beam life time and time of the emittance growth up to acceptance.

For proton beam at the target density of 10^{15} Atoms/cm^2 after one hour of experiment maximum possible gain in the beam intensity is more than two times at the energy below 2 GeV (up to one order of magnitude at 1 GeV), and about 50% at energy of 2.7 GeV.

For circulating deuteron beam the gain in intensity of about 50% can be obtained at energy of 2.11 GeV (which corresponds to the maximum magnetic rigidity). At intermediate energies the gain in the beam intensity is determined by suppression of the intrabeam scattering and for deuteron beam is about two times less than the proton one, however at energy of 1 GeV the possible gain in the luminosity for deuteron beam is about 5 times.

Similar dependence on the particle energy takes place at the target density of 10^{16} Atoms/cm^2, but maximum expected gain in the beam intensity after five minutes of experiment is about 1.5 times higher.

The energy dependence of the maximum gain in the experiment luminosity is explained by the input of the intrabeam scattering into emittance growth. The role of this process fast decreases with the energy increase and at maximum beam energy emittance growth is determined by the single scattering with the target atoms mainly. Thus, the potential efficiency of a beam cooling increases with increase of the beam intensity and decreases with increase of the beam energy.

In the experiment with cluster beam target additional gain in the luminosity can be obtained due to the target dimension in the horizontal plane is 5 mm, which is less than beam dimension corresponded to acceptance limitation. Stabilisation of the horizontal beam dimension during experiment can give additional gain in the luminosity of about 50%.

In the experiment with the pellet target the luminosity is inversely proportional to the circulating beam cross section because of the beam cross section always larger than pellet one. In this case the beam cooling can provide increase the luminosity by several times. When the cooling prevails on the heating effects one can realise the regime with constant luminosity during the time of experiment via compensation of the particle losses by corresponding decrease of the beam emittance.

Thus, in the experiments with the gas jet and cluster beam targets the experiment duration can be about one hour without substantial loss of the luminosity and cooling application can give gain in the luminosity from 50% to 5 - 10 times at energy from 1 to 2.7 GeV. In the experiment with the pellet target the experiment duration can be about 5 minutes and cooling application can give a gain in the luminosity of about 2-3 times in the total range of the beam energy.

2. The possibility of the existing stochastic cooling system application

The effectiveness of the stochastic cooling strongly depends on the ion beam intensity. In this report the possibilities of the stochastic cooling were investigated under assumption that one of the chains is used for cooling of the horizontal degree of freedom, other one - for longitudinal. In this case the stochastic cooling system can be used for luminosity preservation at the target areal density of about 10^{15} Atoms/cm^2 up to ion beam intensity of about $2\text{-}3\cdot10^{10}$ particles. Maximum efficiency of the stochastic cooling corresponds to the maximum beam energy (due to dependence of the mixing factor on the off-momentum factor). The gain in the luminosity is close to the theoretical value and in the experiment with the gas jet target is about 20 – 50%, in the experiment with cluster beam target this value can be higher by about 1.5 times due to stabilisation of the horizontal beam dimension.

At the beam intensity of 10^{11} particles, which corresponds to expected value with new COSY injection system, or at high target density the existing stochastic cooling system is not powerful enough to expect a substantial effect from its application in the experiment with internal target.

3. The possibility of an electron cooling application

Electron cooling system at realistic parameters of the electron beam stabilises the parameters of the intensive (up to 10^{11} particles) ion beam at the target areal density of 10^{15} Atoms/cm^2 in the total energy range required for experiments. Maximum gain in the luminosity corresponds to the minimum beam energy. In the experiment with gas jet target for the proton beam expected gain in the luminosity after one hour of experiment is 2 – 3 times at 1 GeV and decrease to the value of 20 – 50% at 2.7 GeV. For deuteron beam expected gain in the luminosity is about 2 times at energy of 1 GeV and decreases to 50% at 2.11 GeV. In the experiment with cluster beam target additional gain in the luminosity can be obtained due to stabilisation of the horizontal beam dimension and its value is about 1.5 times.

In the experiment with the pellet target maximum gain in the luminosity is expected at minimum beam energy. In this case the experiment duration can be about 5 minutes and gain in the integral luminosity is 2 – 4 times depending on the pellet diameter. The expected average luminosity value exceeds 10^{33} cm^{-2}sec^{-1}. At these parameters one can realise the regime with permanent luminosity during the time of experiment via compensation of the particle losses by corresponding decrease of the beam emittance.

At maximum proton beam energy of 2.7 GeV the electron cooling compensates the beam heating due to interaction with target only at pellet diameter of 40 –50 μm, which corresponds to the luminosity value of 3 - $5\cdot10^{33}$ cm$^{-2}\cdot$sec^{-1}. At maximum pellet diameter the electron cooling does not suppress the beam heating, but it can be used for initial preparation of the beam parameters before the target switching on. In combination with the optimum experiment strategy it can give a gain in the integral luminosity of about 20%. It should be noted that all the simulations in this report were performed under assumption that each moment of time one pellet is in the beam. In the case of low frequency of the pellet production the effective target density has to be calculated taking into account the duty factor. Final conclusion can be expressed as follows: in the experiment with the pellet target at maximum proton beam energy an electron cooling gives substantial gain in the luminosity up to the luminosity level of about $5\cdot10^{33}$ cm$^{-2}\cdot$sec^{-1}.

For deuteron beam an electron cooling can be effectively used in the total energy range and at beam energy of 2.11 GeV and maximum target density the gain in the integral luminosity after five minutes of experiment is about 50% and it increases to several times at less energy or target density.

4. Electron cooling system with circulating electron beam

There are two possible design of new COSY cooling system:
- Traditional configuration of cooling system + HV accelerator,
- Cooling system with circulating electron beam.

Traditional configuration of the cooling system can provide electron beam at low transverse and longitudinal temperature, and the results of numerical simulations demonstrate its ability for ion beam parameters stabilisation.

Electron cooling system with circulating electron beam has substantially low cost, but in such a system the electron beam quality is expected to be rather less than in the HV system. The electron beam quality is determined by a method of the beam acceleration, stability of electron motion in the electron storage ring, number of electrons and the ring circumference.

General attention of this report was attracted to the possibility of the electron cooling system with circulating electron beam. In the electron energy range from 0.5 to 1.4 MeV only a longitudinal magnetic field can provide strong focusing of an intensive electron beam. General parameters of the electron ring with longitudinal magnetic field can be the following: magnetic field value is 1 – 1.5 kG, the ring circumference is about 20 m, electron beam radius is 0.5 mm, maximum current value is 0.5 A. The electron beam acceleration can be provided using RF electron linac or by induction acceleration of the electrons in the ring. The induction acceleration is more attractive from the side of the momentum spread of accelerated beam and installation cost, but it did not tested experimentally. The proposed design of the injection system of the electron ring permits to perform two modes of operation: with the single pass electron beam at injection energy and with the circulating electron beam at the energy of experiment. Some elements of the existing COSY electron cooling system can be used in the new cooling device.

General problems of the proposed cooling system are the following:
- distortion of the electron beam parameters during its injection into the ring,
- motion stability of the electron beam during circulation,
- heating of the electron beam due to its interaction with the cooled ion one,
- coherent energy losses of both beams – ion and electron – due to interaction of the ion beam with the target and energy exchange between beams,
- heating of the longitudinal degree of freedom of the electron beam due to intrabeam scattering.

In the case of induction acceleration of the electron beam more serious problem is to avoid beam heating during crossing of resonances of transverse particle motion.

The period of the electron beam circulation is limited by the heating due to interaction with the ion beam. When the circulation period is about 0.1 second the efficiency of proposed system is the same as one of the traditional electron cooling system. More serious limitation can appear due to transverse-longitudinal relaxation in the electron beam. This problem as well as the stability of the electron motion and electron beam distortion during injection requires experimental investigations. They can be performed at LEPTA installation, which construction is in the final stage in JINR. We plan to begin the experimental program next year and expected term of its completion is two years.

The cost of the cooling system with circulating electron beam estimated using the experience of construction of analogous system in JINR can lies between 1 and 1.5 M$.

Conclusion and recommendations

In the experiments with gas storage cell and cluster beam targets an electron cooling system can be effectively used for the luminosity preservation when the experiment duration is of the order of 1 hour. In this case expected gain in the luminosity is about 2 – 3 times at minimum and intermediate beam energy. At maximum beam energy the effect of cooling application decreases and at the target density below 10^{15} Atoms/cm^2 the experiment can be performed without luminosity loss during long period of time without cooling. Electron cooling stabilises the beam parameters in the total energy range and transverse dimensions of the ion beam during experiment can be 2 – 3 times less than in the case without cooling. This permits to decrease the aperture of the gas storage cell in order to increase the target density.

In the experiment with the pellet target at maximum proton beam energy an electron cooling gives substantial gain in the luminosity up to the luminosity level of about $5 \cdot 10^{33}$ $cm^{-2} \cdot sec^{-1}$ and at experiment duration up to five minutes. Using of an electron cooling system one can realise the regime with permanent luminosity during the time of experiment via compensation of the particle losses by corresponding decrease of the beam emittance. An electron cooling application gives a possibility to optimise the ion beam parameters and experiment duration in order to obtain maximum integral luminosity taking into account the time of the beam storage and acceleration.

The proposed scheme of the electron cooling system with circulating electron beam permits to provide the effective ion beam cooling in the total energy range and in the single pass mode of operation the beam cooling during storage process at injection energy. However, the technical design of such a system requires extensive experimental tests of its general components.

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