SIMULATION OF HIGH-ENERGY ELECTRON COOLING AT COSY WITH BETACOOL PROGRAM

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Abstract

A 2 MeV electron cooling device will be installed at COSY in order to boost the luminosity for future high density internal target experiments, e.g. WASA pellet target experiments. The magnetized electron cooling technique is used to compensate the energy loss and emittance growth due to beam-target interaction. In this article, a numerical simulation of electron cooling process was performed with BETACOOL program. The cooling time is calculated for variant electron cooling parameters. The intrabeam scattering (IBS) and pellet target effect are essential for prediction of equilibrium beam parameters. The influence of the pellet target on the beam parameters is demonstrated.

INTRODUCTION

As the requests of high luminosity for future COSY pellet target experiments, an electron cooling system up to 2MeV was suggested to operate at COSY [1]. This device has been developed together with the Budker Institute in Novosibirsk and will be installed in COSY at the end of this year. The magnetized electron cooling technical solution is used to obtain a powerful 6-dimensional phase cooling.

A simulation study of the beam dynamics at COSY taking into account electron cooling in combination with pellet target and intrabeam scattering effects was performed with BETACOOL program. The BETACOOL program developed by JINR electron cooling group is oriented to simulation of the ion beam dynamics in a storage ring in the presence of cooling and heating effects [2]. To simulate the short scale luminosity variation in pellet target experiments, an additional algorithm has been implemented into BETACOOL program recently [3].

In this paper, the cooling time dependences on electron cooler parameters are calculated with RMS dynamics algorithm method. The suggestion for cooler optimization is obtained from the calculation. The momentum distribution of proton beam at equilibrium between electron, IBS and pellet target is simulated with model beam algorithm method. The Landau distribution caused by beam-target interaction is discussed with different cooling efficiency. In the end of this paper, the short-scale and long-scale luminosities for proposed pellet target experiments are analyzed. The main parameters required in simulation are listed in table 1. The lattice structure of zero-dispersion at target point is used in simulation.

Table 1: The main parameters of simulation

Proton beam parameters	
ion kinetic	2.0 GeV proton beam
Initial emittance (x/y)	0.2 / 0.2 pi*mm*mrad
Initial momentum spread (dp/p)	$2.0*10^{-4}$
Particle number	$2.0*10^{10}$
Electron cooler parameters	
Electron beam radius	5.0 mm
Magnetic field in cooling section	0.2 T
Cooler length	2.69 m
Electron beam current	2.0 A
Electron temperature (trans / longi.)	$1.0 / 1.0*10^{-4}$ eV
Magnetic field misalignment	$2.0*10^{-5}$
Beta function at cooler (hori / vert)	5.5 / 4.5 m
Pellet target parameters	
Effective target thickness	$2.0*10^{15}$ atoms/cm^2
Pellet flux radius	2.5 mm
Pellet velocity	80 m/s
Pellet radius	0.03 mm
Rate of pellet generation	8.0 kHz

OPTIMIZATION OF COOLER

Electron cooling is a fast process to compress the phase space of charged particle beam in storage ring with low temperature electron beam [4]. The phase space is shrinking up to the equilibrium between electron cooling and heating effects. In order to estimate the electron cooling efficiency, the cooling time dependences were calculated with RMS dynamics algorithm in BETACOOL program.

The RMS dynamics algorithm is a simplified model that all effects are described by cooling or heating rates. The rates can be calculated with different models. In this calculation, the Parkhomchuk empirical cooling force formula is applied for magnetized electron cooling process [5]. The Martini's model is used for IBS effect calculation and the pellet target effect is presented in the form related to kick of the ion momentum [6]. The initial parameters of proton beam are listed in table.1.The horizontal (or longitudinal) cooling time was defined as

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the time it takes for the horizontal emittance (or momentum spread) undergoing exponential shrinking to 1/e times its initial value.

Fig. 1 shows the horizontal and longitudinal cooling time dependence on electron beam current. The cooling time decreases as the current is increased. The decreasing becomes slower while the electron current higher than 2.0A. Meanwhile, the cooling time increases faster as the current becomes lower than 1.0A. It seems that the cooling effect is too weak to compensate the IBS and pellet target heating effects as such low current.

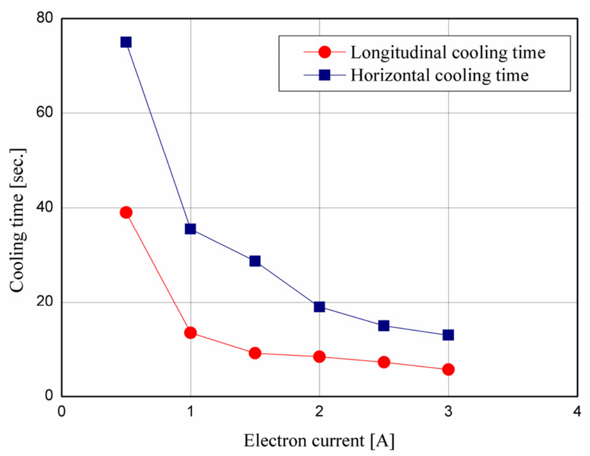

Figure 1: The dependence of cooling time on electron beam current.

The straightness of longitudinal magnetic field in cooling section is one of factors which determine the value of the effective velocity in Parkhomchuk's formula [5]. The cooling time dependence on magnetic field straightness was calculated as shown in Fig. 2. The cooling time increases fast as the magnetic field straightness larger than 10^{-4}.

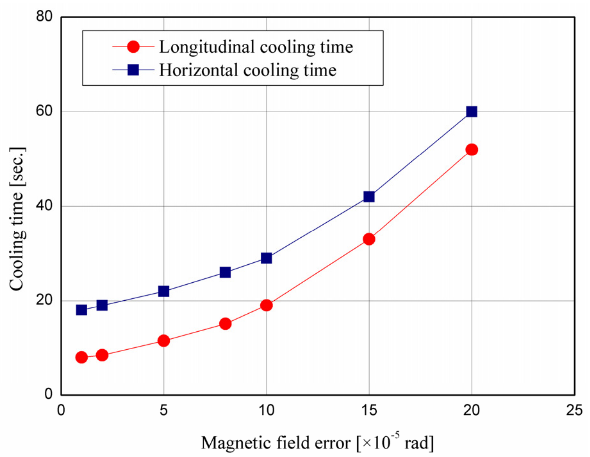

Figure 2: The dependence of cooling time on magnetic field error.

From the calculation of cooling time dependence, it can be seen an electron beam current higher than 1.0A is necessary for compensation of IBS and pellet target effects. Good longitudinal magnetic field straightness less than 10^{-4} is beneficial for fast cooling process.

COOLED BEAM EQUILIBRIUM

For a good resolution of the experiments the momentum spread less than 10^{-4} is required [7]. By the simulation with model beam algorithm in BETACOOL program [6], the equilibrium momentum spread after cooling is plotted as a function of the electron beam current in Fig. 3. The momentum spread is defined as 68% ions enclosed. The calculation result shows that the momentum spread at the equilibrium between electron cooling, IBS and target effect is dominated by intra beam scattering for high electron beam current, as shown in red points if Fig. 3. Moreover, the momentum spread at the equilibrium between electron cooling and IBS only is larger than IBS and target together as electron beam current higher than 1.0A. In addition the heating effect of pellet target is increased dramatically while the electron beam current lower than 1.0A.

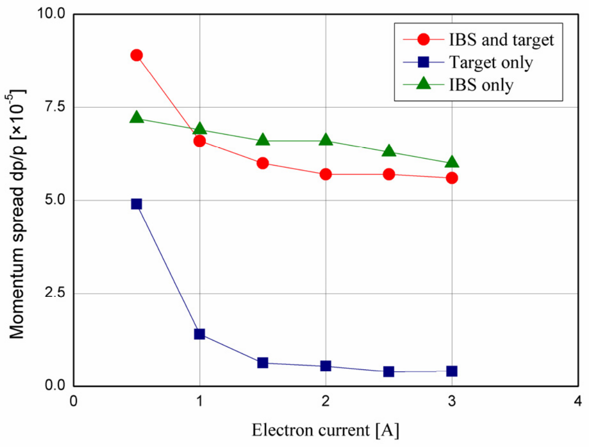

Figure 3: The equilibrium (68%) momentum spread as a function of electron beam current.

Compare with the momentum distribution at various equilibrium in Fig. 4, it can be seen that a momentum distribution with long tail is introduced by the ion-target interaction. The blue line in the figure is the initial momentum distribution before cooling. The red one is the momentum distribution at the equilibrium between cooling and IBS effect only, which is nearly a Gaussian distribution function. The other lines show the momentum distributions at the equilibrium between cooling, IBS and target together. The different cooling rates are obtained by using various electron beam currents. These lines show for proton beam that energy loss straggling in pellet target induced a low energy tail as the Landau distribution [8]. The core part of distribution lies within a narrow momentum interval. For low electron beam current, the cooling efficiency is too weak to compensate the energy loss introduced by beam-target interaction, more and more particles moved to the tail during cooling process, the momentum spread increases fast as shown in Fig. 3. The particles will be loss since out of acceptance.

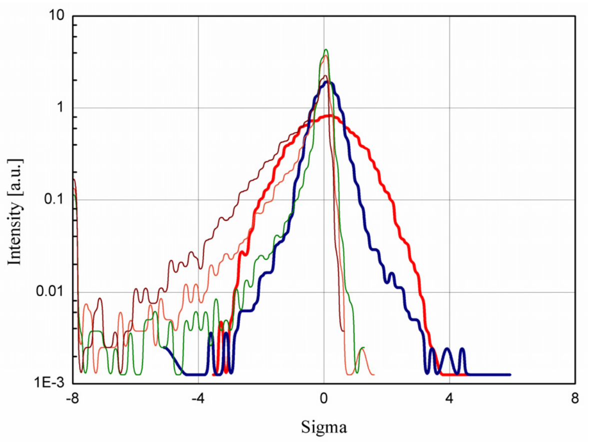

Figure 4: The momentum distribution in equilibrium. The red line is initial distribution before cooling. The blue one is equilibrium distribution of IBS and cooling (Ie=2.0A). The other lines are equilibrium distribution of IBS, pellet target and cooling for different electron beam current.

The simulation of momentum variation caused by the beam-target interaction is provided by Urban model in BETACOOL program. The total energy loss is divided by excitation and ionization of target atoms [6]. Moreover, the energy loss can be calculated by a simplified expression:

$$\frac{dE}{dt} = -4\pi L_c Z_{pellet}^2 Z_{ion}^2 n_{pellet}\left(atoms/m^3\right) r_e^2 \beta^{-1} c(m/s) \cdot m_e c^2 (eV) \tag{1}$$

The momentum evolution is described as below:

$$dp(\Delta t) = \frac{1}{E_k}\frac{\gamma}{\gamma+1}\frac{dE}{dt}\Delta t \tag{2}$$

For pellet target thickness listed in table 1, the density is:

$$n_{t\arg et} = \frac{2.0\times 10^{15}}{1.83\times 10^{4}} = 1.09\times 10^{11}\left(atom/cm^3\right) \tag{3}$$

The energy loss rate is:

$$\frac{dE}{dt} = -1.74\times 10^{-5}(eV/s) \tag{4}$$

The comparison on the momentum evolution calculated by BETACOOL program and simplified formula are shown in Fig. 5. The electron cooling is switched off in simulation. The simulation results are similar obtained by different methods. The momentum shift is larger than $5*10^{-4}$ after 50 seconds. The particles will be loss out of the acceptance. Due to this reason, a powerful electron cooling is necessary to compensate the energy loss and to make particle loss more slowly.

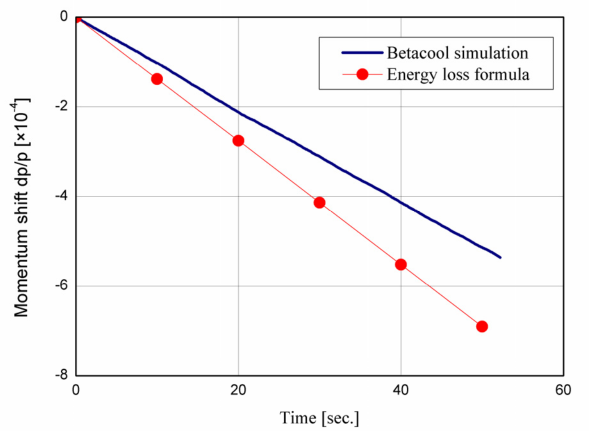

Figure 5: Simulation of the momentum evolution in pellet target experiment. Electron cooling is switched off.

LUMINOSITY

A new algorithm was developed and implemented into the BETACOOL program in order to simulate the short scale luminosity variation that comes up with every pellet going through the beam. The short-scale luminosity variation at one step is shown in Fig. 6. The peak signal is produced by collision of ions with each pellet. The repeat frequency is equal to the Rate of pellet generation.

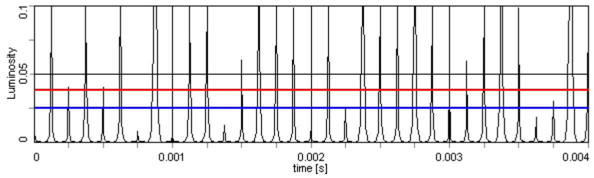

Figure 6: Simulation of short scale luminosity variation. The rate of pellet generation is 80 kHz

The result of long scale luminosity variation shows in Fig. 7. The pellet target is switch on at zero second. The average luminosity depends on the particle number of proton beam and the target thickness, which is show as blue line in Fig. 7. It's nearly constant because the lifetime of proton beam is not considered in the simulation. Usually the detectors are designed for some maximum acceptable event rate. In this simulation an example value of detector limit is given as 10^{32}, which means the count rate value is saturated and equal to the detector limit when it is overloaded ("top-cut" model in simulation) [3]. The event count by the detector is described as the effective luminosity as shown red points in Fig. 7. The effective luminosity increases at the beginning since the phase intensity increased by electron cooling. The equilibrium between cooling, IBS and pellet is obtained around 15 s. The effective luminosity is not changed after 15 s due to the phase intensity is a constant at the equilibrium.

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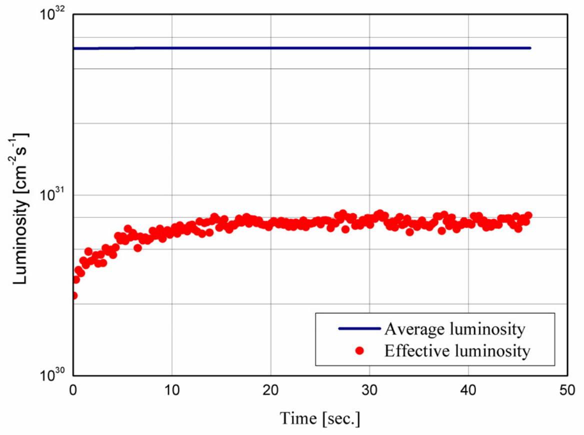

Figure 7: Simulation of long scale luminosity evolution (blue line) and effective luminosity for "top cut" model of detector limit (red point)

CONCLUSION

Simulation results show that the proton beam can be cooled within several seconds using the high density electron beam produced by the 2 MeV cooler at COSY. The equilibrium momentum spread is dominated by the IBS effect for the high intensity electron beam cooling. But for the low electron beam current, the beam-target interaction produces a core of momentum distribution with long tail and lead particle loss. The high efficiency electron cooling is necessary to compensate the beam-target interaction. The effective luminosity is less than average luminosity for "top-cut" model detector.

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