12/22/08

BETACOOL simulations and comparison to experimental data

A. Smirnov, *A. Sidorin*, JINR Dubna Russia
L. Prost, FNAL Batavia USA

1. Simulation of the cooling process with the electron beam

To explain the experimental results at the Recycler one has to get good agreement for different kinds of experimental data:

- equilibrium between electron cooling and intrabeam scattering;
- measurement of drag rates with a low intensity pbar beam;
- measurement of the cooling process with normal density of pbars.

1.1. Simulation of diffusion and equilibrium between ECOOL and IBS

BETACOOL simulations do not have good agreement with data for the coasting beam evolution under the action of intrabeam scattering without any other heating or cooling effects. The standard Martini model of intrabeam scattering for a Gaussian distribution is used in the BETACOOL code. The only fitting parameter here was the initial normalized transverse emittance. At the beginning of the diffusion, the experimental momentum spread growth agrees well with the simulation when the transverse emittance has a value of 0.34 [π mm mrad] (95%, normalized) (Fig. 1.1). Later, the momentum spread evolution agrees with the simulation for an initial emittance of 0.85 [π mm mrad] (95%, normalized). For both initial emittances, IBS heating is very small and transverse emittances practically don't change during the simulation.

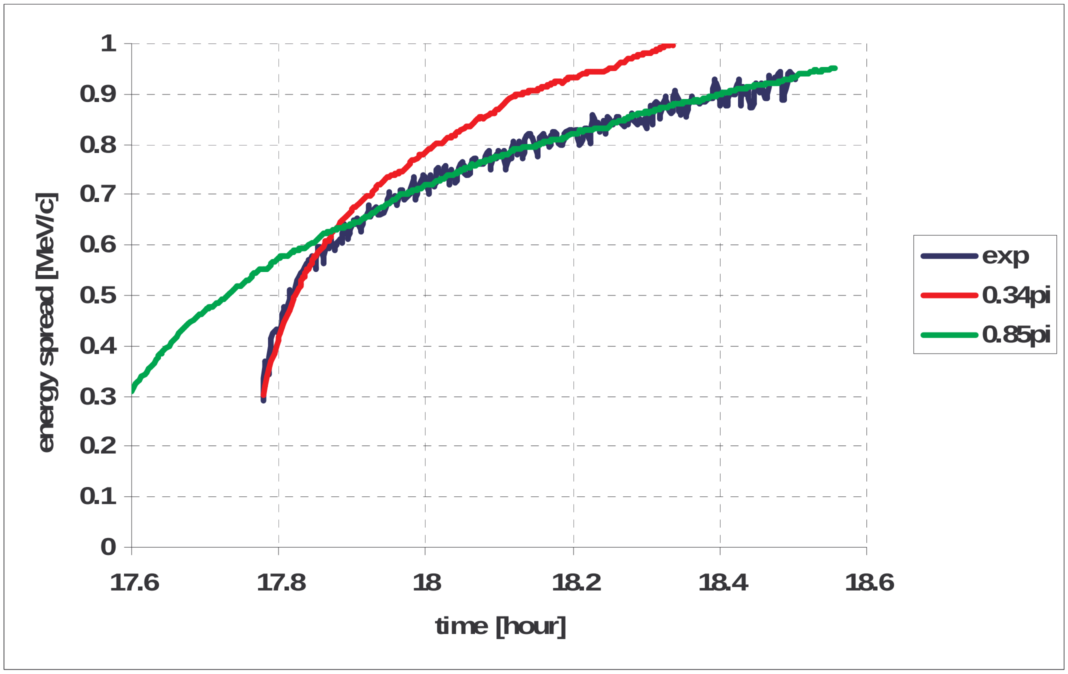


Fig. 1.1. Momentum spread evolution on time without cooling. $N = 1.5\times10^{10}$, blue –experiment, red – simulation with transverse normalized emittance 0.34 [π mm mrad], green – 0.85 [π mm mrad].

To reproduce the momentum spread behavior, additional transverse heating was included. In this case we have two fitting parameters: the initial transverse emittance and the value of the additional heating rate. The diffusion transverse heating rate of 4.3×10^{-8} [(π mm mrad)^2/sec] and initial emittances of 0.27 [π mm mrad] (95%, normalized) were found (Fig. 1.2) to fit the data.

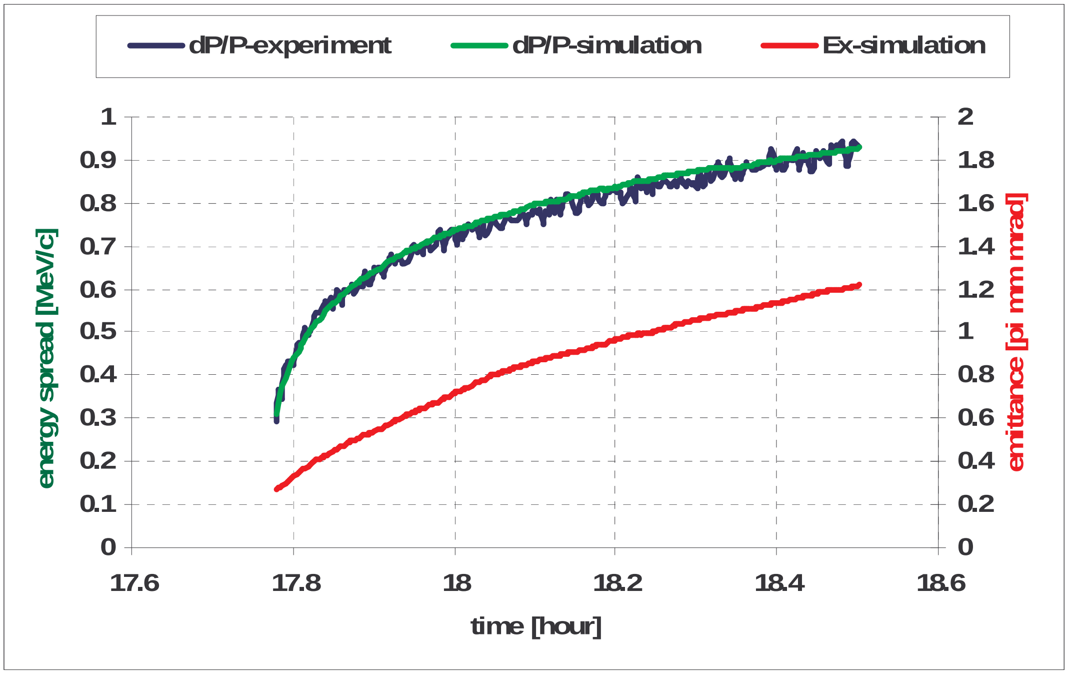
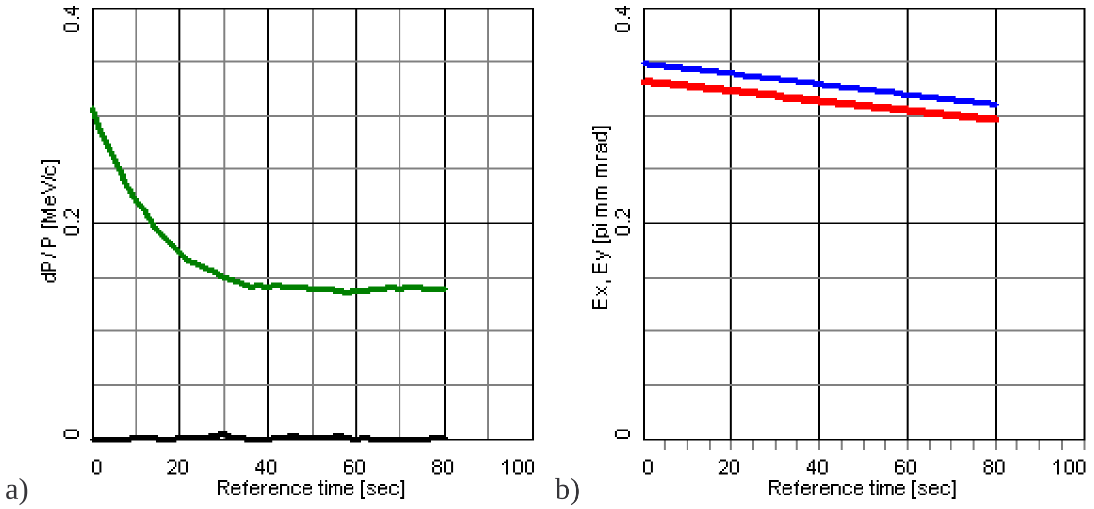


Fig. 1.2. Momentum spread evolution with additional transverse heating 4.3×10^{-8} [(π mm mrad)^2/sec], $N = 1.5\times10^{10}$, blue –experiment, green – simulation, red – evolution of transverse emittance.

The parabolic distribution of electron beam density (0.263 cm radius) without transverse heating and a beam current 0.1 A was used for simulation of the equilibrium between electron cooling and intrabeam scattering. An example of the cooling process for N=1.5×10^{10} particles is shown on Fig. 1.3. This simulation doesn't show the final equilibrium between the transverse and longitudinal temperatures of the pbar beam (transverse is much higher than longitudinal). A long time cooling (about 1 hour) leads to the continuous decrease of the transverse emittances and slow increase of the momentum spread.



a) b)

Fig. 1.3. Evolution of (a) the momentum spread and (b) transverse emittances during the cooling process.

In the experimental conditions, the equilibrium momentum spread is always significantly higher than in the simulations above and does not require several hours to reach, once the transverse emittances are less than ~0.5 π mm mrad (from flying wire measurements). In addition, the longitudinal distribution in the simulation and experimental cases do not coincide well, noticeably at the level of the tail particles (i.e. large momentum offset particles), which practically do not exist in simulations [not shown here].

1.2. Drag force measurements

During measurements of the drag force with low pbar intensity, it was found that the value of the drag force is very sensitive to the initial conditions of the pbar beam. If the pbar beam was cooled for a long time, the drag force value is lager than after a short time of cooling. One of the explanations is that large transverse tails grow due to the process of the drag force measurement. Simulations of the drag force measurements were done with the parabolic distribution of the electron beam without transverse gradient (Table 1.1).

Table 1.1 Simulation of drag force.

Electron beam parameters		
Beam current, mA	100	
Beam radius (parabolic shape), cm	0.263	
Longitudinal temperature / rms velocity, meV / m/s	546 / 310000	
Transverse temperature / rms velocity, meV / m/s	1.8 / 18000	
Voltage jump, kV	2	
Pbar beam parameters		
Pbar number	1.5×10^{10}	
Momentum, GeV/c	8.85	
Initial momentum spread, MeV/c	0.2	
Initial normalized 95% emittance, π mm mrad	0.2	0.8
Drag rate, MeV/c per hour	51	46
Slope of RMS width, MeV/c per hour	10.6	8.75

The results of the drag force simulations with a Gaussian distribution of the transverse emittance are shown on Fig. 1.4-1.6. The momentum spread profile has a symmetrical shape (Fig. 1.4b) after the cooling process. The footprint of the particle invariants has no correlation between particles with large transverse and longitudinal invariants (Fig. 1.6a-b).

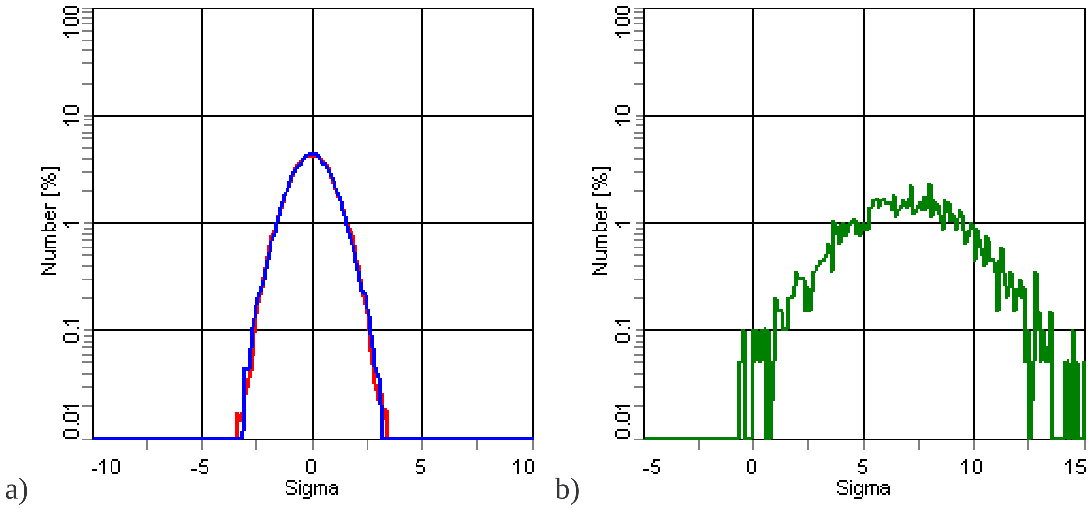


Fig. 1.4. (a) Transverse and (b) longitudinal profiles after simulation of the cooling process. Sigma is the one sigma rms value of the initial emittance or momentum spread.

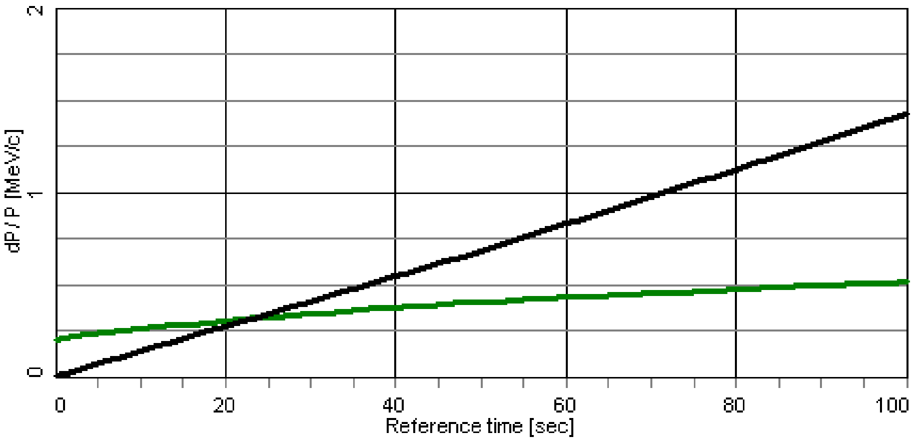


Fig. 1.5. Evolution of the momentum spread (black) and momentum deviation (green).

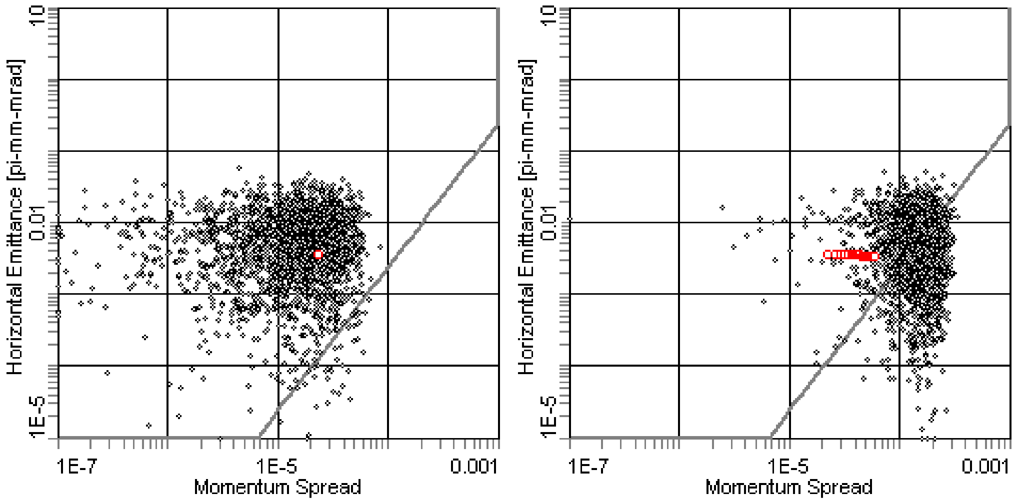


Fig. 1.6. Footprint of particle invariants for (a) the initial distribution and (b) after 100 sec of cooling in units of un-normalized transverse emittance and relative momentum spread.

Simulation results with large tails in the transverse directions are presented on Fig. 1.7-1.9. The core and tails of the transverse distribution were generated from Gaussian distributions with normalized emittances of 0.2 and 2 pi mm mrad (95%), respectively. The number of particles in the tails is about 25% (Fig.1.7a). The overall emittance is 0.8 pi mm mrad (95%, normalized) (Table 1.1).

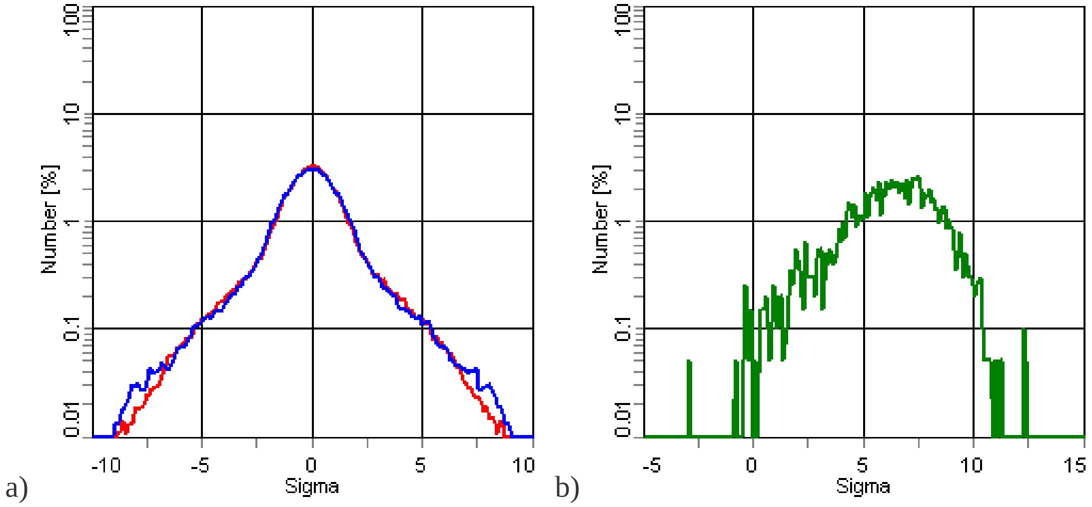


Fig. 1.7. (a) Transverse and (b) longitudinal profiles after simulation of the cooling process.

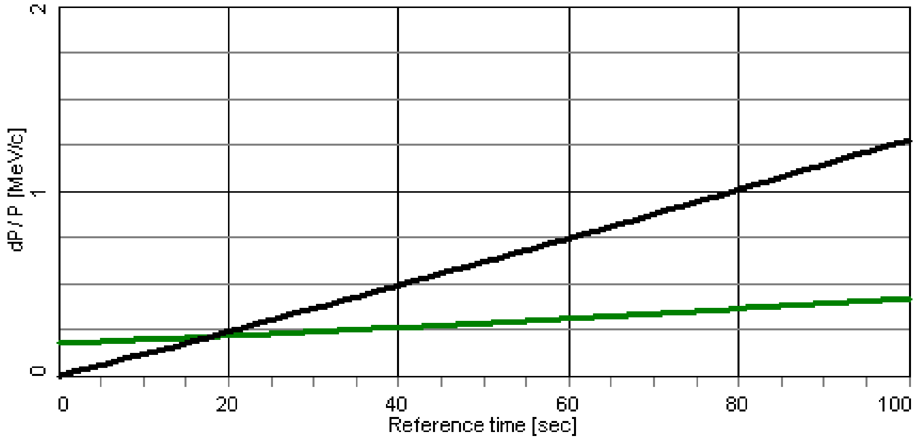


Fig. 1.8. Evolution of the momentum spread (black) and momentum deviation (green).

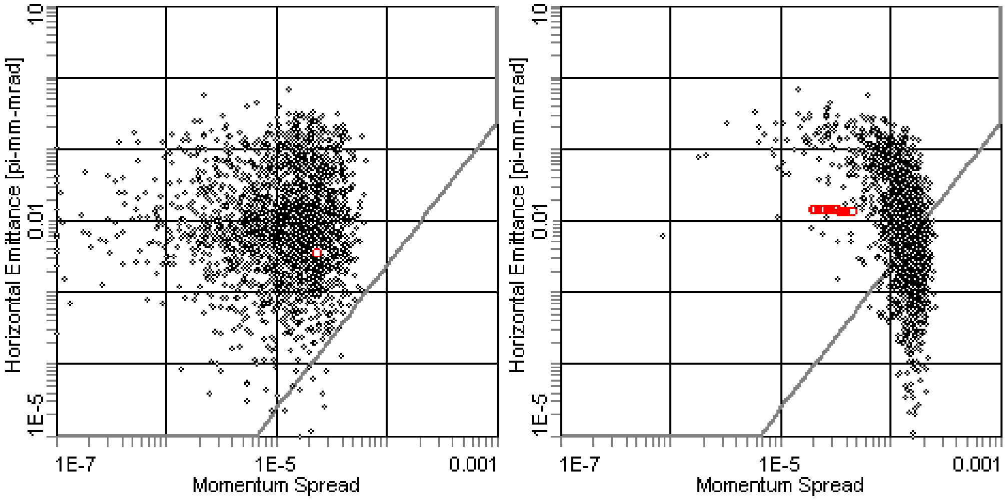


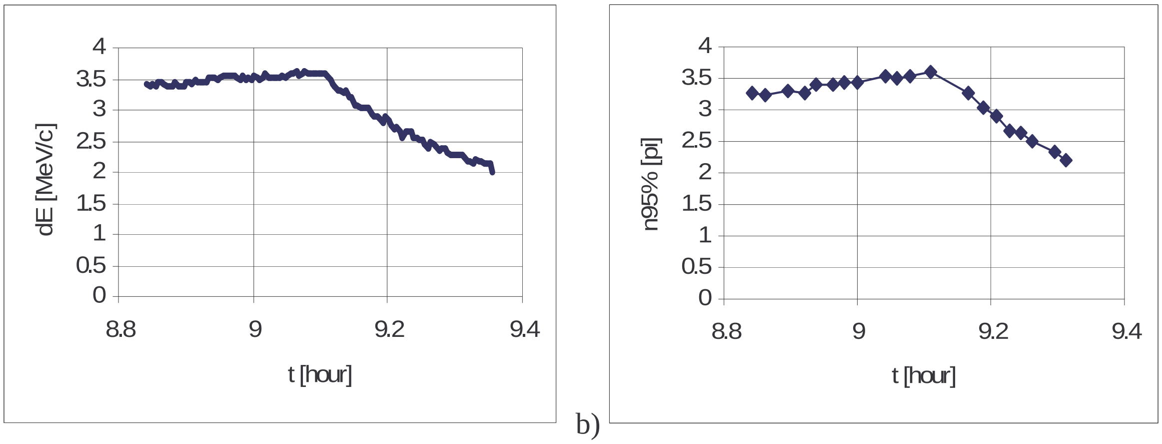
Fig. 1.9. Footprint of particle invariants for (a) the initial distribution and (b) after 100 sec of cooling.

This time, the longitudinal profile has a non-symmetrical shape which originates from the large transverse tails since particles with large transverse invariants practically don't cool down in the longitudinal plane too (Fig. 1.8b). These simulations give a good explanation of the dependence of the drag force on the large transverse tails of the pbar distribution. But they don't explain the behavior of the longitudinal momentum spread during the measurement of the drag force. In the experiment the slope of the momentum spread was at least two times larger than in the simulations.

1.3. Electron cooling force measurement

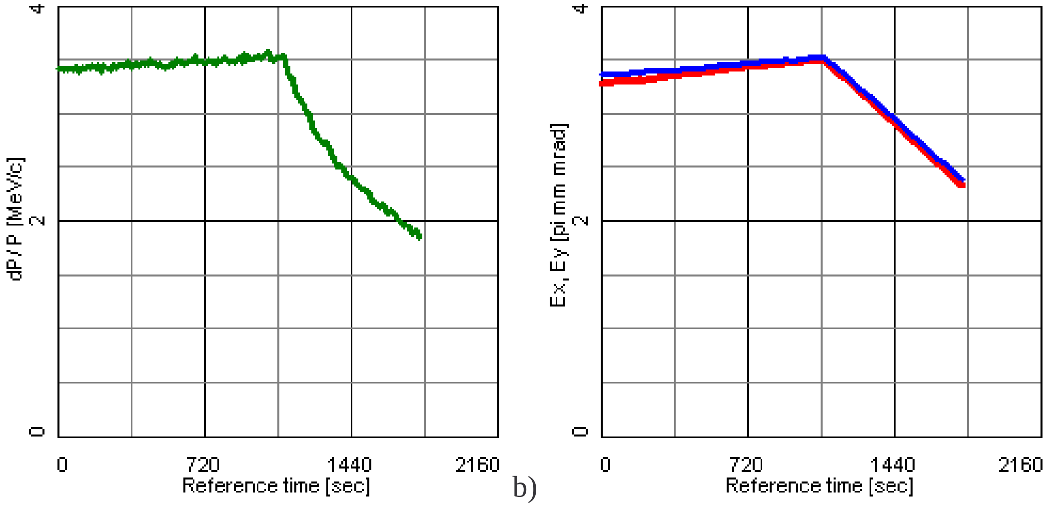
The final simulations were done for the measurement of the cooling force with high pbar intensity. The numerical model of the barrier bucket and the parabolic distribution of the electron beam with 0.1 A were used in the simulations. Experimental results from December 12, 2007 (file 891) and simulations are shown on Fig. 1.10-11. Initially, electron cooling is switched off and is switched on after 15 minutes. Pbar parameters for the experiment and simulation are presented in Table 1.2. The electron beam parameters were the same as in Table 1.1. Beam distributions before and after the cooling process are shown on Fig. 1.12.

An additional transverse heating of 4.3×10^{-8} [$(\pi$ mm mrad$)^2$/sec] was applied. In anyway, transverse and longitudinal diffusion are larger in the experiment than in the simulation. Without additional heating, the simulation value of the transverse diffusion is a few times smaller than in the experiment.



a) b)

Fig. 1.10. Experimental results of the evolution of (a) the momentum spread and (b) transverse emittances.



a) b)

Fig. 1.11. Simulation results of the evolution of (a) the momentum spread and (b) transverse emittances.

Table 1.2. Summary table of the experimental and simulation results

Parameters	**Experiment**	**Simulation**
Longitudinal diffusion, MeV/c/h	0.81	0.39
Transverse diffusion, π mm mrad/h	1.36	0.76
Longitudinal cooling rates, MeV/c/h	11.68	10.76
Transverse cooling rate, π mm mrad/h	8.33	6.24
Pbar number	1.88×10^{12}	

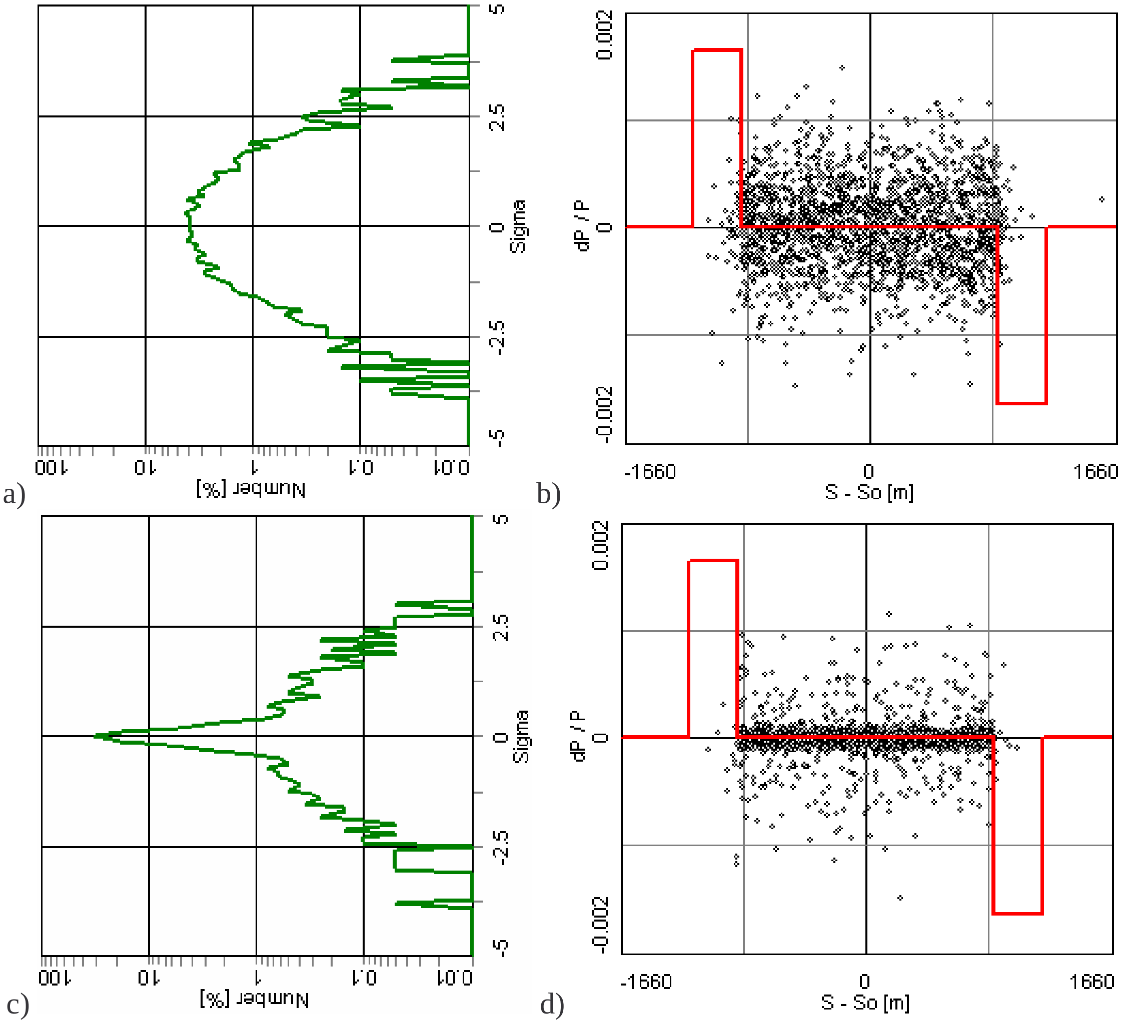


Fig. 1.12. Beam distribution (a,b) before electron cooling was switched on and (c,d) after the cooling process. (a,c) - longitudinal profiles; (b,d) - longitudinal phase space; the red line is the position and amplitude of barrier buckets.

2. Summary

The pbar evolution without cooling can not be described by the intrabeam scattering heating only (Fig. 1.1). Additional diffusion transverse heating of the pbar beam can reproduce the experimental momentum spread evolution (Fig. 1.2). The drag rate measurements can depend on the pbar distribution in the transverse plane. Large transverse tails lead to the decrease of the drag rate force. But simulation results don’t describe the slope evolution of the rms momentum spread with the low intensity pbar beam. Simulations show a good enough agreement with the measurements of the longitudinal and transverse cooling forces with the normal intensity pbar beam.