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PHASE STEP METHOD FOR FRICTION FORCE MEASUREMENT IN FILTER STOCHASTIC COOLING

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Abstract

Voltage step method for friction force measurement in electron cooling is well known. The similar method for friction force measurement in longitudinal stochastic cooling with comb filter is provided. First test of the method during the run at COSY has been implemented.

INTRODUCTION

Stochastic cooling systems (SCS) for High Energy Storage Ring (HESR) and Nuclotron-based Ion Collider fAcility (NICA) are under development in GSI Helmholtz Centre for Heavy Ion Research [1] and in Joint Institute for Nuclear Research [2] respectively. The preparatory experimental work on stochastic cooling for HESR and NICA is carried out at COoler SYnchrotron (COSY) at Forschungszentrum Jülich [1]. During this work hardware solutions and automation techniques for system adjustment had been worked out and tested. The automation technique is based on the cooling process simulation which is described by Fokker-Planck equation (FPE) [3]. One of the notions defining the evolution of the cooling process is drift term of the FPE which is also known as friction force. The measurement of friction force may be fruitful for fine tuning of cooling systems. The approach for friction force measurement in filter stochastic cooling is discussed below.

DESCRIPTION OF THE METHOD

Procedure

Originally the method of longitudinal friction force measurement was widely used in electron cooling [4 – 7]. Cold electrons interchange their temperature with hot ions during the electron cooling process. Cathode voltage of the electron cooler defines energy of electrons. If the mean energy of electrons is slightly different than the one of ions the ion energy distribution evolves to the new equilibrium.

The experimental procedure is the following: at first the mean electron energy is equal to the ion one, then after a rapid voltage step on the cooler cathode the friction force shifts along the energy as shown in Fig. 1 and ion energy distribution starts to evolve as shown in Fig. 3. By the evolution of maximum and/or mean values of ion energy distribution one can evaluate the actual friction force. The evaluation is described in details in the next section.

Similar procedure where the shift of the friction force is provided for momentum stochastic cooling can be done with a comb filter. Such technique is simpler for filter stochastic cooling due to comb filter has more parameters to adjust (see Fig. 2) in comparison with other methods for momentum stochastic cooling. Simulation based on FPE approach [2] shows that proper shift of the friction force along the energy is performed by adding extra delay Δt_{filter} in the long leg of the comb filter and proportional system delay

$$\Delta t_{sys} = \frac{T_{P\to K}}{T_0}\Delta t_{Filter},$$

where $T_{P\to K}$ is time of flight between pickup and kicker for the reference particle and T_0 is the revolution period. So the only difference in procedures for friction force measurement between electron and filter stochastic cooling is that instead of changing one parameter of cathode voltage for electron cooling there are two proportional parameters Δt_{filter} and Δt_{sys} which should be stepped simultaneously.

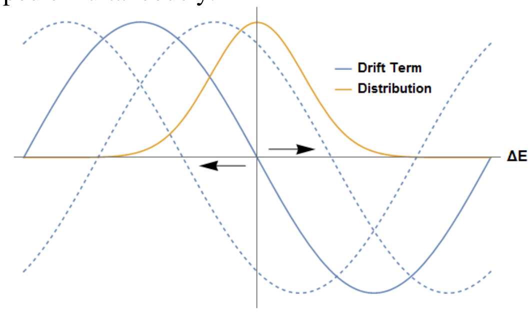

Figure 1: FPE drift term a.k.a. friction force (blue): initial (solid) and shifted to the left or to the right (dashed) in comparison with distribution function (orange).

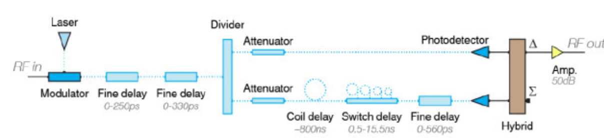

Figure 2: Scheme of optical comb filter

The friction force of the momentum stochastic cooling is alternating and during the adjustment several possible delay combinations lead to cooling. The optimal combination of delay parameters is when system delay is equal to the reference particle's transit time between pickup and kicker and filter delay is equal to the revolution period. If SCS has optimal adjustment the friction force is close to an odd function. In our case we intentionally chosen not optimal adjustment of the system by adding extra system delay in order to have asymmetric friction force. The transfer function of the SCS which is proportional to the friction force is shown in Fig. 4.

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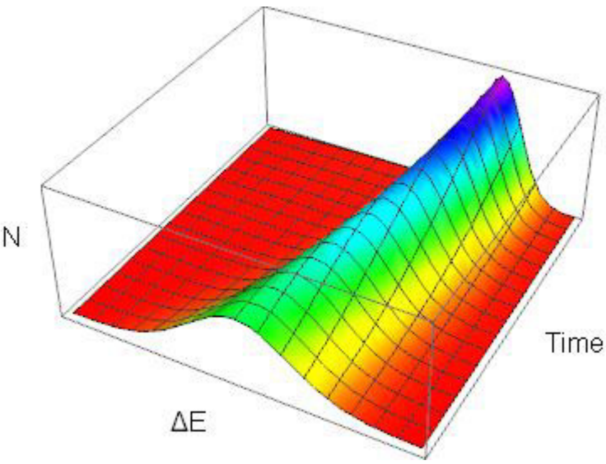

Figure 3: Evolution of ion beam energy distribution due to shift of the friction force.

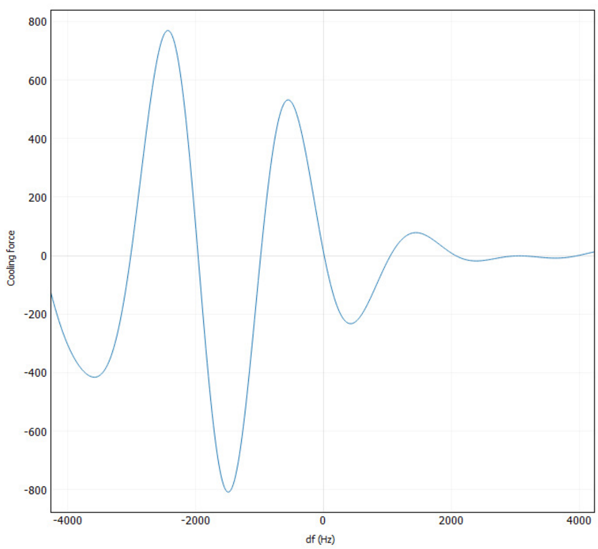

Figure 4: Transfer function of the COSY SCS during the experiment.

Measurements

The first implementation of the method described above has been done at COSY. The parameters of COSY and its stochastic cooling system are given in Table 1.

Table 1: Parameters of Stochastic Cooling at COSY

Parameter	**Value**
Circumference	184 m
Ions	p^+
Energy	2.285 GeV/u
Revolution frequency	1 559 493 Hz
Slip-factor, η	-0.1
Intensity	$3\cdot10^9$ ions
$\Delta p / p_0$	$3\cdot10^{-4}$
Bandwidth	2-4 GHz
Output Power	0 W

Measurements were carried out at the 1400th harmonic of the revolution frequency. Spectrum analyzer saved one spectrum per second. Two measurements are given as an example in the paper. During the first measurement the proton beam was initially accelerated by the filter stochastic cooling phase step, and when the beam reached the new equilibrium energy it decelerated back to the initial state. The spectrogram of the first measurement is shown in Fig. 5 (top) During the second measurement the beam was initially decelerated and then accelerated back. The spectrogram of the second measurement is shown in Fig. 5 (bottom). The difference between measurements is that system gain in the second one is 3 dB higher.

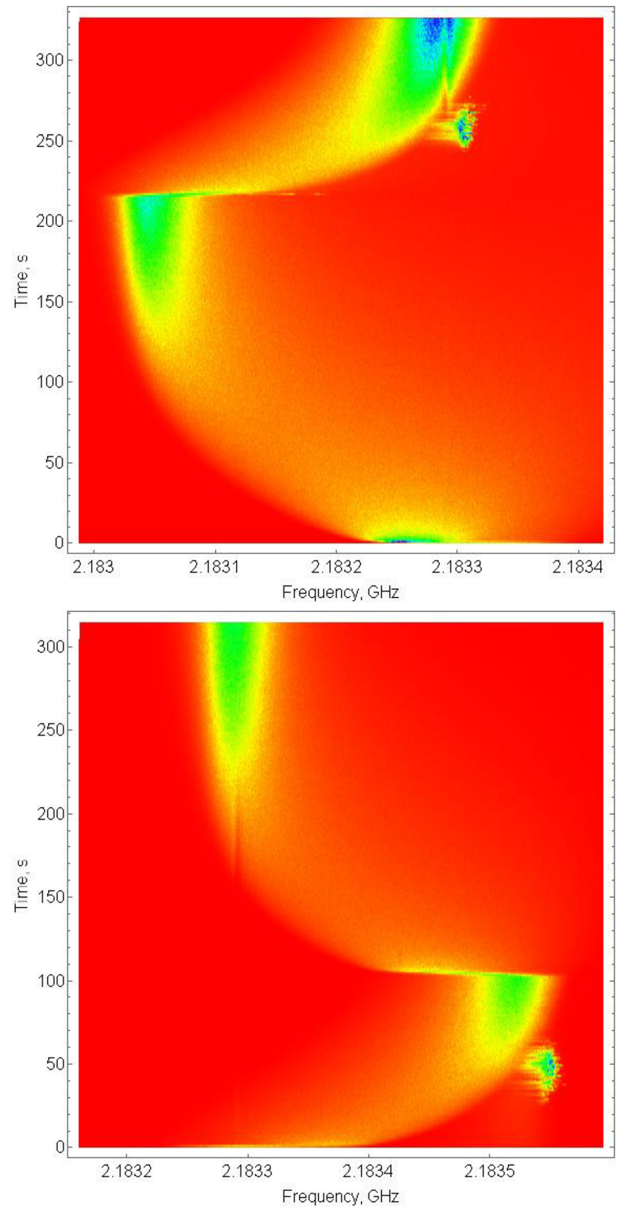

Figure 5: Waterflow spectrogram of the first (top) and second (bottom) measurements.

Processing

Before we started the friction force evaluation we filtered out the outlying noise signal which is clearly seen (in Fig.5 both top and bottom) as a blob right to the signal distribution during the accelerating phase. The noise was filtered by the combination of low pass and minimum

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filters. The frequencies of filters were searched by the rule of thumb in a trade-off between noise reduction and signal loss. Also before the evaluation the spectrograms of schottky noise power vs frequency was converted into the energy distribution functions.

The FPE for the preprocessed energy distribution function Ψ, friction force F and diffusion D is written in the form [3]

$$\frac{\partial \Psi(E,t)}{\partial t}+\frac{\partial}{\partial E}\left(F(E)\Psi(E,t)\right)-\frac{\partial}{\partial E}\left\{D(E)\frac{\partial \Psi(E,t)}{\partial E}\right\}=0$$

Following only the distribution maximum value E_M for which distribution function satisfies the condition

$$\Psi(E_M,t)\Leftrightarrow \left.\frac{\partial \Psi(E,t)}{\partial E}\right|_{E_M}=0$$

we obtain the reduced equation without a diffusion term

$$\frac{\partial \Psi(E_M,t)}{\partial t}+\frac{\partial F(E_M)}{\partial E}\Psi(E_M,t)=0$$

and finally we can trace the exact value of the friction force up to the equilibrium point Eq

$$F(Eq-E)=-\int_{E}^{Eq}\frac{1}{\Psi(E_M,t)}\frac{\partial \Psi(E_M,t)}{\partial t}dE_M$$

Another characteristic value of the distribution is its mean as known as first raw moment M. Its evolution is written as

$$\frac{dM}{dt}=\int E\left[-\frac{\partial}{\partial E}\left(F(E)\Psi(E,t)\right)+\frac{\partial}{\partial E}\left\{D(E)\frac{\partial \Psi(E,t)}{\partial E}\right\}\right]dE$$

The first term is transformed as follows

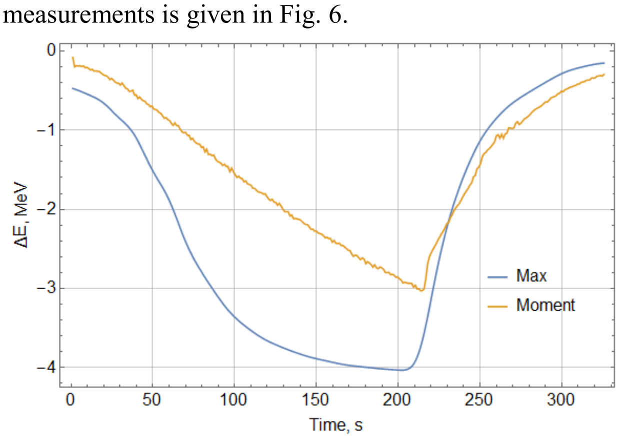
$$\int -E\frac{\partial}{\partial E}\left(F(E)\Psi(E,t)\right)dE=\int F(E)\Psi(E,t)dE=\langle F\rangle_{\Psi}$$

and if we assume that the diffusion is approximately an even function we obtain the second term of the mean evolution is almost zero. So the evolution of distribution mean corresponds to the friction force averaged over the energy distribution function which tends to actual value of the friction force as the distribution function approaches to Dirac δ-function

$$\frac{dM}{dt}\approx\langle F\rangle_{\Psi}\xrightarrow{\Psi\to\delta}F(M)$$

It means that the evolution of mean value for relatively narrow distributions is also applicable for approximate estimation of the friction force.

The evolution of mean and maximum energy distribution function values for first and second measurements is given in Fig. 6.



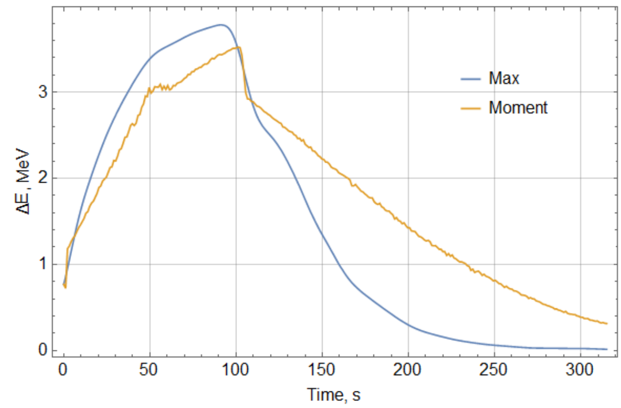


Figure 6: Evolution of maximum (Max) and mean (Moment) energy distribution function values for first and second measurements.

RESULTS

The estimated friction force for both measurements in comparison with theoretical one proportional to the system transfer function is given in Fig. 7. The asymmetry of the theoretical friction force is repeated for both experimental estimations. The 3dB gain difference between two measurements is seen as well. As we suppose the estimation of friction force based on the evolution of the distribution maximum is more precise than the mean evolution. But for approximations the mean evolution can be also used.

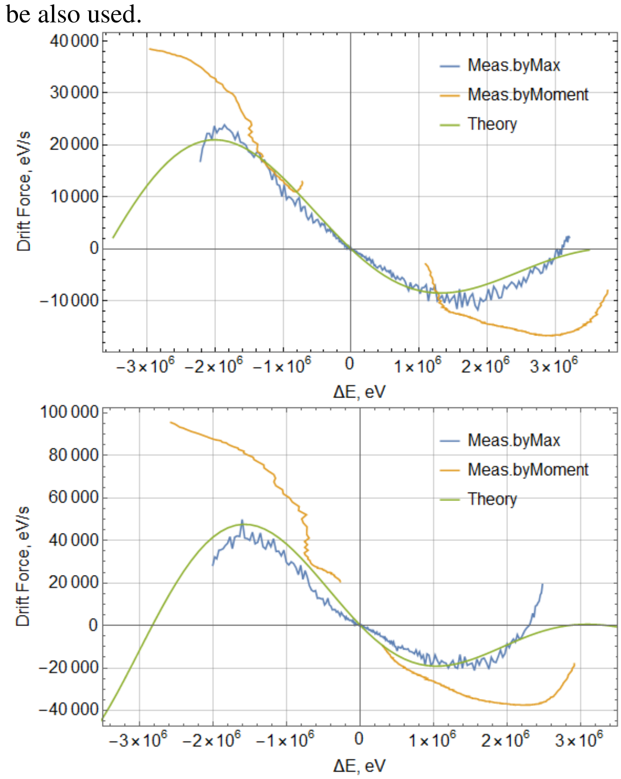


Figure 7: Comparison of theory and measurements for first (top) and second (bottom) measurements.

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CONCLUSION

The presented approach allows one to evaluate the friction force of filter stochastic cooling based on the experimental measurements. First tests of the method were performed at COSY and demonstrated an agreement with the theory.

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