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Memo

DATE: *December 2, 2005*

TO: RHIC E-Coolers

FROM: *Ady Hershcovitch*

SUBJECT: **Minutes of the December 2, 2005 Meeting**

Present: Michael Blaskiewicz, Mike Brennan, Peter Cameron, Xiangyun Chang, Alexei Fedotov, Wolfram Fischer, Harald Hahn, Ady Hershcovitch, Dmitry Kayran, Jorg Kewisch, Vladimir Litvinenko, Derek Lowenstein, William Mackay, Christoph Montag, George Parzen, Vadim Ptitsyn, Thomas Roser, Anatoly Sidorin (JINR Dubna Russia), Triveni Srinivasan-Rao, Gang Wang (SUNY Stony Brook).

Topics discussed: Experimental Studies of Non-magnetized Electron Cooling at the FNAL Recycler. Numerical Calculations and Simulations of the FNAL Studies

The meeting consisted of detailed presentations by Alexei regarding non-magnetized electron beam cooling experiments performed at the FNAL Recycler, and by Anatoly on calculations and simulations of those experiments. Both Alexei and Anatoly had just returned from a visit to Fermi Lab that had a very productive outcome. They had many useful discussions with members of the FNAL electron beam cooling group, learned their system in great details, and they got access to all previous drag rate measurements. Alexei and Anatoly took part in measurements of antiproton (pbar) distribution evolution under electron beam cooling, stochastic cooling, and combined effect of both. They ended up with a wealth of data needed for simulations, which are now in progress.

Experimental Studies of Non-magnetized Electron Cooling at the FNAL Recycler: Alexei opened the meeting by showing the relevance of the FNAL recycler electron beam cooling experiments to RHIC non-magnetized cooling. In principle these experiments should enable benchmark the accuracy of the models for the friction force, and allow for distribution evolution studies under cooling or during drag rate measurements (that require accurate descriptions of both cooling and diffusion in modeling). Also these experiments should allow studying effects of electron cooling together with stochastic cooling (both transverse and longitudinal).

Performed studies were those of pbar distribution under electron beam cooling and stochastic cooling (understanding how they work together; measuring diffusion and cooling rates). And, measurement of drag rate (cooling force) with electron energy jump method was also performed. The results of the studies were that a very large amount of useful data was acquired. Additional measurements are being done by FNAL group upon request. Agreement between measured rate and models within factor of two – better description of electron beam parameters is needed for better agreement – work is now in progress at FNAL. Due to the slower rate of the cooling process at FNAL's higher energy (relative to low energy coolers), it was possible to record distribution evolution under various conditions; data for several experiments, which was recorded, is to be studied in simulations.

A copy of Alexei's talk can be found below.

Numerical Calculations and Simulations of the FNAL Studies: Anatoly followed Alexei by presenting a comparison between calculations and measurements of the friction force in non-magnetized electron beam cooling of pbar. To calculate the friction force components, numerical integration was used with Binney's and Budker's formulae. In BETACOOL simulation transverse heating is simulated in accordance with measured rate due to interaction with residual gas. Longitudinal heating is simulated in accordance with measured diffusion power, and transverse electron spread is used as a fitting parameter.

Comparison of Recycler experiment and simulations yielded agreement within a factor of 2. With increased understanding of the various contributions to electron angles (realistic parameters in simulation rather than fitted) better agreement is expected. In principle, with fitted parameters agreement between simulations and experiments can be as good as 10-20% - but we are not there yet. Results of numerical simulation of non-magnetized friction force are in good agreement with experiments, but the friction force value depends significantly on electron beam quality. Simulation of exact behavior of pbar distribution under drag is rather challenging and is still work in progress. There is, however, qualitative agreement.

Anatoly's presentation is following Alexei's.

Alexei Fedotov's Presentation

FNAL trip report

Experimental Study of Non-magnetized Electron Cooling

at FNAL Recycler

Alexei Fedotov, Anatoly Sidorin

December 2, 2005

First successful demonstration of non-magnetized E-cooling in FNAL Recycler - July 2005.

Cooling of pbars is done with 4.3 MeV electrons (γ=9.5).

Longitudinal heating in Recycler is dominated by IBS.

Transverse heating is dominated by gas scattering.

Purpose of electron cooling is to cool longitudinally up to 600e10 pbars.

Presently, electron cooling is done routinely with electron current Ie=500 mA with offset of e-beam in the vertical direction by about 4 mm (radius of electron beam 4.5 mm).

Relevance to RHIC non-magnetized cooling

Measured cooling rates are within factor of two with expectation. Uncertainty is believed to be due to an estimate of various contributions to transverse angular spread of electron beam.

FNAL e-cooling is directly relevant to RHIC non-magnetized cooling approach:

1. **Allows to benchmark accuracy of the models for the friction force.**
2. **Allows to study evolution of distribution under cooling or during drag rate measurements – requires accurate description of both cooling and diffusion in modeling.**
3. **Allows to study effects of electron cooling together with stochastic cooling (both transverse and longitudinal).**

Possible studies

1. **Study of electron beam – control of electron beam; alignment; radial dependence of transverse angular spread, etc.**
2. **Study of effects of electron cooling and stochastic cooling on pbar beam with typical intensities 150-200e10.**
3. **After shot from Recycler to Tevatron there is a possibility to measure cooling rate on remaining small portion of pbars – about 2-3e10.**

Outcome of the visit

I. We had a lot of useful discussion with FNAL E-cooling group: Sergei Nagaitsev, Alexander Shemyakin, Lionel Prost, others.

II. Learned about their e-cooling system and got details on various parameters which we need to include in simulations.

III. We got access to all previous measurements of drag rate done by FNAL group with details of the measurements – a lot of data to study and simulate.

IV. Took part in measurements of evolution of pbar distribution under e-cooling, stochastic cooling, combined effect.

V. For condition which we wanted, drag rate and measurements of distribution evolution was done for us by Lionel Prost – we have all the data for simulations.

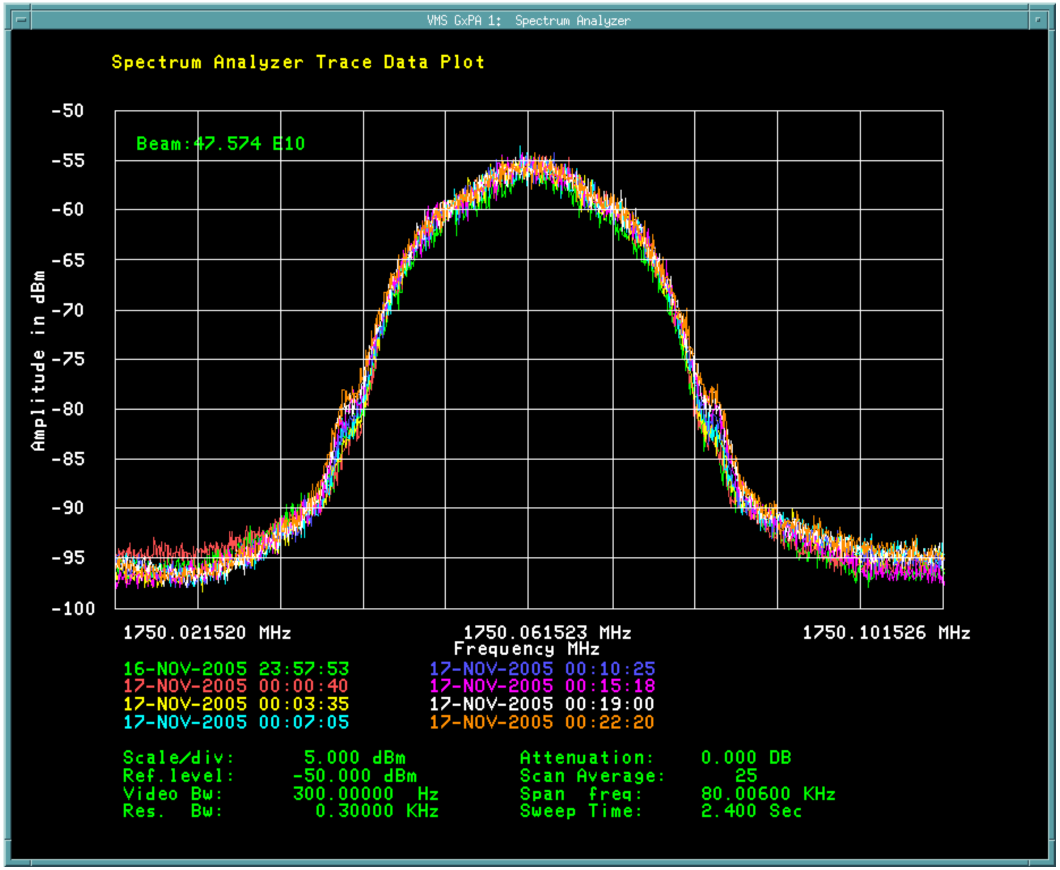
VI. Simulation and study of various aspects are in progress.

Examples of some of the measurements

1. **Study of pbar distribution under electron cooling and stochastic cooling – understanding how they work together; measuring diffusion and cooling rates (11/16/05 L. Prost, A. Fedotov, A. Sidorin).**

2. **Measurement of drag rate (cooling force) with electron energy jump method (11/26/05 L. Prost).**

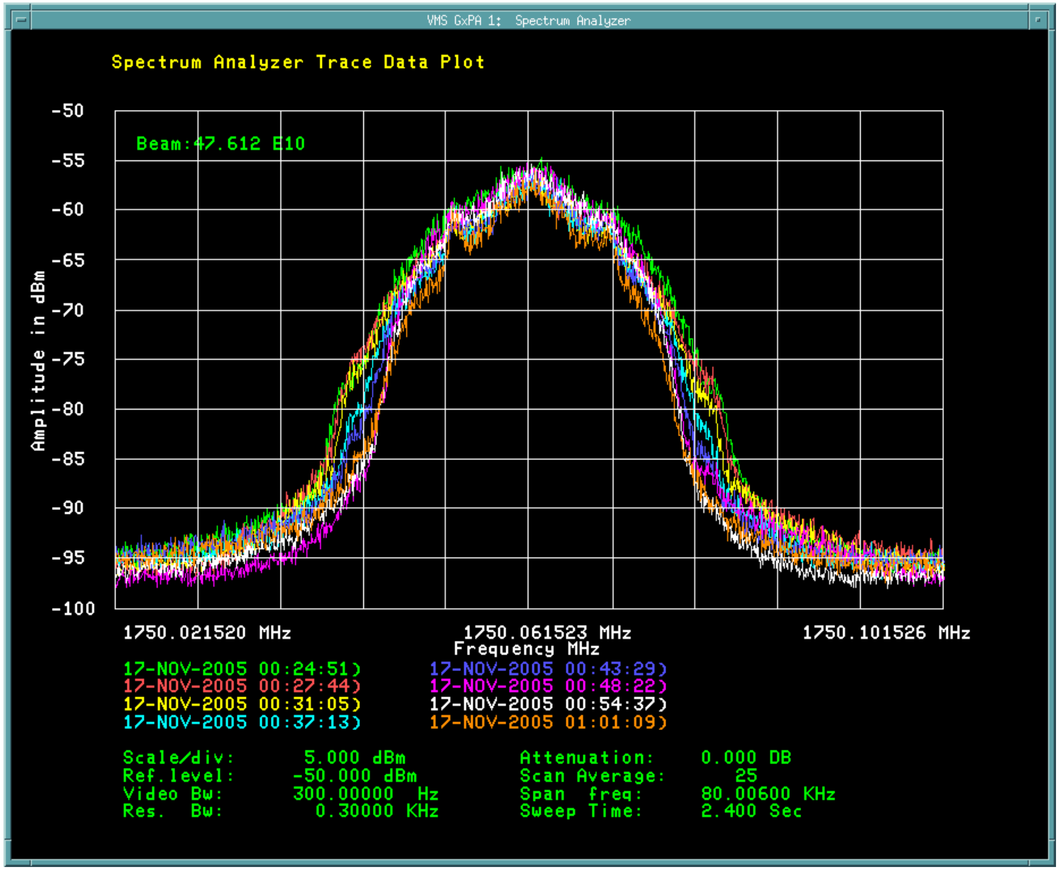
Experiment 11/16/05: Evolution of longitudinal momentum distribution (Stochastic cooling: OFF, E-cooling: OFF)



Pbar intensity

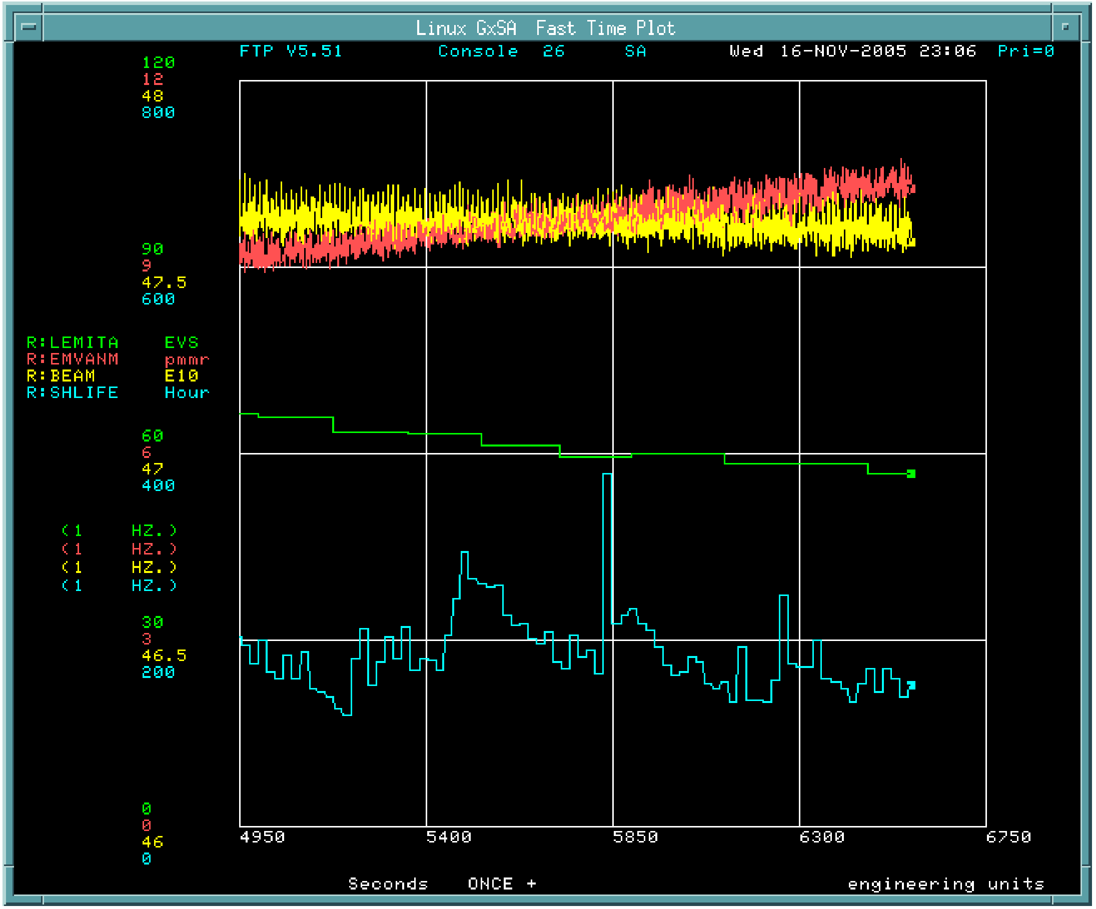
47.7e10

11/16/05: Longitudinal stochastic cooling: ON (E-cooling is OFF)



Cooling of tails with stochastic cooling

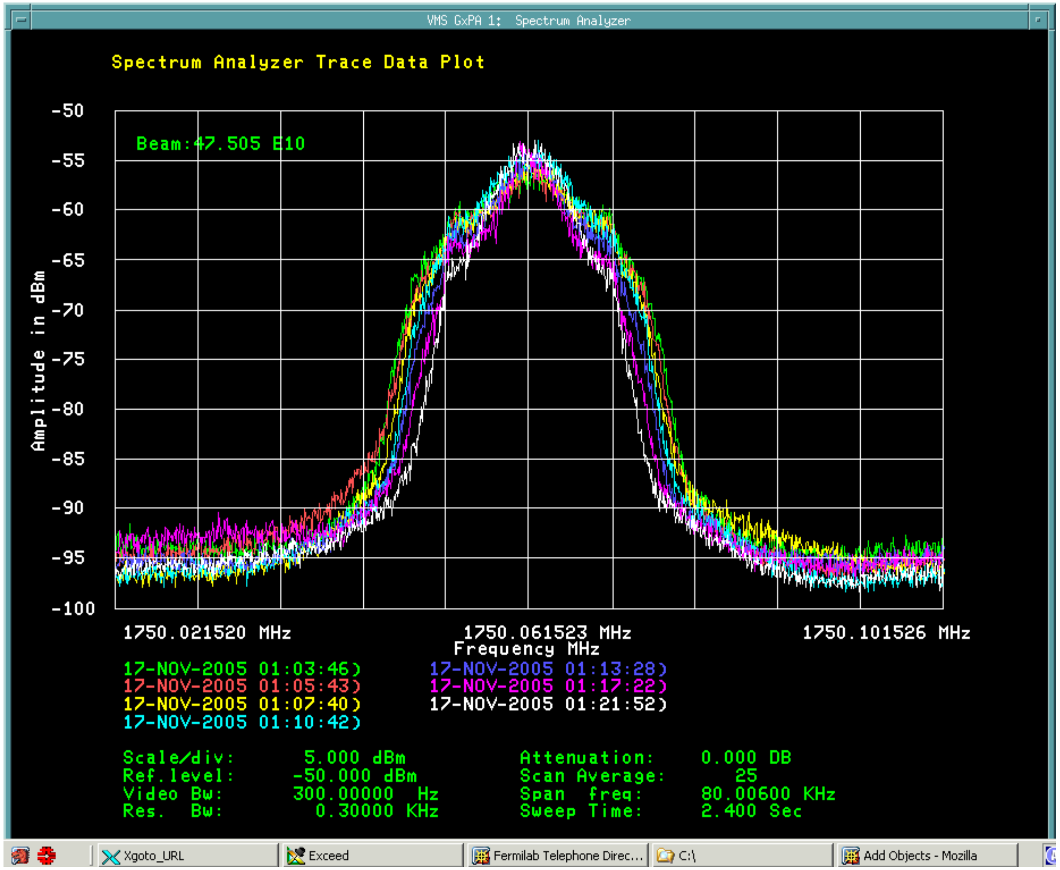
11/16/05: Longitudinal stochastic cooling: ON
E-cooling: OFF



Transverse emittance- increases slightly

Longitudinal emittance – decreases slightly

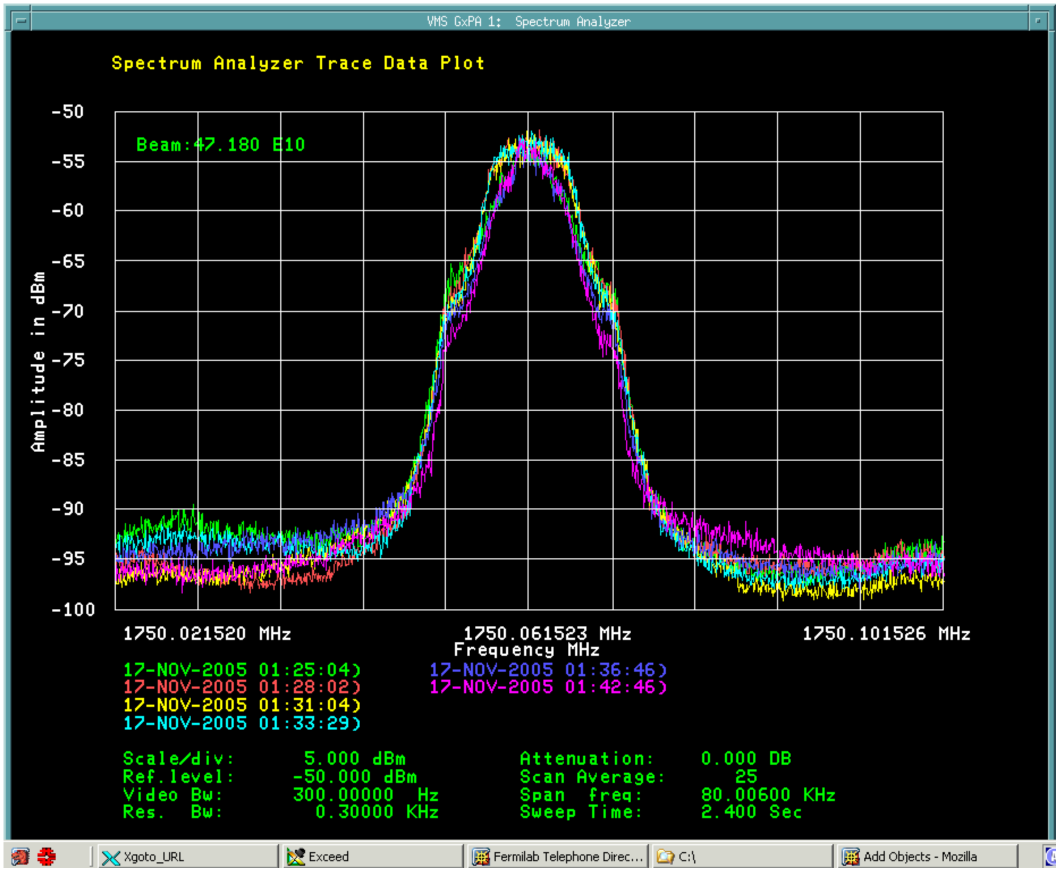
11/16/05: Longitudinal Stochastic cooling: ON
E-cooling: ON



E-cooling:

Ie=500 mA
e-beam on center of pbar beam

11/16/05

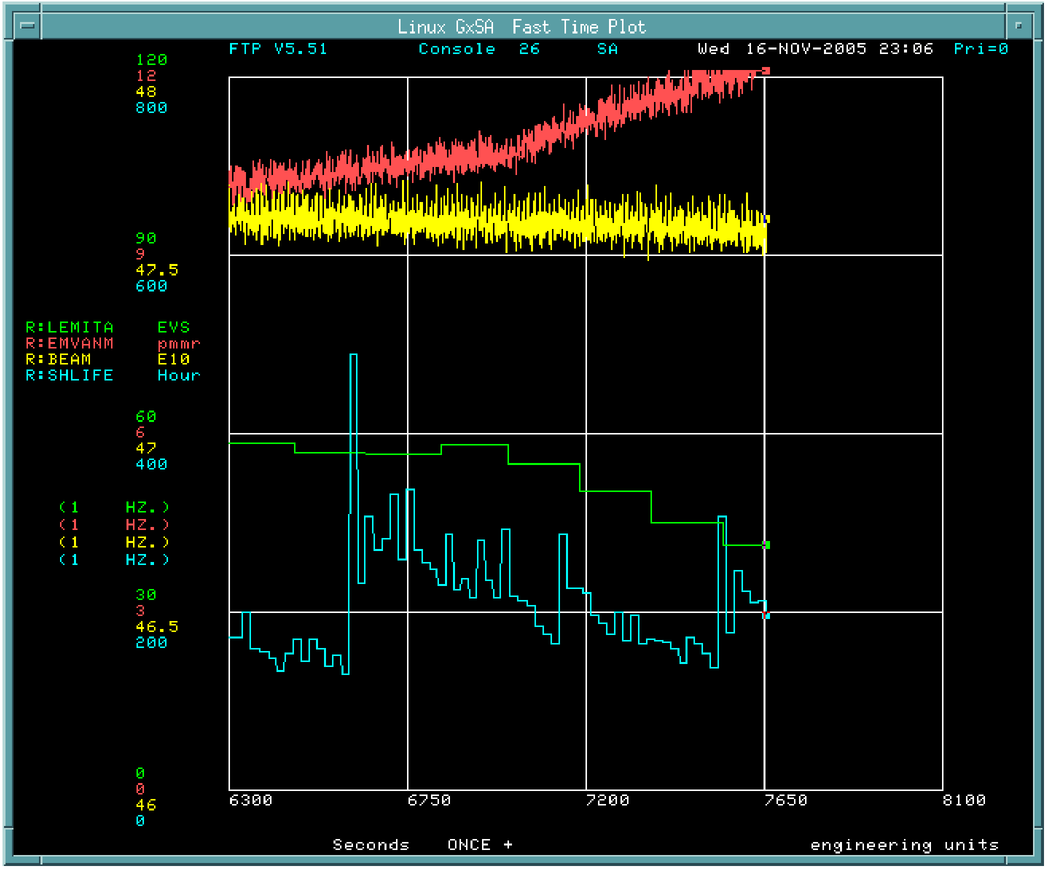


First 4 profiles:
E-cooling ON,
Stochastic cooling – OFF

5th profile:
E-cooling: ON,
Longitudinal Stochastic: ON

6th profile
Transverse Stochastic: ON

11/16/05 (N pbar = 47.7e10, Ie=500mA, ae=4.5mm)

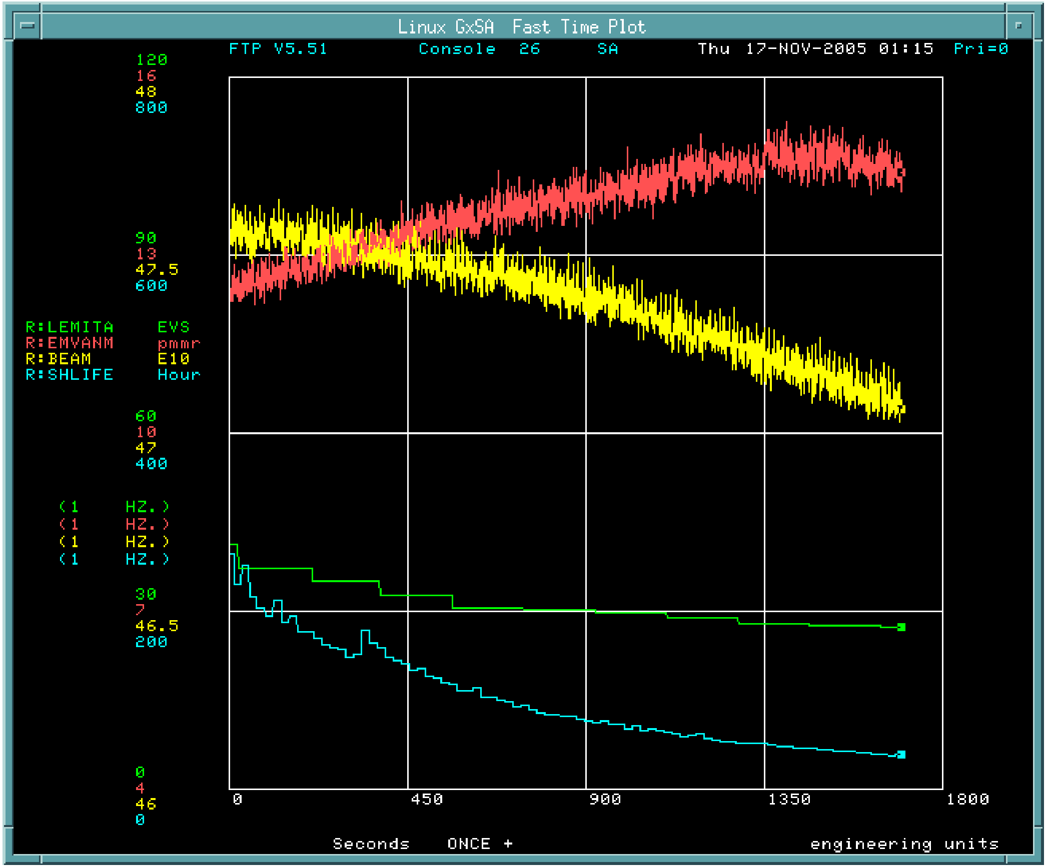


Transverse emittance - stronger growth when E-cooling is ON (with electron beam on center)– presently not understood – various possibilities are being studied

To avoid emittance growth, presently cooling is done with 3-4 mm offset of e-beam.

Longitudinal emittance - fast cooling

11/16/05 Transverse stochastic cooling ON

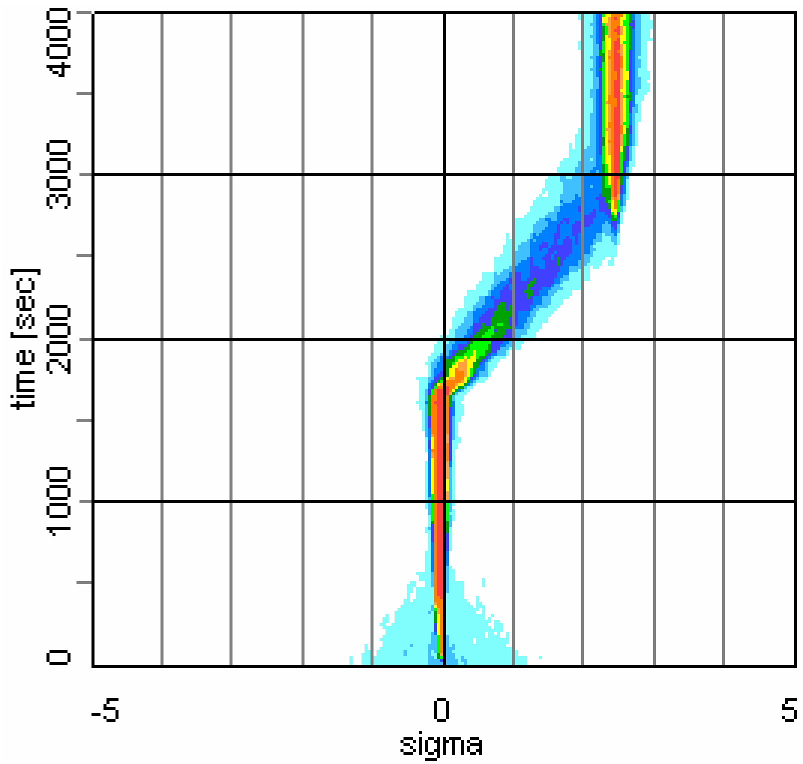


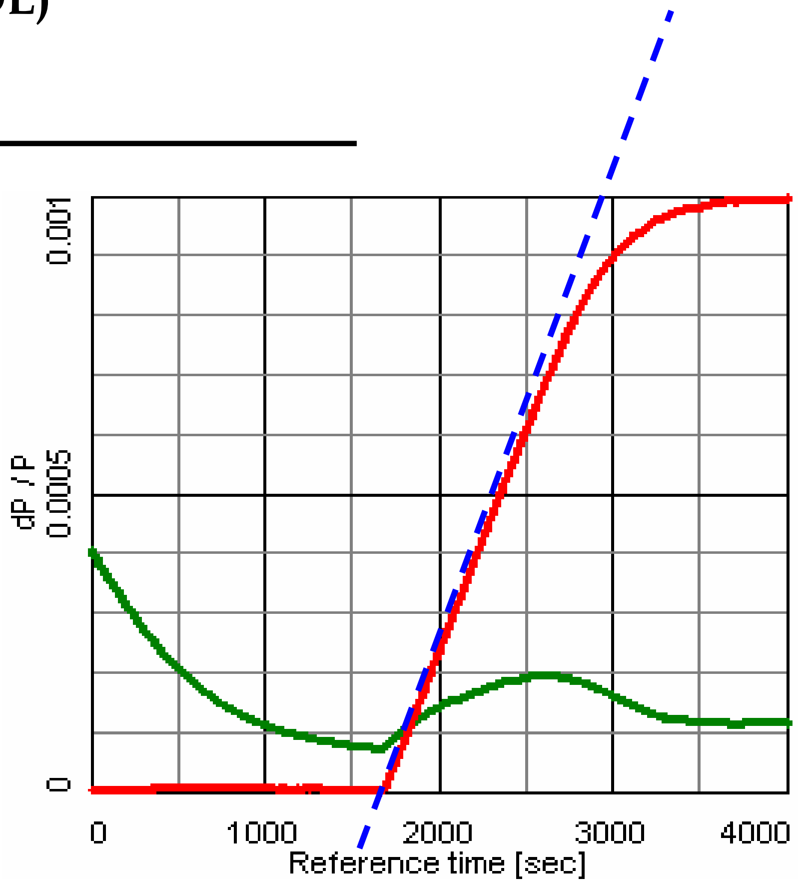
Drag rate measurements and modeling

Steps:

1. **Pbar distribution is cooled first**
2. **Electron energy is changed**
3. **Pbars are dragged towards new energy**
4. **Distribution profiles are recorded and drag rate is extracted**

Example of modeling (BETACOOL)

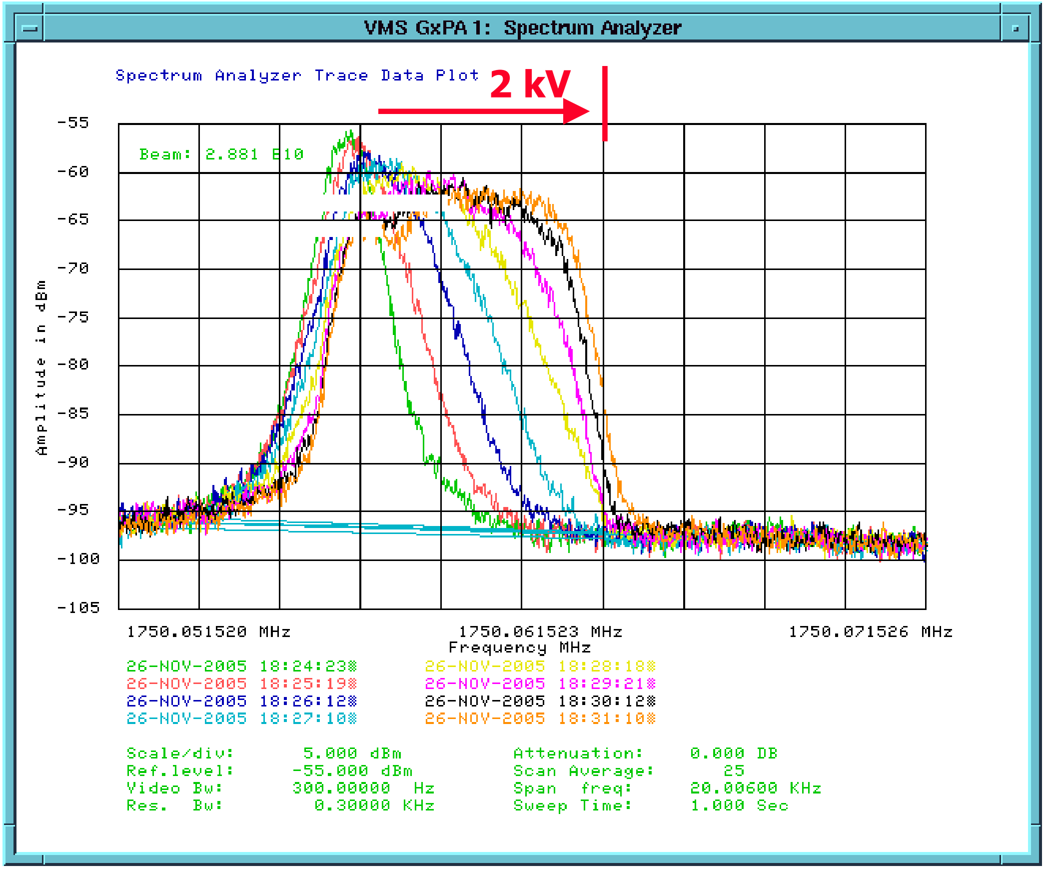




momentum spread on time

momentum spread and momentum deviation on time

11/26/05 Longitudinal momentum distributions after 2kV jump of electron energy (Lionel Prost)



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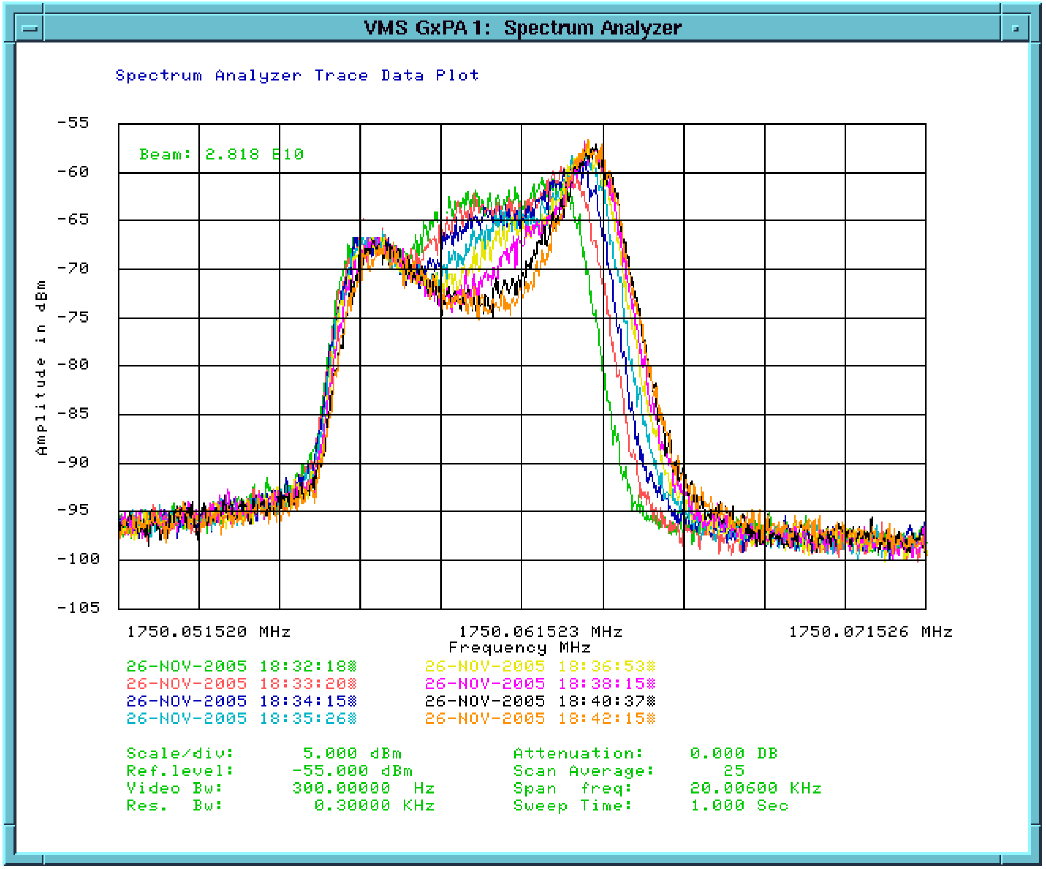

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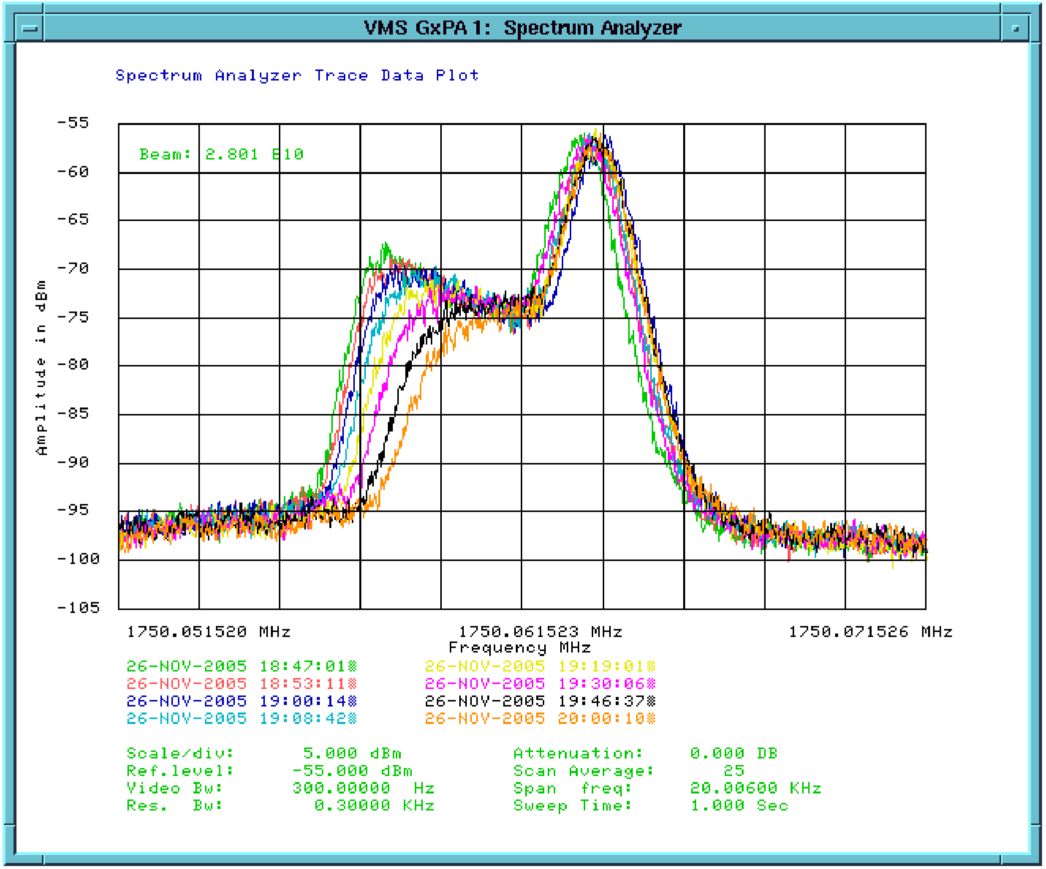
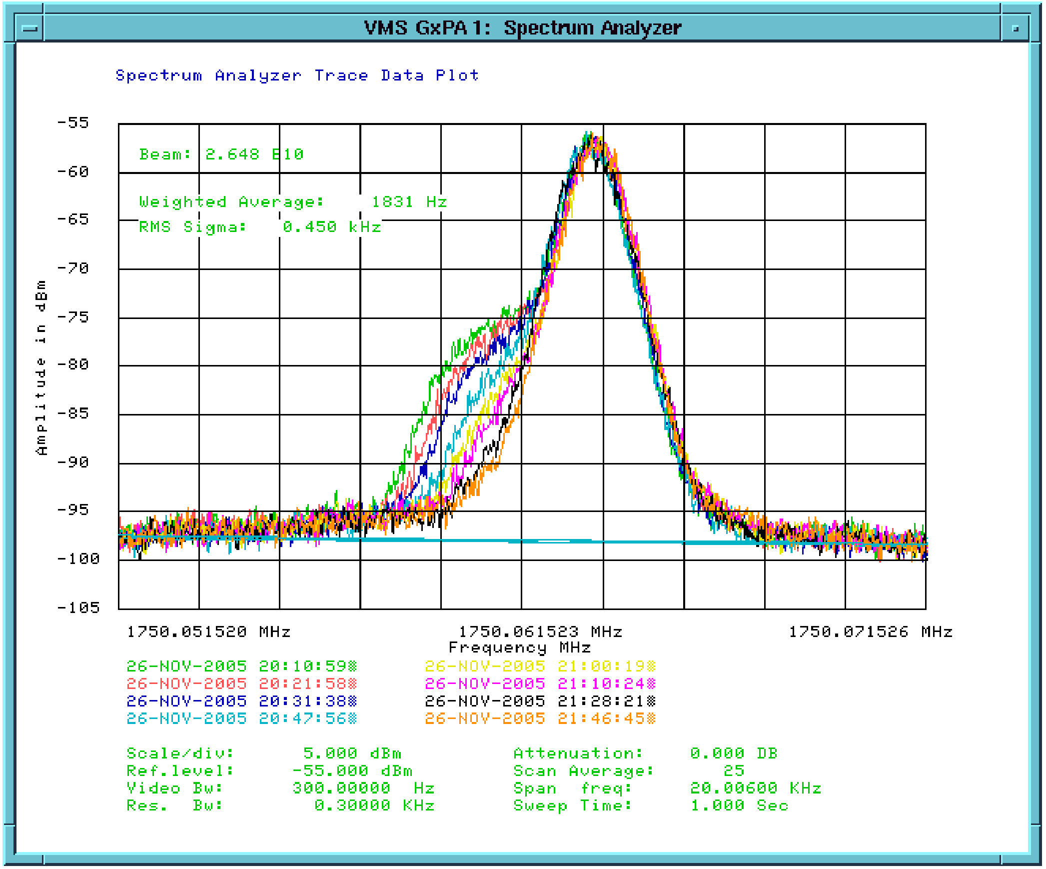


11/26/05 - continue



Summary

1. We have a lot of useful data.
2. Additional measurements are being done by FNAL group upon request.
3. Agreement between measured rate and models within factor of two – better description of electron beam parameters is needed for better agreement – work in progress at FNAL.
4. Due to a very slow process – it is possible to record distribution evolution under various conditions – data for several experiments was recorded – to be studied in simulations.
5. Simulation of exact behavior of distribution under drag is challenging – will be reported in the next talk.

Anatoly Sidorin's Presentation

Calculations and measurements of the friction force in nonmagnetized electron beam

A.Fedotov, A.Sidorin

BNL, 12/02/2005

General formulae for the friction force components

-Numerical integration

-Binney’s formulae

-Chandrasekhar’s (Budker’s) formula

- Results of benchmarking

Drag rate and cooling rate measurements:

- Peculiarity of Recycler cooling system
- Equilibrium with diffusion
- Voltage step method
- Simulation of heating effects
- Comparison of the simulation results with experiment

Friction force in the particle rest frame

Binary collision model

$$\vec{F} = -\frac{4\pi n_e e^4 Z^2}{m} \int \ln\left(\frac{\rho_{\max}}{\rho_{\min}}\right) \frac{\vec{V} - \vec{v}_e}{\left|\vec{V} - \vec{v}_e\right|^3} f(v_e) d^3 v_e$$

$$\rho_{\min} = \frac{Ze^2}{m_e} \frac{1}{\left|\vec{V} - \vec{v}_e\right|^2}$$

$$f(v_e) = \left(\frac{1}{2\pi}\right)^{3/2} \frac{1}{\Delta_\perp^2 \Delta_\parallel} \exp\left(-\frac{v_\perp^2}{2\Delta_\perp^2} - \frac{v_\parallel^2}{2\Delta_\parallel^2}\right)$$

$$F_\perp = -\sqrt{\frac{2}{\pi}} \frac{Z^2 e^4 n_e}{m \Delta_\perp^2 \Delta_\parallel} \int_0^\infty \int_{-\infty}^\infty \int_0^{2\pi} \ln\left(\frac{\rho_{\max}}{\rho_{\min}}\right) \frac{(V_\perp - v_\perp \cos\varphi) \exp\left(-\frac{v_\perp^2}{2\Delta_\perp^2} - \frac{v_\parallel^2}{2\Delta_\parallel^2}\right)}{\left((V_\parallel - v_\parallel)^2 + (V_\perp - v_\perp \cos\varphi)^2 + v_\perp^2 \sin^2\varphi\right)^{3/2}} v_\perp d\varphi dv_\parallel dv_\perp$$

$$F_\parallel = -\sqrt{\frac{2}{\pi}} \frac{Z^2 e^4 n_e}{m \Delta_\perp^2 \Delta_\parallel} \int_0^\infty \int_{-\infty}^\infty \int_0^{2\pi} \ln\left(\frac{\rho_{\max}}{\rho_{\min}}\right) \frac{(V_\parallel - v_\parallel) \exp\left(-\frac{v_\perp^2}{2\Delta_\perp^2} - \frac{v_\parallel^2}{2\Delta_\parallel^2}\right)}{\left((V_\parallel - v_\parallel)^2 + (V_\perp - v_\perp \cos\varphi)^2 + v_\perp^2 \sin^2\varphi\right)^{3/2}} v_\perp d\varphi dv_\parallel dv_\perp$$

$$\rho_{\min} = \frac{Ze^2}{m_e} \frac{1}{V_\perp^2 + V_\parallel^2 + \Delta_\perp^2 + \Delta_\parallel^2}$$

Binney's formulae

$$F_\perp = 2\sqrt{2\pi} \frac{n_e e^4 Z^2 L_C}{m} \frac{V_\perp}{\Delta_\perp^3} B_\perp$$

$$F_\parallel = 2\sqrt{2\pi} \frac{n_e e^4 Z^2 L_C}{m} \frac{V_\parallel}{\Delta_\perp^3} B_\parallel$$

$$B_\perp = \int_0^\infty \frac{\exp\left(-\frac{V_\perp^2}{2\Delta_\perp^2} \frac{1}{1+q} - \frac{V_\parallel^2}{2\Delta_\perp^2} \frac{1}{\left(\Delta_\parallel / \Delta_\perp\right)^2 + q} \right)}{(1+q)^2 \left(\left(\Delta_\parallel / \Delta_\perp\right)^2 + q \right)^{1/2}} dq$$

$$B_\parallel = \int_0^\infty \frac{\exp\left(-\frac{V_\perp^2}{2\Delta_\perp^2} \frac{1}{1+q} - \frac{V_\parallel^2}{2\Delta_\perp^2} \frac{1}{\left(\Delta_\parallel / \Delta_\perp\right)^2 + q} \right)}{(1+q) \left(\left(\Delta_\parallel / \Delta_\perp\right)^2 + q \right)^{3/2}} dq$$

Uniform Maxwellian distribution

$$\Delta_{\parallel} = \Delta_{\perp} = \Delta_e$$

Chandrasekhar's (Budker's) formula

$$\vec{F} = -\frac{\vec{V}}{V^3}\frac{4\pi n_e e^4 Z^2 L_C}{m}\varphi\left(\frac{V}{\Delta_e}\right)$$

$$\varphi(x) = \sqrt{\frac{2}{\pi}}\int_0^x e^{-y^2/2}dy - \sqrt{\frac{2}{\pi}}xe^{-x^2/2}$$

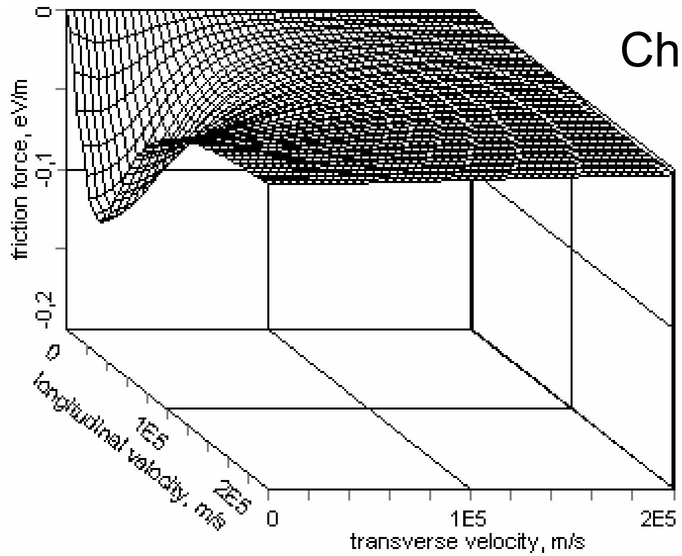
For fast estimation one can use asymptotic formulae

Uniform distribution

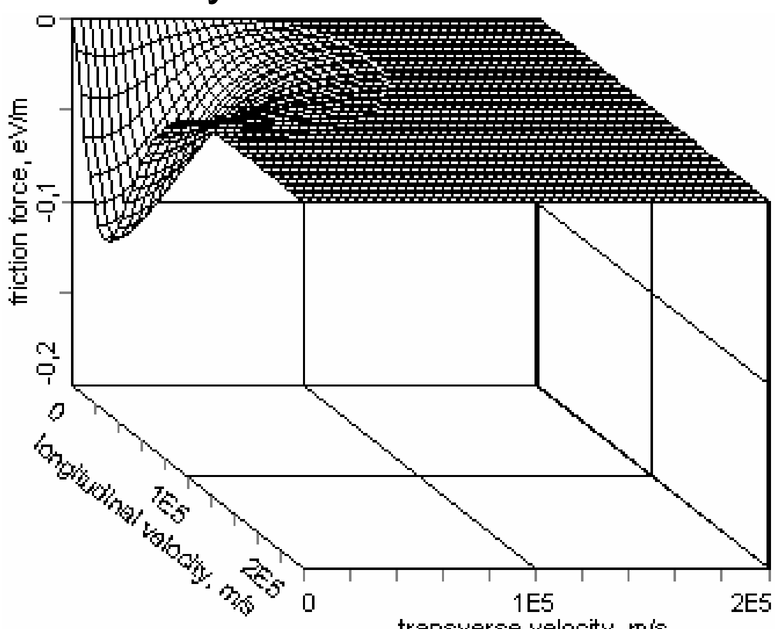
Recycler cooling system

Electron velocity spread 20000 m/s

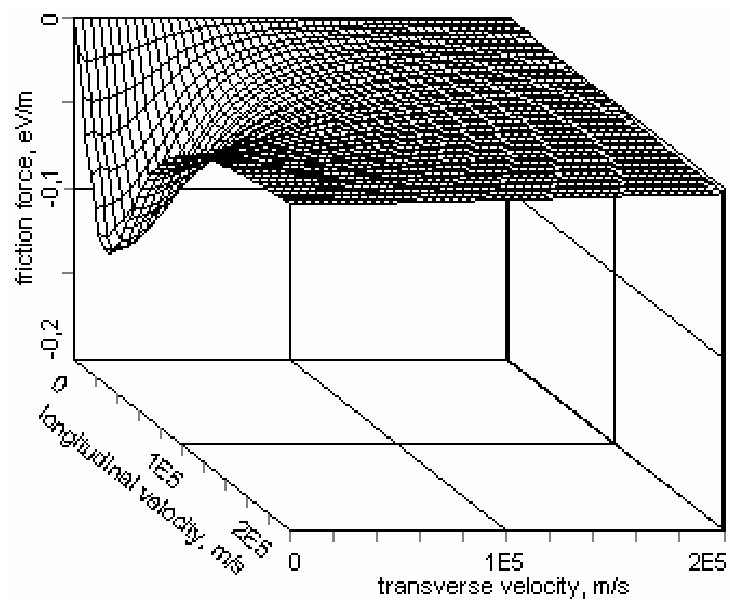
Chandrasekhar



Binney



Numerical

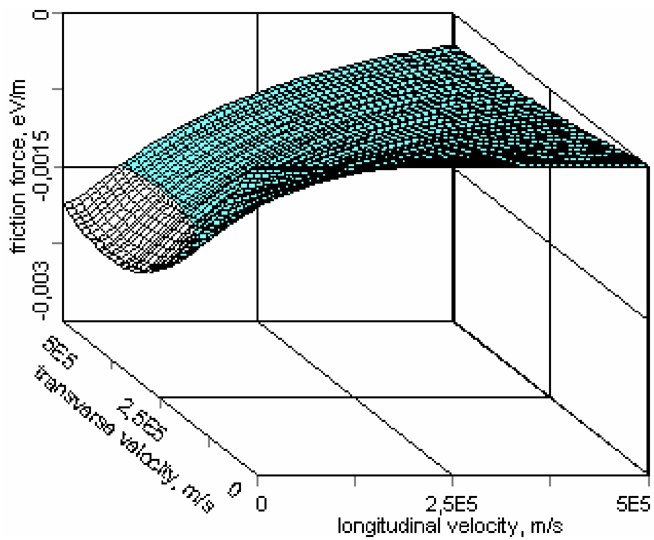


Recycler

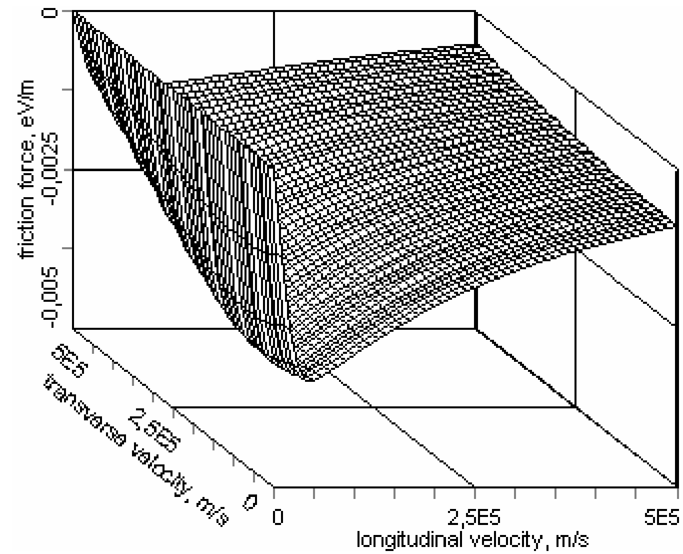
$\Delta_{\parallel}$ = 20000 m/s $\Delta_{\perp}$ = 300000 m/s

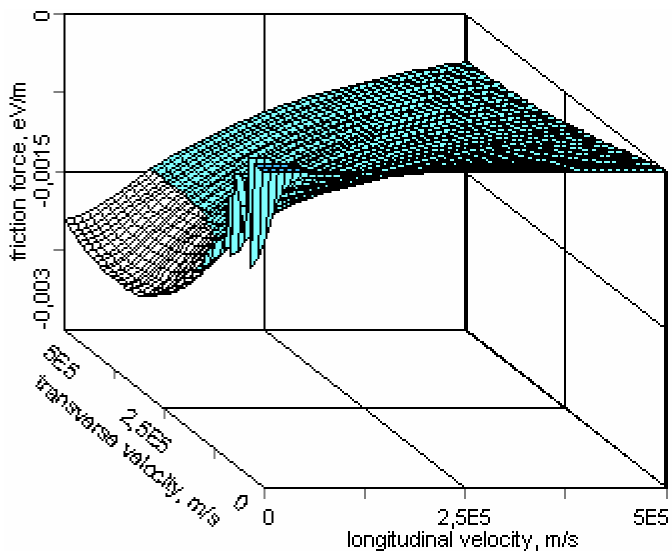
Transverse

Longitudinal

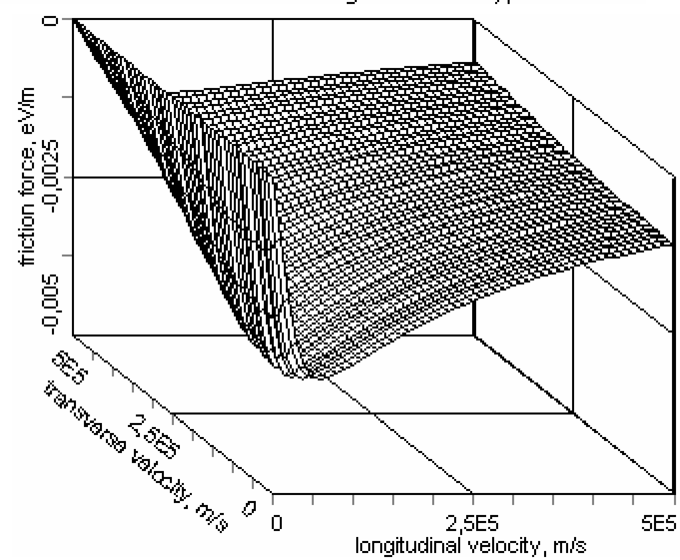


Binney





Numerical



Recycler cooling system

Cooler length 20 m, magnetic field 105 G, beam radius 4.5 mm, current 200 mA

Larmor radius $3 \cdot 10^{-4}$ m > maximum impact parameter $7 \cdot 10^{-5}$ m

Electron energy spread 300 eV -> velocity spread 20000 m/sec

Component	Upper limit, μrad	Present estimation, μrad	Diagnostics	Comments
Temperature	90	60	Calculated	Plan to estimate with OTR
Aberrations	90	50	Simulated	Plan to estimate with OTRs and BPMs
Envelope scalloping	100	200	Movable orifices (scrapers)	For the 0.2 A beam boundary at 10^{-5} level of losses
Dipole motion caused by magnetic field imperfections	100	50	Magnetic measurements + BPMs	In the first 8 modules (i.e. over 16 m)
Beam motion	50	40	BPMs	With a slow feedback
Drift velocity	20	10 < 30	Calculated Movable orifices	For I =0.2 A
Total	200*			

COOL'05

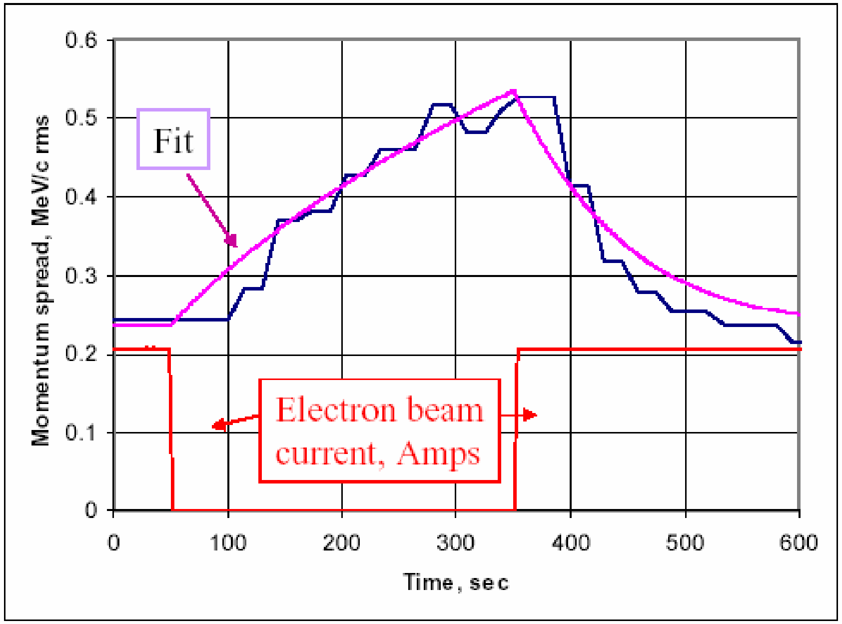
Shemyakin

Thermal velocity spread $3 \cdot 10^{5}$ m/sec

Total estimated spread $6 \cdot 10^{5}$ m/sec

Friction force is investigated al low p-bar intensity $2 \div 6 \cdot 10^{10}$

Equilibrium with diffusion



$$\frac{d\sigma_p^2}{dt} = -2\lambda\sigma_p^2 + D$$

Cooling off

$$\sigma_p(t) = \sqrt{\sigma_{p,0}^2 + Dt}$$

D = 4.8 MeV^2/h

$$\lambda = \frac{D}{2\sigma_{p,eq}^2} \approx 22\,h^{-1}$$

Cooling on

$$\sigma_p(t) = \sqrt{\left(\sigma_{p,0}^2 - \sigma_{p,eq}^2\right)\exp(-2\lambda t) + \sigma_{p,eq}^2}$$

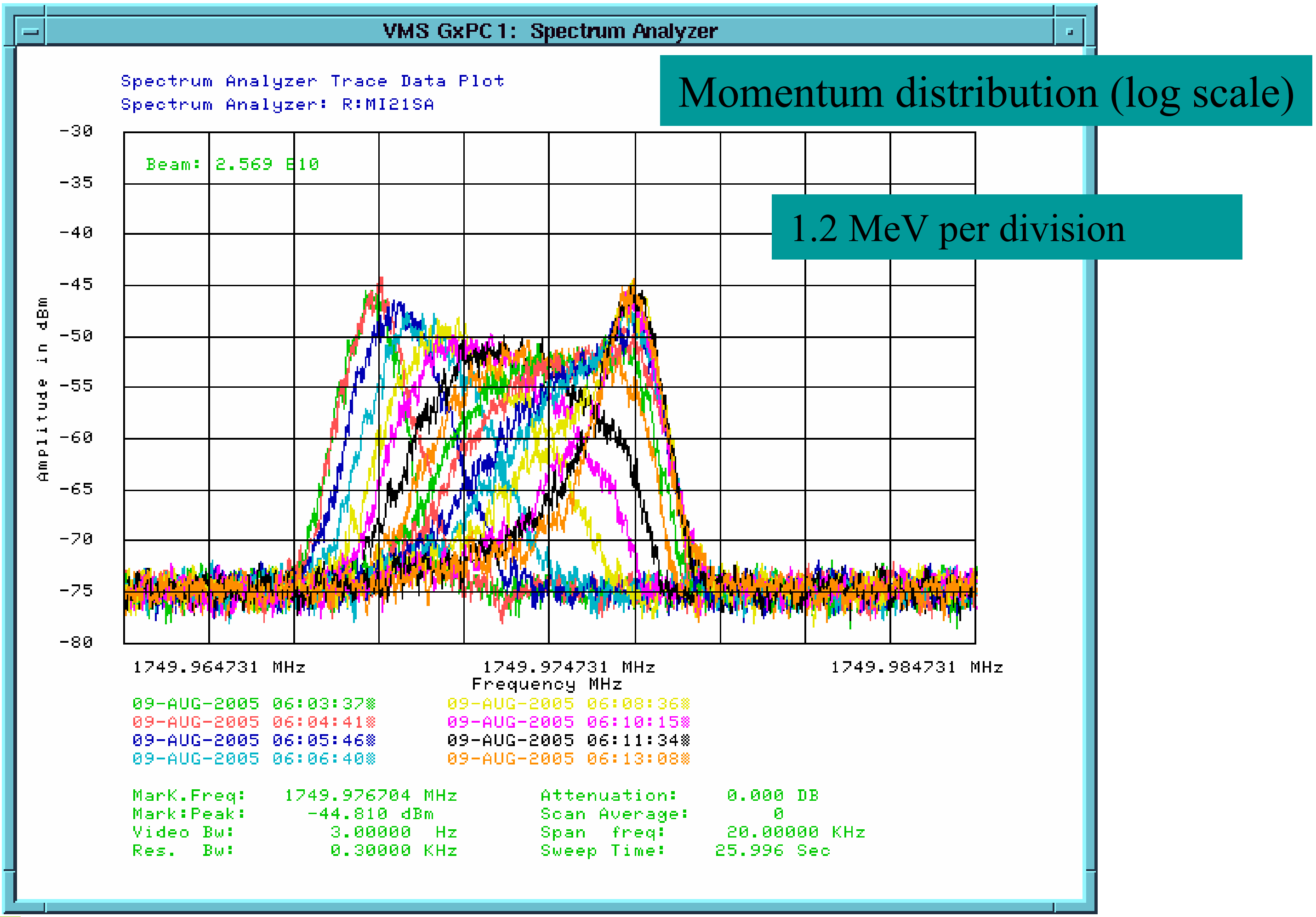
COOL'05

Nagaitsev

$$\lambda \approx 25\,h^{-1} = 0.007\,s^{-1}$$

BETACOOL estimation using Binney's formula at $4{\cdot}10^5$ m/sec transverse electron velocity spread gives 0.0073 s^{-1}

Drag force measurements: electron energy jump by +2 keV

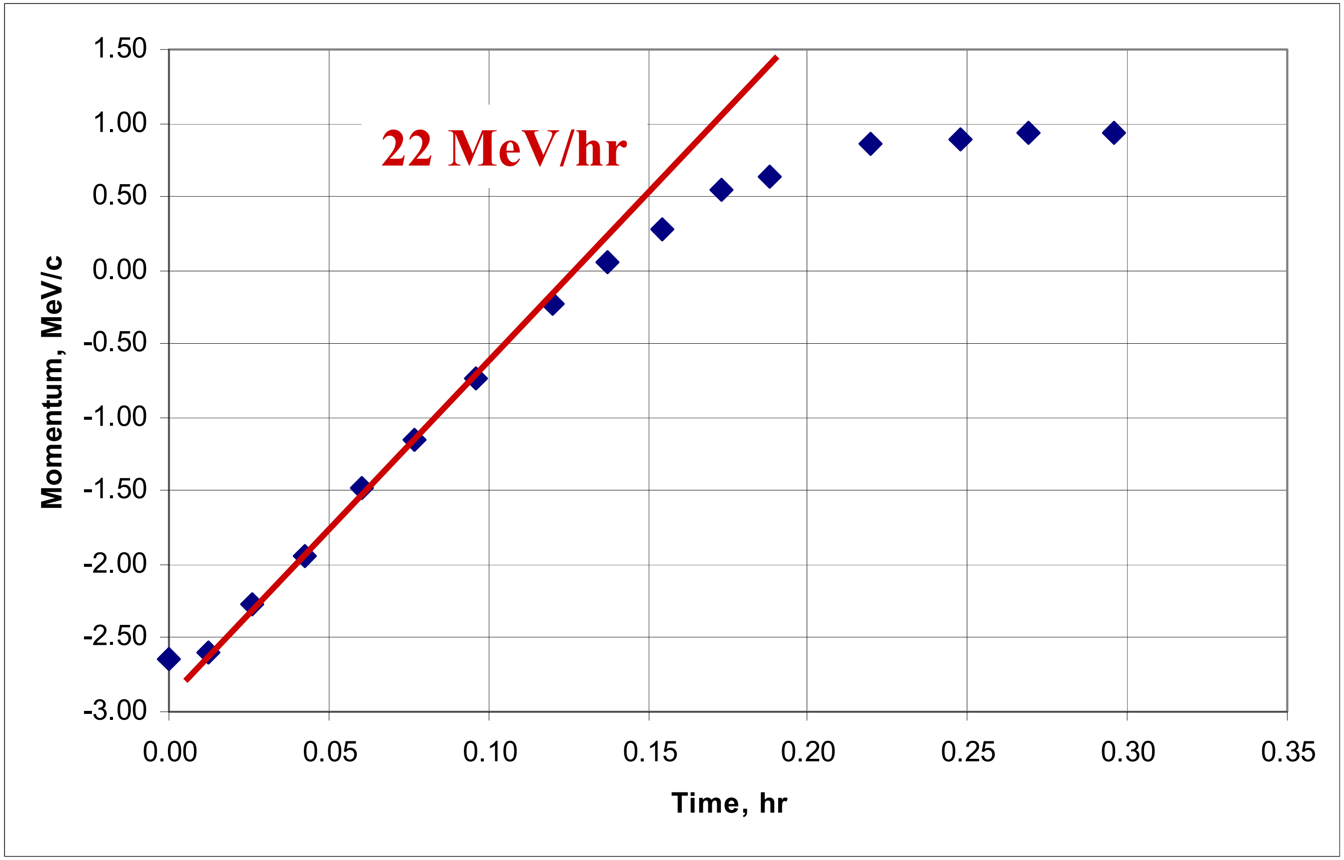


COOL’05

Nagaitsev

Beam emittance was measured by Schottky: 1.5 μm (n, 95%).
In the cooling section this corresponds to a 0.9 mm radius (rms), electron current 200 mA

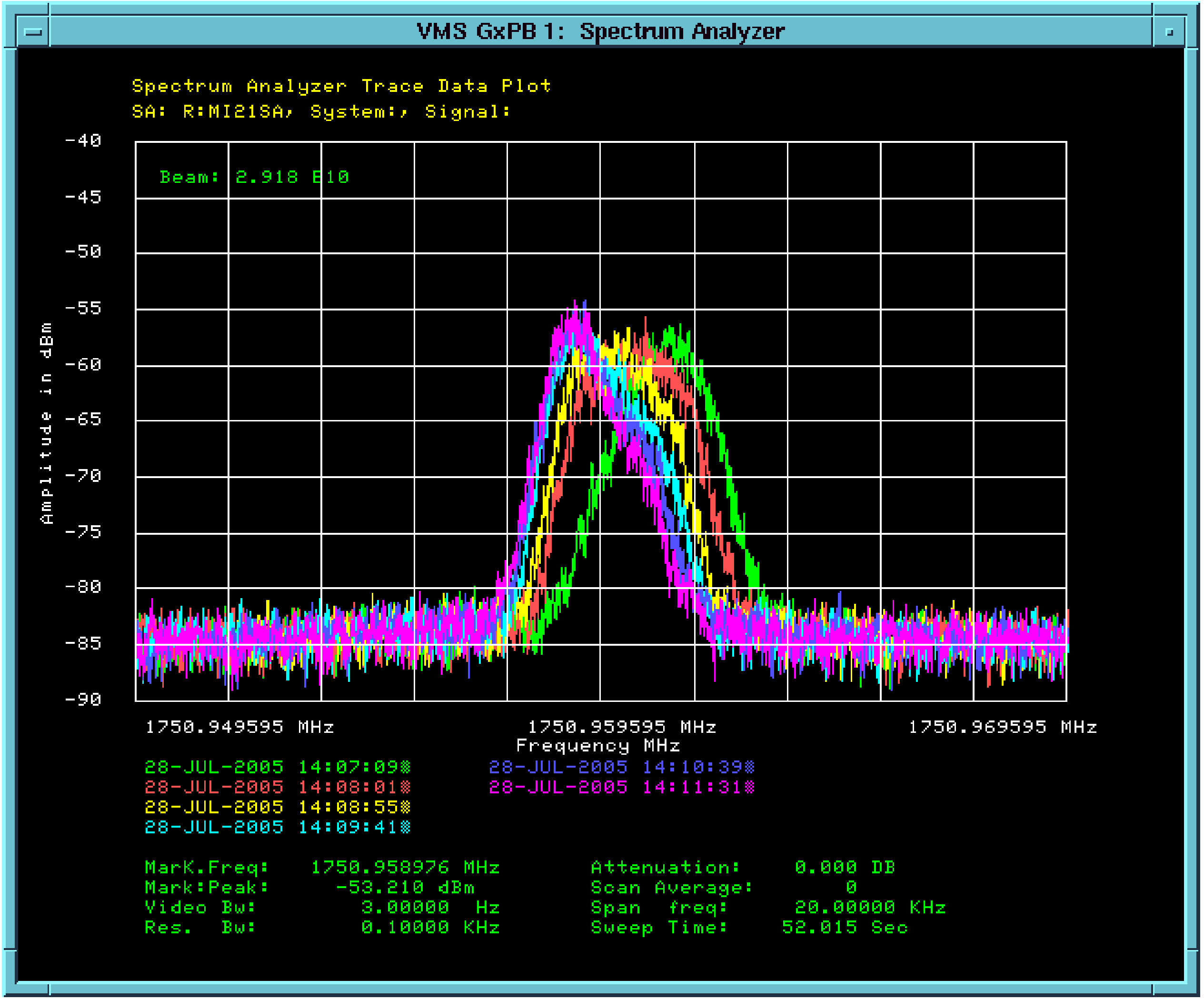
Drag force – voltage jump +2 kV

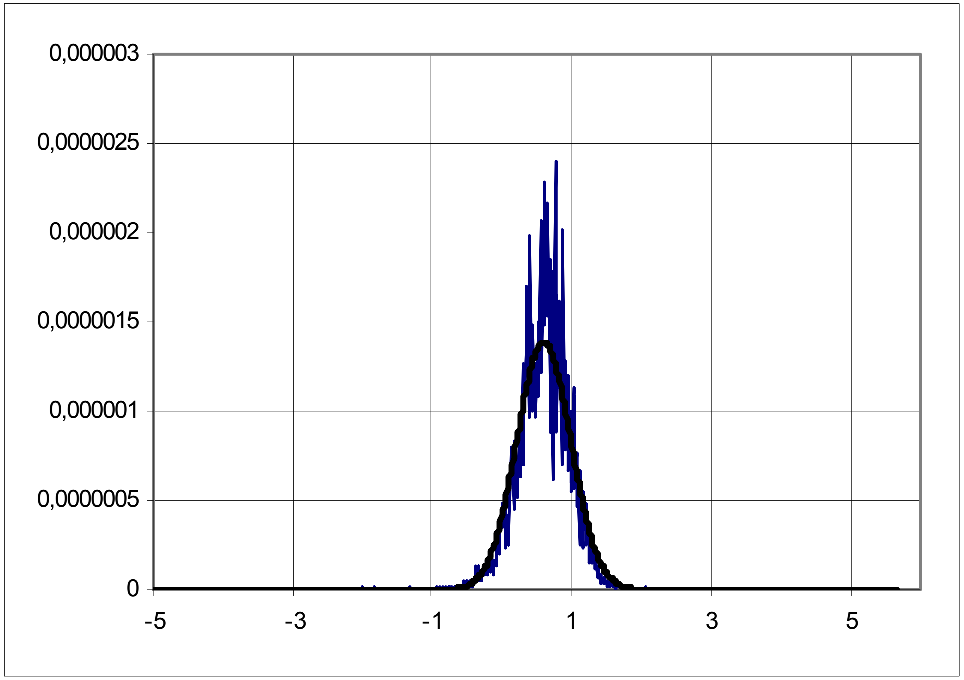


Voltage step 1 keV

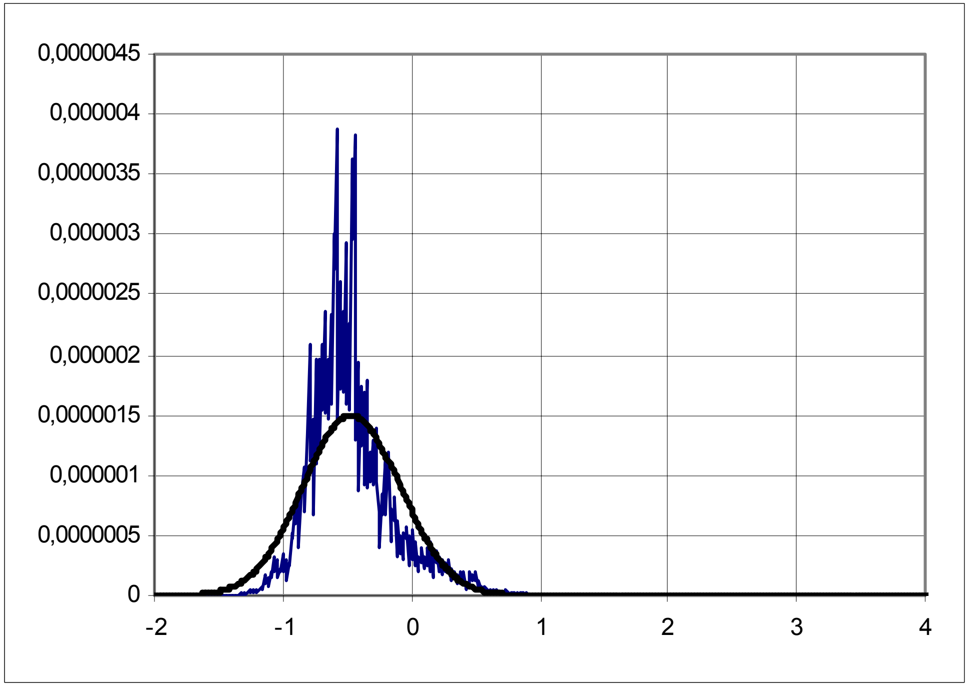
FNAL

Nagaitsev





First trace



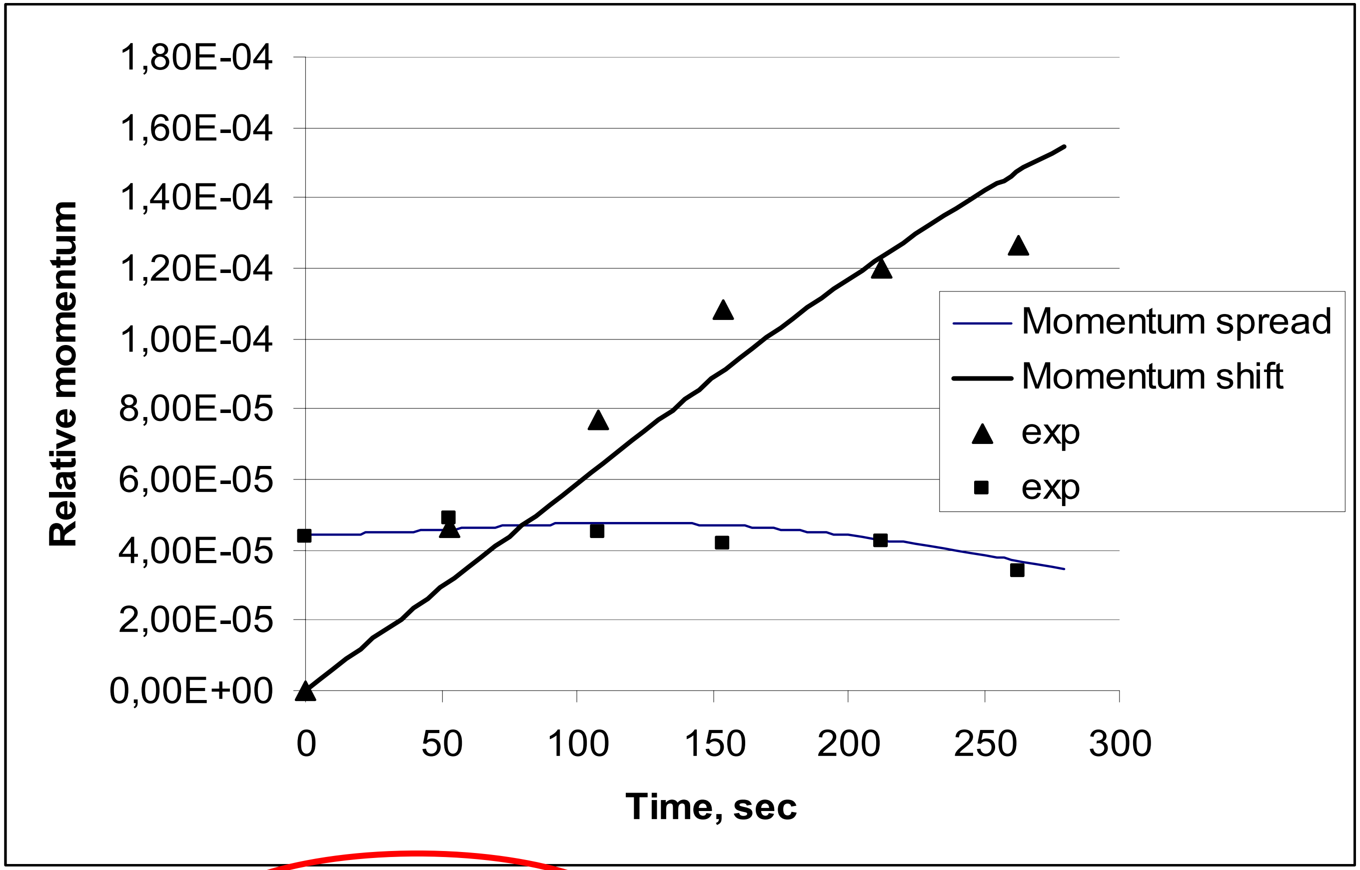
Fifth trace

FNAL

Nagaitsev

Simulation in BETACOOL

1. Transverse heating is simulated in accordance with measured rate due to interaction with residual gas
2. Longitudinal heating in accordance with measured diffusion power
3. Transverse electron spread is used as a fitting parameter



$\Delta_{\perp} = 3 \cdot 10^5$ m/sec, $\Delta_{||} = 2 \cdot 10^4$ m/sec

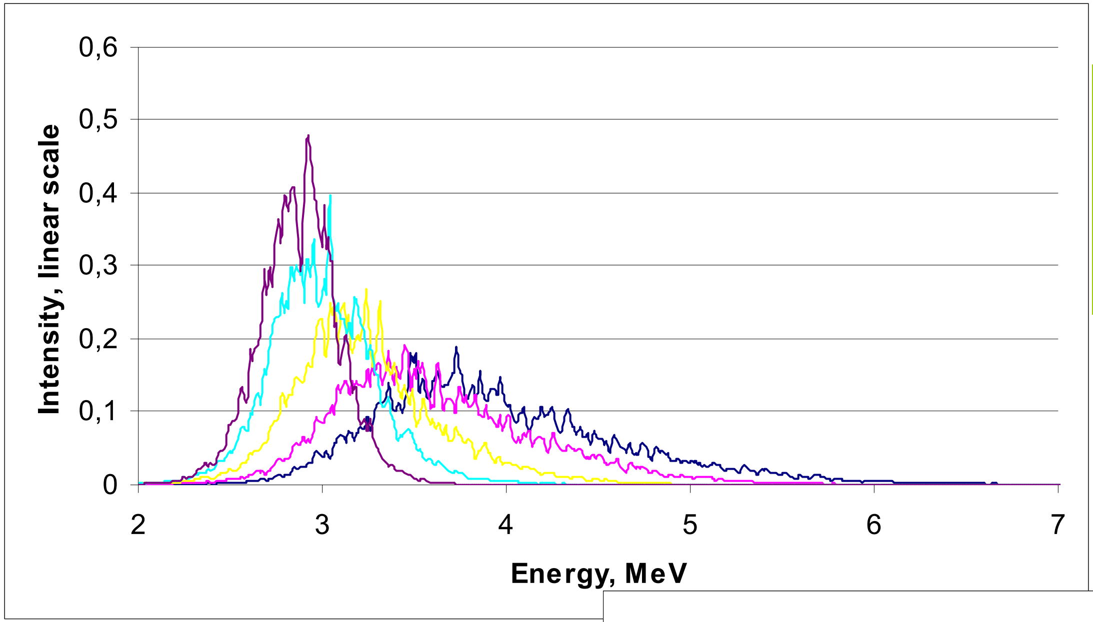
At these parameters $\lambda = 0.0085$ sec^{-1} (experimental value 0.007 sec^{-1})

Comparison of Recycler experiments and simulation:
- Results of numerical simulation of non-magnetized friction force are in good agreement with experiments,
- Friction force value depends significantly on electron beam quality.

Future plans for experiments:
- provide the measurements of the cooling rate and drag rate at the same conditions,
- investigate dependence of electron angular spread on radial coordinate

Simulations in BETACOOL
- Algorithm for envelope scalloping simulation was introduced,
- Investigation of the evolution of antiproton distribution function

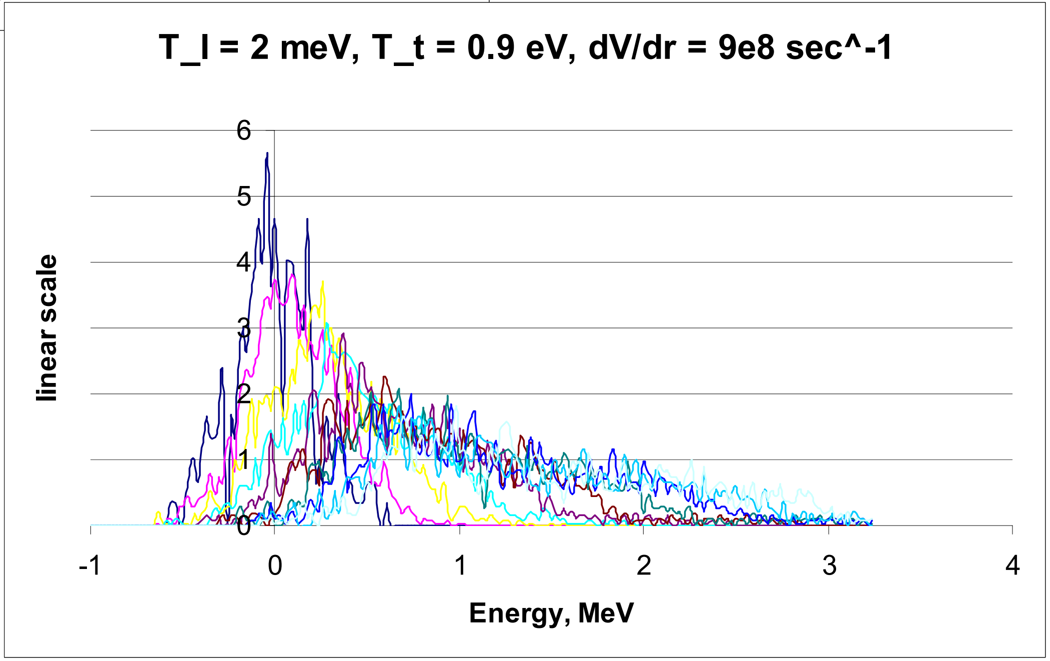
500 mA, 2 keV HV step



FNAL

Measurement

L. Prost



BETACOOL

simulation