Electron cooling for RHIC-II

(non-magnetized approach)

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Outline

1. Goal of RHIC-II cooling and non-magnetized approach
2. Experimental benchmarking of IBS
3. Friction force theory and benchmarking between models

   (BNL in collaboration with Tech-X (Colorado) and Dubna (Russia))
4. Experimental benchmarking

   (BNL in collaboration with FNAL and Dubna (Russia))
5. Recombination and cooling
6. Parameters and cooler performance

Acknowledgements

We thank Collider-Accelerator Department and Accelerator Physics group of RHIC for constant help and support.

We are grateful for FNAL team for providing beam time and experimental measurements for the non-magnetized cooling studies.

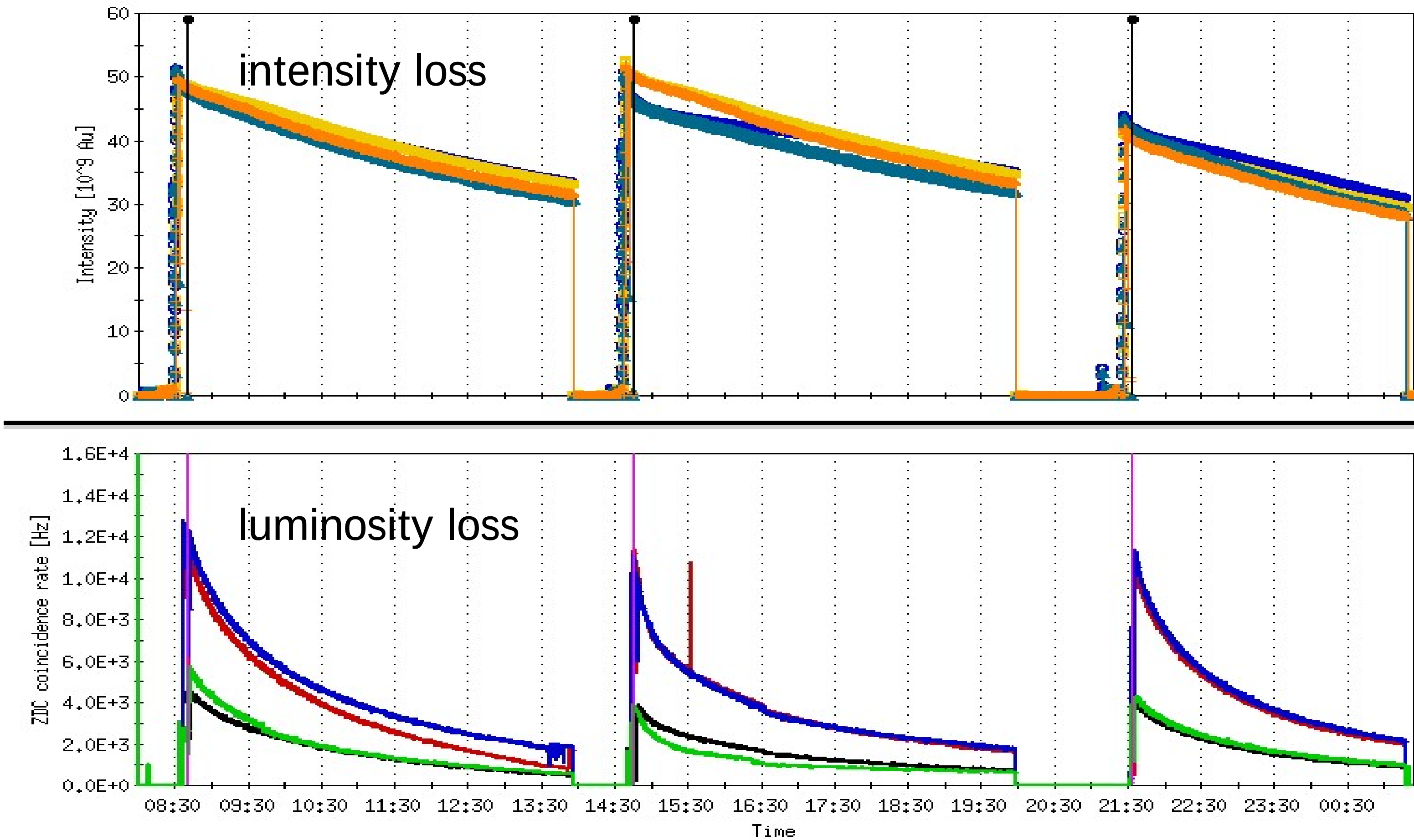
Simulation studies are done together with the Dubna group (using BETACOOL code) and Tech-X group (using VORPAL code).

Collaboration on e-cooling with:

BINP, FNAL, JLAB, GSI, Svedberg Lab, Dubna, Tech-X Inc.

Work supported by the US Department of Energy.

RHIC performance for Au ions – 2004 run



1. Goals for RHIC-II

Present performance of the RHIC collider with heavy ions is limited by the process of Intra-Beam Scattering (IBS) within the ion beam.

To achieve required luminosities for the future upgrade of the RHIC complex (known as RHIC-II) an Electron Cooling system is proposed.

- **The baseline of the heavy-ion program for RHIC is operation with Au ions at total energy per beam of 100 GeV/n. For such an operation, the electron cooling should compensate emittance growth due to IBS.**
- **For RHIC operation with the protons, the electron cooling should assist in obtaining slightly low transverse and longitudinal emittances.**

2. Intra-beam scattering (IBS) in RHIC

Since, the main reason for electron cooling is to compensate emittance growth due to IBS, it was necessary to make sure that the models which we are using in simulations agree with the measurements.

In addition to previous measurements of IBS growth rates in RHIC (W. Fischer et al., EPAC02) dedicated studies of IBS were done:

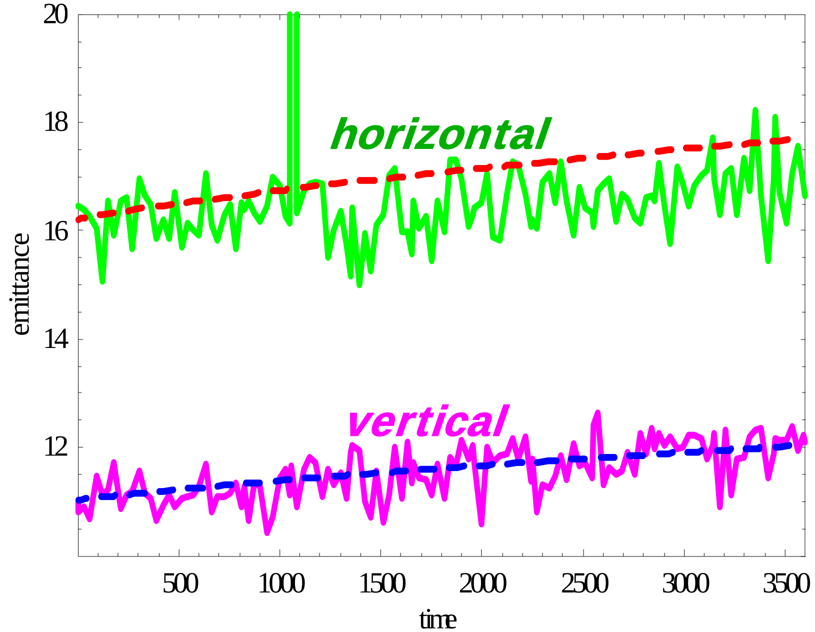
1. with Au ions in 2004.

2. with Cu ions in 2005.

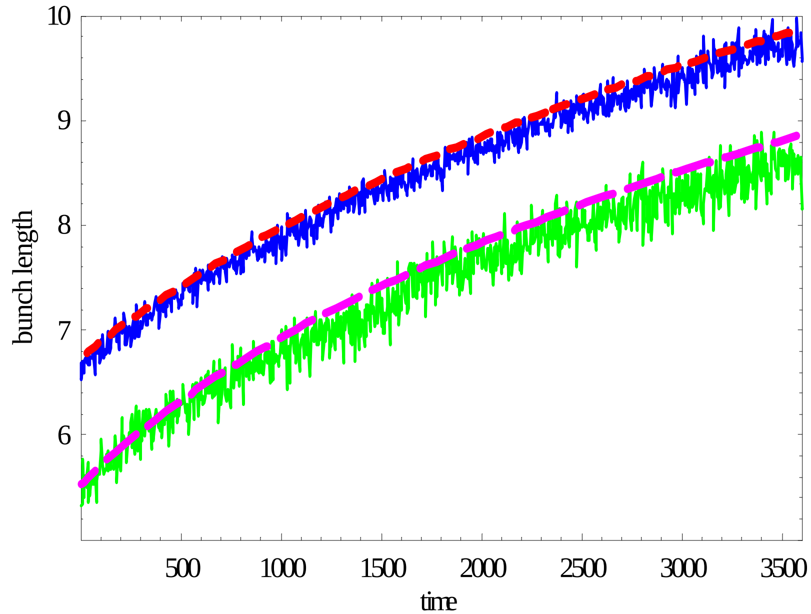
Also, several theoretical models of IBS were implemented and benchmarked within the BETACOOL code.

IBS in RHIC – measurements vs theory
Example of 2005 data with Cu ions.

Simulations – Martini's model of IBS for exact designed lattice of RHIC, including derivatives of the lattice functions.



Growth of 95% normalized emittance [μm] for bunch with intensity N=2.9·10^9



FWHM [ns] bunch length growth for intensities N=2.9·10^9 and 1.4·10^9

IBS in RHIC summary

1. Measurements with Au ions in 2004 gave very good agreement with IBS theory for the longitudinal growth rates but some disagreement for the transverse growth rate.
2. Our subsequent studies led to the conclusion that the disagreement observed is most likely due to the uncertainties in the 2004 measurements.
3. Measurements were improved for the 2005 studies.
4. The latest 2005 data for the Cu ions showed very good agreement with the IBS theory both for the longitudinal and transverse growth rates.

Non-magnetized cooling approach for RHIC

Difference of electron cooling for RHIC and other projects – different goals.

1. **Typical goal in a low-energy cooler – is to achieve very low emittances and momentum spread. This can be done with Magnetized cooling – since transverse temperature of electrons is suppressed, it allows to cool to very low temperatures determined by longitudinal velocity spread of electron beam.**
2. **For RHIC (as FNAL) the goal is mainly to prevent emittance and momentum spread from growing – no need to cool it by orders of magnitude.**

3. Non-magnetized friction force

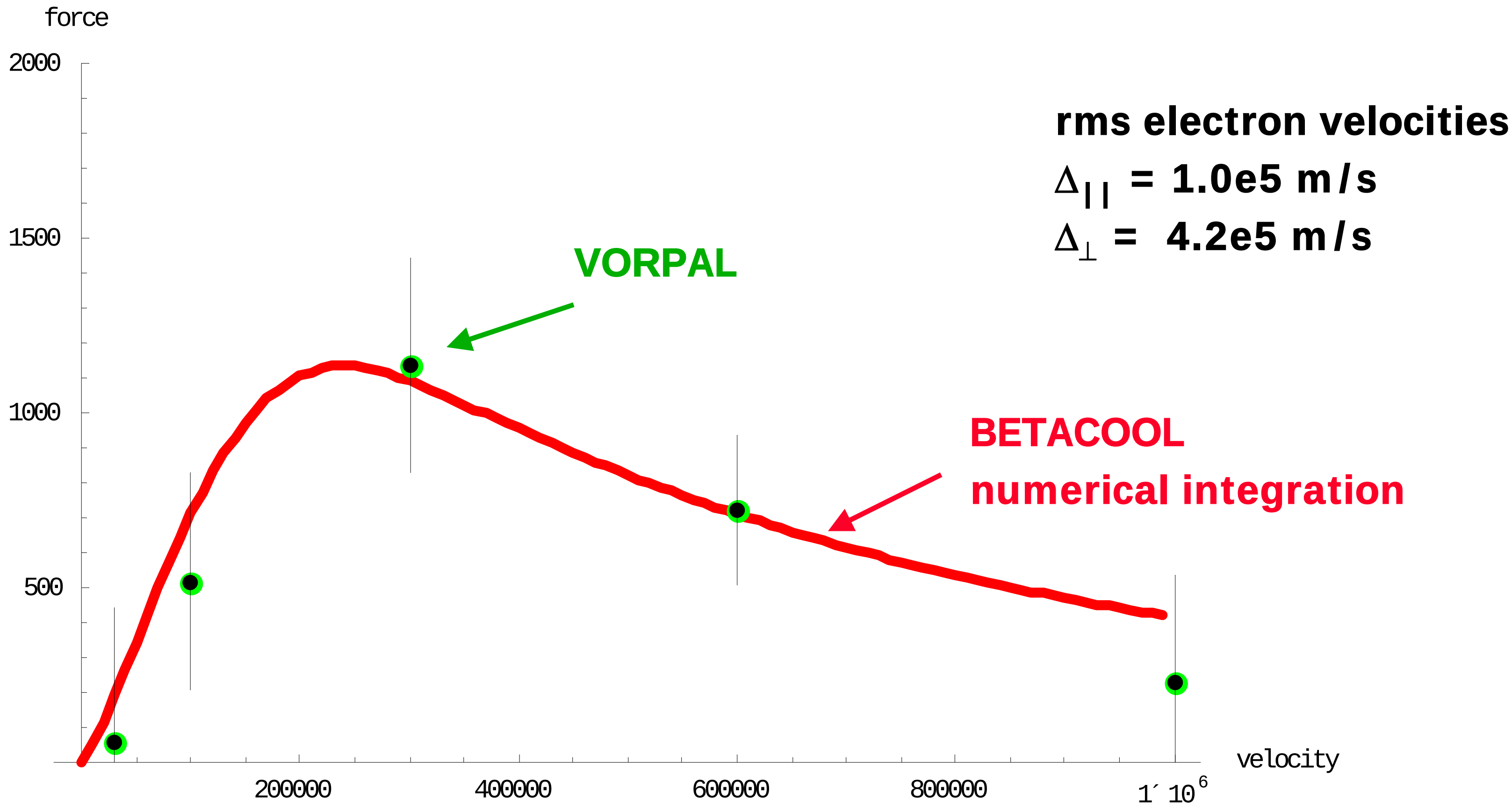
$$\vec{F} = -\frac{4\pi n_e e^4 Z^2}{m} \int L \frac{\vec{V}_i - \vec{v}_e}{\left|\vec{V}_i - \vec{v}_e\right|^3} f(v_e) d^3 v_e$$

For finite anisotropy of electron distribution we calculate friction force numerically in BETACOOL rather than using asymptotic analytic expressions.

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

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

Zero magnetic field B=0, anisotropic velocity distribution of electrons in PRF (error bars: 3*sigma)



Non-magnetized cooling and recombination

One potential problem of Non-Magnetized approach is recombination because now we have very small electron transverse temperatures of the order of

0.5-1 eV.

$$\alpha_{recu} := 3.02 \cdot 10^{-19} \frac{m^3}{s} \cdot \frac{Z^2}{\sqrt{T_{eff}}} \cdot \left[\ln\left(\frac{11.32 \cdot Z}{\sqrt{T_{eff}}}\right) + 0.14 \cdot \left(\frac{T_{eff}}{Z^2}\right)^{\frac{1}{3}} \right]$$

This can be controlled by helical undulator which introduces coherent azimuthal angle:

$$\theta = \frac{eB\lambda}{2\pi pc}$$

which can produce required T_{eff} to suppress recombination

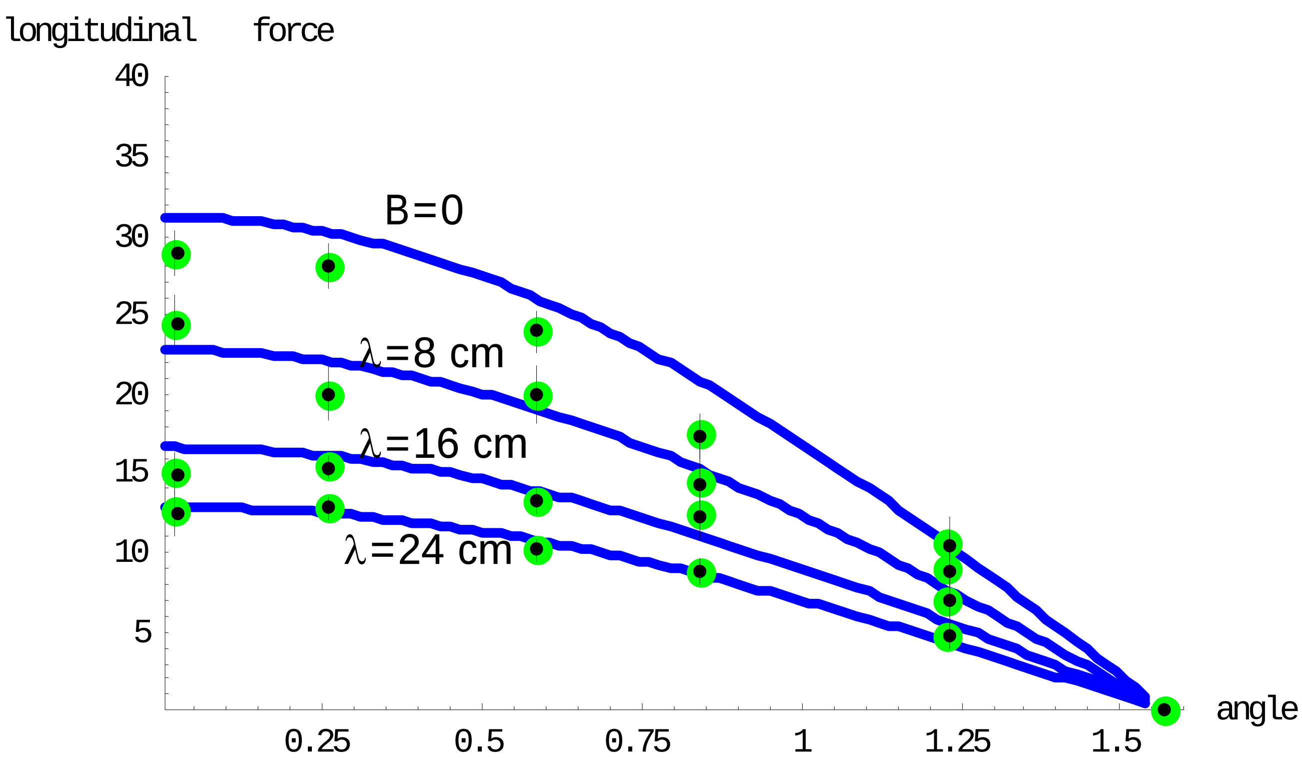
However, this may lead to some reduction in the cooling force by a factor

$$\ln\frac{\rho_{max}}{\rho_{min}} / \ln\frac{\rho_{max}}{r_0}$$

where

$$r_0 = \frac{\theta\lambda}{2\pi}$$

Longitudinal force component at ion velocity of 3e5 m/s - without and with the wiggler (B=10G, λ=8, 16, 24 cm). Curves – numeric evaluation of 3D integrals for the friction force, dots – VORPAL results (Tech-X, Colorado))



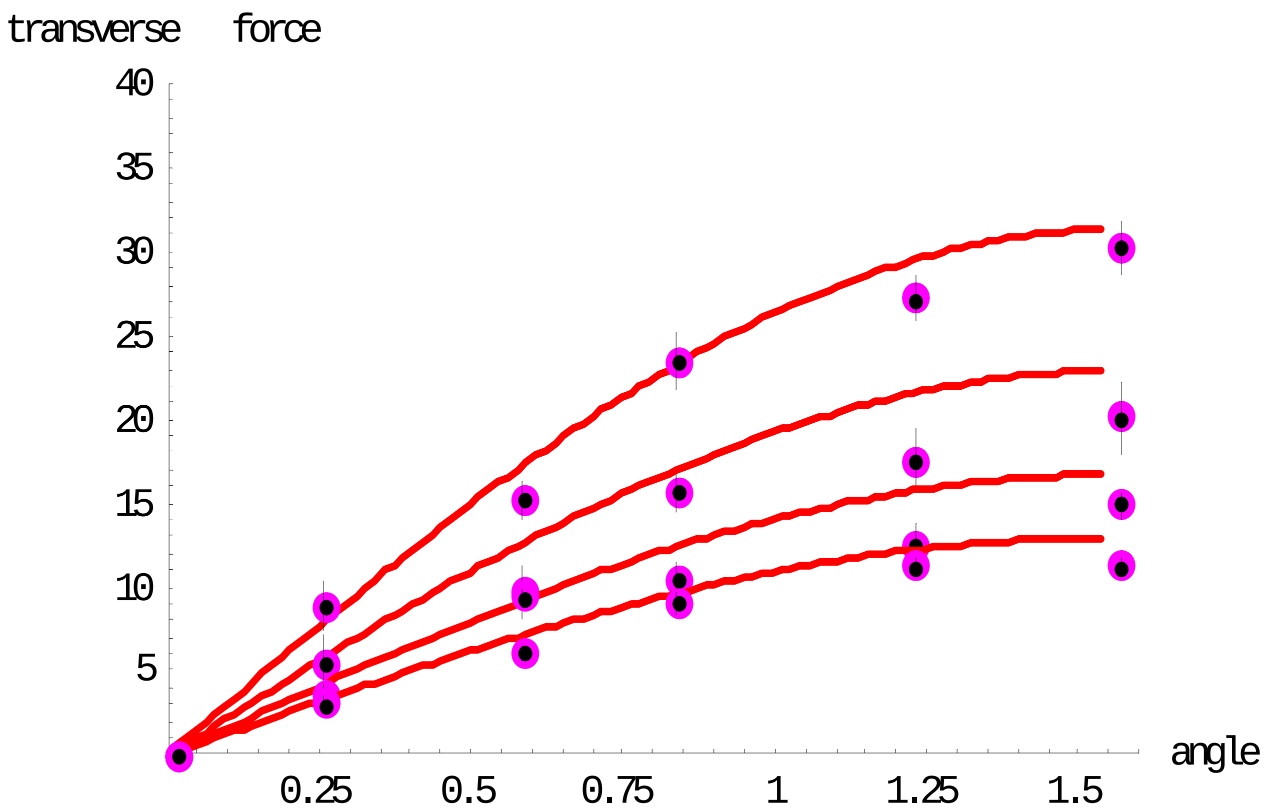
reduction in the force values as expected based on the Logarithm

Wiggler parameters:

B=10 G

λ=8, 16, 24 cm

Transverse force component at ion velocity of 3e5 m/s - without and with the wiggler (B=10G, λ=8, 16, 24 cm). Curves – numeric evaluation of 3D integrals for the friction force, dots – VORPAL results (Tech-X, Colorado))



Non-magnetized force - summary

For anisotropic velocity distribution:

1. Accurate numerical integration for the friction force was implemented in BETACOOL.
2. VORPAL results are in good agreement (10%) with numerical integrals.
3. Reduction in the friction force values due to wiggler field (VORPAL) was found as expected based on reduced values of the Coulomb Logarithm.

Remaining part

- study effect of errors – will be presented by Tech-X Group.

4. Experimental benchmarking: using Recycler (FNAL) E-cooling

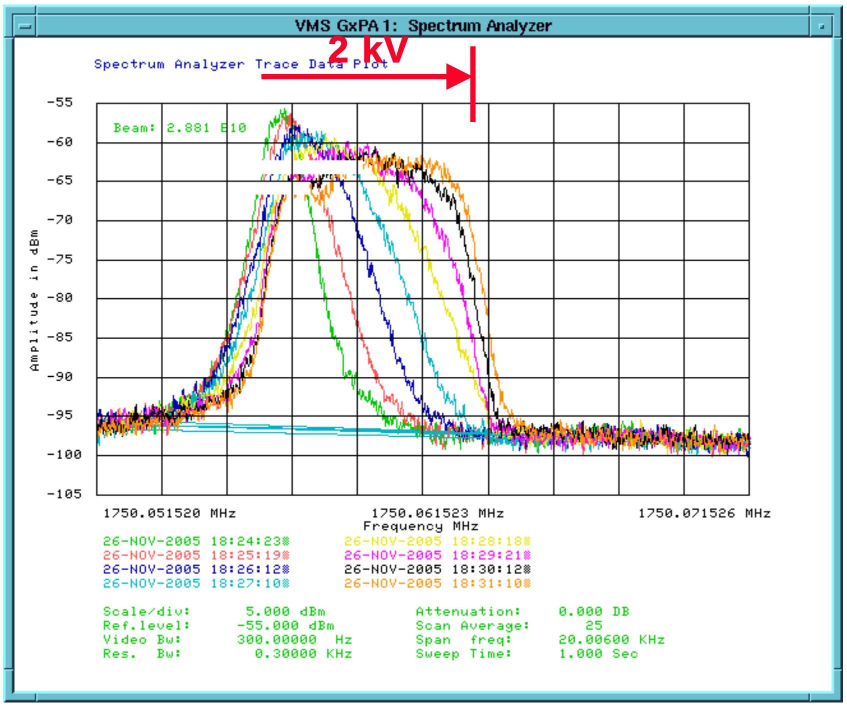
First Non-magnetized cooling was successfully demonstrated:

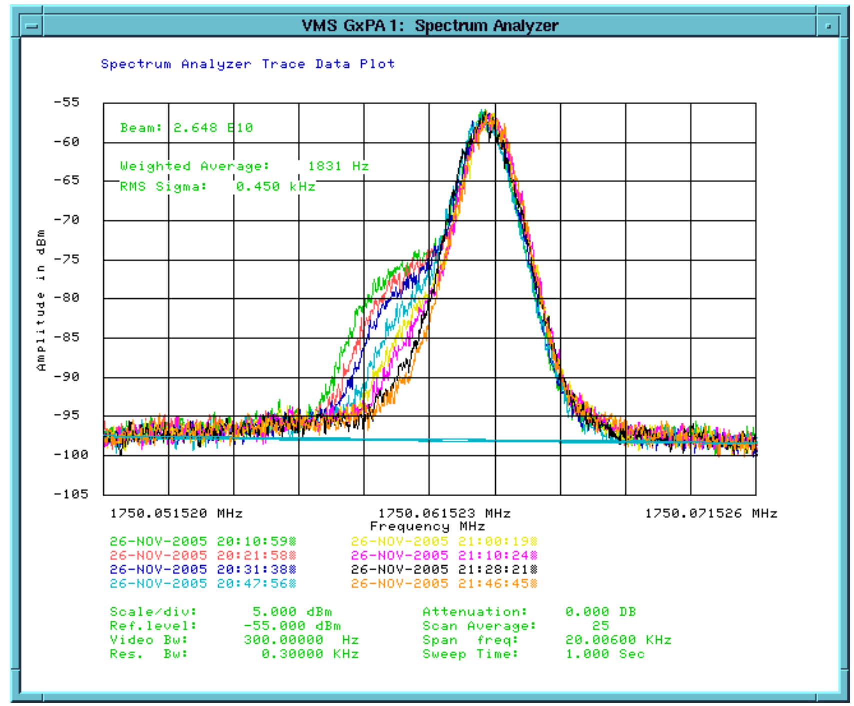
FNAL – July 2005.

FNAL e-cooling :

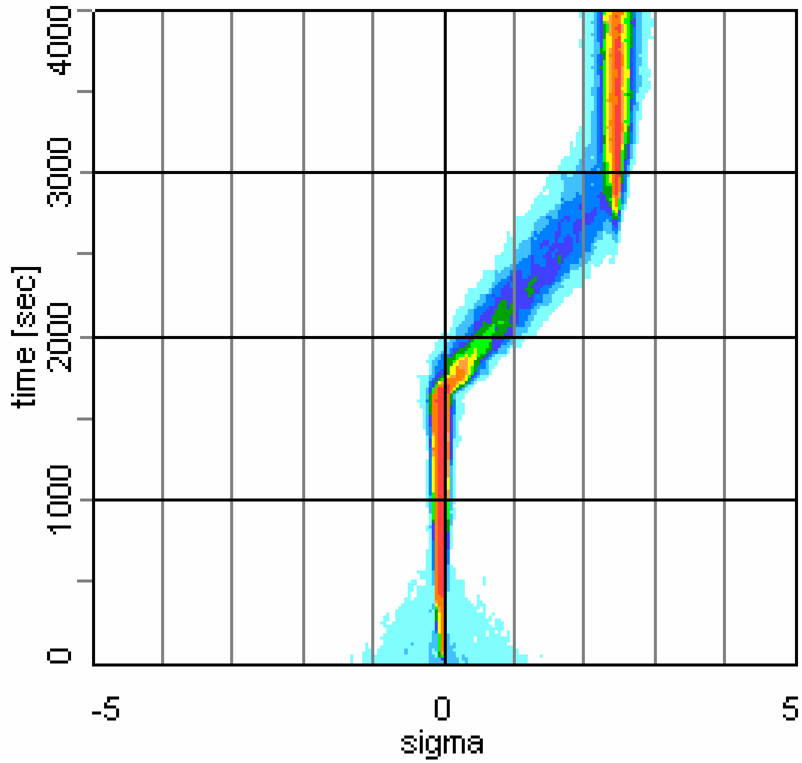
1. **Allows to benchmark accuracy of the models for the friction force**
2. **Allows to study evolution of ion distribution under cooling or during drag rate measurements – requires accurate description of both cooling and diffusion in modeling**
3. **Allows to study effects of electron cooling together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

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

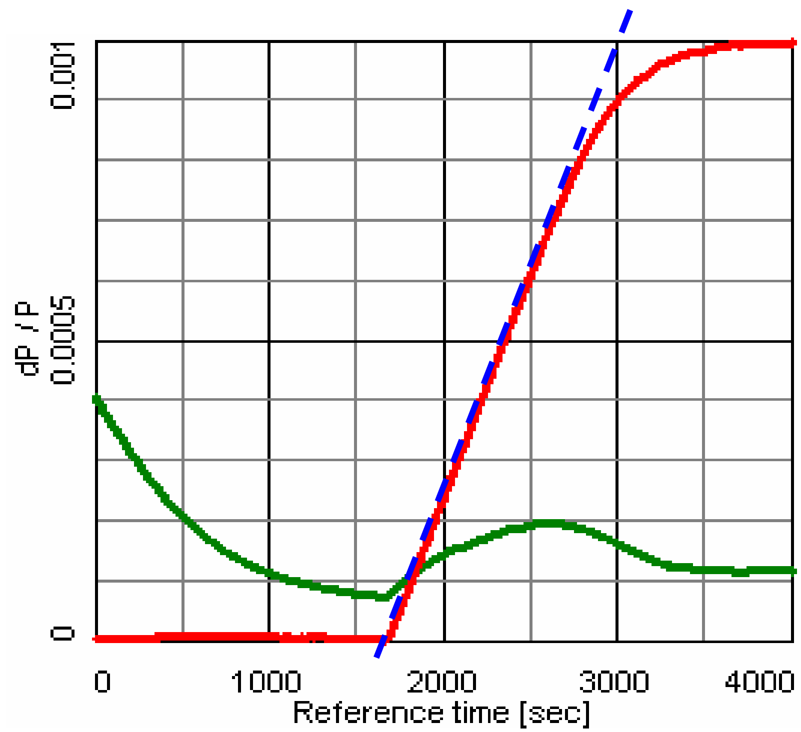




Simulation of the voltage jump method within the BETACOOL

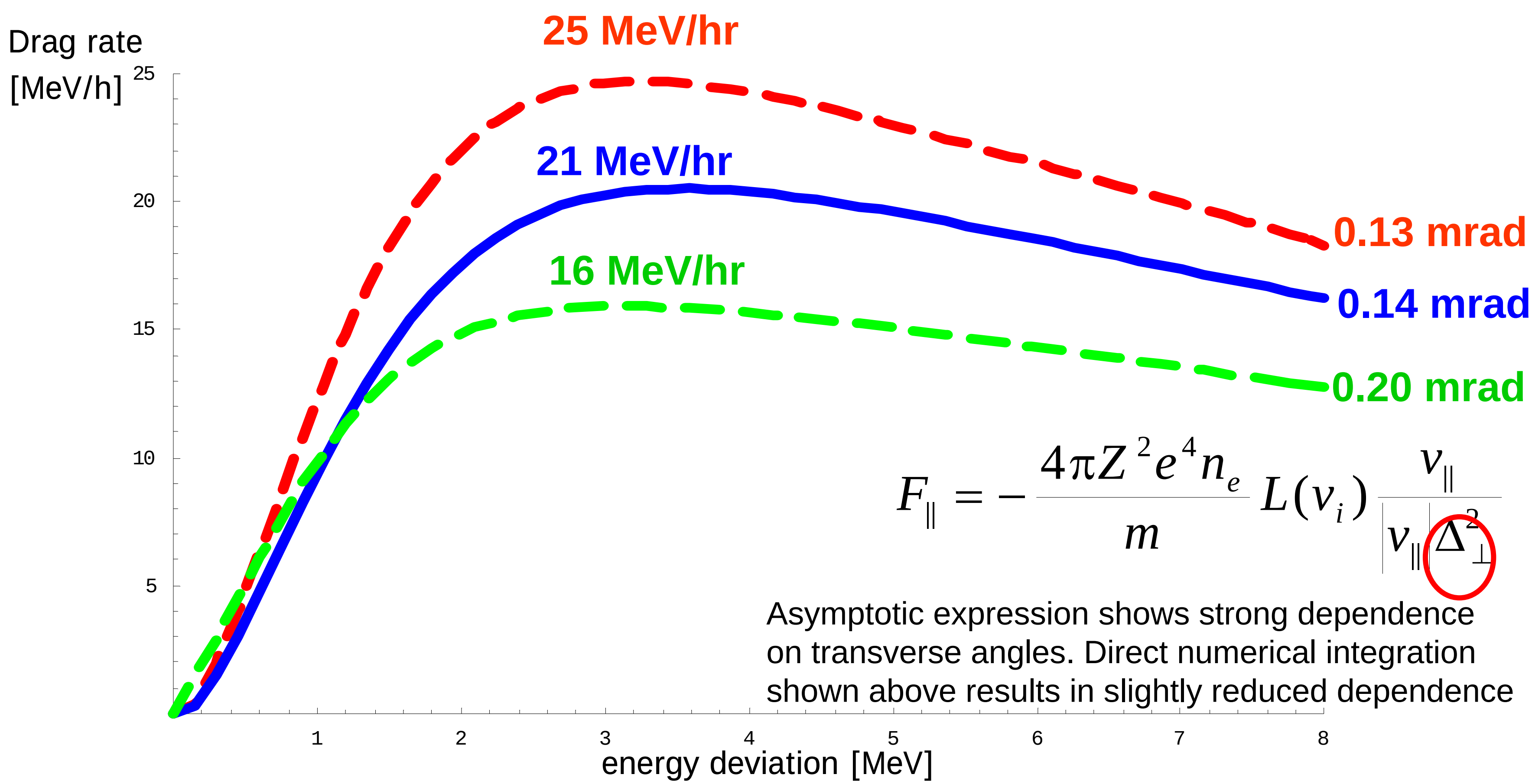


Rms momentum spread in time



Rms momentum spread and momentum deviation in time

BETACOOL- using numerical friction force – dependence on transverse angles (velocities) of electrons



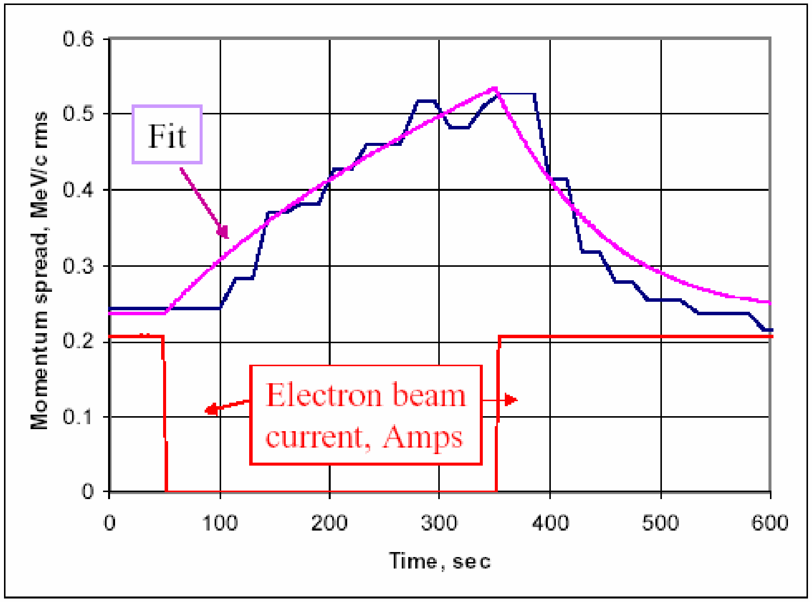
$$F_{\parallel} = -\frac{4\pi Z^2 e^4 n_e}{m} L(v_i) \frac{v_{\parallel}}{|v_{\parallel}|\Delta_{\perp}^2}$$

Asymptotic expression shows strong dependence on transverse angles. Direct numerical integration shown above results in slightly reduced dependence

Cooling rate – based on equilibrium with diffusion

COOL'05

Nagaitsev



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

Cooling off

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

D = 4.8 MeV^2/h

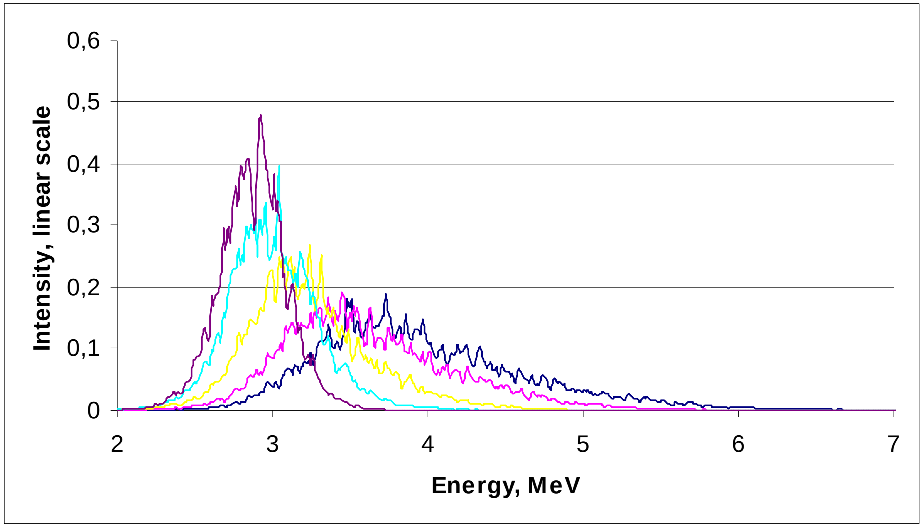
$$\lambda = \frac{D}{2\sigma_{p,eq}^2} \approx 22\, h^{-1}$$

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

Measurements (S. Nagaitsev et al.): $\lambda \approx 25\, h^{-1} = 0.007\ s^{-1}$

BETACOOL simulation (A. Sidorin et al.): 0.0073 s^{-1}

Benchmarking of distribution evolution (500 mA, 2 keV HV step)



FNAL

Measurement 10/31/05

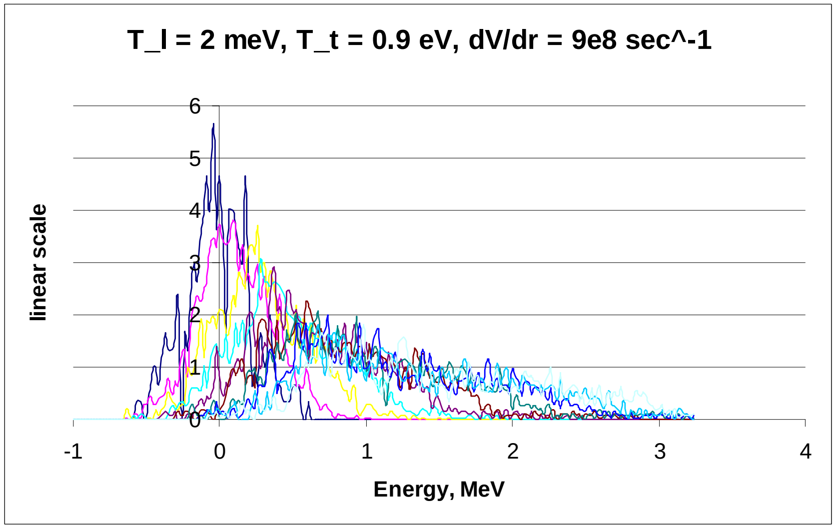
L. Prost

BETACOOL

Simulation

12/03/05

A. Sidorin



Experimental benchmarking summary

- Simulation both for drag rate directly and equilibrium with diffusion are within good agreement with measurement - for details see presentations by FNAL group.

More experimental data and simulations may be needed to study various questions:

- accurate description of electron angles; measurement of velocity gradient within the beam; accurate measurements of equilibrium properties; measurement of current dependence; understanding emittance growth; etc.

5. Recombination estimate

Experimental measurement of recombination coefficient α_r for fully stripped ion (ESR, GSI, 2001) is in good agreement with theoretical models for relative energies > 20 meV.

$$\frac{1}{N}\frac{dN}{dt} = -\frac{\alpha_r n_e}{\gamma^2}\frac{l_{cool}}{C} \qquad \alpha_r = \langle v\sigma(v)\rangle$$

We use numerical integration:

$$\alpha_r = \frac{1}{Int}\int_0^{3\Delta_\perp}\int_{-3\Delta_\parallel}^{3\Delta_\parallel}\sigma(E)\sqrt{(v_\perp + v_{und})^2 + v_\parallel^2}\exp\left(-\frac{(v_\perp + v_{und})^2}{2\Delta_\perp^2} - \frac{v_\parallel^2}{2\Delta_\parallel^2}\right)v_\perp dv_\parallel dv_\perp$$

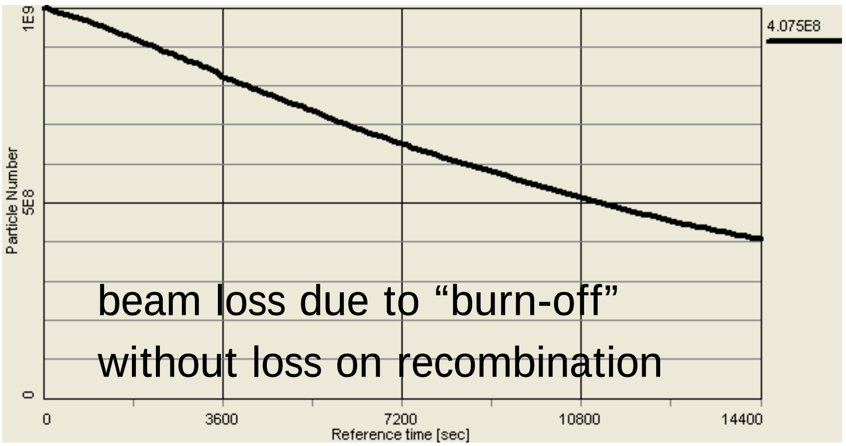
where cross section is given by

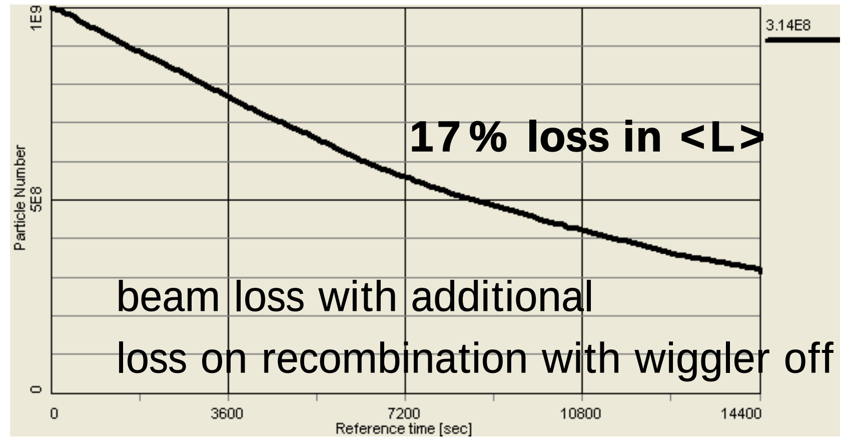
$$\sigma = A\left(\frac{h\nu_0}{E}\right)\left(\ln\sqrt{\frac{h\nu_0}{E}} + 0.1402 + 0.525\left(\frac{E}{h\nu_0}\right)^{1/3}\right)$$

Parameters of undulator for recombination suppression

Magnetic field [G]	10
Period [cm]	8
Introduced effective temperature Teff [eV]	30
Recombination lifetime with Teff [hours]	166

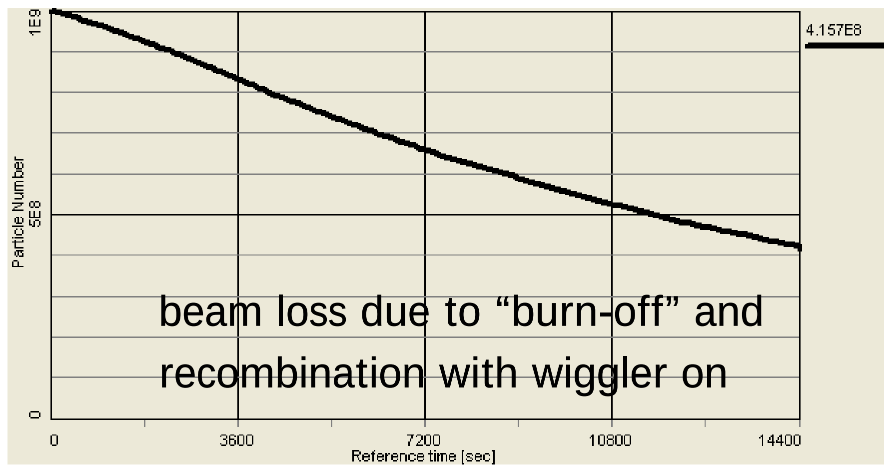
Cooling and recombination (for present baseline parameters of the cooler)





with undulator, the friction force is decreased:

trade-off between cooling and recombination suppression



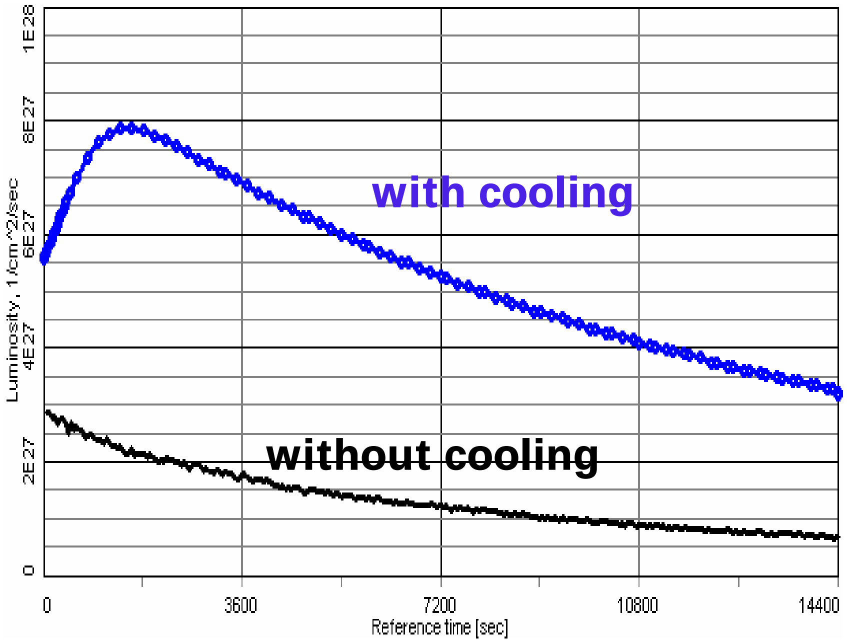
almost all luminosity

is recovered

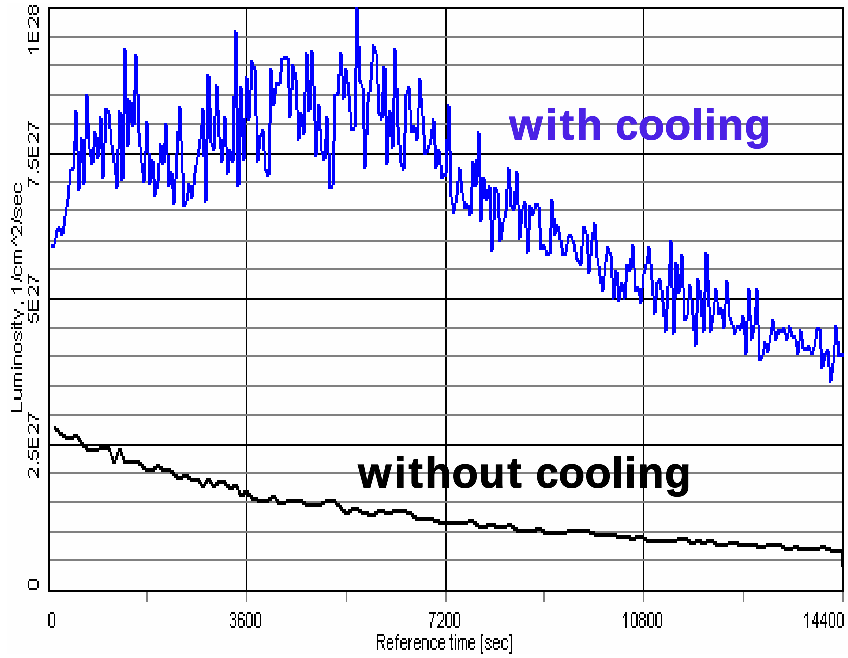
6. Parameters of the cooler (for cooling of Au ions at 100 GeV/n)

Electron kinetic energy [MeV]	**54.3**
Electron charge per bunch [nC]	**5**
Electron cooler length [m]	**80**
Rms emittance normalized [mm·mrad]	**4**
Electron rms momentum spread	**0.0003**
Rms radius of electron beam [mm]	**4.3**
Electron rms bunch length [mm]	**10**

Performance for Au ions
(for present baseline parameters, q=5nC, β*=50cm)

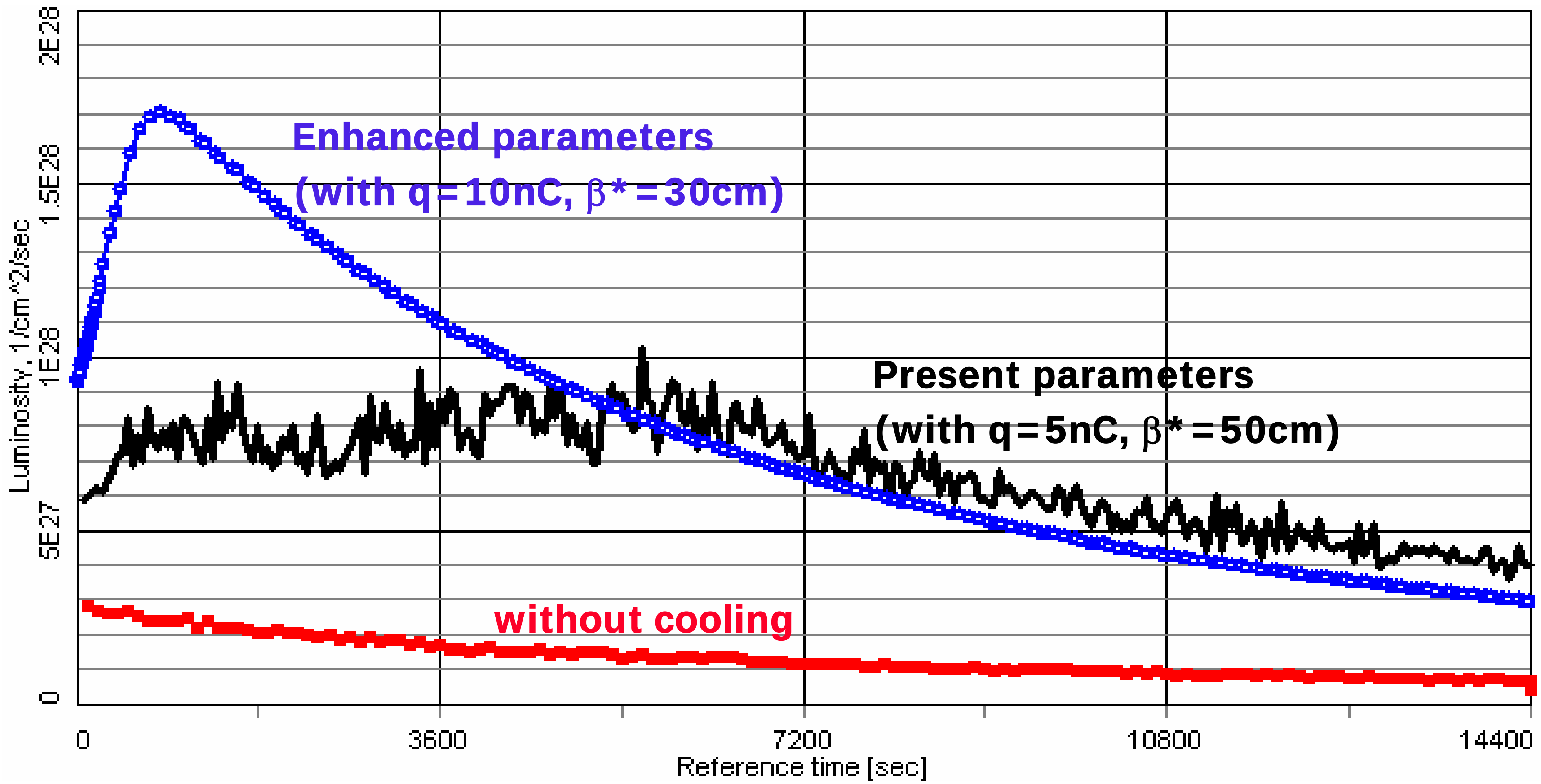


rms dynamics

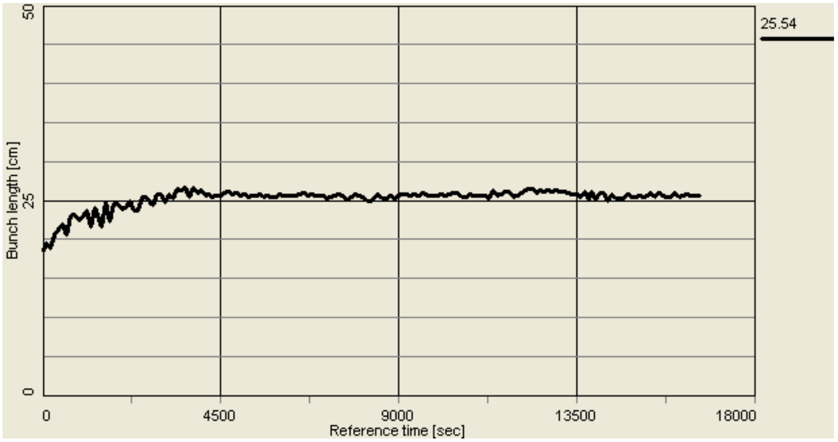


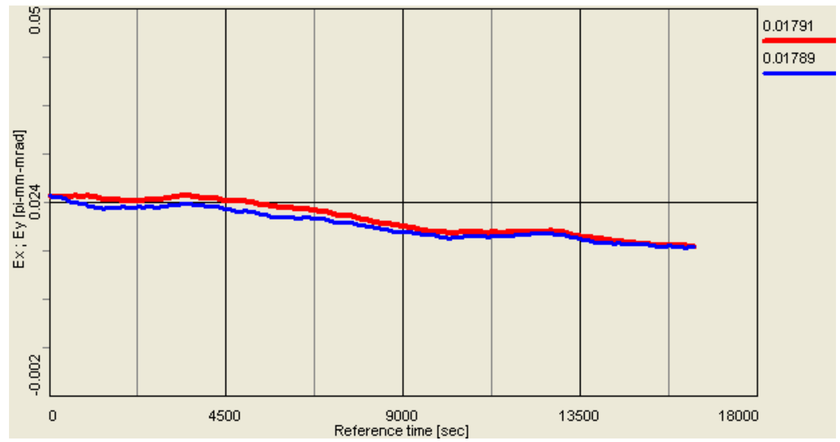
Modeled beam approach, taking into account details of the distribution

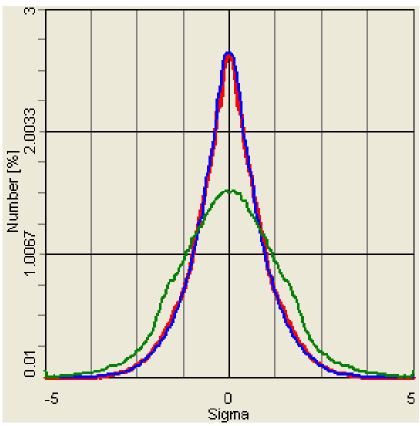
Further possible increase in average luminosity for Au ions (with charge increase in the electron bunch up to 10nC, and β* decrease to 30cm)

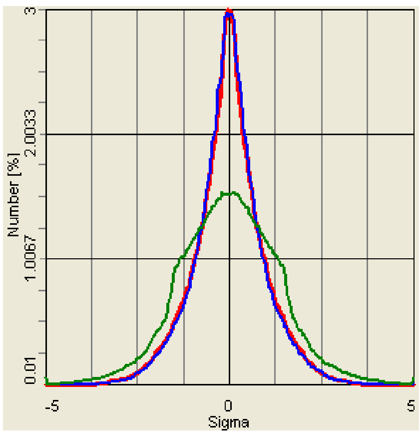


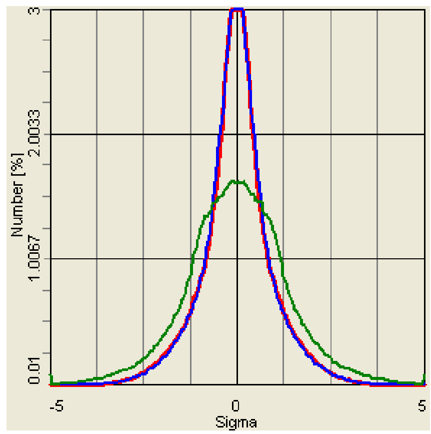
Control of ion rms bunch length with longitudinal painting



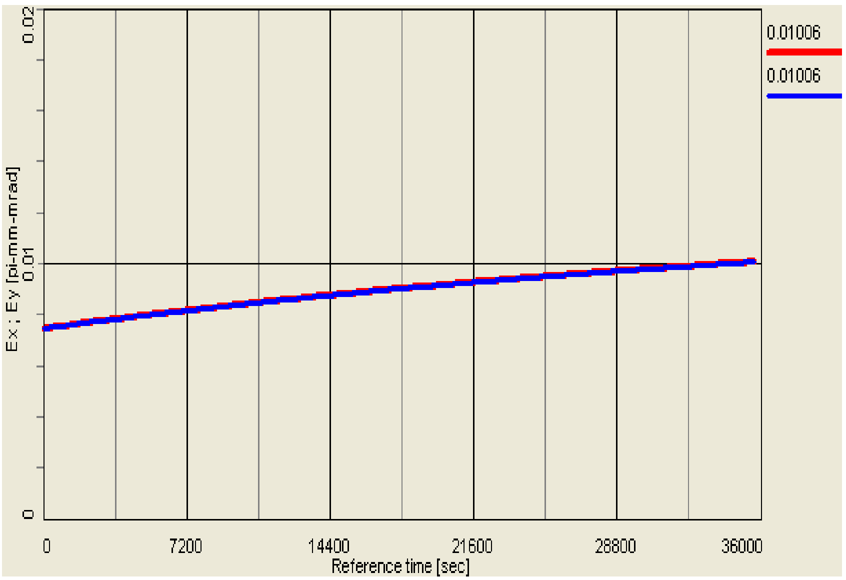


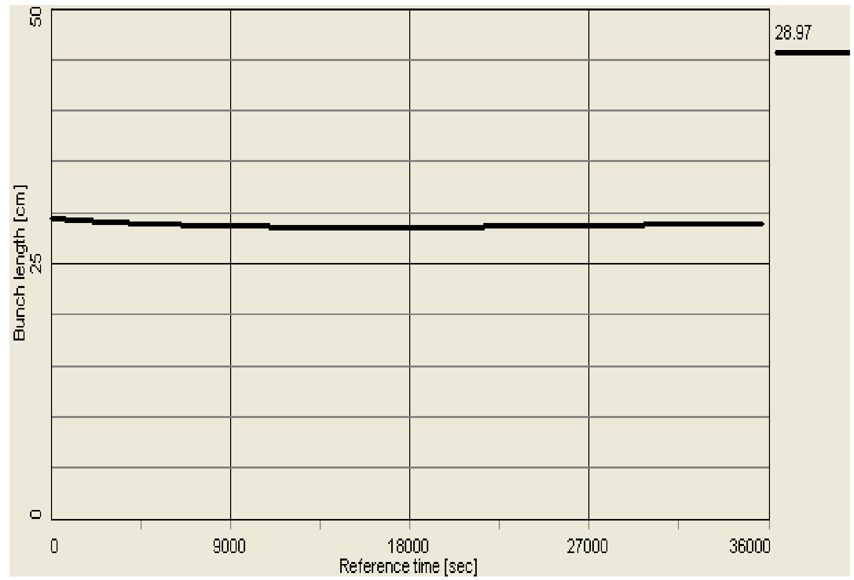






Protons at 250GeV (for RHIC-II parameters). Cooling with present baseline parameters.





only marginal emittance increase in 10 hours

Bunch length is maintained constant

Summary

1. **Benchmarking between measurements of IBS in RHIC and models – good agreement.**
2. **Benchmarking with direct simulations using VORPAL with and without wigglers were performed – good agreement.**
3. **Benchmarking with experimental data for non-magnetized cooling started – good agreement.**
4. **Detailed study of the cooling process and optimization of cooling parameters is in progress.**

Based on performed studies, non-magnetized cooling approach for RHIC-II looks feasible.