Non-magnetized cooling approach

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Outline

1. Goal of RHIC-II cooling and non-magnetized approach
2. Theory and benchmarking between models

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

   (BNL in collaboration with FNAL and Dubna (Russia))
4. Cooling dynamics simulations. Parameters. Recombination and other issues.

Why non-magnetized cooling is sufficient for RHIC?

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

1. **Typical goal – 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.**

Non-magnetized friction force

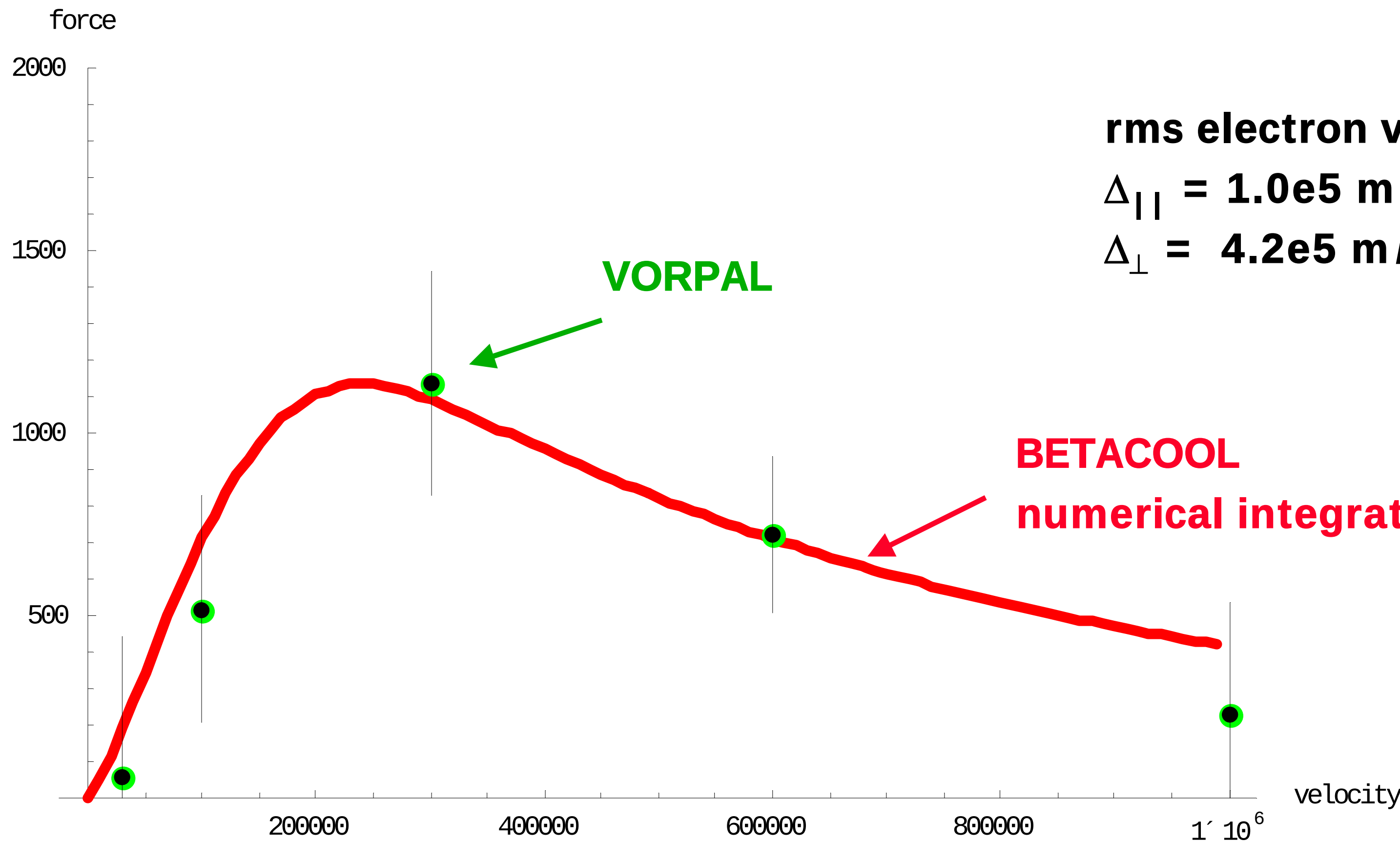
$$\vec{F} = -\frac{4\pi n_e e^4 Z^2}{m} \int L \frac{\vec{V}_i - \vec{v}_e}{\left|\vec{V}_i - \vec{v}_e\right|^3} f(v_e) d^3 v_e$$

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)



rms electron velocities

$\Delta_{||}$ = **1.0e5 m/s**

$\Delta_{\perp}$ = **4.2e5 m/s**

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.

This can be controlled by helical undulators which introduce coherent azimuthal angle:

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

which can produce required T_{eff} to suppress recombination

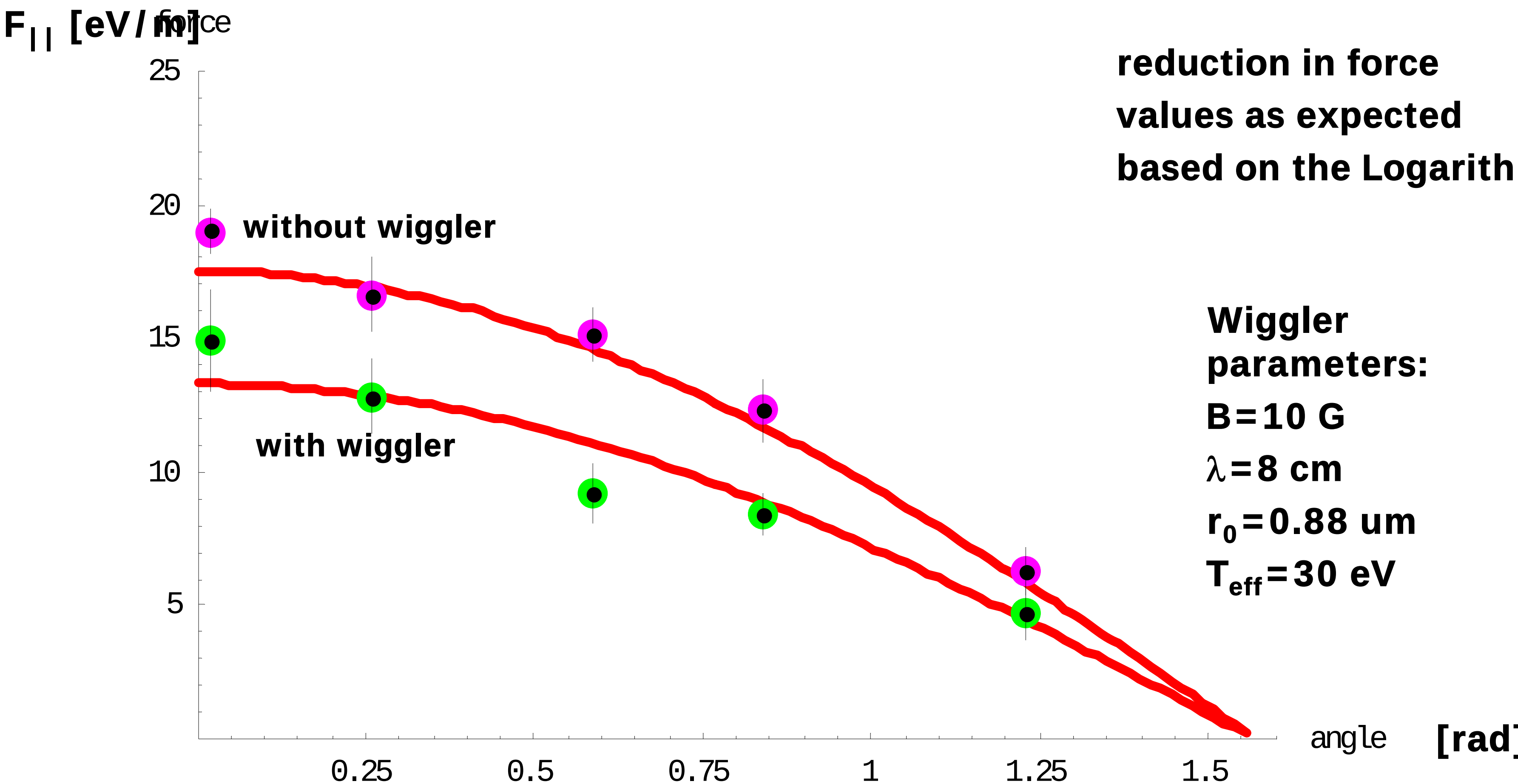
However, this may lead to some reduction in the cooling force by a factor

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

where

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

Longitudinal force component at ion velocity of 3e5 m/s - with and without wiggler (curves – numeric evaluation of 3D integrals, dots – VORPAL (Tech-X, Colorado))



reduction in force values as expected based on the Logarithm

Wiggler parameters:

B=10 G

λ=8 cm

r_0=0.88 um

T_{eff}=30 eV

Non-magnetized force - summary

For anisotropic velocity distribution:

1. **Accurate numerical integration was implemented in BETACOOL**
2. **VORPAL results are in good agreement (10-15%) with numerical integrals**
3. **Reduction in friction force due to wiggler field (VORPAL) was found as expected based on reduced values of the Coulomb Logarithm**

Remaining part

- study for various magnetic fields and wiggler periods.

- study effect of errors.

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)**

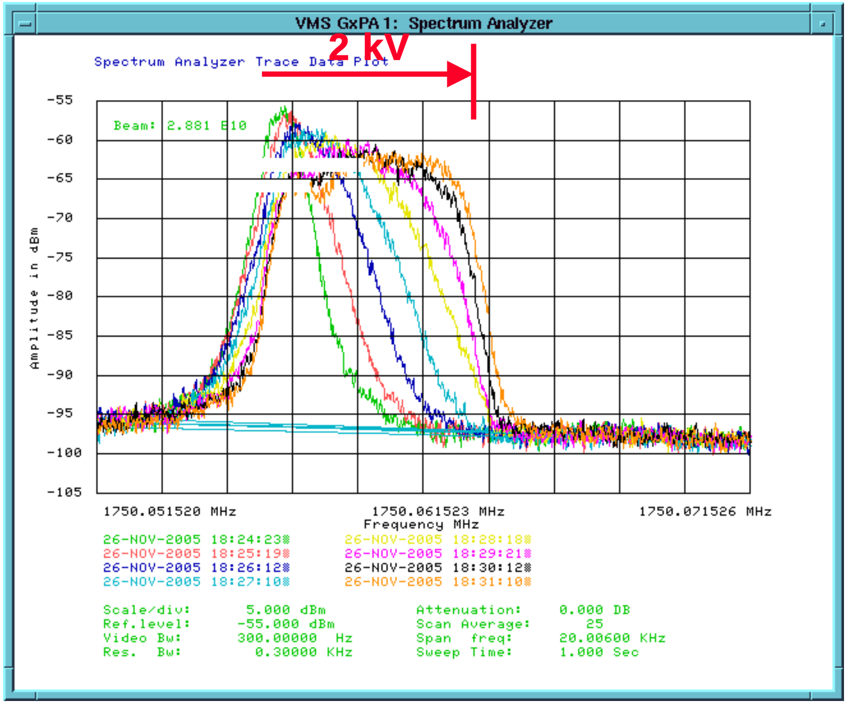
1. Cooling rate – based on measurement with a voltage jump

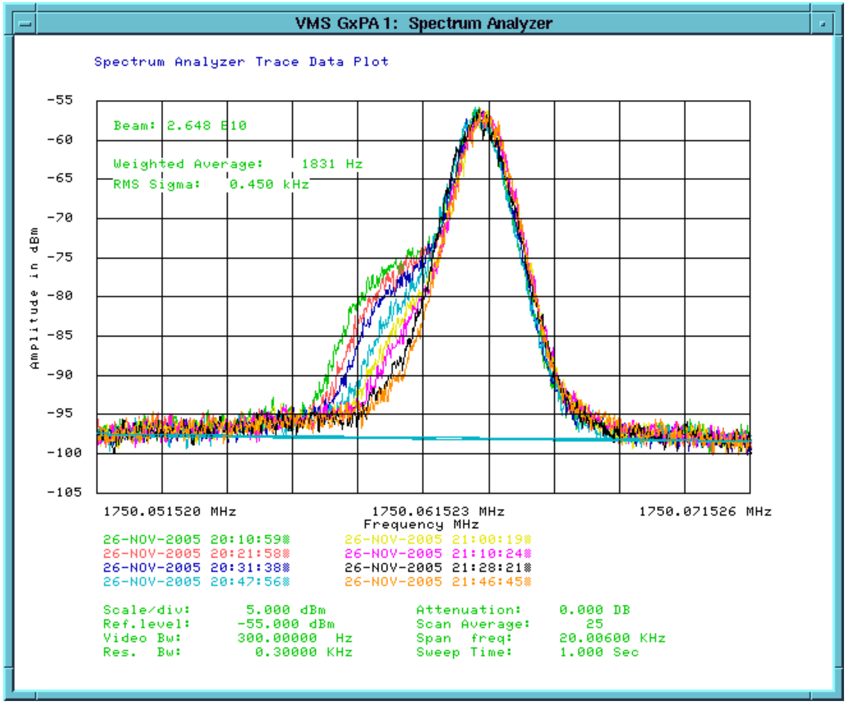
Drag rate measurements were directly modeled using the BETACOOL code:

Steps:

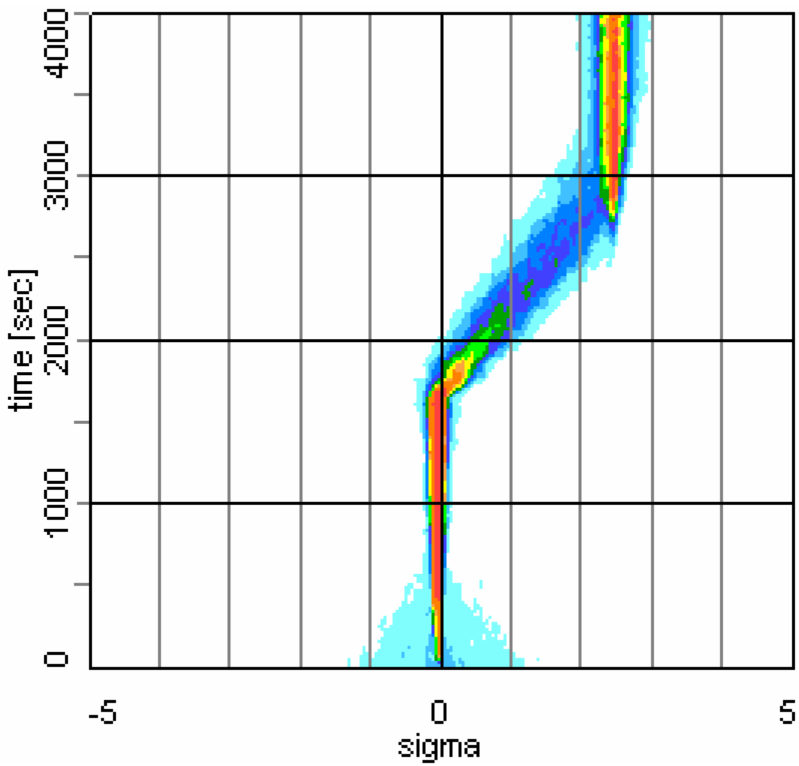
1. Pbar distribution is cooled first
2. Electron energy is changed
3. Pbars are dragged towards new energy
4. Rate of the drag is measured
5. This is repeated for different electron energy jumps to construct a drag-rate curve.

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

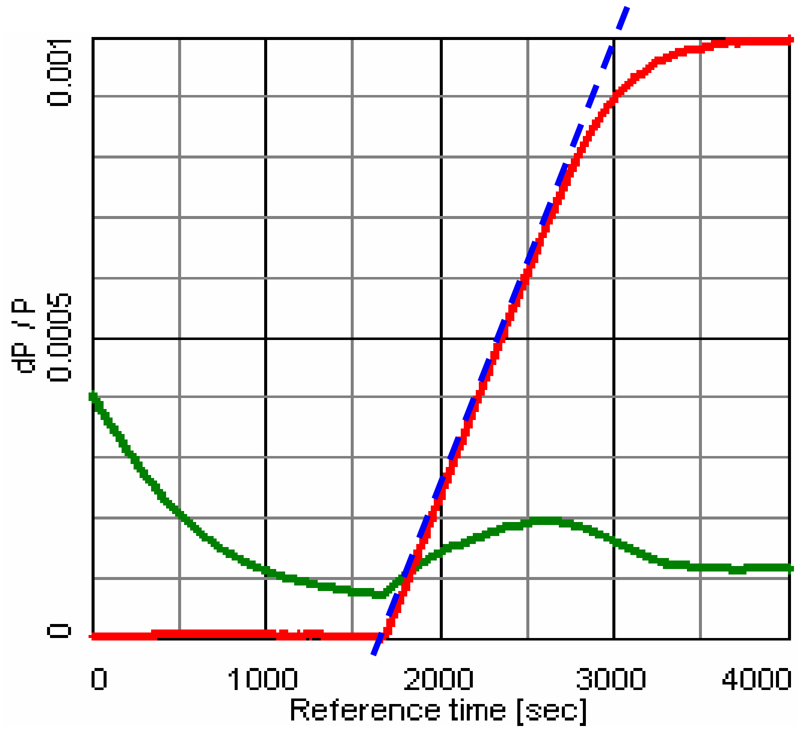




Example for the shift of electron energy (BETACOOL)

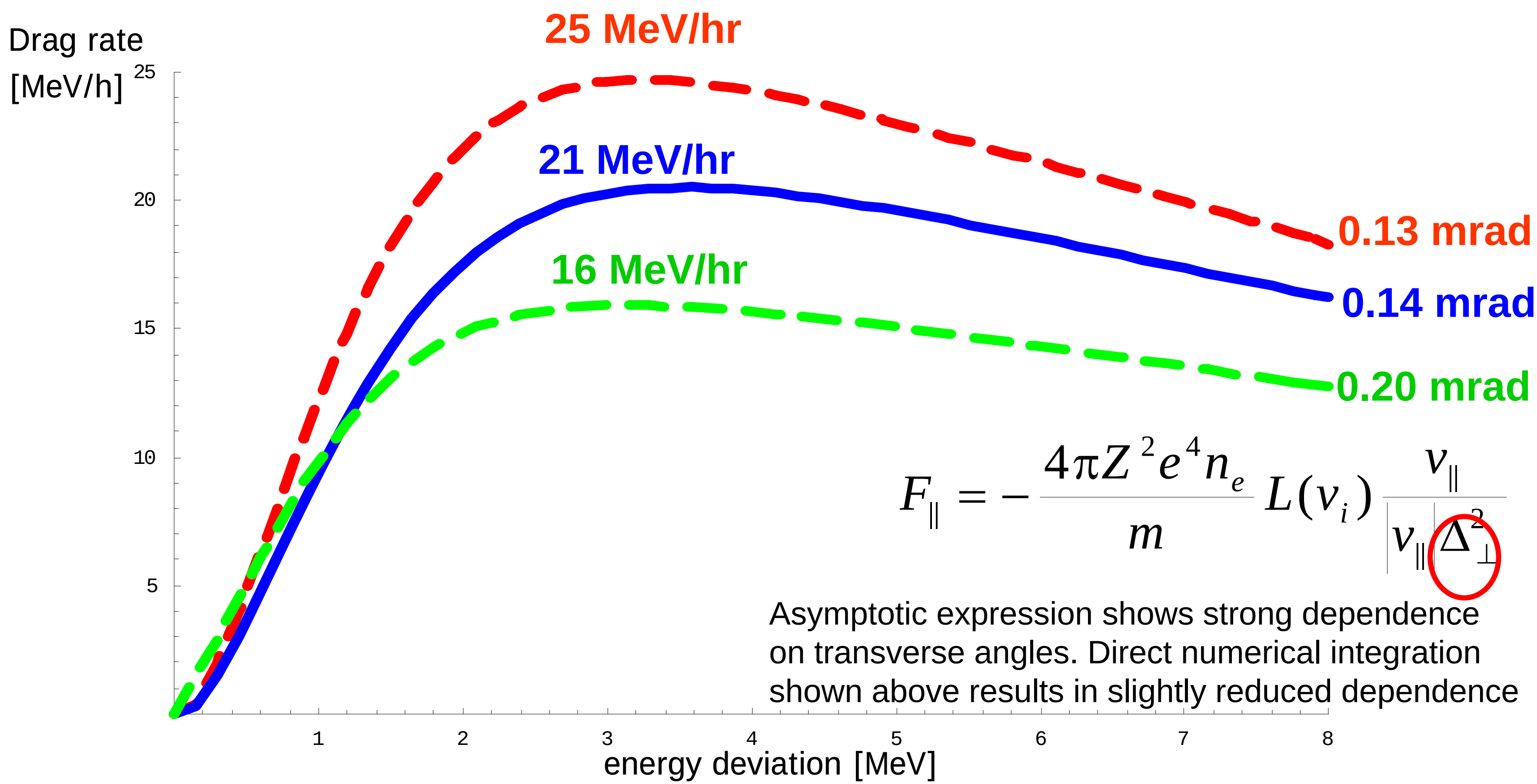


Rms momentum spread in time



Rms momentum spread and momentum deviation in time

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



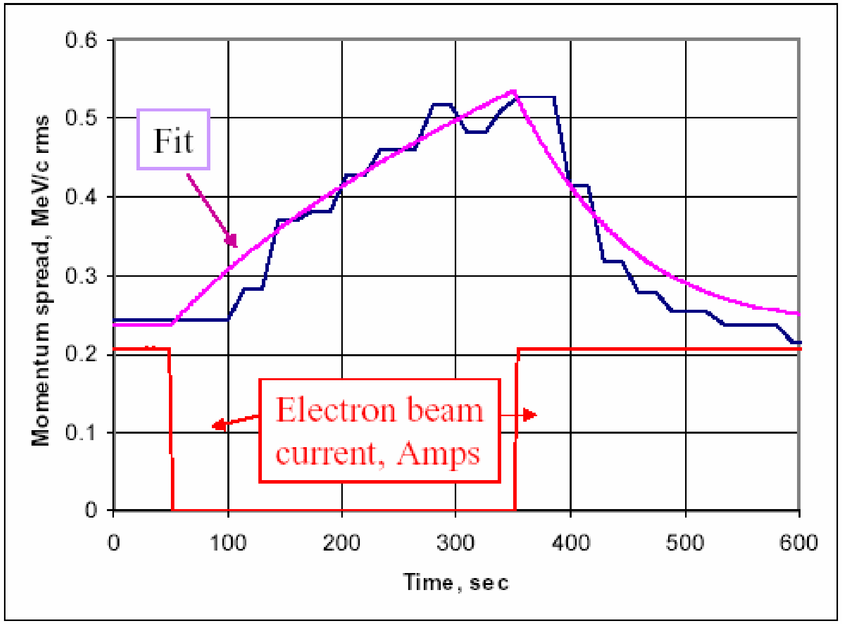
$$F_{\parallel} = -\frac{4\pi Z^2 e^4 n_e}{m} L(v_i) \frac{v_{\parallel}}{|v_{\parallel}| \Delta_{\perp}^2}$$

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

2. 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

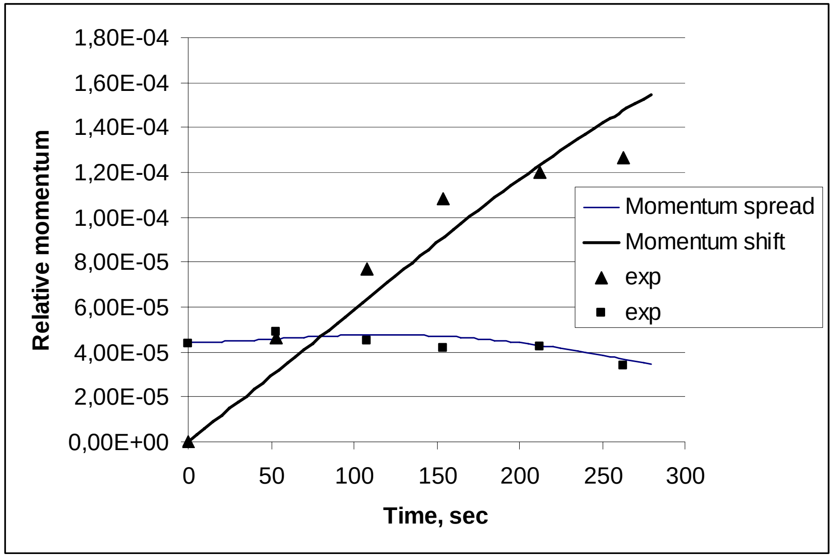
$$\lambda = \frac{D}{2\sigma_{p,eq}^2} \approx 22\, h^{-1}$$

Cooling on $$\sigma_p(t) = \sqrt{\left(\sigma_{p,0}^2 - \sigma_{p,eq}^2\right)\exp(-2\lambda t) + \sigma_{p,eq}^2} \quad \lambda \approx 25\, h^{-1} = 0.007\ s^{-1}$$

BETACOOL (with 4·10^5 m/sec transverse electron velocity spread) gives 0.0073 s^{-1}

Simulation with BETACOOL pbars distributions (A. Sidorin (Dubna) et al.)

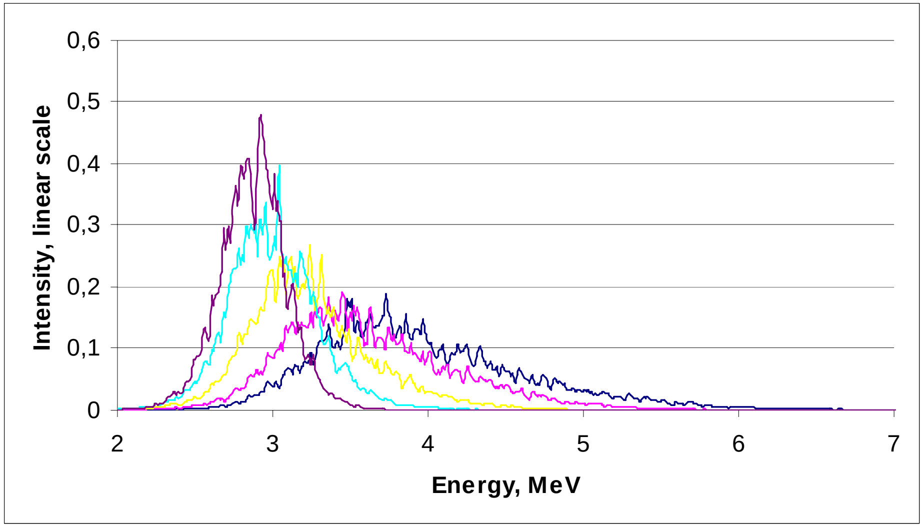
1. Transverse heating is simulated in accordance with measured rate due to interaction with residual gas
2. Longitudinal heating in accordance with measured diffusion power
3. Transverse electron spread is used as a fitting parameter



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

Simulations: λ = 0.0085 sec-1 (experimental value 0.007 sec-1)

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



FNAL

Measurement 10/31/05

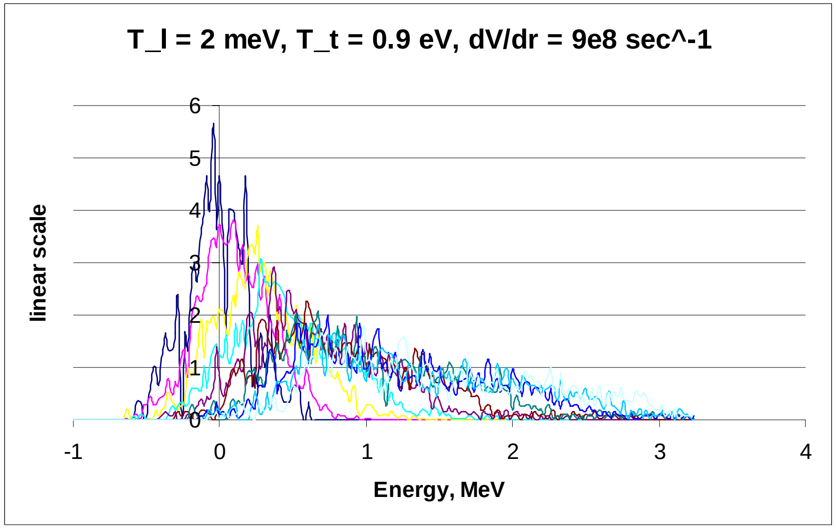
L. Prost

BETACOOL

Simulation

12/03/05

A. Sidorin



Experimental benchmarking summary

- 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.
- Simulation both for drag rate directly and equilibrium with diffusion are within 20% agreement with measurement if smaller angles at beam center are assumed.

More experimental data and simulations are 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.

Parameters for Non-magnetized cooling (under optimization)

Rms momentum spread of electrons =1e-3

Rms normalized emittance: 3e-6 [m rad]

Rms radius of electron beam: 2 mm

Rms bunch length: 1 cm

Charge per bunch: Q=5nC (Ne=3e10)

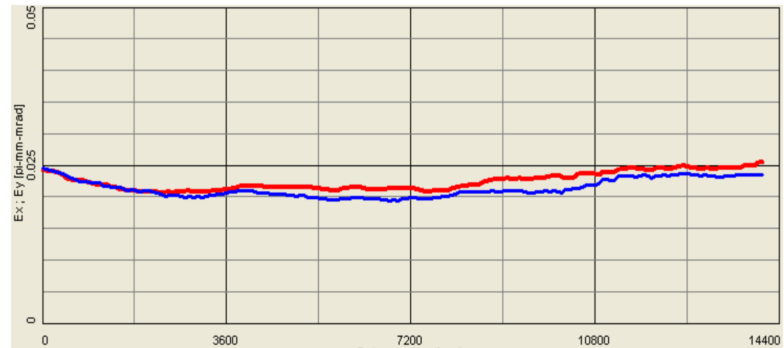
n_e=4e14 m^{-3} (PRF)

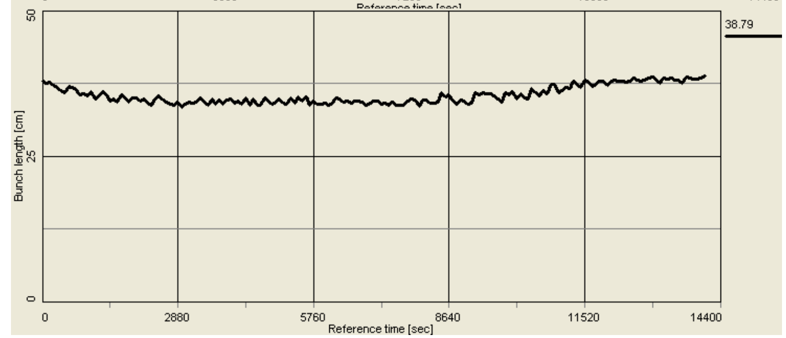
Cooling section: L=60 m

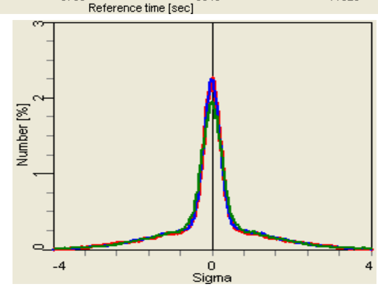
Beta-function in cooling section: 200 m

IBS: Martini's model using exact RHIC lattice

Undulators: B=10 G, λ=8 cm, r_0=0.88 10^{-6} m







Recombination rate

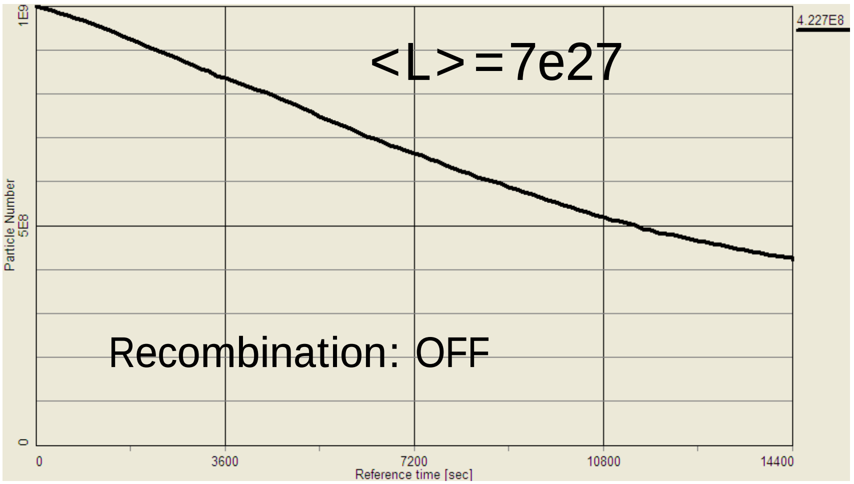
Electron charge Q=5 nC,
cooling length L=60 m and typical parameters
of electron beam:

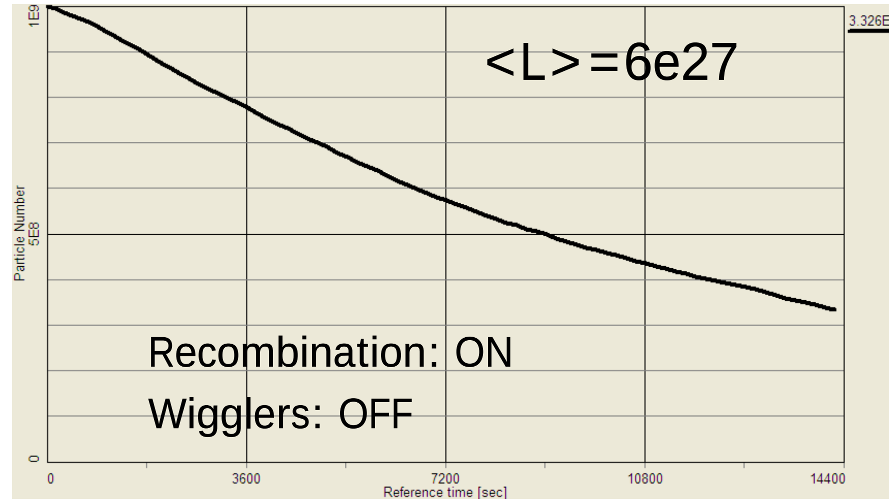
> **For present parameters 30% of the beam would be lost in 4 hours due to recombination.**
> **Wiggler (B=10G, λ=8 cm, Teff=30eV): reduces loss by a factor of 10.**

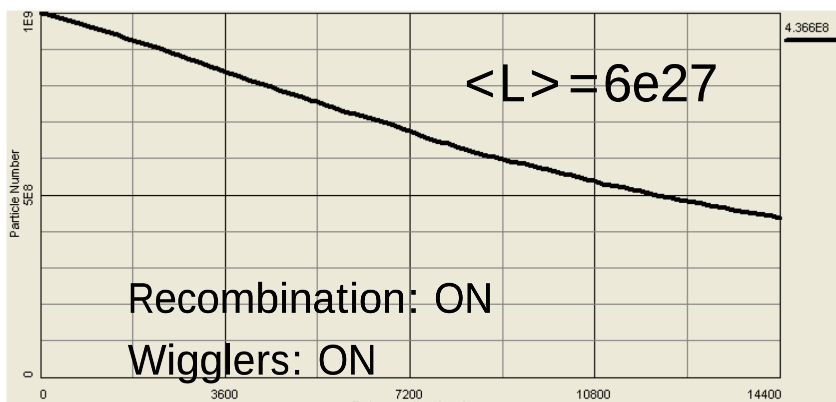
But ion intensity is dramatically decreasing due to the "burn-off"

process (about 60% is "burned" in 4 hours). As a result –
only additional 7-10% is lost on recombination without wigglers.

Number of particles in the ion bunch (as a result of "burn-off", recombination, cooling, IBS)







Integrated luminosity is about the same as without suppression of recombination due to reduction in cooling force

Accuracy of recombination estimate

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

Measured coefficient is higher by about factor of 5 for energies below < 20 meV.

$$\alpha_r = \langle v\sigma(v)\rangle$$

numerical integration

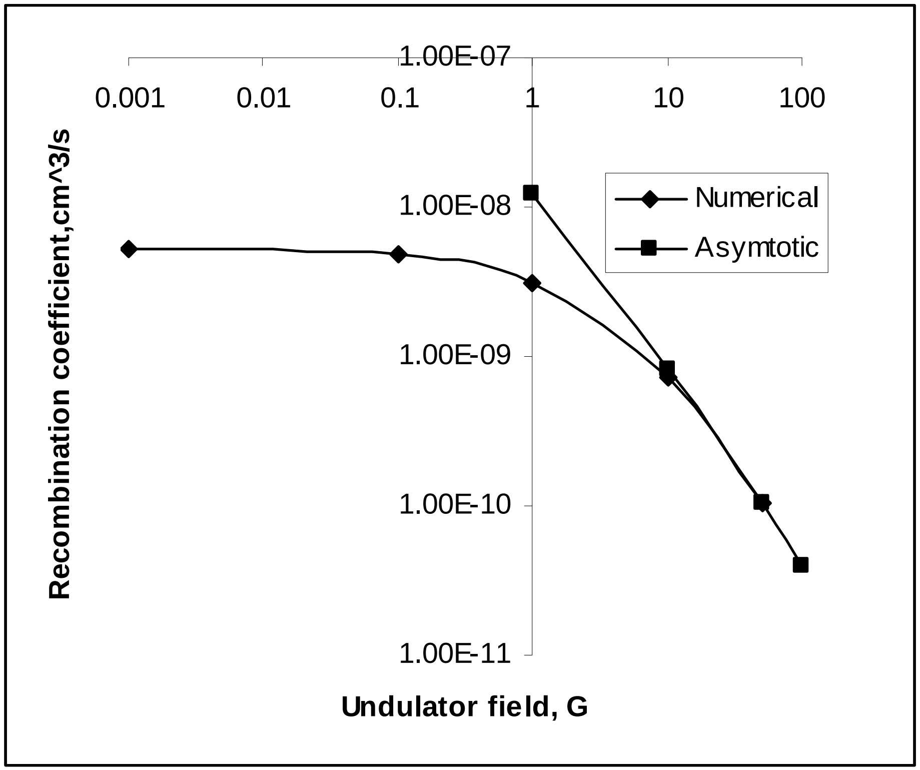
$$\alpha_r = \frac{1}{Int}\int_0^{3\Delta_\perp}\int_{-3\Delta_\parallel}^{3\Delta_\parallel}\sigma(E)\sqrt{\left(v_\perp + v_{und}\right)^2 + v_\parallel^2}\,\exp\left(-\frac{\left(v_\perp + v_{und}\right)^2}{2\Delta_\perp^2} - \frac{v_\parallel^2}{2\Delta_\parallel^2}\right)v_\perp dv_\parallel dv_\perp$$

asymptotic approximation

for flattened electron distribution

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

Numerical integration vs approximate asymptotic expression (A. Sidorin et al.)



Summary for non-magnetized cooling

1. Numerical integration for the friction force was implemented in BETACOOL.
2. Numerical integration for recombination coefficient was implemented in BETACOOL (including velocity spread introduced by wigglers).
3. Benchmarking of numerical integration vs asymptotic expressions for the friction force was performed.
4. Preliminary benchmarking with direct simulations using VORPAL with and without wigglers were performed – very good agreement.
5. Benchmarking with experimental data for non-magnetized cooling started – good agreement.

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