Electron Cooling dynamics at RHIC

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Need for accurate predictions of cooling times

Cooling times for relativistic energies are much longer than for typical coolers:

$$\tau = \frac{A}{Z^2} \frac{\gamma^2}{4\pi r_p r_e n_e c \eta \Lambda_c} \left(\frac{\gamma \varepsilon_{in}}{\beta_{ic}} \right)^{3/2}$$

- standard (order of magnitude) estimate of cooling times for Au ion at RHIC storage energy of 100 GeV gives τ of the order of 1000 sec, compared to a typical cooling time of the order of 0.1 sec in existing coolers
- while an order of magnitude estimate was sufficient for typical coolers it becomes unacceptable for RHIC with a store time of a few hours and fast emittance degradation due to Intra Beam Scattering (IBS)

↓

We need computer simulations which will give us cooling times estimates with an accuracy much better than an order of magnitude.

Outstanding issues

The task of getting accurate estimates for cooling times is further complicated by many unexplored effects for high-energy cooling:

1. Cooling with bunched electron beam.
2. Cooling with "hot" electrons:

	RHIC	Typical coolers
transverse electron temperature:	1000 eV	0.1-1 eV
longitudinal electron temperature:	50 meV	0.1 meV

3. Do we have sufficient magnetized cooling (suppressed transverse temperature)?
4. Understanding of cooling force for RHIC regime.
5. What are the optimum parameters for electron beam?
6. Cooling in a collider brings special treatments of various effects: for example, IBS.
7. Dynamics of cooled ion beam:
   - impact on threshold of collective instabilities,
   - beam-beam parameters, luminosity, etc.

Magnetized cooling force

Derbenev-Skrinsky (D-S) - analytic

$$F_{\parallel}^{A} = -\frac{3}{2}\omega_{pe}^{2}\frac{(Ze)^{2}}{4\pi\varepsilon_{0}}\ln\left(\frac{\rho_{\max}^{A}}{\rho_{\min}^{A}}\right)\left(\frac{V_{\perp}}{V_{ion}}\right)^{2}\frac{V_{\parallel}}{V_{ion}^{3}}$$

$$F_{\perp}^{A} = -\frac{1}{2}\omega_{pe}^{2}\frac{(Ze)^{2}}{4\pi\varepsilon_{0}}\ln\left(\frac{\rho_{\max}^{A}}{\rho_{\min}^{A}}\right)\frac{\left(V_{\perp}^{2}-2V_{\parallel}^{2}\right)}{V_{ion}^{2}}\frac{V_{\perp}}{V_{ion}^{3}}$$

$$\rho_{\max}^{A} = \min\left(r_{beam}, \rho_{\max}\right)$$

$$\rho_{\min}^{A} = \max\left(r_{L}, \rho_{\min}\right)$$

$$r_{L} = V_{\perp,RMS,e}/\Omega_{L}\left(B_{\parallel}\right)$$

Derbenev-Skrinsky-Meshkov (D-S-M) - analytic

$$F_{\parallel}^{A} = -\frac{3}{2}\omega_{pe}^{2}\frac{(Ze)^{2}}{4\pi\varepsilon_{0}}\left(\ln\left(\frac{\rho_{\max}^{A}}{\rho_{\min}^{A}}\right)\left(\frac{V_{\perp}}{V_{ion}}\right)^{2}+2/3\right)\frac{V_{\parallel}}{V_{ion}^{3}}$$

Factor 2/3 without ln offsets "defect" of adiabatic collisions by contributions with large impact parameters so that integral momentum transfer is no longer zero in long. direction when V_tr=0

V. Parkhomchuck (VP) - empiric

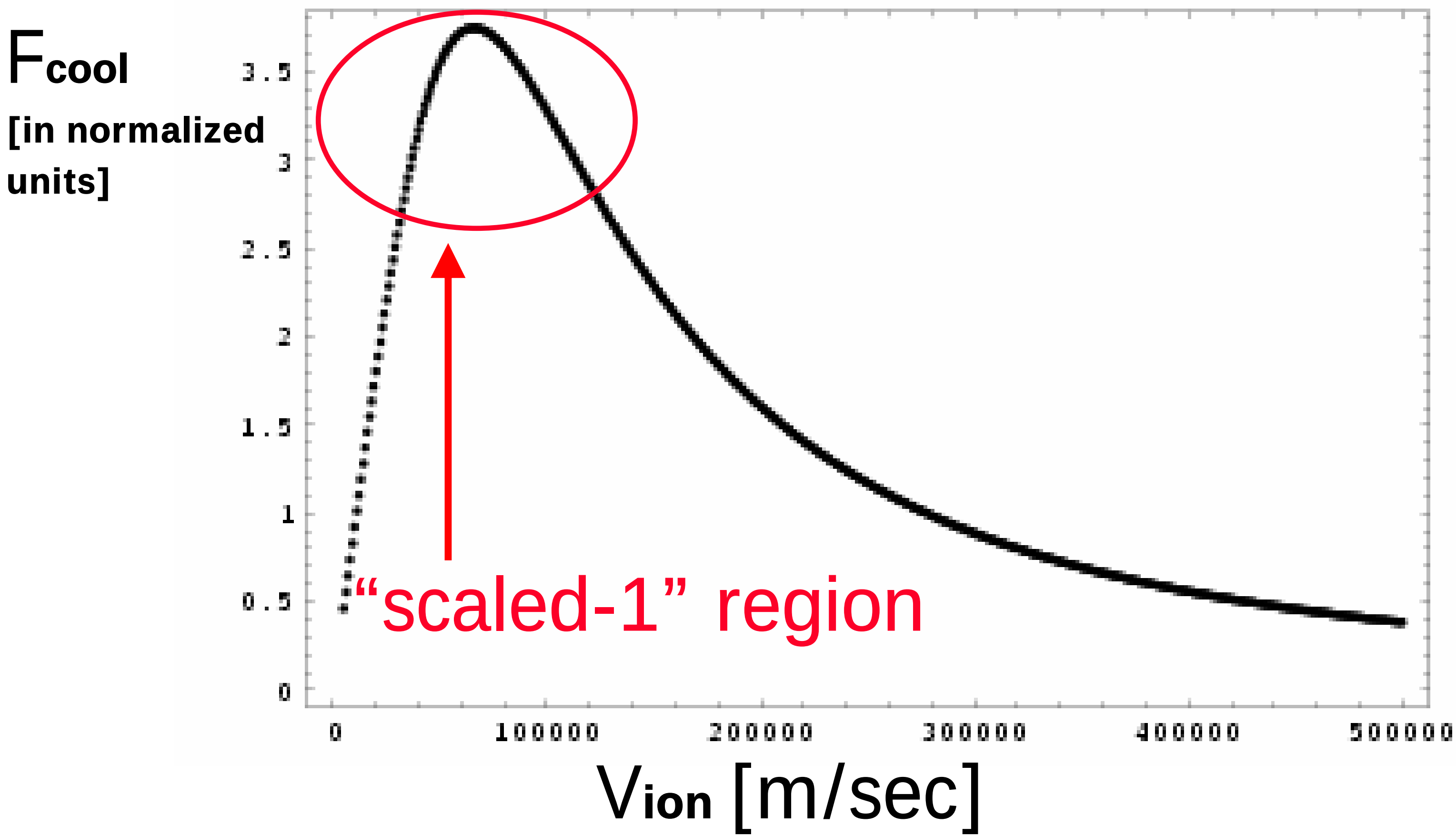
$$\mathbf{F} = -\frac{1}{\pi}\omega_{pe}^{2}\frac{(Ze)^{2}}{4\pi\varepsilon_{0}}\ln\left(\frac{\rho_{\max}+\rho_{\min}+r_{L}}{\rho_{\min}+r_{L}}\right)\frac{\mathbf{V}_{ion}}{\left(V_{ion}^{2}+V_{eff}^{2}\right)^{3/2}}$$

Vorpal code (Tech-X, Colorado)
(direct calculation of friction force via N-body simulations)

- **Primary goal:**
  - Accurately calculate friction and diffusion coefficients for the ions
    - » Resolve differences in analytical calculations
      - Coulomb log >> 1; uniform e- distribution (no space charge)
    - » Determine validity of Z^2 scaling
    - » Understand the effects of beam space charge on friction
    - » Understand the effects of magnetization
      - from weak to strong; effect of field errors
    - » What happens for Coulomb log of order unity (RHIC: 1-2)?
    - » Provide table of coefficients for dynamic codes

Preliminary studies of several regions were performed with Vorpal (http://www.agsrhichome.bnl.gov/eCool/workshop1203)

Calculated F_{cool} based on VP formula for "scaled-1" parameters used in Vorpal simulations



Example of “scaled-1” region of parameters from Vorpal runs

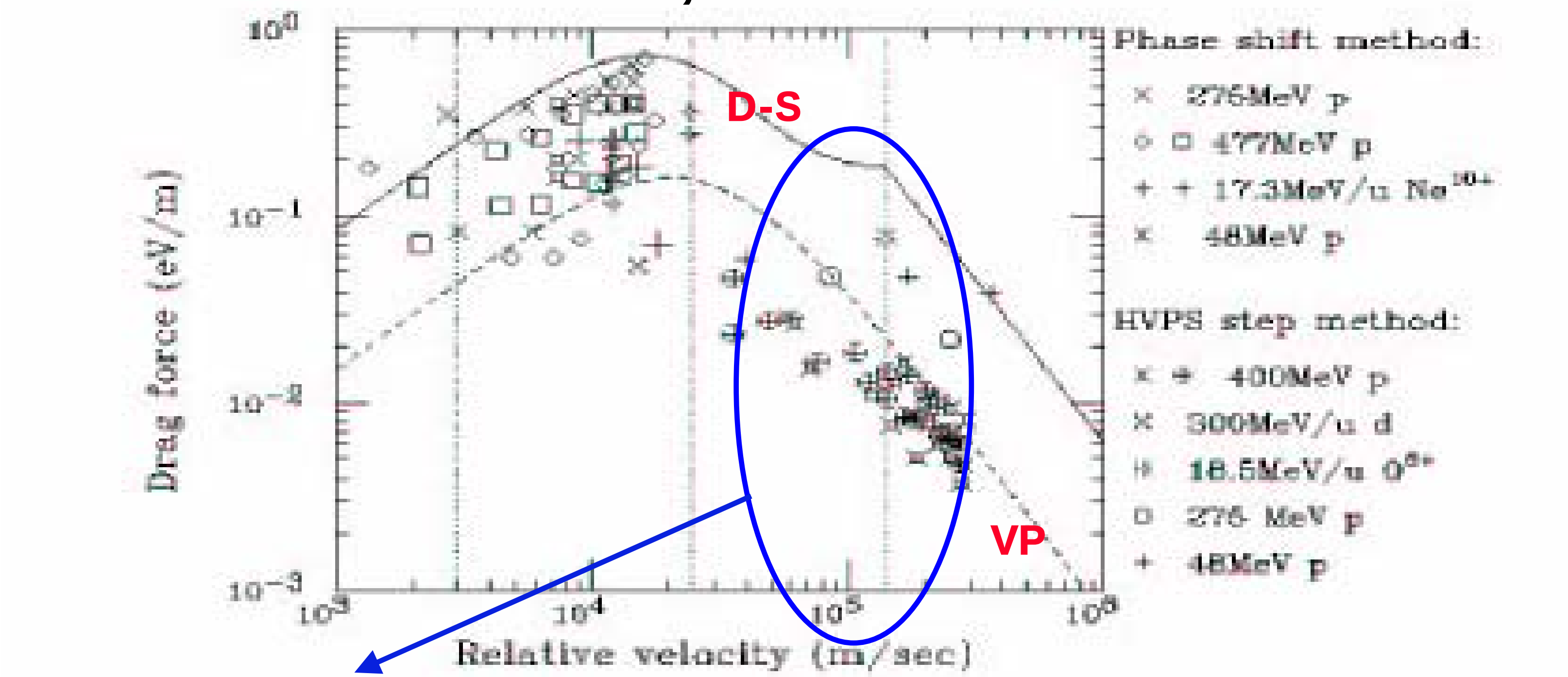
	Vorpal	RHIC
Vion_parallel [m/s]	$5*10^4$	$3*10^5$
Vion_transverse [m/s]	$7*10^4$	$6*10^5$
Zion	5*79	79
Ve_parallel [m/s]	$1*10^3$	$9*10^4$
Ve_transverse [m/s]	$5*10^5$	$9*10^6$
σ_x [m]	0.0001	0.0015
σ_z [m]	0.001	0.05
$n_{e,BF}$ [m^{-3}]	$6.35*10^{14}$	$2.7*10^{15}$
ω_{pe} [rad/s]	$1.4*10^9$	$2.9*10^9$

Example: comparison of δ v_parallel (longitudinal friction force coefficient) between VP formula and direct numerical calculations using Vorpal code.

rms velocity of ion	δv _parallel using VP formula	δ v _parallel Vorpal results
V_tr= V_parallel=12000 m/s	-3.1	-3.5
V_tr=V_parallel=25000m/s	-6.0	-6.5
V_tr=V_parallel=50000 m/s	-8	-10
V_tr=V_parallel=Sqrt[8]*50000 m/s	-6.1	-5

Comparison of D-S vs VP formulas in experiments (longitudinal friction force measurements)

Y-N. Rao et al.: CELSIUS, Sweden'2001:



Longitudinal: D-S significantly overestimates cooling force. VP agrees reasonably well.

Cooling force studies – preliminary conclusions

1. Some benchmarking of analytic formulas for magnetized cooling vs Vorpal were performed:

   - good agreement with VP formula in several tested parameter-regions

   - agrees with D-S formula in some regions and deviates in others

   – more detailed benchmarking is planned (sweeps over parameter range on parallel computer cluster).

2. VP empiric formula with fitting parameters can be used to describe many available experimental measurements with 20-30% accuracy (demonstrated by V. Parkhomchuk).

3. Preliminary simulations using Vorpal code with scaled RHIC parameters were performed to study dependence on longitudinal and transverse temperature of electron beam

Requirements on electron beam temperatures from cooling dynamics

- **Transverse:**

  T_{et}= 500-1000 eV – helps to avoid bad lifetime due to recombination (1000 eV – life time is about 50 hours)

  T_{et}=500 eV → rms velocity Δ_e=9*10^6 m/s (r_L=5*10^{-5}m, B=1T), ρ_{max}/r_L=3.5

  T_{et}=1000eV → Δ_e=12.6*10^6 m/s (r_L=7*10^{-5}m , B=1T), ρ_{max}/r_L=2.5

  Preliminary studies showed that good magnetized cooling is lost at T_{et} above 2000 eV. To preserve magnetized cooling any increase of T_{et} above 1000eV should be accompanied by increase in magnetic field B-> sqrt[T_{et}]

- **Longitudinal:**

  rms energy spread δ_e=3*10^{-4} → rms velocity Δ_{el}=1*10^5 m/s

  Solenoid field angle error θ=1*10^{-5} → effective Δ_{el}= 3*10^5 m/s.

  Cooling force (F → 1/V^2) is presently limited by V effective from solenoid errors.

Development and benchmarking of cooling dynamics codes

SimCool
(BNL/BINP)

1. Cooling – individual particles
2. IBS – i. p. but based on rms rates

+: Can treat time evalution of distributions but many questions:

1) Questions about IBS +
2) Needed synchrotron motion +
3) Needed accurate treatment + of bunch shortening and impact on IBS
4) other

June, 2003

BetaCool
JINR(Dubna)

Cooling – rms rates
IBS – rms rates

-: didn't treat evolution of distribution

In present new version: +

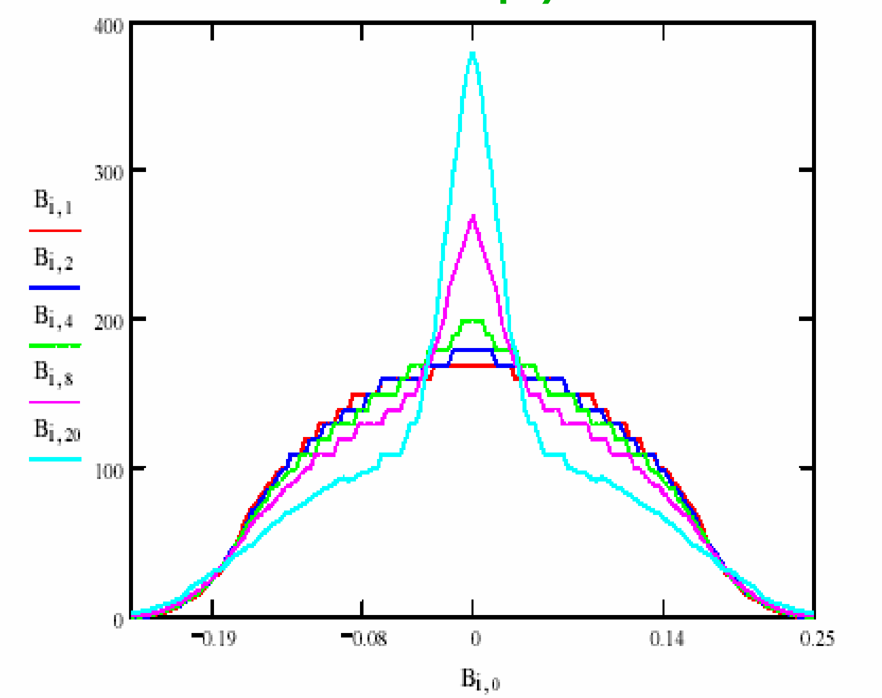
1) SimCool approach is implemented +
2) Various treatments of IBS: +
   2.1) i. p. based on rms rates
   2.2) detailed
   2.3) direct- Molecular Dynamics

January, 2004
Start to converge

Rapid cooling of beam core

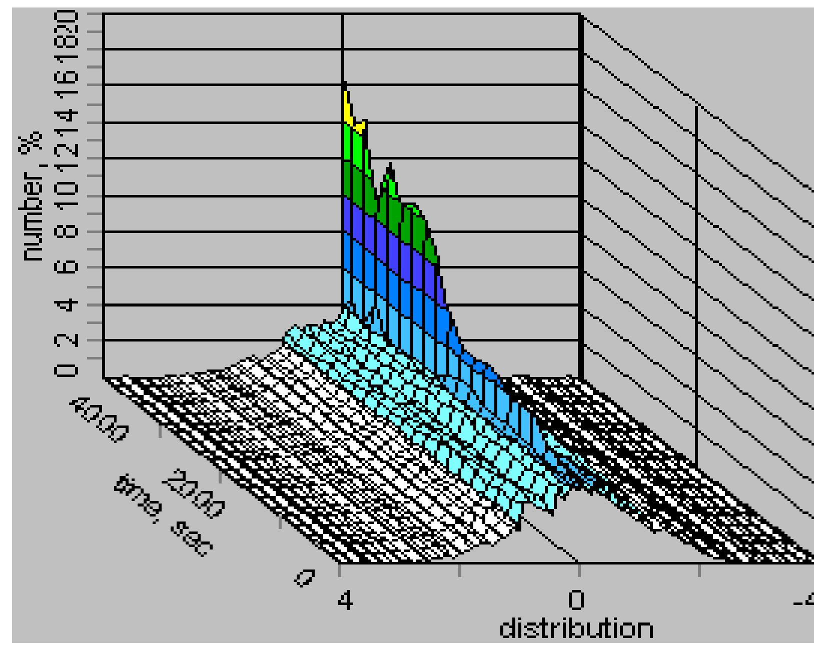
SimCool code

(transverse projection of beam profiles at different time steps)

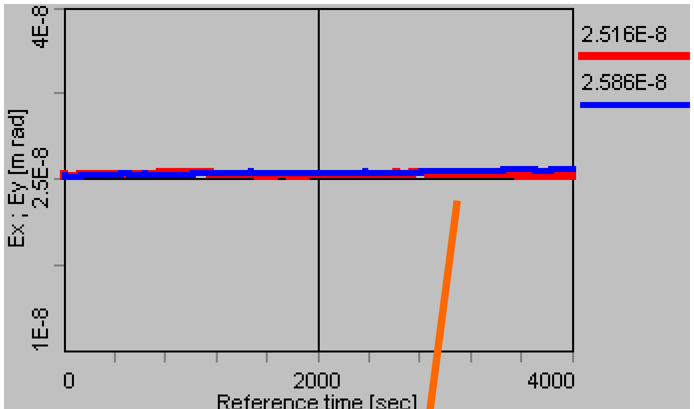


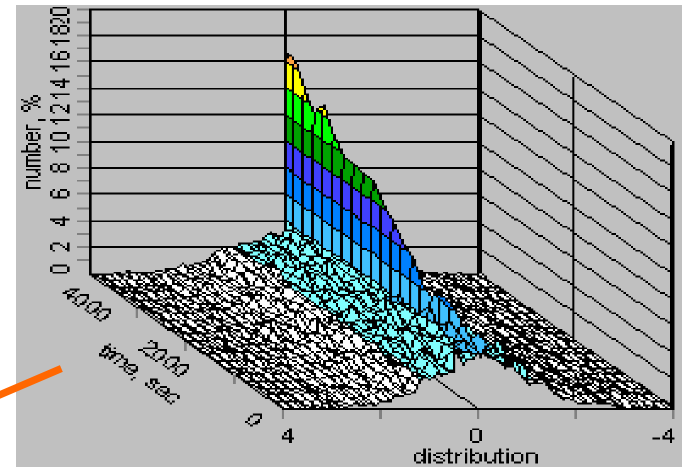
BetaCool code

(time evalution of transverse beam profile)

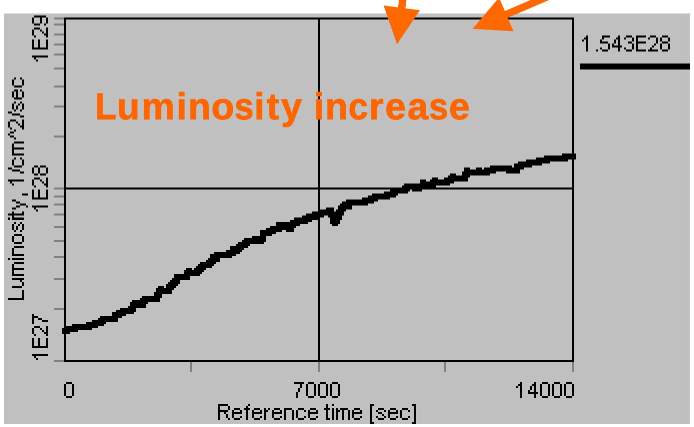


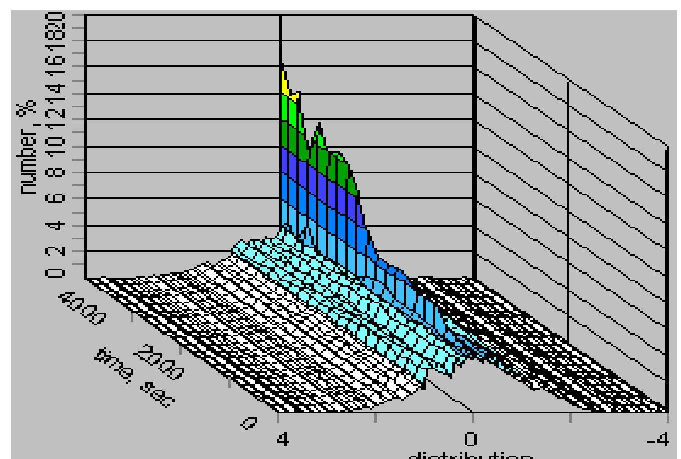
Example: rapid cooling of beam core for almost unchanged rms parameters – effective increase in luminosity





Transverse profile





Longitudinal profile

Cooling in a collider

Electron cooling in collider provides:

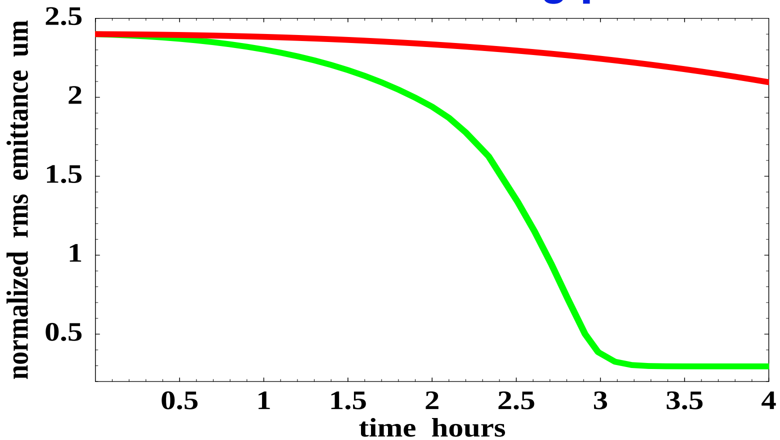
1. control of beam heating due to IBS, noise, beam-beam; reduces beam emittances to a required level.
2. rapid cooling of beam core – rapid luminosity increase.
3. bunch shortening which can lead to a very low beta-star with a subsequent luminosity increase.
4. more effective cooling - using two-stage cooling by first pre-cooling at low energy with a subsequent cooling at higher energy.

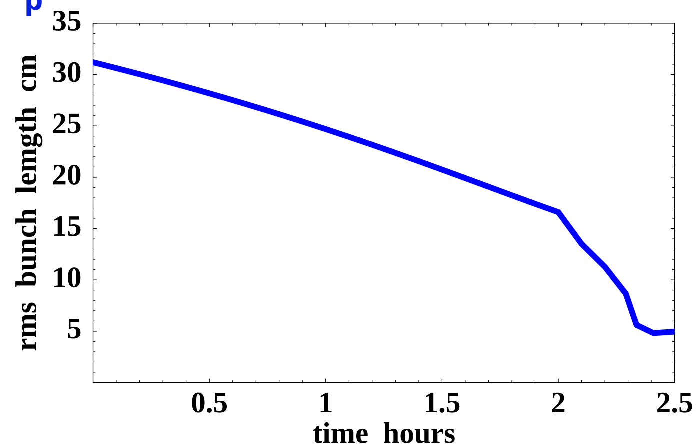
especially for protons

$$\tau = \frac{A}{Z^2} \frac{\gamma^2}{4\pi r_p r_e n_e c \eta \Lambda_c} \left(\frac{\gamma \varepsilon_{in}}{\beta_{ic}} \right)^{3/2}$$

Example of two-stage cooling for proton in RHIC: pre-cooling at low energy

Pre-cooling protons at 27 GeV, $N_p = 1x10^{11}$

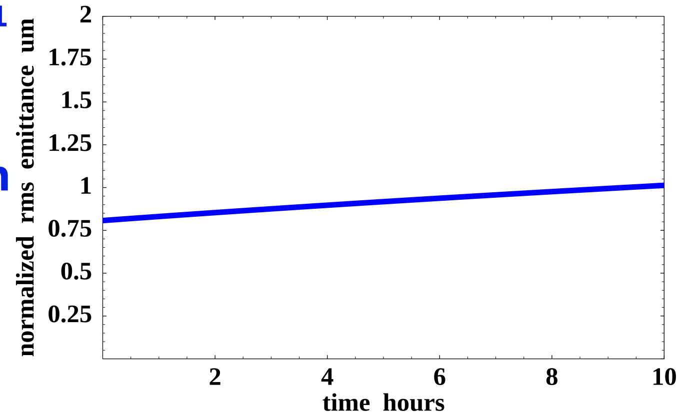




$N_e = 5x10^{10}$ and $1x10^{11}$

$N_e = 1x10^{11}$

Subsequent emittance growth at 250 GeV of initially pre-cooled protons



Impact of cooled beam on ion dynamics

1. Negative impacts of good cooling (rapidly cooled core):

   - beam-beam parameter may be exceeded
   - too much luminosity – rapid beam disintegration in IP

     (always can make cooling worse)

2. Possible positive impacts

   - may help to improve beam-beam limit (as in electron machines with radiation damping)
   - noise, etc. – results in a coherent kick at IP – goes into incoherent motion (with subsequent emittance growth) – cooling can damp such coherent oscillations

Other

Instabilities of cooled beam

1. RMS momentum spread (dp/p) is rapidly reduced by cooling – strong reduction of longitudinal threshold
2. Reduction of threshold for transverse instabilities
3. Transverse emittance cooling:

   - Laslett tune shift and resonance crossing
4. Electron-ion interactions

   - incoherent – electron lens tune shift

   - coherent interaction: both longitudinal and transverse

- Need detailed study/simulations of these effects

Eventually will need:

- control and feedbacks for these instabilities
- control of electron beam distribution and controlled cooling

Possible experiments

Objective:

- **Test various aspects of high-energy cooling using low-energy coolers.**
- **Benchmark simulation codes.**

Several experiments are presently under discussion with GSI/INTAS collaboration:

1. **Measure longitudinal friction force and study dependence of force maximum on the magnitude of solenoid errors.**
2. **Scale magnetic field and transverse temperature of electrons appropriately so that we can study:**

   - dependence on magnetic field in near transition regime

   - transition to bad magnetization.

Other experiments are under discussion.

Preliminary conclusions from topics under study

1. Accurate description of Cooling force - addressed/ in progress:
   - analytic formulas are benchmarked vs Vorpal code
   - empiric formula by VP was studied in simulations
   - need benchmarking vs measurements
2. Requirements on magnetic field and electron temperatures – addressed/in progress:
   - magnetic field of 1-2 T is sufficient for good magnetized cooling
   - transverse temperature of electrons in the range 500-1500 eV is adequate
   - longitudinal temperature of 10-50 meV (δ_p=1-3*10^{-4}) is adequate – cooling is presently limited by effective temperature due to solenoid imperfections
3. Theoretical and experimental studies of IBS: - addressed/ in progress:
   - various analytic formulas were benchmarked in simulations
   - IBS formulas were benchmarked vs plasma treatment
   - detailed IBS (formalism by Burov) is under study
   - IBS for collapsed distribution (bi-Gaussian by Parzen) is under study
   - Experimental studies of IBS at RHIC in progress

Future study topics

1. Continue simulations of cooling dynamics

   - Friction force studies with Vorpal – at a very preliminary stage:

   a) need confirmation of observed effects b) study many remaining topics

   c) simulations for RHIC parameters

   - Detailed benchmarking of dynamics codes SimCool and BetaCool for each individual effect

   - Further development and improved treatment of various effects

2. Optimize parameters for electron beam

3. Optimize parameters for electron cooler.

4. Evaluate full dynamics of cooled ion beam

   - instabilities

   -beam-beam, luminosities

   - cures of instabilities; control of cooling

   - etc.