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Memo

DATE: *July 11, 2003*

TO: RHIC E-Coolers

FROM: *Ady Hershcovitch*

SUBJECT: **Minutes of the July 11, 2003 Meeting**

Present: Rama Calaga, Yury Eidelman (ORNL & BINP Novosibirsk, Russia), Alexei Fedotov, Ady Hershcovitch, Jorg Kewisch, Derek Lowenstein, William Mackay, Stephen Peggs, Anatoly Sidorin (JINR Dubna Russia), Thomas Roser, Jie Wei.

Topics discussed: Simulation & Calculations, Stochastic Cooling.

Simulation & Calculations: Alexei opened the meeting with a report on a recent workshop that was held Monday (June 30) – Wednesday (July 2) to discuss various E-Cooling and simulations issues. Among others the meeting was attended by Burov (FNAL), Ya. Derbenev (JLab), A. Sidorin (Dubna), D. Bruhwiler and D. Abell (Tech-X). Much of the workshop was focused on addressing the differences among analytical expressions and various codes. In the former, differences exist within a factor of 2 – 3, while in the latter; there has been a large difference among codes. Large differences in cooling rates for the RHIC parameters exist between SIMCOOL and BETACOOL. Much of the difference is attributed to the fact that in SIMCOOL the Coulomb logarithm is constant, while in a version of BETACOOL, in which accurate impact parameters (to calculate the Coulomb logarithm) were introduced seem to yield better results. A number of ideas to enhance cooling (increasing solenoidal field, introduction of some "optimal" field imperfections, etc.) were introduced by various workshop participants.

A list of conclusions and suggestions for future computations, simulations and even possible experiments like testing cooling with "high" temperature electrons was drafted. Experiments could be tried at GSI, CELSIUS, or COSY. Attached are Alexei's viewgraphs.

Next Anatoly gave a presentation on the BETACOOL code and on the status of its adaptation for the RHIC parameters. BETACOOL is a complex C++ code that is compatible with Windows. Anatoly described the structure of this computer code for calculating ion beam parameters in RHIC taking into account peculiarity of electron cooling and intrabeam scattering processes that are unique to RHIC. On June 14th, 2002, Anatoly gave an extensive presentation on the BETACOOL code. At this meeting Anatoly focused on the changes that were introduced in BETACOOL. The code was basically rebuilt, and the IBS model was checked and corrected. Minutes of the first presentation, as well as most of its viewgraphs can be found at http://www.rhichome.bnl.gov/RHIC/luminosity/upgrade/minutes/. Attached are Anatoly's viewgraphs for this presentation.

Alexei's Viewgraphs

Summary of RHIC ecooling working meeting (BNL: June 30 –July 2, 2003)

Summary of some outstanding questions:

1. **Some difference between analytic expressions for magnetized cooling force exist (within factor of two). This topic will be revisited.**

2. **Strong difference in cooling force for RHIC parameters between SimCool and BetaCool codes was explained. It is related to the fact that ratio of impact parameters under cooling Log is close to unity. A more accurate impact parameters are now implemented in BetaCool. However, more accurate analyticformulas (beyond Log approximation) for magnetized part of cooling force are required for RHIC regime. This will be also checked with numerical calculations. Also, it is possible to change ecooler parameters to enhance magnetization.**

3. **A more accurate treatment of IBS/Cooling, keeping dependence on individual particle actions (Burov's formalism), was suggested. Such analysis allows more accurate description of distribution evaluation due to both Cooling and IBS.**

4. **The questions of "detailed" formulas vs "beam-averaged" formulas are strongly linked to a question of "cooling strategy": whether one wants to cool beam core or core+tails. The agreement was reached that a strategy based on just cooling the core maybe dangerous – mainly due to the beam-beam and collective instabilities at RHIC. Also, for longitudinal cooling, it seems that optical-stochastic cooling can be adopted to cool tails while ecooling - to cool beam core.**

However, for transverse cooling, application of stochastic cooling requires further detailed study.

5. It was suggested (Burov) that some imperfection of solenoidal field (B-field tolerance) is desired – "optimal" imperfections. Such "oscillation" of electron beam is needed to insure that more ions with low velocities are within the electron beam.

6. Magnetized cooling is much better than pure non-magnetized case for RHIC parameters. However, alternative ways to solenoidal focusing were suggested (Derbenev) – quadrupole focusing ("magnetized"). Such quadrupole focusing requires further detailed study.

7. Dependence on Z^2 for cooling force was discussed. It was explained (Burov) that different dependence on Z (observed in experiments) is not applicable to RHIC parameters. This will be checked with further simulations/experiments.

8. Possibilities to reach low transverse temperature of bunched electron beam were discussed.

9. Status of computer codes for ecooling studies at RHIC and further necessary steps in their development, as well as theory of electron cooling, were discussed.

10. Other alternative schemes of ecooling were discussed.

General summary and plans:

1. Theory:

1.1 Analytic expressions for magnetized cooling force - several formulas exist which agree within a factor of 2. Agree on which formula should be used.

1.2 For RHIC ecooler parameters, ratio of impact parameters under Log becomes close to unity. As a result, available Log approximations are not sufficient. More accurate analytic formulas for this regime are desired. Accurate treatment of this region in simulations is required.

1.3 Agree on values of large/small impact parameters, cooling Coulomb Log and IBS Log.

1.4 Apply "detailed" IBS and Cooling force (Burov's formalism) to study evaluation of beam distribution.

2. Simulations:

2.1 SimCool – run simulations with a more accurate parameters: higher IBS Log, smaller cooling Log, etc. Further development in SimCool and comparison with other codes.

2.2. BetaCool – implement accurate impact parameters for RHIC regime. Study and compare cooling process with SimCool. Compare various formulas and approaches ("detailed" IBS vs beam averaged). Further development, benchmark of analytic formulas with numerical approach and experiments.

2.3 VOPRAL – test analytic formulas for RHIC regime by studying single-ion friction force (dependence on ion temperature etc.). Study dependence on Z^2/A. Friction and diffusion coefficients for BetaCool.

2.4 Collaboration on code benchmarking with GSI team (BetaCool, MOCAC, Ptarget).

3. Experiments:

3.1 In Collaboration with GSI team develop experiments to test some outstanding issues (GSI, Uppsala (CELSIUS), Julich (COSY)).

4. Ecooling approaches:

4.1 Evaluate various ecooling schemes: 1) Linac (present baseline), 2) Linac with recirculator, charge amplifier, 3) electron storage ring and 4) positron storage ring.

4.2 Magnetized beam vs quadrupole ("magnetized") focusing.
4.3 Flat vs round beams
4.4 Stochastic ecooling

Sidorin's Viewgraphs

Software for RHIC Electron Cooling Calculation based on BETACOOL program

Anatoly Sidorin

Electron cooling group,
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1. Peculiarities of RHIC electron cooling system

2. Requirements to software

3. Description of BETACOOL

4. Structure of software for RHIC Electron Cooling Calculation

5. Status and plans

1. Peculiarities of RHIC electron cooling system

Electron energy ~ 50 MeV.

Medium energy electron cooling:

Electrostatic acceleration + energy recuperation (usual configuration)

SSC – 20 MeV electron energy,
First project of COSY cooler – 1.5 MeV,
GSI e-I collider project – up to 15 MeV,
Fermilab Resycler – 4 MeV,
GSI HESR project – 5 MeV.

- DC electron beam,
- uniform electron density,
- low electron temperature ($T_\perp$ ~ 100 meV, $T_\parallel$ ~ 1 meV):
ion velocity in the PRF larger than the electron velocity spread - possible to use non-magnetized electron beam in the cooling section

RF acceleration of electron beam (+ recirculator ring)

PETRA cooling system project ~ 10 MeV,
COSY cooling system project ~ 1.5 MeV,

RHIC cooling system

- bunched electron beam,
- electron bunch length can be shorter than ion one,
- large electron temperature ($T_\perp$ ~ 400 eV, $T_\parallel$ ~ 10 meV):
ion velocity is smaller than electron transverse velocity spread – cooling with magnetized electron beam.

Magnetized cooling

$$\vec{F} = -\vec{V}\left(\frac{C_1 L_{NM}}{\Delta^3_{\perp,e}} + \frac{C_2 L_M}{V_i^3}\right)$$

$$L_M = \ln\frac{R_{max}}{\langle\rho_\perp\rangle}, \qquad L_{NM} = \ln\frac{\langle\rho_\perp\rangle}{\rho_{min}}$$

$$\rho_{min} \sim \frac{Ze^2}{m_e V^2}, \qquad R_{max} = \min\left\{\frac{V_i}{\omega_{p,e}},\quad V_i\tau_{flight},\ a\right\}$$

RHIC:

$$\frac{V_i}{\Delta_{\perp,e}} \sim 0.1$$

(r.m.s. emittance ~ $2\cdot10^{-8}$ $\pi\cdot$m$\cdot$rad, momentum spread ~ 10^{-3})

$$\frac{R_{max}}{\langle\rho_\perp\rangle} \sim 10$$

(magnetic field ~ 1T, L_{cool} ~ 30 m)

General goal of the cooling system is to suppress intrabeam scattering

$$\tau_{cool} < \tau_{IBS}$$

2. Requirements to software

1. Realistic model of the electron beam

2. Realistic calculation of the friction force

3. Realistic calculation of IBS

4. Calculation of influence of the beam alignment - required level of magnetic field homogeneity

5. Calculation of the ion distribution function evolution in time

Long-term beam parameter variation:

Revolution period is of the order of 10^{-5} sec
Characteristic IBS and cooling times are of the order of 10^{3} sec
Time of experiment ~ 10^{4} sec
One needs to calculate the ion beam parameters during ~ 10^{9} revolutions in the ring

Possible solutions:

1. Calculation of mean diffusion coefficient and cooling rates, solution of the equation system for r.m.s. parameters of the ion distribution function:
BETACOOL
(I.Meshkov & Co, JINR)

2. Calculation of the distribution function evolution in time

MOCAC (Monte Carlo simulations)
(P.Zenkevich, A.Bolshakov, ITEP, Moscow),
SIMCOOL
(V.Parkhomchuk, BINP, Novosibirsk)

3. Description of BETACOOL

The physical model to be investigated with the BETACOOL program is based on the following general assumptions:

1) the ion beam has Gaussian distribution over all degrees of freedom, and does not change during the process.
2) algorithm for analysis of the problem is considered as a solution of the equations for r.m.s. values of the beam phase space volumes of three degrees of freedom.
3) maxima of all the distribution functions coincide with equilibrium orbit.

The evolution of the ion beam parameters during its motion inside the storage ring is described by the following system of four differential equations:

$$\begin{cases} \dfrac{dN}{dt} = N\sum_{j}\dfrac{1}{\tau_{life,j}}, \\ \dfrac{d\varepsilon_i}{dt} = \varepsilon_i\sum_{j}\dfrac{1}{\tau_{i,j}}, \end{cases}$$

The following effects are taken into account:

1. Electron cooling,
2. Stochastic cooling,
3. Intrabeam scattering,
4. Scattering on residual gas,
5. Interaction with internal target,
6. Injection of new portion of the ion beam,
7. External heating of the ion beam,
8. Particle loss in the collider regime.

The program was used for design of the new electron cooling systems for the following rings:

ACR and DSR rings in MUSES project, RIKEN,

NUCLOTRON booster, JINR,

TWAC project, ITEP,

NESR project, GSI

Cooling system with circulating electron beam for COSY, Juelich.

The program was tested using experimental results obtained at

COSY, CELSIUS, NIRS and ESR cooler rings.

Disadvantages:

1. Model

BETACOOL program was aimed for electron cooling simulation

in low energy cooling systems based on electrostatic acceleration

of DC magnetized electron beam of the round shape cross-section and uniform electron density. The model of the electron beam was introduced into friction force calculations.

2. Technical

- **the code was made using Borland C++ Builder and can operate only with Windows,**
- **syntax of the C++ Builder was used inside the physical part of the code,**
- **the code structure was not appropriate for further development in order to provide calculation of the distribution function evolution in time,**
- **complicated structure of the code, lack of comments, absence of unification in the variable dimensions.**

4. Structure of software for RHIC Electron Cooling Calculation (new version of BETACOOL)

Library of the friction force models:

Extended formula by Derbenev-Skrinsky
Semi-empirical formula by Parkhomchuk

Non - magnetized

(Comparison between friction force formulae, possibility to use results of numerical calculations)

Library of the electron beam models:

Uniform cylinder

Gaussian cylinder

Gaussian bunch

(Influence of the electron beam geometry on the cooling efficiency)

Library of the methods for integration of the ion motion equation inside cooler:

Electron beam as a thin lens

Numerical methods for integration of the ion motion equation in the cooler

(Beam misalignment)

Library of the IBS models:

Piwinski (smoothed optics structure)

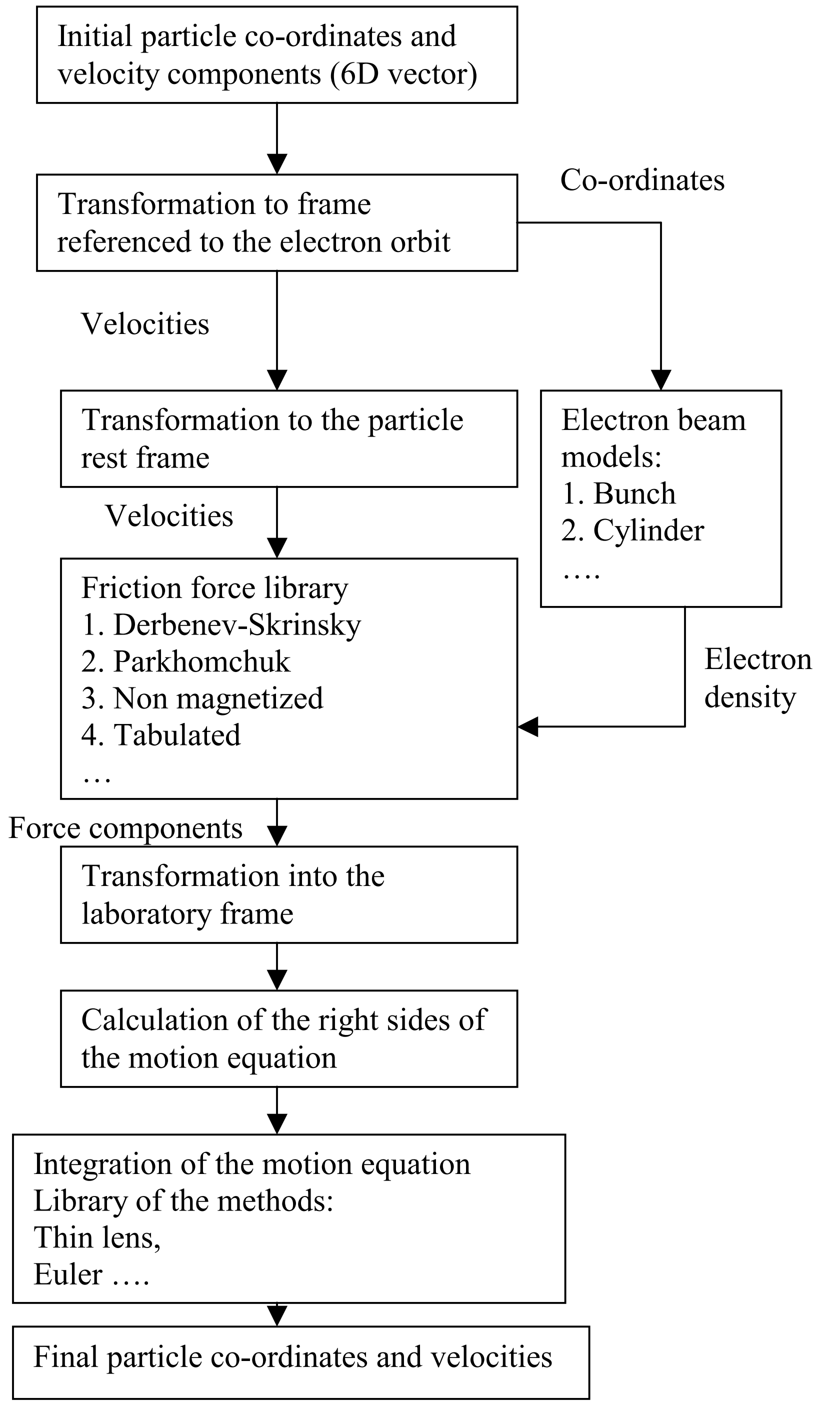
Martini (extended Piwinski)

Jie Wei

Fit of experimental results by diffusion coefficients

(Choice of Adequate model of Intra Beam Scattering)

Block scheme of the particle propagator



Calculation of right sides of the motion equation

1. **Transformation of the ion velocities and coordinates from the frame referenced to the ion orbit to the frame referenced to the electron orbit**

2. **Transformation of the ion velocity from the laboratory frame to the particle rest frame**

3. **Calculation of the friction force in accordance with analytical formulae or by interpolation of numerical results**

4. **Transformation of the friction force from the particle rest frame to the laboratory frame**

5. **Calculation of the right sides**

$$\begin{cases} \dfrac{dx}{ds} = \theta_x \\ \dfrac{d\theta_x}{ds} = \dfrac{F_x}{Mc^2\beta^2\gamma} \\ \dfrac{dz}{ds} = \theta_z \\ \dfrac{d\theta_z}{ds} = \dfrac{F_z}{Mc^2\beta^2\gamma} \\ \dfrac{d(s-s_0)}{ds} = \theta_s \\ \dfrac{d\theta_s}{ds} = \dfrac{F_s}{Mc^2\beta^2\gamma} \end{cases}$$

Thin lens: $\Delta\theta_{x,z} = \dfrac{F}{Mc^2\beta^2\gamma} l_{cool}$

Cooling rates calculation in new version of BETACOOL (mean cooling rates for bunch with given r.m.s. emittances)

1. Single particle calculation:

Change of motion invariants after crossing the cooler are calculated by averaging over the phases of betatron and synchrotron oscillations for particle which invariants of the motion are equal to corresponding two-sigma emittances of the beam.

For the particle with set of initial phases and invariants of the motion the program calculates co-ordinates in accordance with Twiss parameters in the cooler position

The particle is propagated through the cooler

In accordance with Twiss parameters program calculates new values of the invariants and corresponding relative invariant deviations

This procedure is reapited in the loop over phases of oscillations

The rates are averaged over the phase number

$$x_\beta = \sqrt{I_x \beta_x}\sin\varphi, \quad \theta_{x,\beta} = \sqrt{\frac{I_x}{\beta_x}}\left(\cos\varphi + \alpha_x \sin\varphi\right)$$

$$\frac{\Delta p}{p} = \sqrt{2}\frac{\Delta p}{p}_{max}\cos\phi, \; s - s_0 = \sqrt{2}\sigma_s \sin\phi,$$

$$x = x_\beta + D(\Delta p / p), \; \theta_x = \theta_{x,\beta} + D'(\Delta p / p)$$

I_x is equal to two-sigma beam emittance

$$\frac{1}{\tau_{cool}} = \frac{1}{I}\frac{\langle \delta I \rangle}{T_{rev}}$$

$$\langle \delta \vec{I} \rangle = \frac{1}{8\pi^3}\int\int_0^{2\pi}\int \delta \vec{I}\left(\vec{I}, \varphi_x, \varphi_z, \varphi_s\right) d\varphi_x d\varphi_z d\varphi_s$$

2. Monte Carlo calculation

For given r.m.s. emittances program generates array of particles matched with Twiss parameters of the ring in the cooler position

Before crossing the cooler program calculates r.m.s. emittances of the generated bunch - "initial array emittances" (they are not exactly equal to given bunch emittances due to finite number of particles and random number generator quality)

Particle by particle program propagate the bunch through the cooling section

At the exit of the cooler program calculates r.m.s. emittances of the bunch in accordance with Twiss parameters – "final array emittances"

From initial and final array emittances program calculates corresponding rates

Models of the electron beam

1. Uniform round cylinder

It is necessary to compare results of new and last version in order to debug the new version mainly

2. Gaussian bunch of round (or elliptical) cross-section

Basic model for RHIC cooler calculations

Input parameters are:
- **r.m.s. bunch dimensions,**
- **offset between electron and ion bunch centers,**
- **number of electrons in the bunch.**

3. Cylinder of round (or elliptical) cross-section with Gaussian distribution in transverse plane

Input parameters are:
- **r.m.s. dimensions of the cylinder cross-section,**
- **number of electrons per unit of length.**

This model can be used for cooling time calculation in the case when short electron bunch moves forward and back along a long ion bunch during time shorter than cooling time.

5. Status of BETACOOL

1. **Electron cooling simulations was rebuild on the base of object oriented method**

2. **IBS models were checked and corrected**

3. **Program structure is appropriate to perform Monte Carlo simulations**

4. **Interface part is excluded from the physical part and is used for preparation of initial parameters and for post processing (visual presentation of the results).**

5. **Physical part of the program uses dimensional variables: the structure is clear for analysis and check.**

6. **Code of the physical part is written using only ANSI standard of C++ and can be compiled for different platforms.**

Next steps

1. **Calculation of ion distribution function evolution in time**

2. **Usage of numerical results of the friction force calculation**

3. **Preparation of objects to include into UAL**