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Memo

TO: RHIC E-Coolers

FROM: *Ady Hershcovitch*

SUBJECT: **Minutes of the June 14, 2002 Meeting**

Present: Ilan Ben-Zvi, Eric Blum, Michael Brennan, Xiang Yun Chang, Wolfram Fischer, Ady Hershcovitch, Jorg Kewisch, Christoph Montag, Stephen Peggs, Anatoly Sidorin (JINR Dubna Russia), Thomas Roser, Dong Wang, Jei Wei, Wu-Tsung W. Weng, Qiang Zhao.

Topics discussed: Simulation & Calculations.

Simulation & Calculations: Anatoly gave an extensive presentation of the BETACOOOL code development. BETACOOOL 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.

The code is under development in JINR and is based on last version of the BETACOOOL program. This version calculates time evolution of r.m.s. ion beam parameters, as the ion beam is subjected to the action of a few heating and/or cooling effects, which are described in terms of characteristic times of the beam r.m.s. parameter variation. This model assumes Gaussian distribution of the ions in all degrees of freedom. In order to use this program for RHIC electron beam cooling simulation, one needs to change the model of the electron beam and introduce into the program new algorithm for the intrabeam scattering calculation that had been tested for RHIC parameters. Proposed structure of the new computer code facilitates calculations of the ion beam parameter and luminosity as functions of time using a few models of the electron beam and different formulas for the friction force. Models of the ion ring and ion beam are put together in way that facilitate future Monte Carlo simulations and calculations of beam dynamics with arbitrary distribution functions.

As a consequence of physical processes peculiarities, an ideal electron beam would have very low parallel momentum spread for effective cooling, while having a very large transverse energy spread to prevent recombinations. Thus one would like to have an electron beam with a transverse temperature of 1 KeV and a longitudinal spread of 1 meV. To prevent transverse – longitudinal temperature relaxation, a large magnetic field is required.

Below are copies of most viewgraphs from Anatoly's presentation.

The software has to satisfy the following conditions:

1. To be completely compatible with the Microsoft Visual C++6.0 environment.
2. Provide a realistic model for cooling with hot electrons (for recombination reduction) as obtained by a magnetic kick or by other methods.
2. Include a new intrabeam scattering (IBS) calculation option, to be developed in collaboration with C-AD personnel as based on models developed in BNL for RHIC and tested against RHIC performance.
3. Accept a large machine like RHIC, which uses up to 5000 elements, accept directly the MAD Version 8 output file.
4. All graphical output should be amenable to cut-and-paste operations in Windows environment or another convenient graphics-export method, provide convenient control over plot setup (size, axis, title, etc.).
5. Provide annotations in the source-code to simplify understanding and possible alterations.

Initial status of the work

The software is based on BETACOOOL program, developing in JINR during a few years.

Current version of BETACOOOL program calculates an evolution of particle number and r.m.s. parameters of the particle distribution function in the space of invariants of motion. It is assumed, that the distribution functions are Gaussian in all three degrees of freedom. The following effects are taking into account now:

- 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**

The program calculates also general parameters characterising the beam stability:

- incoherent tune shift,
- synchrotron tune depression due to space charge,
- ratio between peak beam current and Keil-Schnell and Schnell-Zotter threshold currents.

The program was tested using experimental results obtained on COSY, CELSIUS, NIRS and ESR cooling systems.

The program was used for design of new electron cooling systems:
ACR and DSR cooling for MUSES project, RIKEN,
Cooling system for TWAC project, ITEP,
Cooling system for NUCLOTRON booster, JINR,
Cooling system for NESR project, GSI
Cooling system with circulating electron beam for COSY, Juelich.

ACR and TWAC cooling system parameters were also calculated using Zenkevich-Bolshakov program (ITEP) - the results are in reasonable agreement.

For DSR ring the program was used for luminosity calculation of electron-ion collisions.

Advantage of the model is a possibility to include into calculations each effect describing by characteristic times of emittance variation. The simplest models of the processes make calculations faster.

Disadvantages:

- the code made using C++ Builder and can work only with Windows, syntax of the C++ Builder is used inside the physical part of the code,

- it is impossible to simulate processes which lead to non Gaussian distribution,

- only one model of the electron beam is used in the simulations: AC magnetised electron beam at round shape of cross-section and uniform electron density,

- calculations of the friction force can be performed using different analytical formulae, but the model of the electron beam is introduced into friction force calculations,

- complicated structure of the code, lack of annotations and comments, absence of unification in the variable dimensions.

At the first step of the code development main aims are to modify the model of IBS calculations and to improve the electron beam model in accordance with RHIC cooling requirements.

Peculiarity of the physical processes

1. Medium energy electron cooling. The electron beam parameters strongly depend on a method of the beam acceleration.
2. General goal of the cooling system is to suppress emittance growth due to intrabeam scattering process. Deep and fast cooling of the ion beam is not necessary and required cooling time is long enough. It means that requirements to the electron beam quality can be not so strong.
3. **One of the most important processes** is ion recombination inside the electron beam. The recombination rate is determined by electron velocity spread mainly and in the case of flattened velocity distribution in the electron beam it is determined by transverse velocity spread. Amplitude value of the friction force in magnetised electron beam is determined by electron momentum spread. To avoid recombination and keep cooling it was proposed to use magnetised electron beam at small momentum spread and big transverse velocity spread. In this case the value of the magnetic field has to be large enough to suppress intrabeam scattering in electron beam leading to transverse-longitudinal relaxation.

(Characteristic time of the temperature growth rate can be estimated by the following empirical expression (MOSOL experiments):

$$\frac{1}{\tau_{relax}} = \frac{1}{T_{||}} \frac{dT_{||}}{dt} \approx \frac{2\pi r_e^2 n_e mc^3 L_C}{T_{||}} \sqrt{\frac{mc^2}{T_{\perp}}} e^{-2.8/\rho n_e^{1/3}},$$
$$\rho = \sqrt{2mc^2 T_{\perp}} / eB$$

Required transverse temperature is about 1 keV, longitudinal - about 1 meV.

4. Ion ring is operated over transition energy, which leads to peculiarities of the IBS calculations.
5. One can expect non Gaussian tails of the particle distribution function.

In principle the program structure has to permit take into account all the physical effects.

Code of physical part of the program

The physical part of the program is made using only C++ standard and required three kinds of files:

1. files of input parameters
2. file of calculation status
3. output files.

(The physical program can be compiled for different operation systems and can be used without interface)

Interface part

Interface is an executed file made using C++ Builder for Windows system

1. Provides a service for work with files of input parameters.
2. Starts the physical part of the program.
3. Controls the calculation process using file of calculation status.
4. Presents in the graphic format results of the calculations from output files online with the physical program run (or after completion of the calculations).

(The interface can be used with physical program made using arbitrary language)

Structure of the physical program

Model of the storage ring

Base of the model - the ring is an array of optic elements

Each optic element has a length and can have three different presentations:

1. List of the lattice parameters
2. 6x6 transformation map
3. Right sides of the particle motion equation

First variant of the ring is required for IBS calculation (can be used also for calculation of the emittance growth due to interaction with residual gas - in this case each element has to include pressure value). It presumes uncoupled transverse motion, zero dispersion in the vertical plane.

Second variant - for beam dynamics calculation in the case of coupled linear motion. For IBS calculations it requires modification of the mathematical model.

Third variant - nonlinear dynamics, direct calculation of space charge effects, electron cooling calculations, heating due to interaction with internal target.

Model of the ion beam

Ion beam can be presented as **array of particles** or as **array of r.m.s. parameters** of the distribution function in the space of the invariants of the motion.

The beam model including array of r.m.s. parameters is used in the current version of BETACOOOL and presumes Goussian distribution.

Beam as an array of particles is required for multi particle simulation.

Each particle can be presented as

array of co-ordinates and momentum (6D vector)

or as an **array of invariants of the motion in the ring (3D vector: two Courant-Snyder invariants, and invariant of longitudinal motion).**

Particle as a 6D vector is used for real time simulations

3D vector for Monte Carlo simulations in the case when characteristic times of the distribution function variation is substantially longer than revolution period.

Models of cooling and heating effects

Each effect calculates ion life time and characteristic times of the beam r.m.s. parameters variation. It includes standard function which uses ring parameters (in the form of lattice functions) and beam parameters (in the form of r.m.s. parameter array) and returns vector of the characteristic times. All the effects are included into list of the effects.

Computation algorithm

1. Reading of initial parameters from file, preparations for calculation

2. Cycle over time

2.1. Step of integration

2.1.1. If the ion beam is presented by r.m.s. parameters of distribution function

(Step of the integration is substantially larger than revolution period)

Cycle over effects and calculation of the characteristic times of all active effects.

One step in the solution of the system of four differential equations:

$$\left\{ \begin{array}{l} N\dot{\epsilon} = N \sum_j \frac{1}{\tau_{life,j}} \\ \dot{\epsilon}_x = \epsilon_x \sum_j \frac{1}{\tau_{x,j}} \\ \dot{\epsilon}_z = \epsilon_z \sum_j \frac{1}{\tau_{z,j}} \\ H\dot{\epsilon}_{lon} = H_{lon} \sum_j \frac{1}{\tau_{lon,j}} \end{array} \right.$$

2.1.2. If the ion beam is presented by array of 3D particles

(Step of the integration is substantially higher than revolution period)

Generation the beam as an array of 6D particles by random generation of phases of betatron and synchrotron oscillations.

Cycle over optic elements, calculations of the right side of the motion equations in each element and cycle over particles in solution of the motion equations.

Calculation of characteristic time of the invariant variation for each particle.

Step over time for each particle and calculations of new values of the motion invariants.

2.1.3. If the ion beam is presented by array of 6D particles (Step of the integration is less than revolution period.)
Cycle over particles and one step of the integration of the motion equations.

For each particle its position inside the ring is calculated, the right sides of the motion equations are calculated depending on the particle position and co-ordinates of other particles.

2.2. Check the aperture limitations.

2.3. Calculation of the r.m.s., stability parameters and luminosity.

2.4. Output the new beam parameters into file.

2.5. Read from the file information about the calculation status (to prolong, to pause and change parameters or to stop the calculations).

For solution of the differential equation different methods can be used. Now Euler and 5 order Runge-Kutta methods with fixed step are realised. The methods are realised in the fixed standard and change of the integration method does not lead to change in other parts of the program.

Model of electron cooling system

1. Electron cooling as an optic element

It has to calculate the right parts of the motion equations.

In principle, the procedure calculating the friction force components requires the following input parameters:

three components of the ion velocity;

parameters of the electron beam:

- local density of the electron beam,**
- transverse velocity spread of the electrons,**
- longitudinal velocity spread of the electrons,**
- local momentum shift of the electrons,**
- angles in horizontal and vertical planes between ion beam axis and direction of mean electron velocity,**
- magnetic field value.**

Different formulae for friction force require different list of parameters, however for more famous formulae all the parameters can be calculated from the presented list.

Methods of the friction force calculation

All the procedures for friction force calculation including into the program can have standard input and output variables:

input:

6D vector of the particle co-ordinates,
list of the electron beam parameters,

output:

6D vector of the right sides of the motion equation.

Model of the electron beam

Input parameters:

ion co-ordinates: vertical, horizontal and distance from the ion bunch center,

distance between centers of the ion and electron bunches.

Output is the list of electron beam parameters required for friction force calculation.

The model of the electron cooling includes:

library of electron beam models

and library of the methods for friction force calculation.

Structure of the algorithm

1. input parameters of the cooling system from the array of the optic elements,
2. input 6D vector of ion co-ordinates,
3. choice of the required model of the electron beam in the library,
4. calculation of the list of the electron beam parameters,
5. choice of the procedure for the friction force calculation from the library,
6. calculation of the right sides of the motion equation.

Electron cooling as an optic element is used when the ion beam is presented as an array of the particles. For 6D vector mode the motion equations are solve directly.

For 3D vector:

initially the phases of betatron and synchrotron oscillations are randomly generated,

the motion equations are solved

and finally the invariant deviations are calculated.

At initial stage of the new version development we plan to realise **three models of the electron beam**:

- to repeat the standard model of the electron beam using in the current version;
- electron beam with uniform density distribution in radial direction and non uniform (Gaussian) in longitudinal direction,
- non uniform density distribution in radial and in longitudinal directions.

It seems to be very attractive to use output of the program calculating electron beam dynamics, but in this case we have to know format of the output file.

For friction force calculation the following formulae will be used:

1. Budker's formula for non magnetised electron beam with uniform velocity distribution,
2. Formulae for non magnetised beam with flattened velocity distribution,
3. Parkhomchuk's formula,
4. Derbenev-Skrinsky-Meshkov formula.

In principle one can realise input of the friction force values calculated with other programs or obtained experimentally. But now there are no ideas how to realise this by standard way.

Electron cooling as an effect

If the ion beam is presented by r.m.s parameters of the distribution function one need to calculate characteristic times of the emittance deviation. It will be performed by averaging the action of the cooling over the phase of oscillations and over invariant of the motion. This procedure was elaborated in the frame of the current BETACOOOL version. and will be modified in order to use standard presentation of the electron cooling as an optic element.

Recombination inside the cooling section

To calculate the recombination coefficient we need to know the following parameters of the electron beam:

-transverse velocity spread of the electrons,

-angles in horizontal and vertical planes between ion beam axis and mean electron velocity.

To calculate recombination rate for ions in the given position of electron beam (or survival probability for single particles) we need also **local density** of the electrons.

All these parameters are in the list of output parameters of the electron beam model.