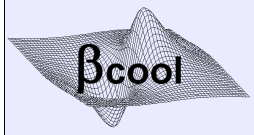
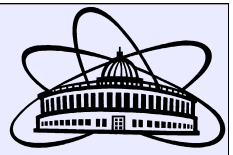




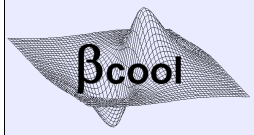
Studies of beam dynamics in cooler rings

I.Meshkov, A.Sidorin, A.Smirnov

JINR, Dubna, Russia

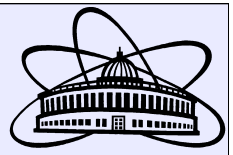
J.Stein, J.Dietrich

FZJ, Juelich, Getmany



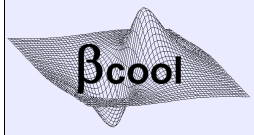
BETACOOL code

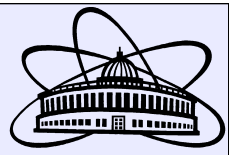
(since 1995)



Collaboration with Scientific Organizations

- BNL (USA)
- Fermilab (USA)
- RIKEN (Japan)
- NIRS (Japan)
- Kyoto Univ. (Japan)
- CERN (Switzerland)
- ITEP (Russia)
- BINP (Russia)
- FZJ (Germany)
- GSI (Germany)
- Erlangen Univ. (Germany)
- Uppsala Univ. (Sweden)





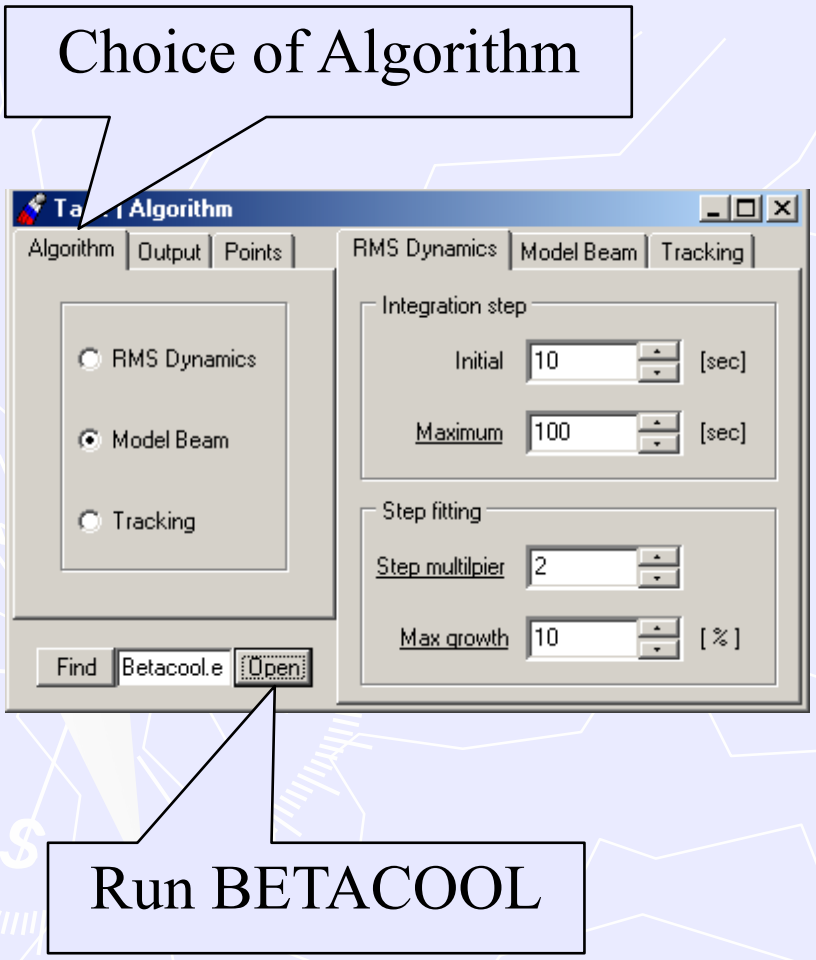
General goal of BETACOOL code:

- Simulation of long-term processes (long - in comparison with the ion revolution period) leading to variation of the ion distribution function in 6 dimensional phase space.
- The ion beam motion inside a storage ring is supposed to be stable and is treated in linear approximation.

Advantages of BETACOOL code:

- Many different effects (ECOOL, IBS, Target, RestGas etc.) can be simulated simultaneously at the same parameters using different algorithms
- Fast estimations on PC
- Graphical interface under Windows
- Control the results and vary parameters during simulation

BETACOOL Algorithms



- **RMS Dynamics** – evolution of RMS parameters of ion beam (Gaussian distribution)
- **Model Beam** – Monte-Carlo method with modeling particles (one integration step per some revolution turns)
- **Tracking** – particles dynamics over the real lattice with using Molecular Dynamics technique (crystalline beam simulation)

RMS Dynamics

$$\begin{cases} \dfrac{d\varepsilon_{hor}}{dt} = \varepsilon_{hor} \sum_j \dfrac{1}{\tau_{hor}}, \\ \dfrac{d\varepsilon_{ver}}{dt} = \varepsilon_{ver} \sum_j \dfrac{1}{\tau_{ver}}, \\ \dfrac{d\left(\frac{\Delta p}{p}\right)^2}{dt} = \left(\dfrac{\Delta p}{p}\right)^2 \sum_j \dfrac{1}{\tau_{lon}}, \\ \dfrac{dN}{dt} = N \sum_j \dfrac{1}{\tau_{life}}, \end{cases}$$

- Ion beam has Gaussian distribution during the calculation
- Each effect calculates vector of growth rates

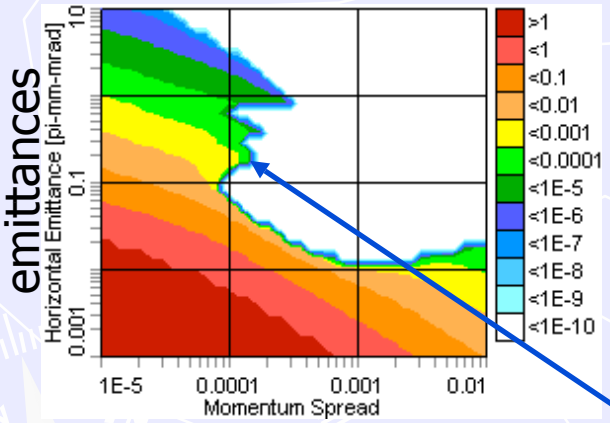
$$\vec{R} = \left\{ \tau_{hor}^{-1}, \tau_{ver}^{-1}, \tau_{lon}^{-1}, \tau_{life}^{-1} \right\}$$

- Algorithm is considered as a solution of the equations for R.M.S. parameters
- Real lattice structure is used for IBS and Rest Gas calculation

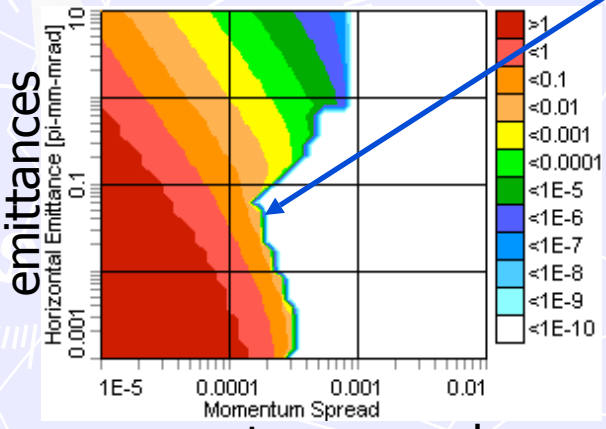
3D Diagrams for HESR

heating and cooling growth rates

IBS (positive)



momentum spread



momentum spread

τ_{hor}^{-1}

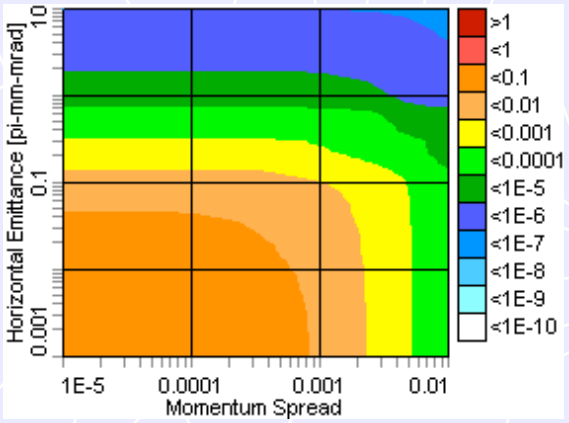
transverse component

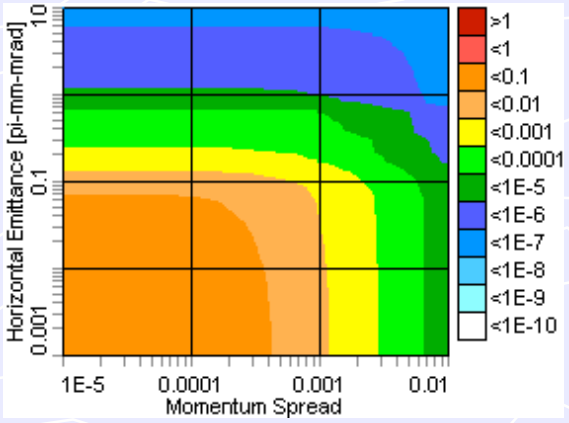
Equilibrium between IBS and ECOOL

τ_{lon}^{-1}

longitudinal component

ECOOL (negative)

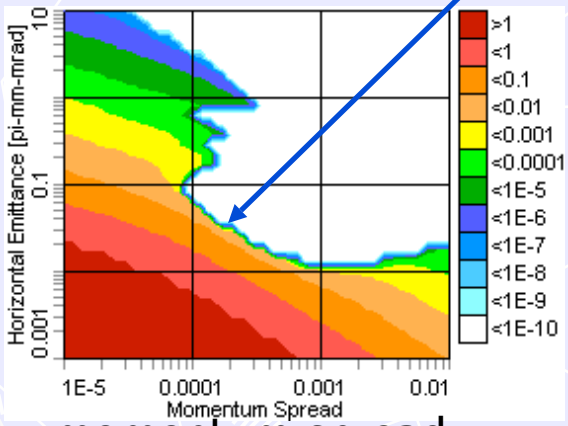




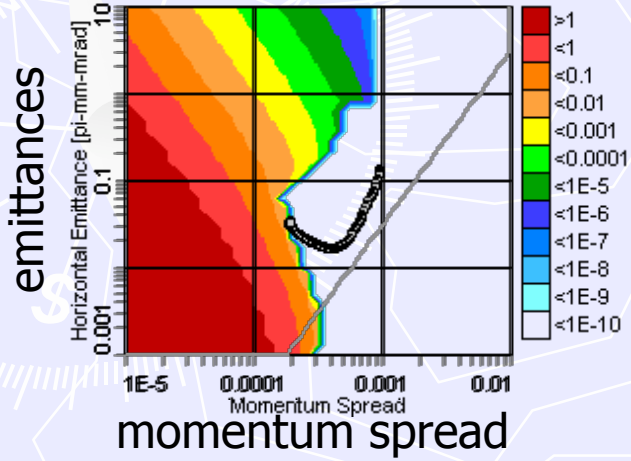
RMS Dynamics for HESR

(ECOOL+IBS)

3D Diagrams

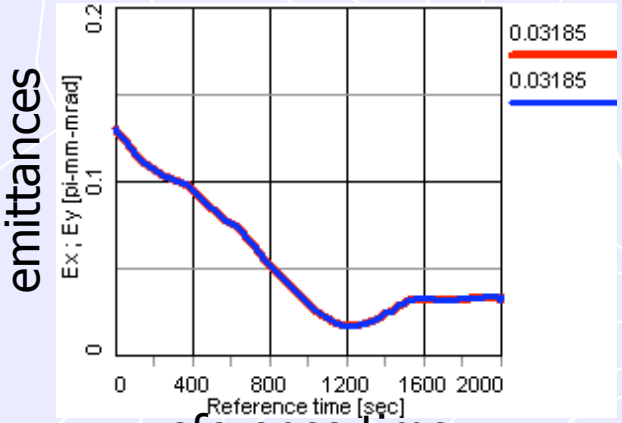


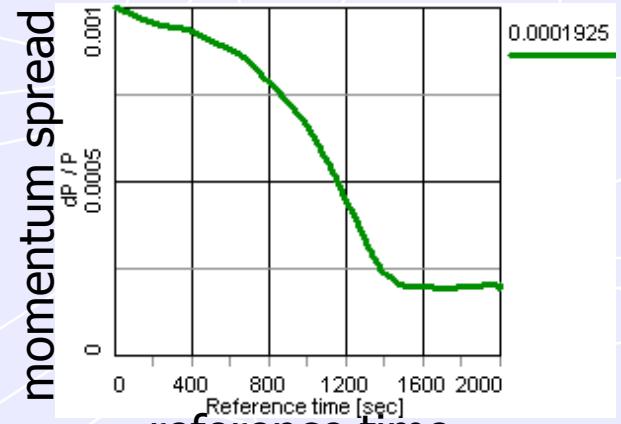
transverse



longitudinal

Beam evolution



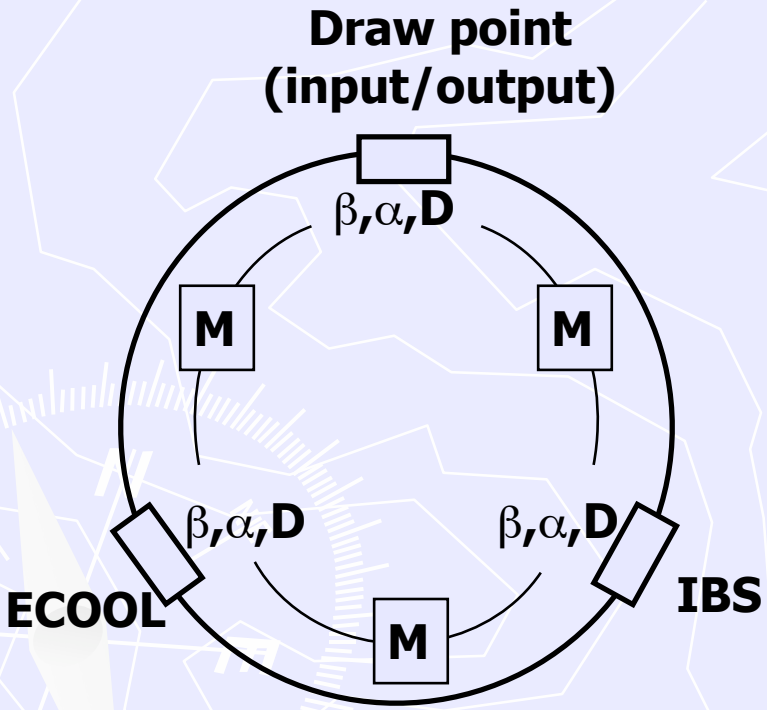


Model Beam algorithm

(based on SimCool code of Novosibirsk group)

- **Ion beam is presented by array of model particles**
- **Simplest model of the ring – only lattice functions in the location of the effects are necessary.**
- **Each effect calculates a kick of the ion momentum components and changes the particle number**
- **One integration step equal some revolution turns**

Scheme of Model Beam Algorithm



- Each Effect is described by lattice function β, α, D.
- Transformation matrix between effects is calculated from lattice functions between them
- Model particles are rotated in accordance with transformation matrix between effects
- Each effect applies kicks and changes momentum components of particles

Examples of Kicks for different effects

- IBS

$$\Delta\theta_i = \sqrt{\left\langle \theta_i^2 \right\rangle} \times random \qquad \left\langle \theta_i^2 \right\rangle = \frac{\varepsilon_i}{\beta_i} \frac{T_{rev}}{\tau_i} N_{turn}$$

here index i corresponds to degree of freedoms

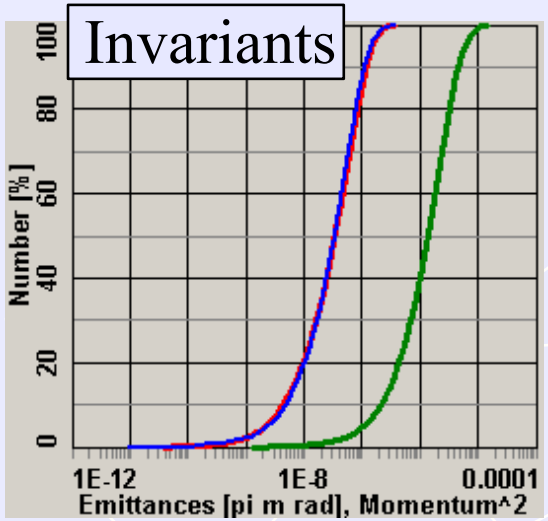
- ECOOL

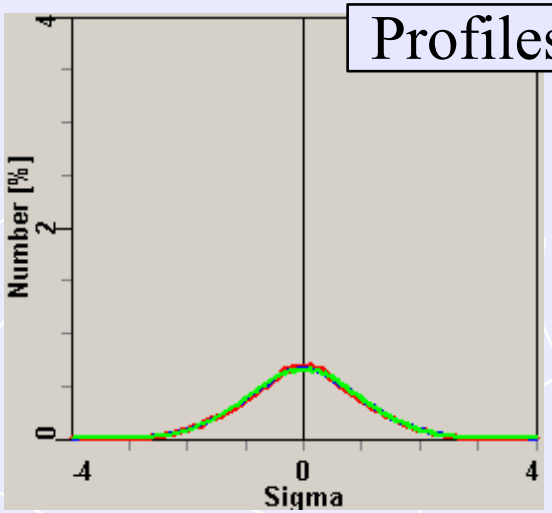
$$\Delta\theta_i = \frac{F_i\left(\vec{X}\right)}{Mc^2\beta^2\gamma} l_{cool} N_{turn}$$

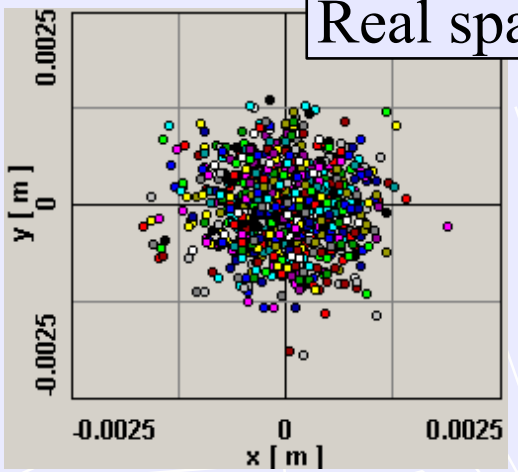
- Additional cooling/ heating

$$\Delta\theta_i = \theta_i \times \begin{cases} \dfrac{T_{rev}}{\tau_i} N_{trun}, & \dfrac{T_{rev}}{\tau_i} N_{trun} > -1 \\ \exp\left(\dfrac{T_{rev}}{\tau_i} N_{trun} \right) - 1, & \dfrac{T_{rev}}{\tau_i} N_{trun} \le -1 \end{cases}$$

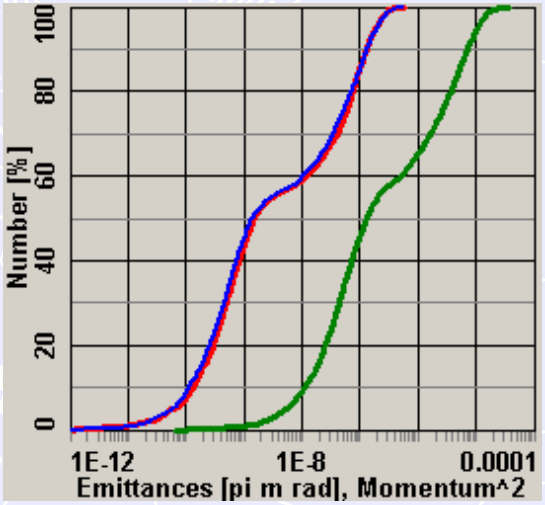
Initial distribution for RHIC

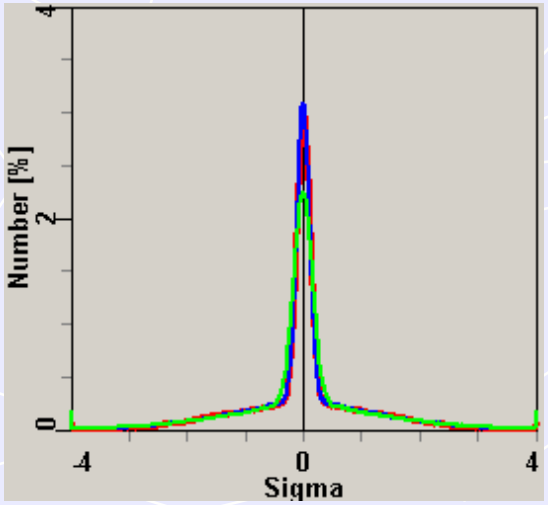


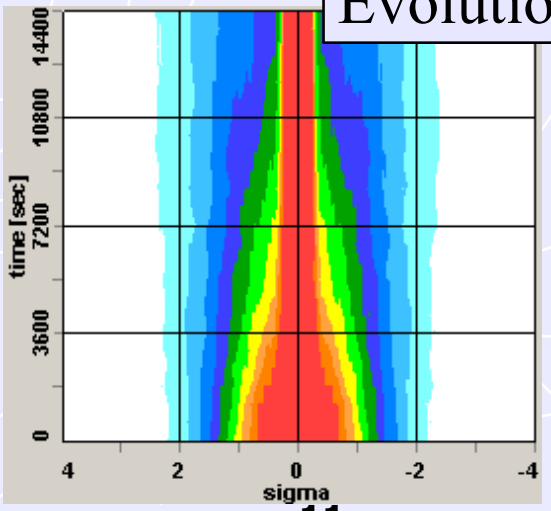




Distribution after 4 hours of cooling







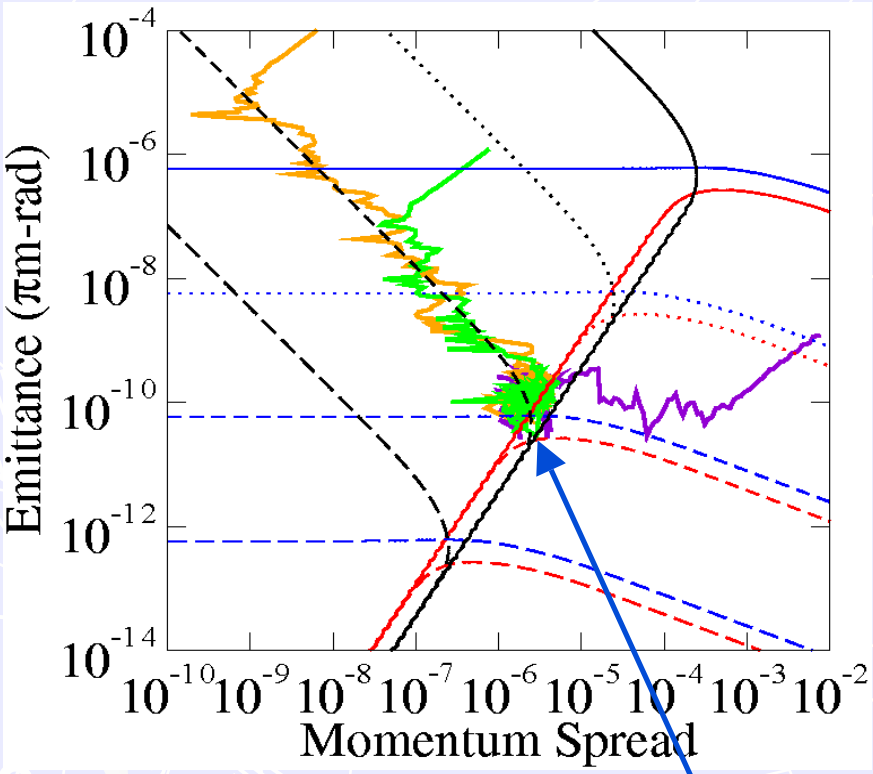
Tracking algorithm

Ion beam is presented by array of real particles

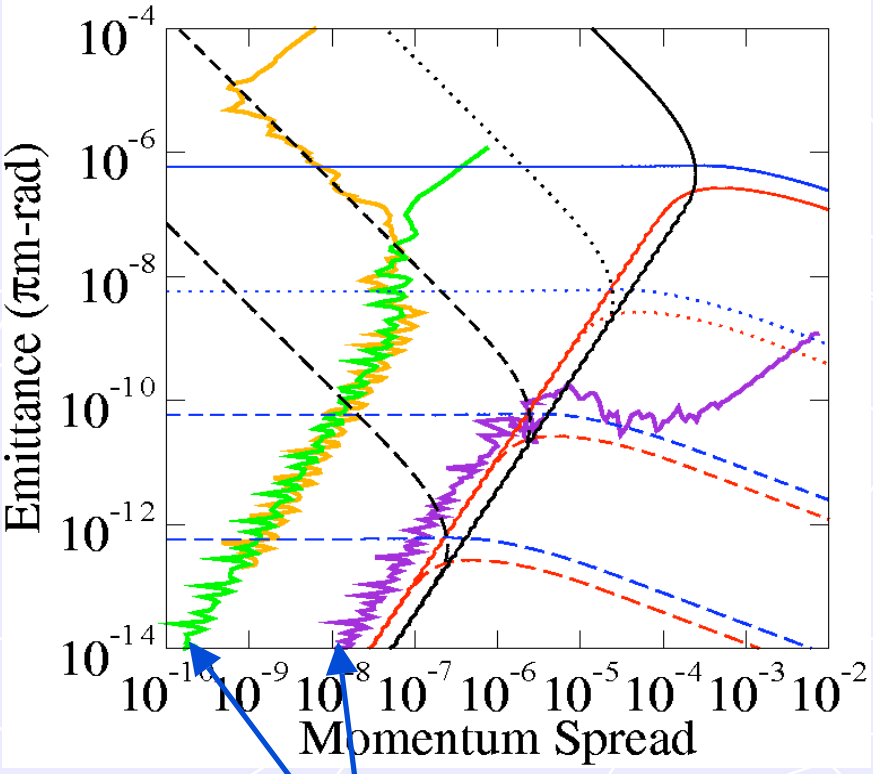
- Each effect is related to some optic element
- The effect works as a transformation map or thin lens
- IBS is calculated as a Coulomb scattering using Molecular Dynamics technique
- The ring structure is imported from modified input MAD8 file

Analytical and MD simulation of IBS for ESR

Equilibrium between ECOOL and IBS



Ordered state of ion beam

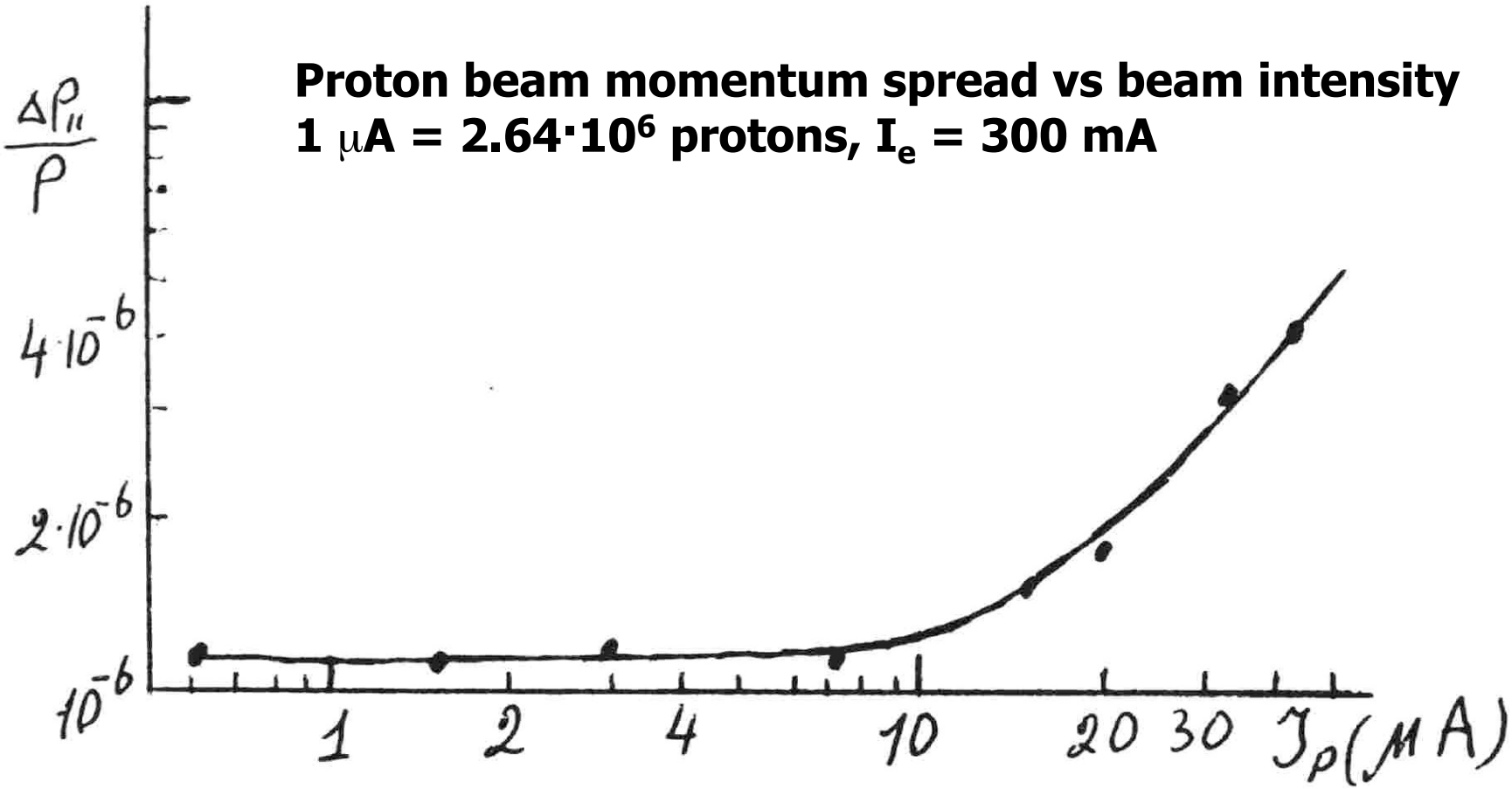


Equilibrium between IBS and Cooling

Ordered state

NAP-M experiments (1979)

Proton beam momentum spread vs beam intensity
1 μA = 2.64·10⁶ protons, I_e = 300 mA

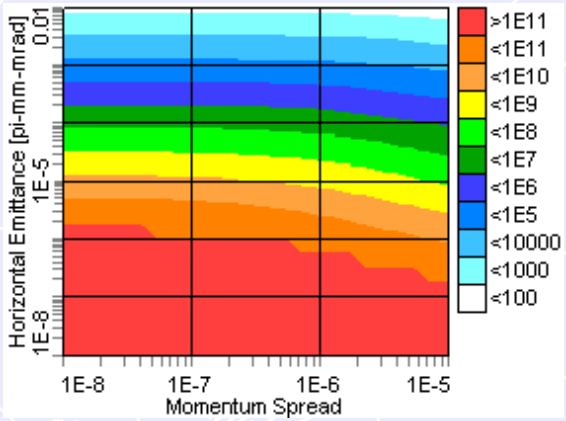


1 3 10 30 100

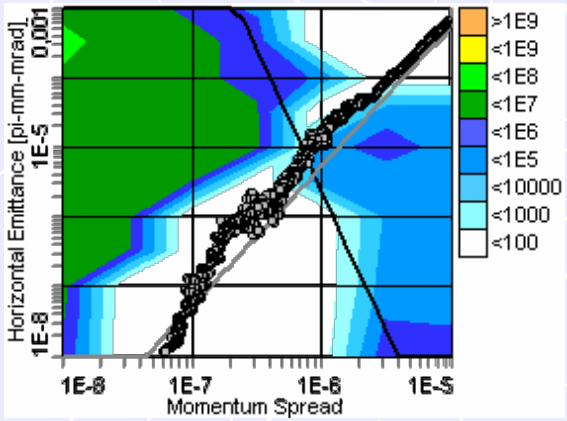
Np , 10^6

Ordered beam simulation for NAP-M
(Np=1e6)

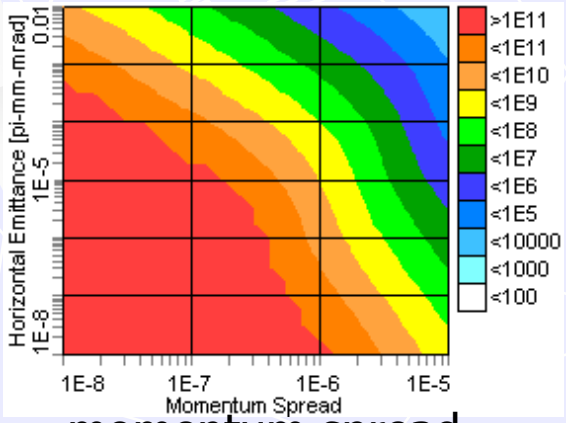
IBS growth rates (Martini model)



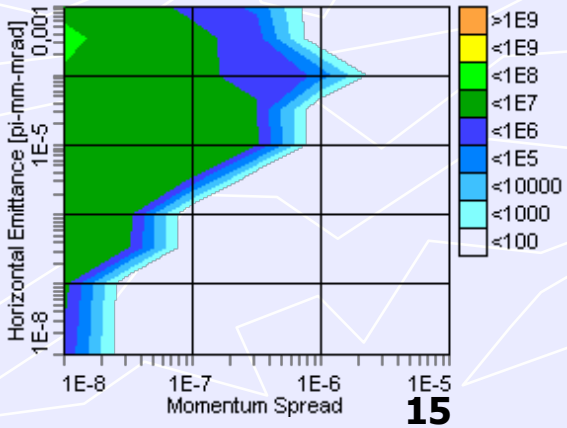
MD simulation



transverse



longitudinal



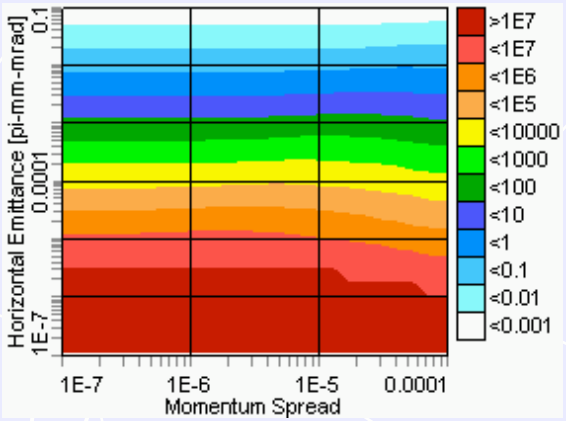
Ordered beam simulation for COSY

Np=1e6

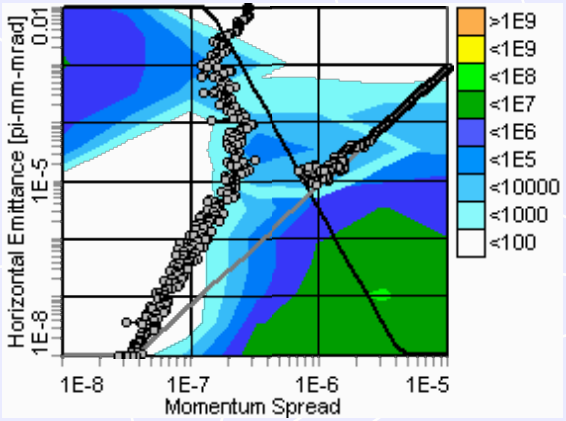
IBS growth rates (Martini model)

MD simulation

emittances

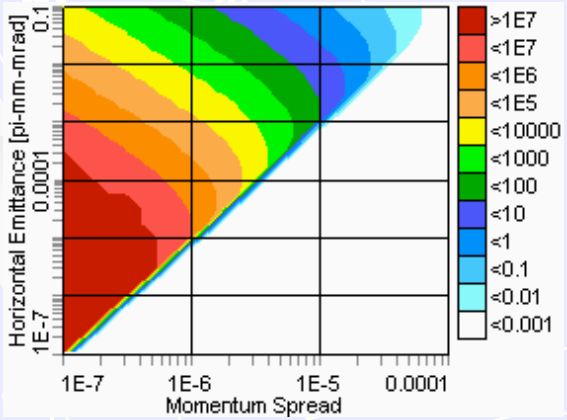


transverse

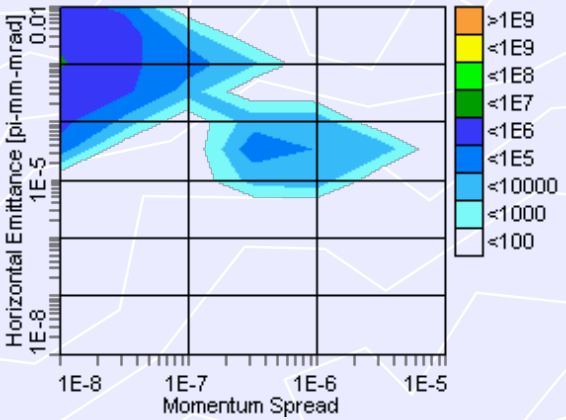


momentum spread

emittances

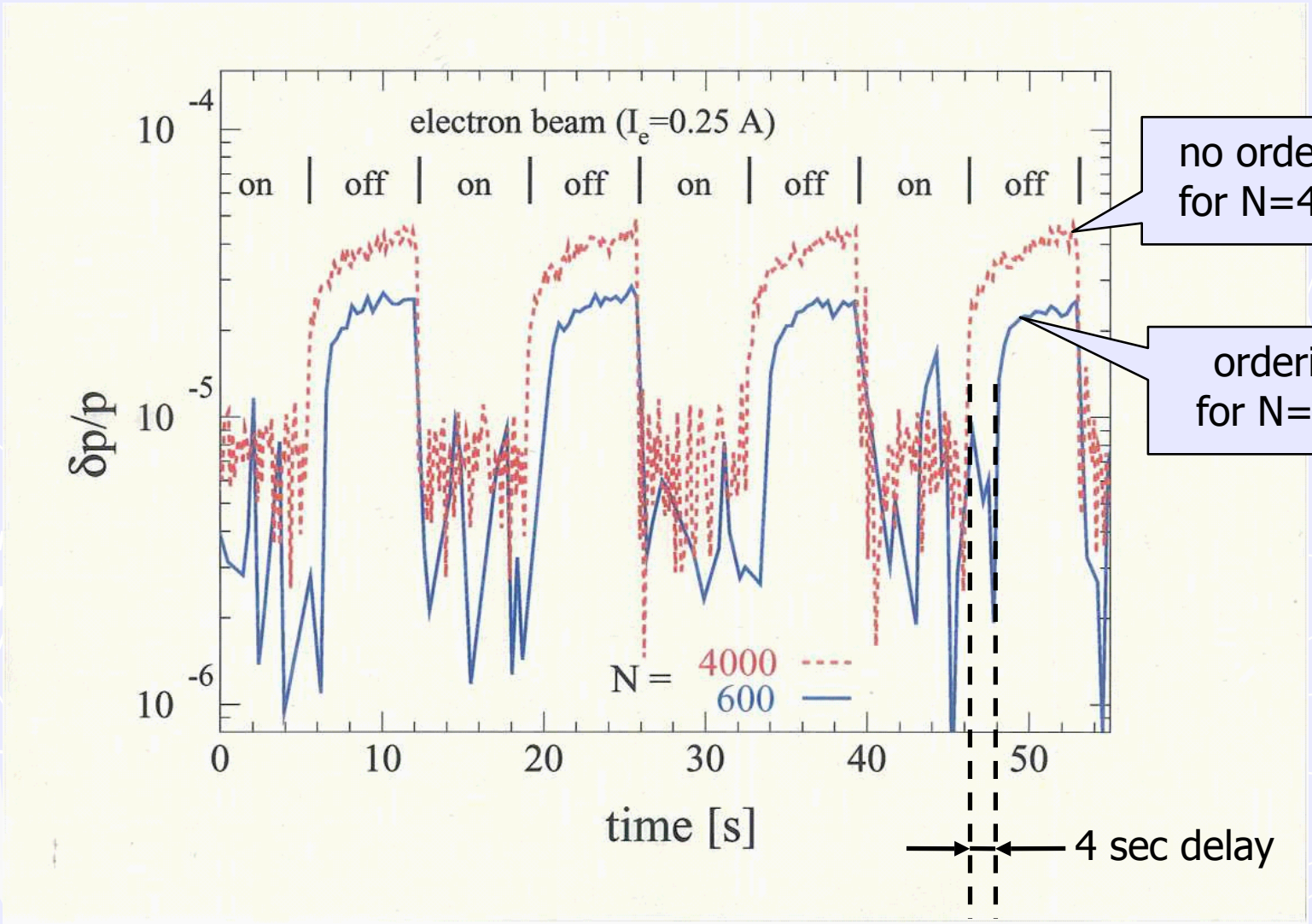


longitudinal



momentum spread

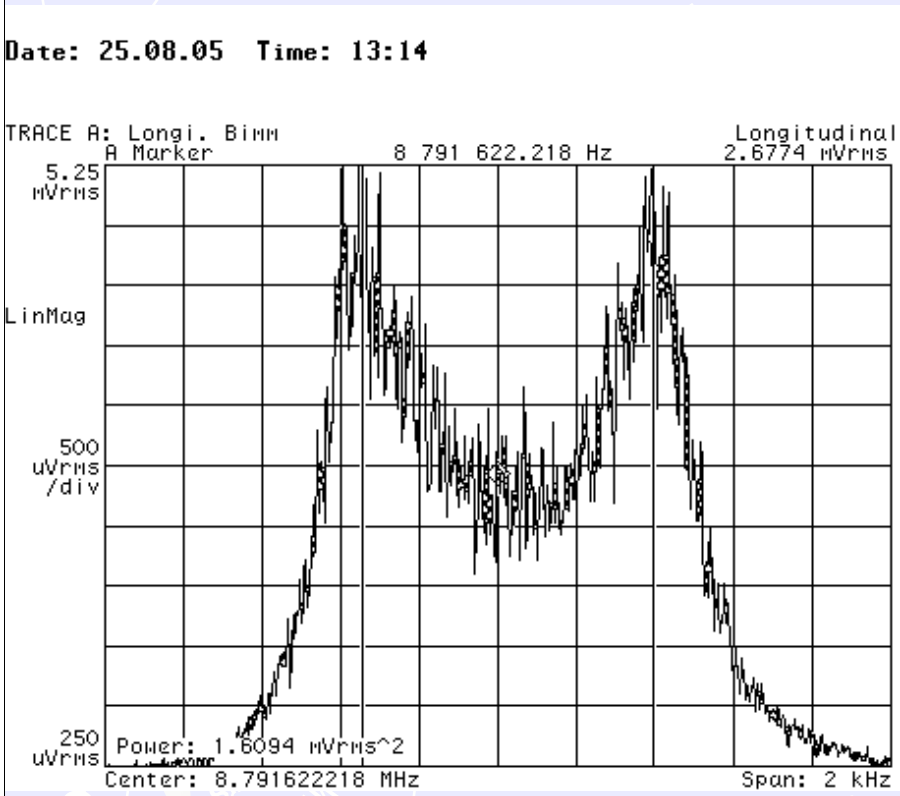
ESR experiments with ordered beam



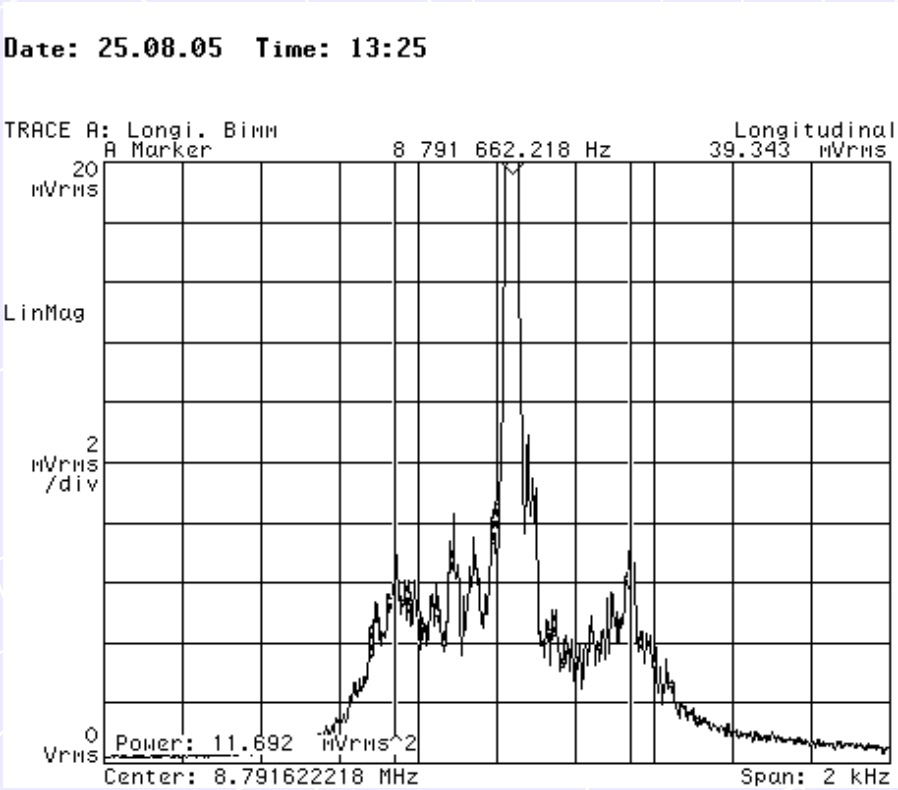
Ion beam can stay in ordered state without cooling for a few seconds

Experiments on COSY

electron cooling (Ie=250mA)
proton beam (E=294 MeV/c, **N=1e9**)



without heating

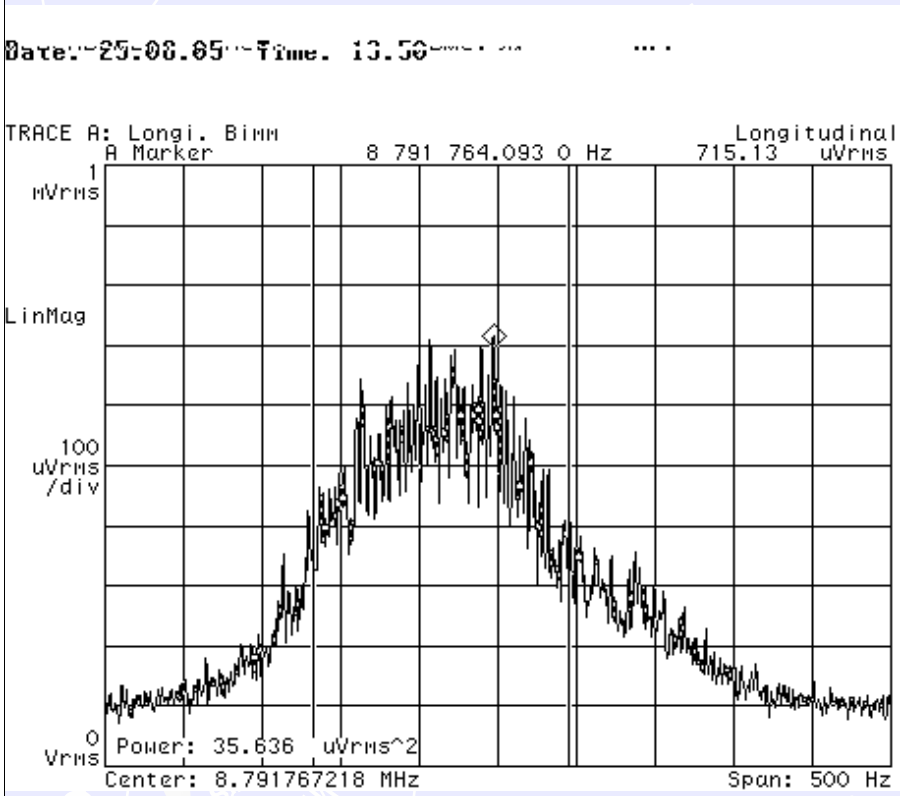


transverse heating with white noise

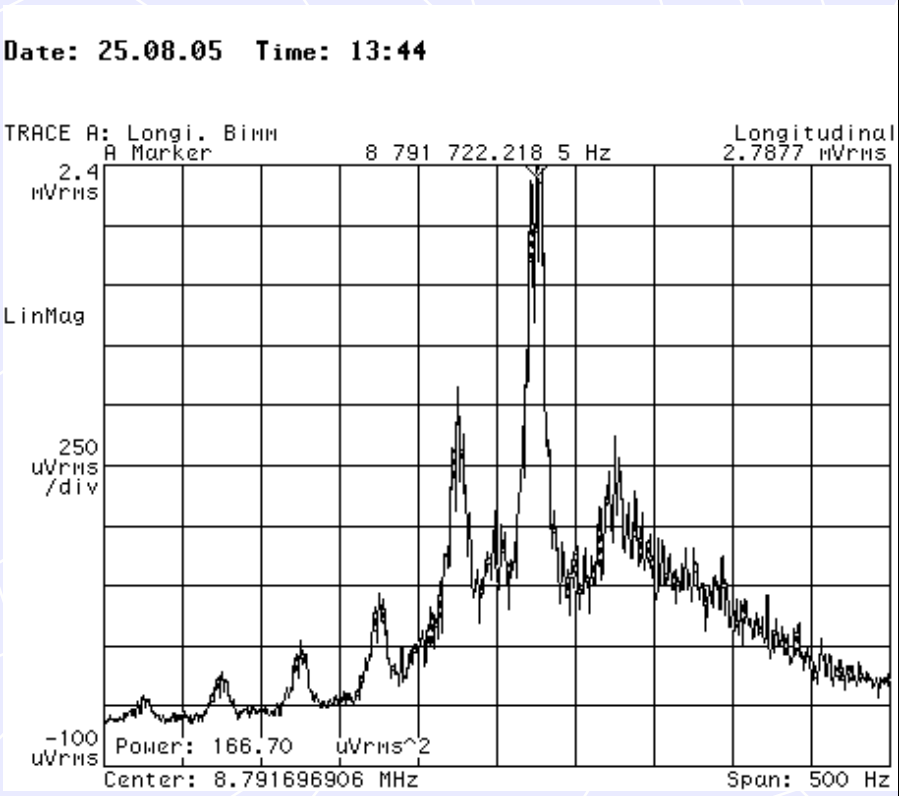
Experiments on COSY

electron cooling (Ie=250mA)

proton beam (E=294 MeV/c, **N=1e7**)

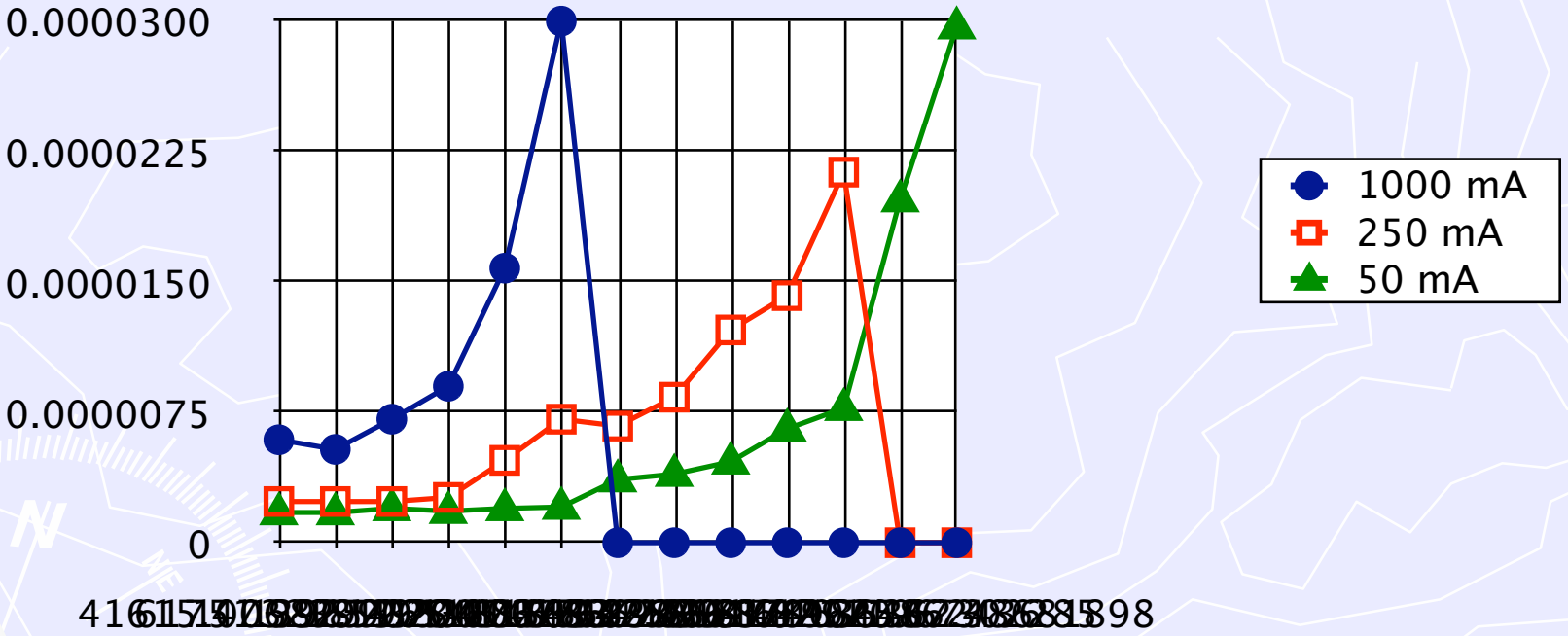


without heating



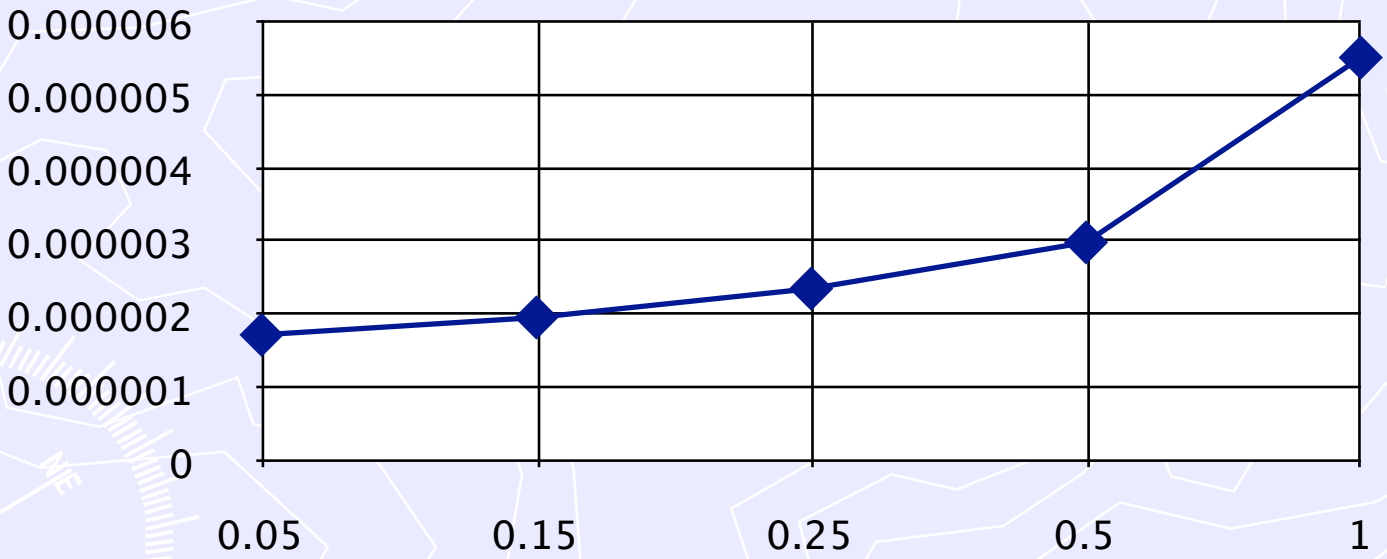
transverse heating with white noise

Experiments on COSY



dependence of momentum spread on proton number
for different currents of electron beam

Experiments on COSY



dependence of minimum momentum spread
on electron beam current

Conclusion

- Achievement of ordered state for proton beam is a complicated task:
  - transition point to ordered state exists for very low momentum spread ($<10^{-6}$)
  - minimum momentum spread of ions is defined by electron temperature
- Possible solution of these problems:
  - increase of the proton energy
  - adiabatic acceleration and expansion of electron beam to reach smallest electron temperature
- The special method of transverse heating is needed to verify the break in the longitudinal component of IBS heating rates