HIGHLIGHTS FROM COULOMB05

Senigallia, Italy, September 12-16, 2005

Elias Métral

Scientific Program : Structure of the workshop

Monday: Hamiltonian microscopic models and mean field theory

Tuesday: Numerical methods and simulation studies of intense beams

Wednesday: Experimentl results on intense beams and FEL

Thursday: Theory and experiments on intense beams and electron clouds

$\Longrightarrow$ **M. Giovannozzi: Resonant multi-turn extraction: principle and experiments**

$\Longrightarrow$ **E. Métral: Observation of octupole driven resonance phenomena with space charge at the CERN Proton Synchrotron**

Friday: Overview of recent projects

M. Pusterla, “Non-conventional approach to beam dynamics in heavy-ion accelerators” (1/2)

- **The theoretical analysis of charge particle beam is almost entirely based on classical mechanics and electromagnetism**

- **However, the presence of many particles in each bunch ($\sim 10^{12}$, $\sim 10^{13}$) generates several phenomena which cannot describe correctly because of the unpredictable initial conditions of the particles in the various bunches and several interactions among them**

  - **IBS**
  - **Beam-strahlung**
  - **Fluctuations of space-charge contribution**
  - **At a macroscopic level: magnet imperfections and misalignments**

M. Pusterla, "Non-conventional approach to beam dynamics in heavy-ion accelerators" (2/2)

- $\Longrightarrow$ A non-conventional formalism was proposed and justified theoretically, that combines the determinism of classical mechanics with a stochastic process $\Longrightarrow$ Beam-lifetimes, beam losses and a halo creation can be predicted

- The approach leads to a nonlinear, and then linear Schrodinger equation for the motion of the charged particles (Nelson's stochastic mechanics) with a completely different interpretation of the fundamental parameters in the equation

  $\Longrightarrow$ Ex: The Planck constant is replaced by the normalized emittance…

Interesting discussions for the new CT extraction of Massimo (1/4)

- **Based on adiabatic trapping of particles into stable islands**
- **3 regimes may in fact appear**
  - **At the beginning of the process the adiabatic theory is not valid. Another theory has to be applied $\Longrightarrow$ Contact with A. Neishtadt (the author of the adiabatic theory) from SRI-Moskow**
  - **In the 2nd regime the adiabatic theory works**
  - **In the 3rd regime, at the end of the trapping and separation of the islands, the idea would be to reduce the chaotic region (which will lead to emittance growth) $\Longrightarrow$ Contact with Y. Elskens (from Univ. Marseille), C. Chandre (from CPT-CNRS, Marseille) and C. Ciraolo (CEA Cadarache), who published a paper on the control of Hamiltonian systems $\Longrightarrow$ They succeeded to create barriers to diffusion**

Interesting discussions for the new CT extraction of Massimo (2/4)

Our strategy of control

Aim: $H = H_0 + \varepsilon V$ chaotic $\longrightarrow$ $H_c = H_0 + \varepsilon V + f$ regular

$f = -\varepsilon V$ energetically expensive solution

$\Rightarrow$ tailoring the control term f

Requirements on f:

- small with respect to the perturbation εV
  > here, we require that $f = O(\varepsilon^2)$
- localized in phase space
  > accessible region, fewer energy for the control
- with a certain shape
  > robustness ...
- other requirements ?

> find a small and apt modification of the system / great influence on its dynamics

Interesting discussions for the new CT extraction of Massimo (3/4)

PRL **94,** 074101 (2005) PHYSICAL REVIEW LETTERS week ending 25 FEBRUARY 2005

Channeling Chaos by Building Barriers

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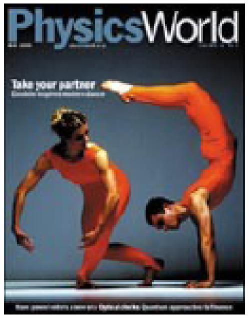
(Received 9 June 2004; published 23 February 2005)



Chaos comes under control

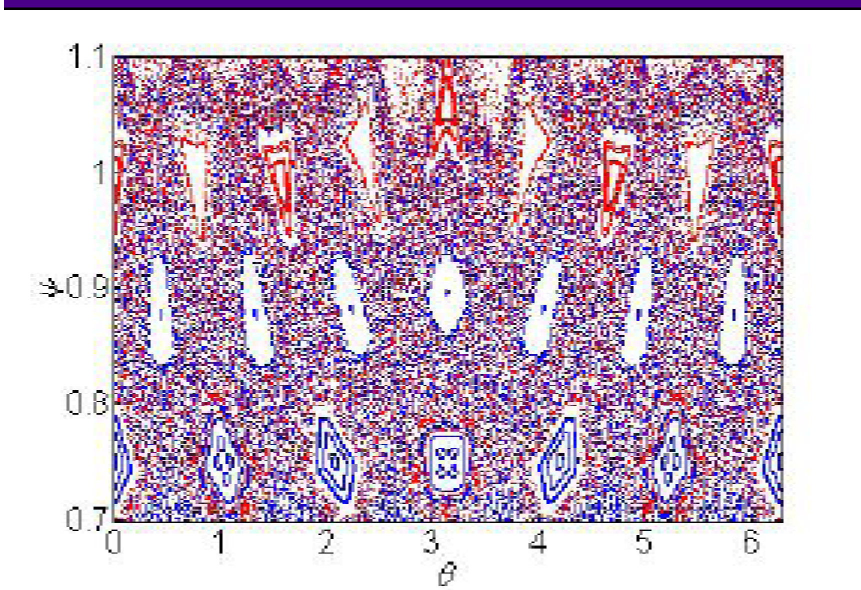
Physics in Action: May 2005

A new way to channel chaos could allow greater control over plasmas such as those in experimental fusion reactors and particle accelerators

Whether you are trying to negotiate a crowded street or searching for an important document in a haphazard filing system, "chaos" is generally seen as a bad thing. But if chaotic systems did not exist, the world would be a rather boring place. The weather, plate tectonics and even the stock market are all examples of chaotic systems: in all these examples the slightest change to the initial conditions can lead to a wildly different outcome, despite the fact that the systems all obey deterministic rules.

But this has not stopped physicists from trying to tame chaos. In particular,we would like to be able to control the chaotic diffusion processes that severely complicate experiments with fusion plasmas and particle accelerators. Now, researchers at the CNRS and Université de Provence in Marseilles have found a way to channel chaos by building barriers to this diffusion, opening up the possibility of controlling a wide range of systems at a minimal energy cost (C Chandre *et al.* 2005 *Phys. Rev. Lett.* **94** 074101).

Interesting discussions for the new CT extraction of Massimo (3/3)



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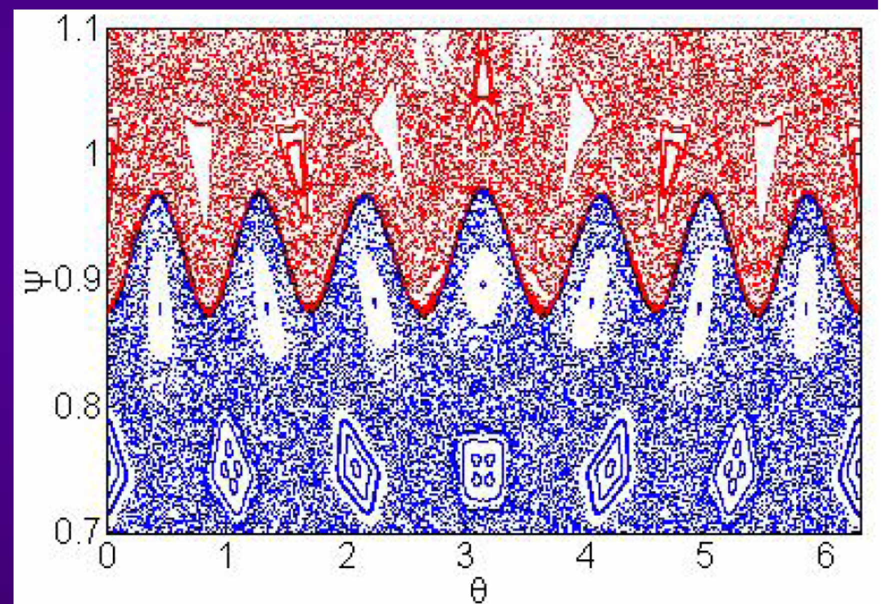


Y. Senichev, “Hamiltonian formalism for halo investigation in high intensity beam”

- **He applied Hamiltonian formalism together with standard theory of perturbation. Using Courant-Snyder together with Floquet method, he obtained the self-consistent system of equations**

⟹ The model of the halo creation was developed

⟹ This was done without external nonlinearities. The nonlinearity comes here from space charge

⟹ The analitical formula for the emittance growth has been derived

⟹ The analitical and the numerical results have been compared and a good agreement was observed

R. Warnock, “Study of Bunch Instabilities by the Nonlinear Vlasov-Fokker-Planck equation”

Summary

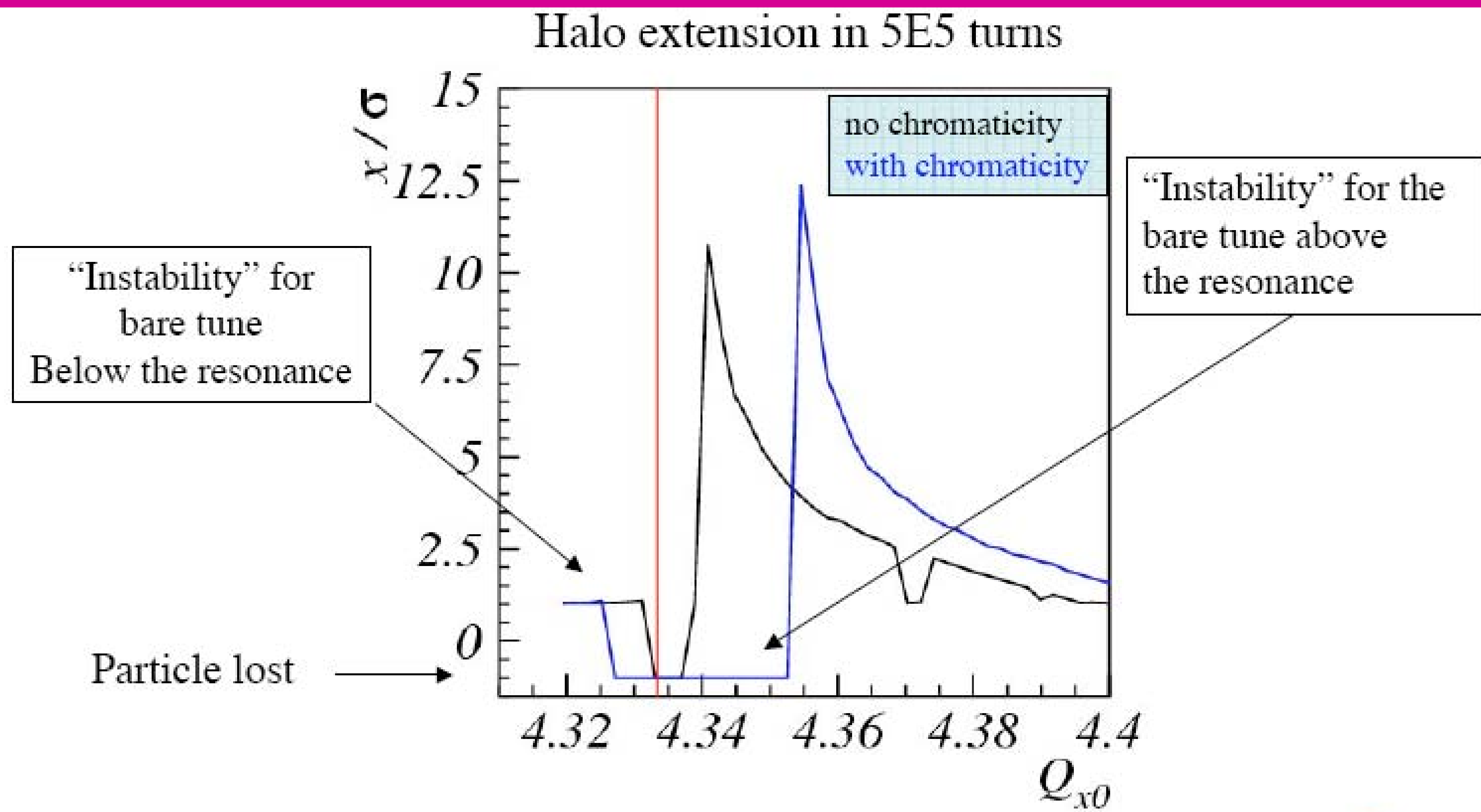
We have improved the theory of longitudinal bunch instabilities in several ways:

- Better solution and analysis of the Haīssinski equation for equilibrium.
- Better formulation of the linearized Vlasov equation for a bunched beam, as a non-singular integral equation, more amenable to numerical solution.
- Introduced a simple and effective method for solution of the nonlinear Vlasov-Fokker-Planck equation, allowing low-noise simulations of time dependent nonlinear phenomena such as the sawtooth mode. Realized in a very simple code.
- Initiated the study of CSR in storage rings by VFP simulation. Explained bursting mode of CSR.

G. Franchetti, "Particle trapping by nonlinear resonances and space charge" ⟹ He added the effect of chromaticity

Halo extension and chromaticity

⟹ The presence of chromaticity makes the vicinity of the resonance more unstable



G. Franchetti Coulomb 05

S. Lund, “Space charge and transport limits of ion beams in periodic quadrupole focusing channels” (1/4)

Good transport of a single component beam with intense space-charge described by a Vlasov-Poisson type model requires:

Lowest Order:

1. Stable single-particle centroid

Next Order:

2. Stable rms envelope

Higher Order:

3. “Stable” Vlasov description

Transport can fail or become “unstable” within the Vlasov model for several reasons:

- Collective modes internal to beam become unstable and grow
  - Large amplitudes can lead to statistical (rms) beam emittance growth
- Excessive halo generated
  - Increased statistical beam emittance and particle losses
- Combined processes above

S. Lund, "Space charge and transport limits of ion beams in periodic quadrupole focusing channels" (2/4)

The depressed particle phase advance provides a convenient measure of space-charge strength

Depressed single-particle phase advance in the presence of uniform space-charge for a particle moving in the matched beam envelope:

$$\boxed{\begin{gathered}\varepsilon_x = \varepsilon_y \equiv \varepsilon \\ \sigma = \varepsilon \int_{s_i}^{s_i+L_p} \frac{ds}{r_x^2} = \varepsilon \int_{s_i}^{s_i+L_p} \frac{ds}{r_y^2}\end{gathered}}$$

$$\lim_{Q \to 0} \sigma = \sigma_0$$

Normalized space charge strength or "depressed tune" :

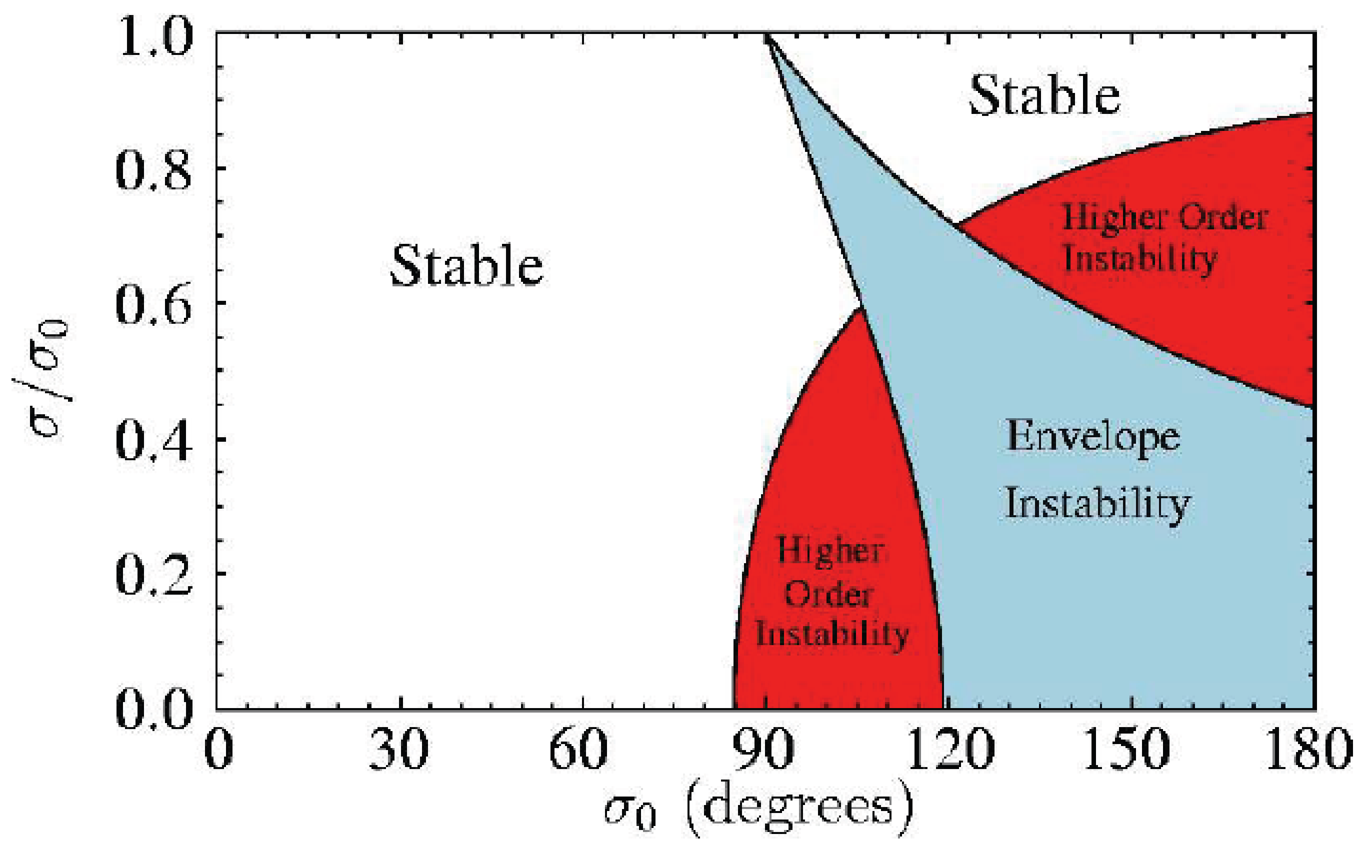
$$\boxed{0 \leq \sigma/\sigma_0 \leq 1}$$

$\sigma/\sigma_0 \to 0$ Cold Beam (space-charge dominated) $\varepsilon \to 0$

$\sigma/\sigma_0 \to 1$ Warm Beam (kinetic dominated) $Q \to 0$

S. Lund, "Space charge and transport limits of ion beams in periodic quadrupole focusing channels" (3/4)

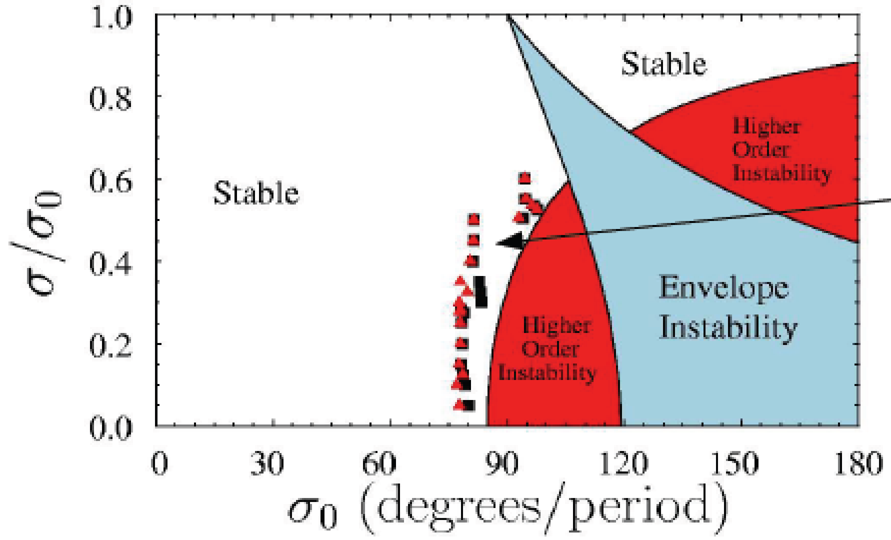
Summary of beam stability with intense space-charge in a quadrupole transport lattice: centroid, envelope, and experiment on higher order emittance growth/particle losses



S. Lund, "Space charge and transport limits of ion beams in periodic quadrupole focusing channels" (4/4)

Core particle simulations: Stability boundary data from a new "halo" stability criterion are in rough agreement with experimental observations for quadrupole transport

- Start at a point (σ_0, σ) deep within the stable region
- While increasing σ_0 vary σ to find a point (if it exists) where initial launch groups [1.05, 1.10] outside the matched beam envelope are pumped to max amplitudes of 1.5 times the matched envelope
  - Boundary position relatively insensitive to specific group and amplitude growth choices



Stability boundary points for two slightly different amplitudes (triangles, squares)

Lagniel also carried out a halo analysis of transport limits in periodic channels but seems to conclude (overly restrictive) that AG transport is unstable for

[Lagniel, Nuc. Instr. Meth. A **345**, 405 (1994)]

C. Benedetti, "Collisional effects in beam dynamics " (1/2)

⟹ He looked only at IBS here. It may be important to understand our experiments on the Montague resonance (dynamical crossing)

I.1 - **The 2D COULOMB OSCILLATORS model**

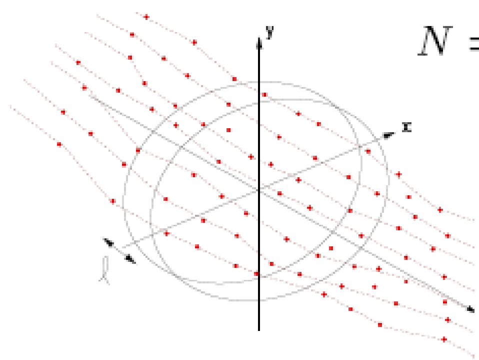
- Coasting beam: N_p particles per unit length, charge e, mass m_p + linear confining forces

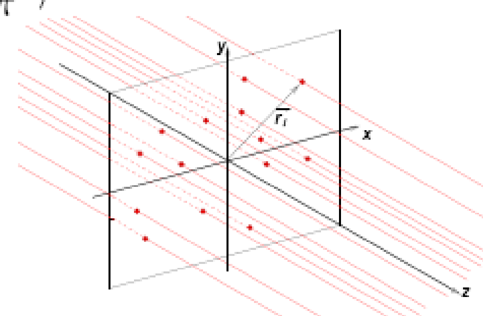
$\Rightarrow$ R_B is the transv. dimension of the beam, $\rho_s \sim N_p/\pi R_B^2$ the mean particles density, $\ell \sim \rho_s^{-1/3}$ the specific length

- Assuming longitudinal coherence $\Rightarrow$ point particles $\rightarrow$ N parallel wires (keeping fixed total mass and charge per unit length)

$\Rightarrow$ N is the # of particles in a cylinder of height ℓ

$$N = (N_p R_B)^{2/3} \pi^{1/3}$$





- $R_b \sim 10$ mm, $N_p \sim 10^{10 \div 11}$ part/m $\Rightarrow$ $N^{phys} \sim 10^{5 \div 6}$ wires

C. Benedetti, “Collisional effects in beam dynamics ” (2/2)

IV - Conclusion & outlook

- The COULOMBIAN OSCILLATORS model has been proposed to study collisional effects in system with long range interactions.

- A scaling law for the relaxation time as a function of the system parameters (N, space charge, emittances, tunes) has been derived on the basis of the Landau kinetic theory for a Gaussian beam

- The validity limit of the scaling law has been checked by using numerical simulation $\Rightarrow$ interplay between collisional effects and non linear phenomena in the case of the Montague resonance has been studied

- Comparison between standard IBS modules and collisional code is required

P.R. Zenkevich, "A New algorithm for the kinetic analysis of intra-beam scattering in storage rings" (1/3)

- **IBS includes:**
  - **1) Multiple IBS**
  - **2) Single-event IBS (Touschek effect). This effect is out of frame of this report**

- **Multiple IBS results in:**
  - **1) Transfer of energy from hot transverse degrees of freedom to cold longitudinal one**
  - **2) Slow growth of 6-dimensional beam emittance due to dispersion function and modulation of Twiss parameters**

P.R. Zenkevich, "A New algorithm for the kinetic analysis of intra-beam scattering in storage rings" (2/3)

- **Gaussian model :**

  Simulation of rms invariants evolution is based on assumption that the beam has Gaussian distribution on all degrees of freedom.

- *Numerical codes for rms invariants evolution:*

  - Mohl and Giannini, Katayama and Rao.

  - BETACOOL (IBS+e-cool+Beam-Target Interaction (BTI)).

- **Why we need kinetic description?**

  - Solution of kinetic equation is not **Gaussian with account of boundary conditions (particle losses).**

  - Non-linear or stochastic effects (for example, e-cooling or beam-target interaction) could result in Non-Gausian tails.

  - These Non-Gaussian tails can be essential; for example particles in tails can significantly influence on detector noises in colliders.

P.R. Zenkevich, "A New algorithm for the kinetic analysis of intra-beam scattering in storage rings" (3/3)

MOnte-CArlo Code (MOCAC)

- The single known three-dimensional numerical code for IBS study is *MOCAC* code (Zenkevich, Bolshakov).
- *MOCAC* program is based on idea to change the real IBS by a set of artificial "scattering" events constructed such a way that the average invariants rates are same as due to real IBS process: so named *Binary Collision Model (BCM).*
- Main drawback of the code: we need in large number of macro-particles and large computer time.
- Here we proposed some approximate "Approximate Model" (AM) where we calculate a motion of the macro-particles in assumption that the beam is Gaussian one.