PHY 564
Advanced Accelerator Physics

Vladimir N. Litvinenko
Yichao Jing
Gang Wang

Department of Physics & Astronomy, Stony Brook University
Collider-Accelerator Department, Brookhaven National Laboratory

Plan to teach you about:

- The fundamental physics and in depth exploration of advanced methods of modern particle accelerators
- Theoretical concept related to the above
- Principle of least actions, relativistic mechanics and E&D, 4D notations
- N-dimensional phase space, Canonical transformations, simplecticity and invariants of motion
- Relativistic beams, Reference orbit and Accelerator Hamiltonian
- Parameterization of linear motion in accelerators, Transport matrices, matrix functions, Sylvester's formula, stability of the motion
- Invariants of motion, Canonical transforms to the action and phase variables, emittance of the beam, perturbation methods. Poincare diagrams
- Standard problems in accelerators: closed orbit, excitation of oscillations, radiation damping and quantum excitation, natural emittance
- Non-linear effects, Lie algebras and symplectic maps
- Vlasov and Fokker-Plank equations, collective instabilities & Landau Damping
- Spin motion in accelerators
- Types and Components of Accelerators

Learning goals

- Have full understanding of transverse and longitudinal particles dynamics in accelerators
- Being capable of solving problems arising in modern accelerator theory
- Understand modern methods in accelerator physics
- Being capable to fully understand modern accelerator literature

Materials

- Lecture notes presented after each class should be used as the main text. Presently there is no textbook, which covers the material of this course.
- Some material can be found in my note which summarizes USPAS lectures: http://www0.bnl.gov/isd/documents/74289.pdf

Optional:

- H. Wiedemann, "Particle Accelerator Physics" Springer, 2007
- S. Y. Lee, "Accelerator Physics", World Scientific, 2011
- L.D. Landau, Classical theory of fields
  - And many more specialized text

Course

- *Relativistic mechanics and E&D. Linear algebra.*
  - This will be a brief but complete rehash of *relativistic mechanics, E&M and linear algebra* material required for this course.
- *N-dimensional phase space, Canonical transformations, simplecticity, invariants*
  - Canonical transformations and related to it simplecticity of the phase space are important part of beam dynamics in accelerators. We will consider connections between them as well as derive all Poincare invariants (including Liouville theorem). We will use a case of a coupled N-dimensional linear oscillator system for transforming to the action and phase variables. We finish with adiabatic invariants.
- *Relativistic beams, Reference orbit and Accelerator Hamiltonian*
  - We will use least action principle to derive the most general form of accelerator Hamiltonian using curvilinear coordinate system related to the beam trajectory (orbit).
- *Linear beam dynamics*
  - This part of the course will be dedicated to detailed description of linear dynamics of particles in accelerators. You will learn about particles motion in oscillator potential with time-dependent rigidity. You will learn how to calculate matrices of arbitrary element in accelerators. We will use eigen vectors and eigen number to parameterize the particles motion and describe its stability in circular accelerators. Here you find a number of analogies with planetary motion, including oscillation of Earth's moon. You will learn some "standards" of the accelerator physics – betatron tunes and beta-function and their importance in circular accelerators.
- *Longitudinal beam dynamics*
  - Here you will learn about one important approximation widely used in accelerator physics – "slow" longitudinal oscillations, which are have a lot of similarity with pendulum motion. If you were ever wondering why Saturn rings do not collapse into one large ball of rock under gravitational attraction – this where you will learn of the effect so-called negative mass in longitudinal motion of particles when attraction of the particles cause their separation.

Course cont..

- *Invariants of motion, Canonical transforms to the action and phase variables, emittance of the beam, perturbation methods, perturbative non-linear effects*
  - In this part of the course we will remove "regular and boring" oscillatory part of the particle's motion and focus on how to include weak linear and nonlinear perturbations to the particles motion. We will solve a number of standard accelerator problems: perturbed orbit, effects of focusing errors, "weak effects" such as synchrotron radiation, resonant Hamiltonian, etc. We will re-introduce Poincare diagrams for illustration of the resonances. You will learn how non-linear resonances may affect stability of the particles and about their location on the tune diagram. You will learn about chromatic (energy dependent) effects, use of non-linear elements to compensate them, and about problems created by introducing them.
- *Non-linear effects, Lie algebras and symplectic maps*
  - This part of the course will open you the door into a complex nonlinear beam dynamics. We will introduce you to non-perturbative nonlinear dynamics and fascinating world of non-linear maps, Lie algebras and Lie operators. These are the main tools in the modern non-linear beam dynamics. You will learn about dynamic aperture of accelerators as well as how our modern tools are similar to those used in celestial mechanics.
- *Vlasov and Fokker-Plank equations*
  - This part of the course is dedicated to the developing of tools necessary for studies of collective effects in accelerators. We will introduce distribution function of the particles and its evolution equations: one following conservation of Poincare invariants and the other including stochastic processes.
- *Radiation effects*
  - You will learn how to use the tools we had developed in previous lectures (both the perturbation methods and Fokker-Plank equation) to evaluate effect of synchrotron radiation on the particle's motion in accelerator. You will see how the effect of radiation damping and quantum excitation lead to formation of equilibrium Gaussian distribution of the particles

Course cont..

- *Collective phenomena*
  - Intense beam of charged particles excite E&M fields when propagate through accelerator structures. These fields, in return, act on the particles and can cause variety of instabilities. Some of these instabilities – such as a free-electron lasers (FEL) – can be very useful as powerful coherent X-rays sources. Others (and they are majority) do impose limits on the beam intensities or limit available range of the beam parameters. You will learn techniques involved in studies of collective effects and will use them for some of instabilities, including FEL. The second part of the collective effect will focus on how we can cool beams, which do not have natural cooling mechanism
- *Spin dynamics*
  - Many particles used in accelerators have spin. Beams of such particles with preferred orientation of their spins called polarized. Large number of high energy physics experiments using colliders strongly benefit from colliding polarized beams. You will learn the main aspects of the spin dynamics in the accelerators and about various ways to keep beam polarized. One more "tunes" to worry about - spin tune .
- *Accelerator application*
  - We will finish the course with a brief discussion of accelerator application, among which are accelerators for nuclear and particle physics, X-ray light sources, accelerators for medical uses, etc. You will also learn about future accelerators at the energy and intensity frontiers as well as about new methods of particle acceleration.

Grading

- **Homework assignments : 40% of the grade**
- **Presentation of a research topic : 40% of the grade**
- **Class Participation : 20% of the grade**

- There will be a substantial number of problems. Most of them are aiming for better understanding of material covered during classes.
- **Presentation on a Research Project:** This presentation will be in place of the final exam. You will pick an accelerator project of your interest from a list provided by the instructors. We allow presentations on papers directly related to your research if they are linked to accelerator physics, but you will have to get it approved by the instructors. The presentations will be in a PowerPoint or equivalent a form. We will grade your presentations on: adequate understanding (good physics), adequate preparation (clear way of presentation, Visual Aids - pictures and figures), adequate references (where you find materials). The research project should be fun and we encourage you to choose an original topic and an original way of presentation. Nevertheless, any topic prepared and presented properly will have high grade.

The Rules *or "feed your pets with healthy food"*

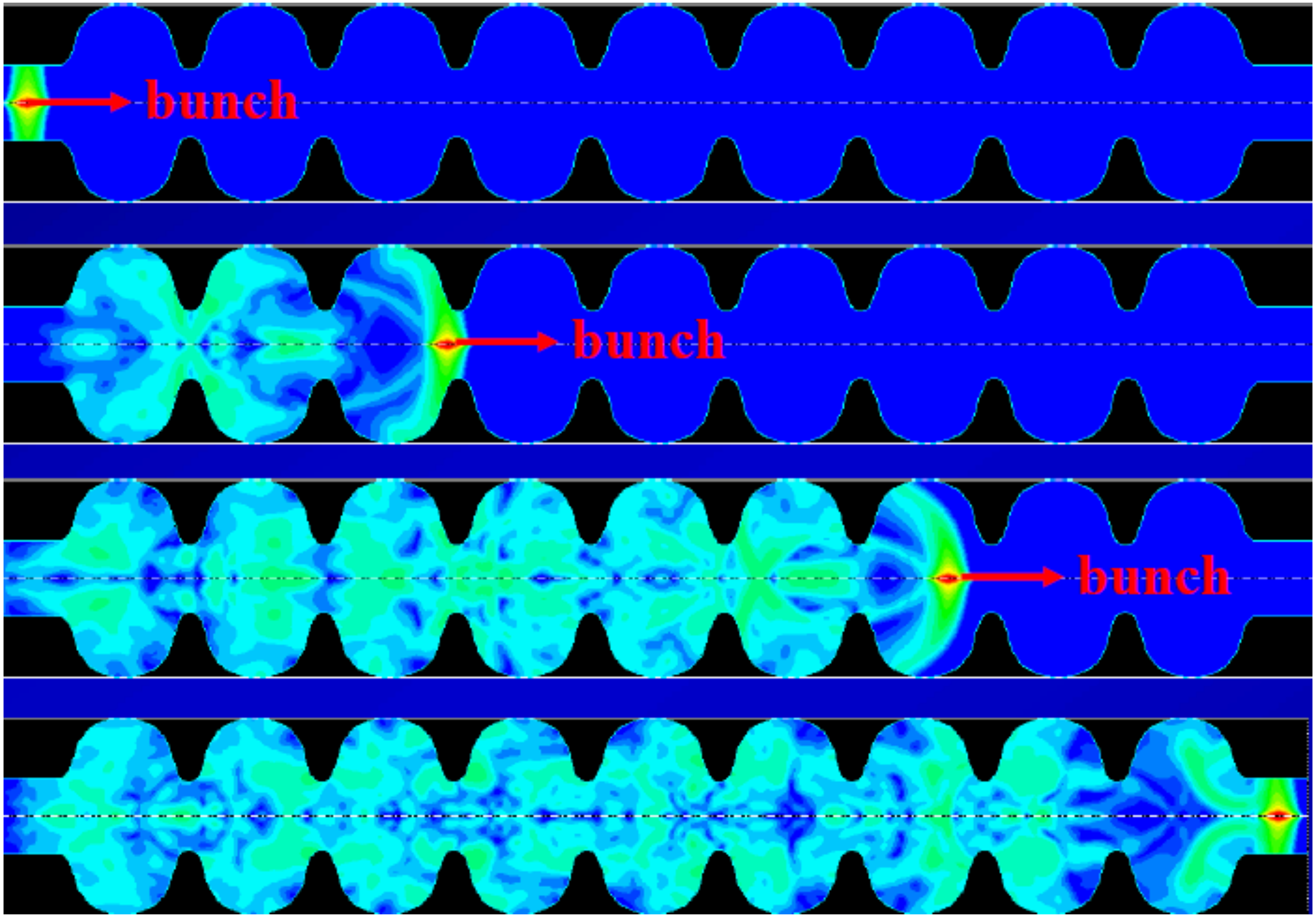
- You may collaborate with your classmates on the homework's if you are contributing to the solution. You must personally write up the solution of all problems. It would be appropriate and honorable to acknowledge your collaborators by mentioning their names. These acknowledgments will not affect your grades.
- We will greatly appreciate your homeworks being readable. Few explanatory words between equations will save us a lot of time while checking and grading your home-works. Nevertheless, your writing style will not affect your grades.
- Do not forget that simply copying somebody's solutions does not help you and in a long run we will identify it. If we find two or more identical homeworks, they all will get reduced grades. You may ask more advanced students, other faculty, friends, etc. for help or clues, as long as you personally contribute to the solution.
- You may (and are encouraged to) use the library and all available resources to help solve the problems. Use of Mathematica, other software tools and spreadsheets are encouraged. Cite your source, if you found the solution somewhere.
- *You should return homework* before the deadline. Homework returned after the deadline could be accepted with reduced grading - 15% per day. Otherwise, it will be unfair for your classmates who are doing their job on time. Therefore, you should be on time to keep your grade high. Exceptions are exceptions and do not count on them (*if your dog eats your homework on a regular basis - feed it with something healthy, eating homework is bad for your pet and for you grade*).

What Accelerators Are Good For?

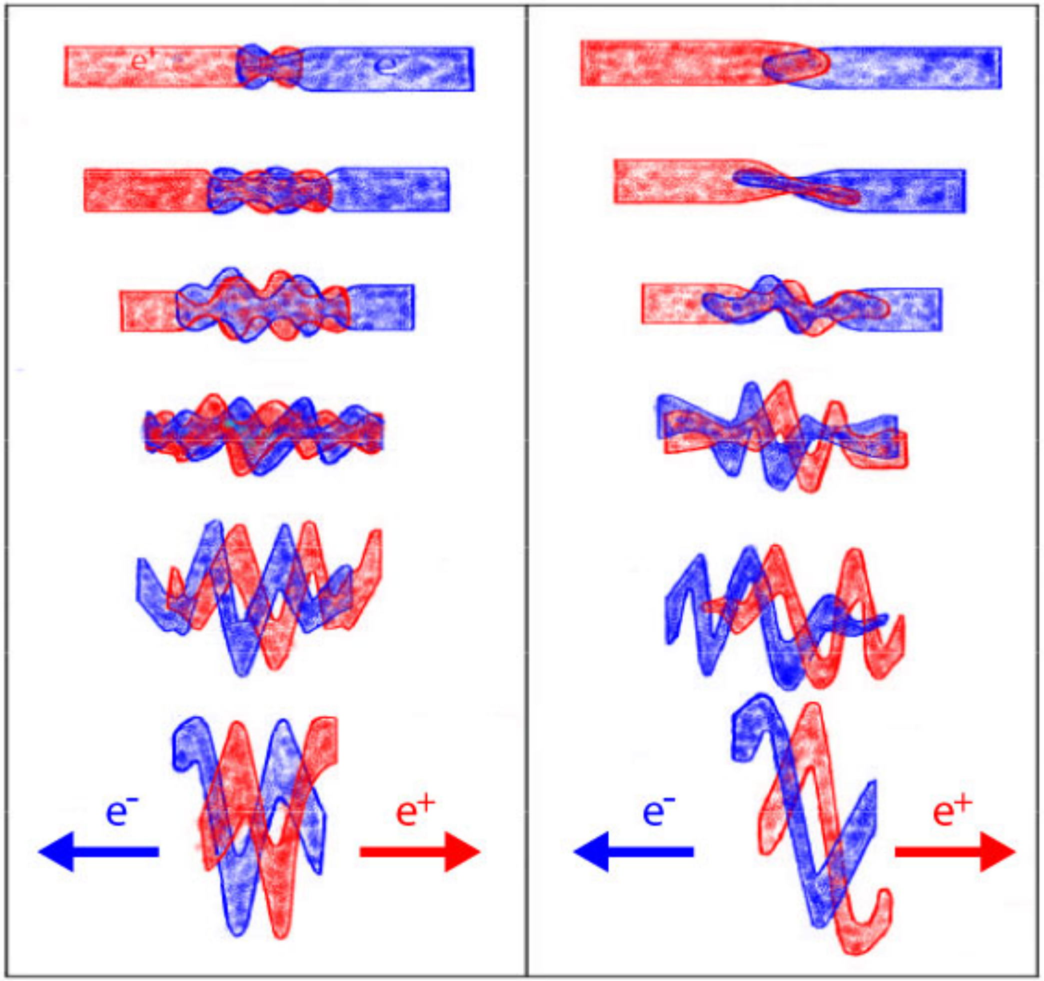
- High Energy Physics
  - Explore the electro-weak bosons Z, W (LEP)
  - Find and exploit "new" and heavy quarks (Tevatron)
  - Find the HIGGS ? (LHC)
  - Well, this list will never be complete .....
- Nuclear Physics (RHIC, SPS)
  - First evidence of a new state of matter, quark gluon plasma? (SPS)
  - Create the QGP and determine its properties (RHIC)
  - Could it be something else? (RHIC II, eRHIC)
- Chemistry, Biology, Medicine, Material Sciences
  - Find the structure of molecules, proteins, cells…
  - Could people survive interstellar travel? (NASAs NSRL)
  - Time-resolved structural changes in a natural (fsec) time scale
- Civil, Industrial and Military Applications
  - Treat cancers, produce isotopes for medical imaging, sterilize products…
  - Scan containers in ports for undesirable content (n's?)
  - High power free electron lasers as weapons for a ship defence………

And also they are fun to design, build and work with, especially on those based on novel concepts

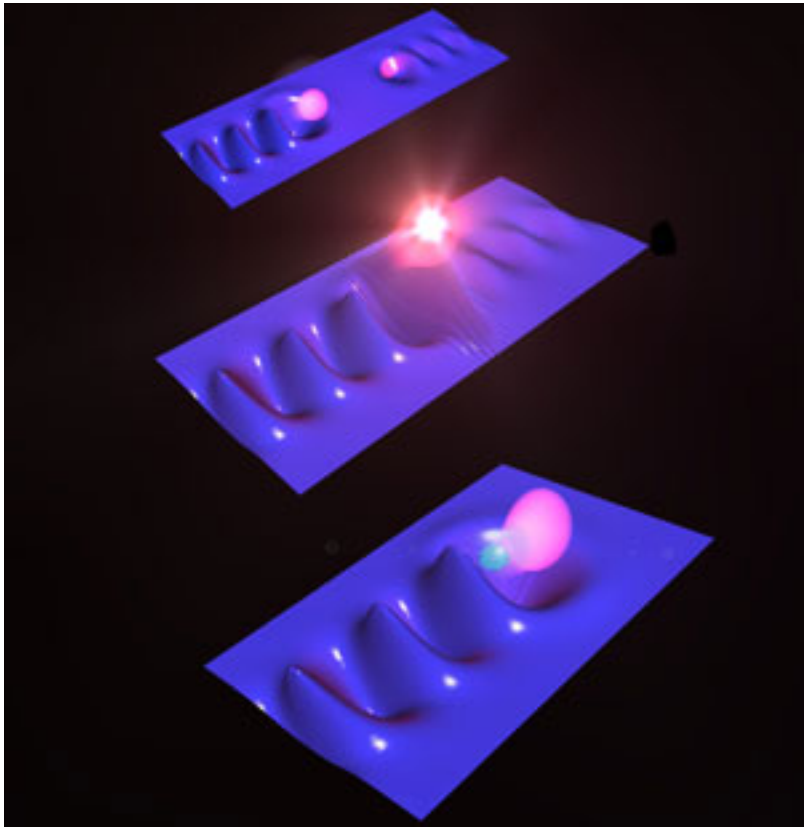
Nontrivial example of accelerator problem: interaction with self-generated wakefields



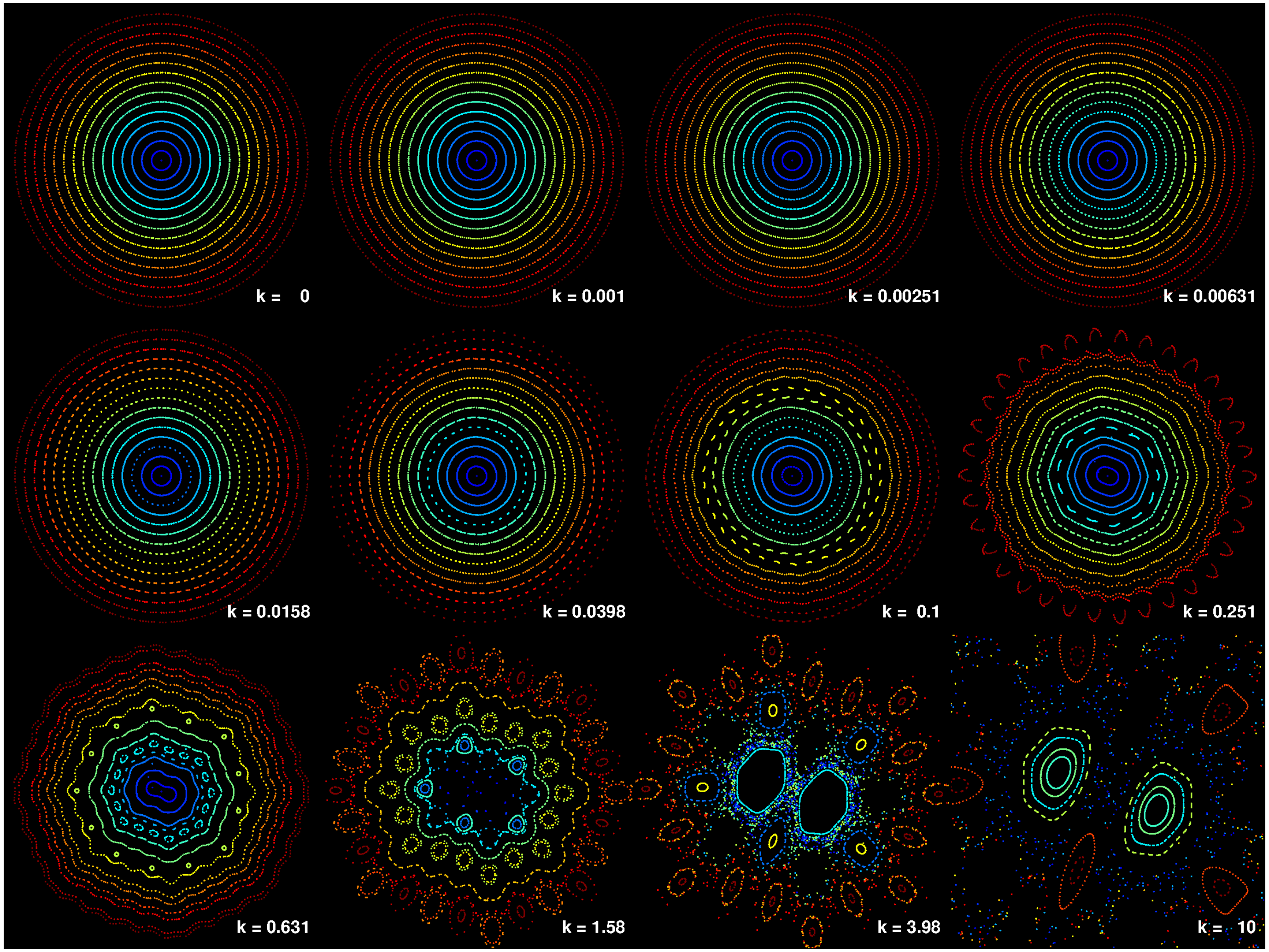
Nontrivial example of accelerator problem: disruption of colliding beams



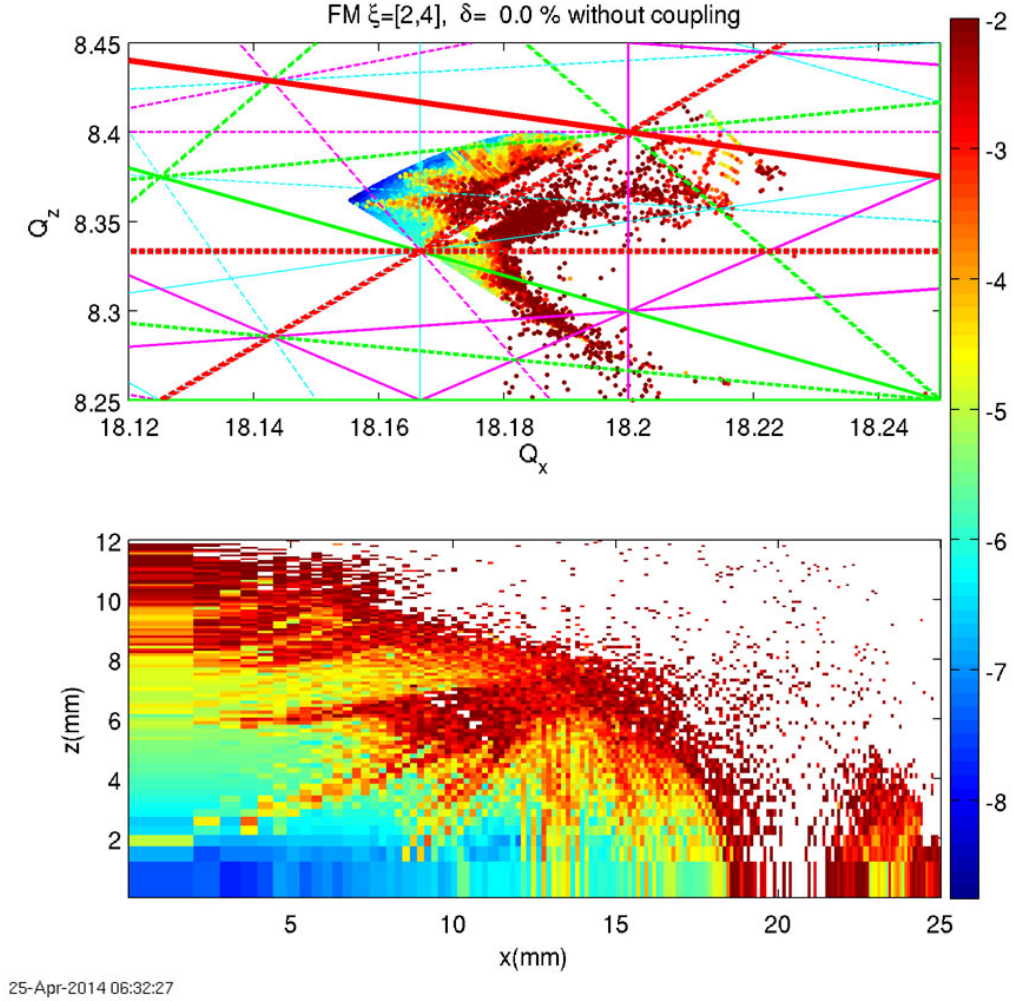
Nontrivial example of accelerator problem: beams in plasma



Nontrivial example of accelerator problem: Non-linear particle's dynamics



Nontrivial example of accelerator problem: Dynamic aperture in rings / Chromatic wall



- ✓ We can not teach you every trick in the books available in accelerator physics

  But we plan to provide you with very solid foundation: so you can explore any topic in modern accelerator physics with confidence

Few notes before diving in real AP

- Mathematics is physicist's friend
- There is nothing more unnatural than "non-relativistic" electro-dynamics
- We are creatures of 4-D (or (4+N)D) world
- Nothing saves you more time than good definitions and notation, hence tensors, matricies, maps, operators…
- …..
- No home works after first class