Concepts of CERN Optics Codes

- **MAD - Traditional Optics Code**
- **PTC – Transition to an more modern Approach**
- **SixTrack – Tracking Engine**

About this talk

- I concentrate on CERN tools since they have penetrated the field of optics design around the world accelerator laboratories.

- At most places you will find one or the other tool, albeit potentially in various incarnations.

- However, there are various other excellent codes: E.G. the SAD code from KEK and SYNERGIA from Fermilab spring to my mind. But there are many others! Both for general and specific tasks.

- Given the limited time and my pleasure and hopefully yours I will try to explain some concepts rather than bore you with long list of features.

History

1. **MAD**
   - **Traces of early MAD versions are difficult to find.**
   - **MAD8 has been introduced in the 1980s by C. Iselin and H. Grote. It is still being used at various places (E.G. BNL, Fermilab).**
   - **MAD9 was a massive re-write till about 2001 in C++ fashionable at the time. It could not been made operational for the LHC in time and maintenance proved to be a major effort.**
   - **MAD-X was started in 2001 by H. Grote and myself. The code was operational as of 2003.**
   - **In 2011 L. Deniau and his team took over and the plan is a complete re-write available in a couple of years.**
2. **PTC**
   - **Etienne Forest has started the PTC project around 2001. In close collaboration with CERN it was integrated from the start into MAD-X**
   - **NormalForm and new approach of accelerator design.**
3. **SixTrack**
   - **Originally "Racetrack" by A. Wrulich 1984.**
   - **Theory by G. Ripken & software development by myself.**
   - **Massive Tracking with run environment by 2001 E. McIntosh and myself.**
   - **Code development is lead since 2012 by R. de Maria from CERN.**

General Concept for MAD-X in View of the LHC 1/2

- Given time constraints at the start of the LHC era we were looking for a pragmatic approach to construct a family of codes to design and commission this complex machine.

- Use as much as possible trusted and versatile code to do the job in a reliable fashion.

- Code Elegance was NOT the primary goal! Instead: Various computer languages. Grande schemes had to delayed to a later day.

- Team of developers of mostly actual users of the code with limited software background.

- Use help of external collaborators.

- Thorough Benchmarking!

General Concept for MAD-X in View of the LHC 2/2

- Provide all reliable features of MAD8. In particular, TWISS, MATCH, ERROR, PLOT, SURVEY, EMIT & DYNAP.

- Drop doubtful modules.

- Build new and consistent modules: APERTURE, IBS, TOUSCHEK, C6T (SixTrack convertor), treatment of LHC two-in-one structure.

- Mildly upgrade where possible: dynamic memory allocation in C, symplectic tracking, SVN repository, HTML documentation, module keepers, debugging etc.

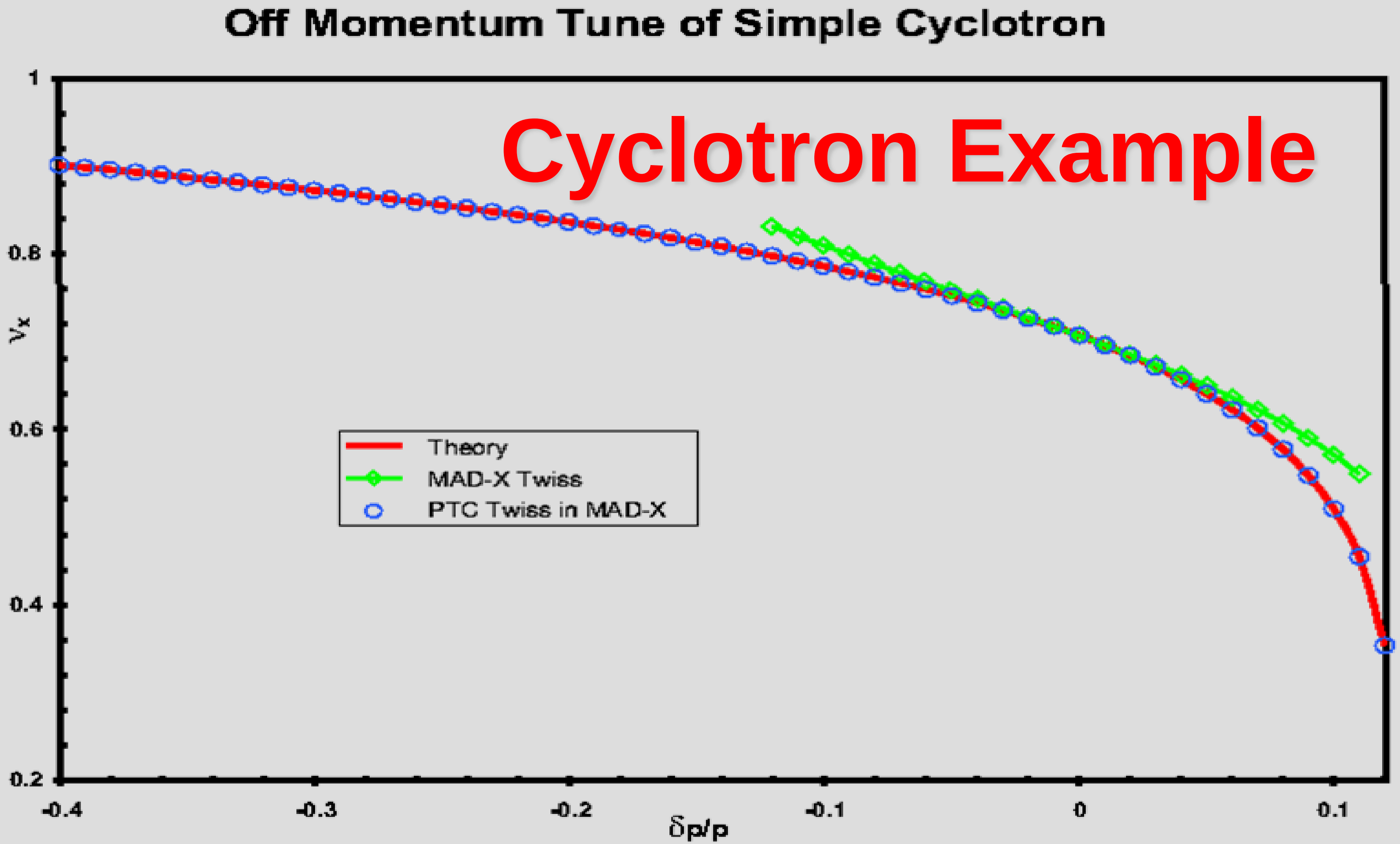
- Modernize MAD language (similar to MAD9).

- Integrate MAD-X with PTC.

PTC Integration

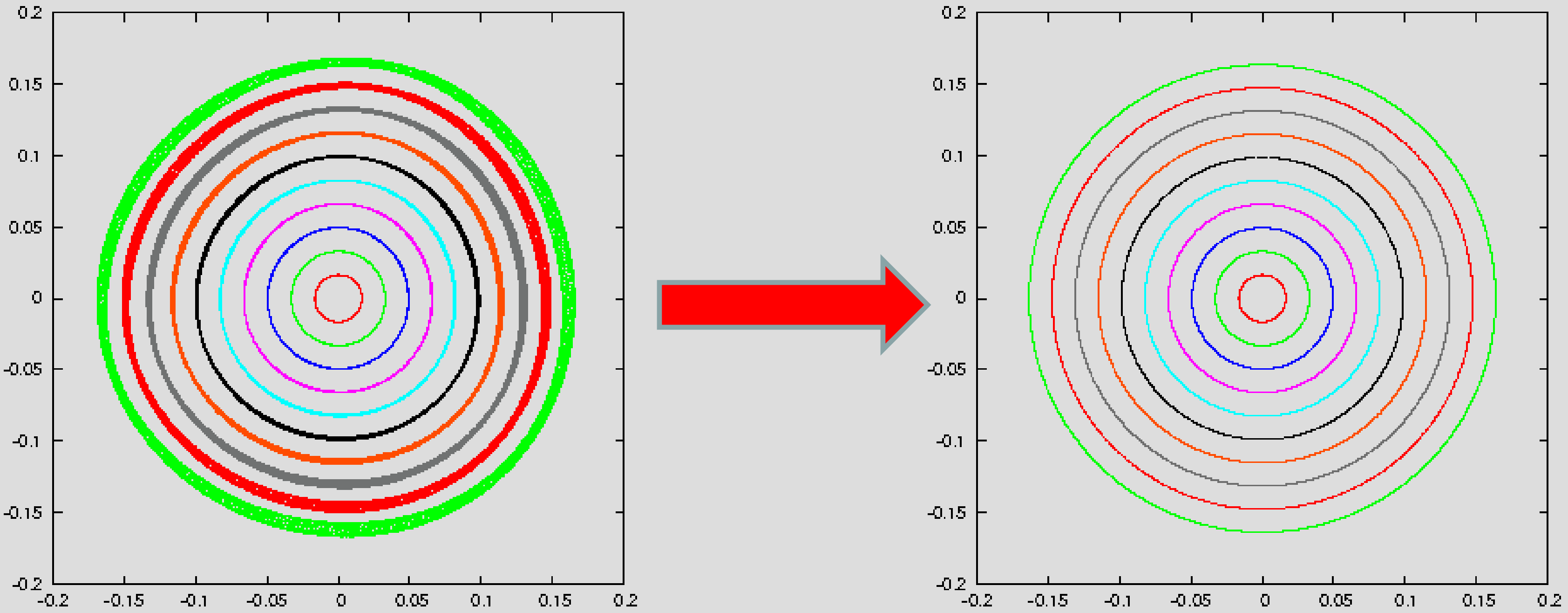
- Link MAD-X accelerator structure with PTC.
- Very thorough benchmarking with the physics of MAD-X ➔ agree with MAD-X when correct or improve!
- Provide truncated Taylor Maps and NormalForm: higher order momentum compaction, detuning with amplitudes, resonance driving terms.
- Create various PTC modules (with equivalent MAD-X output): PTC_TWISS, PTC_NORMAL, PTC_TRACK.
- More modern features: Flexible symplectic integrator, expanded and exact Hamiltonian, choice of coordinate system.
- Besides this compatibility mode there is also a stand-alone mode for a more modern accelerator design!

E. Courant et al, "A comparison of several Lattice Tools for Computation of Orbit Functions of an Accelerator" , published in PAC2003 Portland, shown is ν_x versus $\delta p/p$ for a simple cyclotron. Standard MAD-X (green curve) deviates due to a well known deficiency with respect to $\delta p/p$. In PTC the exact attribute allows to approximate the true Hamiltonian. Note, that PTC operates on the same lattice as provided by MAD-X.



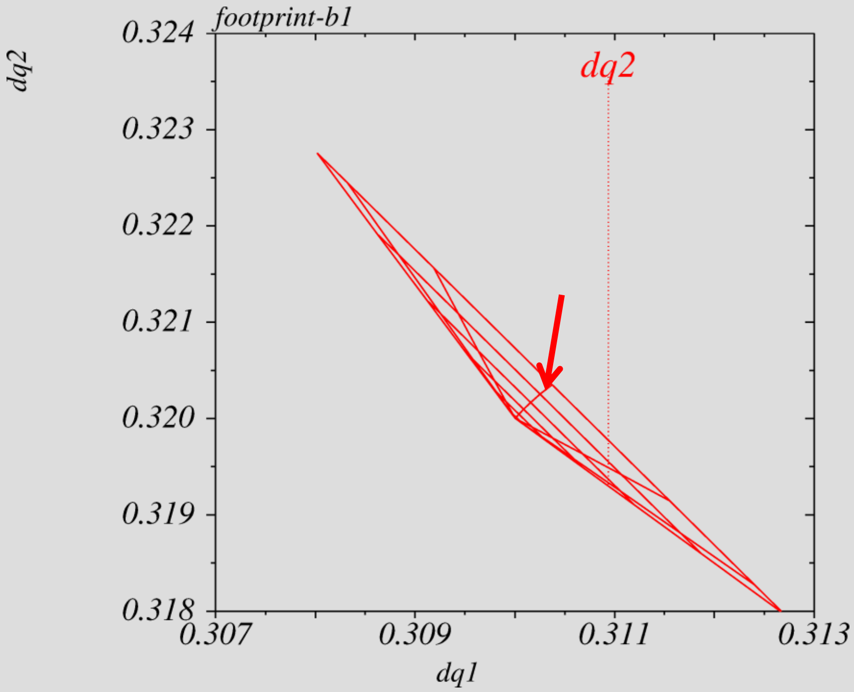
Normal Form LHC Example 1/2

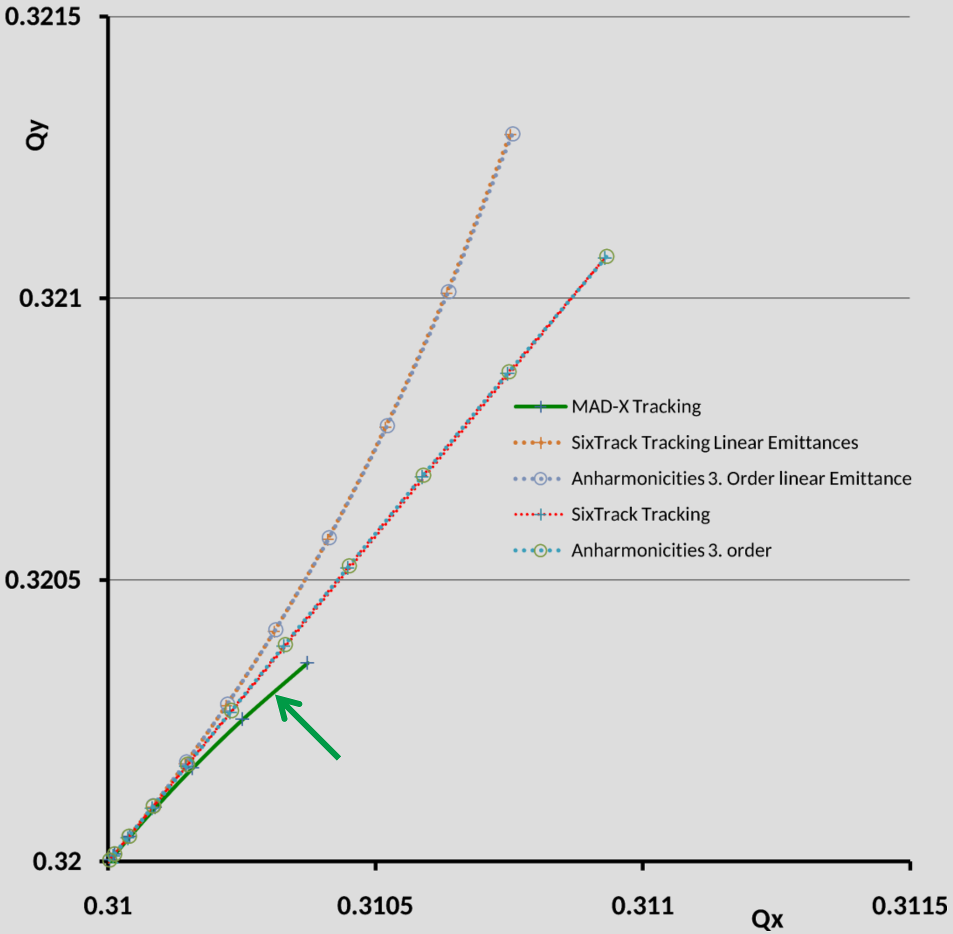
NormalForm is a transformation from the laboratory frame into a Normal Space in which phase space deformation are removed and the dynamics only depend on the action. This transformation allows to determine the non-linear terms of the system: detuning with amplitude and resonance driving terms.



LHC at collision energy with strong Landau damping Octupoles switched on. Horizontal motion from 1 – 10 σ.

Normal Form LHC Example 2/2





PTC Stand-Alone Mode – Example LHC

1. All Accelerator Elements remain thick, i.e. no need to explicitly cut them to introduce Kicks. ➔ Helps in Compatibility Mode as well & it allows to connect other codes like ORBIT.

2. Locate the Accelerator Elements in 3D Space at their actual Position. In fact, ideally one would want to link up PTC with a CAD system, so that the Planning of Elements and Accelerator Structure could directly be checked.

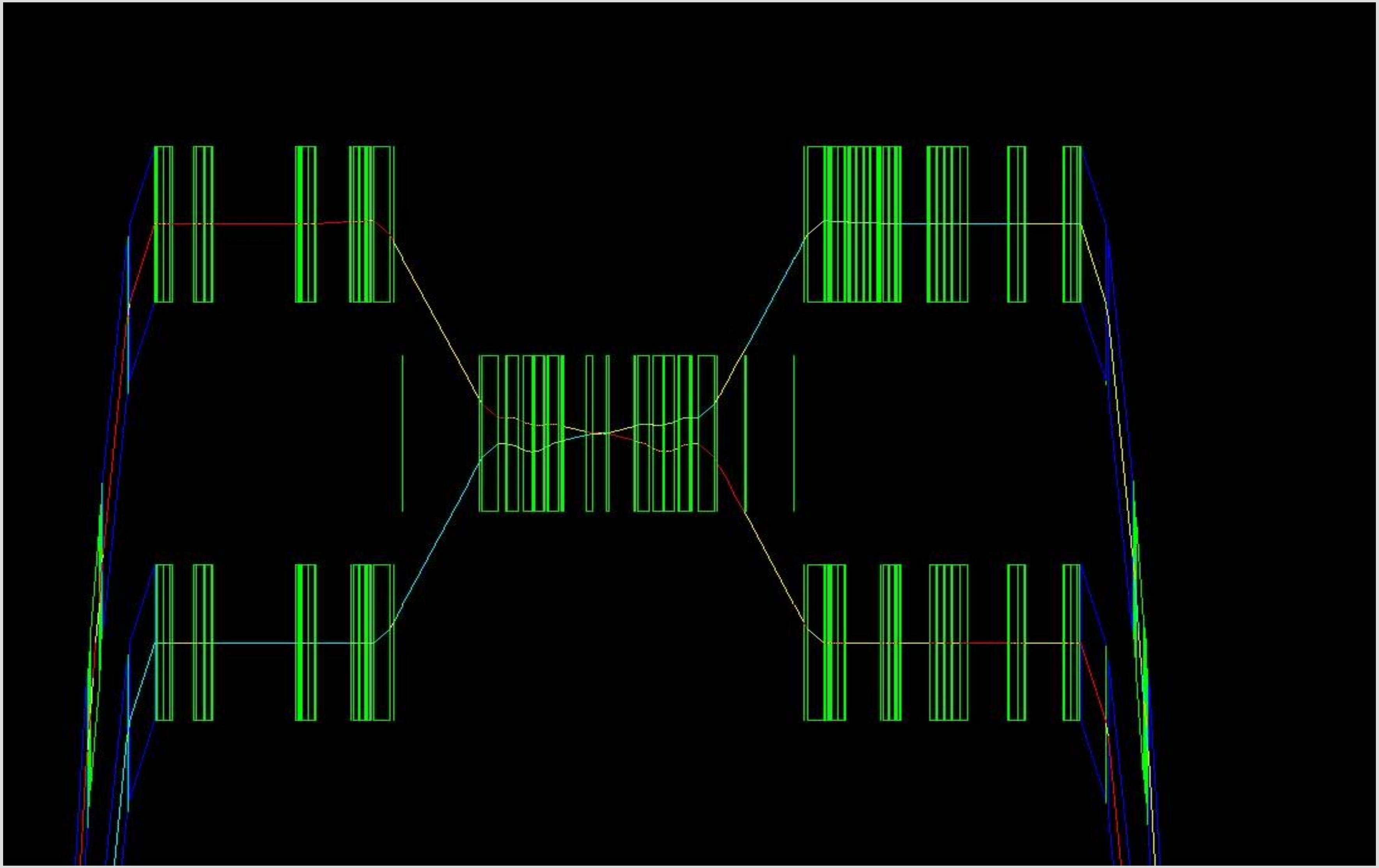
3. There are various ways to link elements between the 2 rings creating Twin and Girder Structures and to allow misalignment of both the individual elements and these more complex structures

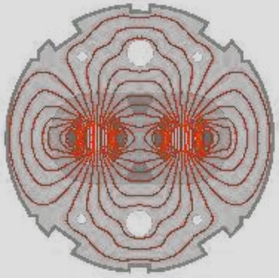
4. Patching of skewed or misaligned Element Positions.

5. Treat arcs, Common Regions, Separation Dipoles and Transfer Lines to construct the full Accelerator Structure.

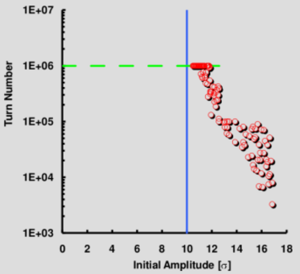
6. This has been fully achieved for the LHC. ➔ Particles are being pushed through the two-in-one structure.

PTC stand-alone: LHC 2-in-1 Structure



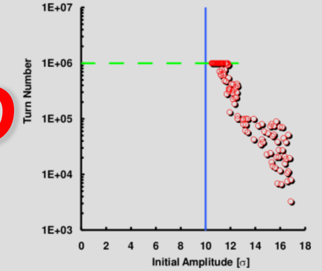


Concepts for Single Particle Tracking with SixTrack

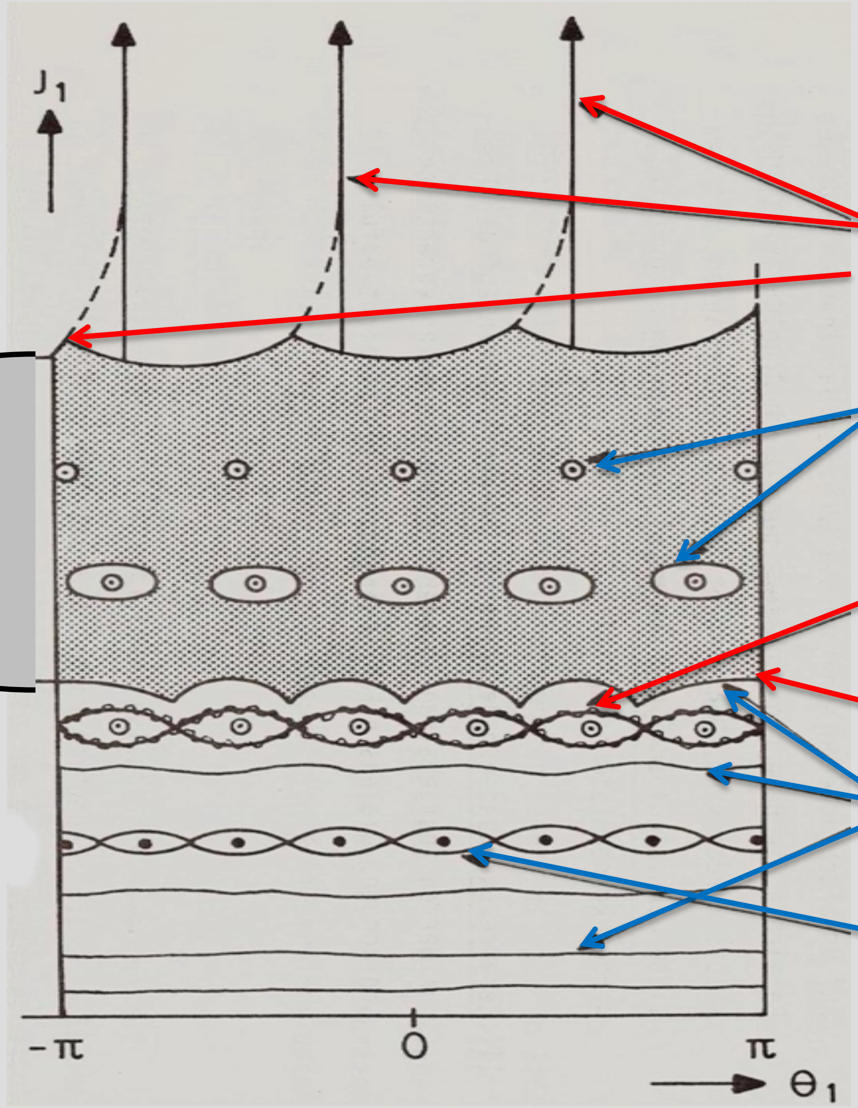


1. Accelerator Structure
   - Optimizing SixTrack for speed while covering all accelerator components.
   - Full benchmarking with MAD-X.
2. Stability Criteria
   - Dynamic Aperture
   - Motion Type: Regular and Chaotic Motion
   - Survival Plot & Resonance Wandering
3. Massive Tracking Engine

Dynamic Aperture Scheme >=2D



Chaotic Sea



Unbounded

Motion

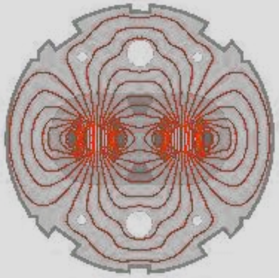
Stable Islands in chaotic sea

Fine chaotic layers in stable regime

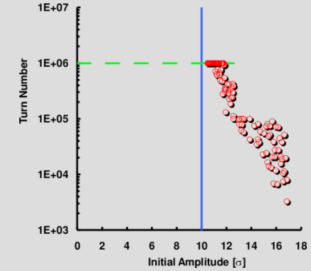
Onset of Global Chaos

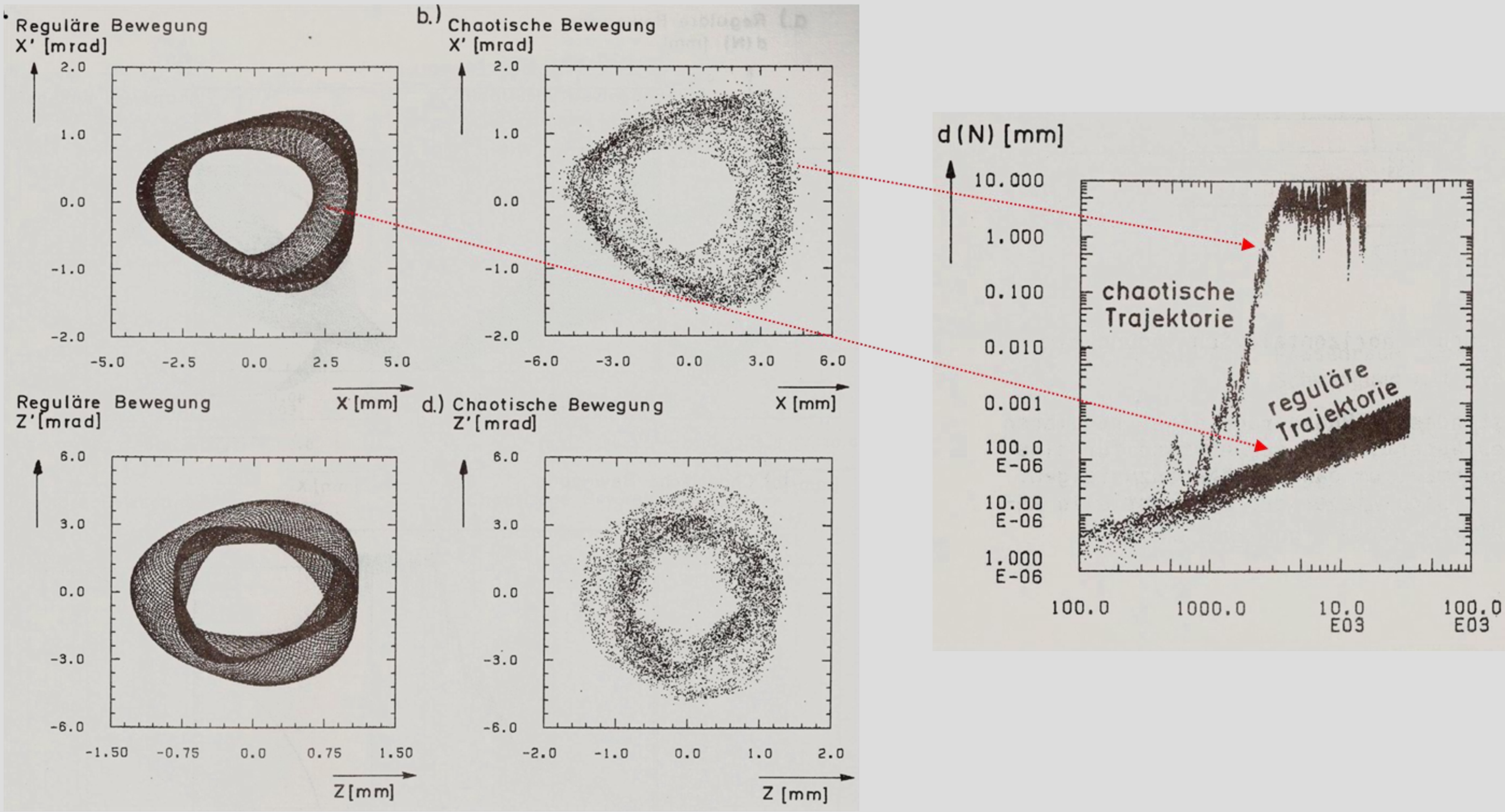
Mostly stable

particle motion

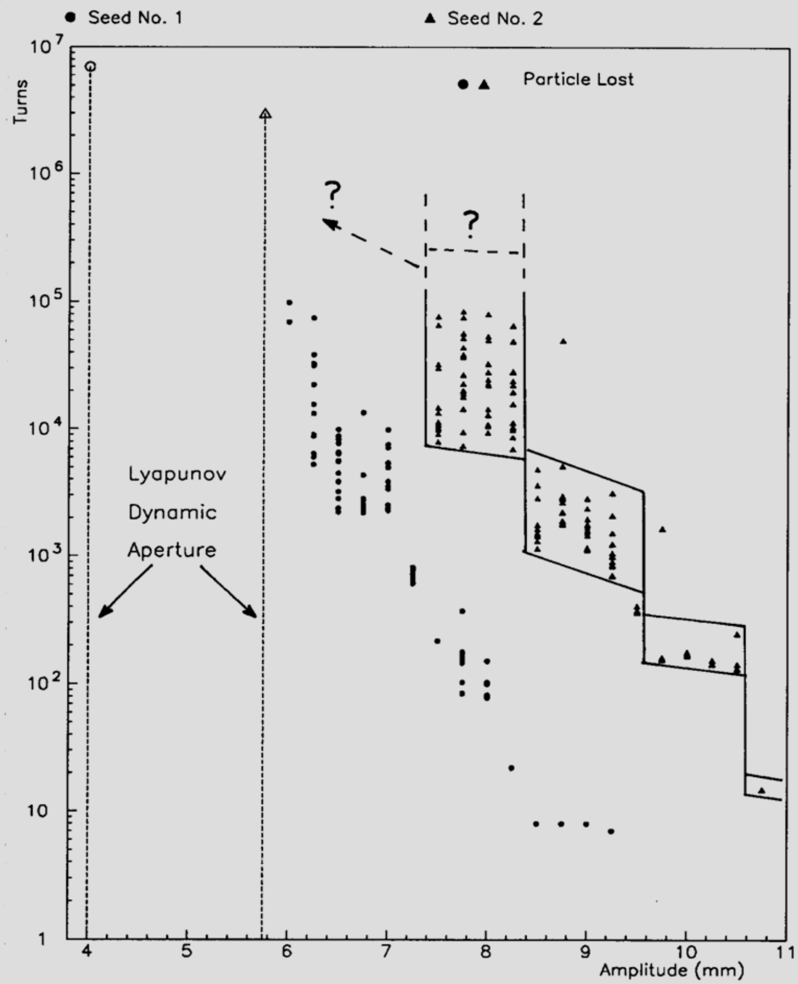


2D Stable and Chaos



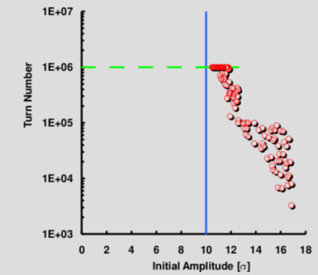


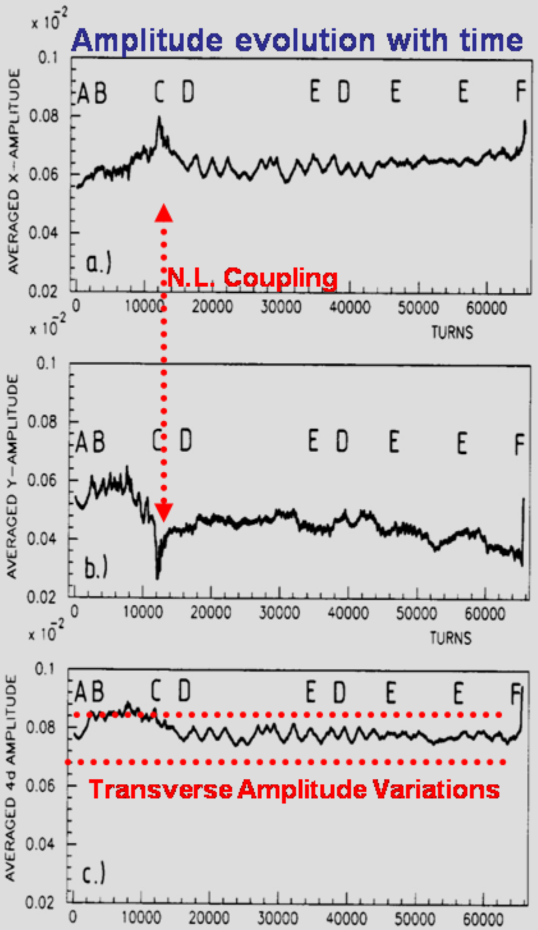
Survival Plots and Resonance Wandering 1/2 (F. Galluccio et al.)

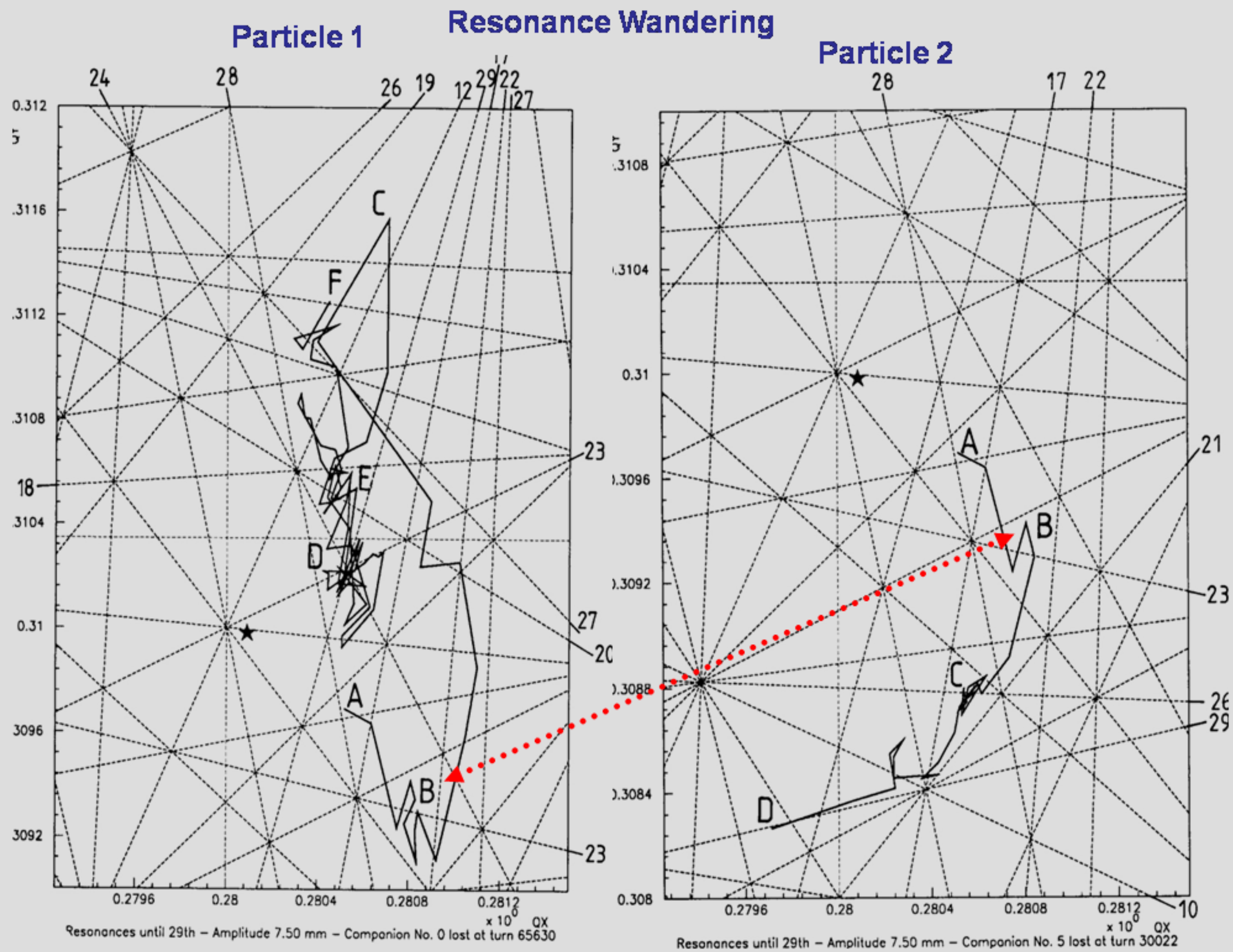


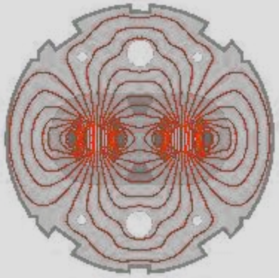
The survival plots depict the number of turns particles stay in the machine for a given amplitude. In this particular example we tracked an ensemble of particles started in a tiny volume of phase space. The width of the survival times tends to grow inverse proportionally with amplitude since the chaotic motion becomes weaker. There is no known method that could predict the evolution to smaller amplitudes toward the onset of global chaos.

Resonance Wandering >=2D 2/2

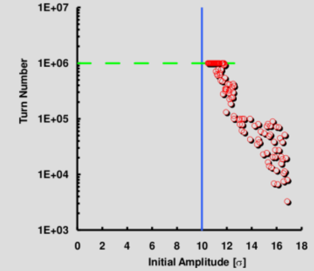






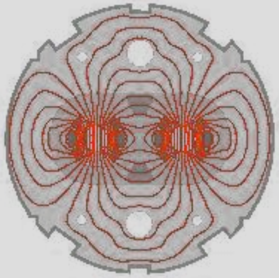


Tracking Engine for massive LHC Tracking Studies 1/2

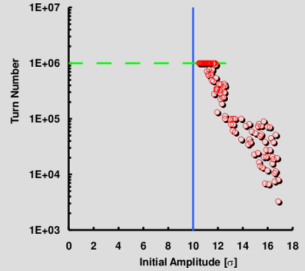


Many Thanks to Eric McIntosh

- For LHC tracking we are using SixTrack which is kept rigorously bug-free while continuously optimizing the code for speed.
- The lattice is transferred from MAD-X. MAD-X, SixTrack & PTC are benchmarked against each other.
- Great care has been taken to sample the 6D phase space appropriately!
- We have prepared a SixTrack run environment which allows to automatically launch 10’000 of jobs at a time and storing all output data in a elaborate directory structure. After all jobs have been finished automatic post-processing procedure are being launched for a full analysis of the data.



Tracking Engine for massive LHC Tracking Studies 2/2



- **Jobs can be sent to various batch systems, e.g. a local CERN batch cluster with hundreds nodes is at our disposal.**
- **Moreover, we have created LHC@Home. Presently about >100'000 volunteers have sign up to contribute world-wide. The so-called BOINC system organizes the flow of jobs to the contributors and sends back the results into our directory structure.**
- **Special care has been taken Eric McIntosh to guarantee bit-by-bit accuracy on any computer platform. A checkpoint-restart mechanism is implemented as well.**

Recent Developments

- **In collaboration with experts from Fermilab MAD-X can now simulate with a frozen model of Space Charge.**
- **A major upgrade driven by L. Deniau of a new MAD including TPSA will be expected in a year or 2.**
- **PTC has started to play an essential role in self-consistent Space Charge studies both in PTC-ORBIT and pyORBIT.**
- **SixTrack remains available for massive tracking with distributed computing. It is continuously upgraded for the needs of HL-LHC by R. de Maria and his team.**