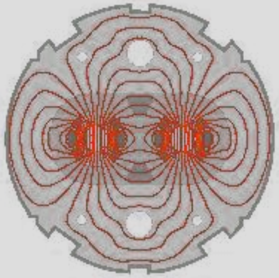
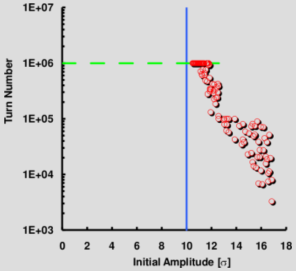
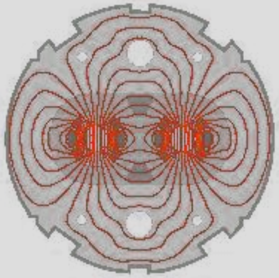


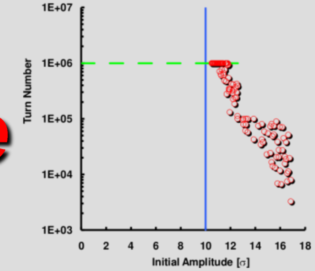
LHC Dynamic Aperture Experiment



- What is the Dynamic Aperture (DA)?
  - Definition & Chaos Criteria
  - Causes for single particle losses
  - Phase Space
  - Survival Plots
  - Measurement (Classic Kick Technique)
  - Simulation & Computing
- DA experiments since the late `80s
  - SPS
  - Tevatron
  - Hera
- LHC DA Experiment (E.H. Maclean, R. Tomàs, F. Schmidt, and T.H.B. Persson)



Definition of Dynamic Aperture



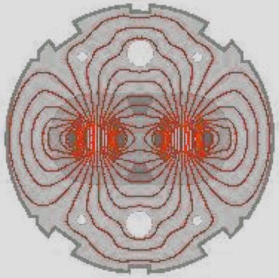
1. **Real World Dynamic Aperture (RW-DA) Definition:**

   Largest Amplitude at which particles remains in the accelerator over a time range of interest.

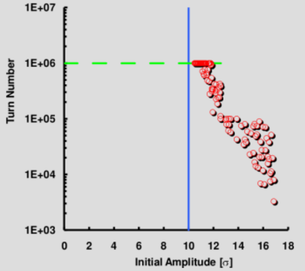
2. **Potential Dynamic Aperture (PO-DA) = Onset of global Chaos**

   - **Largest Amplitude with mainly regular motion.**
   - **Insignificant chaotic layers within the regular regime will be ignored.**
   - **However considerable wide chaotic spikes have to be taken into account**

➔ It turns out that the PO-DA is typically too small as RW-DA estimate



Chaos Criteria



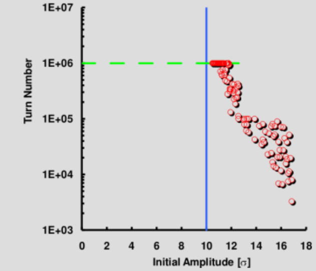
PO-DA Detection ➔ find amplitude with non-zero Lyapunov Exponent:

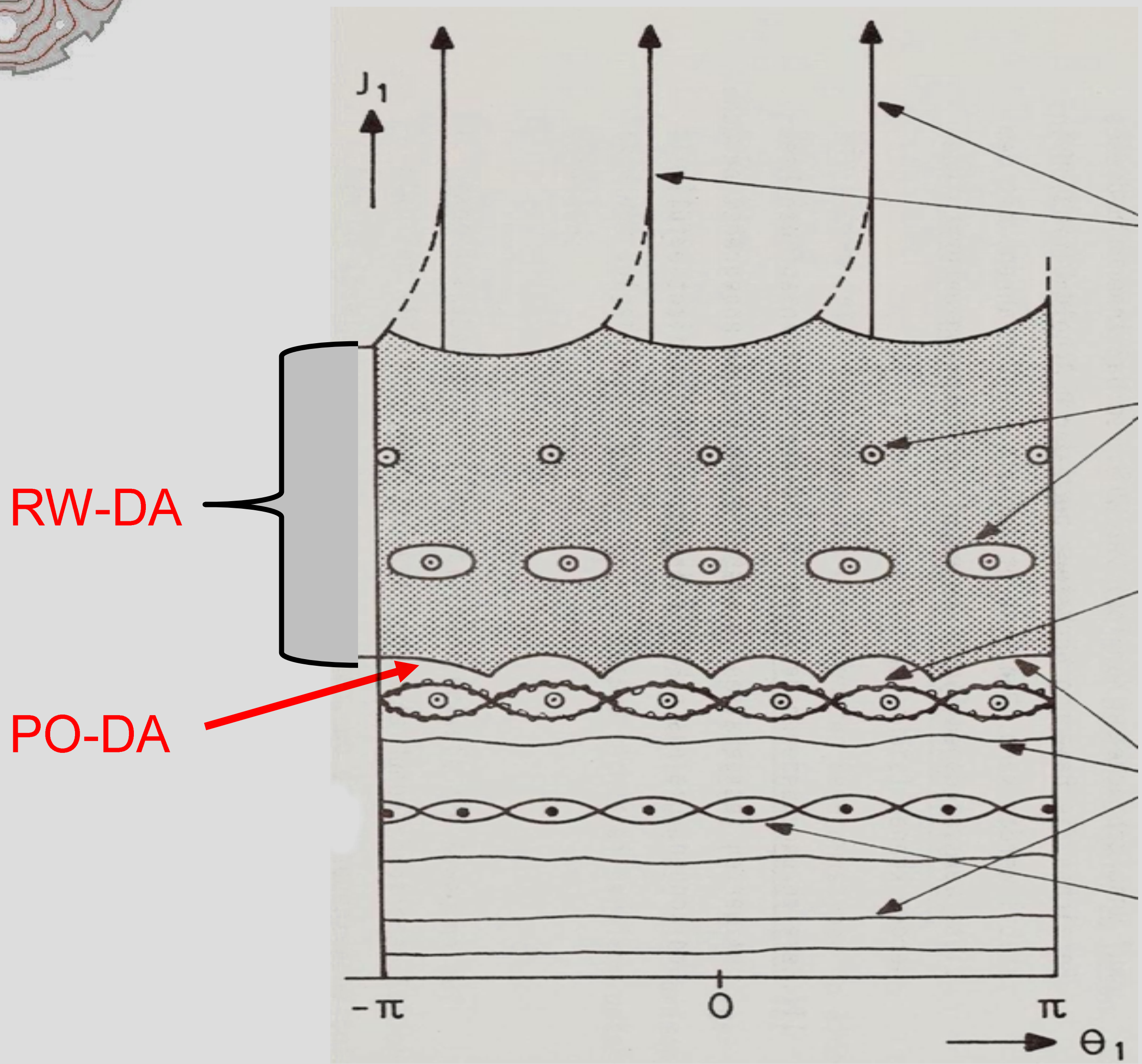
$$\lambda = \lim_{N\to\infty} \lim_{d(0)\to 0} \frac{1}{N} \log \frac{d(N)}{d(0)}$$

In practice, the Lyapunov is rarely evaluated directly.

Instead, one follows the evolution of the distance and most effectively by using the angular distance that is most sensitive to find even weakly chaotic motion

Dynamic Aperture Scheme



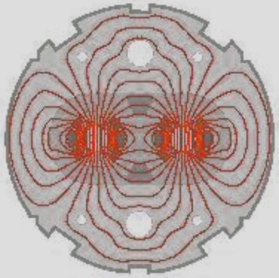


Rapid amplitude growth and loss

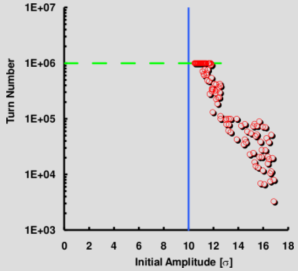
Stable Islands in chaotic sea

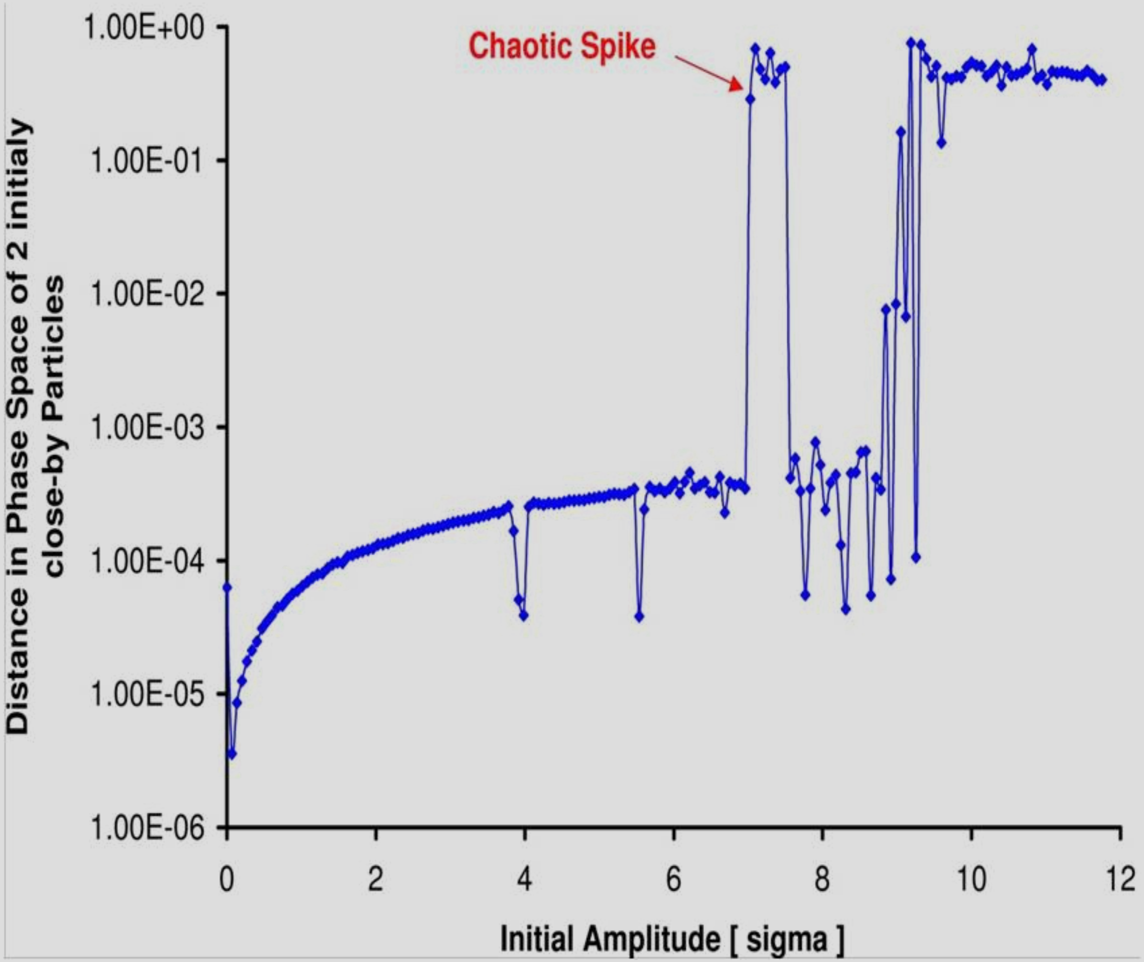
Fine chaotic layers in stable regime

Mostly stable particle motion

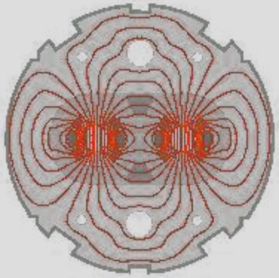


BB Survival Plots (Y. Luo et al.)

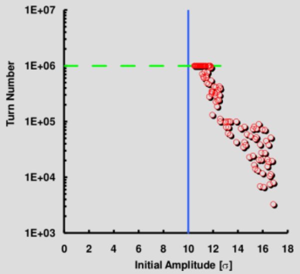




The BB force gives rise to significant broad chaotic "spikes" below the onset of global Chaos and separated by a sizable amplitude range with stable motion. This leads to particle loss at those lower amplitudes. However, this particle loss is slower forcing us to extend the LHC BB tracking to more than 1E6 turns.



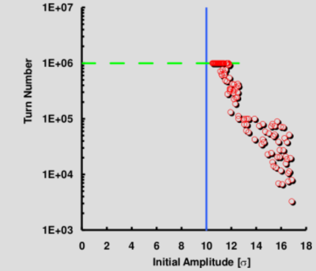
Causes for Single Particle Losses



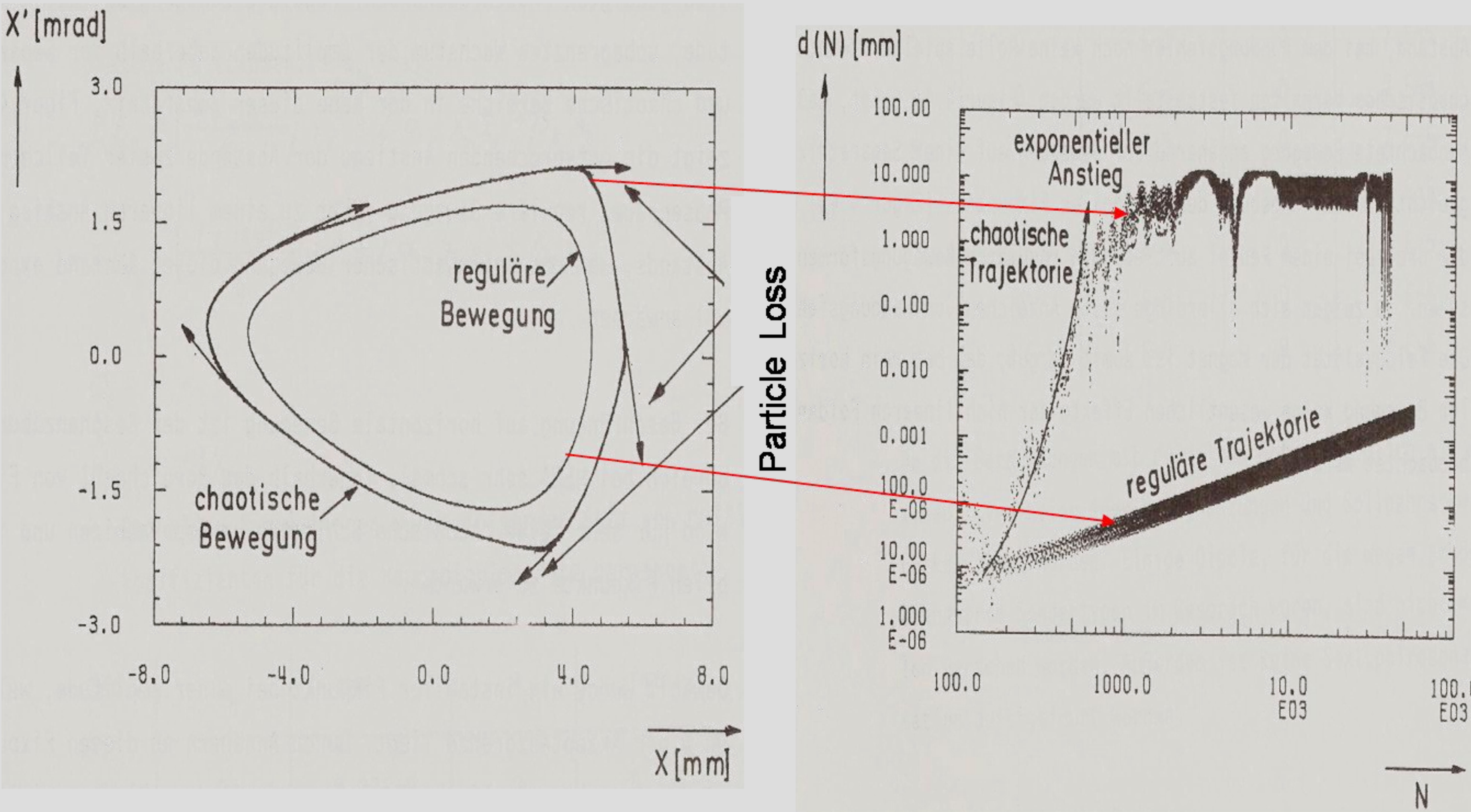
The causes are basically the reason why we are all here!

- **Wanted and un-wanted Multipolar Components**
- **Magnet Misalignments**
- **Tune Modulations due to Power Supply Ripple**
- **Weak-Strong BB Interaction**

DA in 1D

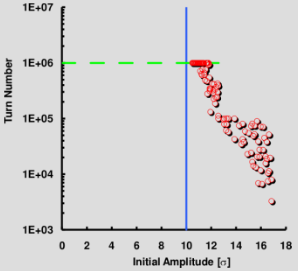


1E+07
1E+06
1E+05
1E+04
1E+03
Turn Number
0 2 4 6 8 10 12 14 16 18
Initial Amplitude [σ]

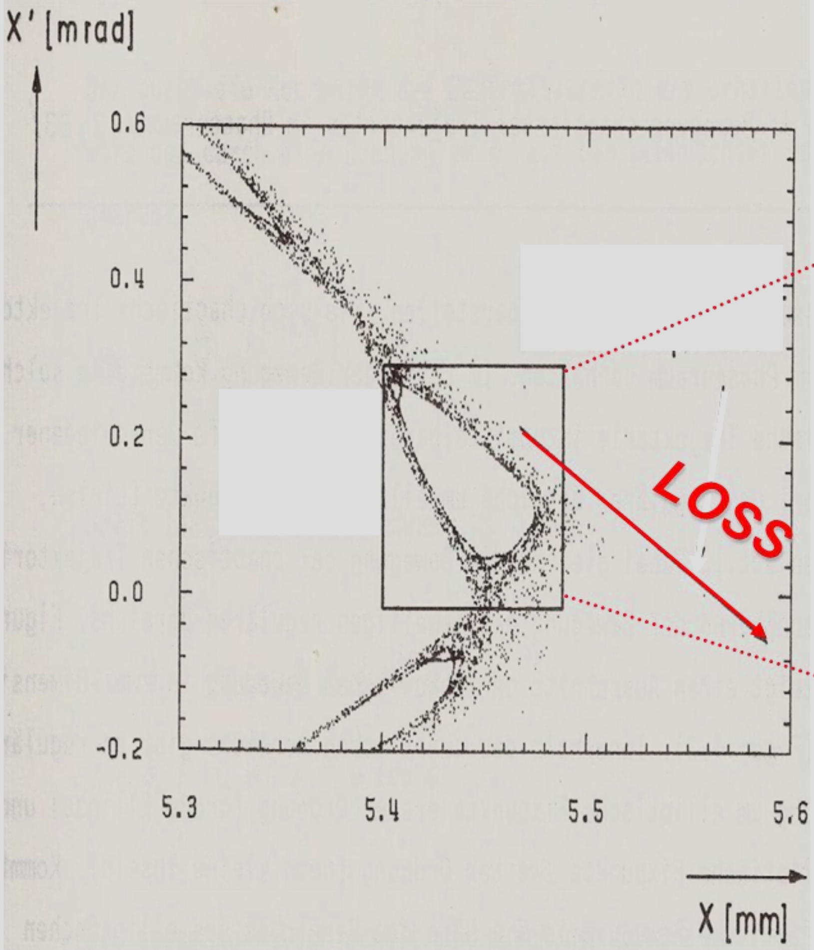


X' [mrad]
3.0
1.5
0.0
-1.5
-3.0
-8.0
-4.0
0.0
4.0
8.0
X [mm]
reguläre Bewegung
chaotische Bewegung
Particle Loss
d(N) [mm]
100.00
10.000
1.000
0.100
0.010
0.001
100.0 E-06
10.00 E-06
1.000 E-06
100.0
1000.0
10.0 E03
100.0 E03
N
exponentieller Anstieg
chaotische Trajektorie
reguläre Trajektorie

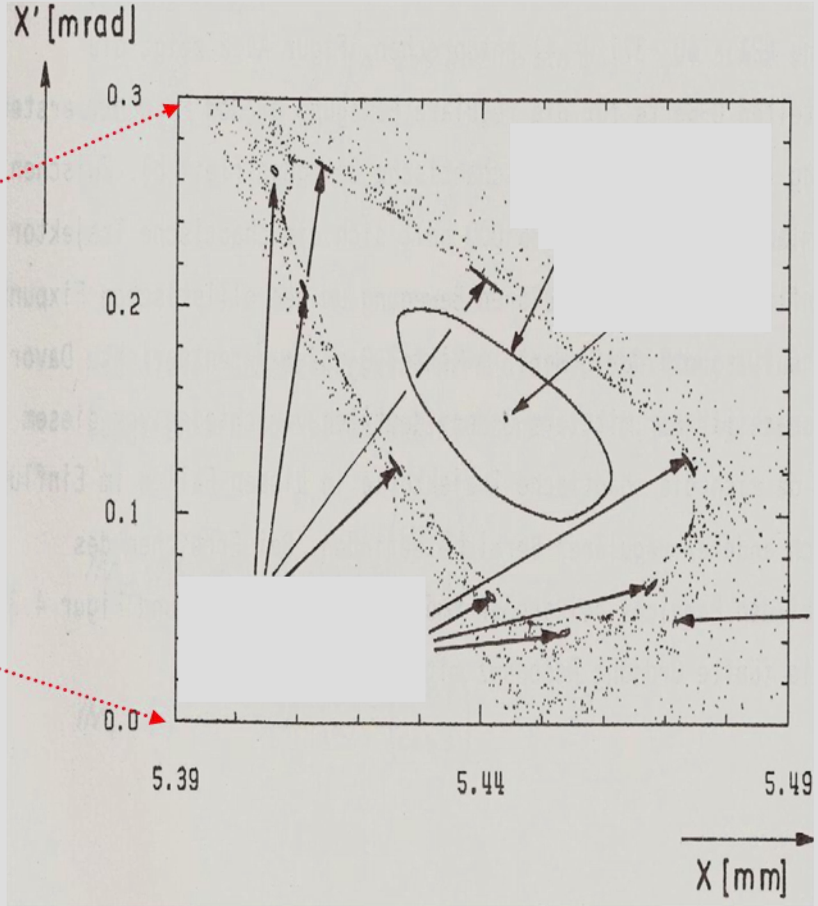
1D close-up



1E+07
1E+06
1E+05
1E+04
1E+03
Turn Number
0 2 4 6 8 10 12 14 16 18
Initial Amplitude [σ]

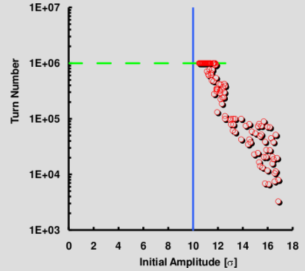


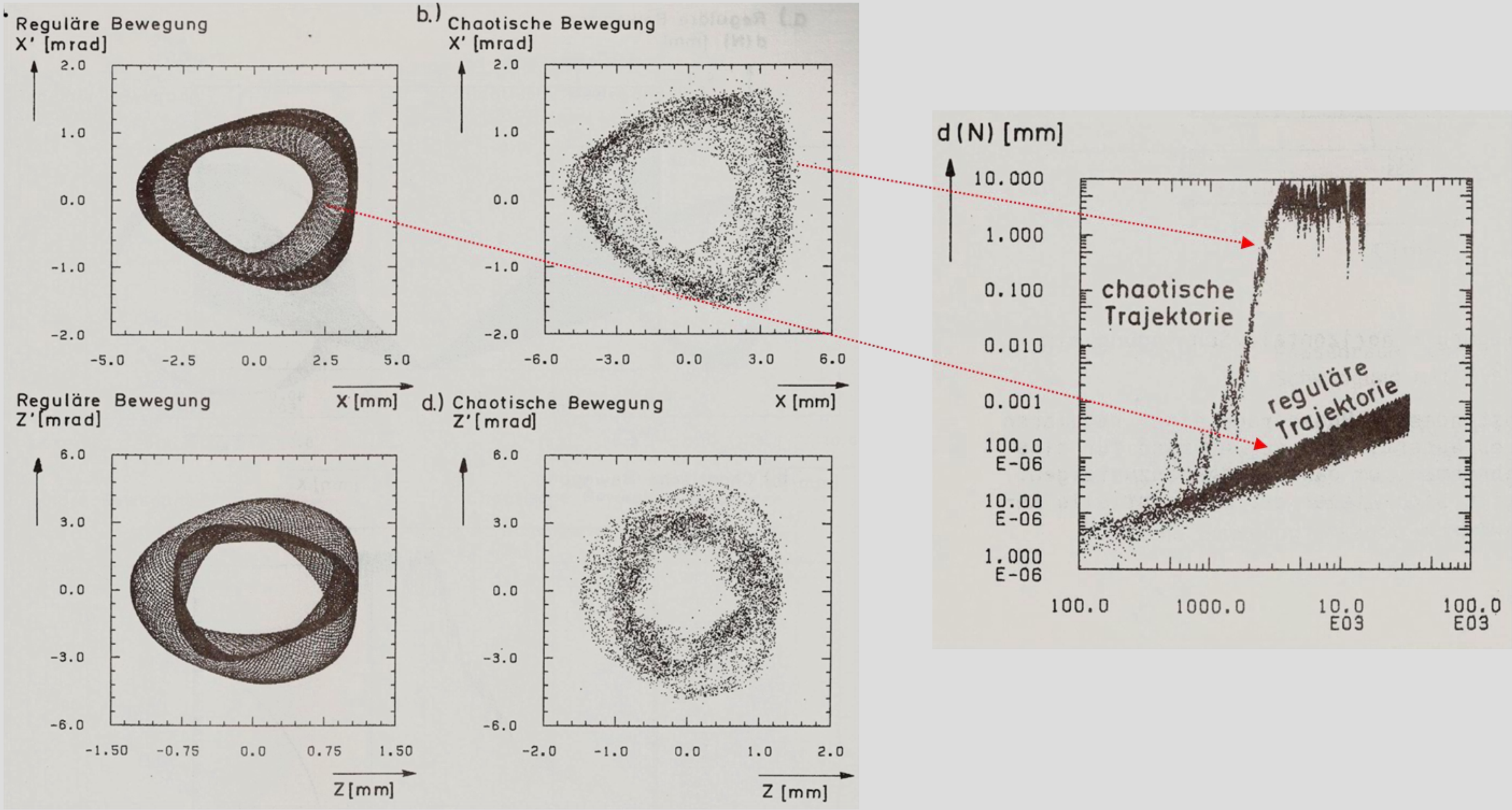
X' [mrad]
0.6
0.4
0.2
0.0
-0.2
5.3
5.4
5.5
5.6
X [mm]
LOSS



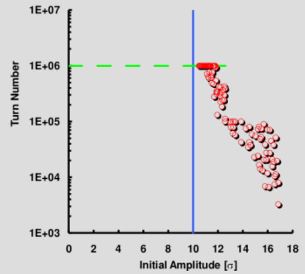
X' [mrad]
0.3
0.2
0.1
0.0
5.39
5.44
5.49
X [mm]

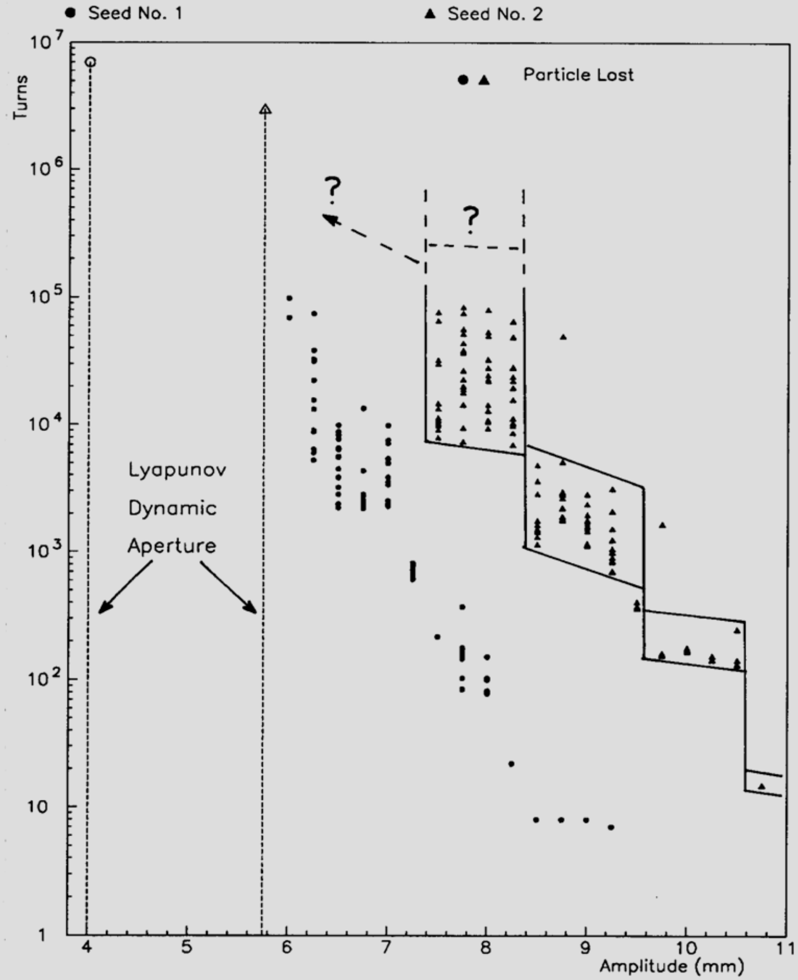
2D Stable and Chaos





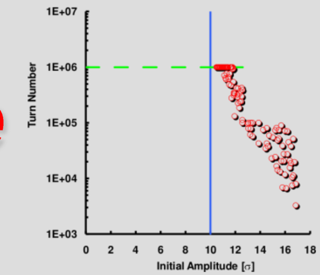
Survival Plots and Resonance Wandering 1/2 (F. Galluccio et al.)

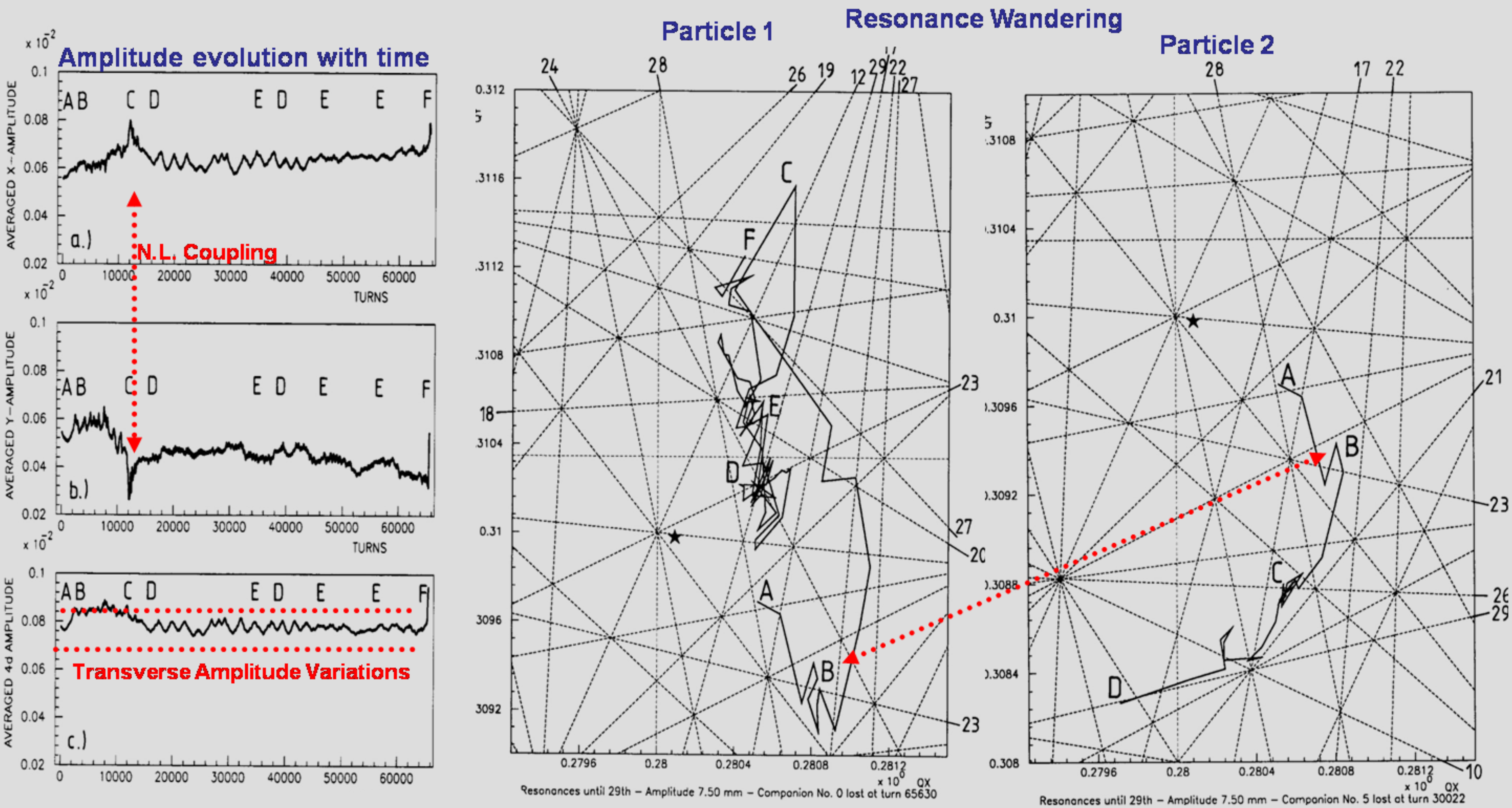




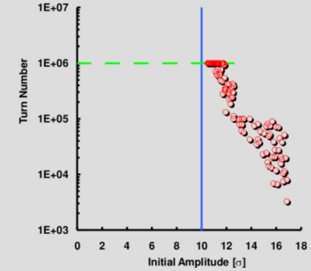
The survival plots depict the number of turns particles stay in the machine for a given amplitude. In this particular example we tracked an ensemble of particles started in a tiny volume of phase space. The width of the survival times tends to grow inverse proportionally with amplitude since the chaotic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

Survival Plots and Resonance Wandering 2/2





Classic Kick Technique



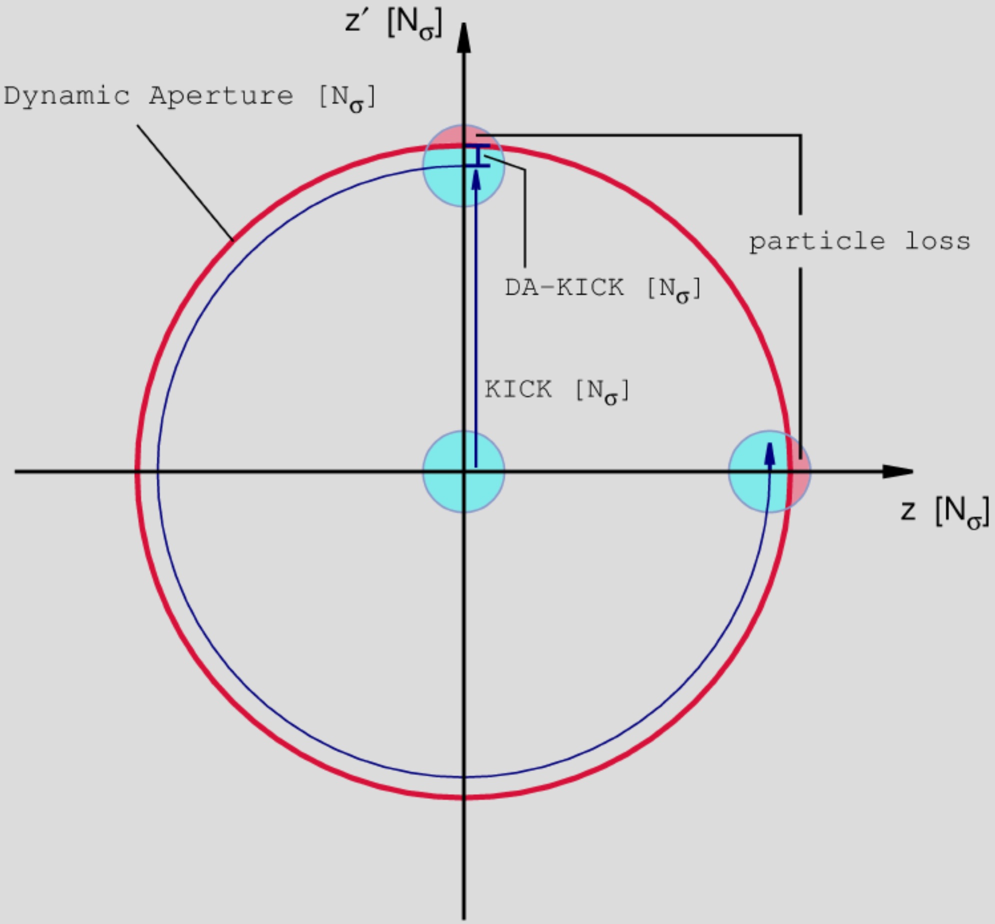
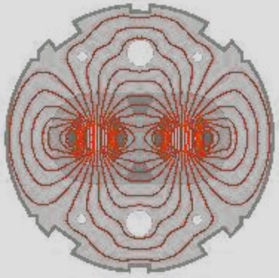
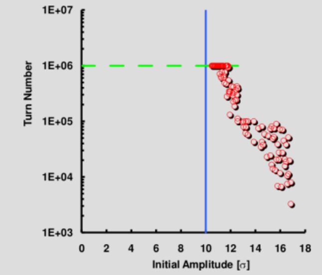


FIG. 2: Illustration of the method used to measure the dynamic aperture. The value of $(DA - N_{\sigma KICK})$ is determined from the beam loss over many turns.

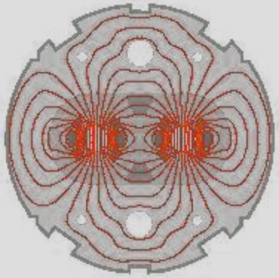


Tracking Engine for massive LHC Tracking Studies 1/2

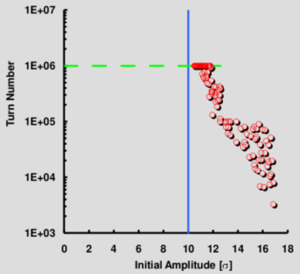


Many Thanks to Eric McIntosh

- 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.



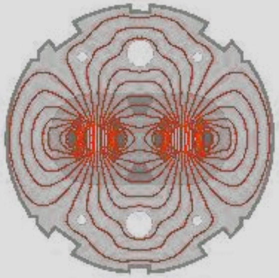
Tracking Engine for massive LHC Tracking Studies 2/2



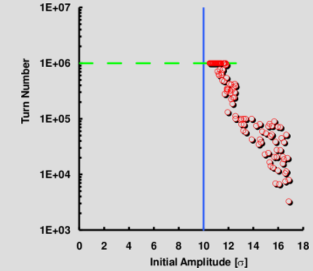
- Jobs can be sent to various batch systems, e.g. a local CERN batch cluster with hundreds nodes is at our disposal.

- 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.



DA Experiments 1988 - 1994



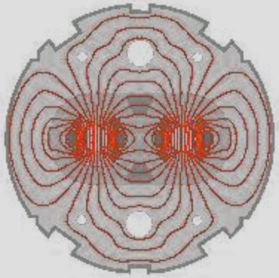
In view of the proposed 2 competing projects the SSC and LHC, experiments have been conducted both at SPS and Fermilab

- **SPS (1988)**
- **E778 (1989) at Tevatron**

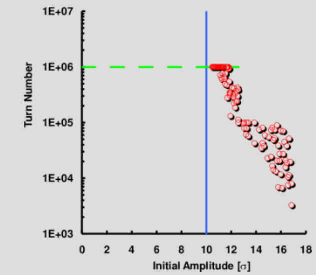
With the following agenda:

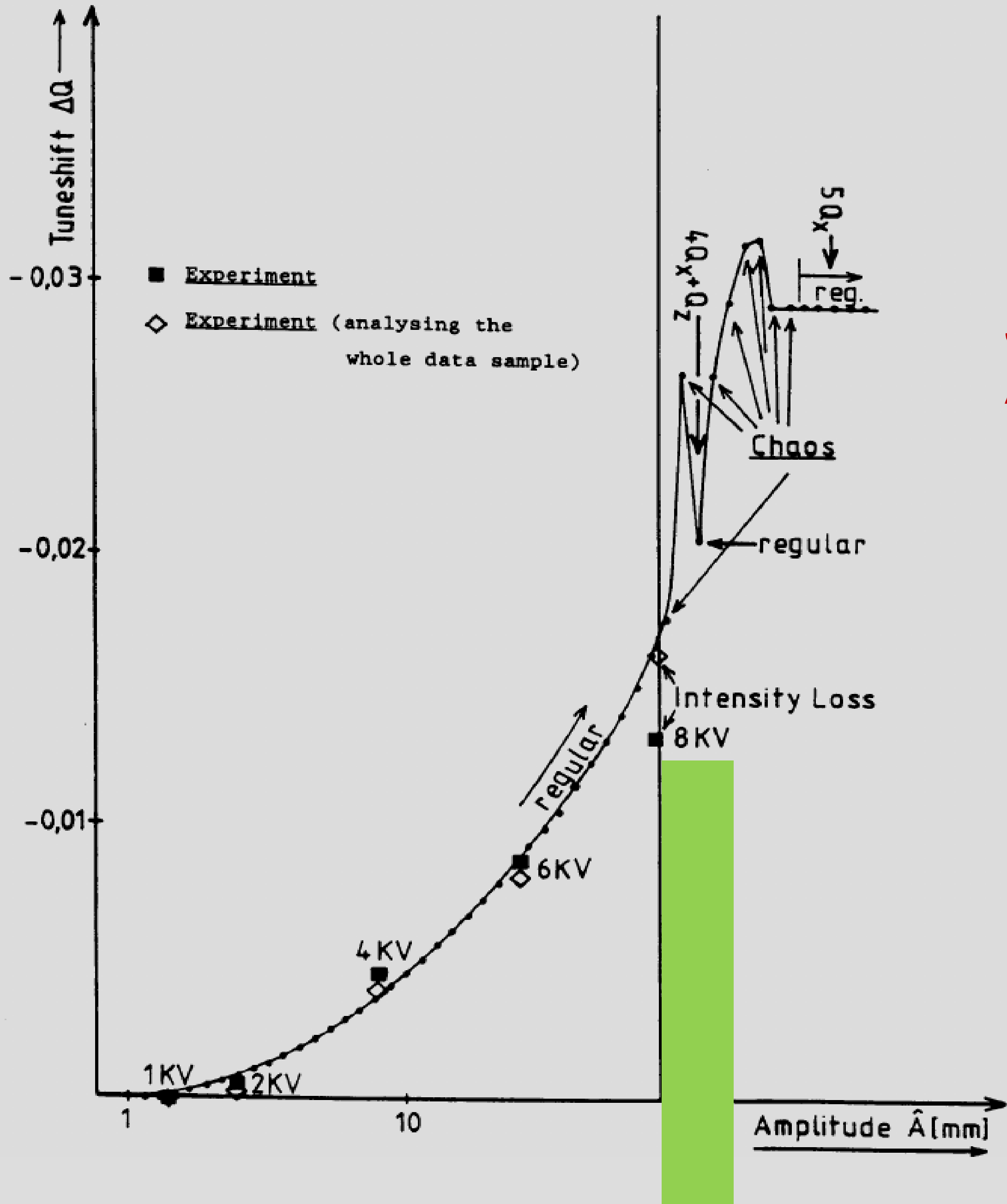
- **DA measurements to compare with simulation code:**
  - **SPS: the machine is too linear, therefore 8 strong sextupoles have been powered with self-compensation of the low order resonances.**
  - **Tevatron: Non-linear but there has never been a complete model of Tevatron including non-linearities**
- **Effect of Resonances**
- **Influence of Tune Modulation**
- **Diffusion speed at large amplitudes**

2004 Hera DA experiment



SPS DA Experiment 1988

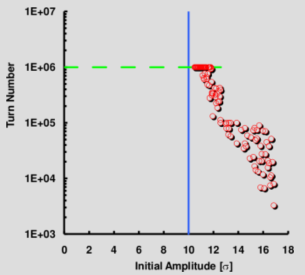


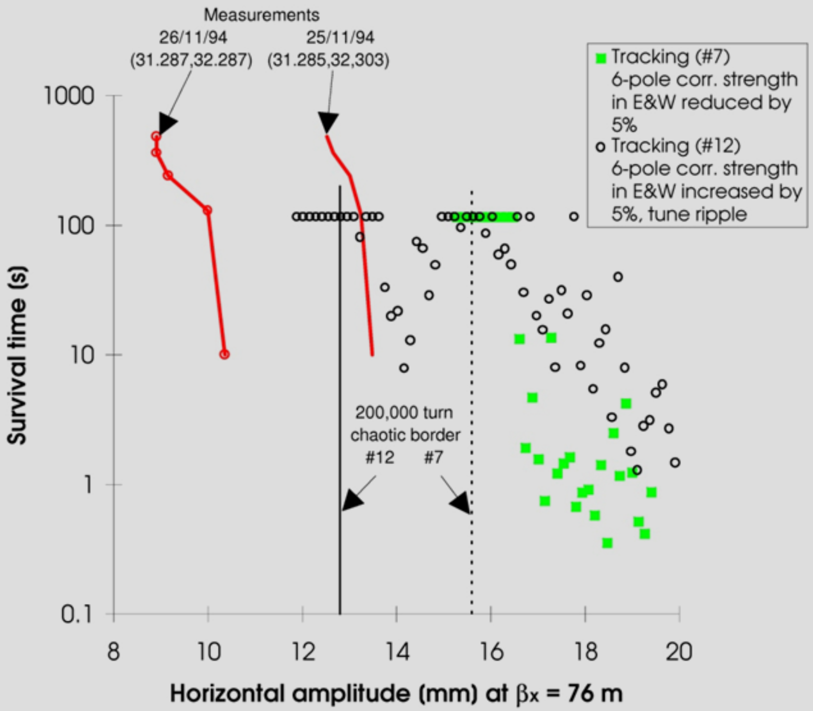


J. Gareyte
A. Hilaire
F. Schmidt

DA Experiment (HERA)

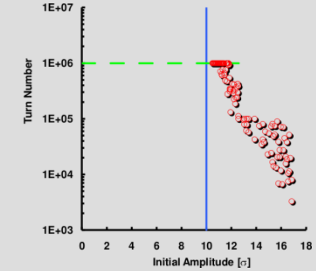
(Wolfram Fischer's PhD thesis)





case		amplitude ratio	transverse acceptance	transverse dynamic aperture	relative difference between measurement and tracking
(Q_x, Q_z)		$\sqrt{A_z}/\sqrt{A_x}$	$A_x + A_z$ [mm · mrad]	$a_{trans} = \sqrt{\beta(A_x + A_z)}$ [mm]	$\left(\frac{a_{trans,track}}{a_{trans,meas}} - 1\right)$ [%]
(31.285,32.303)	measured	$\lesssim 0.39$	2.08–2.39	12.6–13.3	3–23
	tracking	≈ 0	2.29–3.54	12.8–15.6	
(31.287,32.287)	measured	≈ 1	1.01–2.02	8.8–12.4	23–75
	tracking	≈ 0.8	3.11	15.4	

Taking into account all experimental observations it is likely that there exists a yet unknown mechanism that leads to particle loss. The necessary assumption of beam tails right after scraping to obtain consistent aperture values from beam loss experiments (as mentioned in Sec 5.4.1) indicats such a mechanism which may explain the remaining difference of measured and computed dynamic aperture even present for the separated tunes in 1994.



DA Experiments LHC 2012

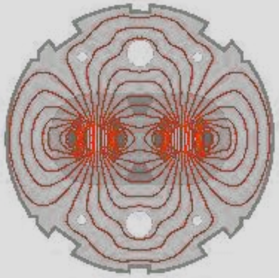
At the LHC in 2011 and 2012 we had 1 shot each to do this DA experiments. We have been fortunate enough to do independent experiments on Beam1 and Beam2

- **Beam1: This was dedicate to a new technique to probe the dynamic aperture according to the inverse logarithm scaling law for the dynamic aperture. This scaling law, derived from tracking data, has been recently used to derive a possible relation between the intensity evolution and dynamic aperture. This has been performed by Massimo Giovannozzi and his team. In fact, Massimo will report about this in a GSI seminar scheduled for this week.**

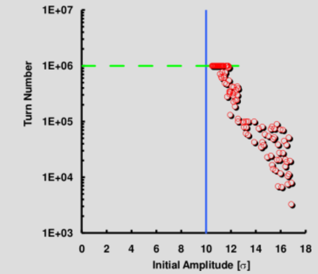
- **Beam2: This part of the experiment determines the DA with the classical kick technique and will be reported here. Rogelio Tomàs and Frank Schmidt have been leading this effort and the PhD student Ewen Maclean was doing all the job! It goes without saying that we are indebted to the machine protection group that allowed us to use the powerful MKA kicker and also the BI experts and the LHC operation team. Report ready for publication:**

E.H. Maclean, R. Tomàs, F. Schmidt, and T.H.B. Persson.

"Measurement of LHC non-linear observables using kicked beams."



Kick Experiment and Simulation Conditions

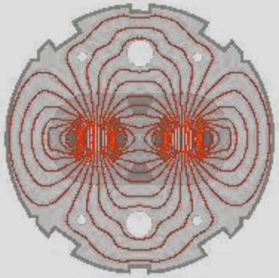


Experiment

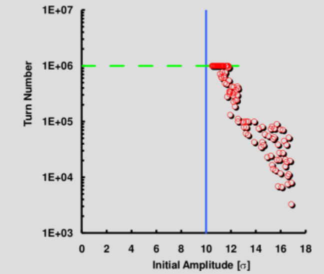
- LHC Injection Energy 450 GeV
- Aperture kicker (MKA) up to ~14 beam sigma
- collimators set to 11.7 beam sigma to protect the triplets
- BPM system calibrated before the experiment
- Wire scanners scale enlarged to cover 12 sigma kicks
- DA Measurement via Loss monitors

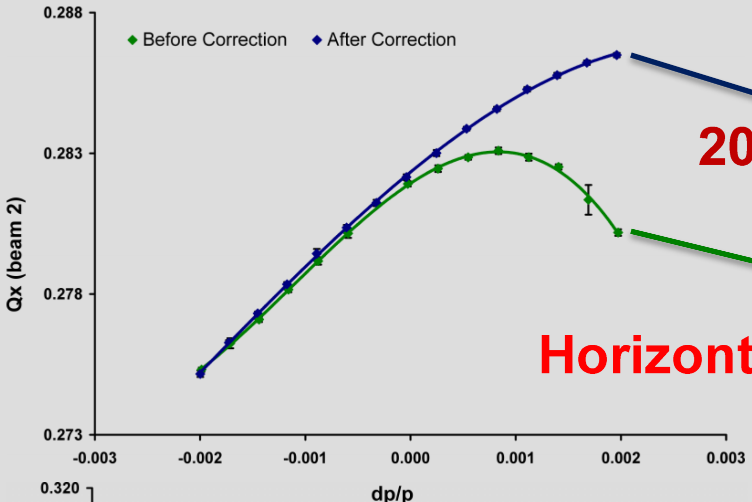
Simulation

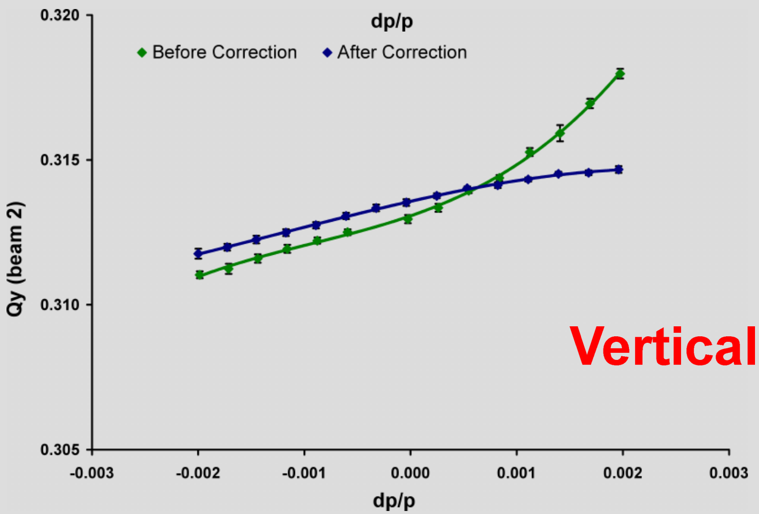
- Latest LHC lattice
- Multipole of machine as build
- Seeds needed for cold-warm variations. The usual 60 seeds tracked.
- Misalignment measurement of all magnets (offsets and tilts)
- For the corrected machine detuning has been matched to the measured ones.

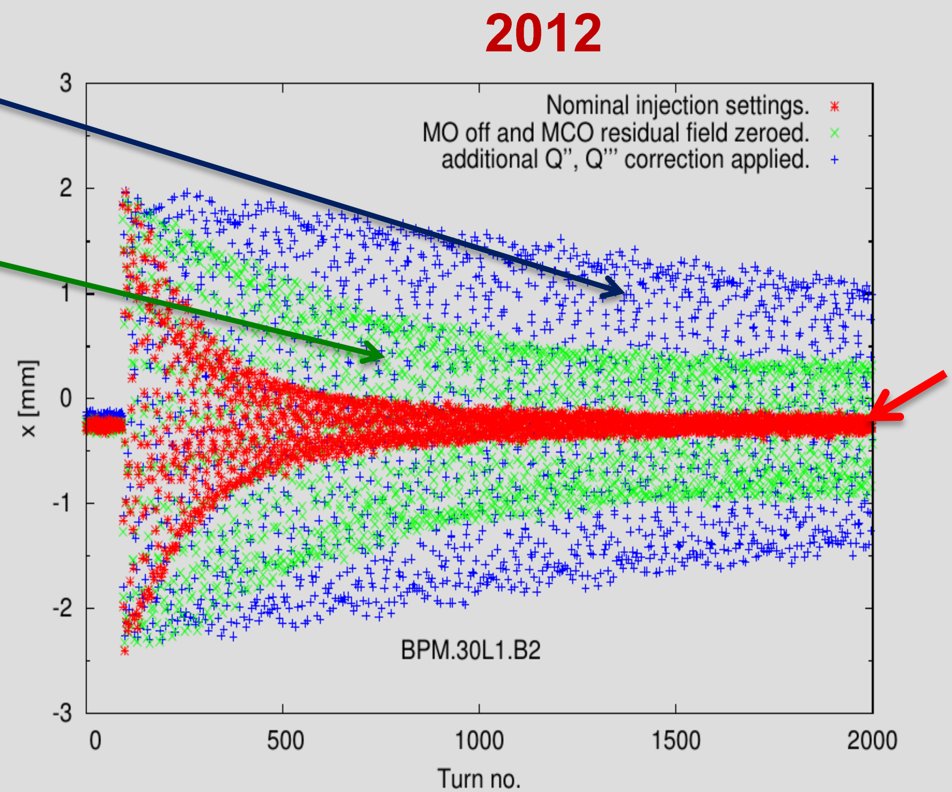


Q” & Q”’ Correction - LHC 1/6



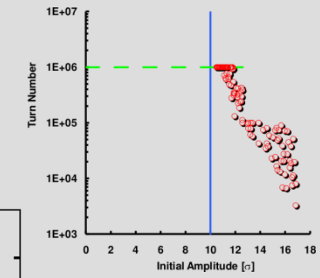


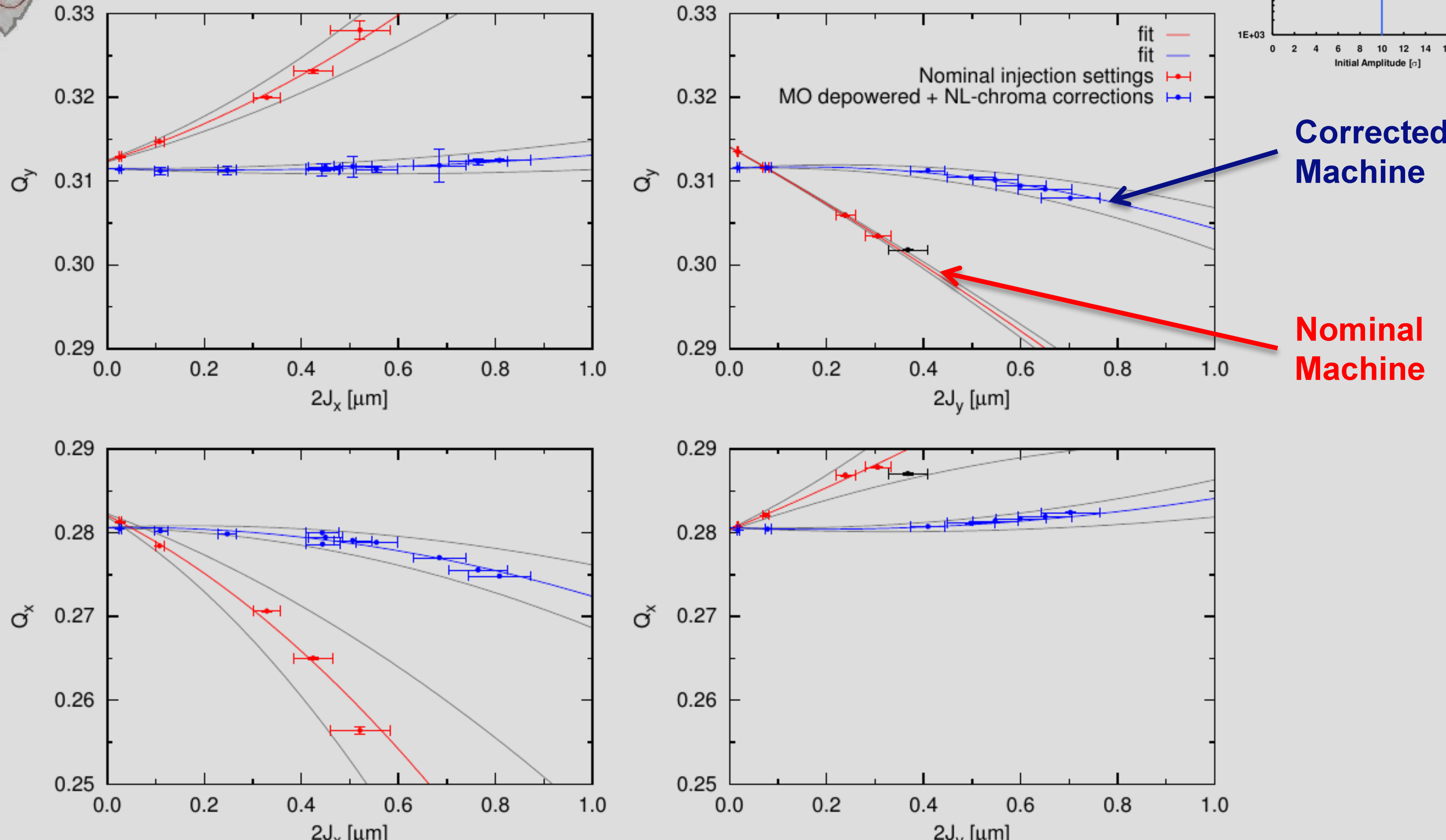




E.H. Maclean, R. Tomàs, F. Schmidt, and T.H.B. Persson.

Detuning with Amplitude - LHC 2/6

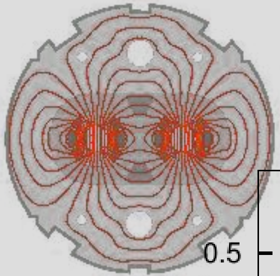


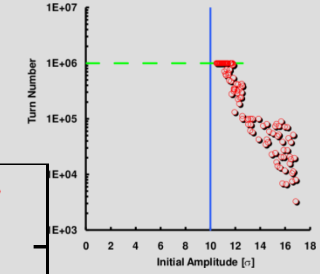


(a) Detuning with amplitude of the LHC at nominal injection settings (red), and with Landau octupoles set to zero and additional corrections for Q'' and Q''' applied (blue). The tune is plotted against the horizontal and vertical single particle emittance of the kicks. Points shown in black represent kicks where there was substantial coupling of the kick into the opposite plane.

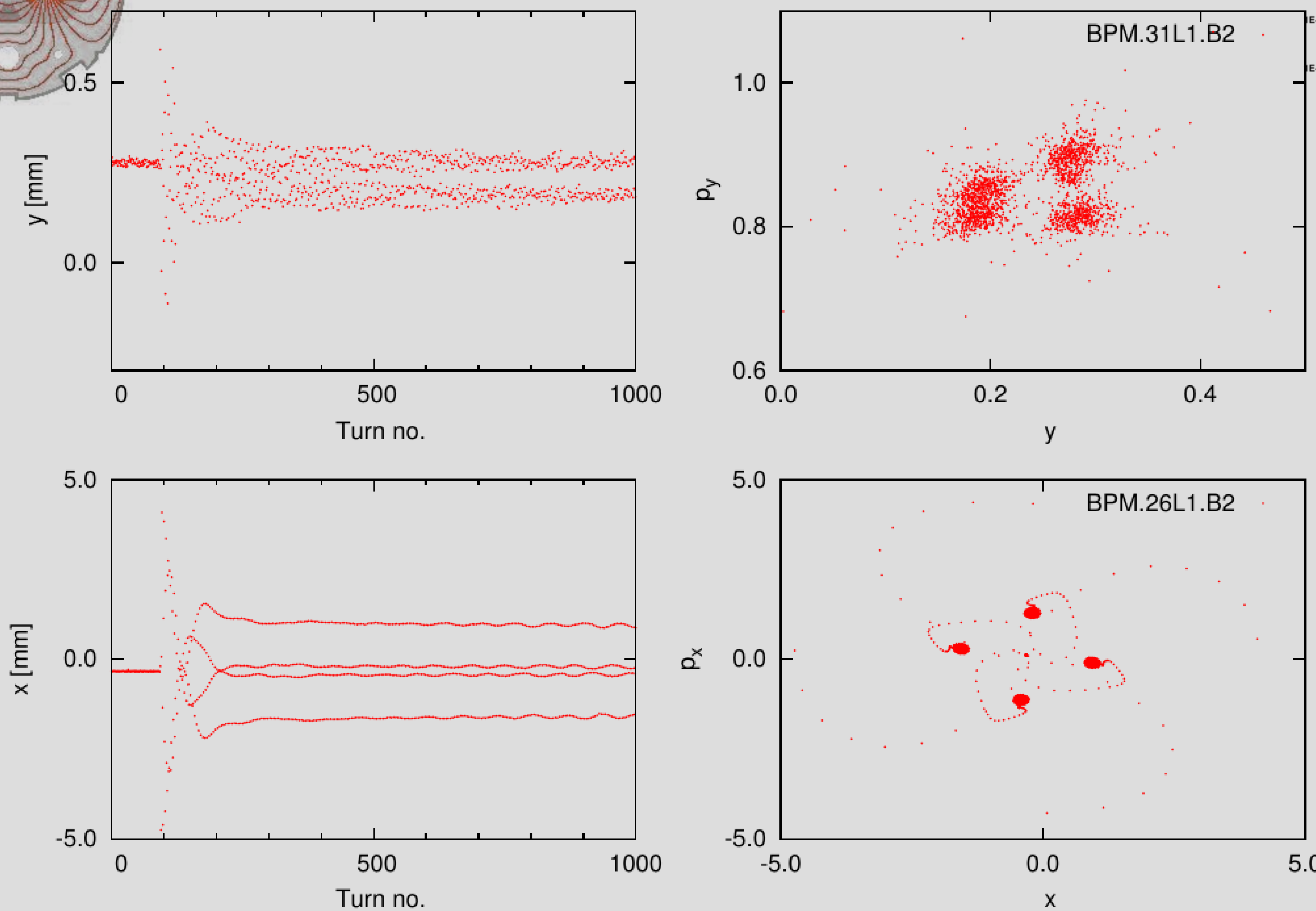
E.H. Maclean, R. Tomàs, F. Schmidt, and T.H.B. Persson.

H&V Resonances - LHC 3/6



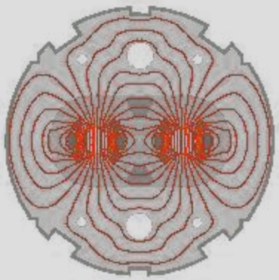


Nominal Machine

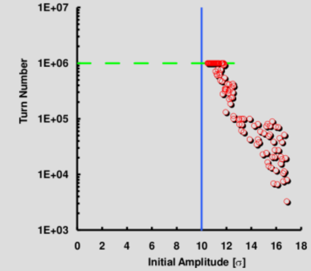


(b) Turn-by-turn (TbT) and phase space data for a $(8.3\sigma_x, 0.6\sigma_y)$ kick with nominal LHC injection settings in the vertical plane at BPM.31L1.B2 (top), and the horizontal plane at BPM.26L1.B2 (bottom).

E.H. Maclean, R. Tomàs, F. Schmidt, and T.H.B. Persson.



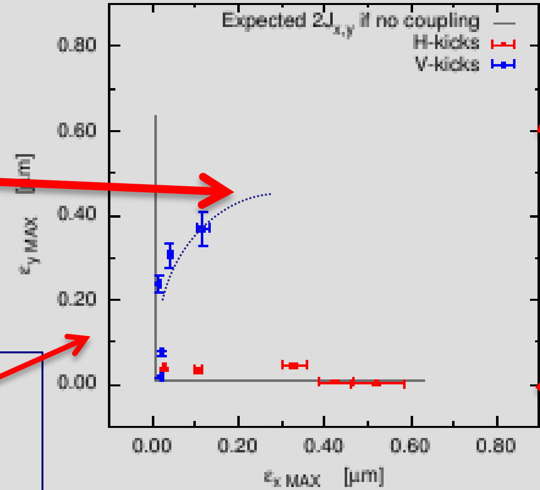
Non-Linear Coupling LHC 4/6



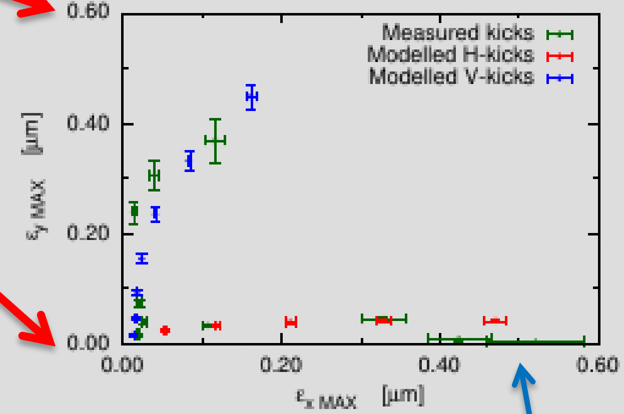
Non-Linear Effect

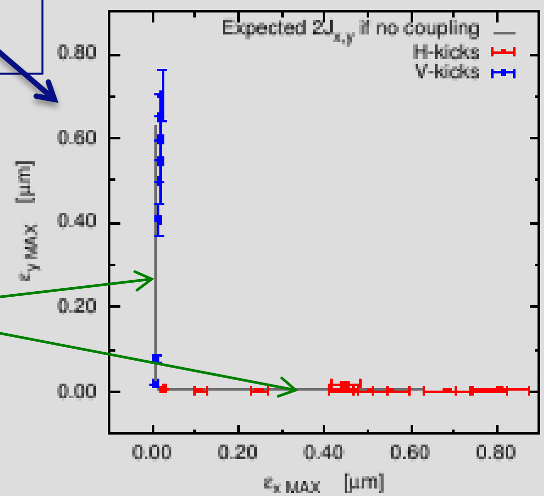
Nominal Machine

Corrected Machine



(a) Nominal injection optics.





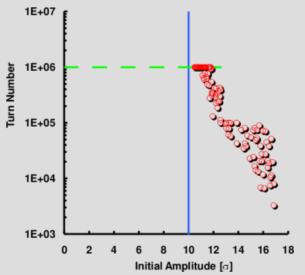
(b) MO depowered to zero, and Q'' and Q''' corrections applied.

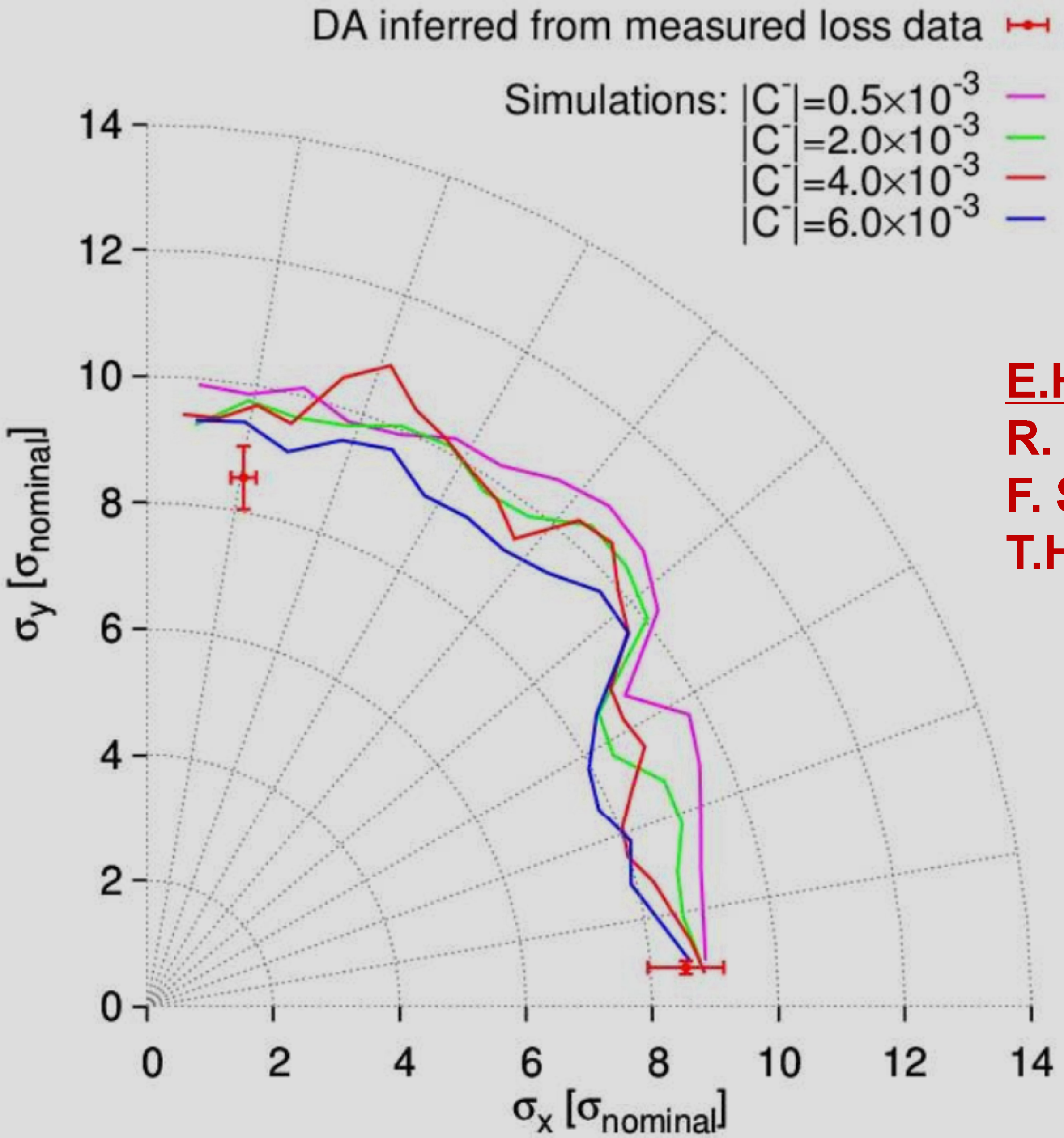
Lines Linear Expectation

Non-Linear Coupling reproduced in Simulations:

Red/Blue: H & V Model
Green: Measurement

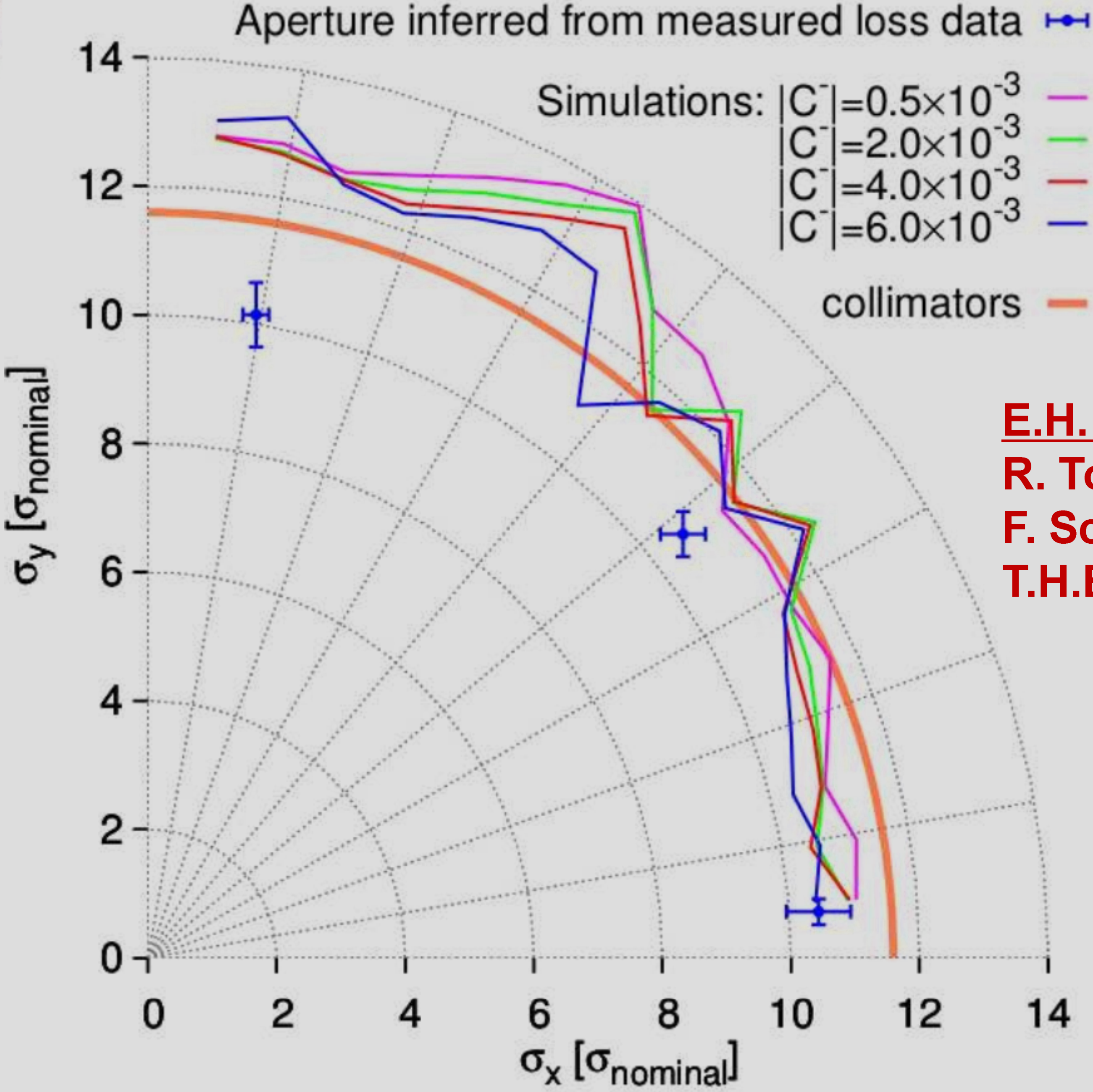
DA Nominal Machine - LHC 5/6

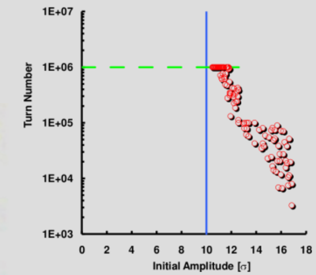




E.H. Maclean,
R. Tomàs,
F. Schmidt, and
T.H.B. Persson.

DA Corrected Machine - LHC 6/6





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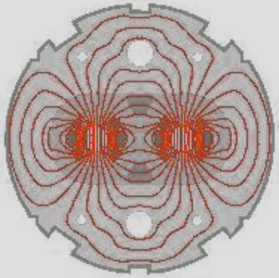
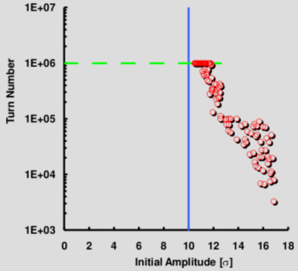
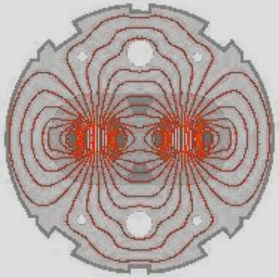


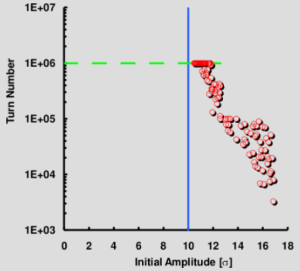
Conclusion 1/2



- After **30 years** of simulations from **HERA, SPS, Tevatron, RHIC** to **LHC** we can conclude that our simulation tools are **reliable**.
- In particular, we can perform any kind of **massive simulation** studies via **distributed** and **scalable** computing facilities.
- The **theoretical** understanding is advanced enough to **understand the non-linear dynamics** caused by **multipolar components**. In particular, we understand single particle loss due to **deterministic chaos**.



Conclusion 2/2



- The 2012 LHC DA experiment (Part II) using the classic kick technique allows to say that we can predict the DA to about 10% rather than the expected factor 2. Reasons are:
  - Excellent knowledge of multipolar components, magnet by magnet, including misalignments (Fidel & Wise)
  - Apparently the power supply ripple is under control

➔ This does increase our confidence in simulation studies for the HL-LHC.

- We are waiting for confirmation from the PART I LHC DA experiment performed on BEAM1 with more modern techniques.