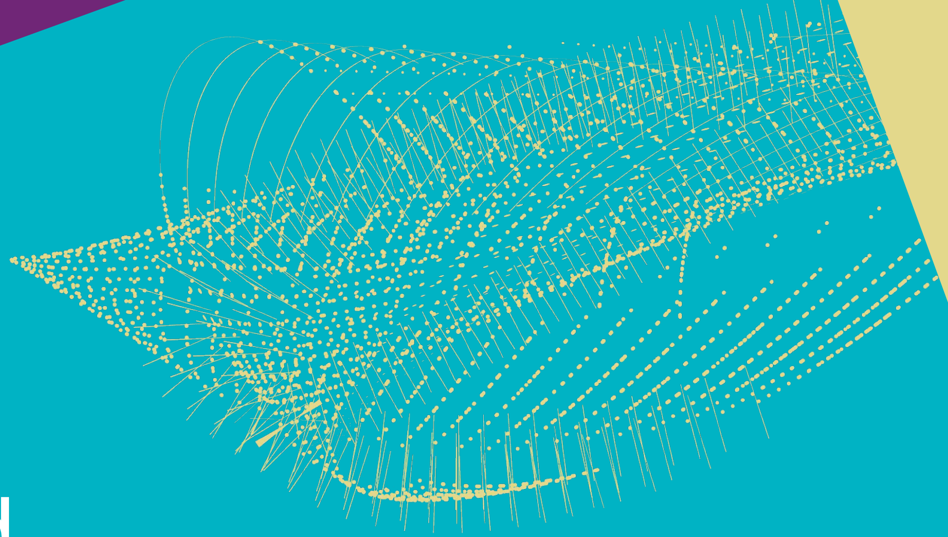
R&D Meeting 10-05-2019



Measurement and correction of nonlinear optics in the LHC

F. Carlier

Attempt to summarize a thesis in 15 minutes

Introduction:
- What are the building blocks of particle accelerators?
- Where do nonlinear perturbations come from?
- How are beam dynamics measured in the LHC

Thesis:
- Stability under AC dipole excitation
- Correction of nonlinear errors in the LHC
- First measurement of beam-beam nonlinearities

Attempt to summarize a thesis in 15 minutes

Introduction: (80%)

- What are the building blocks of particle accelerators?
- Where do nonlinear perturbations come from?
- How are beam dynamics measured in the LHC

Thesis: (20%)

- Stability under AC dipole excitation
- Correction of nonlinear errors in the LHC
- First measurement of beam-beam nonlinearities

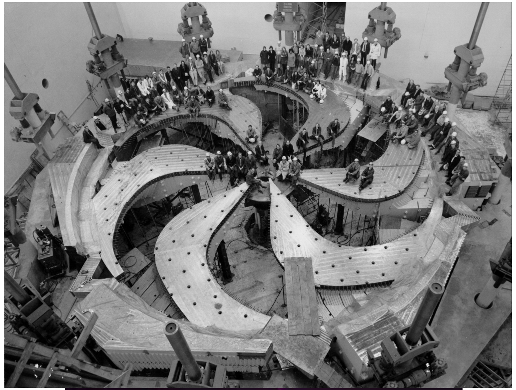
Disclaimer: Lots of information missing, probably more suitable for a seminar

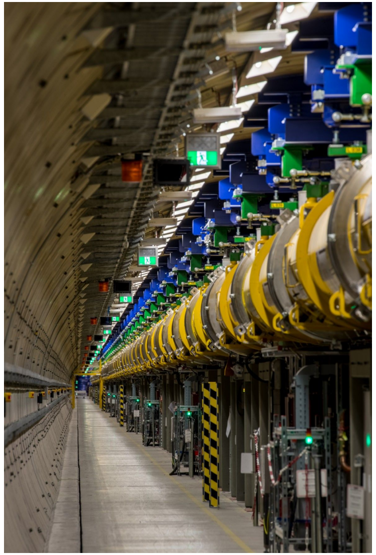
Accelerators are quite common

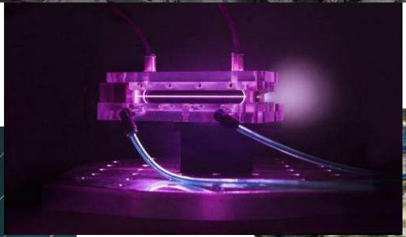
Accelerator physics is probably the only thing Nikhef does not do. **But it's a huge field!**

About 30000 active particle accelerators in the world:

- Colliders
- Light sources
- Synchrotrons
- Medical accelerators
- Linear accelerators
- Cyclotrons
- Electrostatic accelerators
- Wakefield accelerators
- ….







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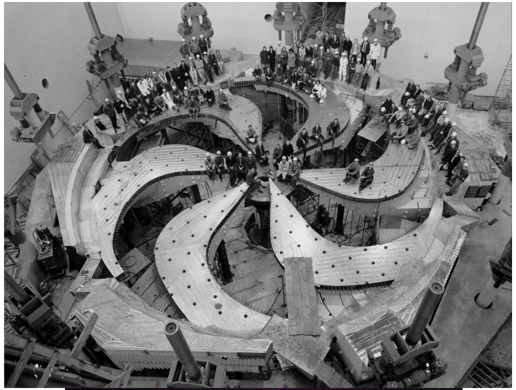
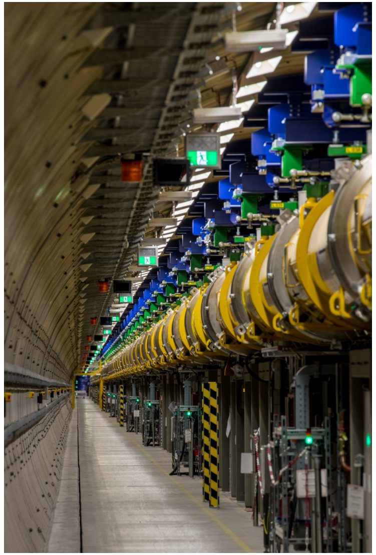
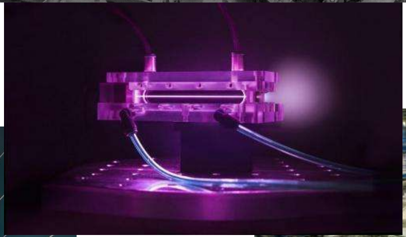


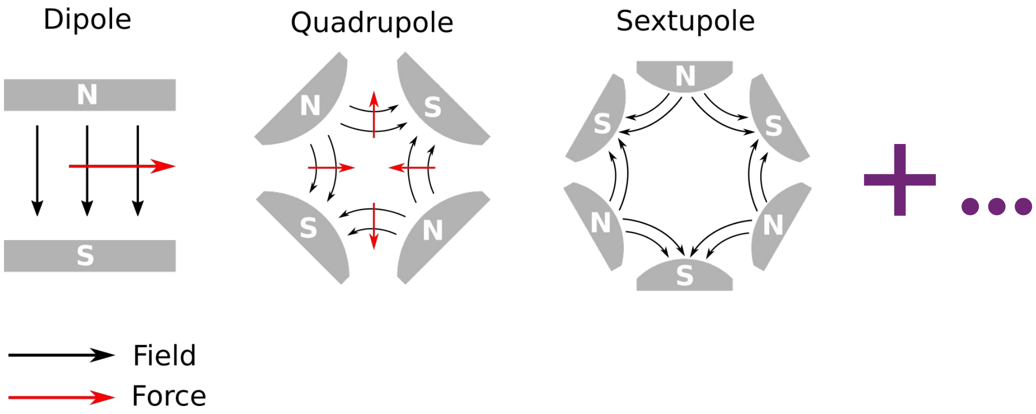


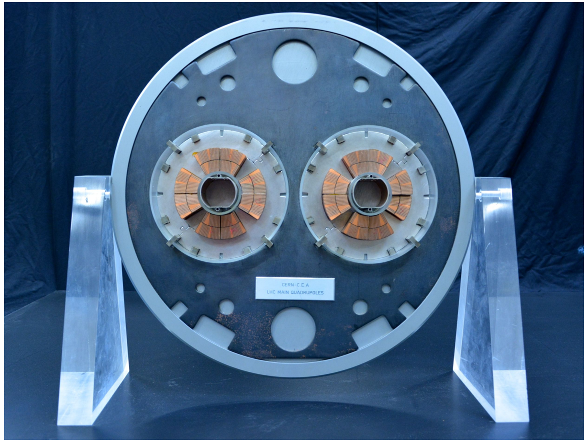


Building blocks of the LHC are magnets

Magnetic fields are used to bend, shape, and control the beams

- Dipoles: change trajectory of bunch
- Quadrupoles: focus or defocus the bunch
- Higher orders: control the nonlinear optics



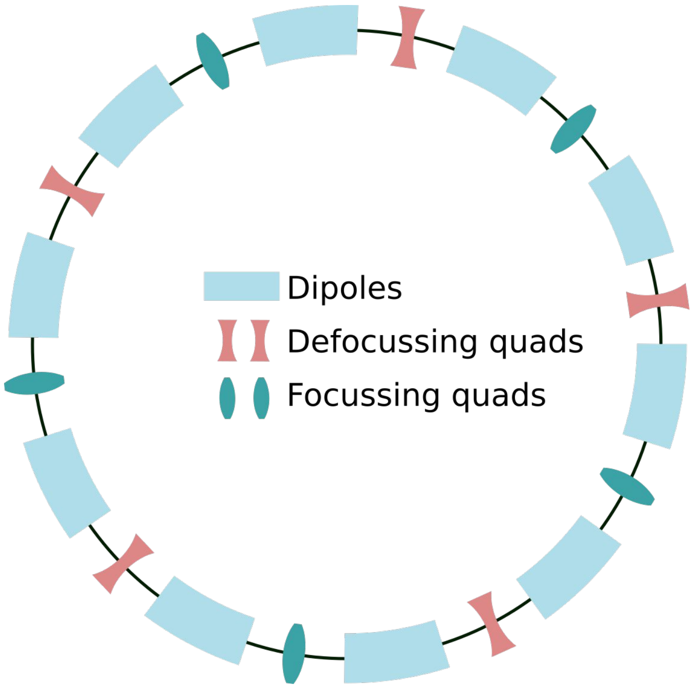


Basic look of the LHC: A lattice of magnets

Alternating focusing and defocusing quadrupoles, interleaved with dipoles.

Still need to add:

- RF cavities (beam acceleration)
- Injection region
- Collision sections
- 2nd beam and beampipe
- Feedback systems
- All instrumentation
- Beam dump
- etc...

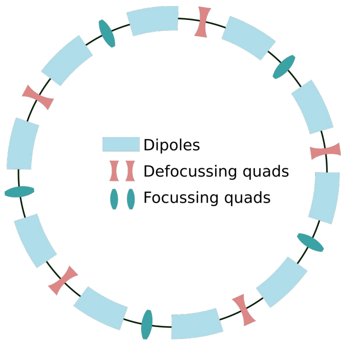


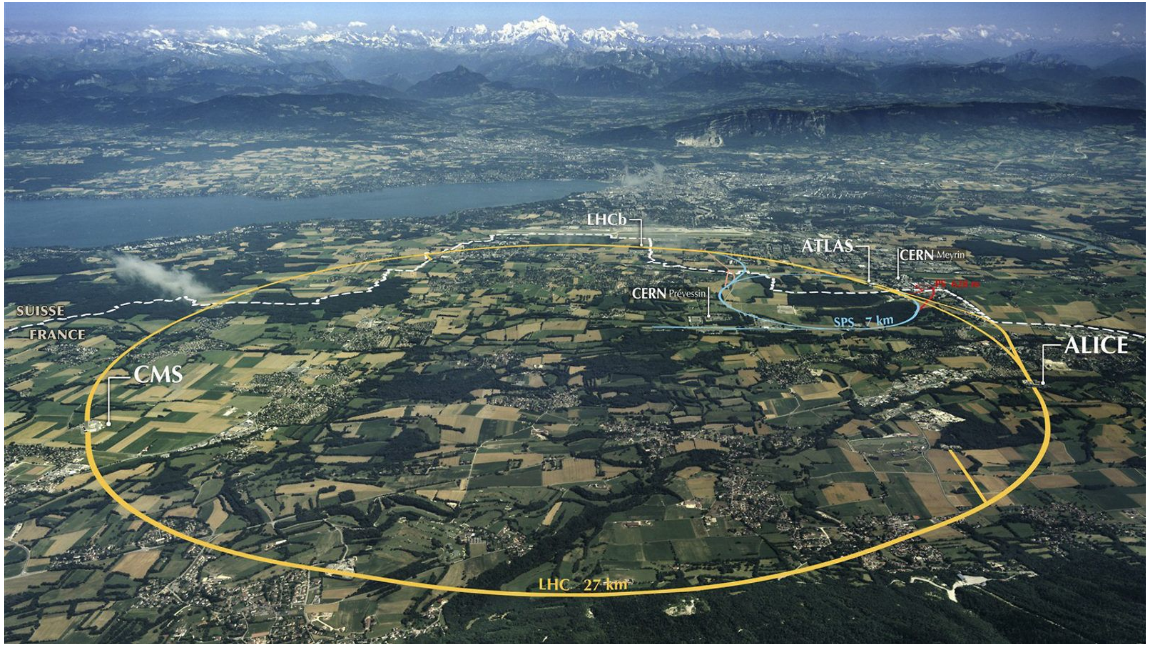
Nikhef

Basic look of the LHC

And multiply to about:

dipoles: 1232
quadrupoles: 392
total magnets: 9593

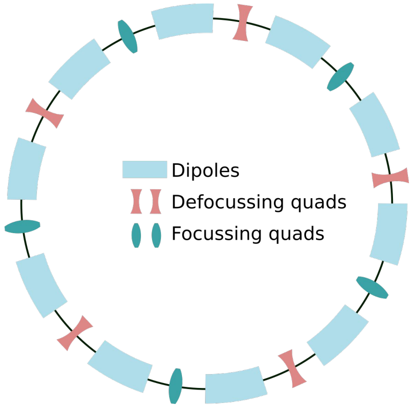


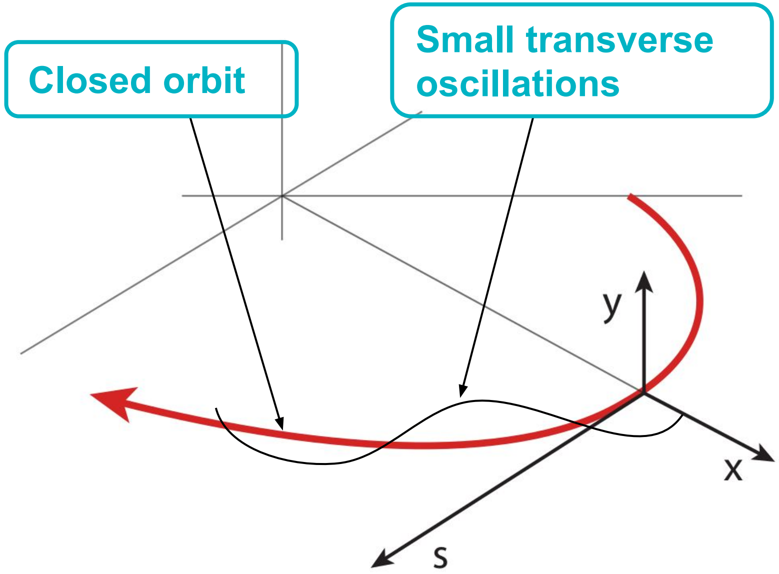


Frame of reference moves on ideal orbit

- Closed orbit (reference orbit) is the ideal trajectory as defined by the bending of the dipoles for a particle with design energy.

- Motion of interest is motion **transverse** to the direction of travel on the closed orbit (x & y).





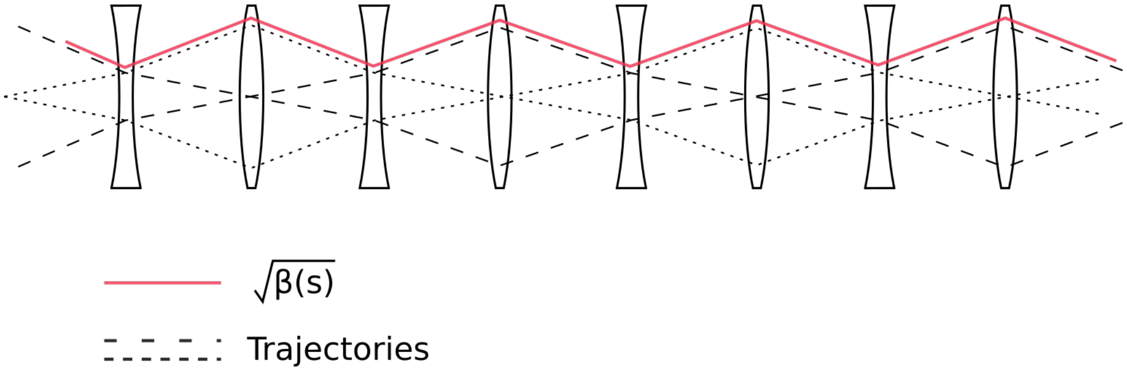
Linear optics from FODO lattice

Alternating focusing and defocusing quadrupoles known as FODO lattice (like in the LHC)

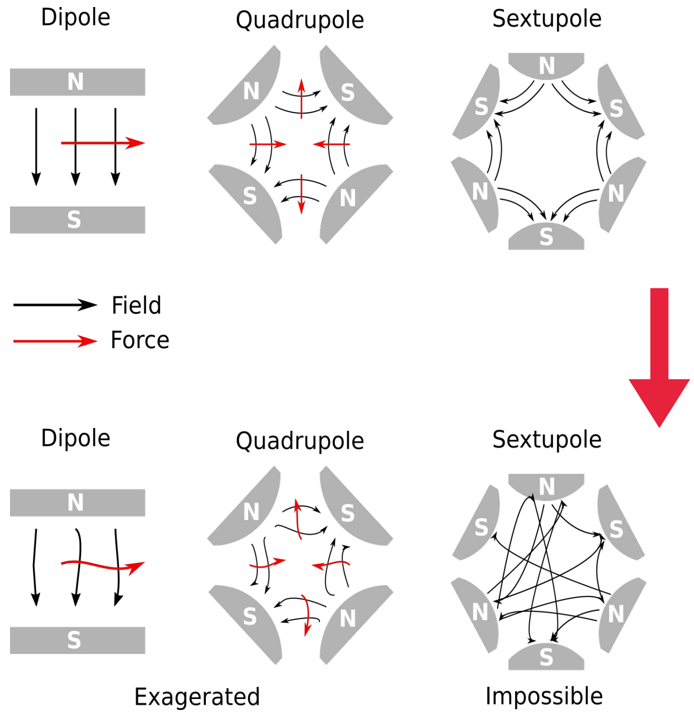
- Defines the linear beam optics
- Beta-function determines the envelope of oscillation amplitude

The total number of oscillations in one turn determines the **tune (Q)**

- Frequency of main linear mode
- Most important design parameter
- Determines resonant modes or not



Unfortunately nothing is perfect



Sources of errors

- Magnetic errors (design or manufactured)
- Misalignment and rotation of magnets

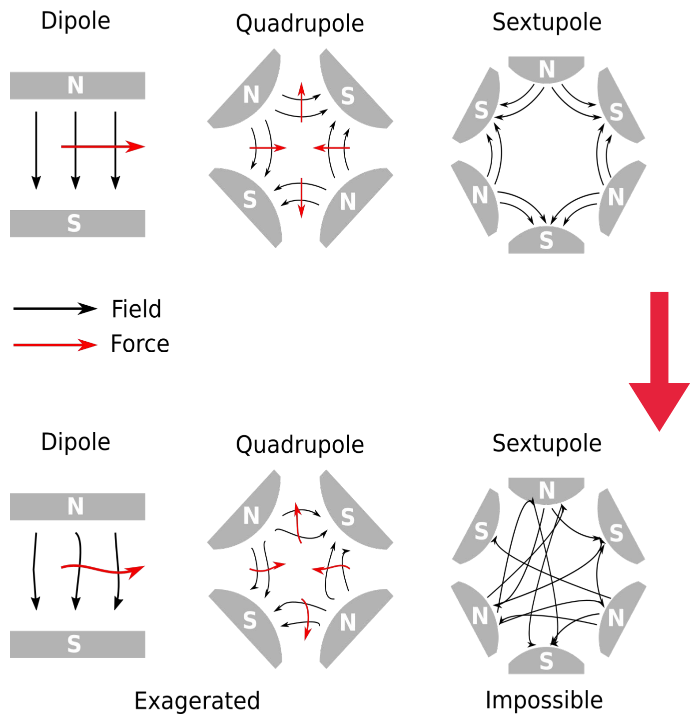
Can be described by a multipolar expansion

$$B_y + iB_x = B_r \sum_{n=1}^{\infty} [b_n(s) + ia_n(s)] \left(\frac{x+iy}{R_r} \right)^{n-1}$$

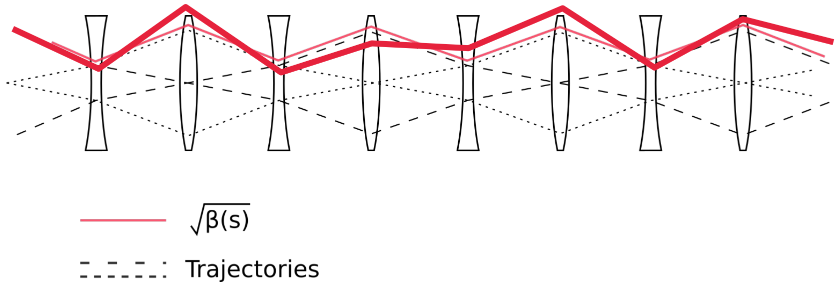
Quadrupole is a linear element (n=2)

- But will contain nonlinear error components (n > 2)
- Referred to as **nonlinear errors or sources**

Unfortunately nothing is perfect



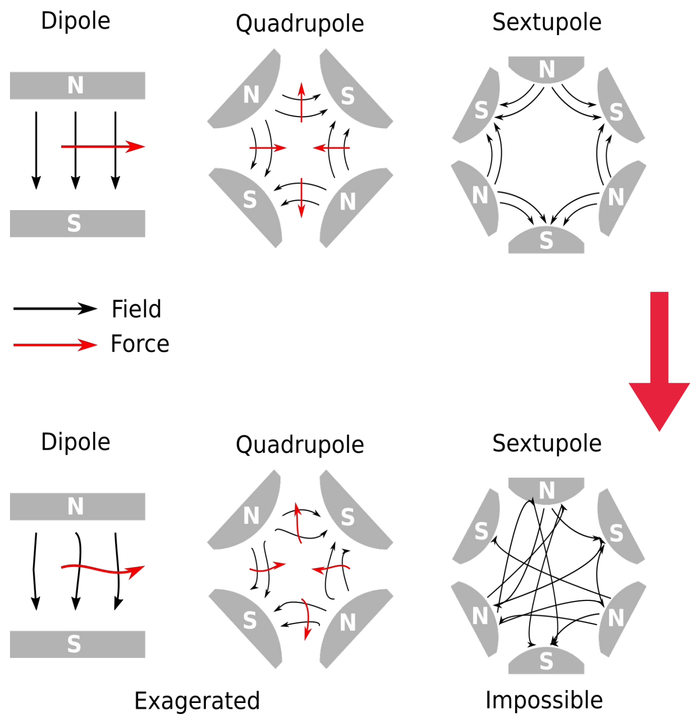
Cause distortion of beam optics!



Nonlinear errors cause:

- Reduction of stable phase-space
- Resonances
- Beam loss
- Instabilities
- Detuning of machine
- etc...

Unfortunately nothing is perfect



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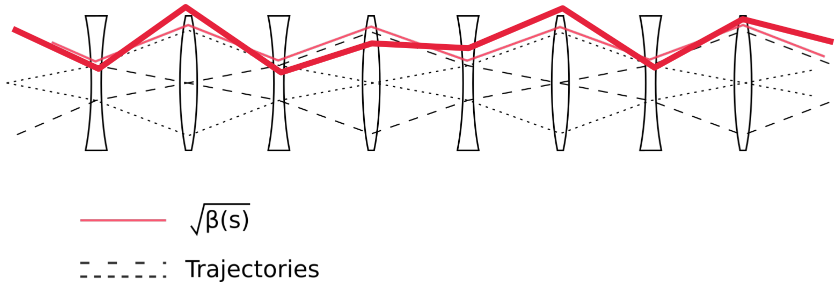

Nonlinear errors cause:

- Reduction of stable phase-space
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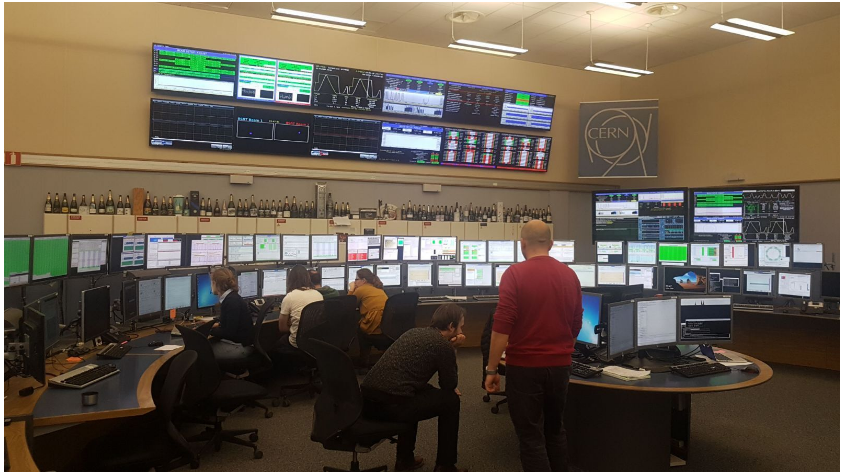
- etc...

Needs to be measured & corrected!

Measuring beam dynamics in accelerators - Overview

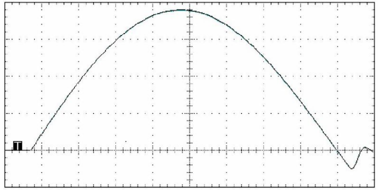
Create transverse oscillation of beam → Measure beam Position (x & y) → Spectral analysis beam position → Relate spectral content to sources



Usually in the middle of the night in the CERN Control Center..

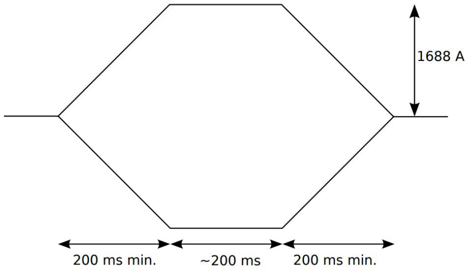
Creating transverse oscillations with AC dipole

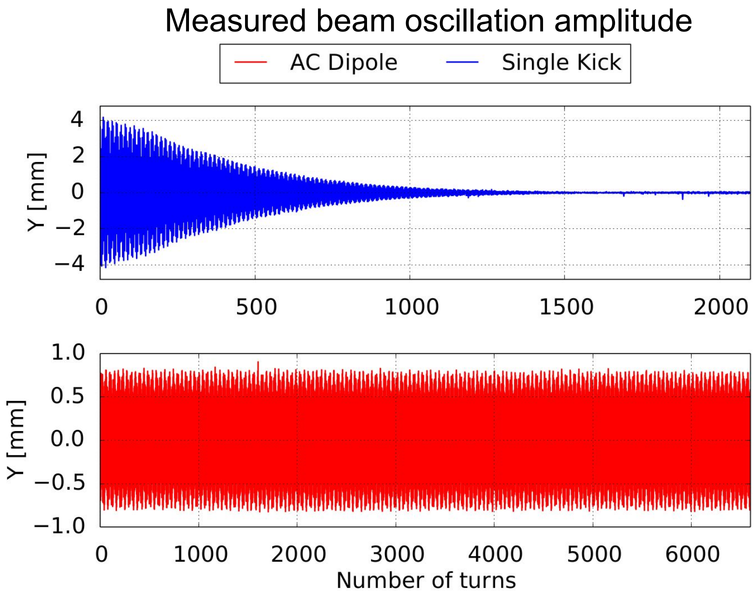
Single dipole pulse kick:



AC dipole with:

- Frequency close to tune, close to resonant
- ramp up, flattop, ramp down of current

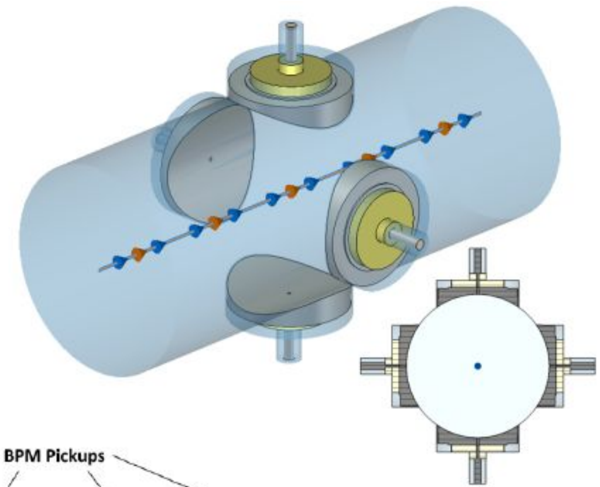




Beam position monitor (BPM) to measure oscillating beam

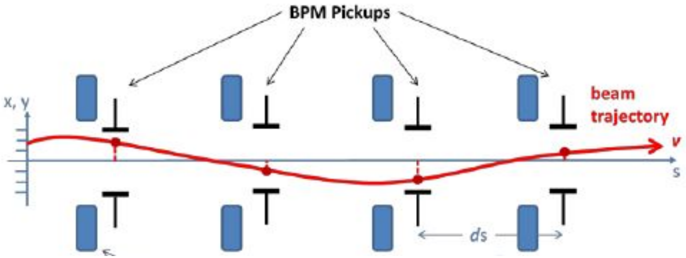
Two opposing pick-ups:

- Charge center of bunch induces different pulses in pick-ups
  s-> Transverse position



BPMs allow a turn-by-turn read out of the transverse beam position

- 550 BPMs per beam in the LHC

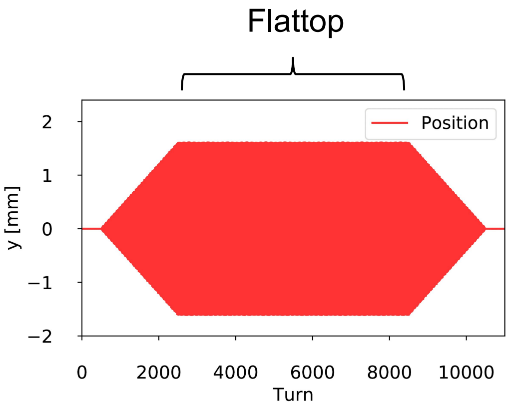


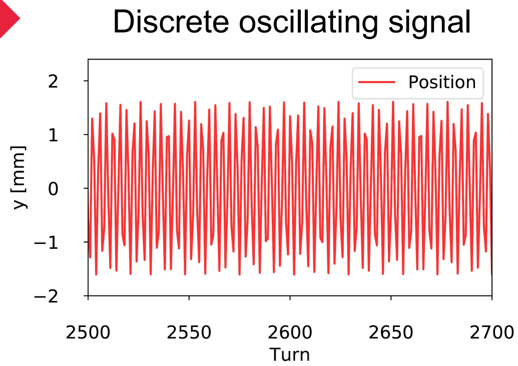
TbT data contains all information on transverse dynamics

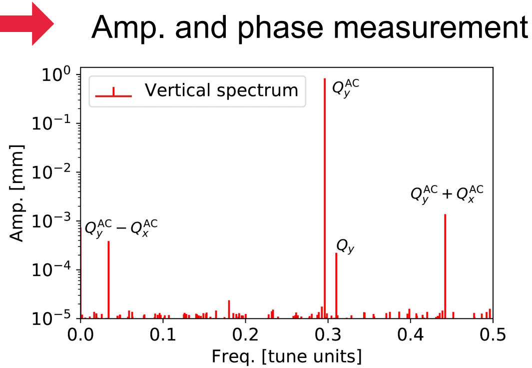
1.
Turn-by-turn data as measured by BPMs

2.
Use only flattop data at peak oscillation amplitude

3.
Spectral analysis reveals all linear and nonlinear modes



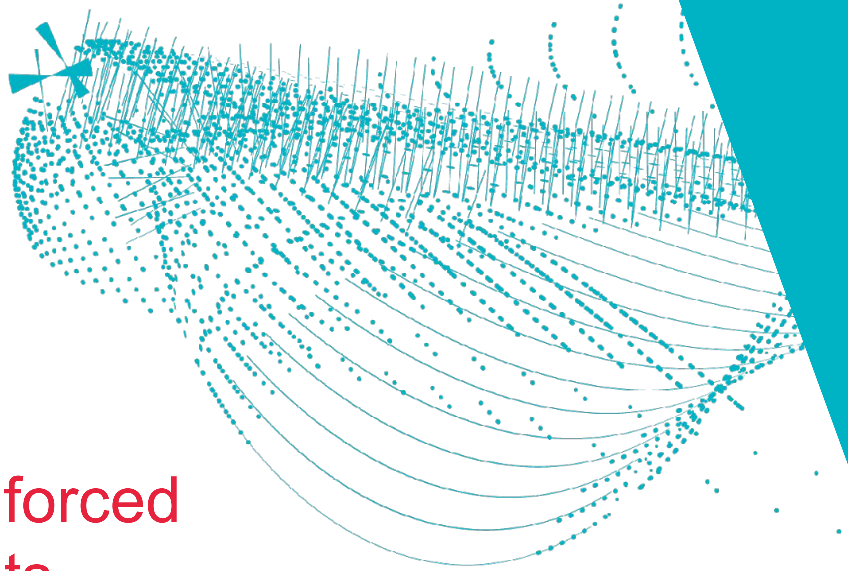




So much for the introduction..

Project I

Experimental demonstration of forced dynamic aperture measurements.

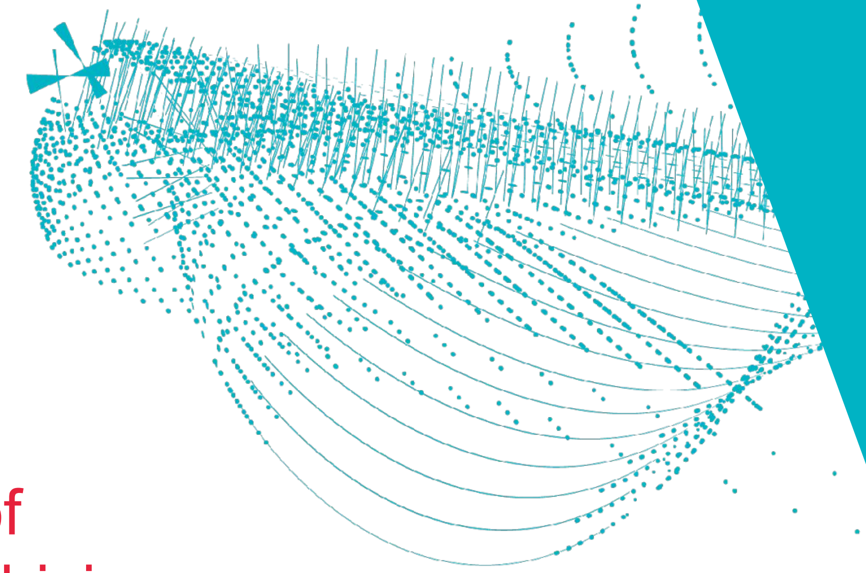


Not discussed today, but published in:

https://journals.aps.org/prab/abstract/10.1103/PhysRevAccelBeams.22.031002

Project II

Measurement and correction of nonlinearities with resonance driving terms (RDT)

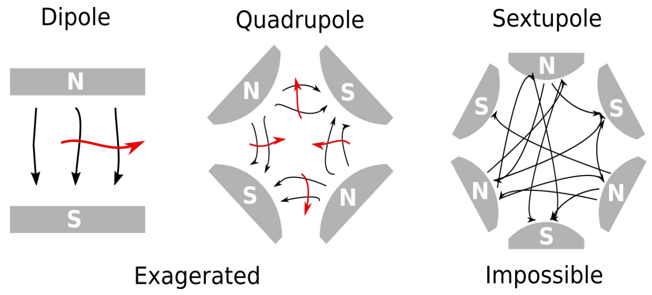


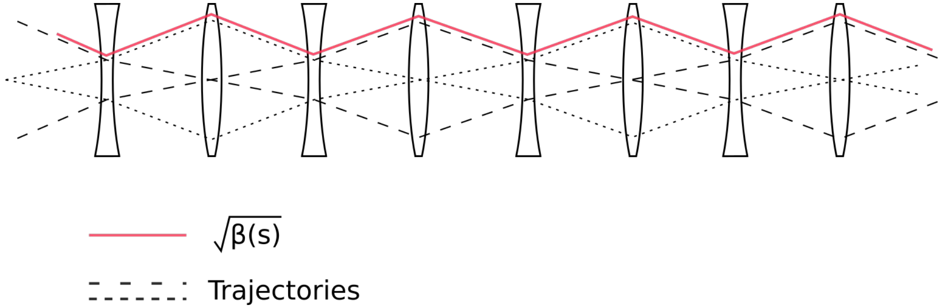
What about nonlinear errors in the LHC?

Effect of nonlinear errors is proportional to the beta-functions

So LHC suffers from nonlinear sources at locations where:

- errors are large
- or betas are large

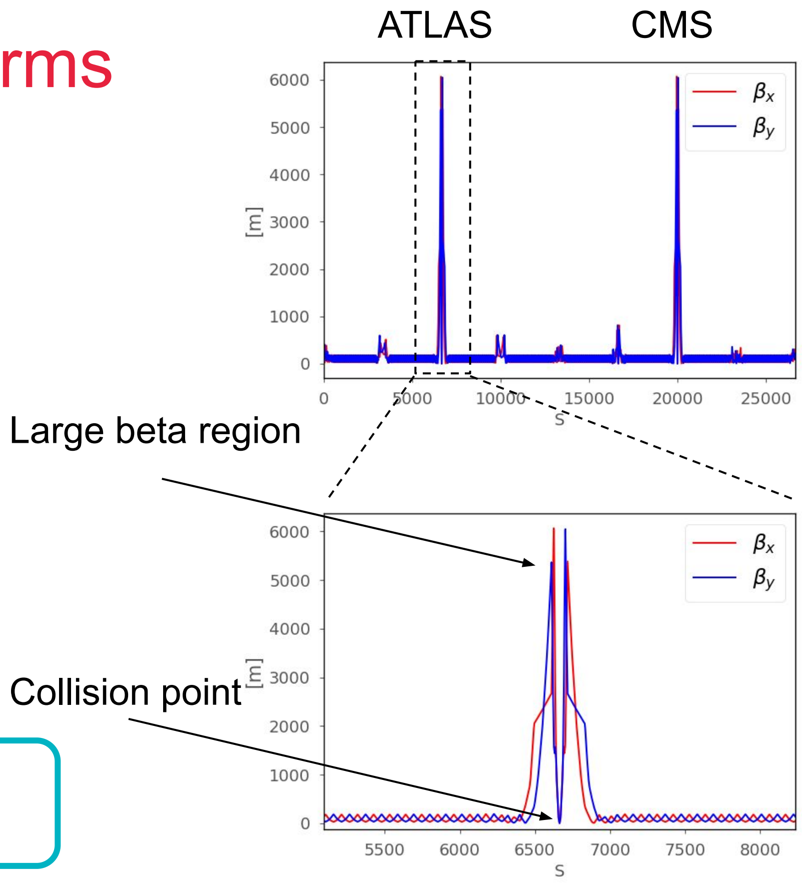




Correction of resonance driving terms

- Focussing regions around ATLAS & CMS are designed with huge beta-functions
  - needed for the final focus.
  - these areas are critical!

- Almost all nonlinear limitations today are due to errors in focussing regions of experiments.



These sources need to be measured and corrected

From spectral content to resonance driving terms

Spectral content reveals all linear and nonlinear modes in the particle motion.

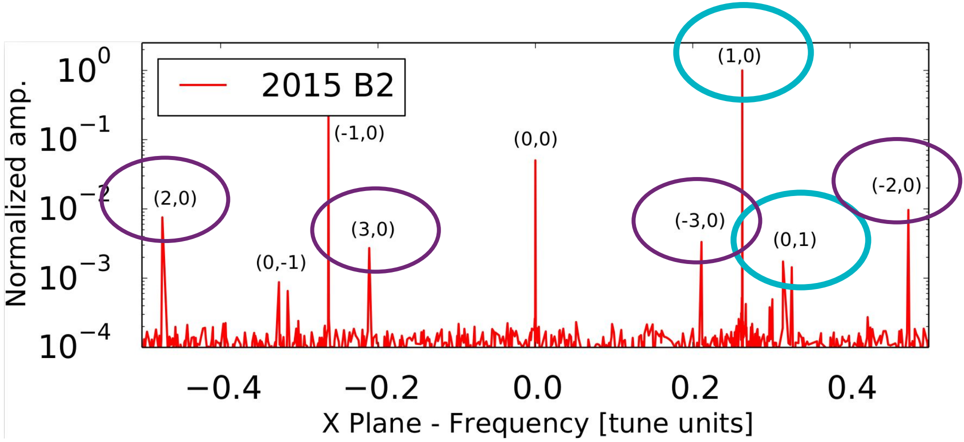
$f'_{jklm,\mathrm{H}}$ are the Resonance driving terms, and is a short notation for a big sausage equation.

$$\xi_{x,-} = |\delta_{x,-}|e^{\mp i(2\pi Q_{xD}\tau-\eta_{x-})} - |\delta_{x,+}|e^{\pm i(2\pi Q_{xD}\tau+\eta_{x+})}$$

$$-2i\sum_{jklm} f'_{jklm,\mathrm{H}}|\delta_{x,-}|^{j-1+k}|\delta_{y,-}|^{l+m} \times e^{i2\pi\{[k-j+1]Q_{xD}\tau+[m-l]Q_{yD}\tau\}} \times e^{i\{[k-j+1]\eta_{x,-}+[m-l]\eta_{y,-}\}}.$$

Nonlinear modes

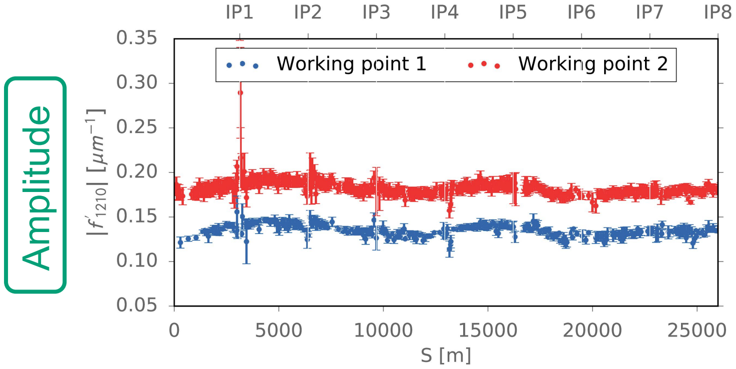
Linear modes

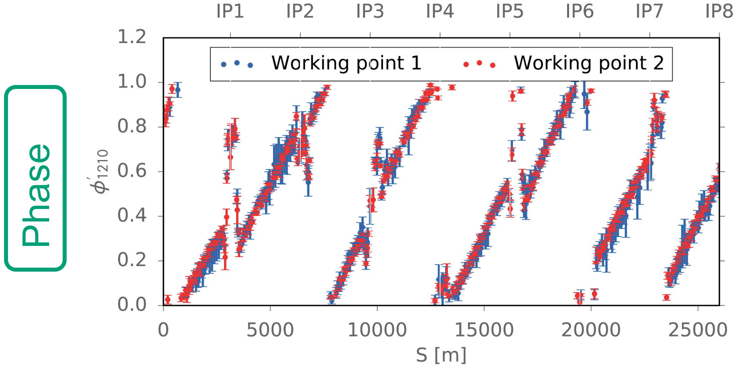


Spectrum at single BPM

The procedure for correcting using RDTs

1. Measure amplitude and phase of $f'_{jklm,\mathrm{H}}$
2. Match model to measured values
3. Find magnet strengths of dedicated correction magnets in insertion regions
4. Check experimentally

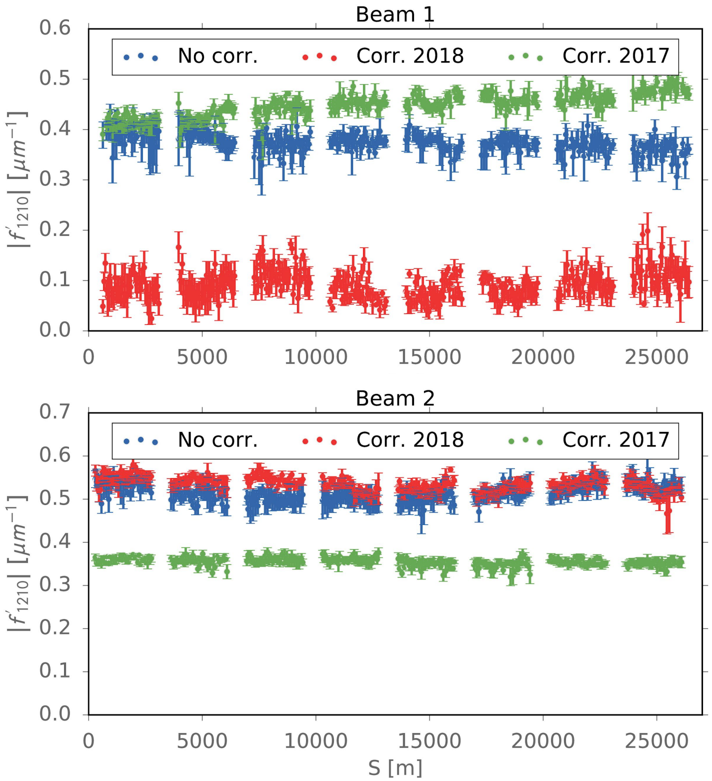




Corrections of Resonance driving terms

Quite successful!

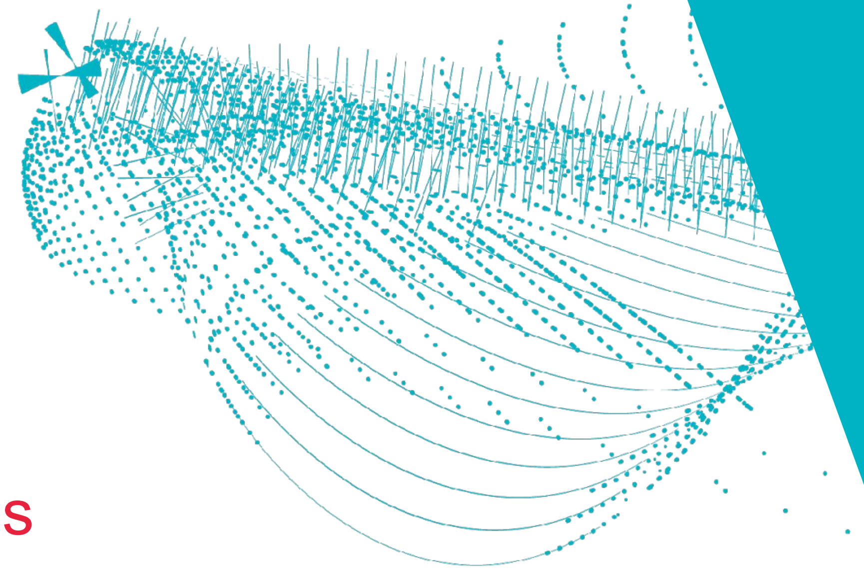
- First correction of RDTs in the LHC
- First correction of skew octupolar sources in a synchrotron
- First correction of nonlinear sources using ac dipoles
- *Still some theoretical aspects that are challenging*



Nikhef

Project III

Measurements of nonlinearities arising from colliding beams



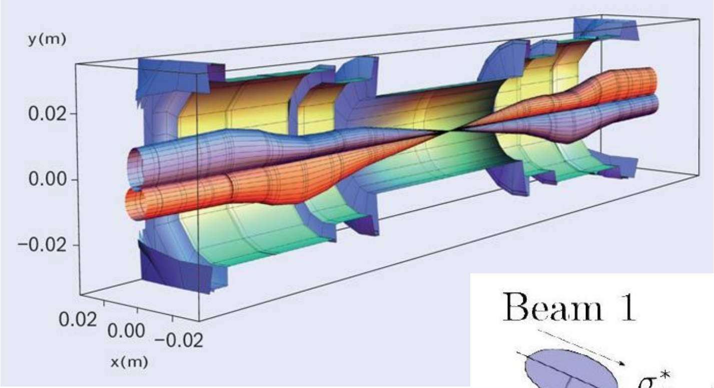
Beam-beam effect coming from colliding beams

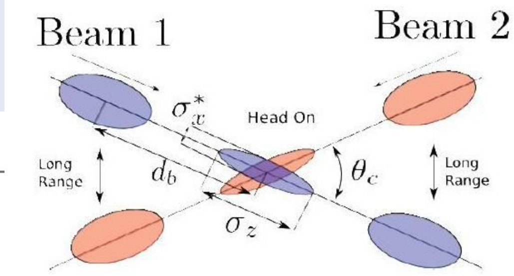
What happens when colliding?

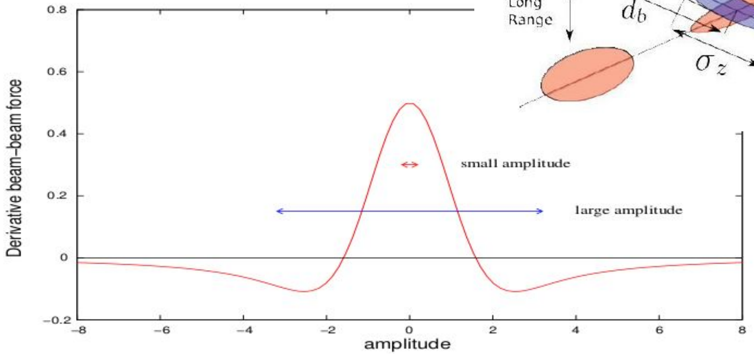
The other Gaussian beam will cause a huge force on the particles

- Big distortion of optics
- Very nonlinear
- Called Beam-beam force

This is one of the next big limitations for operation of future colliders.





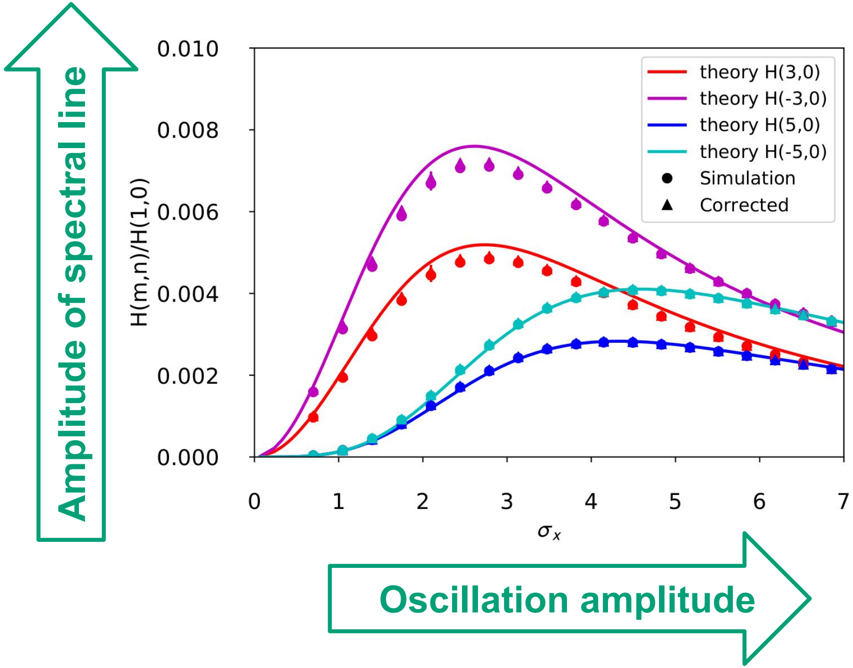


How to apply the RDT method to this problem?

Strength of nonlinearity is dependent on amplitude of oscillation.

- So need a new theoretical approach

Focus on spectral line amplitude instead of specific RDTs.



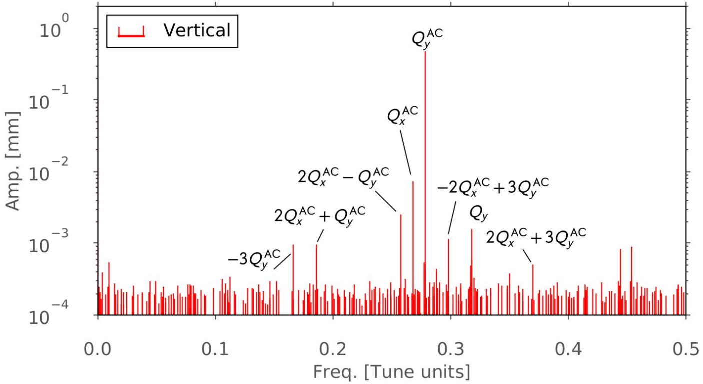
First measurement of beam-beam RDTs in an accelerator

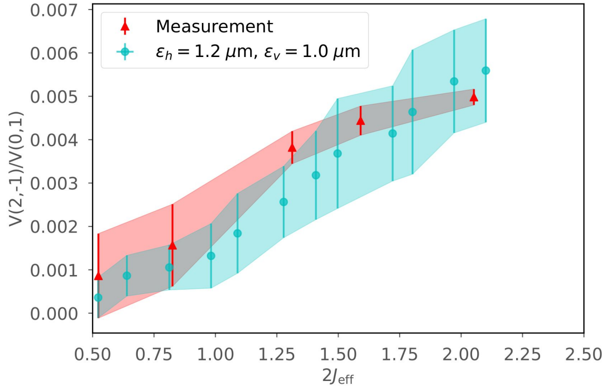
Quite successful!

- Very good agreement between theory and simulation

- First ever measurements of Beam-beam RDTs in an accelerator

- Good agreement between models and measurements





Thank you

(Hopefully I managed to make some things clear)