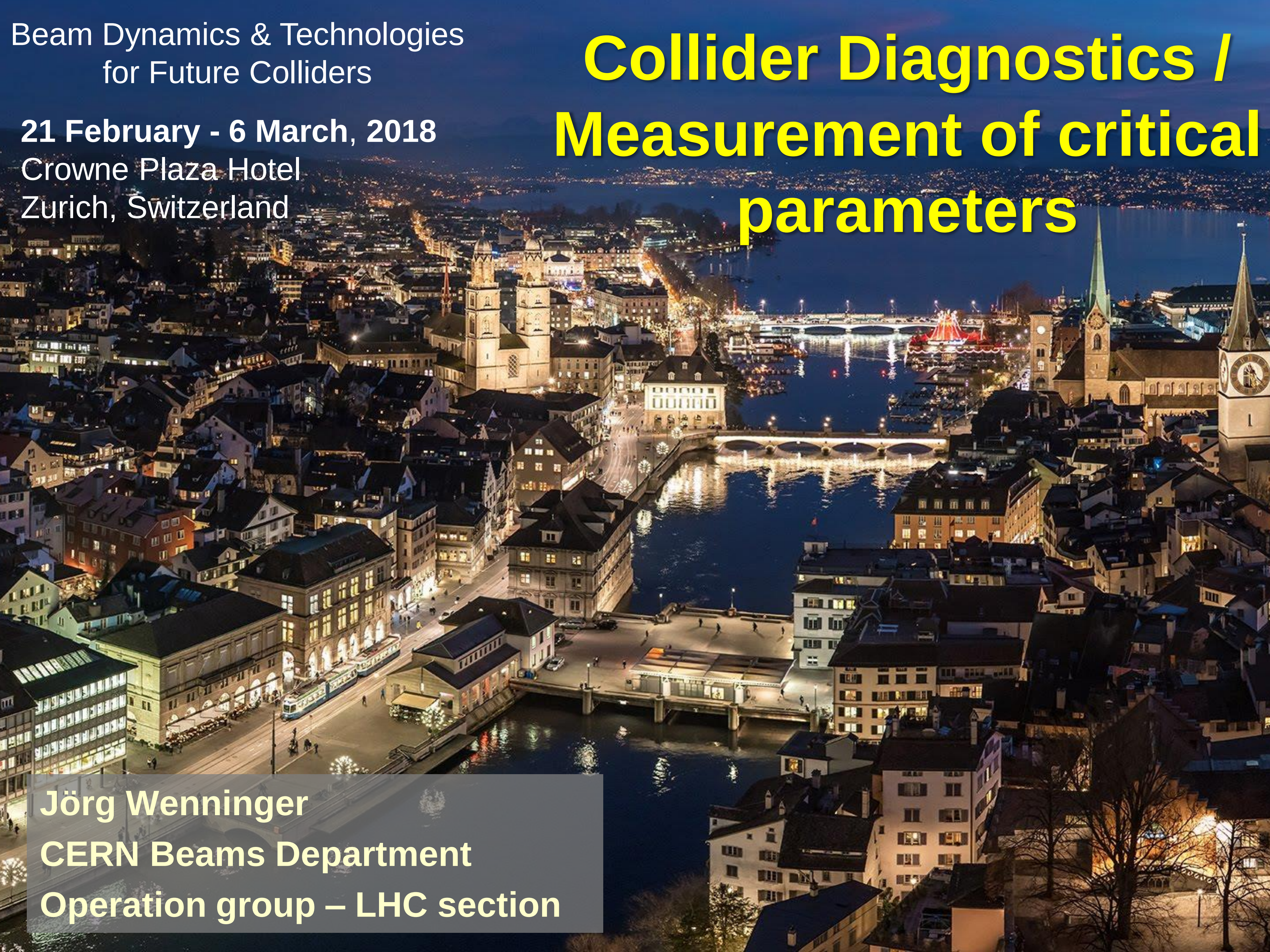

Beam Dynamics & Technologies
for Future Colliders

21 February - 6 March, 2018
Crowne Plaza Hotel
Zurich, Switzerland

Collider Diagnostics / Measurement of critical parameters

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Operation group – LHC section

Introduction

- This presentation discusses a ***selection*** of **high level parameters** that are important for operating a collider (or any modern accelerator):
  - Orbit and dispersion,
  - Tune, coupling and chromaticity,
  - Optics,
  - Aperture,
  - Luminosity and beam tuning at IPs.

- This presentation is **NOT describing** how the **basic accelerator instrumentation** is functioning. It is assumed that the basic concepts for some key instruments are known, although this is not critical to understand this presentation:
  - Beam position monitors (BPMs),
  - Beam intensity monitors,
  - Beam loss monitors,
  - Beam size monitors.

From model to reality - fields

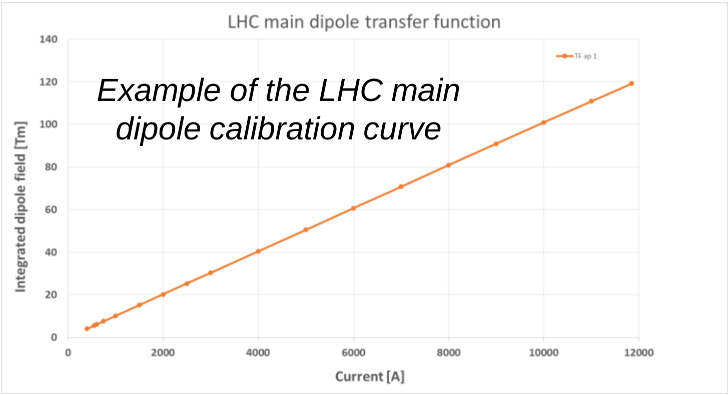
- The **machine model** defined by the accelerator designer must be converted into **electromagnetic fields** and eventually into **currents** for the power converters that feed the magnet circuits (for example).
- **Field imperfections** are introduced when the model is transferred into the real machine. For magnetic fields for example the errors are due to:
  - Beam momentum, magnet measurements and power converter regulation.

Magnet strength → **Magnetic field (gradient)** → **Requested current** → **Actual magnet current**

Beam momentum

Magnet calibration curve (transfer function)

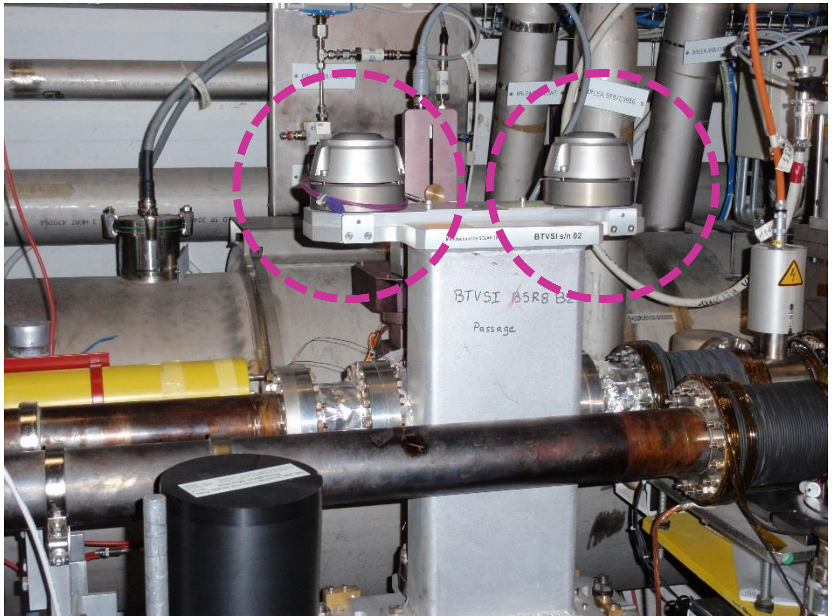
Power converter

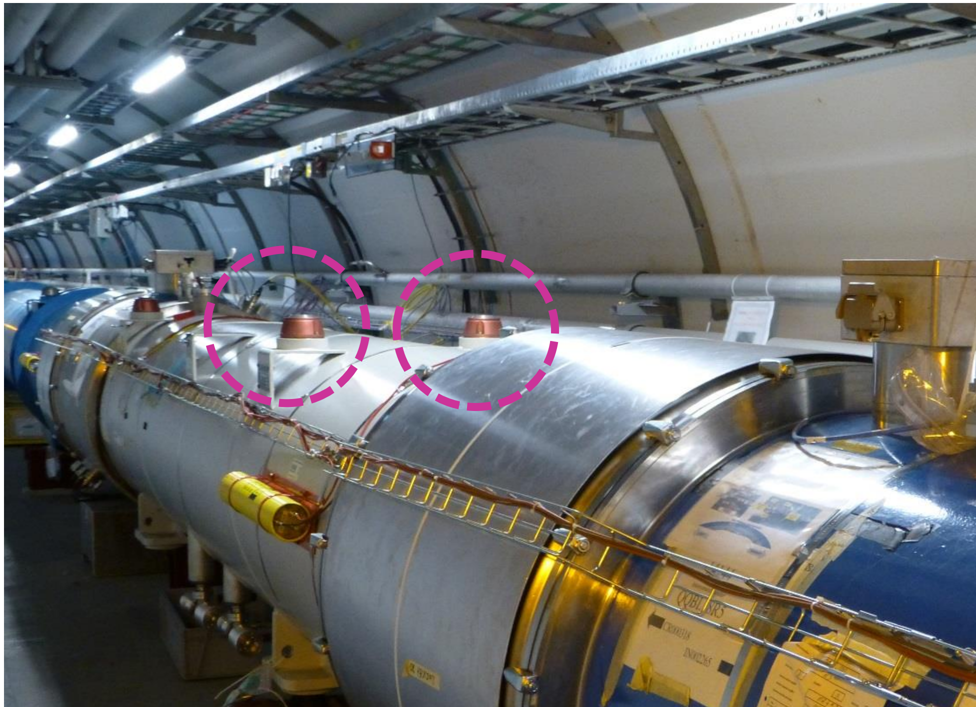


From the lab to the tunnel

From model to reality - alignment

- To ensure that the accelerator elements are in the correct position the alignment must be precise – to the sub-micrometre level for linear colliders !
  - For the hadron machines typical alignment tolerance are ~ **0.1-0.3 mm**.
- The alignment process for a magnet implies:
  - Precise measurements of the magnetic axis in the laboratory with reference to the element alignment markers used by survey teams.
  - Precise in-situ alignment (position and angle) of the element in the tunnel.
- **Alignment errors** are another common source of **imperfections**.





Restoring the model

- As a consequence of **imperfections**, the **actual accelerator** may differ from the **model** to a point where the accelerator may not function well / at all.
  - Beam does not circulate due to misalignments,
  - Incorrect optics due to field errors and alignment errors,
  - Missing beam aperture due to alignment errors,
  - ….
- Over the years many tools were developed to measure and correct accelerator parameters in control rooms and to restore design models or update the actual machine model.
  - In many cases the tools are applied iteratively when an accelerator is bootstrapped and commissioned.
- This presentation provides an overview of measurement and correction techniques for accelerator as well as the optimization of the collision points (luminosity).

Introduction

Orbit and dispersion

Tune and coupling

Chromaticity

Linear and non-linear optics

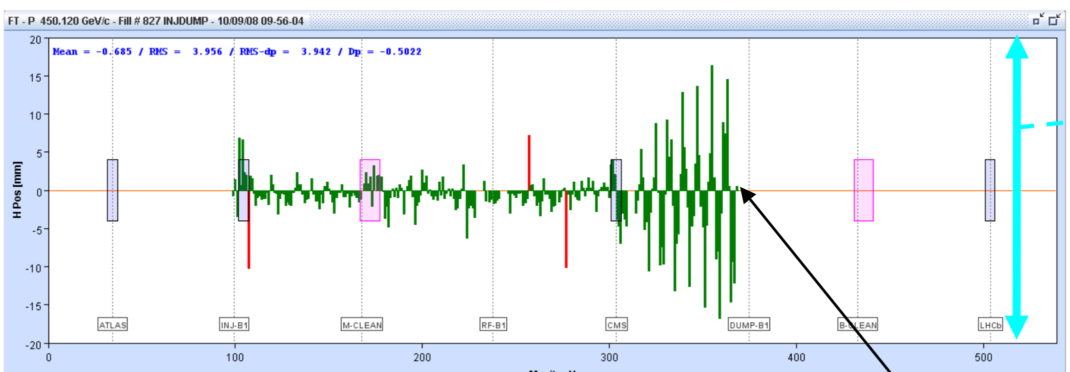
Aperture

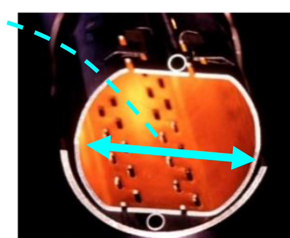
Luminosity

Orbit & trajectory – first steps

- The first problem encountered during machine commissioning is to bring the beam to the end of the linac, respectively circulate it in the storage ring.
  - Level of difficulty depends on the alignment errors and the length of the machine.
- For small accelerators it is usually not a too serious issue as the number of undesired deflections encountered over the length of the accelerator is not too large, but for many km long machines this is far for guaranteed.
  - Trajectory excursion build up randomly along the path of the beam s.
  - For random errors the trajectory amplitudes scale roughly ~ $\sqrt{s}$.

LHC during first turn steering





Beam stopped on a collimator

- The **position response** Δu_i of the beam at position i due to a deflection $\Delta\theta_j$ at position j is given in linear approximation by:

$$\Delta u_i = R_{ij}\,\Delta\theta_j \quad \text{where:} \quad R_{ij} = \frac{\sqrt{\beta_i\beta_j}\cos(|\mu_i-\mu_j|-\pi Q)}{2\sin(\pi Q)}$$

Closed orbit

$$R_{ij} = \sqrt{\beta_i\beta_j}\sin(\mu_i-\mu_j) \qquad \mu_i > \mu_j$$

$$R_{ij} = 0 \quad \mu_i < \mu_j$$

Trajectory

$$\beta = \text{betatron function} \qquad \mu = \text{phase advance} \qquad Q = \text{tune}$$

- To a first approximation we can limit the discussion to deflections generated by misaligned quadrupoles (gradient k, length l_Q) and by steering elements (orbit correctors).
  - For quadrupoles with alignment error δ, the kick is $\Delta\theta = -kl_Q\delta$

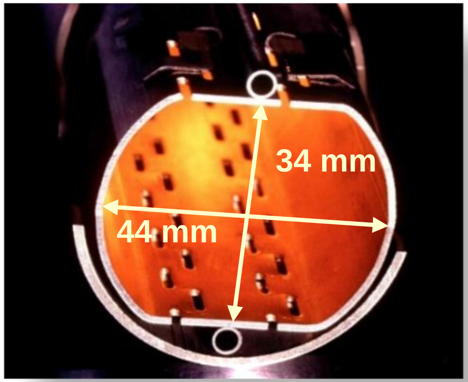
Alignment and initial orbit errors

- For a typical **rms alignment error σ_a** it is possible to estimate the resulting rms orbit error σ_{orb} for a machine (length L) build with a homogenous lattice consisting of N_c FODO cells:

$$\sigma_{orb} \approx \frac{|k| l_Q \beta_{eff}}{4\sin(\pi Q)} \sqrt{N_c}\, \sigma_a \equiv \kappa \sigma_a \quad \propto \sqrt{L}$$

  - **Example**: for the **LHC injection optics κ ≅ 20-30**. For σ_a ~ 0.3 mm, the expected orbit rms σ_{orb} is 6-9 mm. Excursions of ±2σ_{orb} already exceed the mechanical aperture of the vacuum chamber.
  - The situation is likely become worse at FCC-hh !

LHC vacuum chamber



  - **Example**: for the FCC-ee with N_c ~ 1500, **κ ≅ 45**. For σ_a ~ 0.1 mm, the expected orbit rms σ_{orb} is ~5 mm. This does not look too bad, but the FCC-ee lattice is so non-linear (strong focussing) that the beam does not make it around, although the vacuum chamber height is ~ twice as large than LHC.

- The relation between the positions measured at ***N* BPMs** (beam position monitors) and the deflections due to ***M* steering elements** (in general ($N \geq M$) can be cast into a matrix format (**R** = response matrix):

$$\Delta\vec{u} = \mathbf{R}\,\Delta\vec{\theta}$$

$$\vec{u} = \begin{pmatrix} u_1 \\ u_2 \\ \dots \\ u_N \end{pmatrix} \qquad \mathbf{R} = \begin{pmatrix} R_{11} & R_{12} & \dots & R_{1M} \\ R_{21} & R_{22} & \dots & R_{2M} \\ \dots & \dots & \dots & \dots \\ R_{N1} & \dots & \dots & R_{NM} \end{pmatrix} \qquad \vec{\theta} = \begin{pmatrix} \theta_1 \\ \theta_2 \\ \dots \\ \theta_M \end{pmatrix}$$

- To steer the beam deterministically this equation must be inverted, something like :

$$\Delta\vec{\theta}_c = \mathbf{R}^{-1}\Delta\vec{u}_m$$

$\mathbf{R}^{-1}$ is in general a 'pseudo' inverse, a real inverse only exists if $N=M$.

- Response matrix **R** obviously contains a lot of information on the machine optics – later we will see that they are tools to take advantage of that fact to determine and correct the lattice functions.

Orbit & trajectory correction II

- In general the algorithms for beam steering aim to minimize the least square error:

$$\left\| \Delta \vec{\theta}_c - \mathbf{R}^{-1} \Delta \vec{u}_m \right\|^2 = \min$$

- This equation is rather generic, problems of optics and dispersion correction can be cast in a similar form, and the algorithms used for steering are also used or adapted to those problems.

The earlier days of CERN

- The problem of correcting the orbit deterministically came up a long time ago in the first machines.
- B. Autin and Y. Marti published a note in 1973 describing an algorithm that is still in use today in many machines:
  - **MICADO***
  - One of the first deterministic correction algorithms !

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN ISR-MA/73-17

CLOSED ORBIT CORRECTION OF A.G. MACHINES

USING A SMALL NUMBER OF MAGNETS

by

B. Autin & Y. Marti

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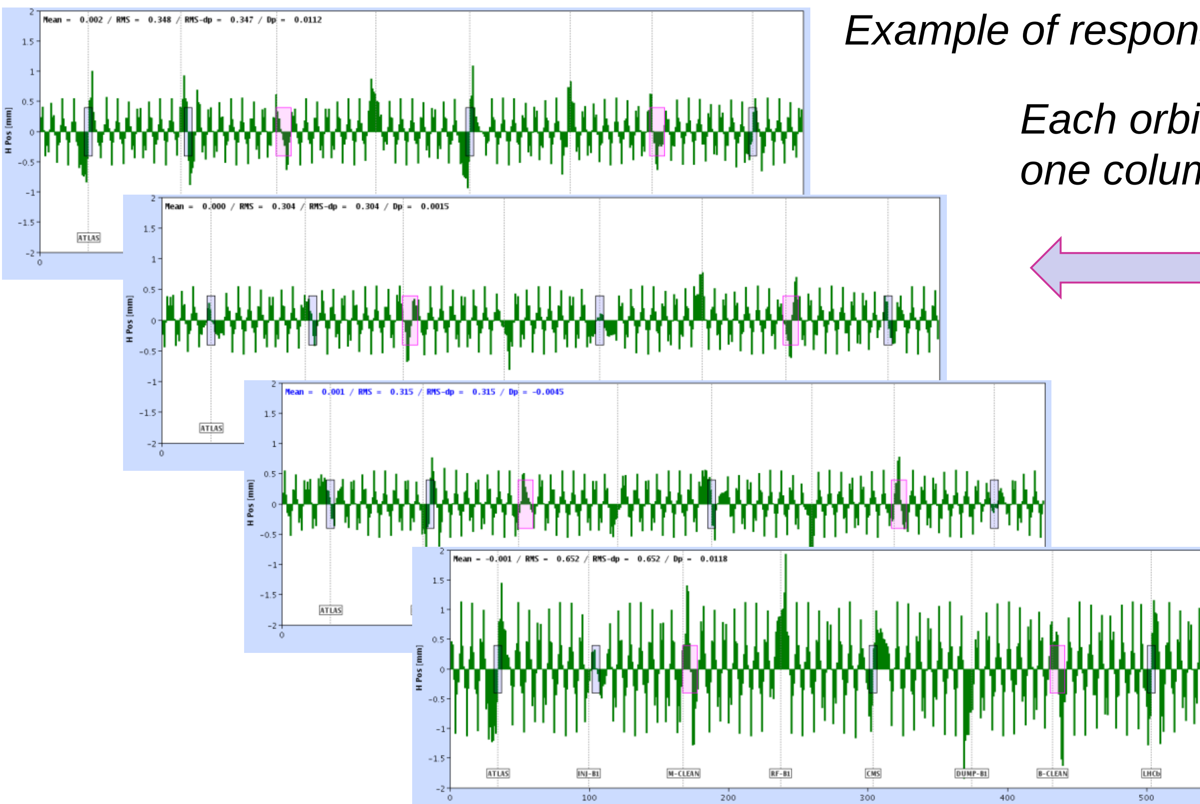
CALL MICADO (A, B, NDIM, M, N, AP, XA, NA, NB, NC, EPS, ITER, DP, X, NX, R, RHO).
```

* MInimisation des CArrés des Distortions d'Orbite.

(Minimization of the quadratic orbit distortions)

MICADO principle

- The intuitive principle of MICADO is rather simple.
- Preparation:
  - The machine model must be used to build the $\boldsymbol{R}$ matrix,
  - Each column of $\boldsymbol{R}$ correspond to the response of all N BPMs to one of the correctors.



Example of responses for LHC

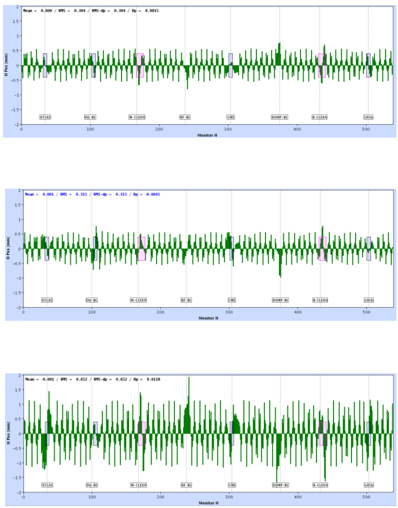
Each orbit response corresponds to one column of $\boldsymbol{R}$

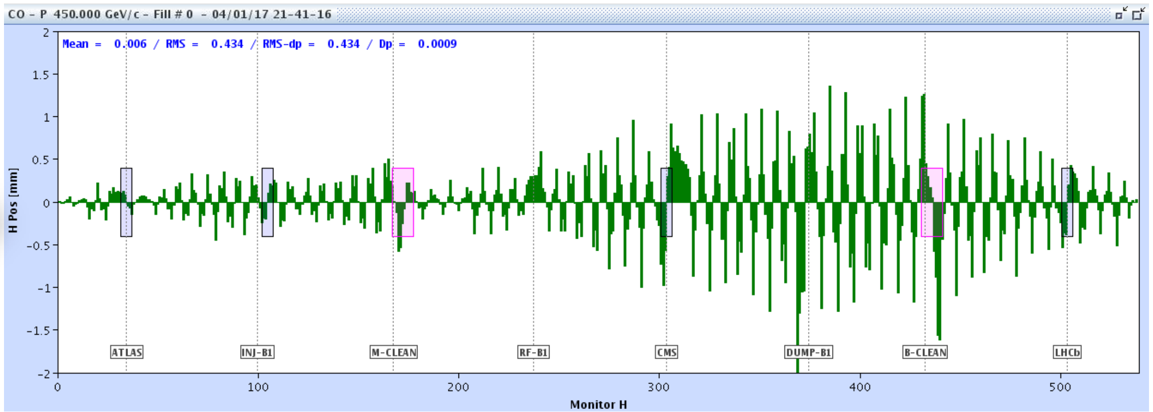
$$\mathbf{R} = \begin{pmatrix} R_{11} & R_{12} & \dots & R_{1M} \\ R_{21} & R_{22} & \dots & R_{2M} \\ \dots & \dots & \dots & \dots \\ R_{N1} & \dots & \dots & R_{NM} \end{pmatrix}$$

■ ■ ■

MICADO principle II

- MICADO compares the response of every corrector with the raw orbit.





…

- MICADO picks out the corrector that hast the **best match** with the orbit, and that will give the largest reduction of $\left\| \Delta\vec{\theta}_c - \mathbf{R}^{-1}\Delta\vec{u}_m \right\|^2$
- The procedure can be **iterated** using the remaining correctors until the orbit is good enough (stop after K steps using K correctors) or as good as it can be by using all available correctors.

Singular Value Decomposition

- **Singular Value Decomposition** (**SVD**) is a generic operation applicable to any matrix **R** that is decomposed into 3 matrices **Z**, **W** and **V**:

$$R = ZWV^T$$

P2 P3

- **W** is a diagonal 'eigenvalue' matrix while **V** is a square matrix that is also ortho-normal:

$$W = \begin{pmatrix} w_1 & 0 & \dots & 0 \\ 0 & w_2 & \dots & 0 \\ \dots & \dots & \dots & \dots \\ 0 & 0 & \dots & w_M \end{pmatrix} \qquad V = \begin{pmatrix} v_{11} & v_{12} & \dots & v_{1M} \\ v_{21} & v_{22} & \dots & v_{2M} \\ \dots & \dots & \dots & \dots \\ v_{M1} & v_{M2} & \dots & v_{MM} \end{pmatrix} \qquad Z = \begin{pmatrix} z_{11} & z_{12} & \dots & z_{1M} \\ z_{21} & z_{22} & \dots & z_{2M} \\ \dots & \dots & \dots & \dots \\ z_{N1} & z_{N2} & \dots & z_{NM} \end{pmatrix}$$

$$VV^T = V^T V = 1 \qquad Z^T Z = 1$$

The columns (vectors) of **V** are related to the columns (vectors) of **Z** by the eigenvalues:

$$\vec{v}_j = \begin{pmatrix} v_{1j} \\ v_{2j} \\ \dots \\ v_{Mj} \end{pmatrix} \qquad \mathbf{R}\vec{v}_j = w_j \vec{z}_j = w_j \begin{pmatrix} z_{1j} \\ z_{2j} \\ \dots \\ z_{Nj} \end{pmatrix}$$

$$VV^T = V^T V = 1$$

↓

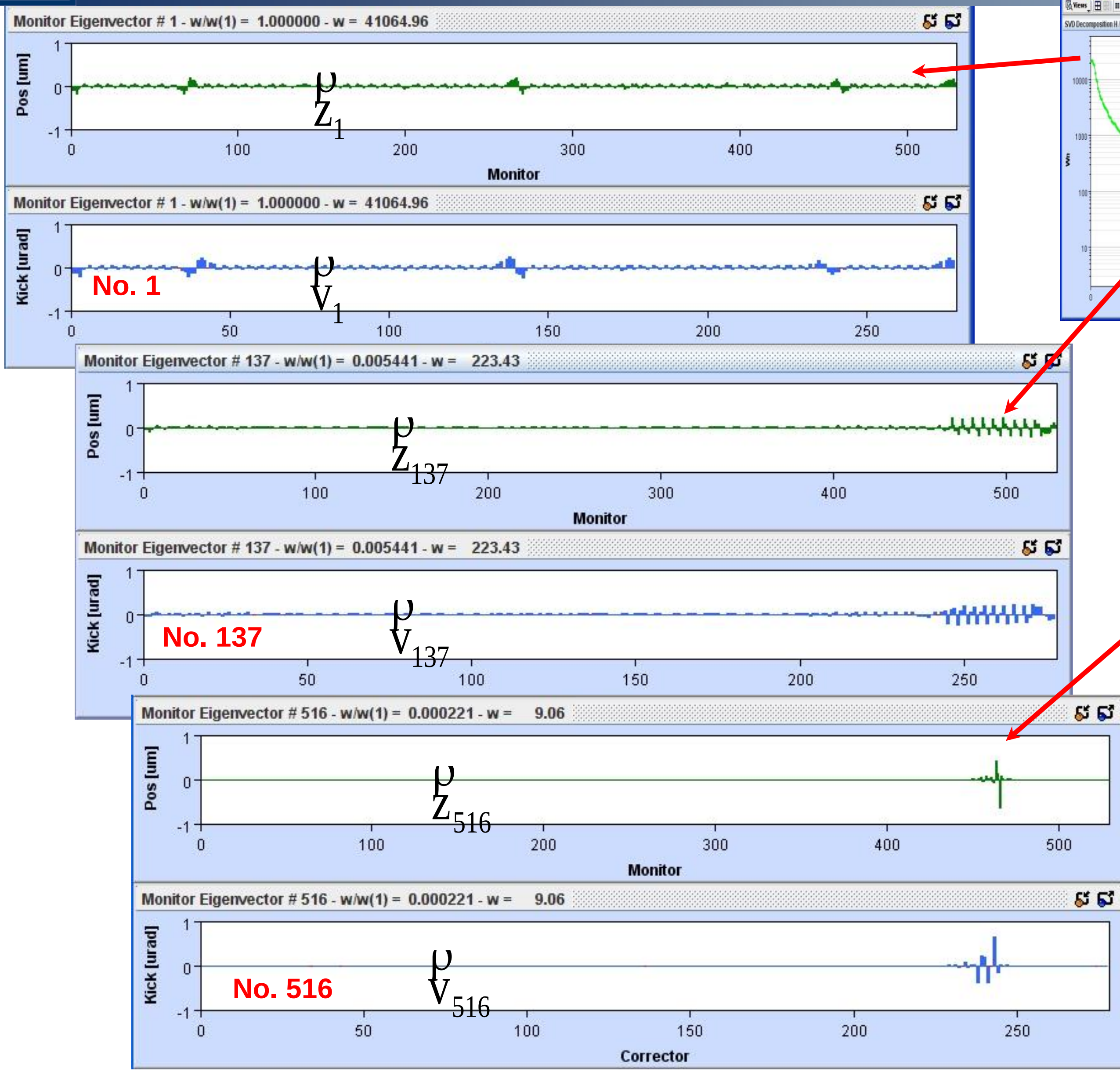
$$\vec{v}_i \cdot \vec{v}_j = \delta_{ij}$$

The vectors form an ortho-normal basis of the 'corrector space'

↕

· = scalar product

Eigenvectors examples for LHC

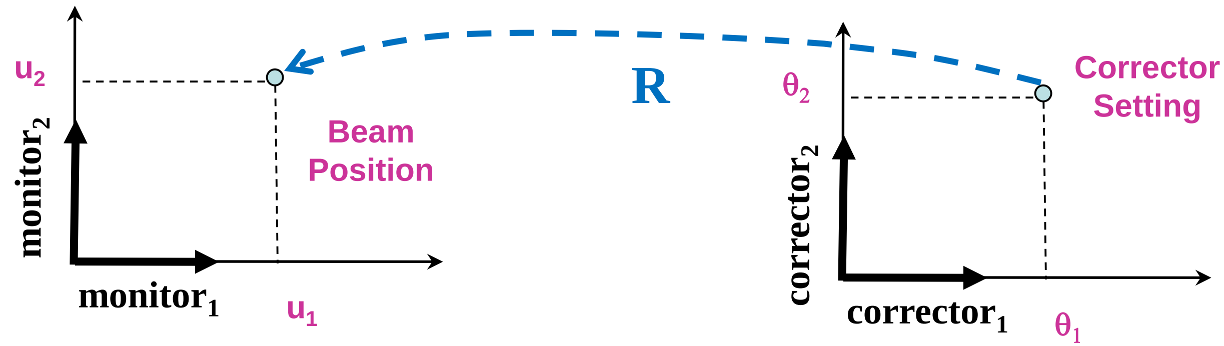


As the eigenvalues decrease, the associated eigenvectors correspond to increasingly local 'structures'

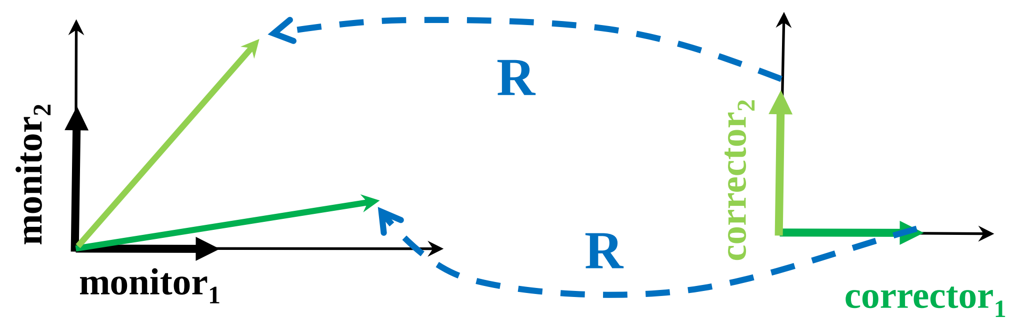
$$\vec{z}_i = \frac{1}{w_i}\mathbf{R}\vec{v}_i$$

What are those eigenvectors and what is the useful 'trick' behind an SVD decomposition?

- The response matrix **R** maps points in 'corrector space' to point in 'beam position' space.
  - The natural basis vectors of those spaces are **physical monitors and correctors**.



- The problem is that **R** maps orthogonal vectors (=correctors) into non-orthogonal responses in monitor space.



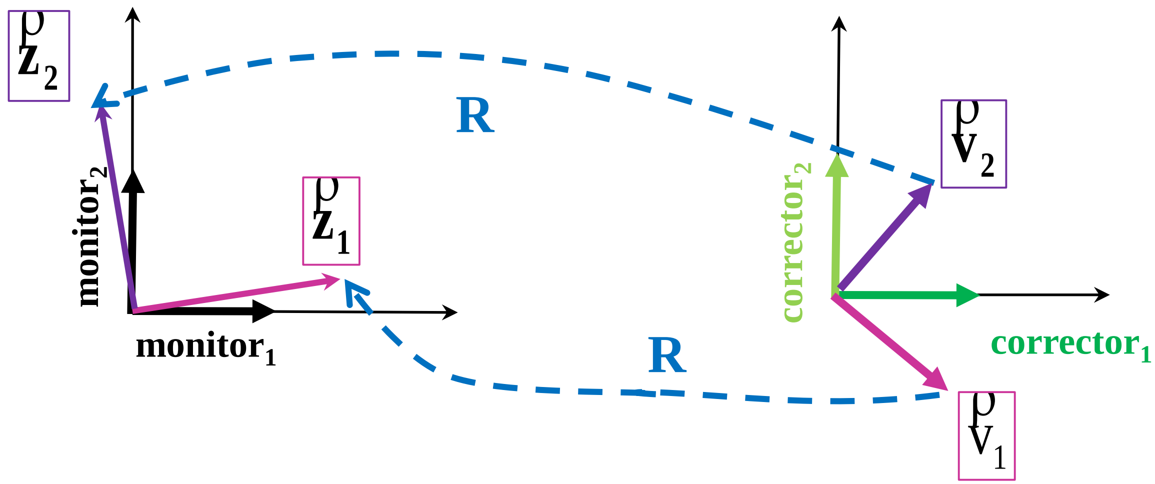
Meaning of eigenvectors II

- The SVD decomposition identifies a **new orthonormal basis of the orbit corrector space** such that **their responses are also orthogonal** !

M vectors for a **N×N** dimensional space

M vectors for a **M×M** dimensional space

$$\vec{\mathbf{z}}_\mathbf{i} \cdot \vec{\mathbf{z}}_\mathbf{j} = \delta_{ij}$$



$$\vec{\mathbf{v}}_\mathbf{i} \cdot \vec{\mathbf{v}}_\mathbf{j} = \delta_{ij}$$

- Every corrector setting can be decomposed into the **v** vectors.
- Every orbit can be decomposed into the **z** vectors plus a residual un-correctable remainder:

$$\vec{\mathbf{u}}_\mathbf{m} = \sum_{i=1}^{M} c_i \vec{\mathbf{z}}_\mathbf{j} + \vec{\mathbf{u}}_\mathbf{residual}$$

- SVD can be used to solve the determine a correction using k out of M eigenvalues.
  - The eigenvalues w_j are typically sorted in descending order: $w_{j+1} \leq w_j$.

$$\Delta\vec{\theta}_c = -\left(VW^{-1}Z^T\right)\Delta\vec{u}_m = -\tilde{R}^{-1}\Delta\vec{u}_m$$

$$W^{-1} = \begin{pmatrix} 1/w_1 & 0 & \ldots & \ldots & \ldots & 0 \\ 0 & \ldots & 0 & \ldots & \ldots & \ldots \\ \ldots & 0 & 1/w_k & \ldots & \ldots & \ldots \\ \ldots & & 0 & 0 & \ldots & \ldots \\ \ldots & & & & \ldots & 0 \\ 0 & \ldots & \ldots & \ldots & 0 & 0 \end{pmatrix}$$

- This operation corresponds intuitively to decompose the measured orbit into the orbit eigenvectors z_i – unique ! – and then to correct the effect of the k largest eigenvectors (since z_i is associated to v_i).

$$Z^T\Delta\vec{u}_m \qquad \vec{z}_j \cdot \vec{u}_m = c_i \qquad \forall i \leq k$$

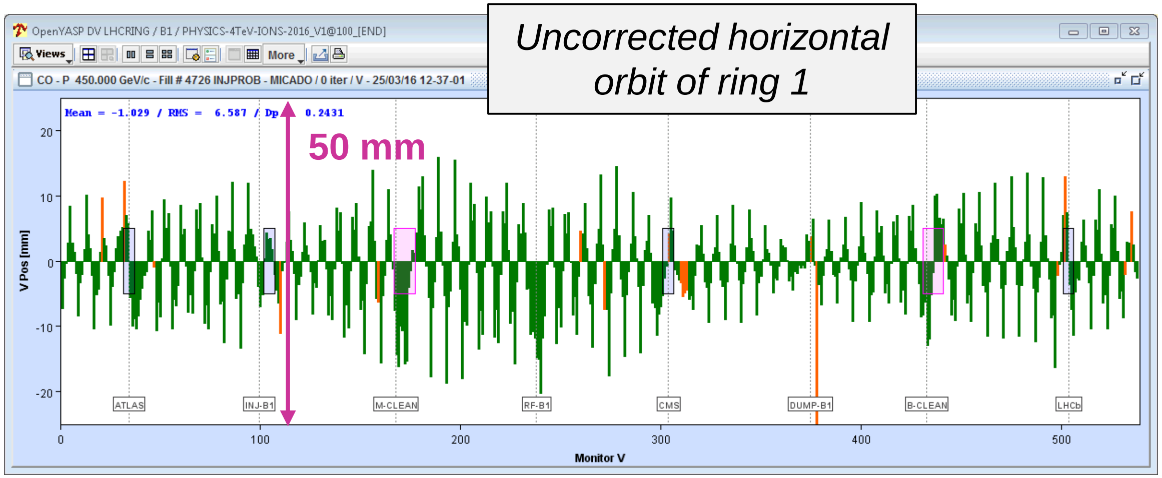
$$\left(W^{-1}Z^T\right)\Delta\vec{u}_m \quad \Longleftrightarrow \quad c_i / w_i$$

$$-\left(VW^{-1}Z^T\right)\Delta\vec{u}_m \qquad -\sum_i^k (c_i / w_i)\vec{v}_i$$

- MICADO picks out individual correctors.
  - With a perfect match of model and machine it will help localize local sources.
  - Well suited in case of clean measurements to identify a single / dominant source.
  - MICADO can be in trouble if the R matrix presents singularities, associated to poor BPM or corrector layout (poor phase conditions…).
- SVD will always use all correctors.
  - With few eigenvalues for the correction, even a local perturbation will be corrected with many elements.
    - Can be a pro if the strength of correctors is limited.
  - The number of eigenvalues controls the locality /quality of the correction. With more eigenvalues local structures will be corrected better.
  - By limiting the number of eigenvalues it is possible to avoid correcting on noise, in particular with eigenvectors that drive large strength and provide little position change.
    - See also later the **MIA technique**.
  - Since the SVD correction can be cast into a simple matrix operation, it is well suited (and always used) for real-time **orbit feedbacks**.

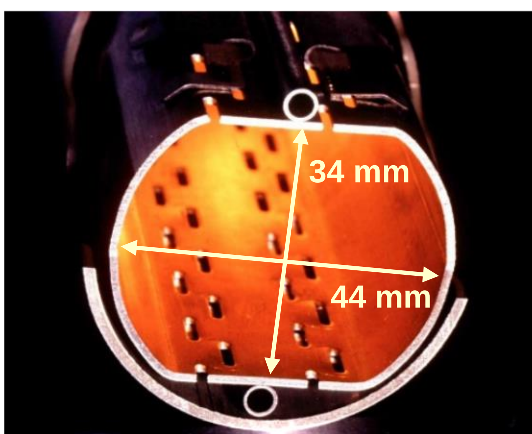
LHC orbit correction example

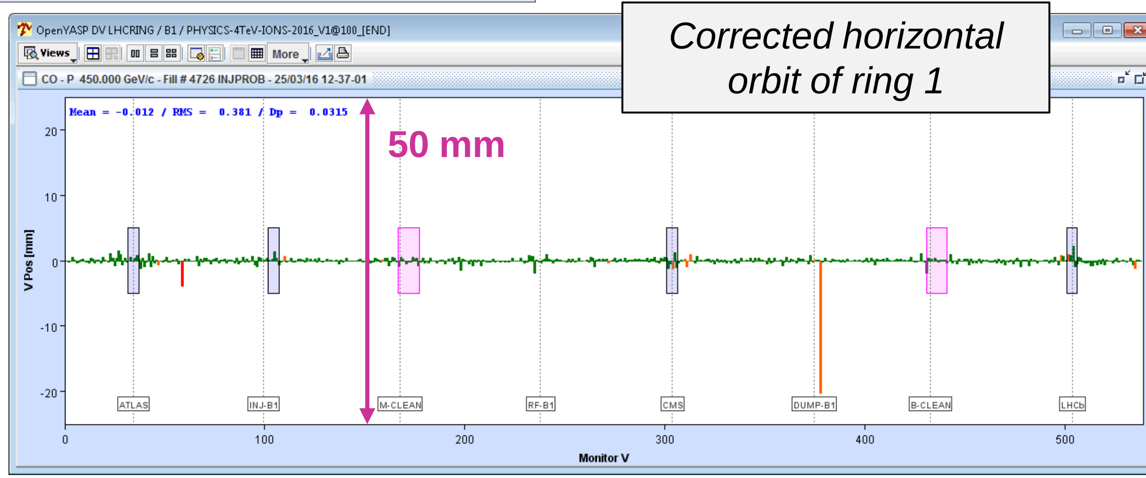
- The raw orbit at the LHC can have large errors (in this example the correctons were unfolded !), but proper correction bring the deviations down by more than a factor 20.



MICADO & SVD

LHC vacuum chamber





Threading

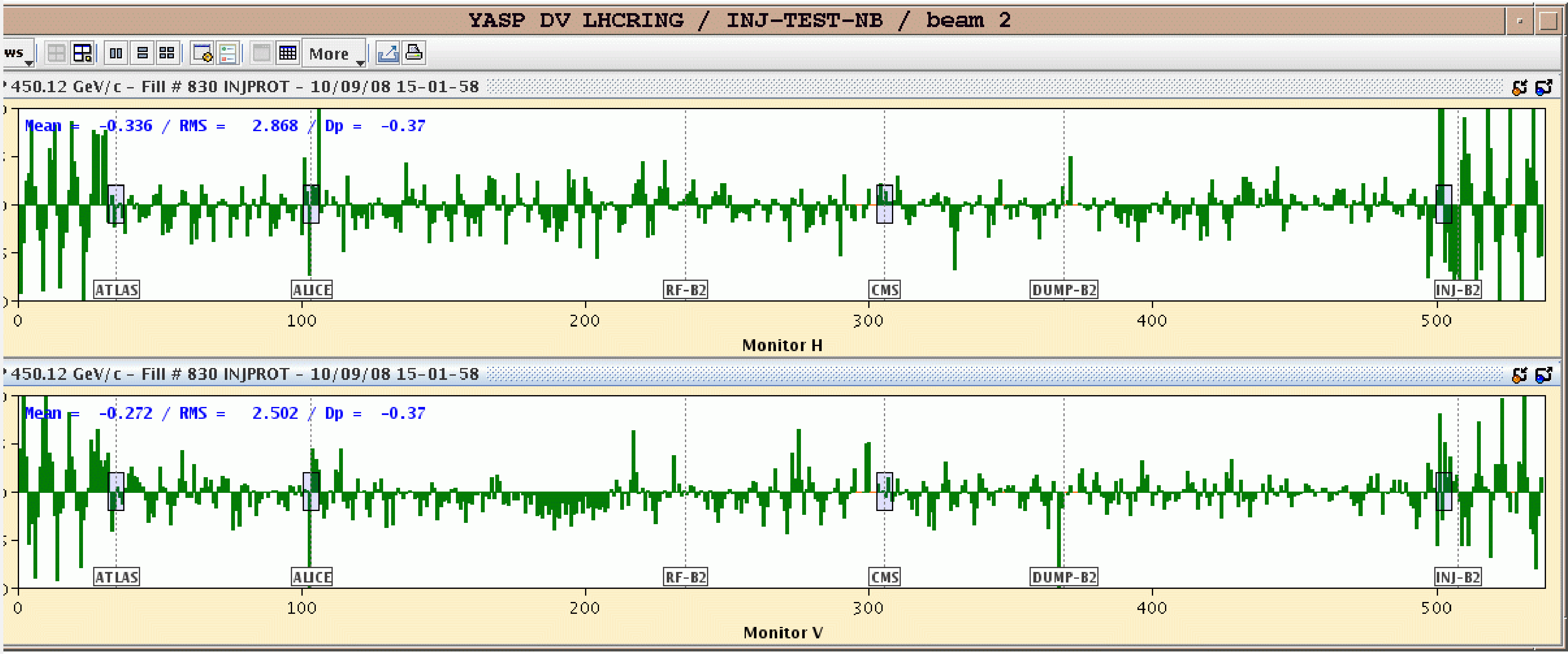
- At synchrotrons of very **large dimension** (10's km) and/or with a **very strong focussing optics**, the beam may not necessary circulate without any corrections when it is injected the first time.
  - Can also be the case for a corrected machine when the tunes are poorly set.
- In such a case it is necessary to **thread the beam around the ring** segment by segment until a few turns are obtained.
  - For superconducting machine one may have to operate at very low intensity / stop the beam at intermediate positions with collimators to avoid quenches.
- Once a few turns are obtained:
  - It may be possible to estimate (and correct) the tunes,
  - The average of the N first turns may be used as estimate for the closed orbit, opening the option to correct directly this estimated closed orbit.
  - To note after a few turns, the exact number depending on the machine, the beam may be debunched and no longer measureable by the BPMs, requiring the RF to be setup for capture for further progress.
    - For example at the LHC the beam debunches over ~30-40 turns.

Very first LHC threading (arc) sector by sector (Sept 2008):

- One beam at the time & one hour per beam, correction with MICADO, 1-3 correctors.
- Collimators used to intercept the beam (1 bunch, 2×10^9 p - 2% of nominal bunch).
- Beam through a sector (1/8 ring), correct trajectory, open collimator and move on.

Beam 2 threading

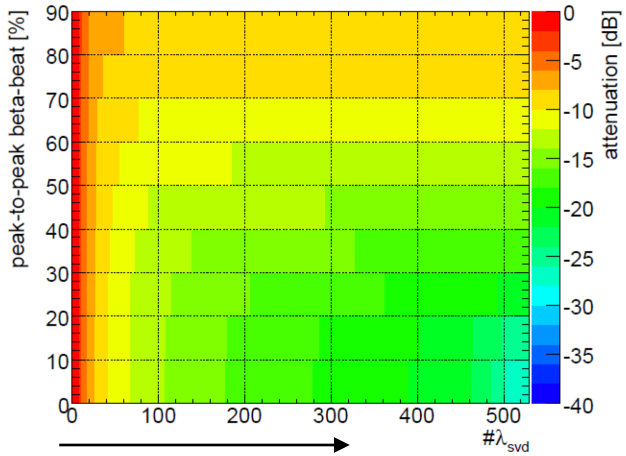
Beam direction



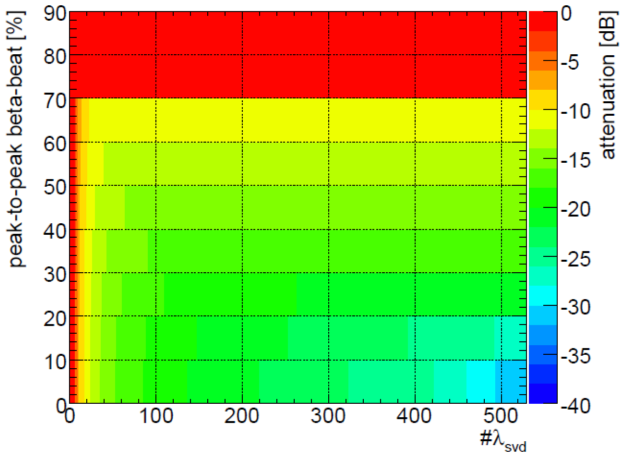
- In particular during the machine commissioning, significant optics errors may be present that could generate divergent orbit corrections.
  - The orbit degrades with a correction instead of improving.
- Typically up to 30-50% beta-beating there are no severe problems, but corrections may require iterations to converge well.
  - Beyond that point corrections can diverge strongly, in particular if low beta sections are present.
  - Errors on the tunes, and in particular **wrong integer tunes**, can generate strongly diverging corrections !

OFB-LHC

LHC orbit correction sensitivity to beta-beating



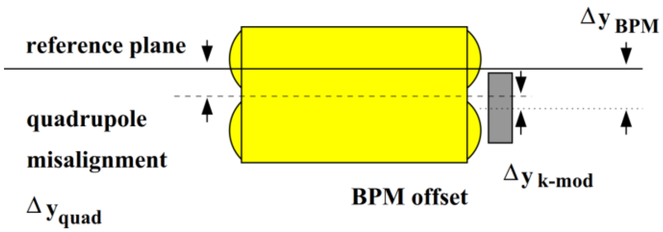
(a) injection optics



(b) collision optics

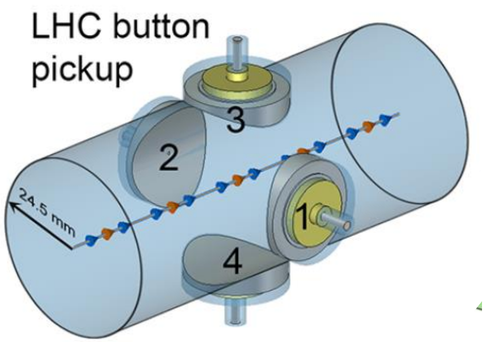
BPM errors

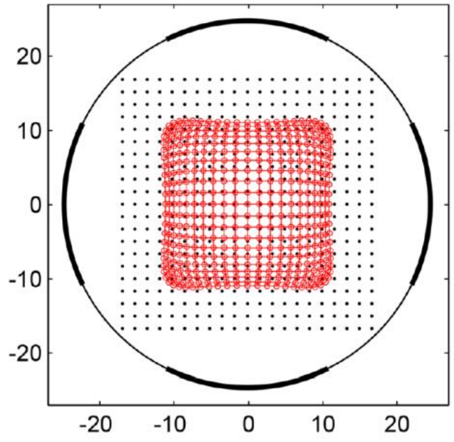
- The **quality of the BPM measurements** used for measurements and corrections are affected by:
  - **Offsets**,
  - **Scale errors and non-linearities,**
  - **Intensity and beam pattern effects.**



- Non-linearities and beam/intensity systematics must be simulated or obtained from laboratory measurements.
  - Non-linearities are due to electrode geometries and to the electronics.
  - Improper correction of such effect can bias beam based measurements.

LHC button BPM





Black points: real beam position,

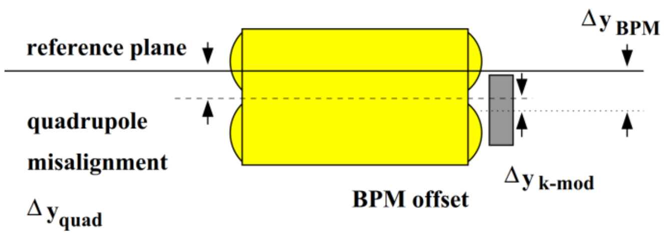
Red points: distorted positions based on a position reconstruction with a linear assumption:

$$x = K_x \frac{S_1 - S_2}{S_1 + S_2} \qquad y = K_y \frac{S_3 - S_4}{S_3 + S_4}$$

BPM-NL

K-modulation

- BPM **offsets**, an important nuisance for orbit corrections, can be measured by a technique called **k-modulation**:
  - The gradient of a selected quadrupole is modulated slightly at a frequency f_{mod},
  - The beam position is varied inside the quadrupole using orbit bumps.
- The beam orbit is modulated at f_{mod}, the modulation amplitude vanishes when the beam is centred in the quadrupole.



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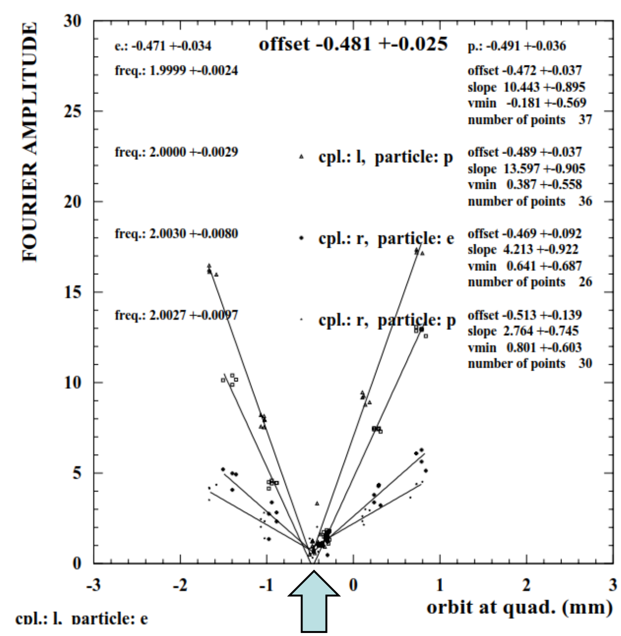
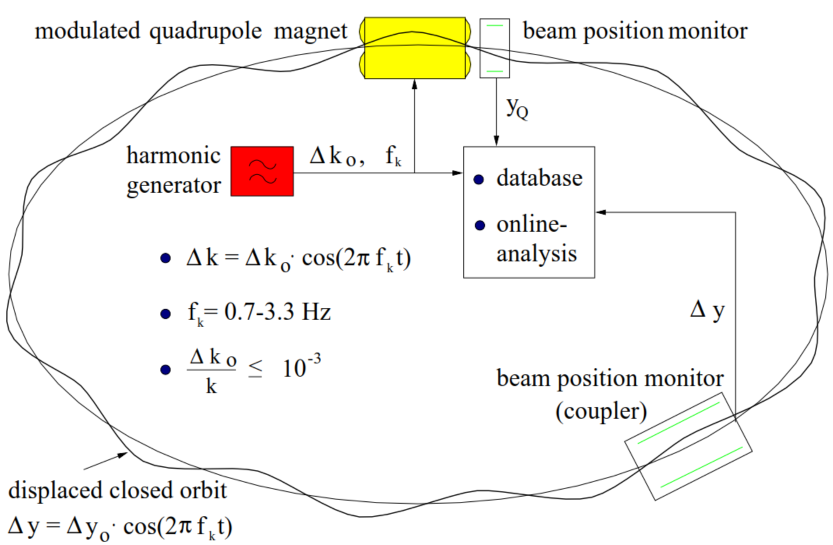
K-modulation at LEP

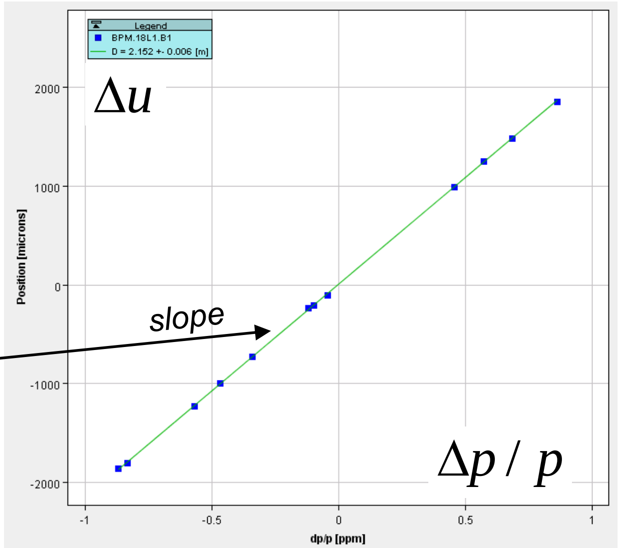


Oscillation amplitude as a function of the orbit bump amplitude



- Closely associated to the orbit is the **dispersion**, which is the derivative of the orbit wrt energy (u=x,y) :

$$D_u(s) = \frac{\Delta u(s)}{\Delta p / p}$$



- In a storage ring there is always non-zero horizontal dispersion (bending!). For flat machines the vertical dispersion is usually ‘0’ by design.
  - For hadron machines the dispersion is in general not critical. Controlling and correcting it follows similar lines to optics correction.
  - At **e^+e^- machines the vertical dispersion can lead to significant vertical emittance ε_y growth**, and to important luminosity performance loss.

$$\varepsilon_y \propto \left(\frac{\Delta p}{p}\right)^2 \left(\gamma D_y^2 - 2\alpha D_y D'_y + D'^2_y\right)$$

Dispersion correction

- **Dispersion errors** may be driven by:
  - **Optics errors** → handled together with the general optics correction,
  - **Coupling** → mainly from the horizontal to the vertical plane,
  - **Steering and alignment errors** → mainly an issue at e^+e^- machines where the emittances may be spoiled – storage rings and linacs !
- Optics and coupling correction will be discussed later, for the moment we focus on the third point, namely steering driven dispersion.

Dispersion free steering

- A technique combining regular steering and dispersion correction was used at SLC and LEP – **dispersion free steering (DFS)** – will be outlined here.

P3

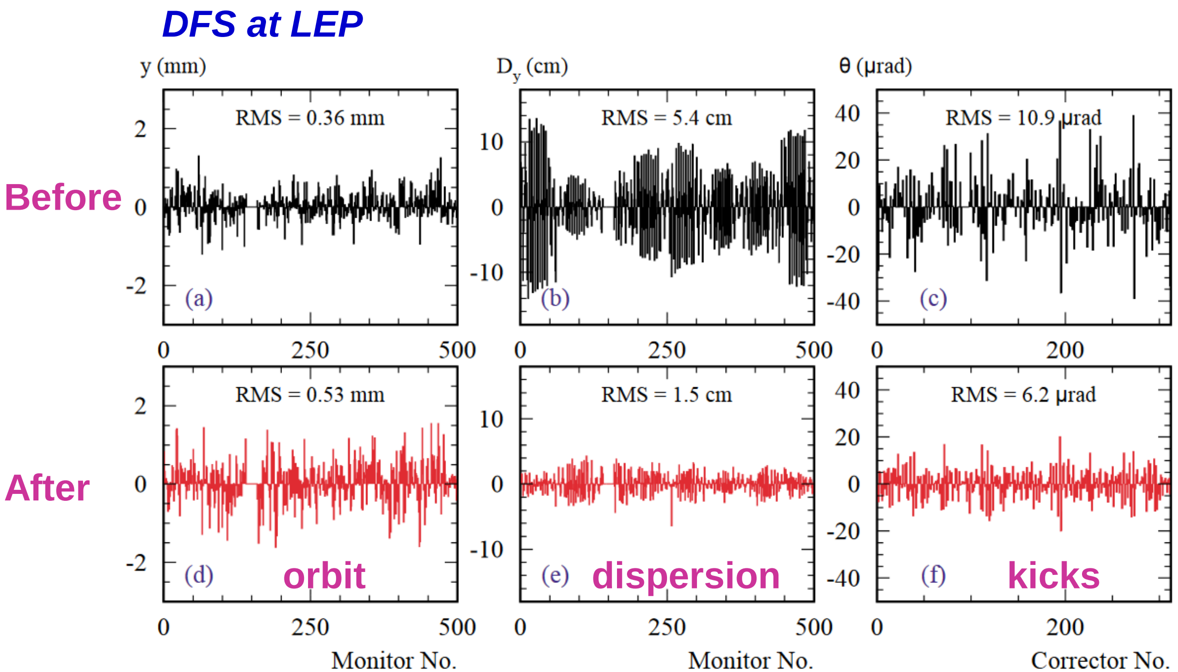
- The principle of DFS relies on the extension of the orbit response matrix to dispersion including the **dispersion response** $\mathbf{S}$ and a **weight factor** α between orbit and dispersion:

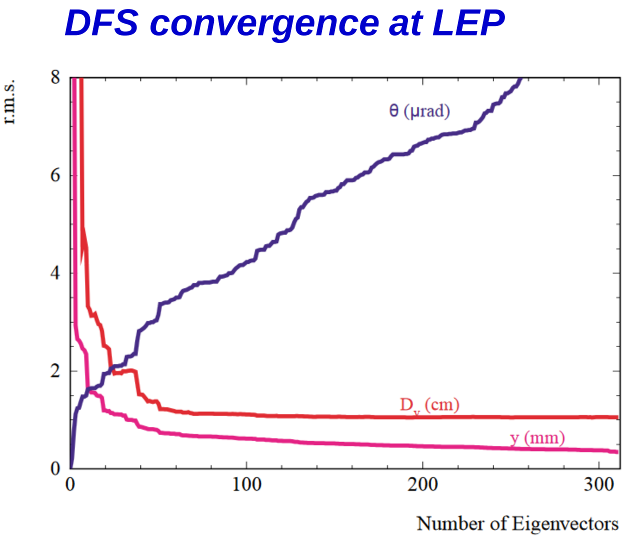
$$\Delta \vec{u} = \mathbf{R}\,\Delta\vec{\theta} \quad \Longrightarrow \quad \begin{pmatrix} (1-\alpha)\,\Delta\vec{u} \\ \alpha\,\Delta\vec{D}_u \end{pmatrix} = \begin{pmatrix} (1-\alpha)\mathbf{R} \\ \alpha\,\mathbf{S} \end{pmatrix} \Delta\vec{\theta}$$

  – The dispersion response may be estimated analytically or from a simulation program like MAD etc.

DISP-RES

- The combined orbit and dispersion correction system can be solved in exactly the same way than the 'normal' steering.





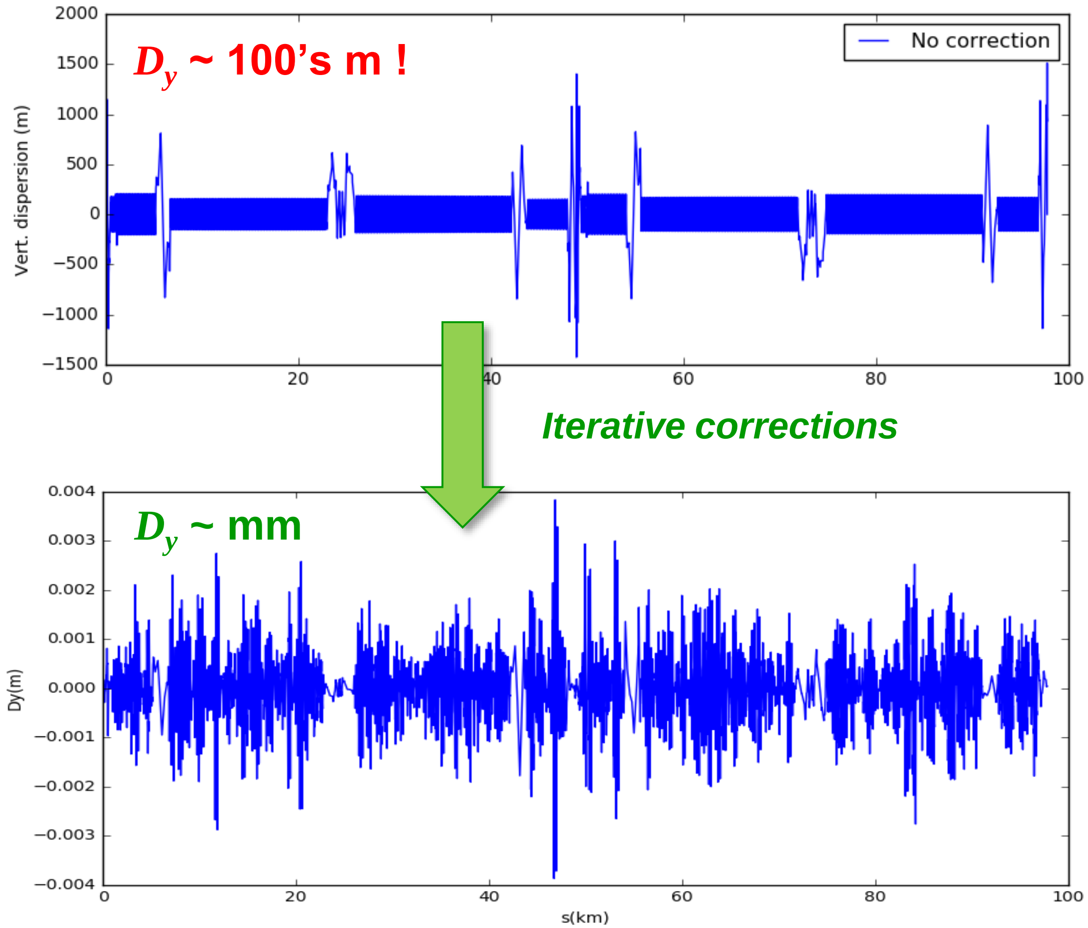
P3

Observe that the orbit rms is <u>degraded</u> while the dispersion rms is <u>improved</u> !

- DFS worked very well for LEP at high energy (not beam-beam limited).
- DFS will be an essential tool to reach FCC-ee design performance as the dispersion plays an even larger role as compared to LEP due to the larger ring size and a smaller target emittance ratio of ~0.1-0.2%.

Dispersion free steering III

- The strong sextupoles required to ensure a very large momentum acceptance at very small β* of 1-2 mm make dispersion correction more complex at FCC-ee.



- The sextupoles at FCC-ee induce large coupling.
- Dispersion and coupling have to be corrected iteratively until convergence.
- This example is for an element misalignment of 0.1 mm rms.
  - But excluding the low β quadrupoles (perfectly aligned)

Courtesy S. Aumon

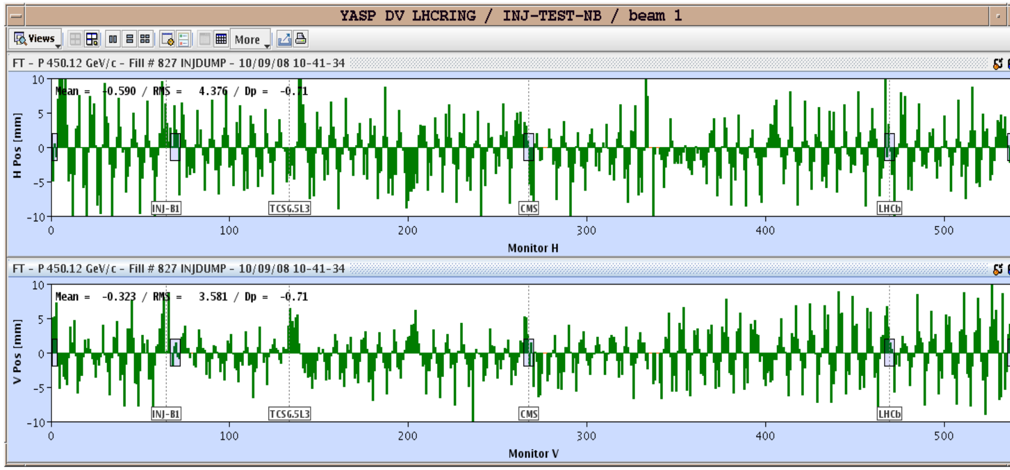
Tune measurement

- The **tune** (number of betatron oscillations per turn):

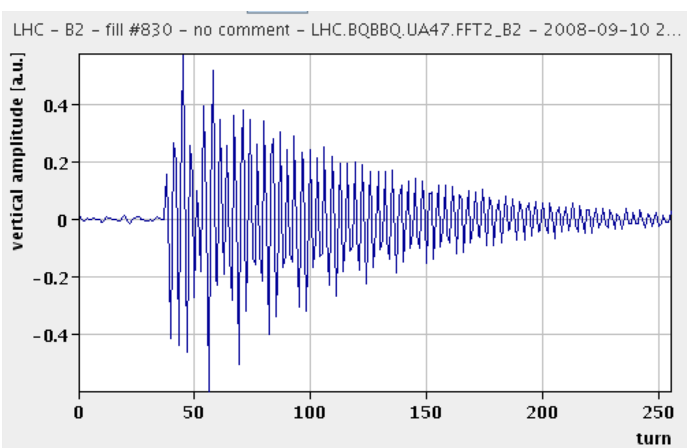
$$Q = N + q$$

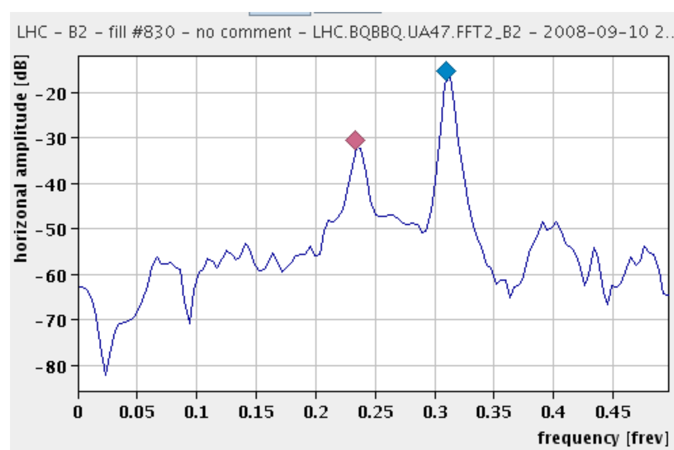
- The **integer tune N** can be observed from the closed orbit or from a kick on the orbit.
  - In large machine N may be wrong before correction !

Uncorrected orbit at the LHC



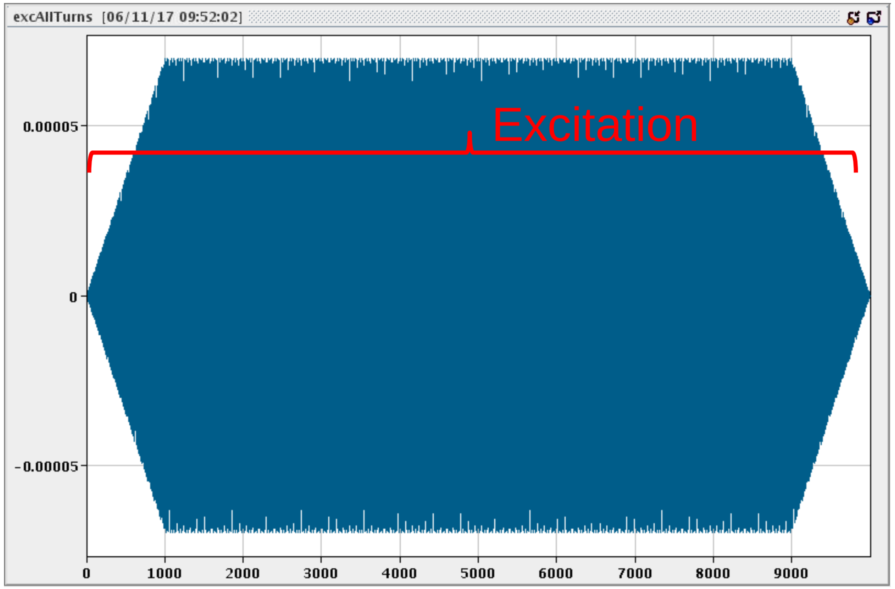
- The **fractional tune q** is obtained from the turn-by-turn data (TbT) of a single position monitor is the beam is given a kick or is oscillating naturally.
  - Fast Fourier Transform (FFT) of oscillation data provides the resonant frequency q.



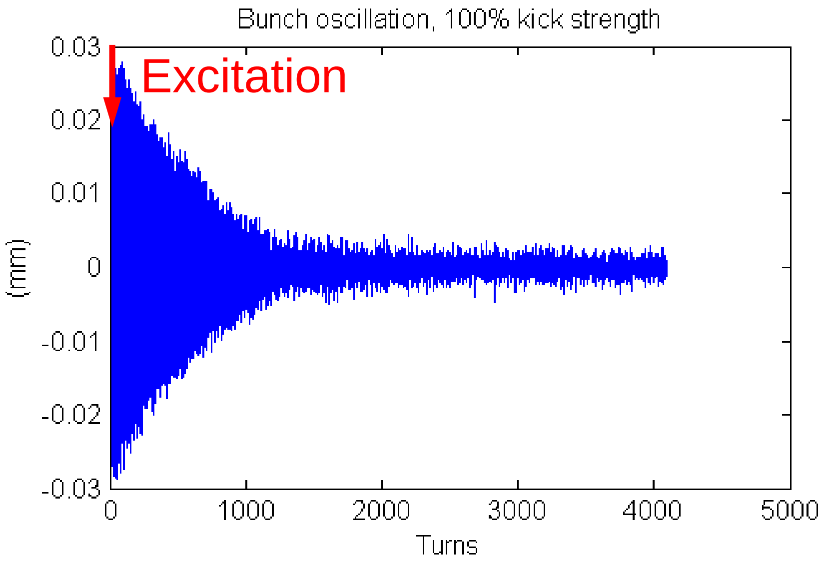


- Two common beam excitation methods:
  - The single kick method followed by a **free** oscillation, damped by decoherence (tune spread due to non-linearities),
  - The AC dipole **forced** excitation at a fixed frequency, usually close to the tune.
    - essentially emittance growth free excitation (if distance to tunes sufficient large),
    - long excitation duration (accuracy thanks to many turns).

Forced AC dipole oscillation (LHC)



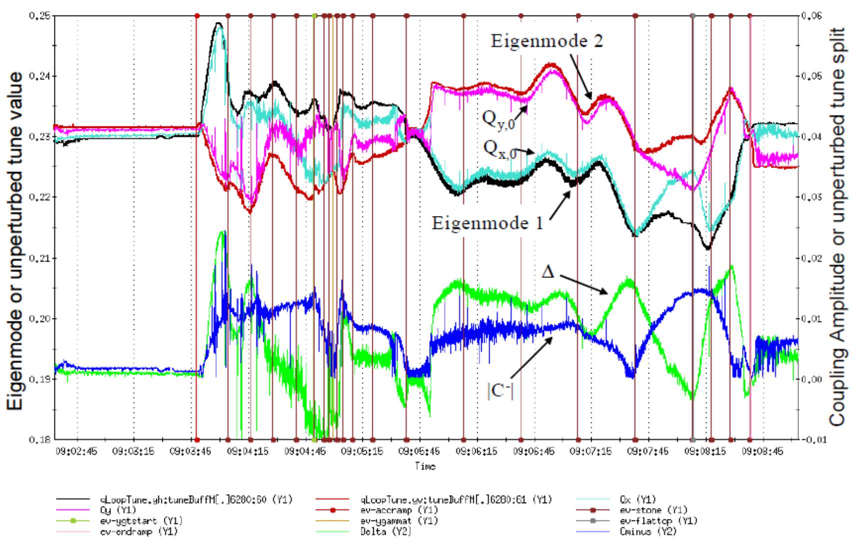
Single kick and free oscillation (LHC)



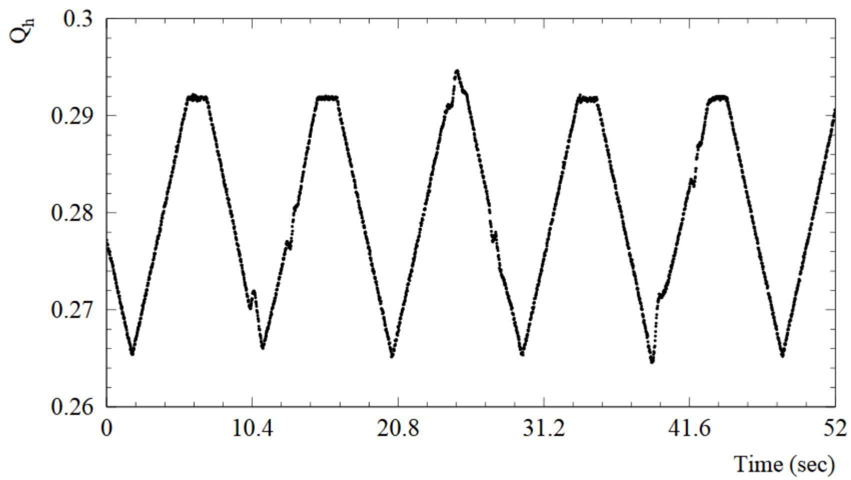
- Phased locking an excitation-measurement system provides a means to track tunes continuously.
  - An exciter shakes the beam on the tune, it remains locked on the tune using the phase of the beam response wrt excitation.
  - ‘Ideal’ for e^+e^- rings where damping will erase the effect of the excitation.
  - Problematic for hadron machine as this technique induces emittance blowup.
    - Used at RHIC, but not at LHC (too strong transverse feedback).

Q-FB-RHIC

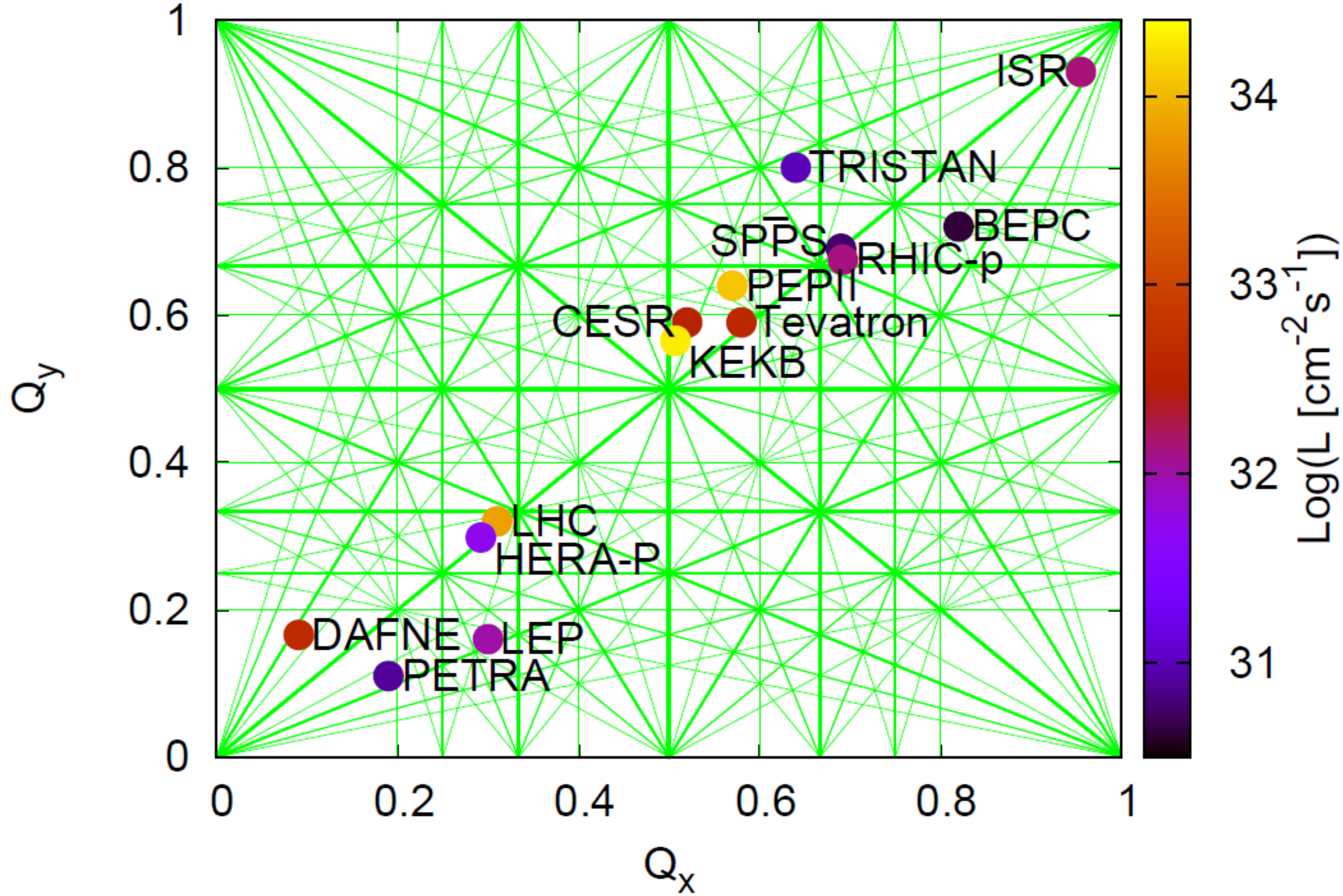
Phased locked tune and coupling (RHIC ramp)



Phased locked tune (and chromaticity) measurement at LEP

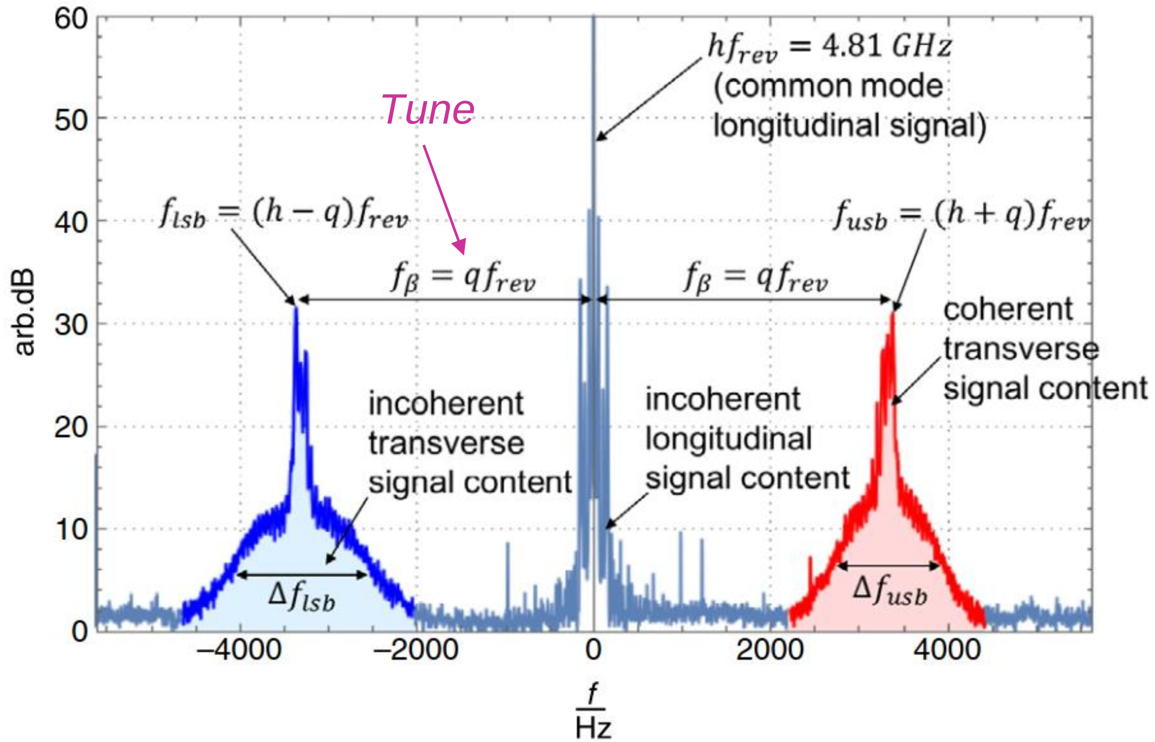


- Collider tune working points.
  - Hadron machines work usually very close to the diagonal (tune space).
  - The tune value may depend on the number of IPs. For example for e^+e^- the tune increment from one IP to the next is often chosen to be close to 0.5.



- A direct and non-invasive technique to measure the tunes uses the Shottky spectrum of the beam.
  - Relies on noise in the beam, no excitation is required – ideal for hadrons.
    - But small signals: detection electrodes must be close to the beam, or the beam must have large charge Z (Shottky signal amplitude ~ Z^2).
  - Can be problematic for bunched beams due to large coherent signals,
  - This devices is also able to provide chromaticity and emittance.

Shottky signals at the LHC



Q-SHOT-LHC

Tune correction

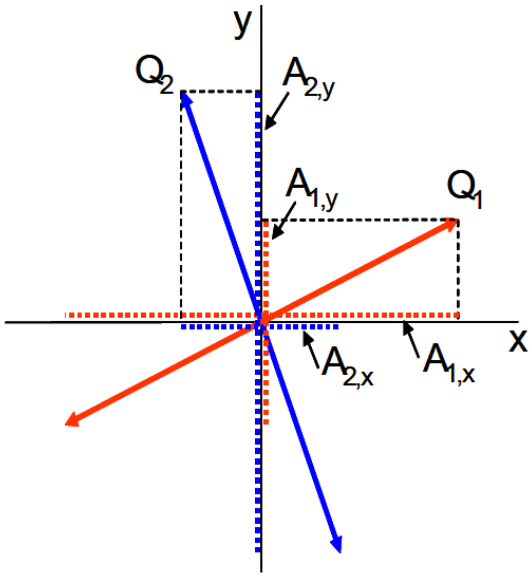
- Tune correction requires two orthogonal knobs for the horizontal and vertical plane.
  - The correction may in principle rely on any group of quadrupoles (at least 2 to be able to correct H and V independently).
  - In larger machine there are often distributed trim quadrupoles grouped in two (or more) families. This spreads out the correction and generates less beta-beating.
- Tune feedbacks are often implemented in machines that must ramp beams, for example LHC.
  - In such cases the challenge is also to obtain a good tune signal with high intensity beams where transverse feedback systems used to stabilize the high intensity beams may ‘kill’ the tune signals by their action !

Coupling

- So far we have considered that the horizontal and vertical planes were uncoupled which is not realistic.
- In all machines there are a variety of sources for coupling between the horizontal and vertical planes. Among the most common causes:
  - Element misalignments (for examples roll angles of quadrupoles),
  - Skew quadrupolar field errors,
  - Solenoids,
  - Orbit offsets in sextupoles.

Coupling measurement

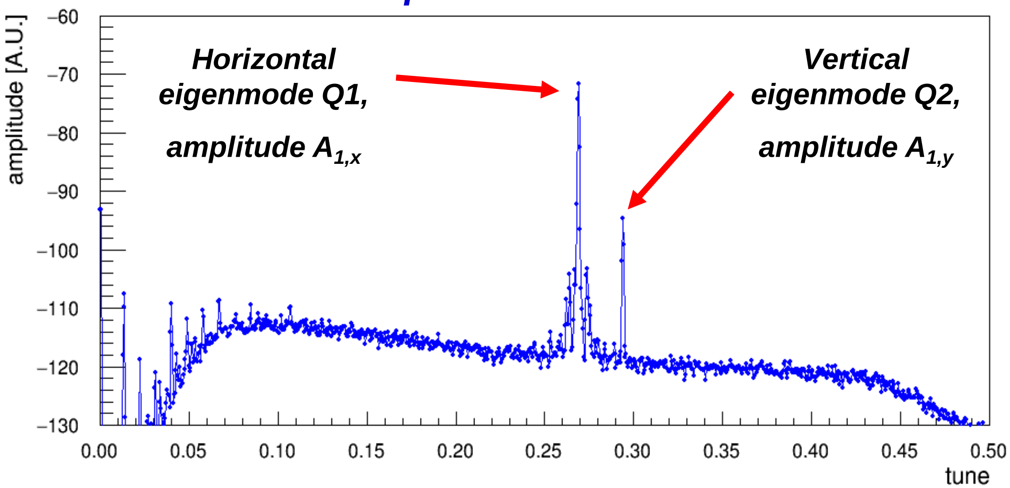
- In the presence of **coupling** the beam **eigen-modes** Q_1 and Q_2 no longer coincide with Q_x and Q_y.
- A first technique to characterise the coupling coefficient C^- consists in measuring the crossed tune peak amplitudes:
  - Vertical tune in horizontal spectrum and vice-versa.
  - Simple measurement, but no phase information.
  - Only the local coupling is obtained, which can differ from th global coupling.



$$\left\| C^- \right\| = \frac{2\sqrt{r_1 r_2}\,|Q_1 - Q_2|}{1 + r_1 r_2}$$

$$r_1 = \frac{A_{1,y}}{A_{1,x}} \qquad r_2 = \frac{A_{2,x}}{A_{2,y}}$$

Horizontal tune spectrum at the LHC



Coupling measurement II

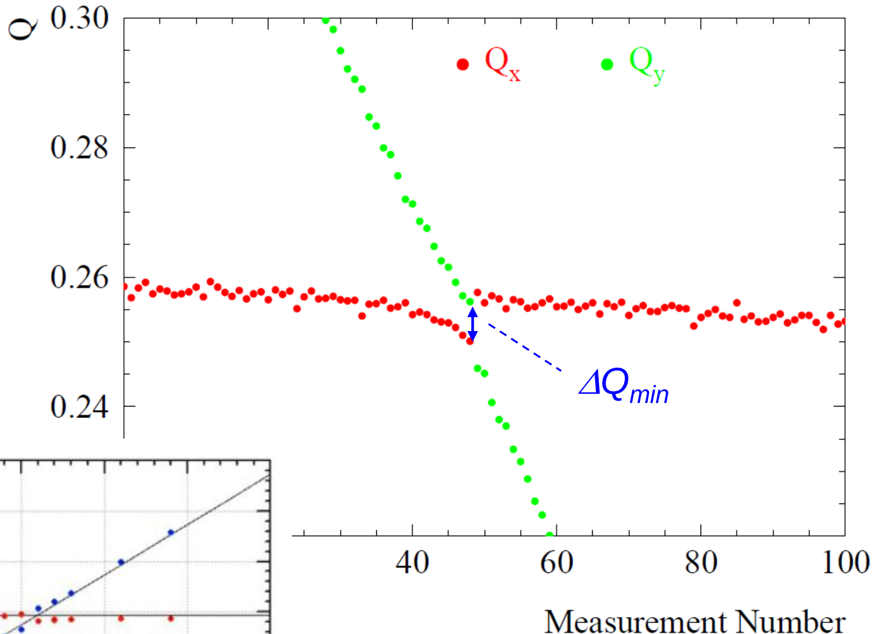
- The global machine coupling can be also determined directly using the **closest tune approach**.
  - Requires to move the tunes close to / across each other.
  - Provides global coupling information from a single location.

LEP-PERF

- The closest distance of approach ΔQ_{min} corresponds to the coupling parameter C^-:

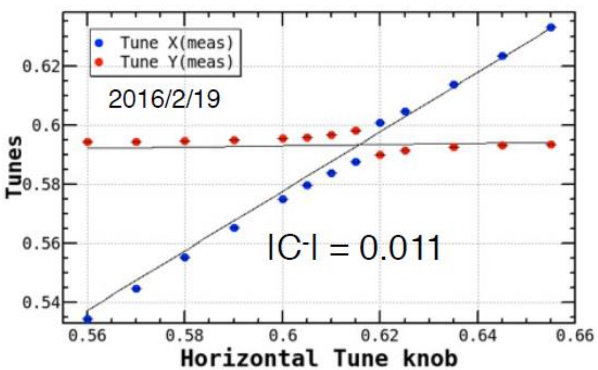
$$\Delta Q_{\min} = \left\| C^- \right\|$$

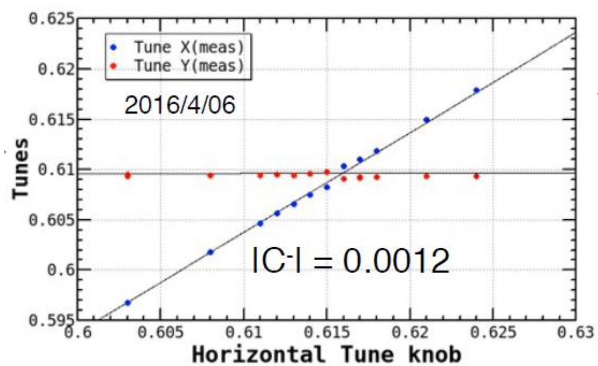
Closest tune measurement at LEP



Q-COUP-KEKB

Closest tune measurements at superKEKB

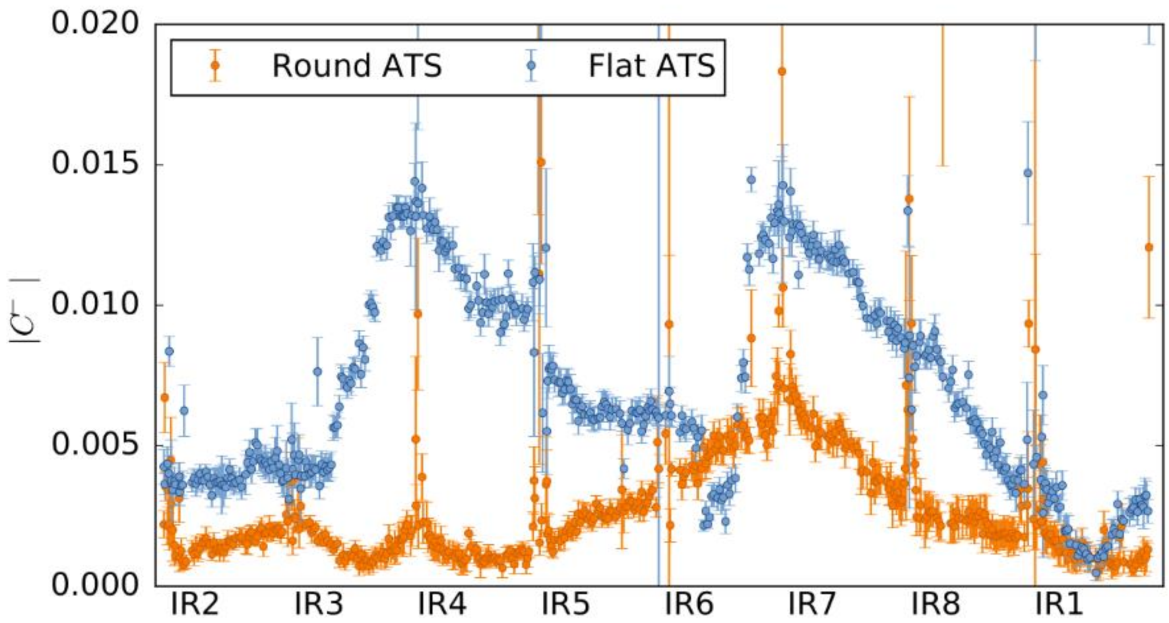




Coupling measurement III

- The coupling can also be determined along the machine using multi-turn beam position data (with e.g. AC dipole excitation) using pairs or groups of BPMs to reconstruct the coupling locally.
  - Provides detailed local coupling information, including phase.
  - Global coupling is obtained by integration of the local coupling.
  - Provides excellent deterministic corrections.

Local coupling measurement at LHC



Q-COUP-LHC

O-NL-LHC

Correction of coupling

- The coupling correction scheme for a machine depends on design details.
  - Ideally experimental solenoids should be compensated by **local anti-solenoids** to correct the coupling source locally.
    - At high energy hadron colliders like LHC, the solenoids of the 4 experiments contribute very little to he machine coupling (due to the high momentum).
  - The global machine coupling is usually corrected with **distributed skew quadrupoles**, either using 2 orthogonal knobs (similar to a tune correction) or with more refined local corrections.
    - For measurements that do not provide phase information (only global coupling), the two orthogonal knobs must be scanned by trial and error to determine a correction.
  - As an alternative, **orbit bumps in sextupoles** may also be used for coupling corrections, but this can lead to problems with dispersion etc. Requires a careful combined correction of both parameters.

Introduction

Orbit and dispersion

Tune and coupling

Chromaticity

Optics linear and non-linear

Aperture

Luminosity

Chromaticity measurement

- The **linear chromaticity** defines the tune dependence on momentum:

$$\Delta Q = Q' \frac{dp}{p}$$

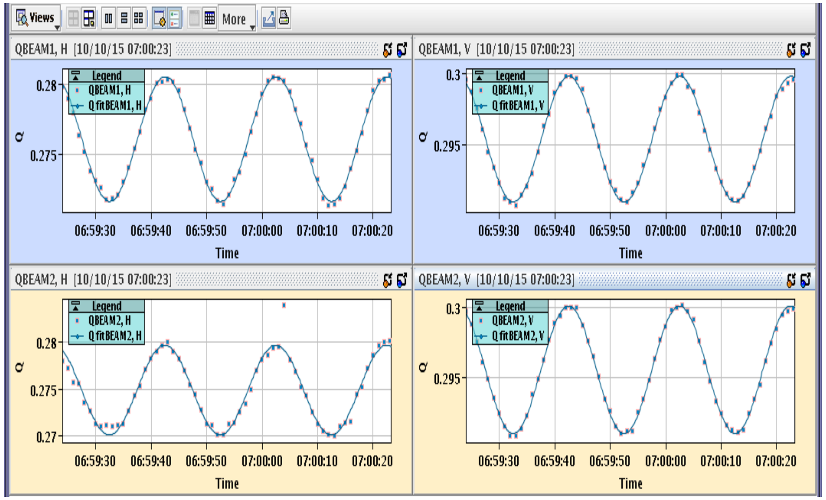
- For a lattice Q' is genrally negative unless Q' is corrected with sextupoles. The typical operation range of Q' in large storage rings is ~ +1 to +20.

- The chromaticity is measured by changing / modulating the energy offset dp/p through the RF frequency while recording the tune change ΔQ.

$$\frac{dp}{p} = \left(\frac{1}{\gamma^2} - \alpha\right)^{-1} \frac{df_{RF}}{f_{RF}} \cong \frac{-1}{\alpha} \frac{df_{RF}}{f_{RF}}$$

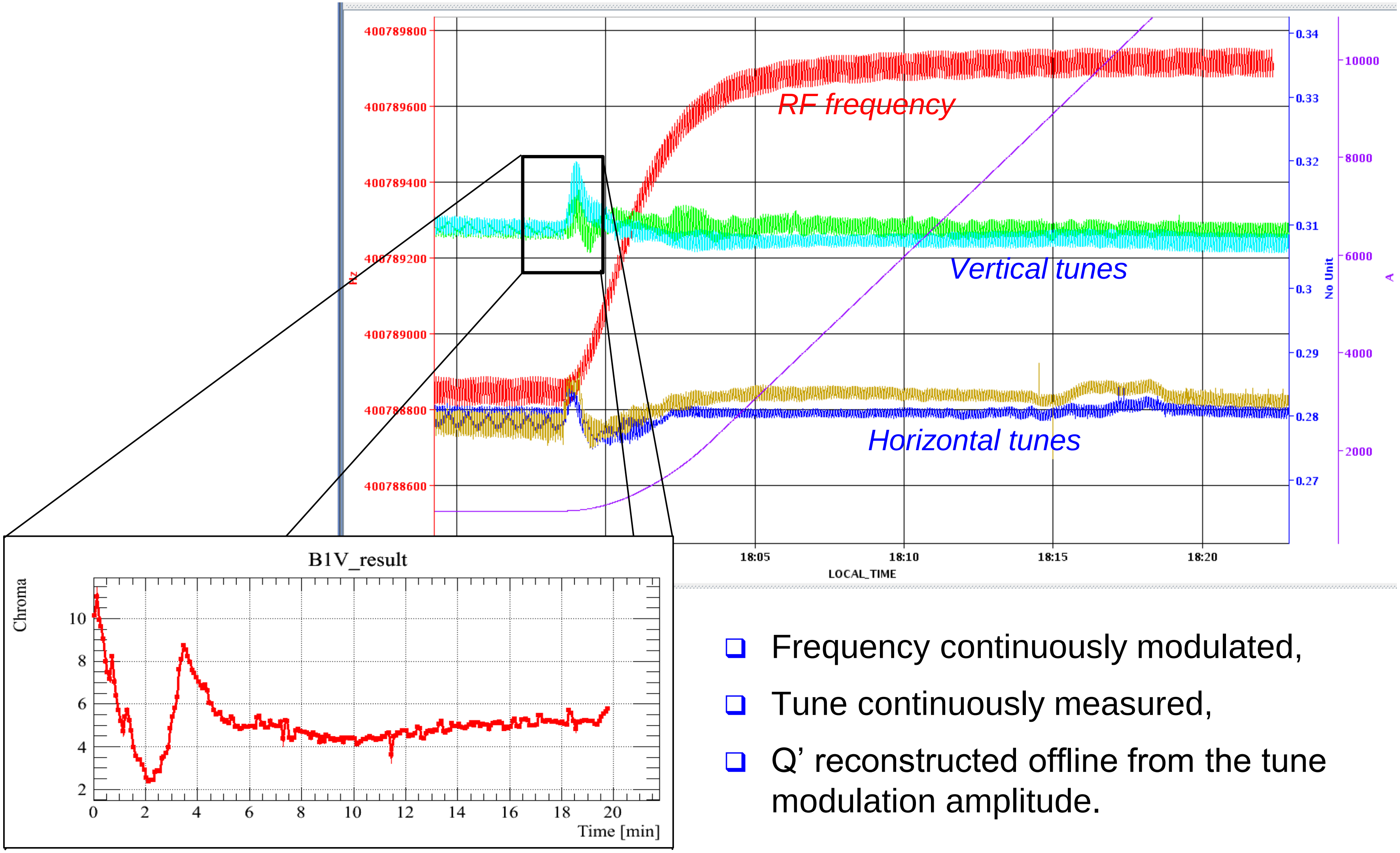
At high energy machines, γ >> 1

Q' measurement by RF frequency modulation at LHC



Chromaticity measurement II

Q' measurement along a ramp by RF frequency modulation at LHC



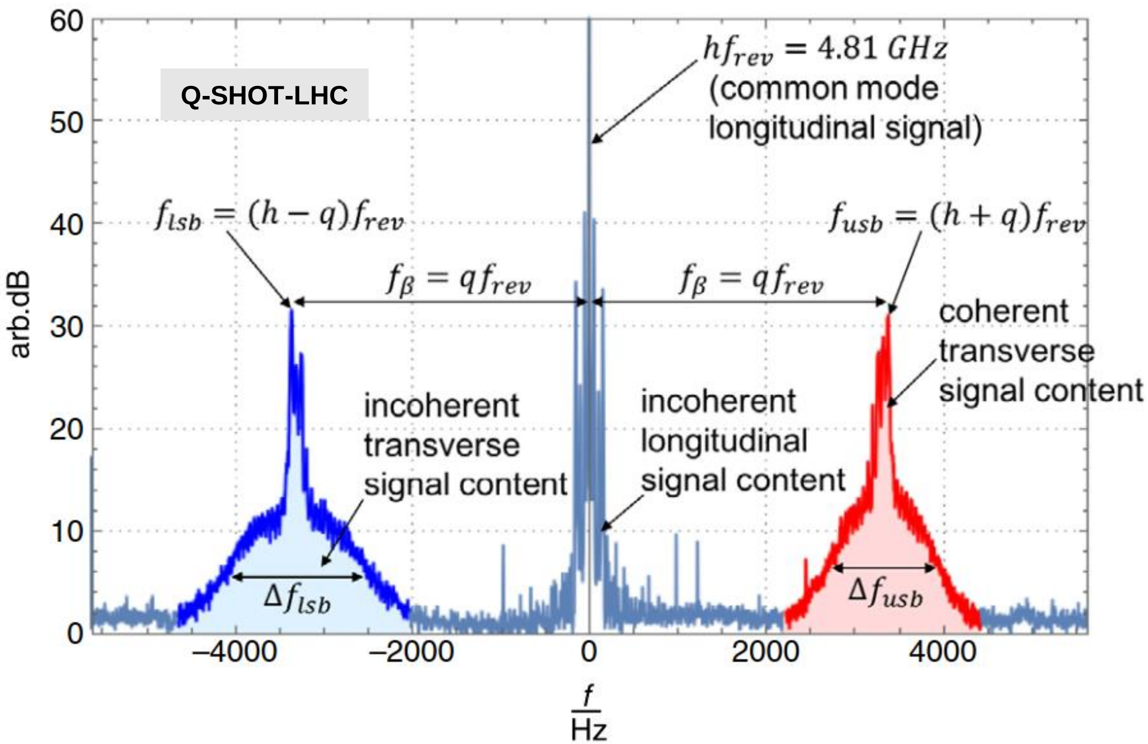
- Frequency continuously modulated,
- Tune continuously measured,
- Q' reconstructed offline from the tune modulation amplitude.

Chromaticity from Shottky

- A Shottky monitor can be used to determine Q’ for hadron beams without the need for a radial modulation.
  - Completely non-invasive measurement.
- Q’ is related to the difference in width of the upper and lower Shottky side-bands:

$$Q' = \eta \left(n \frac{\Delta f_{\text{lsb}} - \Delta f_{\text{usb}}}{\Delta f_{\text{lsb}} + \Delta f_{\text{usb}}} + q \right)$$

Shottky signal at the LHC



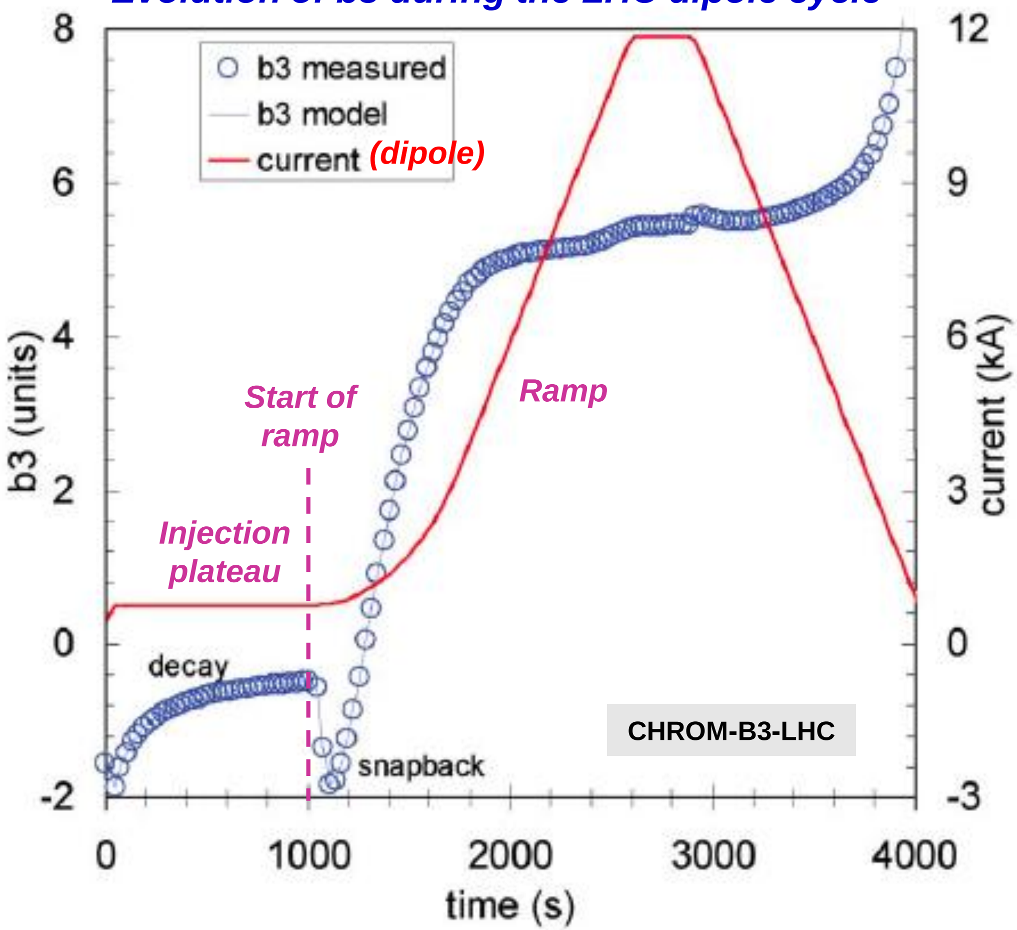
At LHC for example, the Shottky seems to provide good Q’ data at injection for protons, and at ~ all energies for ions (due to Z^2 sensitivity).

Chromaticity and field errors

- In **superconducting machines** like Tevatron, LHC or FCC-hh the **sextupolar field errors** (***b_3***) play an important role and may generate huge chromaticity errors.
- The **field errors** are usually generated in the **dipoles** and due to the important integrated length of the dipoles, the b_3 errors can add up to hundred's of units of Q'.
- Furthermore superconducting machine are affected by **decay** and **snapback** phenomena:
  - While the machine 'sits' at injection for filling, persistent currents (~ eddy currents) flow between the cable strands and may induced large field errors, in particular b_3 components. This leads to a drift of the chromaticity over time.
  - At the start of the energy ramp, the persistent currents 'snap back' to their initial value before decay over a very narrow energy range, leading to large dynamic swings of Q'.

- The b3 errors for the LHC dipole magnets were measured on test benches and on the series production magnets.
  - Higher order field errors were also measured (up to b7).

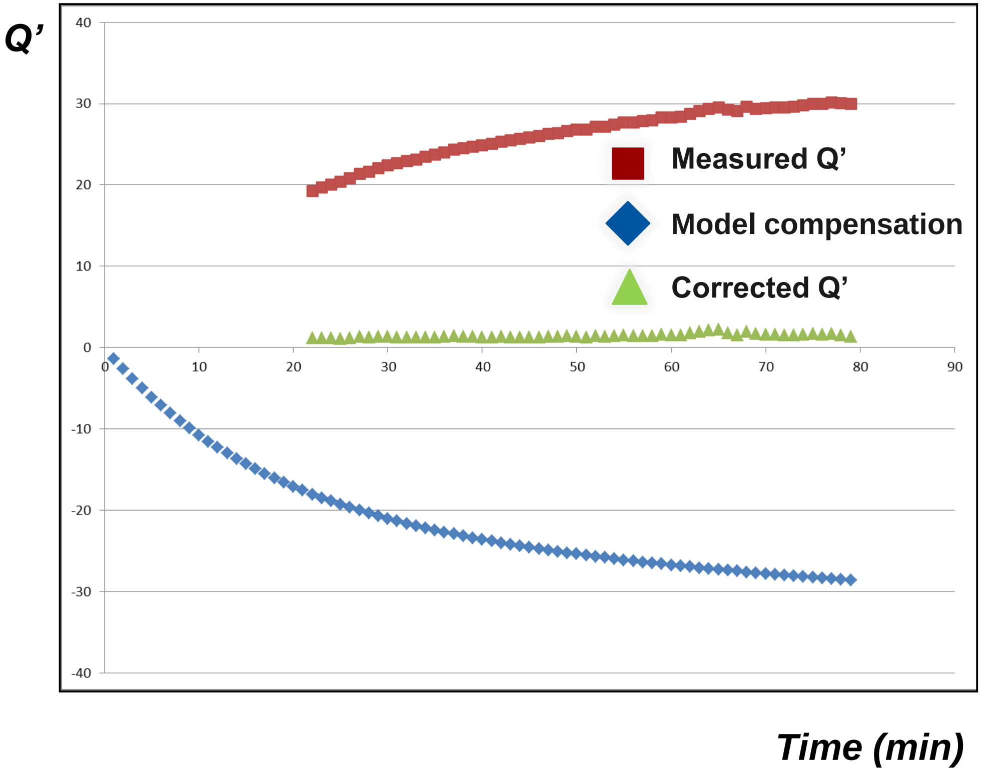
Evolution of b3 during the LHC dipole cycle



- During injection b_3 decays by ~1 unit ≅ 38 units of Q'.
  - **1 unit = relative field (error) of 10^{-4} at a radius of 17 mm**.
- Over the full cycle the swing of b3 is ~7 units ≅ 270 units of Q'.

- To control the LHC chromaticity at injection it is not possible to modulate the frequency for continuous measurements, a model must therefore be available to stabilize Q'.
  - The possibility to use of a Shottky monitor is under investigation.

Evolution of the H chromaticity at injection for LHC

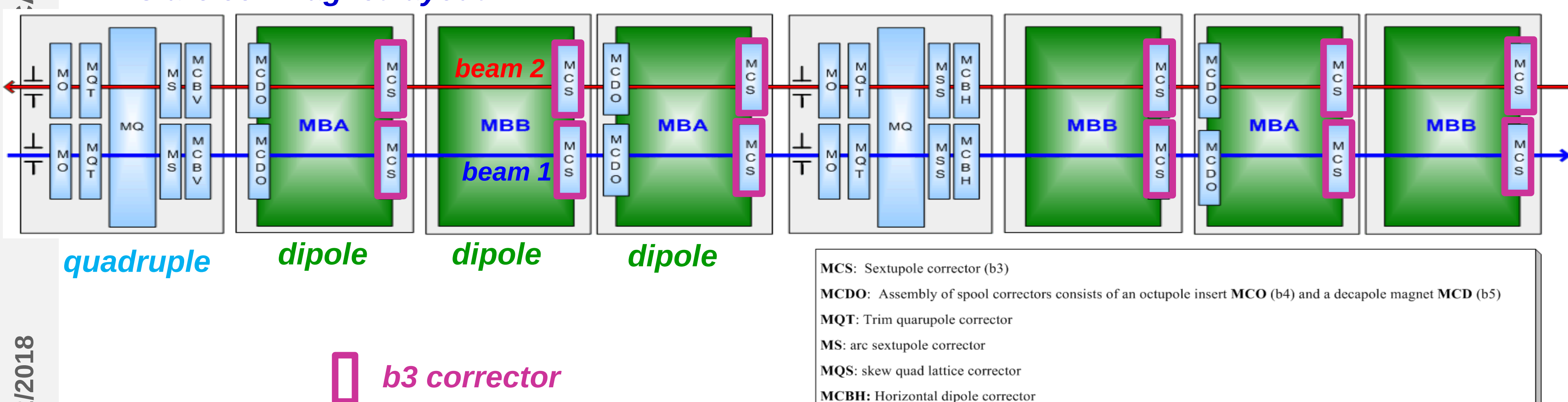


- Continuous Q' measurements over many hours are used to establish models of the decay.
  - Parameters depend on the flat top energy etc
- A decay model is used to stabilize Q' during injection.
  - In general correct within ~ ±2.
- For the snapback a model is used to correct Q' during this short phase.
  - Lasts ~ 30 s at LHC.

Chromaticity correction

- The chromaticity is usually corrected with the **lattice sextupoles**. For small chromaticity trims the corrections are usually distributed over all / many sextupole in the form of orthogonal knobs for the two planes.
- For systematic field errors as they appear in large super-conducting machines, a correction with the lattice sextupoles may lead to poor dynamic aperture !
  - Remember the corrections for LHC reach ~ 300 units !
- A better compensation of field errors is obtained using **dedicated b3 correctors** (~small sextupoles) that are installed next to the dipoles and distributed over the entire machine – **local corrections**.

LHC arc cell magnet layout



MCS: Sextupole corrector (b3)
MCDO: Assembly of spool correctors consists of an octupole insert **MCO** (b4) and a decapole magnet **MCD** (b5)
MQT: Trim quarupole corrector
MS: arc sextupole corrector
MQS: skew quad lattice corrector
MCBH: Horizontal dipole corrector
MCBV: Vertical dipole corrector
MO: Lattice octupole

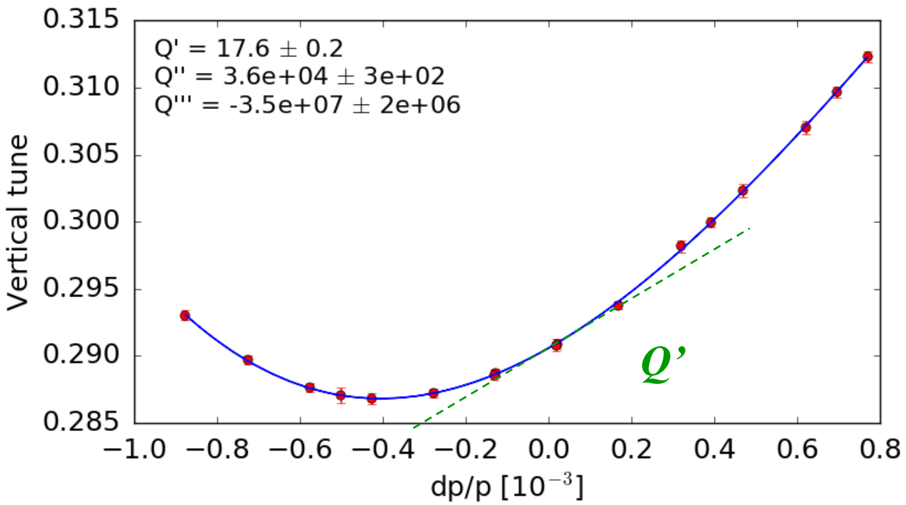
Higher order chromaticity

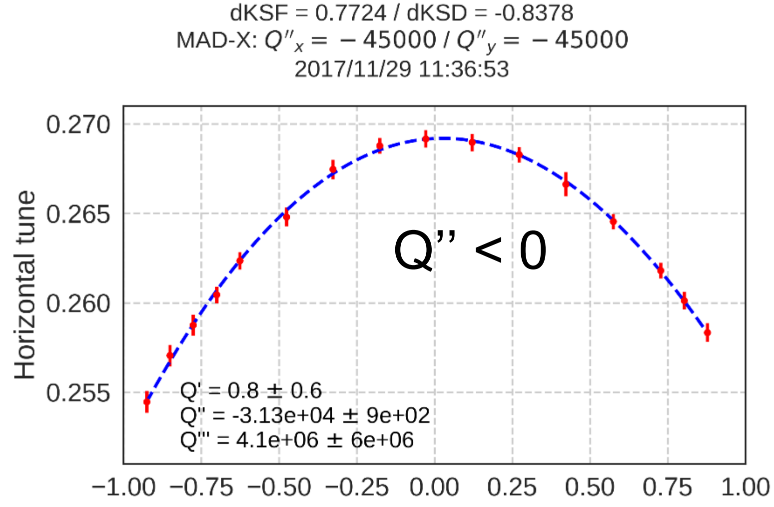
- So far we discussed the linear chromaticity which corresponds to the regime of small *dp/p*:

$$Q' = \lim_{dp/p \to 0} \frac{\Delta Q}{dp/p}$$

- Non-linear chromaticities Q'', Q''' etc (higher order derivatives wrt *dp/p*) are however important for the machine dynamic aperture and for collective effects ('Laudau damping' through tune spread).
  - Measurement of the tune versus dp/p.
  - High order chromaticity gives insight into off-momentum behaviour of optics, feed-down from higher order fields (or field errors) etc.

NL chromaticity measurement at LHC injection





Introduction

Orbit and dispersion

Tune and coupling

Chromaticity

Linear and non-linear optics

Aperture

Luminosity

- The knowledge of the **beam optics** is essential for the good performance of an accelerator. Tools to measure and correct the optics towards a design model are essential at any modern facility.
- The **betatron function error** (beta-beating) at an observation point j due to a number of strength errors Δk_i is given to first order by:

$$\frac{\Delta\beta_j}{\beta_j} \approx \sum_i \frac{\Delta k_i L_i \beta_i}{2\sin(2\pi Q)} \cos(2\pi Q - 2|\mu_j - \mu_i|) = \sum_i B_{ji} \Delta k_i$$

- Contrary to the case of orbit kicks, gradient errors have a **non-linear effect** on the betatron function. A correct treatment must be self-consistent, the equation above is only an approximation.
  - The problem may however be linearized using the matrix elements B_{ji} and solved **iteratively** using the SVD algorithm based on measurements of $\Delta\beta_j$. After each correction iteration the matrix elements B_{ji} must be revaluated.

- There are three main technique to measure and reconstruct the machine optics, and they may be used in combination.
  - **K-modulation**: the strength of individual quadrupoles is modulated to determine the local optics function.
  - **Orbit (trajectory) response**: the orbit or trajectory response matrix is measured with orbit corrector kicks (→ see orbit correction), a fit to the response is used to reconstruct and correct the machine model.
  - **Multi-turn beam position data**: the beam is excited and mutli-turn beam position data is recorded to determine the betatron phase advance between beam position monitors. The betatron function is reconstructed from the phase advance information.

- **K-modulation** was already described as a means to determine BPM offsets wrt quadrupole magnetic centres.
- This technique can also be used to determine the average betatron function inside the modulated quadrupole since the tune change ΔQ due to a gradient change Δk is given by:

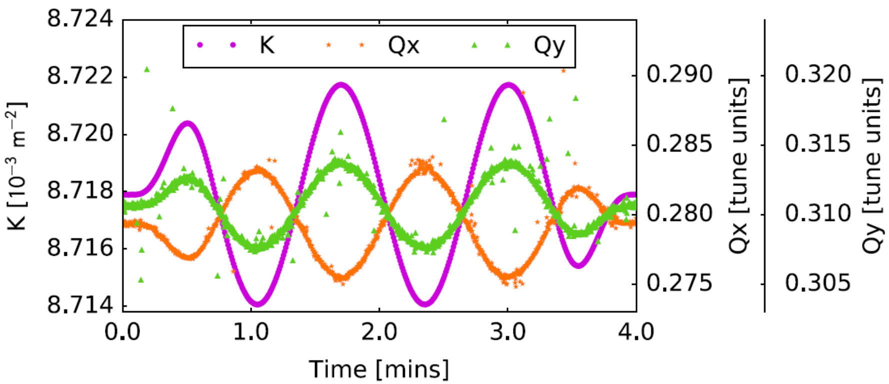
$$\Delta Q_u = \frac{1}{4\pi}\int_{s_0}^{s_0+l} \Delta k \beta_u(s) \mathrm{d}s$$

(integral over the quadrupole length l)

O-KMOD-LHC

O-MT-LHC2

K-modulation at LHC



- The betatron function in the quadrupole is then given by:

$$\beta_u = \frac{2}{l\Delta k}\left[\cot(2\pi Q_u) - \frac{\cos(2\pi(Q_u + \Delta Q_u))}{\sin(2\pi Q_u)}\right]$$

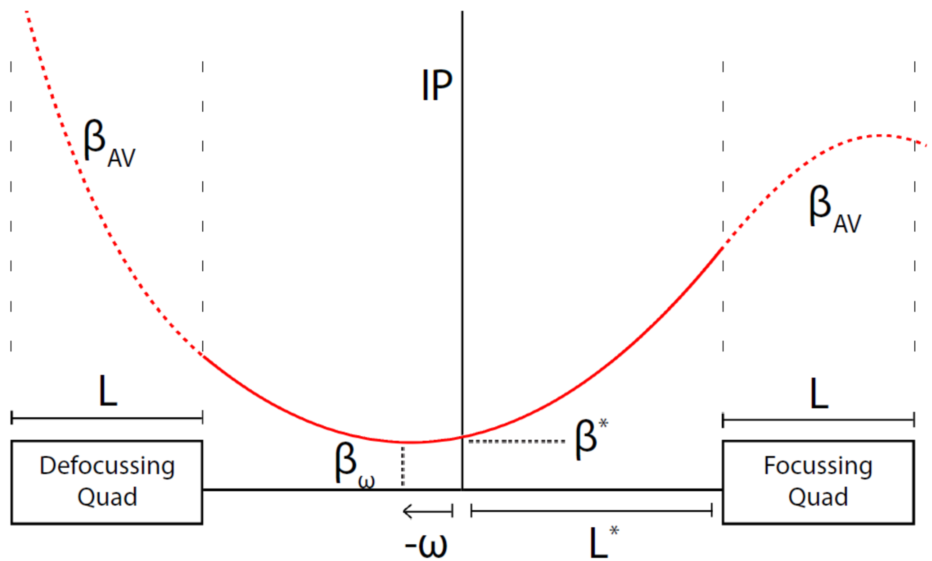
- This technique is powerful and simple but requires quadrupoles to be powered individually which is often the case on synchrotron light sources but applies only to a subset of quadrupoles in large storage rings!
  - Large collider arc quadrupoles are generally powered in series.

β* from K-modulation

- The knowledge of **the betatron function β^* at the interaction points** (IPs) is important for the collider performance.
- The IP is usually surrounded by (low-beta) quadrupoles that focus the beam at the IP, with a drift space between the IP and the first quadrupole.
  - Due to errors, the **betatron function waist β_w** (minimum) may not coincide with the **betatron function β^* at the IP**.
  - The β-function in the surrounding quadrupoles can be obtained from k-modulation and interpolated to the IP to obtain β*.
  - For e^+e^- the experimental solenoid can have a large impact due to the lower beam energy → no longer a 'drift' between IP and low-beta quadrupole.

Example of an IP layout, here the LHC

O-BSTAR-LHC



Ideally:

$$\beta_w = \beta^*$$

and

$$\omega = 0$$

- The concept of **orbit / trajectory response** is to exploit the large amount of information that is encoded in the steering response matrix (**ORM**).
- The principle, available in the popular **LOCO code**, is to excite all / many steering elements in a ring / line and record the BPM response. This provides a measurement of the **response matrix** folded with **BPM calibration factors** b_i and **steerer deflection calibration** factors c_j:

$$\Delta \vec{u} = \mathbf{R}_M \, \Delta \vec{\theta} \qquad R_{ij,M} = \frac{b_i c_j \sqrt{\beta_i \beta_j} \cos(|\mu_i - \mu_j| - \pi Q)}{2 \sin(\pi Q)}$$

O-LOCO-BDYN

- All the elements of $\boldsymbol{R_M}$ are observables for a model fit, fit variables include:
  - BPM and steerer calibration factors ($b_{i,}$, c_j),
  - BPM and steerer roll angles as they generate measurement ‘coupling’,
  - Any selection of quadrupole gradient to fit for β, μ,
  - Skew quadrupoles for coupling.

Orbit (trajectory) response II

- The ORM matrix is linearized in the form of a vector $\vec{r}$:
  - The vector size = the number of elements of $\boldsymbol{R_M}$.

$$r_k = \mathrm{R}_{\mathrm{ij}}^{\mathrm{meas}} - \mathrm{R}_{\mathrm{ij}}^{\mathrm{model}} \quad \forall i, j$$

- The fit parameter vector is composed of (for example): $\vec{c}$
  - BPM calibrations and roll angles,
  - Steering elements calibrations and roll angles,
  - Quadrupole gradients (skew and normal),
  - …

- A response matrix **G** ist constructed with the dependence of each r_i on any c_j.
  - Some elements are obtained analytically, others need a simulation tool (like MAD, PTC, ELEGANT…).

$$\mathrm{G} = \begin{pmatrix} \frac{\partial r_1}{\partial c_1} & \dots & \frac{\partial r_1}{\partial c_M} \\ \dots & \dots & \dots \\ \frac{\partial r_N}{\partial c_1} & \dots & \frac{\partial r_N}{\partial c_M} \end{pmatrix}$$

Orbit (trajectory) response III

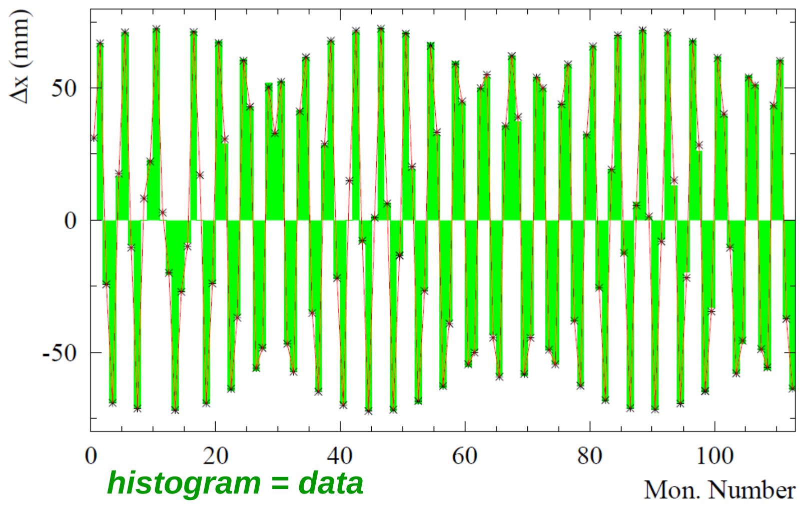
- The response analysis is coupled to an accelerator design tool like MAD, PTC etc in order to determine the sensitivity wrt to the quadrupole gradients etc.
- Once the system is cast in matrix form, it is solved by SVD inversion – structurally equivalent to an orbit correction.
  - The tricks to filter noise by eliminating small eigenvalues as discussed for beam steering can be employed here !
  - A few iteration may be required to converge. At each iteration **G** must be re-evaluated.

$$\left\| \vec{r} - \mathbf{G}^{-1}\Delta\vec{c} \right\|^2 = \min$$

- Note that the size of matrix G grows rapidly !
  - For a machine with 100 BPMs and 100 steering elements, there are 10’000 lines and over 200 columns !

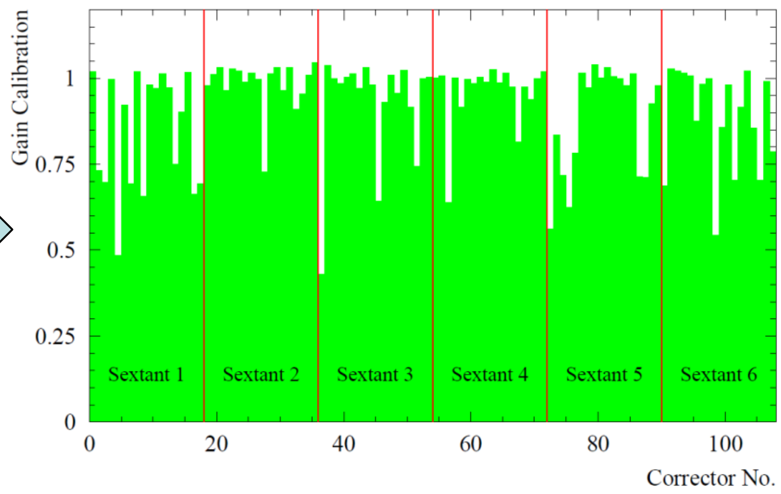
Orbit (trajectory) response III

Orbit response example after fit at SPS

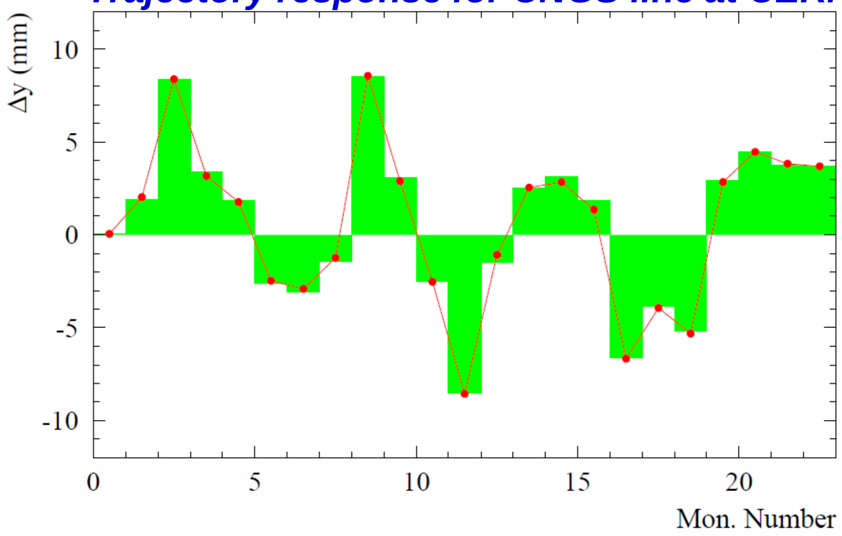


histogram = data

Horizontal orbit corrector calibrations at SPS



Trajectory response for CNGS line at CERN



Some correctors are damaged by radiation (from the time when SPS was a lepton injector for LEP !)

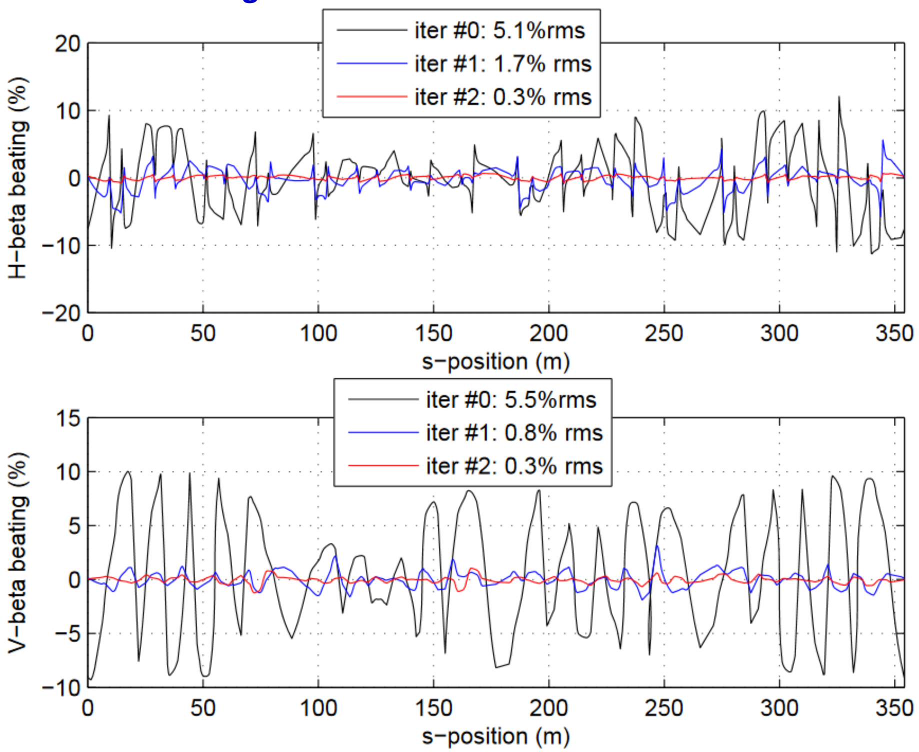
O-LOCO-SPS

O-LOCO-CNGS

Orbit (trajectory) response IV

- Orbit response has been used with a lot of success at synchrotron light sources where it is a standard tool.
  - Typically ~ 100 BPMs, steerers and quadrupoles.
- At very large machines like LHC and FCC-hh, the data volumes are immense and multi-turn methods are faster, therefore the response techniques are mainly useful to calibrate BPMs and steerers.

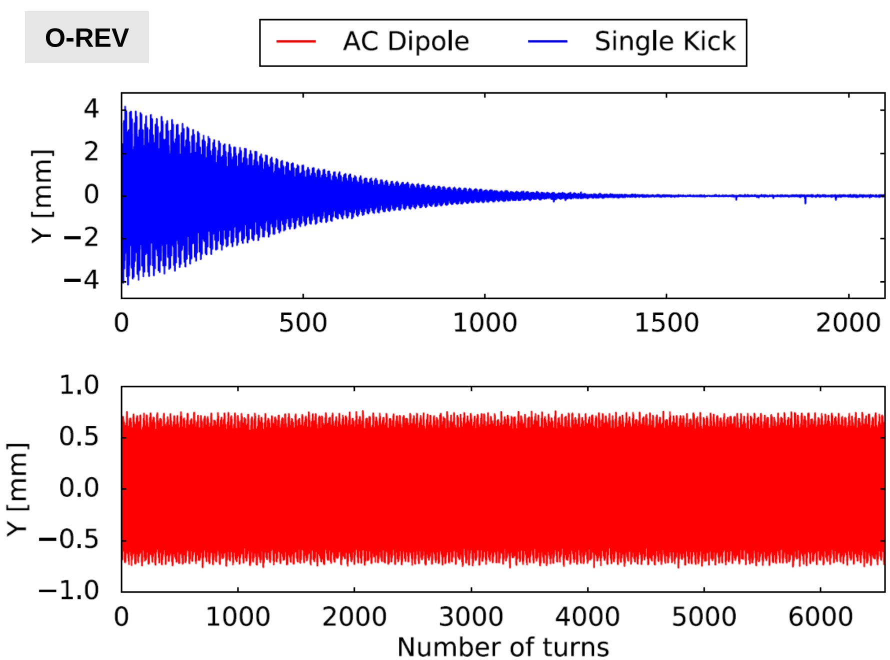
Beta-beating correction with LOCO at SOLEIL



O-LOCO-SOLEIL

Multi-turn optics measurements

- Multi-turn optics measurements rely on a **beam excitation** for a certain number of turns, typically few x 1000 to obtains sufficient resolution.
- The beam oscillation phase is extracted for each BPM, this phase corresponds to the betatron phase μ at each BPM.
  - The betatron phase advance $\Delta\mu$ between BPMs can therefore be extracted in a straightforward way.
  - The phase measurement does not depend on the BPM calibration (but is sensitive to BPM non-linearities).

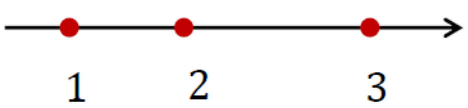


- Exciting the beam with a **single kick** is often limited by the decoherence of the oscillation (or by radiation damping).
  - Limited no of turns → measurement error.
- Excitation by an **AC-dipole** is more favourable since the number of turns can be increased if necessary.

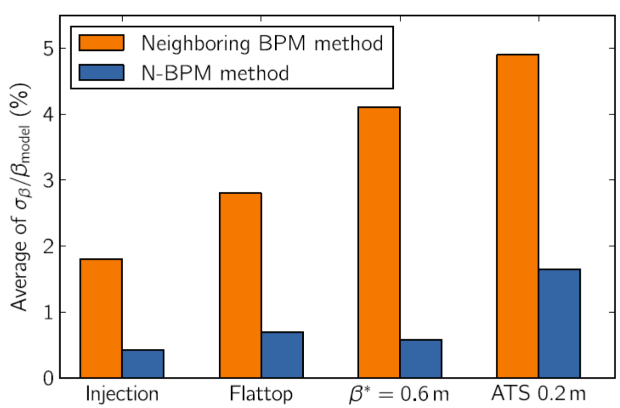
Multi-turn optics measurements II

- The betatron function can be reconstructed from the phases measured at 3 BPMs – this equation assumes that they are no sources of errors between the 3 BPMs – and a model is required:

$$\beta_1^{meas} = \beta_1^{model} \frac{\cot\psi_{12}^{meas} - \cot\psi_{13}^{meas}}{\cot\psi_{12}^{model} - \cot\psi_{13}^{model}}$$



- The raw turn data is often **filtered for noise by SVD** (→ see later) before the phase is extracted, and **multi-BPM interpolation techniques** have been developed to improve the accuracy of this technique.
  - Gain when phase advances to neighbouring BPMs are unfavourable.



O-REV

O-MULTI-BPM

Multi-turn optics measurements III

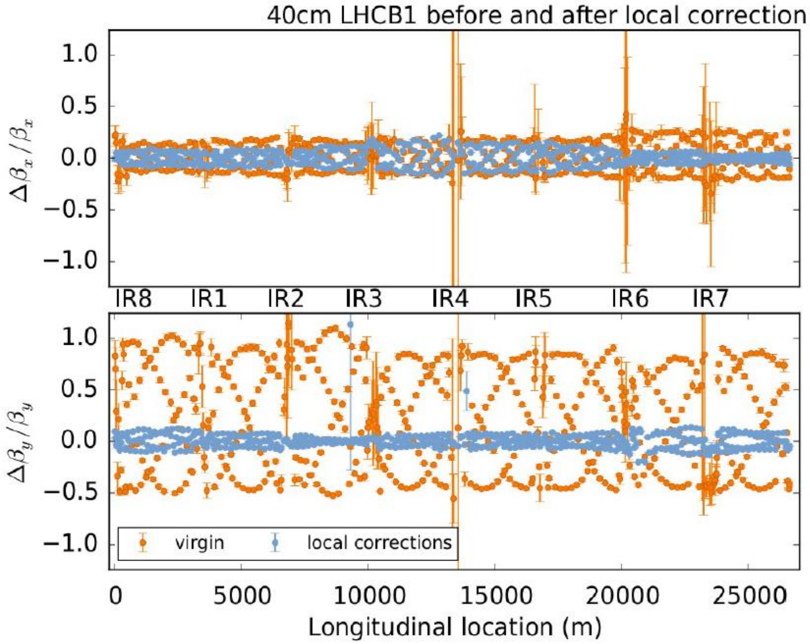
- The advantage of the MT technique is that the optics for both planes is obtained with two measurements – which can be very fast – and for large machines the data size is not as immense as with ORM.
  - In addition this method is not sensitive to BPM calibrations.
- The disadvantage of the MT technique is that a fast kicker is required, and the beam must be excited to **sufficiently large amplitude** compared to the BPM turn-by-turn resolution.
  - One of the limiting factors at LHC with very low β^* because the free aperture for kicking the beam is limited.
  - For ORM the BPM noise is in general not an issue (average over many turns).
- Once the data is prepared an optics modelling tool (MAD, PTC etc) must to used to fit machine errors to data, respectively establish corrections.
  - Alternatively SVD correction can be applied iteratively from the phase or betatron function response matrix.

O-REV

- In a collider with a low-beta section where the peak β is >> than the ring average, the local optics errors may dominate completely the beta-beating.
- In such a configuration it is favourable to first correct the local errors before trying to flatten the beta-beating in the rest of the machine.

O-MT-LHC2

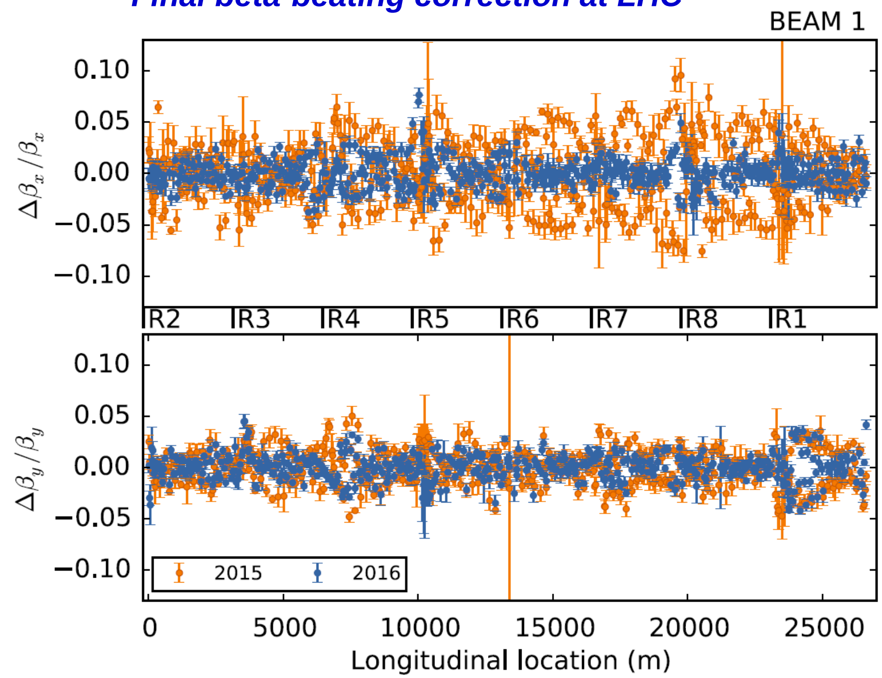
Local beta-beating correction at LHC



Raw β-beating ~ 100%

β-beating with local correction ~10-15%

Final beta-beating correction at LHC



Final β-beating ~ 1-2%

From optics measurements to corrections

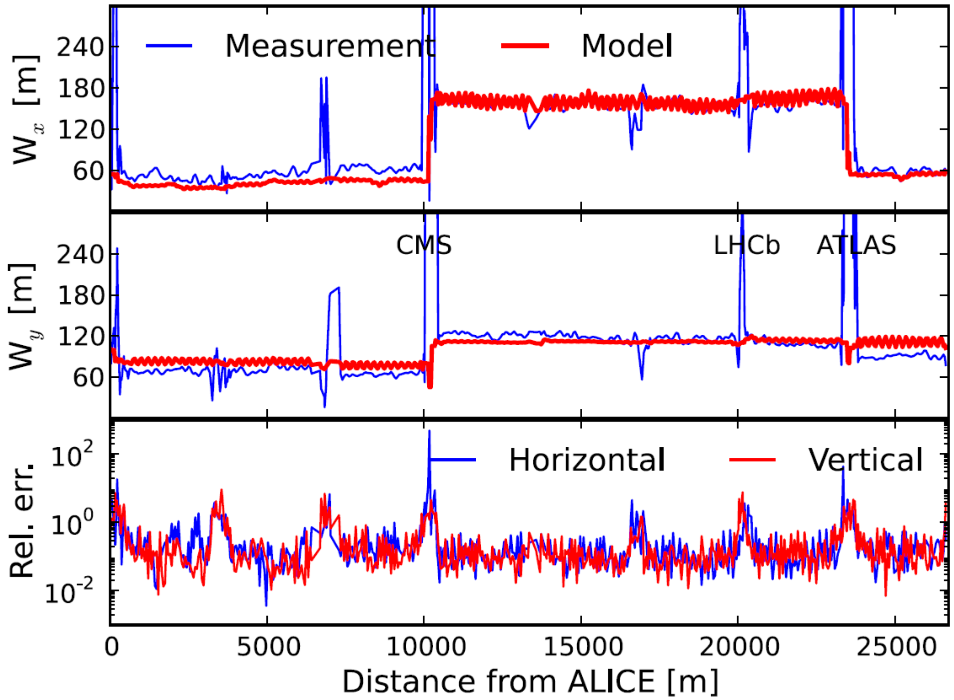
- **K-modulation** and **multi-turn** techniques provide measurements of the real optics (phases, β-functions).
  - To restore the design optics (or at least reduce the deviations), corrections must be evaluated in a second step using directly an optics modelling program or using correction techniques based on response matrices with SVD (or even MICADO) type of algorithms.
- The **response matrix** technique (LOCO) can directly provide errors on gradients etc in the fitting procedure if the appropriate variables are used in the procedure.
  - To restore the design model it is sufficient to apply the errors as corrections to the real machine.
- In all cases, due to measurement uncertainties and to the non-linear response of optical functions to gradient changes, iterations may be required to converge to a satisfactory situation.

❑ For lattices with low-beta section and / or very strong focusing measuring and correcting the on-momentum optics is generally not sufficient.

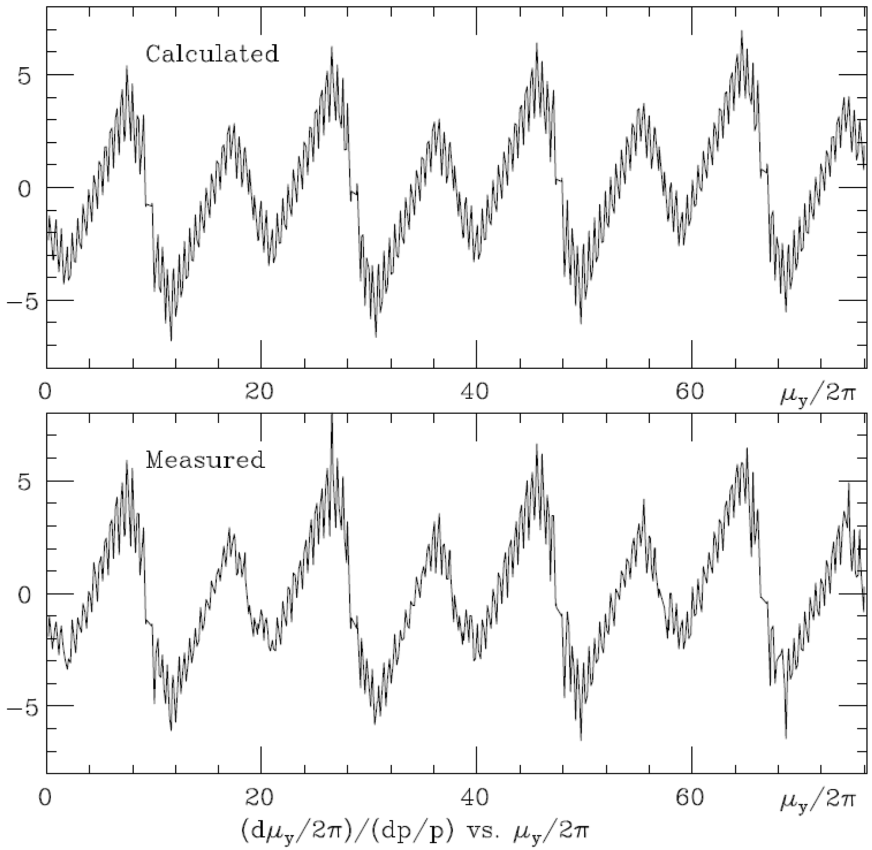
❑ The optics / ORM must also be measured at different momentum offsets to ensure that the optics correction procedure does not degrade the off-momentum properties of the optics.

Montague W function at LHC beam 2

O-MT-LHC1



Chromatic phase advance at LEP



O-CHROM-LEP

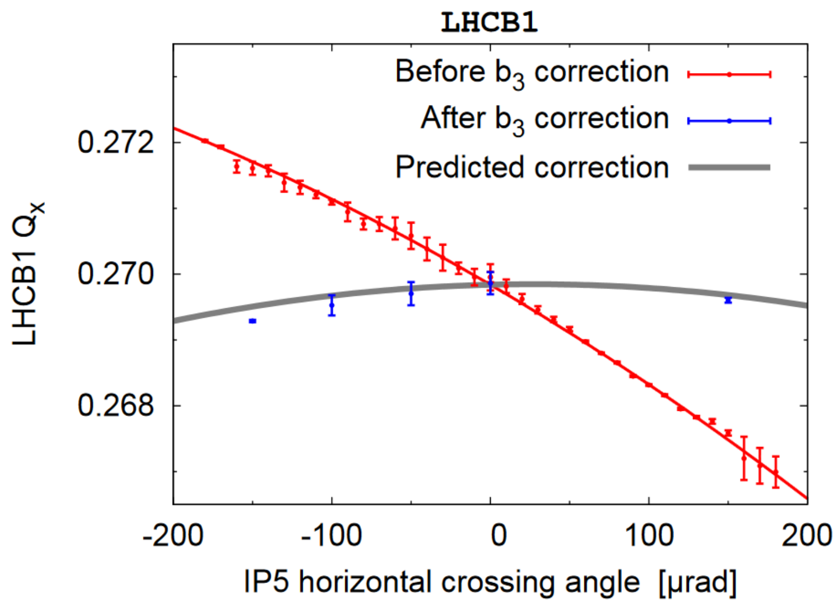
- MT phase advance measurements can also be used to probe the distribution of the sextupoles and the chromaticity correction.
- As an alternative to the Montague functions, it is possible to determine the phase advance for different dp/p settings from which the **chromatic phase advance** change wrt dp/p can be reconstructed between BPMs:

$$\frac{d\mu}{dp/p}$$

Non-linear optics correction

- Higher order field errors may need to be corrected with non-linear (NL) optics corrections.
  - The impact of low-beta quadrupole field errors may be boosted by the very large β-functions at those locations.
- NL optics measurements usually rely on scanning local orbit bumps and recording the tune, or scanning the momentum offset.
- Correction elements include sextupoles, octupoles and local NL correctors (low beta sections).

Local b3 correction for LHC low-beta section



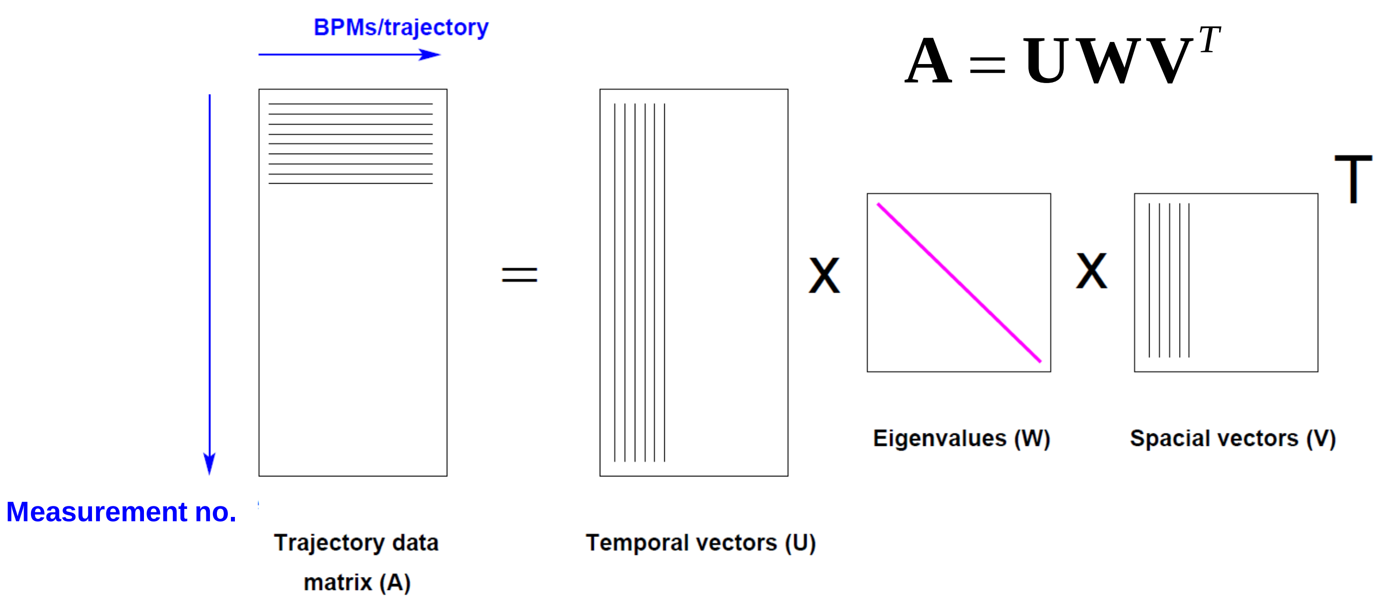
O-NL-LHC

Model Independent Analysis

- The properties of the SVD decomposition find an interesting application in **Model Independent Analysis** (MIA) and **noise filtering**.
- The idea behind MIA is to identify 'patterns' in data, in particular in time series, without using a model (at least not initially).
  - SVD is able to find main components in data series.
- Consider for example of a series of position measurements that are repeated at a certain time interval, not necessarily periodic.
  - For each measurement the beam position at N BPMs is recorded,
  - The data is stored in a matrix that is decomposed by SVD.

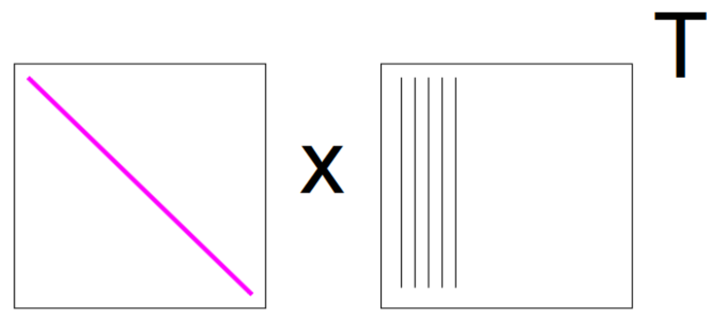
O-MIA-SLAC

$$\mathbf{A} = \mathbf{U}\mathbf{W}\mathbf{V}^T$$



Model Independent Analysis II

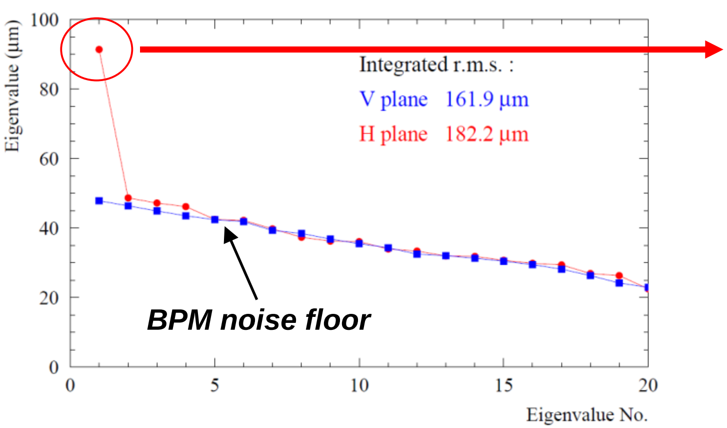
- We are interested in matrices W (eigenvalues) and V (special vectors):
  - The columns of V^T contain orthogonal patterns that are characteristic for the data set ($VV^T = V^TV = 1$).
  - The eigenvalues define the relative 'importance' of each pattern.



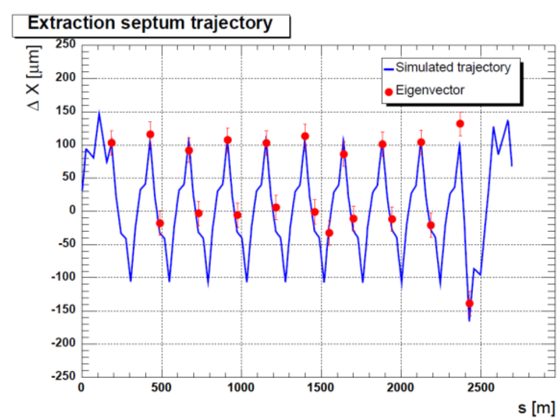
Eigenvalues (W) **Spacial vectors (V)**

- Example application to the SPS-LHC transfer line TI8.

MIA eigenvalues for trajectories



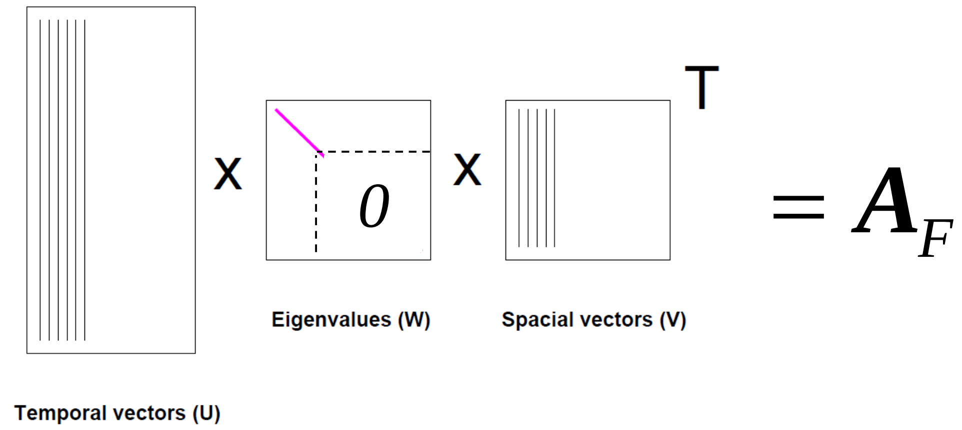
Largest MIA special eigenvector



O-MIA-TI8

A analysis of the spacial pattern with a model points to the extraction septum magnet as source (→ ripple)

- The example presented on the last slide highlights how a coherent pattern emerges from the data without need of applying a model.
- The components of matrix V are by construction orthogonal.
  - When there are multiple sources of patterns, the eigenvectors do not necessarily correspond to physical elements, but rather to linear combinations that form an orthogonal set.
  - A model is required to identify and disentangle the real physical sources.
- The same technique may also be used to apply **noise reduction** on a data set. For that purpose, after SVD, a filtered version A_F of matrix A is '*reconstructed*' using only the dominant eigenvalues and vectors.
  - This is a common technique to improve the quality of multi-turn data for optics measurements, keeping only the few dominant eigenvalues (~10) that contain the beam oscillation information.



Introduction

Orbit and dispersion

Tune and coupling

Chromaticity

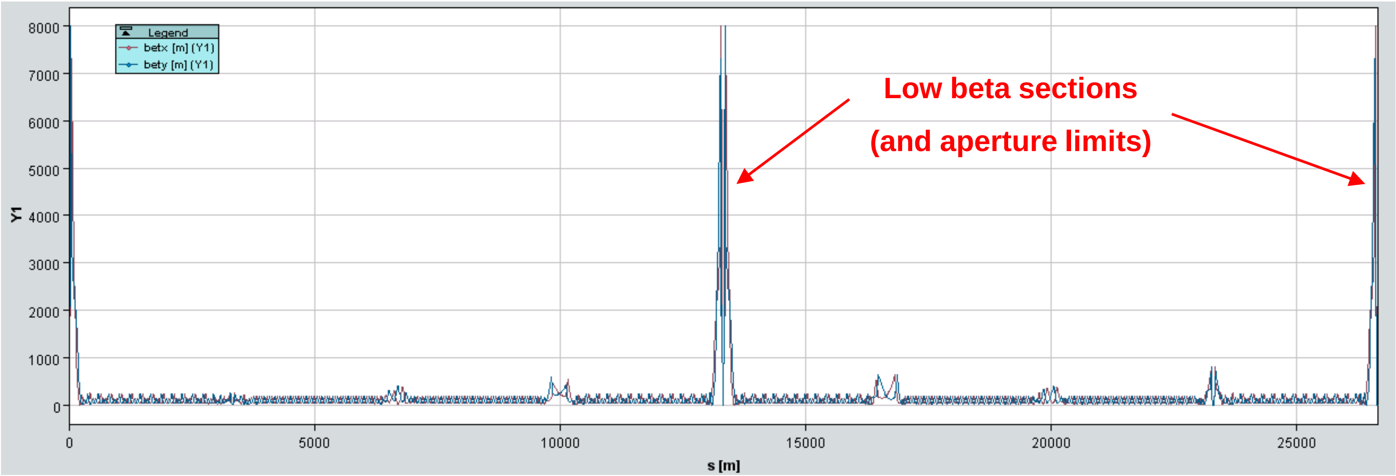
Linear and non-linear optics

Aperture

Luminosity

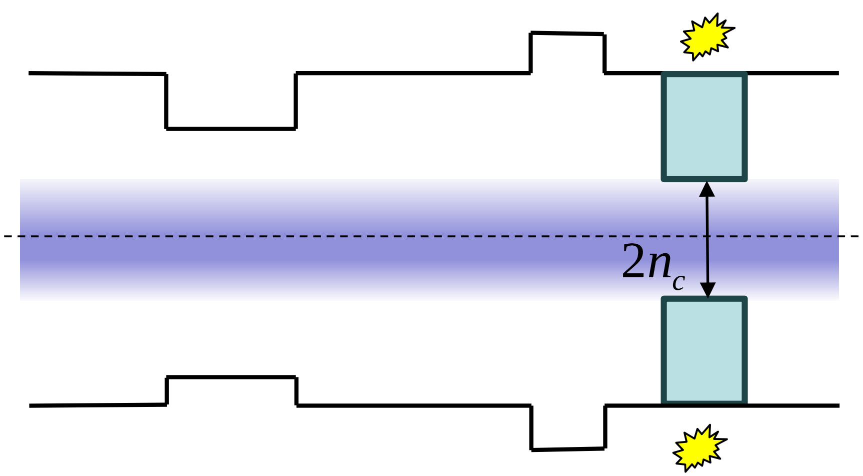
- The **mechanical aperture** of the machine is defined by the **size** and the **alignment** of the various elements and vacuum chambers of a machine.
- A good knowledge of the aperture allows to push performance, in particular for super-conducting machines where uncontrolled particle losses may lead to magnet quenches and beam aborts.
- Aperture restrictions are generally found (by design):
  - At arc superconducting magnets for hadron colliders (cost optimization),
  - In the low-beta section around the IPs where small β^* leads to peaks of the betatron function (and therefore of the beam size) in the low-beta quadrupoles.

Physics production optics of the LHC (2017, β^* = 30 cm)



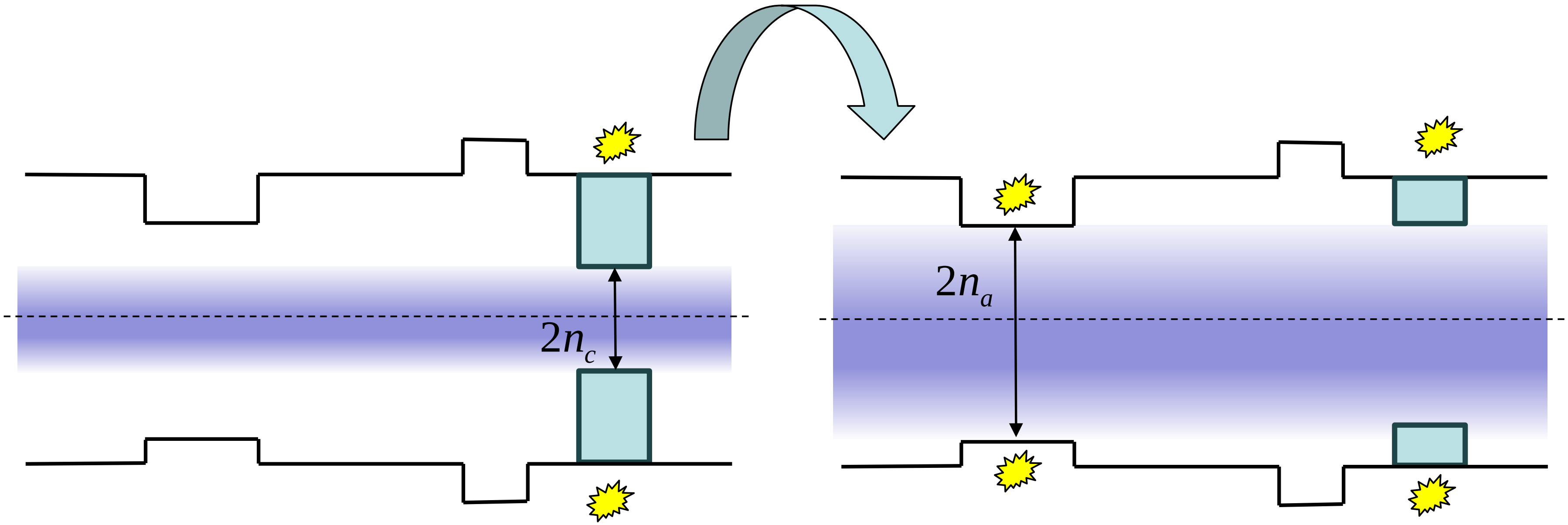
Global aperture measurement

- To determine the aperture of the machine, diagnostics based on **local loss monitors** or **global loss monitors** (beam intensity / lifetime) should be available.
- To determine a global aperture bottleneck observation of local losses is generally sufficient.
- With the help of a collimator or beam scrapper and with local loss monitors, it is possible to determine the global aperture directly in relevant units.
  - The collimator is aligned around the beam to create a well defined beam edge.
  - If the optics at the collimator is known, then the half gap of the collimator opening can be expressed in terms of beam size of $n_c\sigma$.

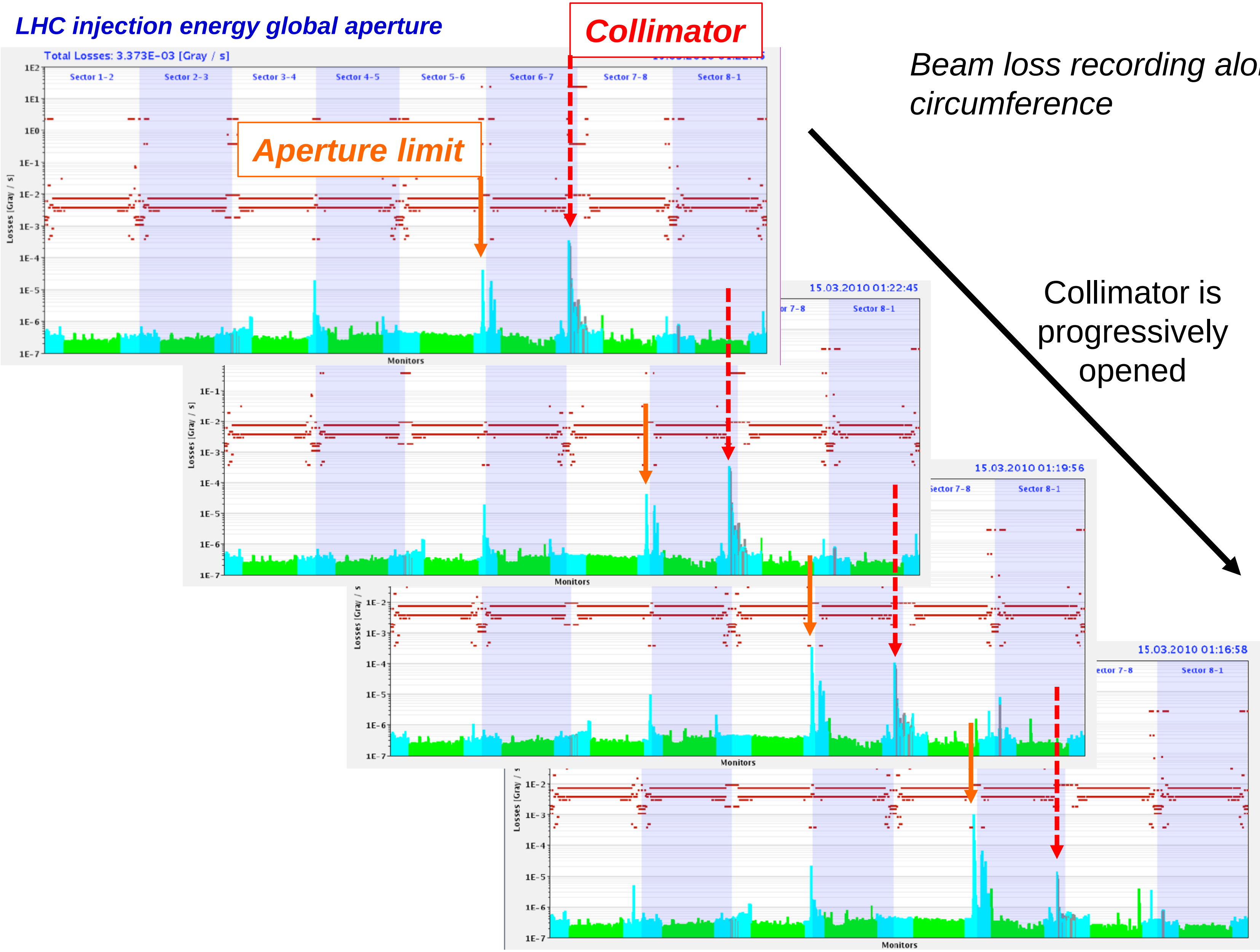


Loss location

- The collimator gap may is opened in steps until the loss location moves away from the collimator.
  - The aperture value can then be expressed in terms of beam size at the collimator.
- To ensure that the beam is filling up the space to the collimator or to the aperture limit, the beam emittance must be increased, for example by noise excitation or kicks.
  - This technique works very well for hadrons.



LHC injection energy global aperture



Beam loss recording along the circumference

Collimator is progressively opened

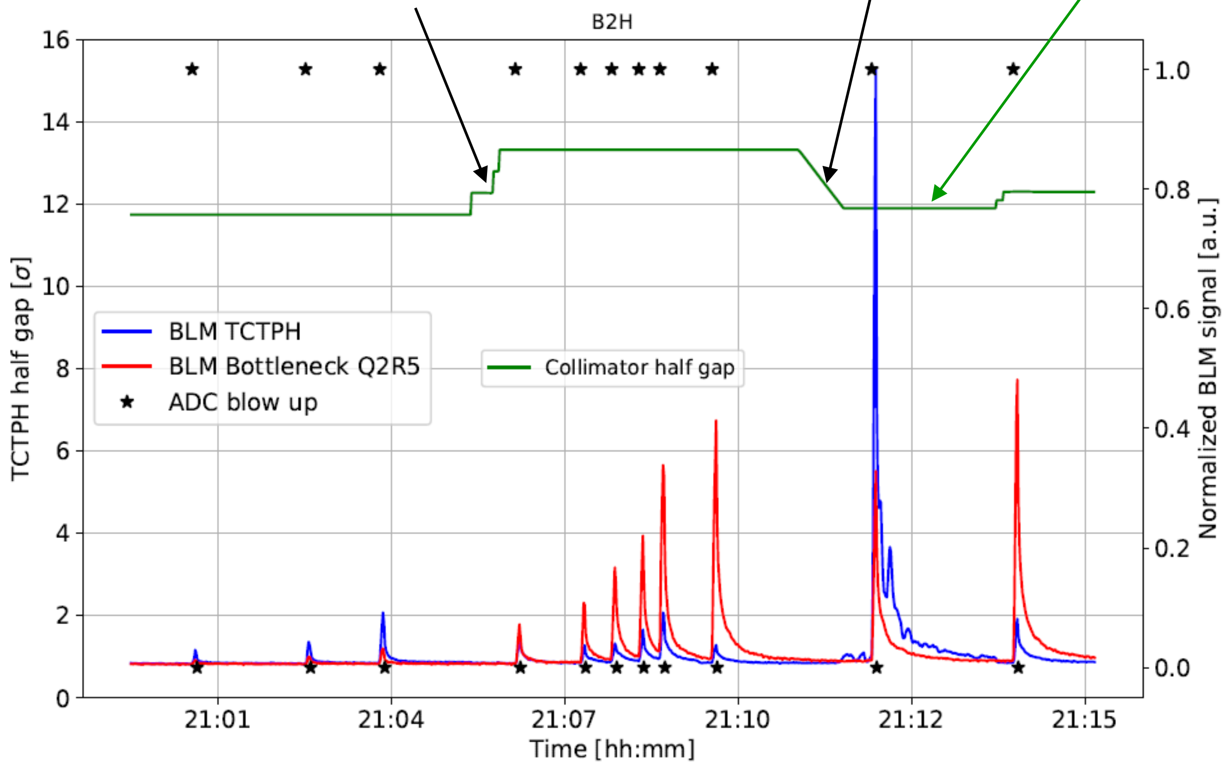
LHC global aperture measurement

A-GLOB-LHC

Collimator (blue=losses, green) is opened, losses increase at aperture bottleneck (red=losses)

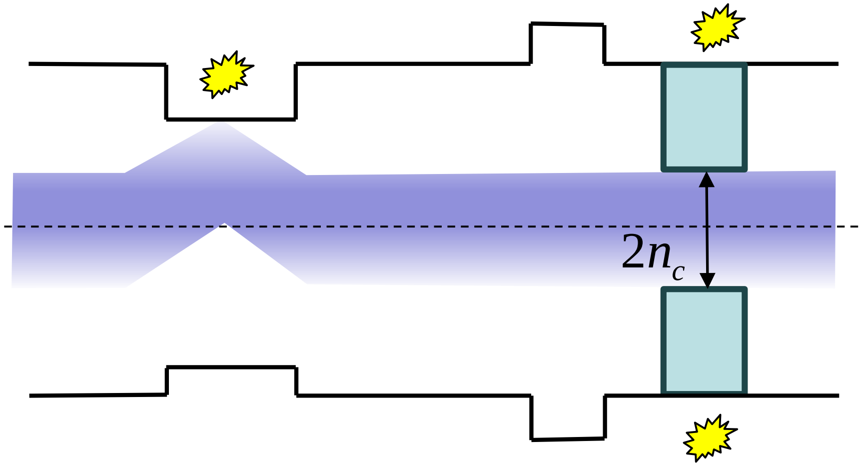
Collimator (blue=losses, green) is closed until losses at collimator dominate.

Global aperture limit



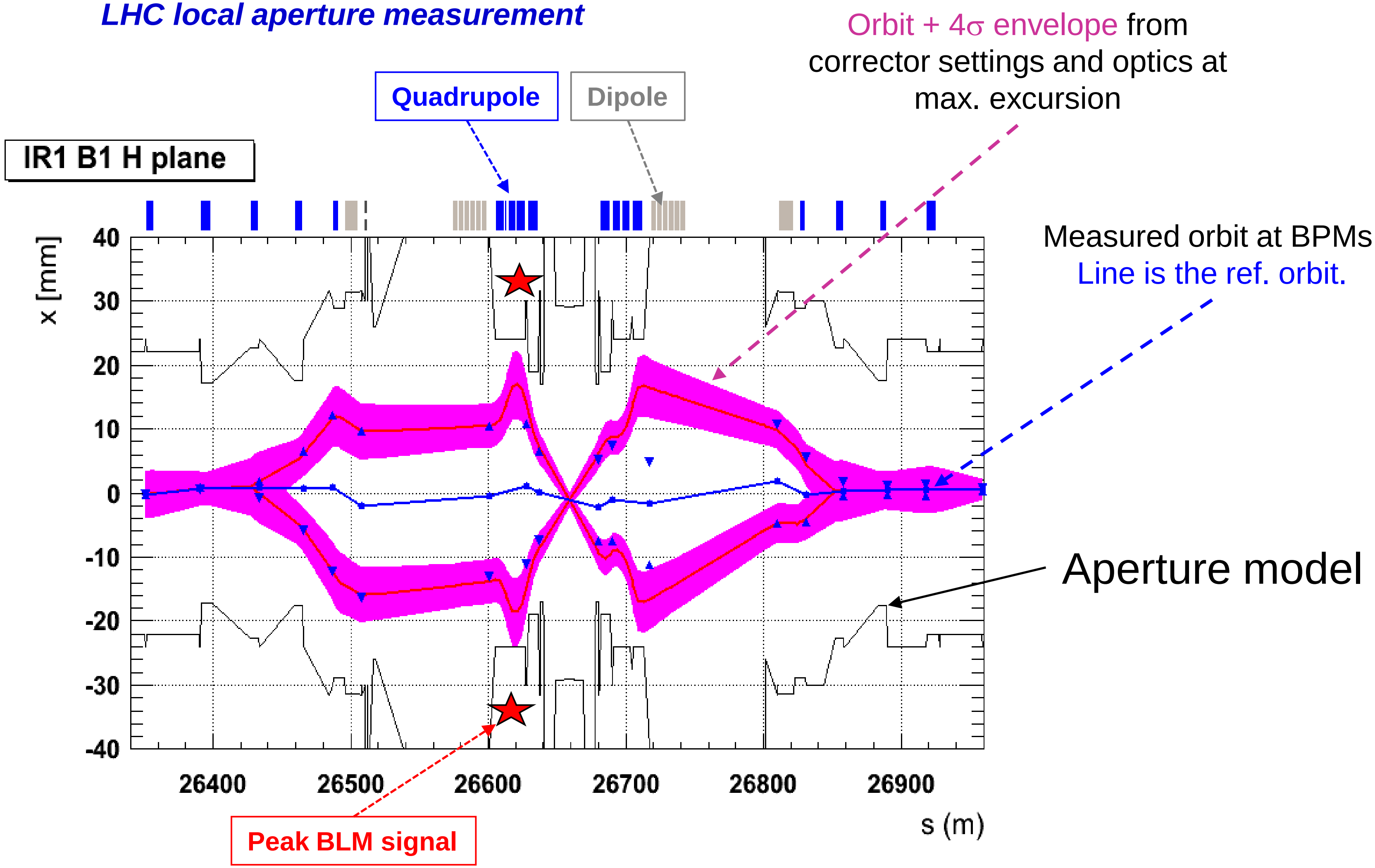
*= beam blowup (noise excitation)

- To determine a local aperture, a similar technique may be used, again with a beam edge defining collimator (if possible), coupled to a local beam movement until the losses move away from the collimator to the location that is probed.



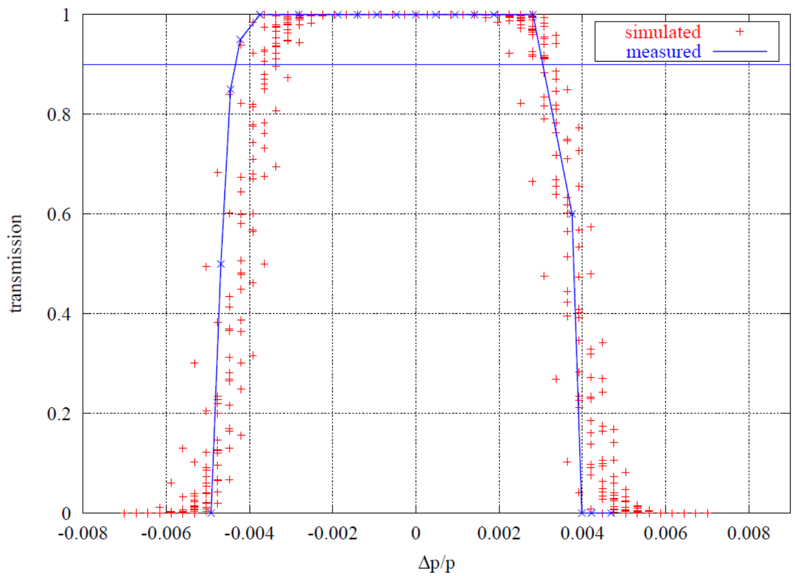
- For a linac or a transfer line, a similar technique may be used to define the global or local aperture downstream of a collimator.
- To make sense of the data an **aperture model of the machine** should be available !

LHC local aperture measurement



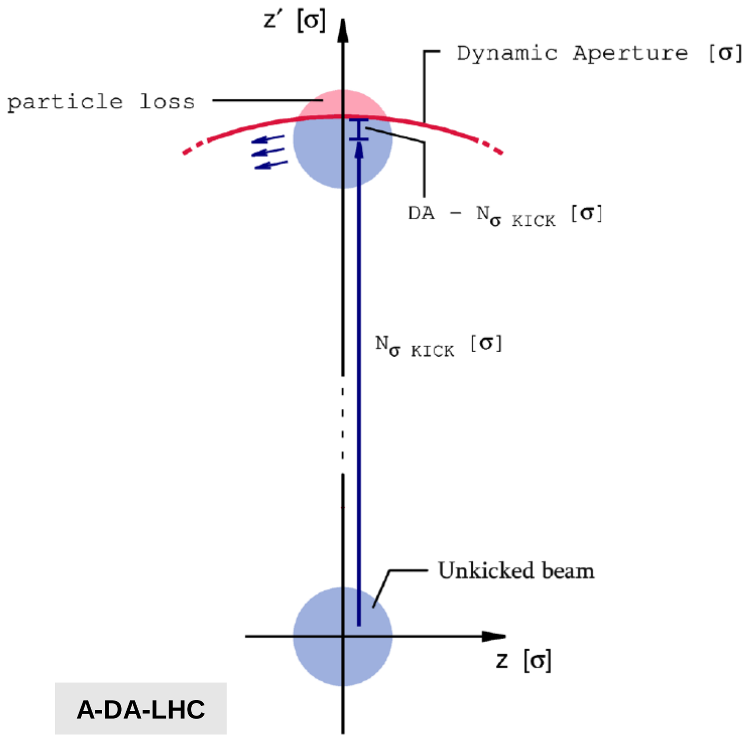
- For linacs or transfer lines, a single technique to probe the overall aperture is to measure the beam transmission as a function of:
  - Oscillation amplitudes with different betatron phases,
  - Momentum offset,
  - …

LHC injection line momentum aperture



A-DP-TI

- The **dynamic aperture (DA)** defines the maximum amplitude at which particles are stable, i.e. have a 'long' (usable) lifetime.
- The DA is defined by the machine optics and its off-momentum and non-linear properties.
  - The DA may be degraded by uncorrected field errors and non-linearities.



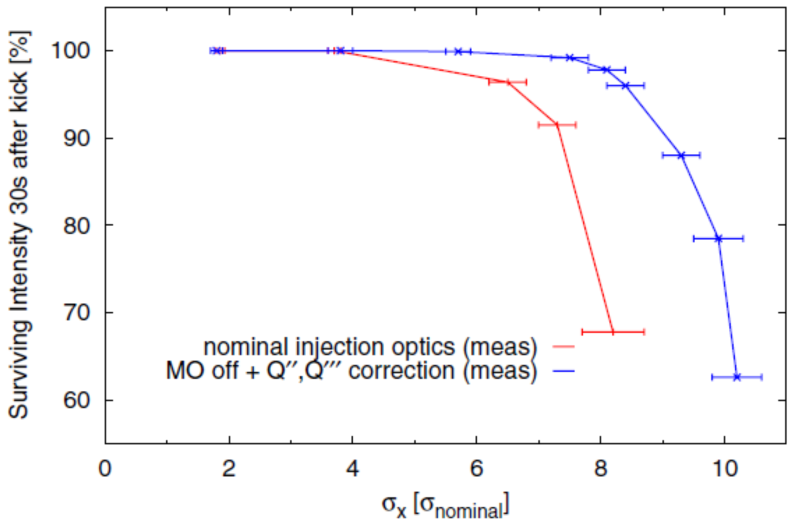
A-DA-LHC

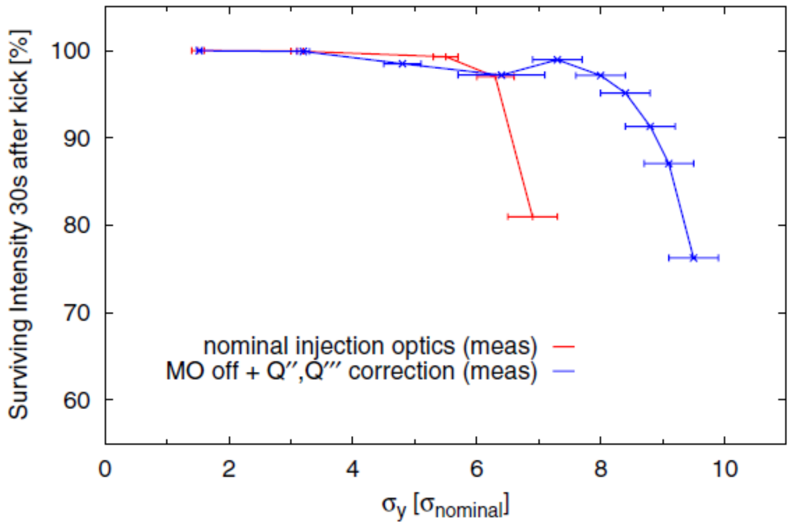
- The classical technique to measure the DA is to **kick the beam** to larger and large amplitudes until the onset of losses.
- As an alternative it is possible to blow up the beam emittance using noise until beam losses occur.
  - A measurement of the beam size cutoff (→ max emittance) gives an indication for the DA.

Dynamic aperture II

A-DA-LHC

DA measurements at the LHC (injection)





Example of DA measurement results at LHC for a nominal injection optics with powered octupoles (red) and a corrected optics (Q'' and Q''') with octupoles switched off (blue).

Introduction

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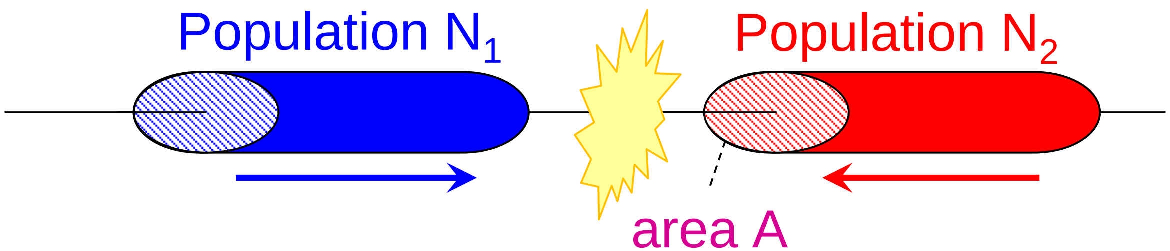
Luminosity

The key parameter for the experiments is the **event rate** ***dN/dt***. For a physics process with *cross-section* σ it is proprotional to the collider **Luminosity** L:

$$dN/dt = L\sigma$$

unit of L *:*
1/(surface × time)



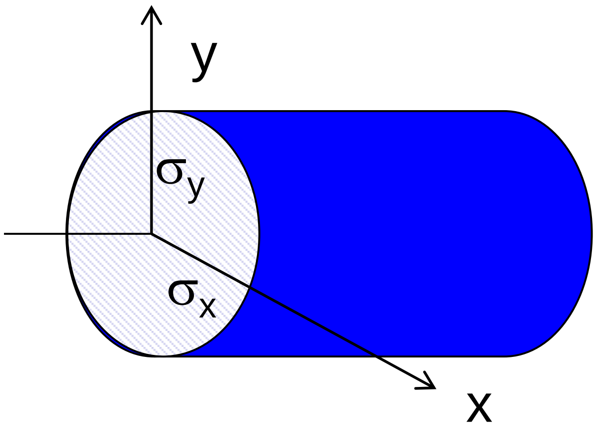
$$\text{Collision rate} \propto \underbrace{\sigma \times \frac{N1 \times N2}{A} \times \text{encounters/second}}_{L}$$

Collider luminosity

The expression for the luminosity L for equal particle populations, Gaussian profiles:

round beams

$$L = \frac{kN^2 f}{4\pi \sigma_x^* \sigma_y^*} F = \frac{kN^2 f \gamma}{4\pi \beta^* \varepsilon} F$$



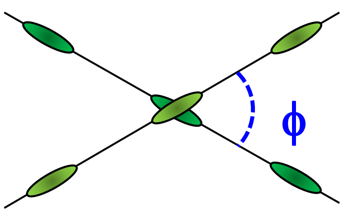
k, N, ε : beam properties

β : property of the beam optics*

F : beam dynamics

- ***σ^*_x, σ^*_y*** *: transverse rms beam sizes - $(\sigma^*)^2 = \beta^* \varepsilon$*
- ***σ_s*** *: longitudinal rms bunch length*
- ***β^* :*** *betatron (beam envelope) function ⇔ optics*
- ***ε :*** *beam emittance (phase space volume)*
- ***k*** *: number of particle packets / bunches per beam.*
- ***N*** *: number of particles per bunch.*
- ***f*** *: revolution frequency = 11.25 kHz.*
- ***F*** *: geometric correction factor (crossing angles...) :*
- ***ϕ*** *: crossing angle at the IP.*

$$\frac{1}{F} = \sqrt{1 + \left(\frac{\sigma_s}{\sigma_x} \tan\frac{\phi}{2}\right)^2}$$

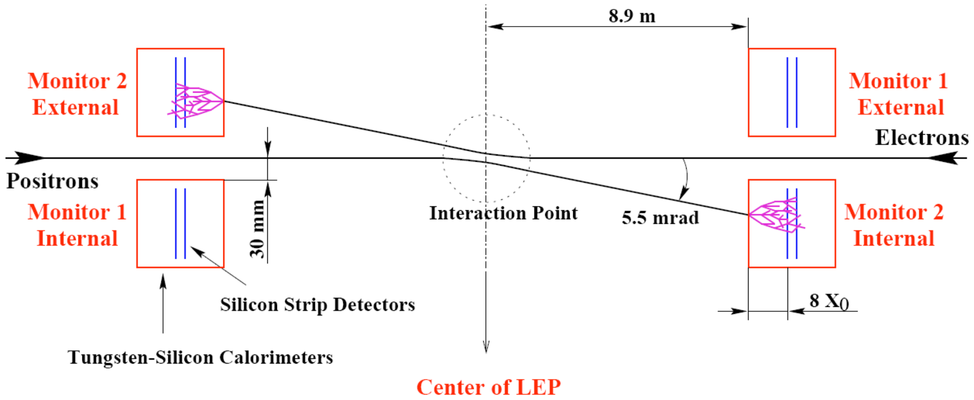


**** refers to the IP***

Collider peak luminosities

Machine	Beam type	Beam energy (GeV)	Luminosity (cm^{-2} s^{-1})
LEP I	e^+e^-	45	2×10^{30}
LEP II	e^+e^-	90-104	$\sim10^{32}$
SLC	e^+e^-	45	2.5×10^{30}
PEP-II	e^+e^-	9 and 3.1	1.2×10^{34}
KEKB	e^+e^-	8 and 3.5	2.1×10^{34}
superKEKB	e^+e^-	7 and 4	8×10^{35}
SppS	p p-bar	270	6×10^{30}
TEVATRON	p p-bar	980	2×10^{32}
RHIC	AuAu	100 (/nucleon)	$\sim10^{27}$
LHC	pp	6’500	2×10^{34}
LHC	PbPb	2’760 (/nucleon)	$\sim10^{27}$
FCC-ee	e^+e^-	45-175	2×10^{34} - 2×10^{36}
FCC-hh	pp	50’000	$\sim10^{35}$
ILC	e^+e^-	45-250	10^{34} - 10^{35}

- At e^+e^- colliders the luminosity is measured using **small angle Bhabha scattering** process $e^+e^- \rightarrow e^+e^-$.
  - At very small angle (up to 100 mrad) this is process has a well known cross section dominated by the electromagnetic force,
  - Provides high rates the smallest angles,
  - **Accuracies of 0.1% achievable** (detector alignment to then 10's of μm level !).



L-CASBI

Layout of Bhabha luminosity monitors at LEP

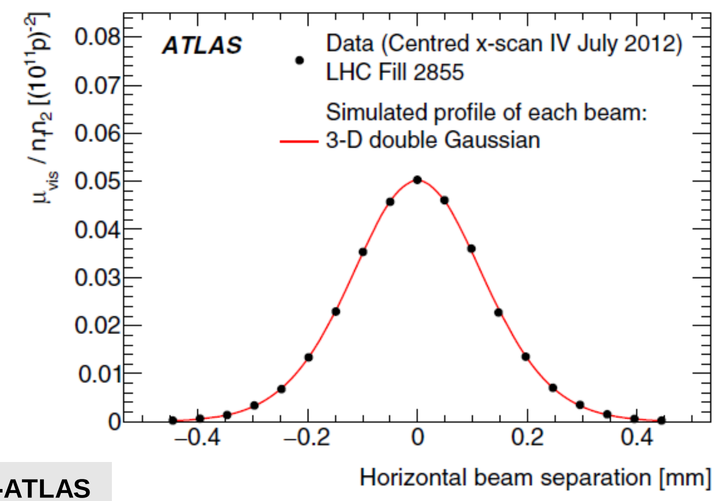
- At hadron colliders the luminosity is measured with high rate processes by event counting.
  - Cross-sections are often poorly known, complex experimental corrections for example when there is a high event pile-up (many collisions / bunch crossing),
  - Very high rates,
  - **Accuracy of ~1% achievable** when coupled to Van de Meer scan techniques.

Luminosity optimization

- To optimize the **beam overlap** for circular colliders, the beams are scanned across each other and the event rate is recorded.
  - A fit to the (typically Gaussian) shape provides the optimum head-on position, as well as the convoluted beam size at the IP.
  - The scan must be performed for both planes.
- For equal sized beams, the luminosity dependence on the beam separations $\Delta x(y)$ is given by:

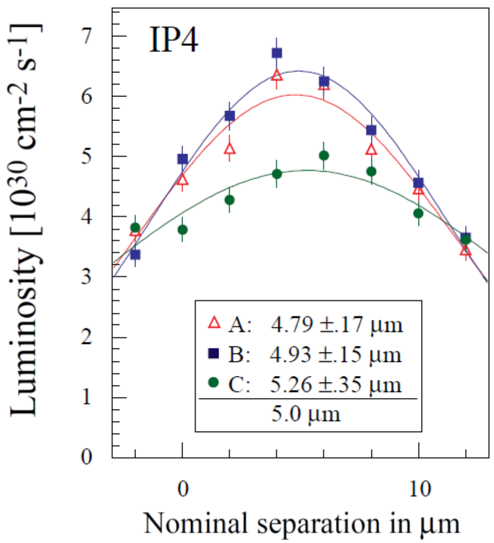
$$L = \frac{kN_1N_2f}{4\pi\sigma_x\sigma_y}\exp\left\{-\frac{\Delta x^2}{4\sigma_x^2}-\frac{\Delta y^2}{4\sigma_y^2}\right\} = L_0\exp\left\{-\frac{\Delta x^2}{4\sigma_x^2}-\frac{\Delta y^2}{4\sigma_y^2}\right\}$$

Luminosity optimization at LHC



L-VDM-ATLAS

Luminosity optimization at LEP



A,B,C label bunches in a train

L-CASBI

Van de Meer scans

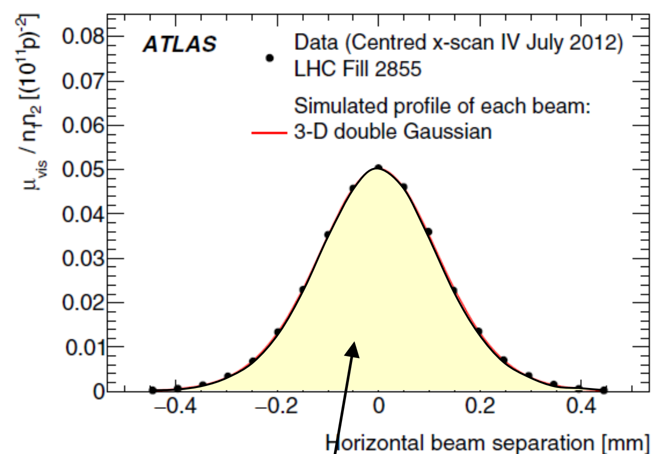
- The **Van de Meer scan** is a variant of a luminosity scan that provides an absolute measurement of the luminosity, introduced by S. van de Meer at the CERN Intersecting Storage Rings (ISR).

L-VDM

- The concept is based on the observation that the event rate (~ L) is given by:

$$\dot{N}(\Delta x, \Delta y) = \dot{N}_0 \exp\left\{-\frac{\Delta x^2}{4\sigma_x^2} - \frac{\Delta y^2}{4\sigma_y^2}\right\} \Rightarrow \begin{array}{l} \int \dot{N}(\Delta x, \Delta y = 0)\, d(\Delta x) = \dot{N}_0 \sqrt{4\pi}\,\sigma_x \\ \int \dot{N}(\Delta x = 0, \Delta y)\, d(\Delta y) = \dot{N}_0 \sqrt{4\pi}\,\sigma_y \end{array}$$

$$\Rightarrow \quad \frac{\dot{N}_0}{\int \dot{N}(\Delta x, \Delta y = 0)\, d(\Delta x)} = \sqrt{4\pi}\,\sigma_x \qquad \frac{\dot{N}_0}{\int \dot{N}(\Delta x = 0, \Delta y)\, d(\Delta y)} = \sqrt{4\pi}\,\sigma_y$$



Ratio of peak to area measures the beam size !

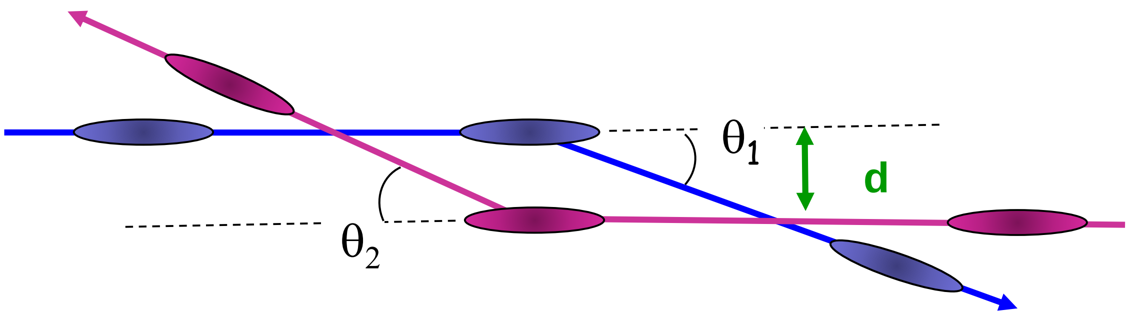
- The beam sizes can be extracted without the need of an absolute 'rate' scale, only the x,y scales must be known accurately !
- If in addition the **bunch populations are measured accurately**, it is possible to obtain the **absolute luminosity** from such scans.
  - At LHC the errors on ***L* are ~ 1-2%**.

L-CASBI

L-VDM-REV

Beam-beam deflection

- An alternative to the luminosity measurement for beam optimization at an IP is the **beam-beam deflection scan**, in particular for linear colliders.
  - Rely on shape of the beam-beam deflection to determine the optimum beam overlap.
  - Beam positon monitors on each side of the IP are used to reconstruct the deflection angles θ_1, θ_2 (and / or $\theta_1+\theta_2$).



Focusing lens for e^+e^-

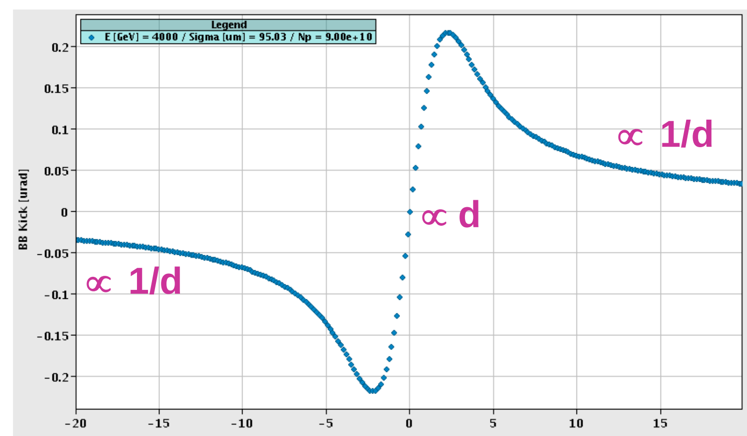
Defocusing lens for pp

- For round beams the deflection is given by:

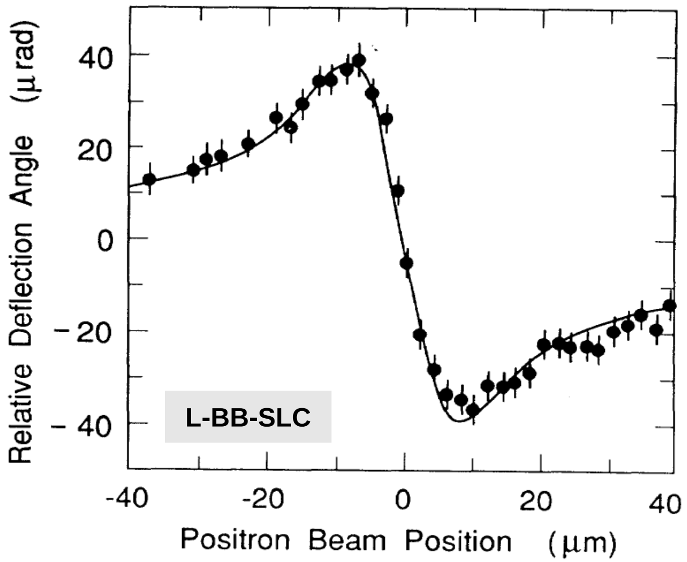
$$\theta_1(d)+\theta_2(d)=\theta_{BB}(d)=\pm\frac{4Nr_{p(e)}}{d\,\gamma}\left(e^{-d^2/4\sigma^2}-1\right)$$

$r_{p(e)}$: classical radius of the proton (electron)

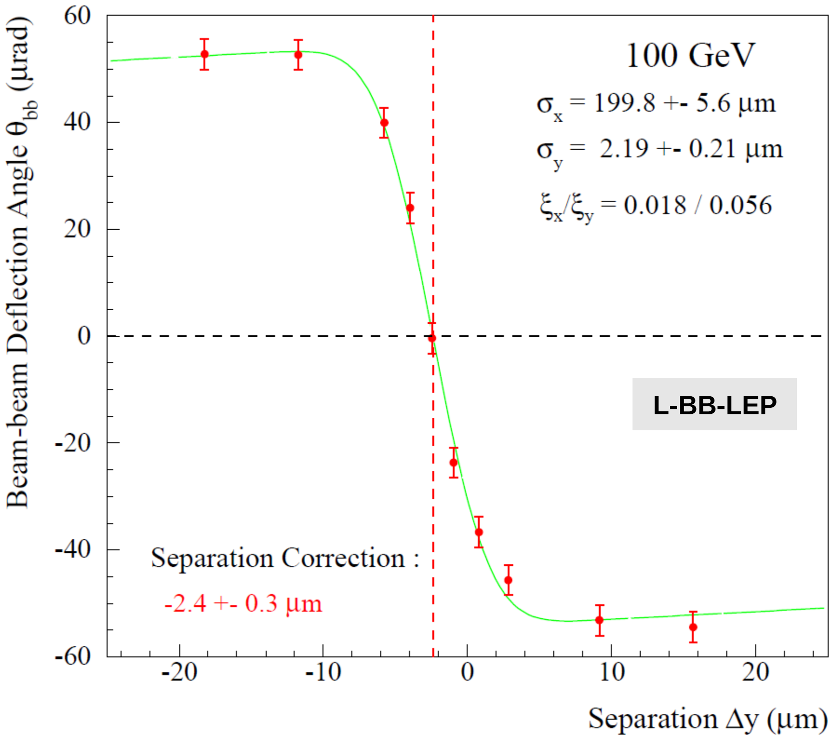
The sign (±) depends on the relative beam charge (- for pp, + for e^+e^-)



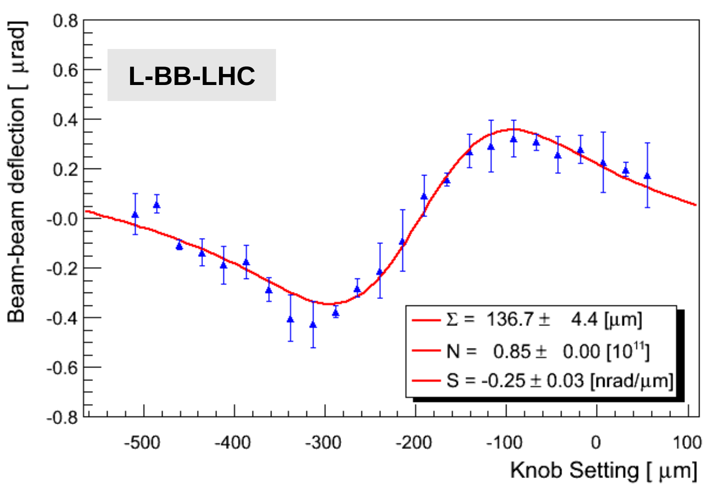
e+ BB deflection scan at SLC



Vertical BB deflection scan at LEP



BB deflection observation at LHC



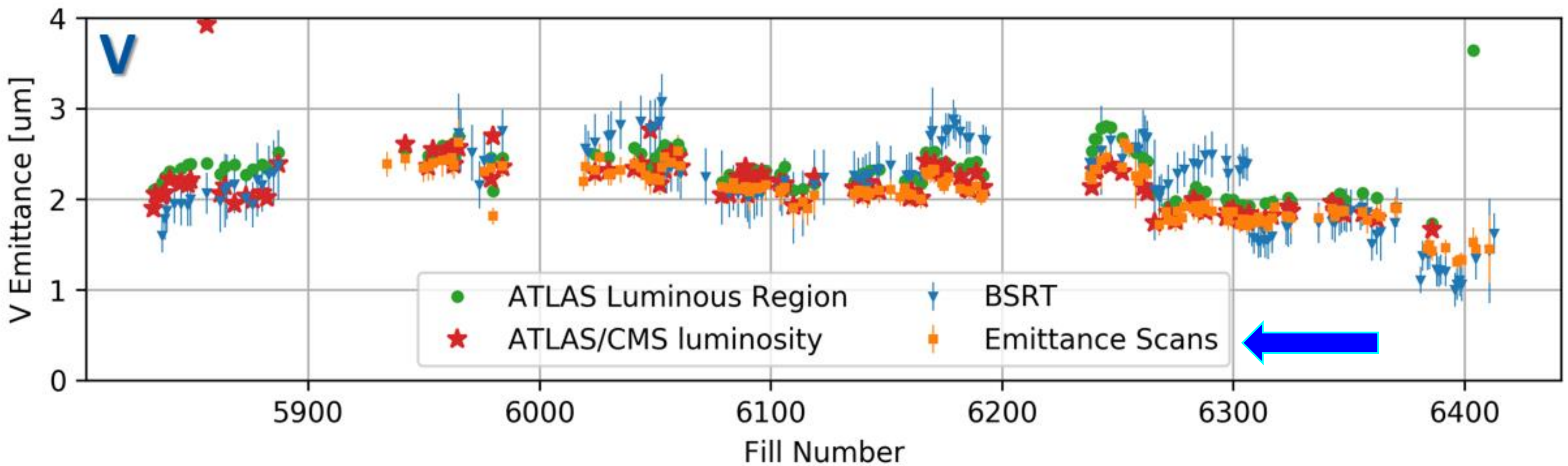
*Note the difference in **deflection scale** of ~100 between SLC/LEP and LHC due to much **larger beam-beam tune shift** ξ and **smaller** β^*. The slope of the BB deflection is:*

$$\frac{d\theta_{bb}}{du}(\theta_{bb}=0) = -\frac{4\pi\xi}{\beta^*}$$

Beam sizes and emittances

- Both BB deflection and beam overlap / VDM scans provide diagnostics on the **convoluted transverse sizes** of the two colliding beams.
  - In the equations presented previously equal sizes were assumed for both beams.
- Combined with the knowledge of the IP β-function (β*) of both beams, the **emittance** of the beams may be deduced in each plane.
  - In the presence of dispersion at the IP the energy spread will also play a role.
  - Beware of **dynamic β-function changes** due to the **beam-beam force**.
    - For hadron colliders this is a % level effect, for e^+e^- colliders with very large beam-beam tune shifts the correction may be > 10% !

Vertical beam emittance evolution at LHC



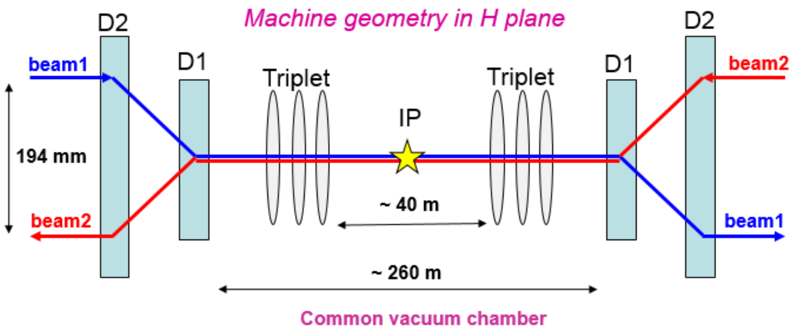
BSRT = synchrotron radiation diagnostics

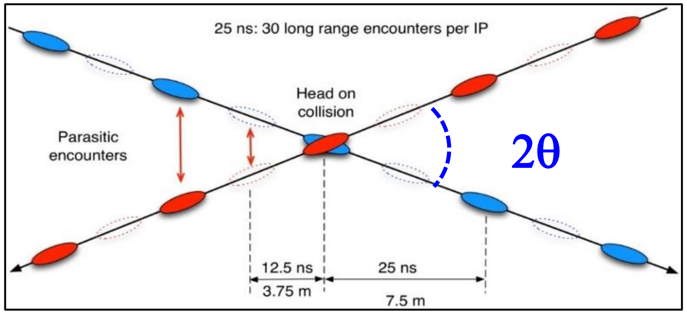
Emittance scan = beam over lap scan

Long range beam-beam

- **Long range (LR) beam-beam** effects appear when the counter-rotating beams are subject long distance encounters (without colliding).
  - Typically in vacuum chambers around experiments where the beams 'see each other'.
- Since high luminosity colliders operate with **many closely spaced bunches** a large **number of such long distance encounters** can add up to impact the beam dynamics: **orbit, tunes, chromaticities**.
  - Bunch-by-bunch differences appear due to varying encounter patterns.

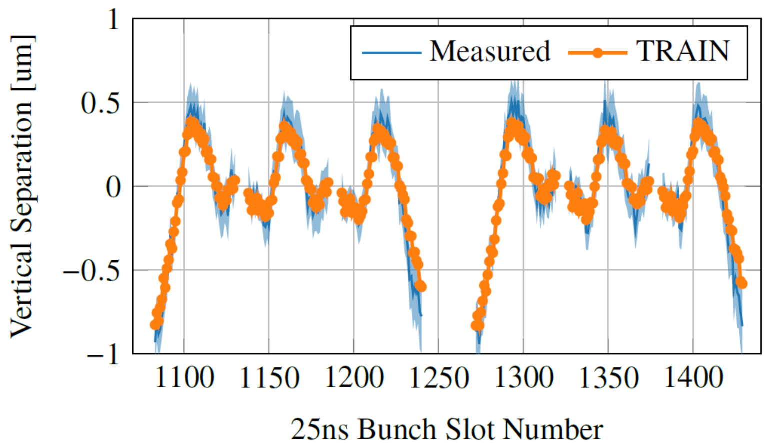
Layout of the LHC interaction region





*The two LHC beams cross at an angle and share a **common vacuum chamber over ~ 200 m** (bunch distance is **7.5 m** only).*

Differences in LR encounters along the bunch trains lead for example to orbit differences following a characteristic pattern – see below.



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