CERN Summer School 2017
Introduction to Accelerator Physics

Part IV

by
Verena Kain CERN BE-OP

Many thanks to G. Rumolo and K. Li for material

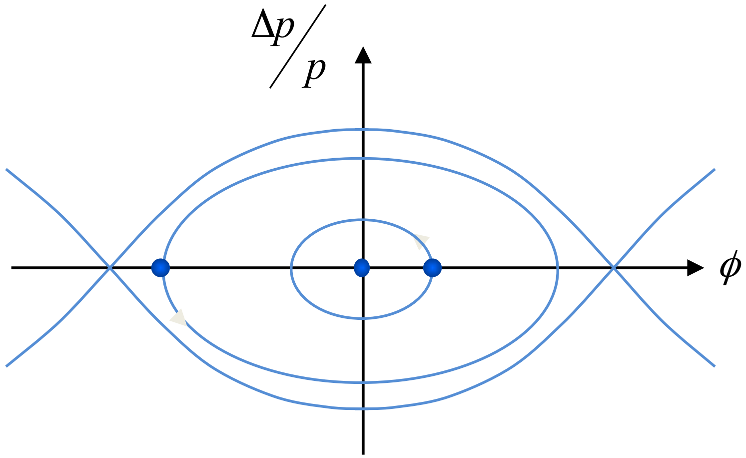
What's next?

- Imperfections, collective effects
- Electron Cloud effect

Reminder from last lecture

RF acceleration in a synchrotron

Beam has distribution in momentum. Momentum spread needs to fit into ***RF bucket.***



RF buckets: number of RF buckets around the ring = h

$$\omega_{RF} = h\omega_{rev}$$

Synchrotron motion

$$\frac{d^2\Delta\phi}{dt^2} + \frac{\eta\cdot f_{RF}}{R\cdot p_s} q\cdot V(\sin\phi - \sin\phi_s) = 0$$

Transverse-longitudinal coupling

$$\begin{pmatrix} D_x \\ D'_x \end{pmatrix} = \frac{d}{d(dp/p)} \begin{pmatrix} x \\ x' \end{pmatrix} = \beta_0 \frac{d}{d\delta} \begin{pmatrix} x \\ x' \end{pmatrix}$$

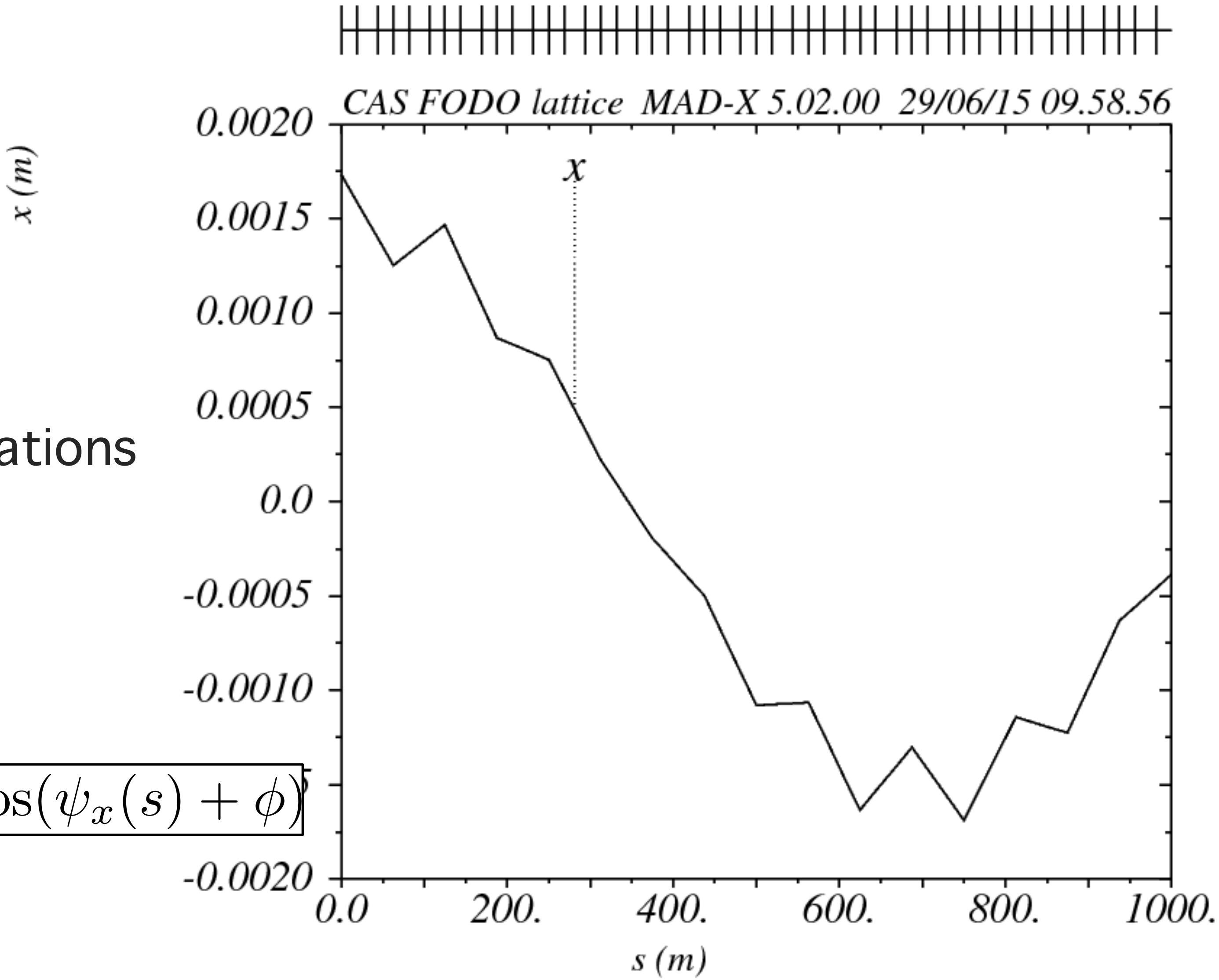
Reminder: The trajectory around the ring

Where as the beta functions are several 100 m

The trajectories are in ~ mm

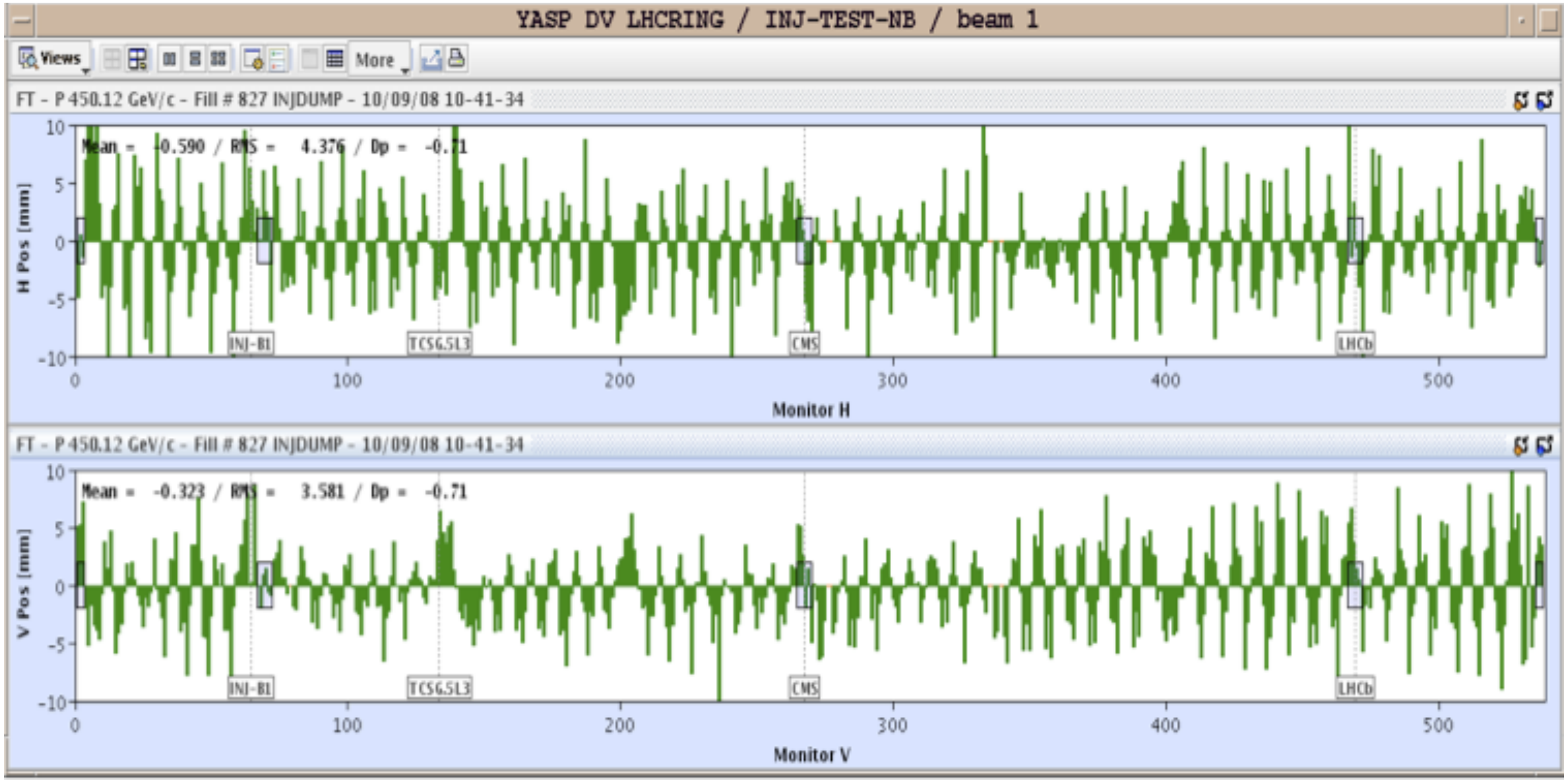
The number of oscillations around the ring is less than 1.

$$x(s) = \sqrt{2J_x\beta_x(s)}\cos(\psi_x(s)+\phi)$$



LHC example

Tunes $Q_x = 64.28$, $Q_y = 59.31$



Reminder: The Tune

The number of oscillations per turn is called “tune”

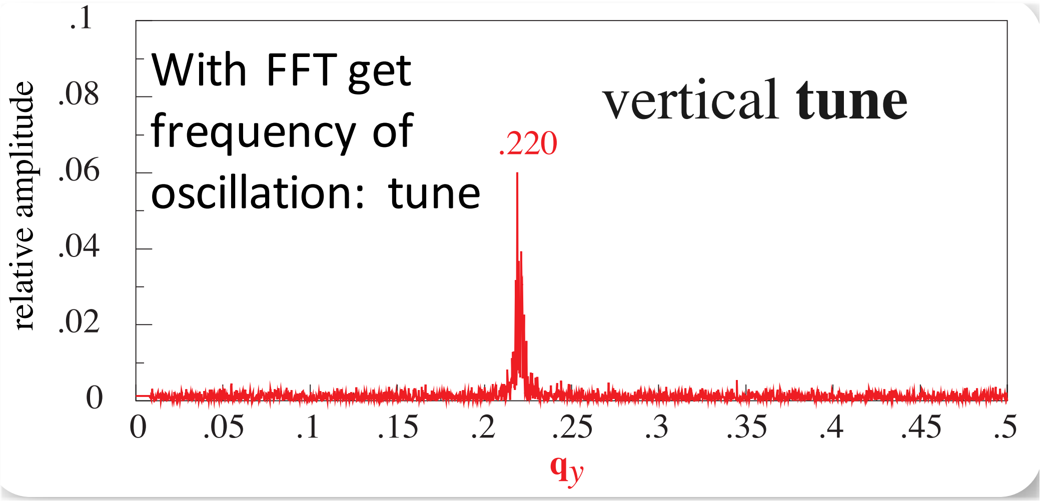
$$Q = \frac{\psi(L_{turn})}{2\pi} = \frac{1}{2\pi} \oint \frac{ds}{\beta(s)}$$

The tune is an important parameter for the stability of motion over many turns.

It has to be chosen appropriately, measured and corrected.

Measure beam position at one location turn by turn

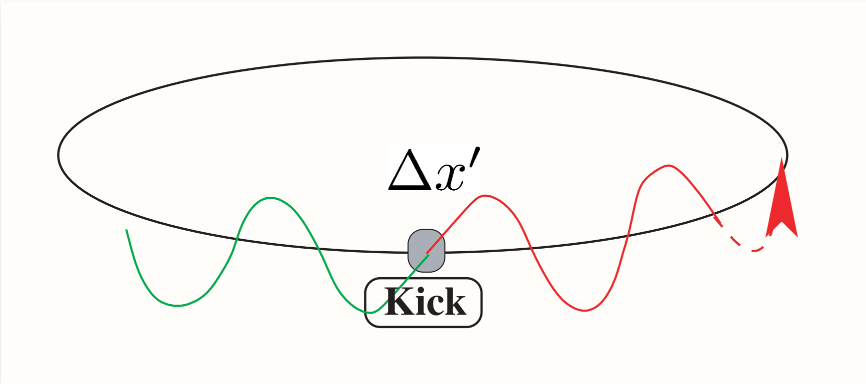
Beam position will change with $\propto \cos(2\pi Q i)$



The Tune

The choice of phase advance per cell or tune and hence the focusing properties of the lattice have important implications.

Misalignment of quadrupoles or dipole field errors create orbit perturbations



The perturbation at one location has an effect around the whole machine

$$\begin{pmatrix} x \\ x' - \Delta x' \end{pmatrix} = M_{turn} \cdot \begin{pmatrix} x \\ x' \end{pmatrix}$$

$$x(s) = \frac{\Delta x'}{2} \cdot \sqrt{\beta(s_0)\beta(s)} \frac{\cos(\pi Q - \psi_{s_0 \to s})}{\sin(\pi Q)}$$

➔ diverges for Q = N, where N is integer.

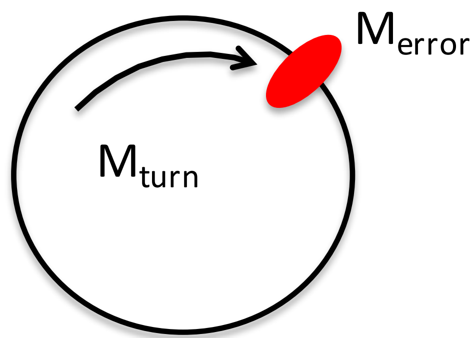
Gradient Error

What happens if there is an error in the quadrupole field?

Assume at one location in the ring quadrupole error of Δk over a distance l.

The effect on the focusing properties: the distorted one-turn matrix

$$M_{dist} = M_{error} \cdot M_{turn}$$



Remember: can write M from s_0 to s as function of β, α and ψ.

$$M = \begin{pmatrix} \sqrt{\frac{\beta}{\beta_0}}(\cos\psi + \alpha_0 \sin\psi) & \sqrt{\beta\beta_0}\sin\psi \\ \frac{(\alpha_0-\alpha)\cos\psi-(1+\alpha\alpha_0)\sin\psi}{\sqrt{\beta\beta_0}} & \sqrt{\frac{\beta_0}{\beta}}(\cos\psi - \alpha\sin\psi)) \end{pmatrix}$$

Gradient Error

$$M = \begin{pmatrix} \sqrt{\frac{\beta}{\beta_0}}(\cos\psi + \alpha_0 \sin\psi) & \sqrt{\beta\beta_0}\sin\psi \\ \frac{(\alpha_0-\alpha)\cos\psi-(1+\alpha\alpha_0)\sin\psi}{\sqrt{\beta\beta_0}} & \sqrt{\frac{\beta_0}{\beta}}(\cos\psi - \alpha\sin\psi)) \end{pmatrix}$$

One-turn matrix: $\psi_{turn} = 2\pi Q$

$$M_{turn} = \begin{pmatrix} \cos 2\pi Q + \alpha \sin 2\pi Q & \beta \sin 2\pi Q \\ -\gamma \sin 2\pi Q & \cos 2\pi Q - \alpha \sin 2\pi Q \end{pmatrix}$$

$$M_{dist} = M_{error} \cdot M_{turn}$$

Assuming a small error over a short length:

$$M_{error} = \begin{pmatrix} \cos(\sqrt{k}s) & \frac{1}{\sqrt{k}}\sin(\sqrt{k}s) \\ -\sqrt{k}\sin(\sqrt{k}s) & \cos(\sqrt{k}s) \end{pmatrix} \rightarrow \begin{pmatrix} 1 & 0 \\ -\Delta kl & 1 \end{pmatrix}$$

Gradient Error

The new one-turn matrix:

$$M_{turn_{dist}} = \begin{pmatrix} \cos 2\pi Q + \alpha \sin 2\pi Q & \beta \sin 2\pi Q \\ -\gamma \sin 2\pi Q & \cos 2\pi Q - \alpha \sin 2\pi Q \end{pmatrix} =$$

$$= \begin{pmatrix} 1 & 0 \\ -\Delta kl & 1 \end{pmatrix} \cdot \begin{pmatrix} \cos 2\pi Q_0 + \alpha \sin 2\pi Q_0 & \beta \sin 2\pi Q_0 \\ -\gamma \sin 2\pi Q_0 & \cos 2\pi Q_0 - \alpha \sin 2\pi Q_0 \end{pmatrix}$$

With $Q = Q_0 + \Delta Q$, ΔQ small and $\mathrm{Trace}(M_{dist}) = \mathrm{Trace}(M_{error}.M_{turn})$:

$$\Delta Q = \frac{1}{4\pi} \beta \Delta k \cdot l$$

β at the error location

The quadrupole error leads to a tune change. The higher the β, the higher the effect.

And also a change of the beta functions.

Gradient Error

A gradient error also leads to changes of the beta functions: beta-beat

The relative beta function change:

$$\frac{\Delta\beta(s)}{\beta(s)} = -\frac{1}{2\sin 2\pi Q}\beta(s_0)\cos[2(\psi(s_0)-\psi(s)) - 2\pi Q]\cdot\Delta k\cdot l$$

➔ diverges for Q = N, N/2; where N is integer.

Linear and Non-linear Imperfections - Resonances

Amplitudes grow for Q = N or N/2 in case of quadrupole error

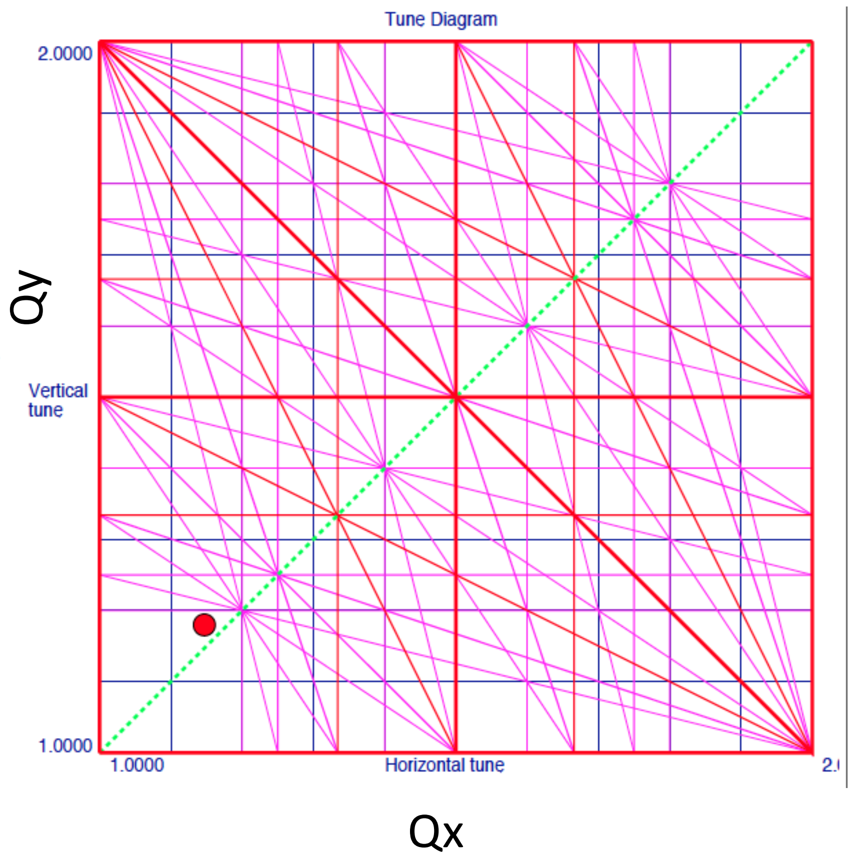
Sextupole perturbation: Q = N or N/3

Octupole perturbation: Q = N, N/2, N/4 etc.

In general: avoid small integers n,m, N where

$$nQ_x + mQ_y = N$$

Working point has to be carefully chosen!!



The effect of non-linear fields

Non-linear equation of motion:

$$\frac{d^2 x}{ds^2} + K(s) \cdot x = \frac{F_x}{v \cdot p}$$

The Lorentz force from the non-linear magnetic field

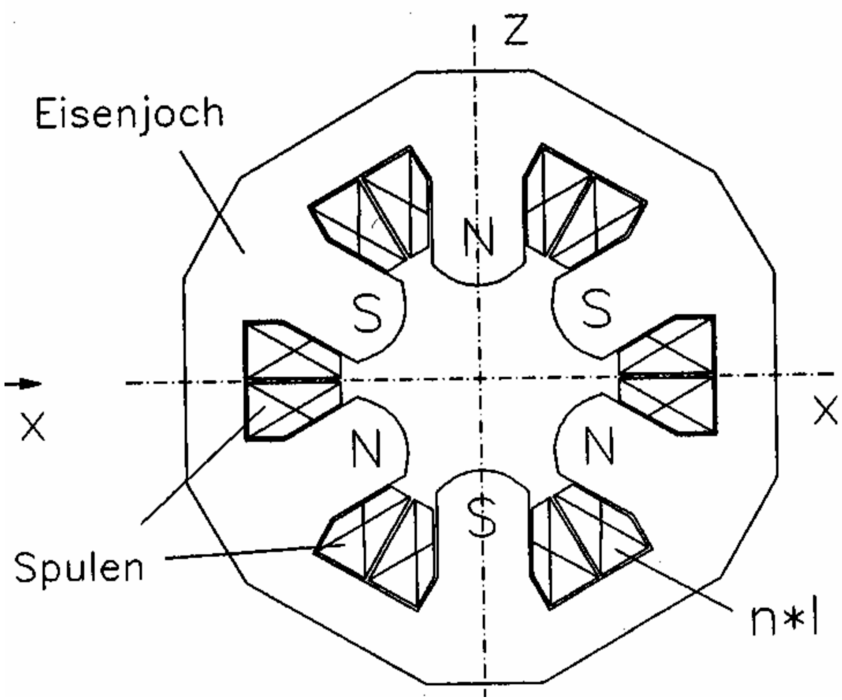
The magnetic field of multipole order n:

$$B_y(x,y) + i \cdot B_x(x,y) = (B_n(s) + iA_n(s)) \cdot (x+iy)^n$$

The normal and skew coefficients:

$$B_n(s) = \frac{1}{(n)!} \frac{\partial^n B_y}{\partial x^n} \qquad A_n(s) = \frac{1}{(n)!} \frac{\partial^n B_x}{\partial x^n}$$

Example: sextupole



$$B_x = \tilde{g}xy$$
$$B_y = \frac{1}{2}\tilde{g}(x^2 - y^2)$$

$$\Downarrow$$

$$\frac{\partial B_x}{\partial y} = \frac{\partial B_y}{\partial x} = \tilde{g}x$$ Linear rising "gradient"

The equations of motion become:

$$x'' + K_x(s) = -\frac{1}{2}m_{sext}(s)(x^2 - y^2)$$
$$y'' + K_y(s) = m_{sext}(s)xy$$

Effect of sextupoles on phase-space

Sextupoles create non-linear fields.

Depending on the tune the phase-space becomes more and more distorted. Motion becomes unstable close to the third order resonance.

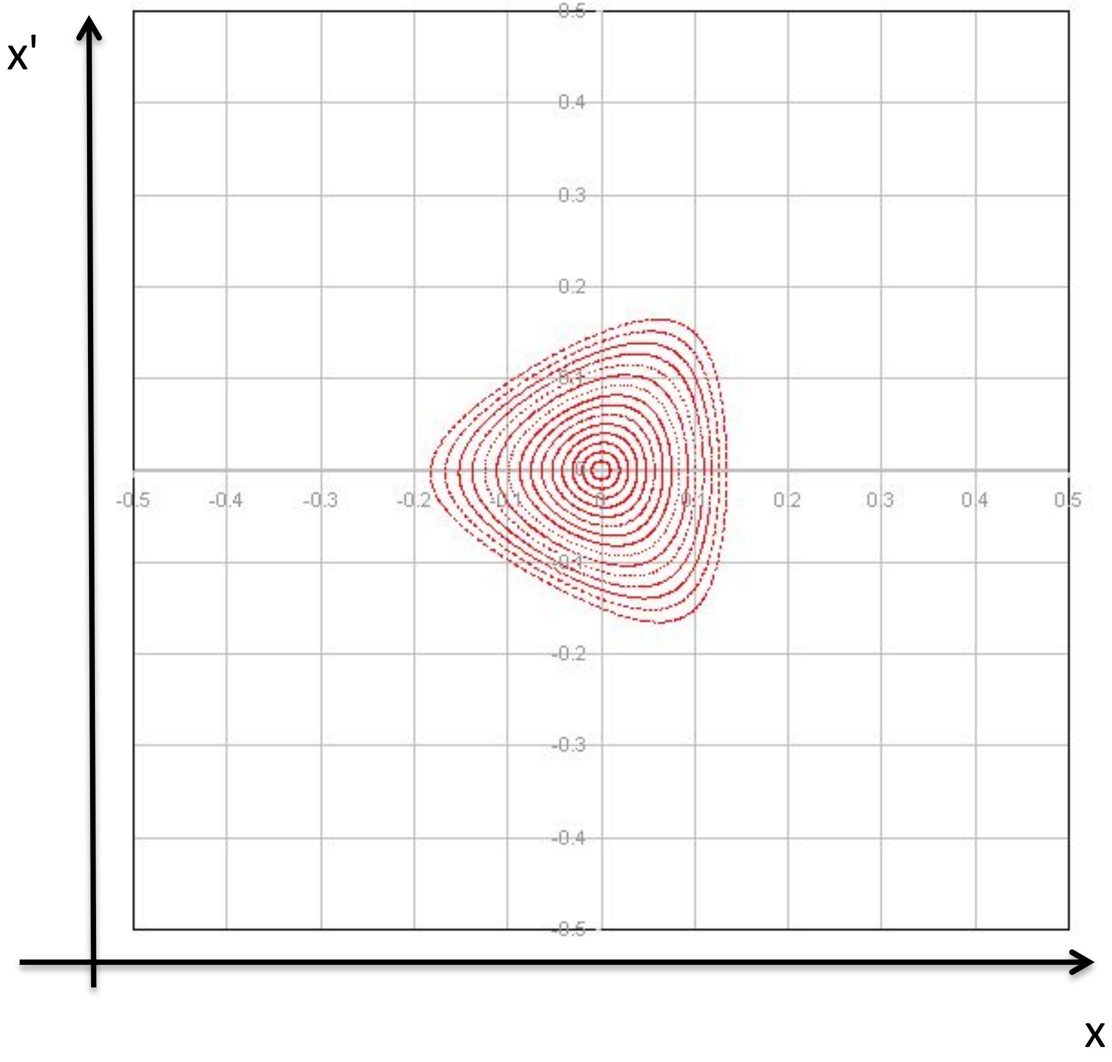
The sextupole kicks:

$$\Delta x' = -\frac{1}{2} m_{sext} l (x^2 - y^2)$$

$$\Delta y' = m_{sext} l x y$$

Amplitude of separatrix (unstable fixed points):

$$\propto \frac{Q - \frac{p}{3}}{m_{sext}}$$



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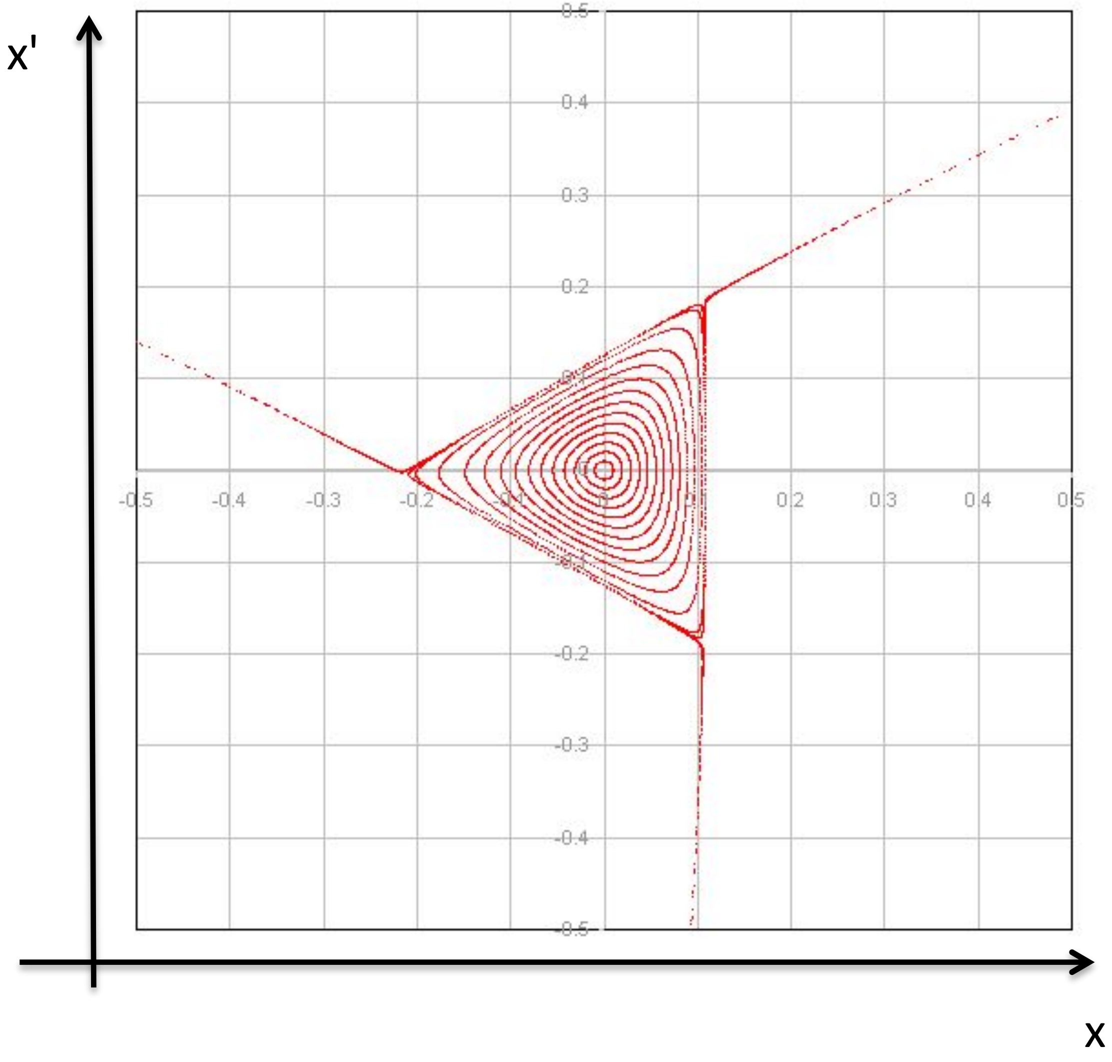


Chromaticity

The normalized quadrupole gradient is defined as

$$k = \frac{g}{p/e} \qquad\qquad p = p_0 + \Delta p$$

$$k = \frac{eg}{p_0 + \Delta p} \approx \frac{e}{p_0}\left(1 - \frac{\Delta p}{p_0}\right) g = k_0 + \Delta k$$

$$\Delta k = -\frac{\Delta p}{p_0} k_0$$

...a gradient error. Particles with different $\Delta p/p$ will have different tunes.

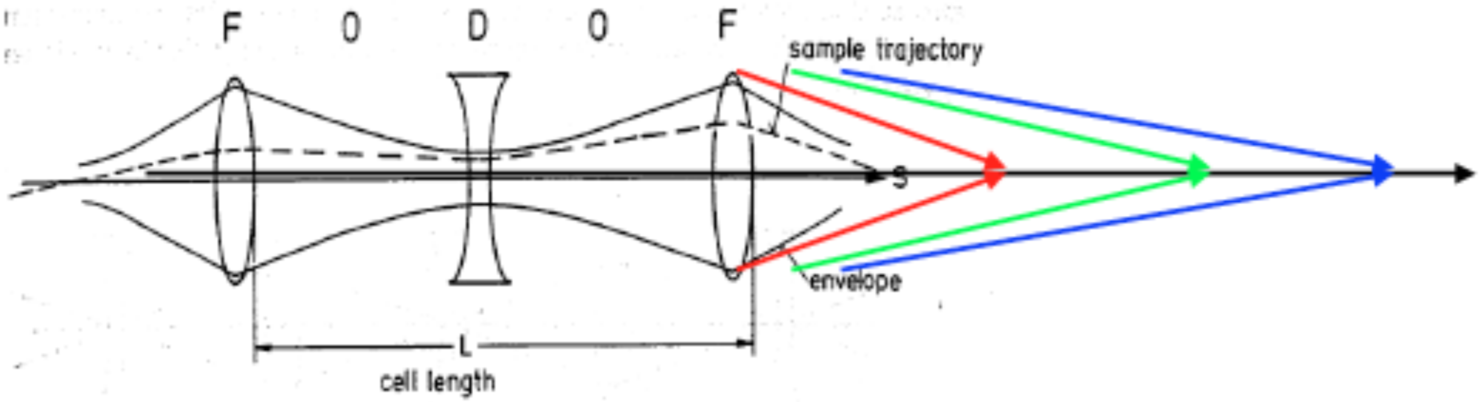


Figure 29: FODO cell

Chromaticity: Q'

The tune change for different Δp/p:

$$\Delta Q = \frac{1}{4\pi}\beta \Delta k \cdot l \qquad \Rightarrow \qquad \Delta Q = -\frac{1}{4\pi}\frac{\Delta p}{p_0} k_0 \beta l$$

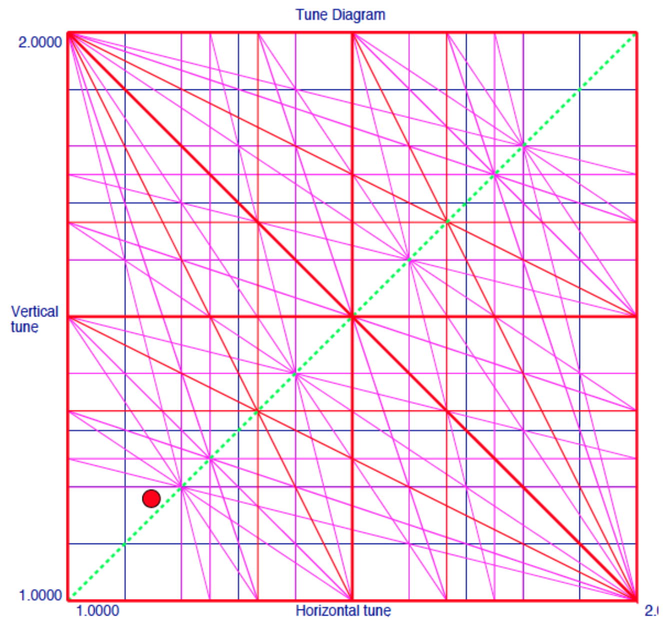
Definition of chromaticity:

$$\Delta Q = Q' \frac{\Delta p}{p} \qquad \boxed{Q' = -\frac{1}{4\pi}\oint k(s)\beta(s)ds}$$

With the beam momentum spread indicates the size of the tune spot in the tune diagram.

Chromaticity is created by quadrupole fields in the horizontal and vertical plane.

Chromaticity: Q'



We cannot leave chromaticity uncorrected:

Example LHC

Q'= 250 [no units]

$\Delta p/p = +/- \; 0.2 \times 10^{-3}$

$\Delta Q_h = 0.13 \ldots 0.43$!!!! ➔ Particles will go across resonance lines and will be lost.

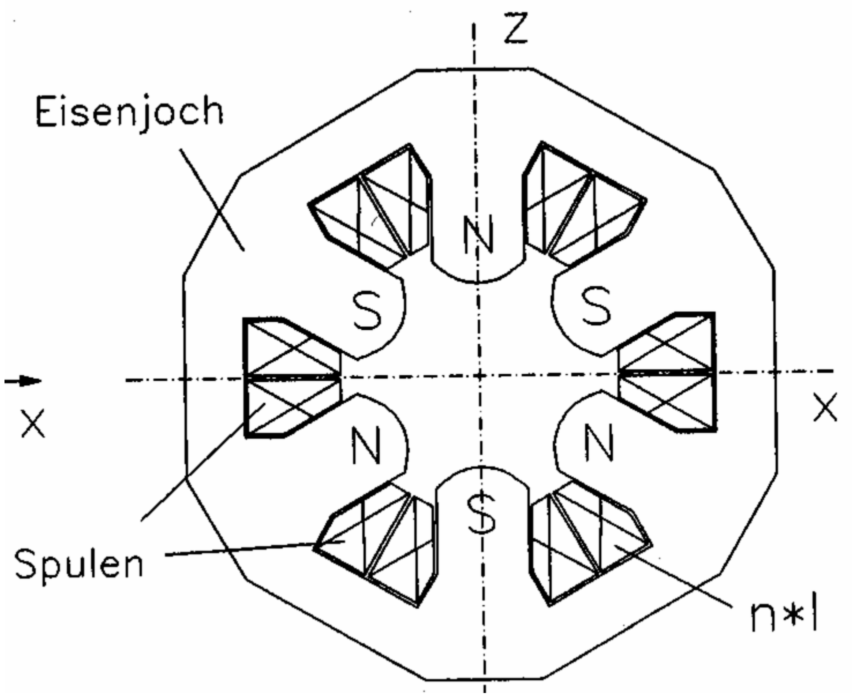
How to correct chromaticity?

Sextupole fields at locations of dispersion:

1) Sort the particles according to momentum: $x_D(s) = D(s)\frac{\Delta p}{p}$
2) Magnetic field with linear rising "gradient"

Correcting chromaticity

Sextupole magnets:



$$B_x = \tilde{g}xy$$

$$B_y = \frac{1}{2}\tilde{g}(x^2 - y^2)$$

$$\Downarrow$$

$$\frac{\partial B_x}{\partial y} = \frac{\partial B_y}{\partial x} = \tilde{g}x$$ Linear rising "gradient"

Sextupoles give a normalized quadrupole strength of:

$$\boxed{k_{sext} = \frac{\tilde{g}x}{p/e} = m_{sext}x \rightarrow k_{sext} = m_{sext}D\frac{\Delta p}{p}}$$

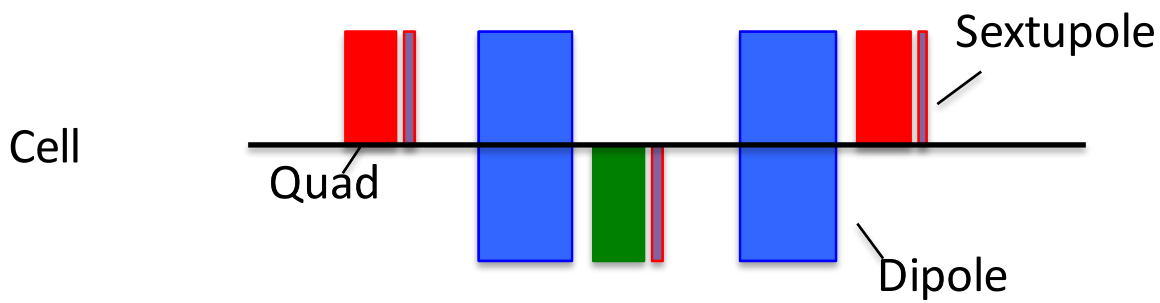
Correcting chromaticity

Only need dispersion in horizontal plane to correct chromaticity in horizontal and vertical plane.

$$Q' = -\frac{1}{4\pi}\oint\{k(s) - m(s)D(s)\}\beta(s)ds$$

Calculate m such that chromaticity vanishes.

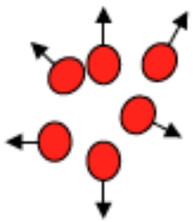
Add two families of sextupoles in your regular FODO lattice at the location with maximum dispersion: next to the quadrupoles



Collective Effects

Three categories: can cause beam instabilities, emittance blow-up, beam loss,...

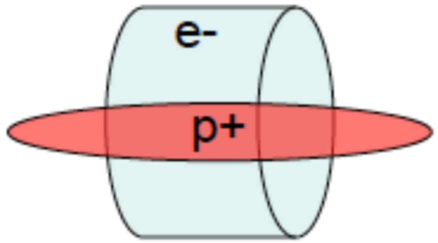
Beam-self: beam interacts with itself through space charge.



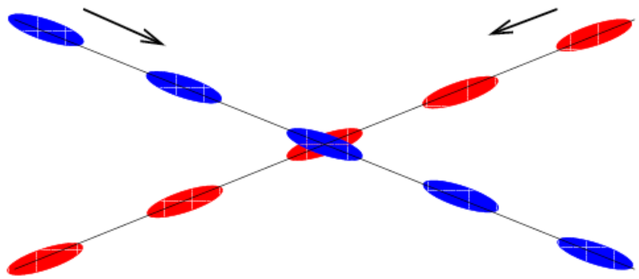
Tune spread $\propto \frac{1}{\beta^2\gamma^3}$

THE limitation in low energy machines

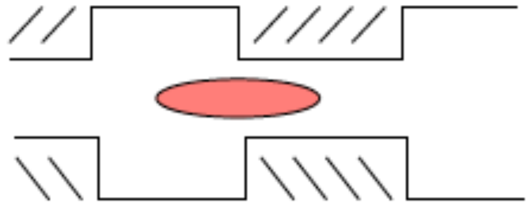
Beam-beam: colliding beams in colliders or ambient electron clouds (e-p instability).



Colliding beams. Tune spread/shift due to head-on collisions and long range collisions.



Beam-environment: beam interacts with machine (impedance-related instabilities).



Beam induces field in accelerator environment. Wake fields.
Wake fields can act back on trailing beam.

Fourier transform of Wake field is impedance.

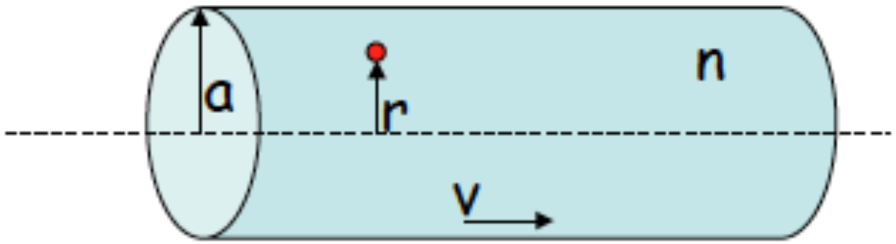
Can lead to component heating and/or instability.

Space-Charge Effect

The simplest and most fundamental of all collective effects

A simple approximation (direct space charge): beam as long cylinder.

Total force (E, B fields) on test particle in beam: uniformly charged cylinder of current I



$$F_r = F_E + F_B = \frac{eI}{2\pi c\beta\varepsilon_0\gamma^2 a^2} r$$

$$F_x = \frac{eI}{2\pi c\beta\varepsilon_0\gamma^2 a^2} x$$

$$x''(s) + K(s)x = \frac{F_{SC}}{m\gamma\beta^2 c^2}$$

Space charge ➔ gradient error

➔Defocusing

➔ Tune shift

$$x''(s) + \left(K(s) - \frac{2r_0 I}{ea^2\beta^3\gamma^3 c}\right) x = 0$$

$$r_0 = \frac{e^2}{4\pi\varepsilon_0 m_0 c^2}$$ Classical particle radius

Space-Charge Effect

Tune shift from gradient error

$$\Delta Q_x = \frac{1}{4\pi}\int_0^{2\pi R}\beta(s)\Delta K_{SC}(s)ds = -\frac{r_0 R I}{e\beta^3\gamma^3 c}\left\langle\frac{\beta_x(s)}{a^2(s)}\right\rangle$$

For cylindrical beam

$$\Delta Q_x = -\frac{n r_0}{2\pi\varepsilon_x\beta^2\gamma^3}$$

$$\varepsilon_x = \frac{a^2}{\beta_x}$$

$$I = \frac{ne\beta c}{2\pi R}$$

$$\boxed{\begin{array}{l}\propto \dfrac{n}{\varepsilon_{x,y}} \\ \propto \dfrac{1}{\gamma^3}\end{array}}$$

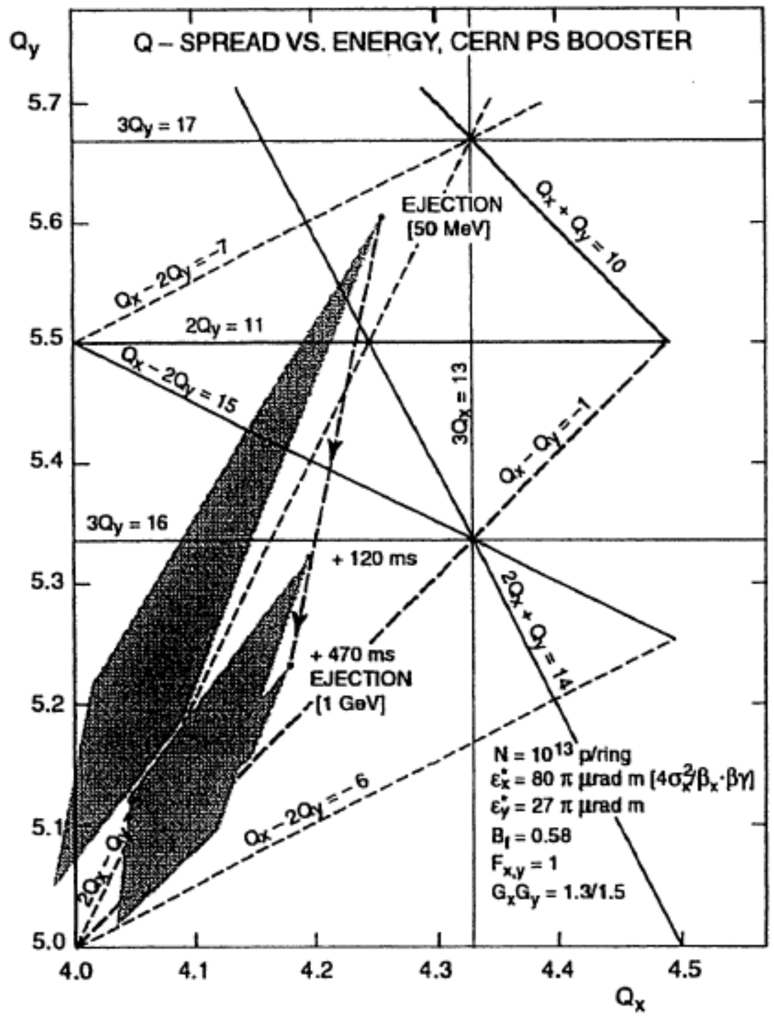
Not all particles in a beam will receive the same tune shift.

Variation in particle density, variation of space charge tune shift across bunch

➔ Tune spread

Space-Charge Effect

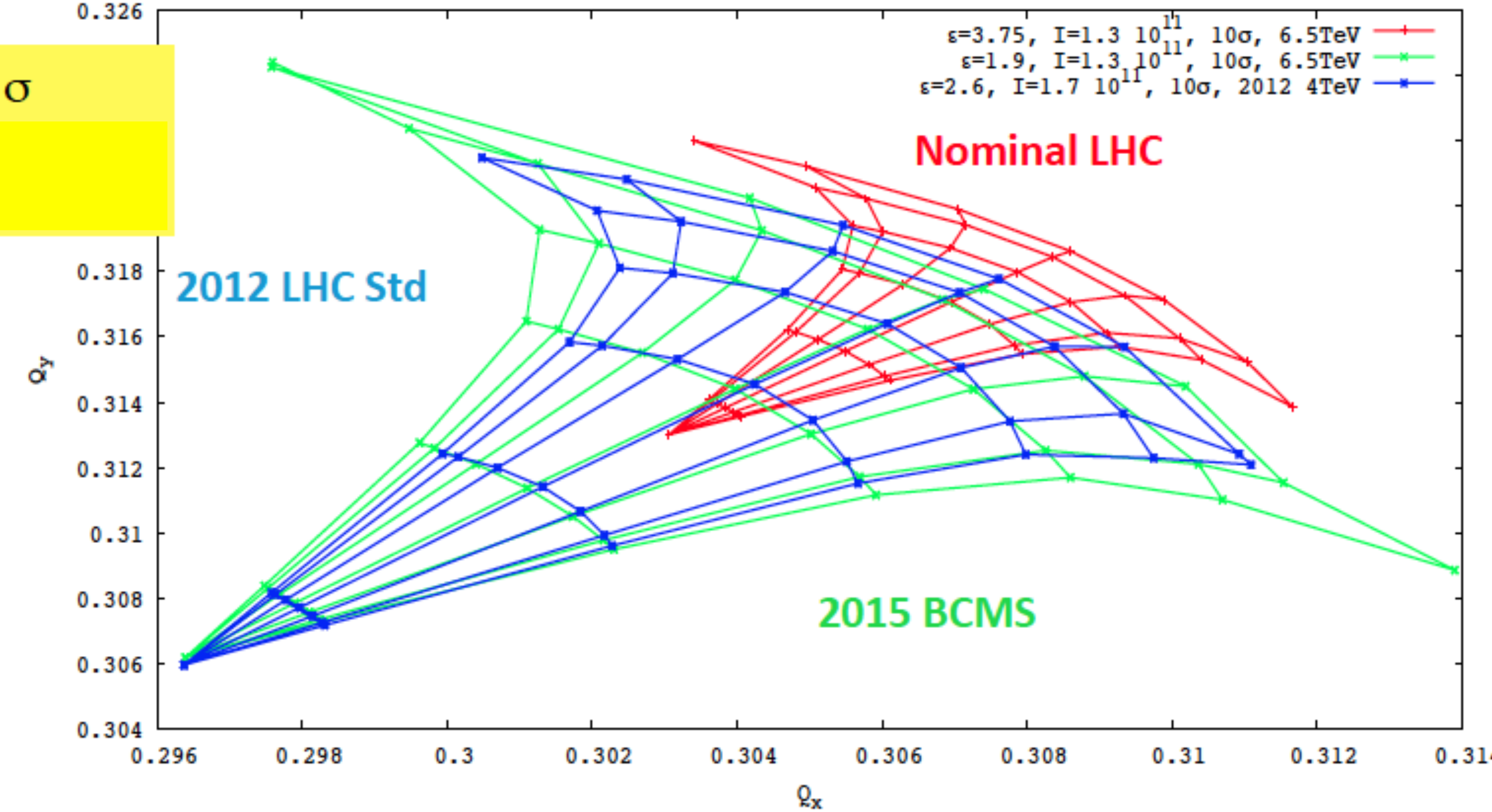
Space charge in the CERN PS booster for high intensity beams:



Not so easy to avoid resonances!!

Beam-beam tune footprint

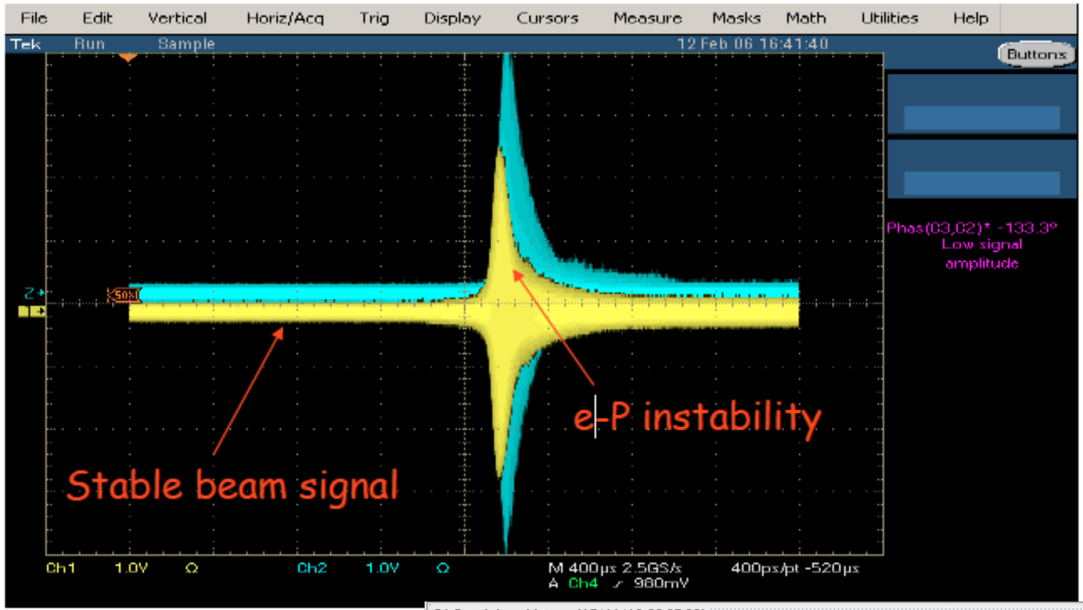
LR separation 10 σ

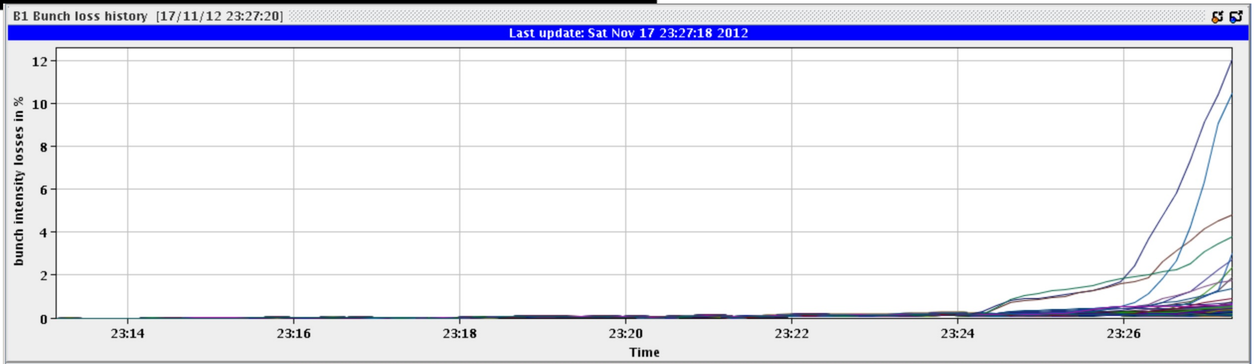


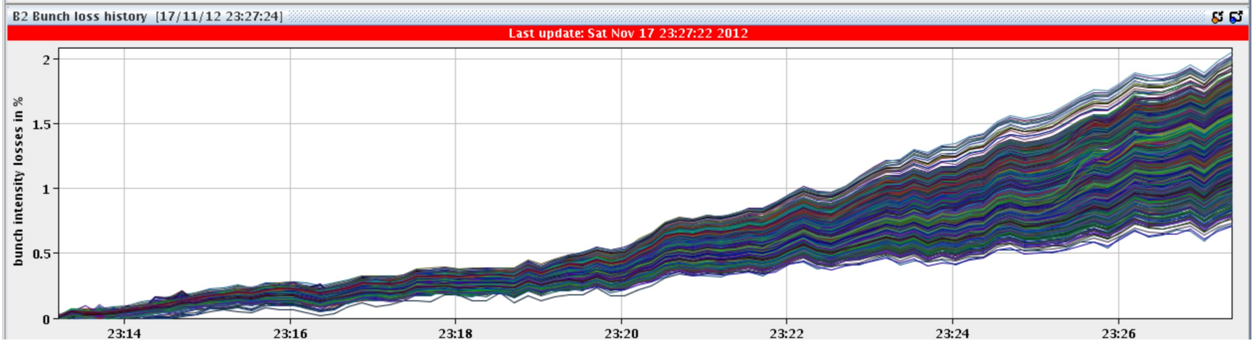
Courtesy T. Pieloni

Instability – what does it look like?

E.g. Fast rising coherent oscillation, beam losses, emittance blow-up







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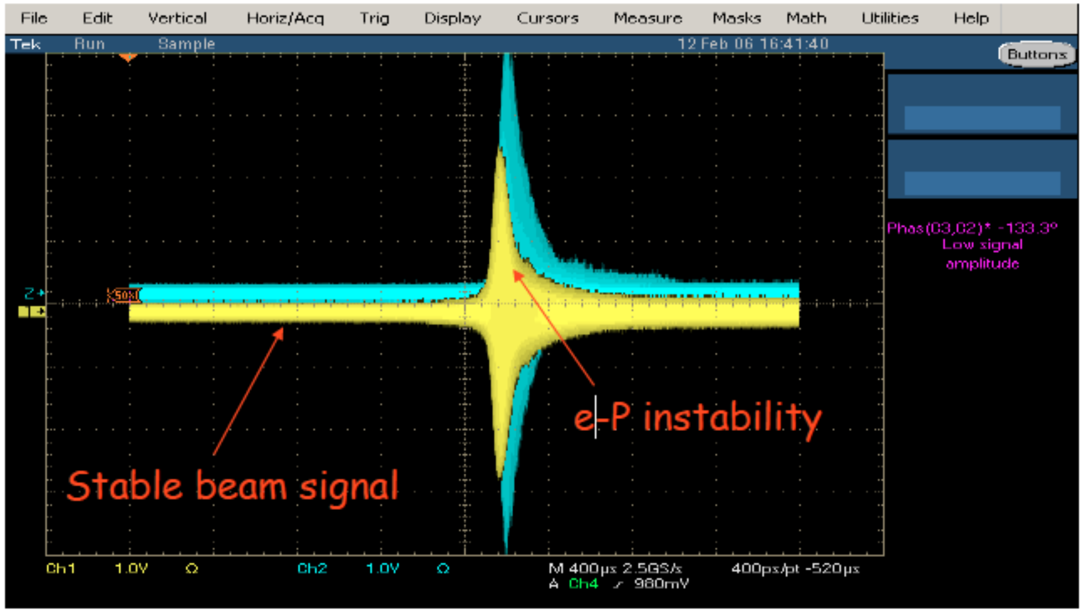
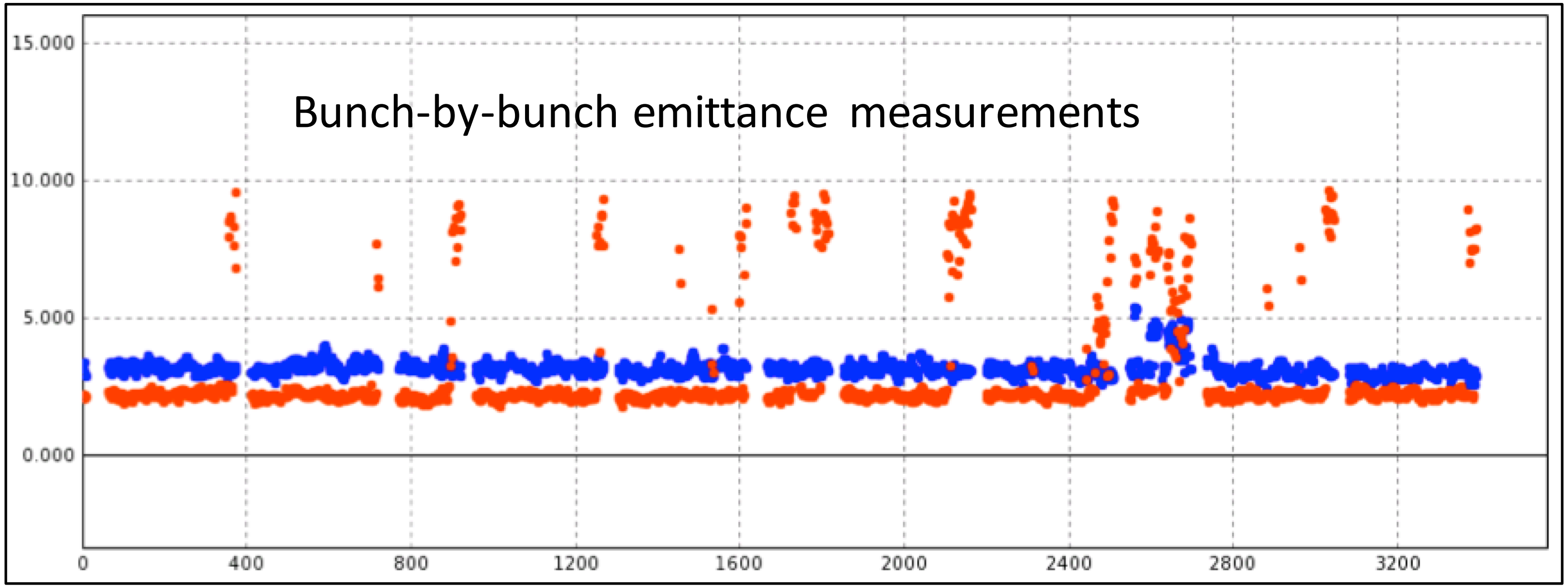
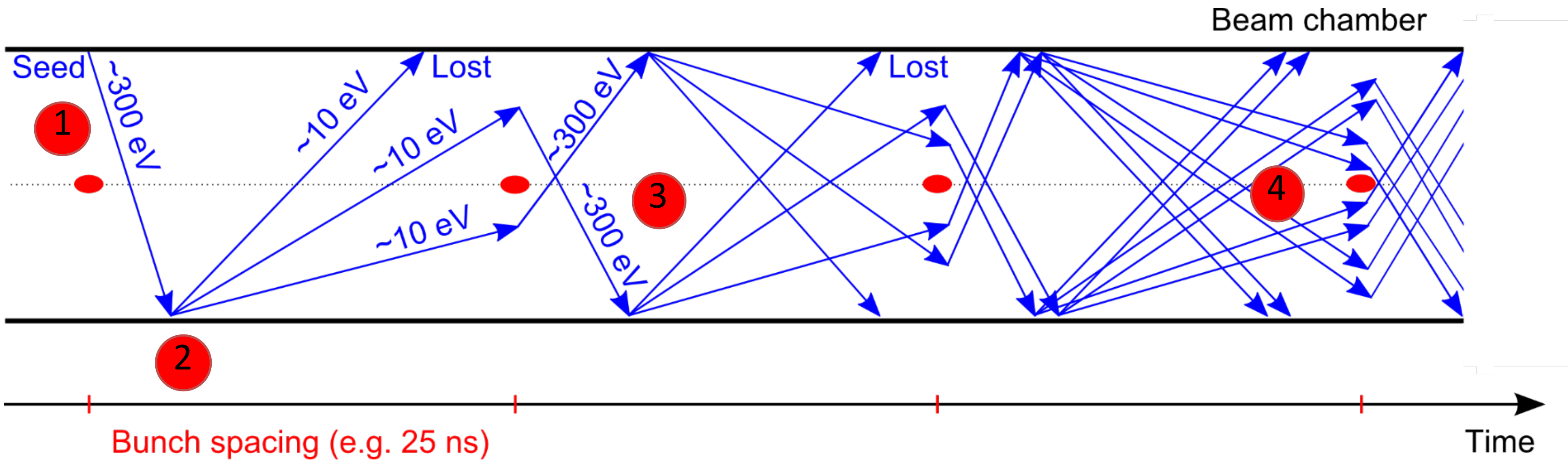


Possible mitigation:
Transverse feedback with sufficient bandwidth
Increase tune spread for ***Landau Damping***: higher chromaticity, octupole fields, tune spread from head-on collisions



Electron cloud – One of the LHC Challenges

In high intensity accelerators with positively charged beams and closely spaced bunches electrons liberated from vacuum chamber surface can multiply and build up a cloud of electrons.



Electrons are generated through:

- Residual gas ionization
- Photo-electrons with synchrotron radiation
- Desorption from the losses on the wall

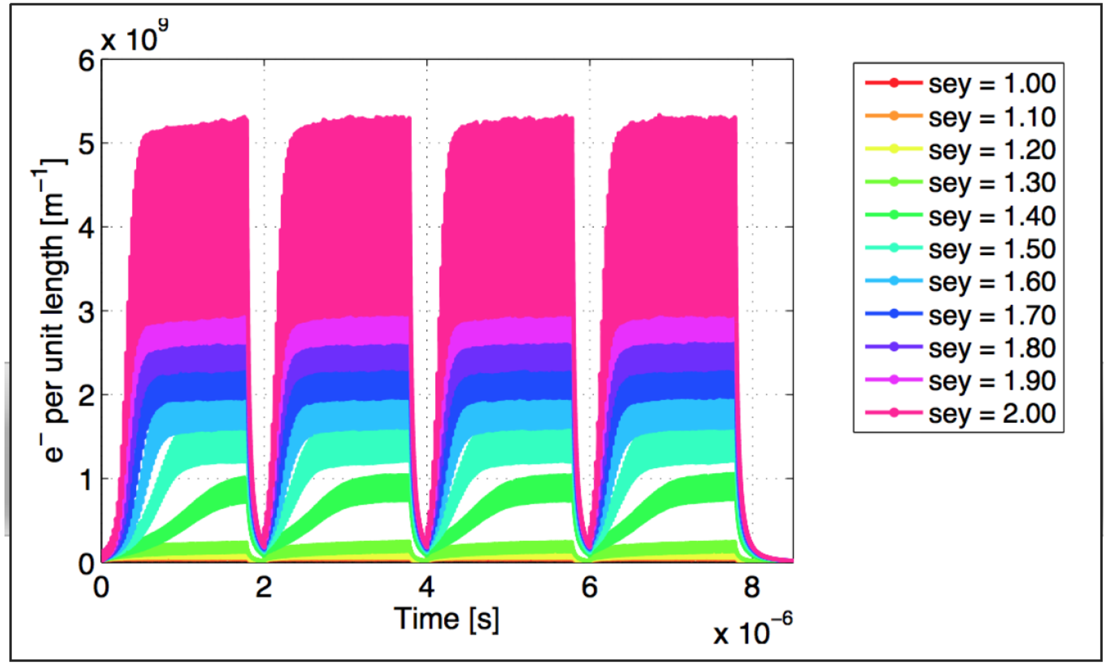
1) Seed electrons accelerated by beam
2) Produce secondary electrons when hitting chamber
3) Secondary electrons accelerated, producing more electrons on impact
4) May lead to exponential growth of electron density (multipacting)
5) Trailing bunches interact with cloud

Electron cloud

After the passage of several bunches leads to a dynamic steady state – electron cloud

The electron density depends on the *Secondary electron Emission Yield:* dangerous if SEY > 1

= ratio between emitted and impacting electrons



Example: LHC proton bunches 25 ns

Courtesy to G. Rumolo et al.

Electron cloud - signature

Fast pressure rise, outgassing

Additional heat load

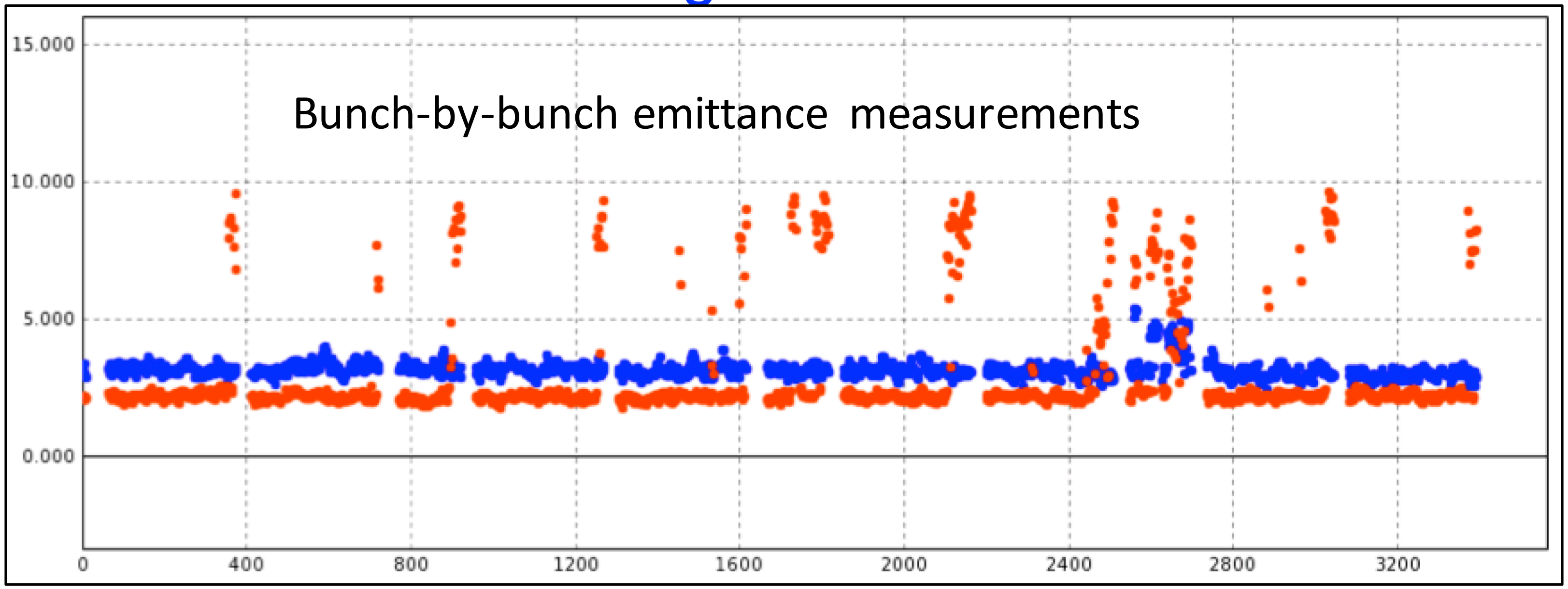
Synchronous phase shift due to energy loss

Tune shift along bunch train

Coherent instability

- Single bunch effect affecting last bunches of train
- Coupled bunch effect

- Poor beam lifetime and emittance growth

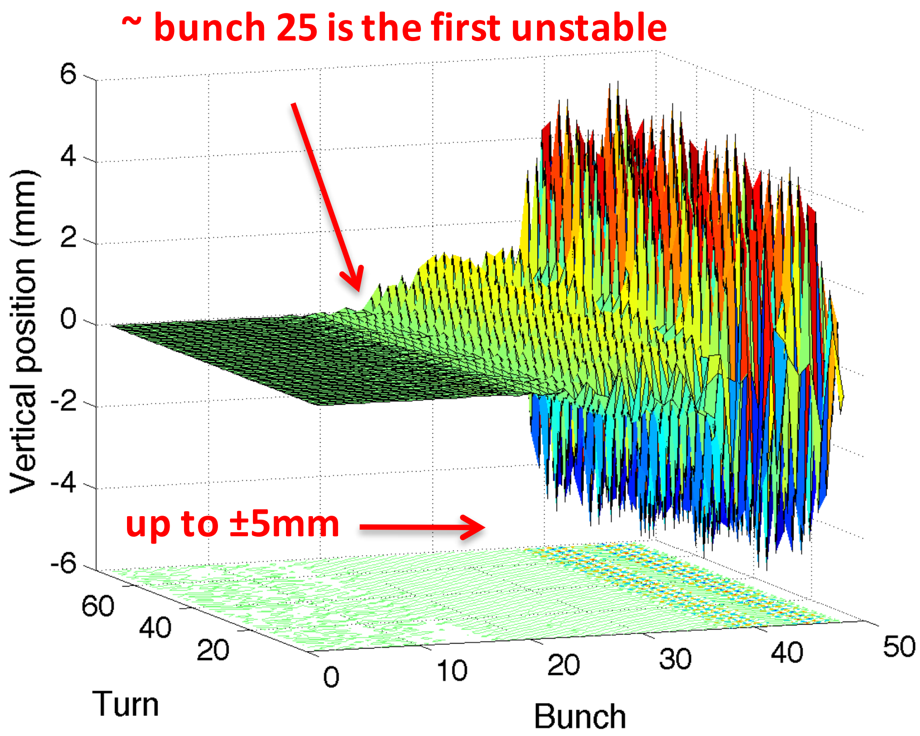


The electron cloud instability

The LHC nominal bunch spacing is 25 ns. During LHC run 1 25 ns operation was not possible due to e-cloud instability

First injection tests with a train of 25 ns 48 bunches on 26/08/2011:

Typical signature: the tails of the batches are more affected.



Beam becomes unstable immediately after injection.

The beam dump was triggered shortly afterwards due to high losses.

Electron cloud mitigation

- Strong reduction of e-clouds with larger bunch spacing:
  - **E.g. 50 ns bunch spacing**

- The e-cloud can 'cure itself': the impact of the electrons cleans the surface (Carbon migration), reduces the electron emission probability and eventually the cloud disappears.
- ***'Beam scrubbing'*** consists in producing e-cloud deliberately with the beams in order to reduce the SEY until the cloud 'disappears'.
  - *Done at 450 GeV injection energy – to first order e-cloud energy independent.*

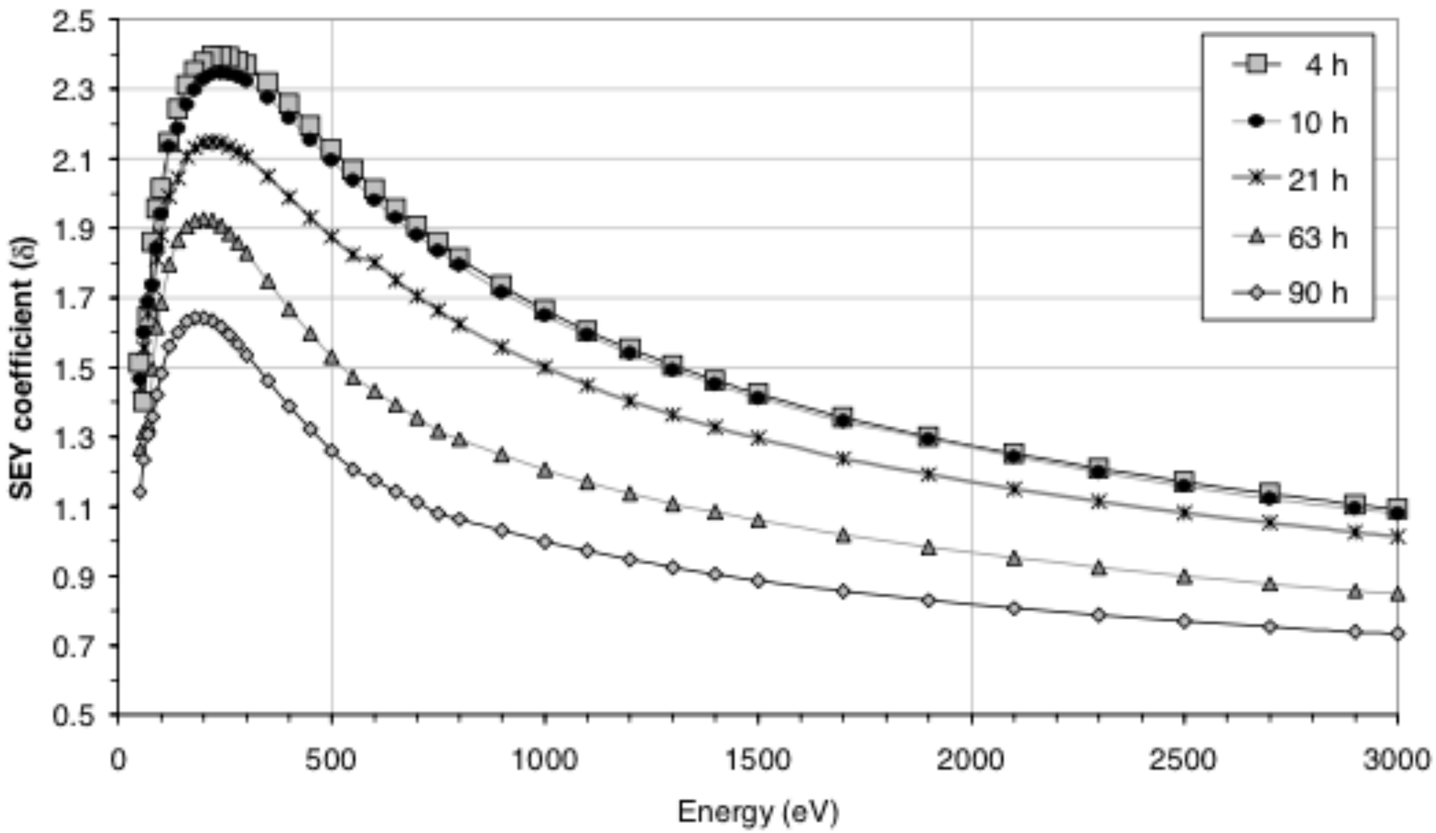
- In April 2011 25 ns beams were used to '***scrub'*** the LHC vacuum chamber at 450 GeV to prepare operation with 50 ns.
- Dedicated *scrubbing runs* are now part of the LHC start-up schedule every year

Electron Cloud – Self-conditioning of the surface

Exposure to high electron currents and emission can induce structural changes in surface

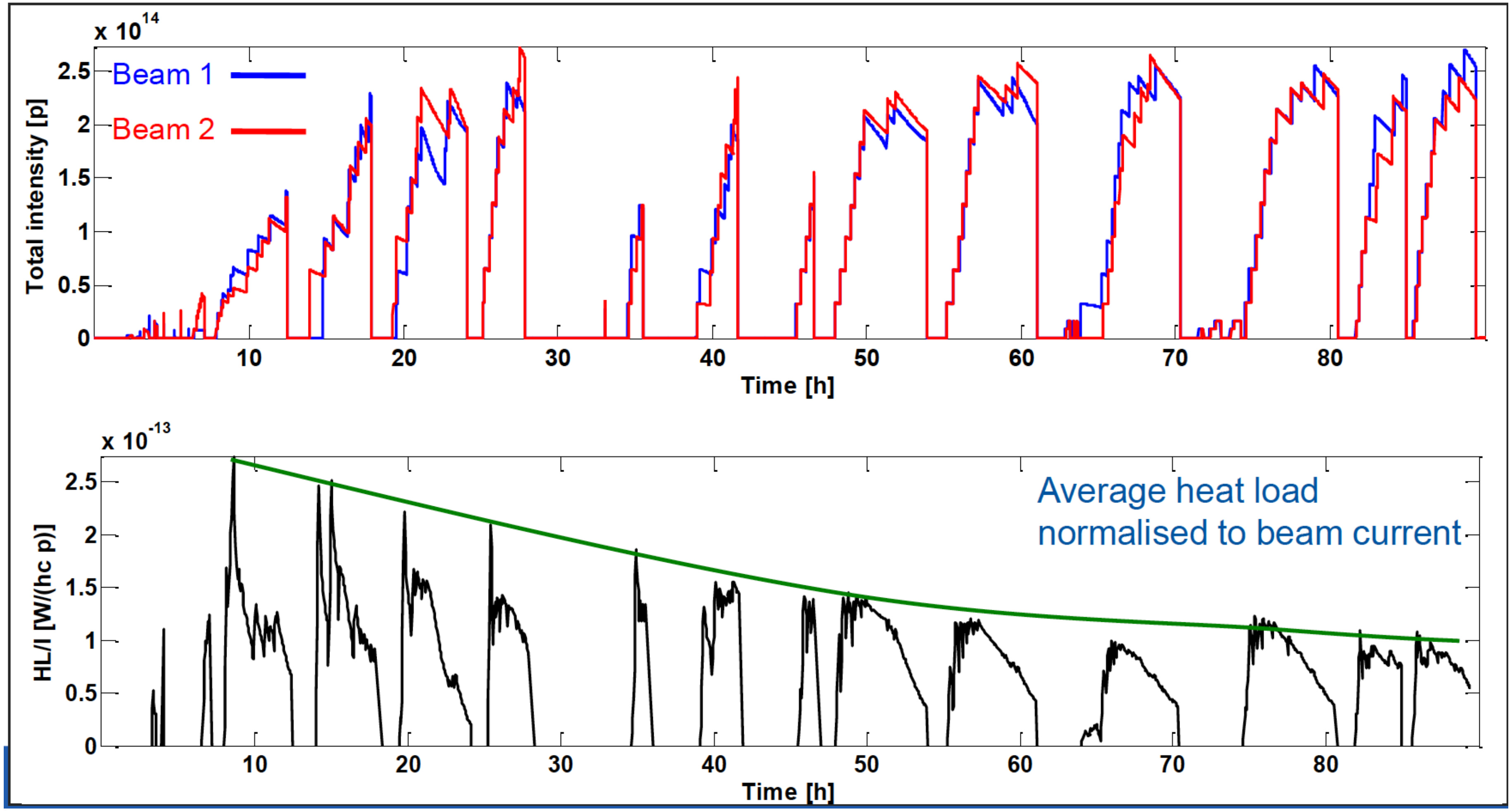
Leads to lower yield of secondary electrons

From M. Jimenez et al, Proc of Mini-ecloud WS 2003



Electron Cloud – Self-conditioning of the surface

Beam induced scrubbing is revealed through improved accelerator conditions: **decrease of pressure rise and heat load**, better beam quality

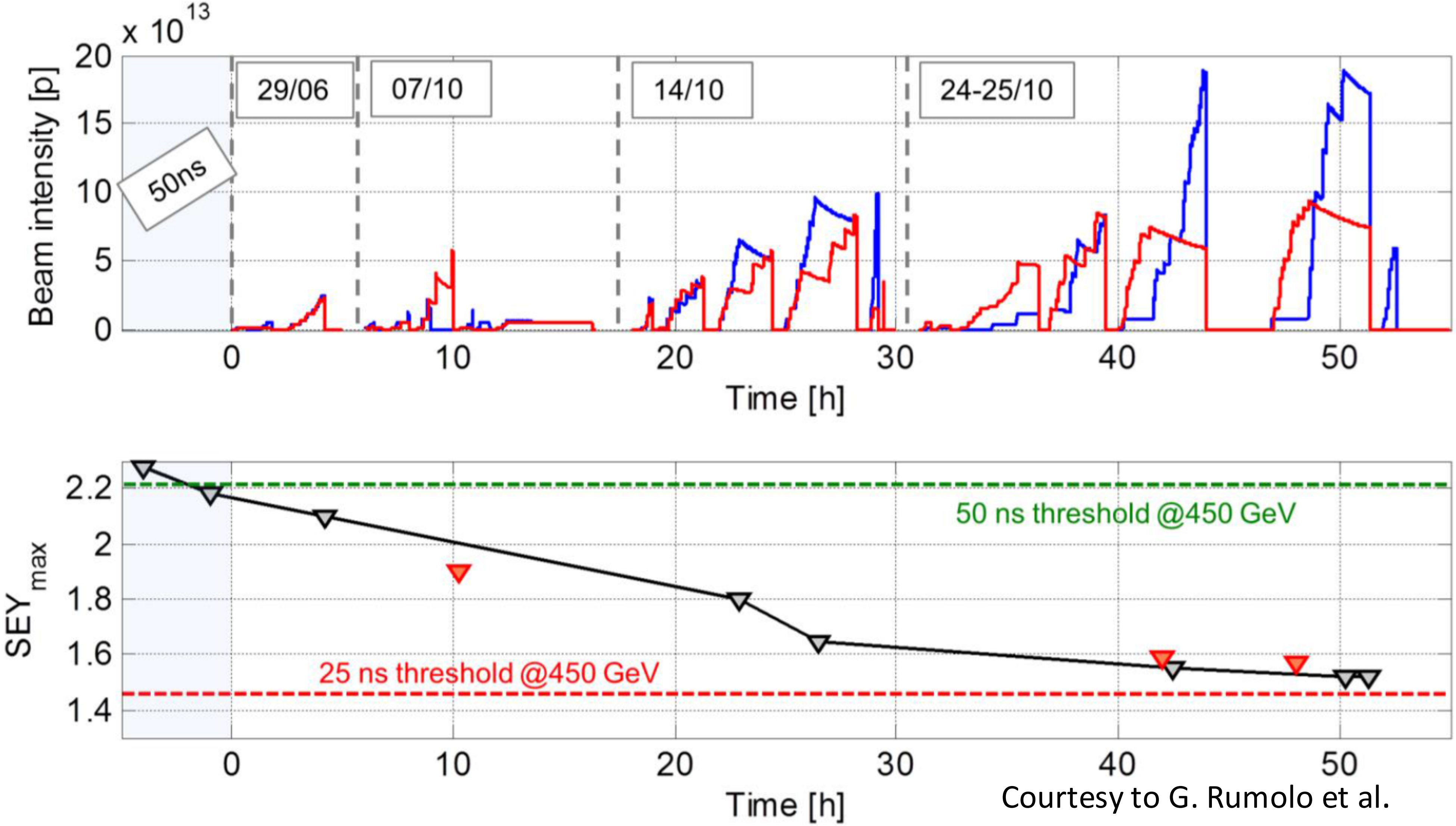


Courtesy to G. Rumolo et al.

Scrubbing in the LHC – run 1

Scrubbing during LHC run 1: Evolution of the SEY in the LHC arcs

- Reconstructed from the heat load data

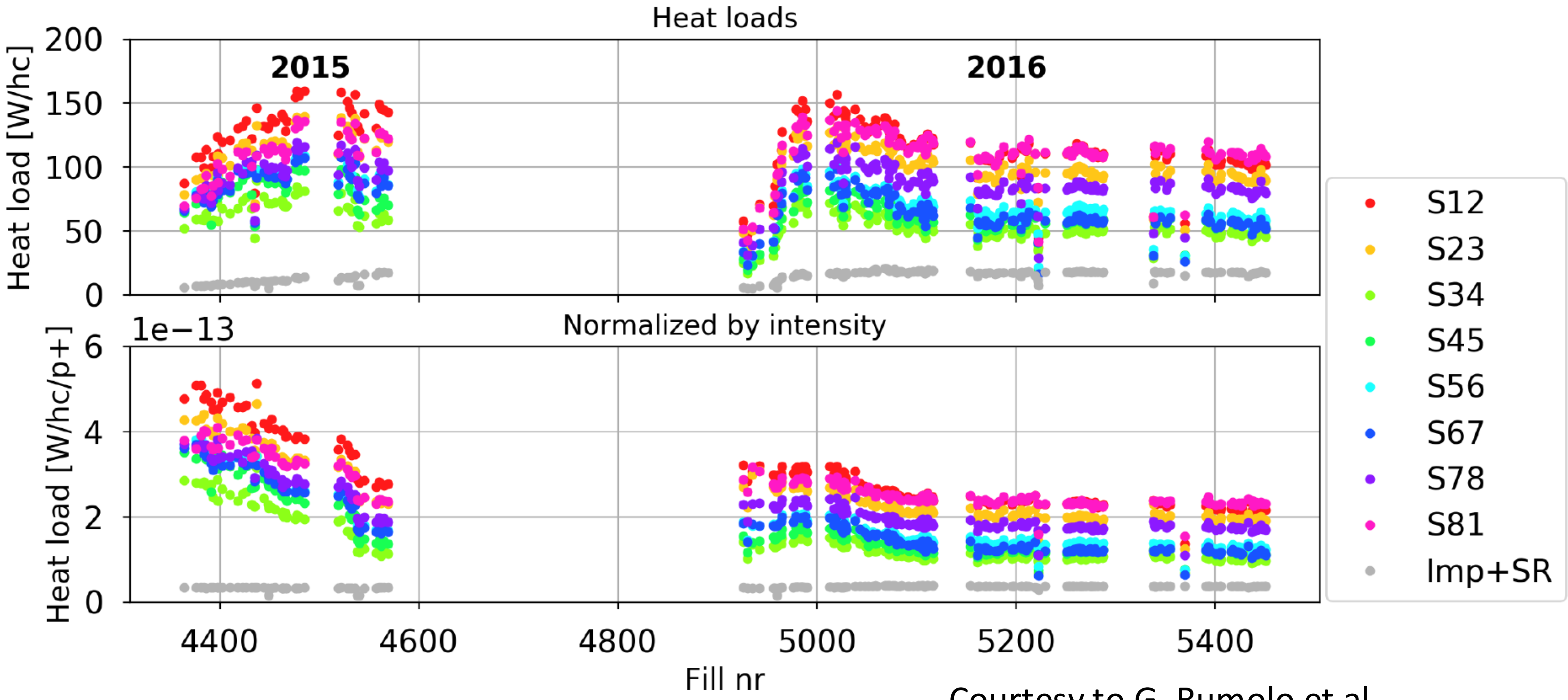


Courtesy to G. Rumolo et al.

LHC - Electron cloud evolution

LHC Run 2: scrubbing, scrubbing – preparation for 25 ns

SEY further improving with physics fills. Instability mitigation had to be in place: high octupole currents, high chromaticity, transverse feedback high gain

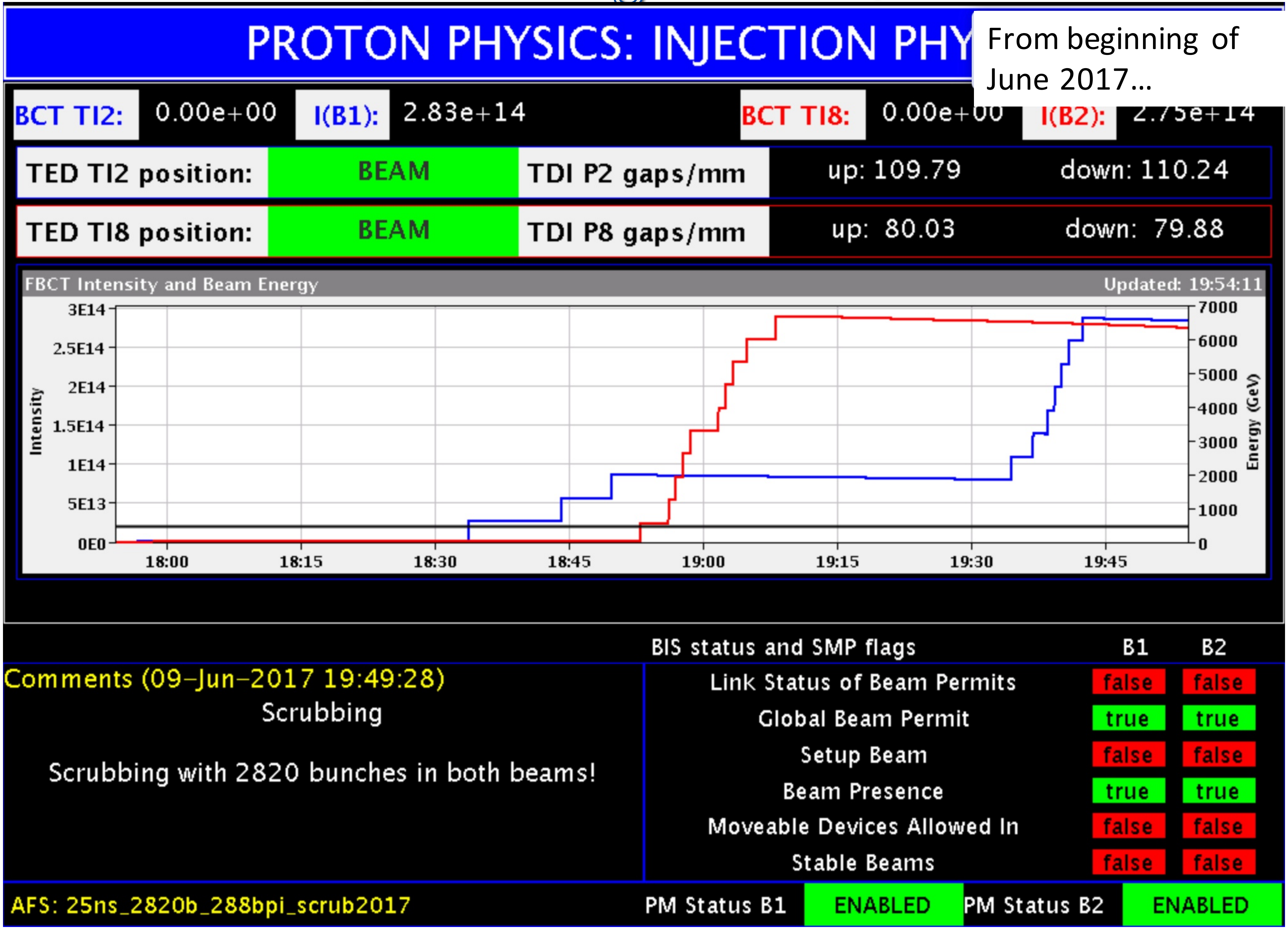


Courtesy to G. Rumolo et al.

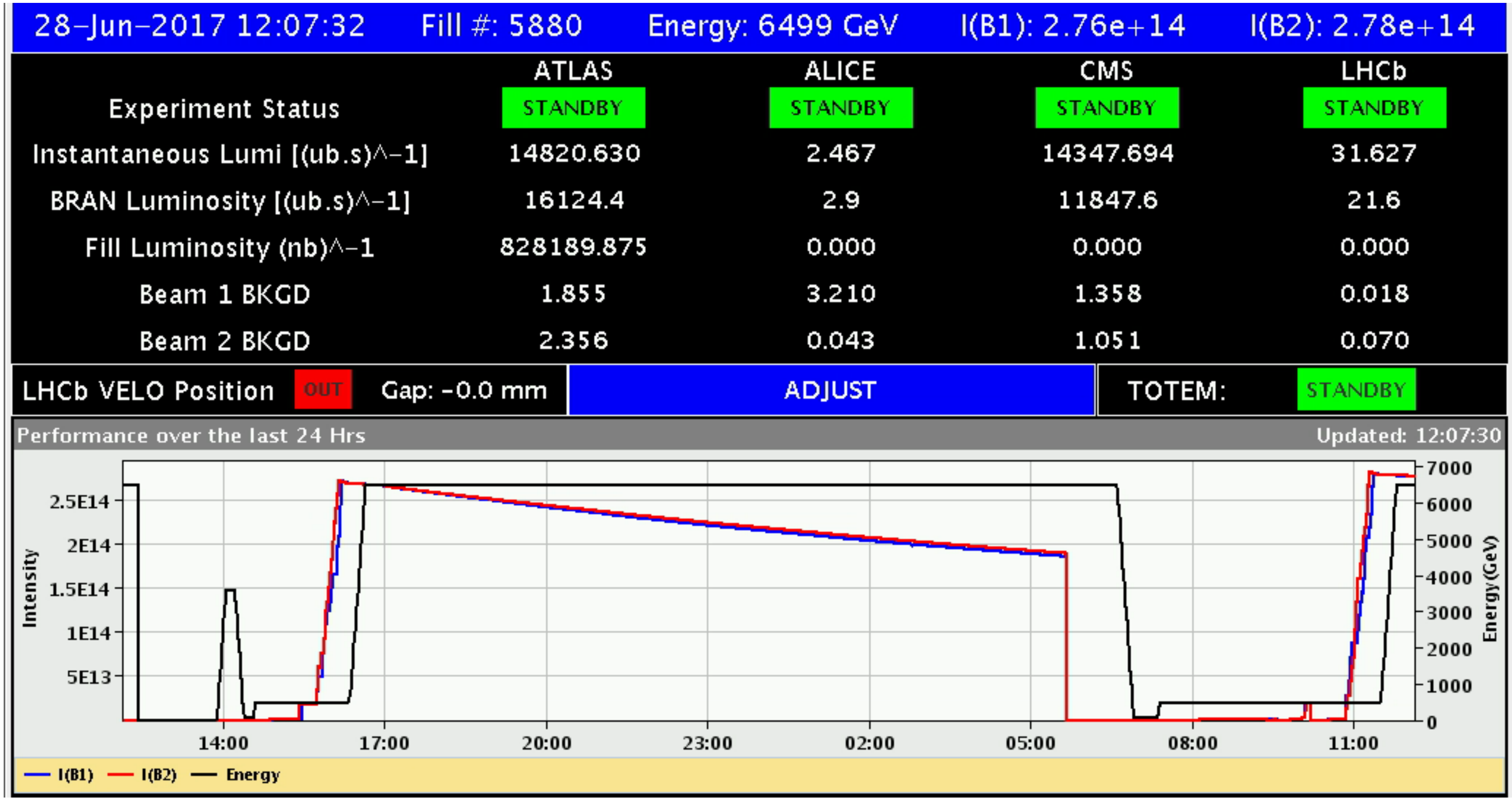
Saturation of scrubbing? Why do different sectors behave differently? Will this be enough for *High luminosity LHC*?

LHC scrubbing run in 2017…

From beginning of June 2017…



"Now": running with 2556 bunches per beam spaced by 25 ns



Tomorrow

The Large Hadron Collider....