CERN

Beam dynamics and measurement techniques for LHC and its High Luminosity Upgrade

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- Fundamental concepts of beam dynamics
  - Basics & CERN accelerator complex
  - Transverse beam dynamics and relevant quantities
  - Longitudinal beam dynamics and relevant quantities
  - Advanced concepts: Collective interactions (space charge, impedance, electron clouds)

- Upgrade of the LHC injector complex
  - Goals vs. present performance
  - Upgrade plans
  - Beam dynamics challenges

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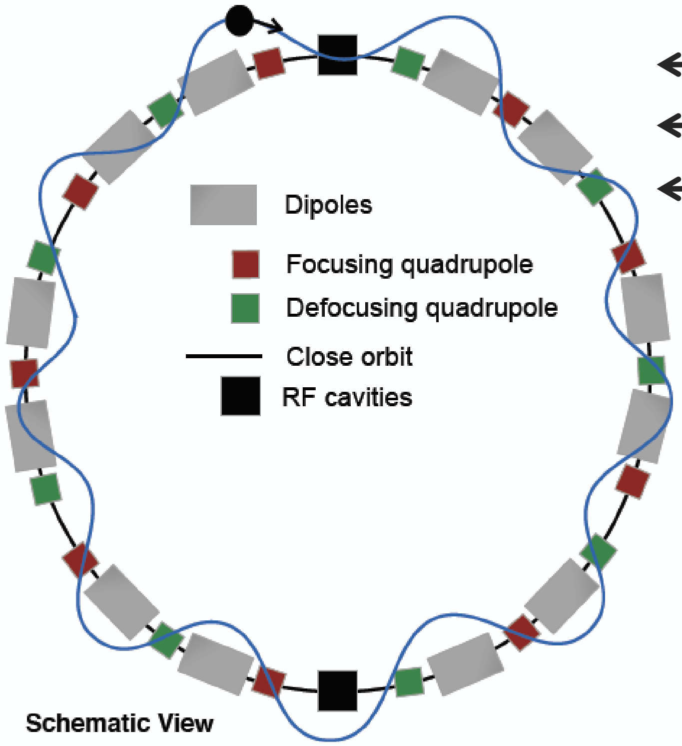
Synchrotrons



Dipole magnets to bend the beam on the circular orbit

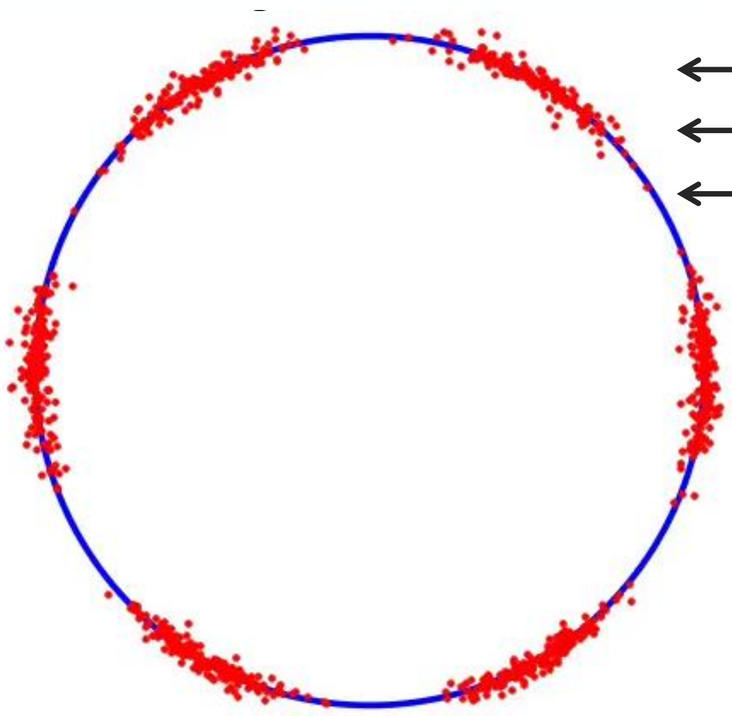
Quadrupole magnets to keep beam focused

Radio Frequency (RF) cavity to accelerate the beam

Lorentz force

- Motion of single particle is described by $\vec{F} = q(\vec{E} + \vec{v} \times \vec{B})$
- Main characteristics of synchrotrons
  - Use electric fields to accelerate and magnetic fields to guide particles
  - Design orbit is fixed at a given radius independently of the beam energy (magnetic field is increased proportional to momentum)
  - Beam is accelerated over many revolutions passing through the same RF cavity
  - Accelerating RF is synchronized with particle revolution frequency → "Synchrotron"

Synchrotrons



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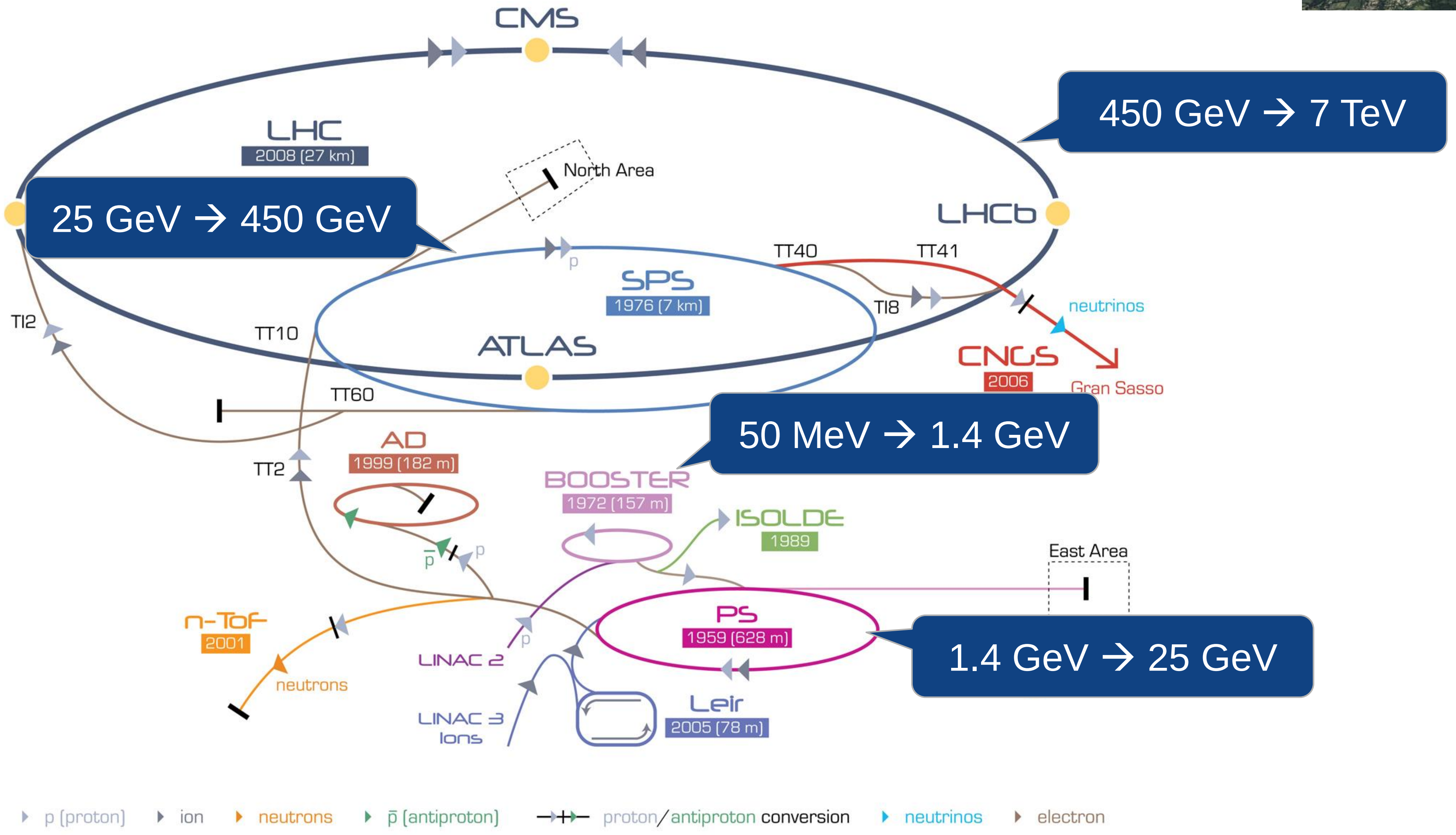
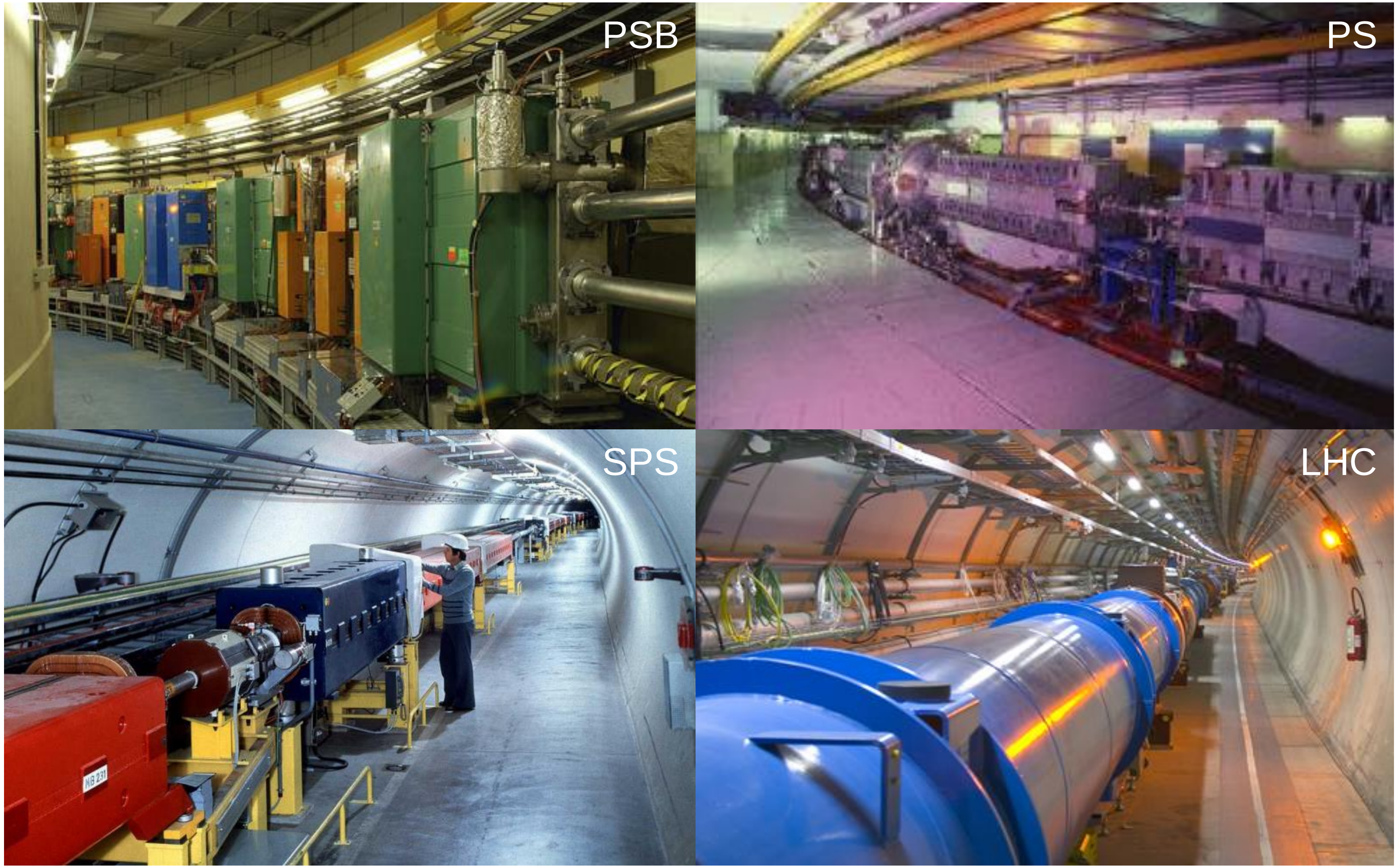
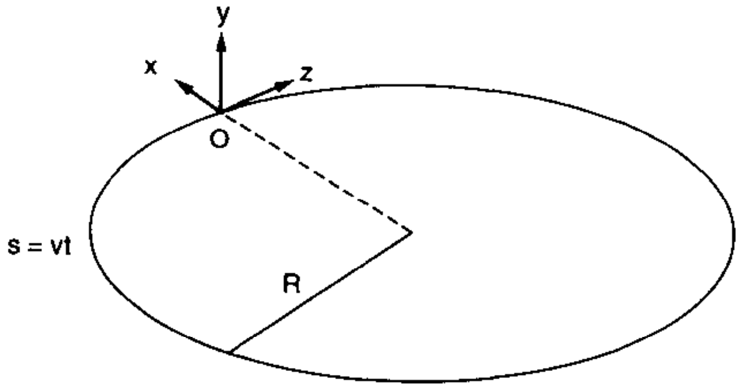
CERN accelerator complex



CERN accelerator complex

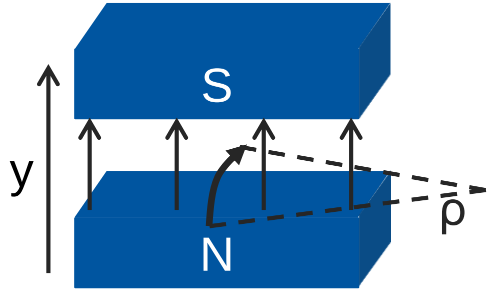


Reference system



- We use a co-moving coordinate system to describe the individual particle motion around the reference orbit
  - The origin O is moving along with the “synchronous particle”, i.e. a reference particle that has the design momentum and follows the design orbit
  - Mean radius R is defined through machine circumference C = 2π R
  - Transverse coordinates x (Horizontal) and y (Vertical) relative to reference particle (x,y << R), typically x is in the plane of the bending
  - Longitudinal coordinate z relative to reference particle
  - Position along accelerator is described by independent variable s = vt

Motion in dipoles: the magnetic rigidity



dipole magnets: uniform magnetic field in y direction

- In a uniform magnetic field B, a particle with charge e, velocity v, rest mass m and Lorentz factor γ follows a circular trajectory with bending radius ρ

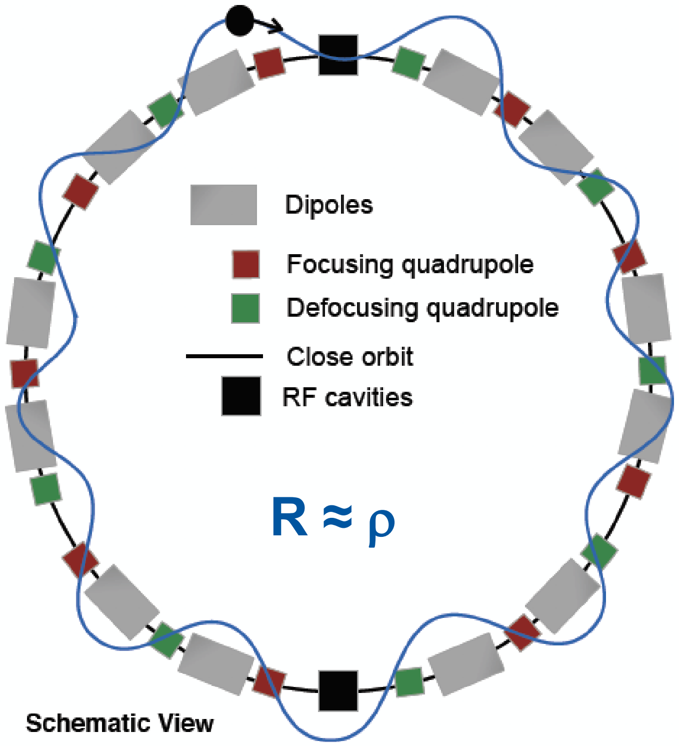
$$\underbrace{evB}_{\text{Lorentz force}} = \underbrace{\frac{\gamma m v^2}{\rho}}_{\text{Centrifugal force}} \longrightarrow \boxed{B\rho = \frac{p}{e}}$$

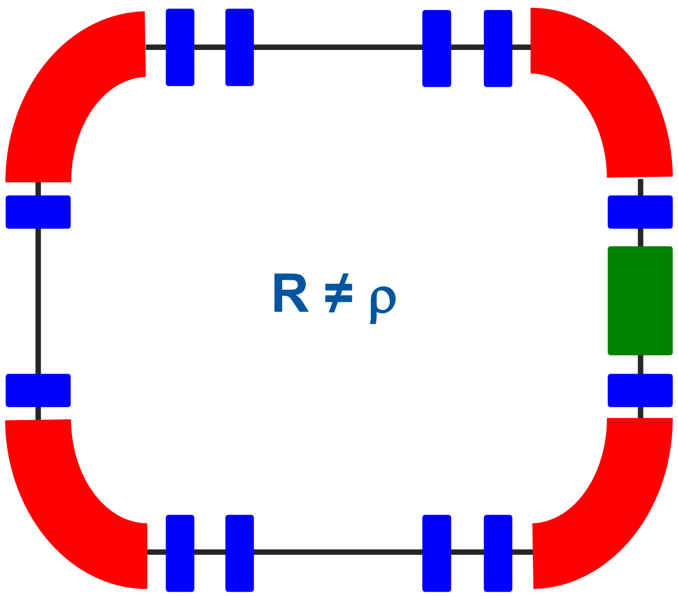
magnetic rigidity

- In a synchrotron, magnetic field of dipole magnets, reference trajectory (orbit) around the machine and reference momentum are linked by the relation on magnetic rigidity

Motion in dipoles

- N.B. The average radius of the machine R is different from the curvature radius in dipole magnets ρ

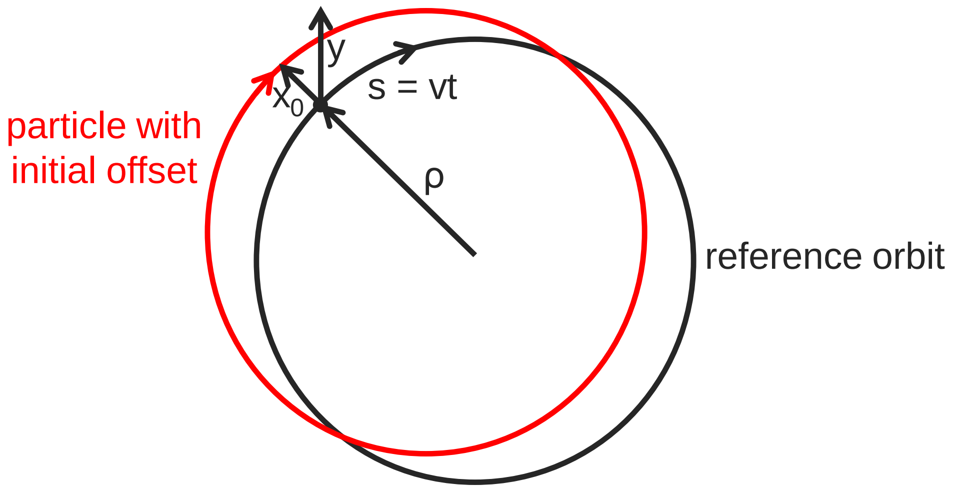




$R = \rho + L_{ss}/2\pi$

Motion in dipoles: Weak focusing

- Inside a dipole magnet
  - A particle displaced vertically keeps its offset unchanged
  - A particle displaced horizontally moves around the design orbit

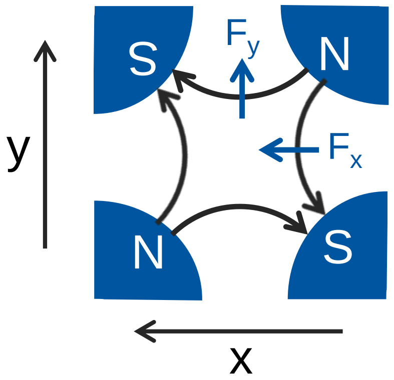


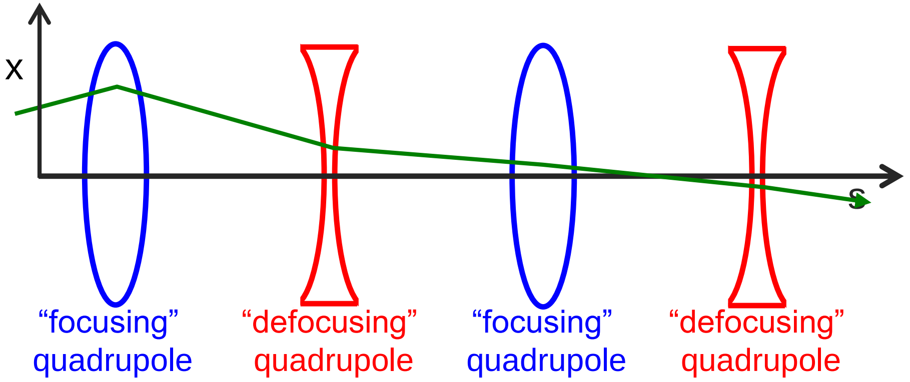
$$x = x_0 \cos(\omega t + \phi) \qquad \omega = \frac{v}{\rho}$$

$$x'' \equiv \frac{d^2x}{ds^2} = \frac{d^2x}{v^2dt^2} = -\frac{1}{\rho^2}x$$

- This is the **weak focusing** in **horizontal** plane

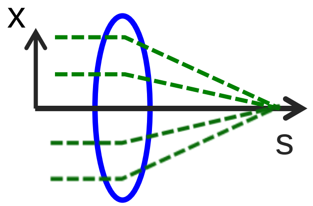
Motion in quadrupoles: Strong focusing





- Magnetic field proportional to offset results in linear restoring force

$$B_y = -gx \qquad \longrightarrow \qquad F_x = -evgx$$
$$B_x = -gy \qquad \qquad \qquad F_y = +evgy$$



- Force is focusing in one plane while defocusing in the other → need to alternate focusing and defocusing quadrupoles (“alternating gradient lattice”) to achieve overall focusing in a particle accelerator or transfer line
- In accelerator design we use the normalized quadrupole strength $K = \frac{g}{B\rho}$

General equations of motion

- Consider linear fields (dipoles + quadrupoles) and on-momentum particles

quadrupoles ↘ dipoles ("weak focusing") ↙

$$\left.\begin{aligned} x'' - \left(K(s) - \frac{1}{\rho(s)^2}\right) x = 0 \\ y'' + K(s)\, y = 0 \end{aligned}\right\} \quad \text{can be written as:} \quad \begin{aligned} x'' + K_x(s)\, x = 0 \\ y'' + K_y(s)\, y = 0 \end{aligned}$$

- Linear equations with s-dependent coefficients
  - equivalent to harmonic oscillator with s-dependent dependent frequency
  - in a ring (or transport line with symmetries), the focusing terms are periodic:

$$K_x(s) = K_x(C + s) \qquad\qquad K_y(s) = K_y(C + s)$$

  - Not straightforward to derive analytical solutions for whole accelerator …

General equations of motion

- The general solution of Hill's equations ("**betatron motion**") can be written as

$$u(s) = \sqrt{2J_u\beta_u(s)}\cos\left(\psi_u(s) + \psi_u(s_0)\right)$$

$$u'(s) = -\sqrt{\frac{2J_u}{\beta_u(s)}}\left[\alpha_u(s)\cos\left(\psi_u(s)+\psi_u(s_0)\right) + \sin\left(\psi_u(s)+\psi_u(s_0)\right)\right]$$

$$\beta_u(s), \quad \alpha_u(s) = -\frac{\beta_u'(s)}{2}, \quad \gamma_u(s) = \frac{1+\alpha_u(s)^2}{\beta_u(s)}$$

"Twiss" parameters at s

$$\psi_u(s) = \int \frac{ds}{\beta_u(s)}$$

Betatron phase

- The beta function is defined by the **envelope equation** (follows from Hill's equation)

$$2\beta_u\beta_u'' - \beta_u'^2 + 4\beta_u^2 K_u = 0$$

- The "action" ***J_u*** **is a constant of motion** (i.e. independent of *s*)

$$2J_u = \gamma_u u^2 + 2\alpha_u u u' + \beta_u u'^2$$

General transfer matrix

- The **general transfer matrix** from location s_0=0 to s is obtained as

$$\begin{pmatrix} u(s) \\ u'(s) \end{pmatrix} = \mathcal{M}_u(s|s_0) \begin{pmatrix} u(s_0) \\ u'(s_0) \end{pmatrix}$$

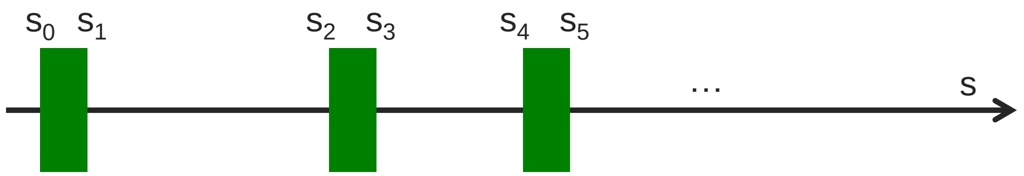
$$\mathcal{M}_u(s|s_0) = \begin{pmatrix} \sqrt{\frac{\beta_u(s)}{\beta_u(s_0)}}(\cos\Delta\psi_u + \alpha_u(s_0)\sin\Delta\psi_u) & \sqrt{\beta_u(s_0)\beta_u(s)}\sin\Delta\psi_u \\ \frac{\alpha_u(s_0)-\alpha_u(s)}{\sqrt{\beta_u(s_0)\beta_u(s)}}\cos\Delta\psi_u - \frac{1+\alpha_u(s_0)\alpha_u(s)}{\sqrt{\beta_u(s_0)\beta_u(s)}}\sin\Delta\psi_u & \sqrt{\frac{\beta_u(s_0)}{\beta_u(s)}}(\cos\Delta\psi_u - \alpha_u(s)\sin\Delta\psi_u) \end{pmatrix}$$

$$\Delta\psi_u = \int_0^s \frac{ds}{\beta_u(s)}$$

→ **betatron phase advance**

General transfer matrix

- This general transfer matrix based on beta functions can also be written as the multiplication of individual rotation matrices representing the transfers through single elements



$$\mathcal{M}(s_n|s_0) = \underbrace{\mathcal{M}(s_n|s_{n-1}) \ldots \underbrace{\mathcal{M}(s_2|s_1) \cdot \underbrace{\mathcal{M}(s_1|s_0)}_{\text{from } s_0 \text{ to } s_1}}_{\text{from } s_0 \text{ to } s_2}}_{\text{from } s_0 \text{ to } s_n}$$

One-turn transfer matrix

- Now we consider **transfer matrix for a full machine circumference *C***
  - The optics functions must be *periodic* and are therefore *uniquely defined*!

$$\beta_u(0) = \beta_u(C) = \beta_u \qquad \alpha_u(0) = \alpha_u(C) = \alpha_u$$

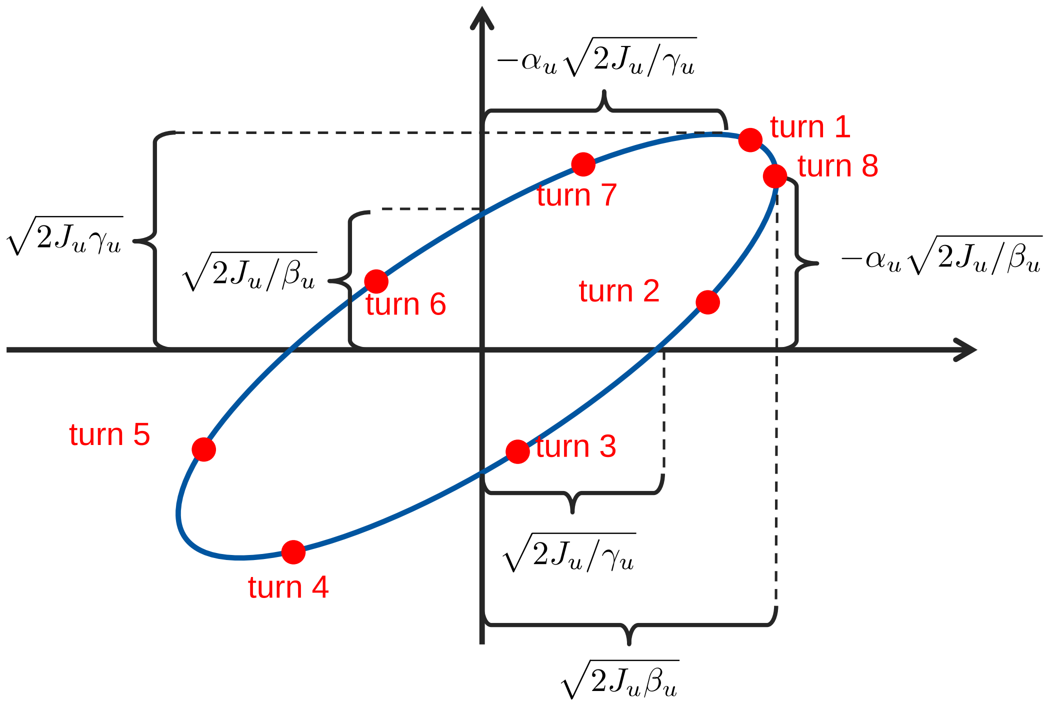
  - The phase advance over one turn is usually expressed as the **betatron tune Q_u**, which corresponds to the **number of betatron oscillations per turn**

$$\phi_u = \int_0^C \frac{ds}{\beta_u(s)} \longrightarrow \boxed{Q_u \equiv \frac{1}{2\pi}\int_0^C \frac{ds}{\beta_u(s)}}$$

- One turn transfer matrix:

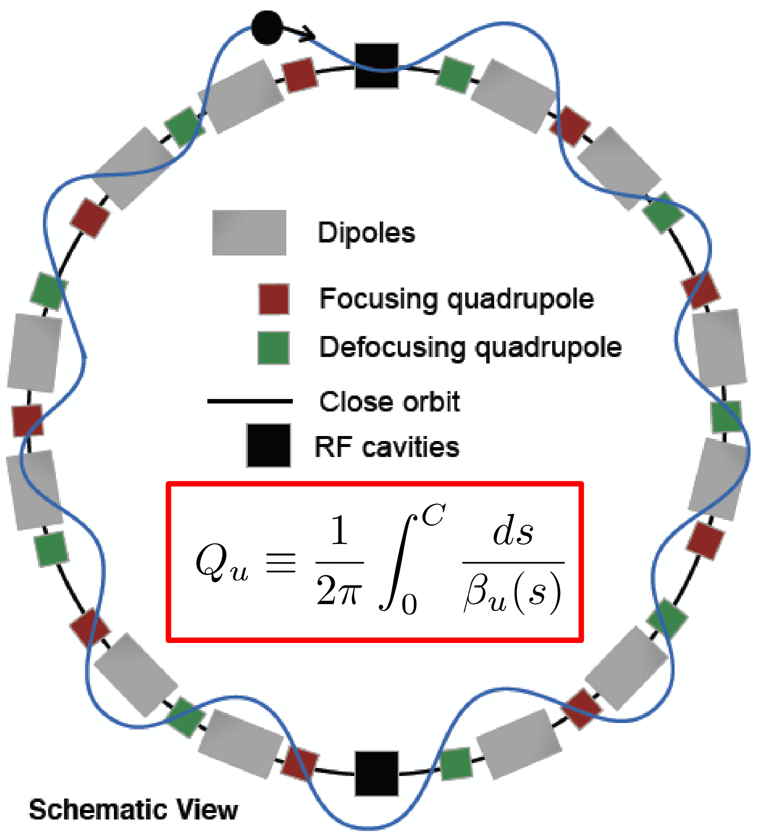
$$\boxed{\mathcal{M}_u(C|0) = \begin{pmatrix} \cos\phi_u + \alpha_u \sin\phi_u & \beta_u \sin\phi_u \\ -\frac{1+\alpha_u^2}{\beta_u}\sin\phi_u & \cos\phi_u - \alpha_u \sin\phi_u \end{pmatrix}}$$

Phase space



- The **phase space coordinates** (*u, u'*) of a single particle at a given location *s* in the machine **lie on the phase space ellipse** when plotted for several turns.
- The **values of the Twiss parameters** and therefore the orientation of the phase space ellipse **depend on the s location** in the machine. The phase space area enclosed by the ellipse is invariant and equal to $2J_u\pi$.

The machine tune



$$Q_u \equiv \frac{1}{2\pi} \int_0^C \frac{ds}{\beta_u(s)}$$

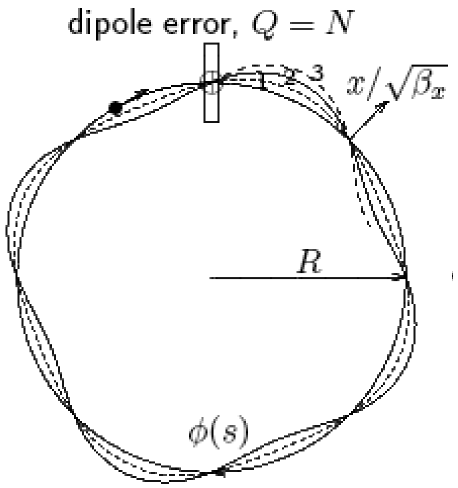
- The number of betatron oscillations that particles perform over one turn in both transverse directions defines two fundamental parameters in the operation of any accelerator

→ **Horizontal and vertical tunes**

- Particles always arrive at the same position turn after turn only if the tune is an integer number.
- Machine tunes are typically proportional to the machine size

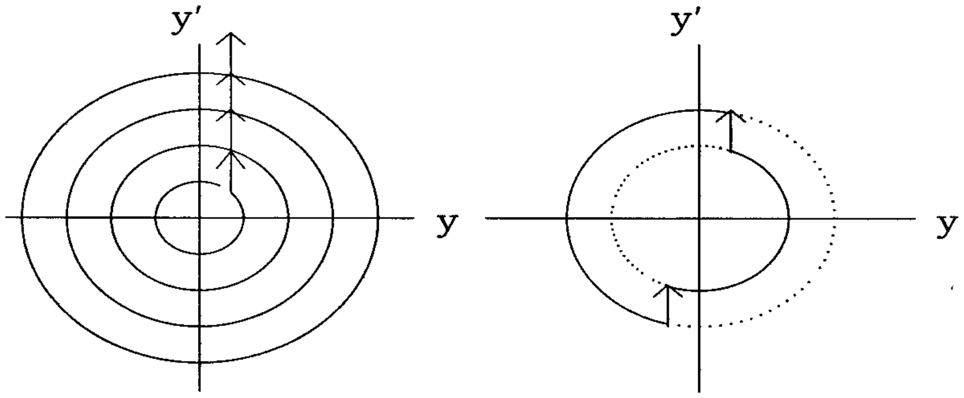
The machine tune and resonances

- In the presence of optical machine imperfections the values of the betatron tunes should not be on or close to a rational fraction
  - Dipole errors deflect a particle each turn in phase if tune is an integer N



closed orbit instability

Effect of dipole error in phase space



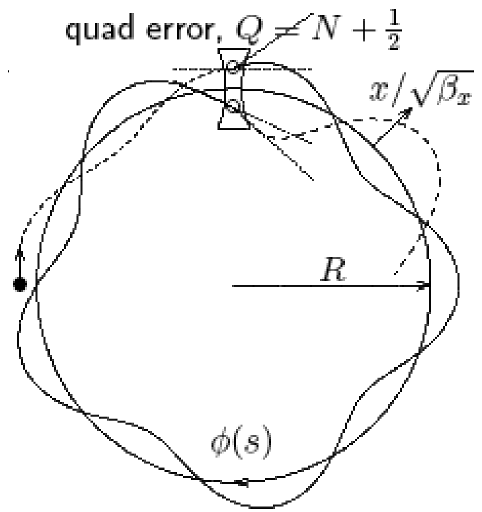
Q = N
dipole kicks add up

Q = N/2
cancellation
after two turns

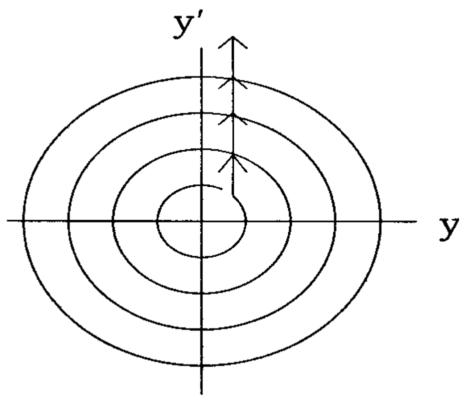
The machine tune and resonances

- In the presence of optical machine imperfections the values of the betatron tunes should not be on or close to a rational fraction
  - Dipole errors deflect a particle each turn in phase if tune is an integer N
  - Quadrupole errors are in phase if tune is an integer N or a half integer N+1/2

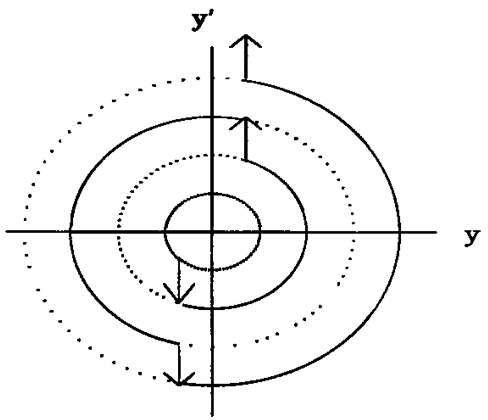
Effect of quadrupole error in phase space



beam size grows each turn



Q = N
quadrupole
kicks add up



Q = N/2
quadrupole
kicks add up

The machine tune and resonances

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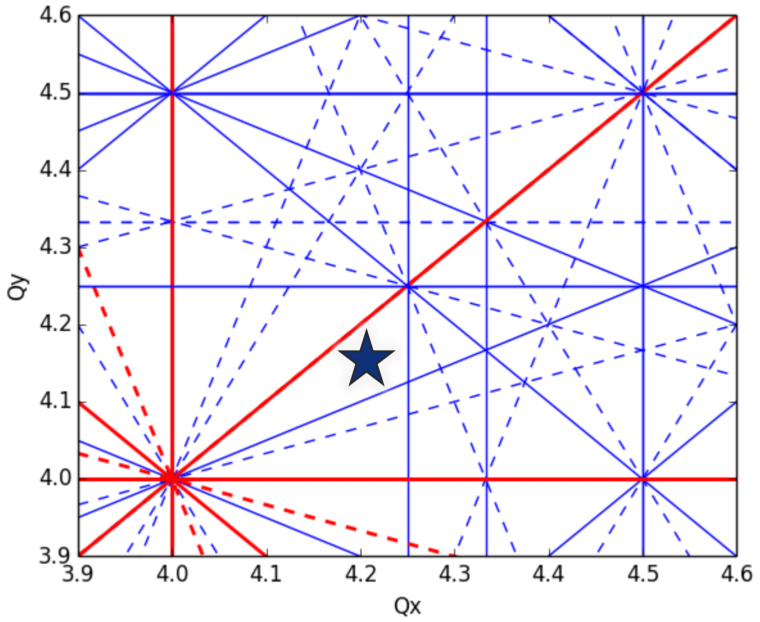
  - Dipole errors deflect a particle each turn in phase if tune is an integer N
  - Quadrupole errors are in phase if tune is an integer N or a half integer N+1/2
  - The 2 dimensional resonance condition is $kQ_x + lQ_y = m$ for *k, l, m* integers



$|k| + |l| \longrightarrow$ order of the resonance

Resonance lines ("forbidden") can be represented in the tune space, their excitation depends on the magnetic errors → Important to have an accurate magnetic model of the machine!

The "**working point**" is defined by the tunes of the machine (as determined by the focusing)

The machine tune and resonances

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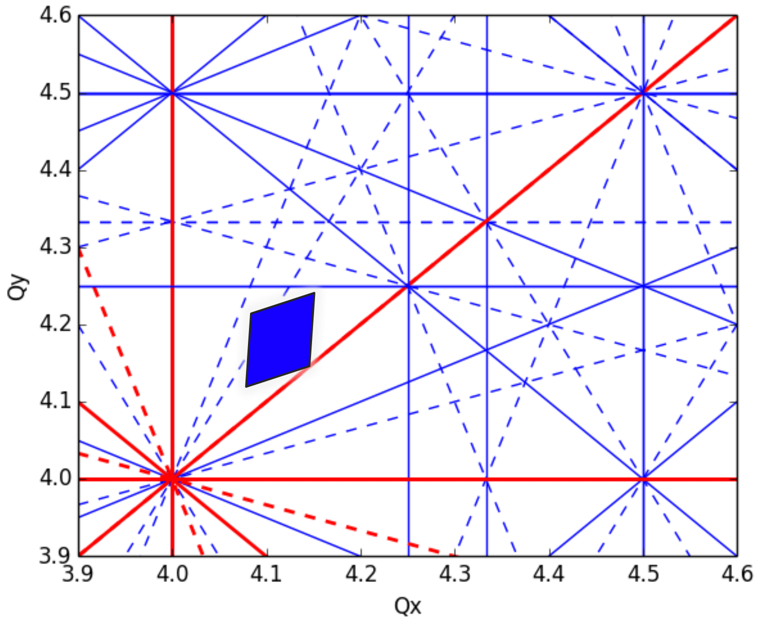


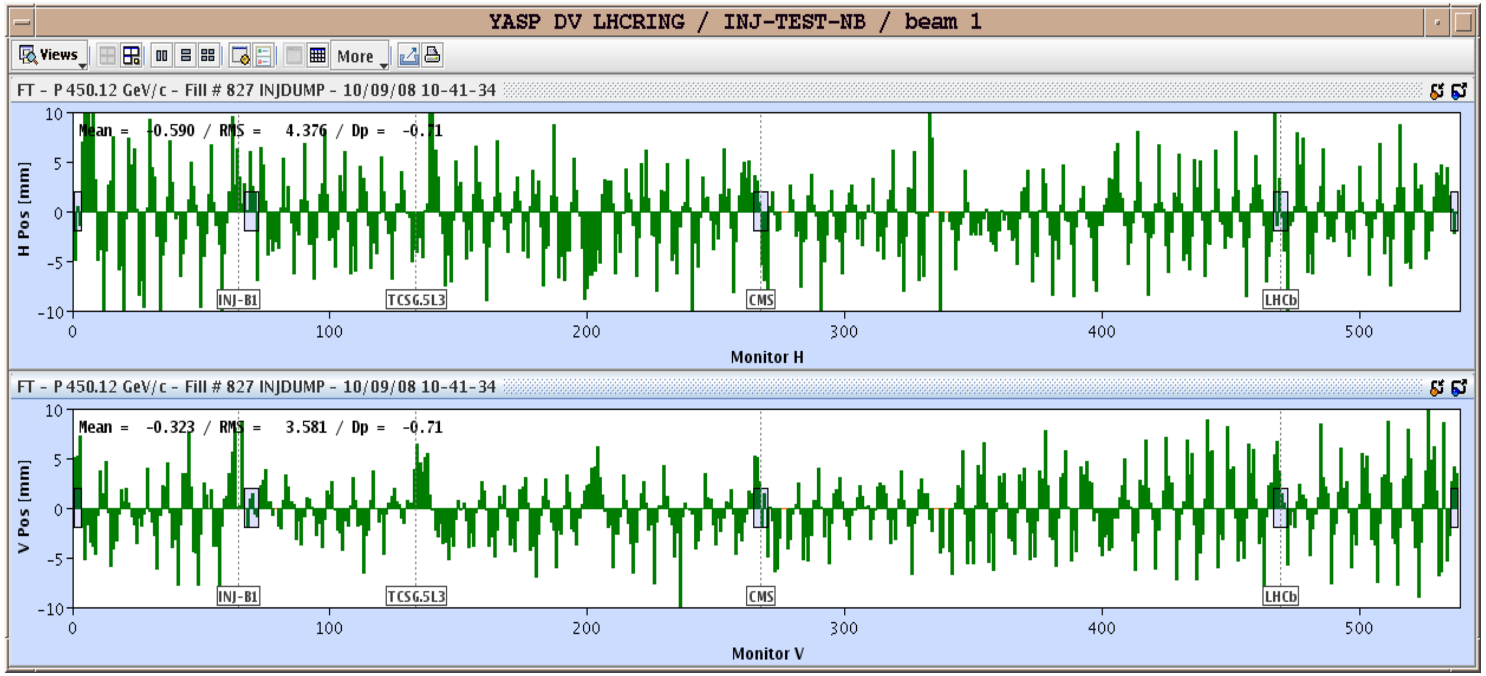
More complicated picture …

A beam is made of several particles oscillating at slightly different frequencies (for various reasons) → The area covered by all these tunes is the **beam tune footprint**

The challenge is to find the best area to fit the footprint (avoid resonance lines excited in the machine)

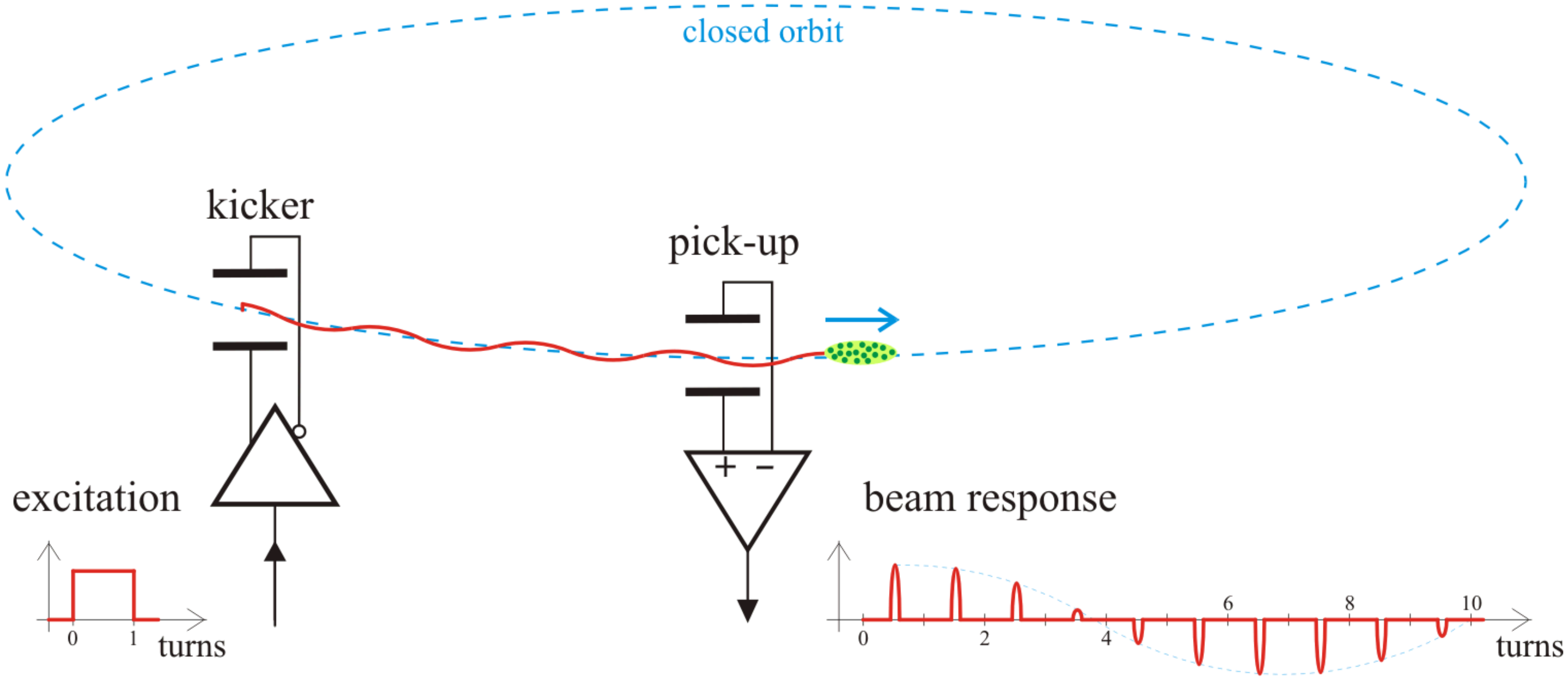
Tune measurements

- To see the full betatron oscillation and **measure the integer part of the tune**, several beam position monitors (BPM's) are needed – usually 4-10 times the tune – which can detect the beam transverse offset (horizontal and vertical) at different locations along the ring over the same turn



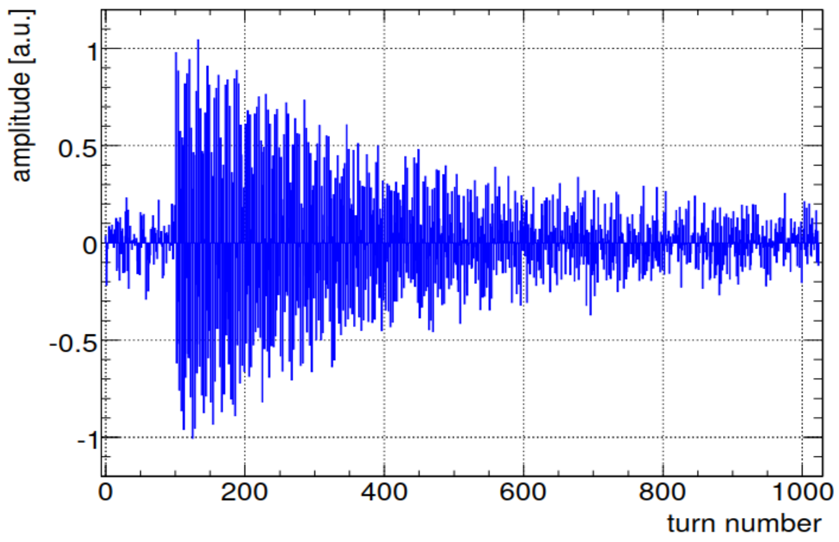
Tune measurements

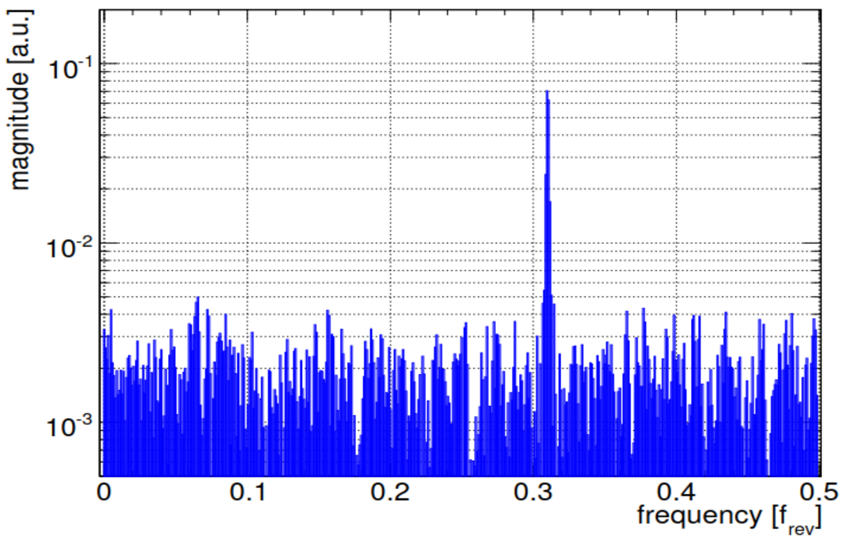
- To **measure the fractional part of the tune**, one beam position monitor (BPM) is sufficient
- The beam is excited through a 'kicker' and its position at the location of the BPM is recorded over several turns



Tune measurements

- To **measure the fractional part of the tune**, one beam position monitor (BPM) is sufficient
- The beam is excited through a ‘kicker’ and its position at the location of the BPM is recorded over several turns
- The Fourier transform of this signal provides the fractional part of the tune

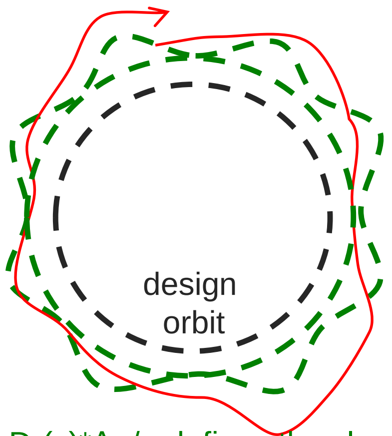




Off-momentum particles: Dispersion

- A particle with momentum $p_0+\Delta p=p_0(1+\delta)$ will move on a different orbit

$$x'' + K_x(s)\,x = \frac{1}{\rho(s)}\frac{\Delta p}{p}$$



$D_x(s)*\Delta p/p$ defines the closed orbit for off-momentum particles

$$x(s) = \sqrt{2J_x\beta_x(s)}\cos\left(\psi_x(s)+\psi_x(s_0)\right) + D_x(s)\frac{\Delta p}{p}$$

solution of $x'' + K_x(s)\,x = 0$

particular solution with "dispersion" D_x

$$D_x''(s) + K_x(s)D_x(s) = \frac{1}{\rho(s)}$$

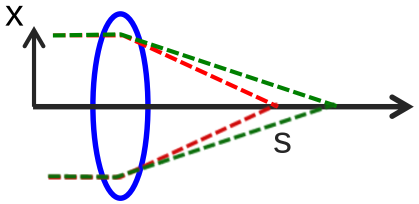
Other effects for off-momentum particles

- The path length of the particles changes, to the lowest order in δ, by

$$\Delta C = \oint \frac{x}{\rho(s)} ds = \left[\oint \frac{D_x(s)}{\rho(s)} ds \right] \delta \quad \Rightarrow \quad \alpha_0 \equiv \frac{\Delta C / C}{\Delta p / p_0} = \frac{1}{C} \oint \frac{D_x(s)}{\rho(s)} ds$$

- Particles with different momenta are focused differently by the quadrupoles, leading to different tunes

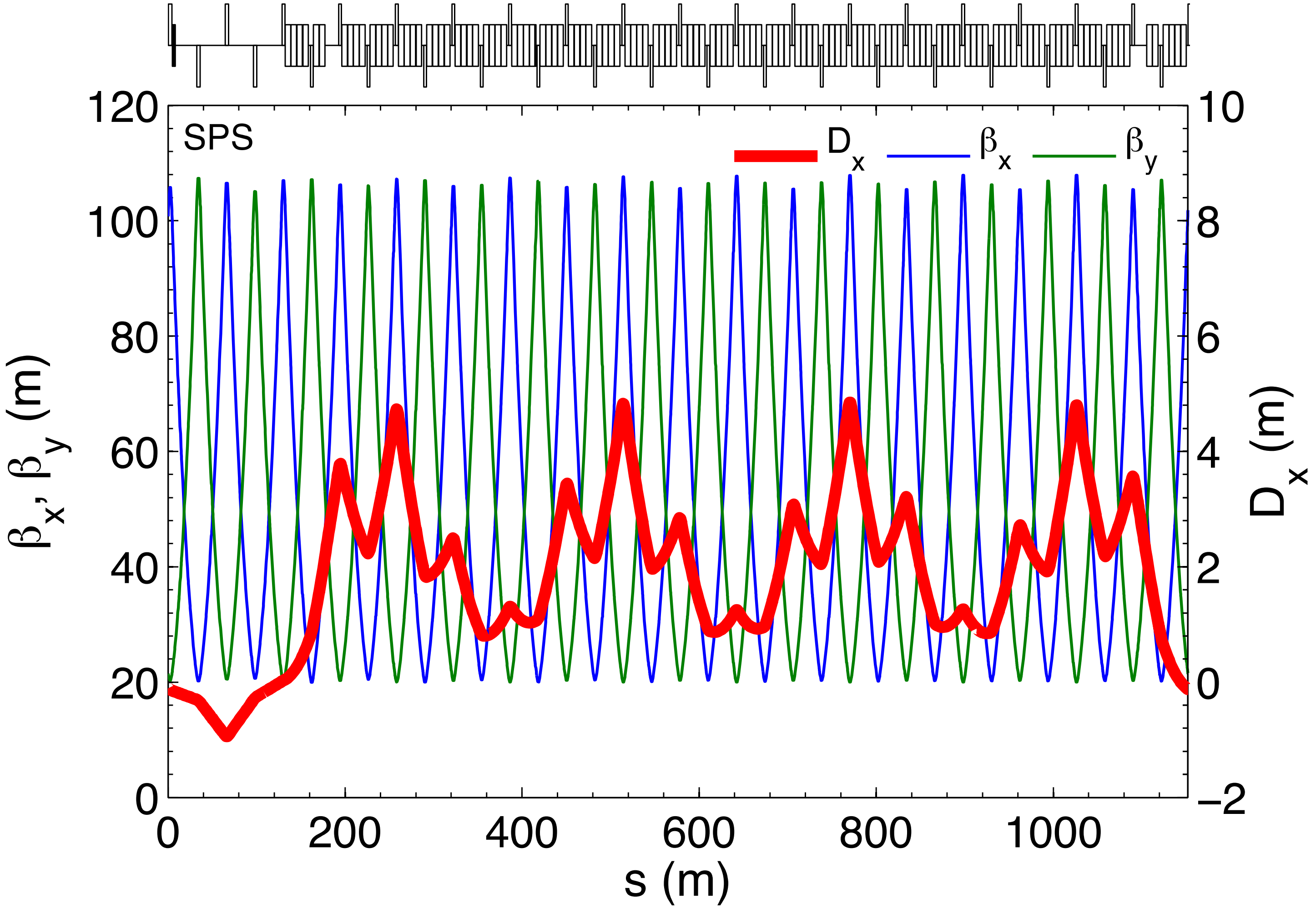
→ **Chromaticity** is the ratio between tune variation and momentum offset



$$\xi_{x,y} = \frac{\Delta Q_{x,y} / Q_{x,y}}{\delta}$$

Example of beta functions and dispersion

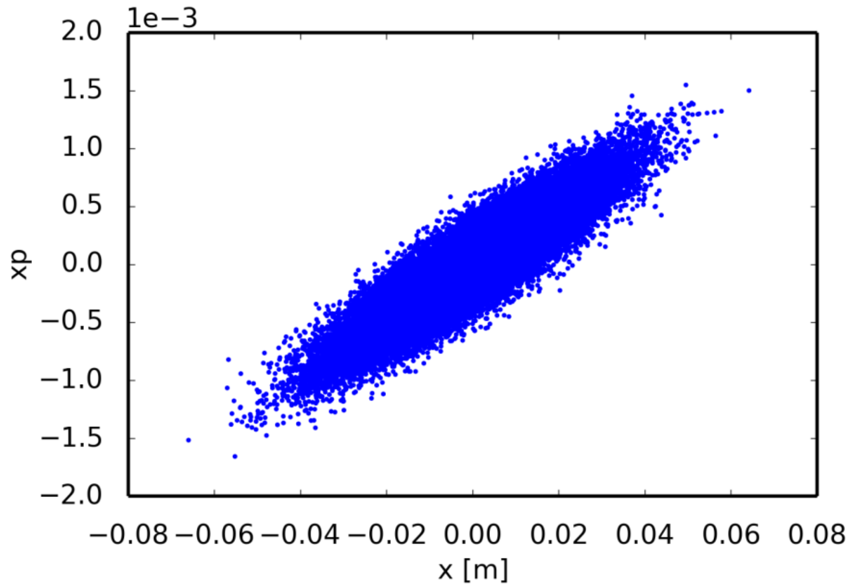
CERN Super Proton Synchrotron (SPS)



From single particles to a beam

- Up to now we have described the motion of individual particles …
- A beam consists of N particles which can be described by a particle distribution function

$$\int \psi(u,u')\,du\,du' = N$$



statistical moments of the distribution

$$\langle u\rangle = \frac{1}{N}\int u\psi(u,u')\,du\,du'$$

$$\langle u'\rangle = \frac{1}{N}\int u'\psi(u,u')\,du\,du'$$

$$\sigma_u^2 = \frac{1}{N}\int (u-\langle u\rangle)^2\,\psi(u,u')\,du\,du'$$

$$\sigma_{u'}^2 = \frac{1}{N}\int (u'-\langle u'\rangle)^2\,\psi(u,u')\,du\,du'$$

$$\sigma_{uu'} = \frac{1}{N}\int (u-\langle u\rangle)\,(u'-\langle u'\rangle)\,\psi(u,u')\,du\,du'$$

From single particles to a beam

- The **beam size in the u-u' phase space** is usually quantified by the **rms statistical emittance** (also called geometrical emittance)

$$\varepsilon_u = \sqrt{\sigma_u^2 \sigma_{u'}^2 - \sigma_{uu'}^2}$$

  - The transverse momentum in the accelerator is given by $p_u = m\beta c\gamma u'$
  - Liouville theorem → volumes in the canonical phase space **u – $\mathbf{p_u}$** are invariant under Hamiltonian evolution

- We define the **normalized emittance**, which is independent of beam energy

$$\varepsilon_u^n = \beta\gamma\varepsilon_u$$

- However there are effects that can lead to emittance blow-up, such as scattering between particles, non-linearities, wake fields, space charge…

From single particles to a beam

- For a steady (matched) distribution, the rms geometrical emittance is related to the rms beam sizes and beta functions at a certain accelerator location by

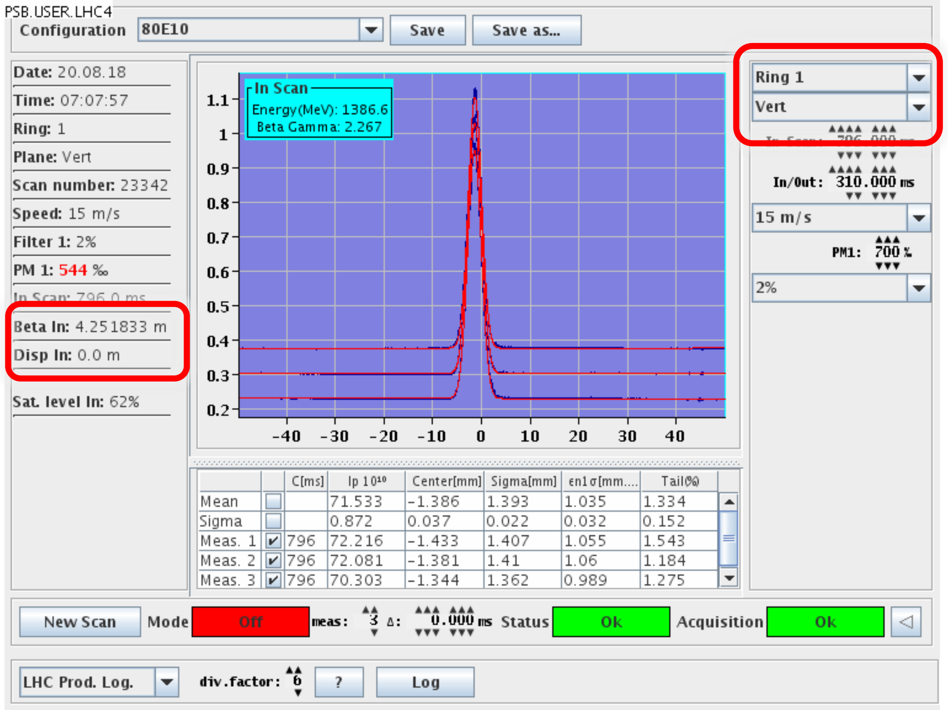
$$\sigma_x(s) = \sqrt{\beta_x(s)\epsilon_x + D_x^2(s)\delta^2}$$

$$\sigma_y(s) = \sqrt{\beta_y(s)\epsilon_y}$$

- This provides a way to measure beam emittances in a ring, by measuring directly beam profiles and assuming the knowledge of the machine optics (and momentum distribution in the horizontal plane)

Emittance measurement with flying wire

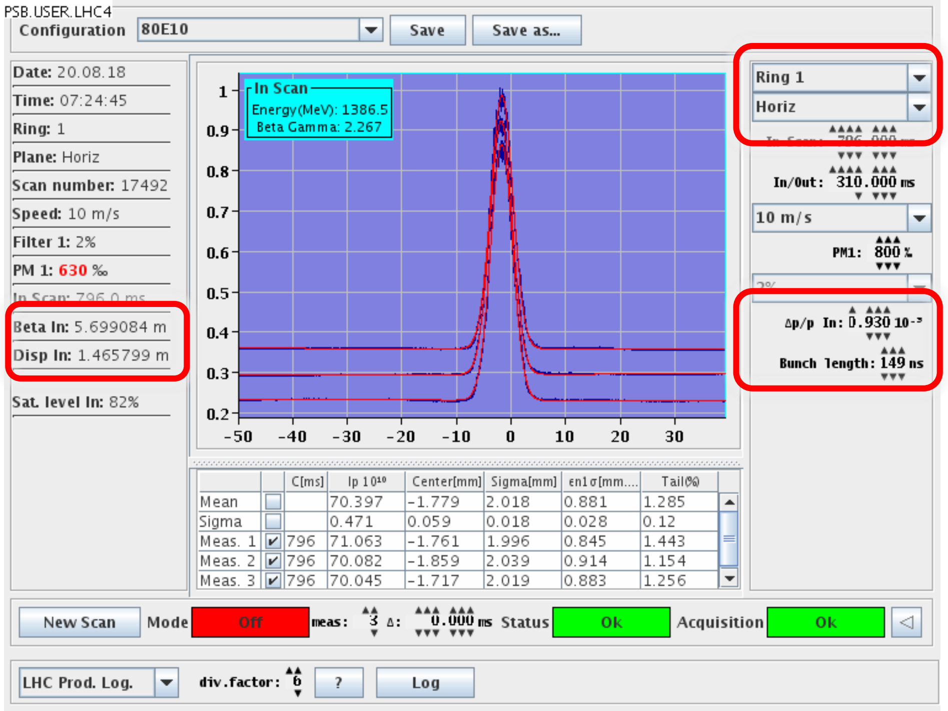
- In the vertical plane, the beam profile is measured and the beam emittance is derived knowing the beta function at the location of the measurement device (in this case, a wire flown across the beam over several turns)



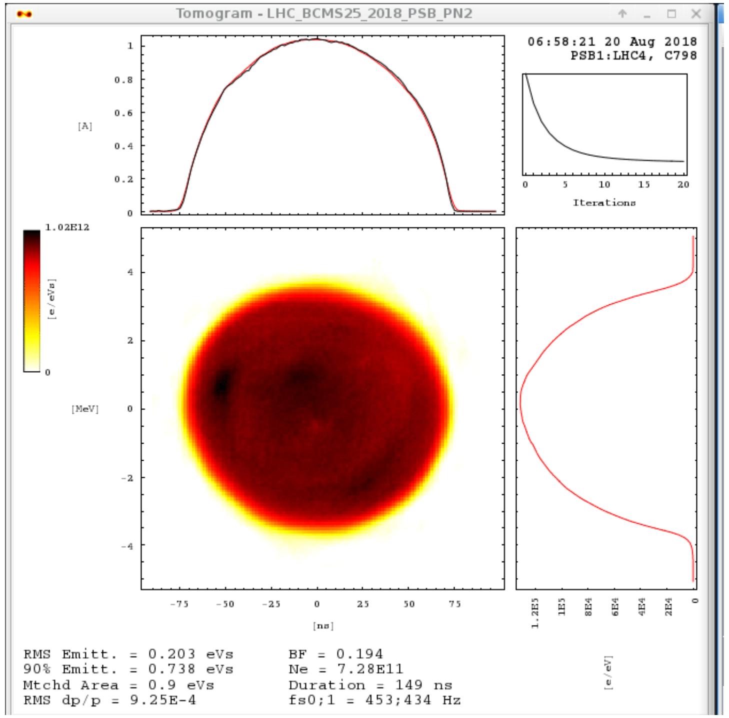
- Several measurements to reduce statistical fluctuation
- Obtain sigma of beam horizontal distribution, but also position of the beam at wire location and beam intensity – if calibrated
- Estimate population in the tails and Gaussian-ity of the profile

Emittance measurement with flying wire

- In the horizontal plane, the beam profile is measured and the beam emittance is derived knowing the beta function and the dispersion at the location of the measurement device, as well as the momentum spread of the beam



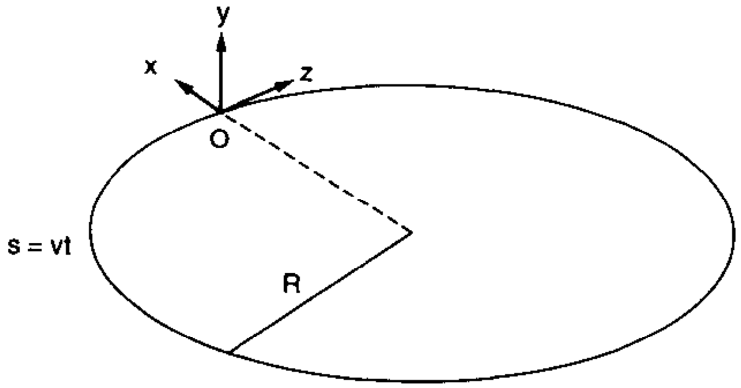
		C[ms]	Ip 10¹⁰	Center[mm]	Sigma[mm]	εn1σ[mm....	Tail%
Mean			70.397	-1.779	2.018	0.881	1.285
Sigma			0.471	0.059	0.018	0.028	0.12
Meas. 1	✔	796	71.063	-1.761	1.996	0.845	1.443
Meas. 2	✔	796	70.082	-1.859	2.039	0.914	1.154
Meas. 3	✔	796	70.045	-1.717	2.019	0.883	1.256



- Fundamental concepts of beam dynamics
  - Basics & CERN accelerator complex
  - Transverse beam dynamics and relevant quantities
  - **Longitudinal beam dynamics and relevant quantities**
  - Advanced concepts: Collective interactions (space charge, impedance, electron clouds)

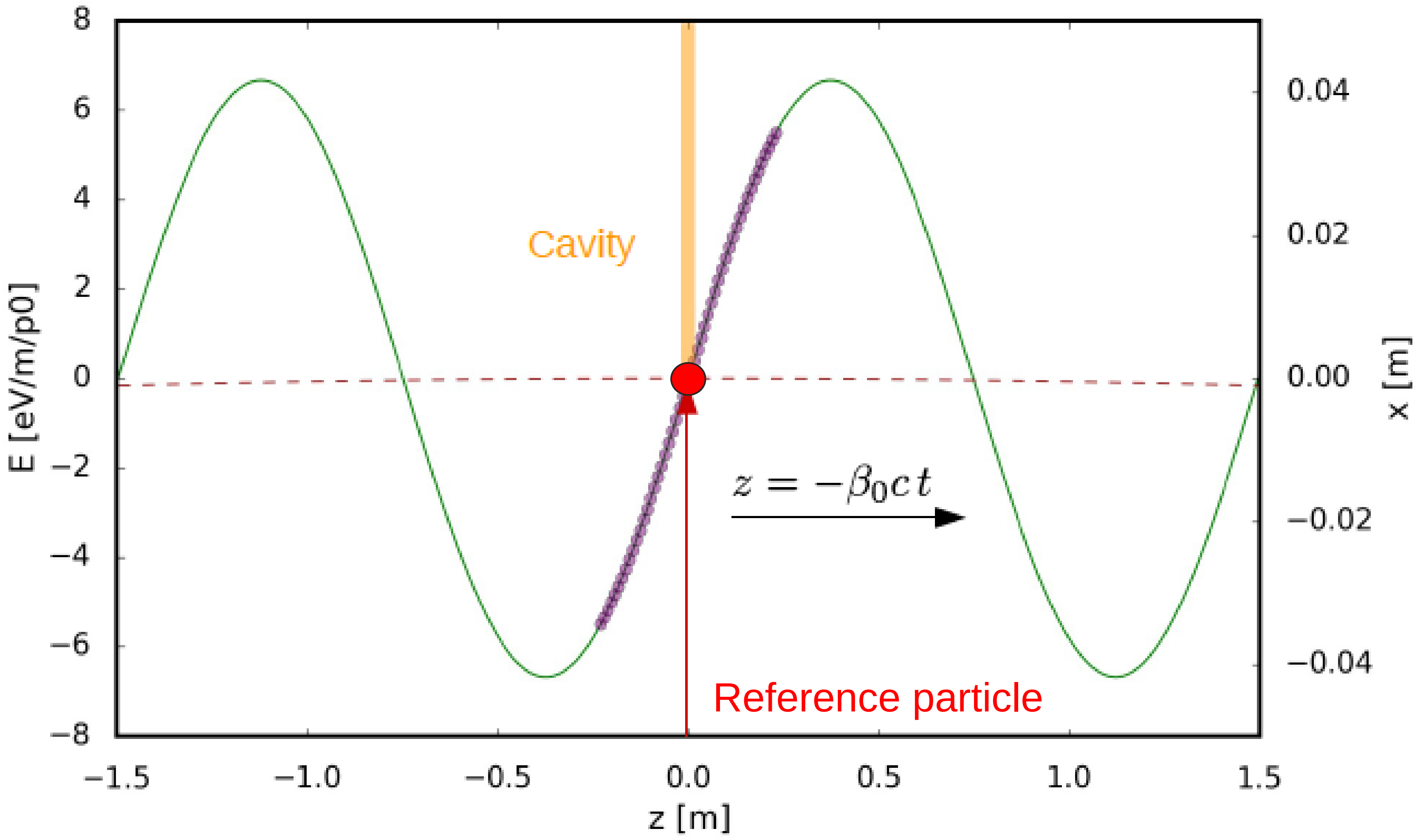
- Upgrade of the LHC injector complex
  - Goals vs. present performance
  - Upgrade plans
  - Beam dynamics challenges

Longitudinal motion of particles

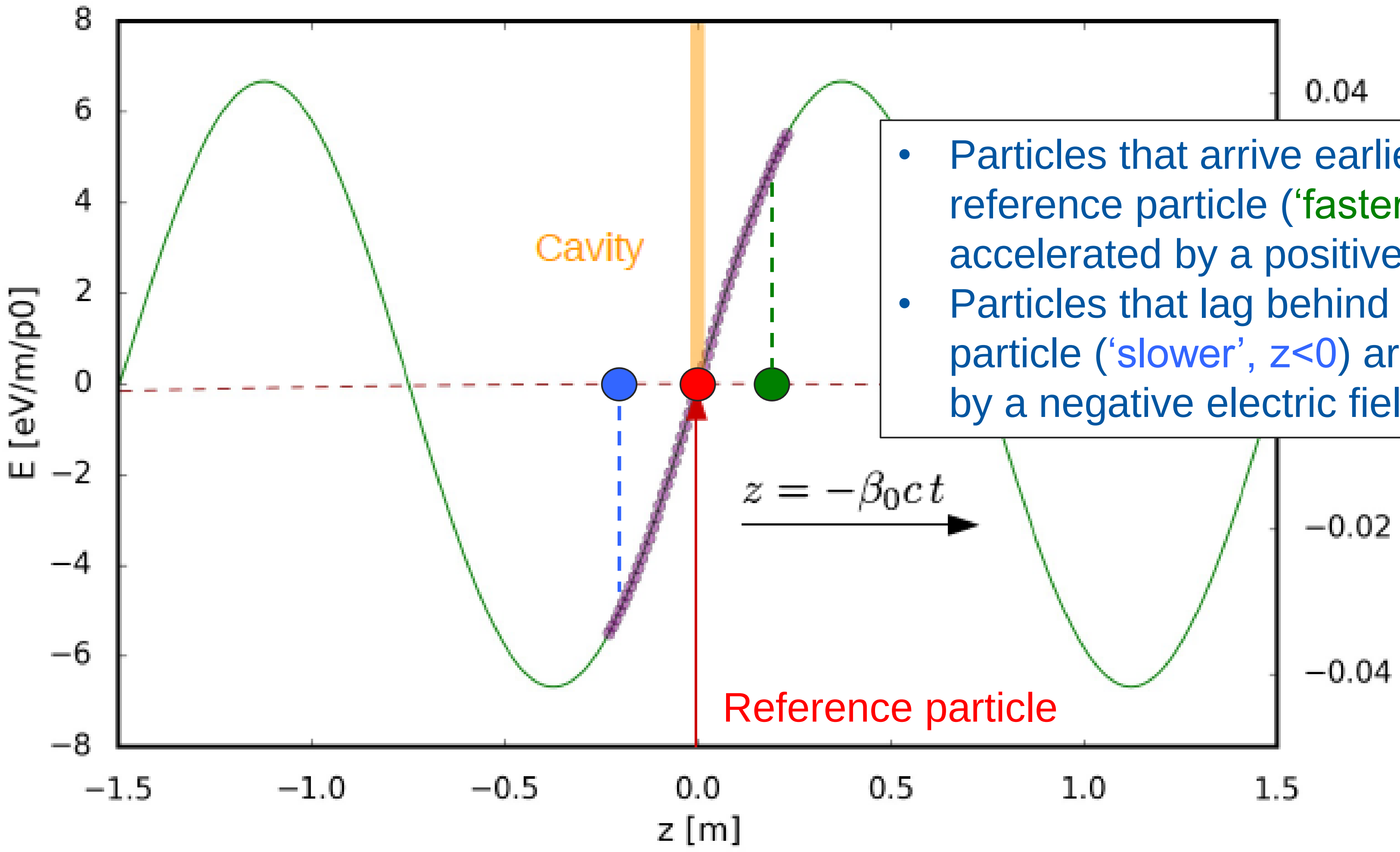


- The particle in z=0 has the reference momentum p_0 and is moving on the reference orbit
  - It does not ‘slip’ longitudinally
  - It is called synchronous particle
- The synchronous particle
  - Is synchronized with the zero crossing of the electric field in the cavity if no acceleration
  - Is synchronized with ΔE per turn matching the acceleration rate (dB/dt)

Longitudinal motion of particles



Longitudinal motion of particles



- Particles that arrive earlier than the reference particle (‘faster’, z>0) are accelerated by a positive electric field
- Particles that lag behind the reference particle (‘slower’, z<0) are decelerated by a negative electric field

Longitudinal focusing

- Does the situation on the previous slide provide longitudinal focusing?
- ‘Faster’ particle in an accelerator (i.e. particles with shorter revolution time than the reference particle) does not necessarily imply ‘more energetic’ particle …

$$T = \frac{C}{\beta c}$$

$$\frac{\Delta T}{T_0} = \frac{\Delta C}{C_0} - \frac{\Delta \beta}{\beta_0}$$

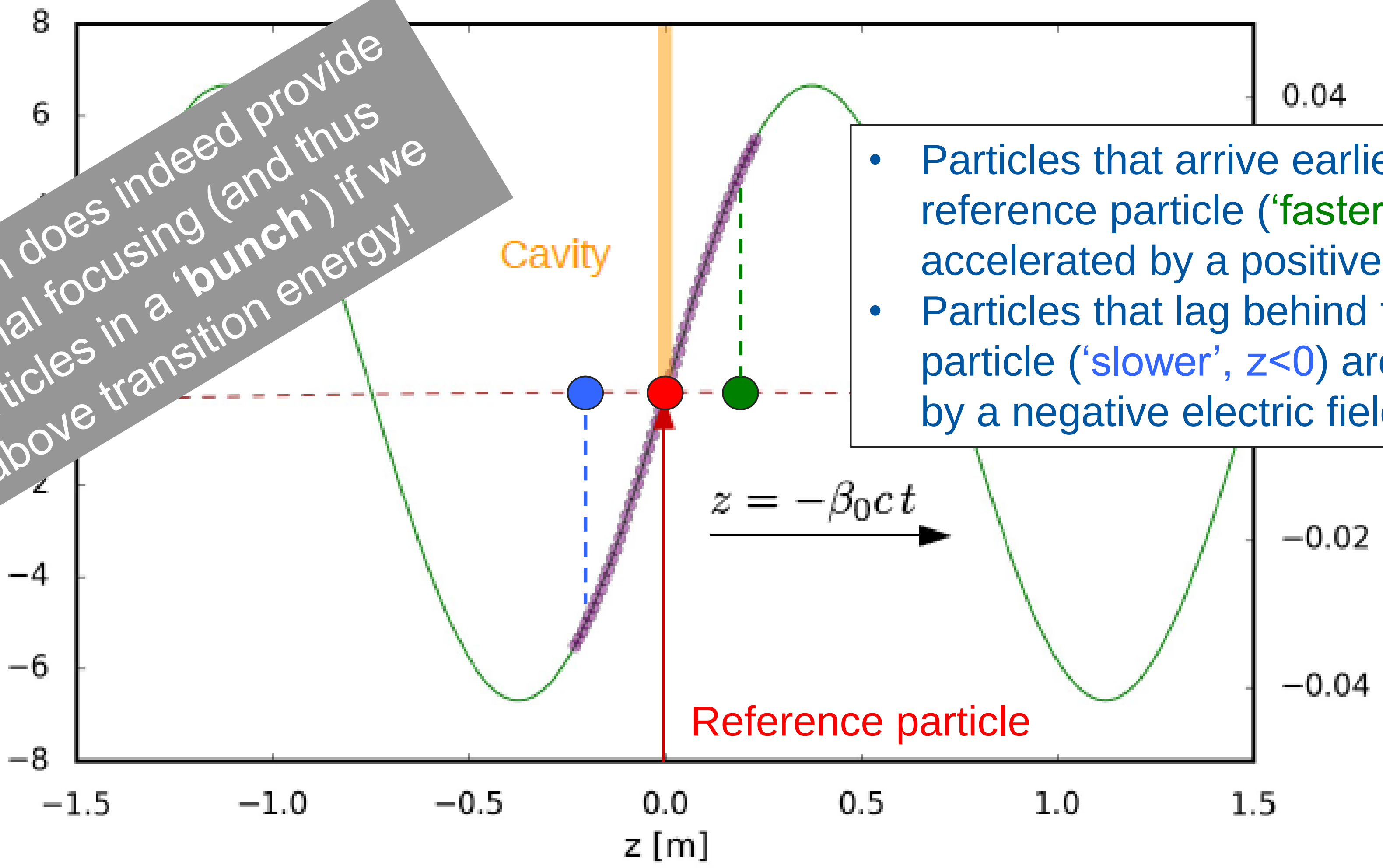
$$\Rightarrow \quad \frac{\Delta T}{T_0} = \underbrace{\left(\alpha - \frac{1}{\gamma^2}\right)}\delta = \eta\delta$$

Particles with higher energy, or positive momentum deviation (δ>0), are only ‘faster’ is $\gamma < \gamma_t$ (=1/$\sqrt{\alpha}$), or $\eta<0$

Longitudinal focusing

- The momentum compaction α, and therefore the transition energy γ_t, are defined by the machine optics
- A machine is operating **above transition** when the energy of the reference particle is above transition energy ($\gamma > \gamma_t$ or $\eta > 0$)
  - More energetic particles take longer to go around, so you need to accelerate particles to effectively slow them down
- A machine is operating **below transition** when the energy of the reference particle lies below transition energy ($\gamma < \gamma_t$ or $\eta < 0$)
  - More energetic particles take shorter times to go around, so you need to accelerate particles to effectively make them faster
- Some synchrotrons cross transition during acceleration
  - Right at transition energy, all particles take the same time to go around and the longitudinal phase space of the beam is ‘frozen’

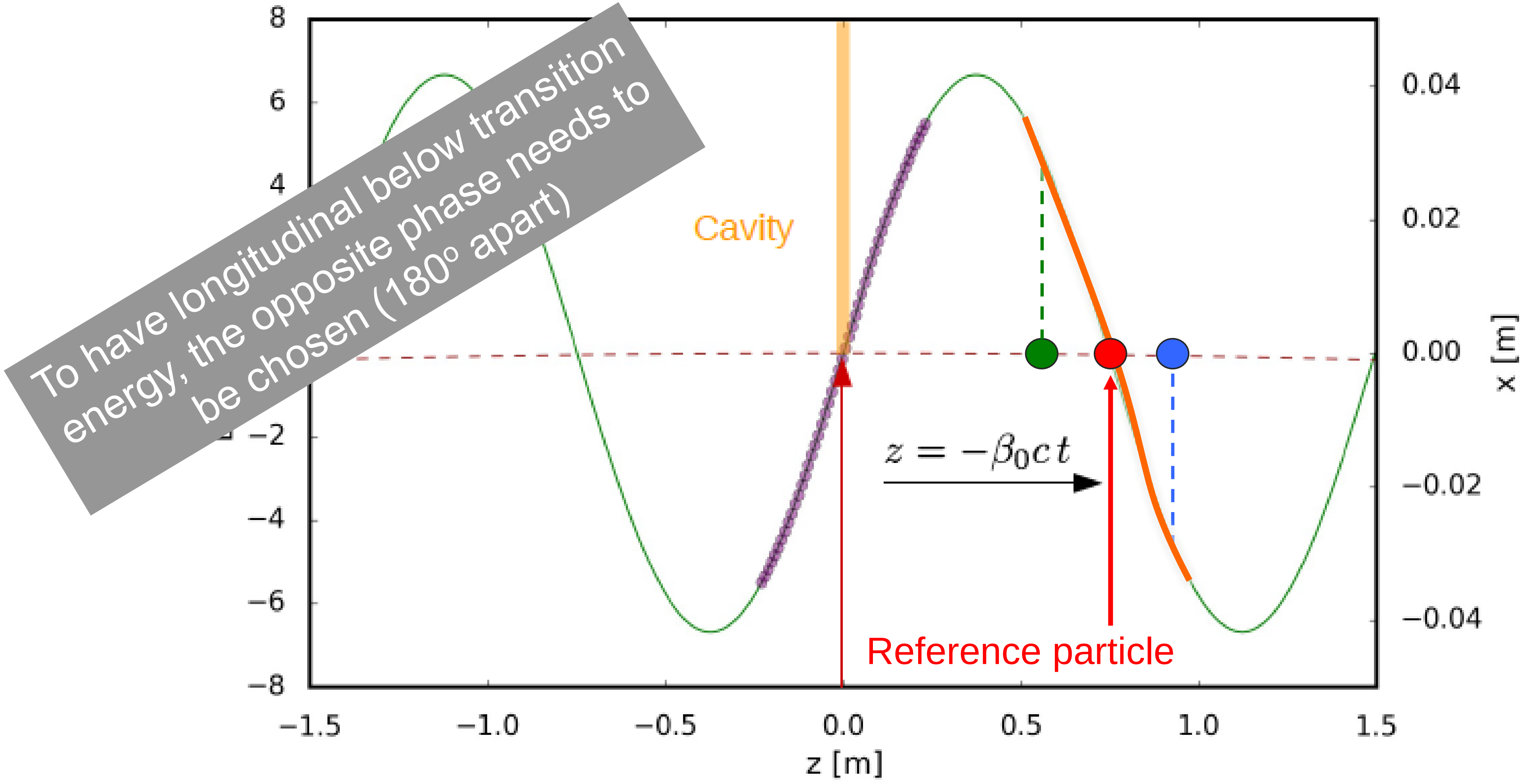
Longitudinal focusing



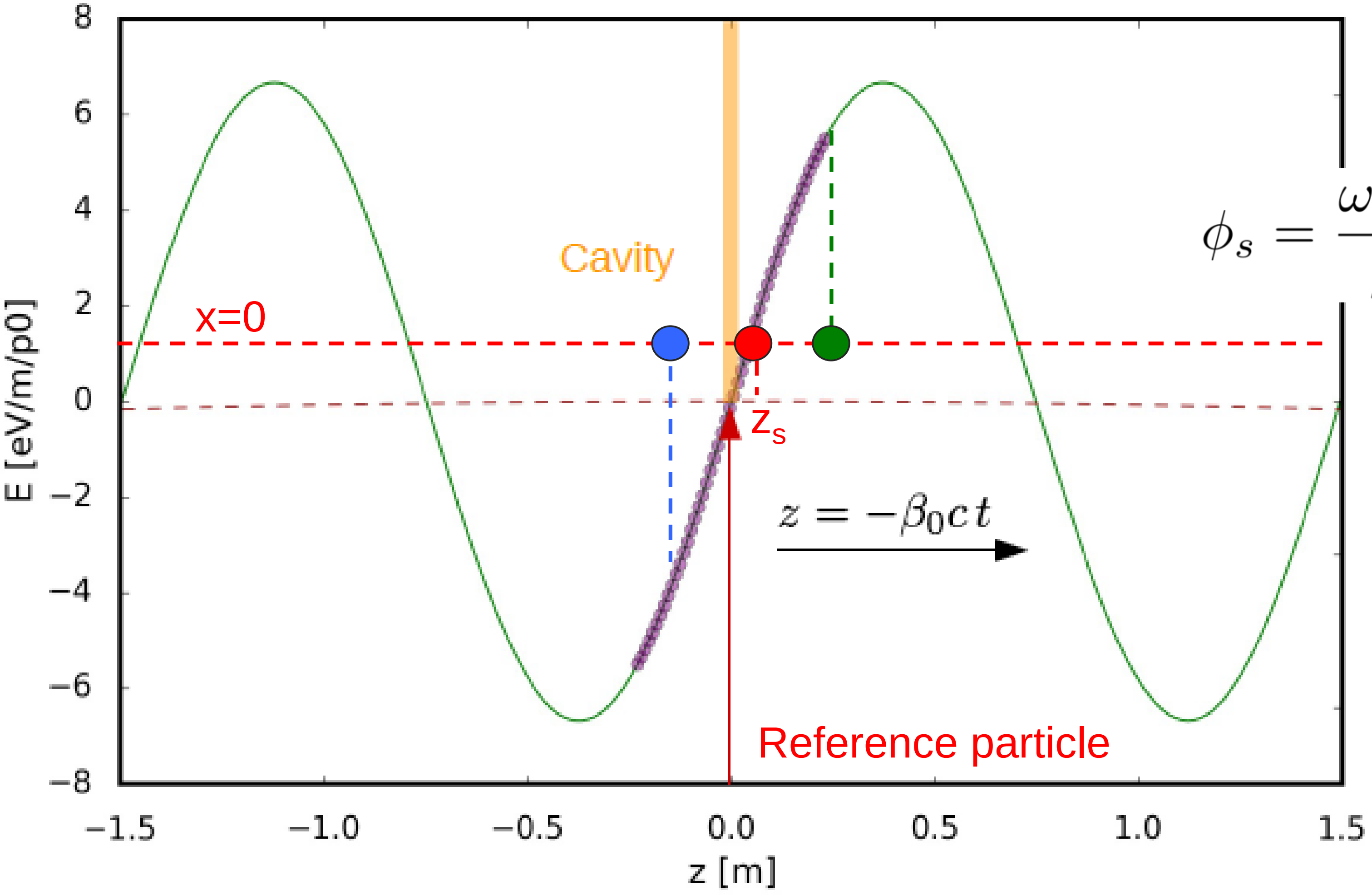
This situation does indeed provide longitudinal focusing (and thus keep particles in a '**bunch**') if we are above transition energy!

- Particles that arrive earlier than the reference particle ('faster', z>0) are accelerated by a positive electric field
- Particles that lag behind the reference particle ('slower', z<0) are decelerated by a negative electric field

Longitudinal focusing



Acceleration (above transition)

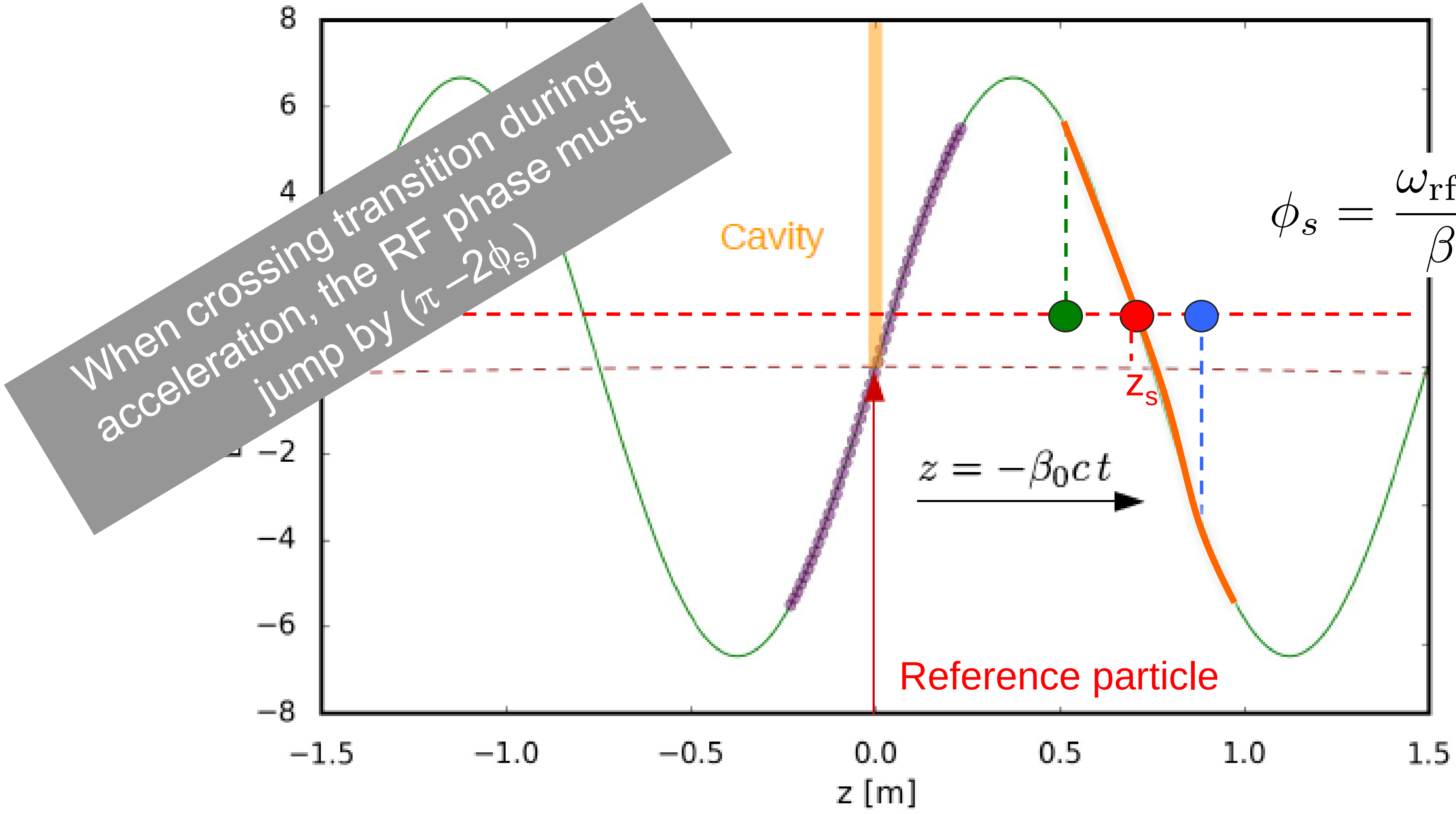


$$\phi_s = \frac{\omega_{\rm rf} z_s}{\beta c} = \arcsin\left(\frac{\Delta E}{eV_m}\right)$$

The energy gain per turn ΔE is defined by the rate of increase of the magnetic field dB/dt

The radiofrequency ω_{rf} is a multiple of the revolution frequency, $h\omega_0$

Acceleration (below transition)



$$\phi_s = \frac{\omega_{\rm rf} z_s}{\beta c} = \pi - \arcsin\left(\frac{\Delta E}{eV_m}\right)$$

The energy gain per turn ΔE is defined by the rate of increase of the magnetic field dB/dt

The radiofrequency ω_{rf} is a multiple of the revolution frequency, $h\omega_0$

Equation of longitudinal motion

$$\ddot{\zeta} + \underbrace{\left(\frac{e V_m h \eta \beta c}{p_0 C R} \cos \Phi_s \right)}_{\omega_s^2} \zeta = 0$$

$(z - z_s)$

Synchrotron tune

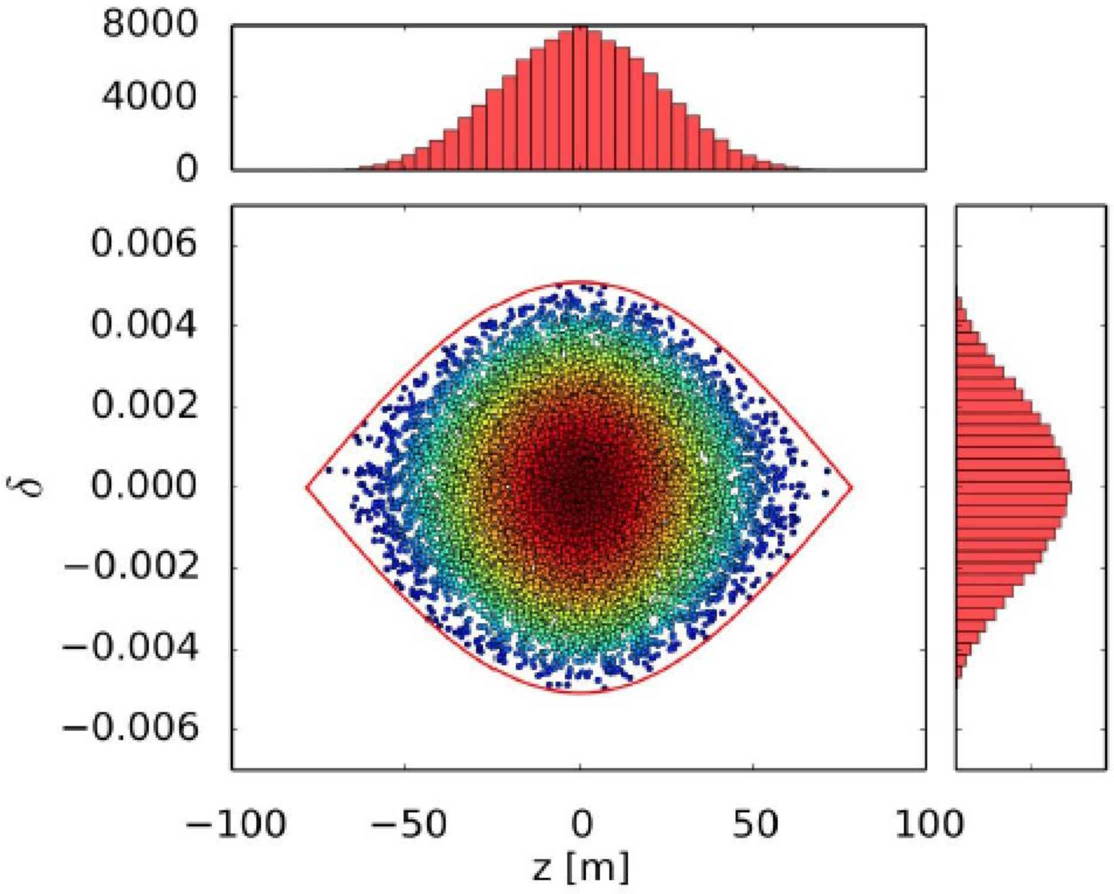
$$Q_s = \frac{\omega_s}{\omega_0} = \sqrt{\frac{V_m[\mathrm{MV}] h \eta \cos \Phi_s}{2\pi \beta^2 E_0[\mathrm{MeV}]}}$$

$$\text{Note that}: \; \eta \cos \Phi_s = |\eta \cos \Phi_s| \geq 0$$

Synchrotron tune

- The inverse of the **synchrotron tune** $1/Q_s$ represents the period of the synchrotron oscillation expressed in number of turns
- It is clearly determined by the strength of the RF cavity focusing (RF voltage and stable phase), the distance from transition (η), the particle energy (E_0)
- The synchrotron period is usually **tens to thousands of turns**
  - Much longer than the betatron period, which is a fraction of turn → a particle performs several transverse oscillations over one turn, but then takes many turns to complete one full synchrotron oscillation
  - However, much shorter than the timescale of the acceleration (seconds to minutes, typically millions of turns)

A 'bunch' of particles

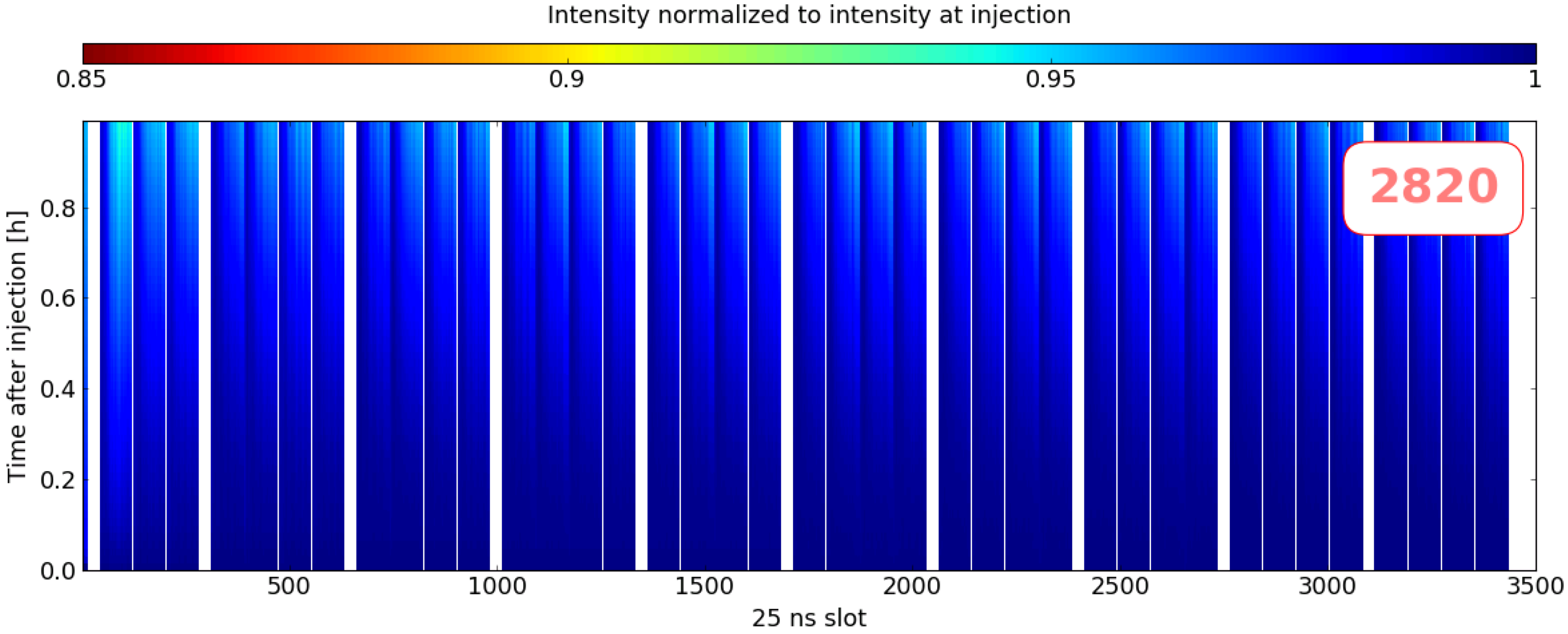


- Particles circulate in longitudinal phase space with Q_s in the core and lower frequencies at large amplitudes
- The distribution is stationary if rms bunch length (σ_z), rms momentum spread (σ_δ) and synchrotron tune (Q_s) satisfy

$$\frac{R|\eta|\sigma_\delta}{Q_s \sigma_z} = 1$$

- Each of the two beams in the LHC is made of **~2800** of such bunches!

A view on the beam in the LHC



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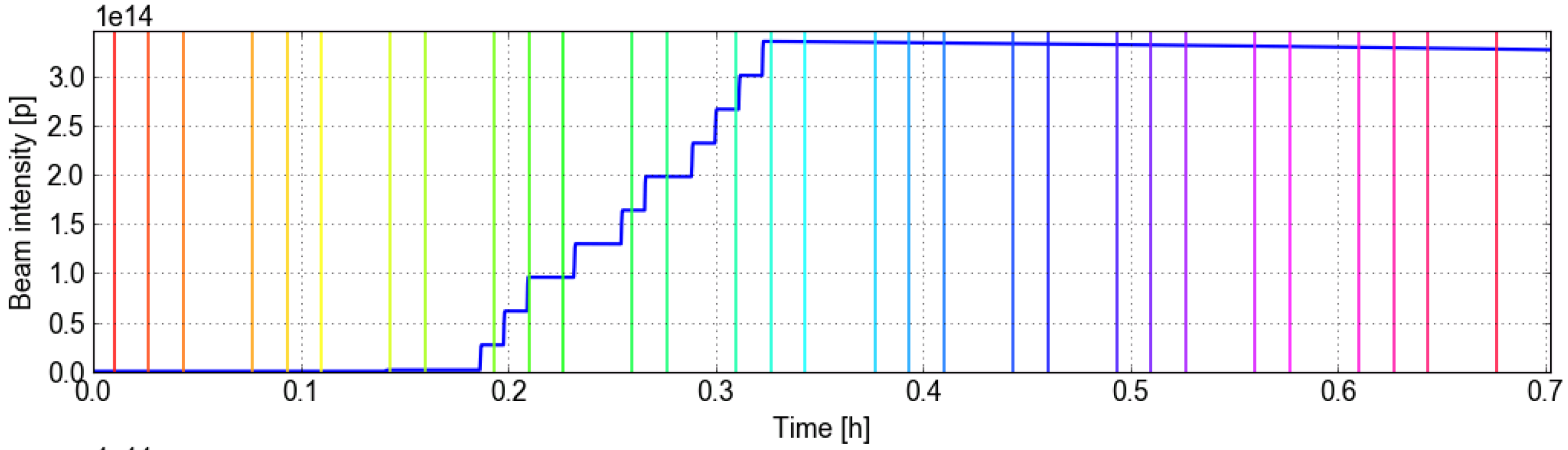
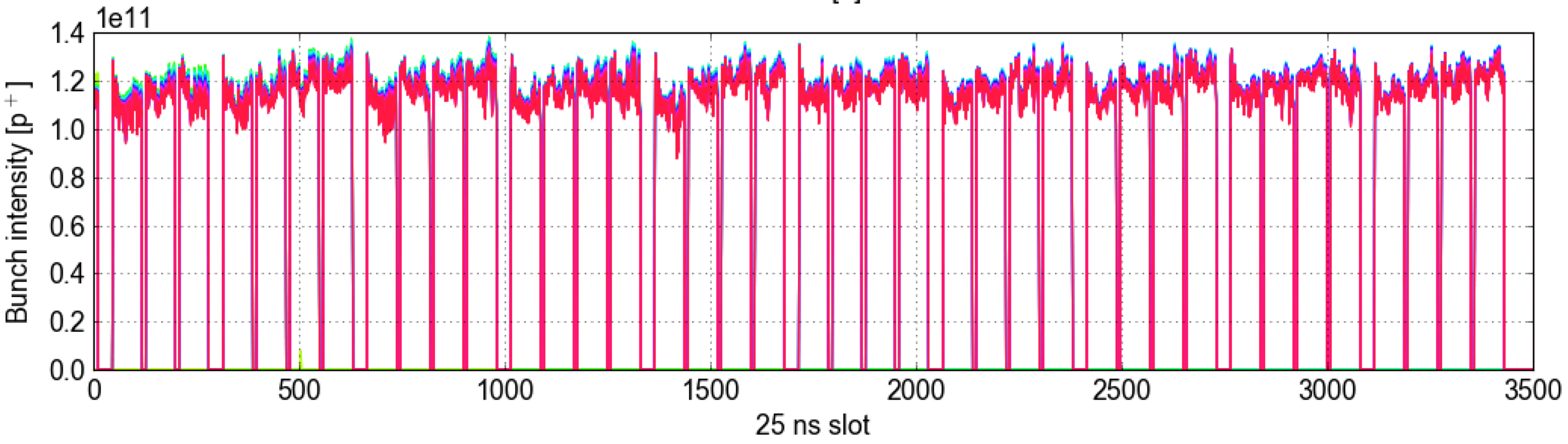
- To monitor beam in the LHC it is essential to look at the **bunch by bunch evolution of the beam parameters**
  - Bunch by bunch beam intensity (e.g. over one hour in the above plot)

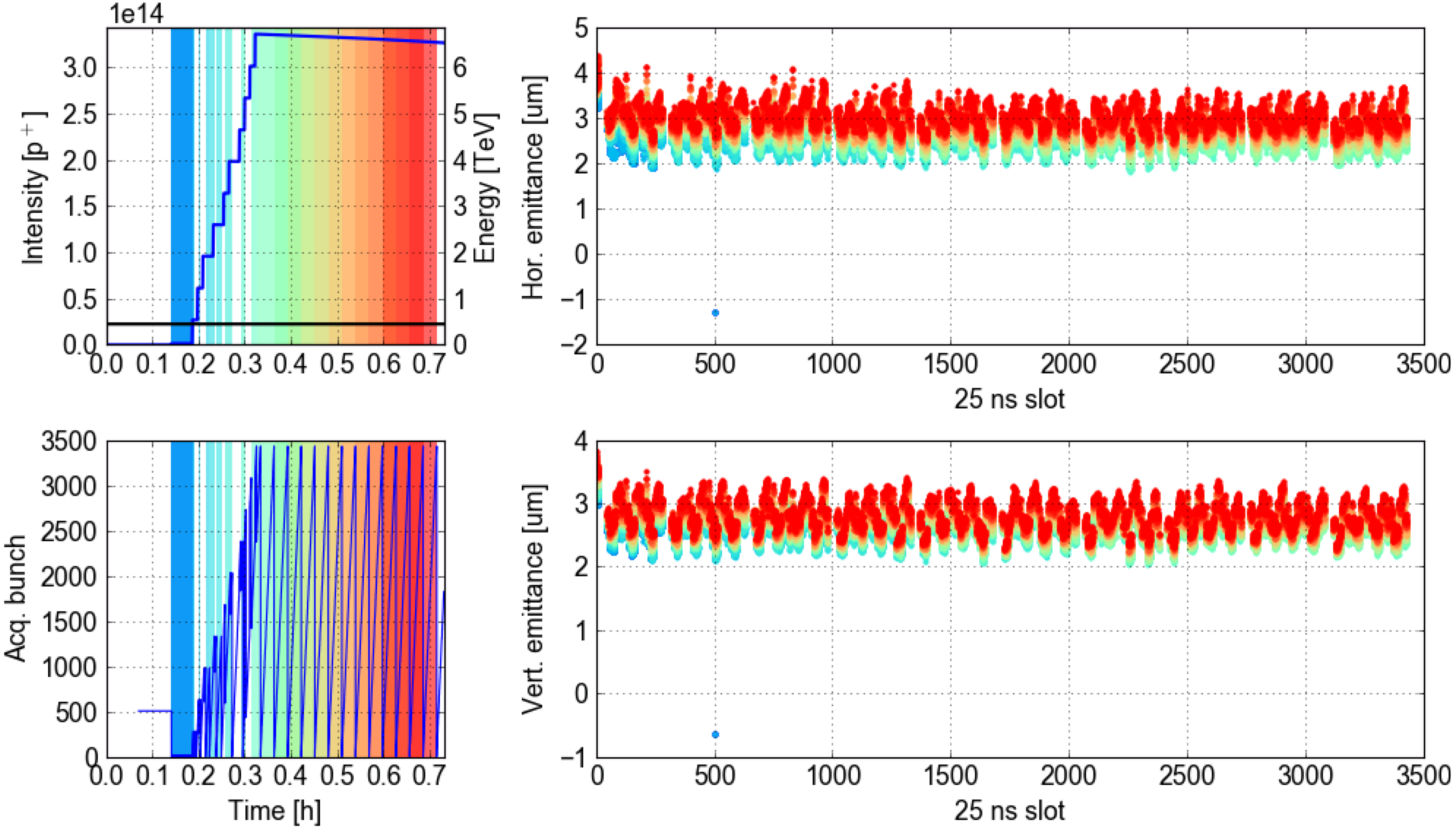
A view on the beam in the LHC





- Visualize total beam intensity in LHC
- Colored snapshots of bunch-by-bunch intensity

A view on the beam in the LHC



- Visualize total beam intensity in LHC
- Colored “snapshots” of bunch-by-bunch emittance (each snapshot takes several minutes)

- Fundamental concepts of beam dynamics
  - Basics & CERN accelerator complex
  - Transverse beam dynamics and relevant quantities
  - Longitudinal beam dynamics and relevant quantities
  - **Advanced concepts: Collective interactions (space charge, impedance, electron clouds)**
- Upgrade of the LHC injector complex
  - Goals vs. present performance
  - Upgrade plans
  - Beam dynamics challenges

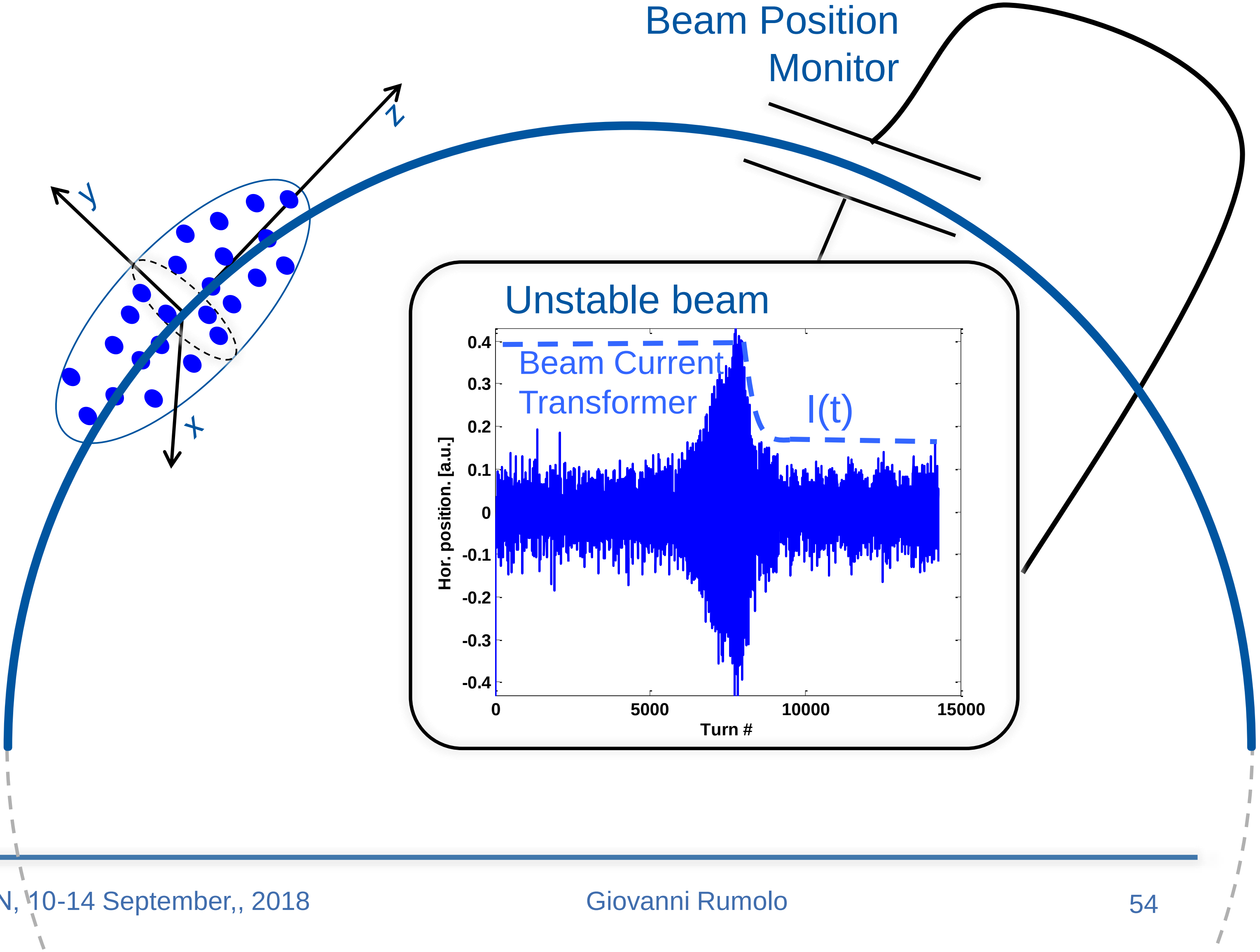
Effects on the beam

- When a particle beam is circulating in an accelerator, its dynamics depends unfortunately on much more than ideal magnets and RF cavities
- Some effects do not depend on the beam intensity, e.g.
  - Magnet misalignments and errors
  - Interaction with residual gas in the vacuum chamber
  - Synchrotron radiation
- Some other effects depend on beam parameters and specifically its intensity
  - Interaction with own space charge
  - Parasitic electromagnetic interactions with surrounding environment
  - Creation and accumulation of secondary particles
  - Beam-beam interactions in colliders

Multi-particle or collective effects
- Coherent
- Incoherent

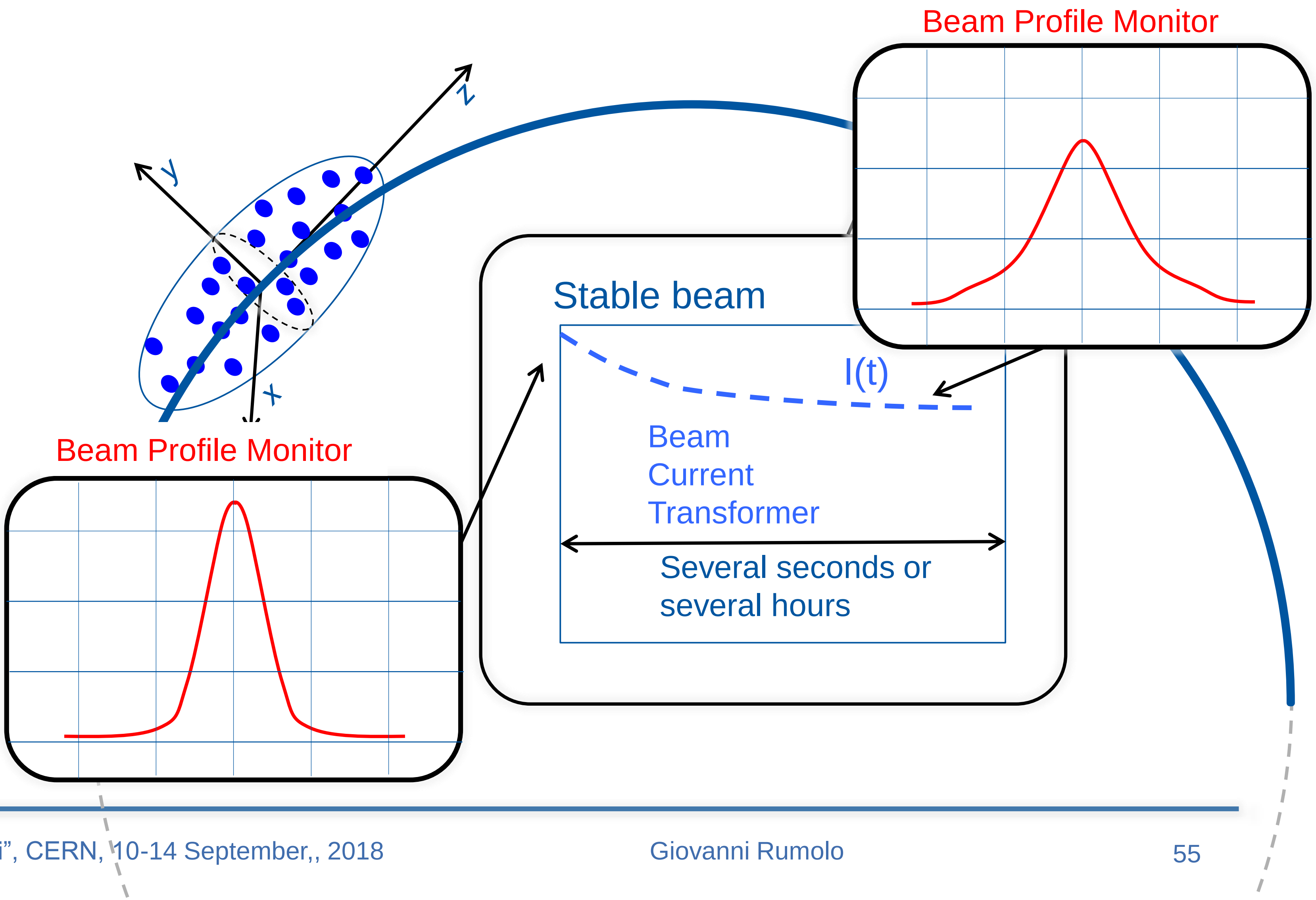
Coherent effects on the beam

- Coherent effects:
  Beam instabilities
  - The beam centroid, as detected by a BPM, exhibits an exponential growth typically on the time scale of tens to thousands of turns, usually associated with beam loss and/or emittance growth!



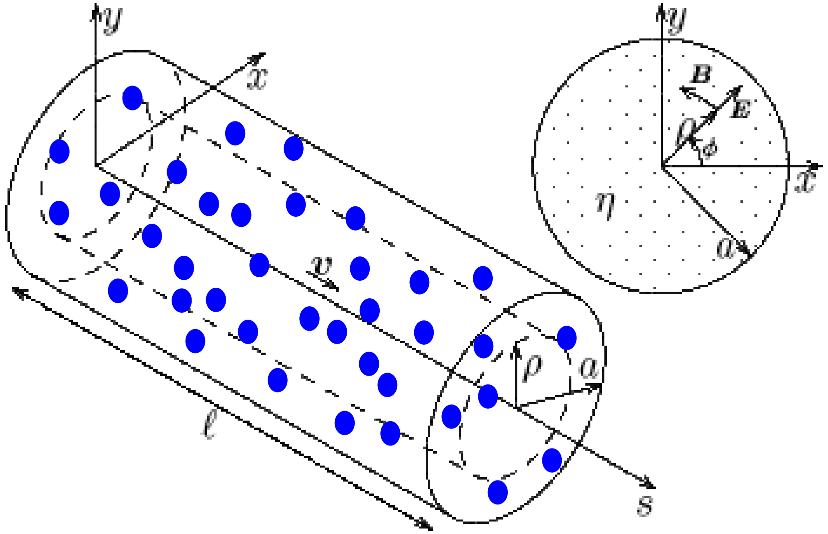
Incoherent effects on the beam

- Incoherent effects: Beam lifetime
  - A beam exhibits slow losses (on the time scale of the cycle or store) and emittance growth visible from a beam profile measurement device, possibly associated to development of halo or tails



Space charge

- The space charge of the beam itself is source of an additional driving term on each beam particle – to be added to the external bending and focusing
  - Repulsive electric and attractive magnetic interactions add up to a globally repulsive force (perfect cancelation only for β=1), which acts like a defocusing quadrupole → tune shift

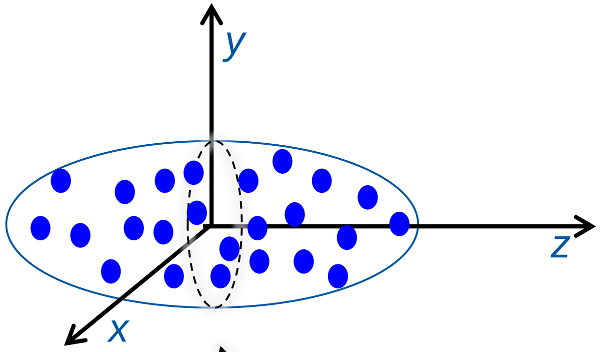


$$\vec{F} = \vec{F}_E + \vec{F}_B = e\left(\vec{E} + \vec{v} \times \vec{B}\right) =$$

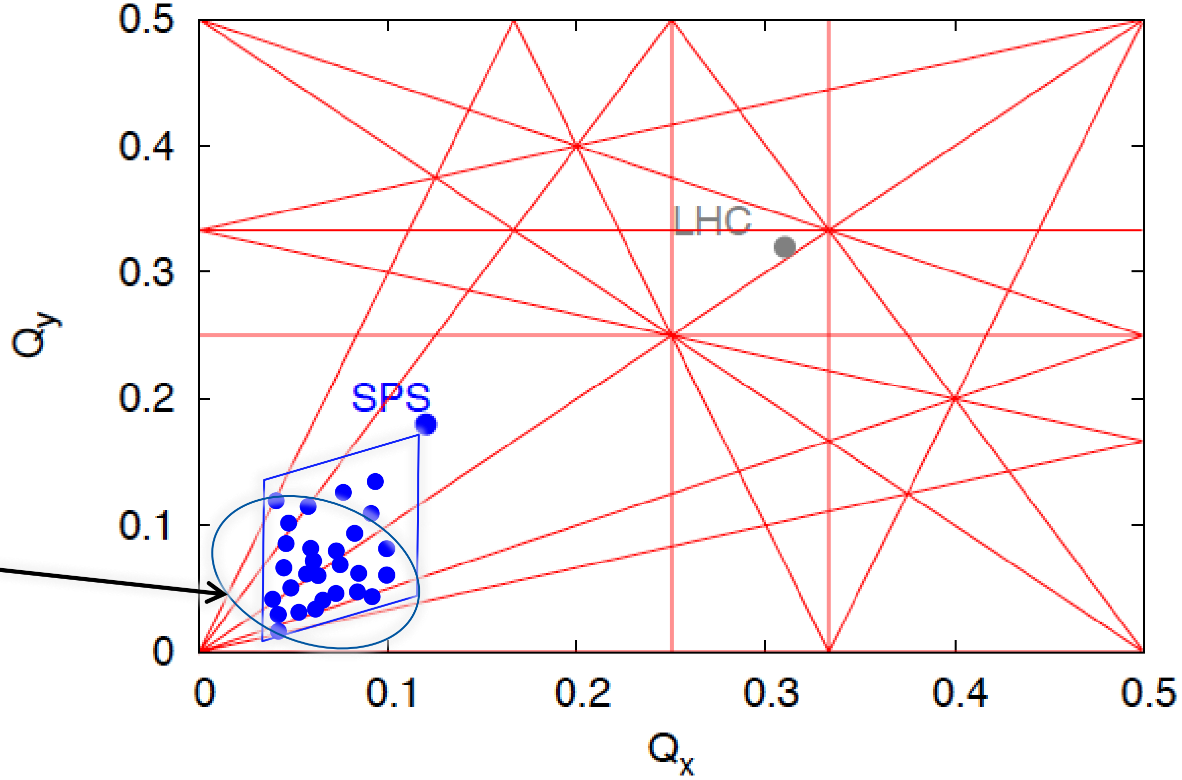
$$= \frac{e\lambda\vec{\rho}}{2\epsilon_0 \pi a^2}(1-\beta^2) = \frac{e\lambda\vec{\rho}}{2\pi\epsilon_0\gamma^2 a^2}$$

$$= \frac{e\lambda}{2\pi\epsilon_0\gamma^2 a^2} \cdot (x \cdot \hat{x} + y \cdot \hat{y})$$

Space charge tune shift

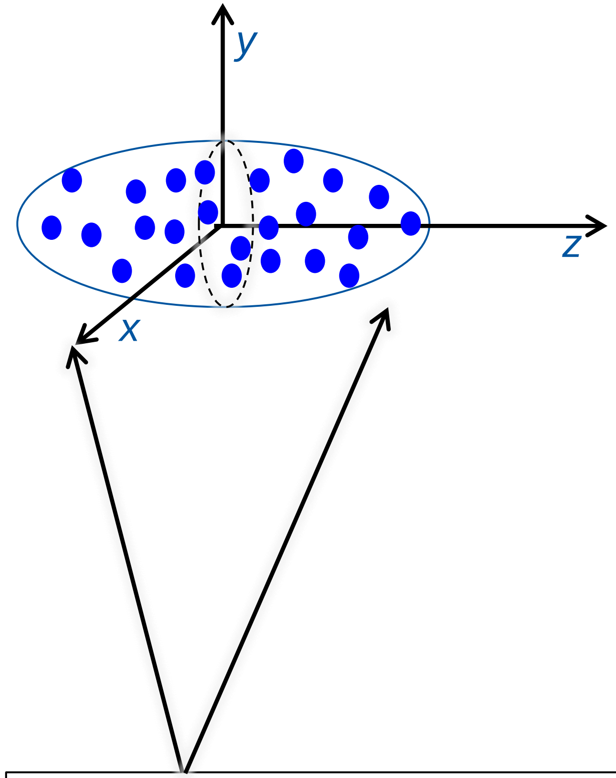


$$\Delta Q_{x,y}(z) = -\frac{r_0 \lambda(z) C}{2\pi e \beta \gamma^2 \epsilon_{xn,yn}}$$



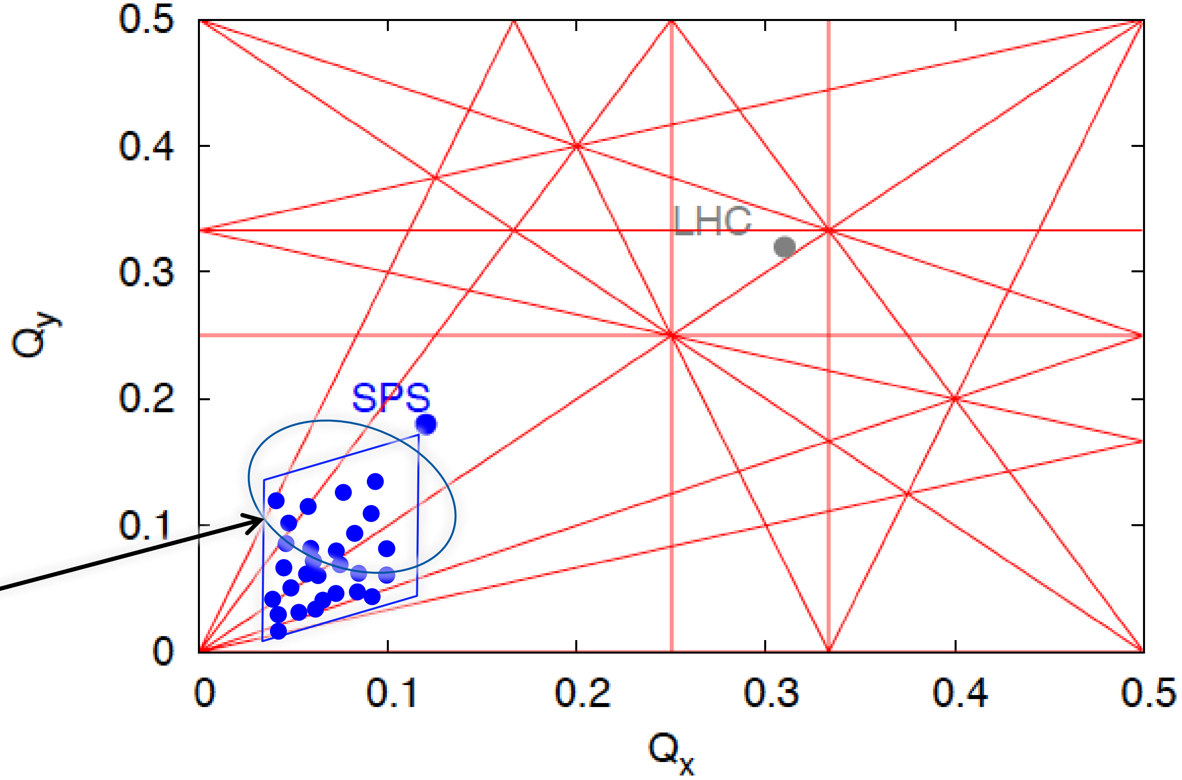
Particles oscillating close to the bunch peak density

Space charge tune shift



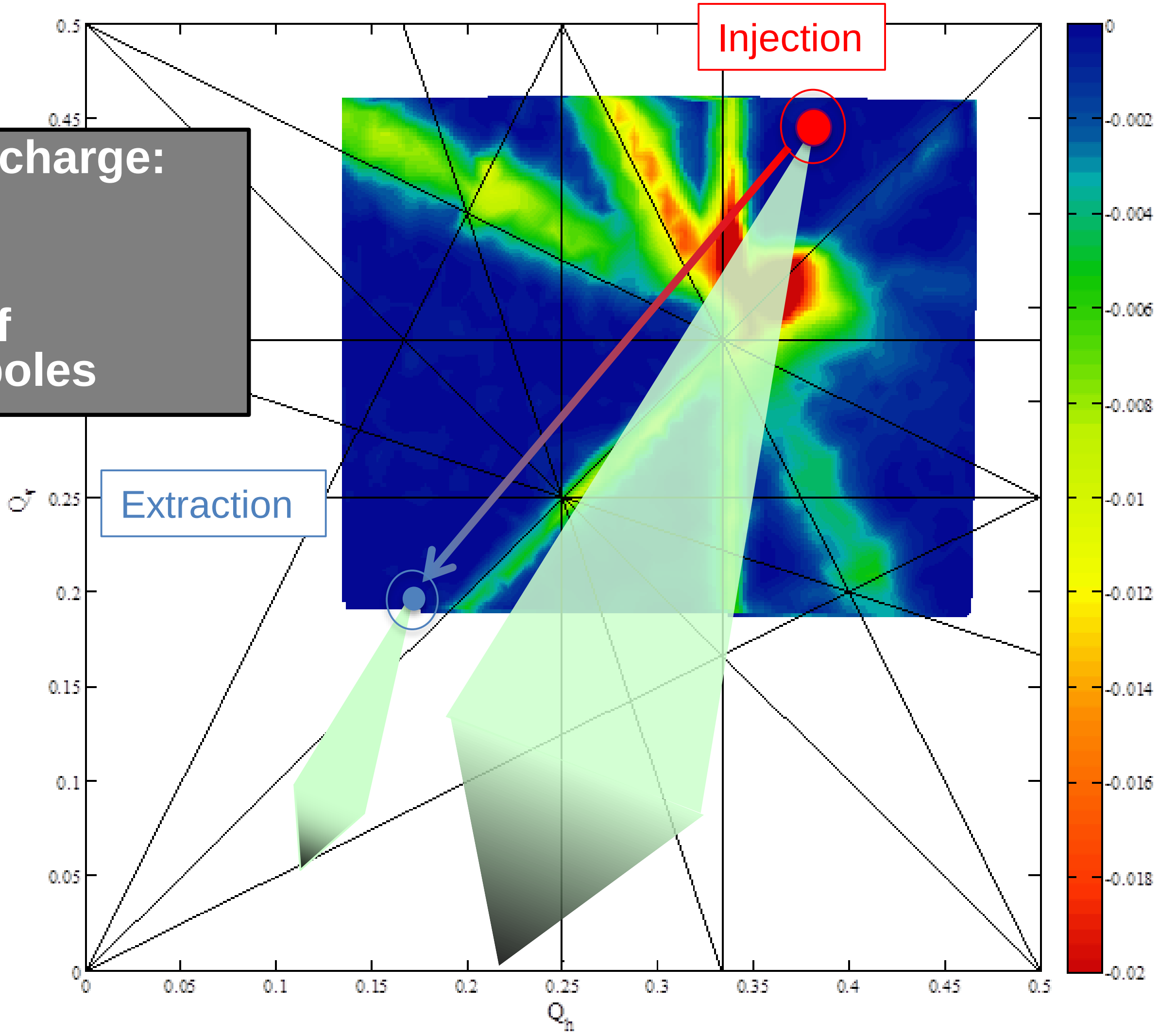
$$\Delta Q_{x,y}(z) = -\frac{r_0 \lambda(z) C}{2\pi e \beta \gamma^2 \epsilon_{xn,yn}}$$

Particles at the tails of the bunch feel less strong space charge forces



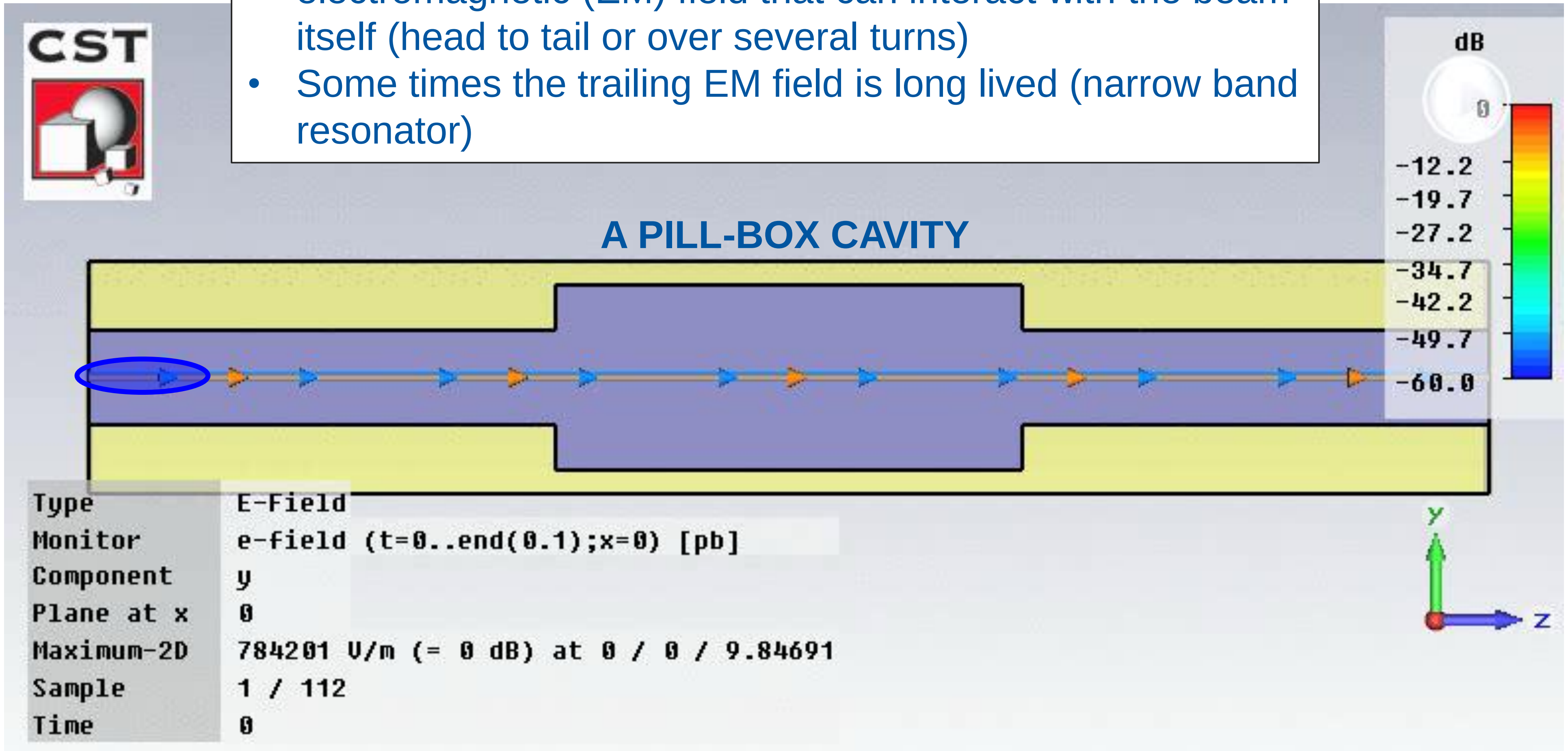
Example: The PS-Booster

What helps against space charge:
- **Fast cycling**
- **Dynamic working point**
- **Active compensation of resonances with multipoles**



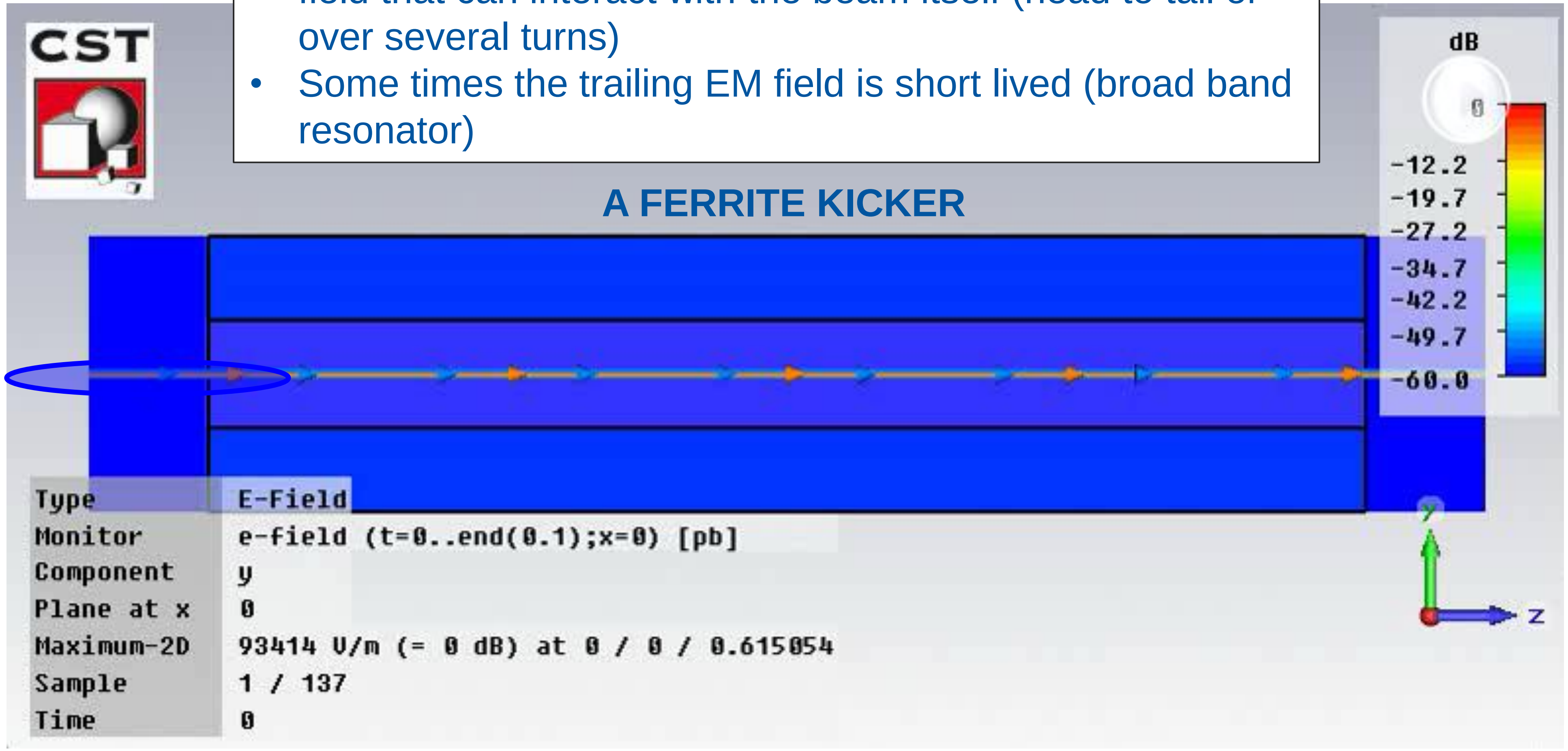
Wake fields and impedances

- A beam going through an accelerator device excites electromagnetic (EM) field that can interact with the beam itself (head to tail or over several turns)
- Some times the trailing EM field is long lived (narrow band resonator)



Wake fields and impedances

- A beam going through an accelerator device excites EM field that can interact with the beam itself (head to tail or over several turns)
- Some times the trailing EM field is short lived (broad band resonator)



Wake fields and impedances: definitions

- The electromagnetic interaction of a particle beam with an accelerator device is described by its
  - **Wake function** in time domain → The integrated force felt by a witness particle following a source particle while crossing the device (wake potential when the source is a bunch)

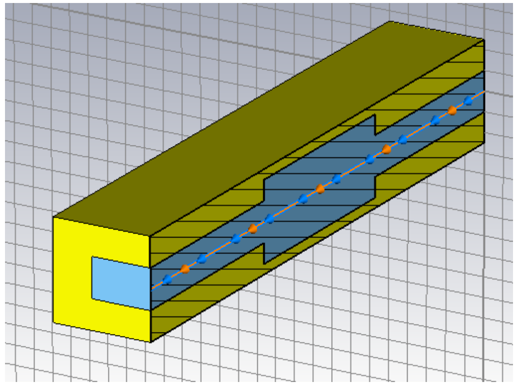
$$W(z) = -\frac{1}{e^2}\int_0^L F(s,z)\,ds$$

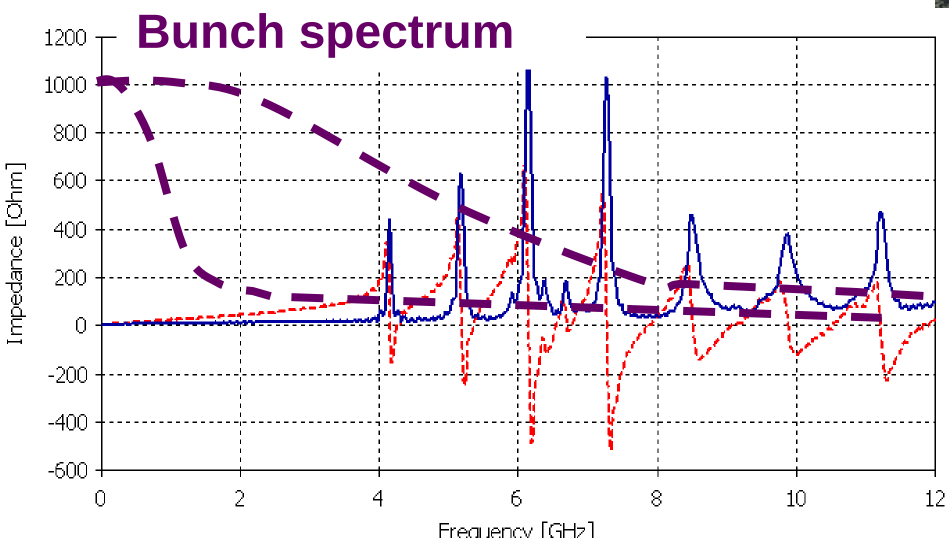
  - **Beam coupling impedance** in frequency domain → The Fourier transform of the wake function

$$Z(\omega) = \int_{-\infty}^{\infty} W(z) \exp\left(-\frac{i\omega z}{c}\right) \frac{dz}{c}$$

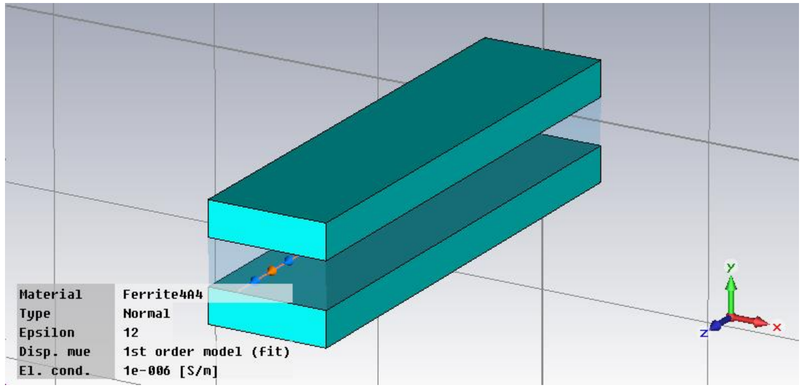
Wake fields and impedances

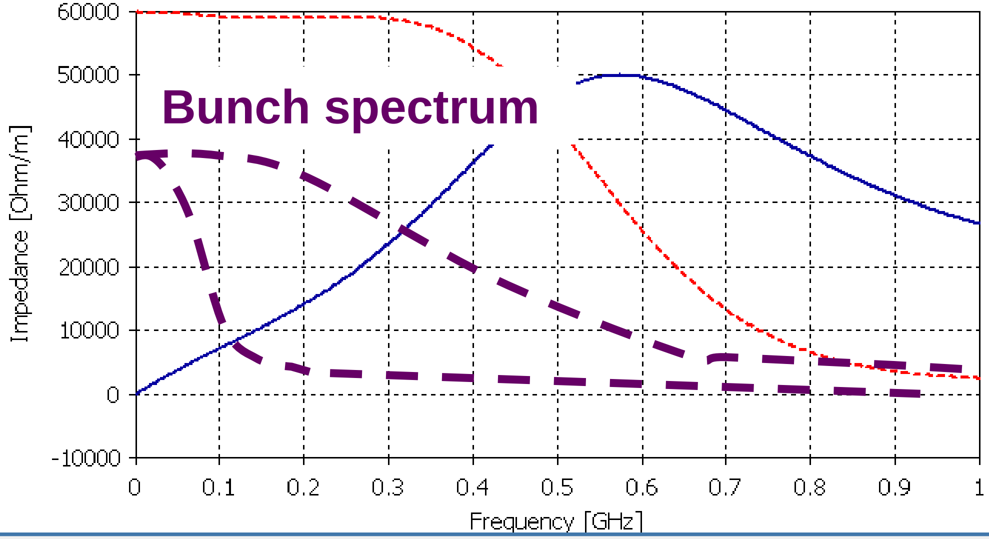
Cavity: example of structure with resonating modes (narrow band)





Kicker: example of structure with fast decaying wake (broad band)



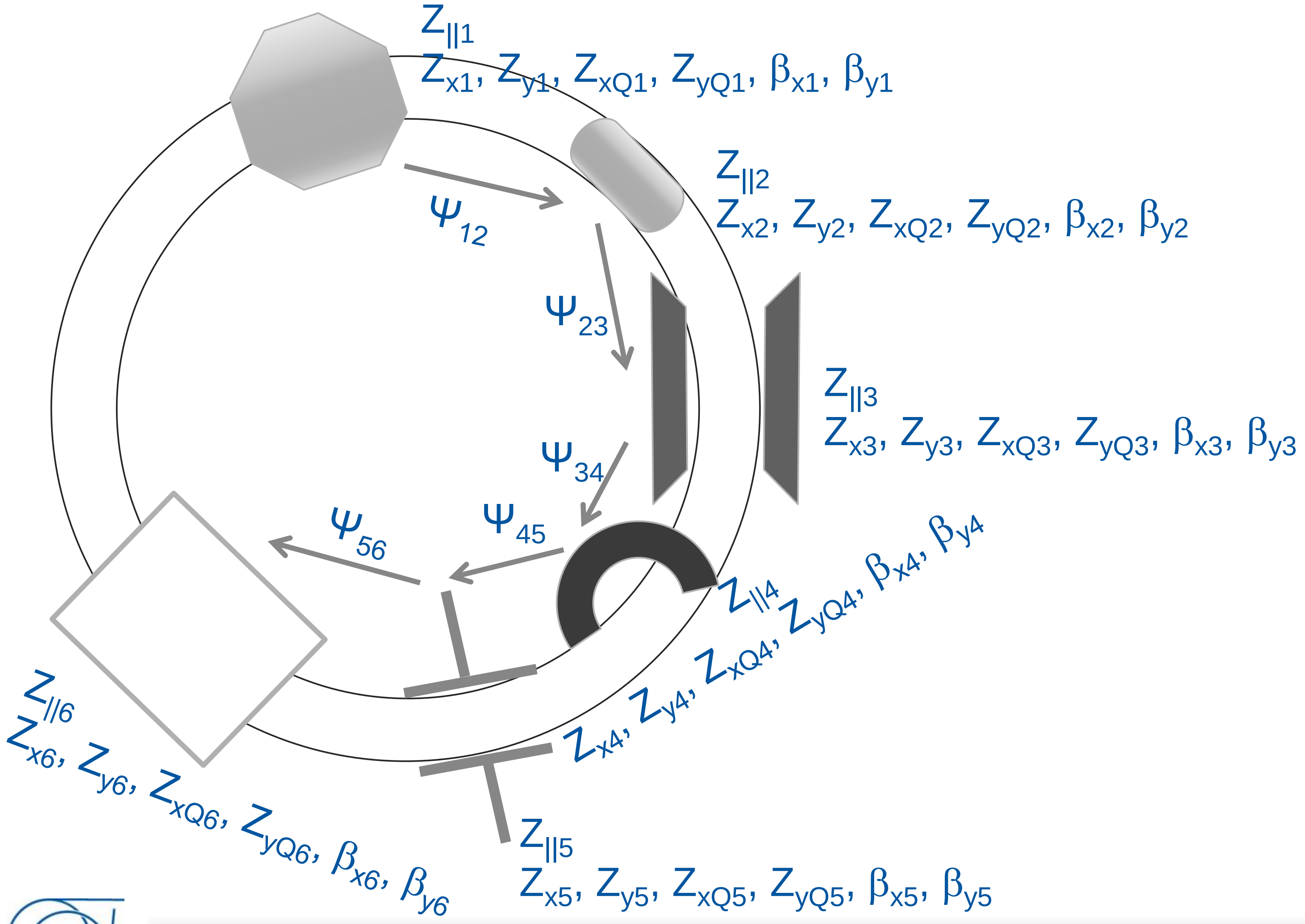


Wake fields and impedances: effects

- A beam loses energy in the creation of wake fields
  - Energy deposited in specific devices can lead to excessive heating, outgassing or damage
  - Energy deposited on cold devices can be critical for cryogenic system
  - Global energy loss over one turn has to be compensated by the RF system

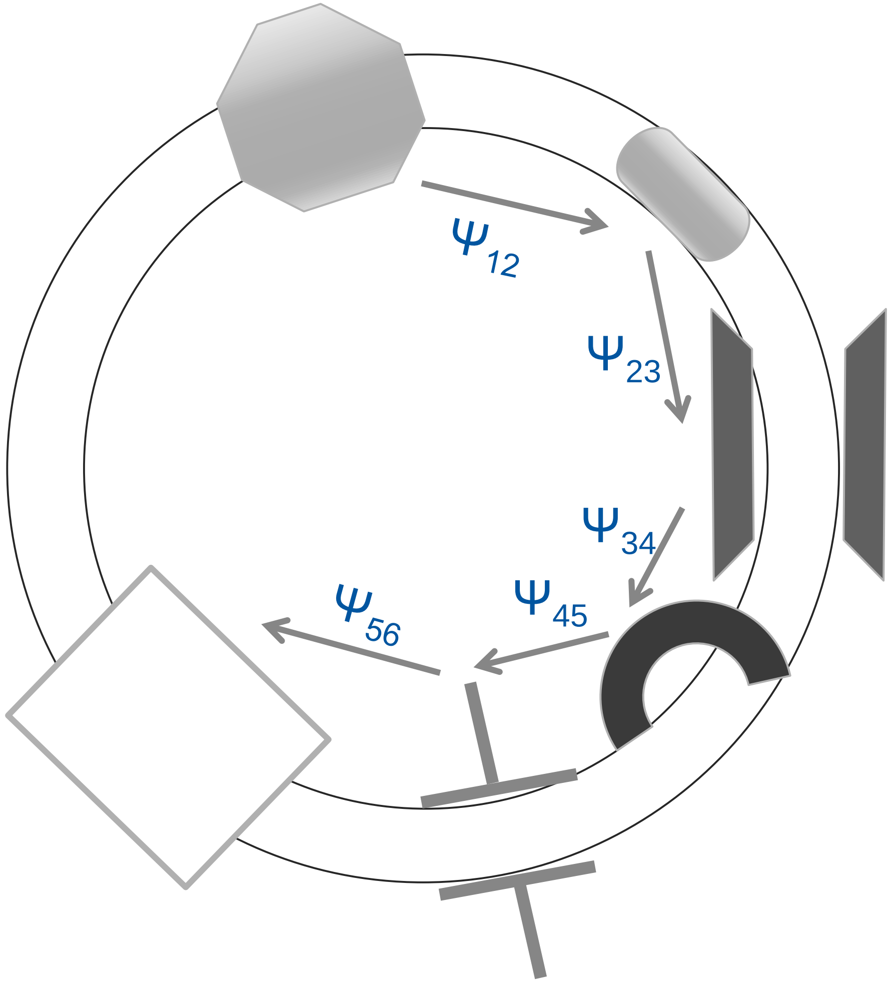
- Wake fields can act resonantly with the beam
  - The beam becomes unstable
  - Instabilities can manifest themselves in all three planes (x, y and z)
  - Instabilities can be single-bunch or multi-bunch

Wake fields and impedances: effects



- Local and global
  - Wake/impedance effects are local, as energy is lost by and fed back into the beam in each device according to its beam coupling impedance
  - Effects of all the wakes/impedances add up over a turn and can globally affect the beam

Wake fields and impedances: effects



$$Z_{x,y}(\omega) = \frac{1}{\langle \beta_{x,y} \rangle} \sum_{n=1}^{M} \beta_{(x,y)n} Z_{(x,y)n}(\omega)$$

$$Z_{||}(\omega) = \sum_{n=1}^{M} Z_{||n}(\omega)$$

$$Z_{RW||}(\omega) = \oint Z_{RW||}(s;\omega) ds$$

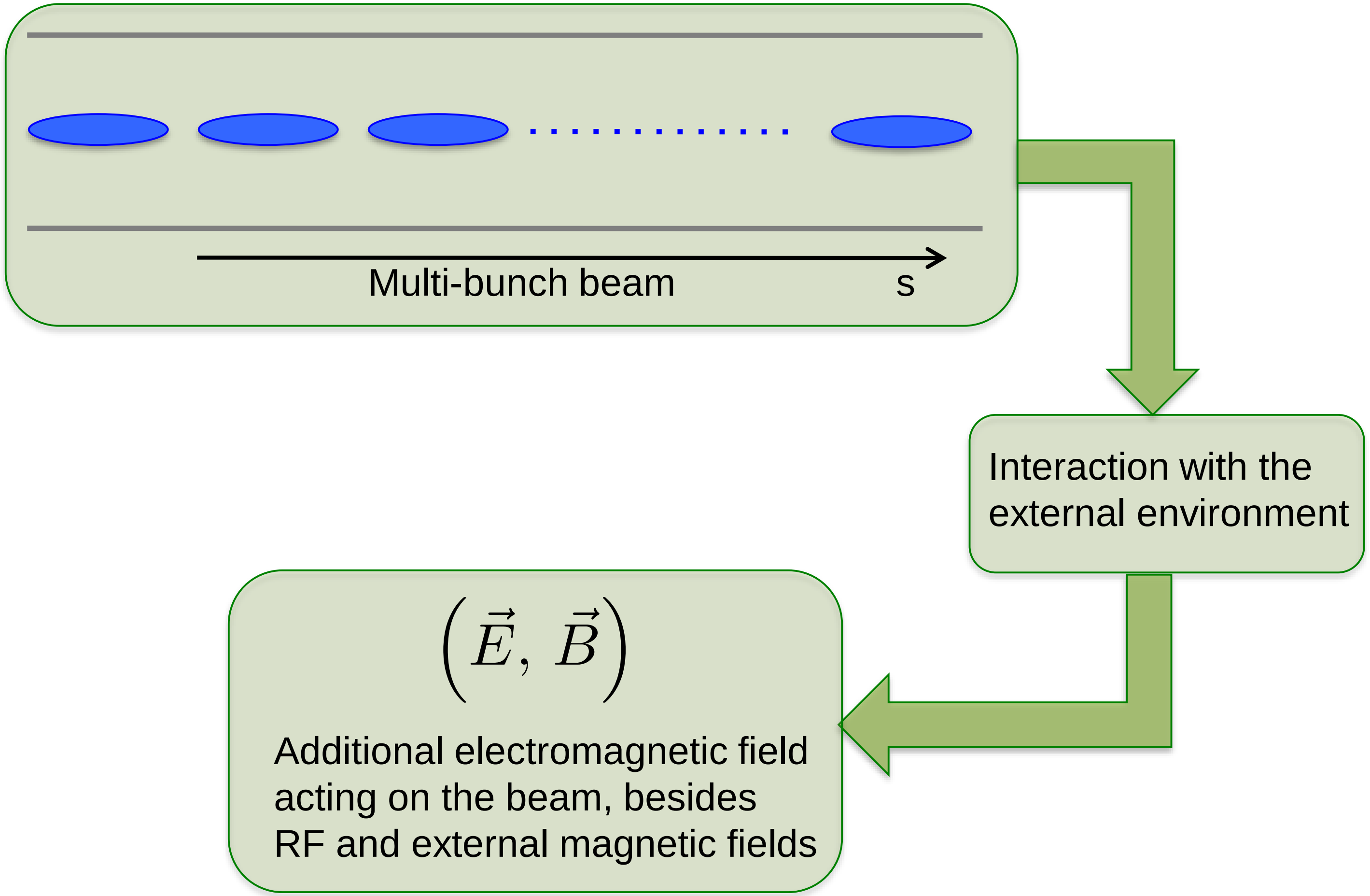
$$Z_{RWQ(x,y)}(\omega) = \frac{1}{\langle \beta_{x,y} \rangle} \oint \beta_{(x,y)}(s) Z_{RWQ(x,y)}(s;\omega) ds$$

Wake fields and impedances: measurements

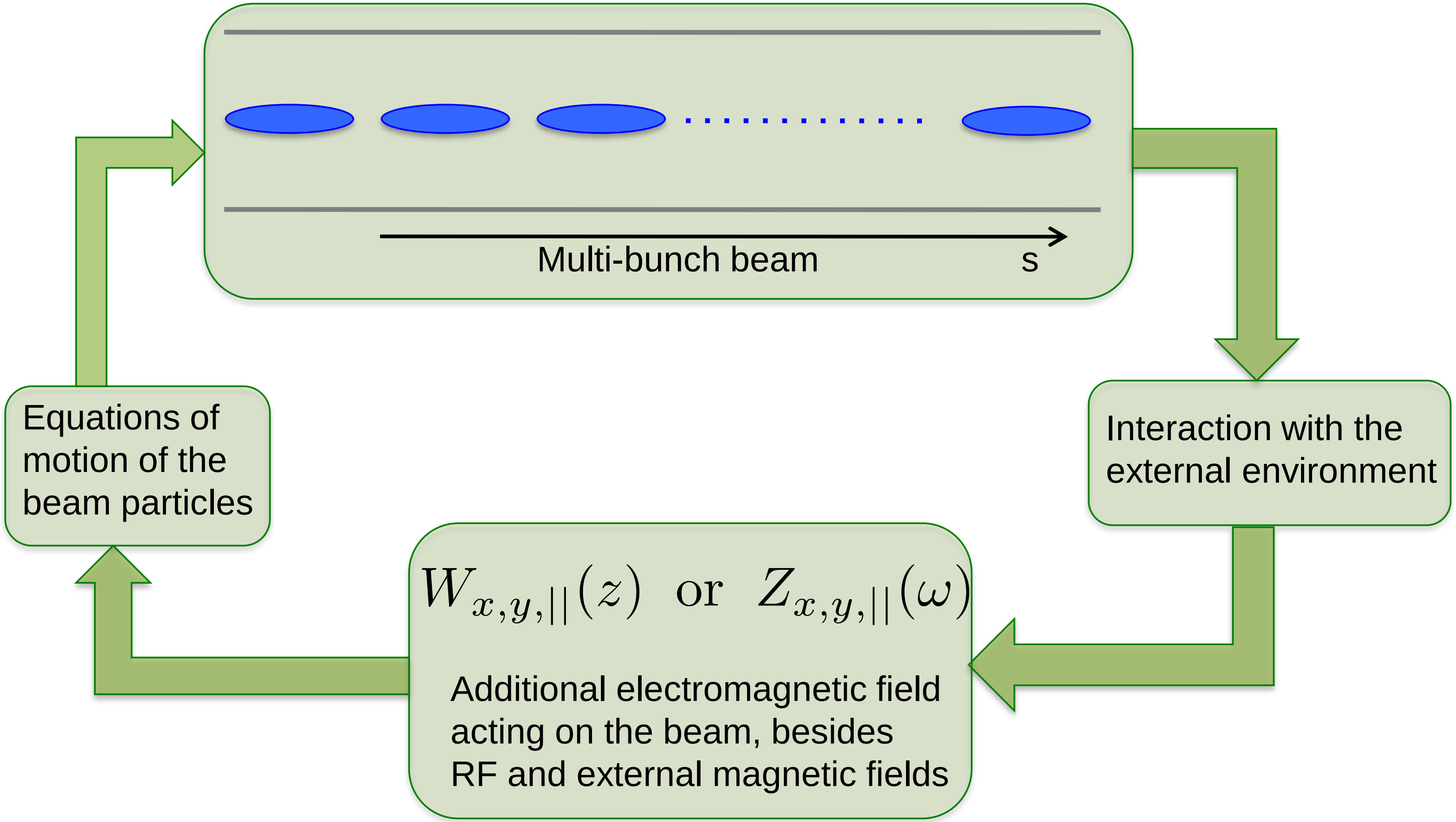
- Impedances and wake potentials of a device are usually
  - Calculated through electromagnetic simulators (wakefield function built in or using post-processing)
  - Determined in a laboratory by measuring the electromagnetic response of the device to a pulse sent on a stretched wire along the axis of the device

- The global impedance of an accelerator is
  - Estimated through the impedance model starting from the impedances of the single elements
  - Measured with beam through indicators like stable phase shift (energy loss), betatron and synchrotron tune shift with bunch intensity, instability thresholds and growth rates

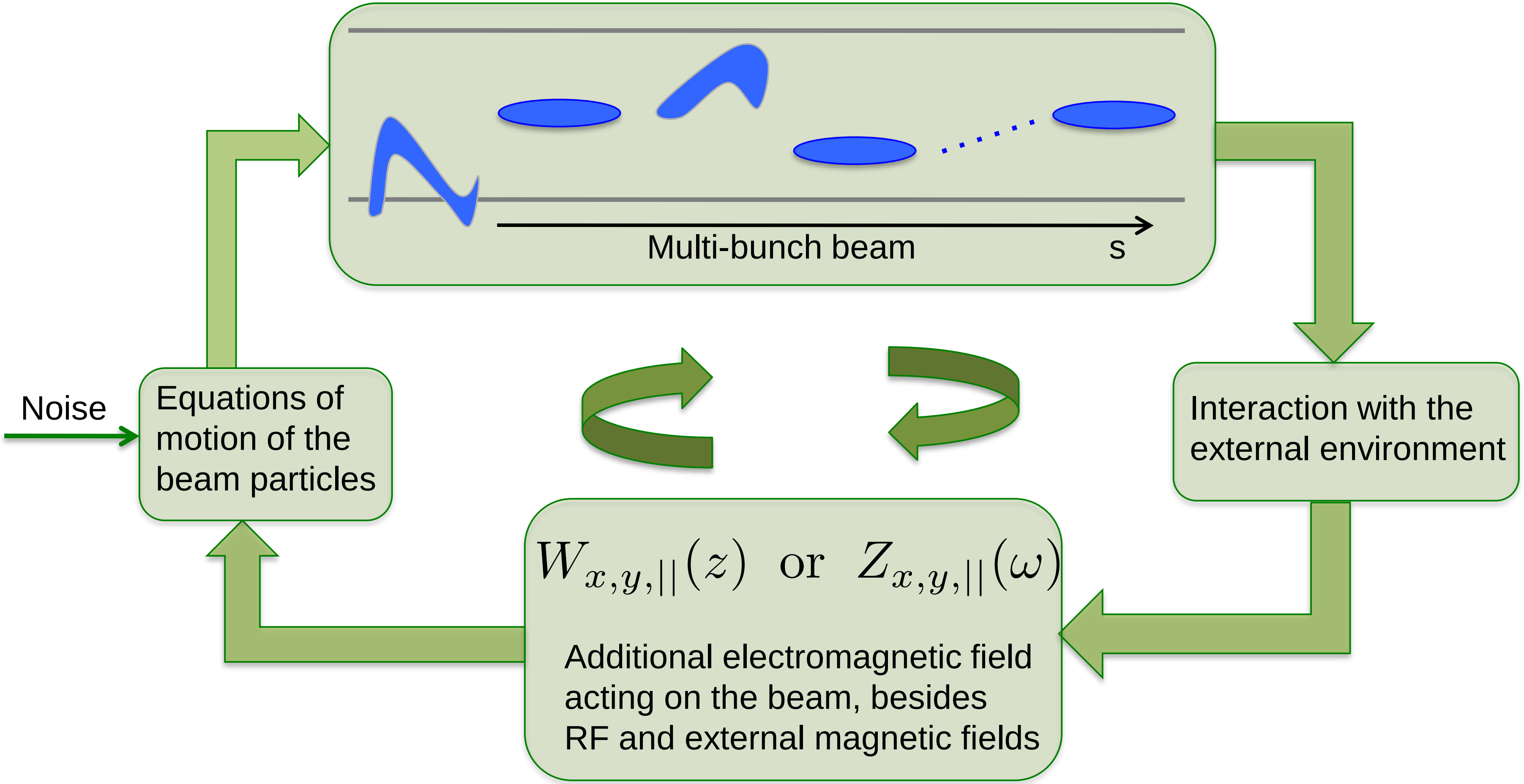
Instability loop



Instability loop



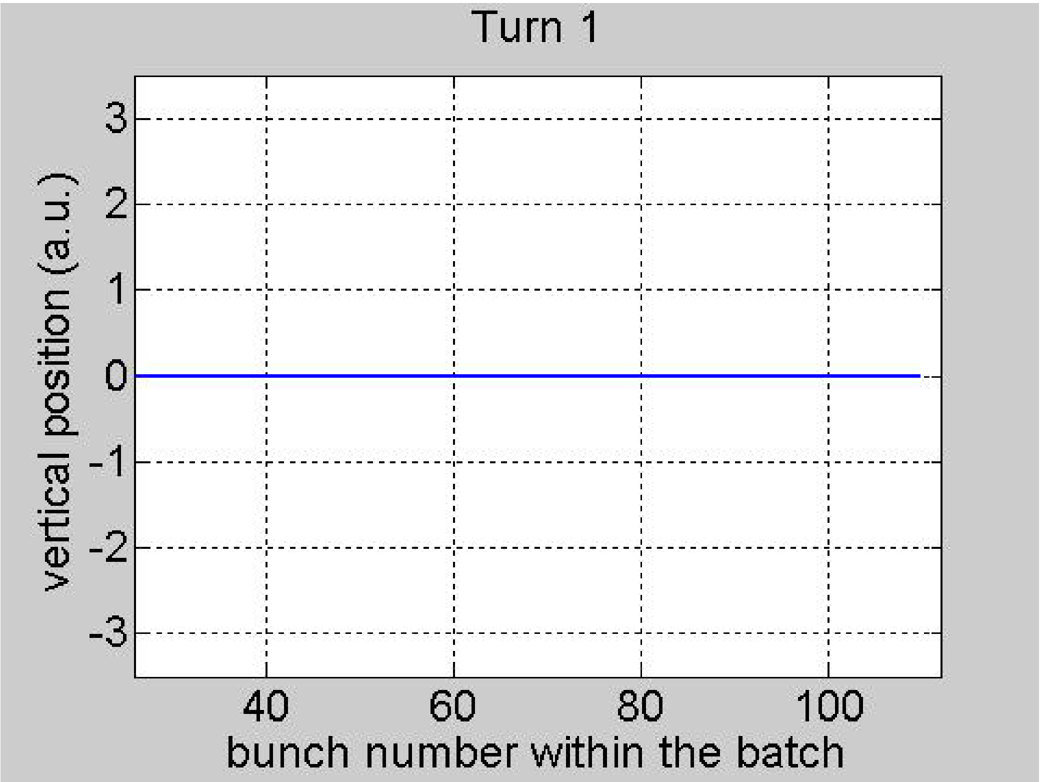
Instability loop



Instability example

- Coupled bunch instability
  - Turn after turn the oscillation amplitude of some bunches grows
  - A coherent pattern builds up along the bunch train

Train of 72 bunch at the SPS injection

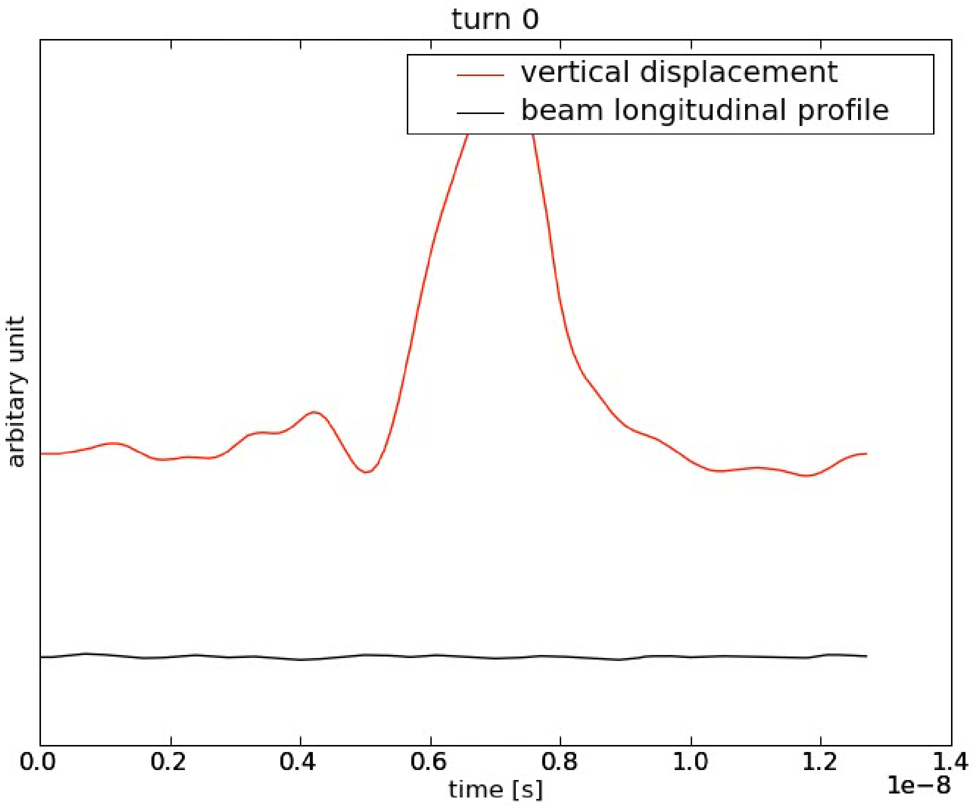


Instability example

- Coupled bunch instability
  - Turn after turn the oscillation amplitude of some bunches grows
  - A coherent pattern builds up along the bunch train

- Single bunch instability
  - Turn after turn the oscillation amplitude of parts of the bunch grows – until there are losses and the coherent motion damps
  - A coherent pattern builds up along the bunch from tail to head

Single SPS bunch above instability threshold



The electron cloud

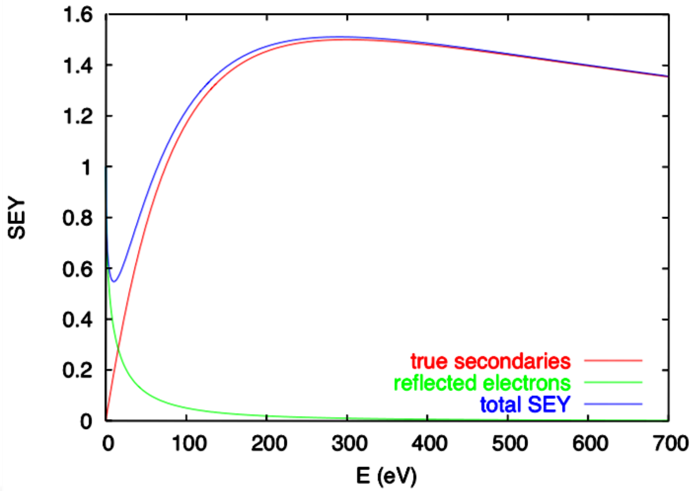
Generation of electrons inside the vacuum chamber (primary, or seed, electrons)

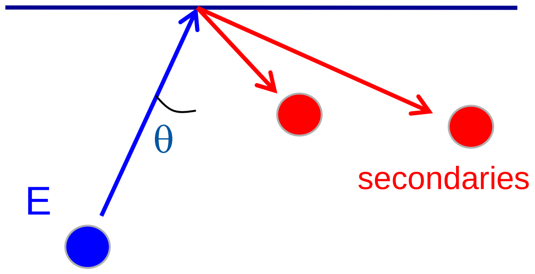
- **Residual gas ionization**
- **Photoelectrons from synchrotron radiation**
- **Desorption from the losses on the wall**

The electron cloud

Generation of electrons inside the vacuum chamber (primary, or seed, electrons)

- **Acceleration of primary electrons in the beam field**
- **Secondary electron production when hitting the wall**



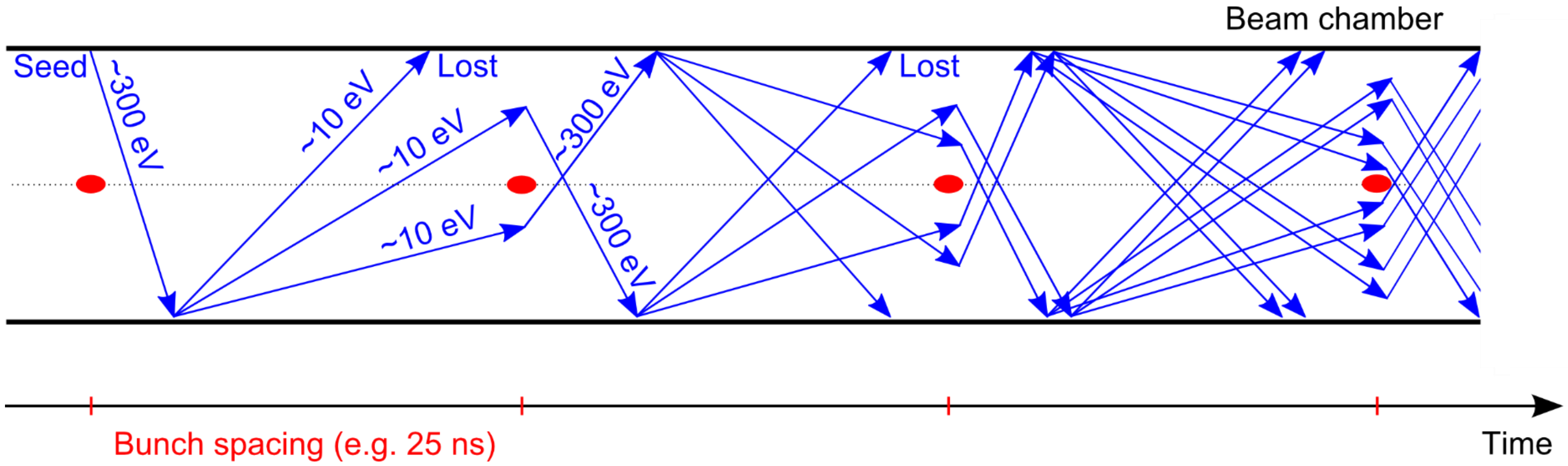


Dangerous if **Secondary Electron Yield (SEY) > 1**

The electron cloud

Generation of electrons inside the vacuum chamber (primary, or seed, electrons)

- **Acceleration of primary electrons in the beam field**
- **Secondary electron production when hitting the wall**
- **Avalanche electron multiplication**



The electron cloud

Generation of electrons inside the vacuum chamber (primary, or seed, electrons)

↓

- **Acceleration of primary electrons in the beam field**
- **Secondary electron production when hitting the wall**
- **Avalanche electron multiplication**

↓

After the passage of several bunches, the electron distribution inside the chamber reaches a dynamic steady state (electron cloud)

The electron cloud

Generation of electrons inside the

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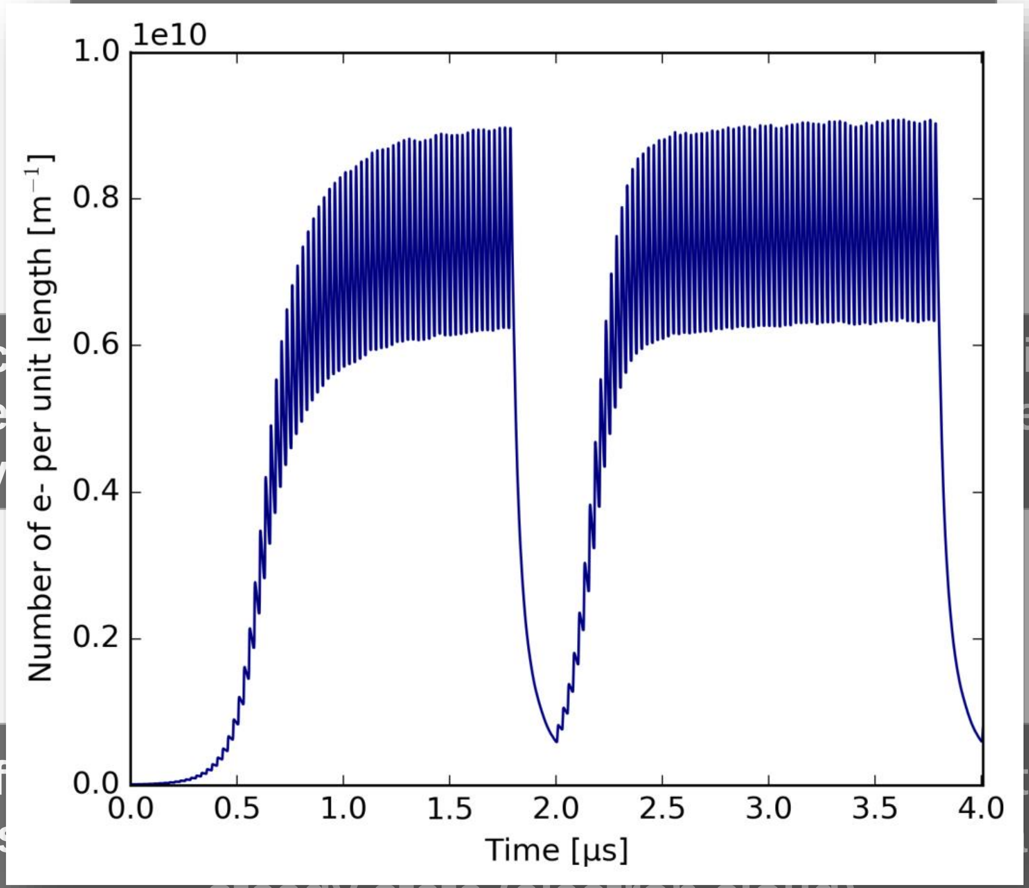
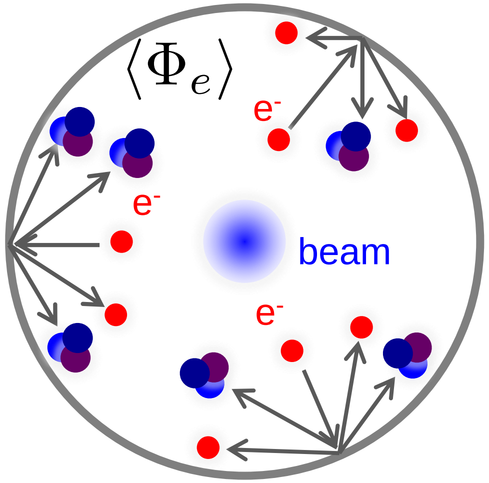
steady state (electron cloud)



The electron cloud

- The presence of an e-cloud inside the vacuum chamber of an accelerator ring is revealed by several typical signatures
  - Fast pressure rise, outgassing
  - Additional heat load
  - Baseline shift of the pick-up electrode signal
  - Synchronous phase shift due to the energy loss

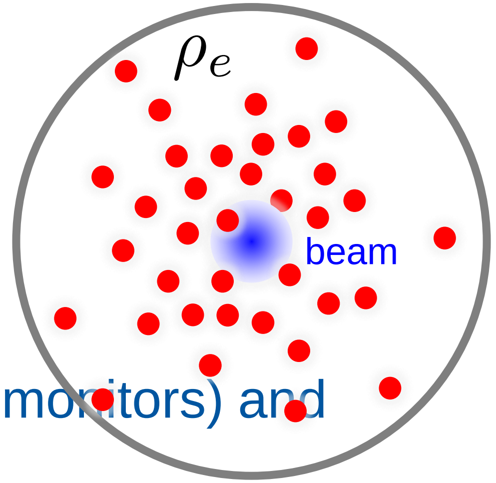


$$\Delta P \propto \int \eta_e(E) \langle \Phi_e(E) \rangle dE$$

$$\Delta W = \int \langle \Phi_e(E) \rangle E dE$$

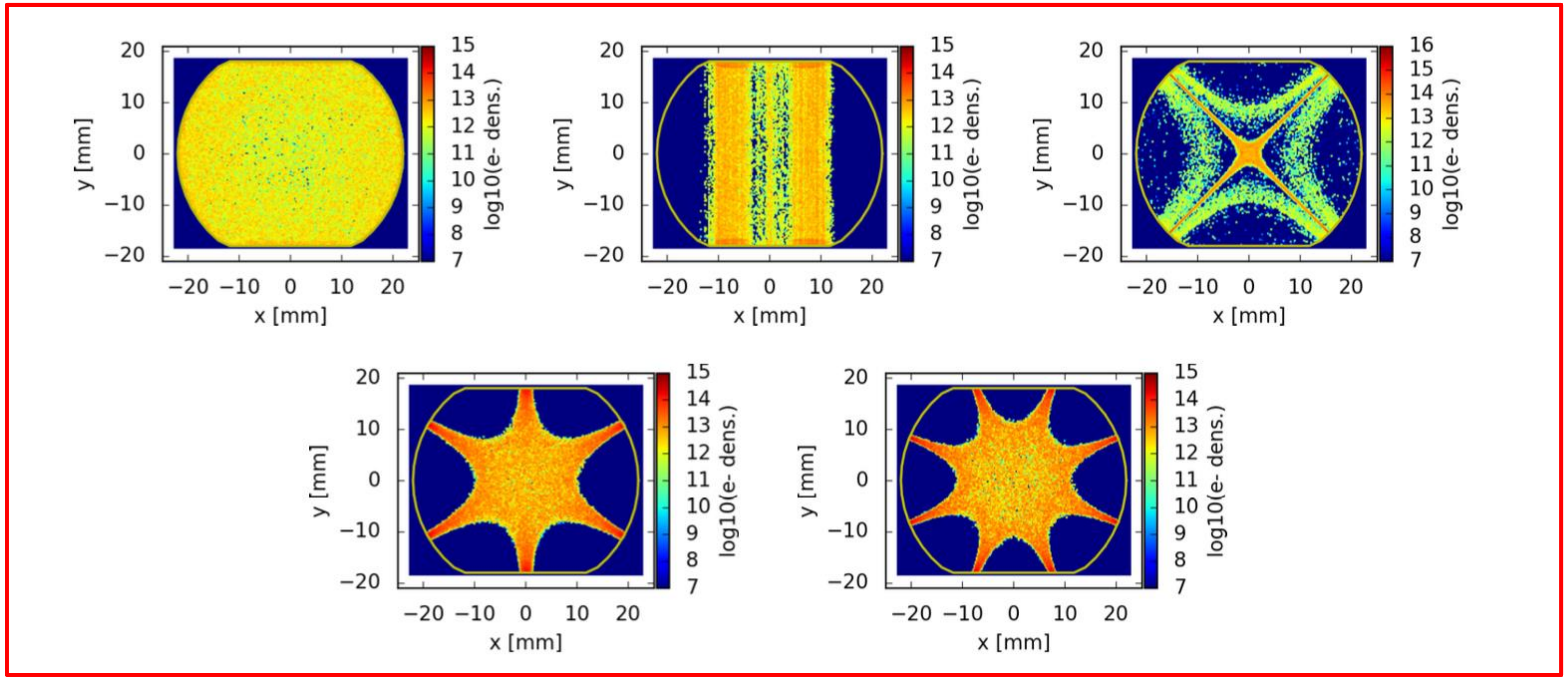
The electron cloud

- The presence of an e-cloud inside the vacuum chamber of an accelerator ring is revealed by several typical signatures
  - Fast pressure rise, outgassing
  - Additional heat load
  - Baseline shift of the pick-up electrode signal
  - Synchronous phase shift due to the energy loss
  - Tune shift along the bunch train
  - Coherent instability
  - Single bunch effect affecting the last bunches of a train
  - Coupled bunch effect
  - Poor beam lifetime and emittance growth
  - Active monitoring: signal on dedicated electron detectors (e.g. strip monitors) and retarding field analysers



The electron cloud

- The LHC arc is made of dipoles, quadrupoles, drift sections and short higher order multipoles
- The electron cloud takes different shapes according to the magnetic field



Electron cloud measurements

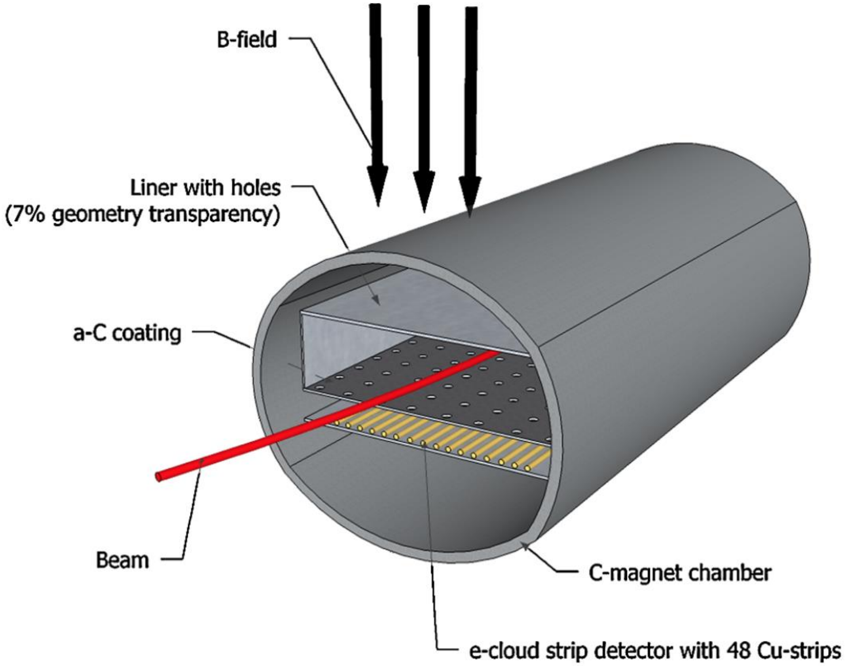
- Local measurements of the electron cloud are also possible
  - Through dedicated detectors
  - By inferring it from heat load or pressure rise

- Global measurements of electron cloud (integrated effect over the ring)
  - Stable phase shift (bunch-by-bunch energy loss)
  - Tune shift, instabilities

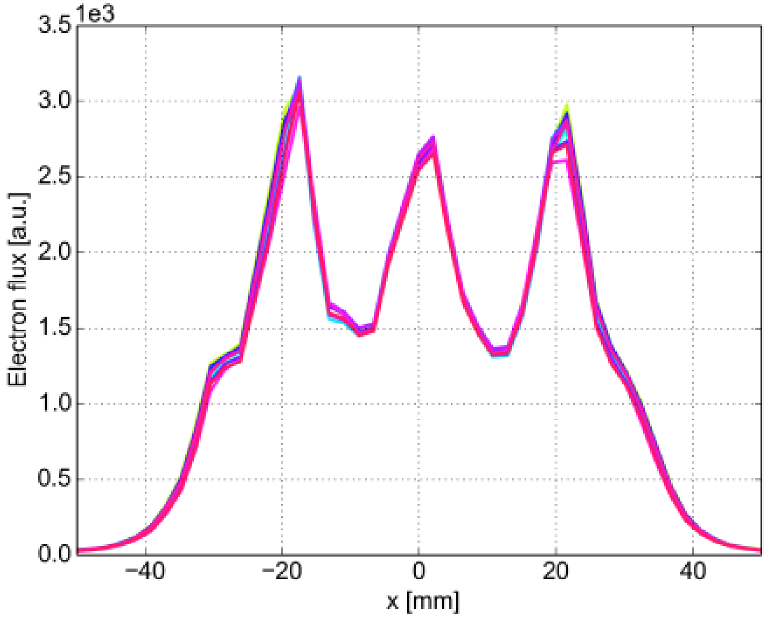
- Laboratory measurements are important to determine the SEY of the surfaces exposed to the beam and its evolution with electron bombardment

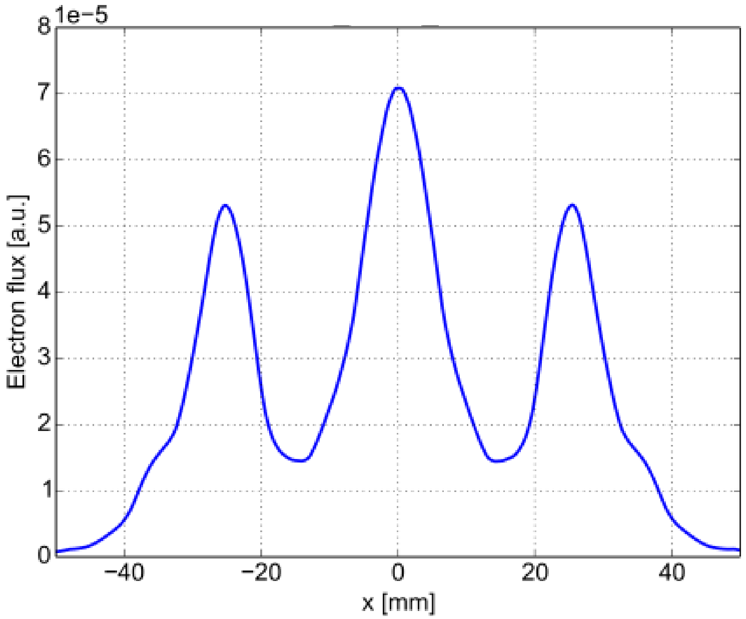
Direct detection of the electron cloud

- Direct measurements of e-cloud possible in SPS thanks to strip monitor in region with adjustable magnetic field



B = 42 G





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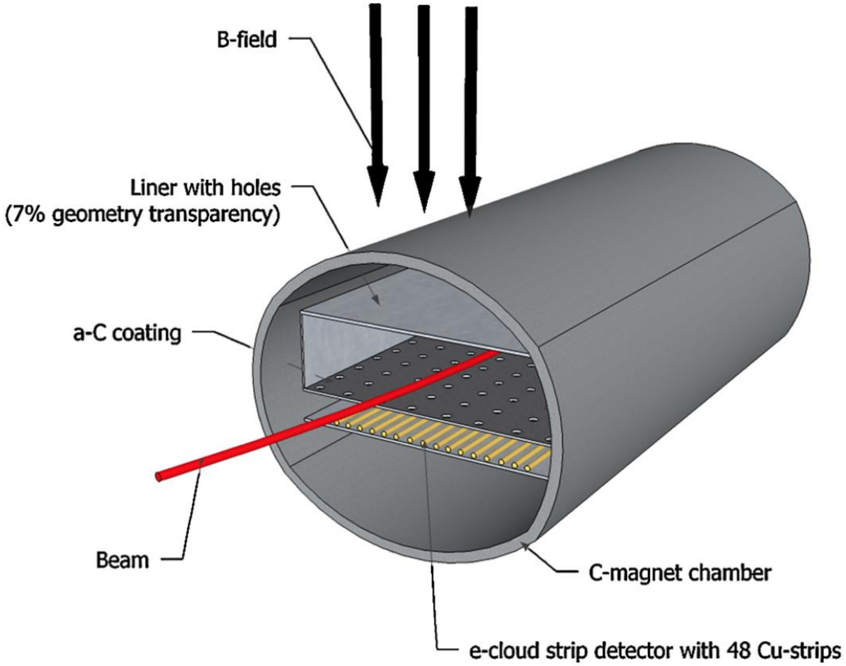
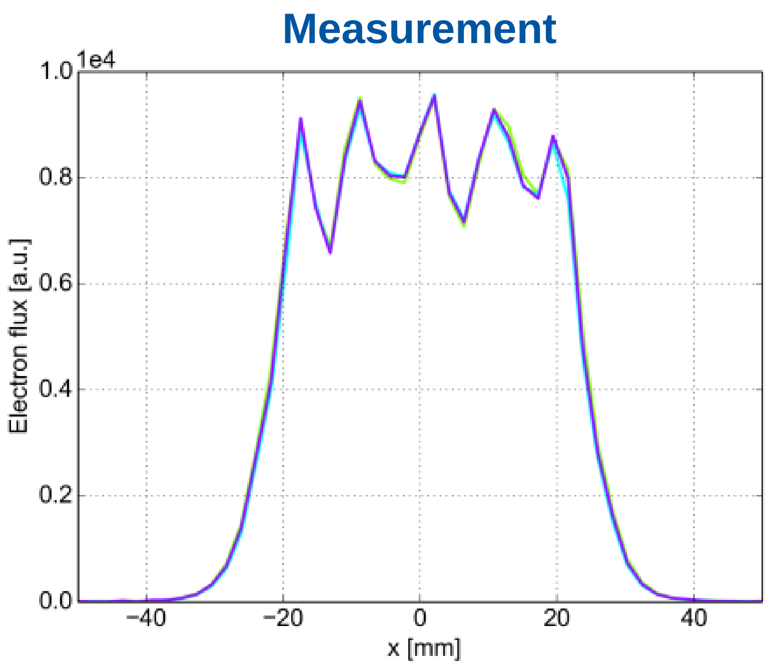
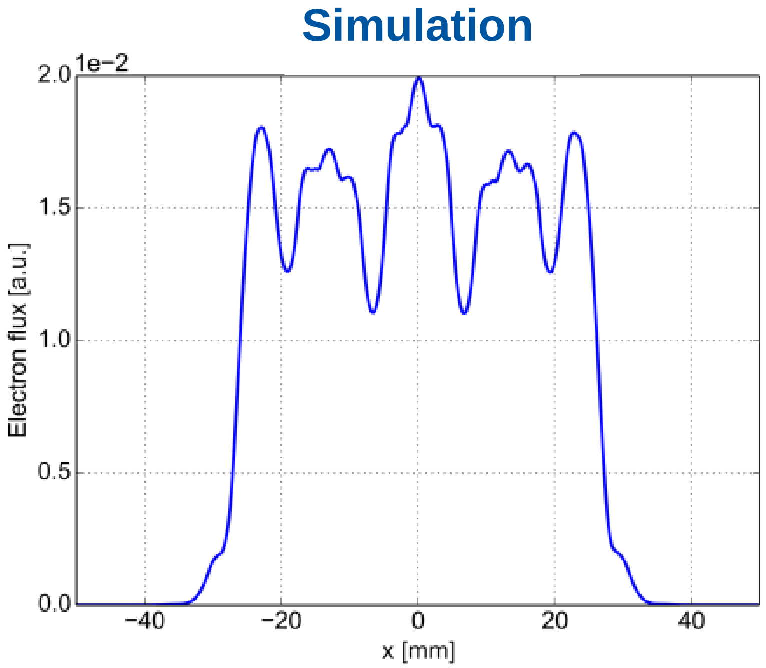


B = 83 G





Direct detection of the electron cloud

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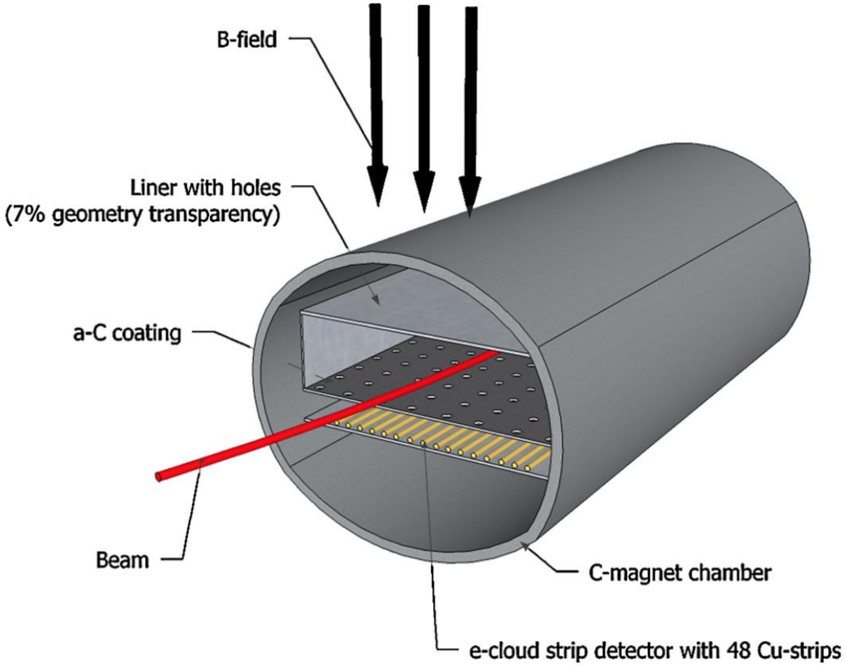
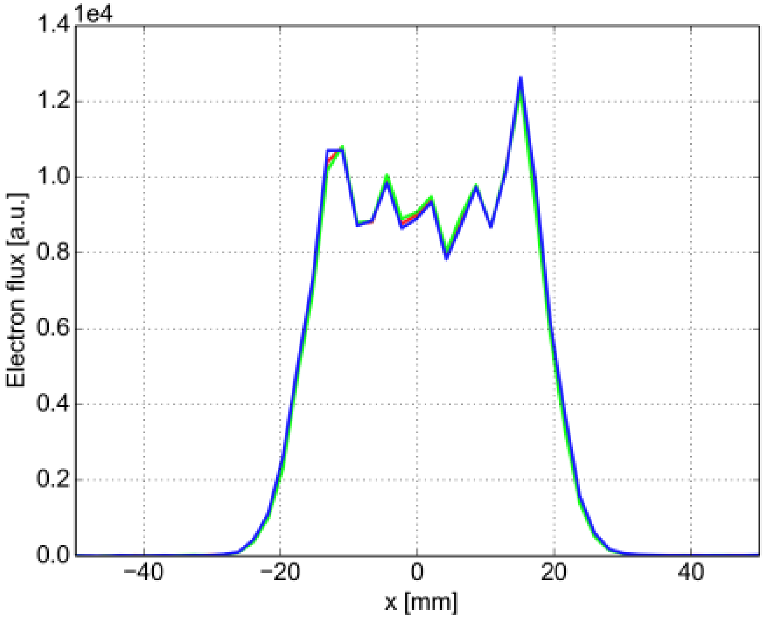
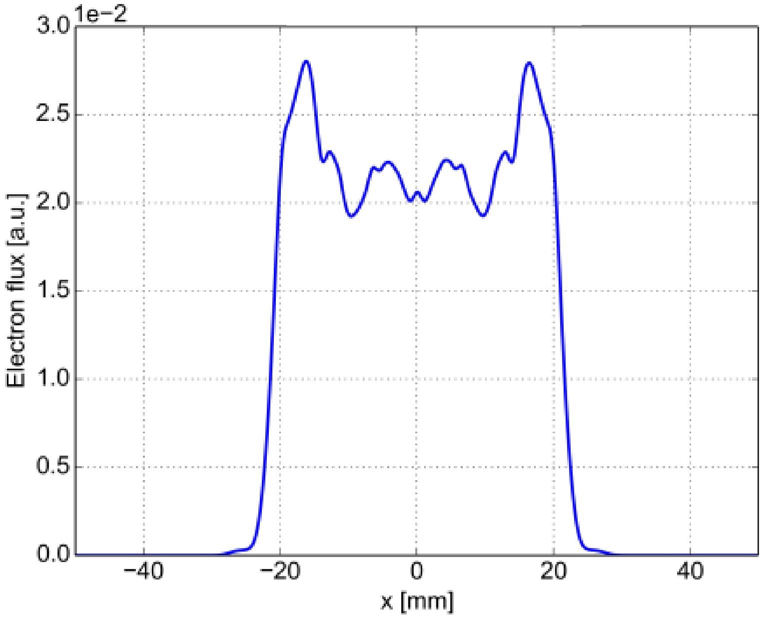


B = 125 G

Measurement

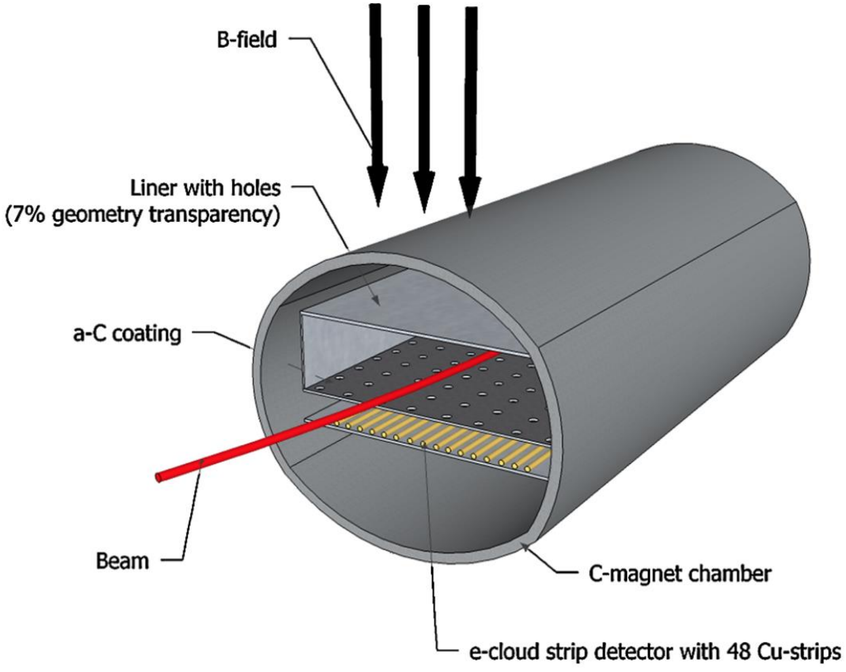


Simulation

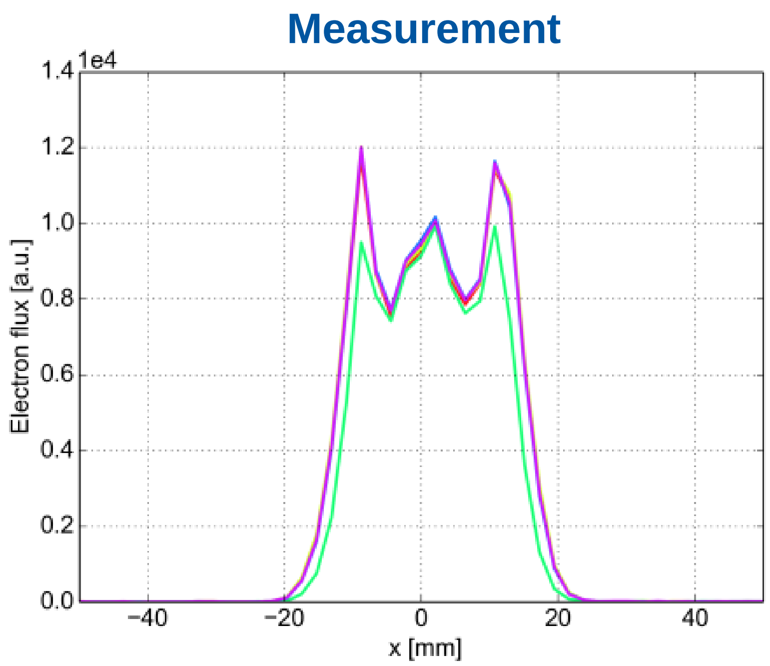


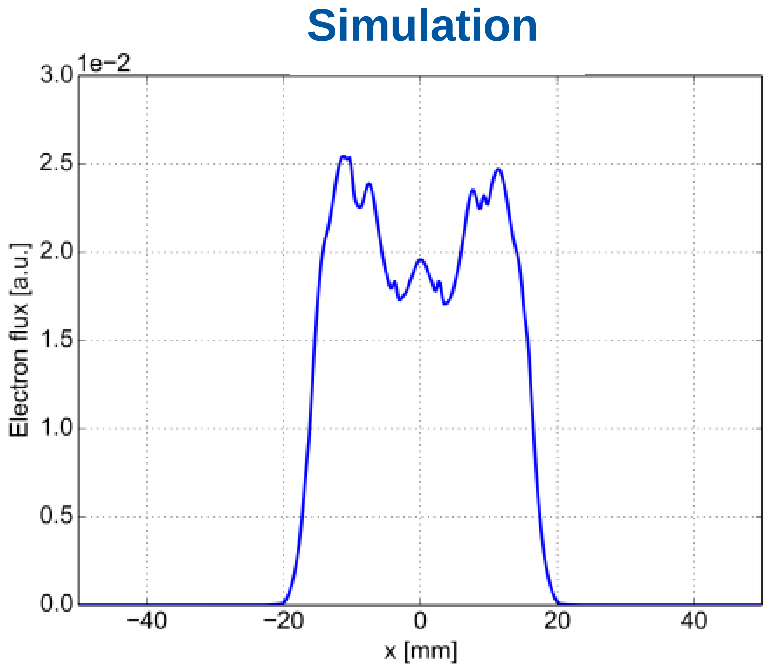
Direct detection of the electron cloud

- Direct measurements of e-cloud possible in SPS thanks to strip monitor in region with adjustable magnetic field



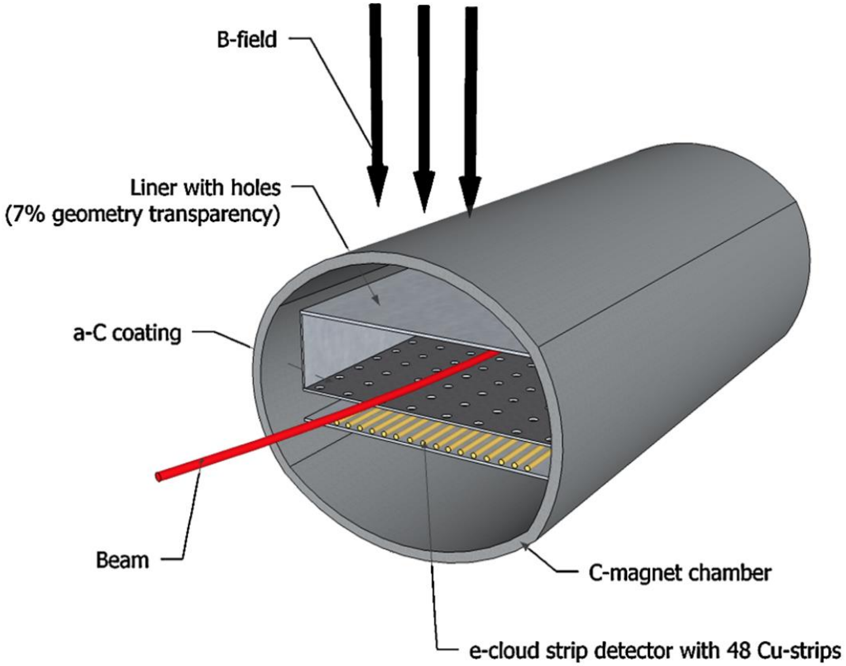
B = 175 G



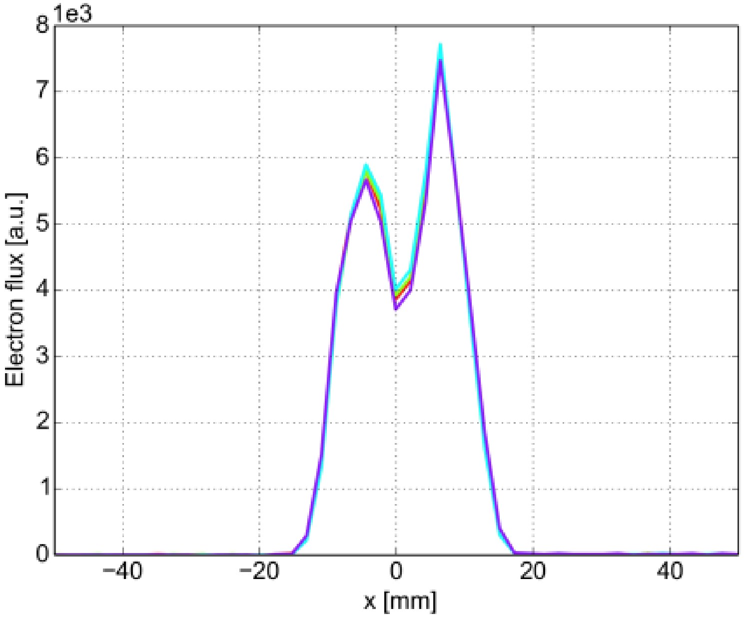


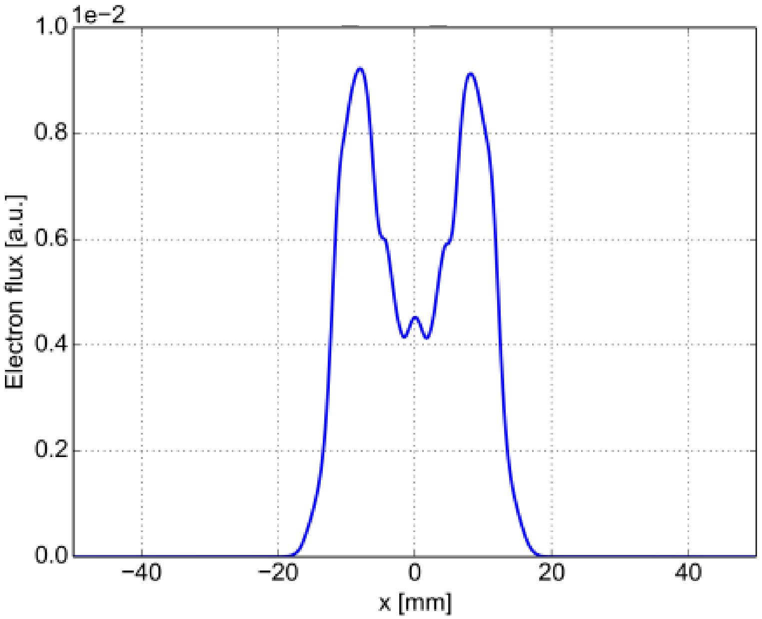
Direct detection of the electron cloud

- Direct measurements of e-cloud possible in SPS thanks to strip monitor in region with adjustable magnetic field



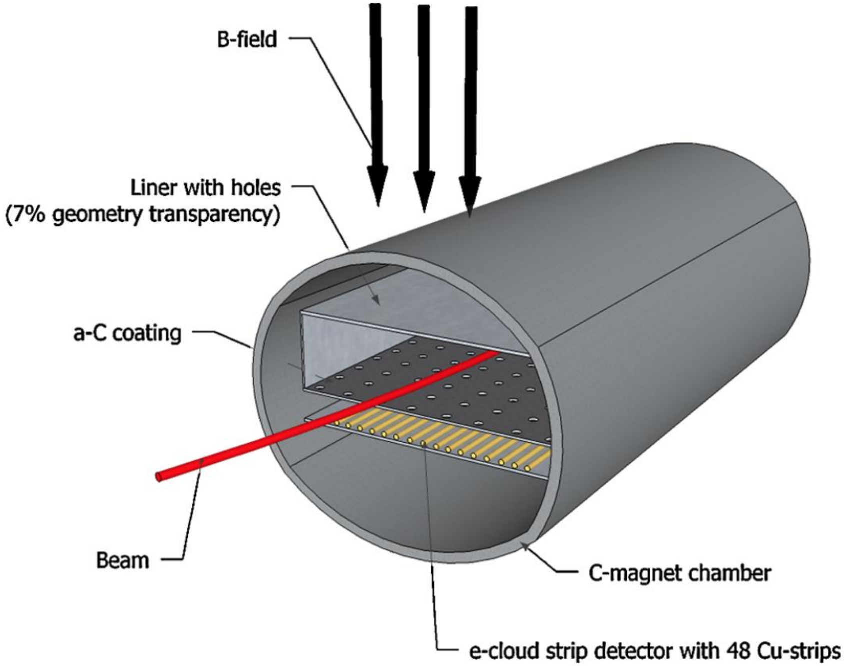
B = 250 G





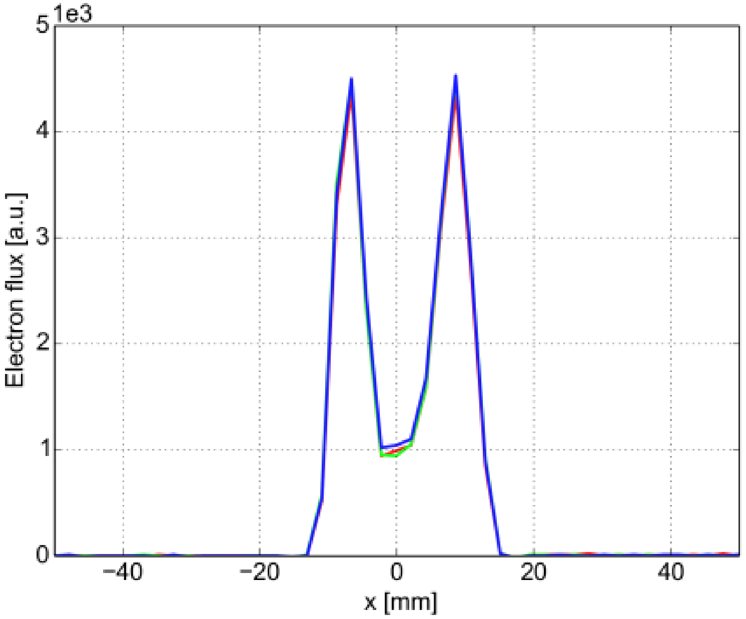
Direct detection of the electron cloud

- Direct measurements of e-cloud possible in SPS thanks to strip monitor in region with adjustable magnetic field

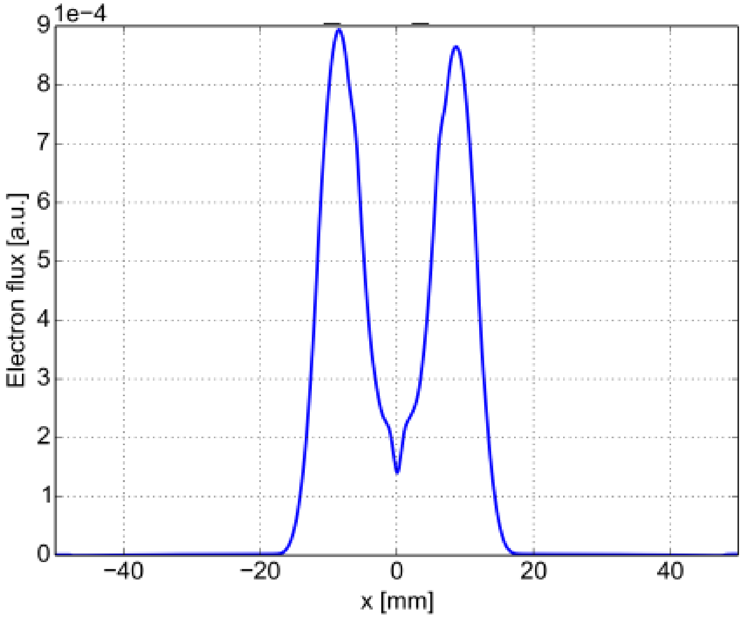


B = 833 G

Measurement

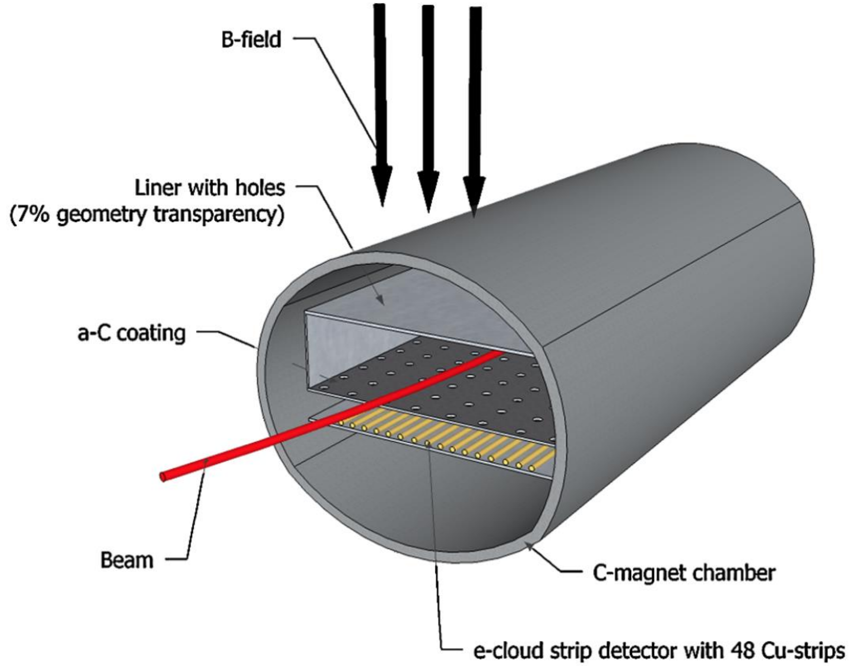


Simulation



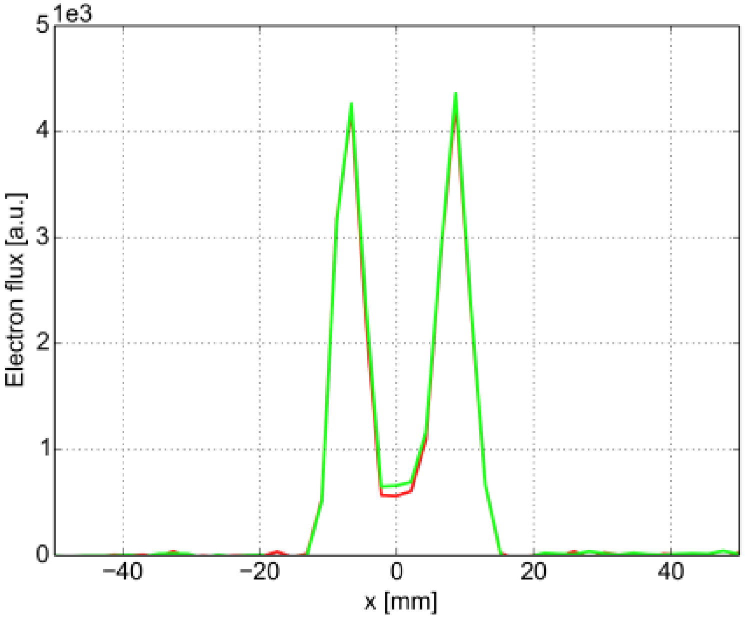
Direct detection of the electron cloud

- Direct measurements of e-cloud possible in SPS thanks to strip monitor in region with adjustable magnetic field

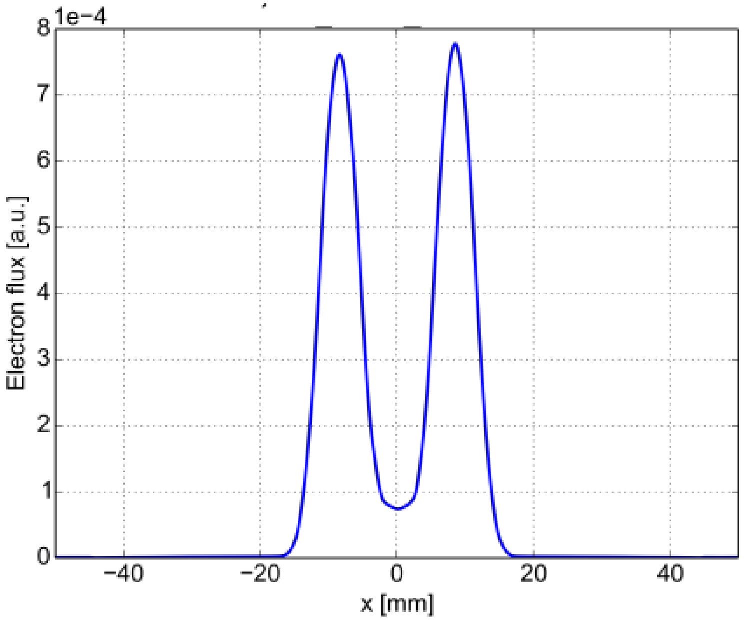


B = 1000 G

Measurement

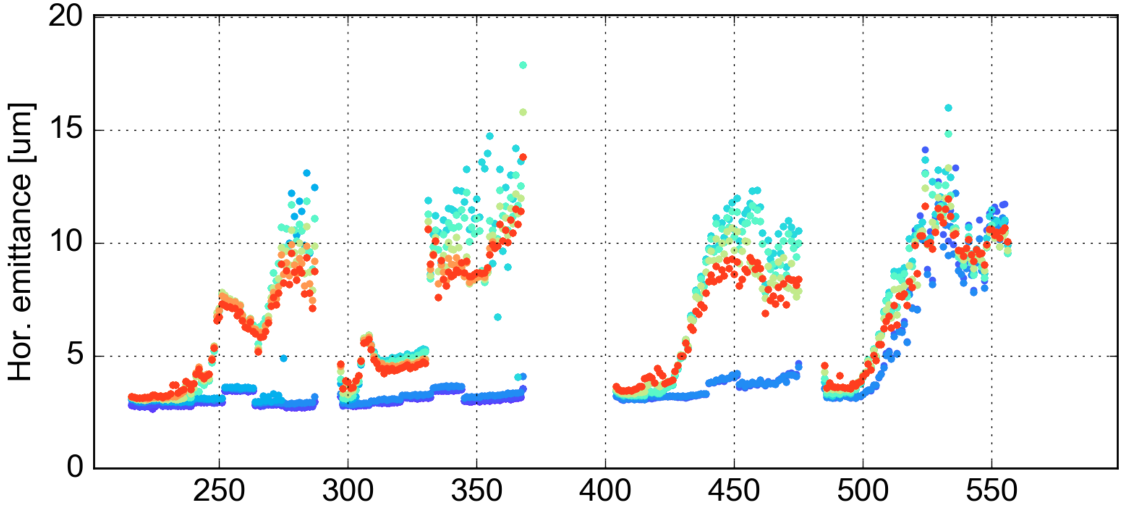


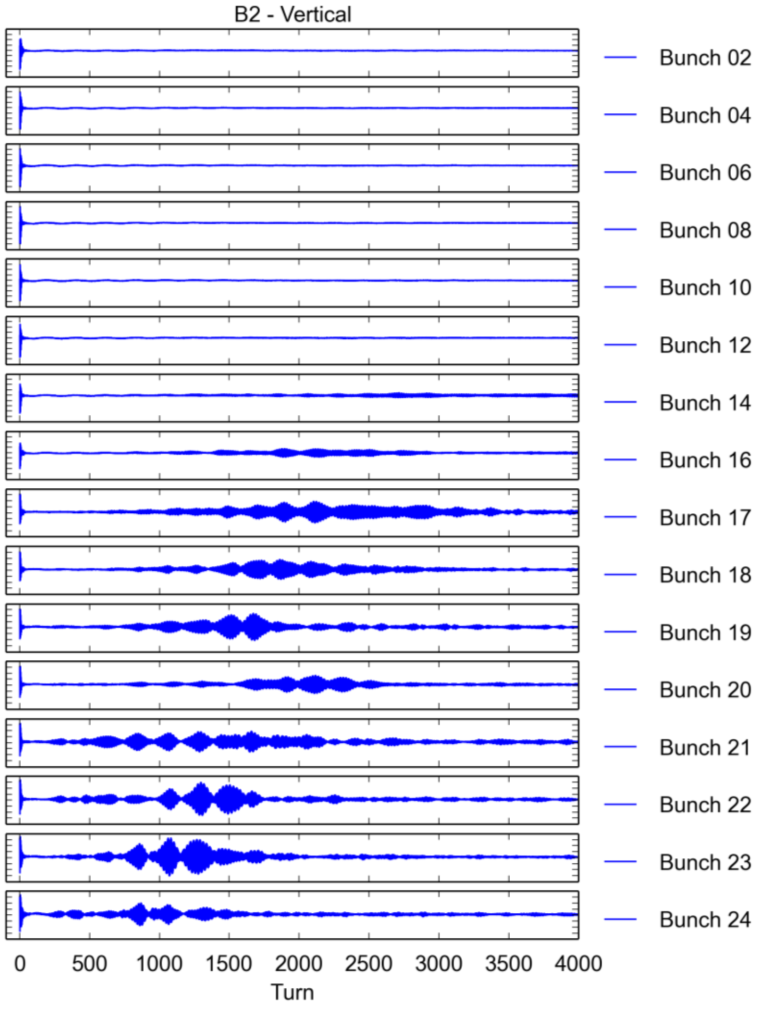
Simulation



The electron cloud in the LHC

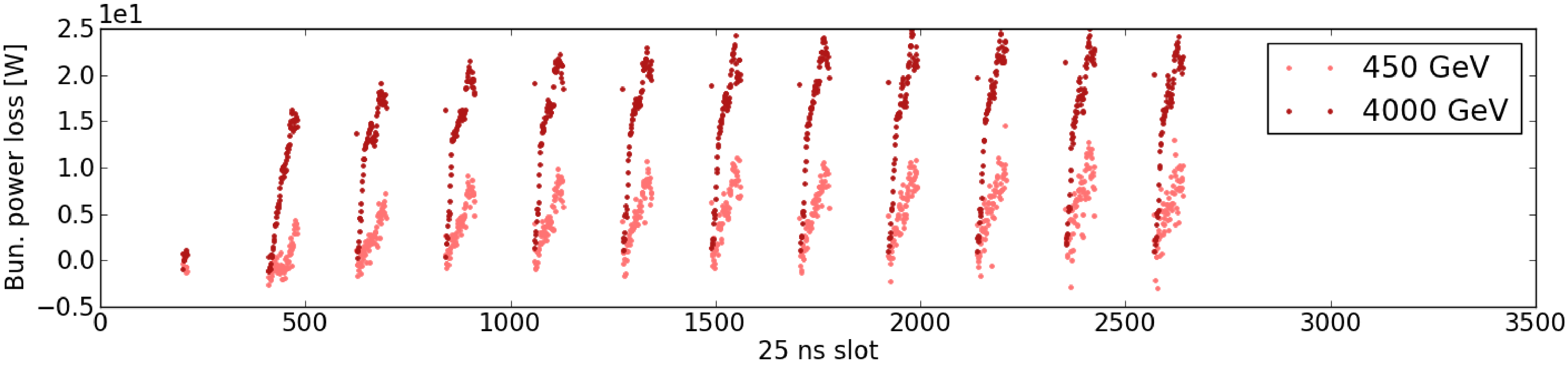
- The effects of the electron cloud in the LHC are clearly measurable
  - Instabilities developing on bunches towards the end of the trains
  - Beam losses and emittance growth





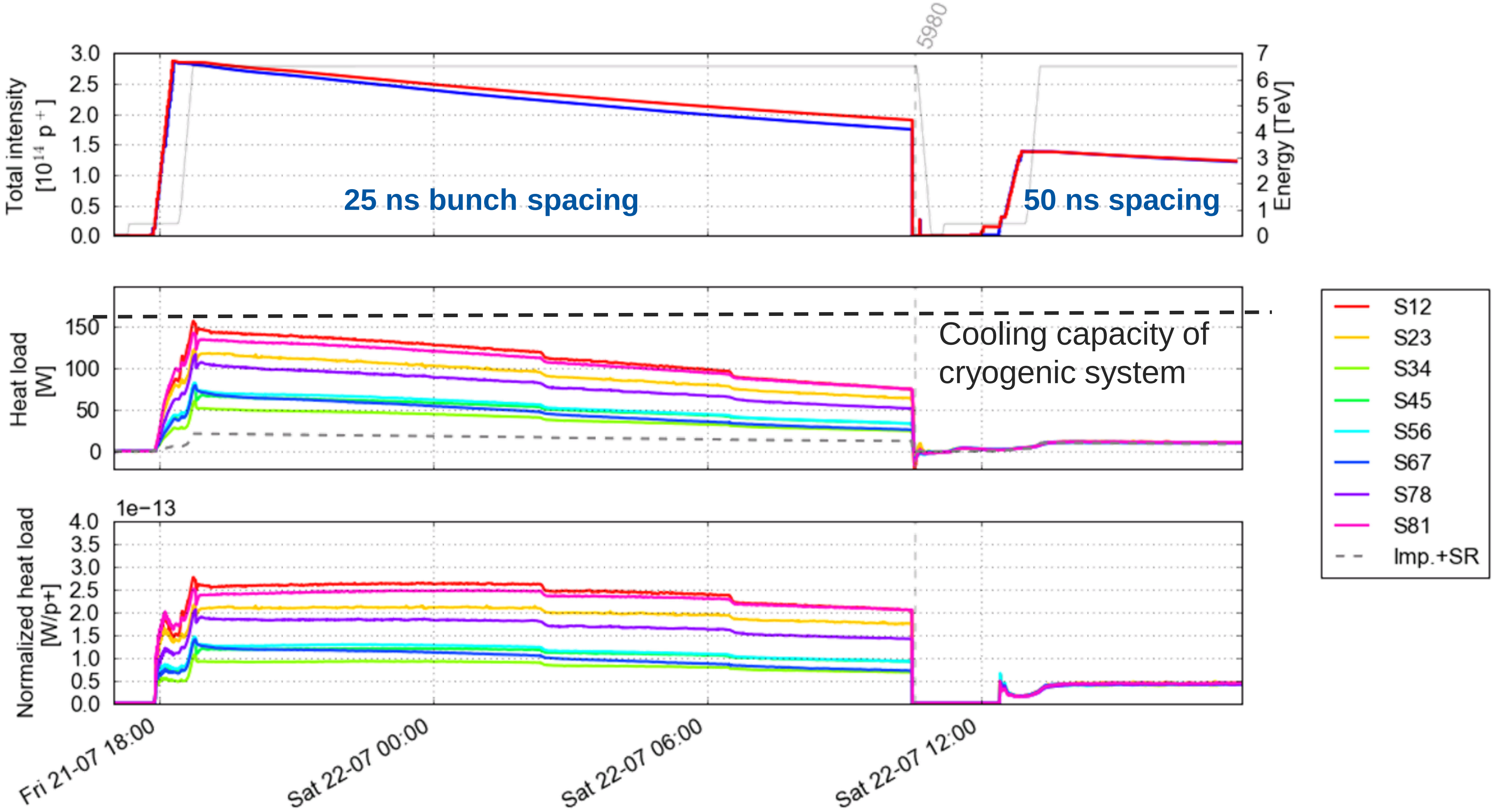
The electron cloud in the LHC

- The effects of the electron cloud in the LHC are clearly measurable
  - Bunch by bunch synchronous phase shift to compensate for the energy loss, which reveals the pattern of build up of the e-cloud along the bunches



The electron cloud in the LHC

- The effects of the electron cloud in the LHC are clearly measurable
  - Heat loads in the cold beam screen of the arcs



The electron cloud in the LHC

- Fortunately with the present range of beam parameters the electron cloud does not prevent the LHC operation, mainly because
  - Knobs to stabilise the beam can be efficiently employed (transverse feedback, octupole detuning, chromaticity)
  - The effect of electron cloud, which appears very severe at the beginning of operation in e-cloud dominated regime, then decreases in time thanks to the ‘**beam induced scrubbing**’ (i.e. decrease of the SEY of the surface under intense electron bombardment)
  - Low e-cloud filling patterns can be used as back up (at the expense of the number of bunches)
  - Local limitations due to electron cloud activity can be lifted by local implementation of e-cloud mitigating measures (e.g. solenoid, surface coating)

→ It remains one of the main challenges when running with future beam parameters!

- Fundamental concepts of beam dynamics
  - Components of an accelerator and basic definitions
  - Transverse beam dynamics and relevant quantities
  - Longitudinal beam dynamics and relevant quantities
  - Advanced concepts: Collective interactions (space charge, impedance, electron clouds)

- Upgrade of the LHC injector complex
  - Goals vs. present performance
  - Upgrade plans
  - Beam dynamics challenges

Goals of upgrades in a nutshell (HL-LHC)

The **High Luminosity LHC (HL-LHC, 2026 – 2037)** upgrade

- **Performance:**
  - Aims at **3000 (4000) fb^{-1}** total integrated luminosity (wrt ~190 fb^{-1} provided in Run1+2)
  - Based on operation at levelled luminosity of **5 (7.5) x 10^{34} cm^{-2}s^{-1}** by lowering β^*

Beam properties @LHC injection

	N_b (x 10^{11} p/b)	$\varepsilon_{x,y,}$ (μm)	Bunch spacing	Bunches
HL-LHC beam	2.3	2.1	25 ns	4x72 per injection

- **Sustainability/availability:**
  - Change/upgrade systems vulnerable to breakdown/ageing and improve infrastructure, especially in view of future operation in a higher radiation environment
- **Challenge: Employ cutting edge accelerator technology to push innovation!**

Goals of upgrades in a nutshell (LIU)

The **LHC Injectors Upgrade (LIU)**

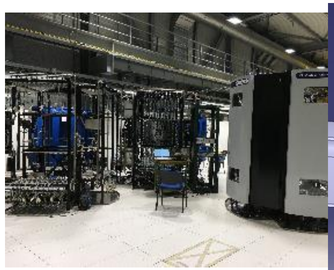
- Performance:
  - Aims at **matching the beam parameters** at LHC injection with HL-LHC target
  - Needs to deploy **means** to overcome **performance limitations** in all injectors!

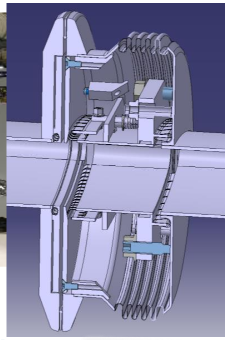
Beam properties @LHC injection

	N_b (x 10^{11} p/b)	$\varepsilon_{x,y,}$ (μm)	Bunch spacing	Bunches
HL-LHC target	**2.3**	**2.1**	**25 ns**	**4x72 per injection**
Present	1.3	2.7	25 ns	4x72 per injection

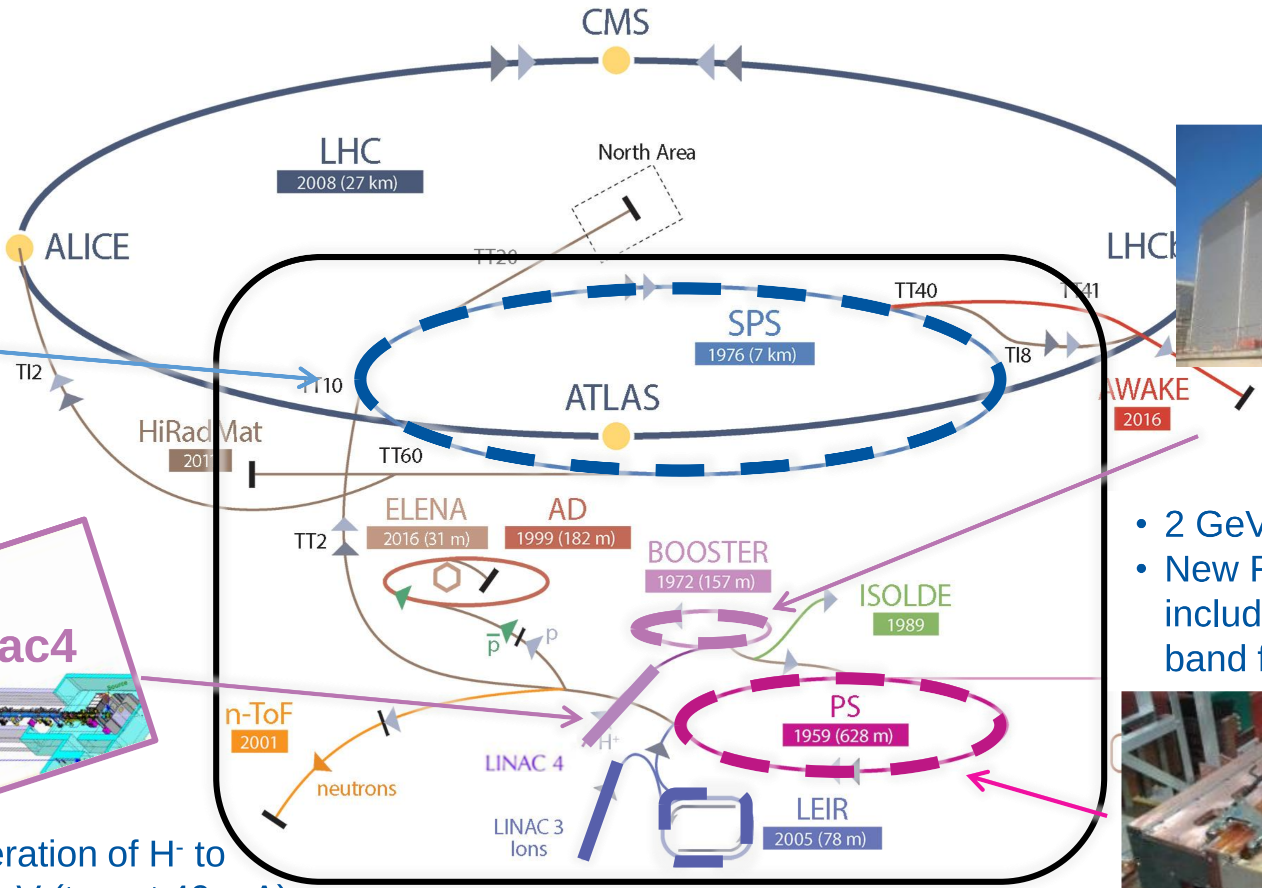
- Sustainability/availability:
  - Ensure and improve injectors' availability/reliability well into the HL-LHC era by upgrading sensitive/ageing equipment, improve radioprotection and services

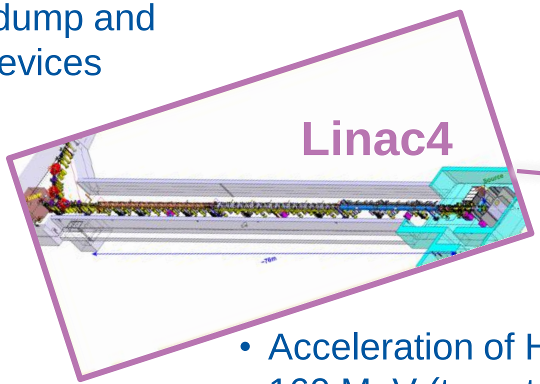
A view on LHC Injectors and LIU



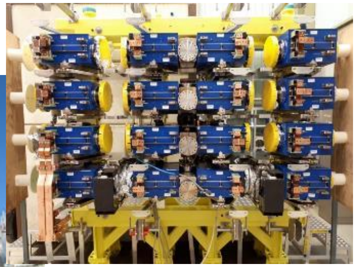


- Main RF system (200 MHz) upgrade
- Longitudinal impedance reduction & anti-ecloud coating
- New beam dump and protection devices



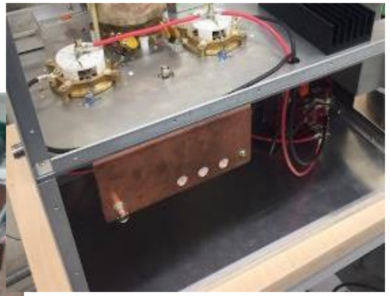


- Acceleration of H^- to 160 MeV (target 40 mA)
- Details of commissioning in **next talk by G. Bellodi**

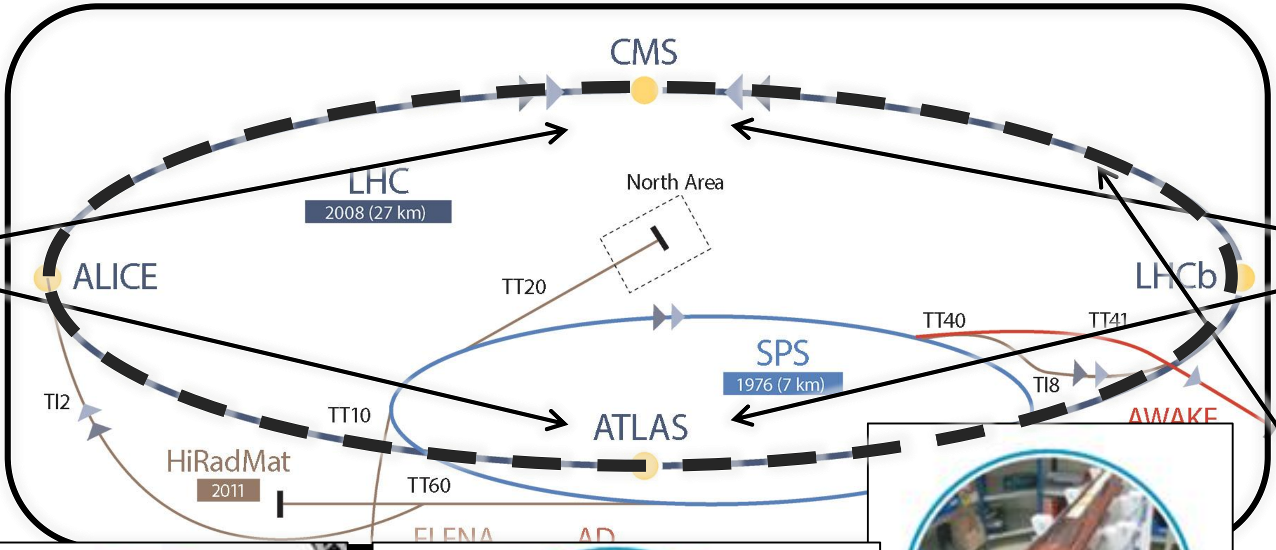


- 160 MeV H^- charge exchange injection
- Acceleration to 2 GeV with new main power supply and new RF

- 2 GeV injection
- New RF equipment including broad-band feedback



A view on LHC and HL-LHC



3

"CRAB" CAVITIES

8 superconducting "crab" cavities for each of the ATLAS and CMS experiments to tilt the beams before collisions.

1

FOCUSING MAGNETS

12 more powerful quadrupole magnets for each of the ATLAS and CMS experiments, designed to increase the concentration of the beams before collisions.

6

SUPERCONDUCTING LINKS

Electrical transmission lines based on a high-temperature superconductor to carry current to the magnets from the new service galleries to the LHC tunnel.

7

CRYOGENICS

2 new large 1.9 K helium refrigerators for HL-LHC near ATLAS and CMS

2

CIVIL ENGINEERING

2 new caverns and two new 300-metre service galleries, two new large shafts; new technical buildings on surface in P1 and P5 (ATLAS and CMS)

4

BENDING MAGNETS

2 pairs of shorter and more powerful dipole bending magnets to free up space for the new collimators.

5

COLLIMATORS

15 to 20 new collimators and 60 replacement collimators to reinforce machine protection.

Timeline of the projects

Proton Runs

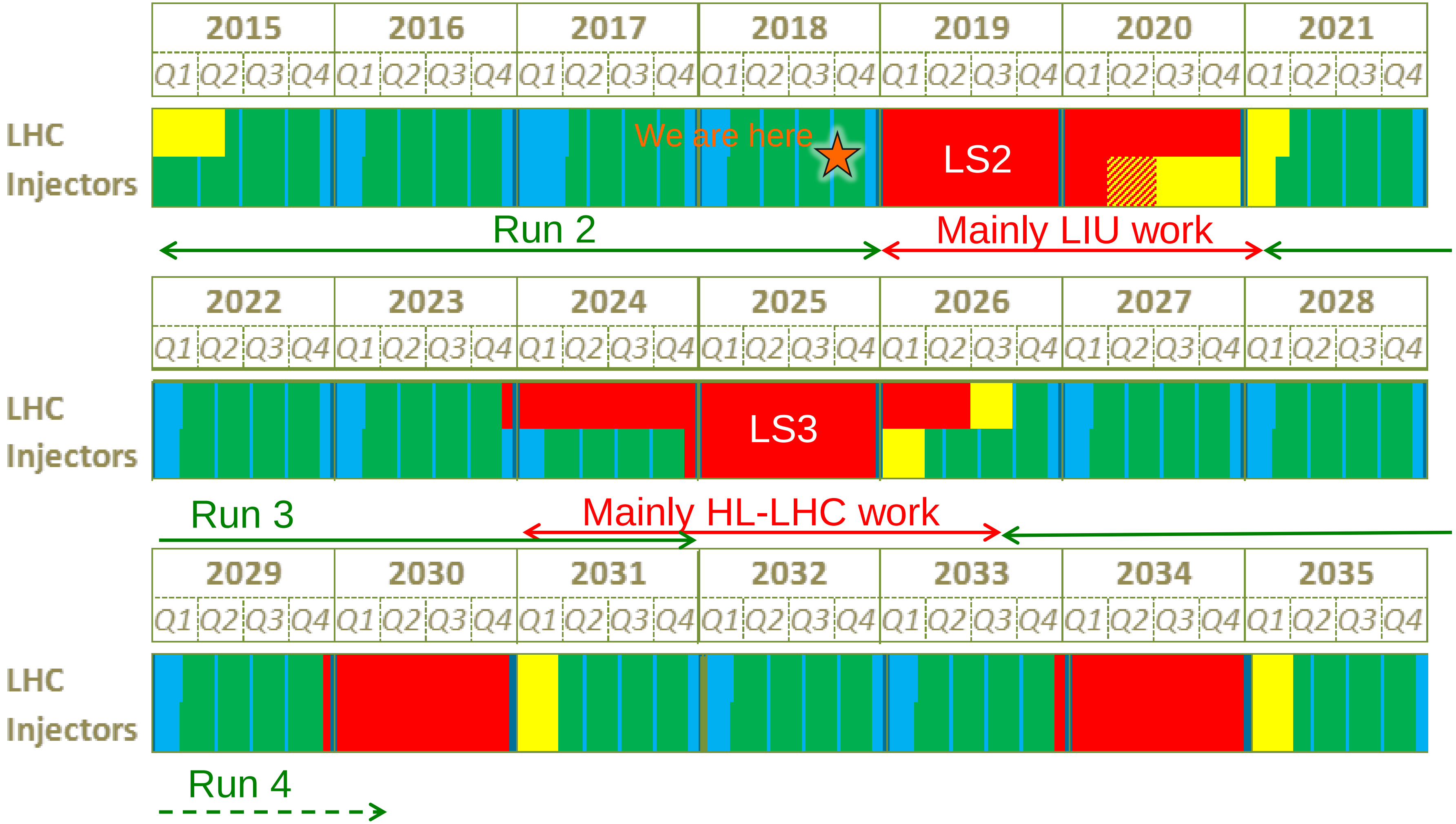
Technical Stops

Long Shutdowns

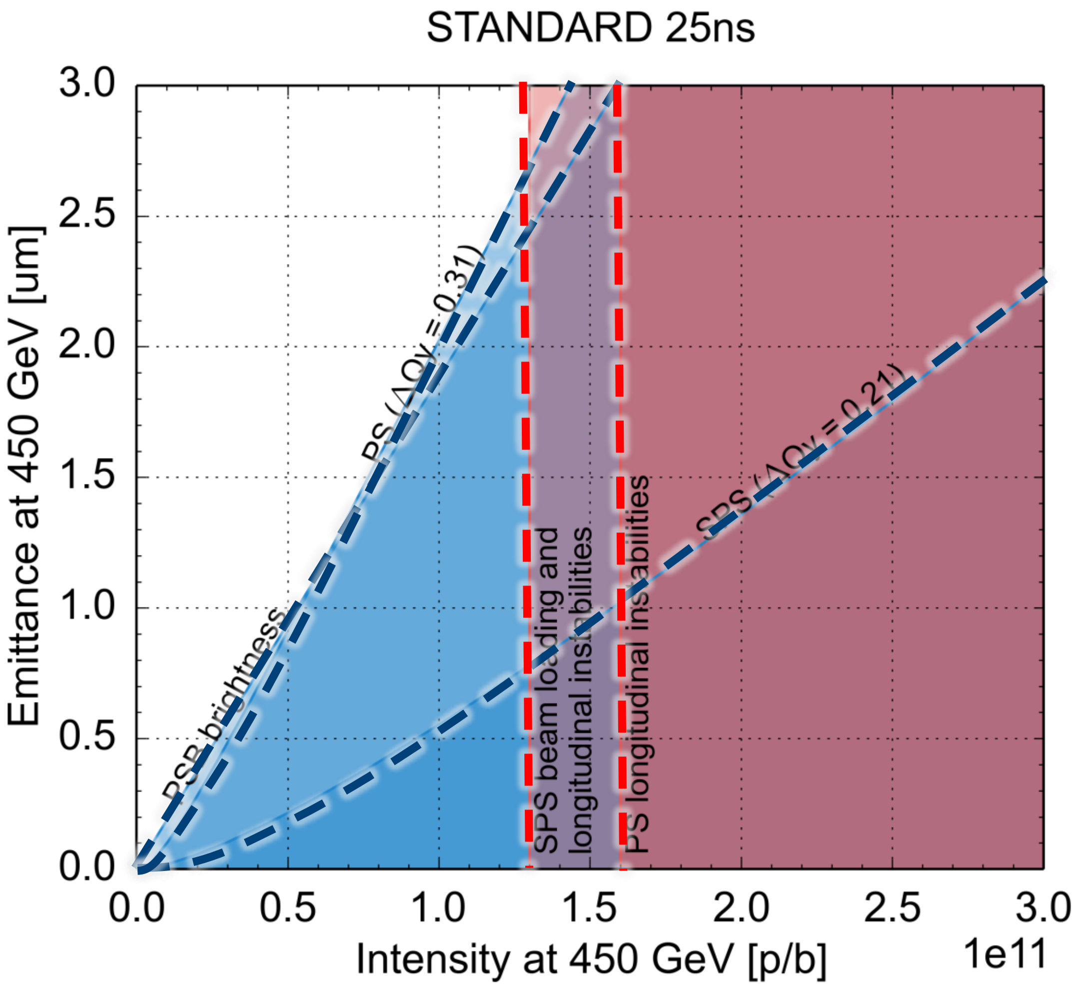
Beam Commissioning

Run 3: LIU beam commissioning through the injector chain

Run 4: HL-LHC run with a period of 'luminosity learning'



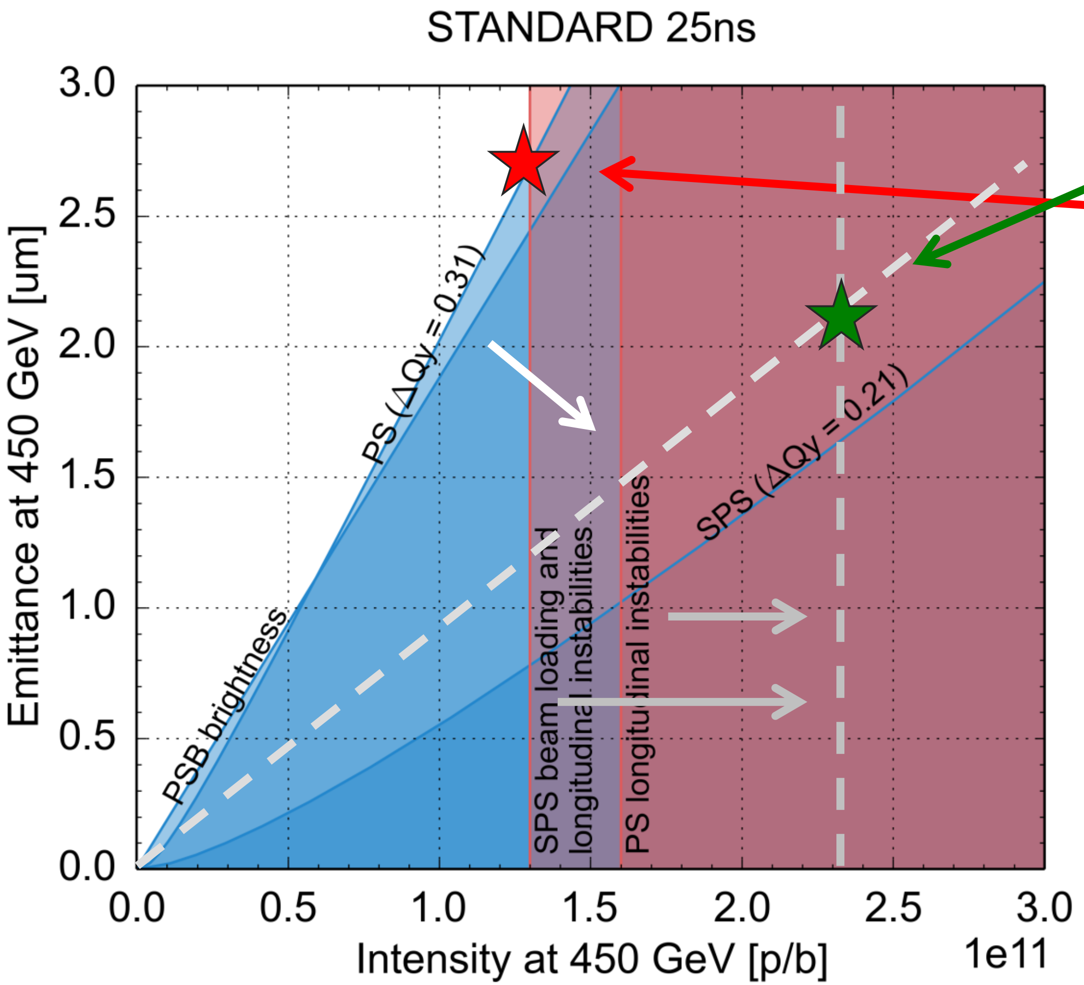
Present LHC injectors' limitations



	N_b (x 10^{11} p/b)	$\varepsilon_{x,y}$ (μm)
HL-LHC target	**2.3**	**2.1**
Present	1.3	2.7

- **PSB injection**: Brightness limited by efficiency of multi-turn injection process and space charge effects
- **PS and SPS injection**: Brightness limited by space charge – $\Delta Q<0.31$ (PS) and 0.21 (SPS), to limit beam degradation
- **PS cycle**: Bunch intensity limited by longitudinal coupled bunch instability
- **SPS cycle**: Bunch intensity limited by RF power, electron cloud, beam instabilities

Present LHC injectors' limitations



	N_b ($\times 10^{11}$ p/b)	$\varepsilon_{x,y}$ (μm)
HL-LHC target	2.3	2.1
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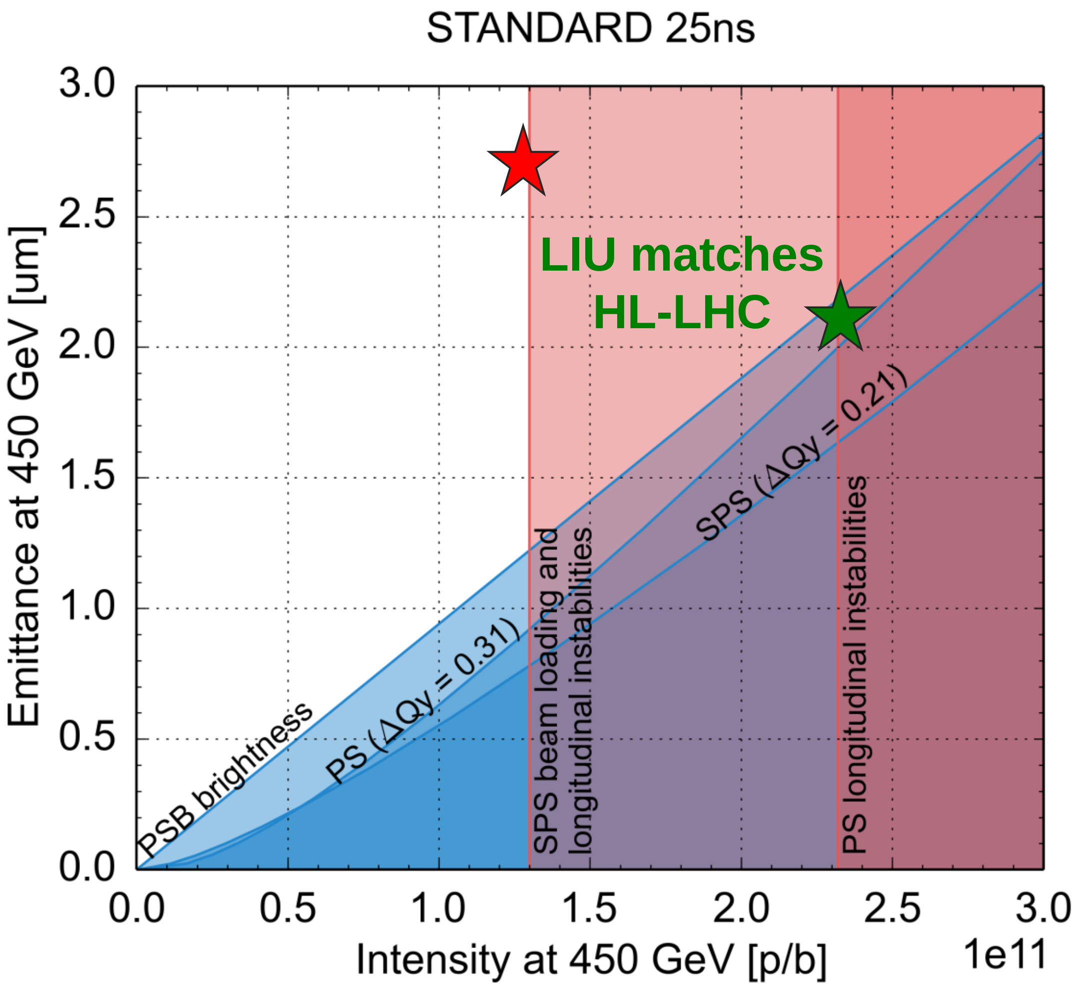
Future LHC injectors' performance



	N_b (x 10^{11} p/b)	$\varepsilon_{x,y}$ (μm)
HL-LHC target	**2.3**	**2.1**
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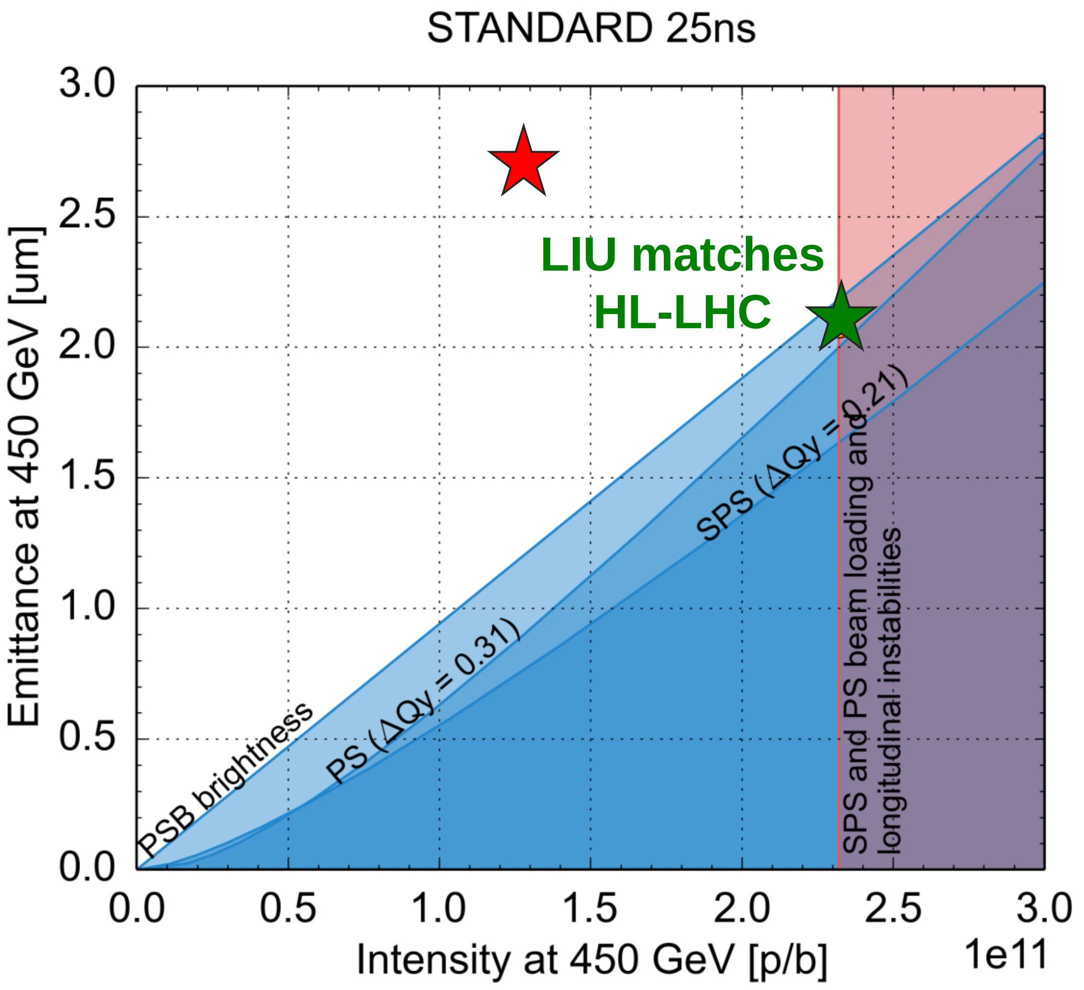
- **PSB injection**: from **Linac4**, reduced space charge (160 MeV) and H^- injection
- **PS injection**: Reduced space charge (2 GeV)
- **PS cycle**: Longitudinal feedback system

Future LHC injectors' performance

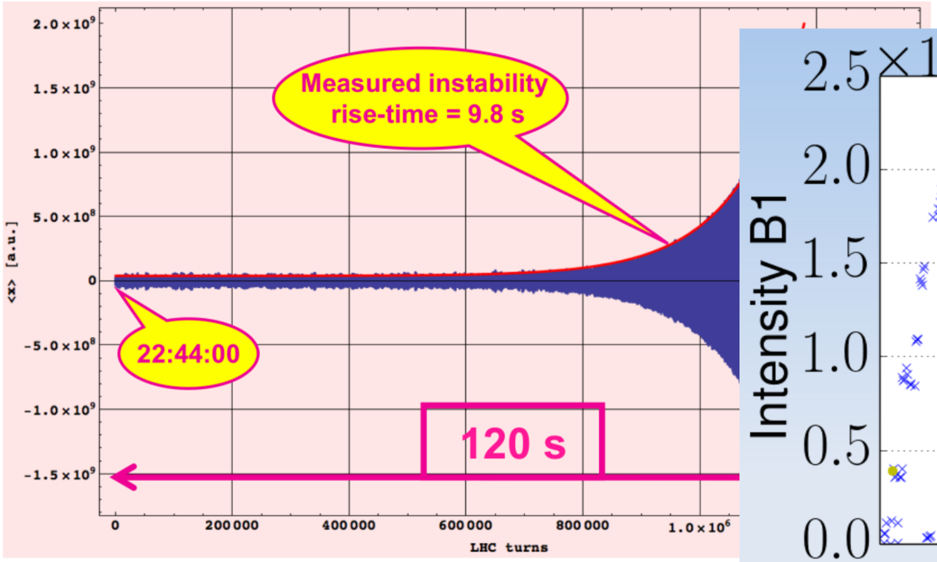


	N_b (x 10^{11} p/b)	$\varepsilon_{x,y,}$ (μm)
HL-LHC target	**2.3**	**2.1**
Present	1.3	2.7

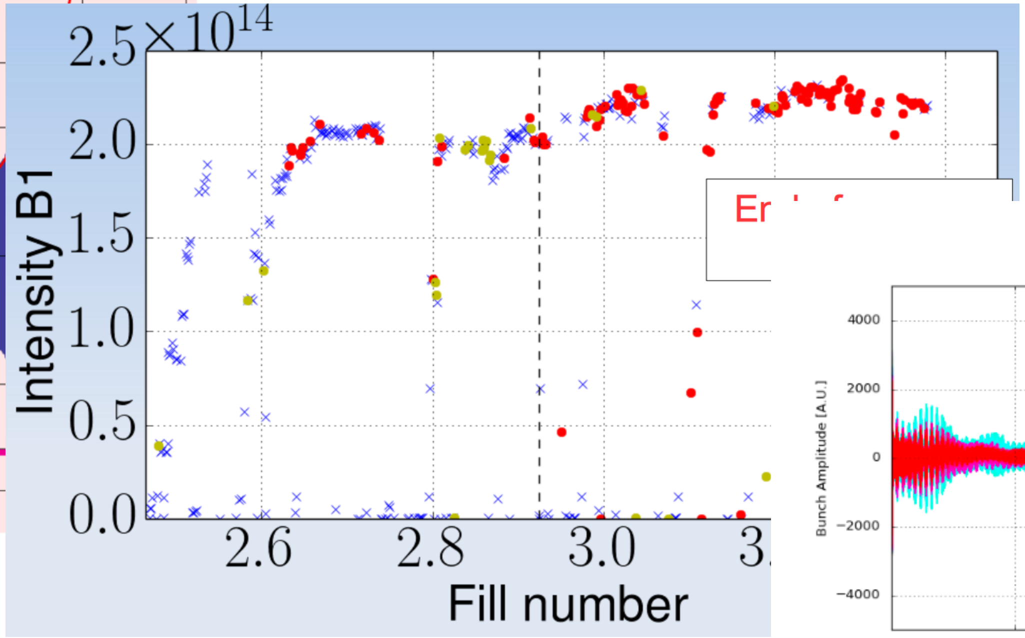
- **PSB injection**: from **Linac4**, reduced space charge (160 MeV) and H^- injection
- **PS injection**: Reduced space charge (2 GeV)
- **PS cycle**: Longitudinal feedback system
- **SPS cycle**: RF power upgrade, longitudinal impedance reduction, beam scrubbing & partial a-C coating, low γ_t optics

HL-LHC beam stability

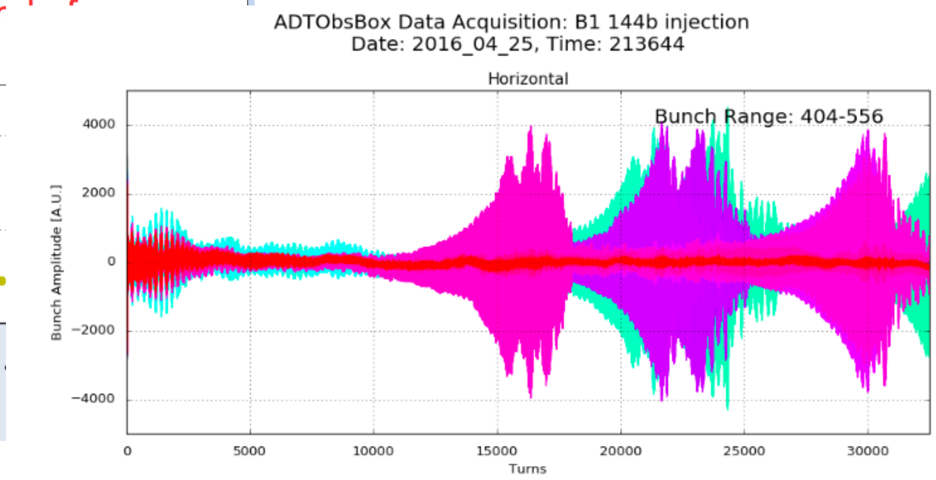
- **LHC transverse beam instabilities** observed with different types of beams and at different stages of the LHC cycle



2010, **single bunch** during the ramp



2011-12, **50 ns beam** during β* squeeze or while adjusting the beams to collide

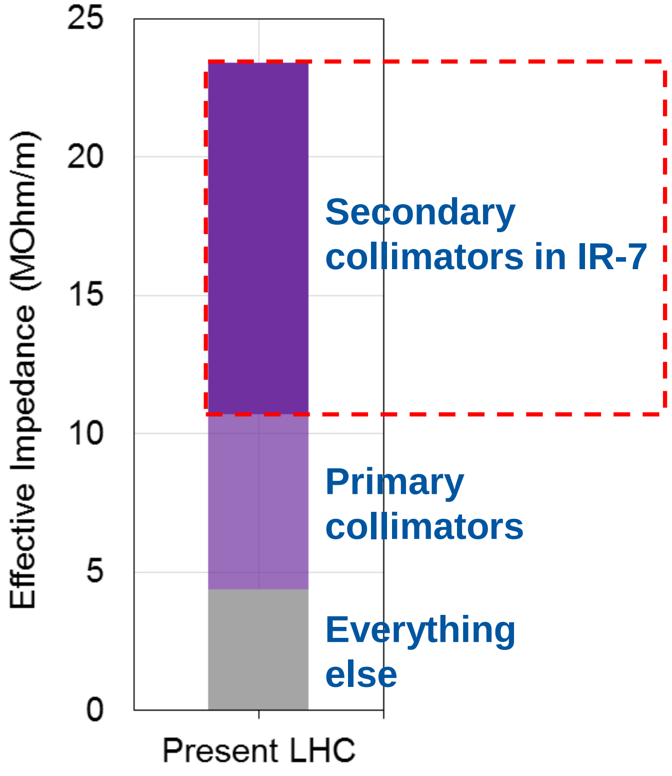


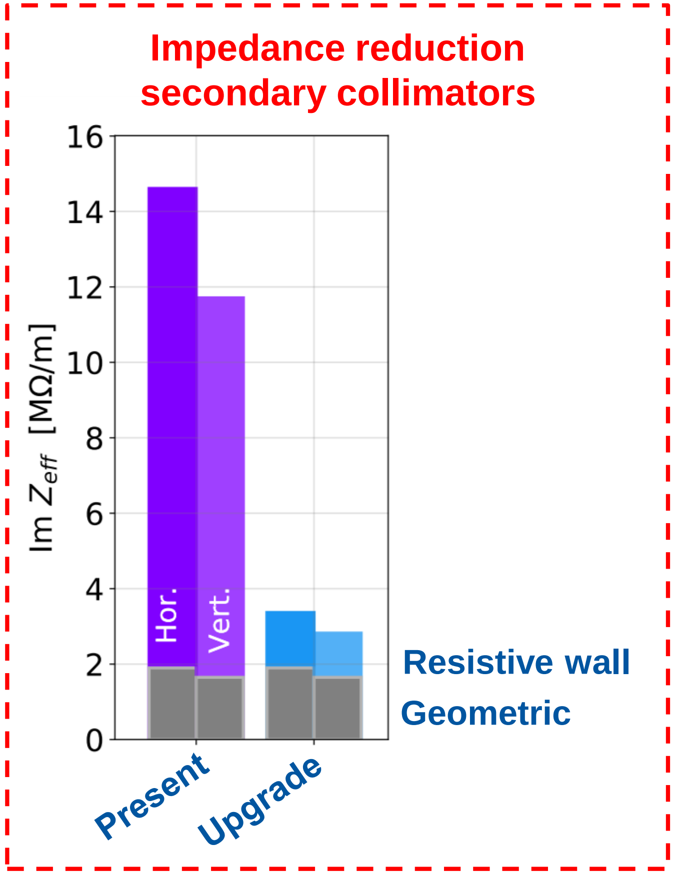
2015-18, **25 ns beam** at injection

HL-LHC beam stability

- **LHC transverse beam instabilities** observed with different types of beams and at different stages of the LHC cycle
- Sources are mainly **transverse impedance** and, at least with 25 ns beams, **electron cloud**
- Controlled through **“extreme” machine settings**, e.g. at 6.5 TeV Q’=+15, octupole strength close to maximum, maximum damper gain and bandwidth
  - Need to gain some margin with stabilisation knobs **for operation with HL-HLC beam parameters** (double intensity) → Impedance reduction

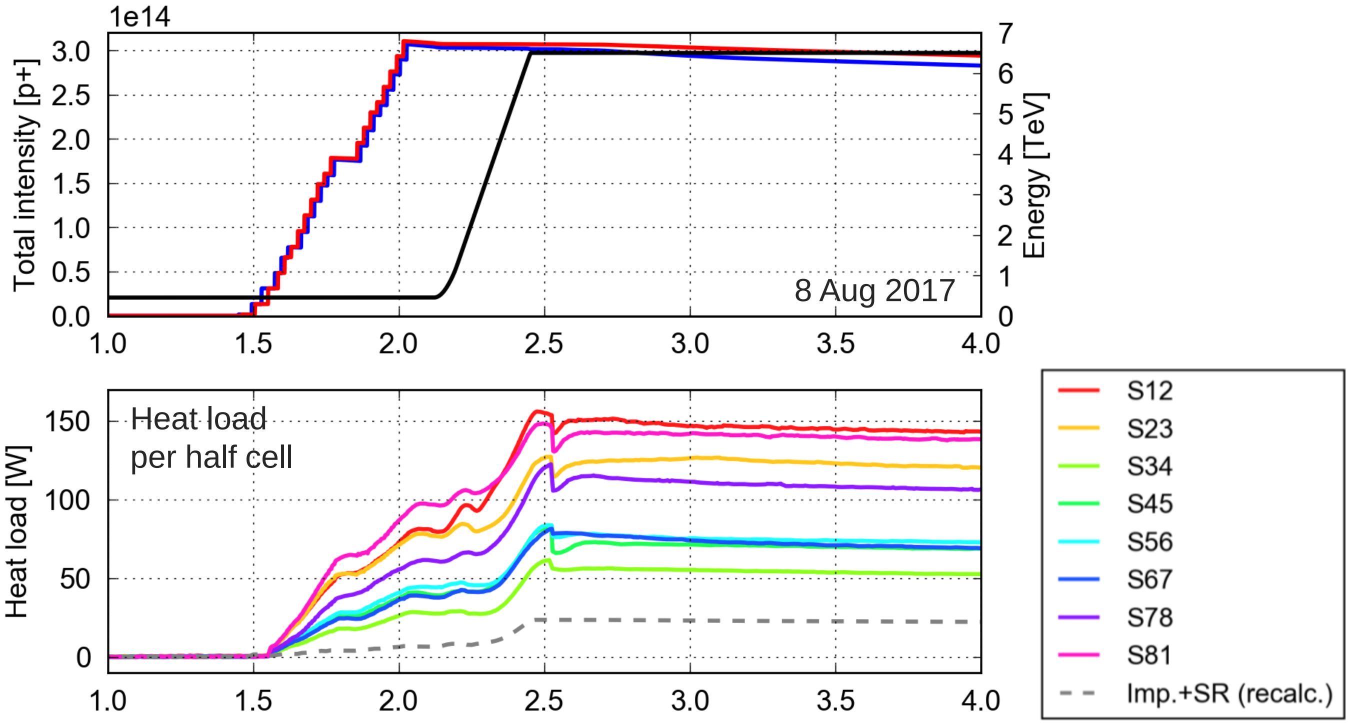
HL-LHC beam stability





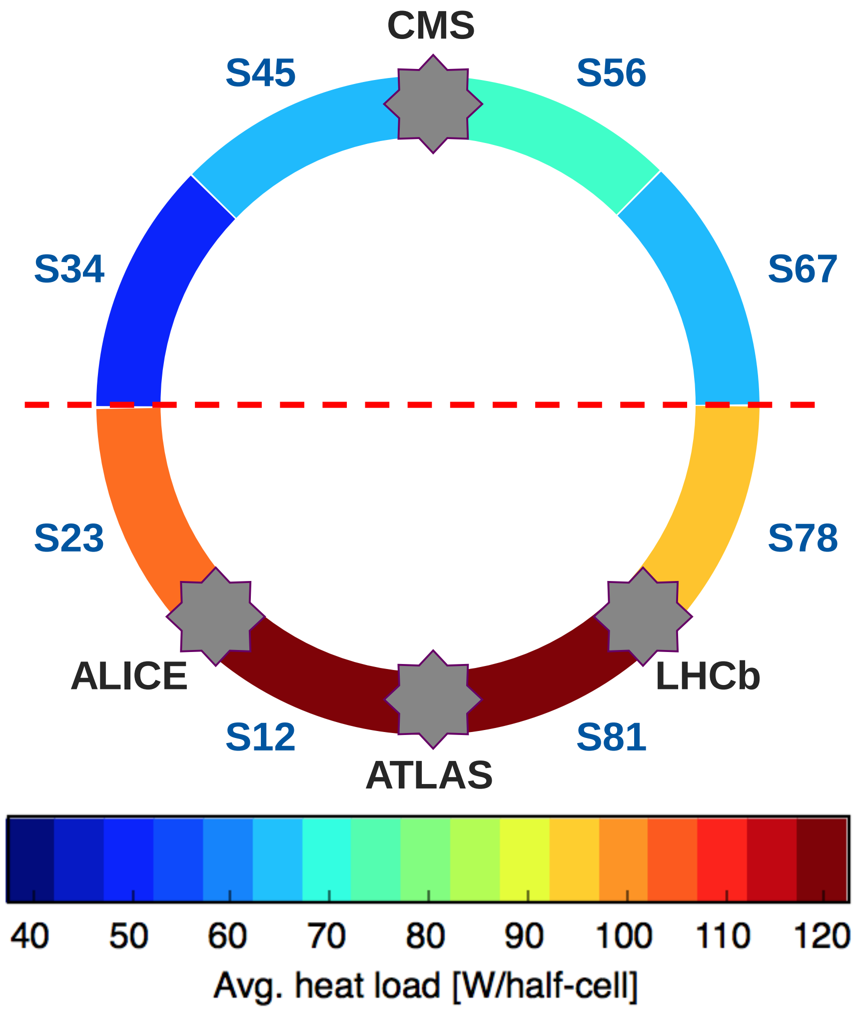
- Due to the small gaps, at 6.5 TeV the most critical impedance contributor (80%) is **collimators**
- Within HL-LHC secondary collimators replaced by new ones **with Mo-Gr jaws** having same robustness and higher conductivity → One order of magnitude lower RW impedance

Beam induced heat load in LHC



- High heat load on beam screen in cold regions (cryo limit 160 W/hc in the arcs)
  - With 25 ns beams
  - Much higher than calculation from impedance + synchrotron radiation
  - Different among arcs
- Most observations compatible with electron cloud, probably localised in some magnets (or even some parts of magnets)

Beam induced heat load in LHC



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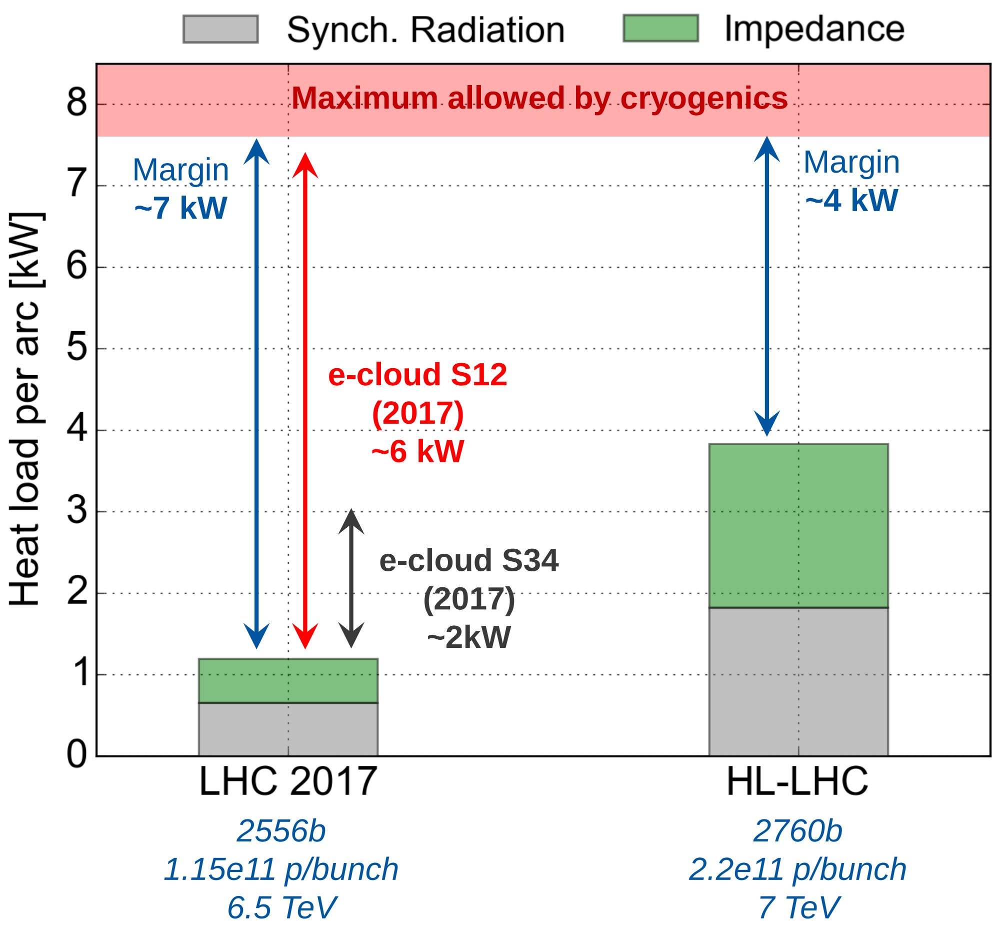
  - With 25 ns beams
  - Much higher than calculation from impedance + synchrotron radiation
  - Different among arcs
- Most observations compatible with electron cloud, probably localised in some magnets (or even some parts of magnets)

Beam induced heat load in HL-LHC

- Two fold issue for HL-LHC
  - Less margin for cryostat with HL-LHC parameters (three-fold contribution from impedance and synchrotron radiation)
  - How does the additional load scale with bunch intensity? → We can make a prediction only if we assume it is caused by electron cloud



Some other challenges in HL-LHC

- Beam-beam interaction
  - Head-on and long range collisions at the interaction points

- Incoherent emittance growth along the cycle
  - Caused by several sources including Intra-Beam Scattering, noise from power converters, etc.

- Active control of the beam halo for machine protection
  - Cleaning techniques under study to cope with potentially very harmful beam halo

One final word

- Building or upgrading + operating a large particle accelerator relies on
  - **Laboratory measurements** → Magnets (n-poles, but also fast pulsing magnets), RF systems, power converters, electronics components, impedances, material properties (vacuum, conductivity, resistance, radiation hardness, SEY, etc.)
  - **Beam based measurements** → Beam current, bunch by bunch intensity, closed orbit, betatron tunes, synchrotron tune, beam positions, beam sizes, bunch length, momentum spread, stable phases, electron clouds, heat loads, …

- You will see an important sample of techniques and applications in the next lectures!

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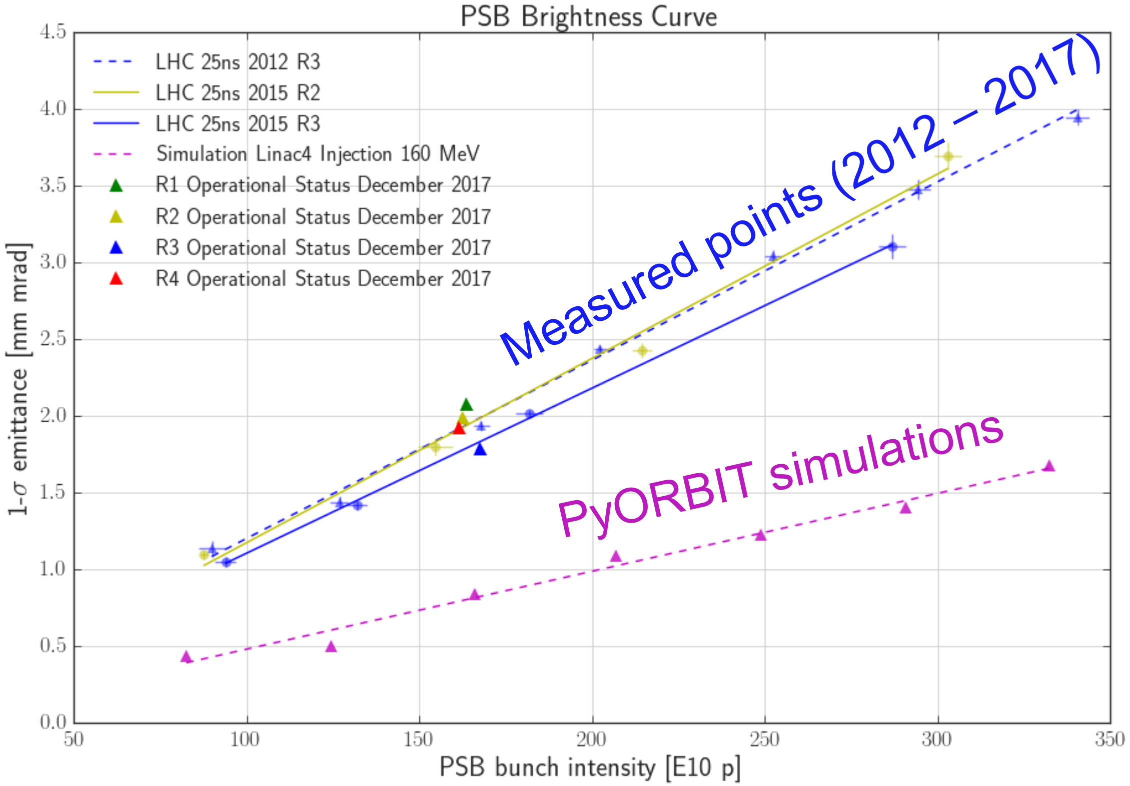
THANK YOU FOR YOUR ATTENTION

Lifting the brightness limitations

- Halve the slope of the **PSB brightness line**
  - 160 MeV H$^-$ charge exchange injection from Linac4 replacing 50 MeV multiturn injection from Linac2



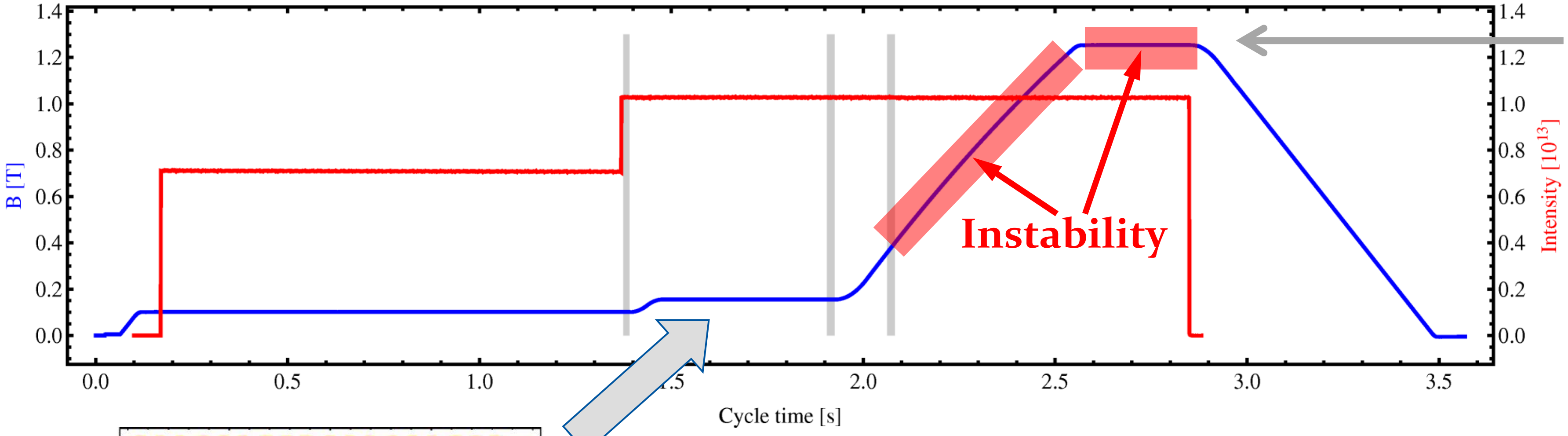
$$\left[\frac{(\beta\gamma^2)_{160\,\mathrm{MeV}}}{(\beta\gamma^2)_{50\,\mathrm{MeV}}}\right] = 2$$

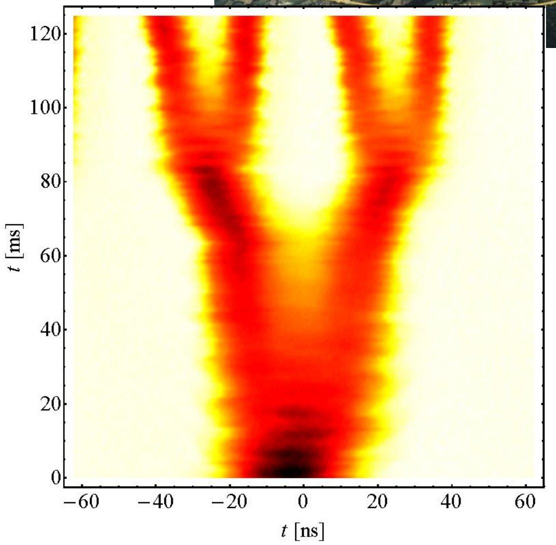
Lifting the brightness limitations

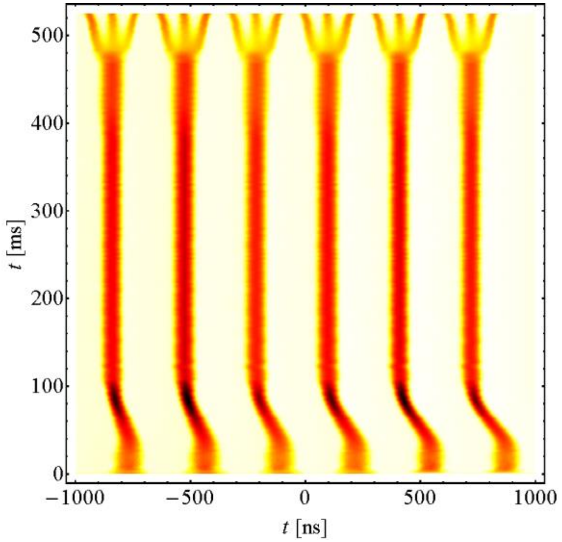
- Halve the slope of the **PSB brightness line**
  - 160 MeV H^- charge exchange injection from Linac4 replacing 50 MeV multiturn injection from Linac2
- Reduce **space charge at PS injection** to accommodate same tune spread as current LHC beam (ΔQ_y=-0.31)
  - Increase of PS injection energy from 1.4 GeV to 2 GeV
  - Increase of longitudinal emittance (compatibly with other constraints) at transfer in order to gain from decreasing λ_{max} and increasing $\delta=(\delta p/p_0)$

$$\Delta Q_{x,y} = \frac{\lambda_{\max} r_p}{2\pi\beta^2\gamma^3} \oint \frac{\beta_{x,y}(s)ds}{\sqrt{\epsilon_{x,y}\beta_{x,y}(s) + D^2_{x,y}(s)\delta^2}\left(\sqrt{\epsilon_x\beta_x(s) + D^2_x(s)\delta^2} + \sqrt{\epsilon_y\beta_y(s) + D^2_y(s)\delta^2}\right)}$$

Lifting the PS intensity limitation





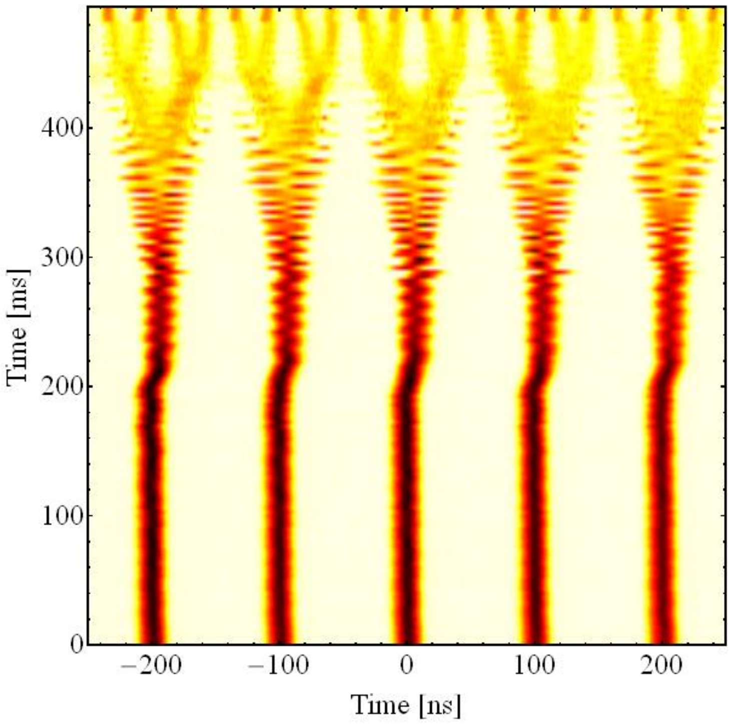


- Bunch current limited to **1.6e11 p/b at extraction**
- Above 1.6e11 p/b **longitudinal coupled bunch instabilities** appear on the ramp and at flat top for nominal longitudinal emittance
  - Dipolar oscillation, caused by **10 MHz RF system impedance** (as found also in simulations)

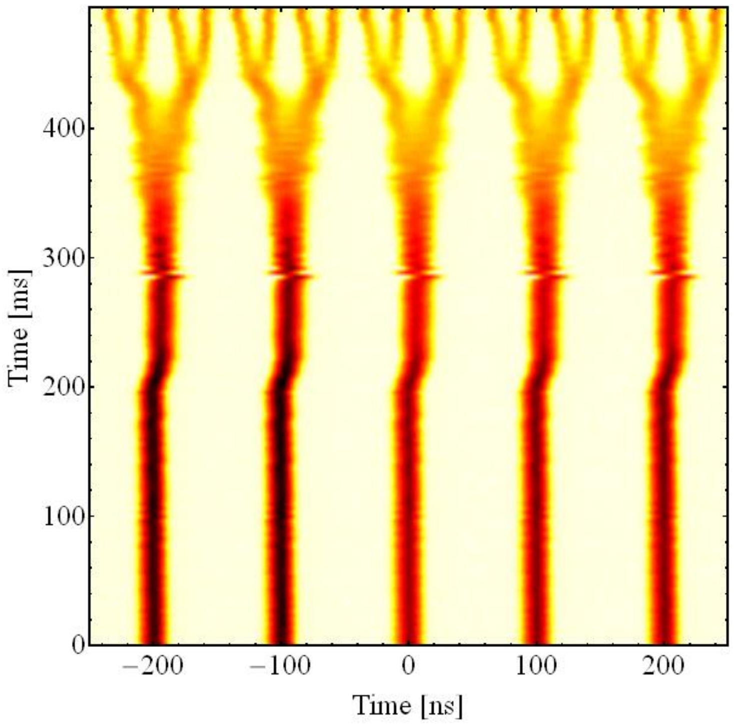
Lifting the PS intensity limitation

- **Longitudinal feedback** based on broad-band Finemet cavity as kicker installed and deployed over the last three years → stabilizes above 2e11 p/b

Feedback off ($N_b = 1.8 \cdot 10^{11}$ ppb)



Feedback on ($N_b = 1.8 \cdot 10^{11}$ ppb)

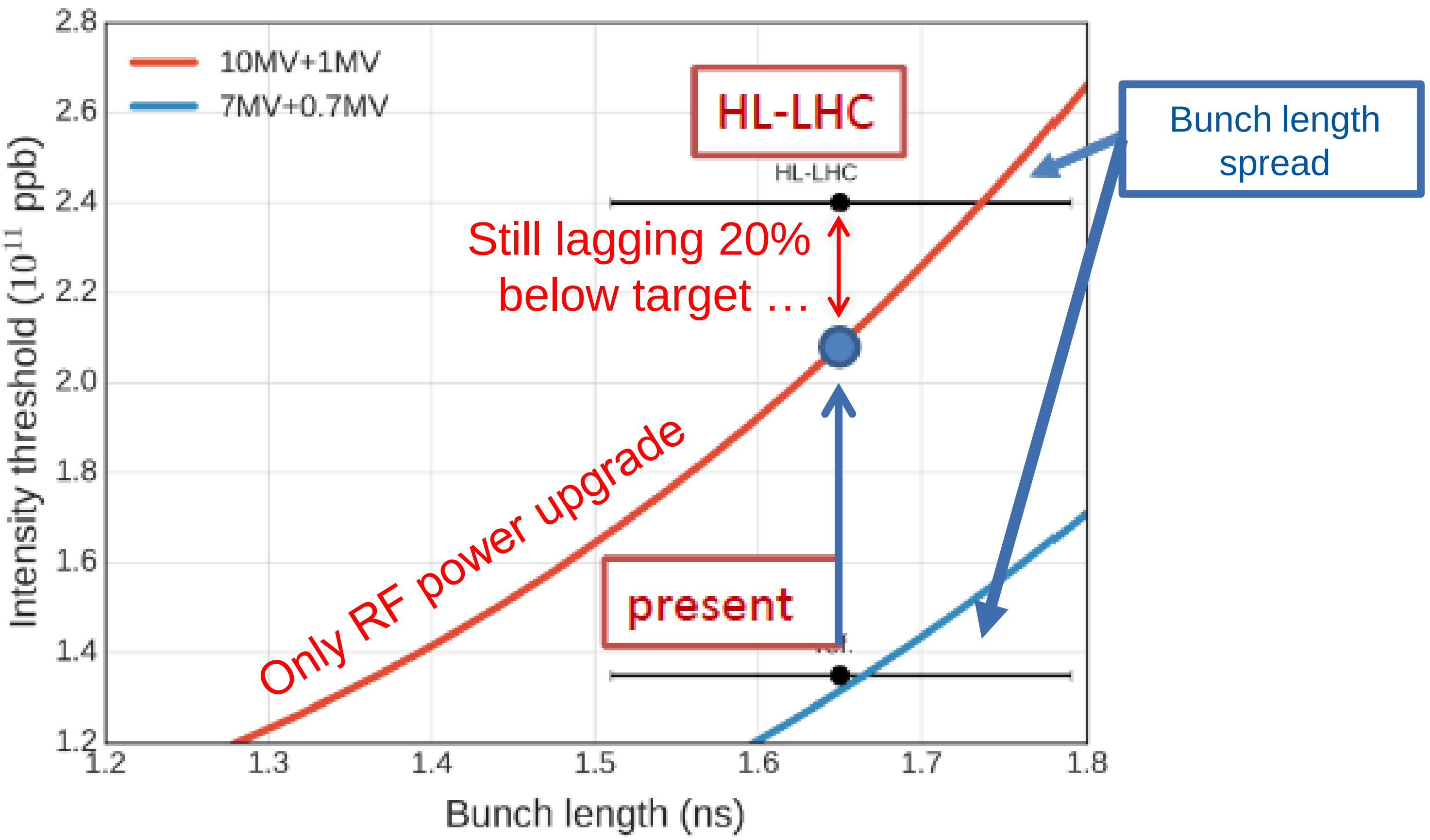


Lifting the PS intensity limitation

- **Longitudinal feedback** based on broad-band Finemet cavity as kicker installed and deployed over the last three years → stabilizes above 2e11 p/b
- **Impedance reduction** of the 10 MHz cavities with upgrade of power amplifier → currently tested on one cavity, to be deployed on all cavities in LS2
- Ongoing study on the option of a **higher harmonic (‘Landau’) cavity** to have another weapon against longitudinal instabilities and reach the target LIU/HL-LHC intensity

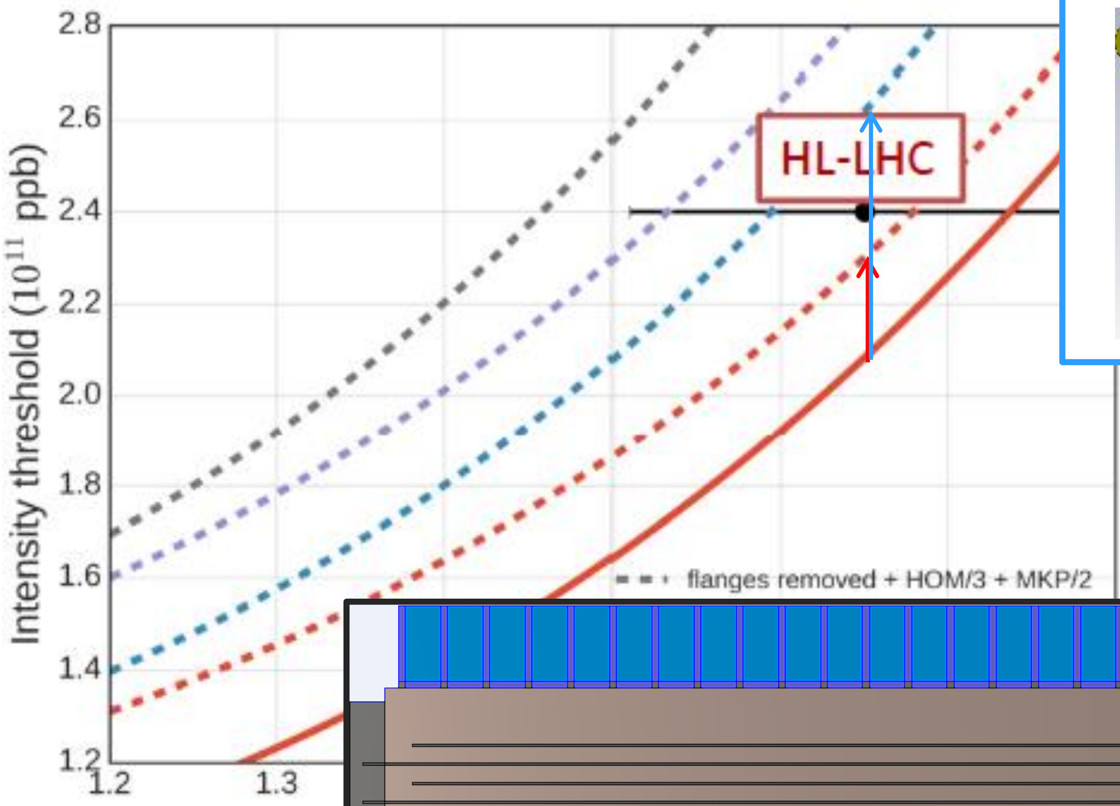
Lifting the SPS intensity limitation

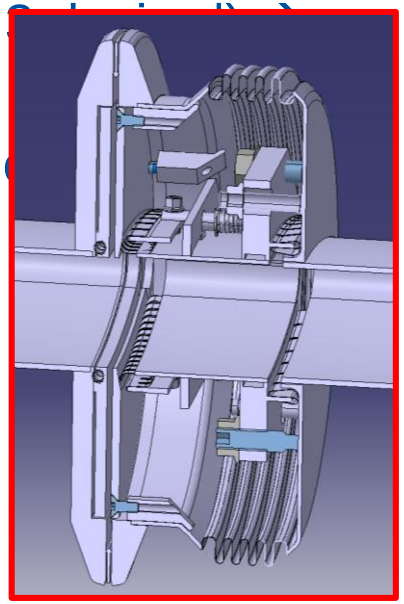
- **Beam loading** in the present 200 MHz TW RF system – intensity limited to about 1.3e11 p/b
- **Longitudinal instabilities** during ramp with very low threshold currently cured by
  - 800 MHz RF system in bunch shortening mode
  - Controlled emittance blow-up (with constraint of 1.7 ns bunch length at extraction)



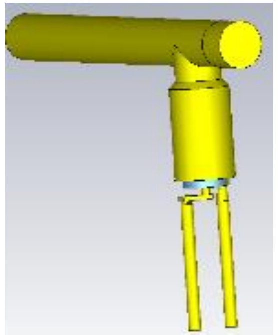
Lifting the SPS intensity limitation

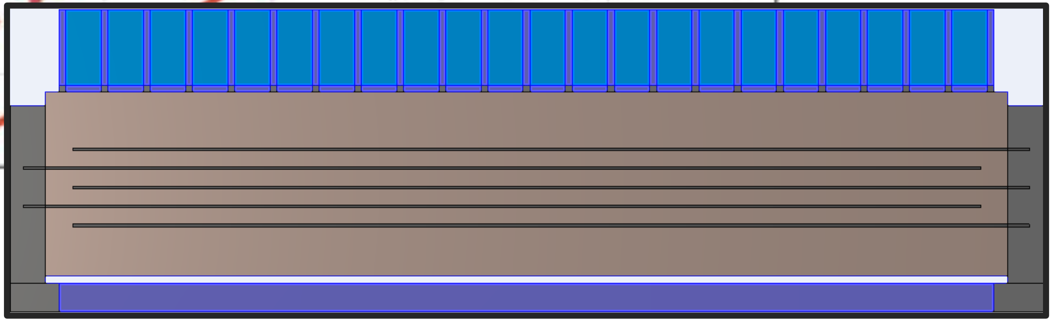
- **Impedance reduction** needed in addition
  - Shielding of a subset of vacuum flanges
  - Enhanced damping of HOMs of 200 MHz (factor
    baseline for LIU
  - Serigraphy on the
    kickers MKP





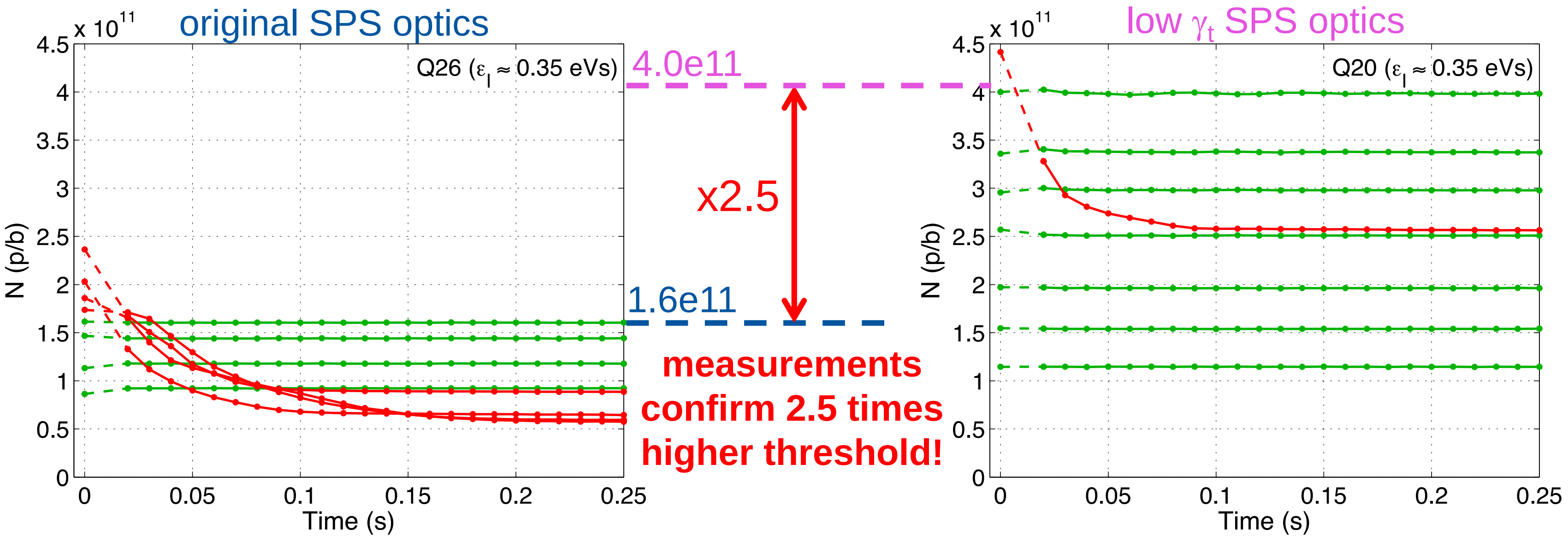
new HOM coupler





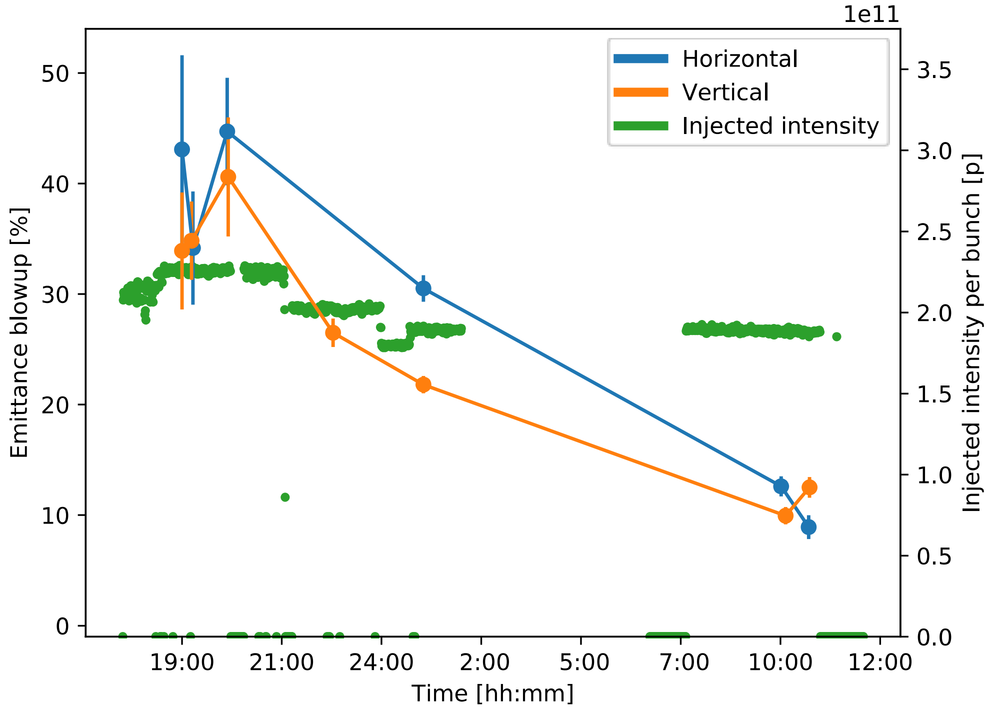
Other SPS intensity limitations?

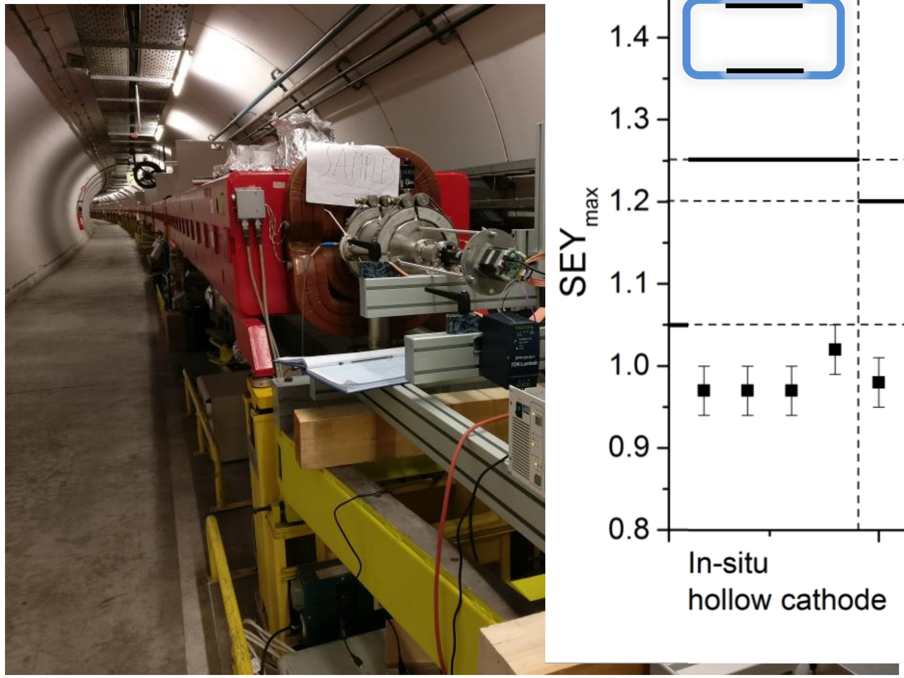
- **Transverse Mode Coupling Instability (TMCI)** threshold was raised from 1.6e11 p/b to 4e11 p/b when switching to a low gamma transition (γ_t) optics

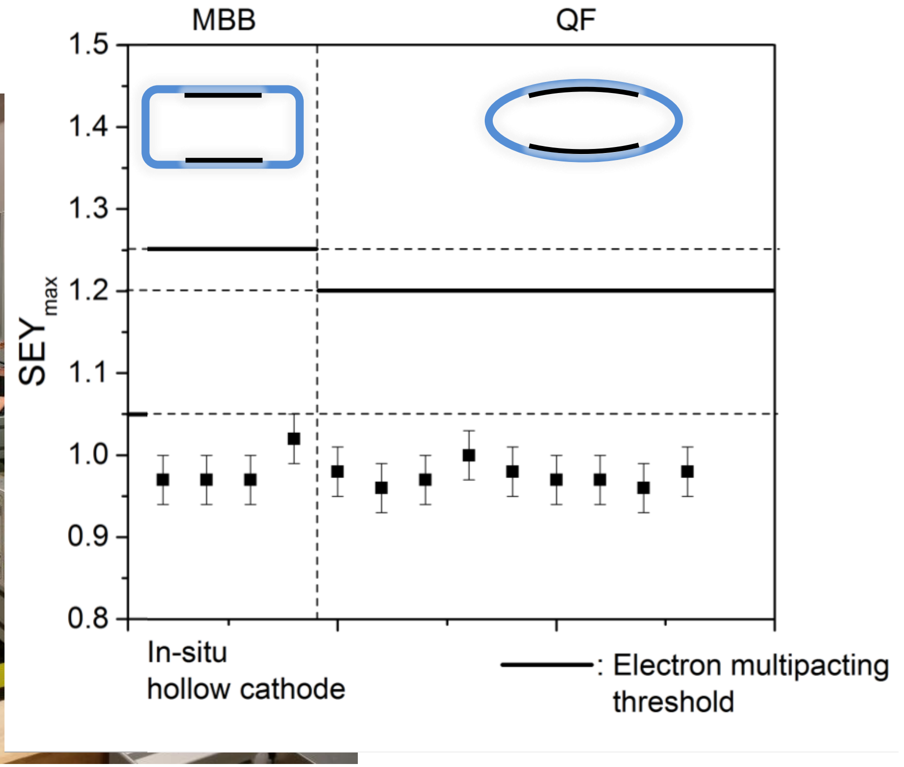


Other SPS intensity limitations?

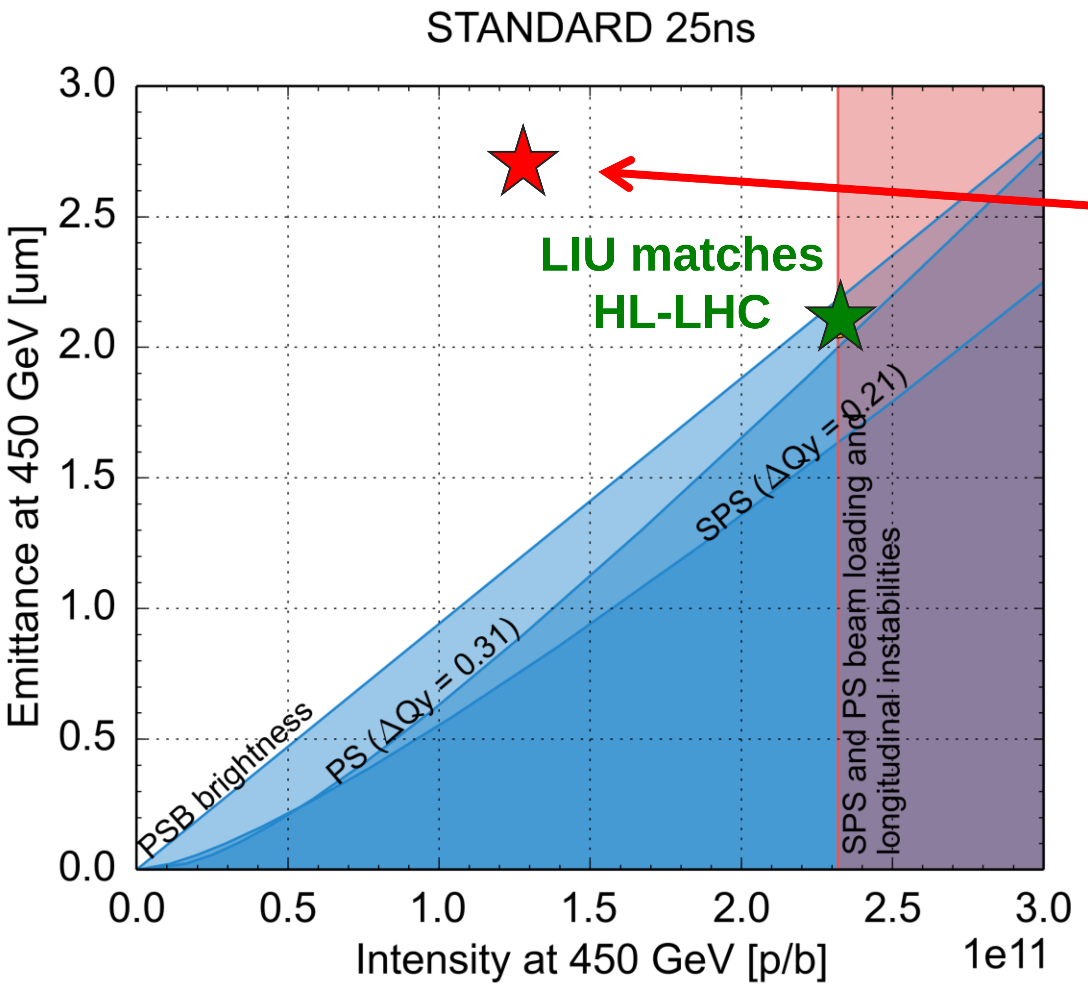
- **Electron cloud mitigation** relies mainly on
  - Beam induced scrubbing
  - Coating with a-C the chambers of the focusing quadrupoles and adjacent drift chambers







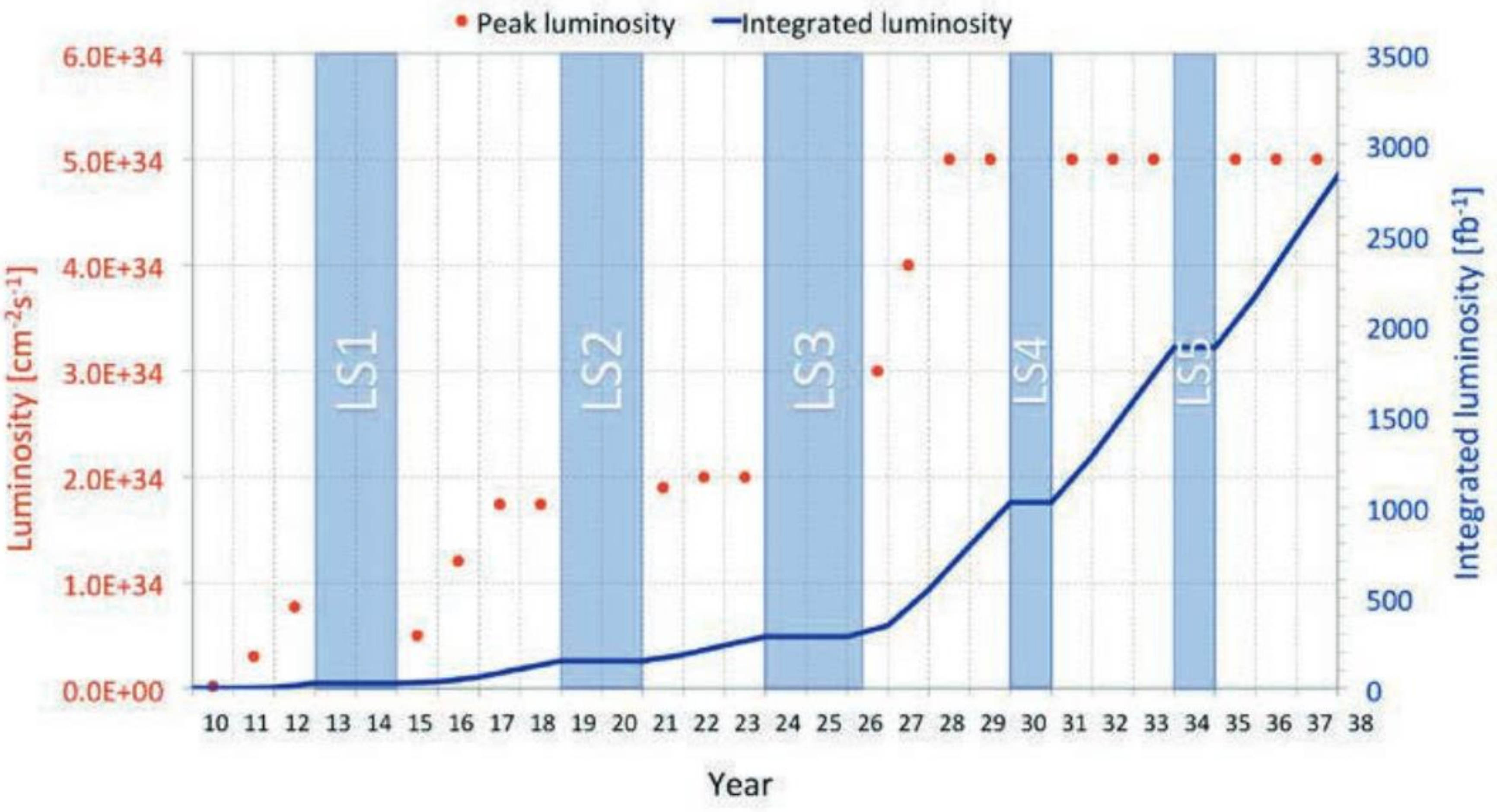
Summary: Future LIU performance



	N_b (x 10^{11} p/b)	$\varepsilon_{x,y,}$ (μm)
HL-LHC target	**2.3**	**2.1**
Present	1.3	2.7

- **PSB injection**: from Linac4
- **PS injection**: 2 GeV, larger longitudinal emittance
- **PS cycle**: Longitudinal coupled bunch feedback system, impedance reduction
- **SPS cycle**: RF power upgrade, longitudinal impedance reduction, beam scrubbing & partial a-C coating, low γ_t optics

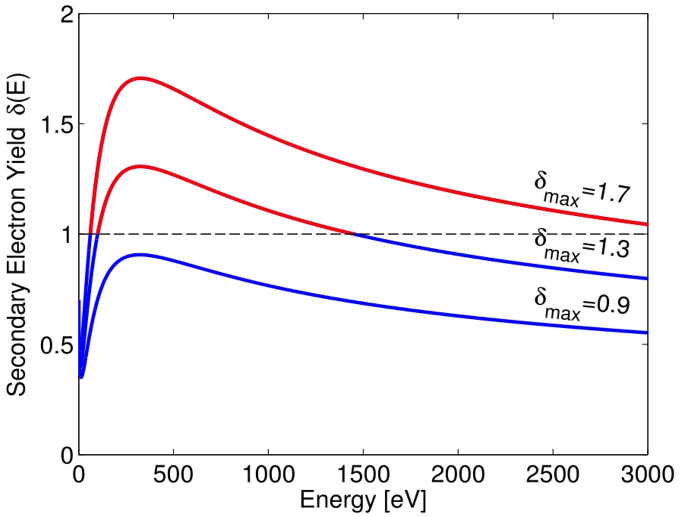
Luminosity projection



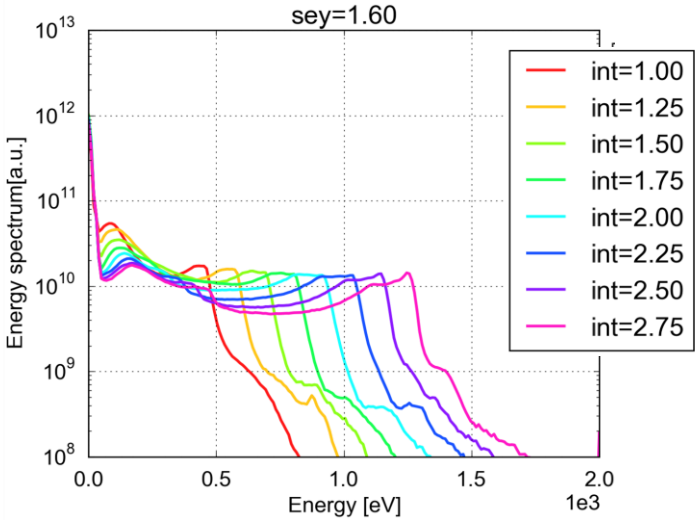
E-cloud build up with intensity

Underlying mechanism:

When the SEY decreases the **energy window for multipacting** becomes narrower

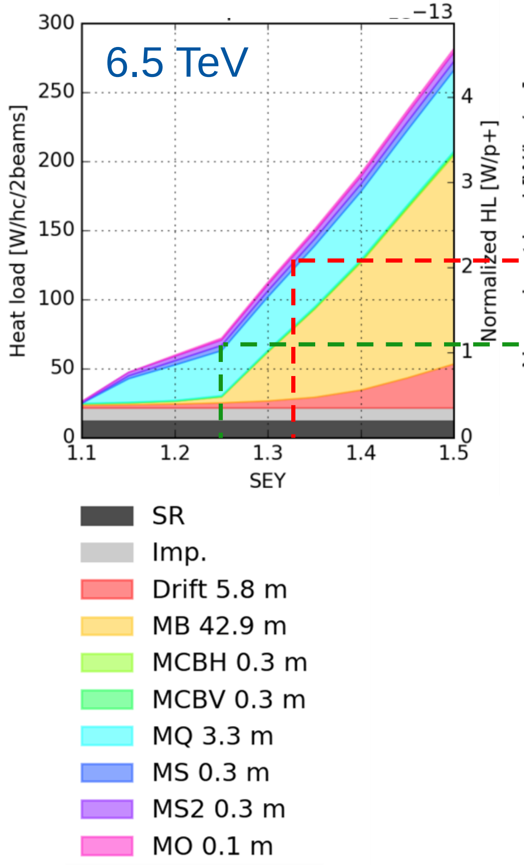


For high bunch intensity the e- spectrum drifts to higher energies and can move outside the most efficient region

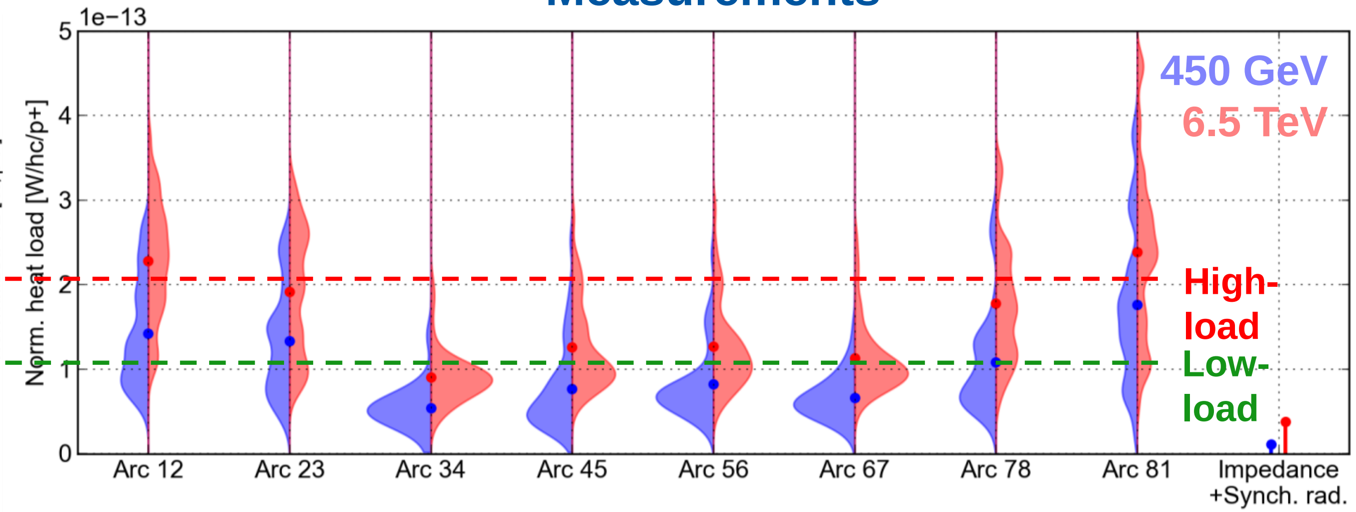


Inferring the average SEY

Simulations



Measurements



	(blue)	(red)
Fill	6674	6674
Started on	12 May 2018 02:35	12 May 2018 02:35
T_sample [h]	1.70	2.40
Energy [GeV]	450	6499
N_bunches (B1/B2)	2556/2556	2556/2556
Intensity (B1/B2) [p]	2.84e14/2.86e14	2.79e14/2.83e14
Bun.len. (B1/B2) [ns]	1.17/1.34	1.09/1.08
H.L. exp. imped. [W]	6.17	8.97
H.L. exp. synrad [W]	0.00	11.95
H.L. exp. imp.+SR [W/p+]	1.08e-14	3.72e-14
T_nobeam [h]	1.15	1.15

Inferring the average SEY

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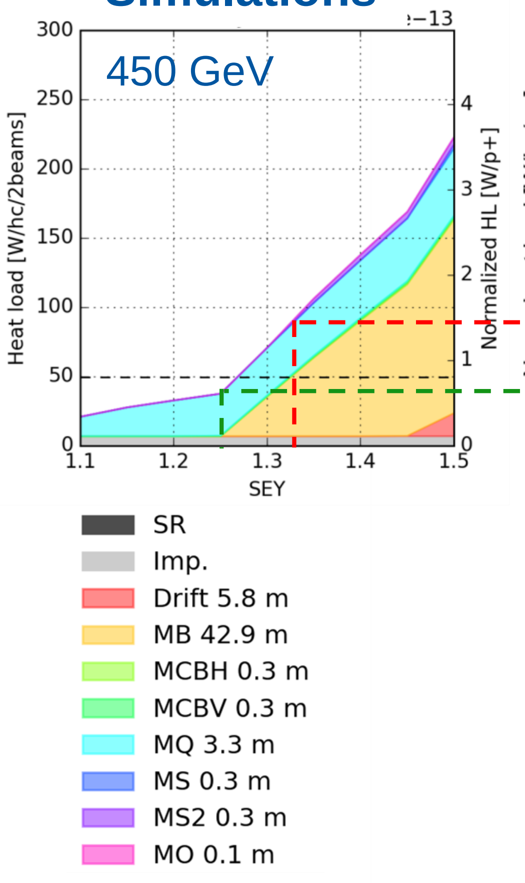

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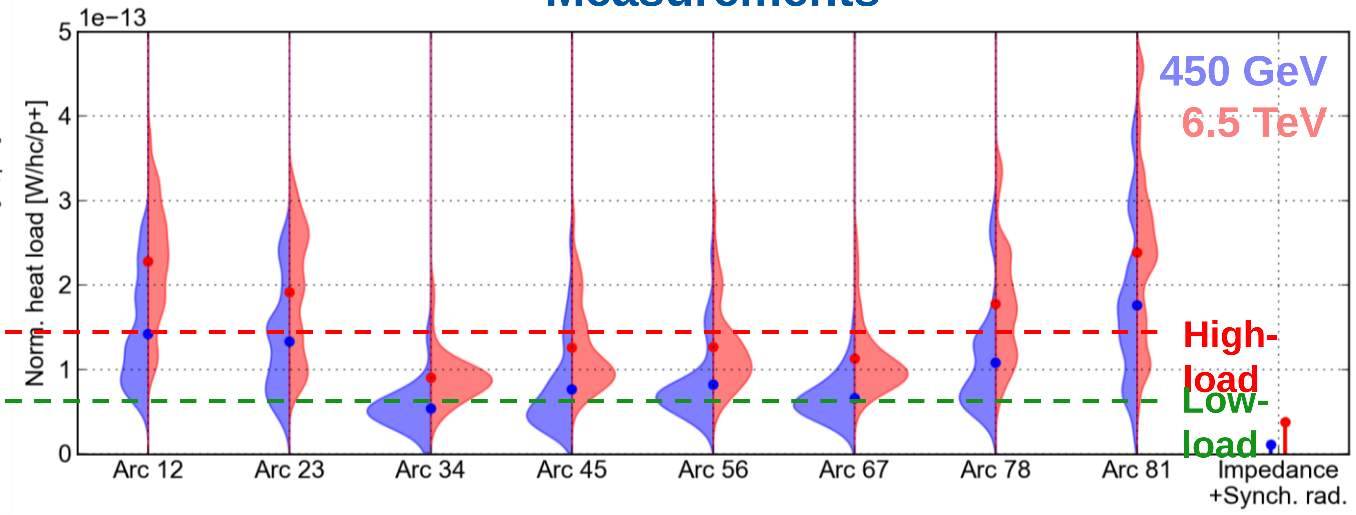

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