



*Accelerator & Technology Sector  
Beams Department  
Accelerator Beam Physics Group*

# Particle Accelerators and Beam Dynamics

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Summer Student Lectures 2024

# Disclaimer

## Based on:

- K. Schindl: “Space charge”
- S. Albright: “Longitudinal Optimisations for Space Charge Reduction in the CERN PSB”
- Y. Papaphilippou : “Introduction to Accelerators”
- Summer student lectures:
  - B. Holzer, V. Kain, and M. Schaumann
- CERN accelerator school (CAS):
  - F. Tecker: “*Longitudinal beam dynamics*”
  - G. Rumolo, K.Li : “*Instabilities Part I: Introduction – multiparticle systems, macroparticle models and wake functions*”
  - X. Buffat and T. Pieloni: “*Beam-beam effects*”
- Joint Universities Accelerator School (JUAS):
  - F. Antoniou, H. Bartosik and Y. Papaphilippou: “*Linear imperfections*” and “*nonlinear dynamics*”
- Books:
  - K. Wille: “*The Physics of Particle Accelerators*”
  - S.Y. Lee: “*Accelerator Physics*”
  - A. Wolski: “*Beam Dynamics in High Energy Particle Accelerators*”
  - H. Wiedemann: “*Particle Accelerator Physics*”

Images: cds.cern.ch

10/07/2024

# Overview

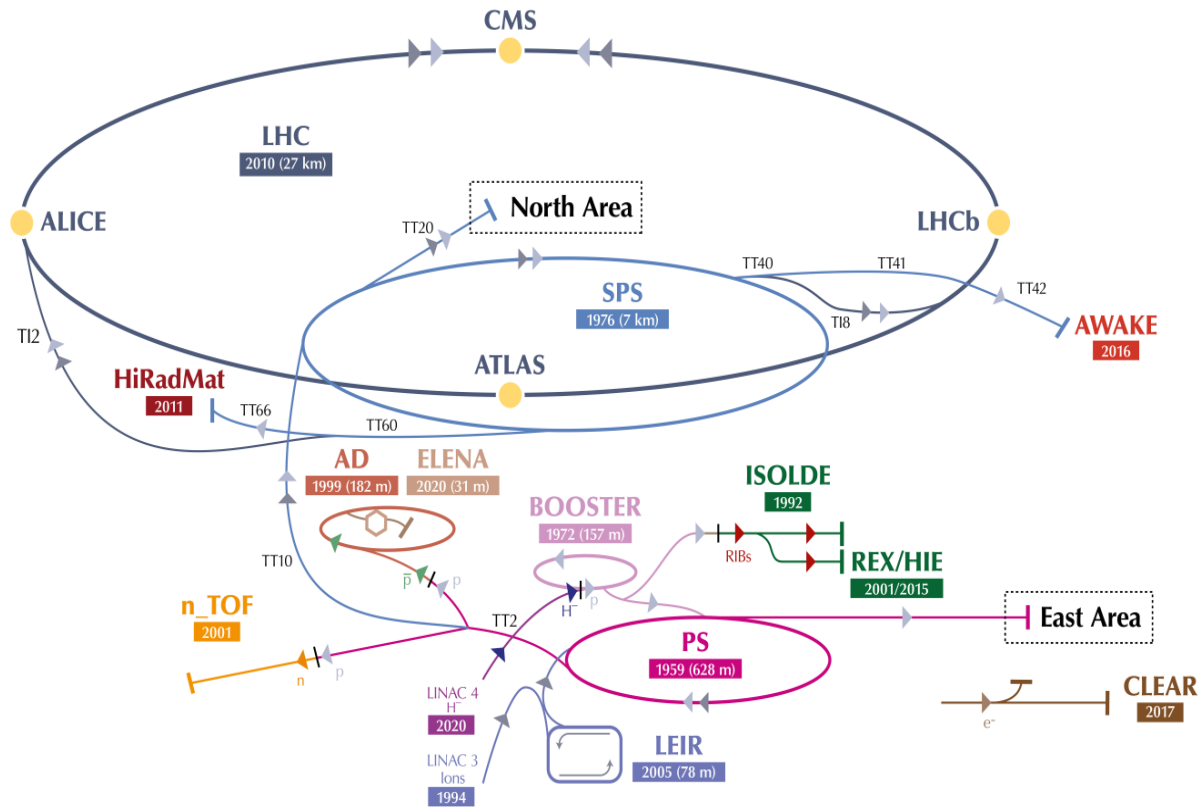
## I. Introduction to Accelerators

## II. Accelerator beam dynamics

## III. CERN accelerator complex

- Proton Synchrotron Booster
  - Space charge
- Proton Synchrotron
  - Tailoring of bunches
- Super Proton Synchrotron
  - Instabilities
- Large Hadron Collider
  - Beam-beam effects

# Reminder: CERN Accelerator Complex



## CERN **Proton** chain

1. LINAC-4 160MeV (**H-**)
2. Proton Synchrotron Booster 2GeV
3. **Proton Synchrotron** 26GeV
4. Super Proton Synchrotron 450 GeV
5. Large Hadron Collider 7TeV

## CERN Ion chain

We'll focus on the **proton** beams towards the LHC

▶  $H^-$  (hydrogen anions) ▶ p (protons) ▶ ions ▶ RIBs (Radioactive Ion Beams) ▶ n (neutrons) ▶  $\bar{p}$  (antiprotons) ▶  $e^-$  (electrons)

LHC - Large Hadron Collider // SPS - Super Proton Synchrotron // PS - Proton Synchrotron // AD - Antiproton Decelerator // CLEAR - CERN Linear Electron Accelerator for Research // AWAKE - Advanced WAKEfield Experiment // ISOLDE - Isotope Separator OnLine // REX/HIE - Radioactive EXperiment/High Intensity and Energy ISOLDE // LEIR - Low Energy Ion Ring // LINAC - LInear ACcelerator // n\_TOF - Neutrons Time Of Flight // HiRadMat - High-Radiation to Materials

# CERN Accelerator Complex – Linac 4



- **Linac 4:** Linear Accelerator 4  
→ *Note how most complexes start on a linac, beams goes through multiple accelerating stages fast!*
- CERN's newest accelerator
- 1<sup>st</sup> run: **2019**
- Main purpose: to increase the injection energy of the PSB to 160 MeV.

# CERN Accelerator Complex – Linac 4



- **Linac 4:** Linear Accelerator 4
    - Note how most complexes start on a linac, beams goes through multiple accelerating stages fast!
  - CERN's newest accelerator
  - 1<sup>st</sup> run: **2019**
  - Main purpose: to increase the injection energy of the PSB to 160 MeV.
- 
- It accelerates negative hydrogen ions,  $H^-$ , to 160 MeV.
    - $H^-$  beam guided through a stripping foil at PSB injection to produce the protons: "Charge exchange injection".

# CERN Accelerator Complex



# CERN Accelerator Complex – PSB



- **PSB**: Proton Synchrotron Booster
- The first circular accelerator of the Complex
- 1<sup>st</sup> run: **1972**
- Main purpose: to increase the number of protons that PS can accelerate.



- It comprises 4 superposed rings  
→ *Essentially, they are 4 different synchrotrons with common characteristics (magnets, etc.)*



# PSB – Space Charge

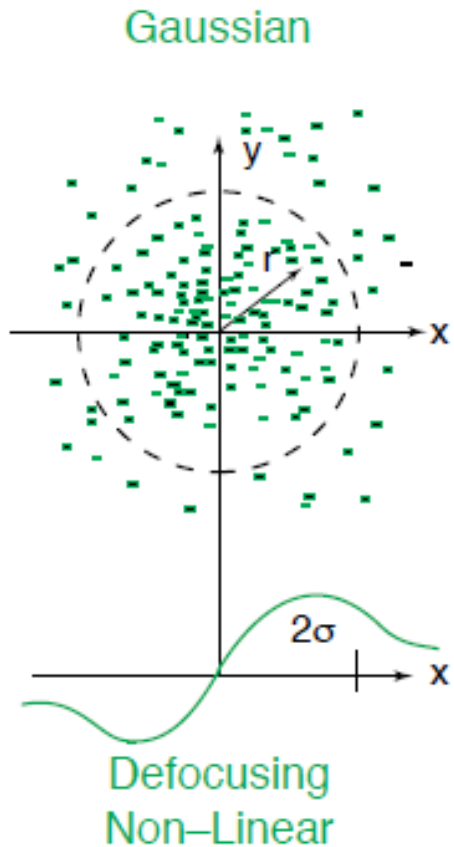


- **PSB: Proton Synchrotron Booster**
- ***The first circular accelerator of the Complex***
- ***Main purpose: to increase the number of protons that PS can accelerate.***

Why did we need a new accelerator to increase the number of protons???

- ***We wanted to increase the number of protons while maintaining a small emittance***
  - Emittance defines the beam size – **larger emittance would require a larger aperture**
  - Emittance cannot decrease along the chain – **luminosity depends on the emittance “set” in the injectors**
- At low energies, the coulomb forces developing within the bunch dominate the dynamics – **SPACE CHARGE**

# PSB – Space Charge



## SPACE CHARGE

Non-Linear continuous kick

→ Coulomb forces between the moving particles



Self-fields that move with the beam

- The **frequency of the betatron motion** changes
- **Different particles** in the same bunch will have a different tune

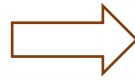
## Incoherent tune spread

Gaussian Distributions: 
$$V_{sc}(x, y) = \frac{r_0 N_B}{\beta^2 \gamma^3 \sqrt{2\pi} \sigma_s} \int_0^\infty \frac{-1 + e^{-\frac{x^2}{2\sigma_x^2 + t} - \frac{y^2}{2\sigma_y^2 + t}}}{\sqrt{(2\sigma_x^2 + t)(2\sigma_y^2 + t)}} dt$$

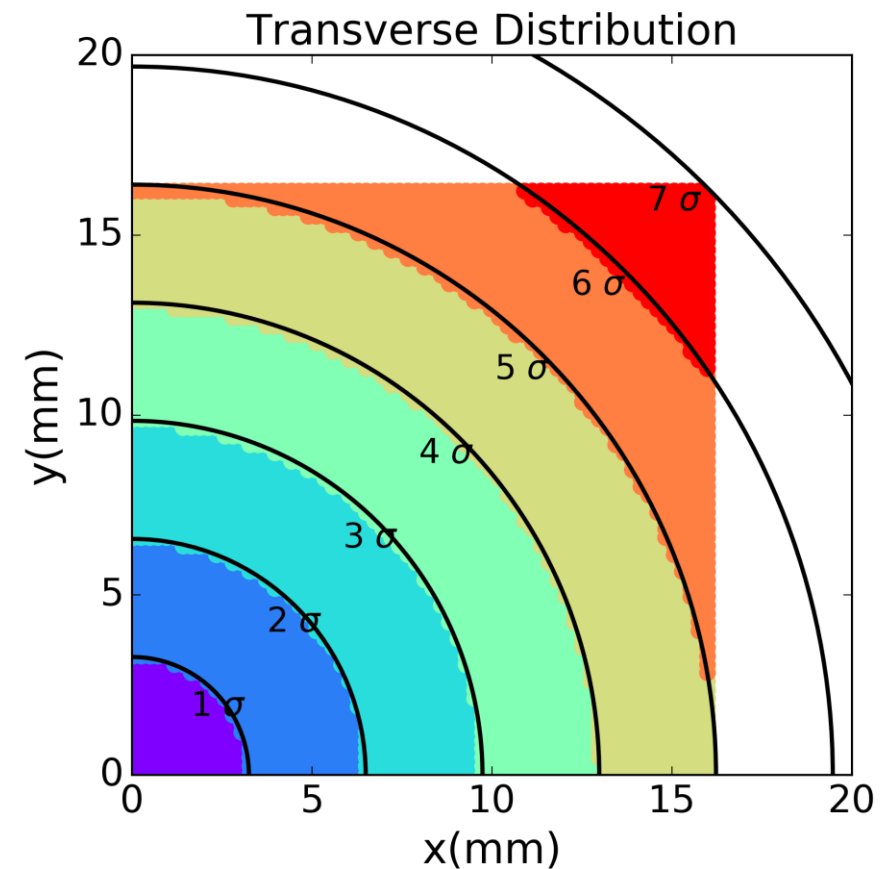
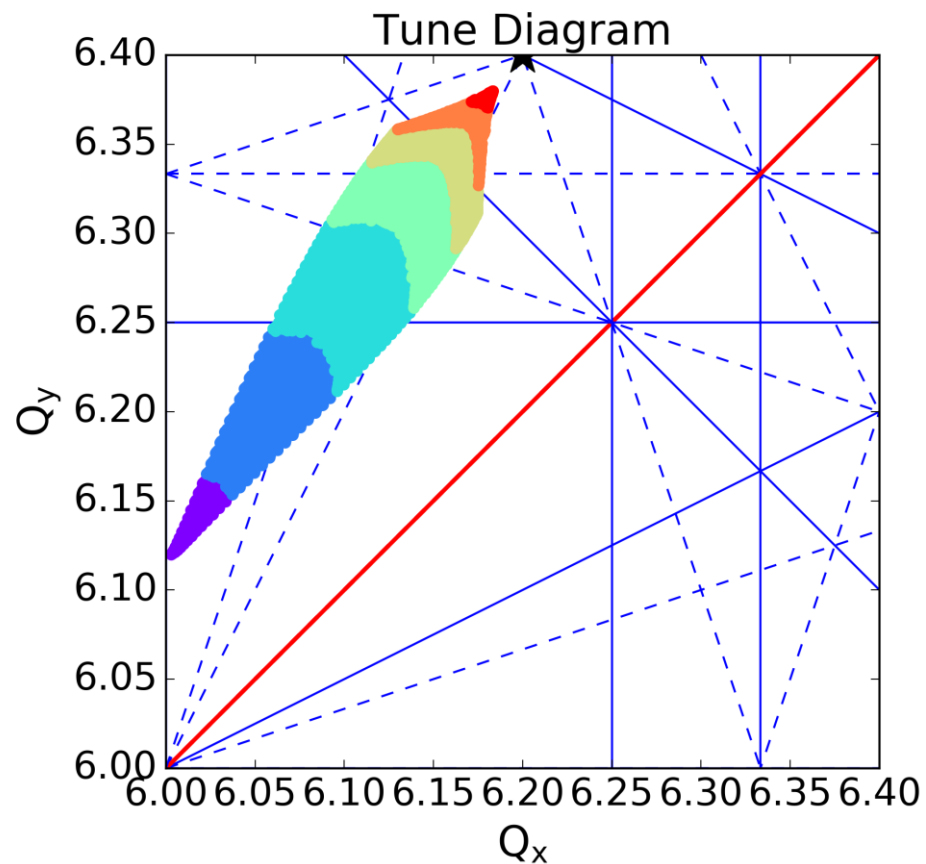
1. Transverse Amplitude
2. Energy
3. Transverse Beam Size
4. Bunch Intensity
5. Longitudinal Parameters

# PSB – Space Charge

## 1. Transverse Amplitude

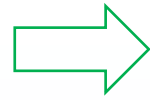


The closer to the center of the bunch the larger the detuning

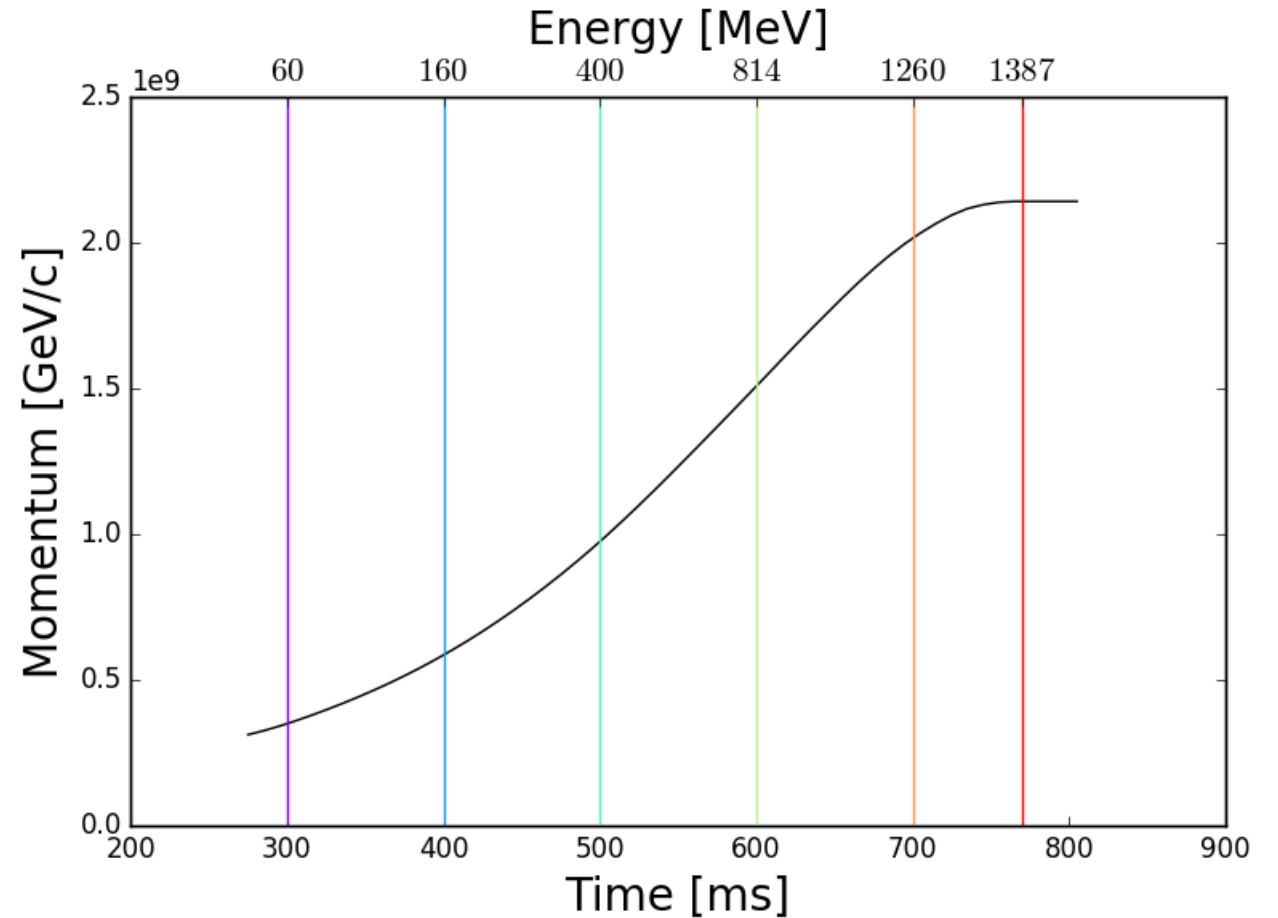
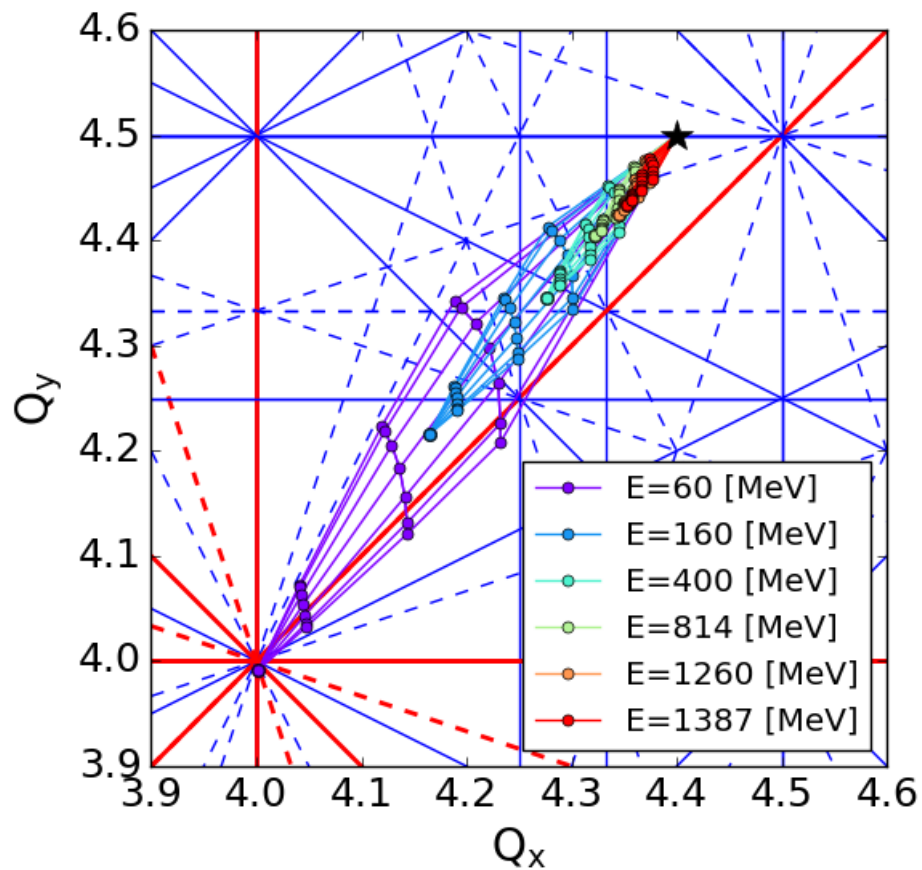


# PSB – Space Charge

## 2. Energy



The lower the energy  
the larger the detuning

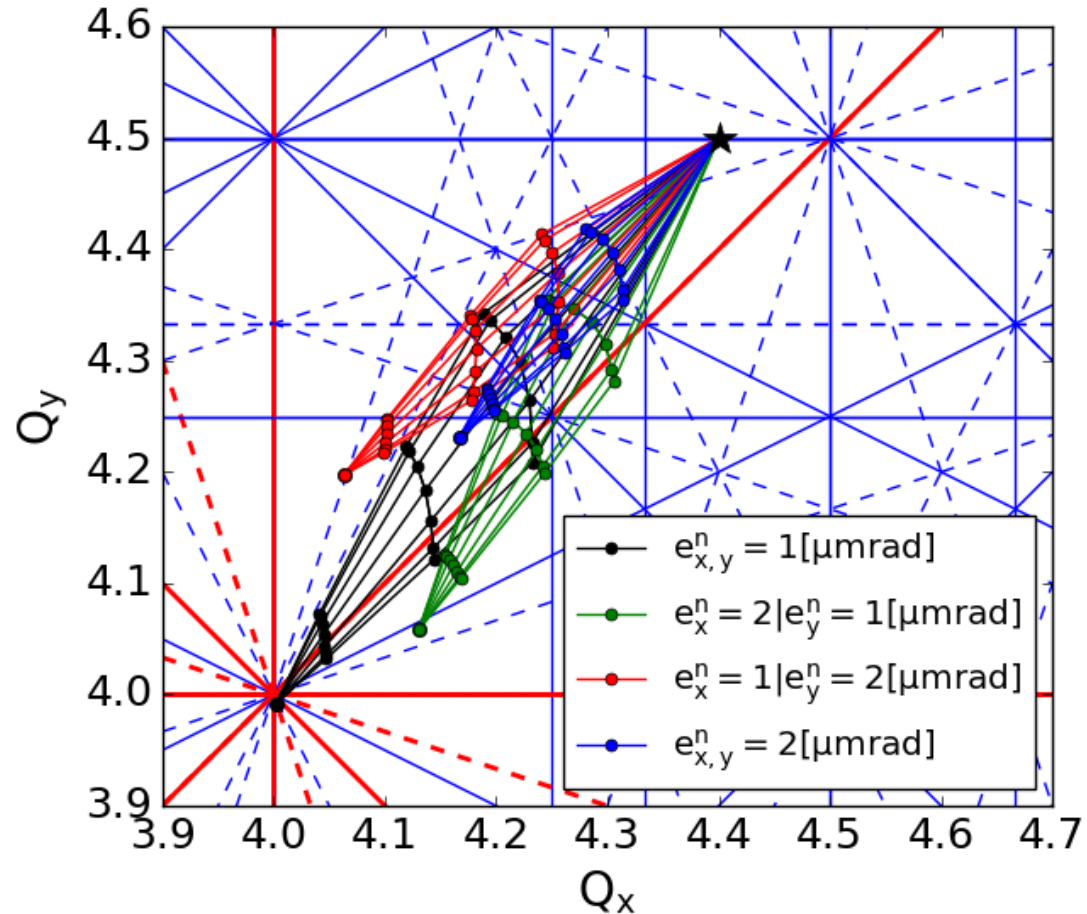


# PSB – Space Charge

## 3. Transverse Beam Size



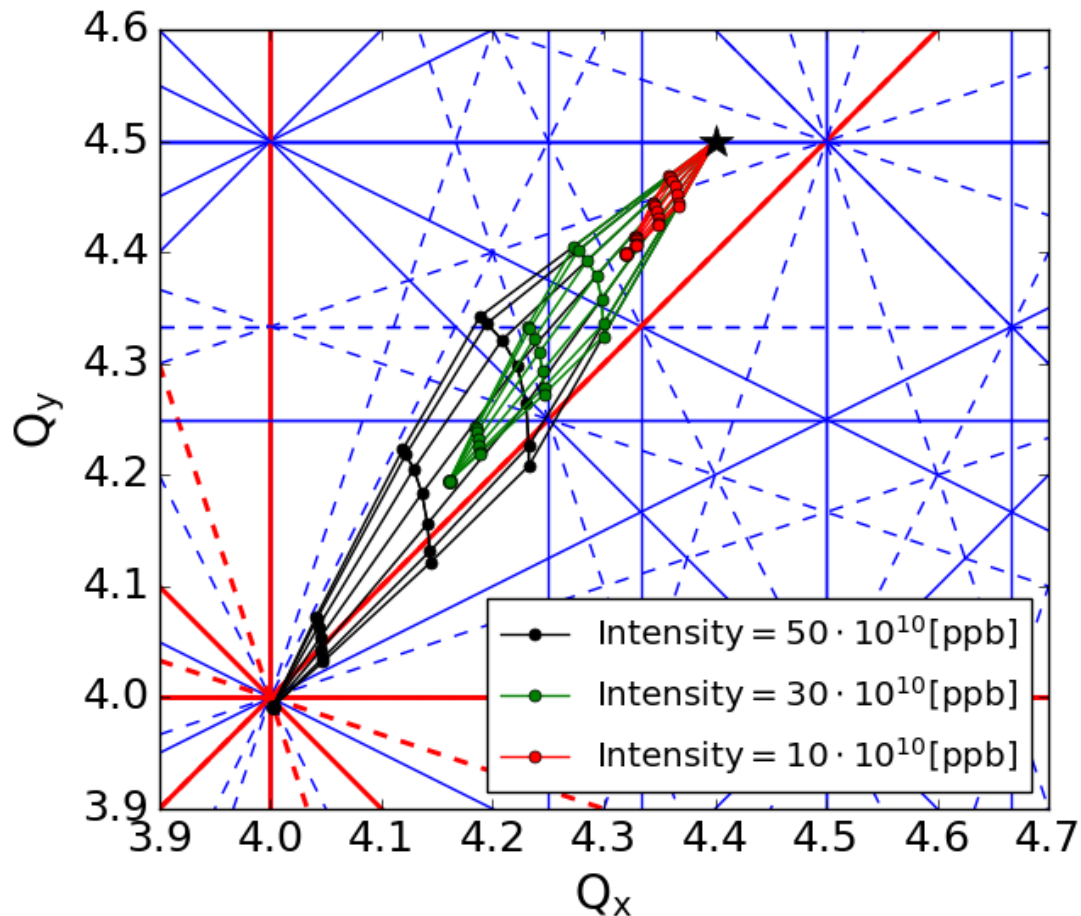
The smaller the emittance  
the larger the detuning



Emittance x (mm mrad)	Emittance y (mm mrad)
<b>1</b>	<b>1</b>
<b>2</b>	<b>1</b>
<b>1</b>	<b>2</b>
<b>2</b>	<b>2</b>

# PSB – Space Charge

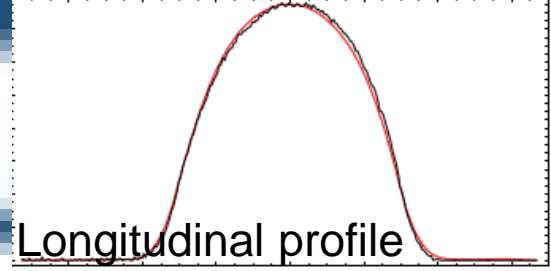
## 4. Bunch Intensity



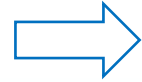
The larger the intensity  
the larger the detuning

Intensity ( $10^{10}$ ppb)
50
30
10

# PSB – Space Charge

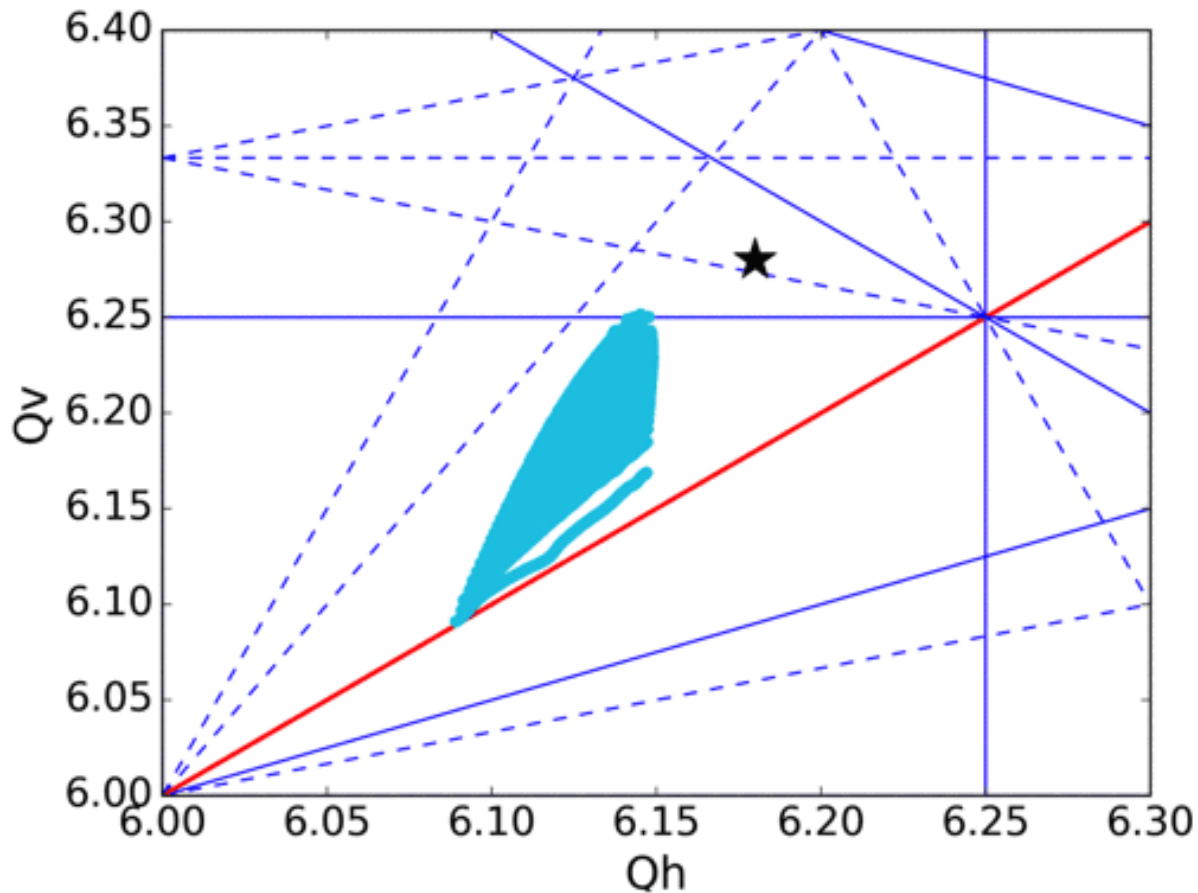


## 5. Longitudinal Settings

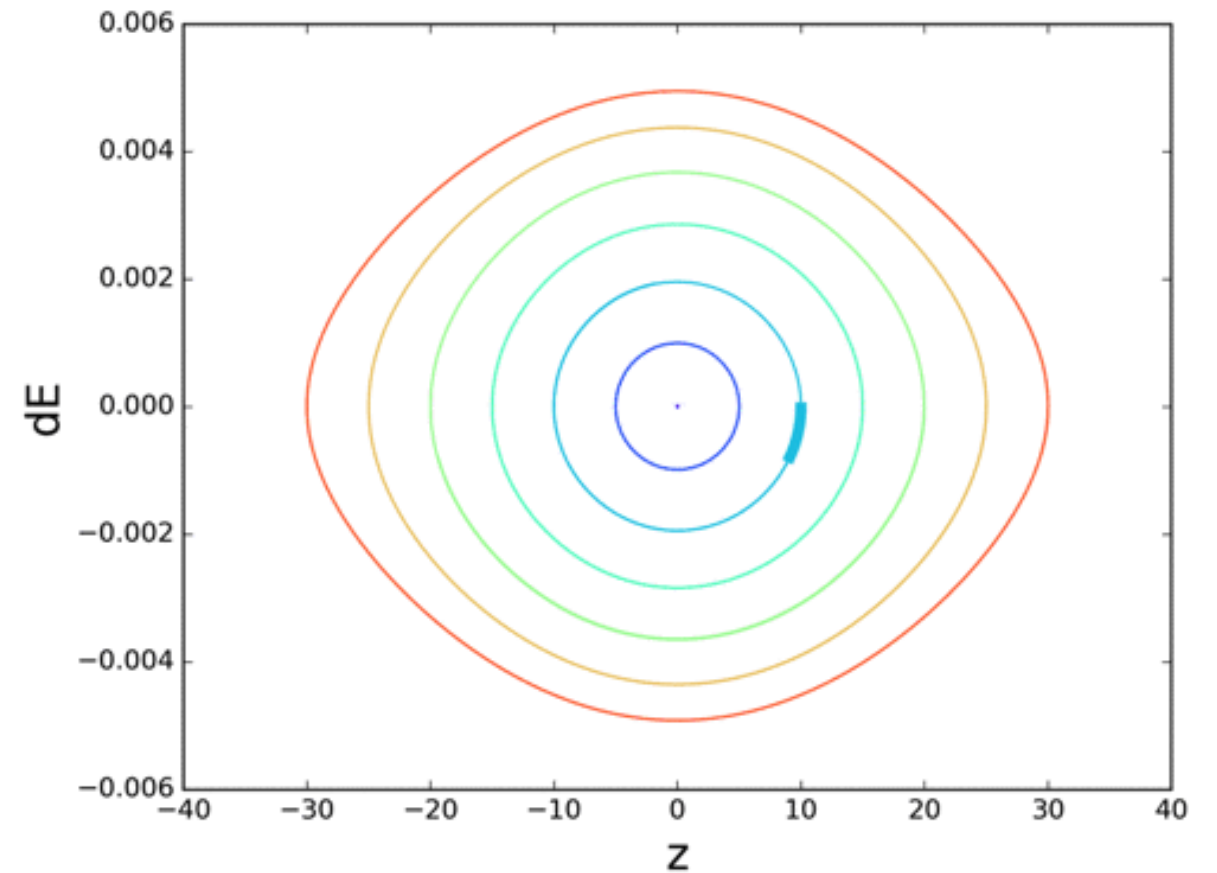


- Smaller bunch length – larger detuning
- Detuning changes with the synchrotron motion

Tune Diagram

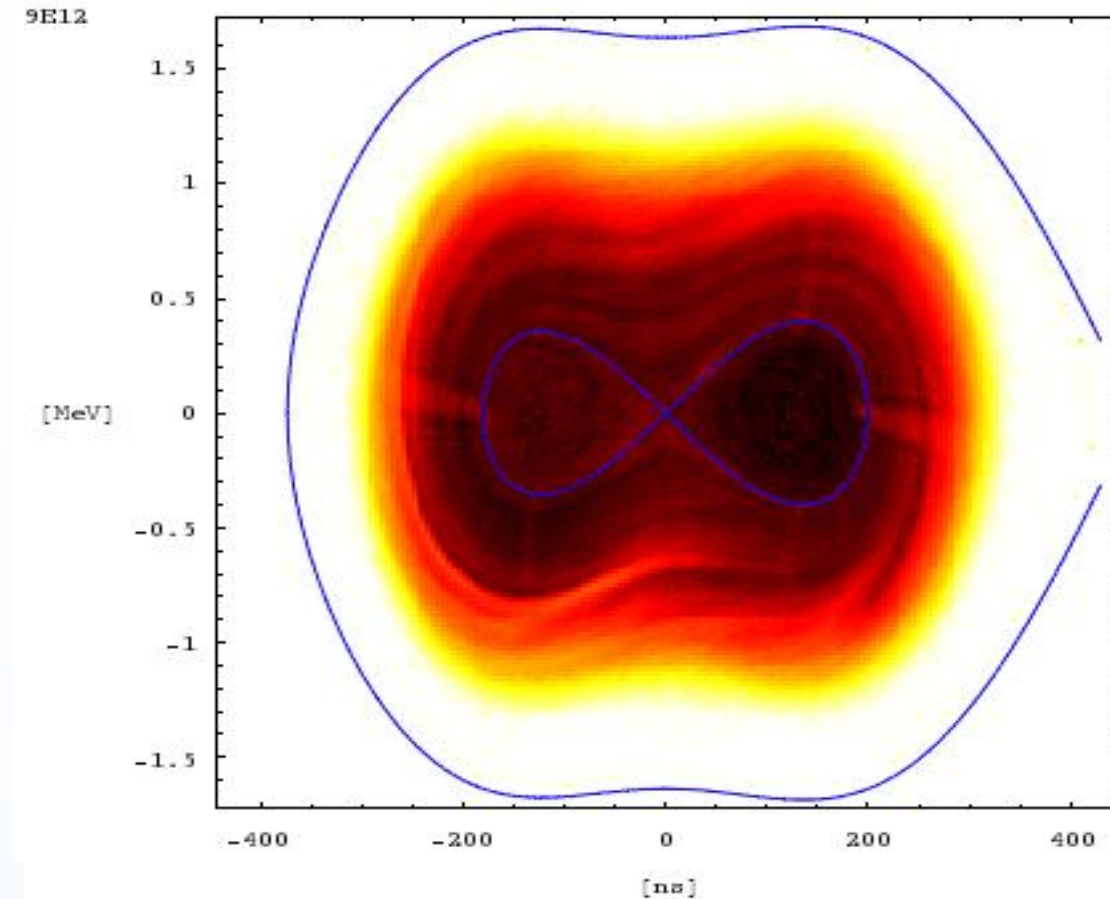


Longitudinal Phase Space



# PSB – Space Charge

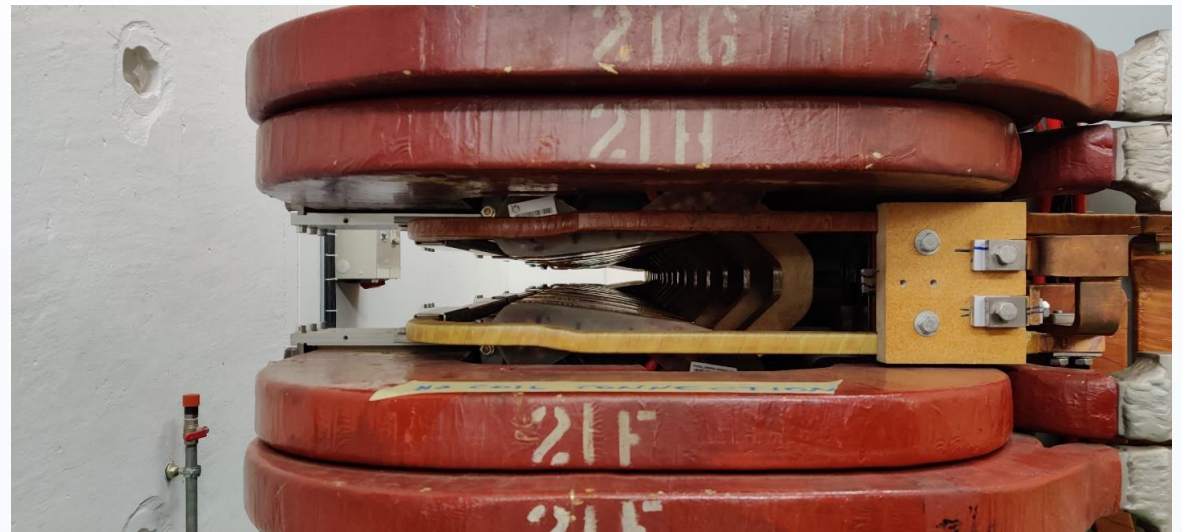
- Since space charge is caused by the beam itself it cannot be avoided
- Some “mitigation” strategies:
  - Starting the acceleration right after injecting the beam – **minimize the time at low energy** (also increased injection energy → L4 & PSB!)
  - Use nonlinear magnets (sextupoles & octupoles) to mitigate resonances – **minimize effects on losses & emittance blow-up**
  - Use an **additional RF system** pulsing on a **higher harmonic** to reduce the longitudinal line density & elongate the bunches





# CERN Accelerator Complex – PS

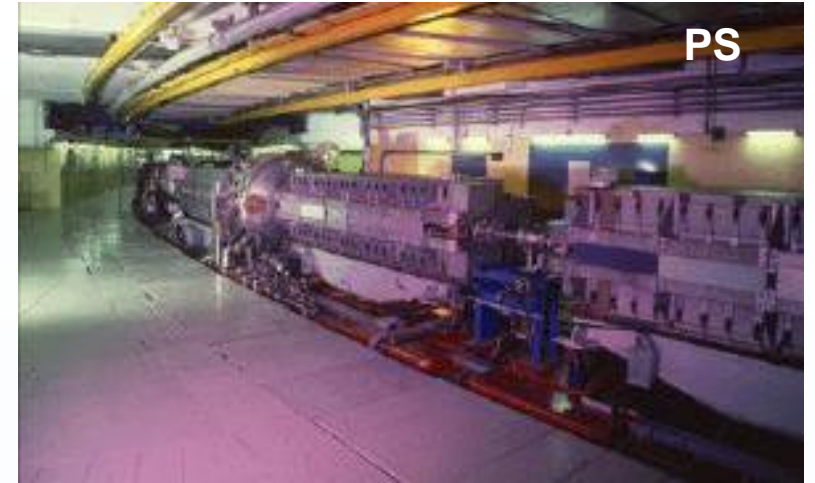
- **PS:** Proton Synchrotron
  - CERN's first accelerator
  - 1<sup>st</sup> run: **1959**
  - Even today it accelerates beams (***protons and ions***) for the LHC and other CERN experiments
  - The bunches and their spacing is defined in the PS
- 
- Consists of 100 combined function magnets
- ***The same magnet bends and focuses the beam!***



# PS – Tailoring of bunches

- **PS:** Proton Synchrotron
- *The bunches and their spacing is defined in the PS*

How can we change the number of bunches & the space between them?



→ *We need more RF systems so that we can have additional “harmonics” (similar to the PSB case shown before)*

→ Changing the voltage ratios and the phase of the different systems:

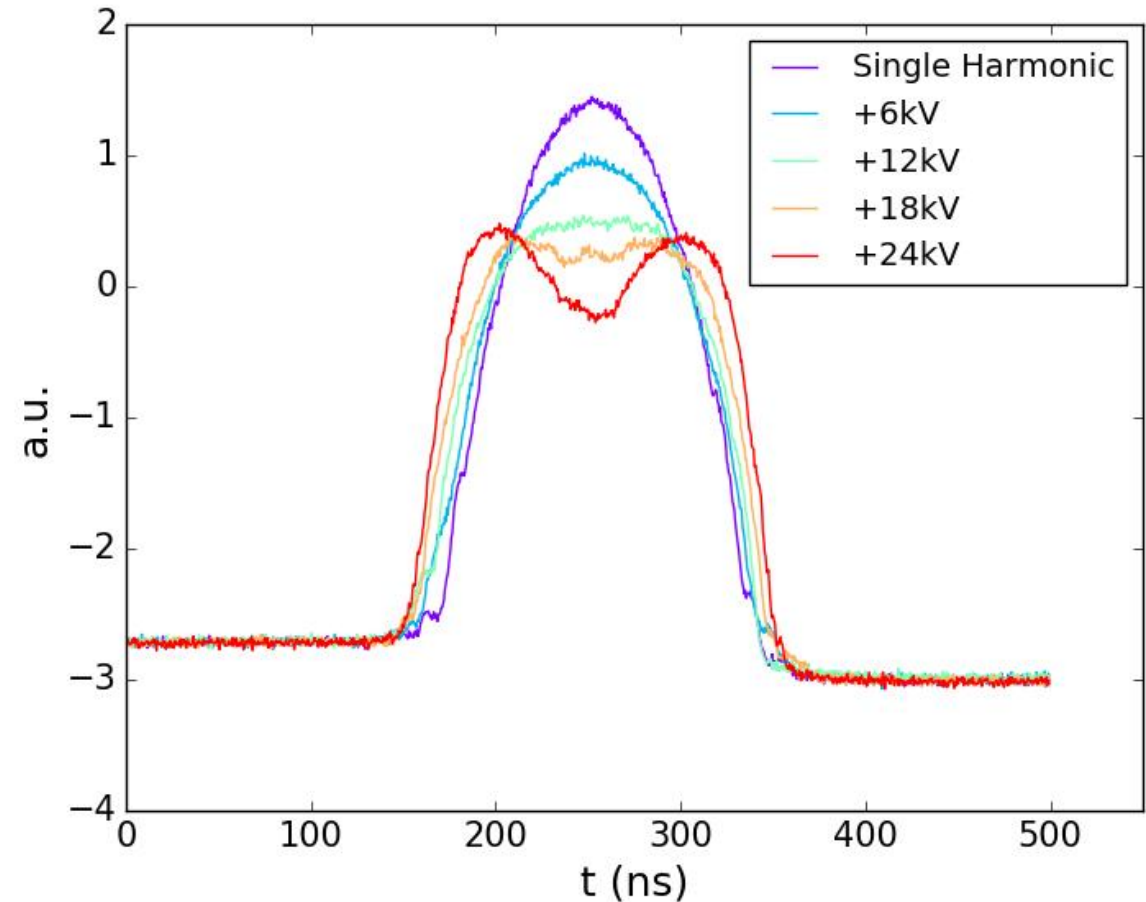
→ Merge bunches

→ Split bunches

→ Rotate bunches

# PS – Tailoring of bunches

- Changing the voltage ratios (also adjusting phases etc) of the different systems we can change the shape of the bunch (& the longitudinal profile)
- We start with a single RF system
- We include a second RF system at  $h_2=2h_1$  and we start changing the contribution of the 2 systems (voltage)
- If we keep changing the contributions of the two systems we can fully separate the bunches!

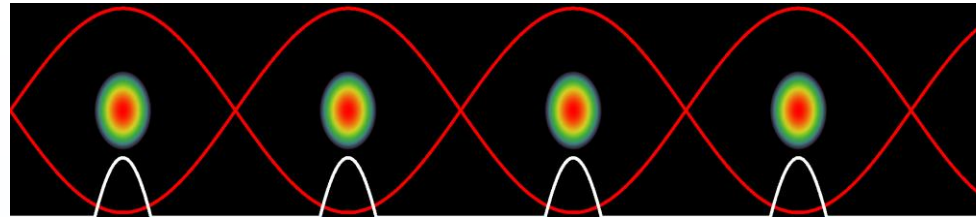


# PS – Tailoring of bunches

## LHC bunches in the PS

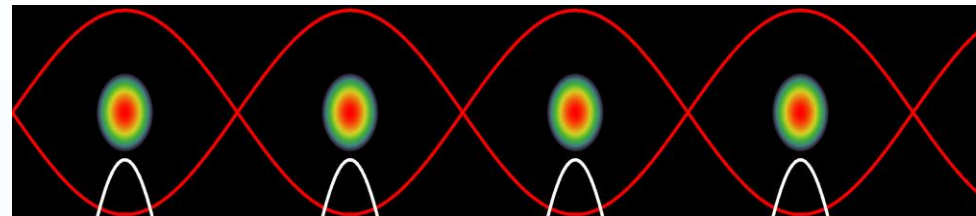
- The PSB can provide **up to 4 bunches per injection** (one out of each ring)
- Two injections in the PS (4+2)
- *One bucket is kept empty*
- Each **bucket** is split in three after the second injection

### 1. Inject four bunches (h=7)

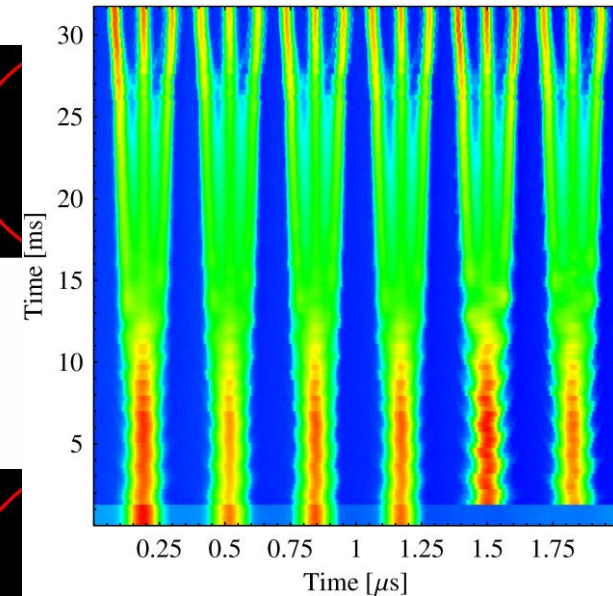
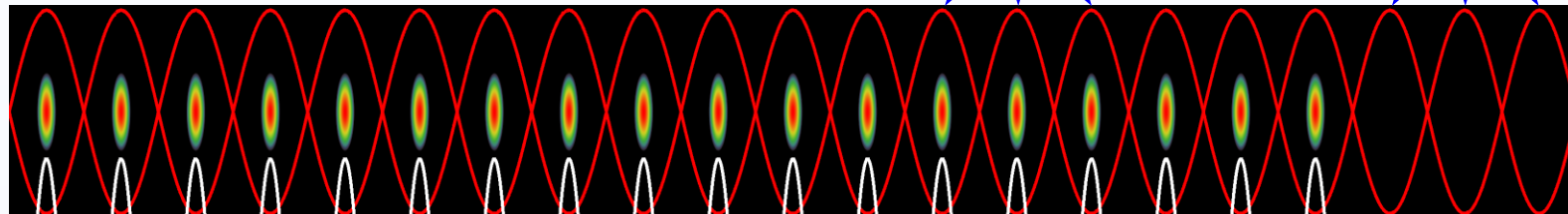


Wait 1.2 s for second injection

### 2. Inject two more bunches (h=7)



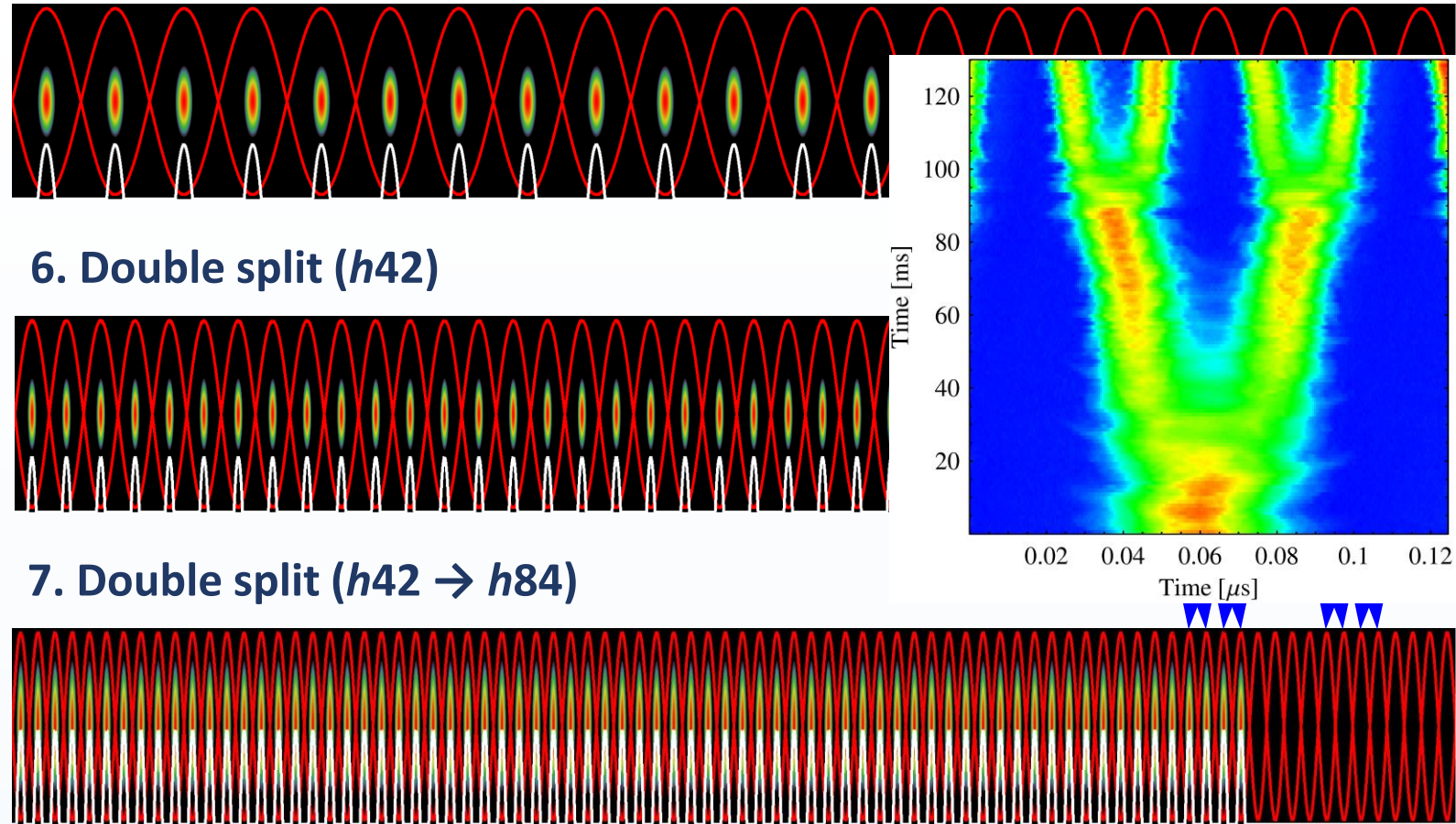
### 3. Triple split after second injection (h=21)



# PS – Tailoring of bunches

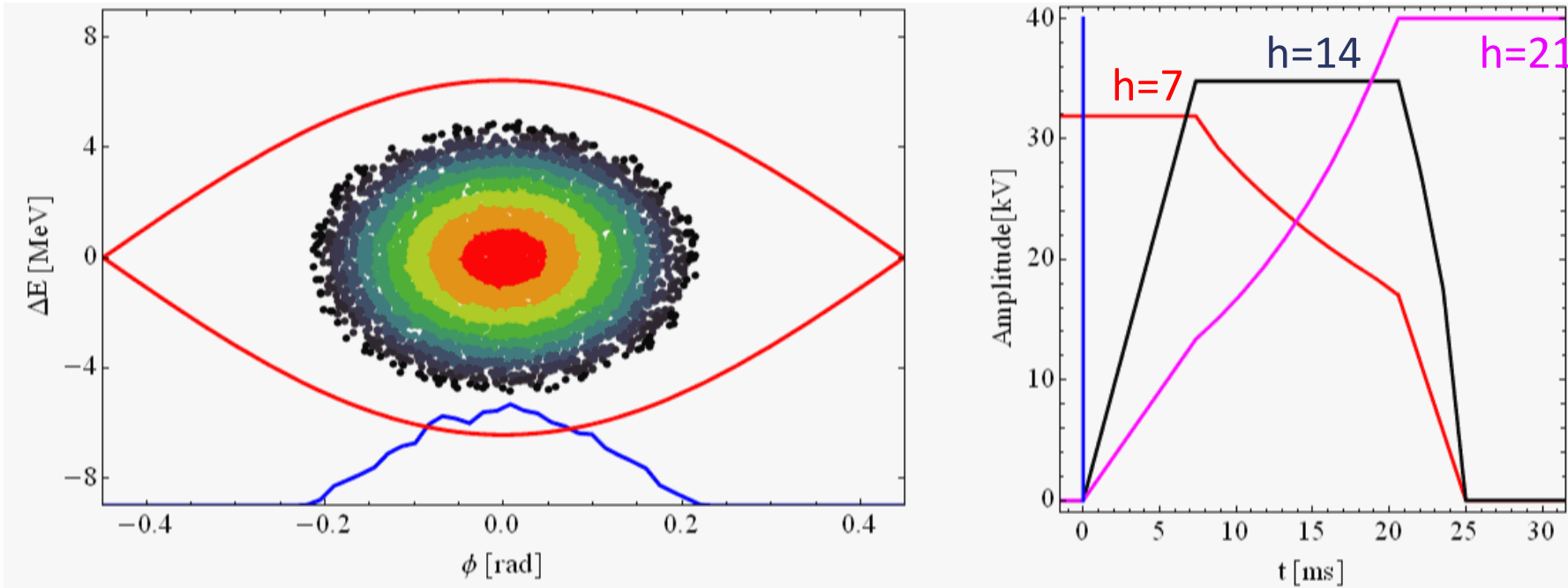
## LHC bunches in the PS

- The PSB can provide **up to 4 bunches per injection** (one out of each ring)
- Two injections in the PS (4+2)
- *One bucket is kept empty*
- Each **bunch** is split in three after the second injection
- **Two** times a **double** splitting
- **Bunch rotation** before extraction



F. Tecker: “Longitudinal beam dynamics” (CAS)

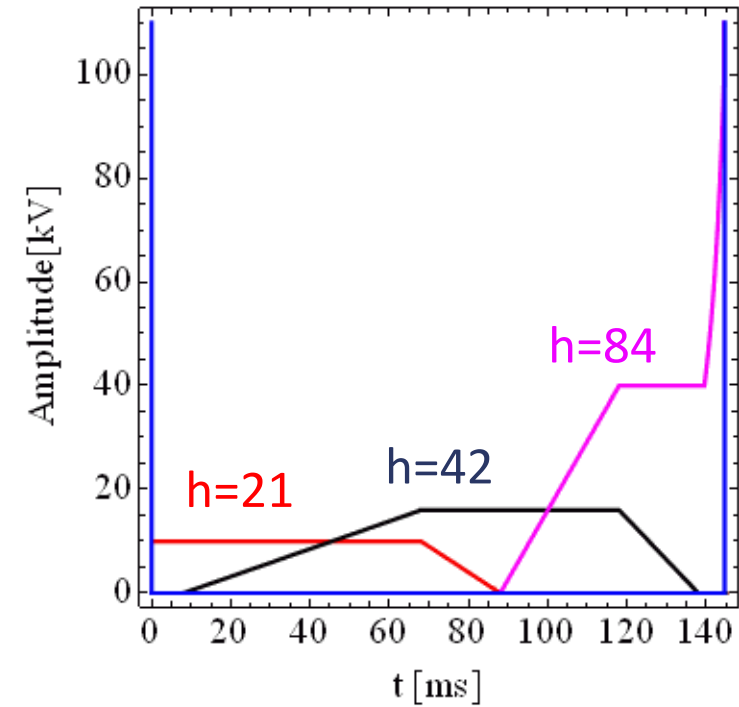
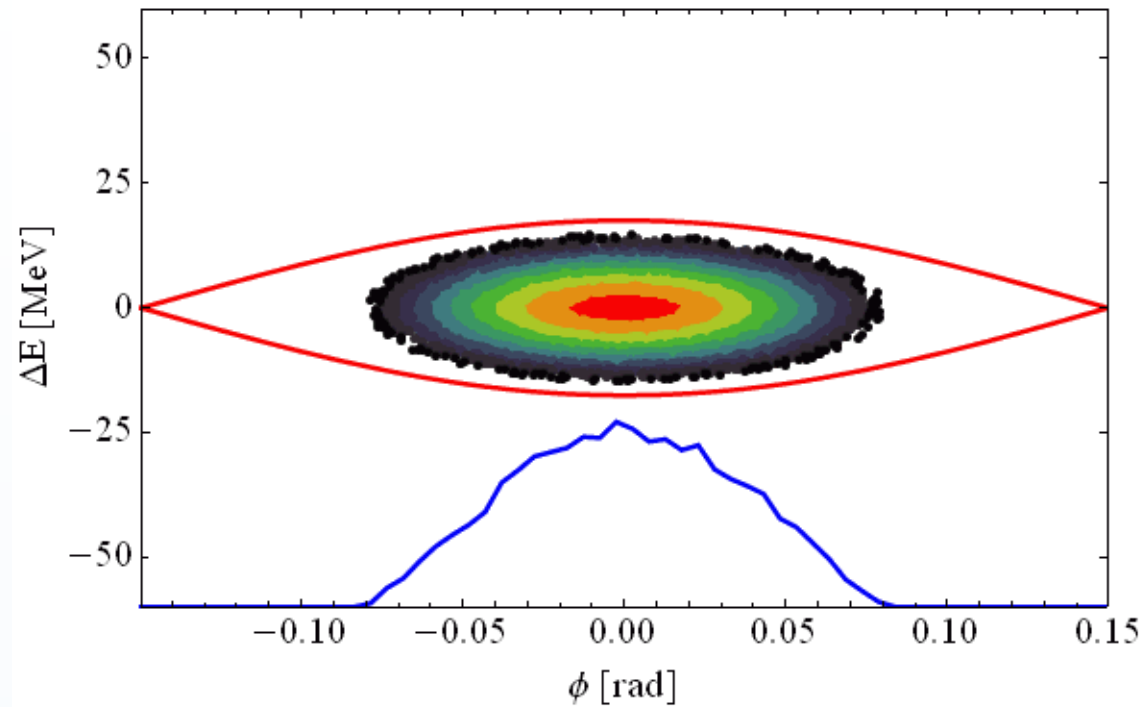
# PS – Tailoring of bunches



Triple splitting

F. Tecker: “Longitudinal beam dynamics” (CAS)

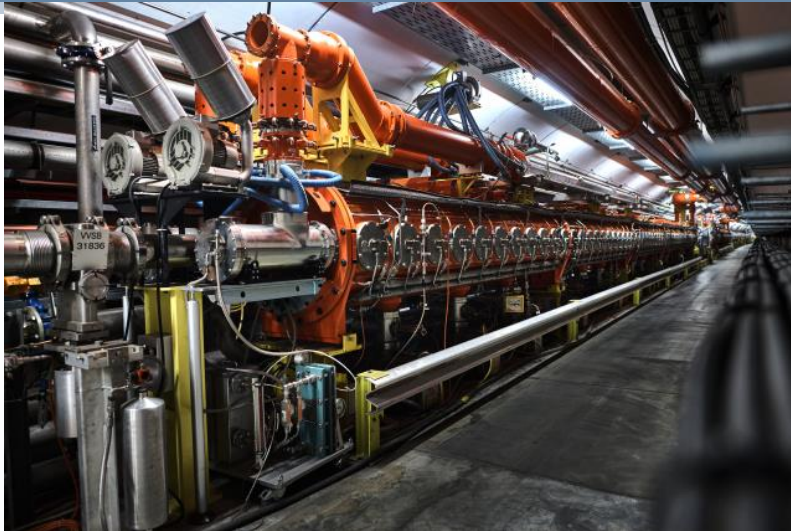
# PS – Tailoring of bunches



Two times double splitting and bunch rotation

F. Tecker: “Longitudinal beam dynamics” (CAS)

# CERN Accelerator Complex – SPS



- **SPS:** Super Proton Synchrotron
- The 2<sup>nd</sup> largest accelerator at CERN with a circumference of 7km
- 1<sup>st</sup> run: **1976**
- ***Discovery of the W and Z bosons during its operation as a collider***
  
- Today it operates as an accelerator producing beams (***protons and ions***) for the LHC and other CERN experiments
- For the LHC, it accumulates short high intensity bunches for several injections

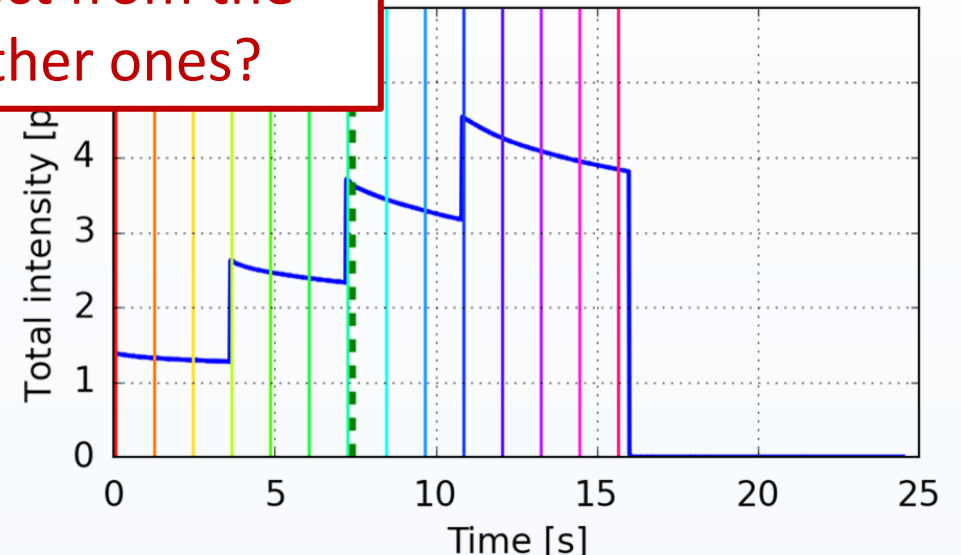
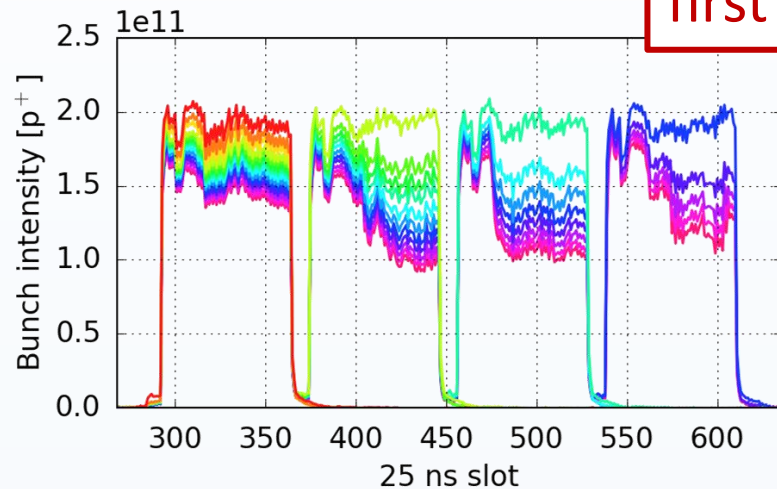


# SPS – Instabilities



- **SPS: Super Proton Synchrotron**
- **For the LHC, it accumulates short high intensity bunches for several injections**
- Injecting 4 \* 72 bunches in the SPS we start observing beam losses
- Looking more carefully in the intensity evolution of each bunch – *losses mainly for the later bunches*

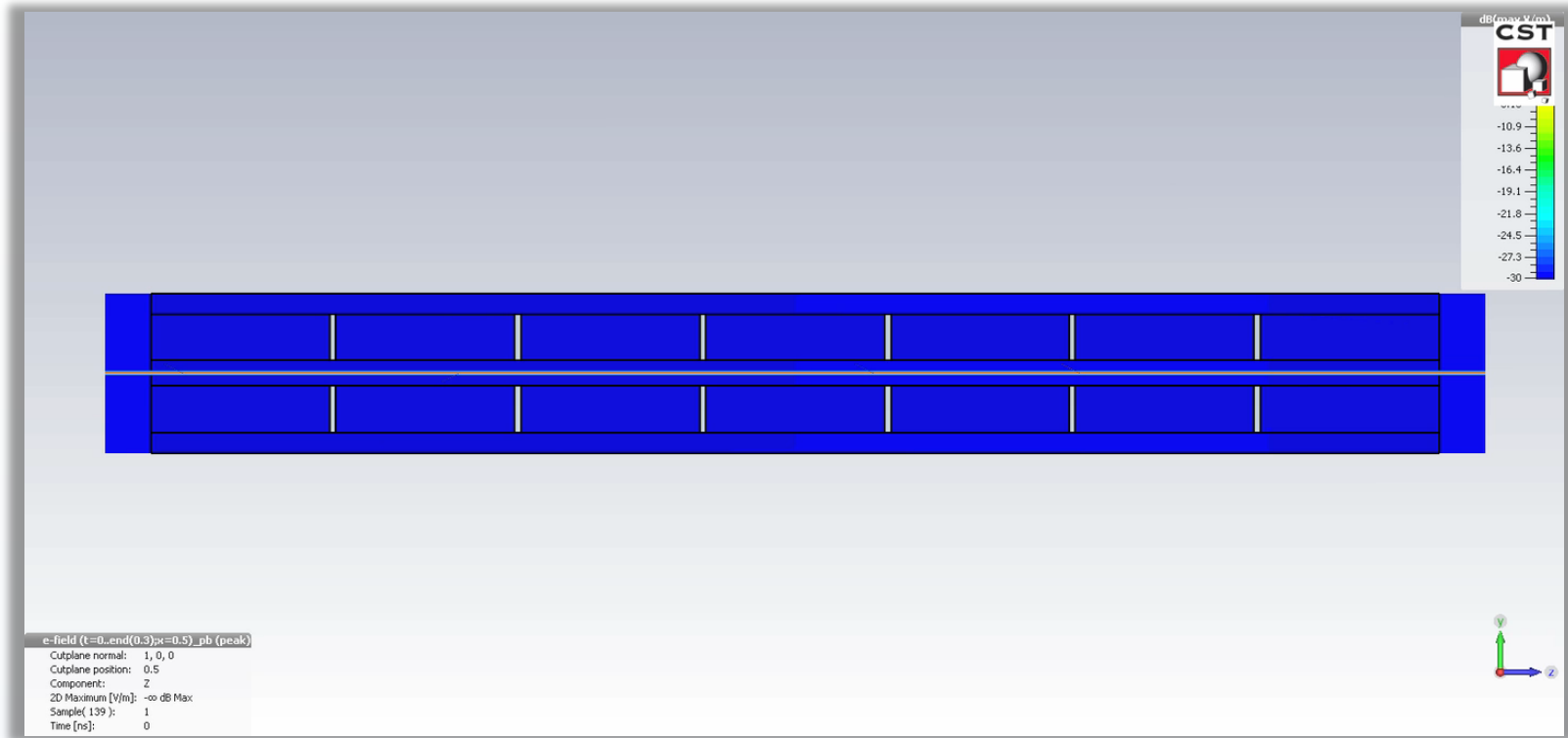
Could we have an effect from the first bunches to the other ones?



G. Rumolo, K.Li : “Instabilities Part I: Introduction – multiparticle systems, macroparticle models and wake functions”

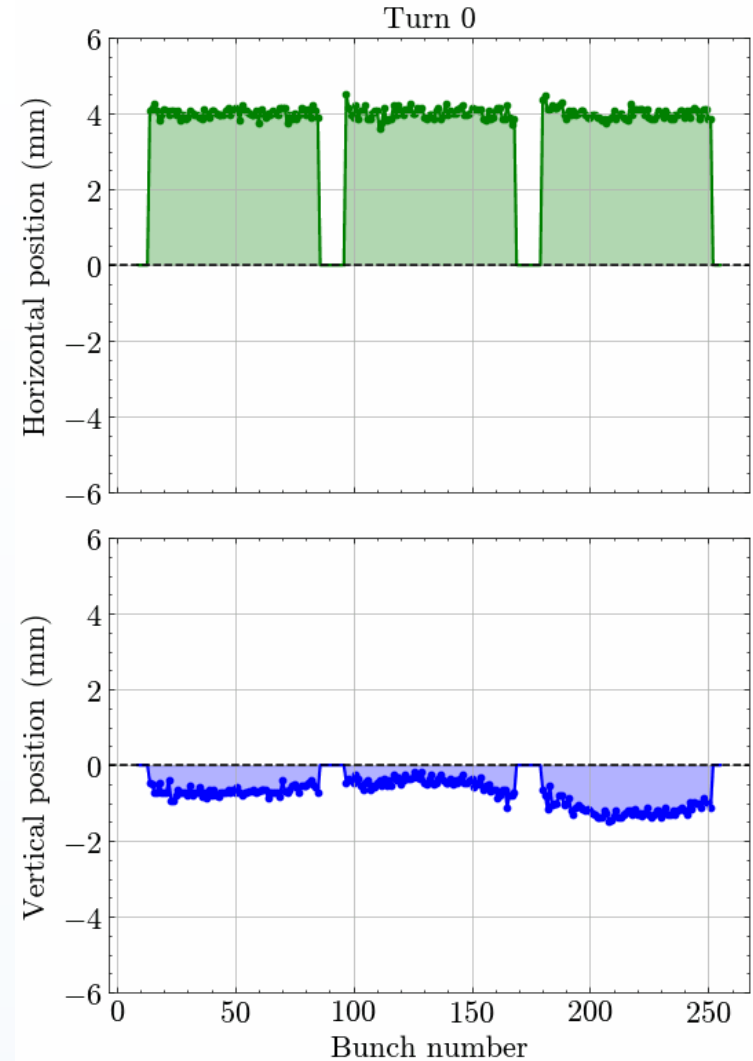
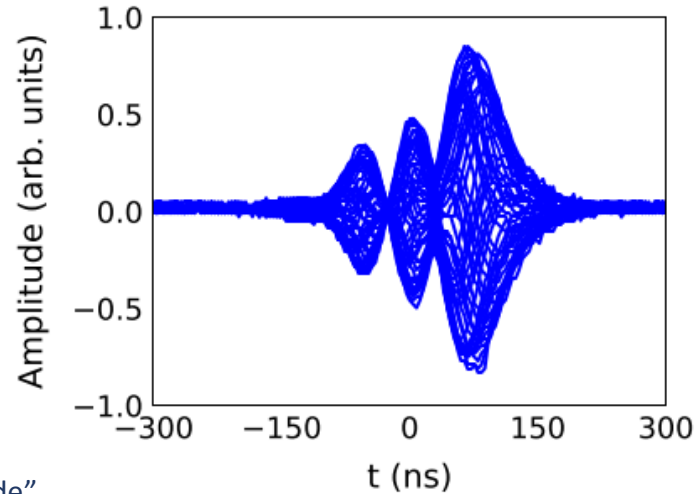
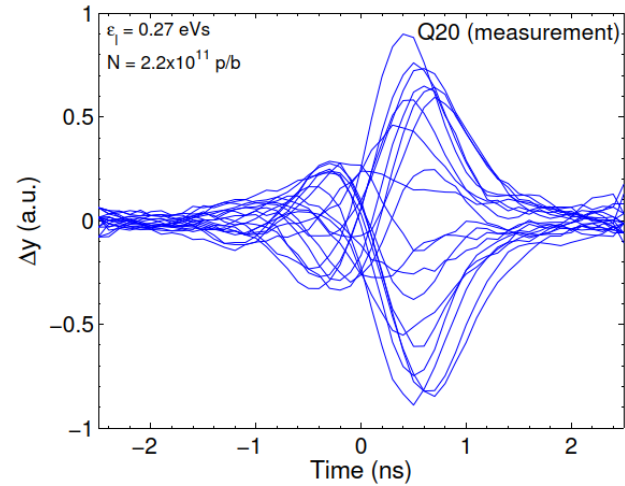
# SPS – Instabilities

- In fact, the bunches can interact with the environment in the accelerator (vacuum pipe, cavities, instrumentation devices etc)
- As the bunches move on the s direction, they can create fields: **“Wakefield”**
- The wakefield depends on the distribution of our bunches and can cause a **collective response**



# SPS – Instabilities

- This collective response can result in “*intra-bunch*” motion
- The amplitude of this motion can increase in time leading to **large losses**
- In case of multiple bunches in a ring, “*bunch-by-bunch*” motion, some of them can be affected more than others



I. Mases et al.: “Transverse beam stability and MKP-S heating test”

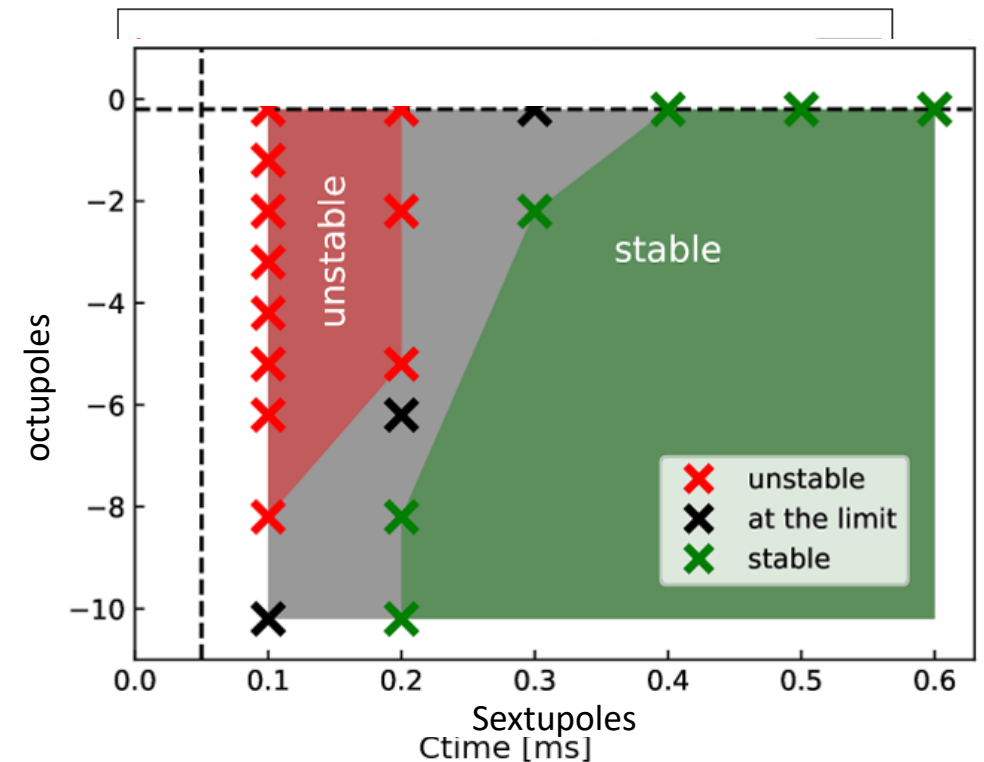
H. Bartosik: “Beam dynamics and optics studies for the LHC injectors upgrade”

E. Koukovini-Platia et al.: “Source of horizontal instability at the CERN Proton Synchrotron Booster”

# SPS – Instabilities

## *Curing Instabilities*

- Careful **modelling** of the electromagnetic properties of our equipment allows for predictions of certain instabilities
  - **Changes in the design or the materials** of a piece of equipment could suppress this response
  - **Changes in our working conditions (WP)** to avoid the instability
- **Feedback systems** – observe the bunch motion and apply “kicks” to cancel any deviations from the desired state
- **Introduce nonlinear elements** – they can change the incoherent tune spread and help damping the coherent instability



C. Antuono et al: “PSB impedance and stability studies”

E. Koukovini-Platia et al: “Source of horizontal instability at the CERN Proton Synchrotron Booster”

C. Zannini et al: “The SPS transverse instabilities at injection”

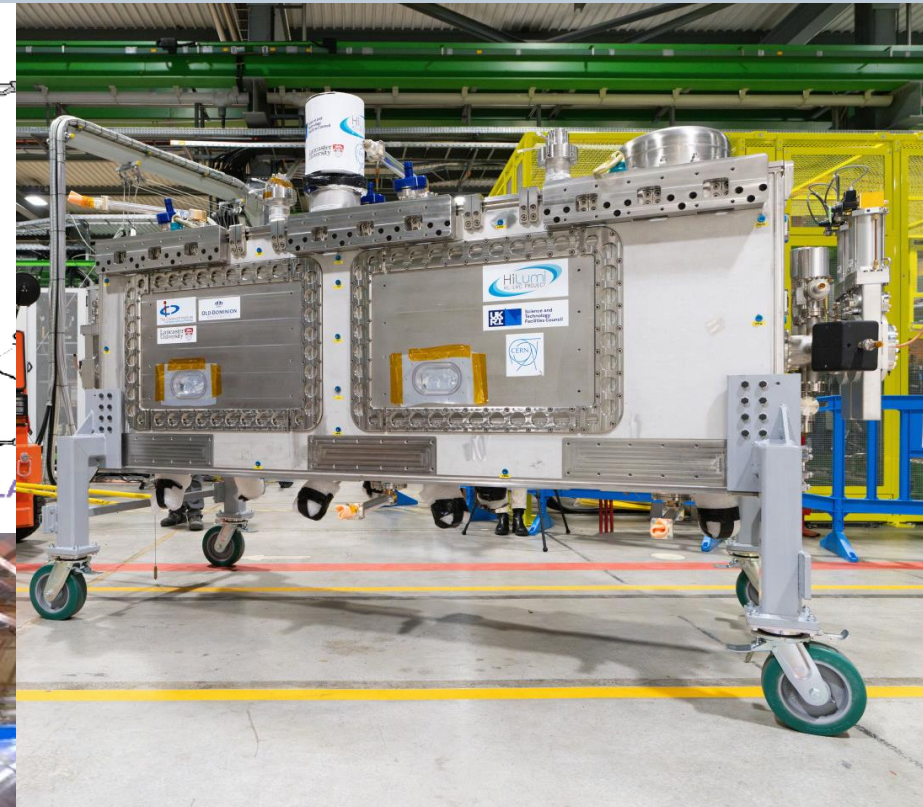
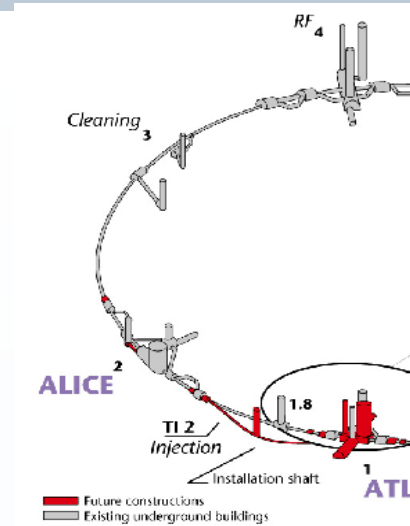
# CERN Accelerator Complex – LHC

- **LHC**: Large Hadron Collider
- The largest accelerator at CERN with a circumference of **26.7km**
- 1<sup>st</sup> run: **2008**
- Two beams circulate in opposite directions driven by **1232 superconducting dipoles**, 14.3m long with up to 8T field in temperatures of 1.9 K
- Operates with protons and ions



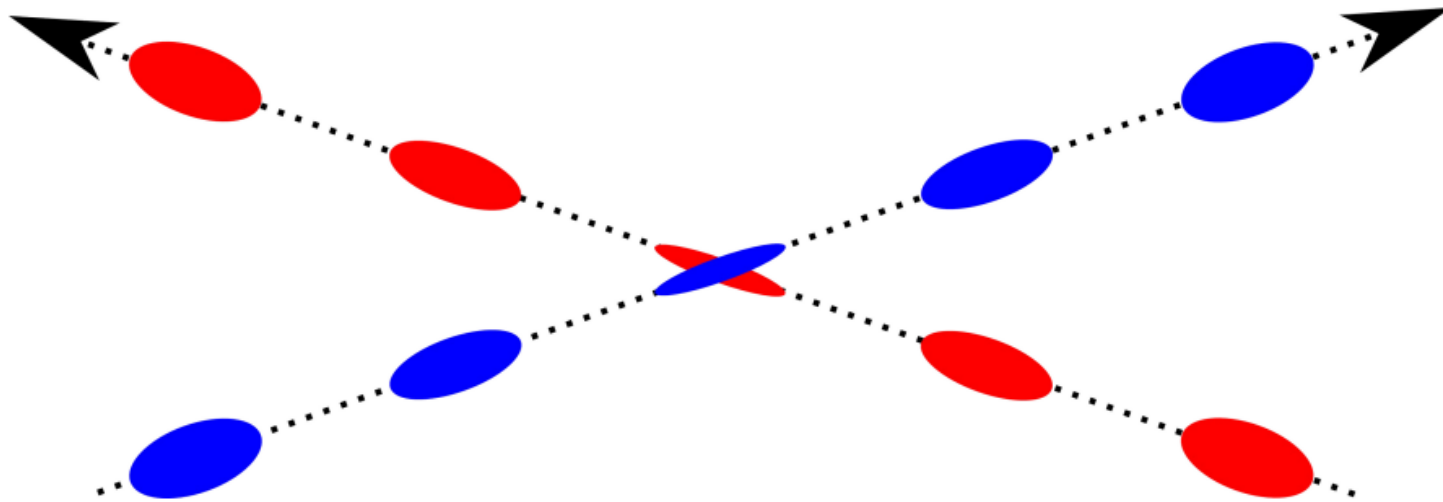
# CERN Accelerator Complex – LHC

- There are 8 interaction points, in 4 of which the detectors of the main experiments (**ATLAS**, **CMS**, **ALICE**, **LHC-B**) are placed
- The main purpose: push the high energy regime → production, detection and study of *Higgs boson*
- Ongoing works for its upgrade until 2029
- *High Luminosity LHC (HL-LHC)* to increase LHC performance ( $\sim x10$ )



# LHC – Beam-beam

- **LHC**: Large Hadron Collides
- **Two beams circulate in opposite directions**
- **There are 8 interaction points (4 collision points)**



Does the interaction affect the dynamics of the system?

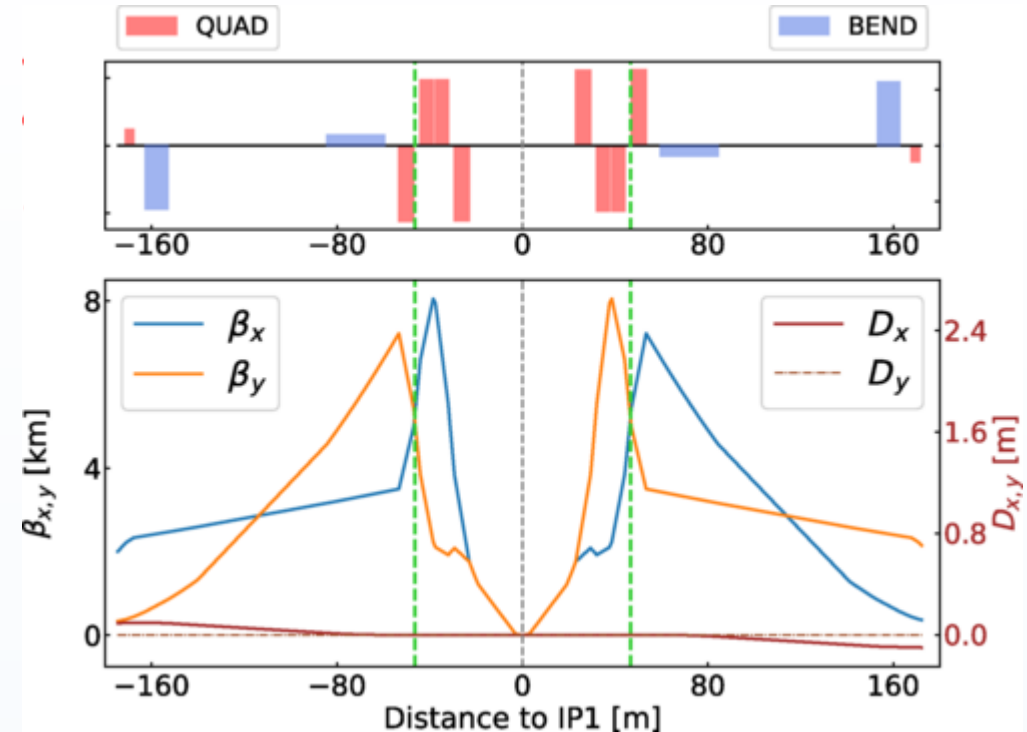
# LHC – Beam-beam

Does the interaction affect the dynamics of the system?

*Of course!*

- Even the **optics** change drastically to accommodate the need for squeezing down the beamsize!
  - To minimize the beta functions for the collision – ***huge increase of the beta functions in the close vicinity of the interaction point***
- The interaction of the two beams is **the strongest nonlinearity** in the accelerator

➤ *We will only consider part of these effects*



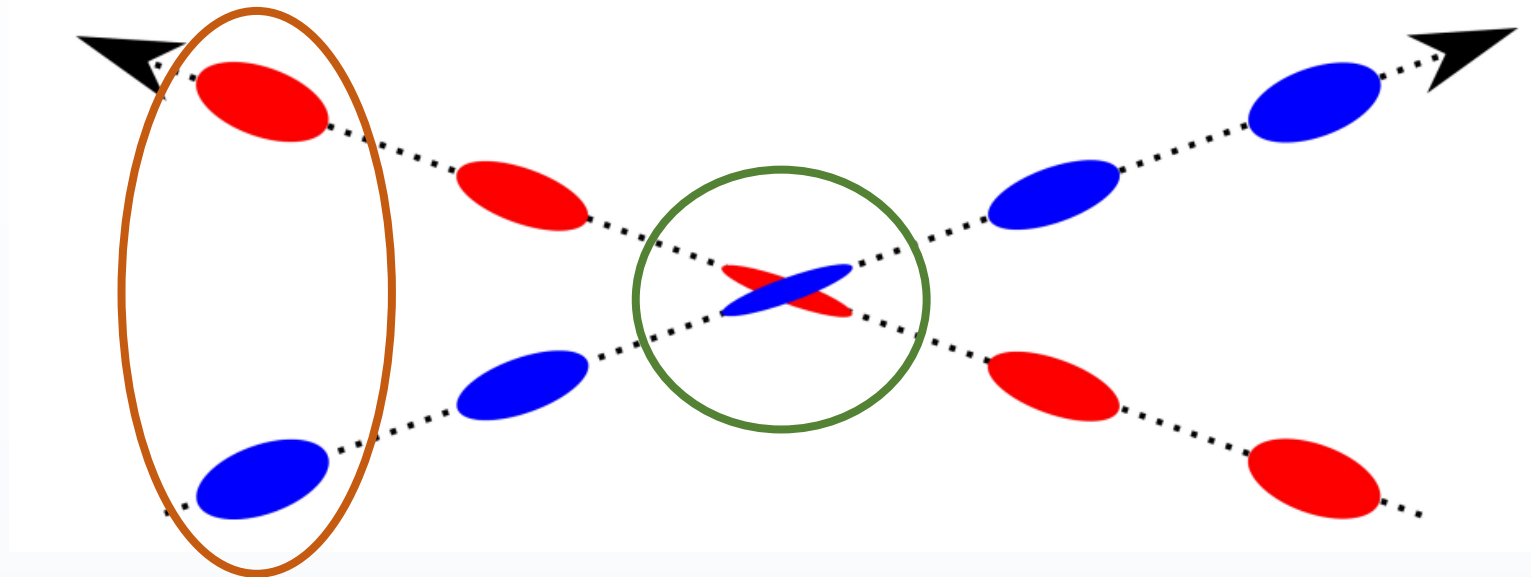
F. Soubelet et al: "Rigid waist shift: A new method for local coupling corrections in the LHC interaction regions"



# LHC – Beam-beam

We can define two different regimes for the beam-beam force

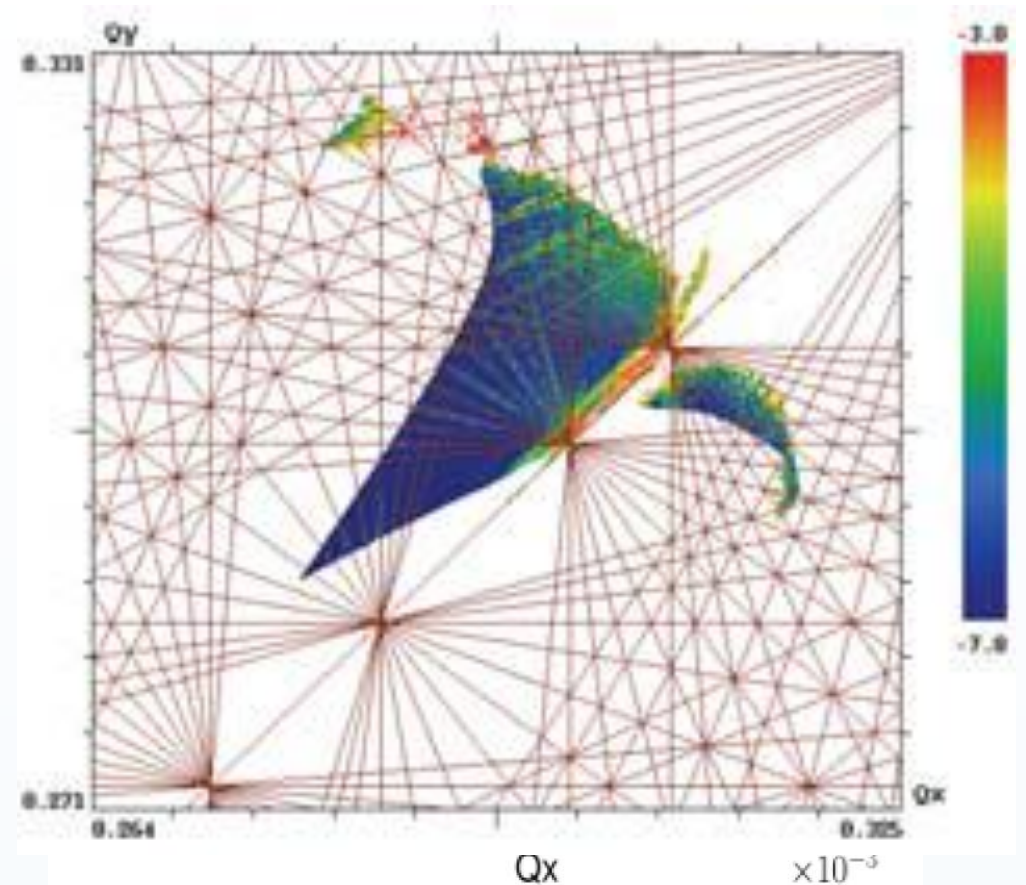
- The interaction for the colliding bunches – **Head On**
- The interaction for the non-colliding bunches – **Long Range**
- **Both strongly nonlinear**  
→ **Tune spread!**



# LHC – Beam-beam

- The contribution of the **Head On** and the **Long Range** on the spread are very different.
- **Reminder:** the tune spread coming from space charge looks very similar to the head-on!
- In reality, during collisions, the two contributions are combined!

→ ***Dangerous resonances are overlapped!***

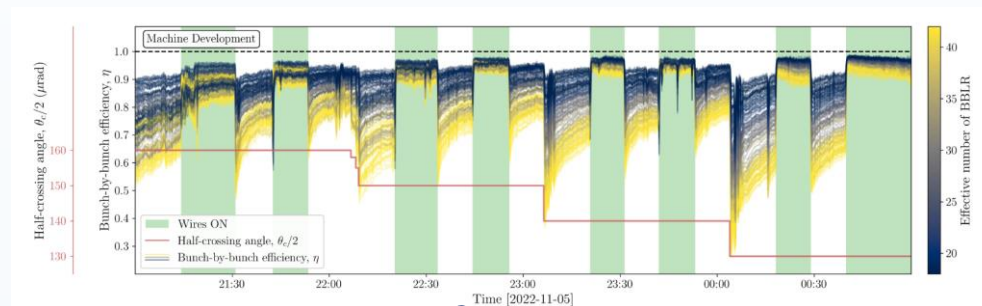


S. Fartoukh et al., PRSTAB, 2015

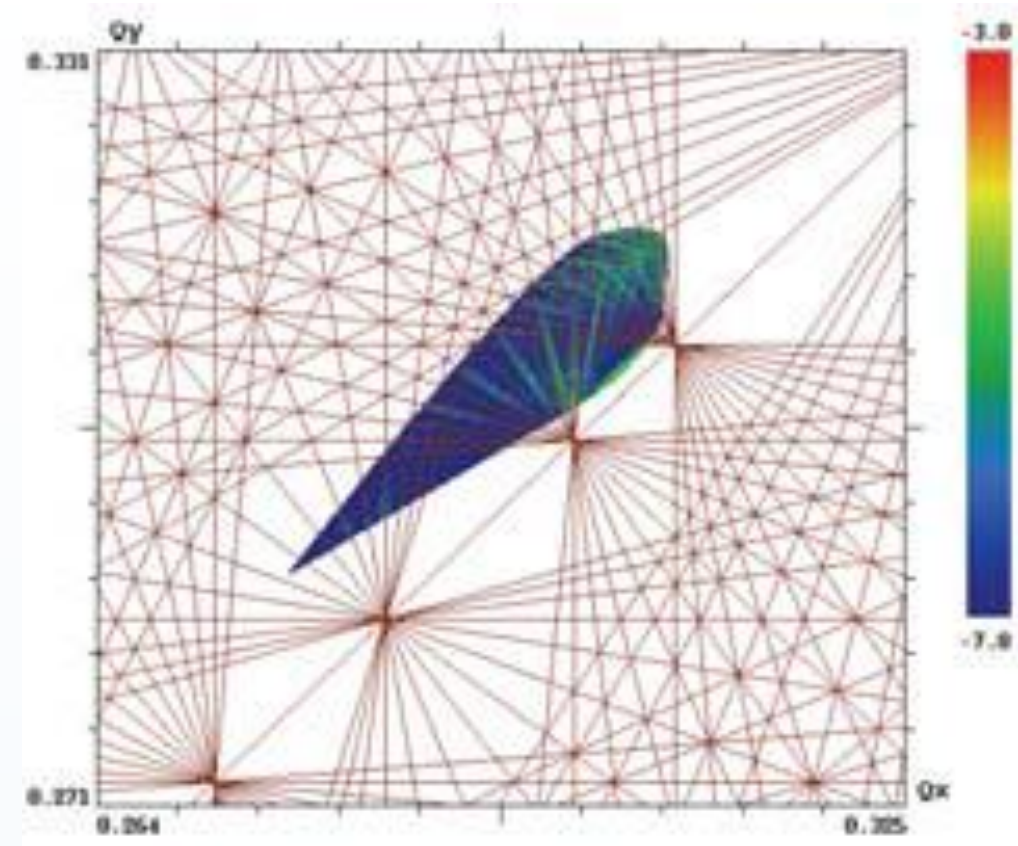
# LHC – Beam-beam

Mitigation strategies:

- The contribution of the long-range interaction is very similar to that of a wire in the vicinity of the beam
  - *Attempting compensation with a wire – tunespread shape dominated by the head on contribution*
- To avoid losses from strong resonances
  - careful tune choice
  - apply corrections using dedicated elements (up to dodecapole correctors installed in the LHC!)



P. Belanger et al., HL LHC collaboration meeting 2023



S. Fartoukh et al., PRSTAB, 2015

# Summary

- Delivering high Luminosity for the LHC experiments can be very challenging
- The various accelerators at CERN work together to produce high quality beams
  - *Some since 1959!*
- Each accelerator has different characteristics that can lead to very different dynamics!
- ***We tried giving a single (partial!) example of some effects, but*** In most cases multiple of these are **co-existing!**
  - PSB: space charge + instabilities + bunch splitting (not for LHC)
  - PS: bunch tailoring + space charge + instabilities + transition crossing
  - SPS: instabilities + space charge + transition crossing (not for LHC p+)
  - LHC: beam-beam + instabilities + optics perturbations ...
- ***In our continuous efforts to improve our beams for all the CERN experiments we end up with more challenges that we need to overcome!***

# Hi-Lumi LHC

