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

# Particle Accelerators and Beam Dynamics

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Summer Student Lectures 2023

# 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

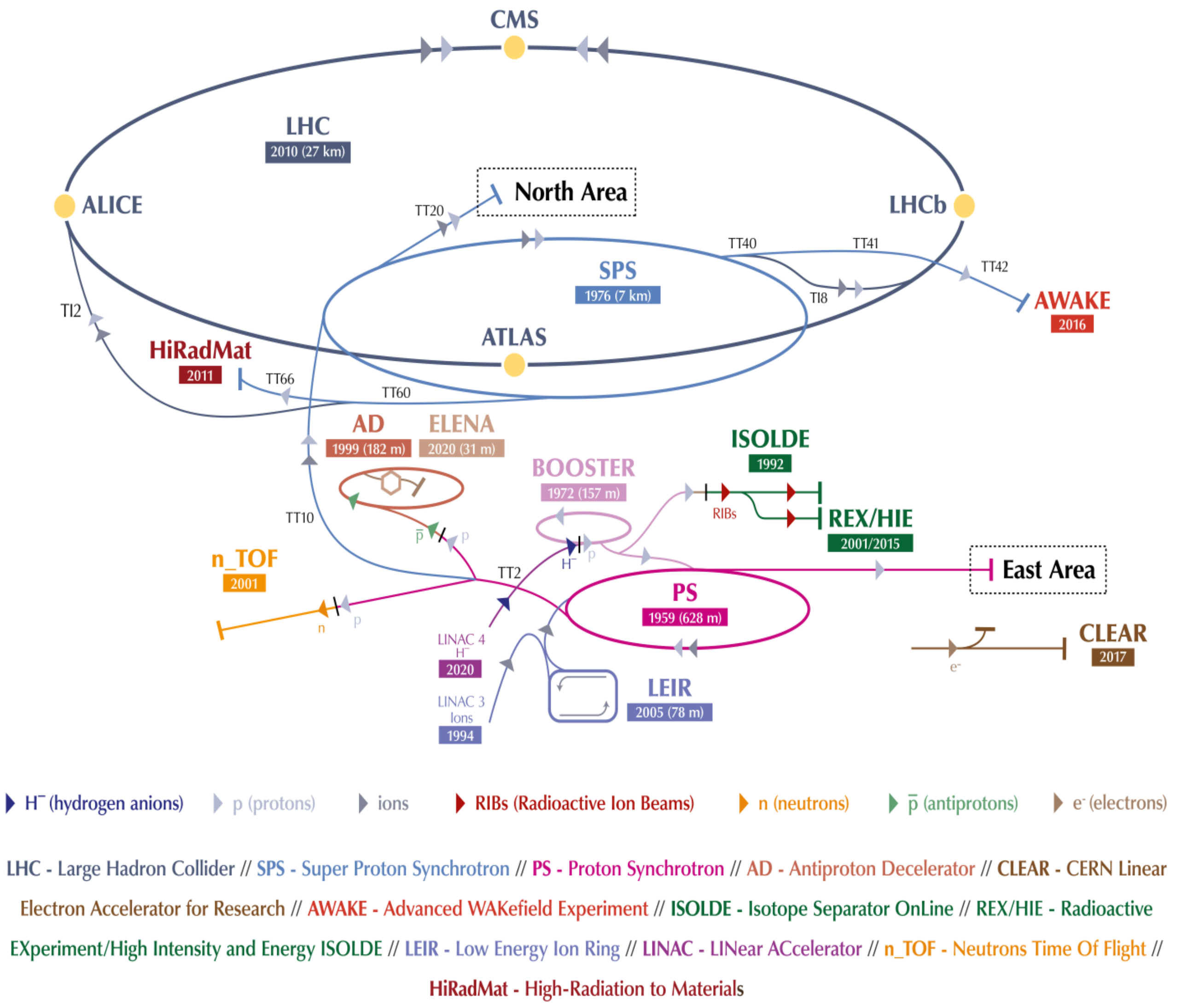
# Overview

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 Synchtrotron** 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***

- Brief overview of each synchrotron up to the LHC
- Examples of main limitation in each machine

# CERN Accelerator Complex

# CERN Accelerator Complex – PSB


- **PSB**: Proton Synchrotron Booster
- The first circular accelerator of the Complex
- 1$^{st}$ 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???

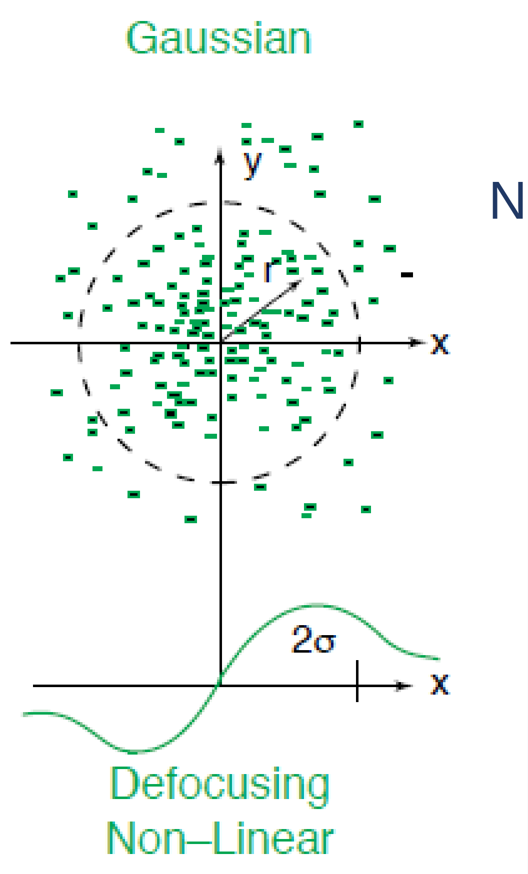
→ ***We wanted to increase the number of protons while maintaining a small emittance***

→ 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*** → Coulomb forces between the moving particles

↓

Self-fields that move with the beam

Non-Linear continuous kick ←

**Incoherent tune spread**

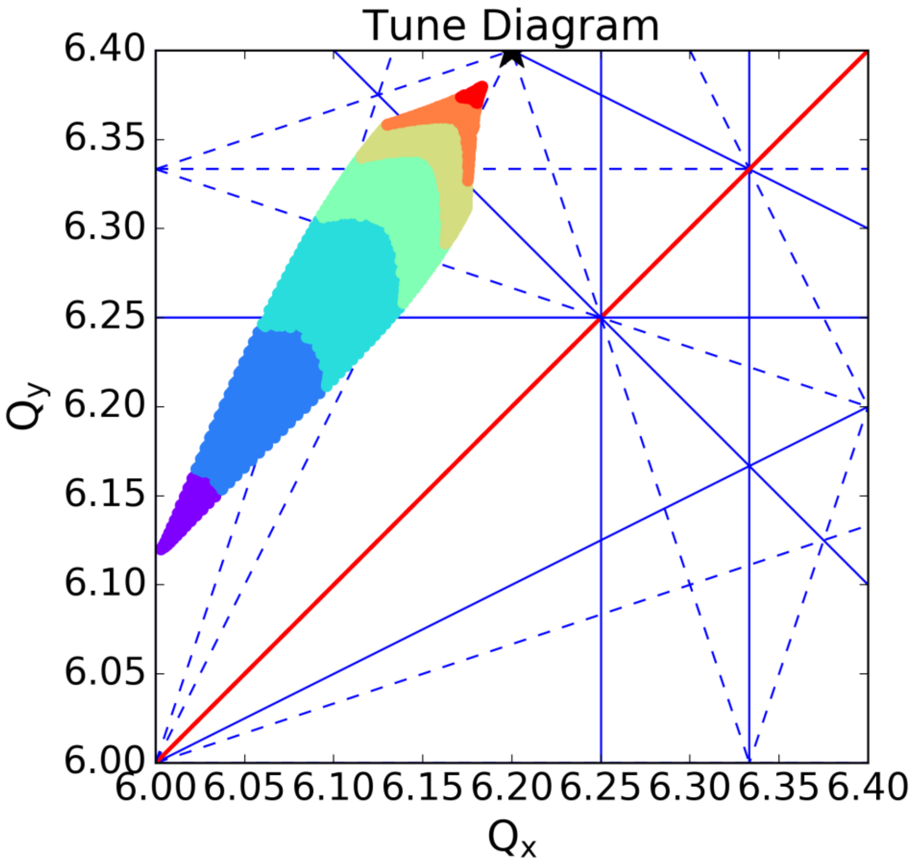
- The ***frequency of the betatron motion*** changes
- ***Different particles*** in the same bunch will have a different tune

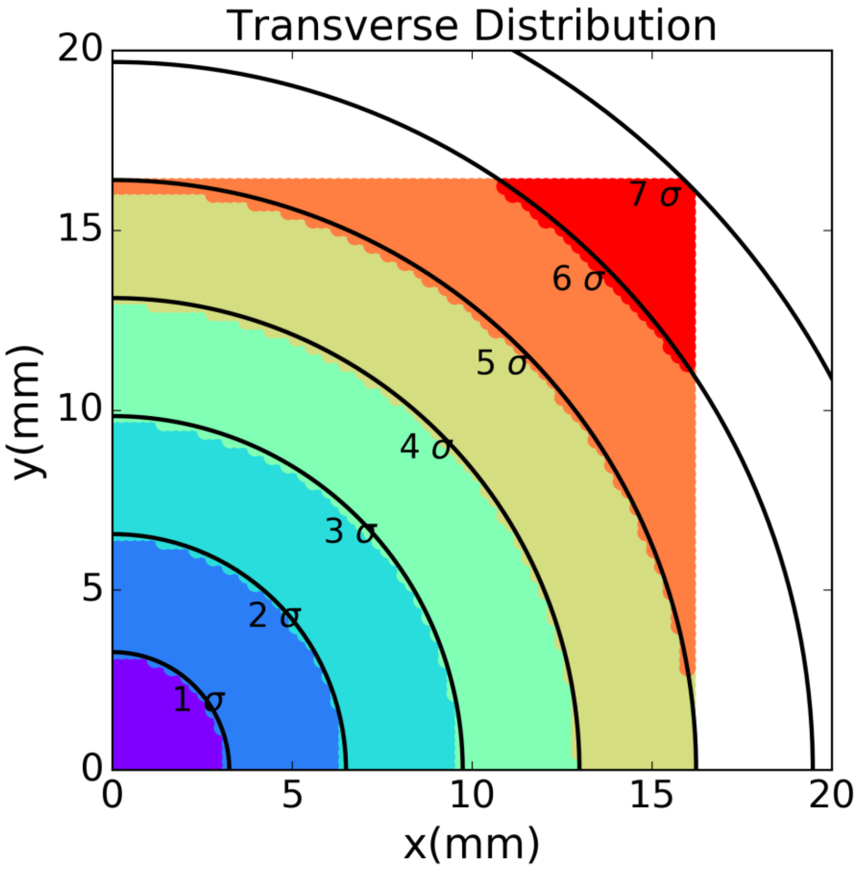
**Gaussian Distributions**: $V_{sc}(x,y) = \frac{r_o N_B}{\beta^2\gamma^3\sqrt{2\pi}\sigma_s}\int_0^\infty \frac{-1+e^{-\frac{x^2}{2\sigma_x^2+t}-\frac{y^2}{2\sigma_y^2+t}}}{\sqrt{(2\sigma_x^2+t)(2\sigma_y^2+t)}}dt$

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

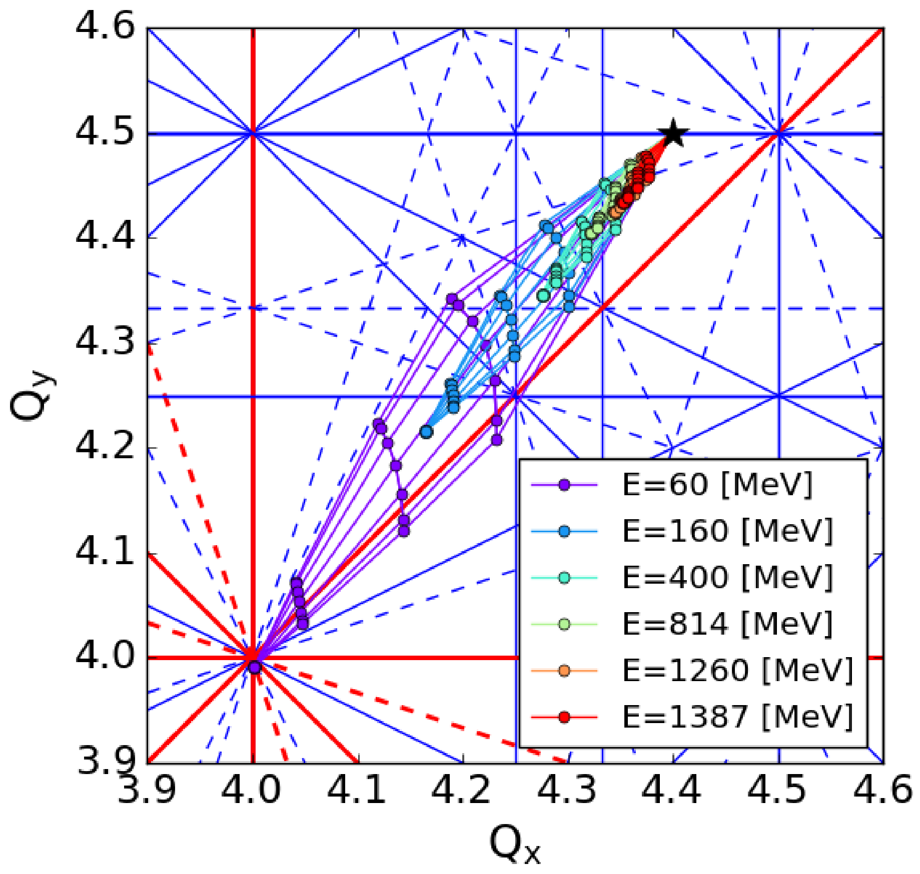


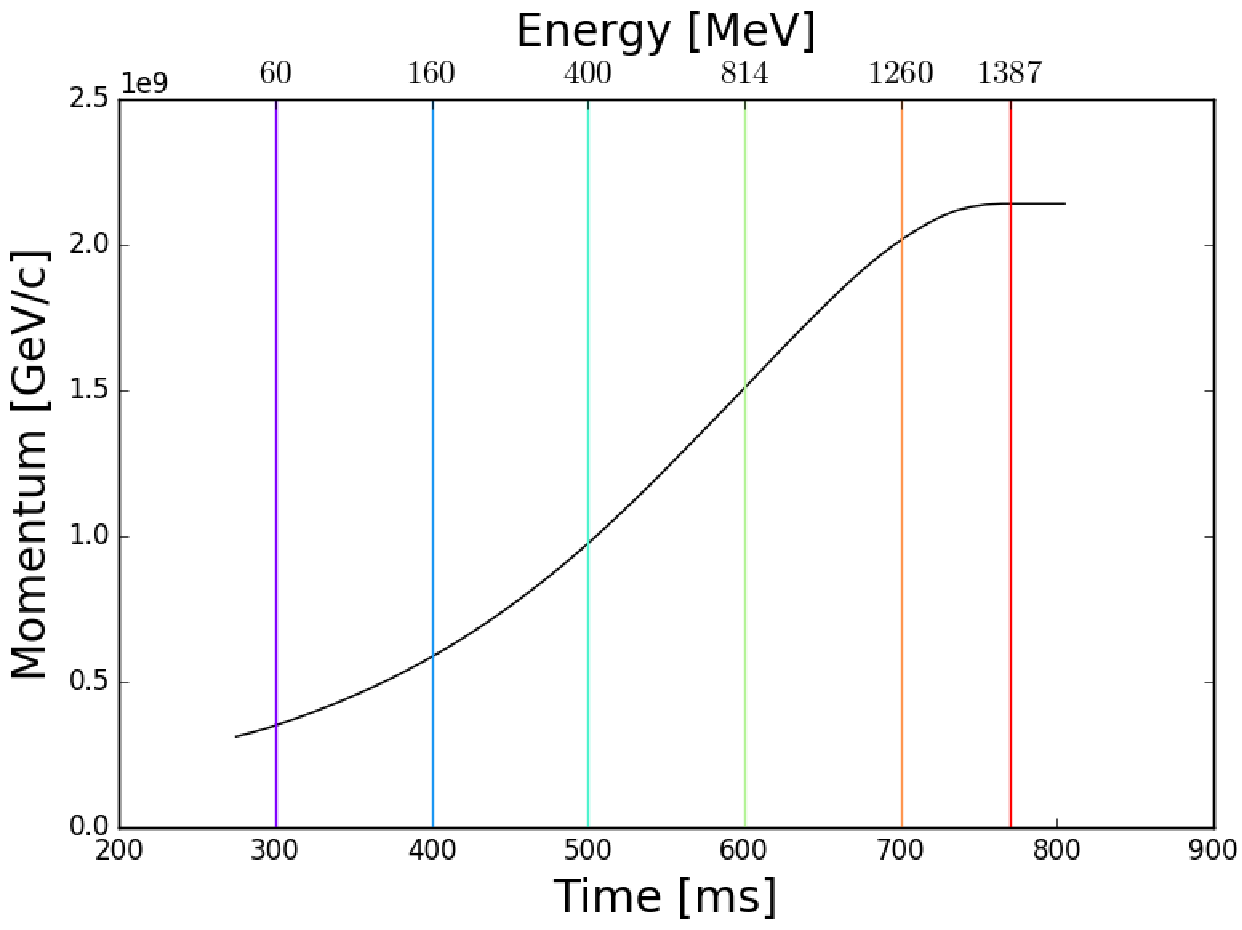



# PSB – Space Charge

## 2. Energy

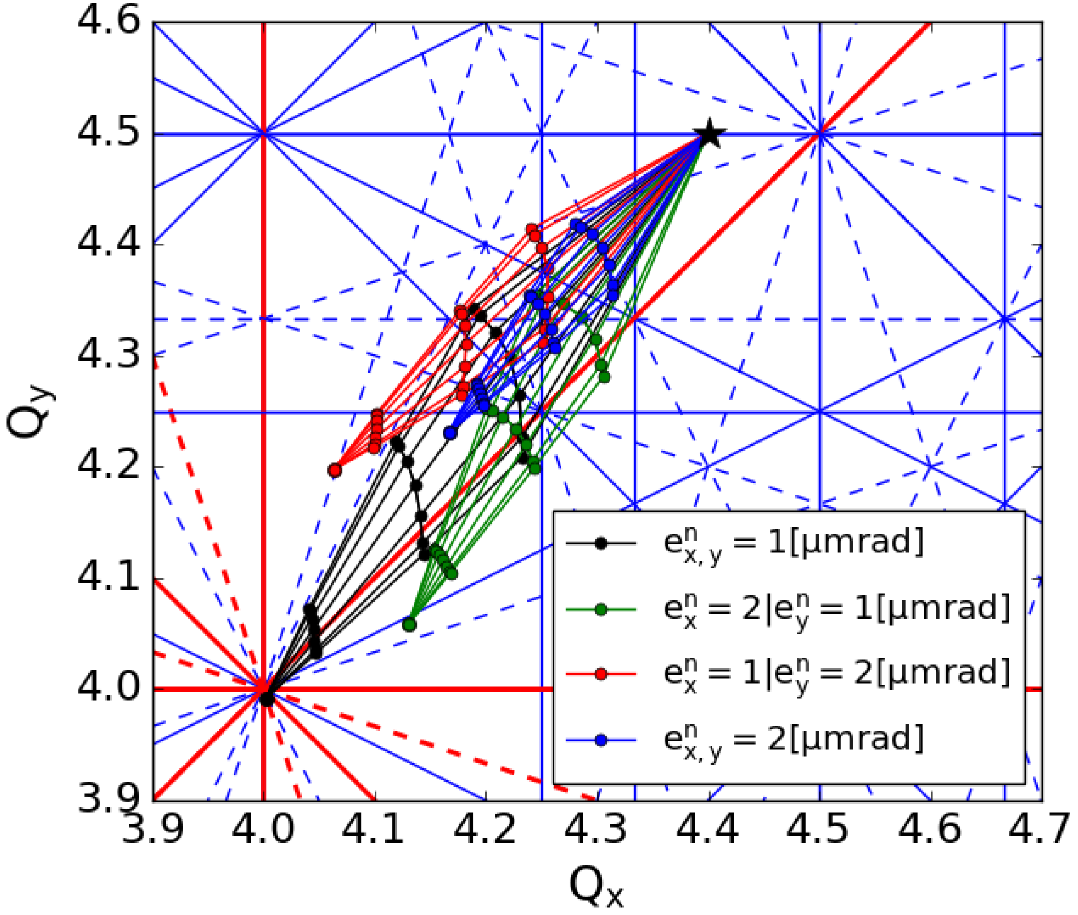
The lower the energy
the larger the detuning



# PSB – Space Charge

## 3. Transverse Beam Size

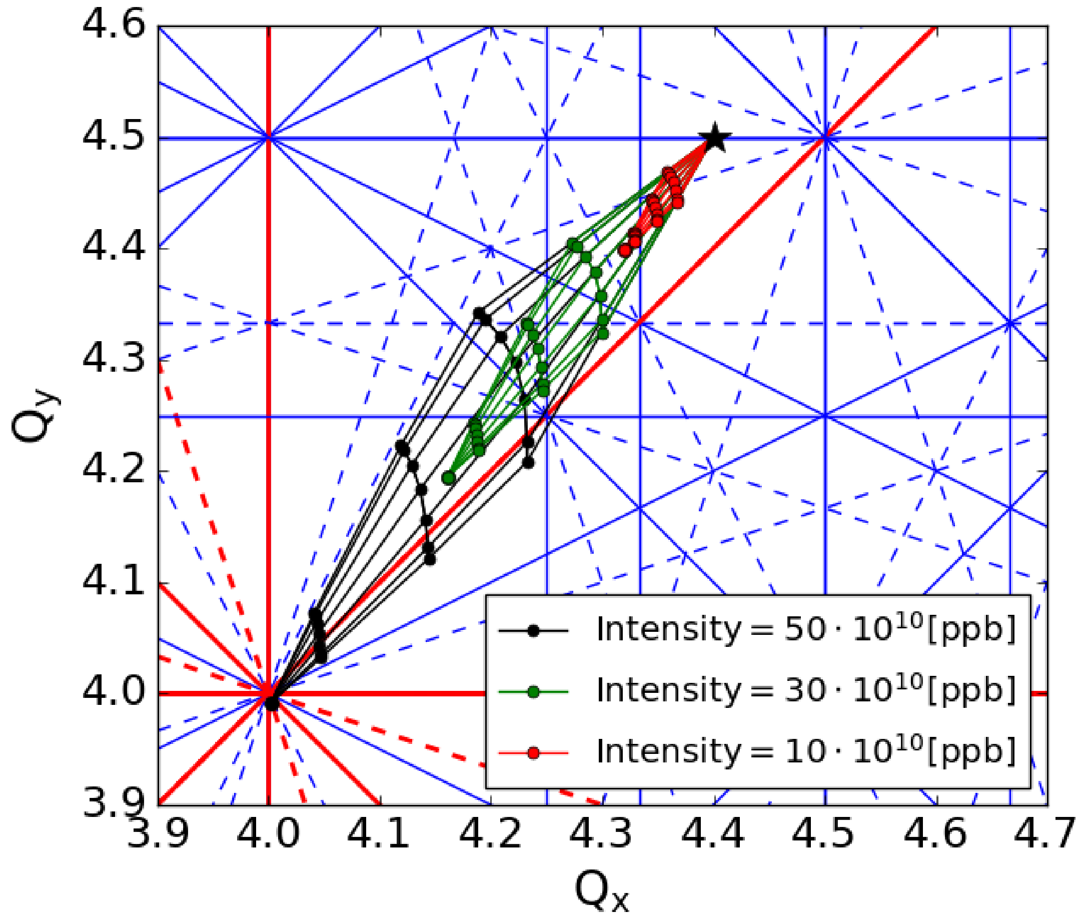



The smaller the emittance the larger the detuning

| Emittance x (mm mrad) | Emittance y (mm mrad) |
|---|---|
| 1 | 1 |
| 2 | 1 |
| 1 | 2 |
| 2 | 2 |

# PSB – Space Charge

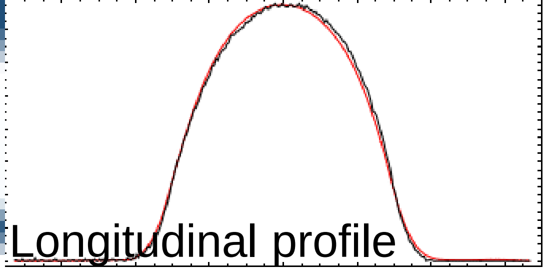
## 4. Bunch Intensity



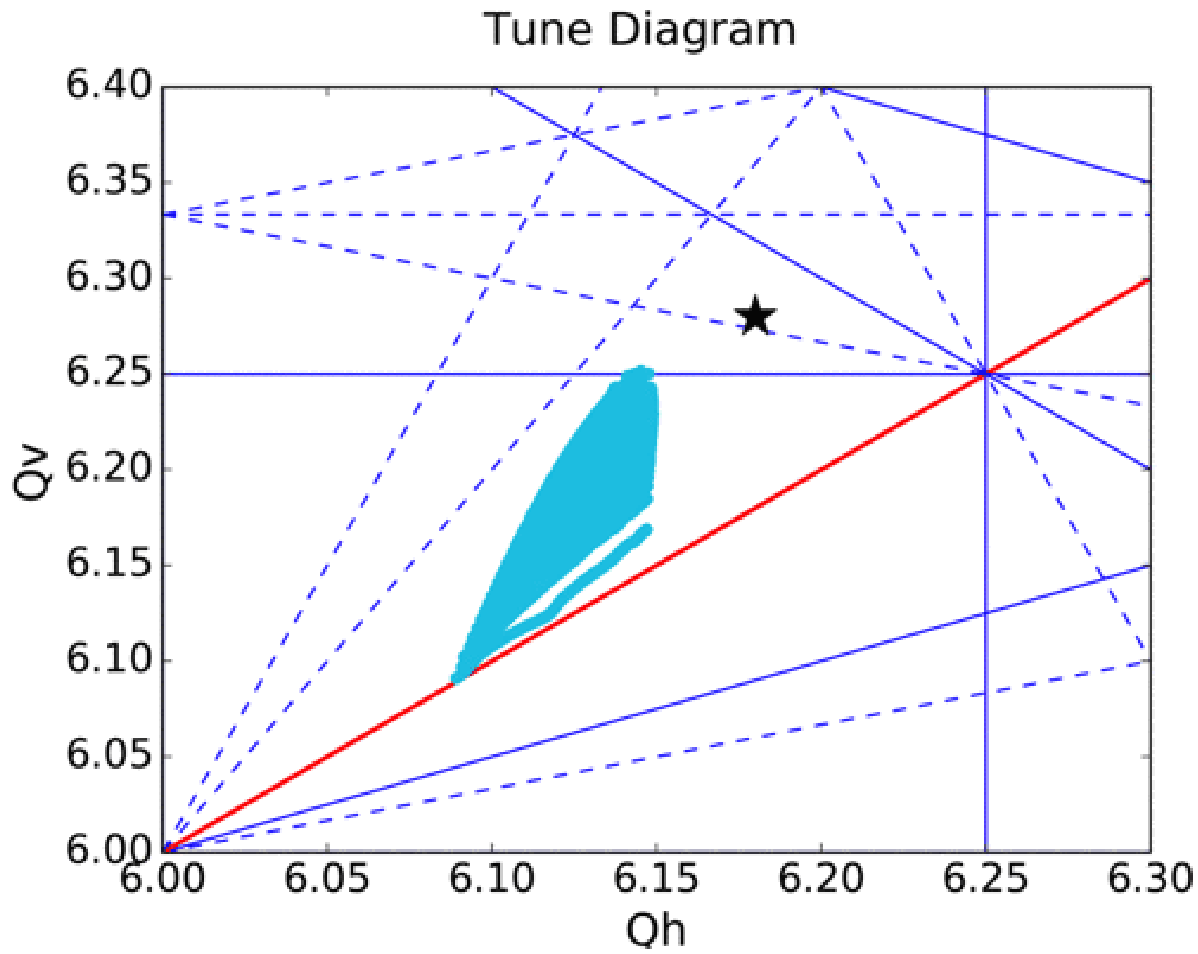

The larger the intensity
the larger the detuning

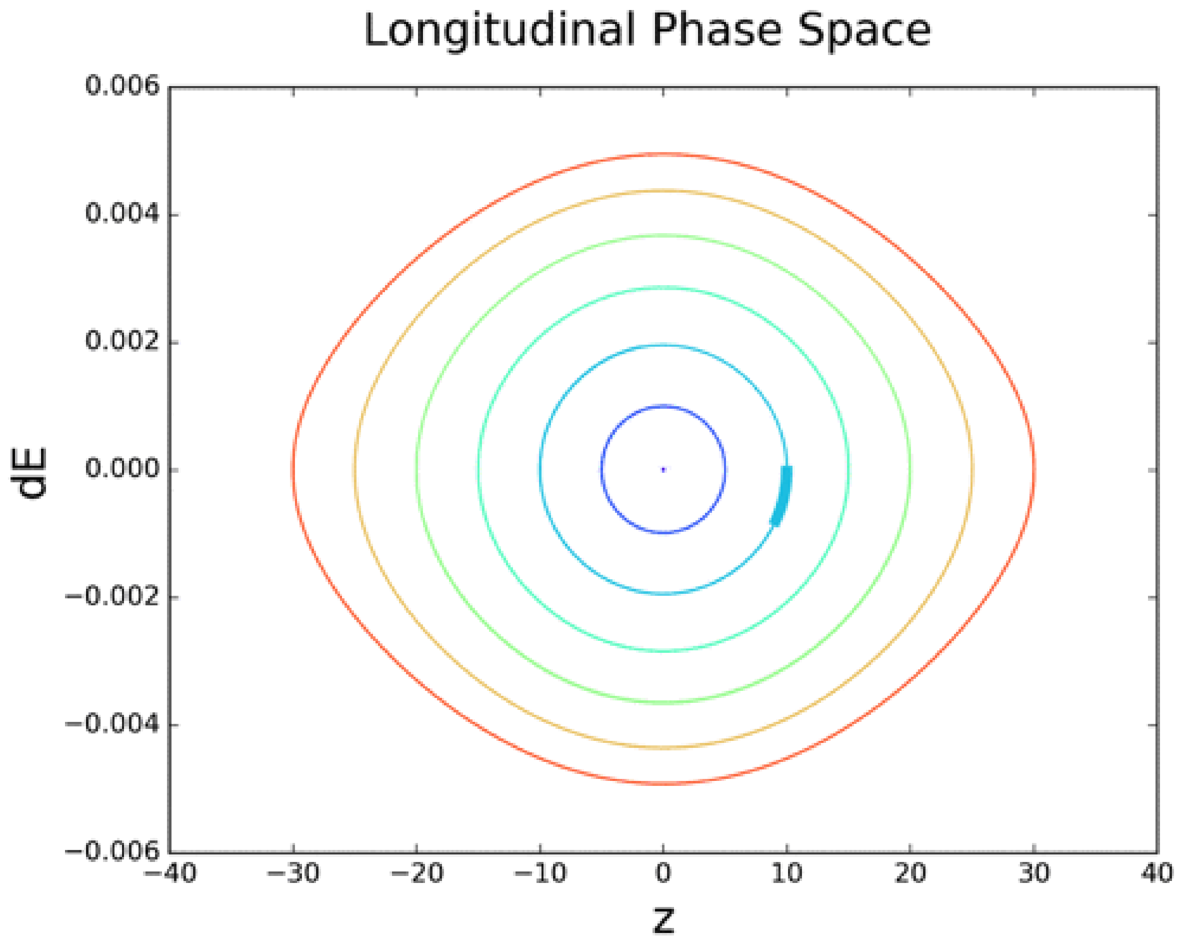
| Intensity ($10^{10}$ ppb) |
|---|
| 50 |
| 30 |
| 10 |

# PSB – Space Charge



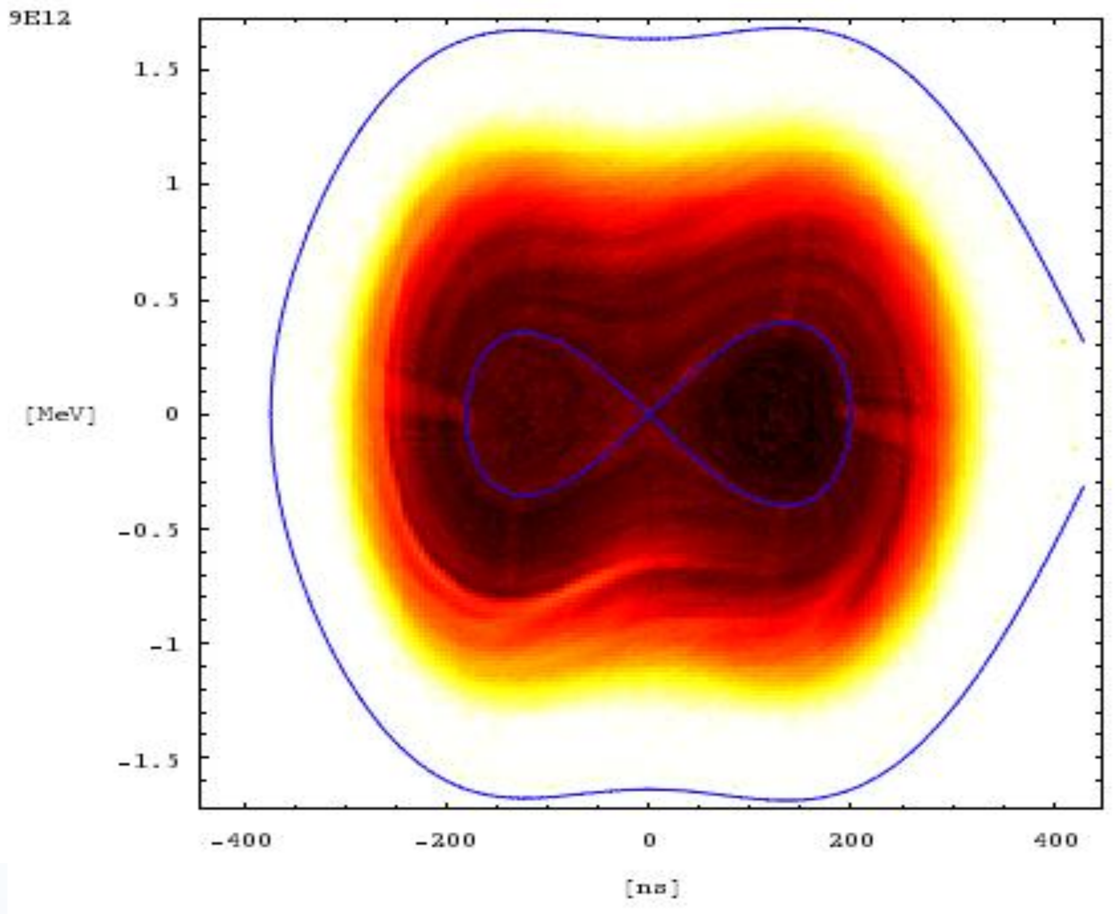

5. Longitudinal Settings ⇒
- Smaller bunch length – larger detuning
- Detuning changes with the synchrotron motion



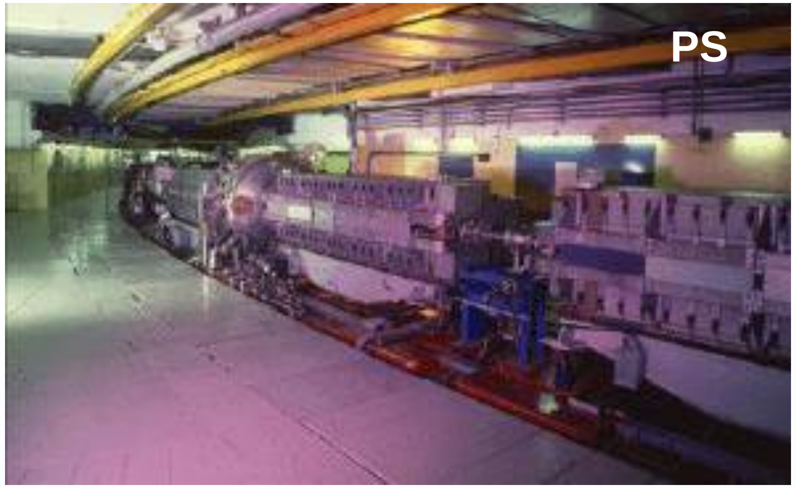
# PSB – Space Charge

- **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***
  - 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



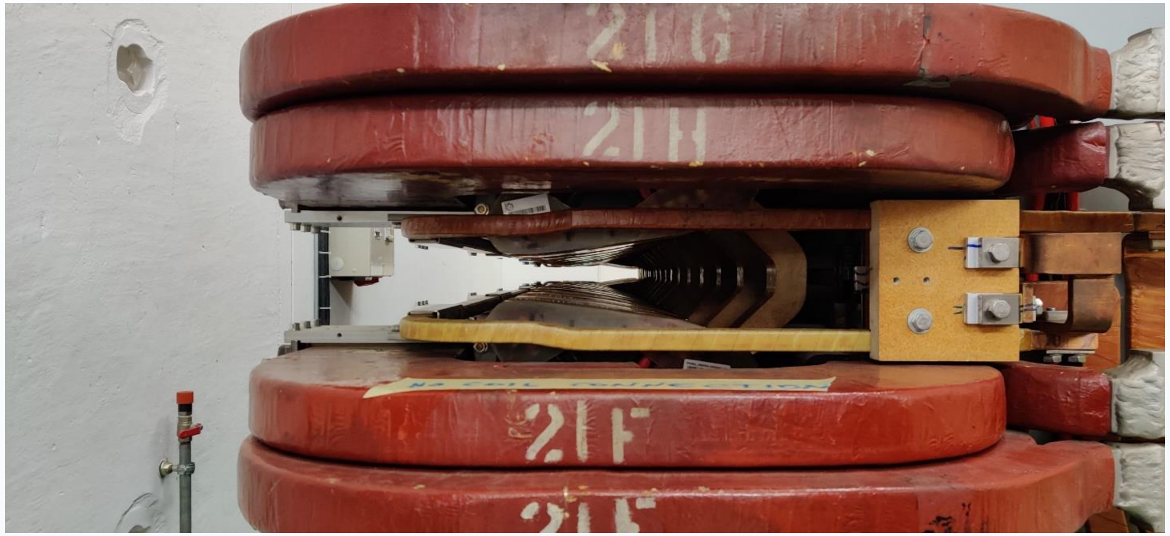
# CERN Accelerator Complex – PS

- **PS**: Proton Synchrotron
- CERN's first accelerator
- 1st 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



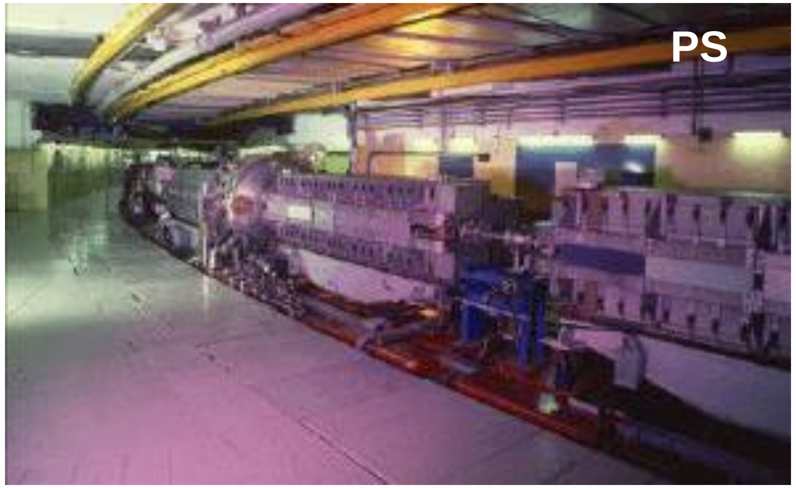

- Consists of 100 combined function magnets

→ ***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

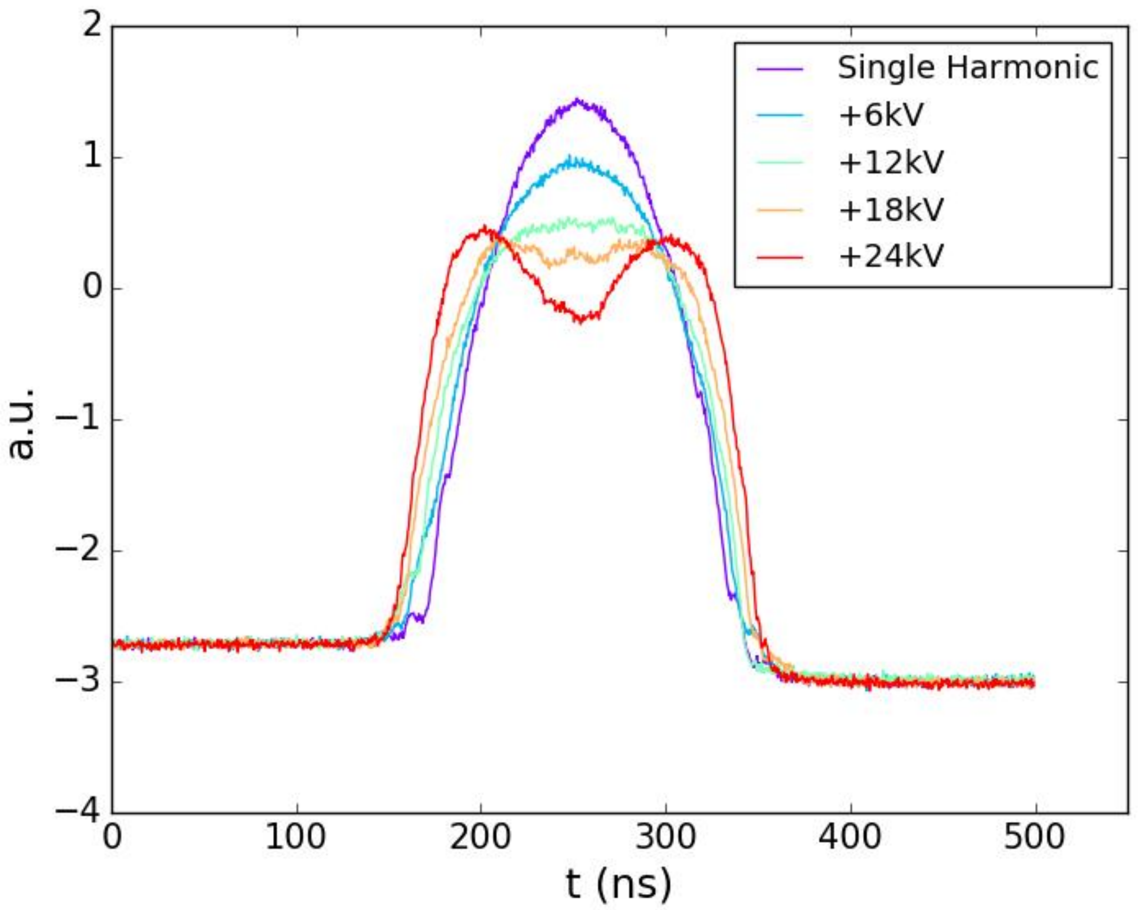
→ Rotate bunches

# 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!

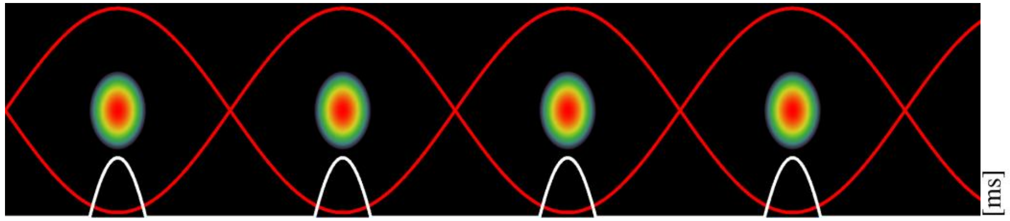


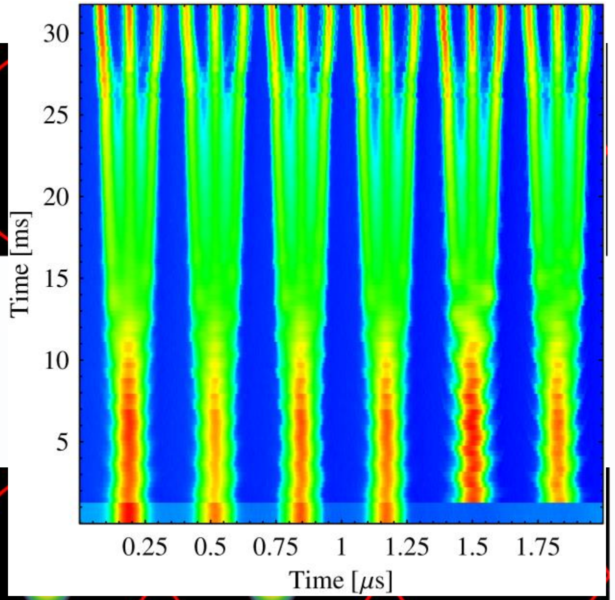
# PS – Tailoring of bunches

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

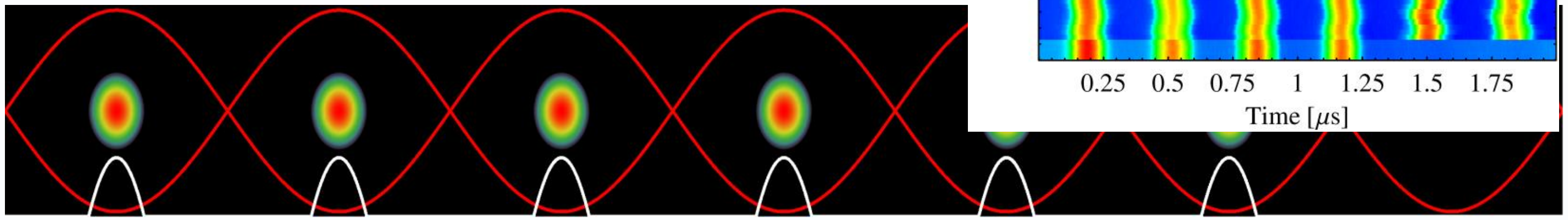
**1. Inject four bunches (h=7)**



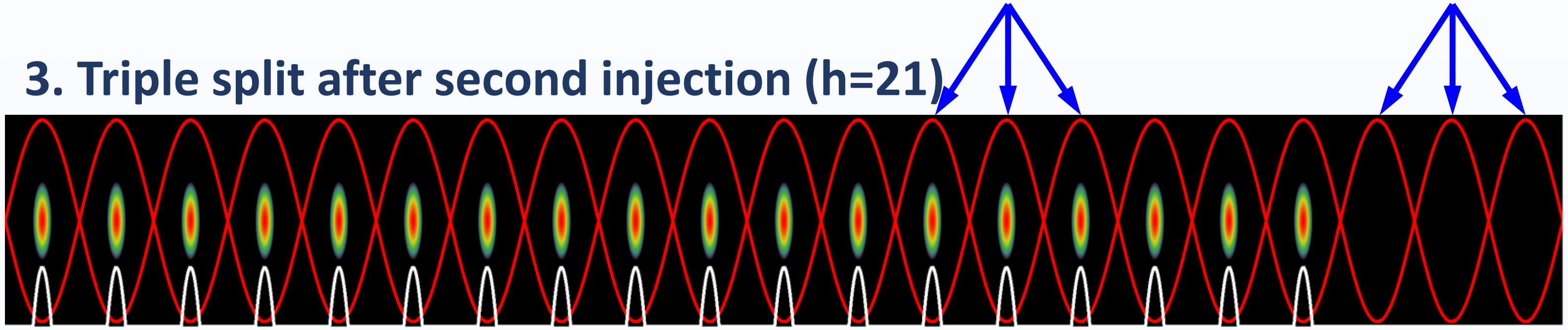



**Wait 1.2 s for second injection**

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



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



F. Tecker: *"Longitudinal beam dynamics" (CAS)*

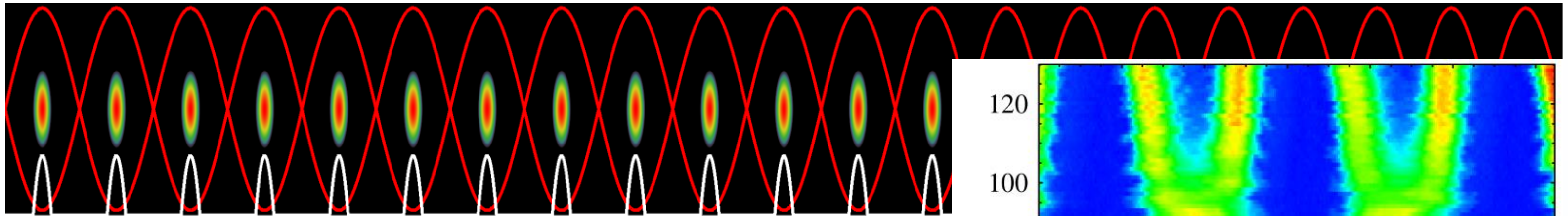
# PS – Tailoring of bunches

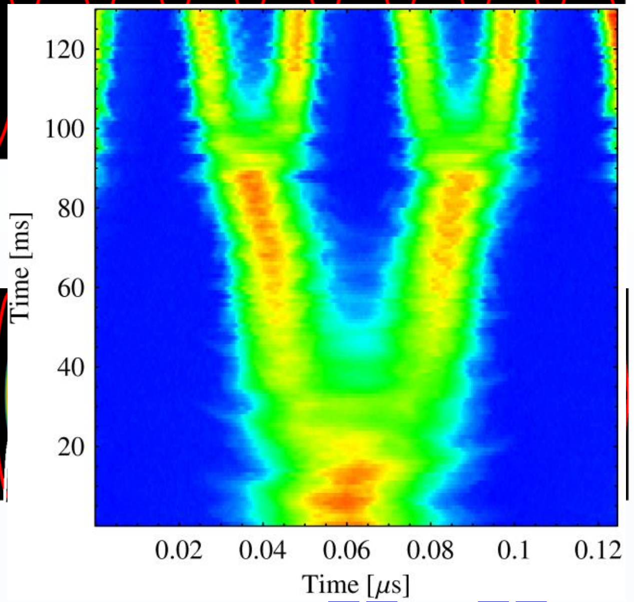
LHC bunches in the PS

- 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

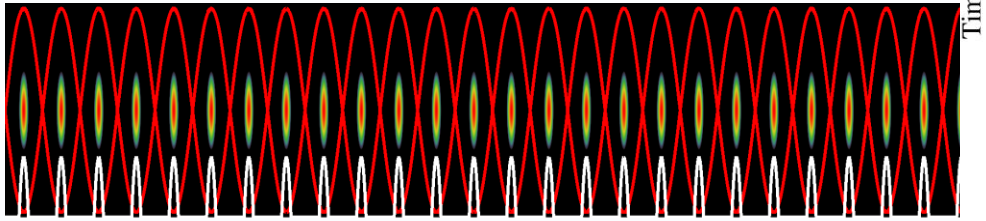
- **Two** times a **double** splitting

- ***Bunch rotation*** before extraction

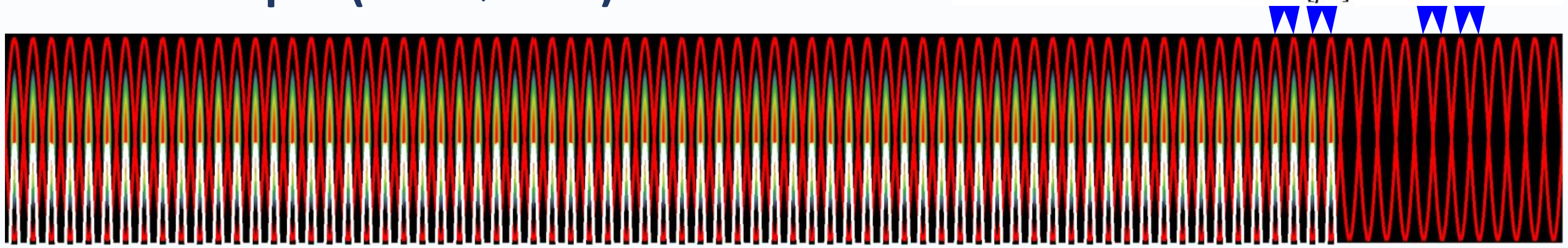





**6. Double split (*h*42)**

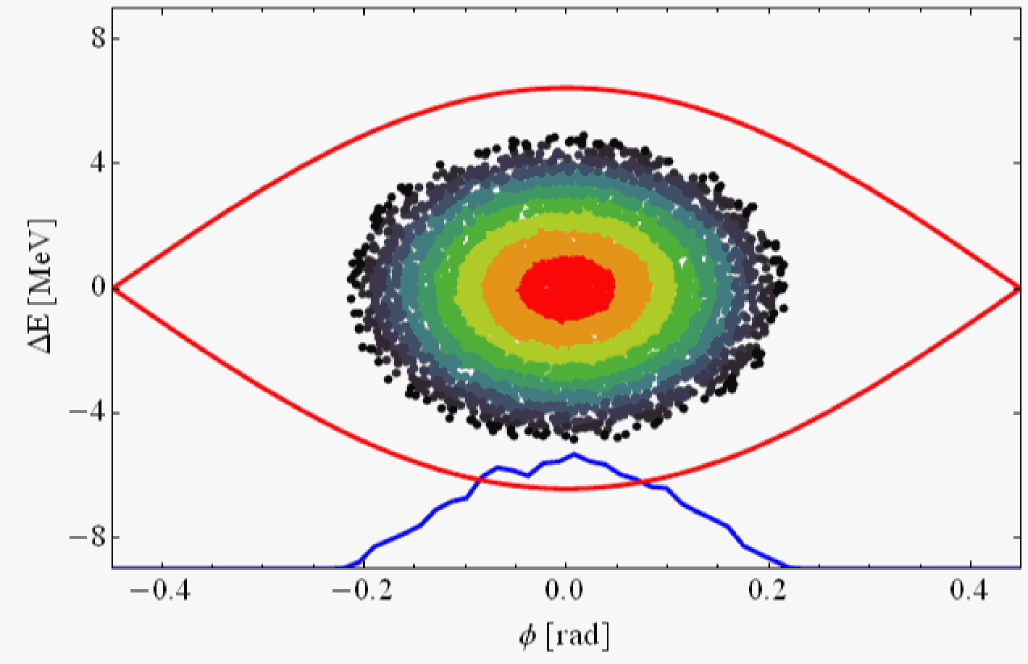


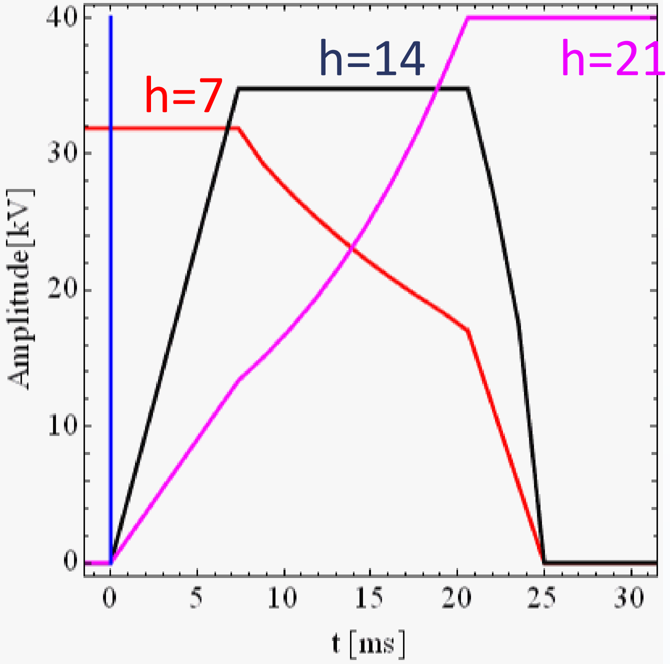
**7. Double split (*h*42 → *h*84)**



F. Tecker: *"Longitudinal beam dynamics" (CAS)*

# PS – Tailoring of bunches

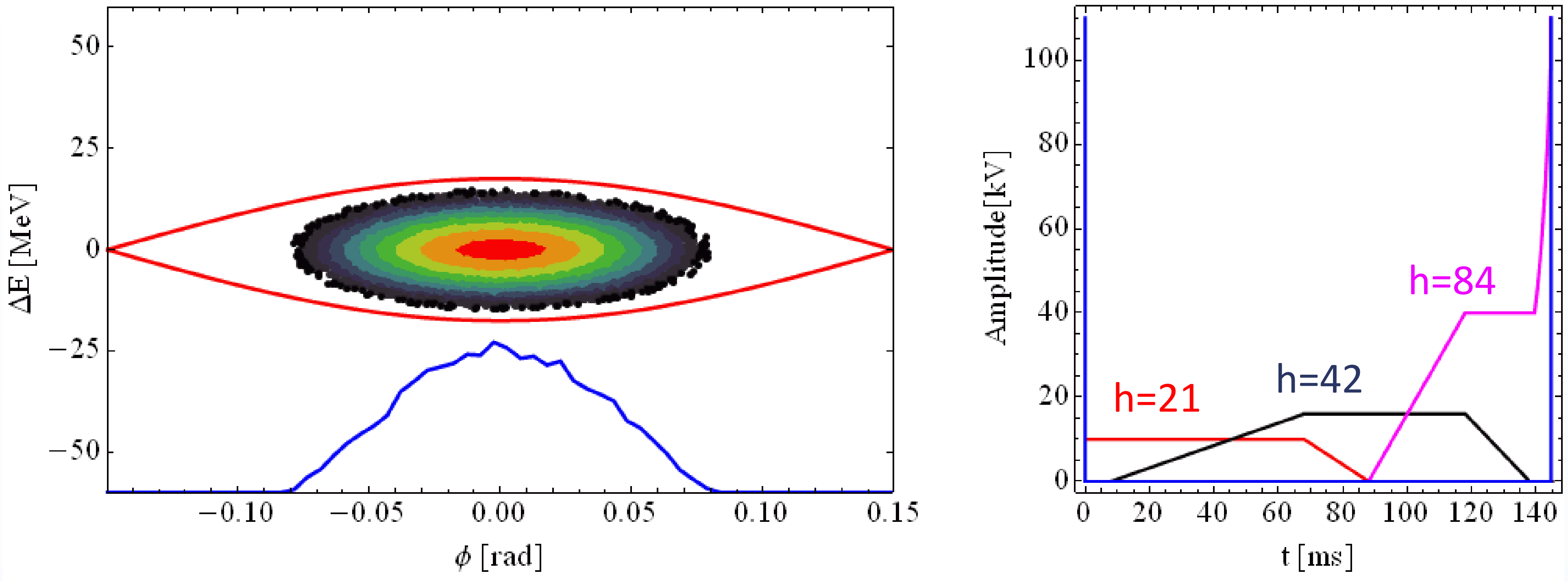



Triple splitting

F. Tecker: *"Longitudinal beam dynamics" (CAS)*

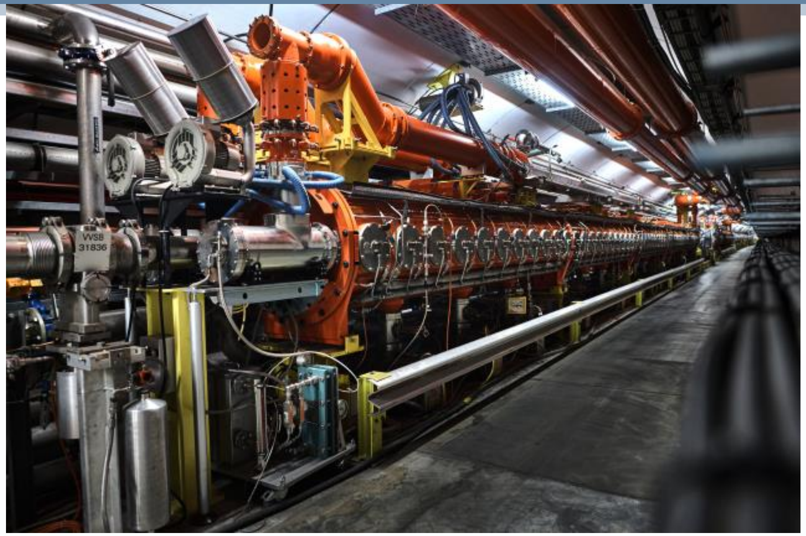
# PS – Tailoring of bunches




Two times double splitting and bunch rotation

F. Tecker: *"Longitudinal beam dynamics" (CAS)*

# CERN Accelerator Complex – SPS



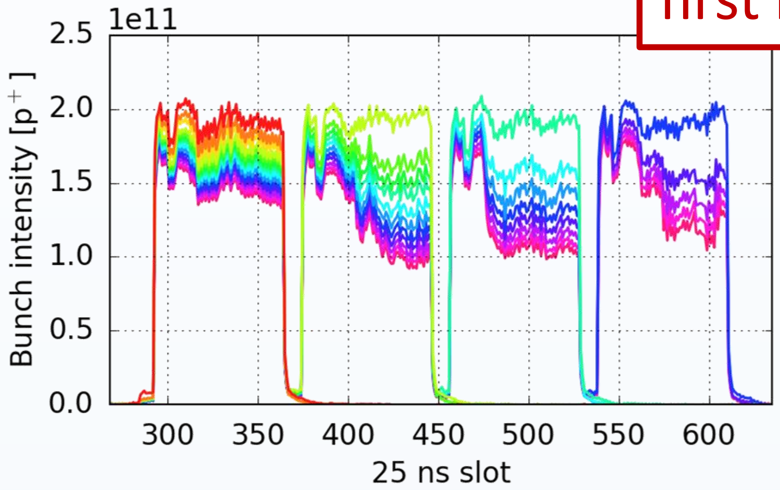

- **SPS**: Super Proton Synchrotron
- The 2nd larger accelerator at CERN with a circumference of 7km
- 1st run: ***1976***
- ***Discovery of the W and Z bosons during its operation as a collider***

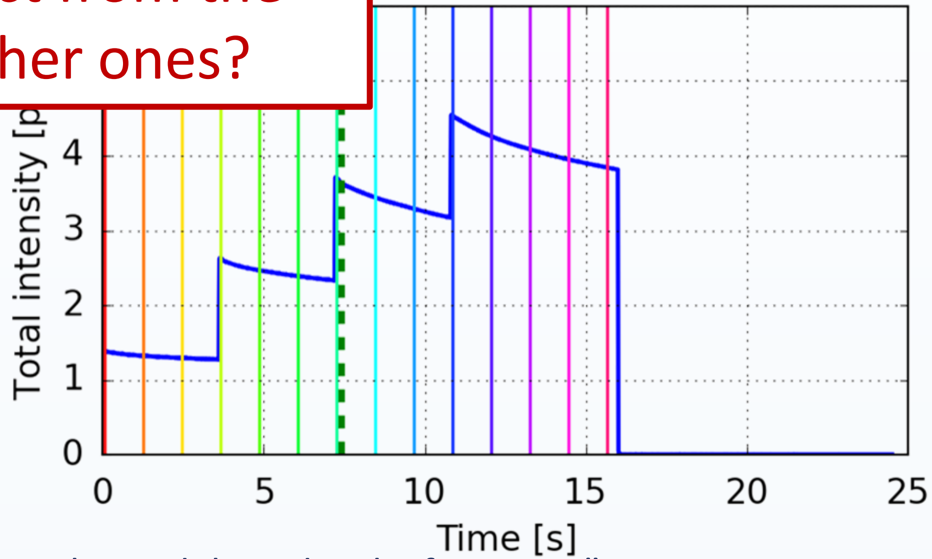
- Today it operates as an accelerator producing beams (***protons and ions***) for the LHC and other CERN experiments
- For the LHC, it accumulates short high intensity bunches for several injections

# 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?

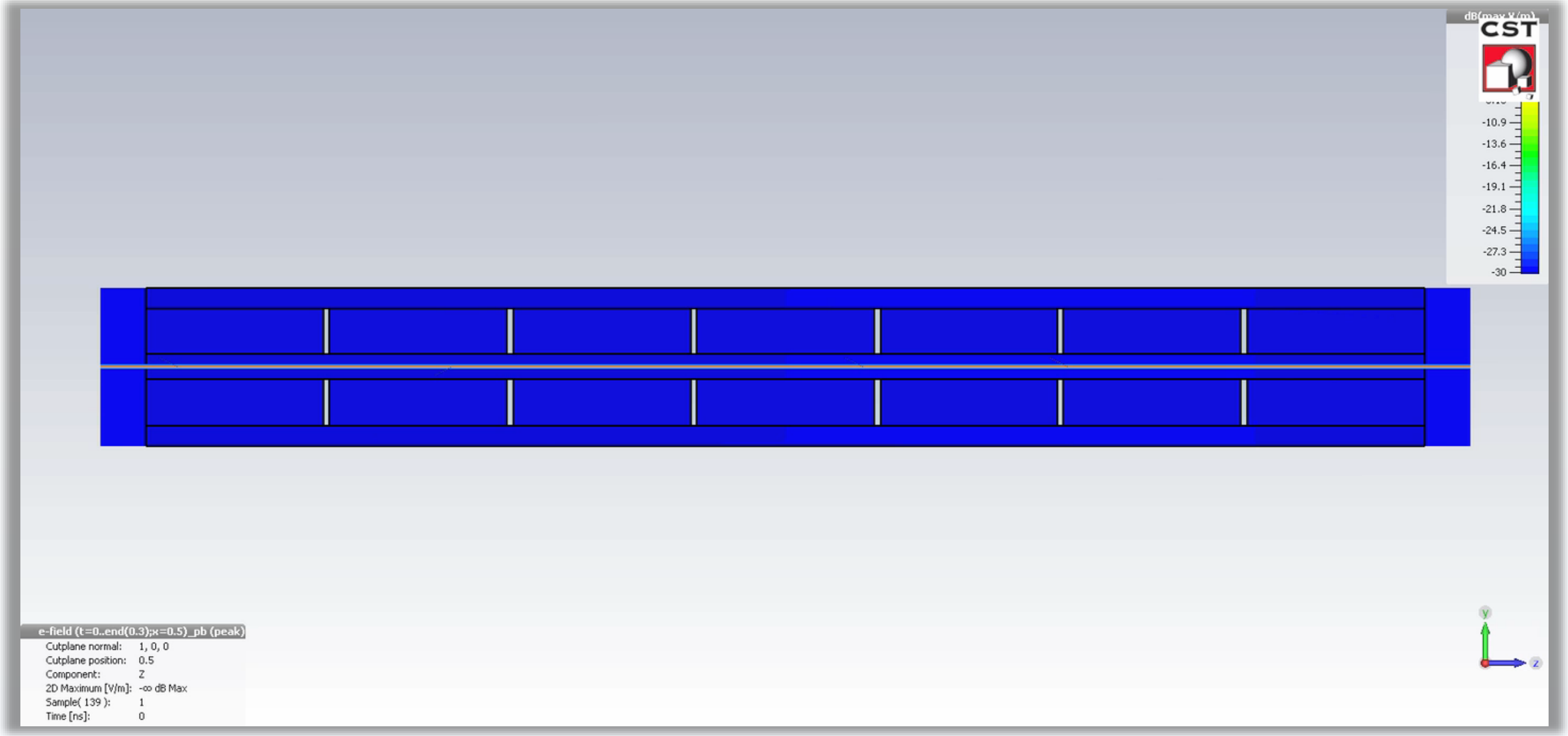



G. Rumolo, K.Li : "Instabilities Part I: Introduction – multiparticle systems, macroparticle models and wake functions"

# SPS – Instabilities

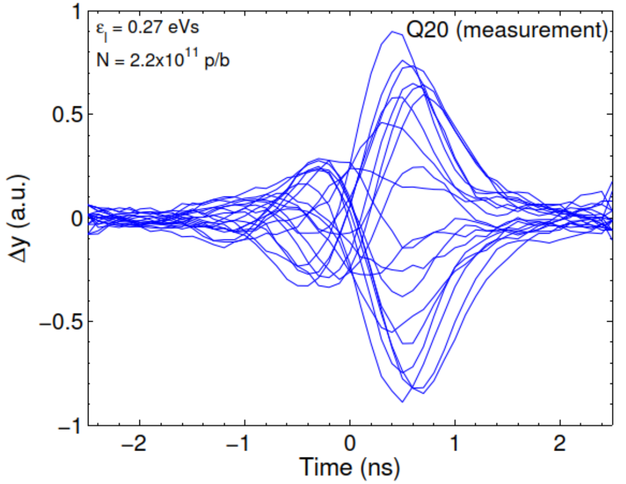
- In fact, the bunches can interact with the environment in the accelerator (vacuum pipe, cavities, instrumentation devices etc)
- As the bunches move on the s direction, they can create fields: “**Wakefield**”
- The wakefield depends on the distribution of our bunches and can cause a **collective response**

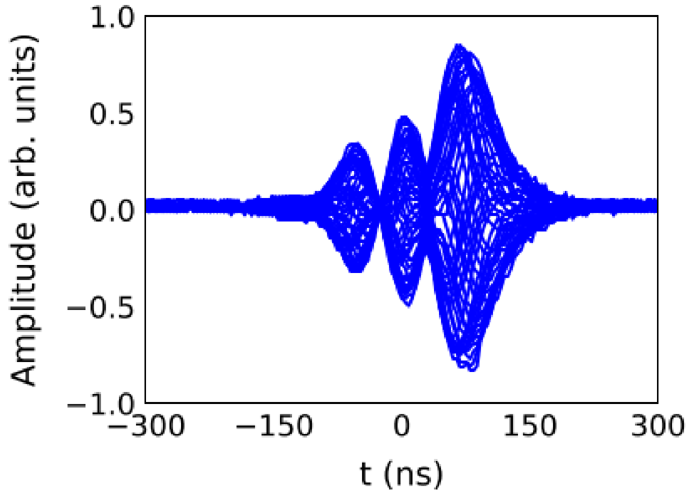


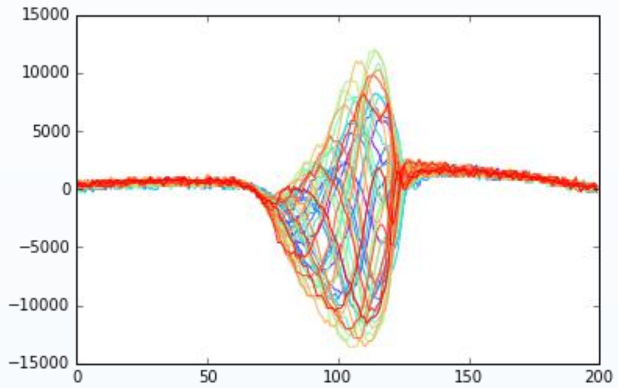

G. Rumolo, K.Li : “Instabilities Part I: Introduction – multiparticle systems, macroparticle models and wake functions”

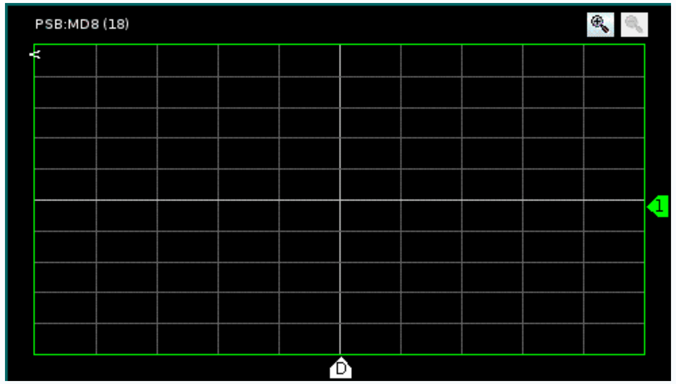
# SPS – Instabilities

- This collective response can result in “***intra-bunch***” motion
- The amplitude of this motion can increase in time leading to **large losses**



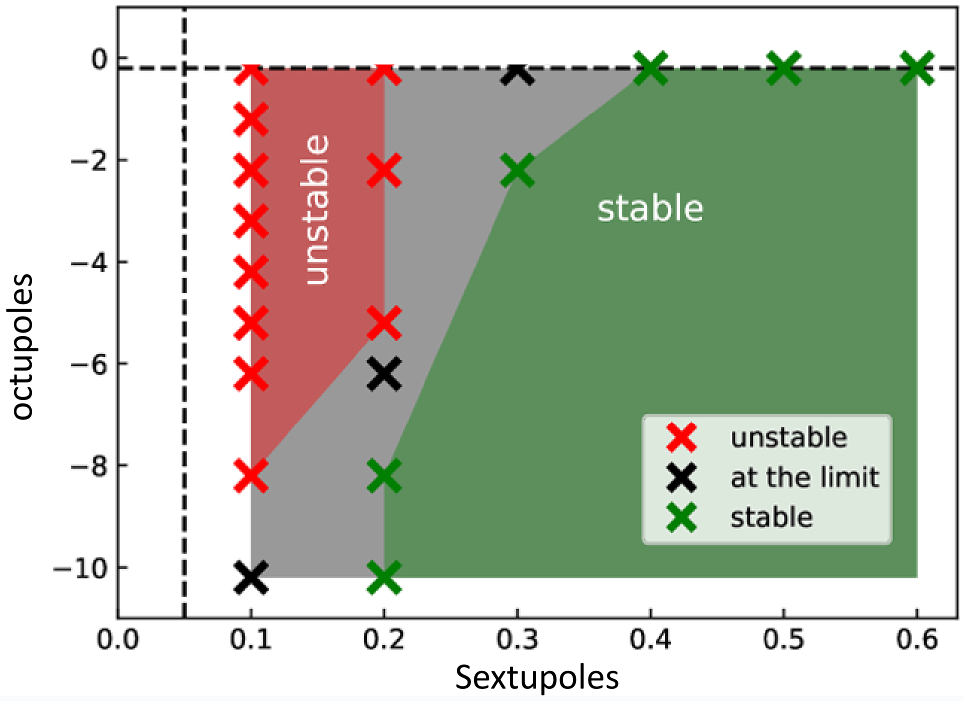

H. Bartosik: “Beam dynamics and optics studies for the LHC injectors upgrade”

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
- **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

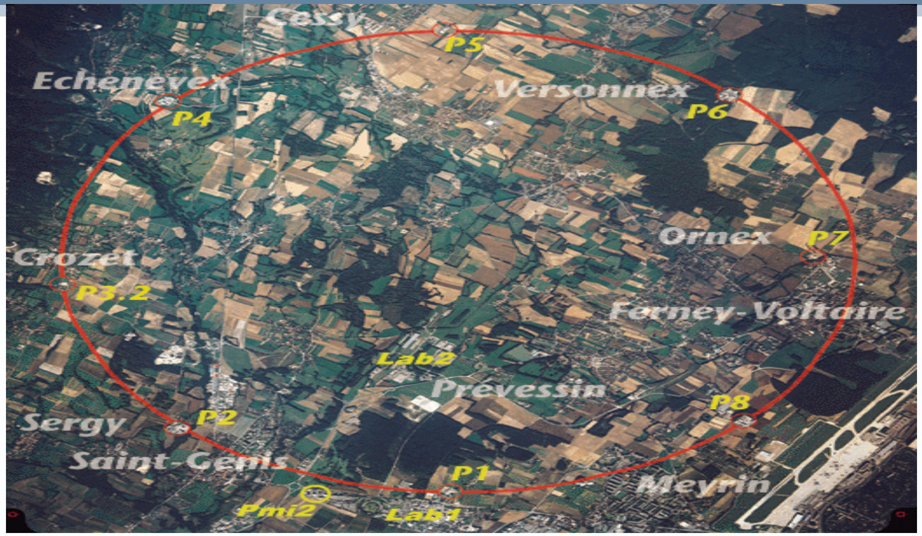



E. Koukovini-Platia et al: "Source of horizontal instability at the CERN Proton Synchrotron Booster"

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

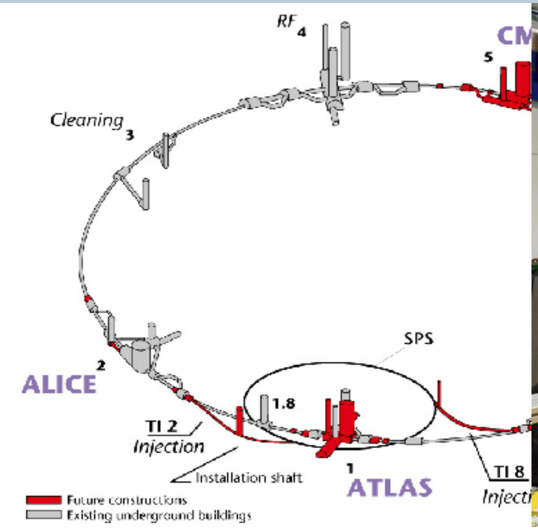
# CERN Accelerator Complex – LHC

- **LHC**: Large Hadron Collider
- The largest accelerator at CERN with a circumference of **26.7km**
- 1st 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

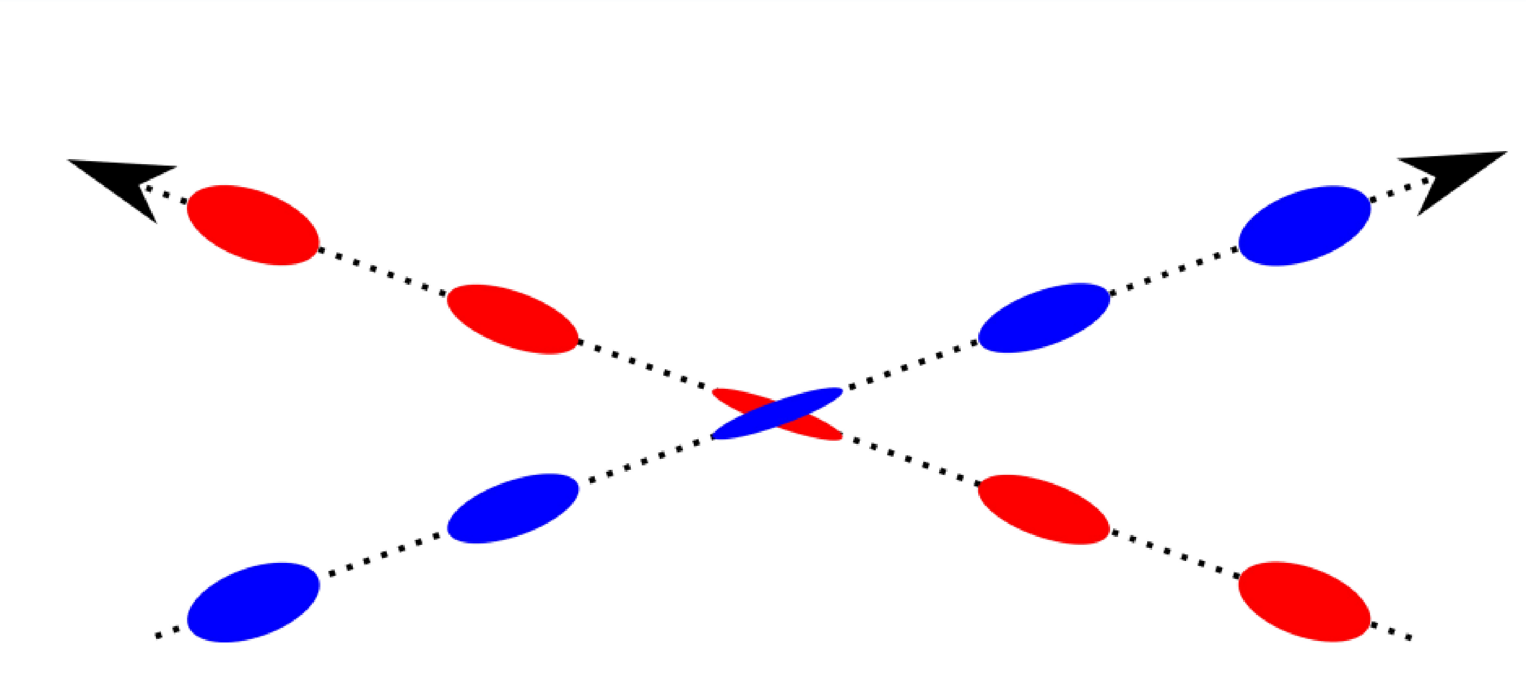
- There are 8 interaction points, in 4 of which the detectors of the main experiments (**ATLAS, CMS, ALICE, LHC-B**) are placed
- The main purpose: the production, detection and study of ***Higgs bosons***




- Ongoing works for its upgrade until 2029
- *High Luminosity LHC (**HL-LHC**) to increase LHC performance (~x10)*

# LHC – Beam-beam

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



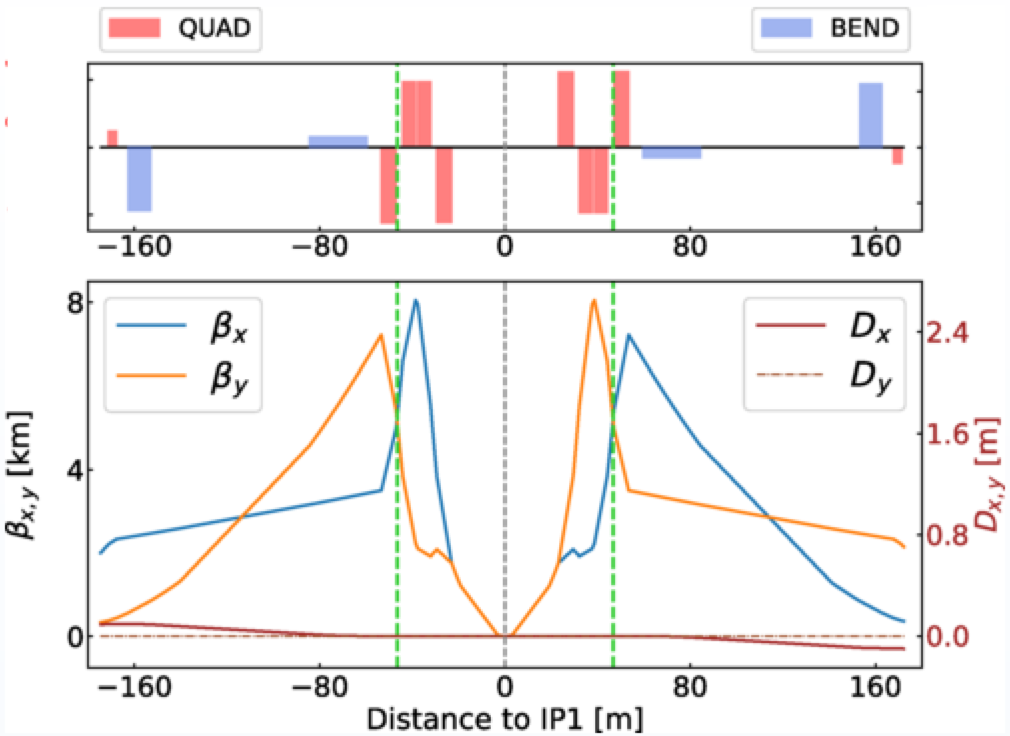

Does the interaction affect the dynamics of the system?

# 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*

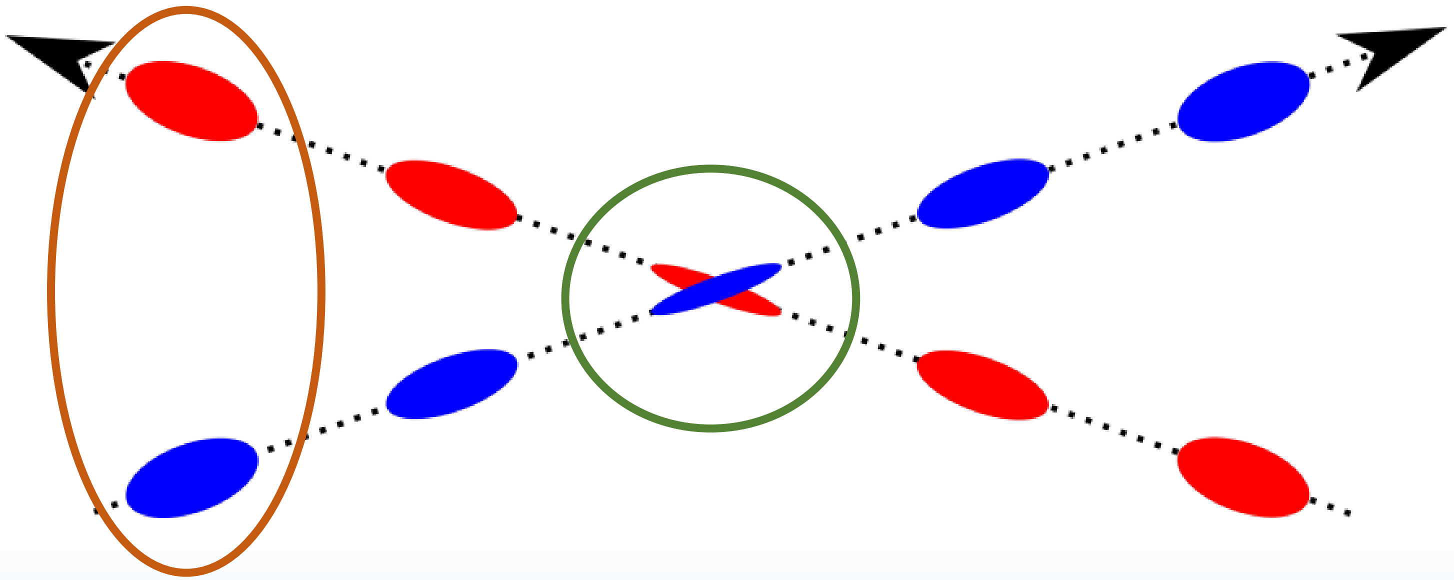
F. Soubelet et al: "Rigid waist shift: A new method for local coupling corrections in the LHC interaction regions"

# 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***

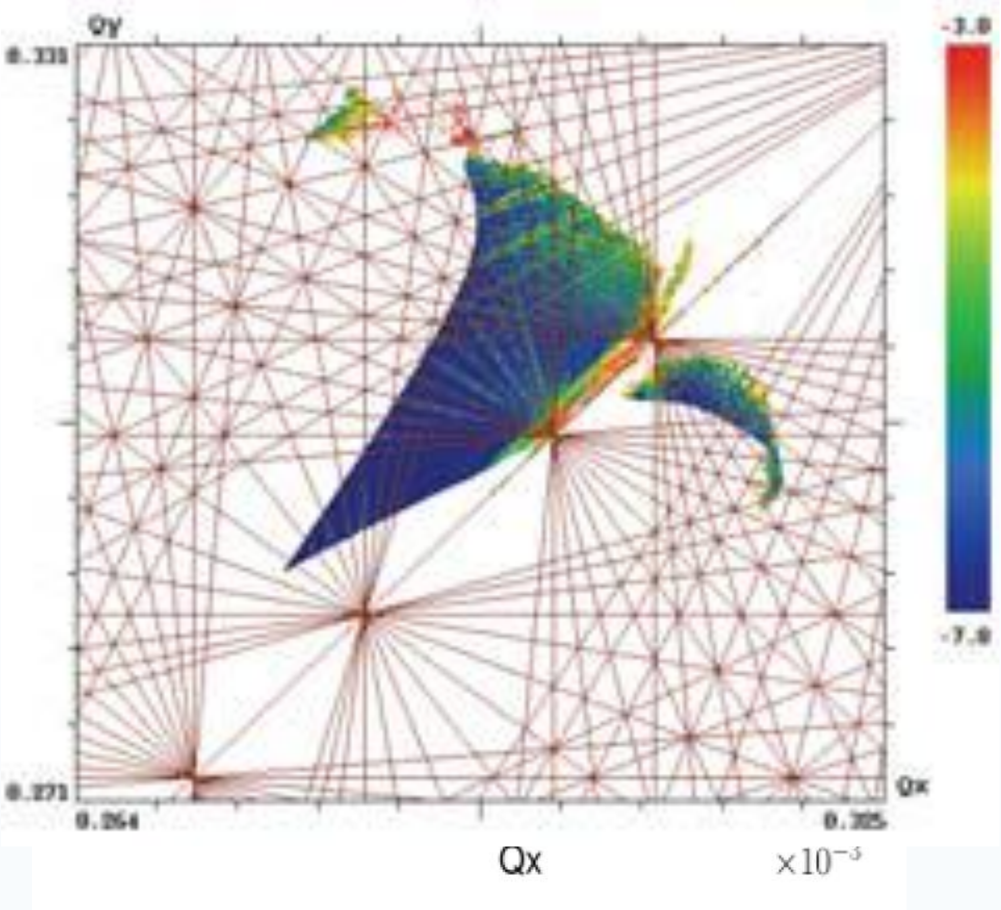
→ ***Tune spread!***



# LHC – Beam-beam

- The contribution of the ***Head On*** to the tune spread is much larger than the ***Long Range***.
- ***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!***

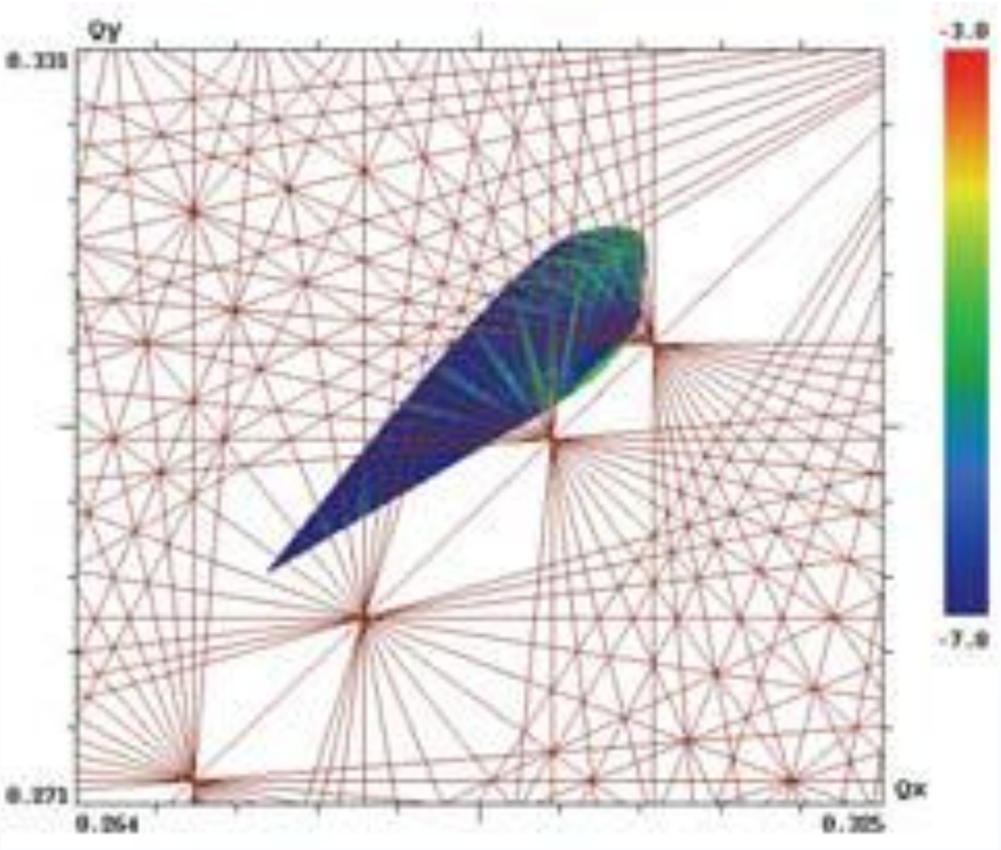



S. Fartoukh et al., PRSTAB, 2015

# 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!)




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)
  - 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!***