The CERN Accelerator School

CERN

# Designing a synchrotron - A real life example

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**CERN Accelerator School**
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# Purpose of the Lectures

- Review several **aspects** of **beam dynamics** (mostly) presented in the introductory CAS lectures, applied to the **design** and **operation** of a **real synchrotron**
  - ☐ Choice of basic parameters
    - Energy, bending field and circumference
  - ☐ Optics design
    - Cell optics, insertions, transition energy
  - ☐ Collective effects
    - Instabilities, Space-charge
  - ☐ Electron/Positron beam dynamics
    - Equilibrium beam properties, energy loss/turn, damping time

# Choosing a Synchrotron

- Our choice is the CERN **Super Proton Synchrotron** (SPS)
- From its design and operation, it has shown enormous **versatility** used for several purposes and serving various applications
  - ☐ High energy **synchrotron** serving **fixed target** experiments (West Area, North Area, CNGS, HIRADMAT)
  - ☐ **Collider** of protons and anti-protons (W and Z bosons discovery in 1983)
  - ☐ Accelerating **electrons** and **positrons** and injecting them to the Large Electron-Positron (**LEP**) Collider
  - ☐ Accelerating **protons** for the Large Hadron Collider (**LHC**)
  - ☐ Accelerating **ions** for **fixed target** physics and the **LHC**
  - ☐ Extracting protons for exciting plasma for a **plasma wakefield acceleration** experiment (AWAKE)

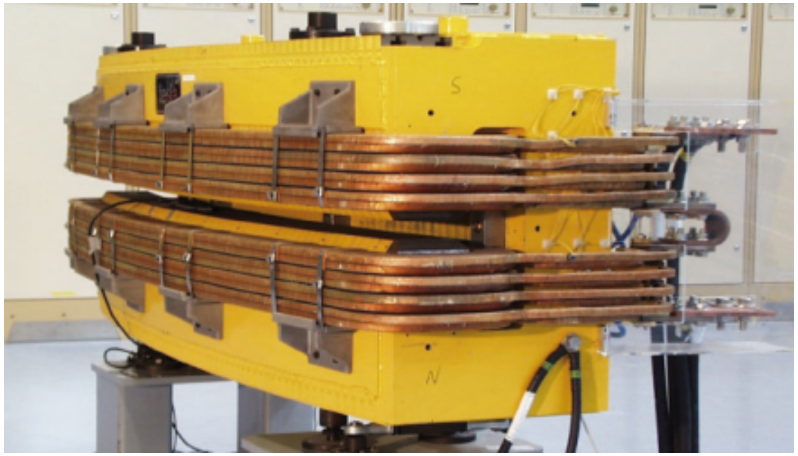
# Basic parameters energy, bending field and circumference

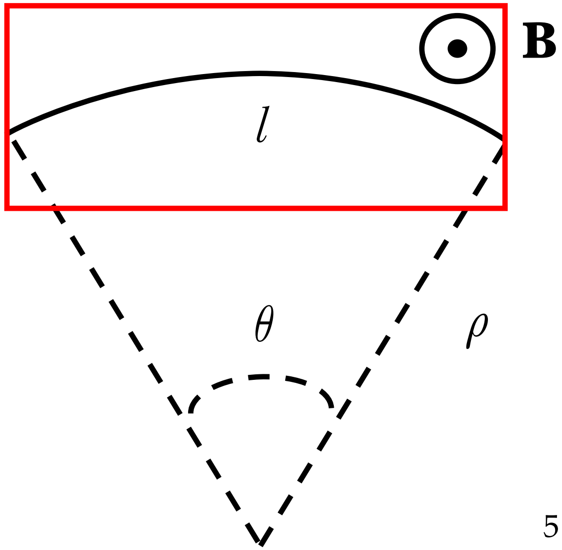
# Energy and bending field

- Consider accelerator ring for particles with energy $E$ with $N$ dipoles of length $L$ or effective length $l$, i.e. measured on beam path
  - **Bending angle** $\theta = \frac{2\pi}{N}$
  - **Bending radius** $\rho = \frac{l}{\theta}$
  - The magnetic rigidity is $B\rho = \frac{\beta E}{q}$
  - The **integrated dipole strength** is

$$Bl = \frac{2\pi}{N}\frac{\beta E}{q}$$

- By imposing a dipole field, the dipole length is fixed and vice versa
- The higher the field, the shorter or smaller number of dipoles can be used





# Circumference

- The **filling factor**, is defined as the ratio of the total length of the bending path, with respect to the circumference

$$k_f = \frac{Nl}{C}$$

- The ring **circumference** becomes

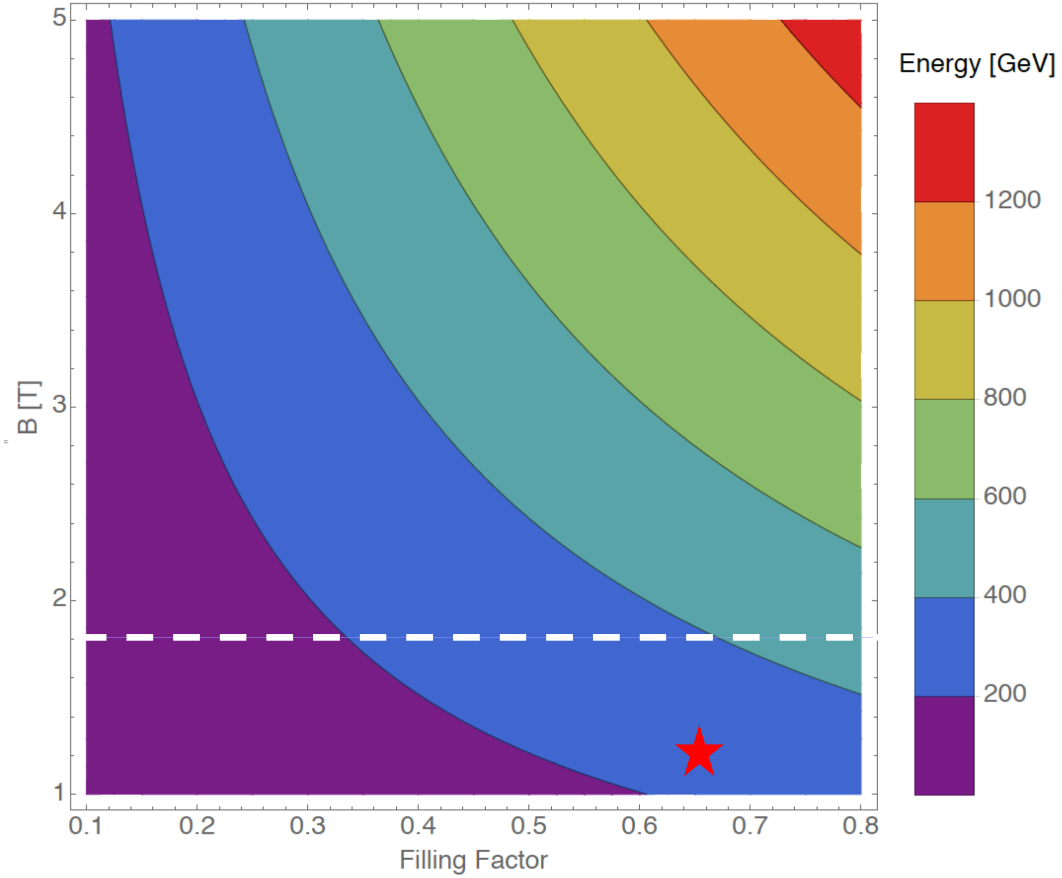
$$C = \frac{2\pi}{k_f B} \frac{\beta E}{q}$$

- The ring **circumference** (**cost**) is driven by the bending **field** choice (**technology**), the **energy** reach (**physics** case, applications) and the design of the **lattice cells** (optics)

# Designing the SPS

- The maximum possible circumference between the CERN I (Meyrin) and CERN II (Prevessin) site was

$$C_{\mathrm{SPS}} = 11C_{\mathrm{PS}} = 2\pi \times 1100\ \mathrm{m} \approx 6912\ \mathrm{m}$$



- Combined function magnets with **1.2 T** field (PS-like) would give an energy of no more then ~**260 GeV** for a highly packed lattice

# Designing the SPS

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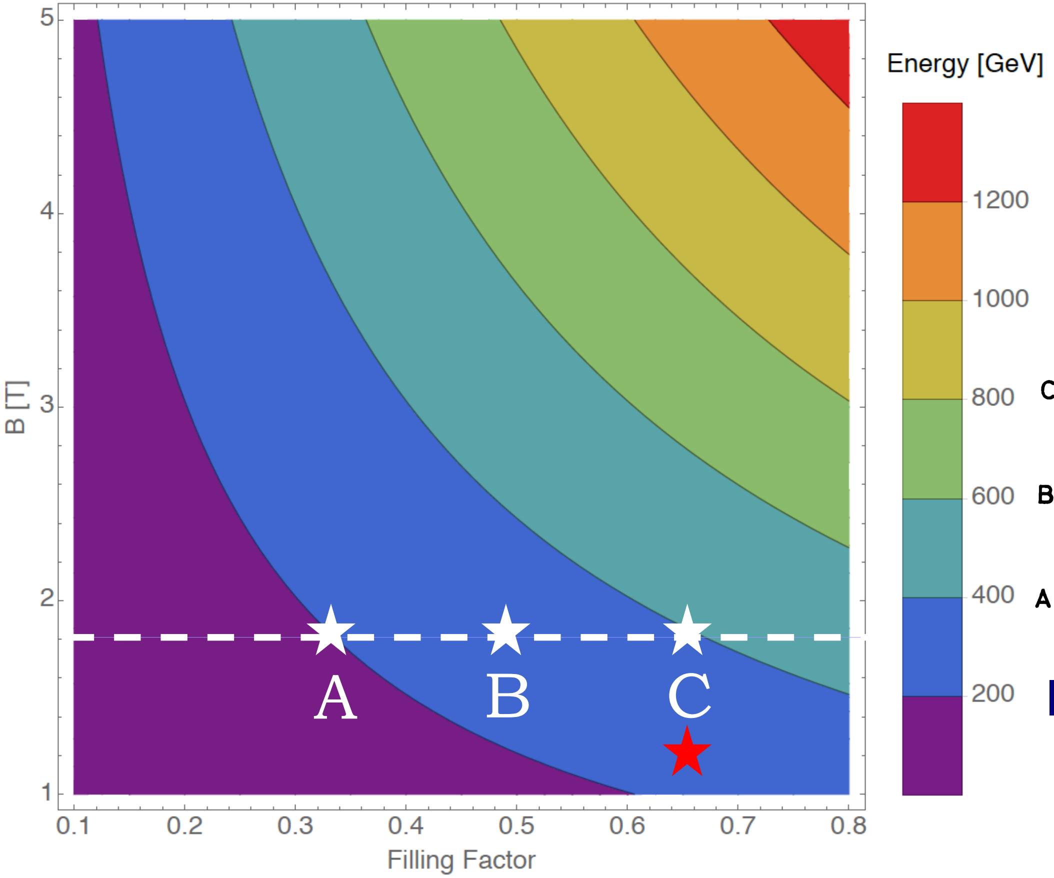
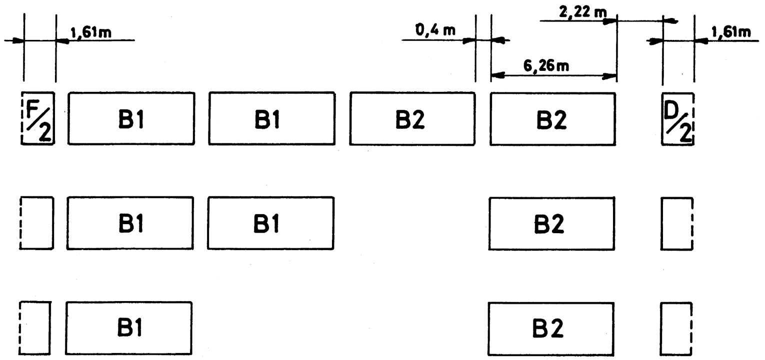


| Stage | Energy (GeV) | Magnets per semi-period* |
|---|---|---|
| A | 200 | 2 |
| B | 300 | 3 |
| C | 400 | 4 |



- Staged approach with **1.8 T dipoles** could reach from 200 to 400 GeV

The 300 GeV Program, CERN/1050, 14/01/1972

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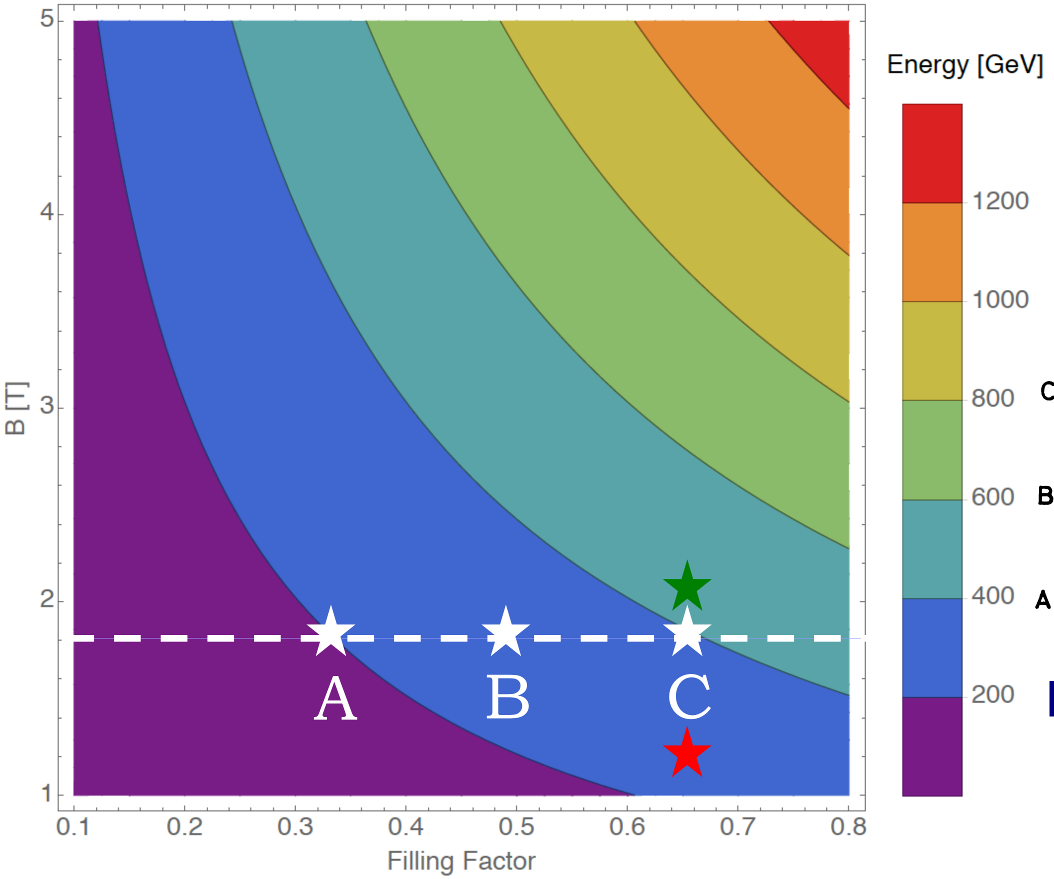

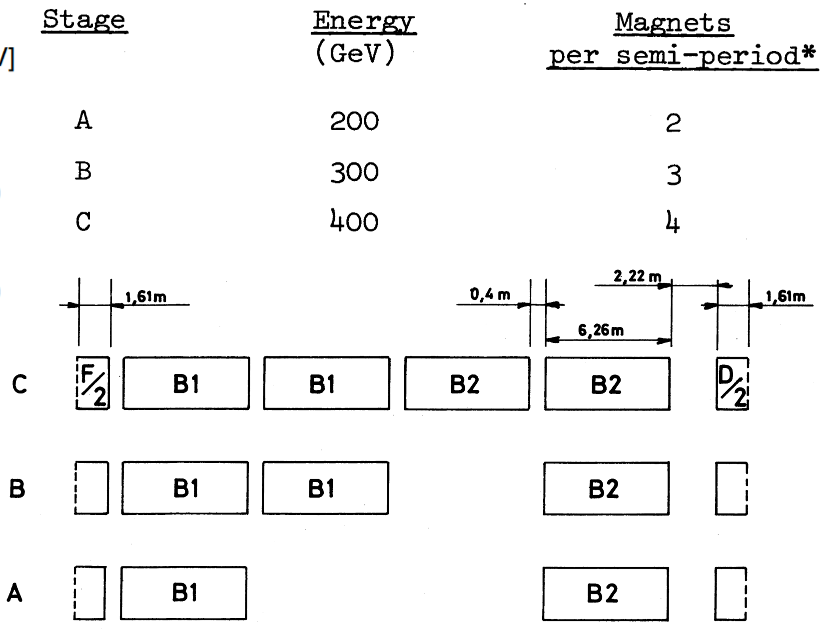

| Stage | Energy (GeV) | Magnets per semi-period* |
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- SPS dipoles have been pushed to beyond **2 T** to reach **450 GeV**

The 300 GeV Program, CERN/1050, 14/01/1972

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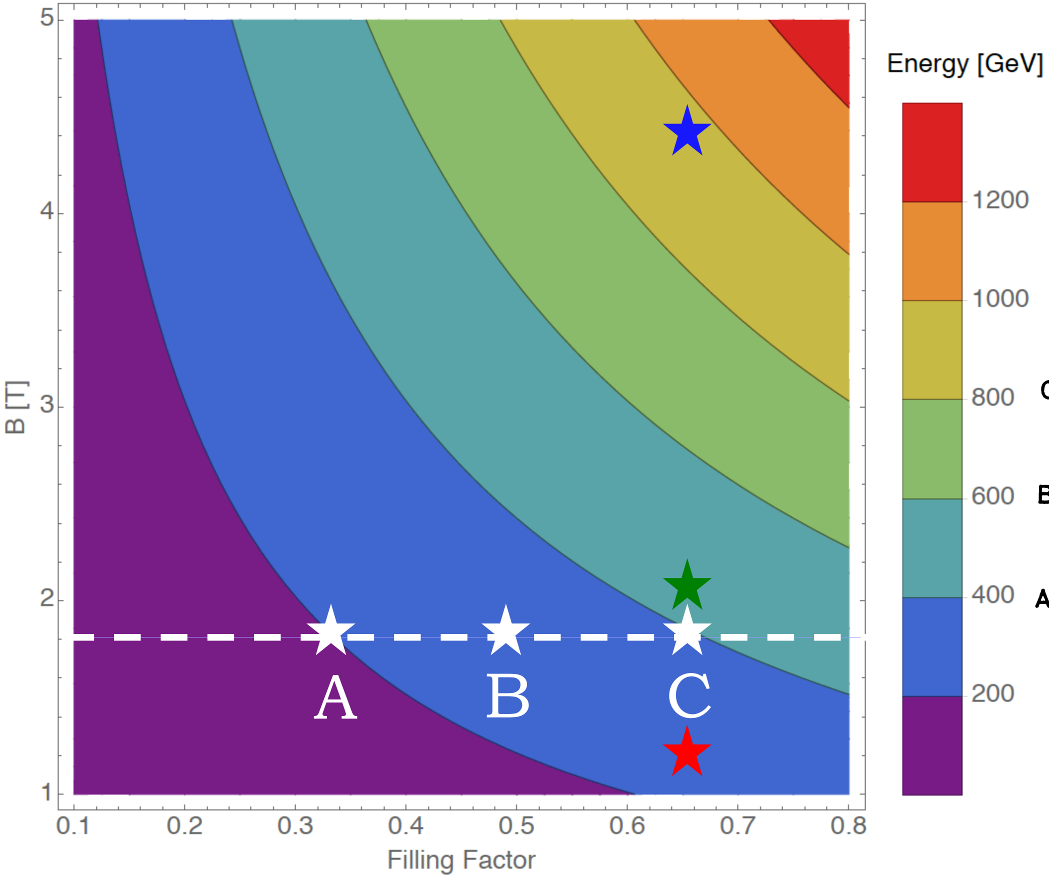

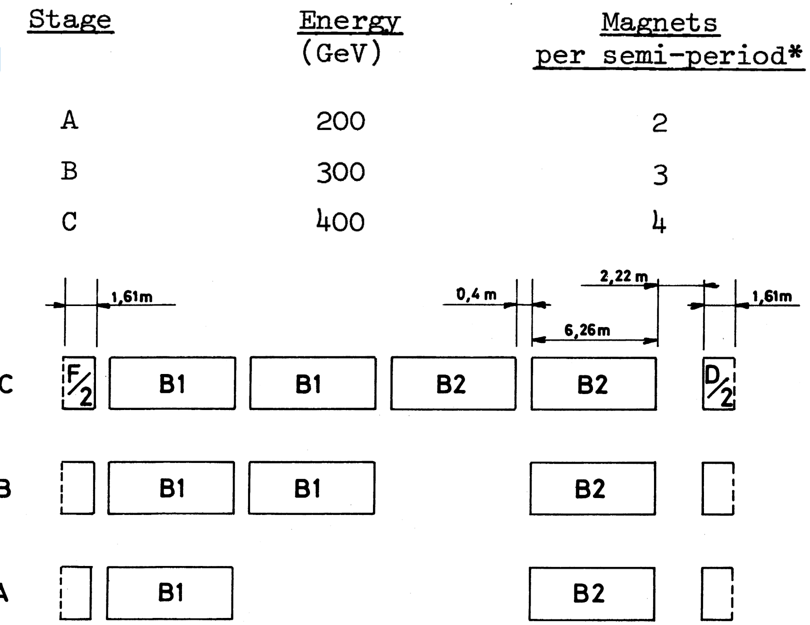

| Stage | Energy (GeV) | Magnets per semi-period* |
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- SPS dipoles have been pushed to beyond **2 T** to reach **450 GeV**

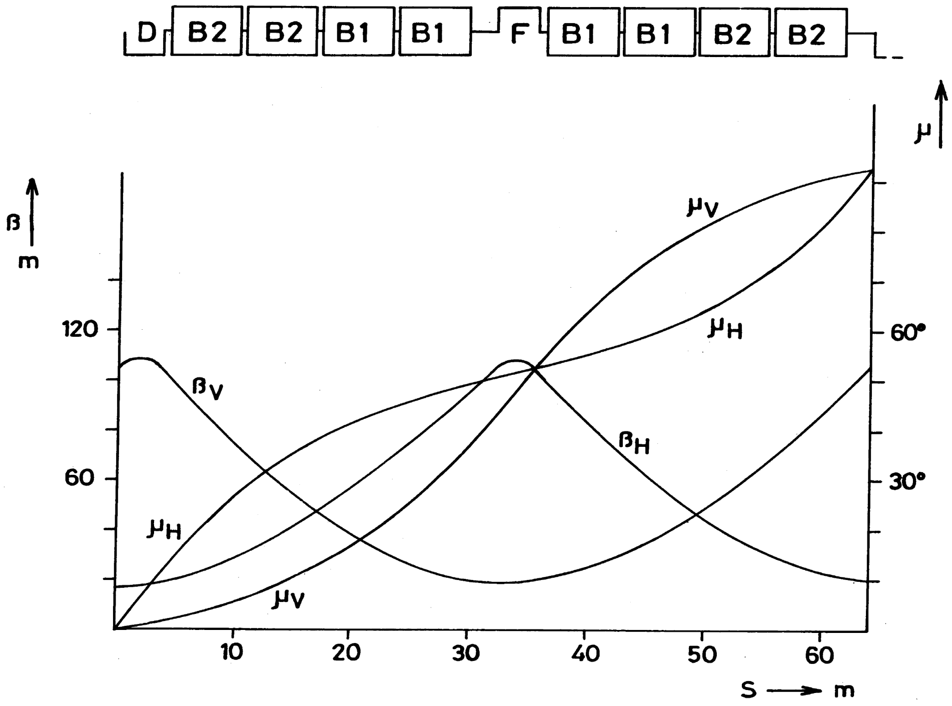
- **Super-conducting** option could raise the energy to **1 TeV**

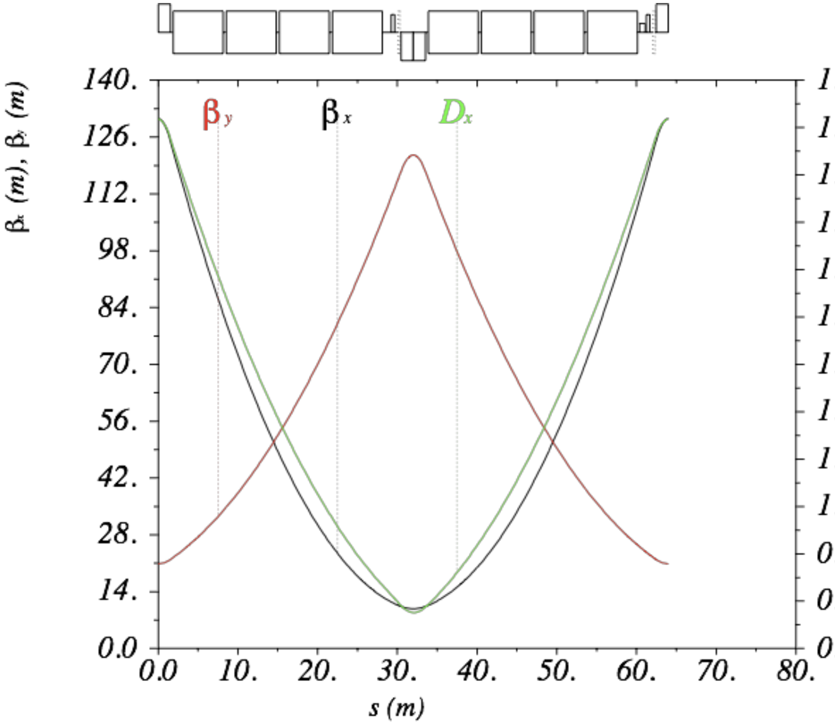
# Optics design

# Basic cell

- **FODO cell** of around **65 m** long with phase advances of **π/2**
- **Beta** function **maxima** slightly above **100 m**

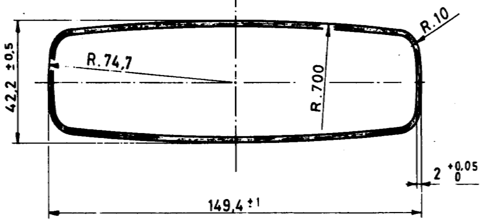
The 300 GeV Program, CERN/1050, 14/01/1972



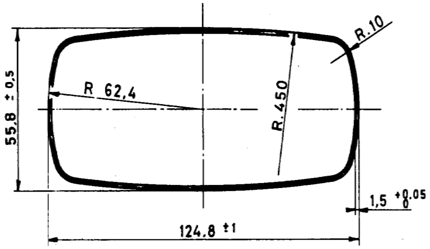


# Magnet aperture

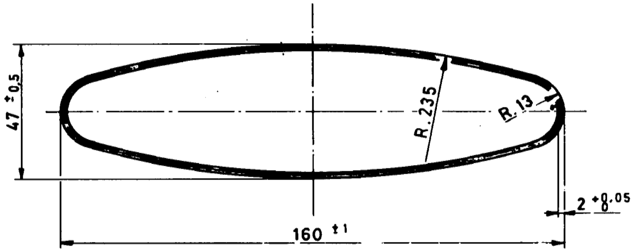
- Magnet apertures follow beta function and dispersion evolution



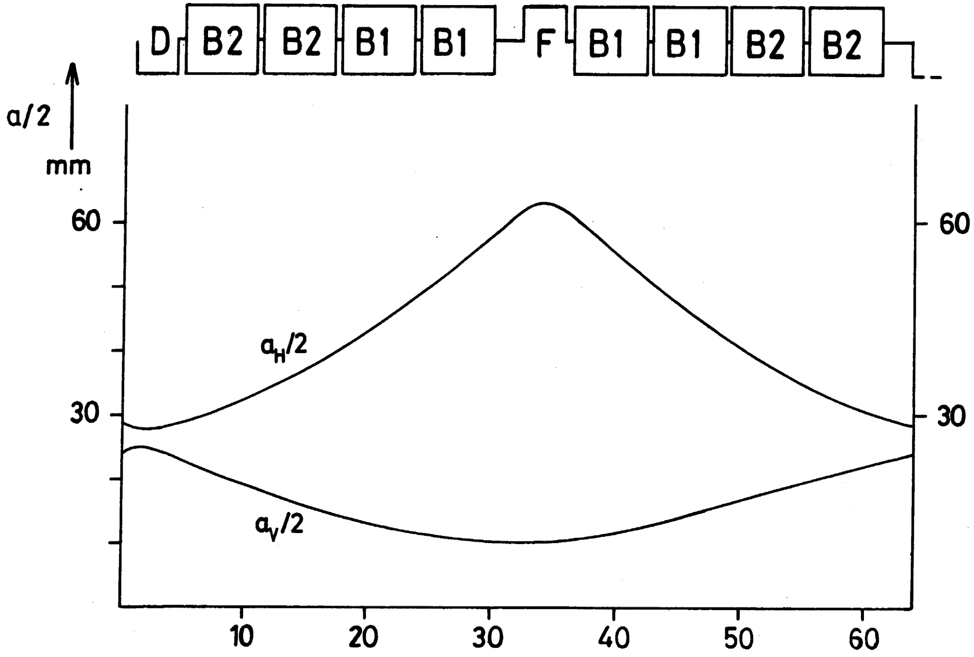
**Dipole B1**

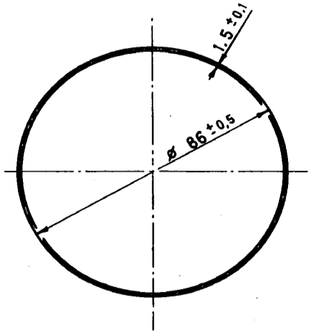


**Dipole B2**



**Quadrupole F**





**Quadrupole D**

The 300 GeV Program, CERN/1050, 14/01/1972

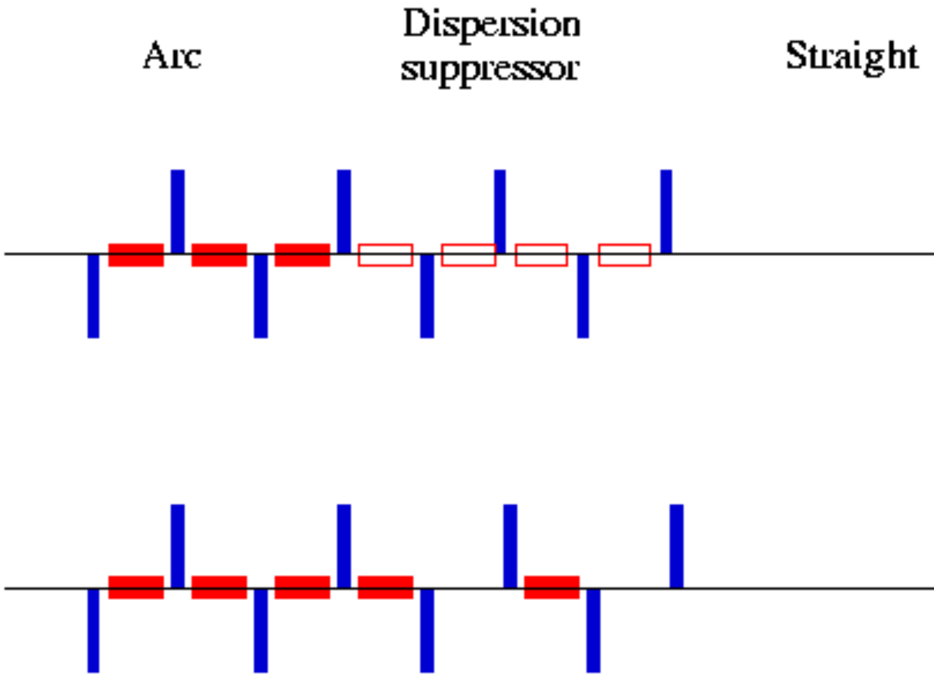
# Dispersion suppression

- **Dispersion** has to be **eliminated** in **special areas** like injection, extraction or interaction points (orbit independent to momentum spread)
- Use **dispersion suppressors**
- Methods for suppressing dispersion
  - **Eliminate two dipoles** in a FODO cell (missing dipole)
  - Set last dipoles with **different bending angles**

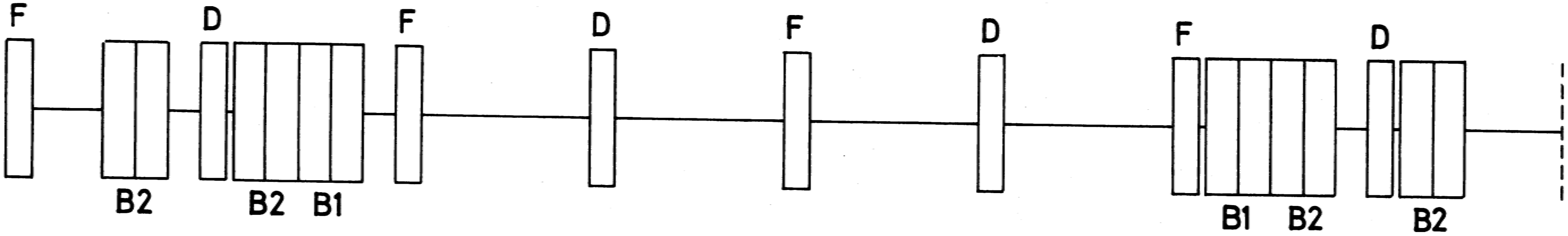
$$\theta_1 = \theta\left(1 - \frac{1}{4\sin^2\mu_{\mathrm{HFODO}}}\right)$$

$$\theta_2 = \frac{\theta}{4\sin^2\mu_{\mathrm{HFODO}}}$$

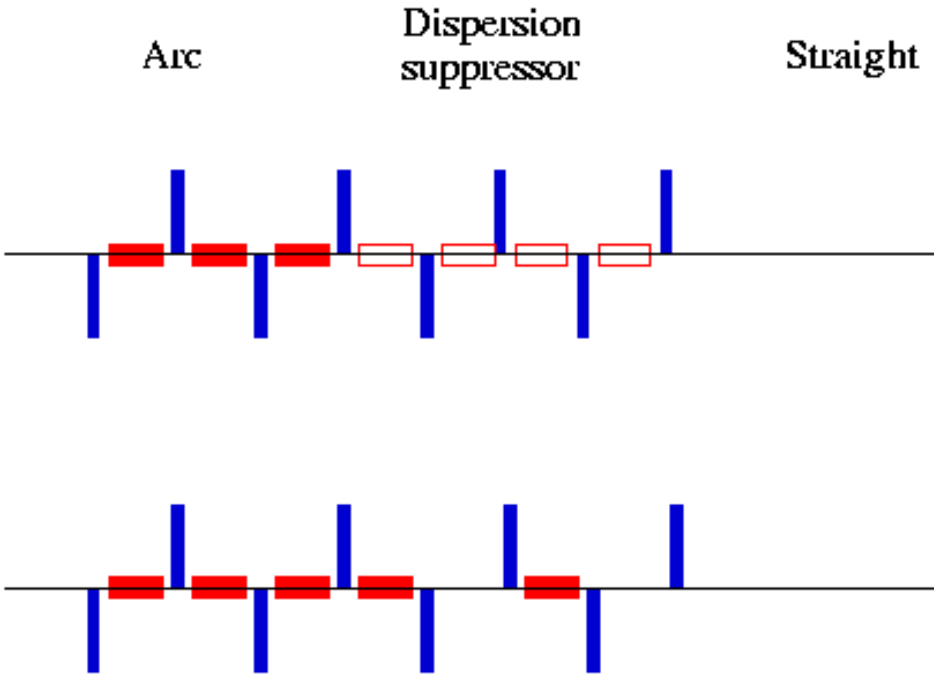
  - For equal bending angle dipoles, the FODO phase advance should be equal to **π/2**



# Dispersion suppression in the SPS

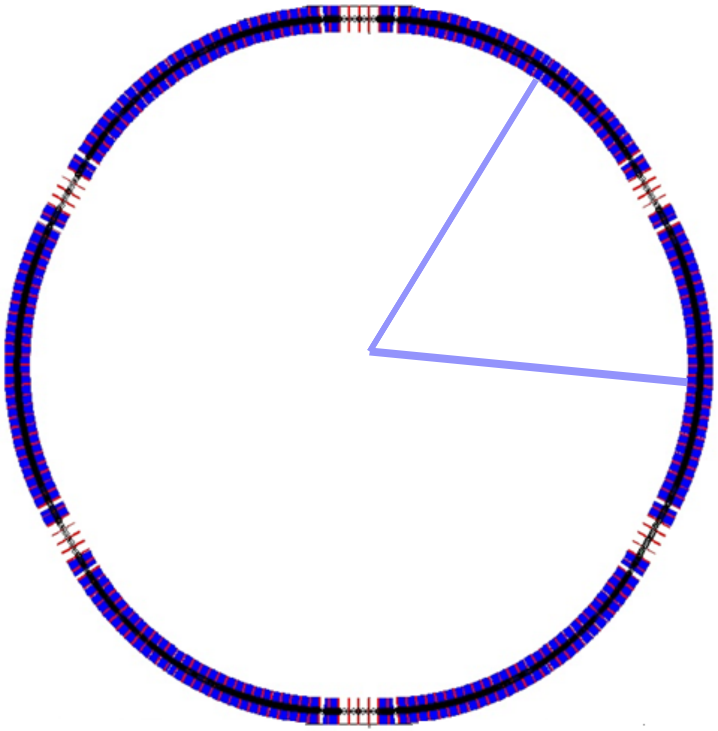


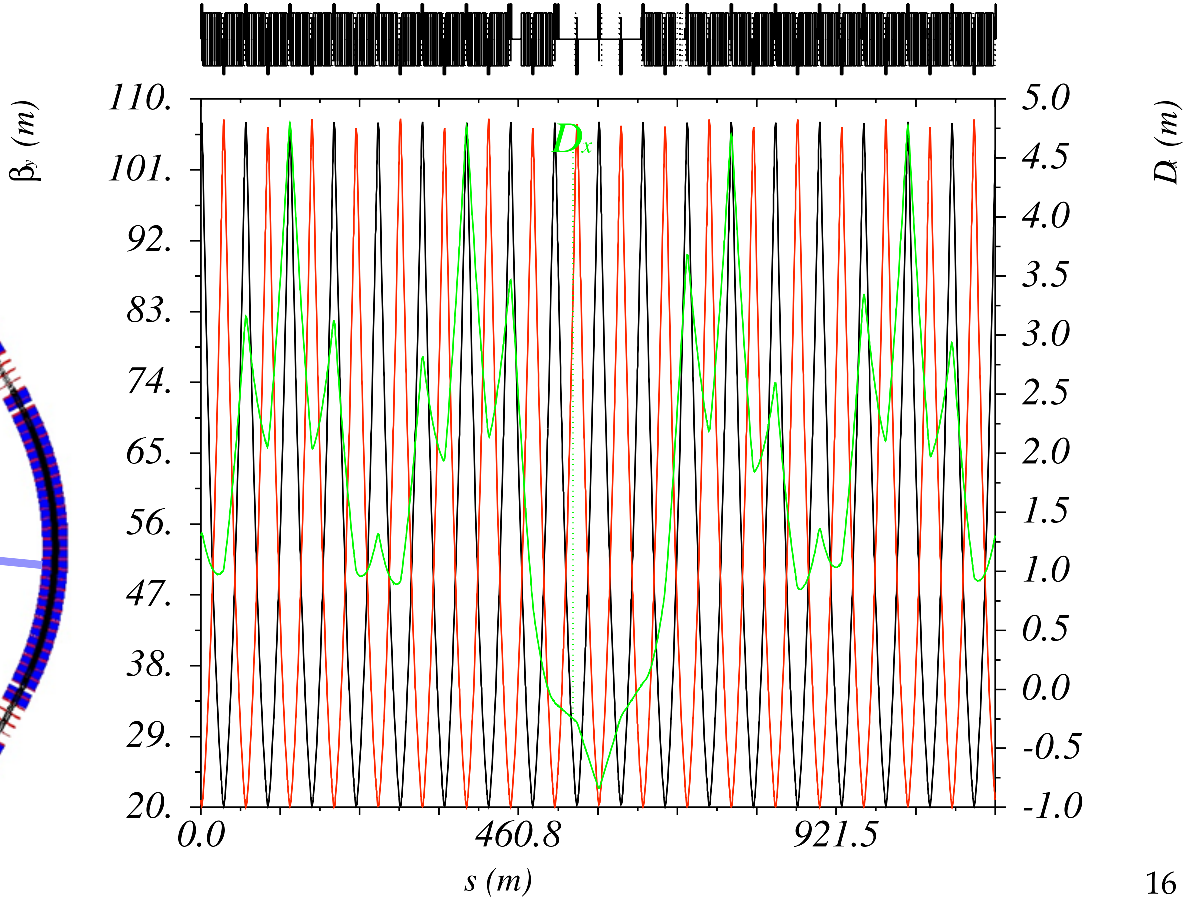
- In the SPS, all dipoles are powered in series, i.e. dispersion suppressor cells looks like a missing dipole, but they are not!
- Dispersion suppression is achieved by tuning the phase advance of the arc, to a multiple of **2 π**
- Dispersion oscillates through the arc and vanishes at the edges



# Ring optics

- Ring is composed by 6 identical sectors (“sextants”) with 16 cells in the arc and 2 cells in the straight section
- The cell phase advance of π/2 brings the tunes to 26-27 (**Q26**)



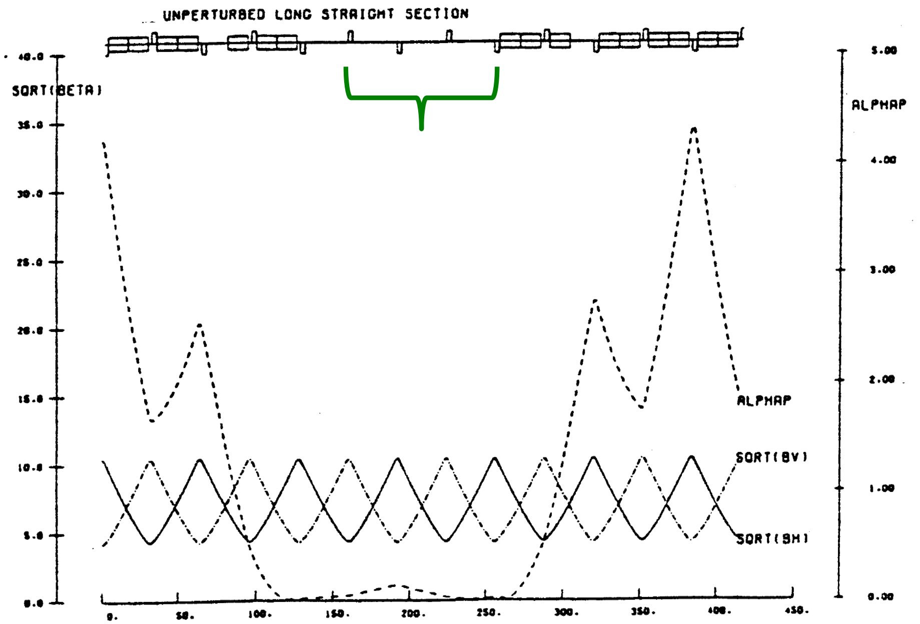


# Sp$\bar{p}$S collider insertion optics

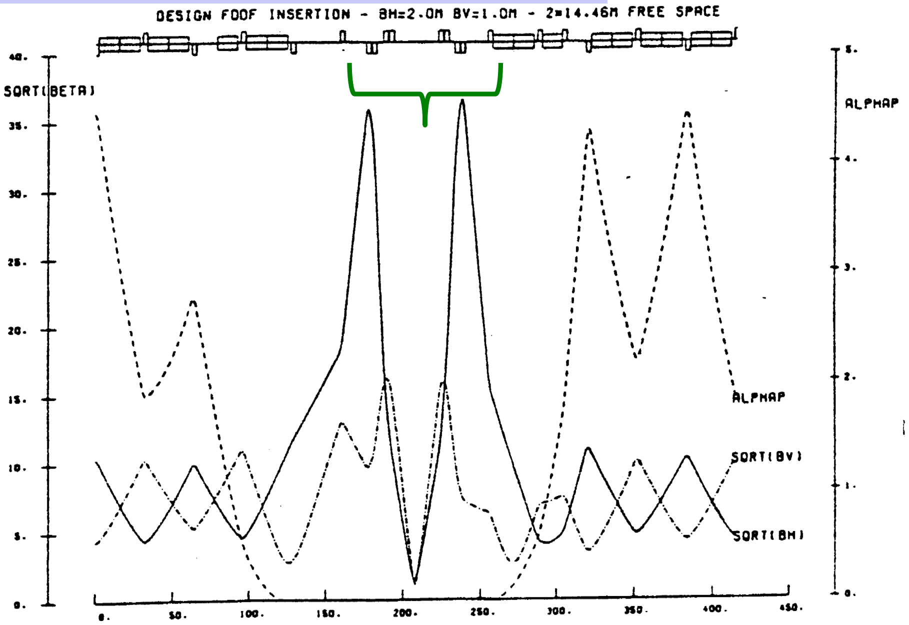
- Replace two straight section quadrupoles with **2 doublets** (4 quadrupoles)
- Equip adjacent left/right quadrupoles with individual bipolar power convertors
- Achieved **low β*** of 1.3/0.65 m

P. Faugeras et al., CERN-SPS-80/11, CERN-SPS-83/29

UNPERTURBED LONG STRAIGHT SECTION



DESIGN FODF INSERTION - BH=2.0M BV=1.0M - 2=14.46M FREE SPACE



# Magnet system

# SPS dipole magnets

- 744 dipoles (MBAs and MBBs) with 6.26 m length and different gaps

| | |
|---|---|
| Number of magnets | 744 |
| Year of 1st operation | 1976 |
| Maximum field on beam axis [T] | 2.02 |
| Physical vertical aperture [mm] MBA/MBB | 38.5/51.5 |
| Yoke assembly [Solid,Laminated,Welded,Glued] | L,W |
| Coil technology [Copper,Aluminium,Glass-epoxy,Mica,Other] | C,G |
| Maximum voltage to ground [V] (worst case 2 spare converters) | 4150 |
| Operation | Cycled |
| Maximum cooling water velocity [m/s] | 9 |
| Operational temperature [C°] | 40 |

D. Tommasini CERN/TE-Note-2010-003

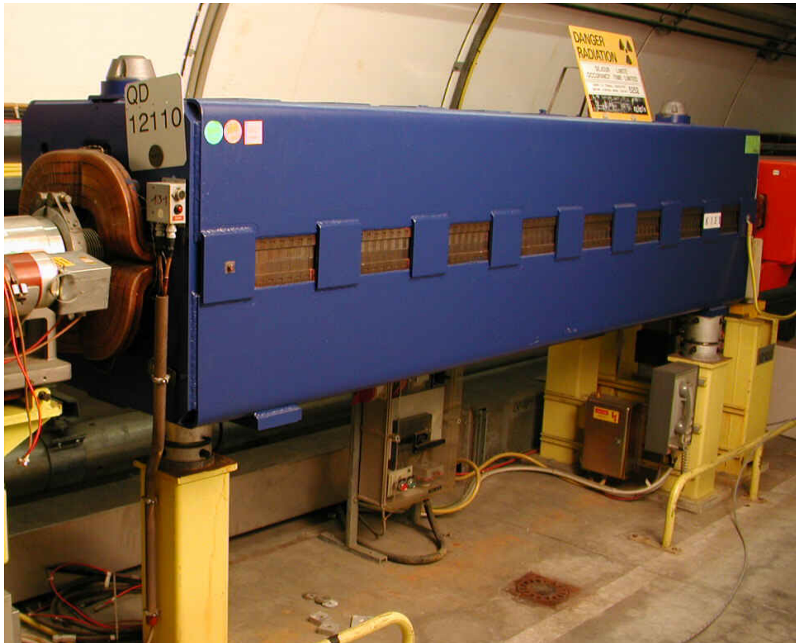
- Maximum field of **2.02 T**, for reaching 450 GeV
- High mechanical stress on coils

# SPS quadrupoles

- 216 quadrupoles (102 QF, 100 QD, 6 QFA and 8 QDA)
- Maximum gradient of 22 T/m, corresponding to a pole-tip field of around **1 T**
- Normal operation necessitates almost the full gradient @ 450 GeV

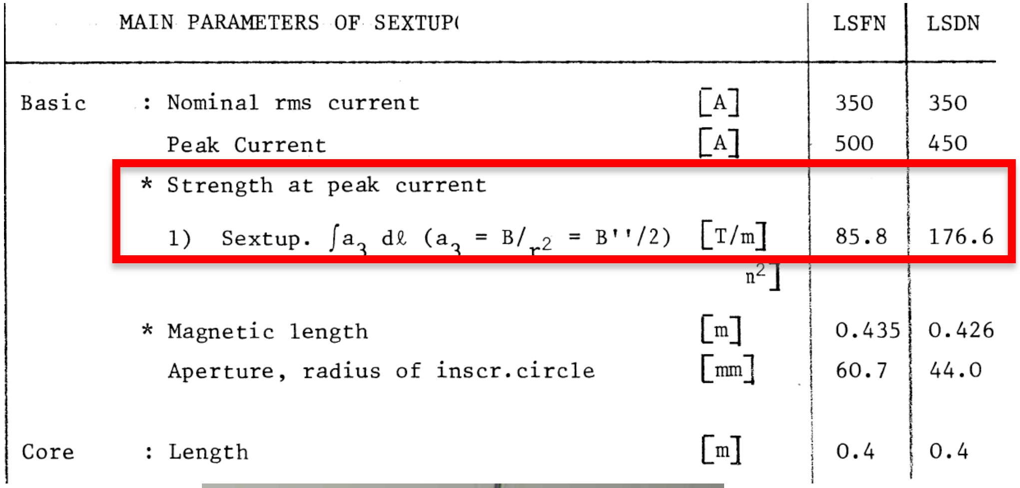
**D. Tommasini CERN/TE-Note-2010-003**

| | |
|---|---:|
| Number of magnets | 216 |
| Year of 1st operation | 1976 |
| Maximum gradient [T/m] | 22 |
| Physical vertical aperture [mm] | 88 |
| Yoke assembly [Solid,Laminated,Welded,Glued] | L,W |
| Coil technology [Copper,Aluminium,Glass-epoxy,Mica,Other] | C,G |
| Maximum voltage to ground [V] | 3450 |
| Operation | Cycled |
| Maximum cooling water velocity [m/s] | 3.6 |
| Operational temperature [C°] | 40 |



# SPS sextupoles

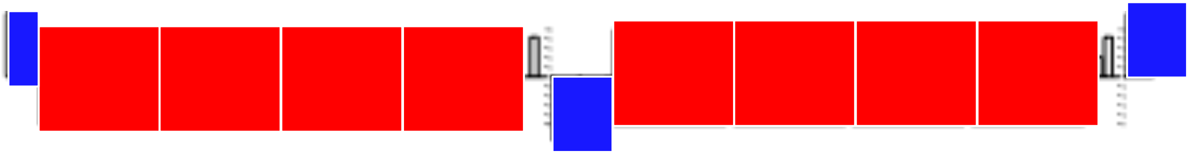
M. Giesch, CERN/SPS/80-3/AMS, 1980



| MAIN PARAMETERS OF SEXTUP( | | | LSFN | LSDN |
|---|---|---|---|---|
| Basic | : Nominal rms current | [A] | 350 | 350 |
| | Peak Current | [A] | 500 | 450 |
| | * Strength at peak current | | | |
| | 1) Sextup. $\int a_3 \, d\ell$ ($a_3 = B/r^2 = B''/2$) | $[T/m^2]$ | 85.8 | 176.6 |
| | * Magnetic length | [m] | 0.435 | 0.426 |
| | Aperture, radius of inscr.circle | [mm] | 60.7 | 44.0 |
| Core | : Length | [m] | 0.4 | 0.4 |

- 54 “focusing” and 54 “defocusing” 0.4 m long sextupoles in two (three for F) families (24 and 30), with different apertures
- Maximum pole-tip field of around **0.8 T**
- Around 80% and 60% in operational conditions

# The SPS arc cell



# Transition energy and slippage factor

# Transition energy

- Transition energy (or momentum compaction factor) is defined as

$$\frac{1}{\gamma_t^2} = \alpha_p = \frac{1}{C}\oint \frac{D(s)}{\rho(s)} ds$$

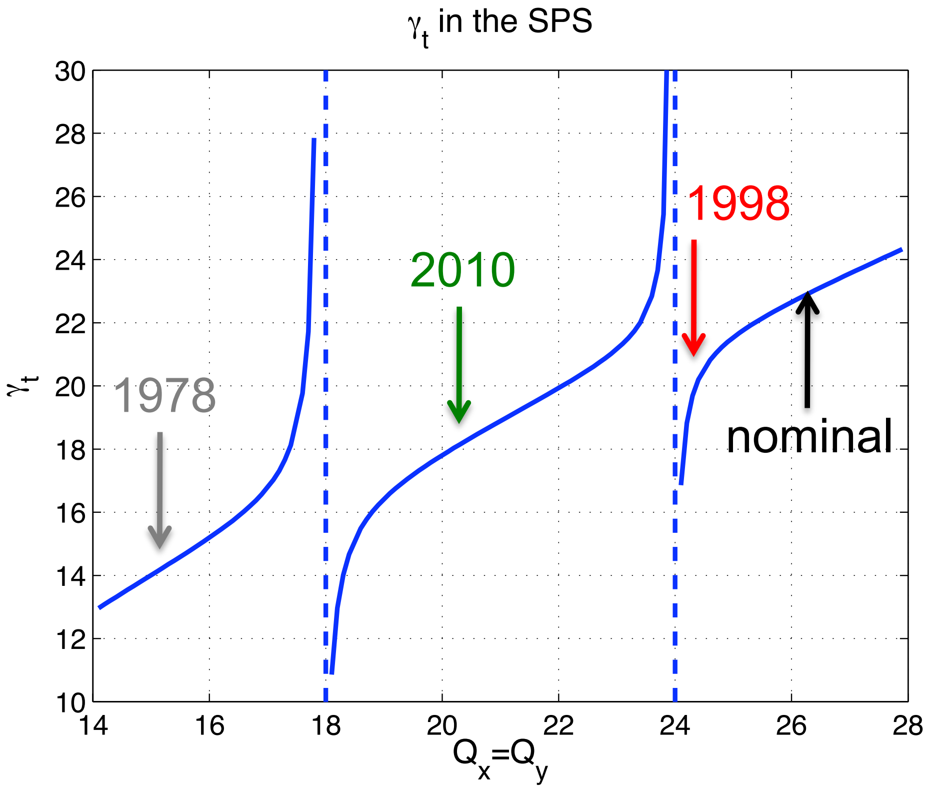
- The higher the dispersion oscillation in the bends, the lower the transition energy

↓

**Quadrupoles**

- Note also that, for FODO cells (SPS lattice), $\gamma_t \approx Q_x$, meaning that lowering the transition energy implies **lowering** the **horizontal tune**
- High intensity beams can be injected in the SPS above transition avoiding losses and operational complexity of transition jump scheme

# Transition energy vs SPS working point



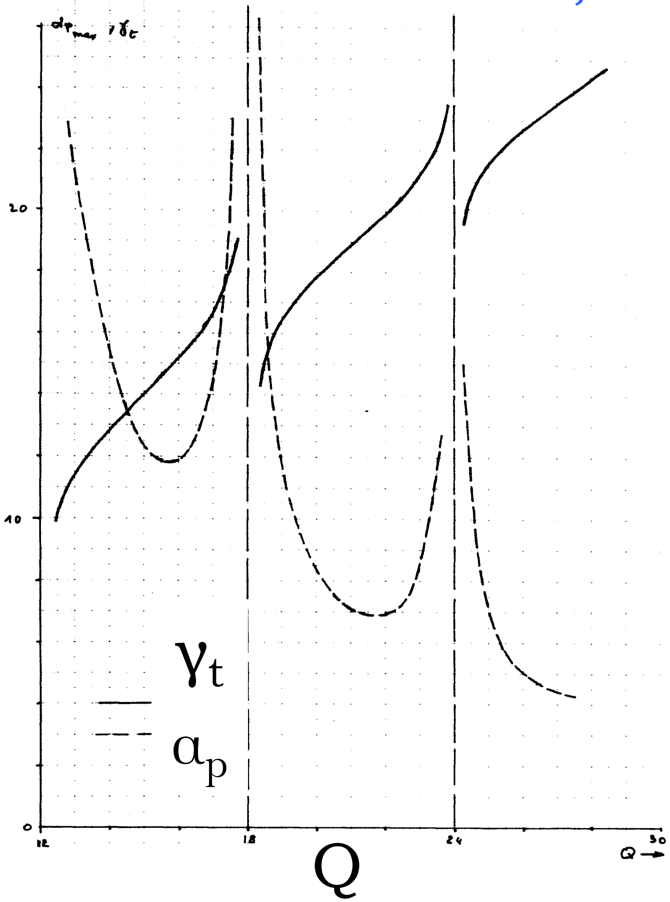
- Resonant oscillation of dispersion function close to the "Resonant integer tunes" (multiples of **super-periodicity 6**) → asymptotic behavior of $\gamma_t$, (difficult for routine operation)
- $\gamma_t$ is a linear function of horizontal tune $Q_x$ elsewhere

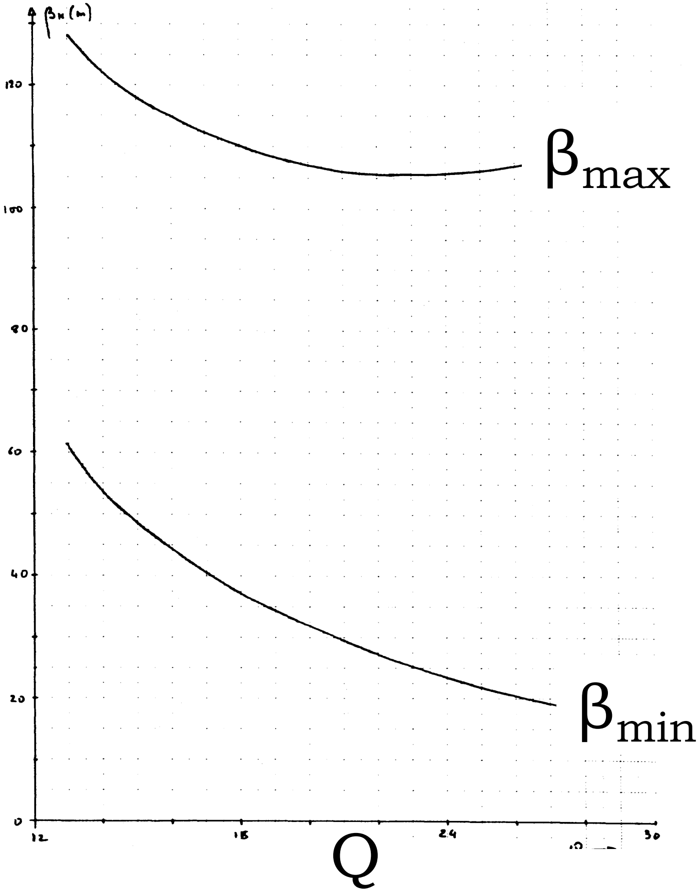
- Nominal SPS working point for LHC proton beams ($\gamma_t$~23)
- D. Boussard et al., SPS improvement note No 147, 1978; Injection above transition as TT10 was not ready for 26 GeV/c ($\gamma_t$~14)
- G. Arduini et al., CERN/SL-Note 98-001, 1998; "Resonant tune" ($\gamma_t$~20)
- Low $\gamma_t$, 2010 - "Resonant arc" with small dispersion in long straight sections ($\gamma_t$~18)

# Avoiding transition energy with Q15

- Injection beam line **TT10** has not been upgraded to 26 GeV in 1978 and limited to **16 GeV**
- **Injection above transition** is possible if SPS integer part of the tune is lowered to 15 ($\gamma_t$~14)

D. Boussard et al., SPS improvement note No 147, 1978





# Manipulating optics for curing instabilities

# Instability thresholds and slippage factor

**YP et al, IPAC 2013**

- **Transverse** instabilities
  - **TMCI** at injection - single bunch instability in vertical plane
    - Threshold at $1.6\text{x}10^{11}$p/b ($\varepsilon_l$=0.35eVs, τ=3.8ns) with low vertical chromaticity

$$\boxed{N_{\text{th}} \propto \frac{\varepsilon_l}{\beta_y}\eta}$$

  - **E-cloud** vertical instability for 25ns beam
    - Threshold higher than $1.2\text{x}10^{11}$p/b

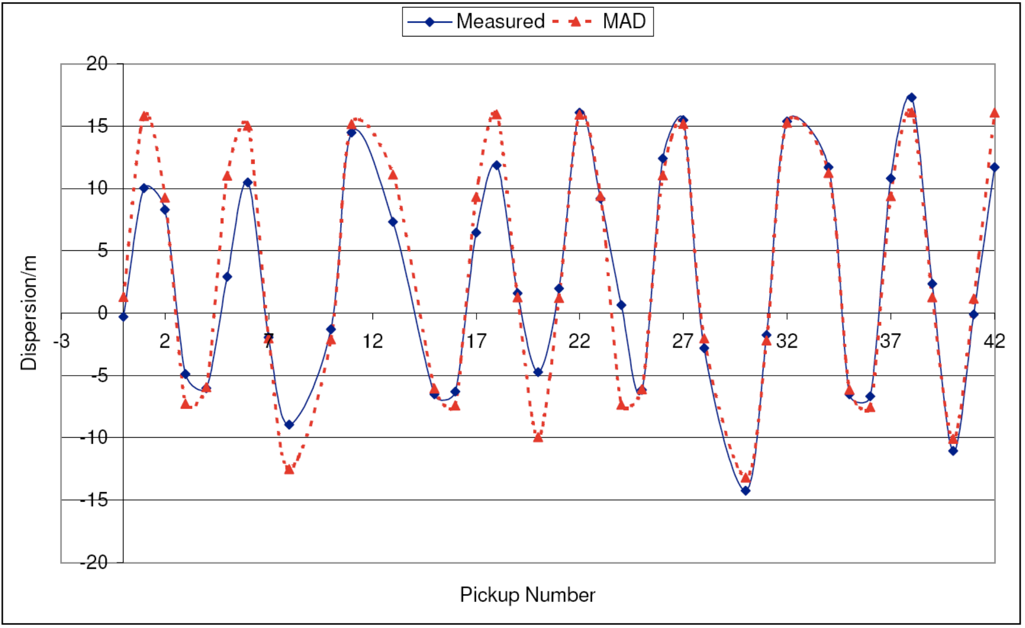
$$\boxed{N_{\text{th}} \propto Q_s \propto \sqrt{\eta}}$$

- **Longitudinal** instabilities
  - Single bunch and coupled bunch
    - Threshold at $2\text{x}10^{10}$p/b for single harmonic RF (800 MHz cavity use is mandatory)

$$\boxed{N_{th} \propto \epsilon_l^{5/2}\eta}$$

# Resonant tune

- By setting the SPS **integer tune** to a multiple of 6, large dispersion wave can be introduced (dispersion becomes even negative) by overall reducing transition energy
- Successfully establishing cycle in the SPS and measuring dispersion very close to the one of MAD
- 3-fold increase of the slippage factor can be achieved (model)
- “Difficult” beam conditions (especially for injection)
- Need optics were dispersion is suppressed in straight section

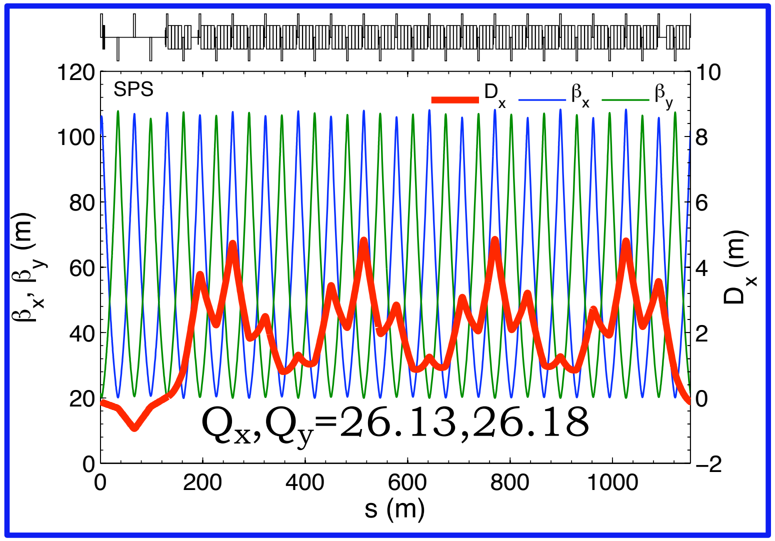


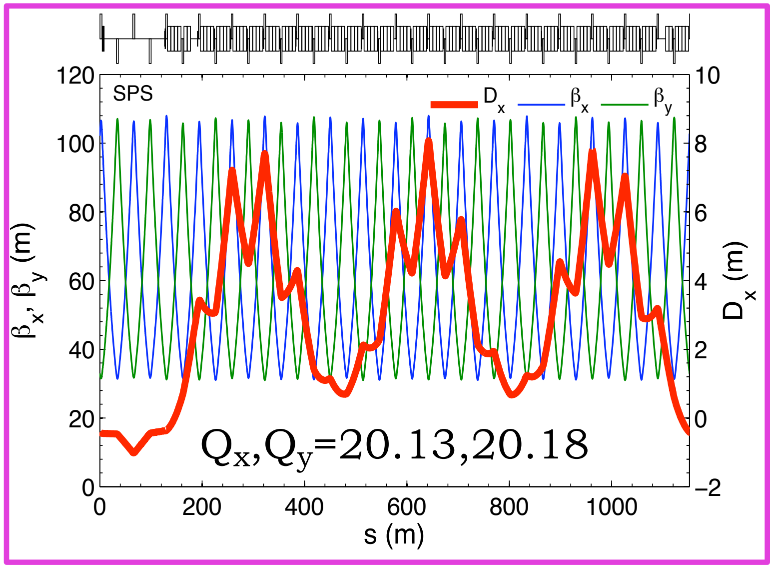
G. Arduini et al., CERN/SL-Note 98-001 (MD), 1998

| $Q_h$ | $Q_v$ | $\gamma_{tr}$ | $\eta\ (10^{-3}$ |
|---|---|---|---|
| 24.18 | 24.22 | 18.54 | 1.61 |
| 24.29 | 24.32 | 19.59 | 1.30 |
| 26.62 | 26.58 | 23.23 | 0.551 |

# Q20 optics

Moving FODO phase advance from 4/16*2π (π/2) to **3/16*2π (3π/8)**

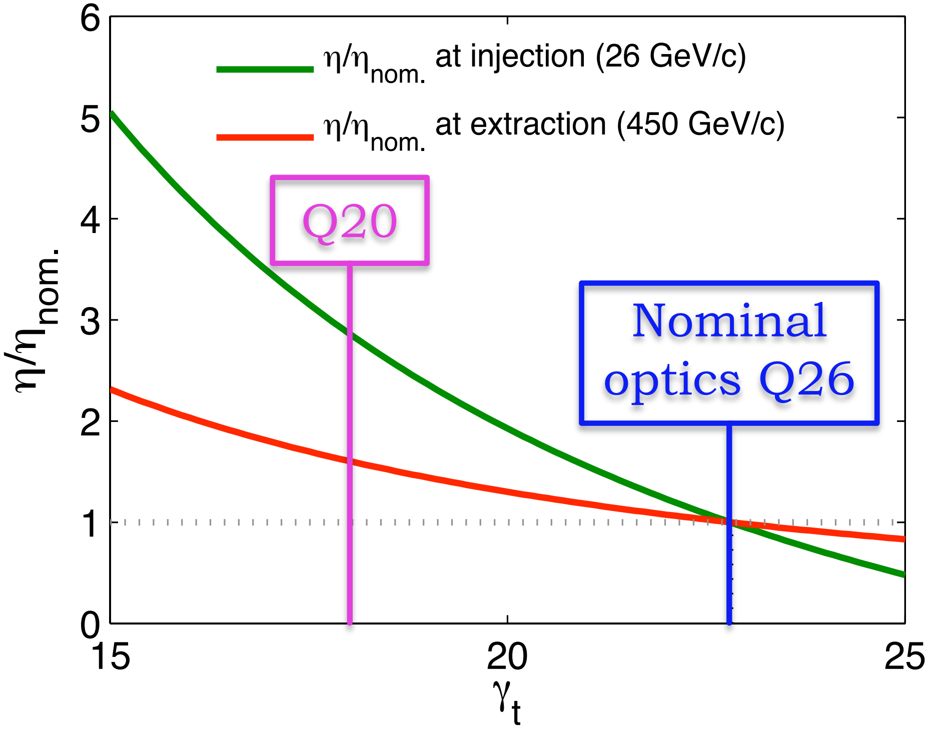




$$\eta = \frac{1}{\gamma_t^2} - \frac{1}{\gamma^2}$$

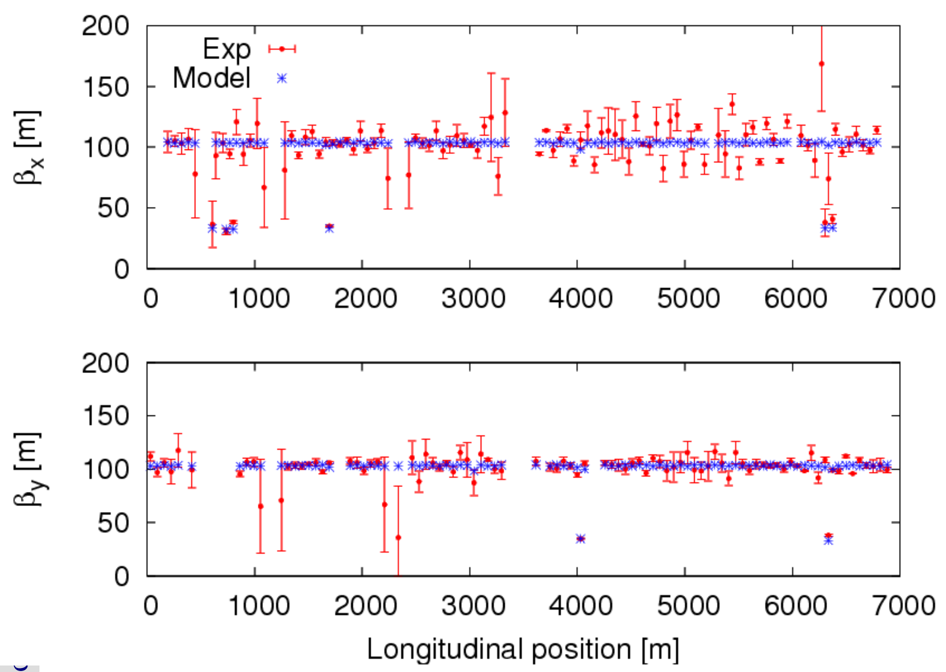
$$\gamma_{t_{FODO}} \approx Q_x$$

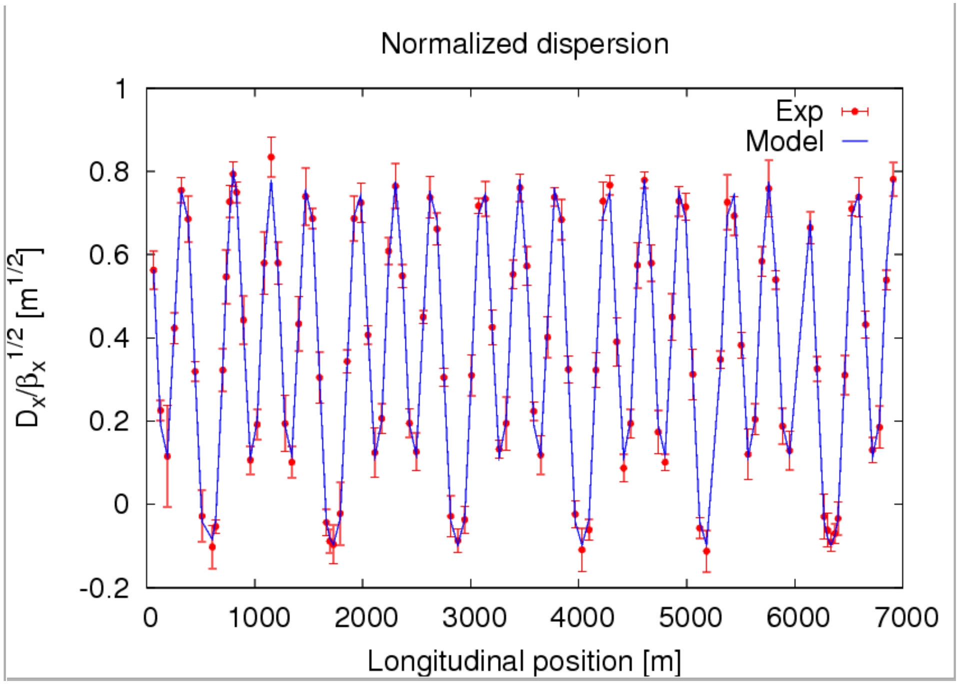
Slippage factor increased by a factor of **2.8** at **injection** and **1.6** at **flat top**



Slip factor relative to nominal SPS optics

# Q20 Optics measurements

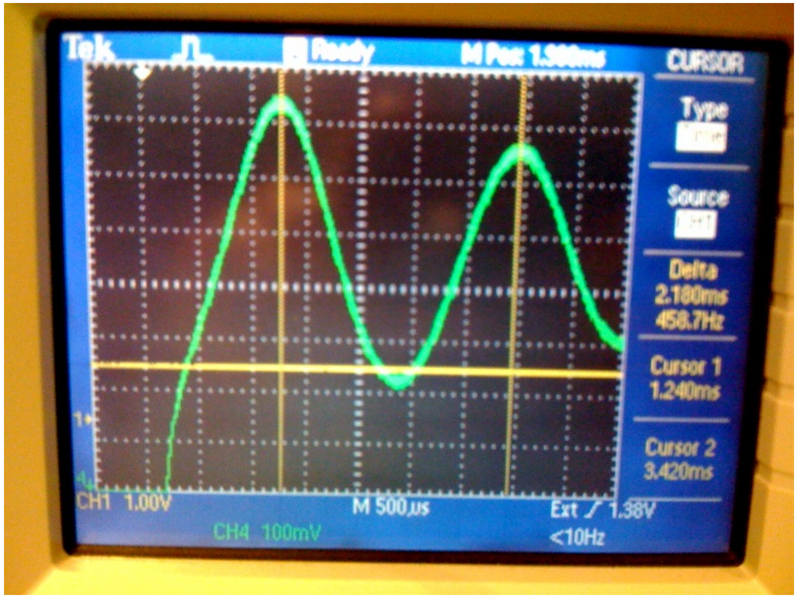




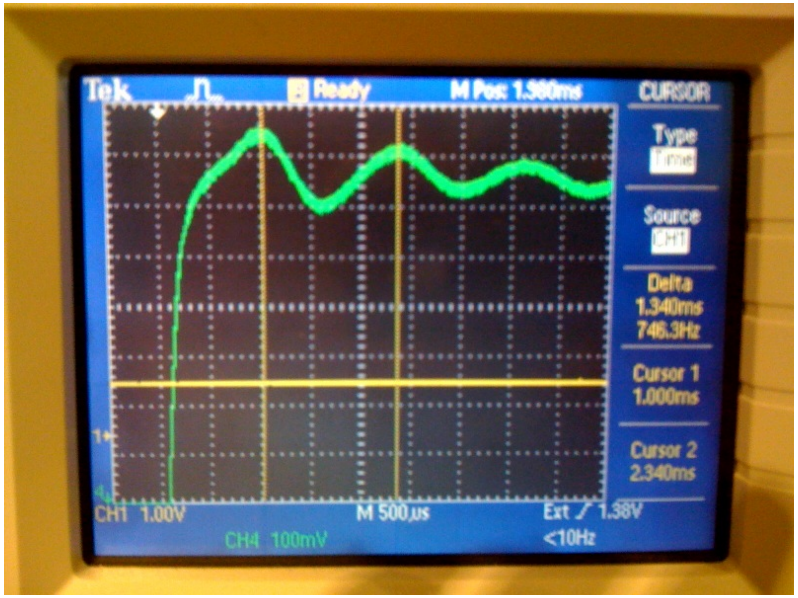
- **Measurement** of the optics functions of the new lattice
  - **Beta beating** around 20% in horizontal and 10% in vertical plane
  - Normalized **dispersion** in striking agreement with the model

# Synchrotron frequency

- Measured synchrotron frequency from “quadrupole” oscillations at injection
  - Same RF-voltage for both optics
- Ratio of Synchrotron frequencies ~ **1.63** corresponds to an **increase** in slippage factor $\eta$ by **factor 2.65** (MADX prediction: 2.86)



Q26: Fs=458/2=229Hz,
Qs=0.0106/2=0.0053

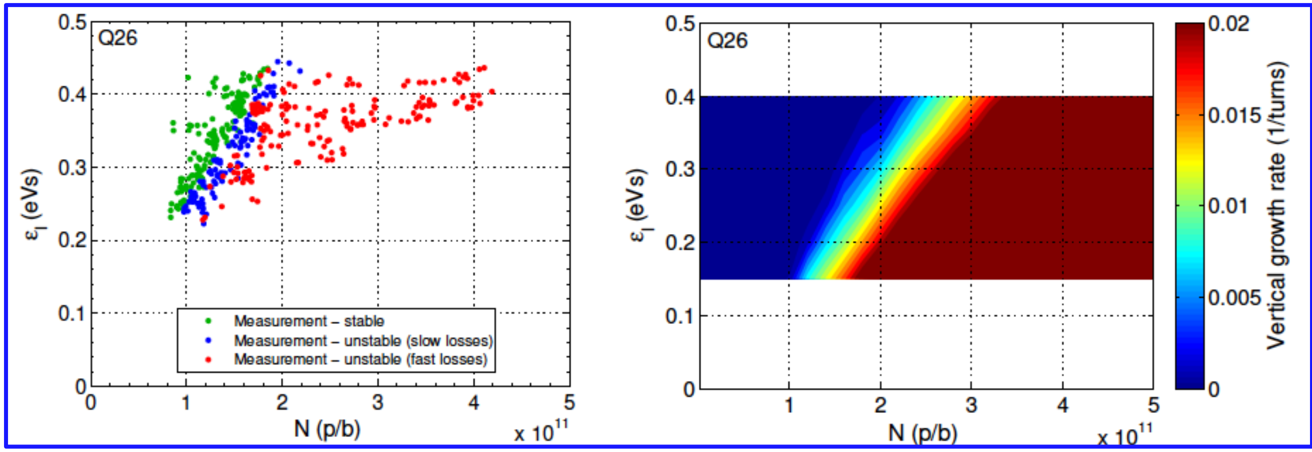


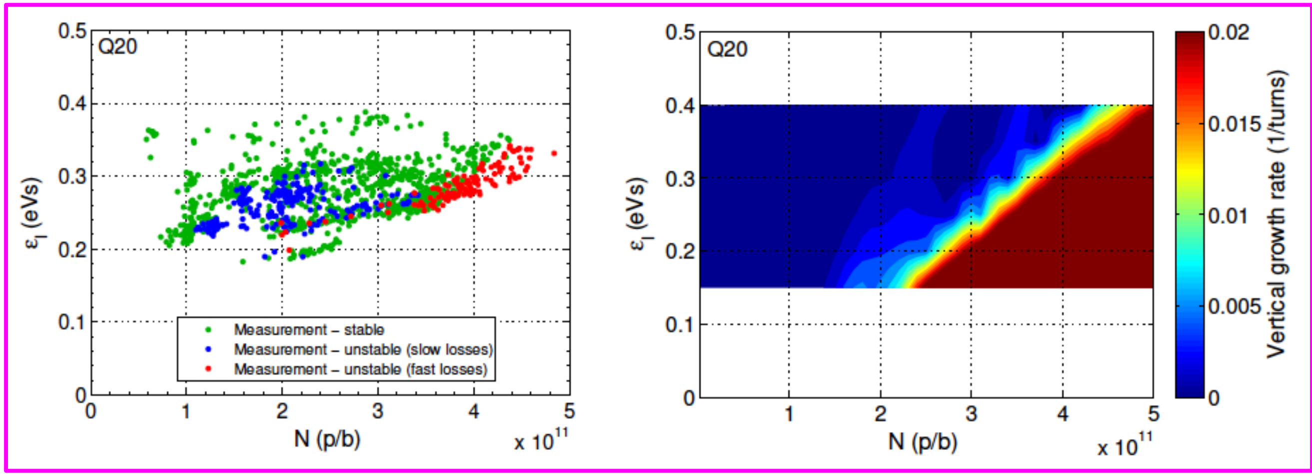
Q20: Fs=746/2=373Hz,
Qs=0.0172/2=0.0086

# TMCI threshold

- In **nominal optics**, measured/simulated threshold at **$1.6\times10^{11}$p/b** for low chromaticity
  - High-chromaticity helps increasing threshold, but also losses along the cycle become excessive
- Measured/simulated threshold in **Q20** > **$4\times10^{11}$p/b!!!**

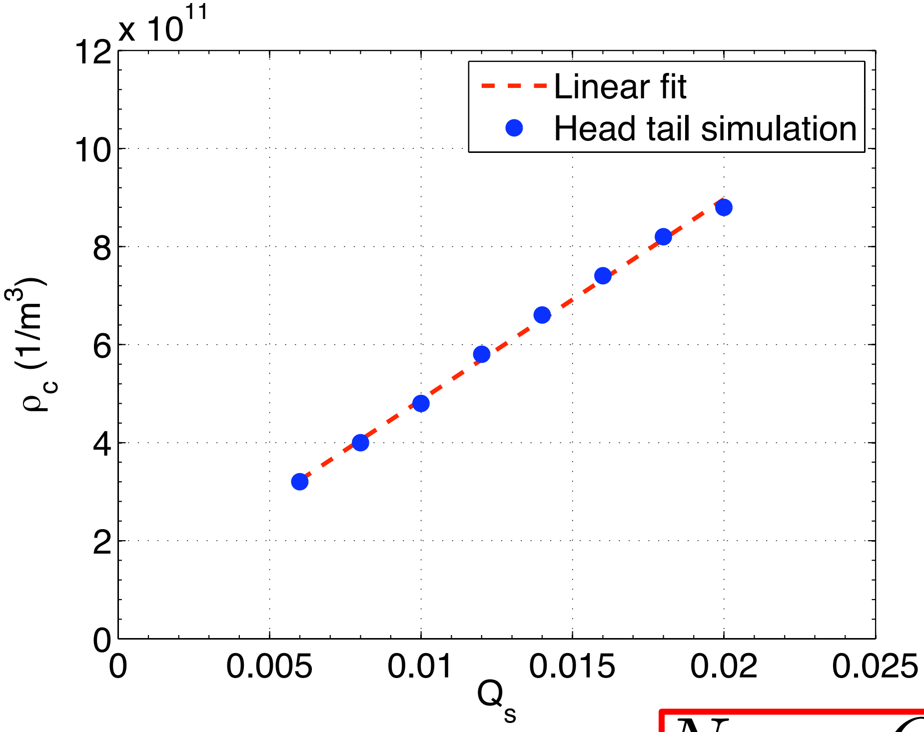
$$N_{\text{th}} \propto \frac{\varepsilon_l}{\beta_y}\eta$$

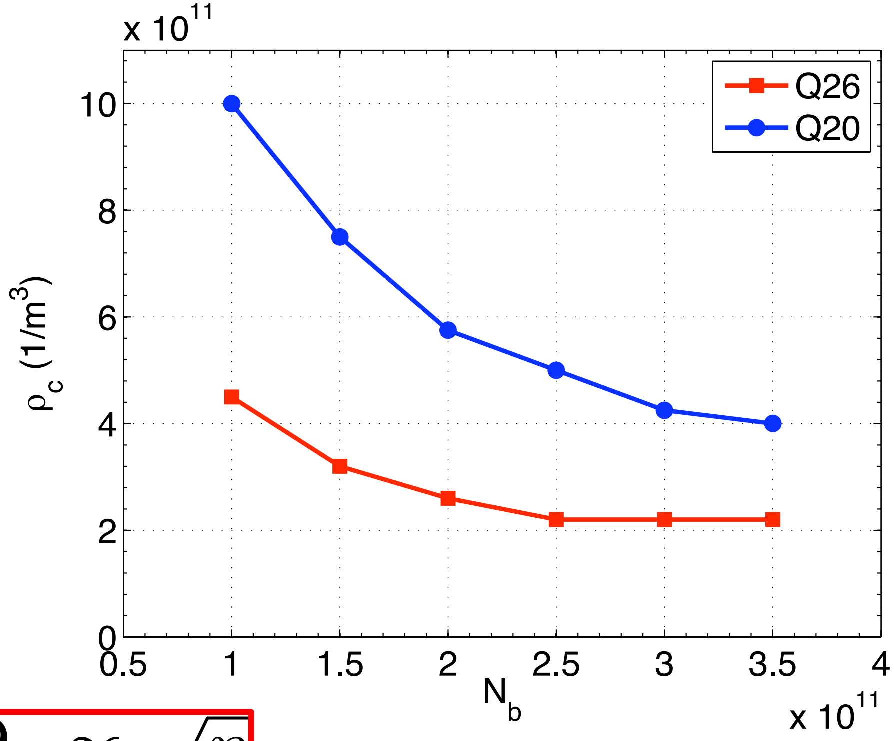




H. Bartosik et al,
IPAC 2014

# E-cloud instability





$$\boxed{N_{\mathrm{th}} \propto Q_s \propto \sqrt{\eta}}$$

- ❑ Simulations with HEADTAIL code
  - ❑ Injection energy, uniform cloud distribution, located in dipole regions
- ❑ Linear scaling with Synchrotron tune demonstrated
  - ❑ Clearly higher thresholds predicted for **Q20**

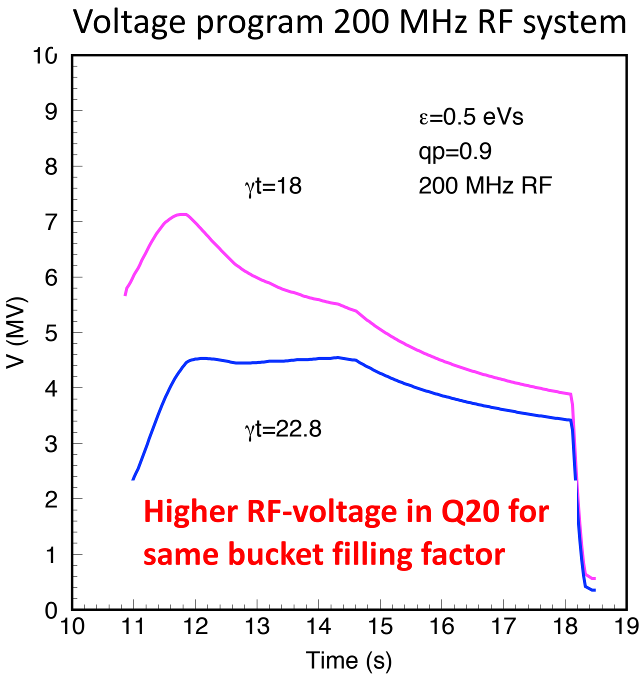
**More margin with Q20 if e-cloud becomes issue for high intensity**

**H. Bartosik et al, IPAC2011**

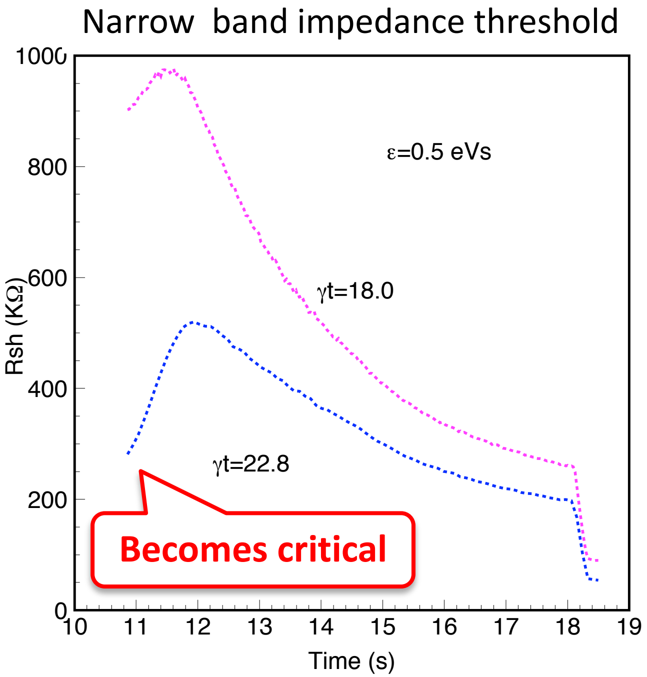
# Longitudinal impedance threshold

$$\boxed{N_{th} \propto \epsilon_l^{5/2}\eta}$$

**E. Shaposhnikova**



Higher RF-voltage in Q20 for same bucket filling factor



Becomes critical

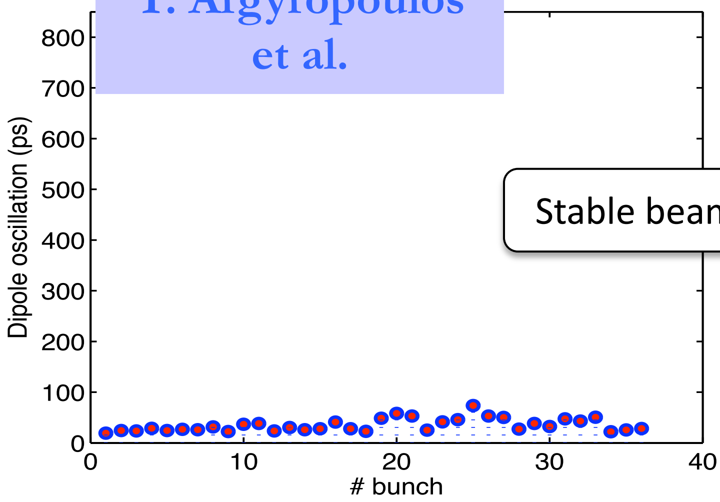
- ❑ Impedance threshold has minimum at flat top
  - ❑ Controlled longitudinal emittance blow-up during ramp for **Q26**
  - ❑ Less (or no) longitudinal emittance blow-up needed in **Q20**
- ❑ Instability limit at flat bottom
  - ❑ Critical with **Q26** when pushing intensity
  - ❑ Big margin with **Q20** (factor of 3)

The CERN Accelerator School

# Longitudinal beam stability

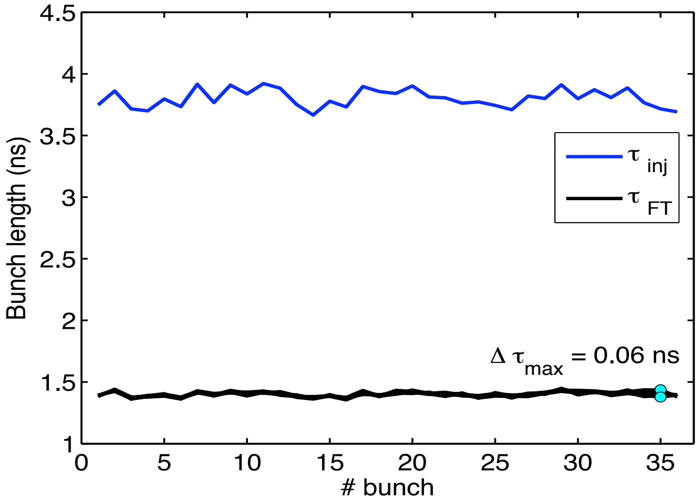
CERN

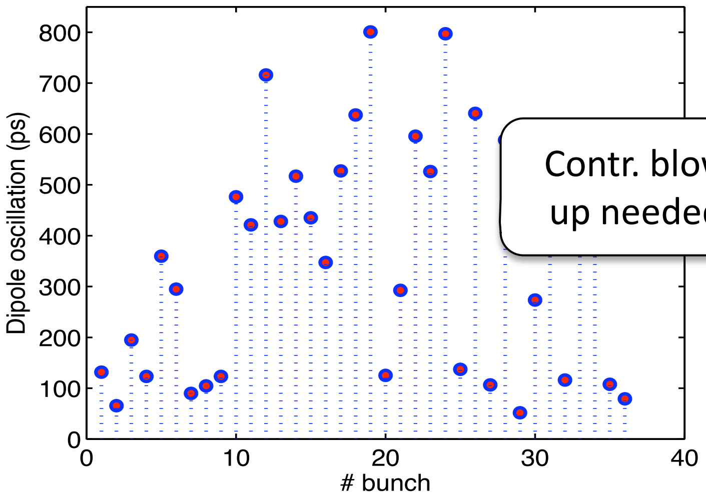
**T. Argyropoulos et al.**



Stable beam

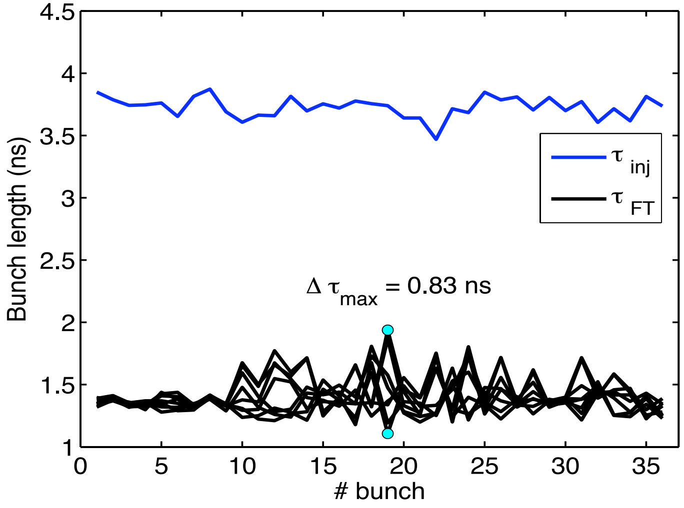
SPS-Q20 ($1.6\times10^{11}$ p/b) double harmonic RF





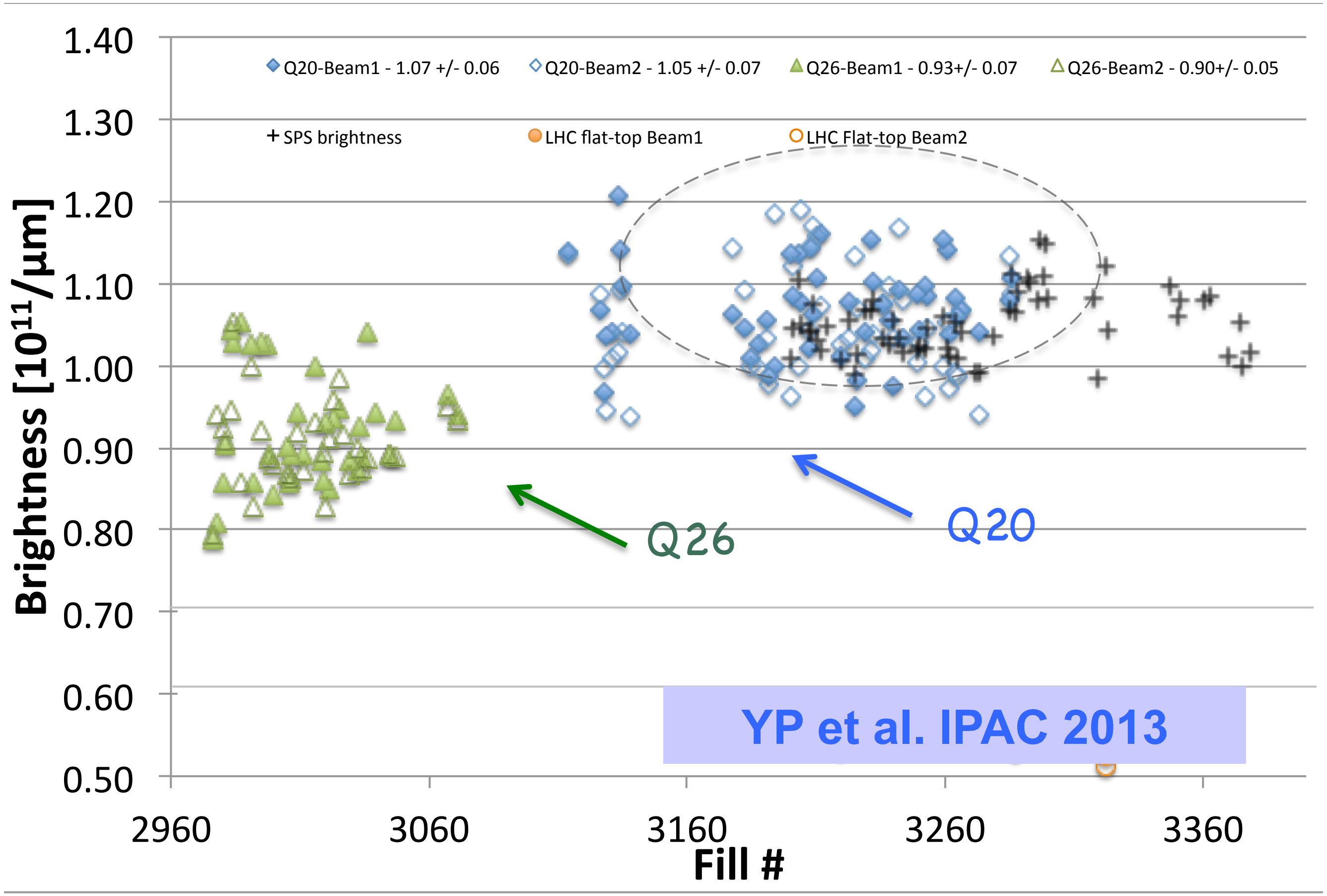
Contr. blow-up needed!

SPS-Q26 ($1.6\times10^{11}$ p/b) double harmonic RF



# LHC brightness with SPS Q20

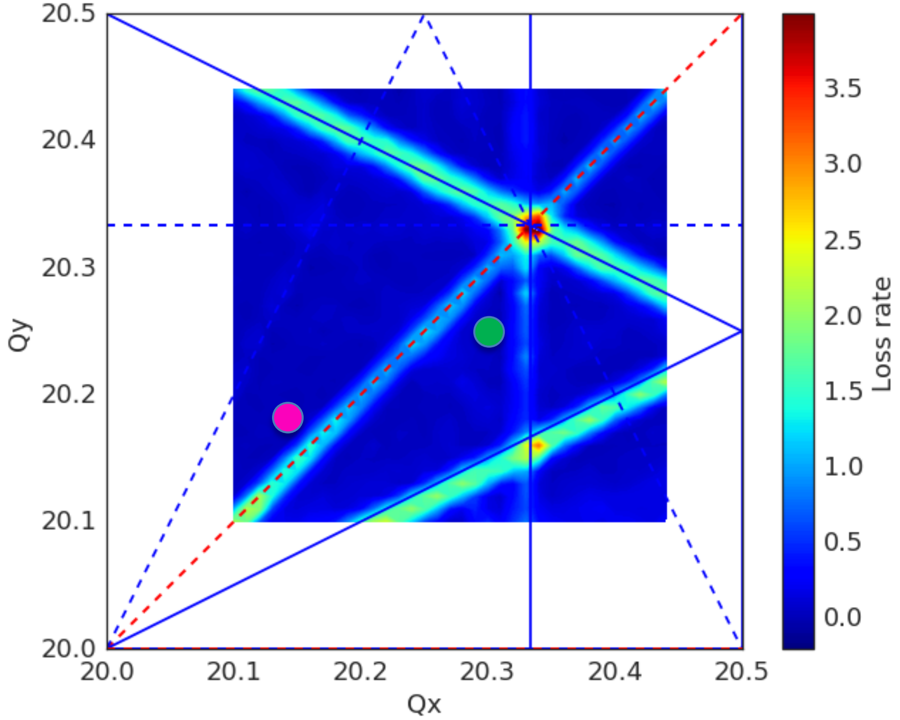
- Operational deployment of Q20 optics for LHC beams since 2012 allowing around **20% brighter beams on LHC flat bottom**
- Opened way for **ultra-high brightness beams** of HL-LHC era



YP et al. IPAC 2013

# Non-linear dynamics

# Loss map for low brightness beam



● proton working point

● ion working point

<u>resonances:</u>

red: systematic

blue: non-systematic

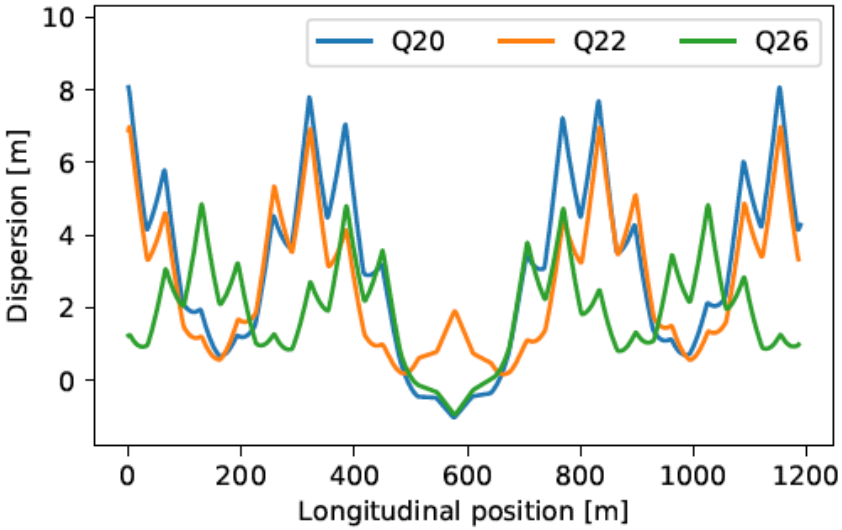
– upright

- - skew

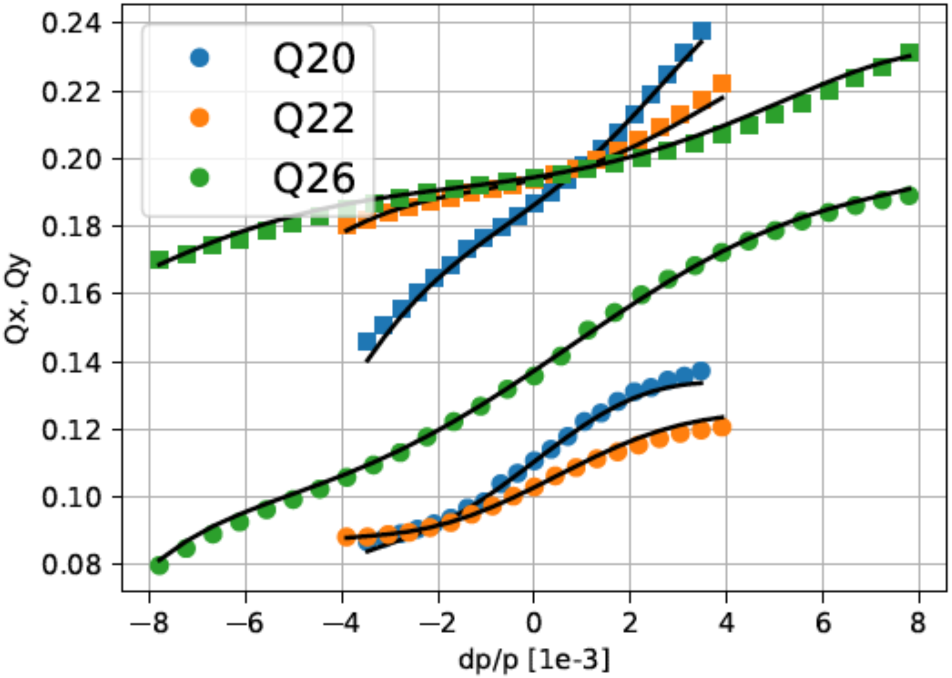
**H. Bartosik et al. HB2018**

- Dynamic tune scan for identification of resonances
  - Losses around 3rd order (normal) resonances and the diagonal clearly observed
  - Faint traces of 4th order resonances
  - Operational working point for protons 20.13/20.18 (moved up for high brightness beams)

# Non-linear model through chromaticity



**M. Cartla' et al. IPAC2018**



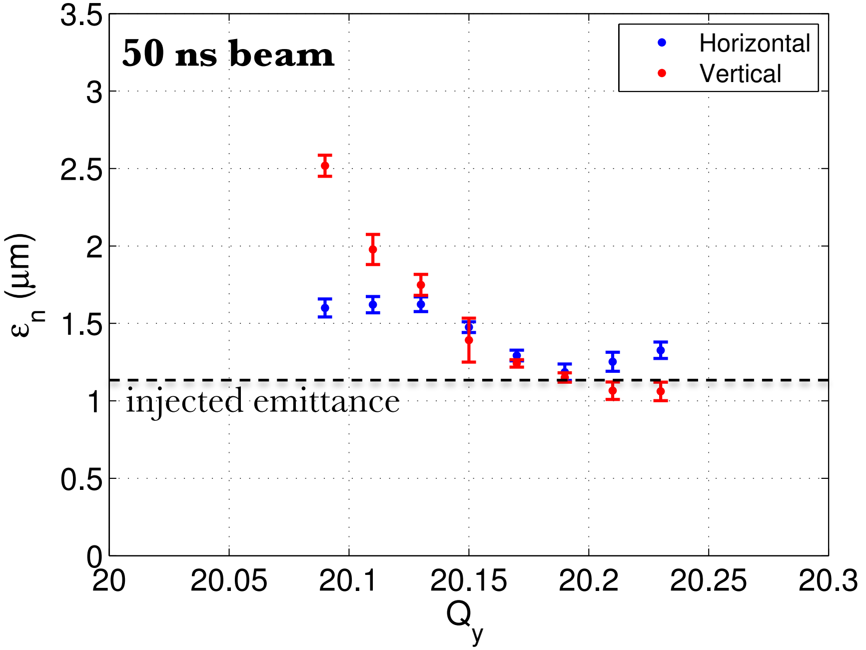
$$Q = \underbrace{Q_0}_{\text{Quadrupoles}} + \overbrace{Q'}^{\text{Sextupoles}}\left(\frac{\delta p}{p}\right) + \underbrace{Q''}_{\text{Octupoles}}\left(\frac{\delta p}{p}\right)^2 + \underbrace{Q'''}_{\text{Decapoles}}\left(\frac{\delta p}{p}\right)^3 + \ldots$$

- Estimate **"effective"** magnet **multi-poles** that reproduce non-linear chromaticity measurement for three different optics

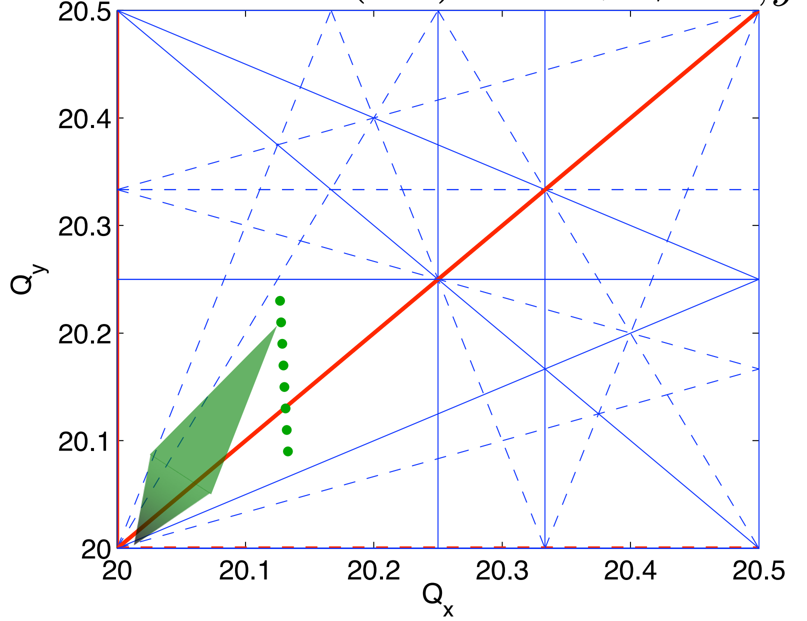
# Space-charge

# Space-charge tune spread

emittance at end of flat bottom



$$\Delta Q_{x,y} = -\frac{r_0 N_p C}{2(2\pi)^{3/2}\sigma_z \beta\gamma^2 \epsilon_{x,y}}$$

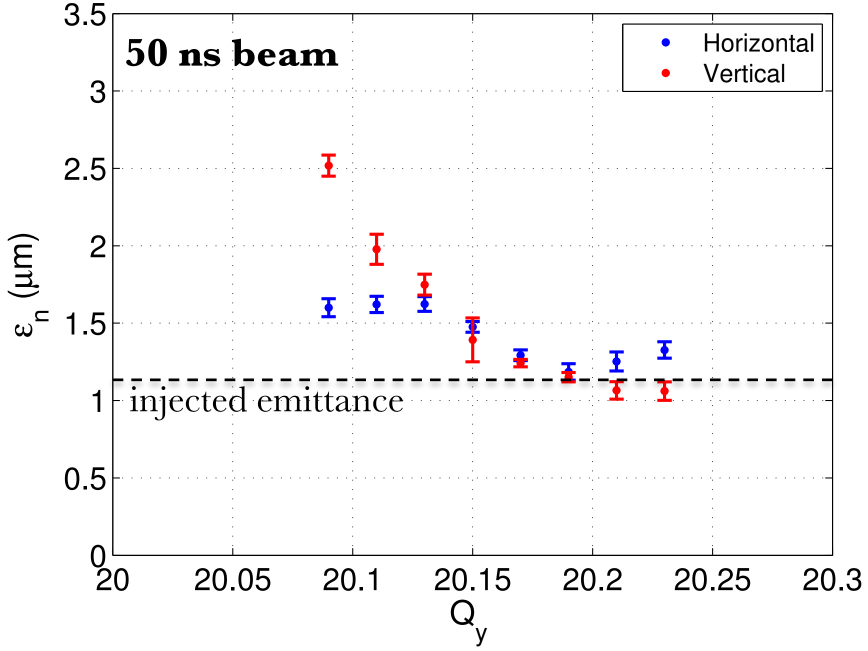


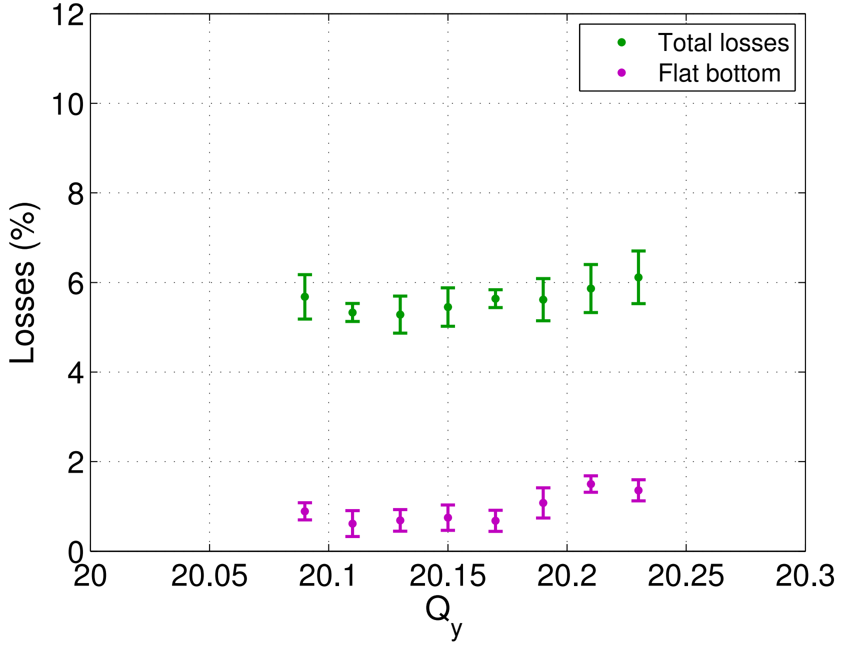
- **Vertical tune scan** with high brightness beam for 10 s storage time
  - ☐ N = $1.95\times10^{11}$ p/b (at injection)
  - ☐ ε ~ 1.1 µm (at injection)
  - ☐ Transmission to flat top around 94% (very small losses on flat bottom)
  - ☐ Budget of 10% losses and 10% blow-up allows for tune spread of ΔQy=0.21

**$\Delta Q_x/\Delta Q_y$ ~ 0.10/0.20**

# Space-charge tune spread

emittance at end of flat bottom



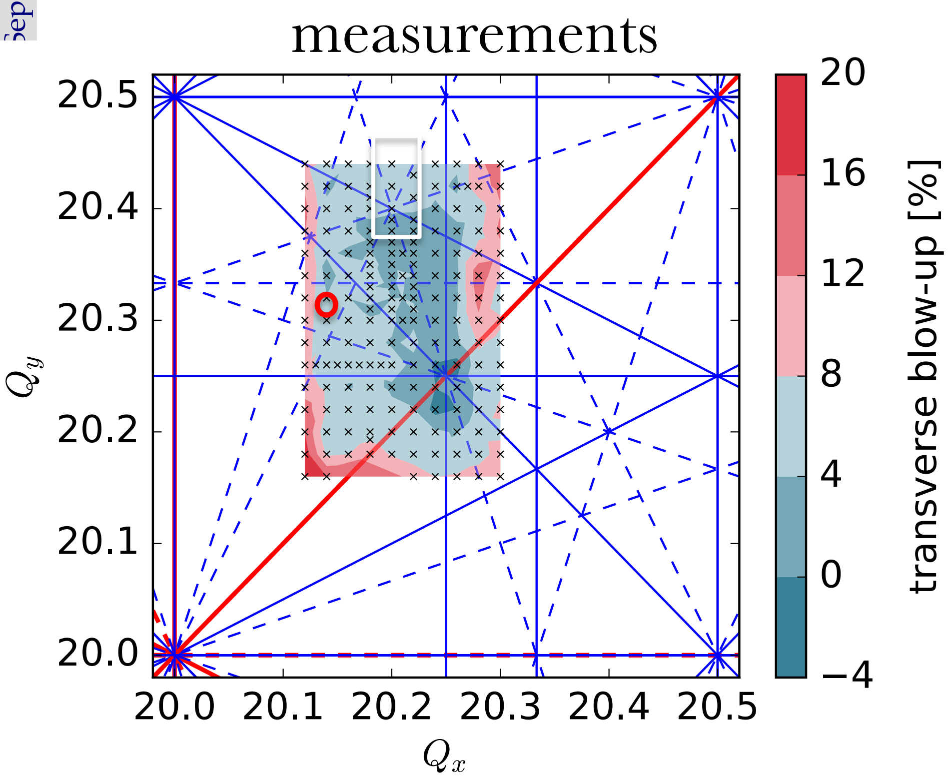


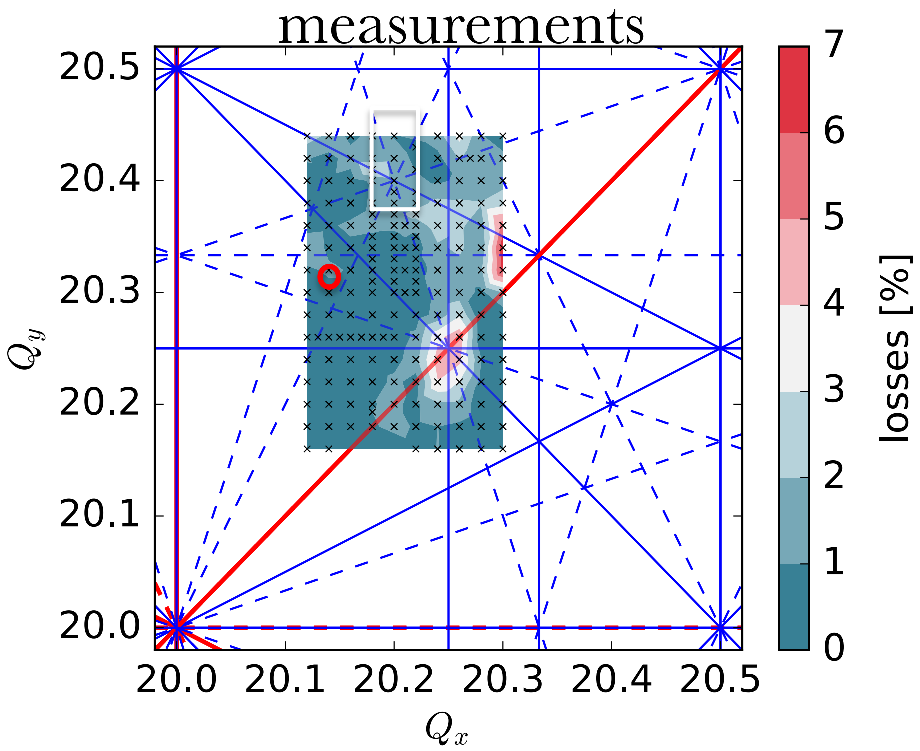
- **Vertical tune scan** with high brightness beam for 10 s storage time
  - N = 1.95x10$^{11}$ p/b (at injection)
  - ε ~ 1.1 µm (at injection)

  } **$\Delta Q_x/\Delta Q_y$ ~ 0.10/0.20**
  - Transmission to flat top around 94% (very small losses on flat bottom)
  - Budget of 10% losses and 10% blow-up allows for tune spread of ΔQy=0.21

# Exploration of tune diagram with SC

- Tune scan with high brightness single bunch beam for 3 s storage time
  - Blow-up at integer resonances as expected (tune spread ΔQx, ΔQy ~ 0.10,0.19)
  - **Margin for higher brightness for working points in white box** (enhanced losses only close to Qx + 2Qy = 61 normal 3rd order resonance and around 4Qx = 81 normal 4th order resonance)

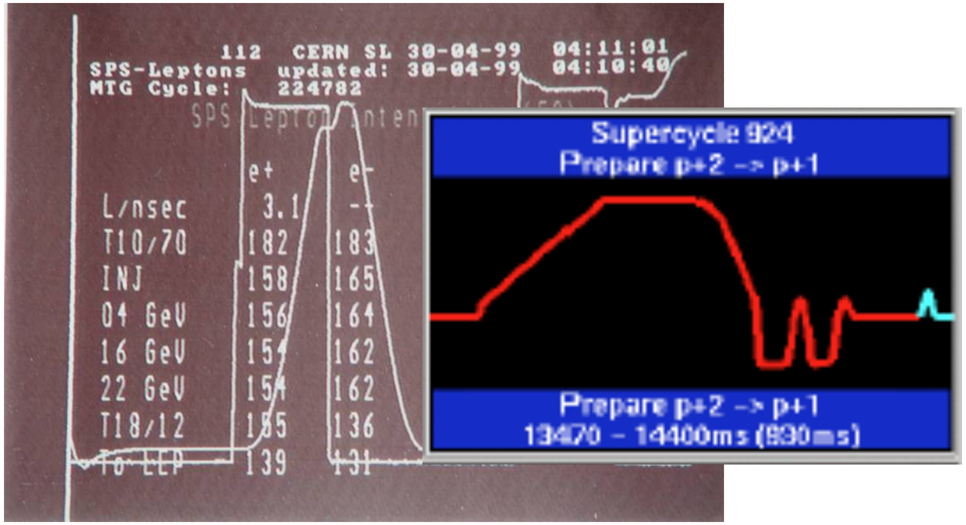




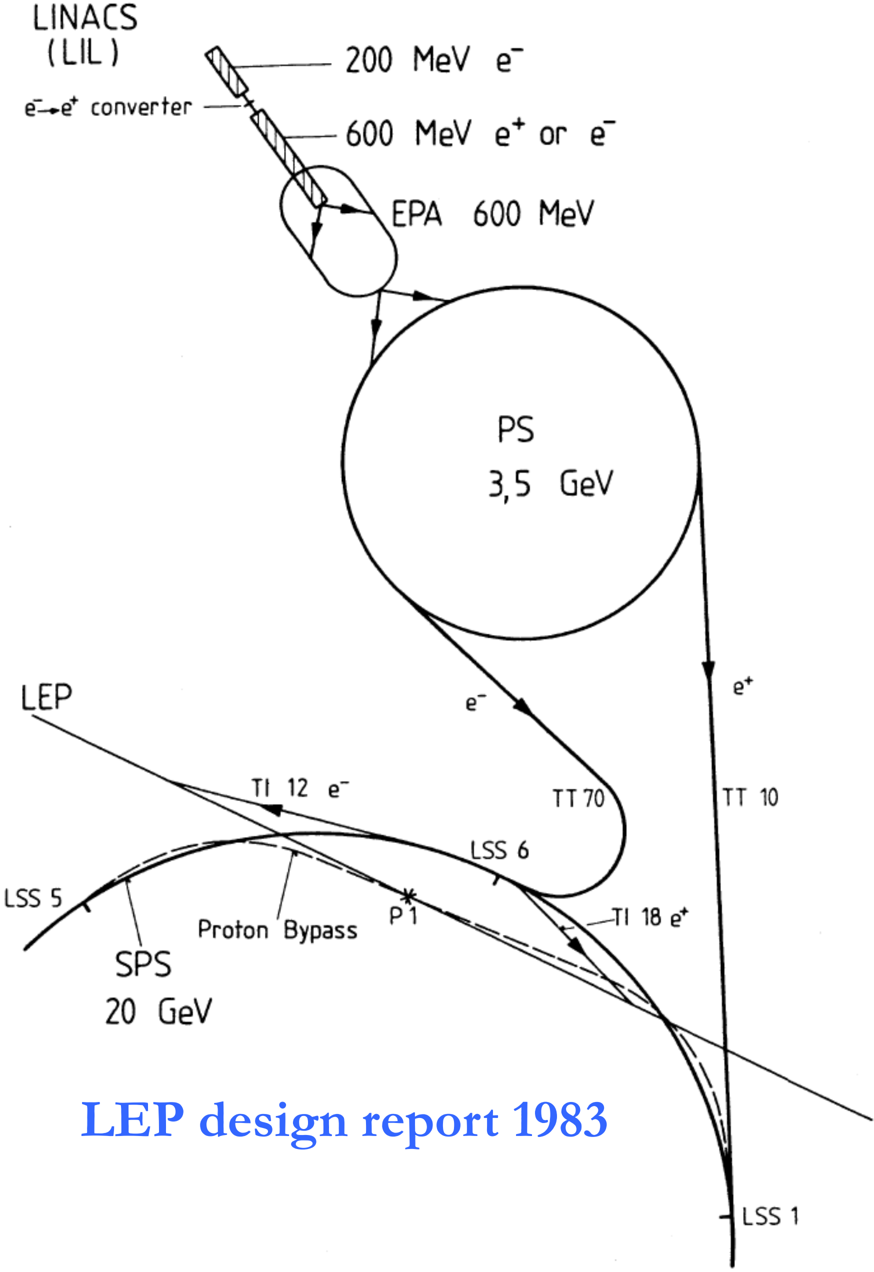
# Electron-positron dynamics

# SPS as LEP Injector

P. Collier – Academic Training 2005

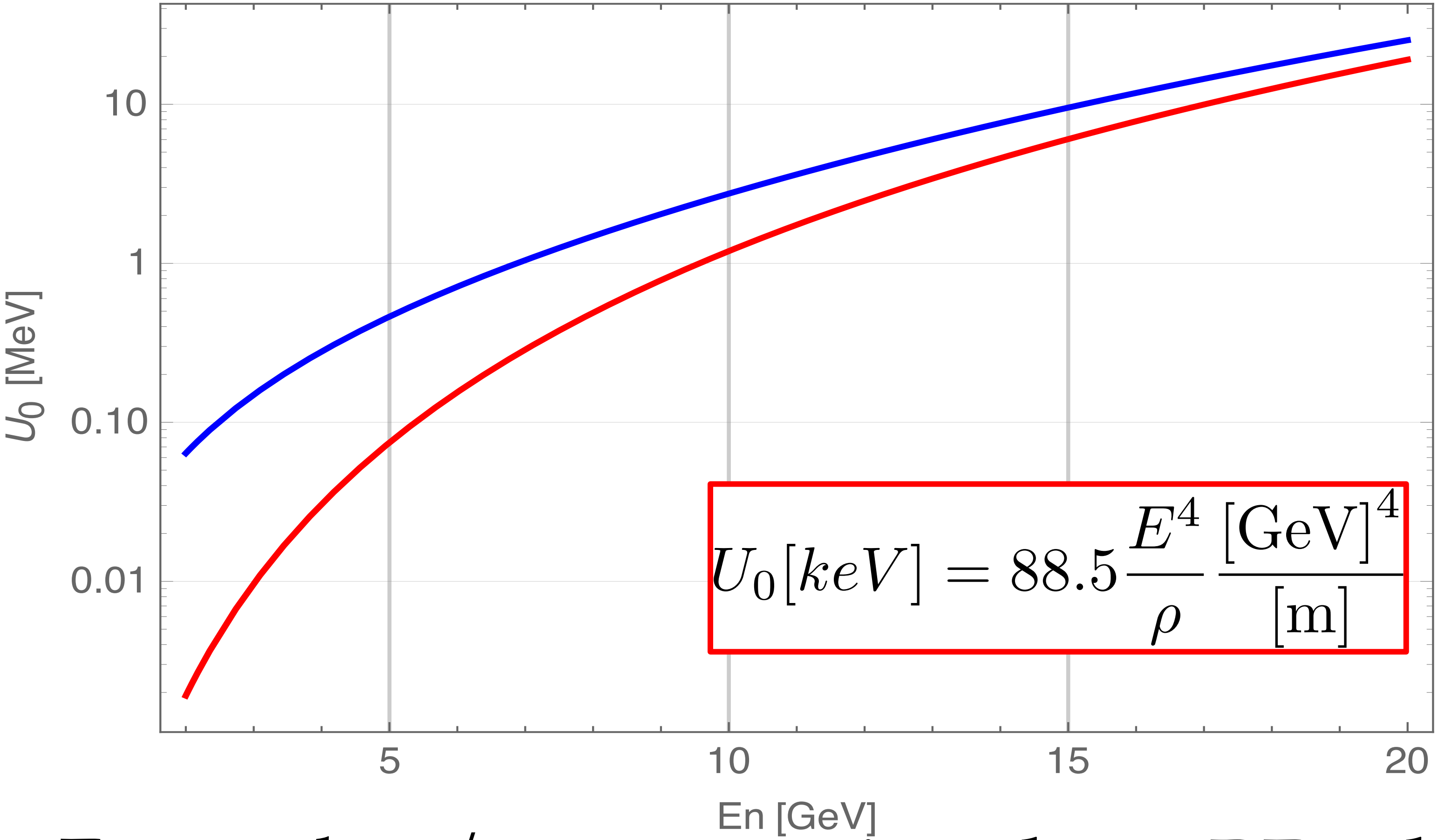


- LEP filling interleaved with proton operation
- 4 cycles with 4 bunches (2e$^+$, 2e$^-$) evolved to 2 cycles with 8 bunches (~**2.5x10$^{10}$** p/b)
- Energy to LEP: 18 → 20 → 22 GeV
- Lots of RF for leptons (200MHz SWC, 100MHz SWC, 352MHz SC),
- 2 Extractions in Point 6 towards LEP



LEP design report 1983

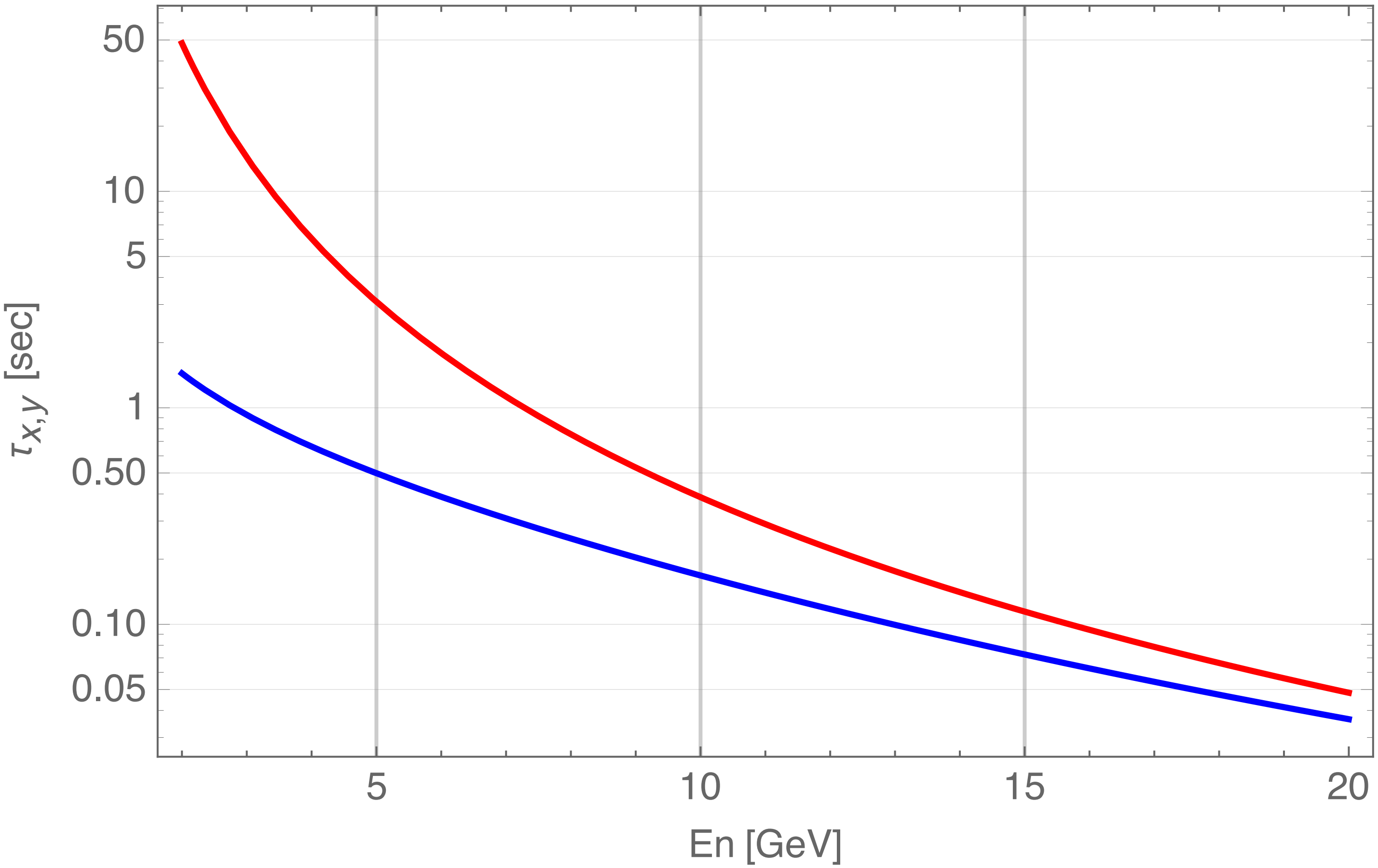
# Energy loss/turn



$$U_0[keV] = 88.5\frac{E^4}{\rho}\frac{[\mathrm{GeV}]^4}{[\mathrm{m}]}$$

- Energy loss/turn necessitate **large RF voltage** (30 MV) at high energy
- Impact of a 2-m **3.5T** **damping wiggler** is mild at high energies

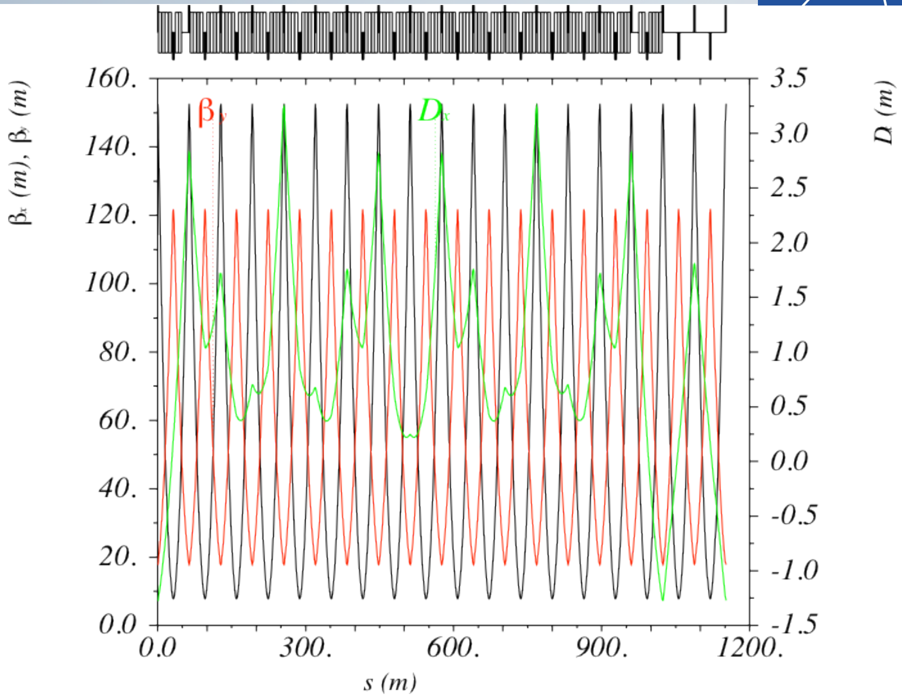
# Damping time

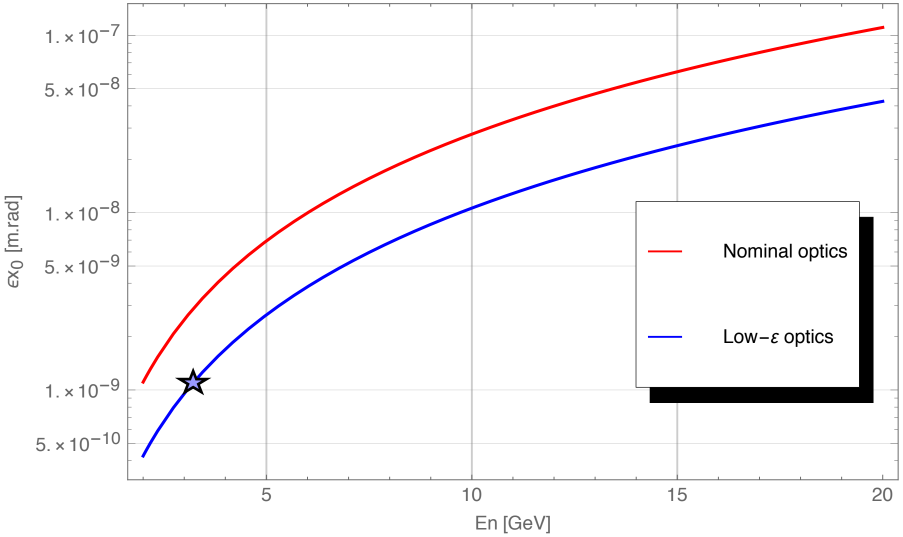


- **Damping time** at injection (3.5 GeV) **very large (9 s)**
- A 2-m **3.5T** **damping wiggler** could enhance damping for low energies to below 1 s (good for instabilities)

# SPS low emittance optics

- Move horizontal phase advance to 135 deg. i.e. $3\pi/4$ (**Q40 optics**) which is optimal for low emittance in a FODO cell
- **Emittance** with nominal optics @ **3.5 GeV** of 3.4 nm **drops to 1.3nm**
- Further reduction can be achieved with damping wiggler





# Summary

- Using the 40+ years experience since the design and operation of the Super Proton Synchrotron (SPS), reviewed several beam dynamics concepts
  - ☐ Choice of basic parameters
    - Energy, bending field and circumference
  - ☐ Optics design
    - Cell optics, insertions, transition energy
  - ☐ Collective effects
    - Instabilities, Space-charge
  - ☐ Electron/Positron beam dynamics
    - Equilibrium beam properties, energy loss/turn, damping time