Designing a synchrotron - A real life example

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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 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)

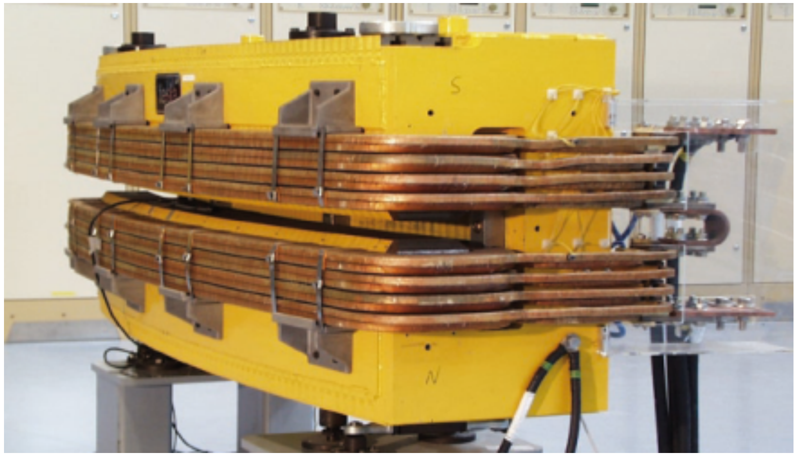
Basic parameters energy, bending field and circumference

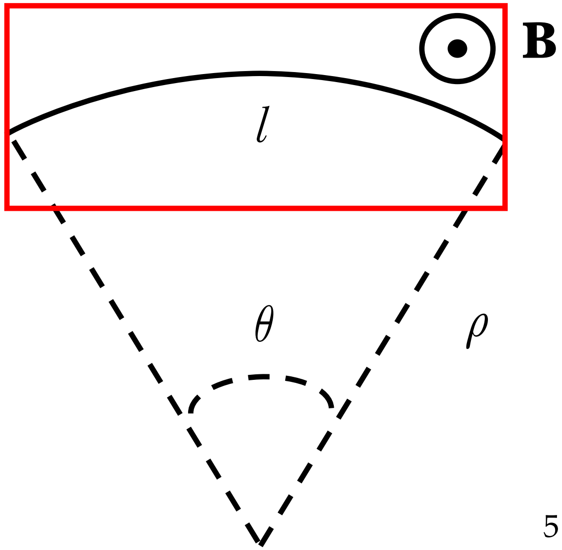
Energy and bending field

- 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** $\theta = \dfrac{2\pi}{N}$
  - **Bending radius** $\rho = \dfrac{l}{\theta}$
  - The magnetic rigidity is $B\rho = \dfrac{\beta E}{q}$
  - 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

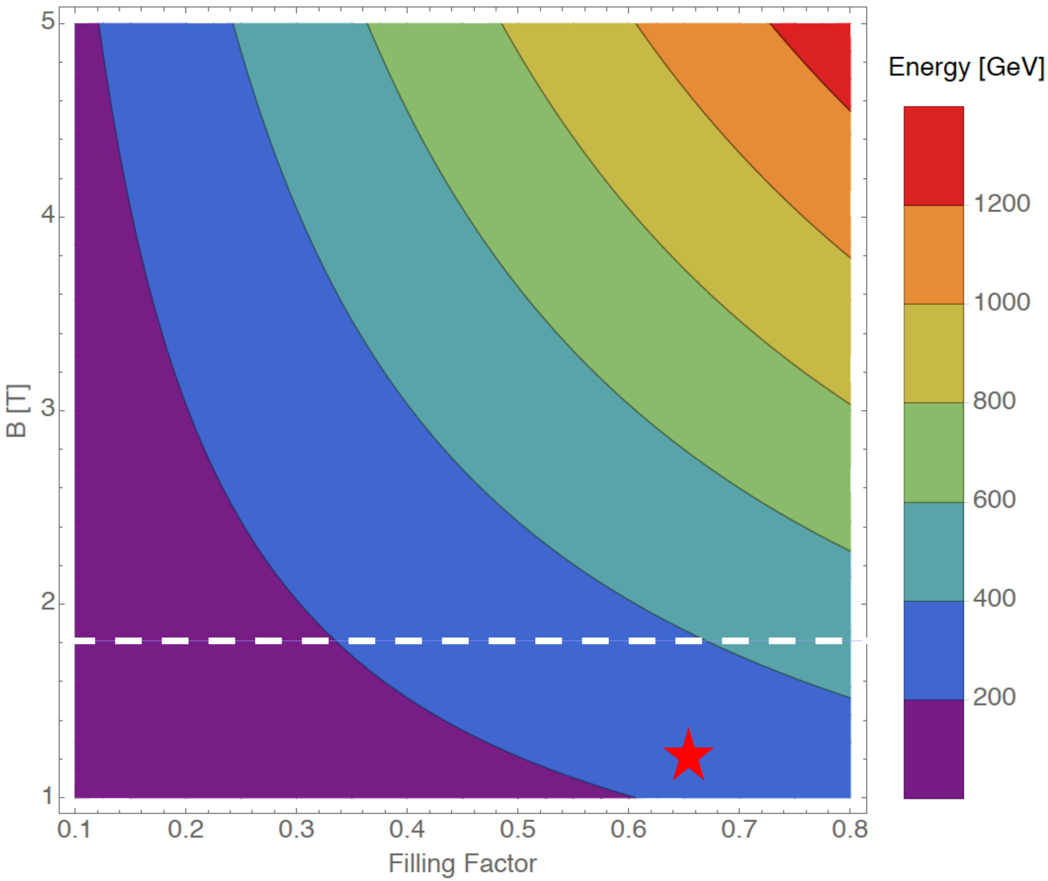
$$C = \frac{2\pi}{k_f B}\frac{\beta E}{q}$$

- 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

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



- 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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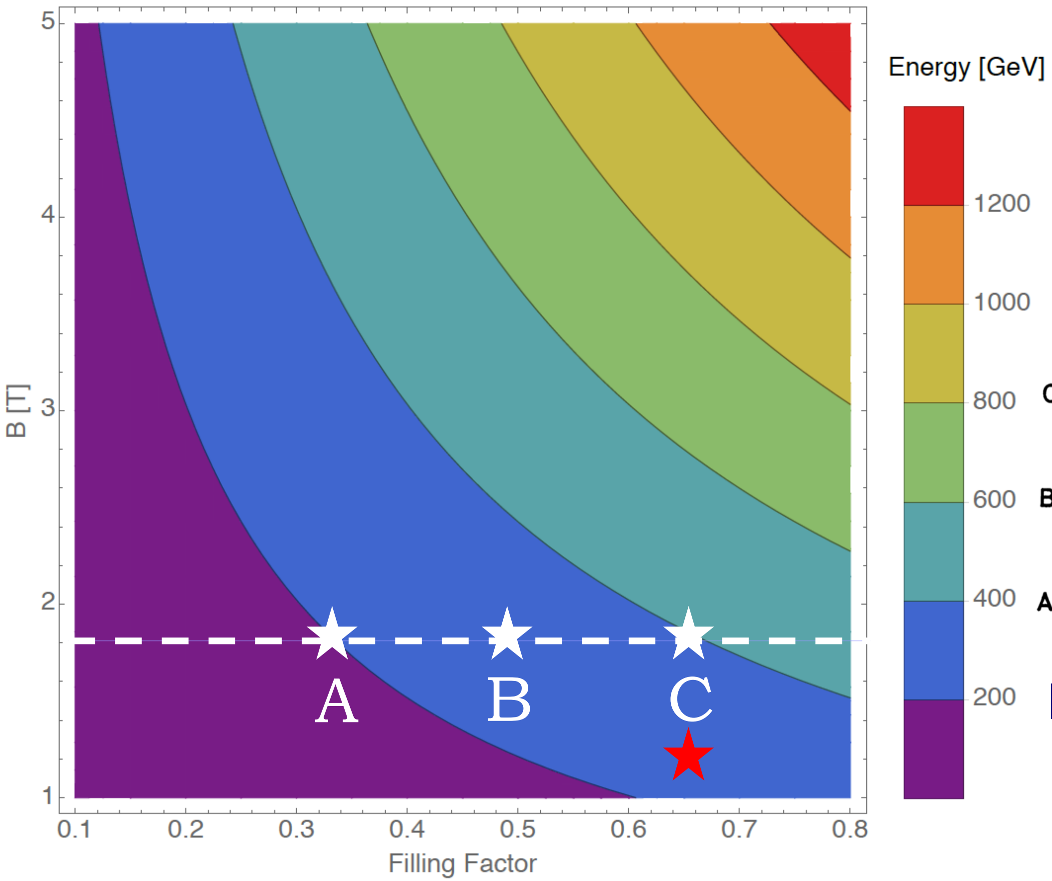
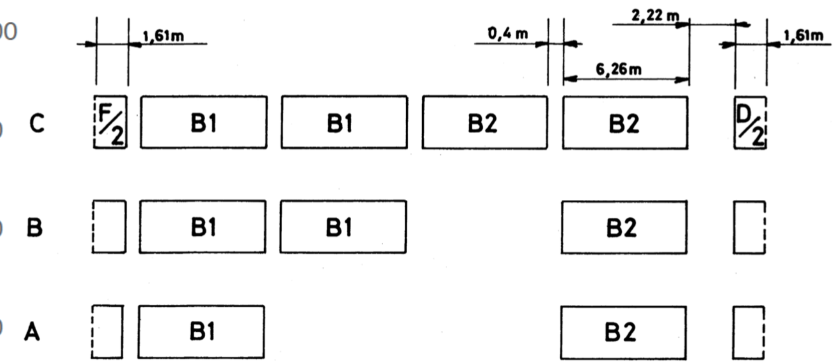


Stage	Energy (GeV)	Magnets per semi-period*
A	200	2
B	300	3
C	400	4



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

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

Designing the SPS

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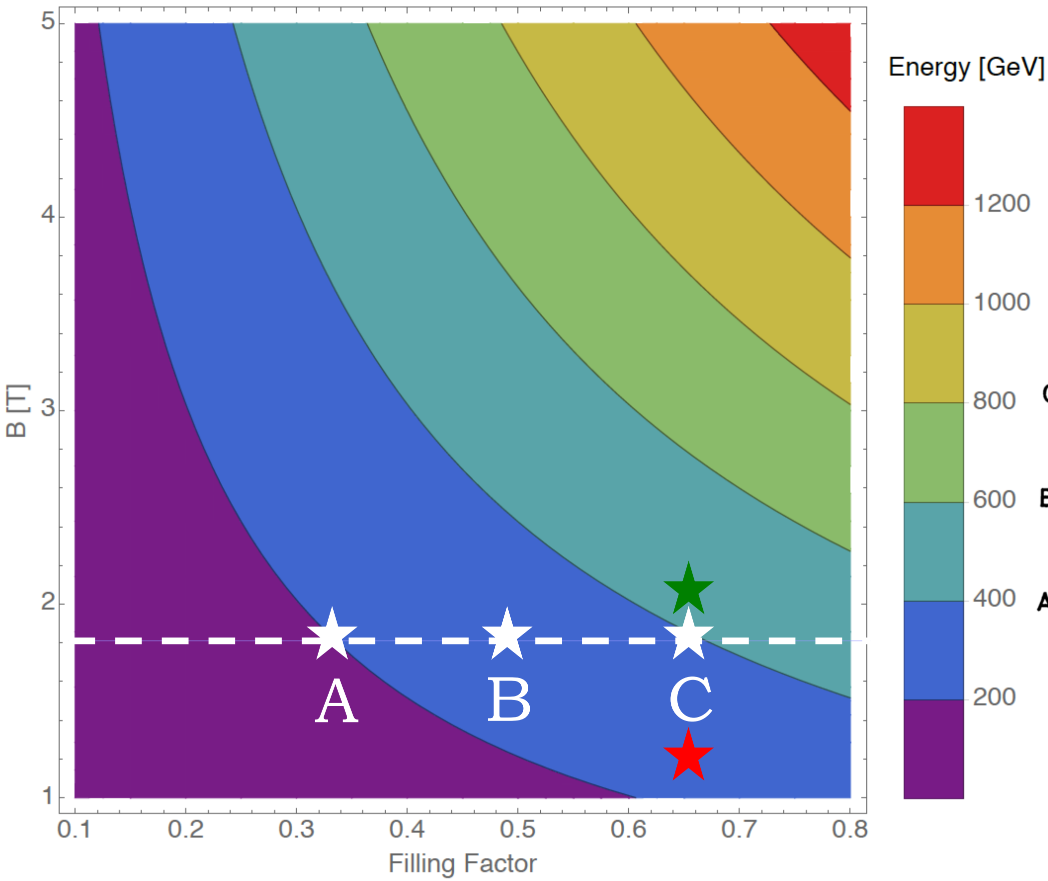

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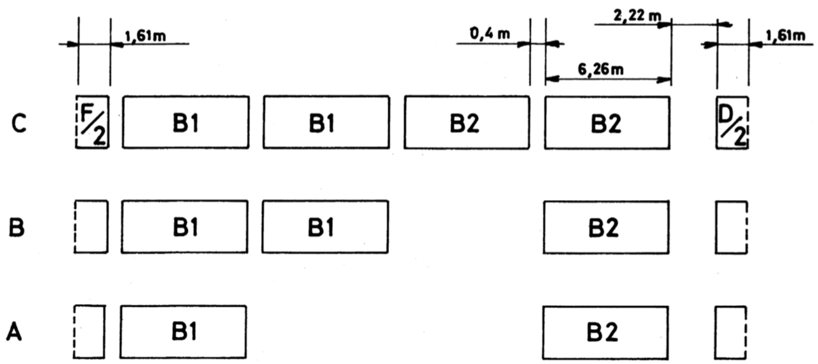

- SPS dipoles have been pushed to beyond **2 T** to reach from **450 GeV**

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

Designing the SPS

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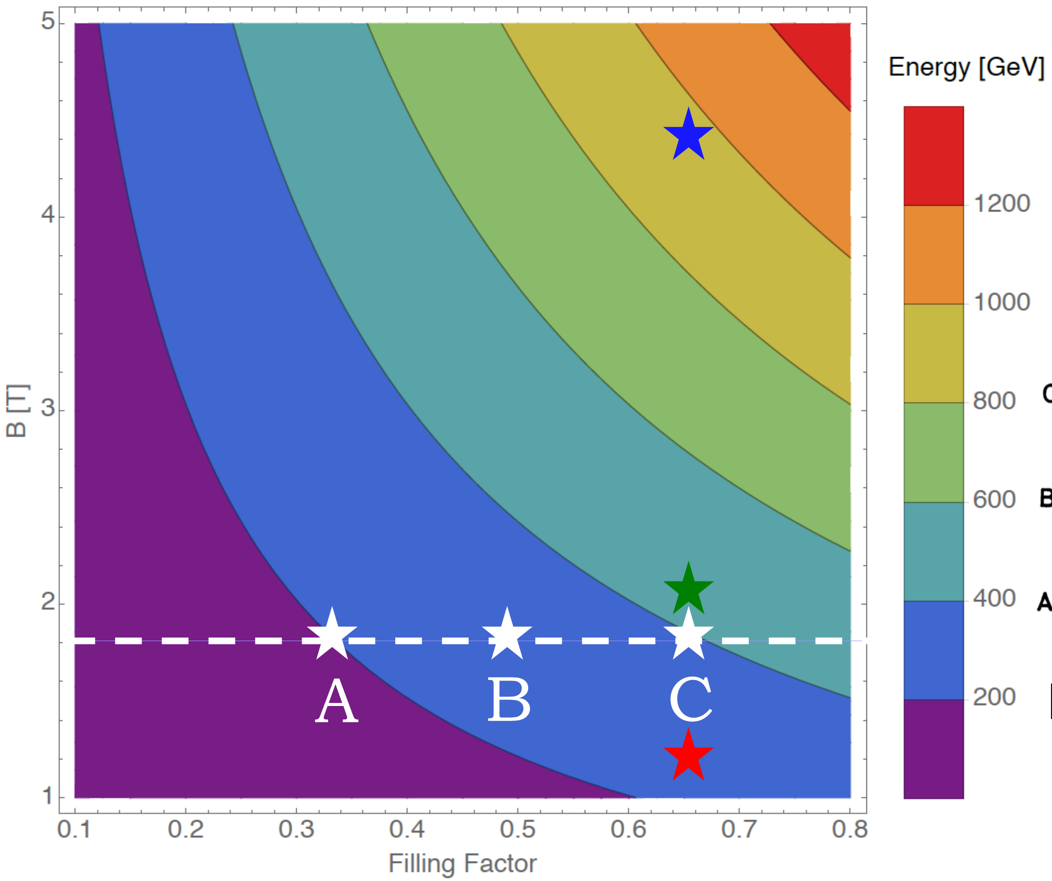

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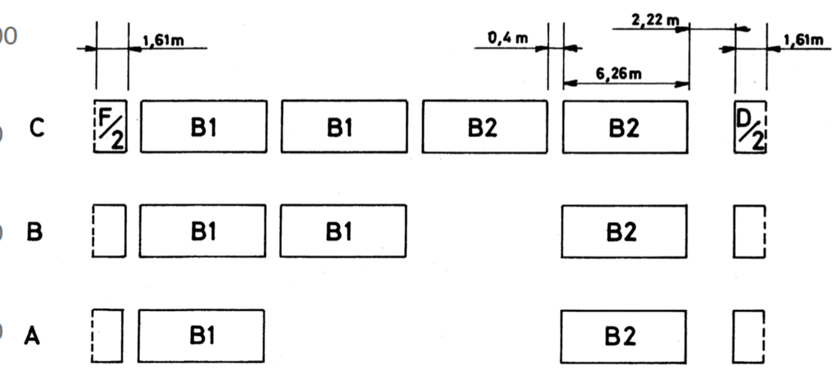


- SPS dipoles have been pushed to beyond **2 T** to reach from **450 GeV**

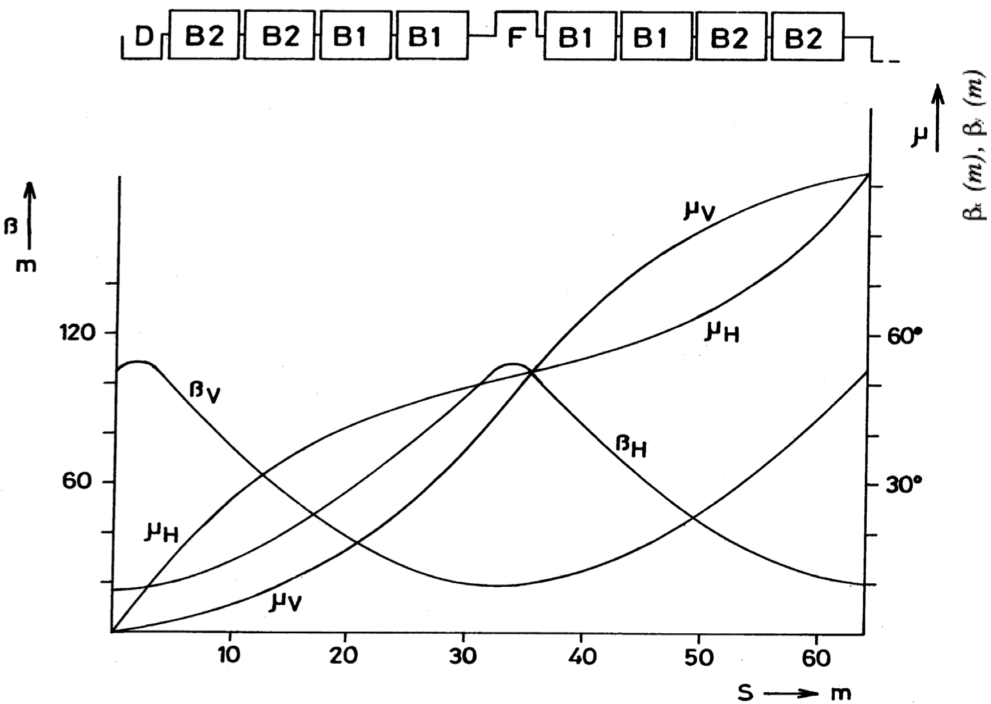
- Super-conducting option could raise the energy to **1 TeV**

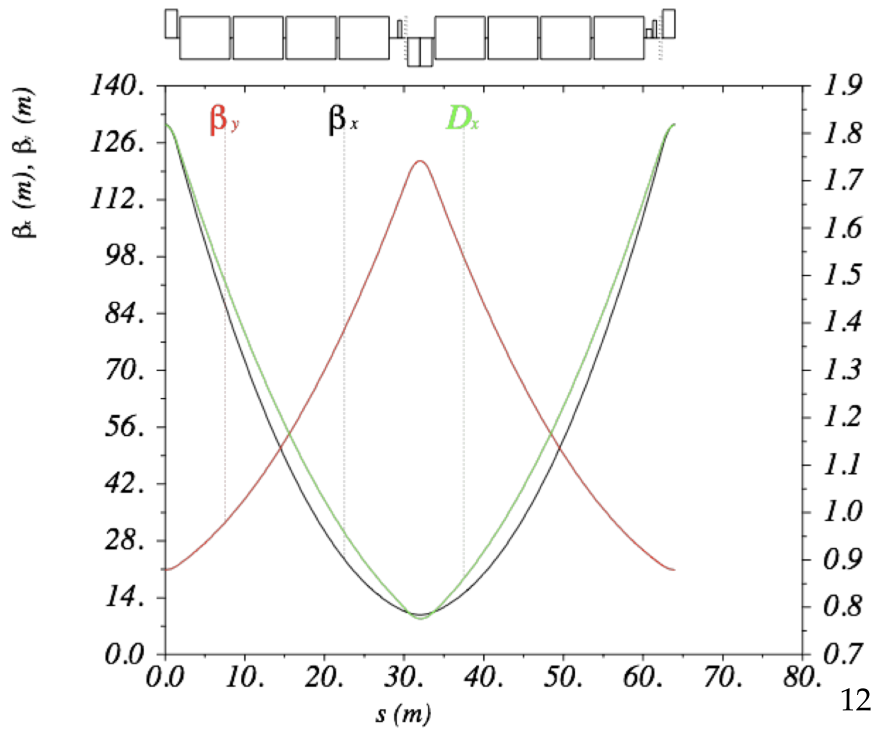
Optics design

Basic cell

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

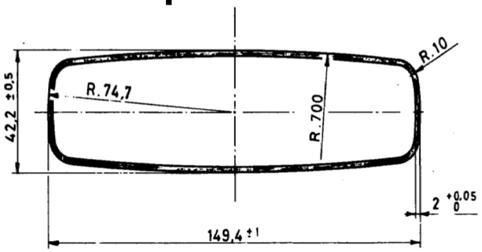
The 300 GeV Program, CERN/1050, 14/01/1972



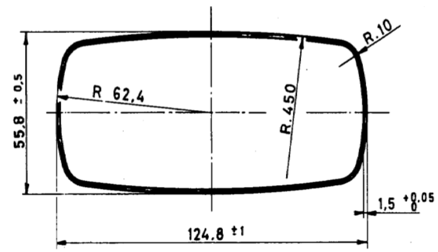


Magnet aperture

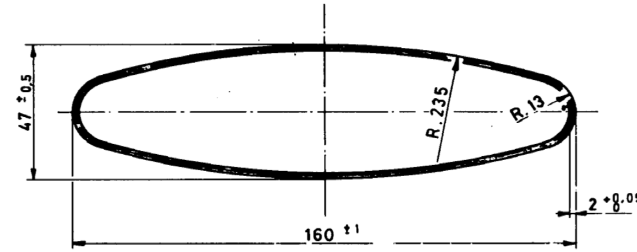
- Magnet apertures follow beta function and dispersion evolution



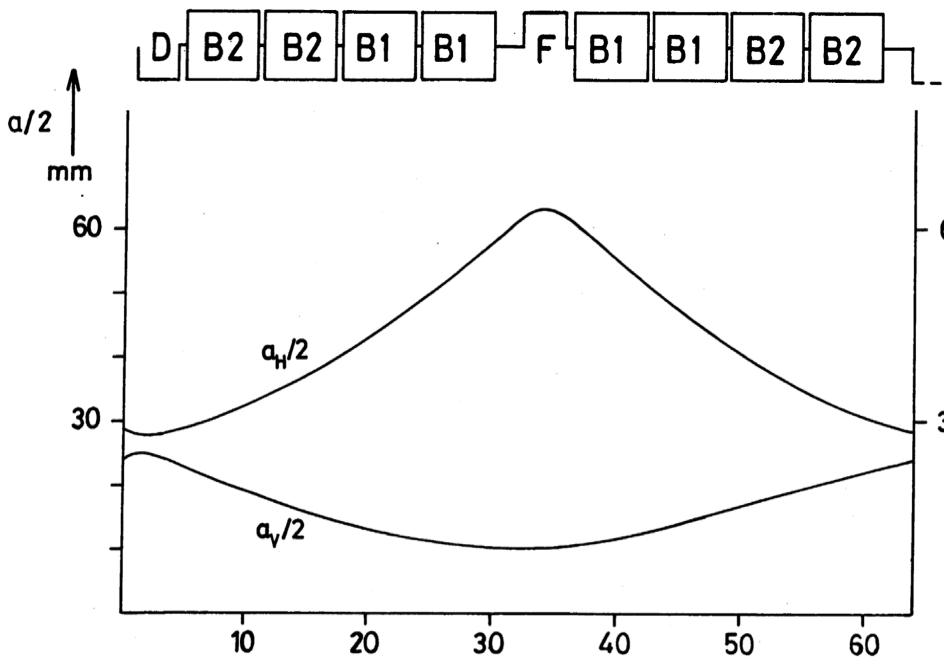
Dipole B1

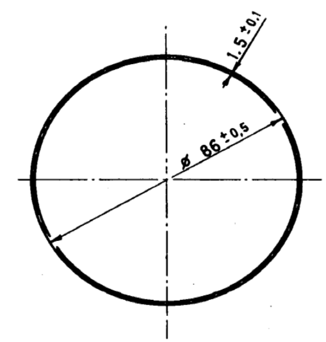


Dipole B2



Quadrupole F





Quadrupole D

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

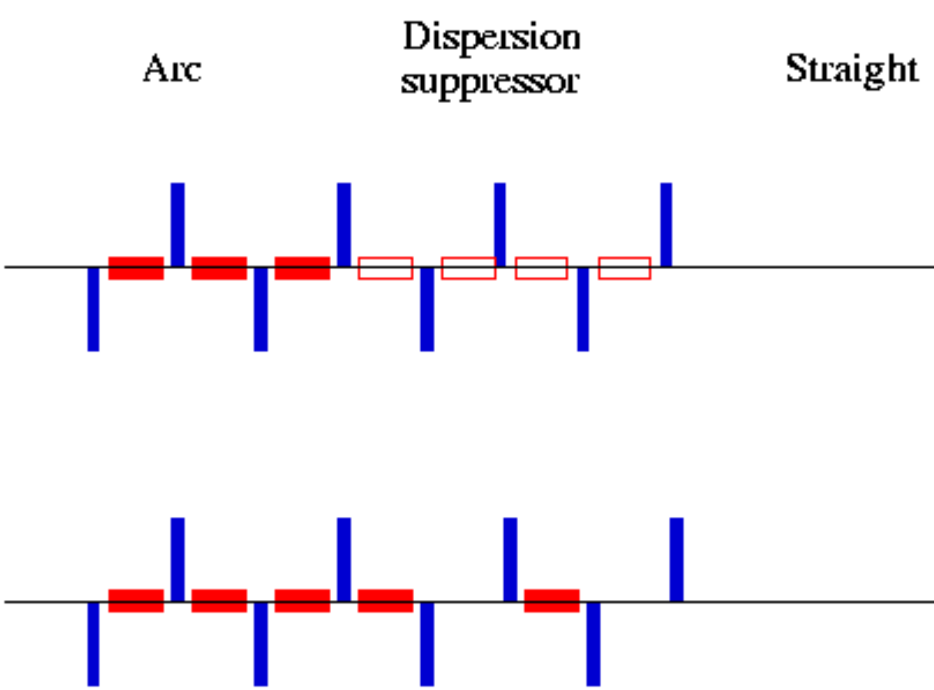
Dispersion suppression

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

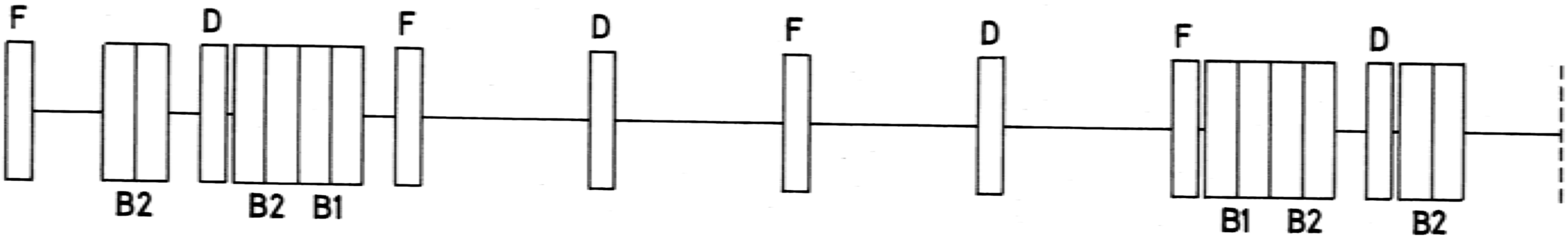
$$\theta_1 = \theta\left(1 - \frac{1}{4\sin^2\mu_{\mathrm{HFODO}}}\right)$$

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

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



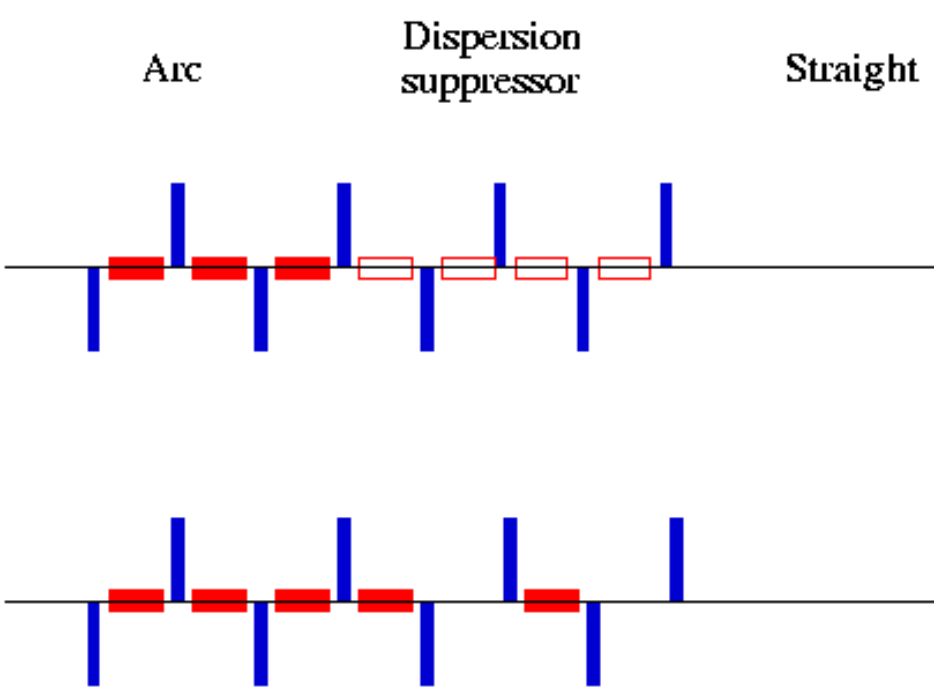
Dispersion suppression in the SPS



- In the SPS, all dipoles are powered in series, i.e. dispersion suppressor cells looks like a missing dipole, but they are not!

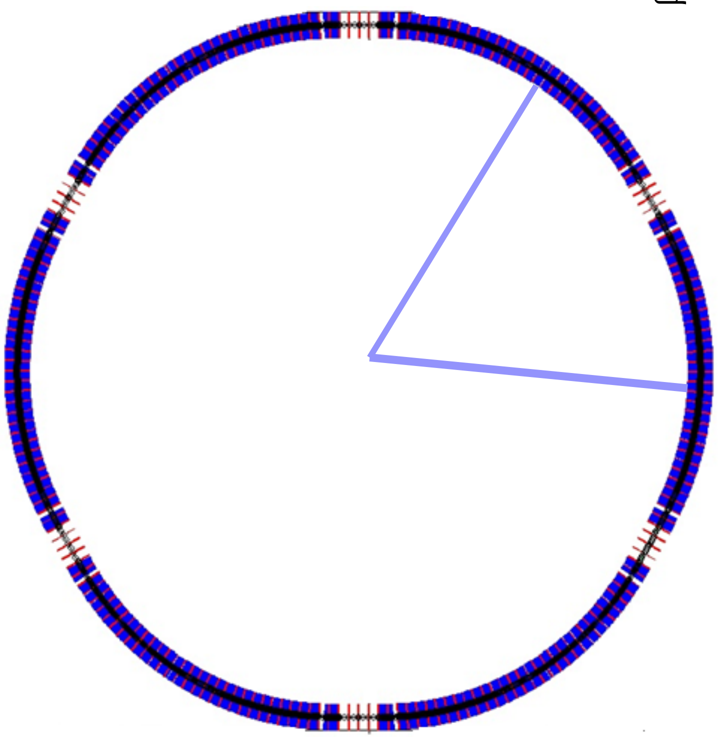
- Dispersion suppression is achieved by tuning the phase advance of the arc, to a multiple of **2 π**

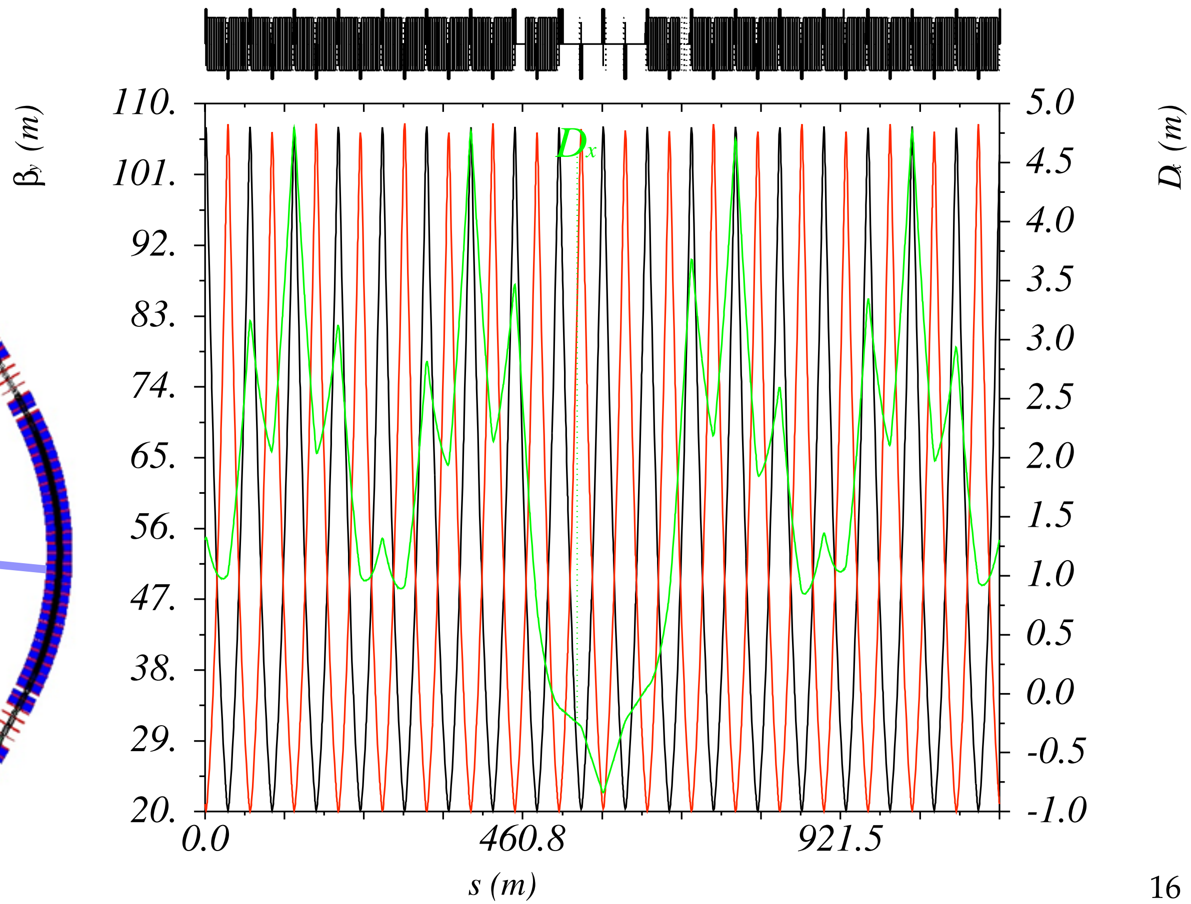
- Dispersion oscillates through the arc and vanishes at the edges



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**)

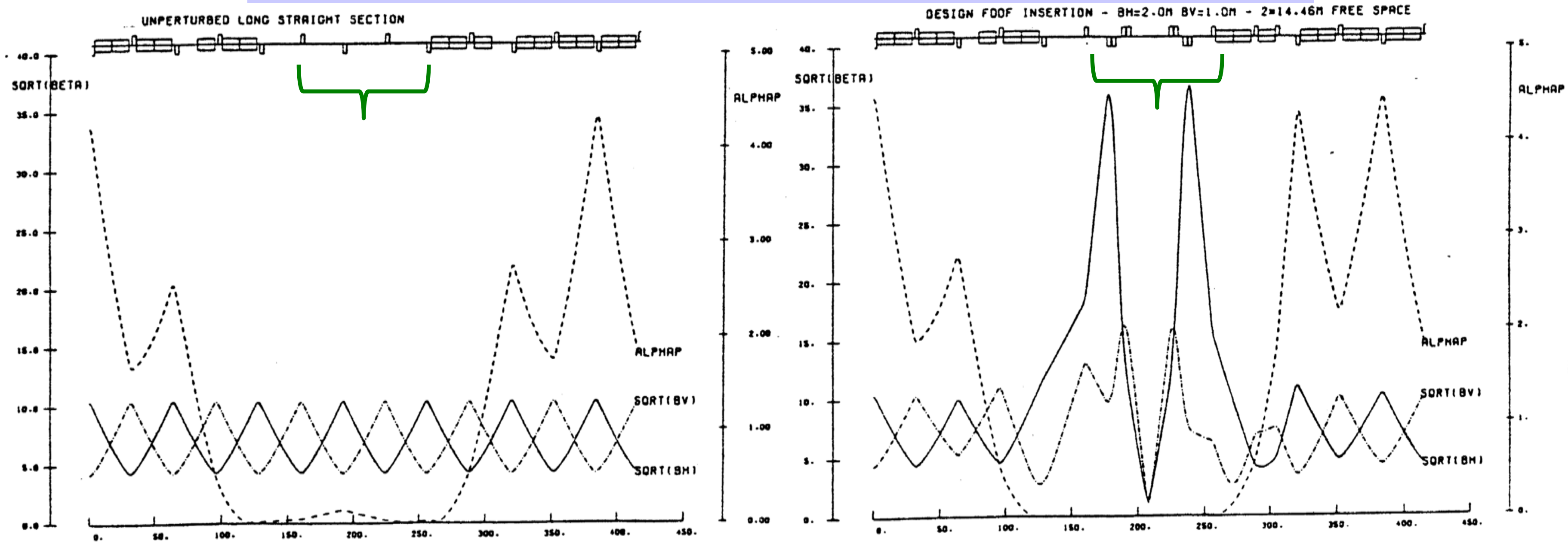




$Sp\bar{p}S$ collider insertion optics

- 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



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

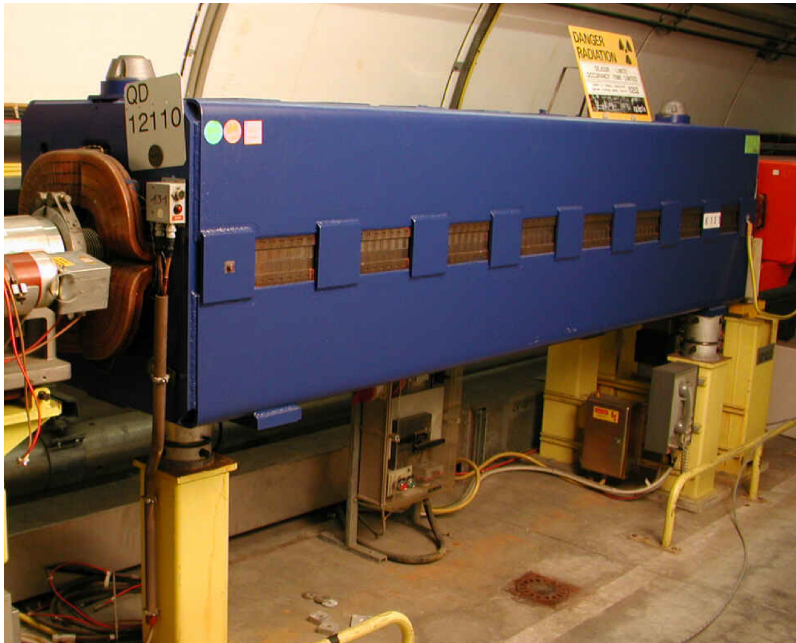
- Maximum field of **2.02 T**, for reaching 450 GeV
- High mechanical stress on coils

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



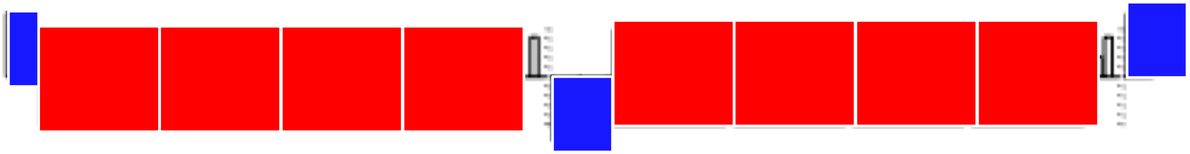
SPS sextupoles

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

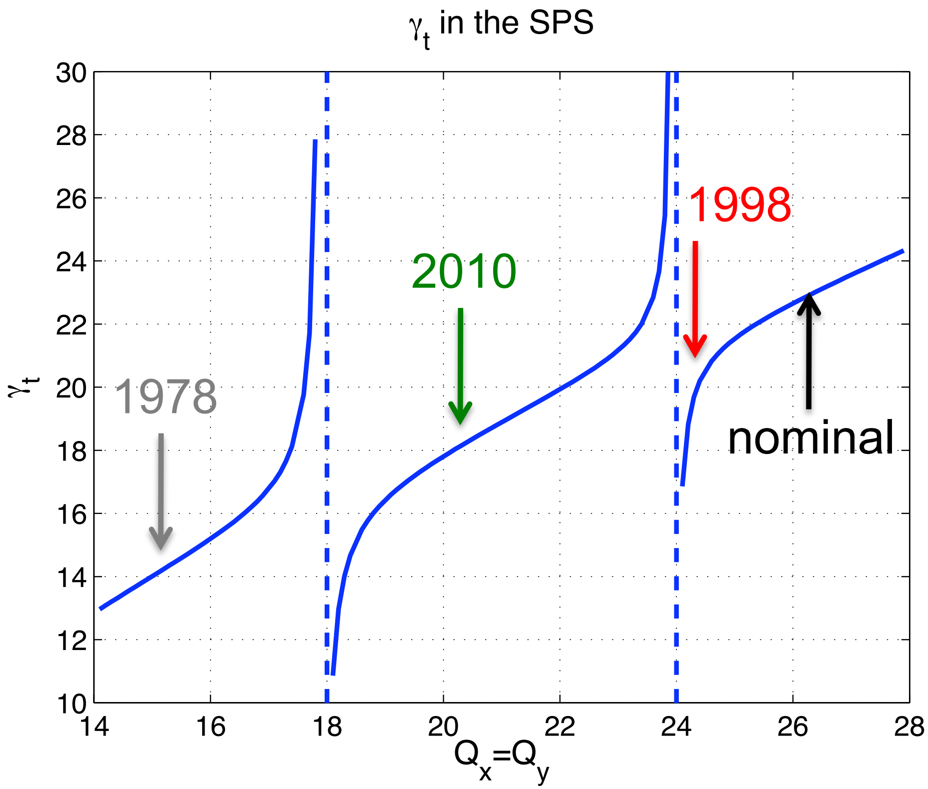
Transition energy

- 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



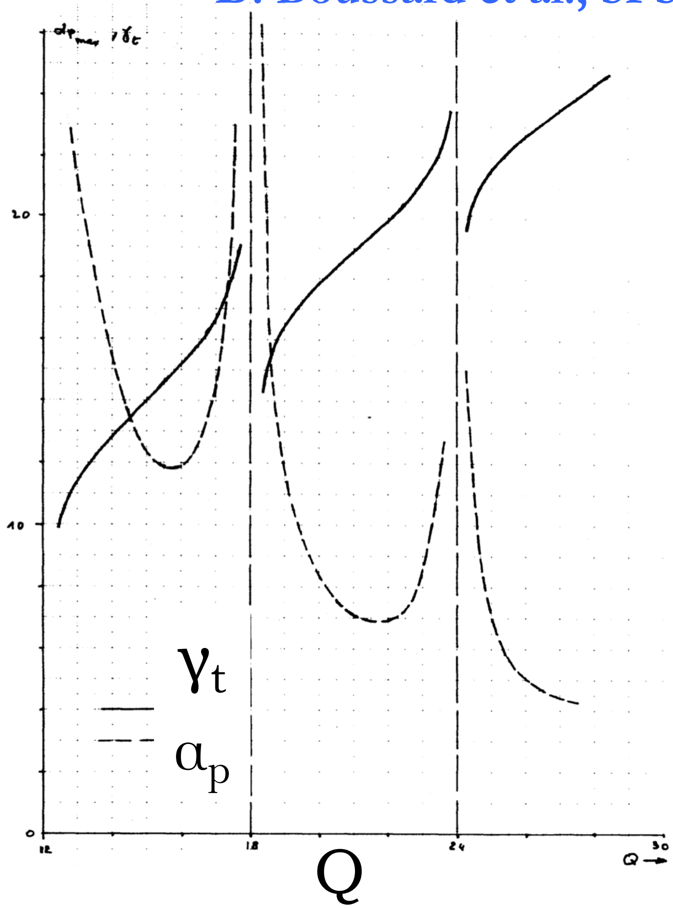
- Resonant oscillation of dispersion function close to the "Resonant integer tunes" (multiples of **super-periodicity 6**) → asymptotic behavior of $\gamma_{t,}$ (difficult for routine operation)
- γ_t is a linear function of horizontal tune Q_x elsewhere

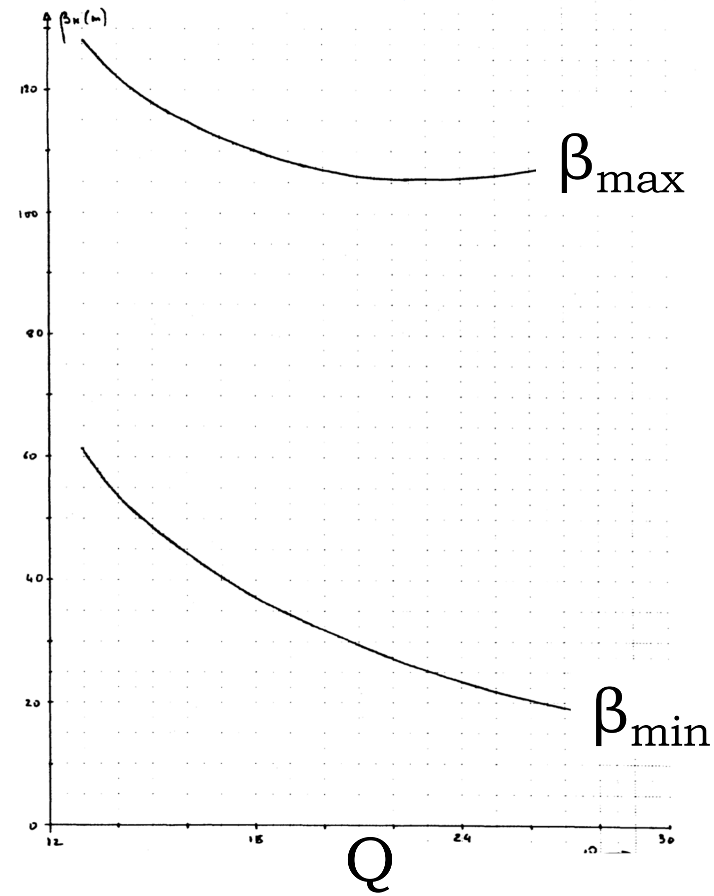
- Nominal SPS working point for LHC proton beams (γ_t~23)
- D. Boussard et al., SPS improvement note No 147, 1978; Injection above transition as TT10 was not ready for 26 GeV/c (γ_t~14)
- G. Arduini et al., CERN/SL-Note 98-001, 1998; "Resonant tune" (γ_t~20)
- Low γ_t, 2010 - "Resonant arc" with small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

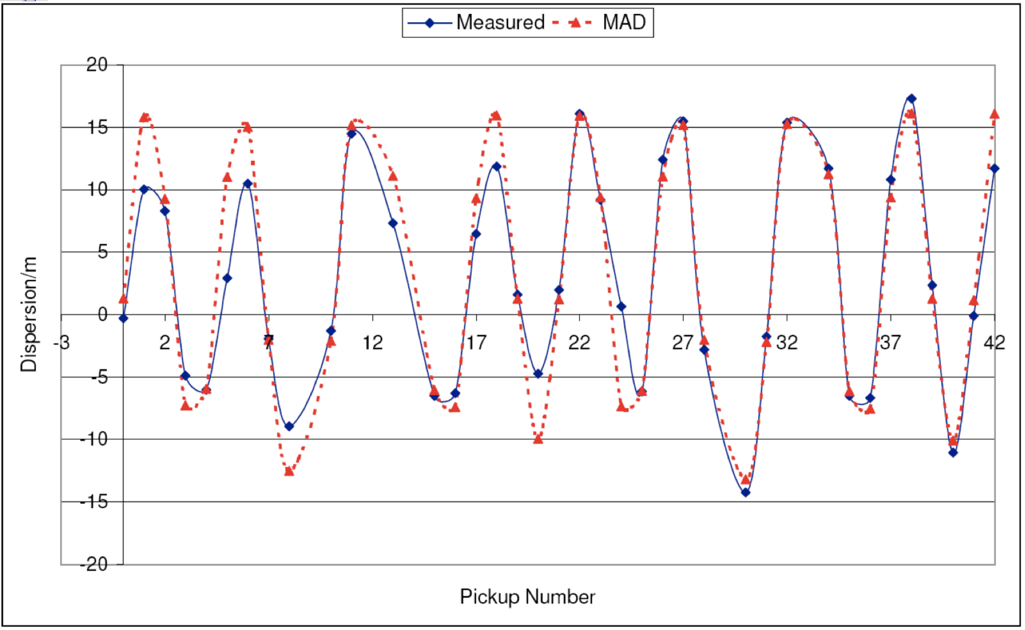
$$\boxed{N_{\text{th}} \propto Q_s \propto \sqrt{\eta}}$$

- 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

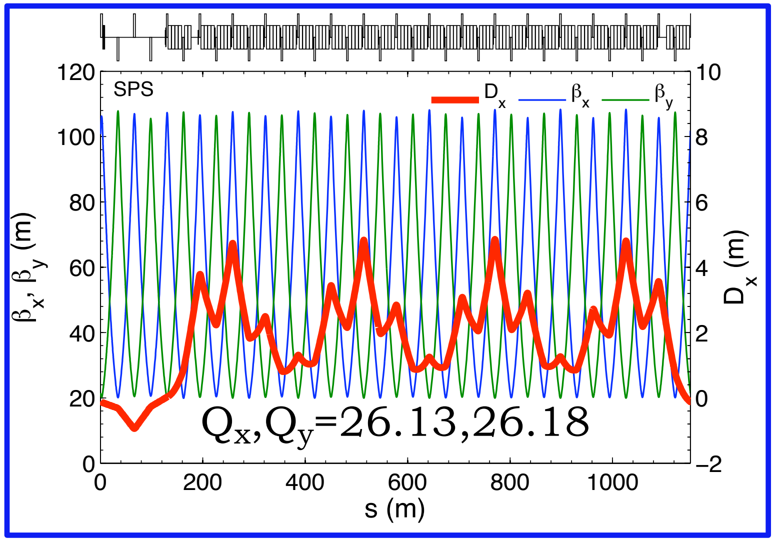


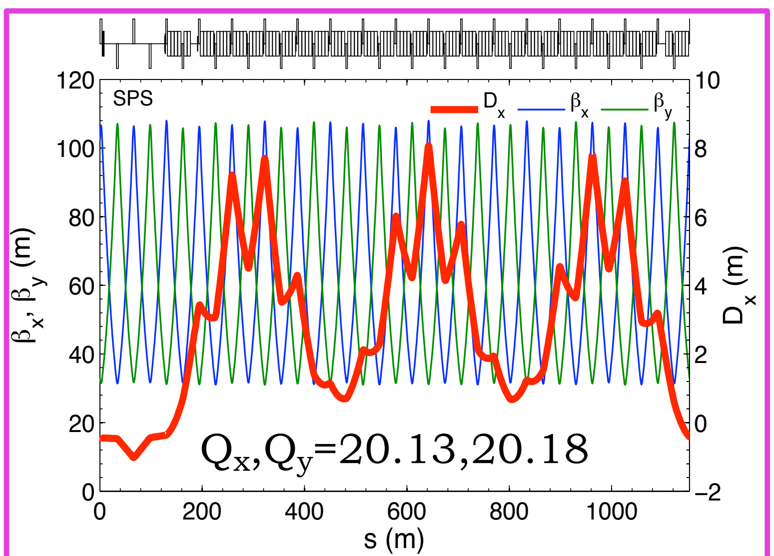
G. Arduini et al., CERN/SL-Note 98-001 (MD), 1998

Q_h	Q_v	γ_{tr}	η (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)**

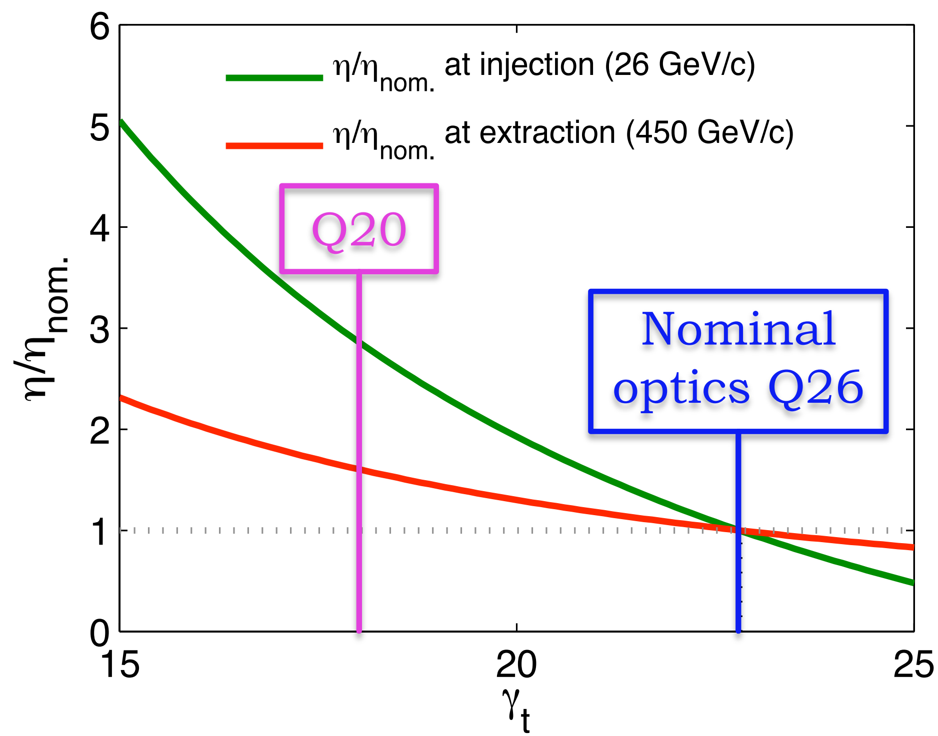




$$\eta = \frac{1}{\gamma_t^2} - \frac{1}{\gamma^2}$$

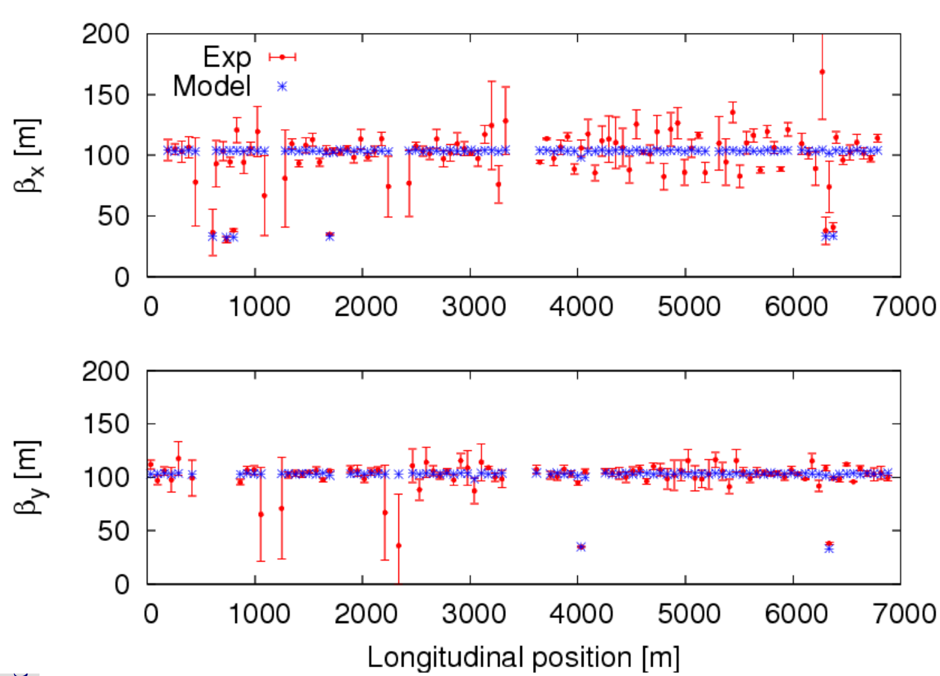
$$\gamma_{t_{FODO}} \approx Q_x$$

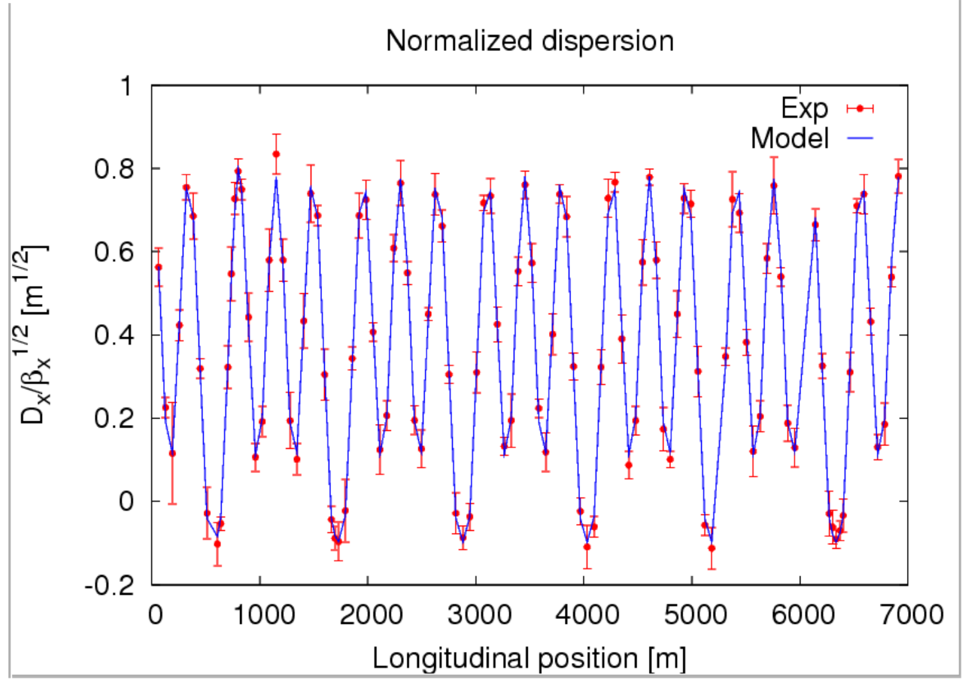
Slippage factor increased by a factor of **2.8** at **injection** and **1.6** at **flat top**



Slip factor relative to nominal SPS optics

Q20 Optics measurements

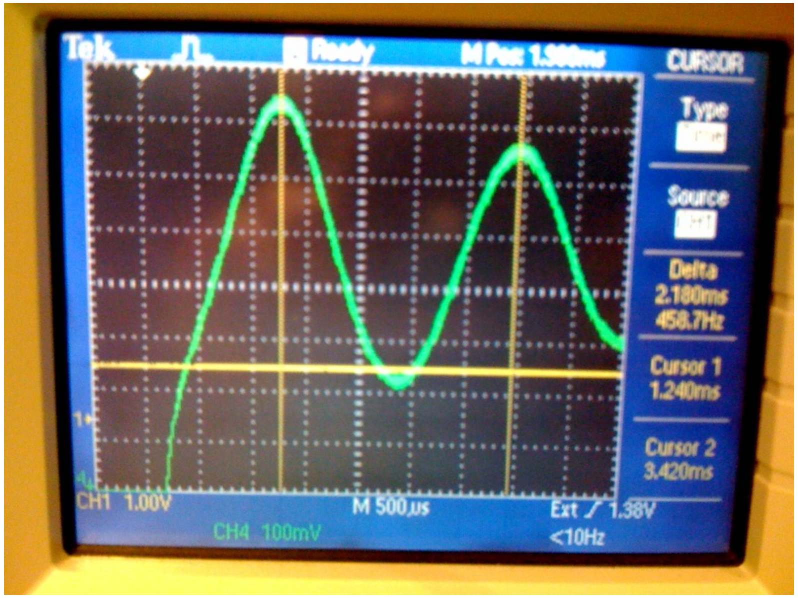




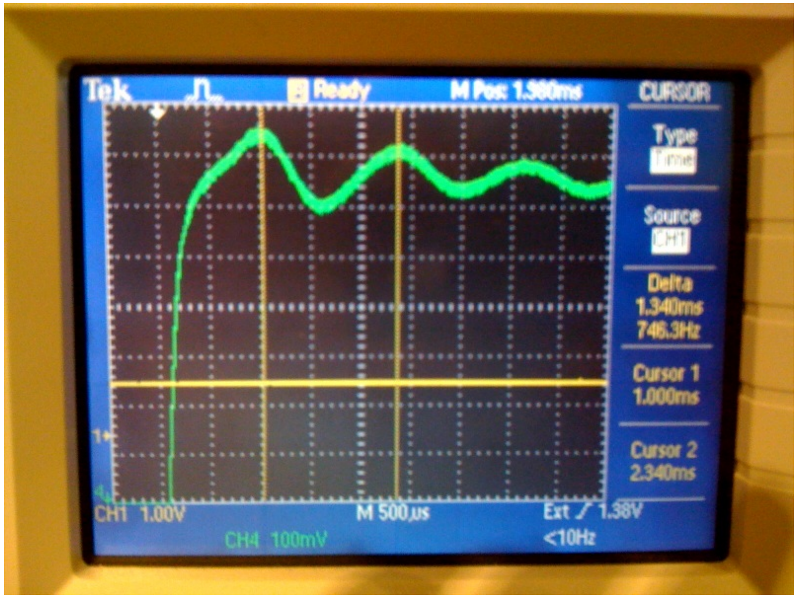
- Measurement of the optics functions of the new lattice
  - Beta beating around 20% in horizontal and 10% in vertical plane
  - Normalized dispersion in striking agreement with the model

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 η by factor 2.65 (MADX prediction: 2.86)



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

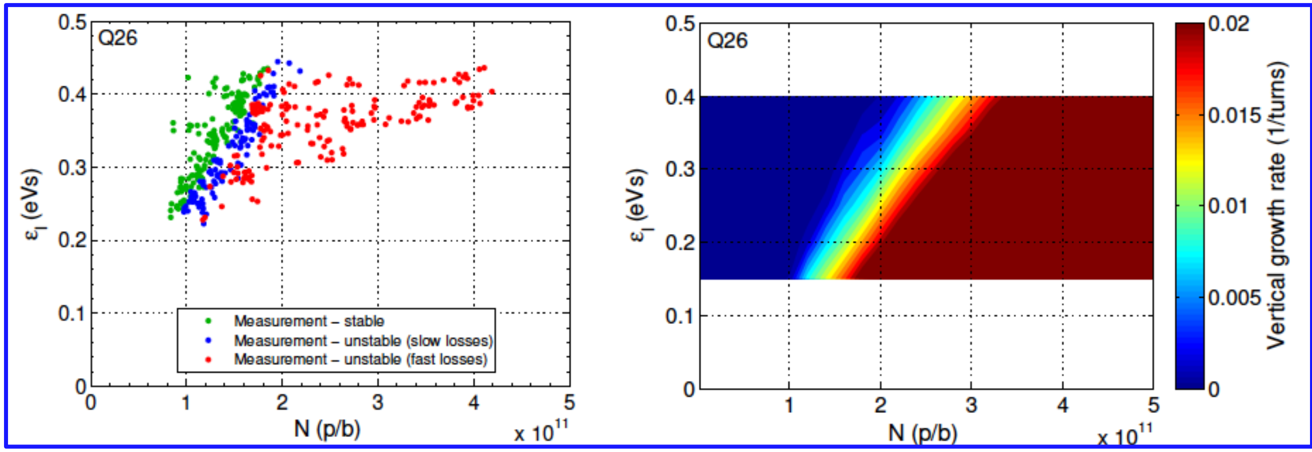


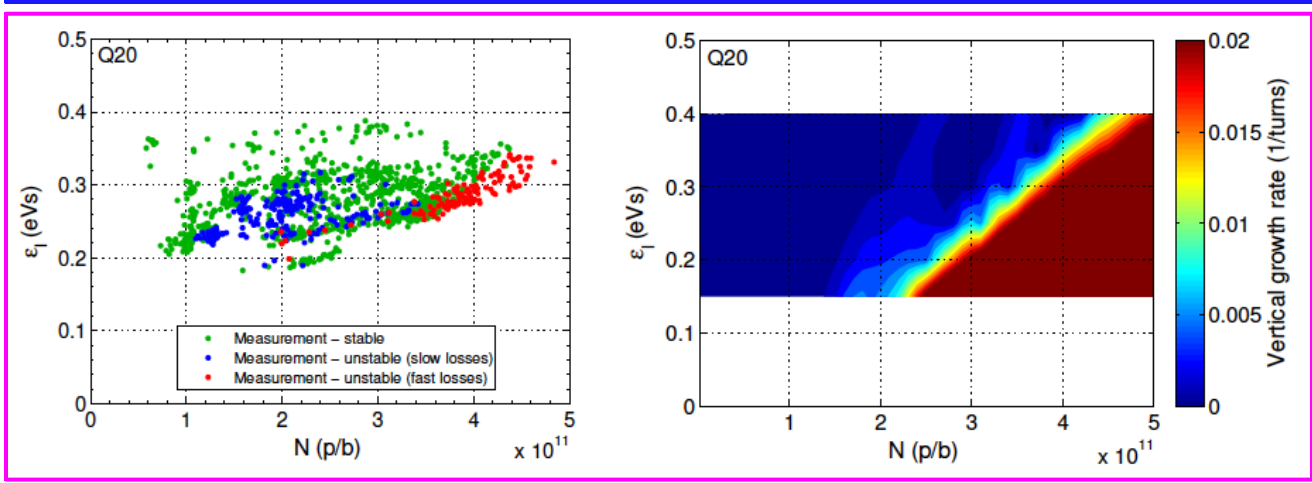
Q20: Fs=746/2=373Hz,
Qs=0.0172/2=0.0086

TMCI threshold

- In nominal optics, measured/simulated threshold at 1.6×10^{11} p/b for low chromaticity
  - High-chromaticity helps increasing threshold, but also losses along the cycle become excessive
- Measured/simulated threshold in Q20 > 4×10^{11} p/b!!!

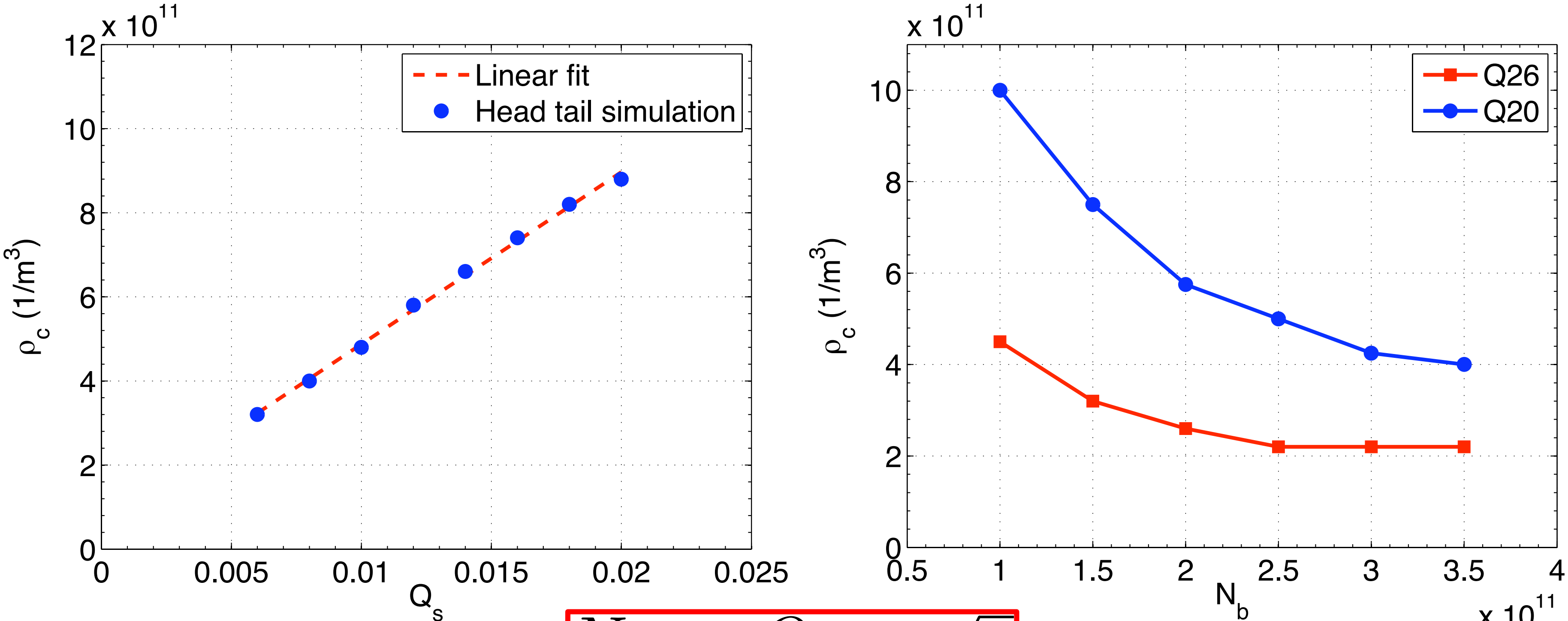
$$\boxed{N_{\mathrm{th}} \propto \frac{\varepsilon_l}{\beta_y}\eta}$$





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**

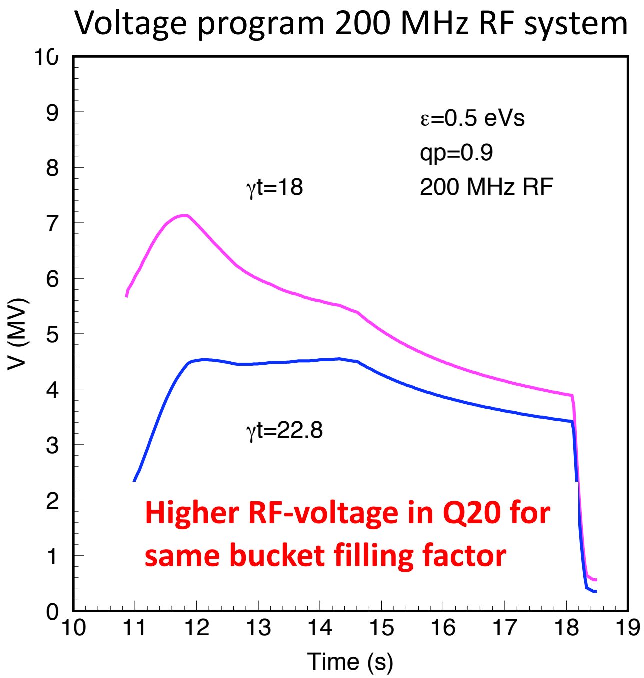
More margin with Q20 if e-cloud becomes issue for high intensity

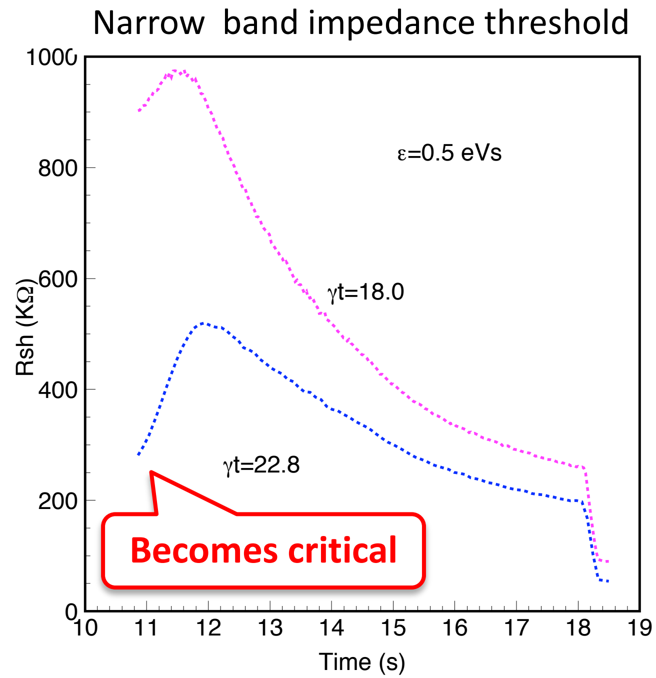
H. Bartosik et al, IPAC2011

Longitudinal impedance threshold

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

E. Shaposhnikova

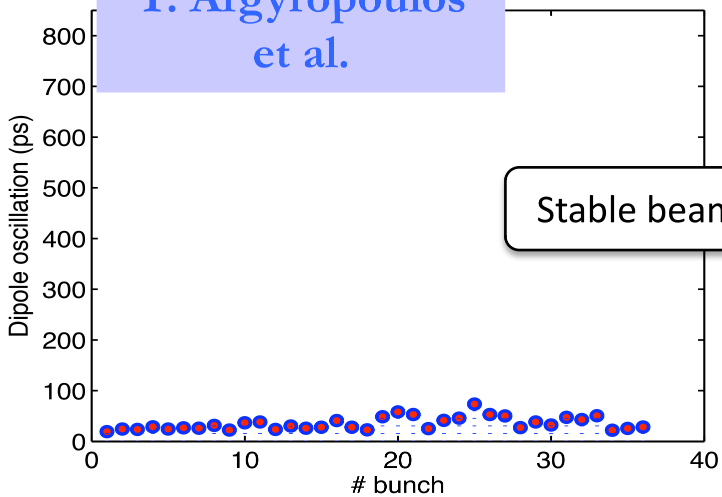




- Impedance threshold has minimum at flat top
  - Controlled longitudinal emittance blow-up during ramp for **Q26**
  - Less (or no) longitudinal emittance blow-up needed in **Q20**
- Instability limit at flat bottom
  - Critical with **Q26** when pushing intensity
  - Big margin with **Q20** (factor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

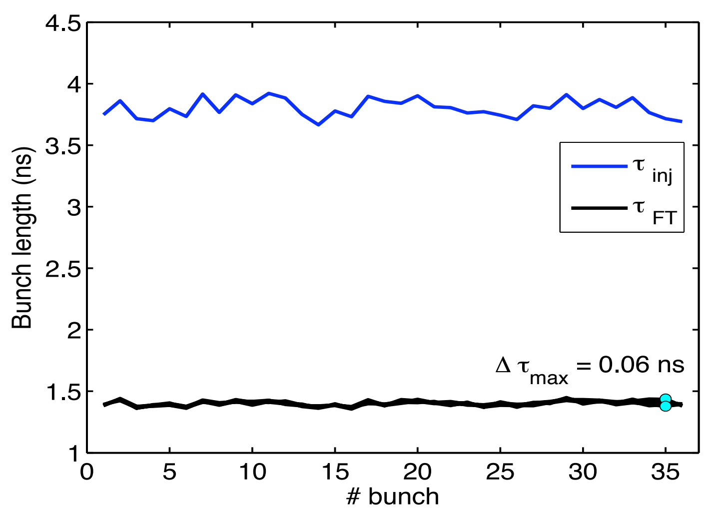
Longitudinal beam stability

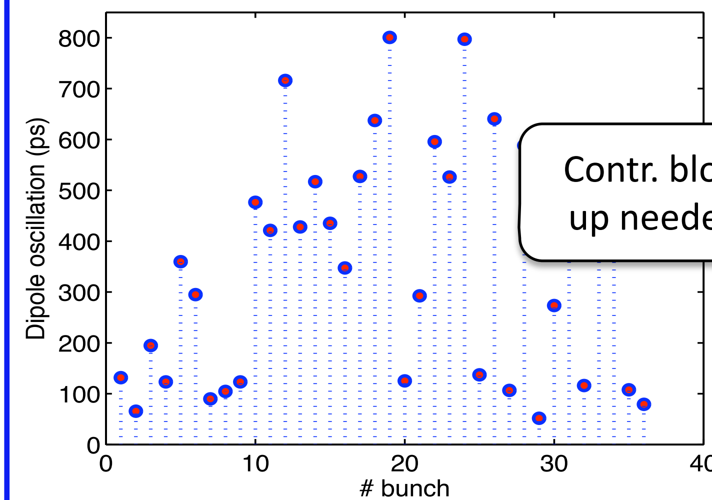
T. Argyropoulos et al.



Stable beam

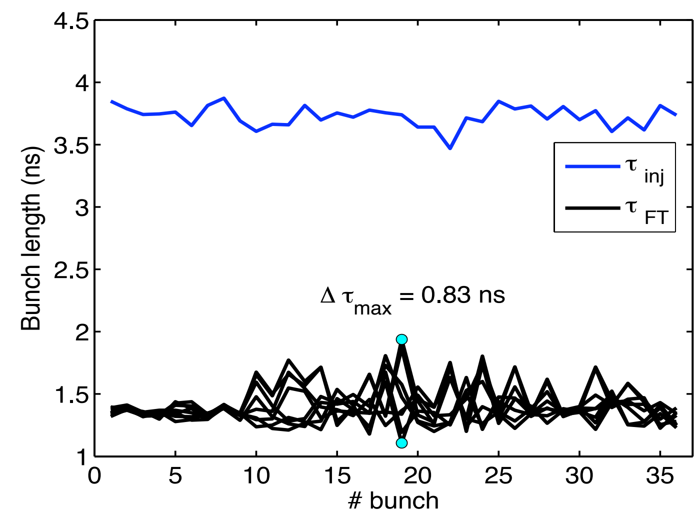
SPS-Q20 ($1.6x10^{11}$ p/b) double harmonic RF





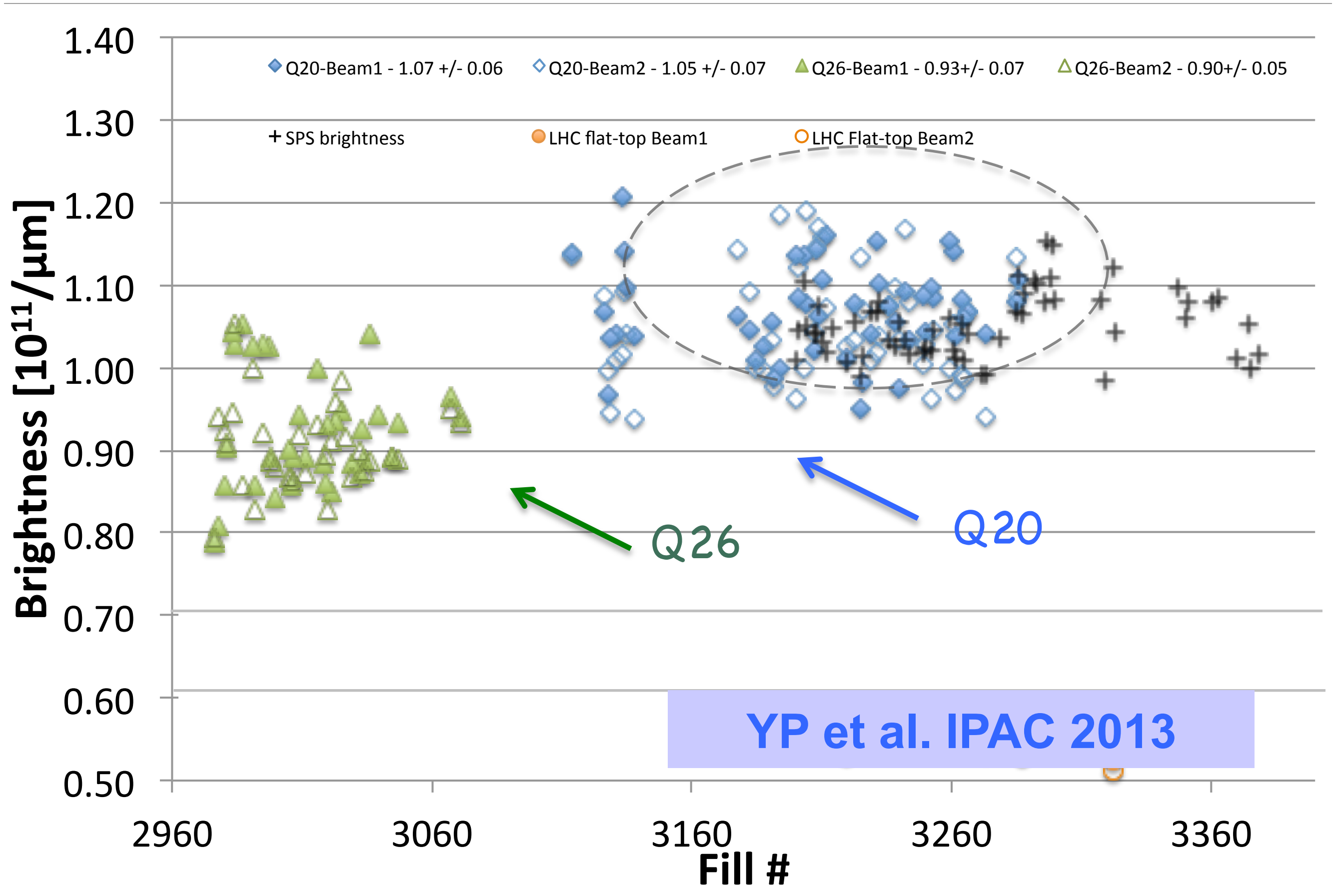
Contr. blow-up needed!

SPS-Q26 ($1.6x10^{11}$ p/b) double harmonic RF



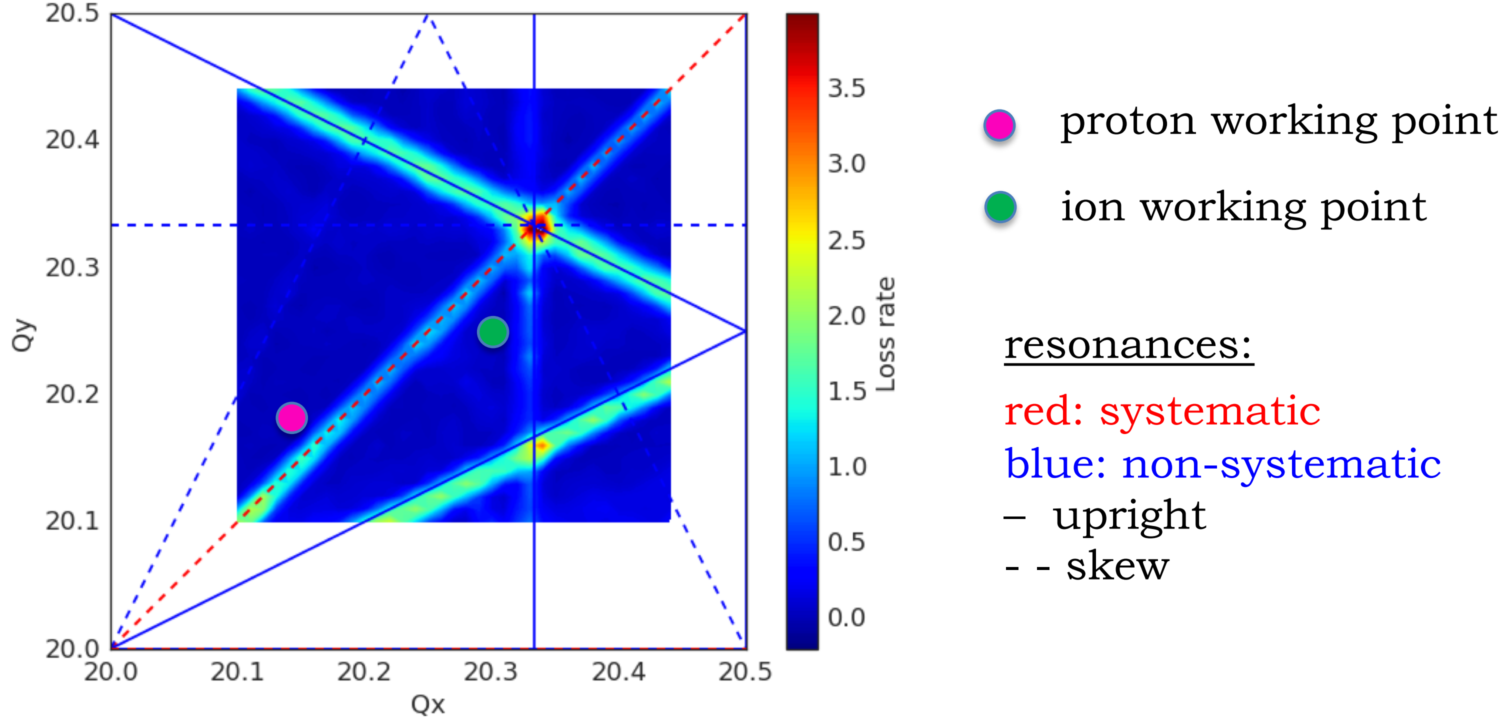
LHC brightness with SPS Q20

- 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



Non-linear dynamics

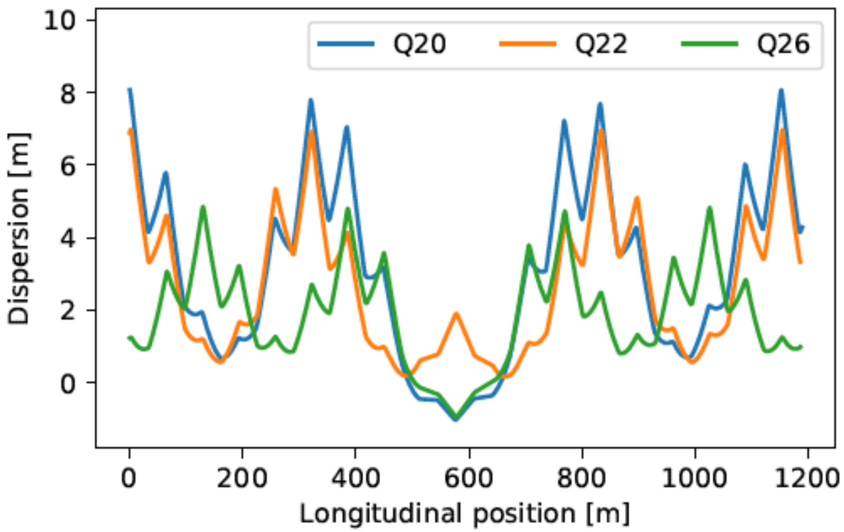
Loss map for low brightness beam



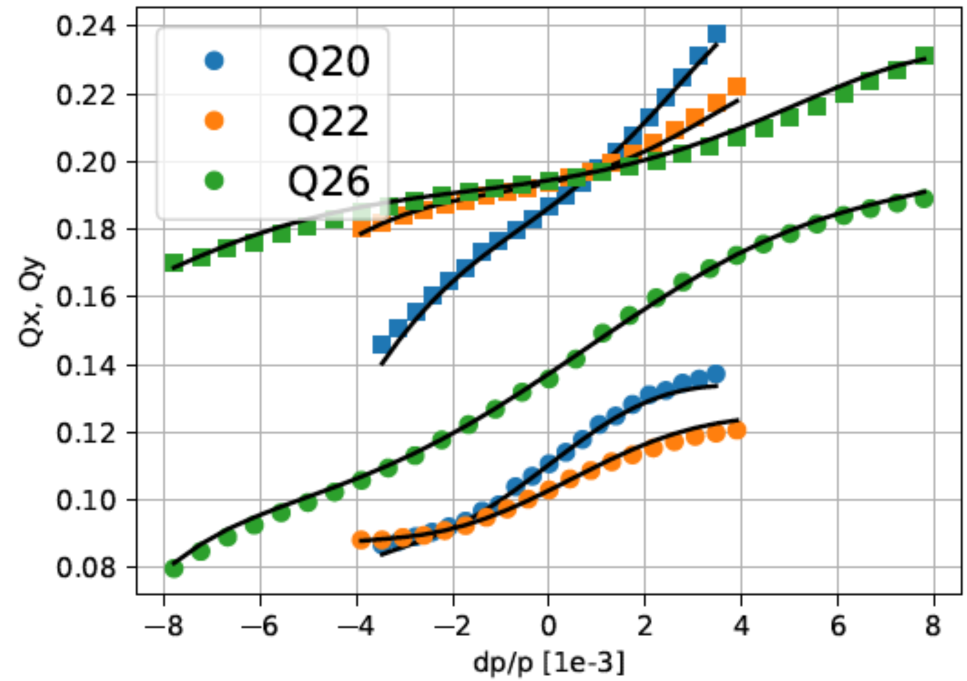
H. Bartosik et al. HB2018

- 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



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

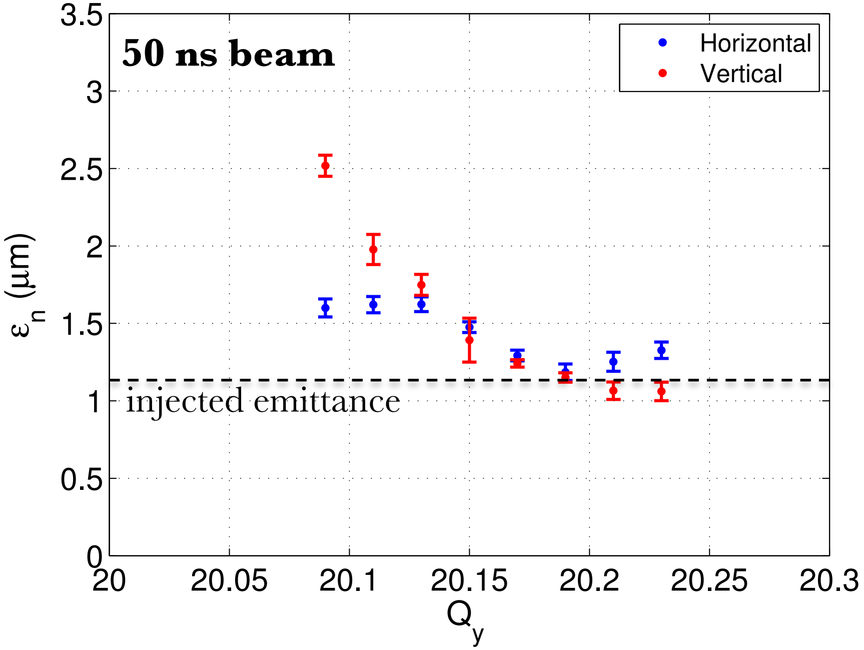
- Estimate "effective" magnet multi-poles that reproduce non-linear chromaticity measurement for three different optics

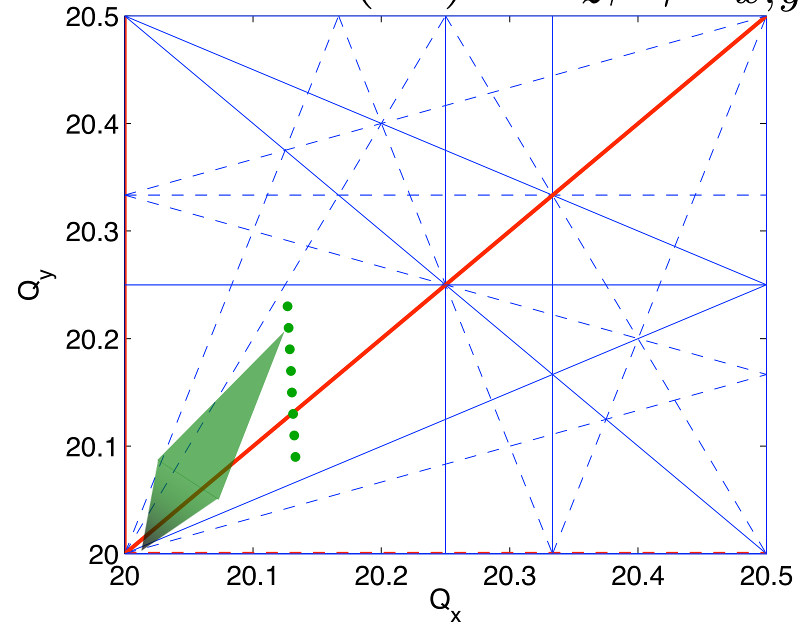
Space-charge

Space-charge tune spread

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

emittance at end of flat bottom



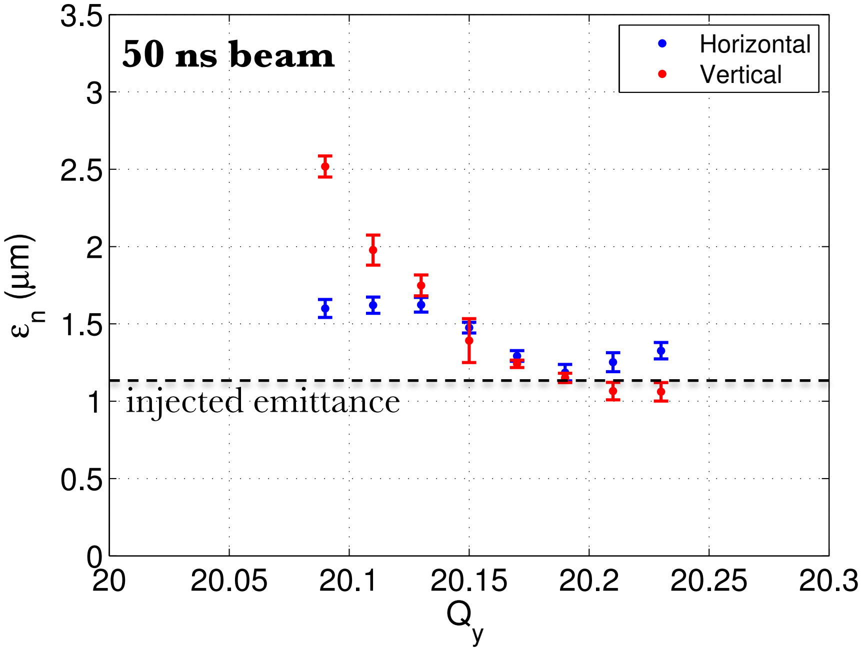


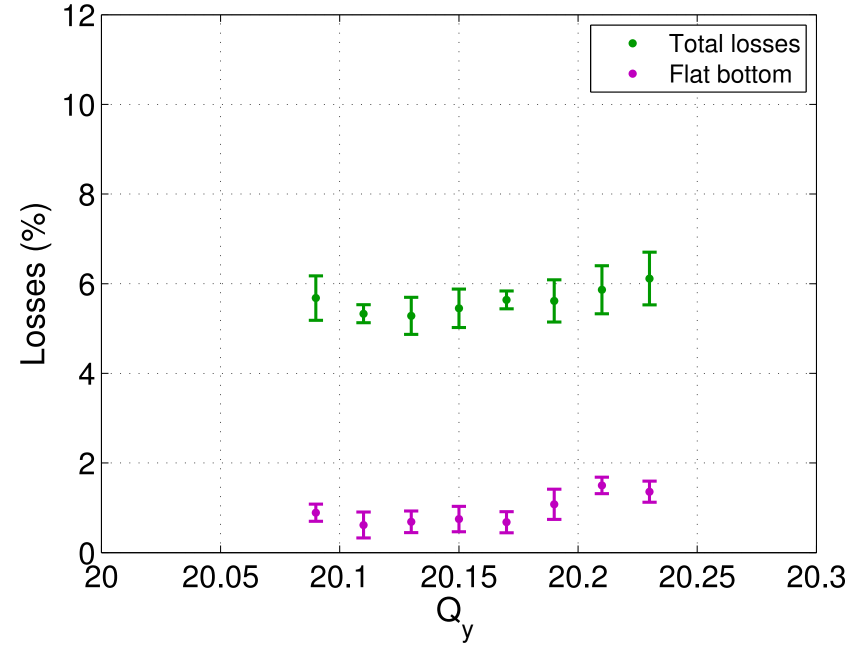
- Vertical tune scan with high brightness beam for 10 s storage time
  - N = 1.95x10[11] p/b (at injection)
  - ε ~ 1.1 μm (at injection)
  - Transmission to flat top around 94% (very small losses on flat bottom)
  - Budget of 10% losses and 10% blow-up allows for tune spread of ΔQy=0.21

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

Space-charge tune spread

emittance at end of flat bottom





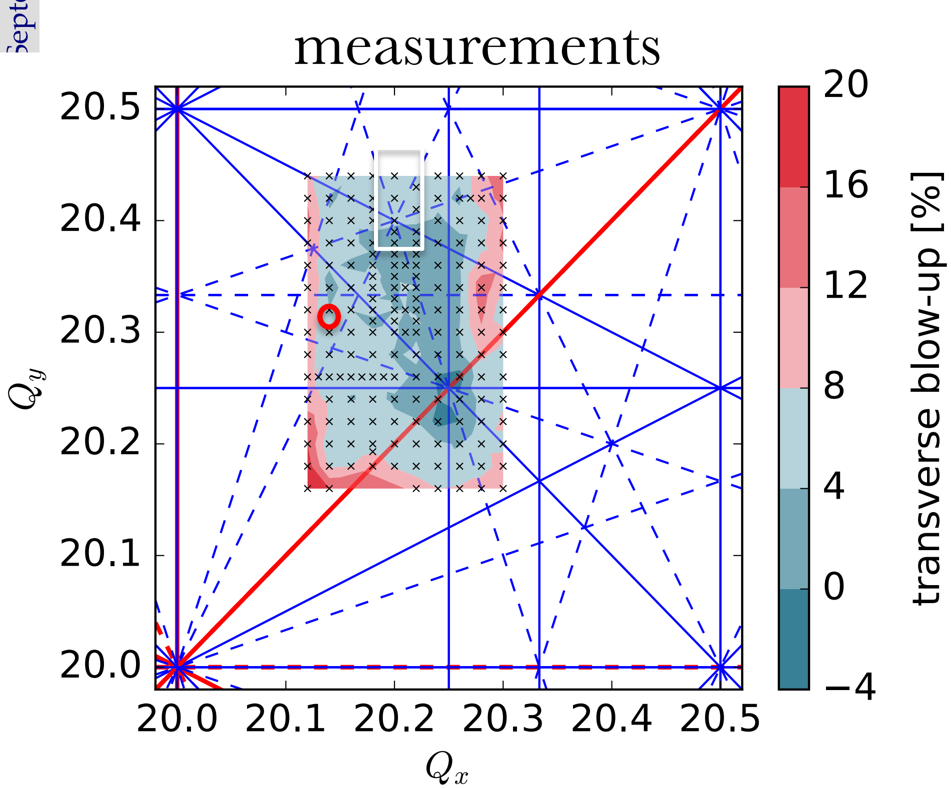
- Vertical tune scan with high brightness beam for 10 s storage time
  - N = 1.95x10^{11} p/b (at injection)
  - ε ~ 1.1 μm (at injection)

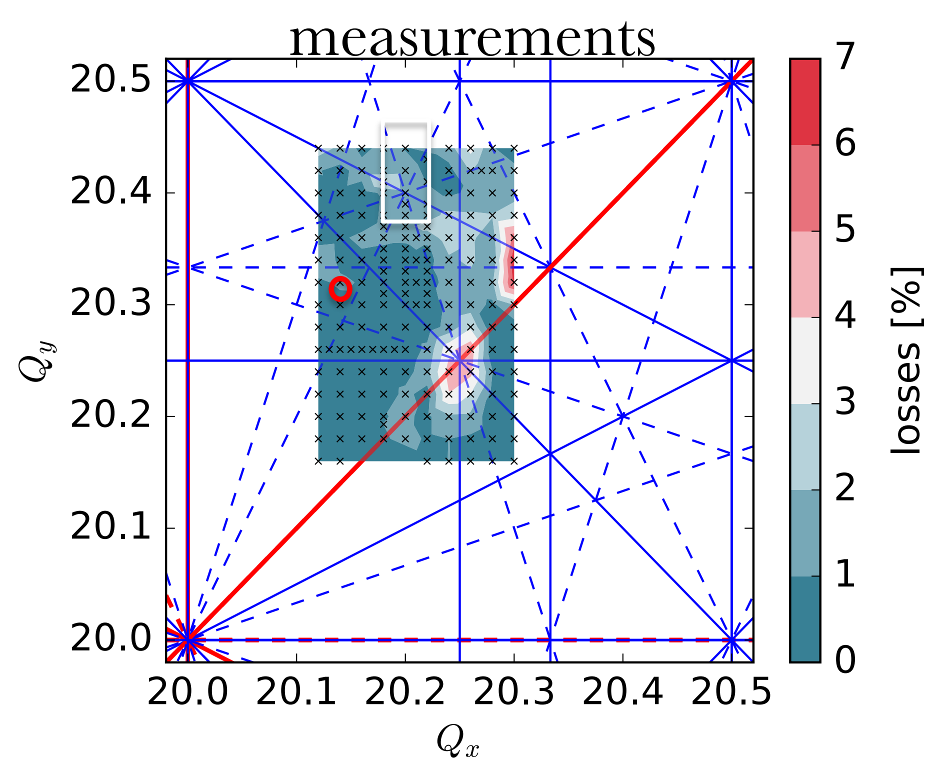
  $\Delta Q_x / \Delta Q_y$ ~ 0.10/0.20

  - 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)

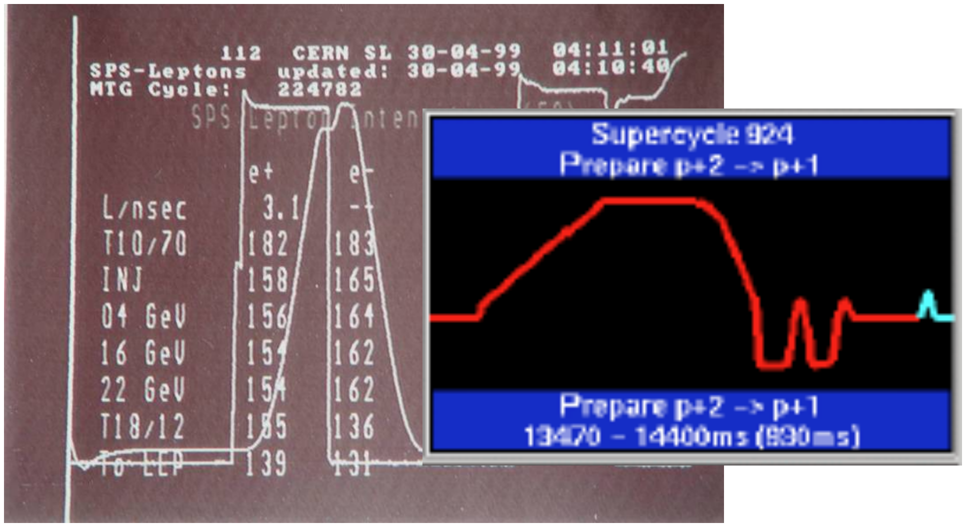




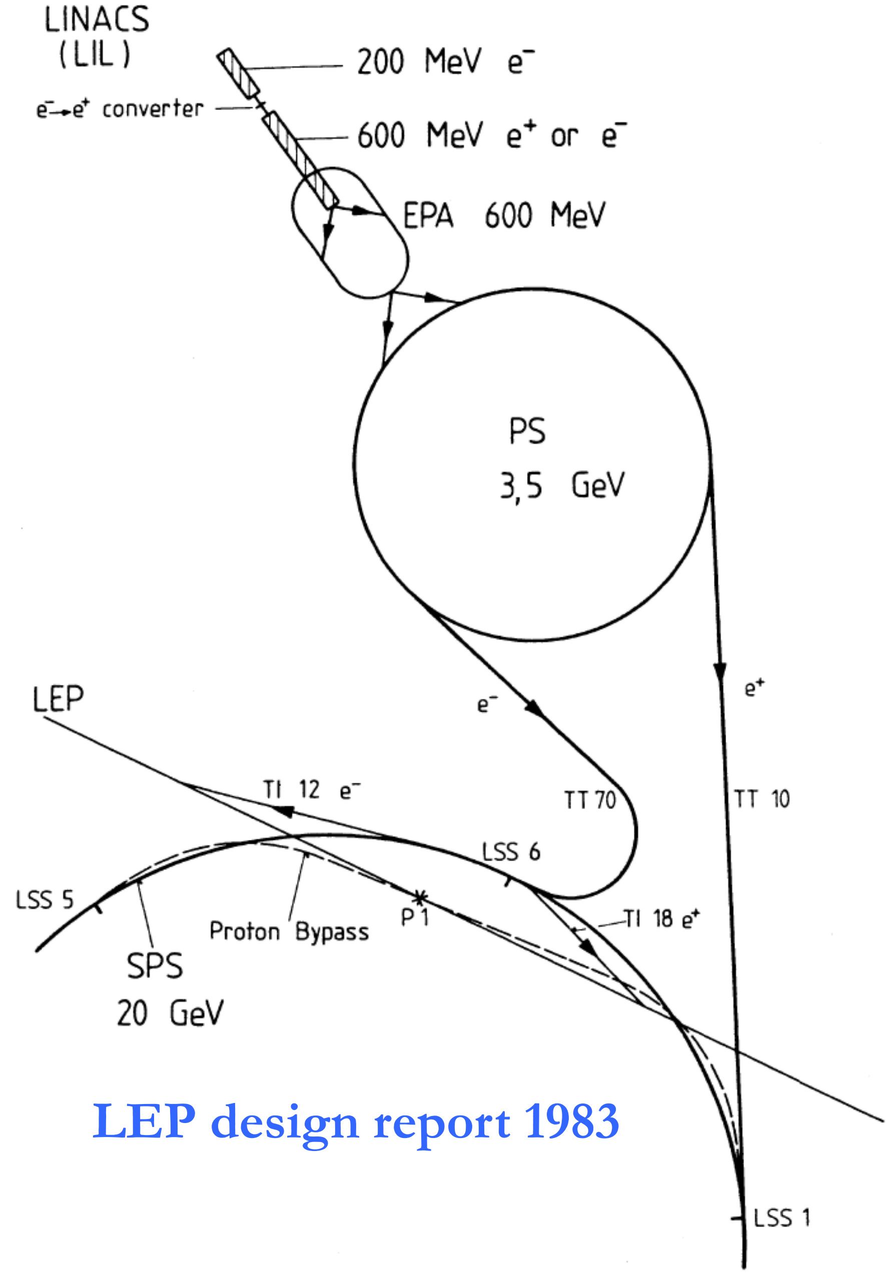
Electron-positron dynamics

SPS as LEP Injector

P. Collier – Academic Training 2005

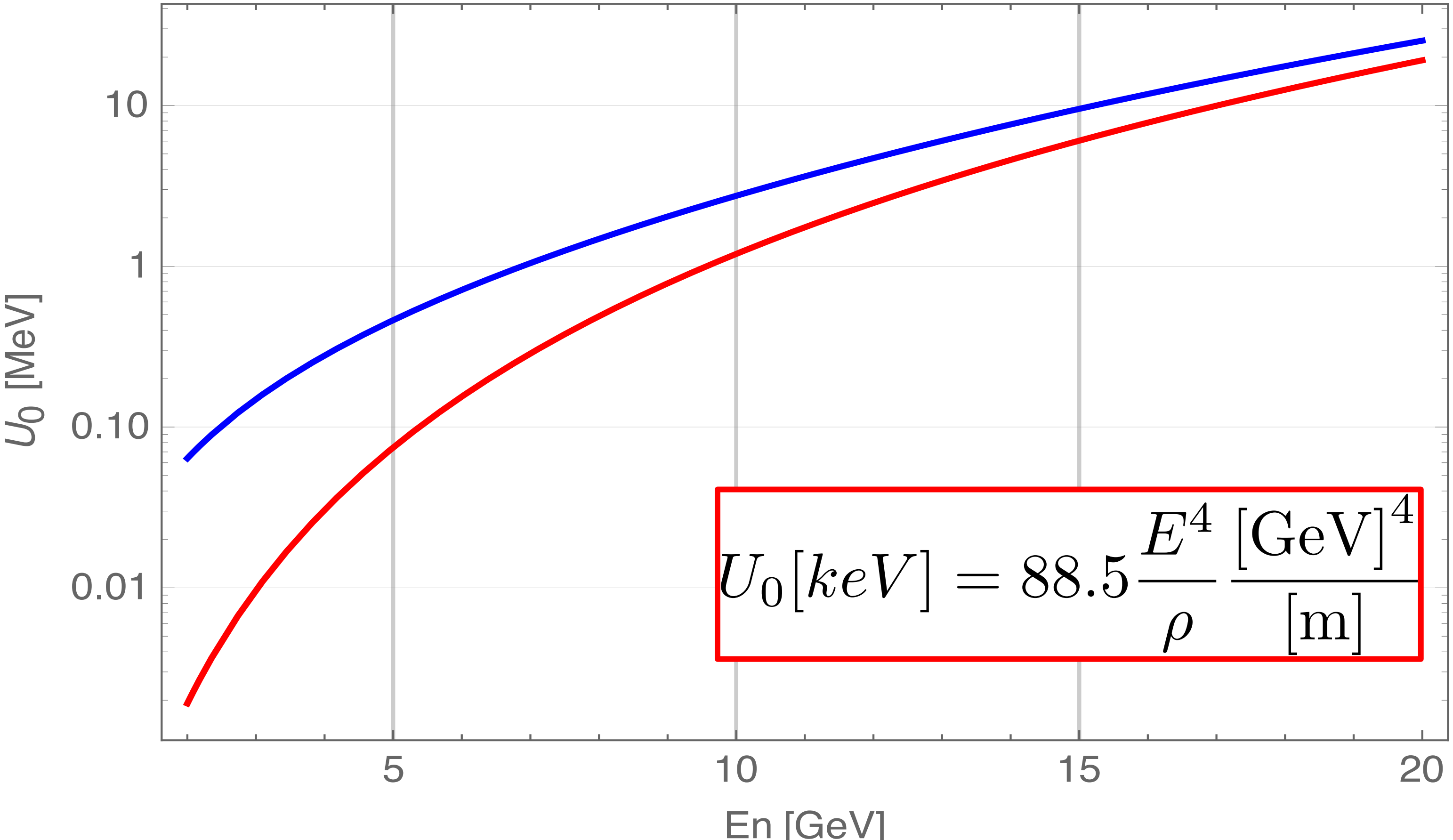


- LEP filling interleaved with proton operation
- 4 cycles with 4 bunches ($2e^+$, $2e^-$) evolved to 2 cycles with 8 bunches (~**2.5x10^{10}** p/b)
- Energy to LEP: 18 → 20 → 22 GeV
- Lots of RF for leptons (200MHz SWC, 100MHz SWC, 352MHz SC),
- 2 Extractions in Point 6 towards LEP



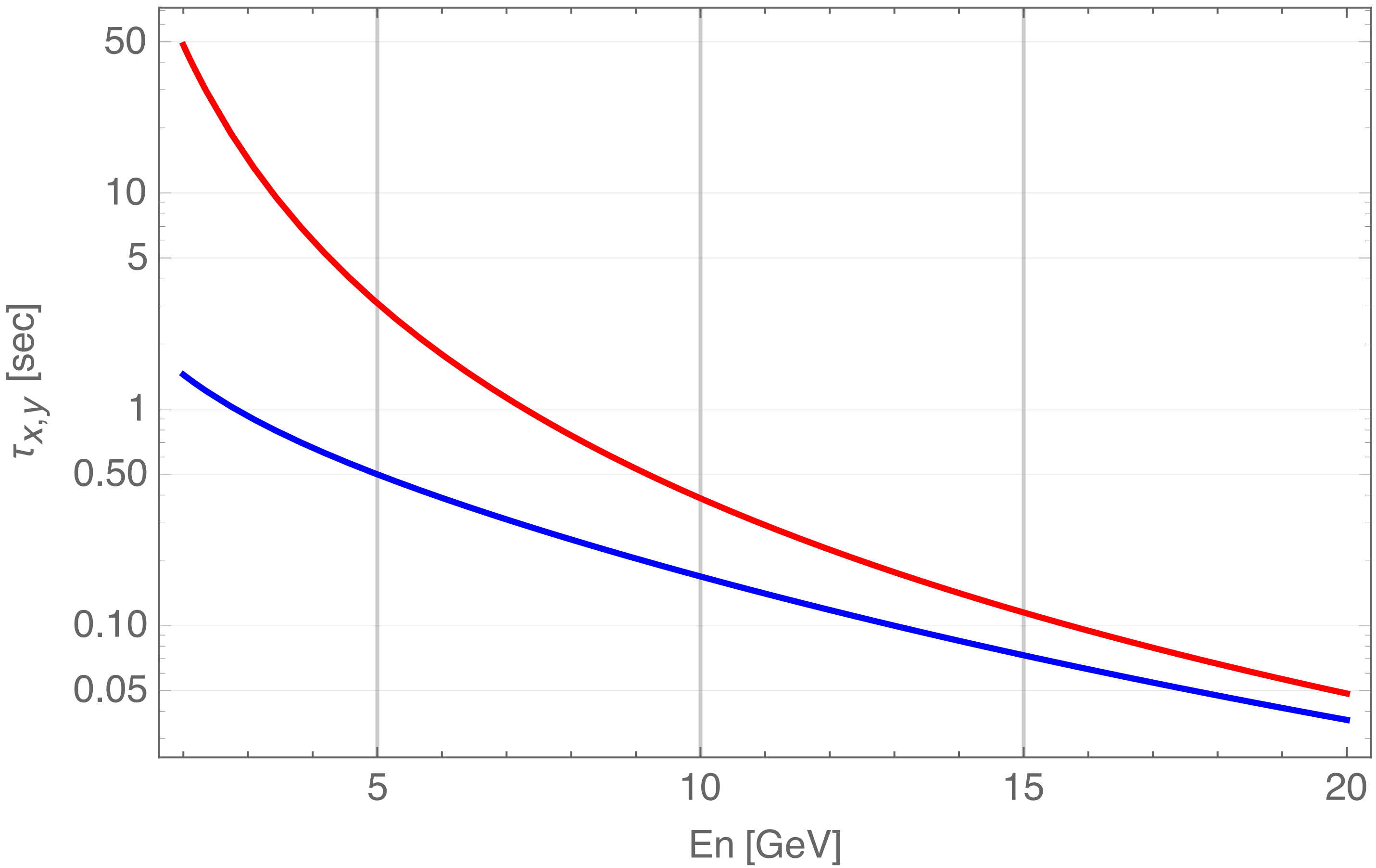
LEP design report 1983

Energy loss/turn



- 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

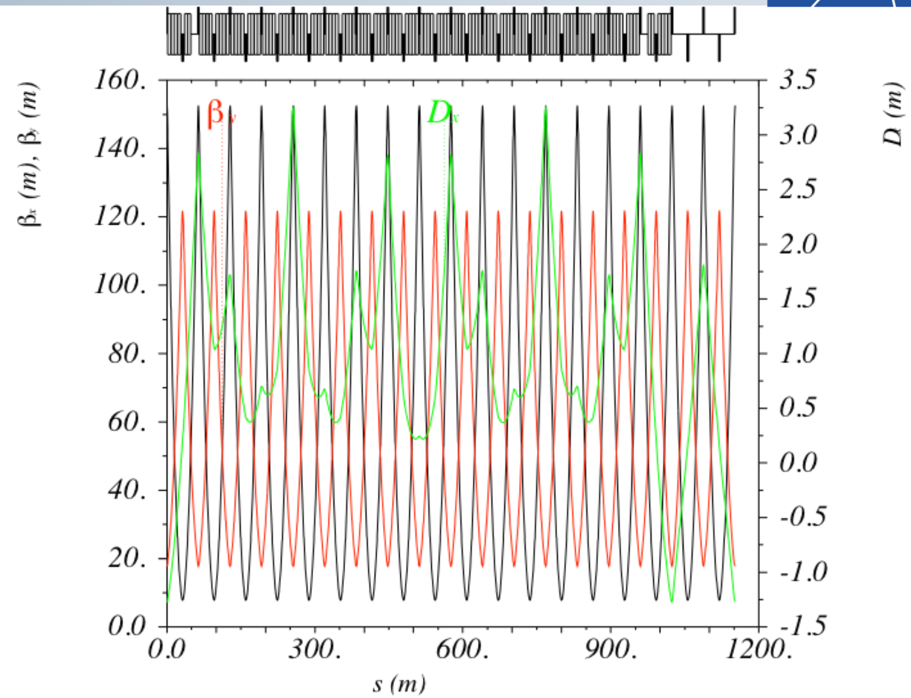
Damping time

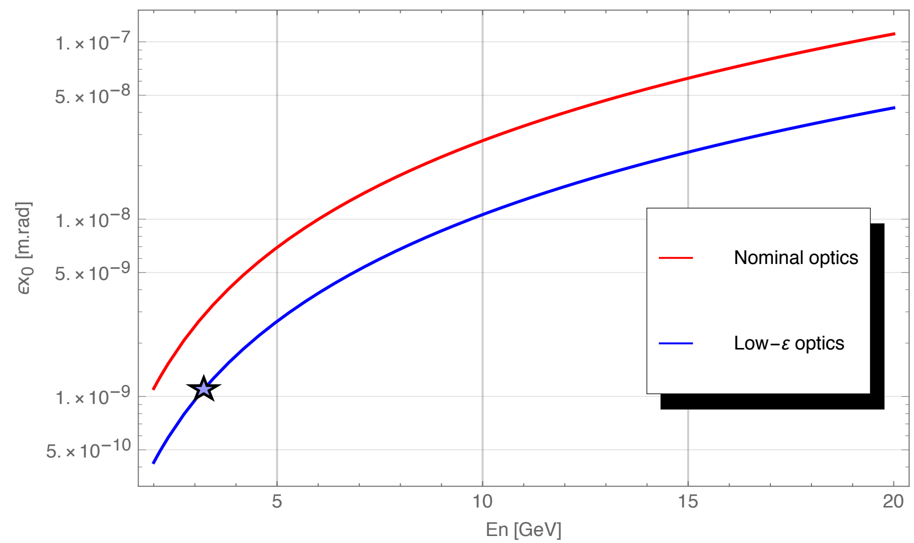


- **Damping time** at injection (3.5 GeV) **very large (9 s)**
- A 2-m **3.5T damping wiggler** could enhance damping for low energies to below 1 s (good for instabilities)

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 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