Designing a synchrotron - A real life example

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CERN Accelerator School
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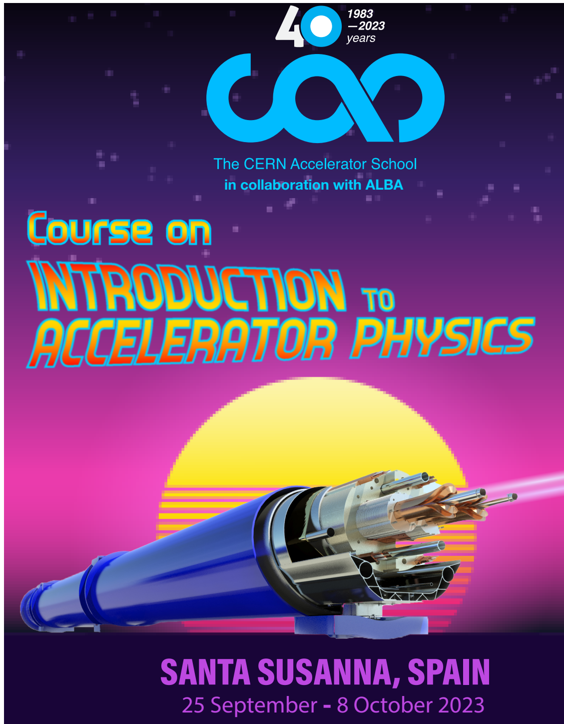

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Purpose of the Lectures

- Review several **aspects** of **beam dynamics** (mostly) presented in the introductory CAS lectures, applied to the **design** and **operation** of a **real synchrotron**

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  - ❑ Choice of **basic parameters**
    - Energy, bending field and circumference
  - ❑ **Optics** design
    - Cell optics, insertions, transition energy
  - ❑ **Collective effects**
    - **Instabilities, Space-charge, e-cloud**
  - ❑ **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

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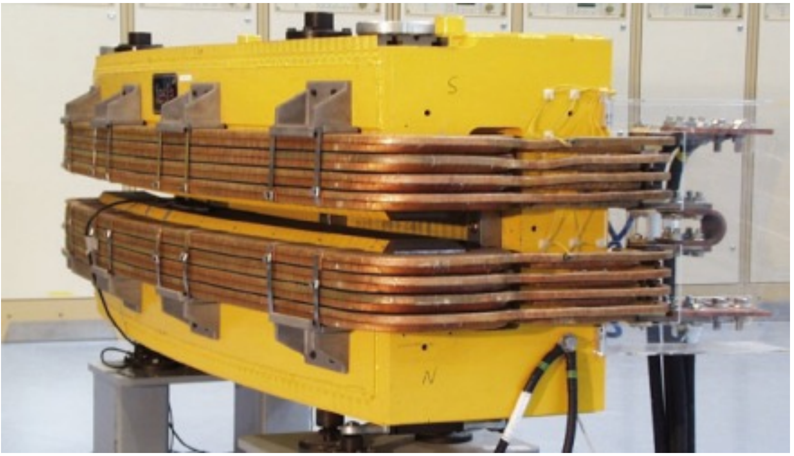
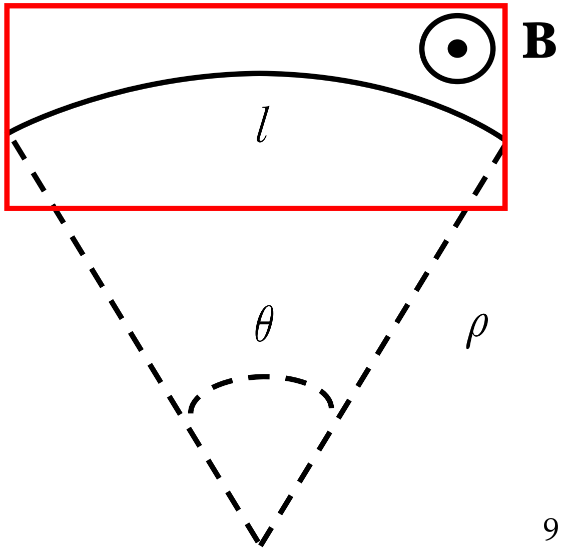
  - High energy **synchrotron** serving **fixed target** experiments (West Area, North Area, CNGS, HIRADMAT)
  - **Collider** of protons and anti-protons (W and Z bosons discovery in 1983)
  - Accelerating **electrons** and **positrons** and injecting them to the Large Electron-Positron (**LEP**) Collider
  - 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





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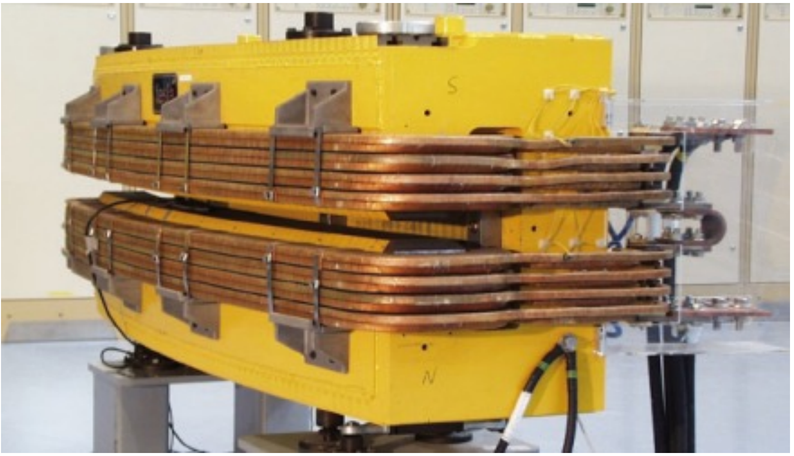
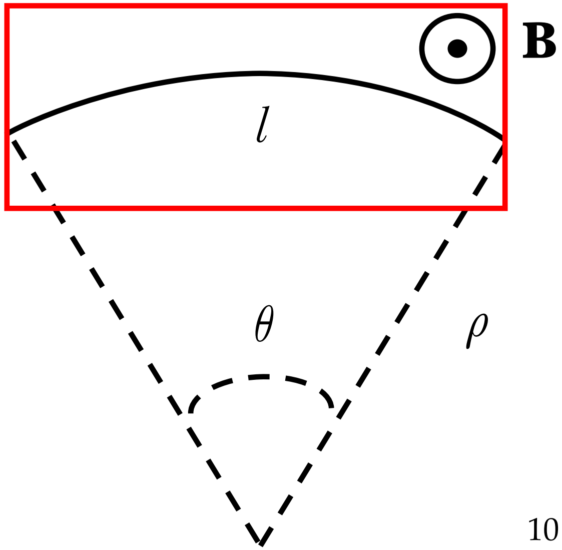


  - **Bending angle** $\theta = \frac{2\pi}{N}$
  - **Bending radius** $\rho = \frac{l}{\theta}$
  - The **magnetic rigidity** is $B\rho = \frac{\beta E}{q}$
  - The **integrated dipole strength** is

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



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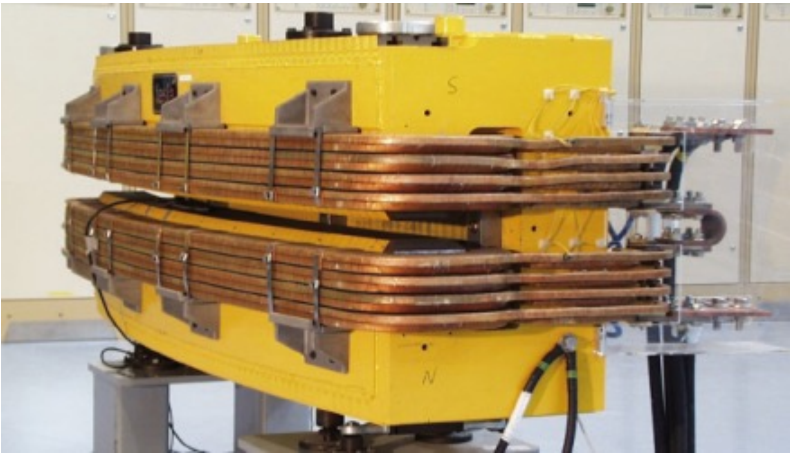

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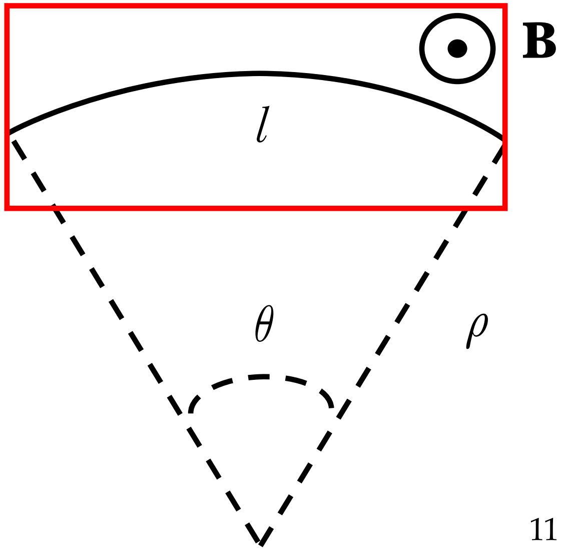
- By imposing a **dipole field**, the **dipole length** is **fixed** and vice versa
- The **higher** the **field**, the **shorter** or **less dipoles** can be used



Circumference

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

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

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

- The ring **circumference** becomes

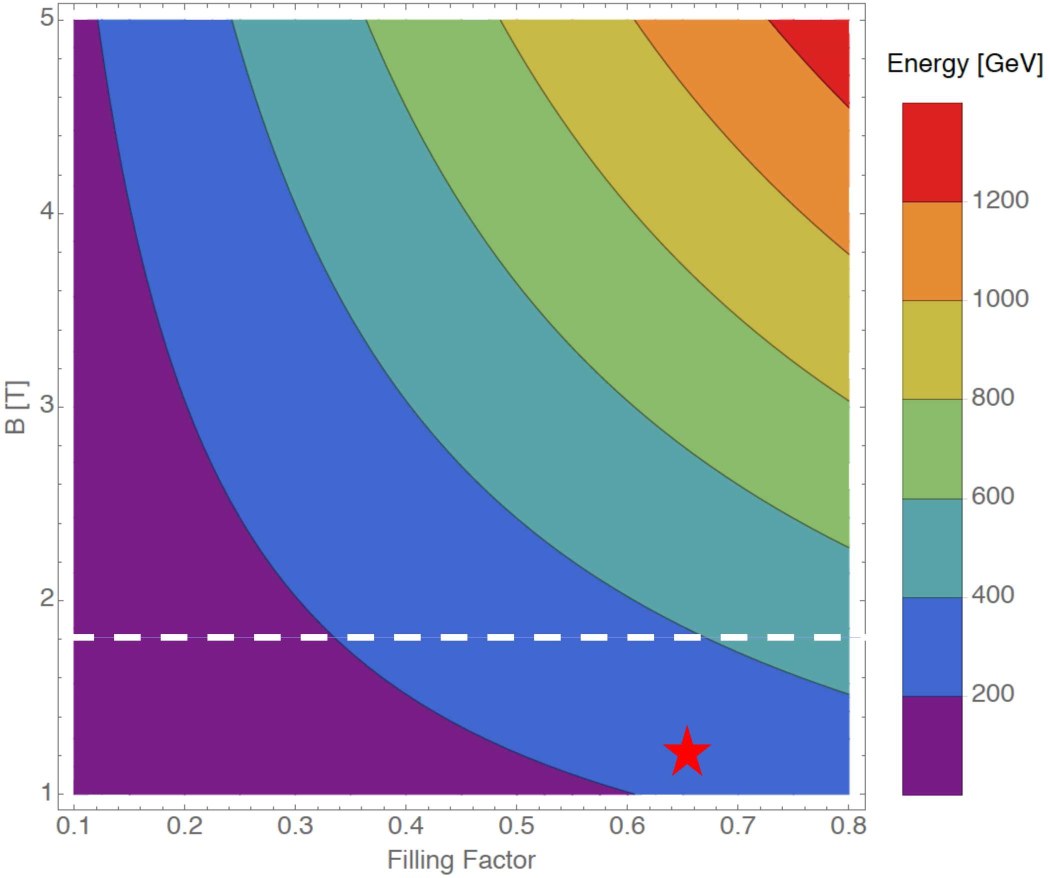
$$C = \frac{2\pi}{k_f B}\frac{\beta E}{q}$$

- 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

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



- 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

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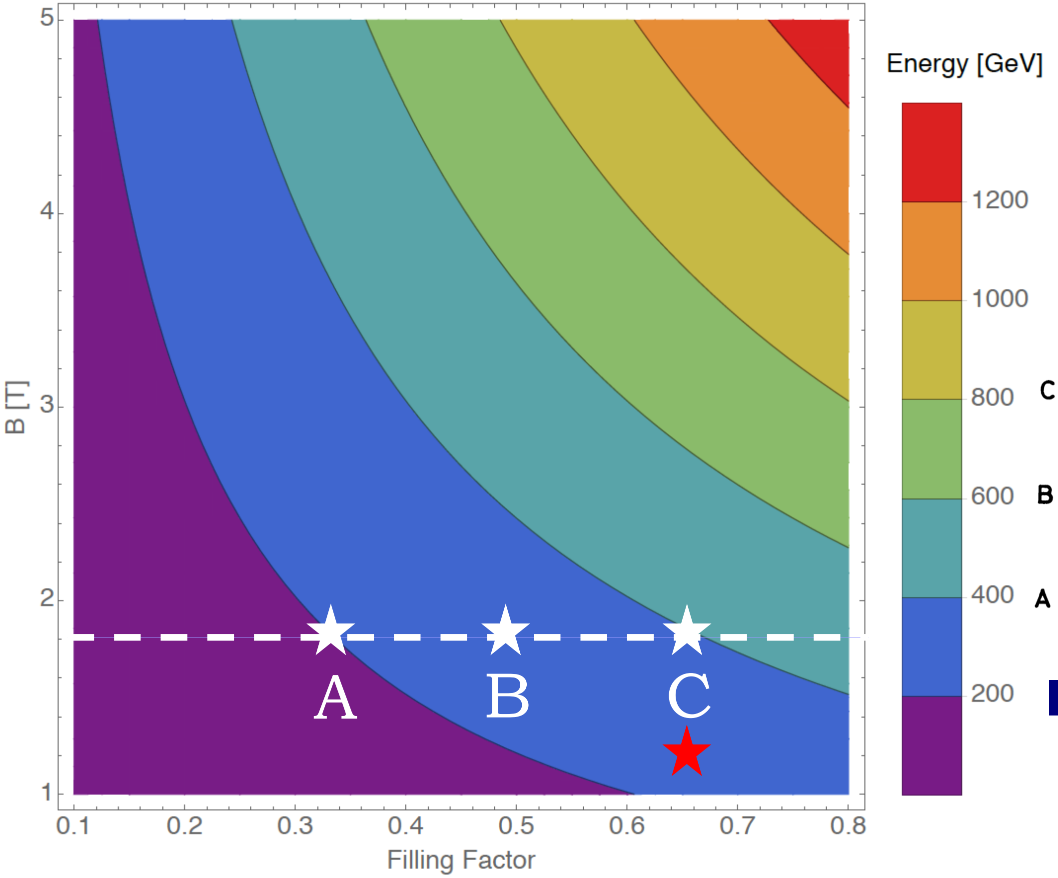

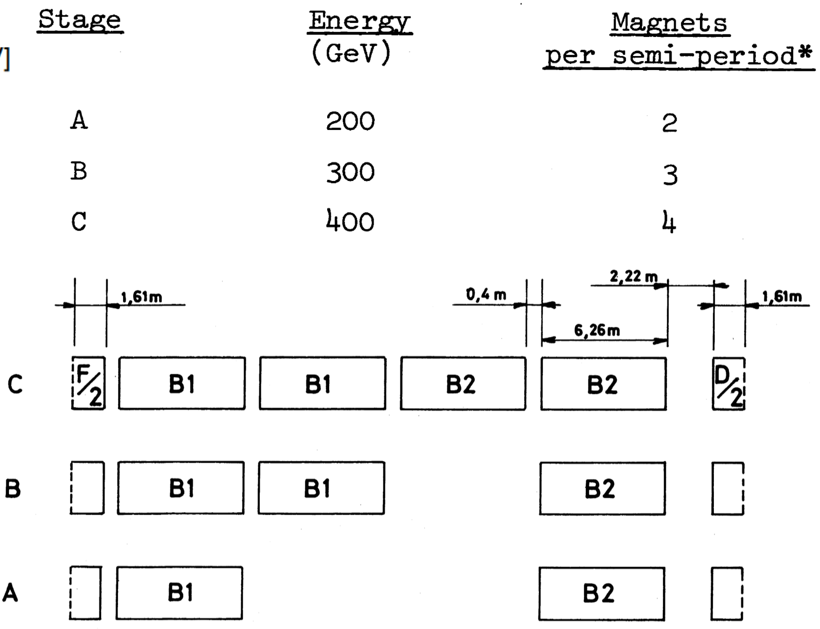

Stage	Energy (GeV)	Magnets per semi-period*
A	200	2
B	300	3
C	400	4

- 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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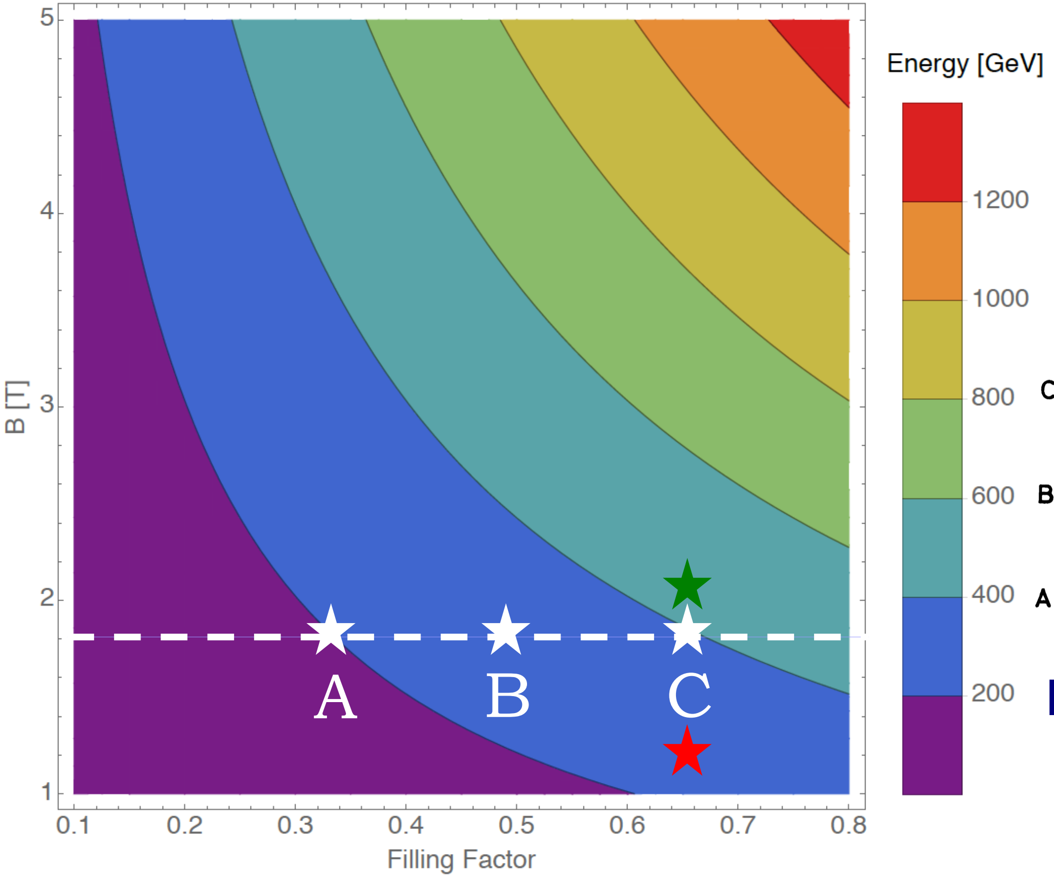

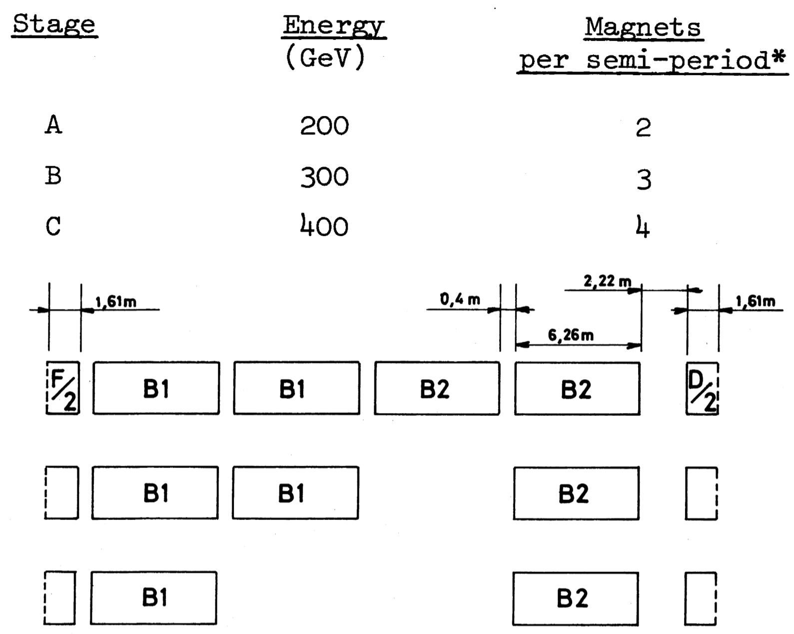

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- SPS dipoles have been pushed to beyond **2 T** to reach **450 GeV**

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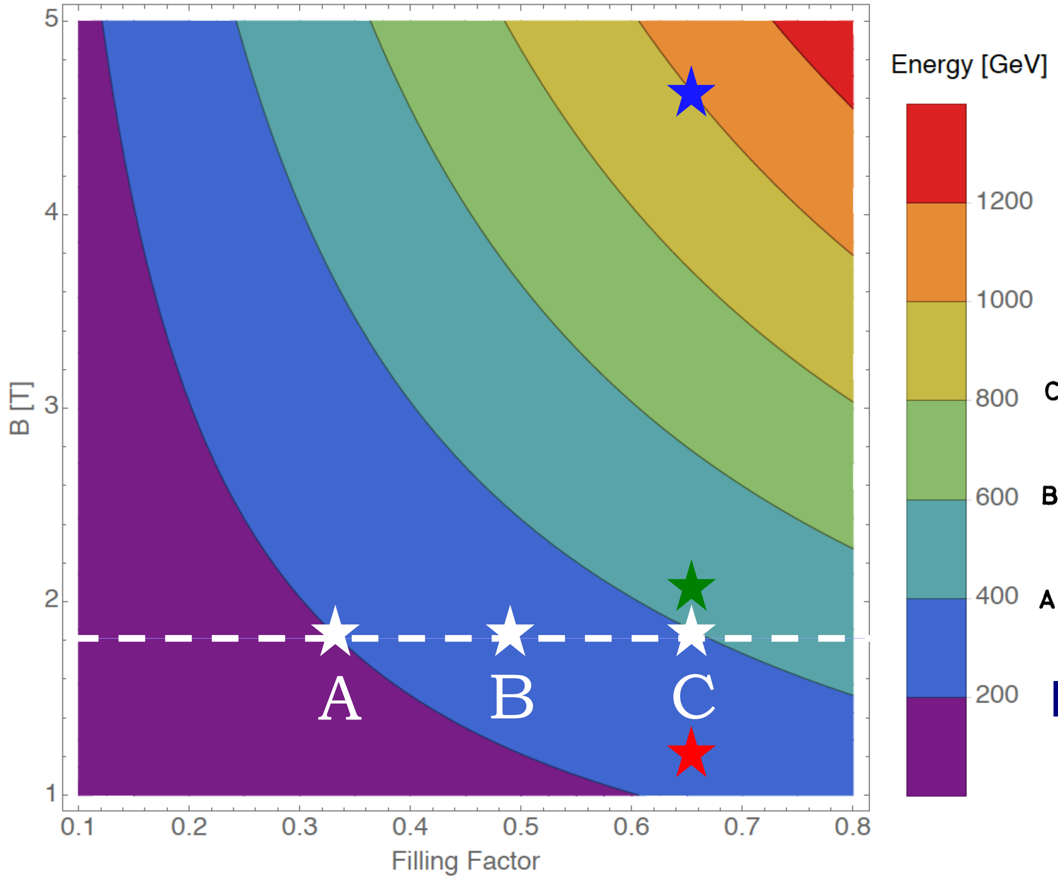

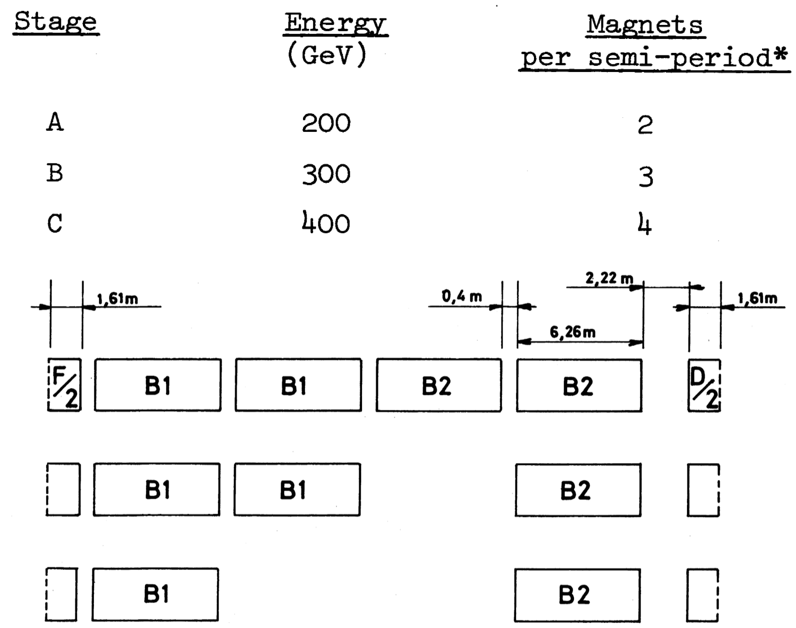

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- SPS dipoles have been pushed to beyond **2 T** to reach **450 GeV**

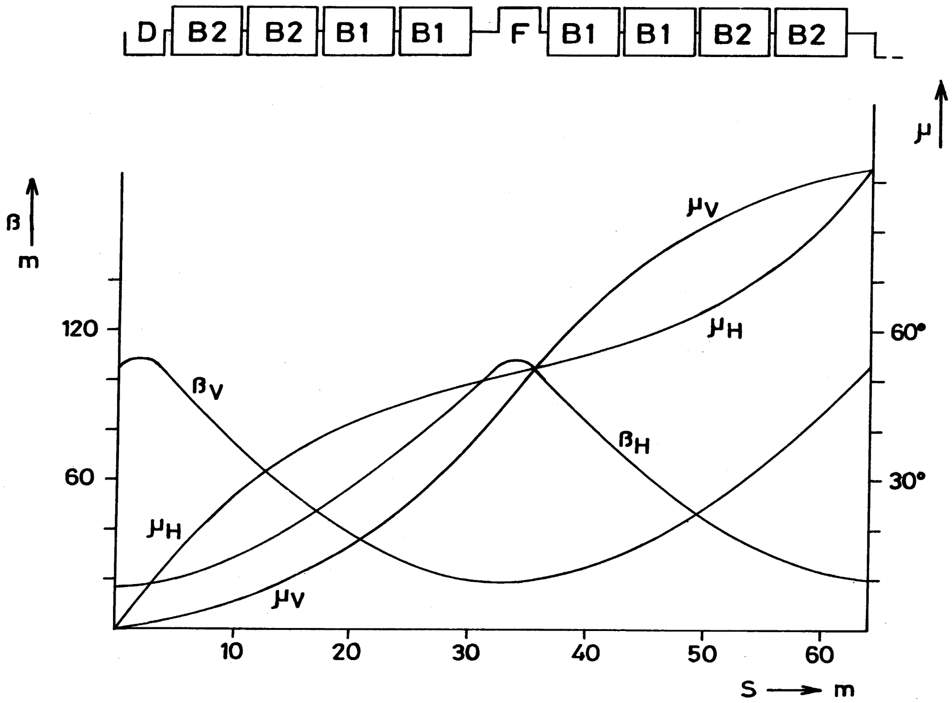
- **Super-conducting** option could raise the energy to **1 TeV**

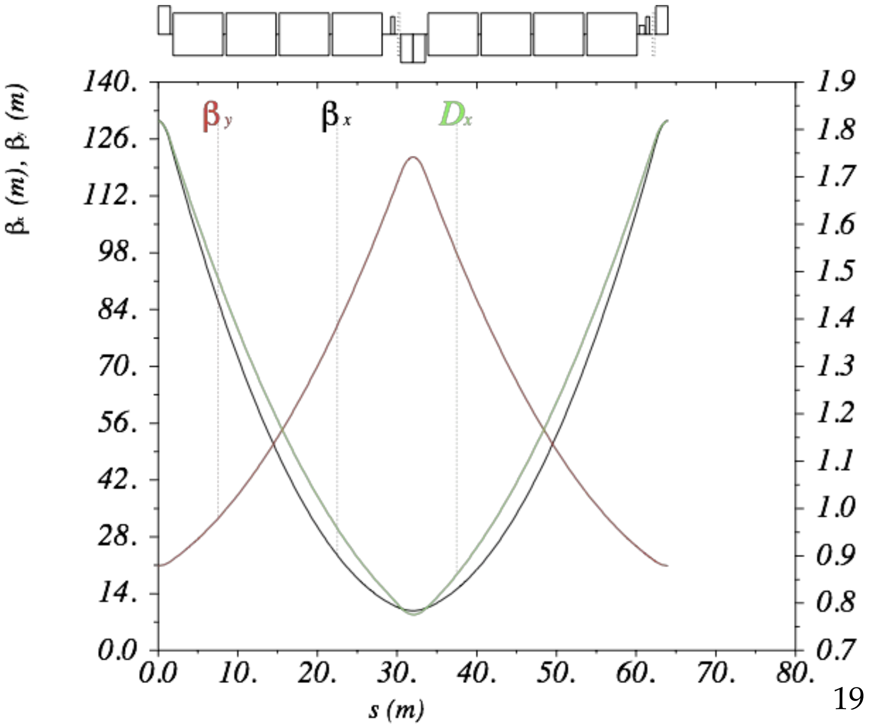
Optics design and Magnet system

Basic cell

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

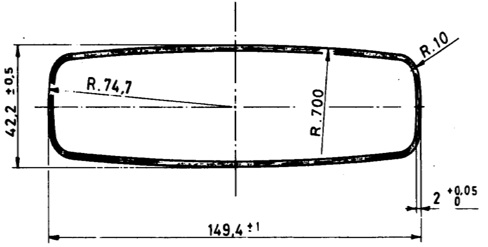
The 300 GeV Program, CERN/1050, 14/01/1972



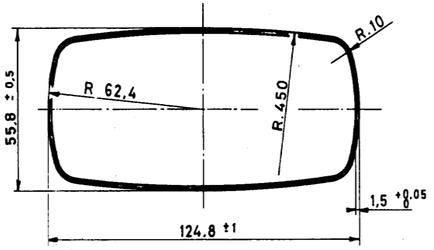


Magnet aperture

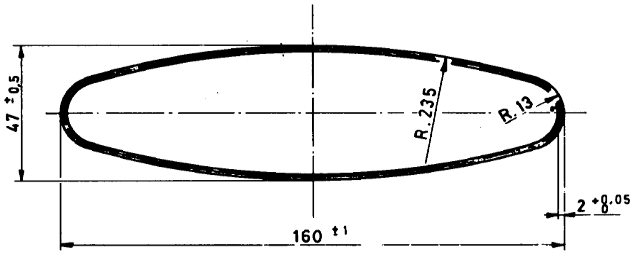
- Magnet apertures follow beta function and dispersion evolution



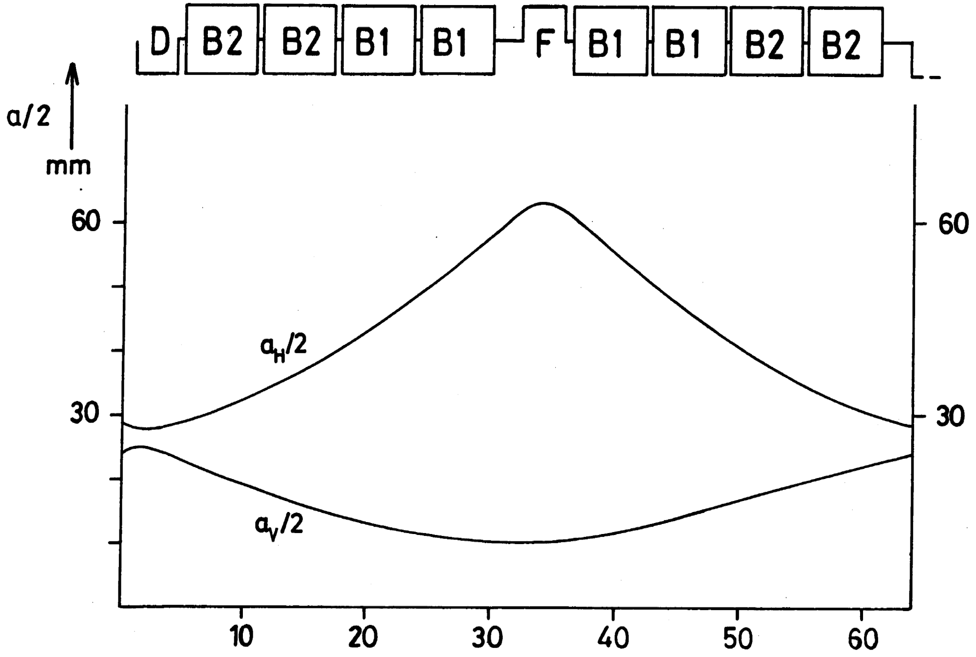
Dipole B1

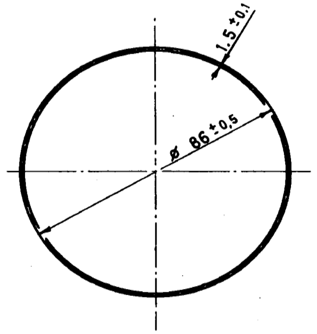


Dipole B2



Quadrupole F





Quadrupole D

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

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

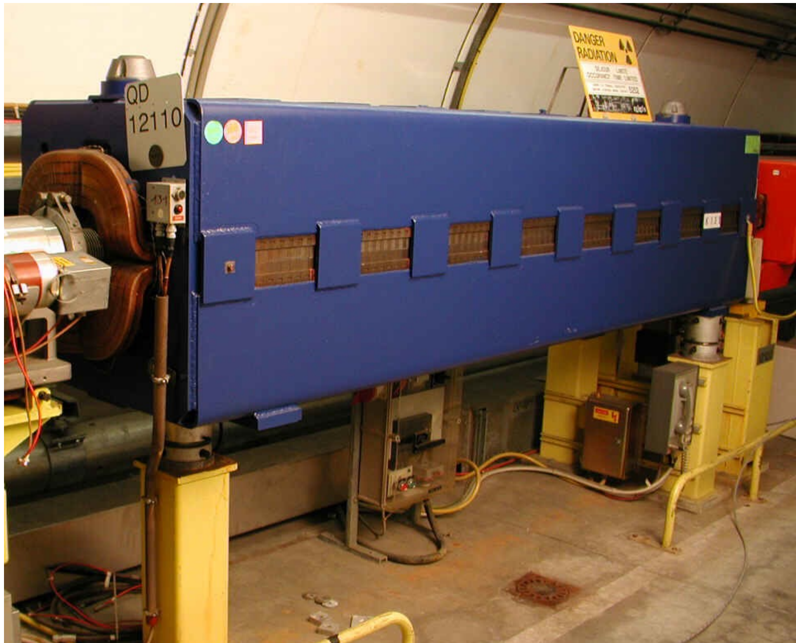
- Maximum field of **2.02 T**, for reaching 450 GeV
- High mechanical stress on coils

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

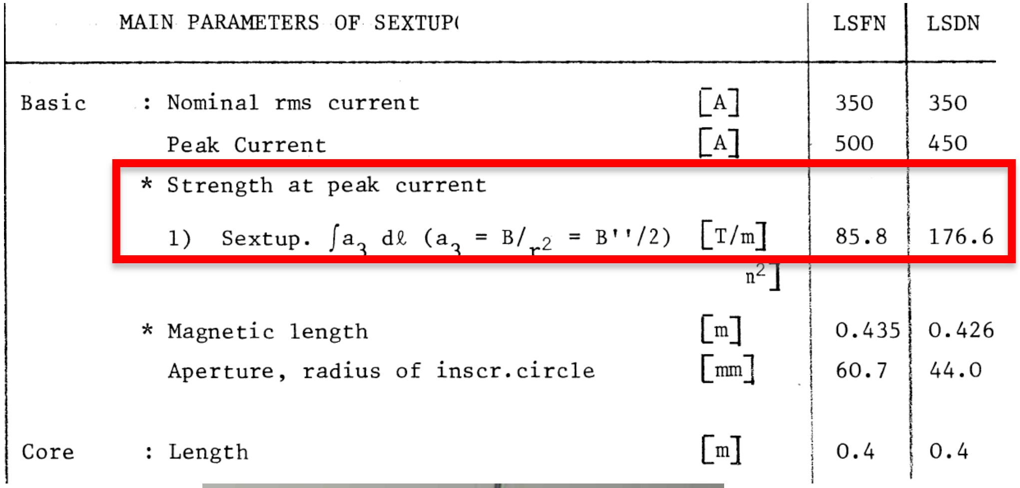
D. Tommasini CERN/TE-Note-2010-003

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

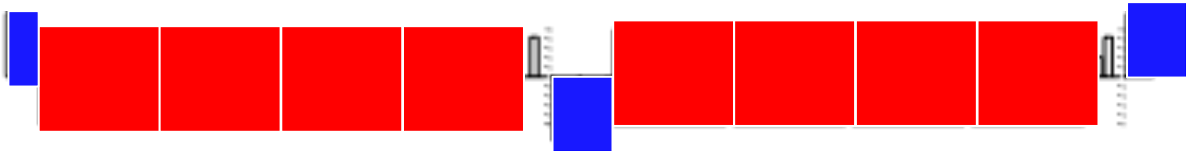
M. Giesch, CERN/SPS/80-3/AMS, 1980



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] n^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



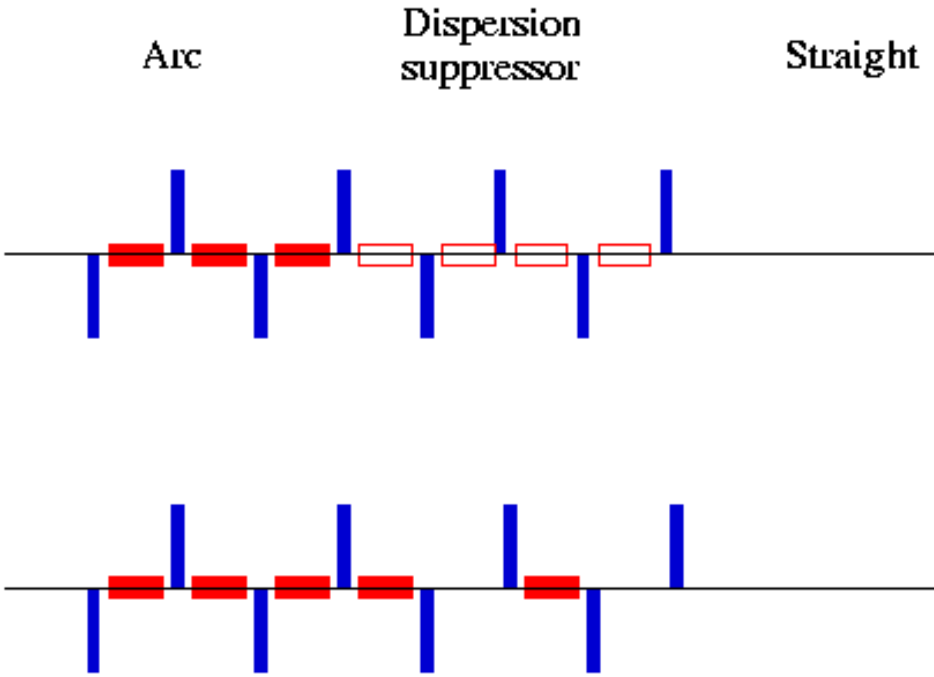
Dispersion suppression

- **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**

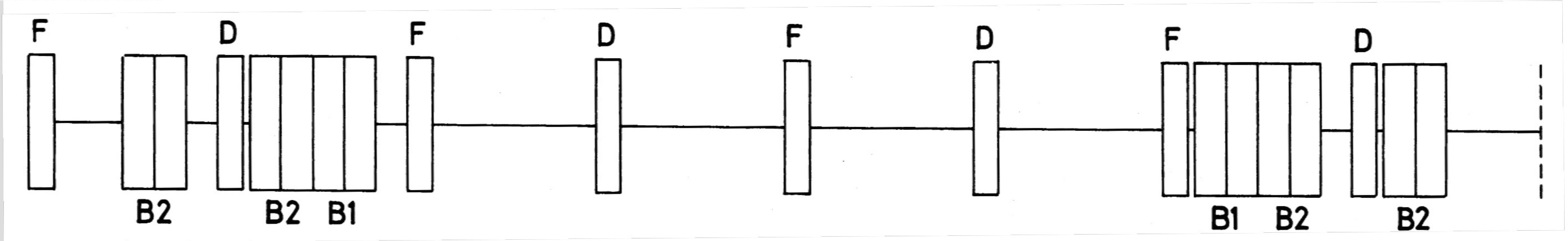
$$\theta_1 = \theta(1 - \frac{1}{4\sin^2\mu_{\rm HFODO}})$$

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

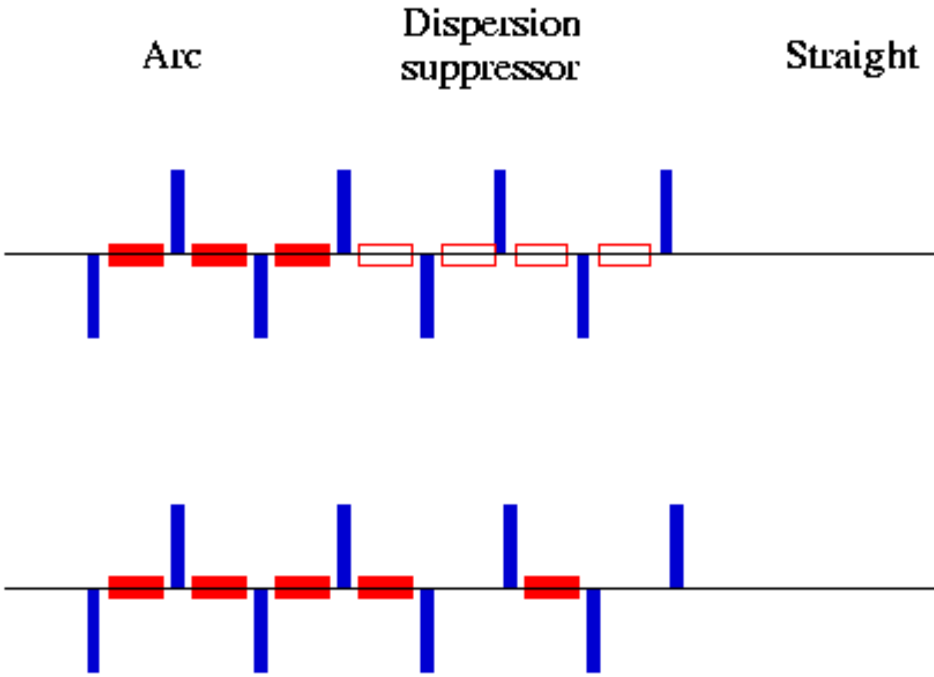
  - ☐ For **equal bending angle** dipoles, the FODO phase advance should be equal to **π/2**



Dispersion suppression in the SPS

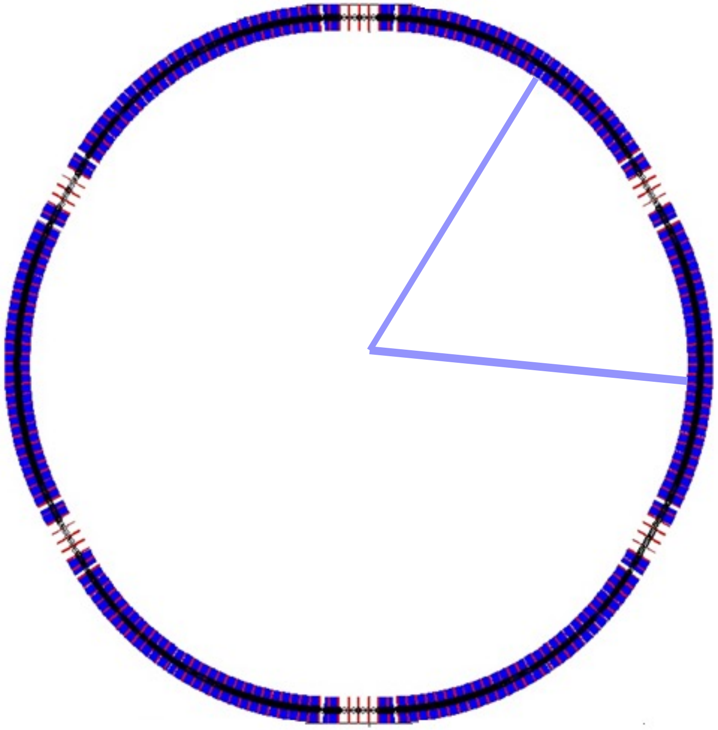


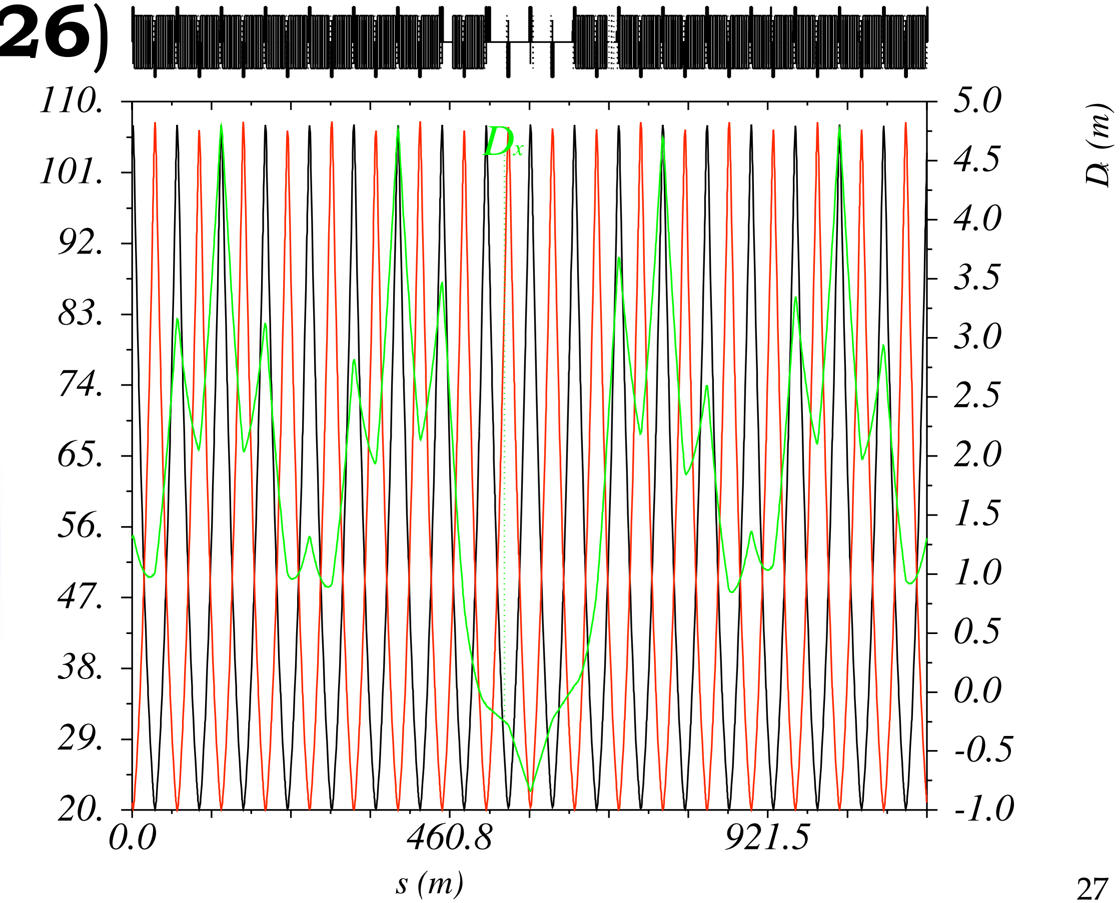
- In the SPS, all **dipoles** are powered in **series**, i.e. dispersion suppressor cells looks like a missing dipole, but they are not!
- Dispersion suppression is achieved by tuning the **phase advance** of the arc, to a **multiple** of **2 π**
- **Dispersion oscillates** through the arc and vanishes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



Ring optics

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

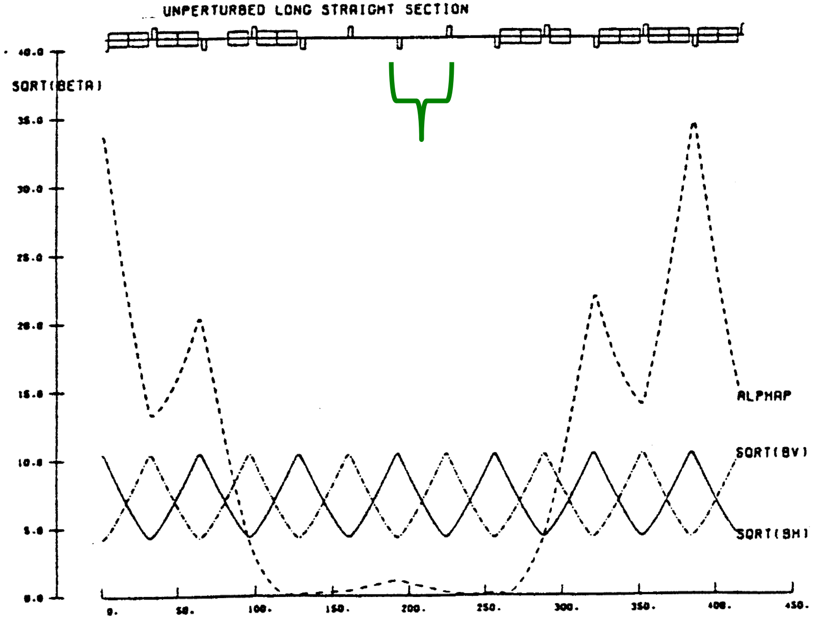


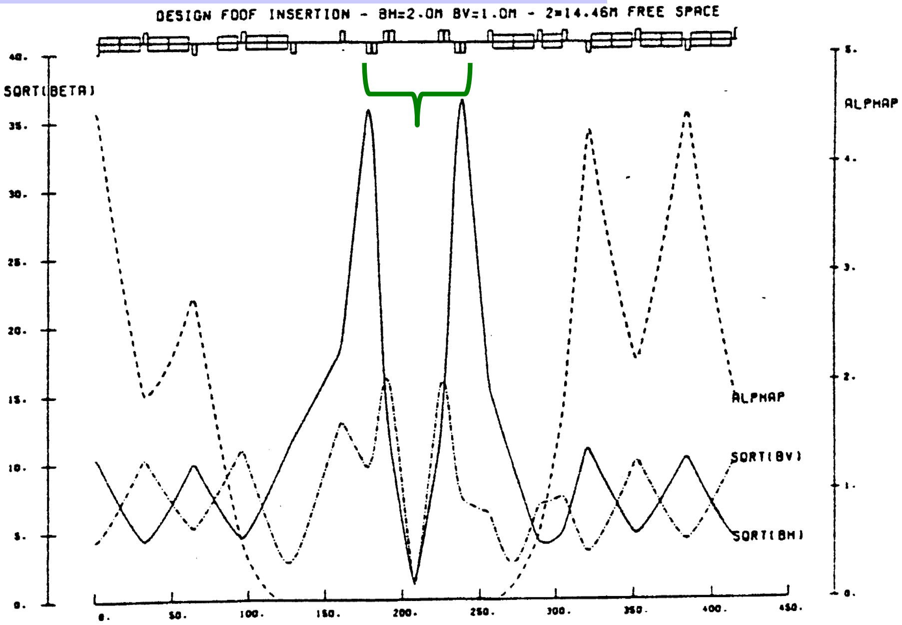


Sp$\bar{p}$S collider insertion optics

- 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





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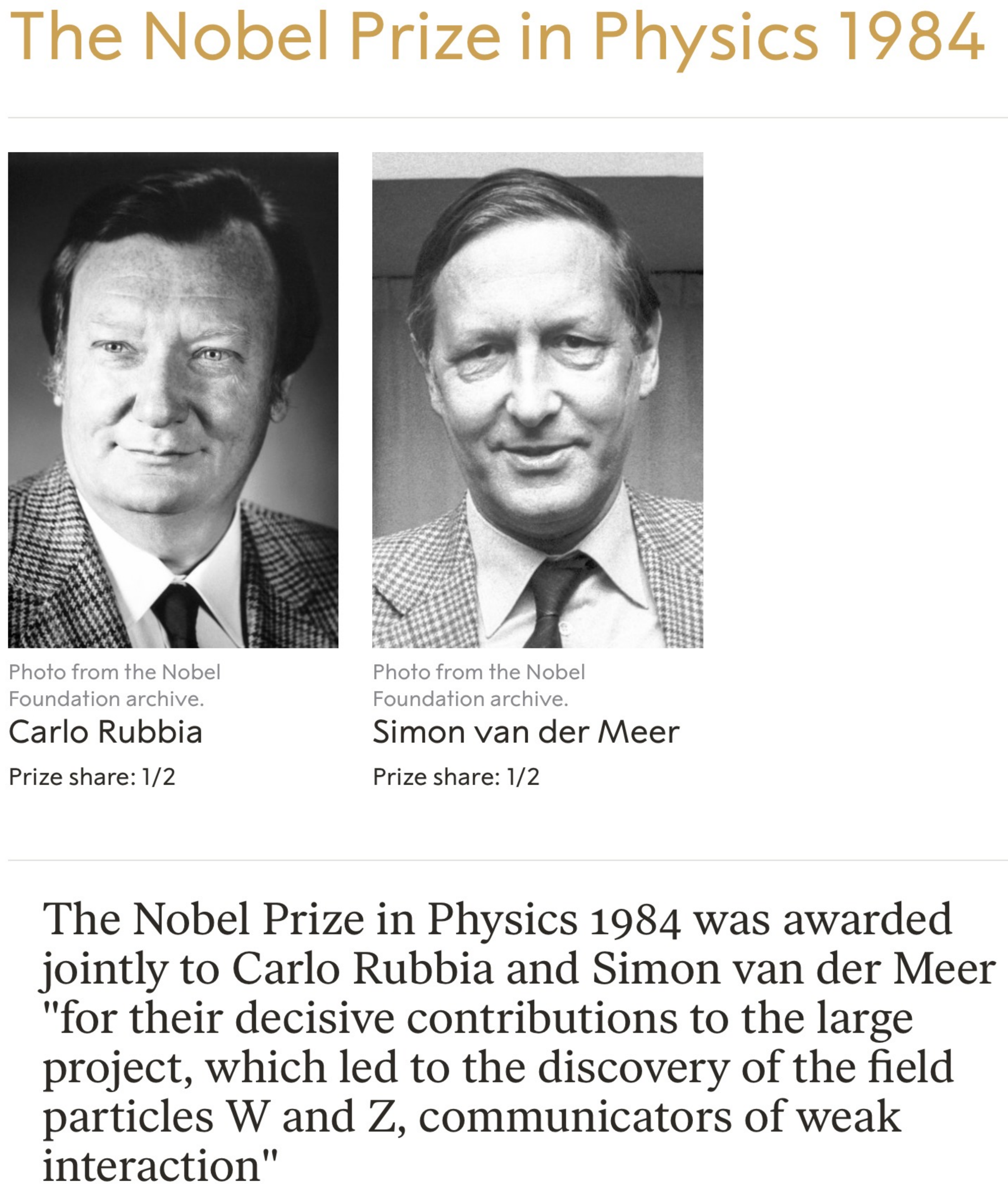


The Nobel Prize in Physics 1984

Photo from the Nobel Foundation archive.

Carlo Rubbia

Prize share: 1/2

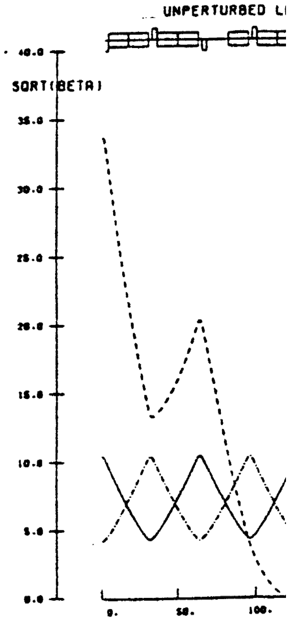
Photo from the Nobel Foundation archive.

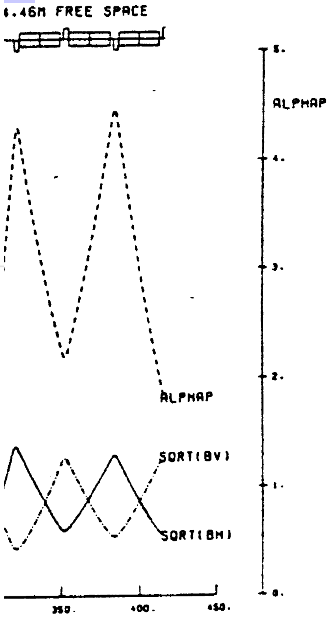
Simon van der Meer

Prize share: 1/2

The Nobel Prize in Physics 1984 was awarded jointly to Carlo Rubbia and Simon van der Meer "for their decisive contributions to the large project, which led to the discovery of the field particles W and Z, communicators of weak interaction"

- Repla rupoles with
- Equi poles with vertors
- Achie





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

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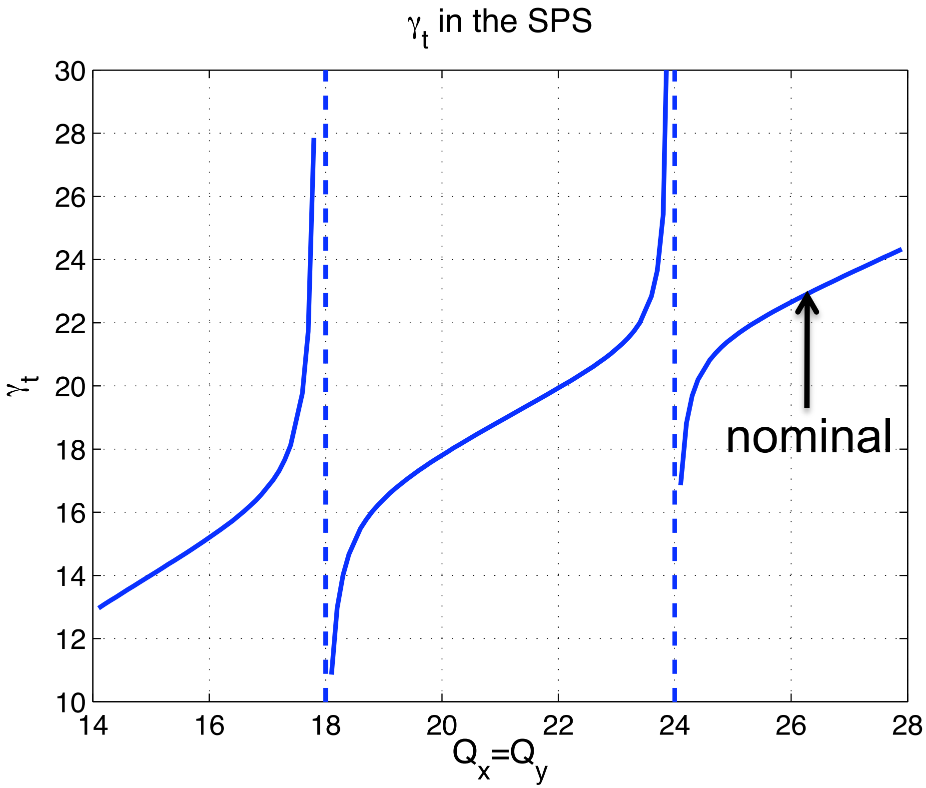
Quadrupoles

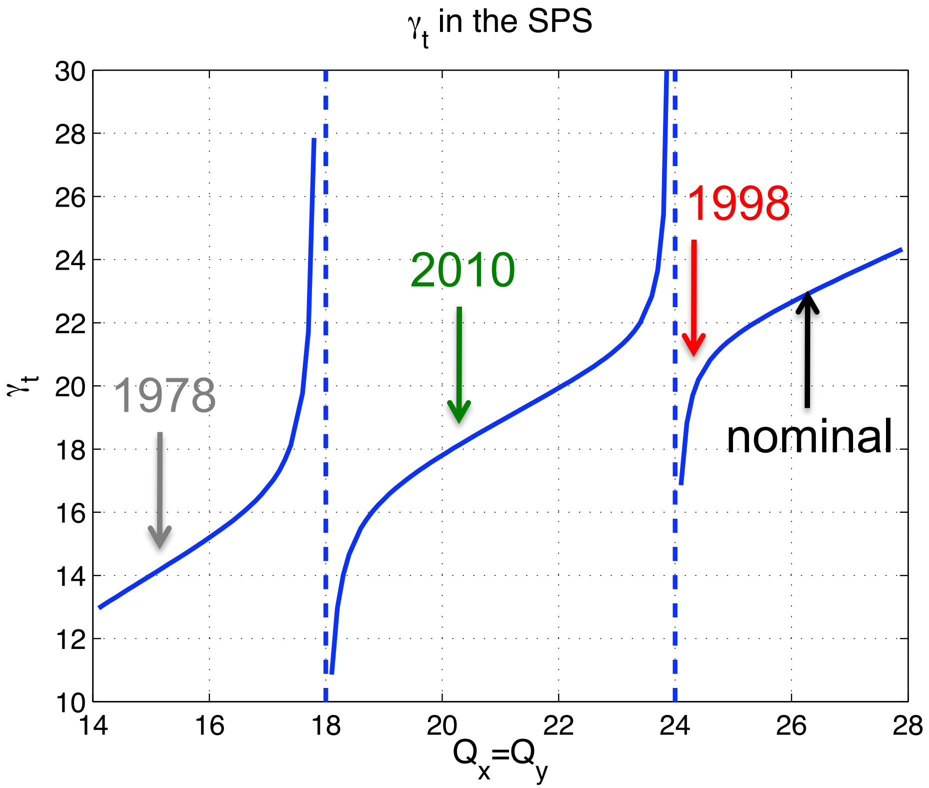
- Note also that, for FODO cells (SPS lattice), $\gamma_t \approx Q_x$, meaning that lowering the transition energy implies **lowering** the **horizontal tune**
- High intensity beams can be injected in the SPS **above transition** avoiding losses and operational complexity of transition jump scheme

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

Transition energy vs SPS working point



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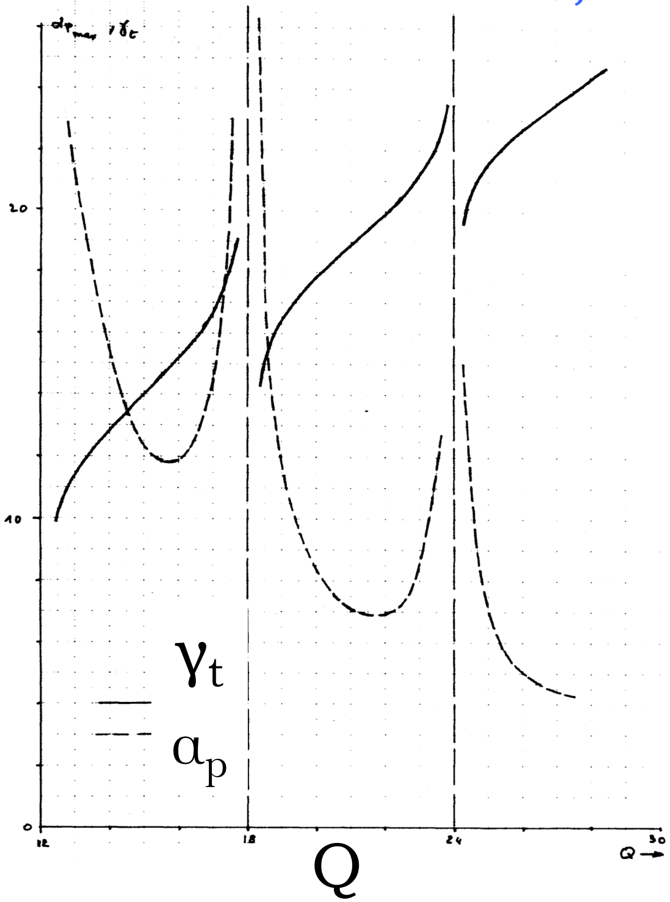
- γ_t is a linear function of horizontal tune Q_x elsewhere

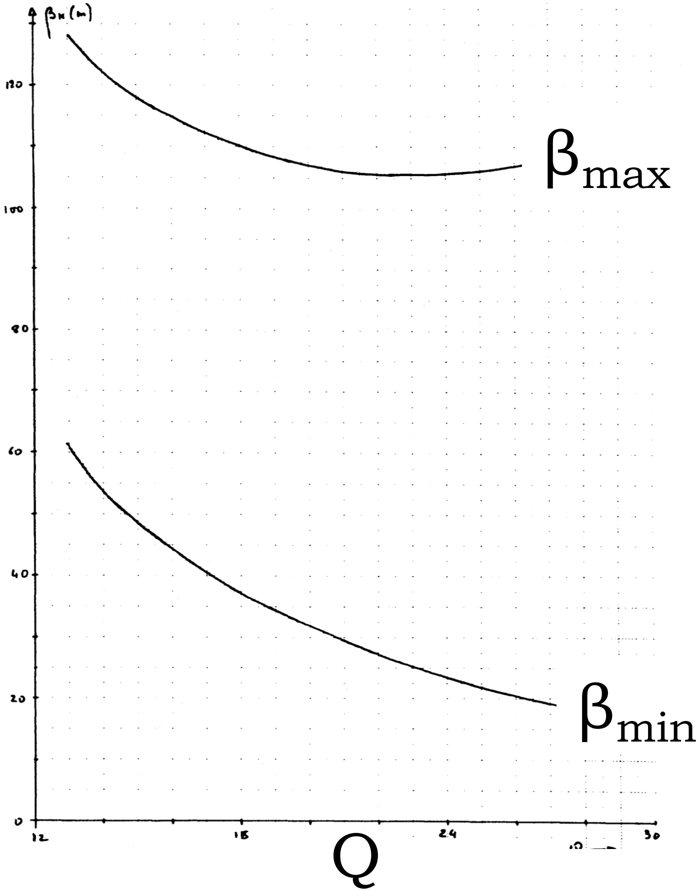
- Nominal SPS working point for LHC proton beams (γ_t~23)
- D. Boussard et al., SPS improvement note No 147, 1978; Injection above transition as TT10 was not ready for 26 GeV/c (γ_t~14)
- G. Arduini et al., CERN/SL-Note 98-001, 1998; "Resonant tune" (γ_t~20)
- Low γ_t, 2010 - "Resonant arc" with small 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 1.6×10^{11}p/b (ε_l=0.35eVs, τ=3.8ns) with low vertical chromaticity

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

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

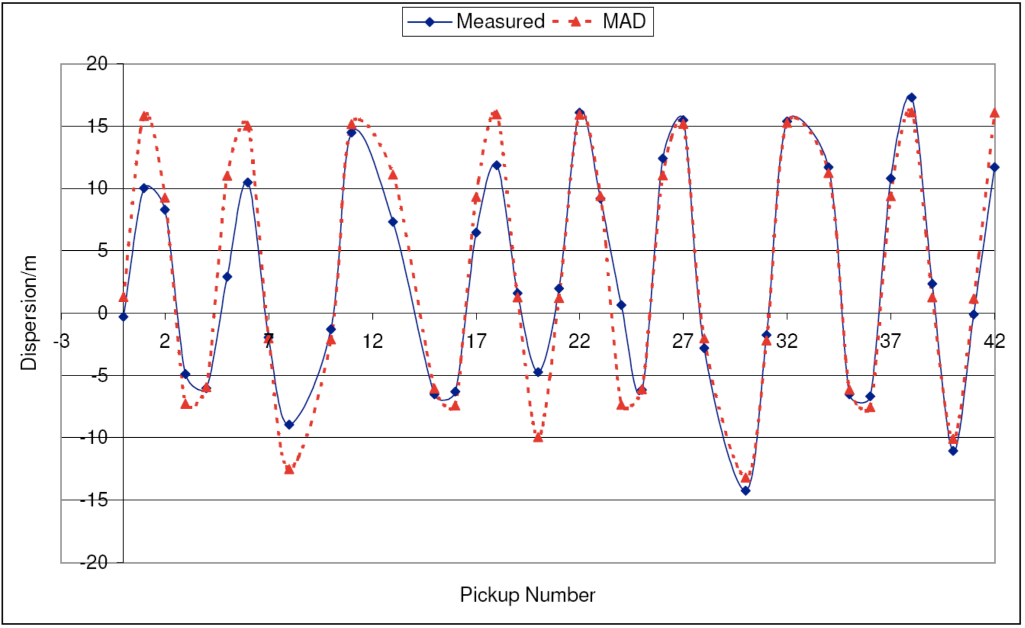
$$\boxed{N_{\rm th} \propto Q_s \propto \sqrt{\eta}}$$

- **Longitudinal** instabilities
  - Single bunch and coupled bunch
    - Threshold at 2×10^{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

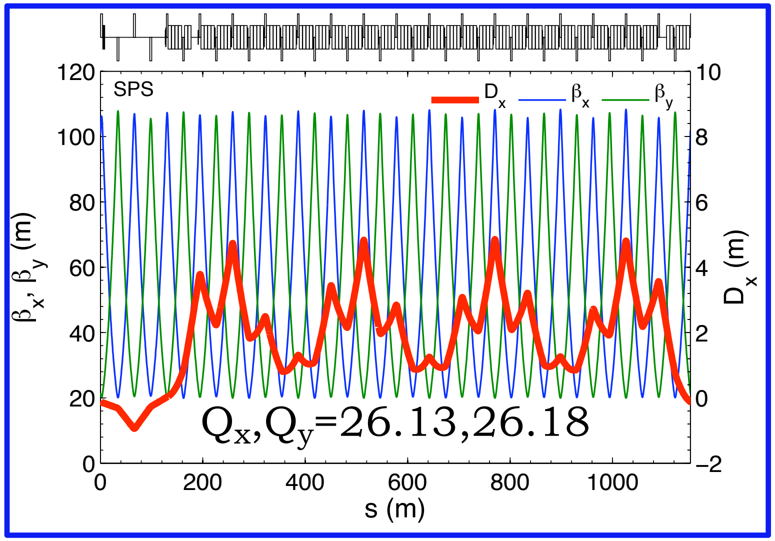


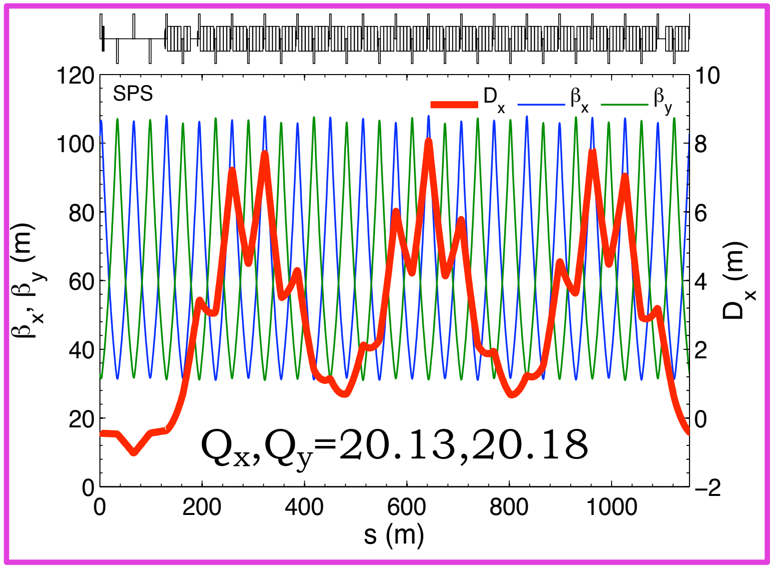
G. Arduini et al., CERN/SL-Note 98-001 (MD), 1998

Q_h	Q_v	γ_{tr}	$\eta\ (10^{-3}$
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)**

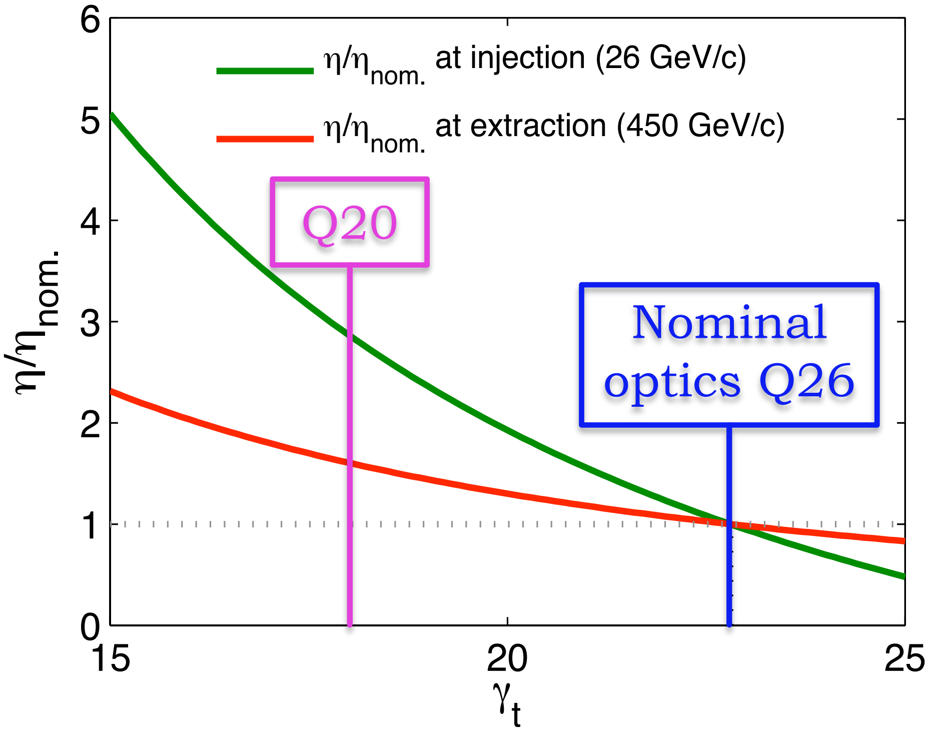




$$\eta = \frac{1}{\gamma_t^2} - \frac{1}{\gamma^2}$$

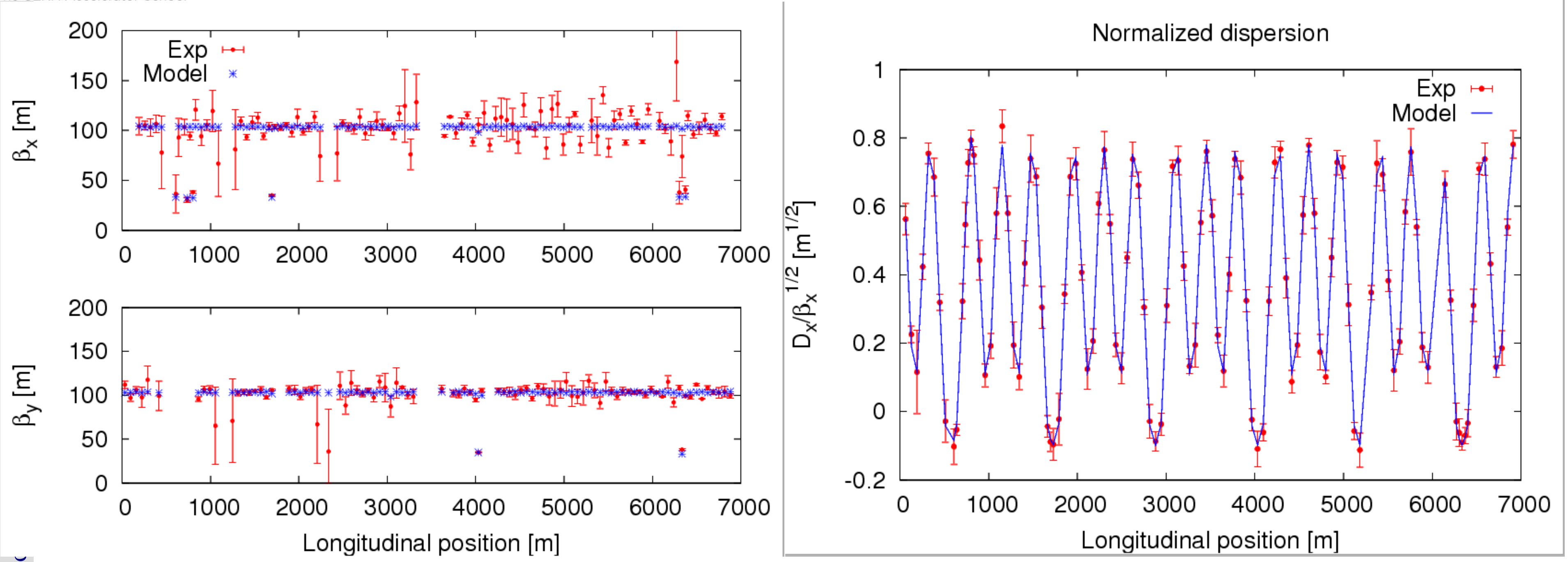
$$\gamma_{t_{FODO}} \approx Q_x$$

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



Slip factor relative to nominal SPS optics

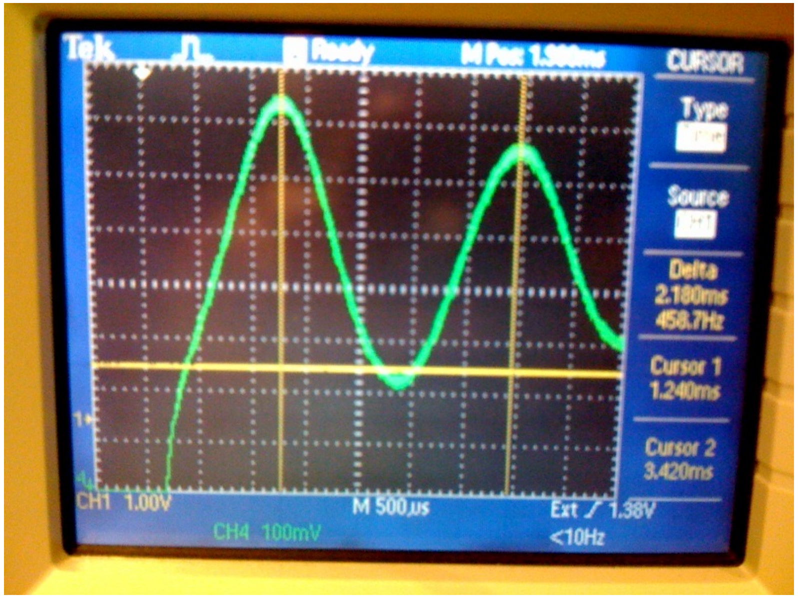
Q20 Optics measurements



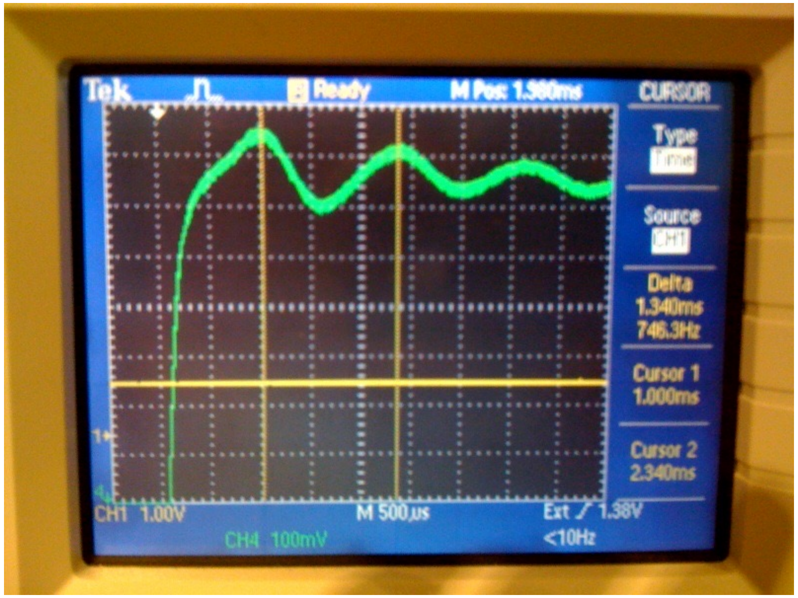
- **Measurement** of the optics functions of the new lattice
  - **Beta beating** around 20% in horizontal and 10% in vertical plane
  - Normalized **dispersion** in striking agreement with the model

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 η by **factor 2.65** (MADX prediction: 2.86)



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

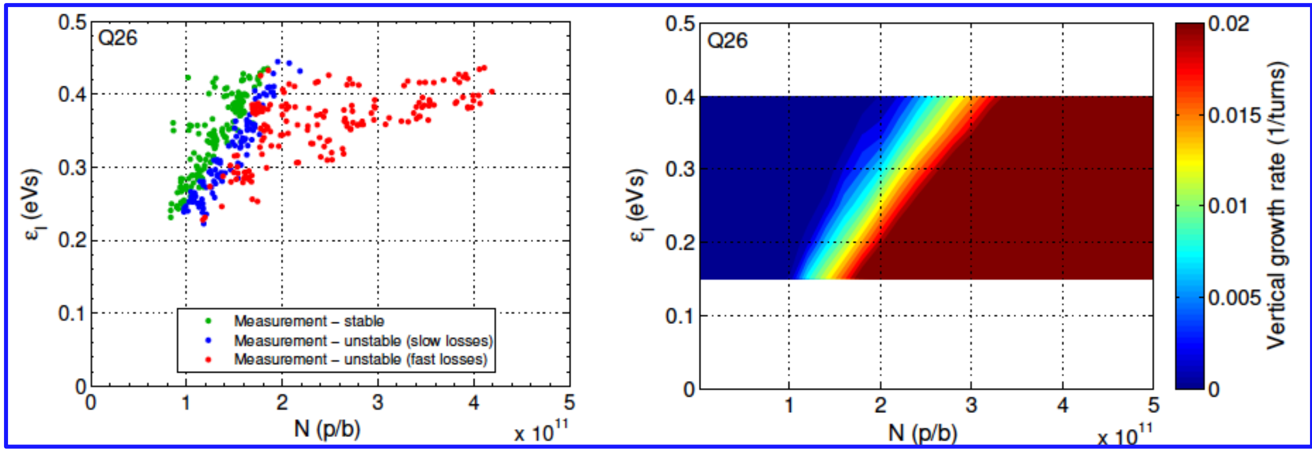


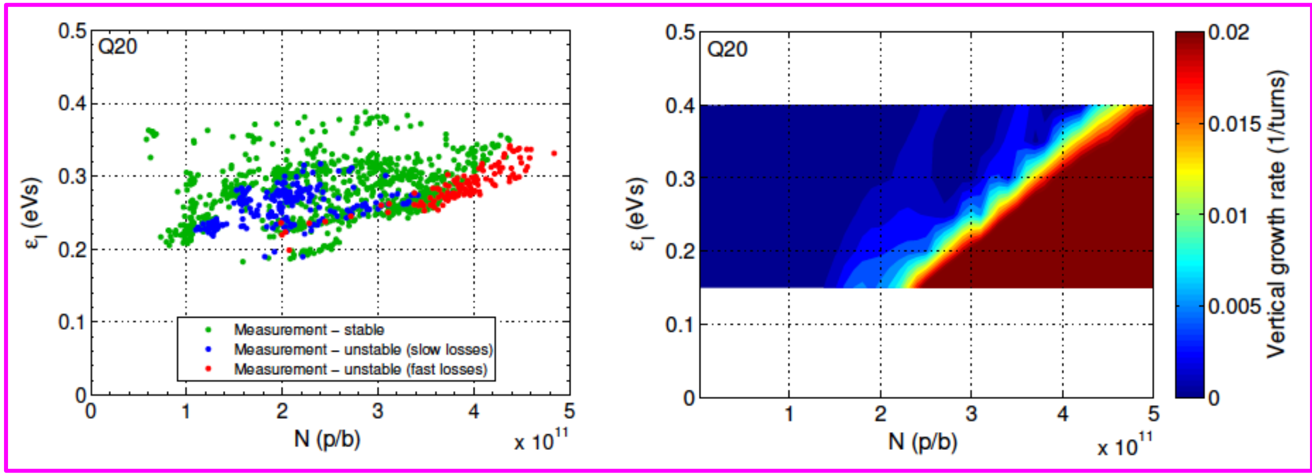
Q20: Fs=746/2=373Hz, Qs=0.0172/2=0.0086

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!!!**

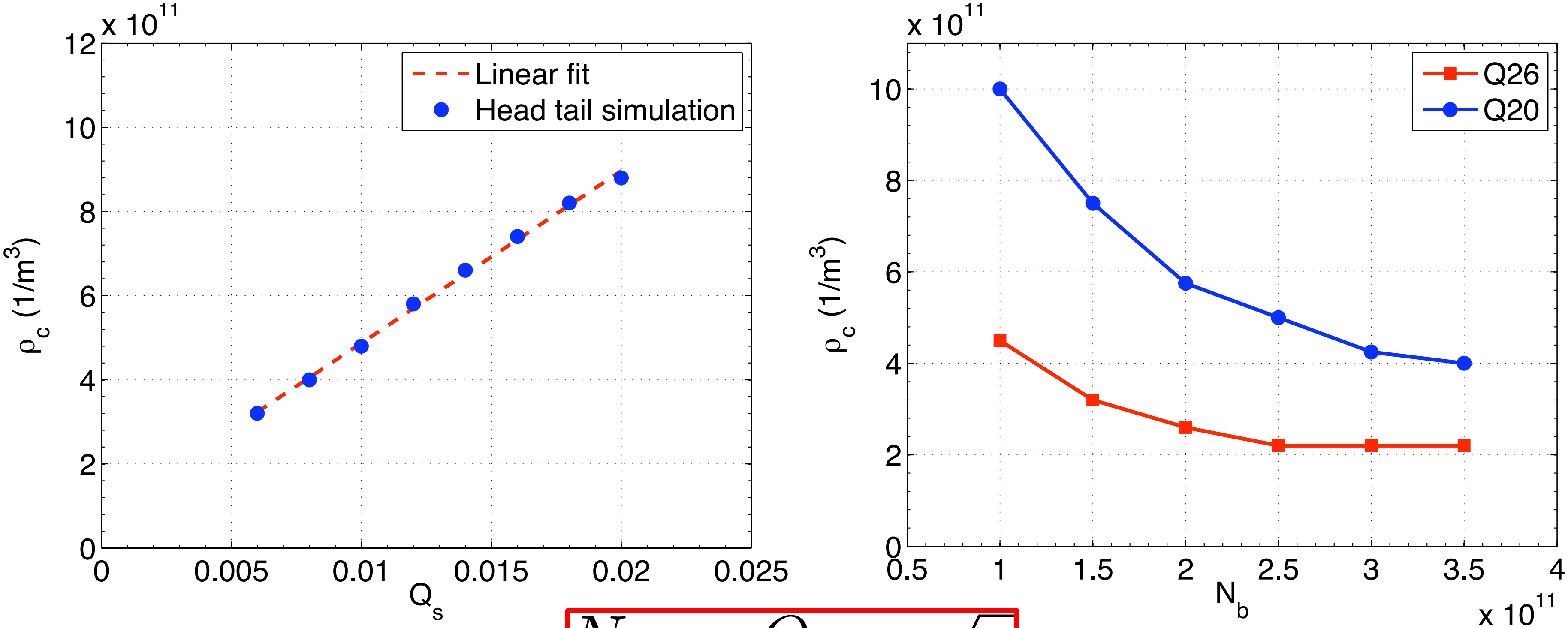
$$N_{\text{th}} \propto \frac{\varepsilon_l}{\beta_y}\eta$$





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**

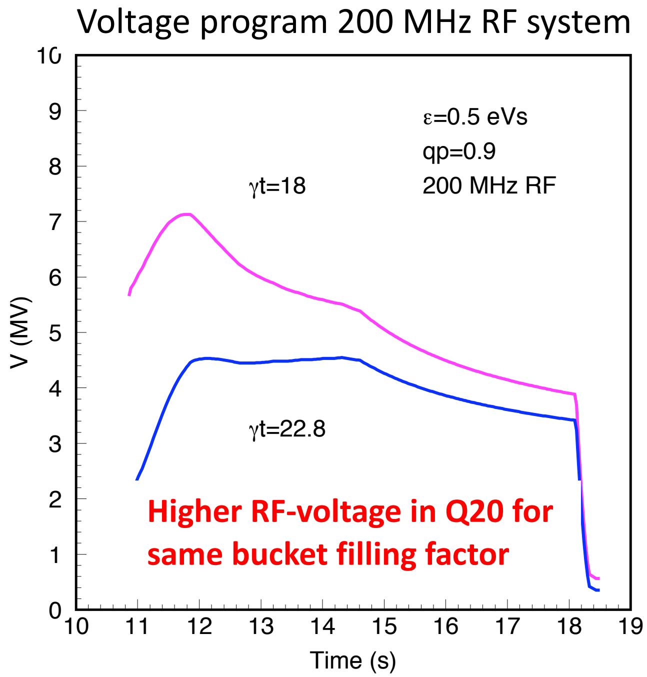
More margin with Q20 if e-cloud becomes issue for high intensity

H. Bartosik et al, IPAC2011

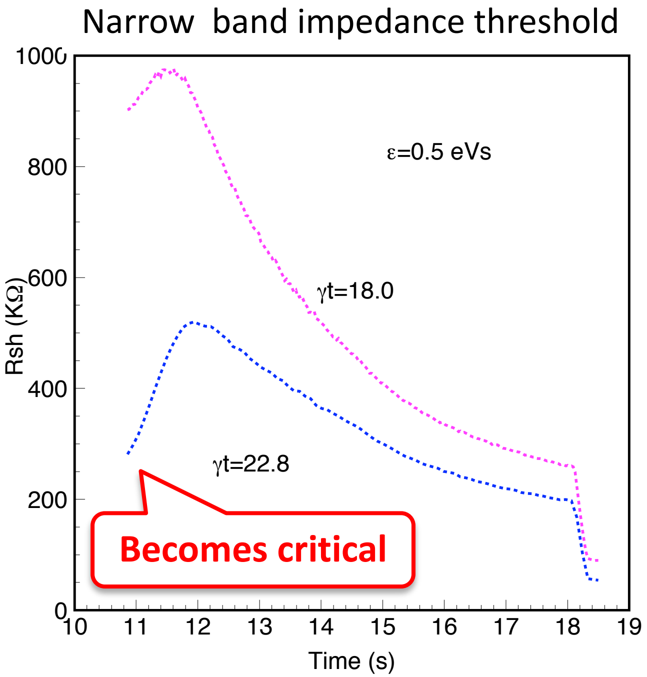
Longitudinal impedance threshold

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

E. Shaposhnikova



Higher RF-voltage in Q20 for same bucket filling factor

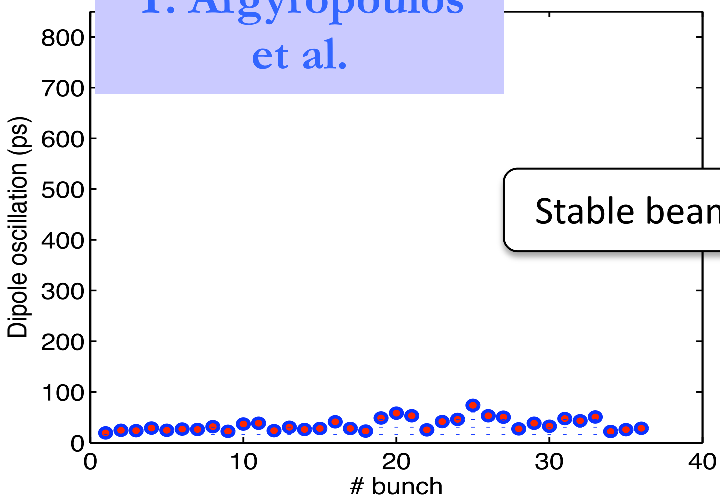


Becomes critical

- 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)

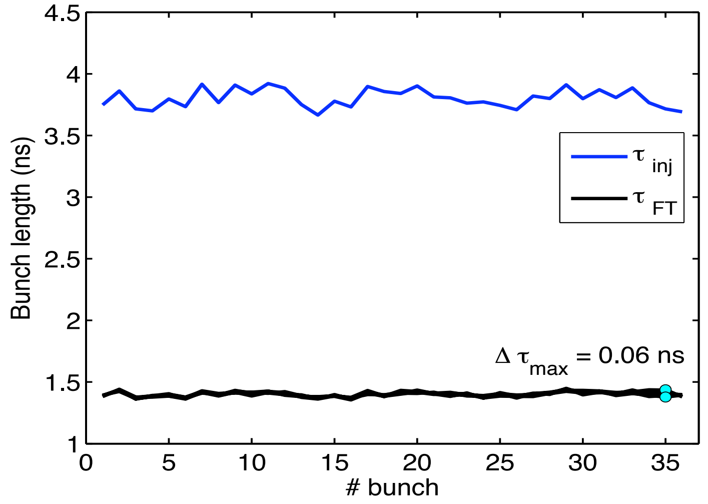
Longitudinal beam stability

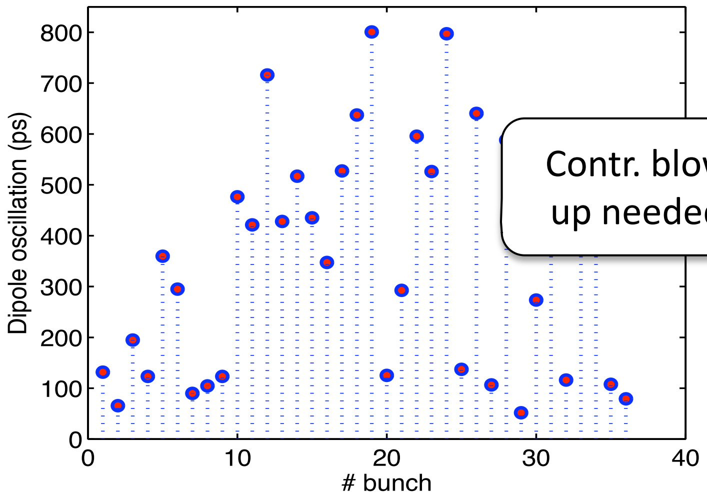
T. Argyropoulos et al.



Stable beam

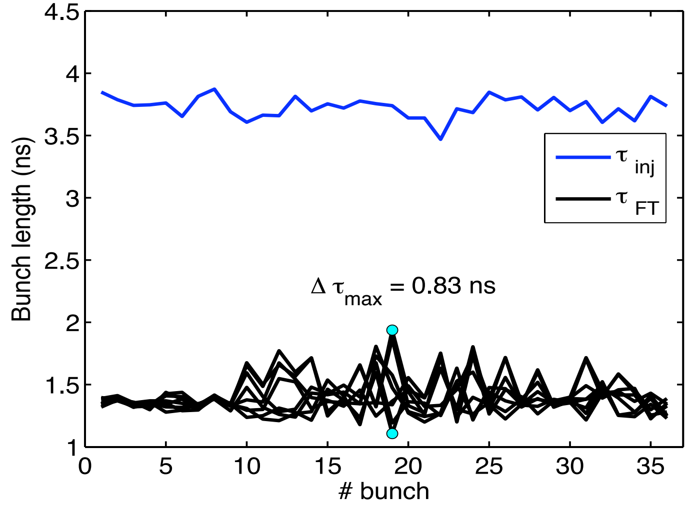
SPS-Q20 (1.6x10^{11} p/b)
double harmonic RF





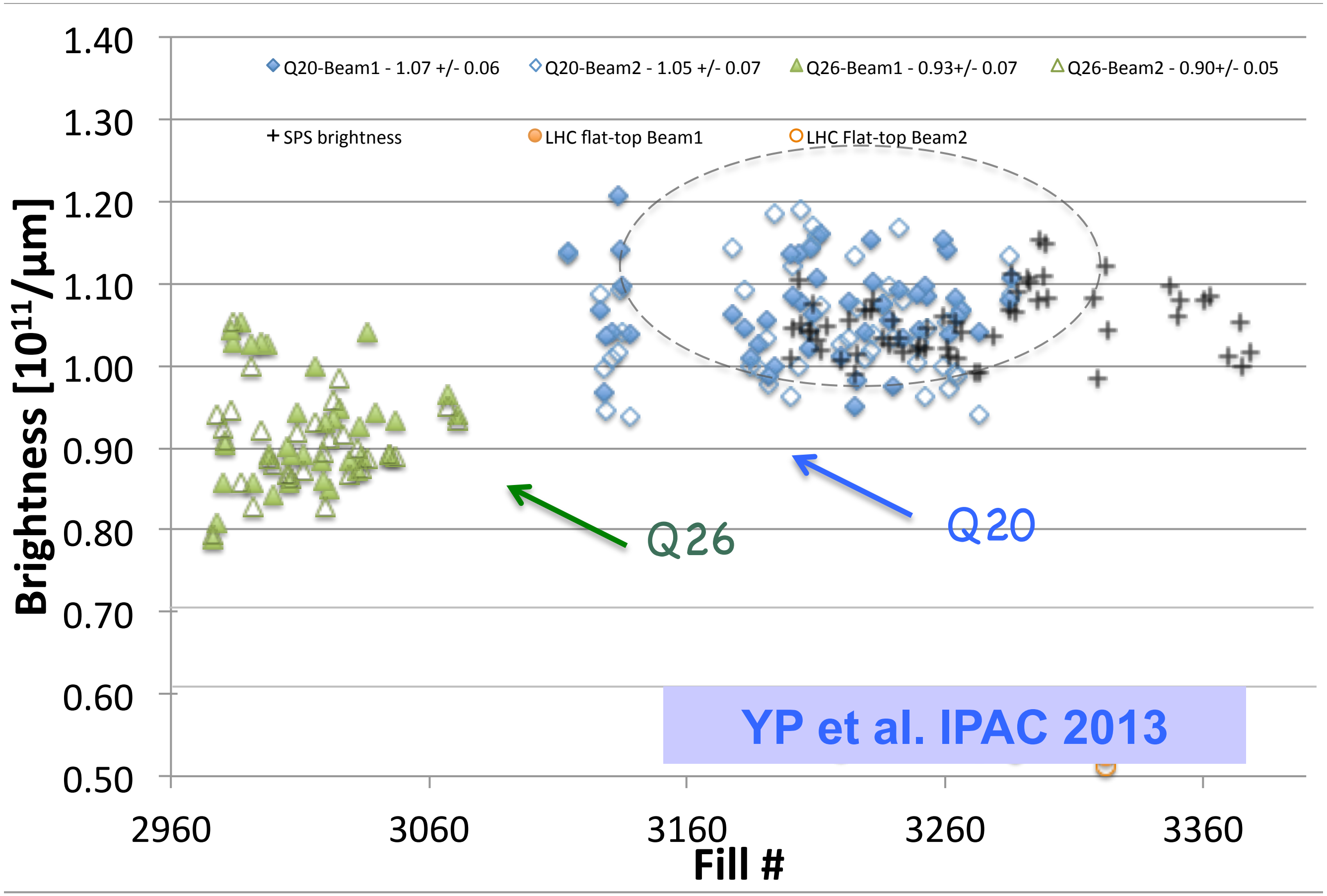
Contr. blow-up needed!

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



LHC brightness with SPS Q20

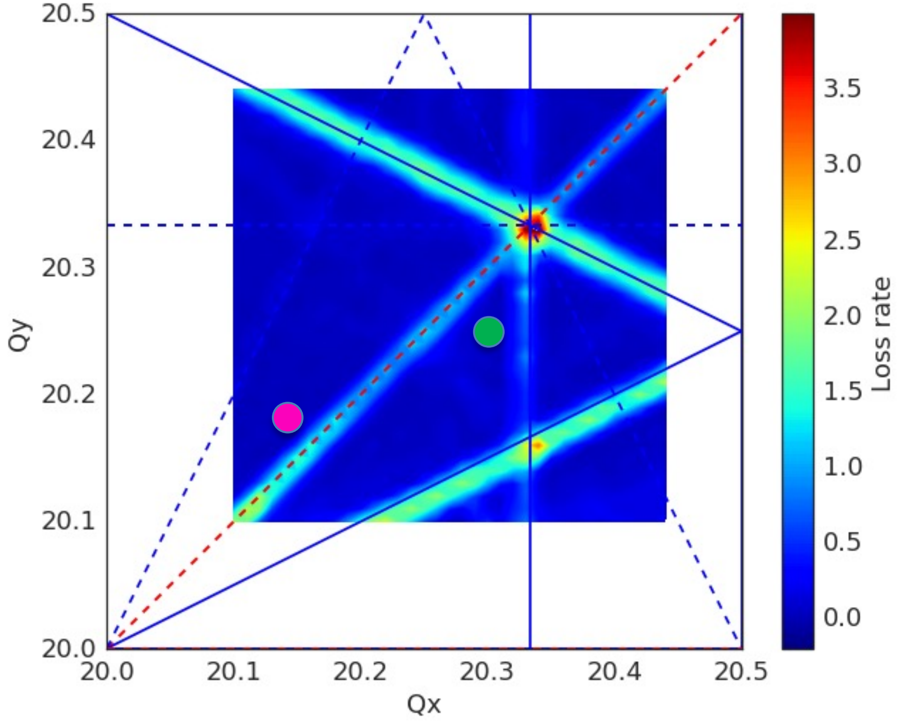
- Operational deployment of Q20 optics for LHC beams since 2012 allowing around **20% brighter beams on LHC flat bottom**
- Opened way for **ultra-high brightness beams** of HL-LHC era



YP et al. IPAC 2013

Non-linear dynamics

Loss map for low brightness beam



● proton working point

● ion working point

resonances:

red: systematic

blue: non-systematic

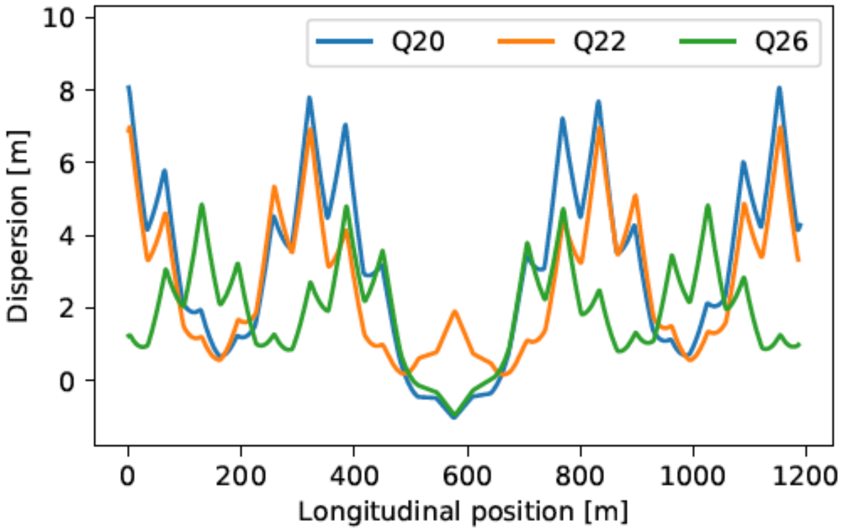
– upright

- - skew

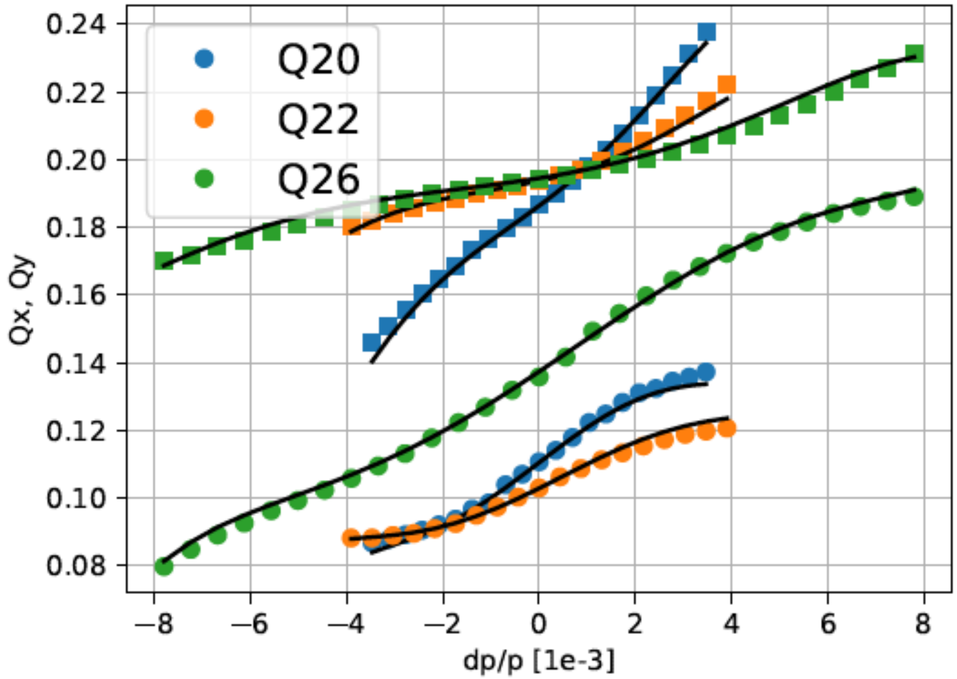
H. Bartosik et al. HB2018

- 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



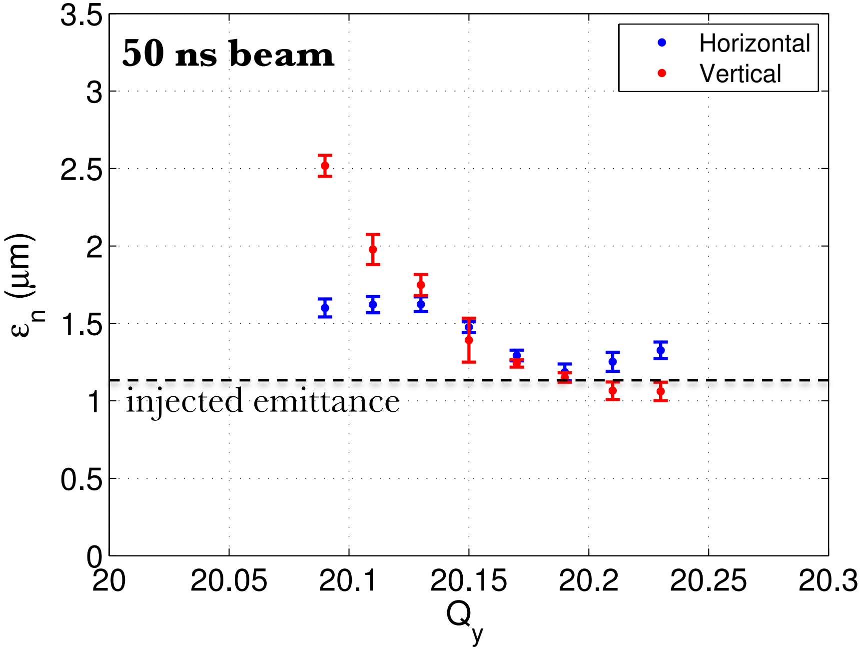
$$Q = \underbrace{Q_0}_{\text{Quadrupoles}} + \overbrace{Q'}^{\text{Sextupoles}}\left(\frac{\delta p}{p}\right) + \underbrace{Q''}_{\text{Octupoles}}\left(\frac{\delta p}{p}\right)^2 + \underbrace{Q'''}_{\text{Decapoles}}\left(\frac{\delta p}{p}\right)^3 + \ldots$$

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

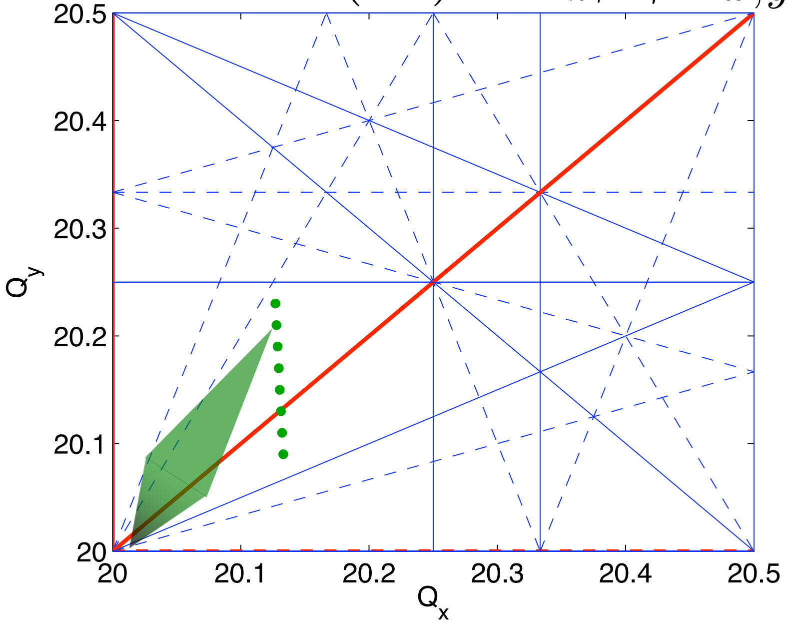
Space-charge

Space-charge tune spread

emittance at end of flat bottom



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

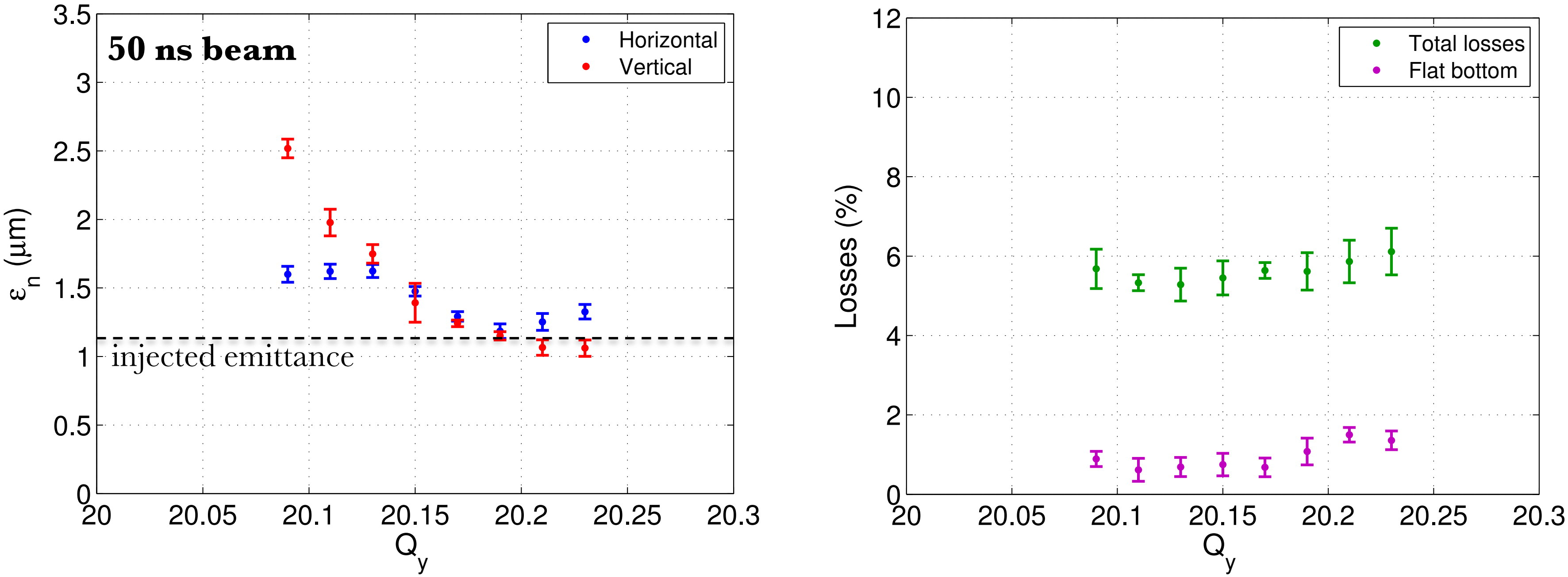


- **Vertical tune scan** with high brightness beam for 10 s storage time
  - ☐ N = 1.95×10^{11} p/b (at injection)
  - ☐ ε ~ 1.1 µm (at injection)
  - ☐ Transmission to flat top around 94% (very small losses on flat bottom)
  - ☐ Budget of 10% losses and 10% blow-up allows for tune spread of ΔQy=0.21

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

Space-charge tune spread

emittance at end of flat bottom



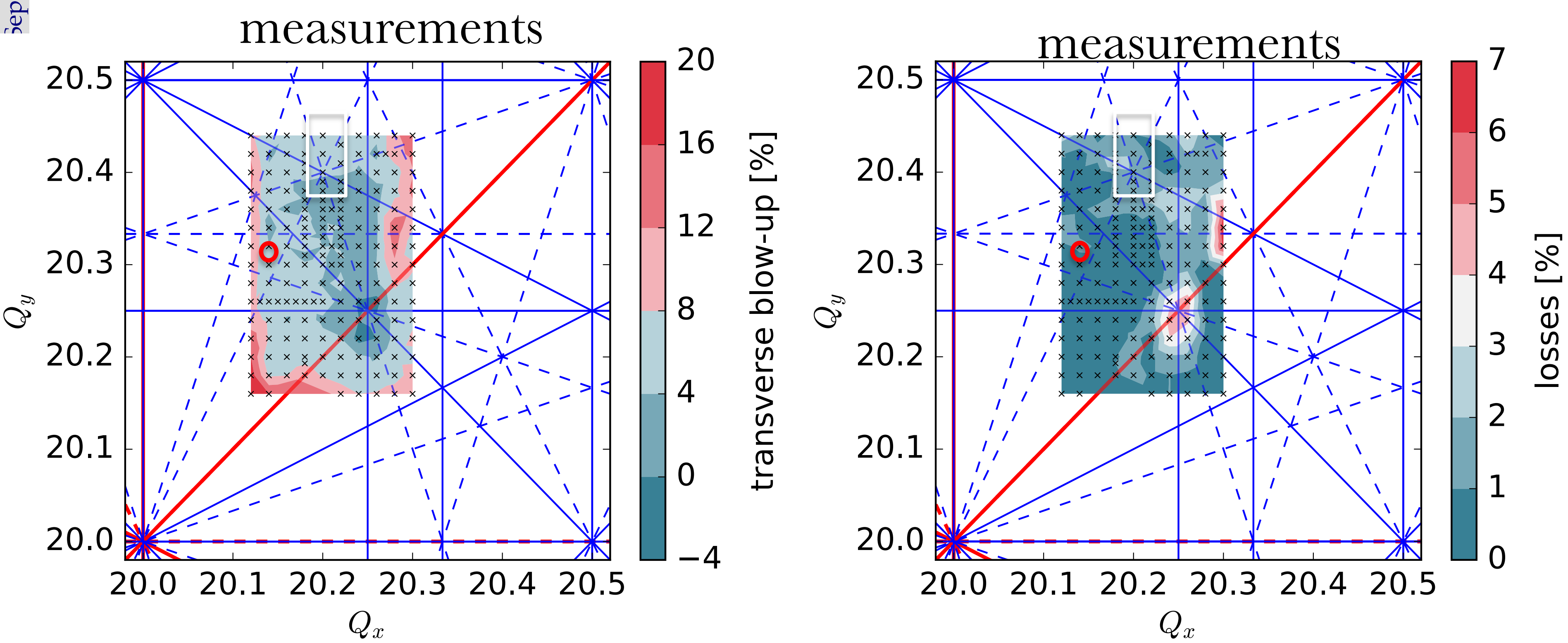
- **Vertical tune scan** with high brightness beam for 10 s storage time
  - N = 1.95x10^{11} p/b (at injection)
  - ε ~ 1.1 μm (at injection)

  $\Delta Q_x/\Delta Q_y$ ~ 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

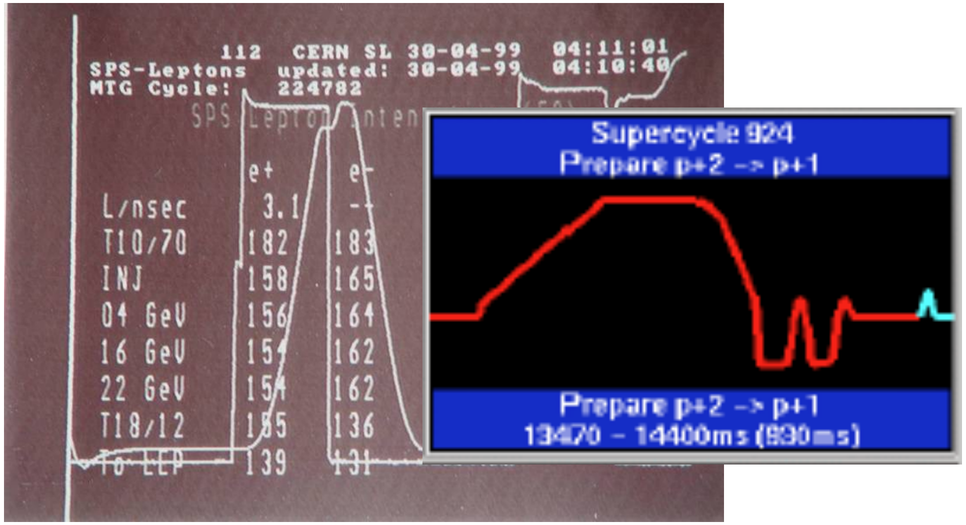
- Tune scan with high brightness single bunch beam for 3 s storage time
  - Blow-up at integer resonances as expected (tune spread ΔQx, ΔQy ~ 0.10,0.19)
  - **Margin for higher brightness for working points in white box** (enhanced losses only close to Qx + 2Qy = 61 normal 3rd order resonance and around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



Electron-positron dynamics

SPS as LEP Injector

P. Collier – Academic Training 2005



112 CERN SL 30-04-99 04:11:01
SPS-Leptons updated: 30-04-99 04:10:40
MTG Cycle: 224782

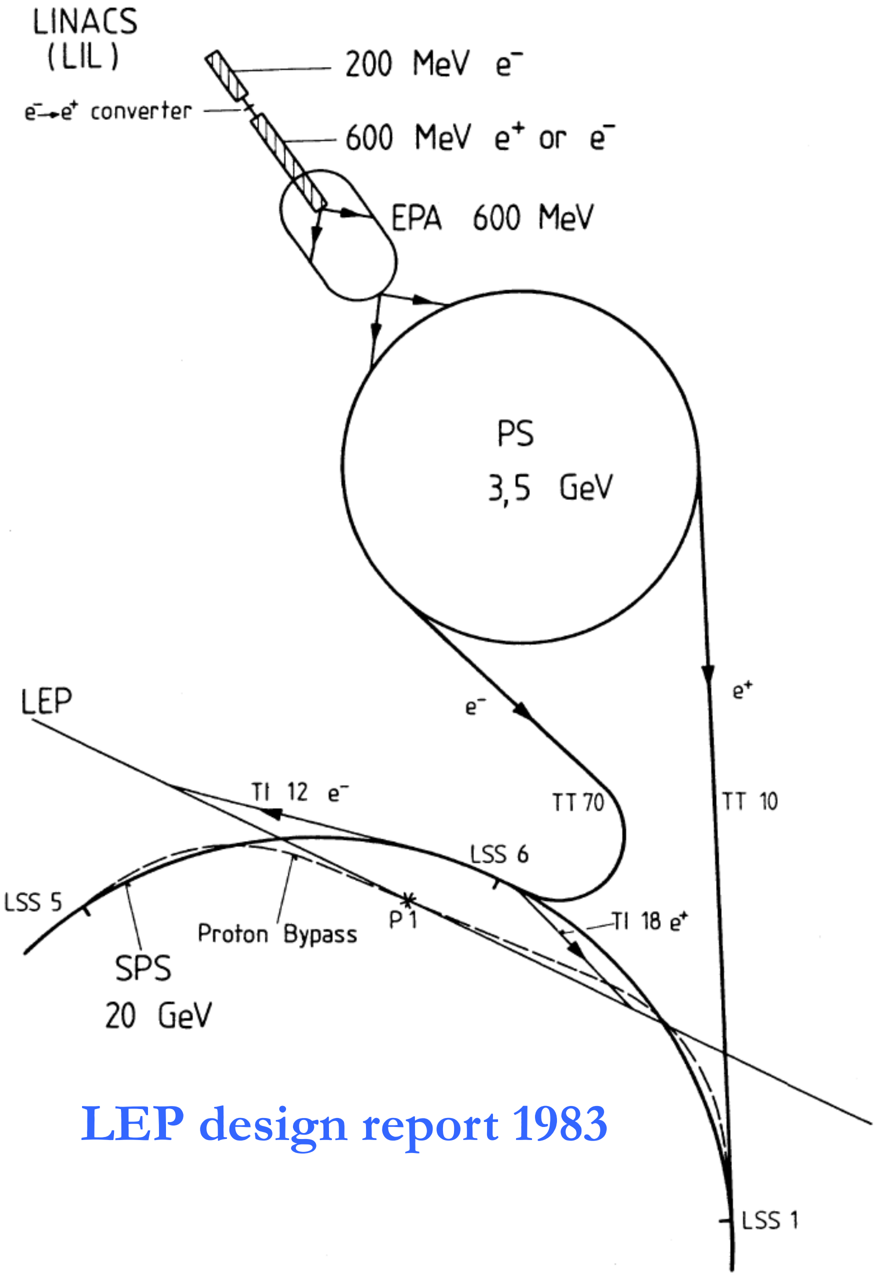
SPS Lepton Intensity

	e+	e-
L/nsec	3.1	--
T10/70	182	183
INJ	158	165
04 GeV	156	164
16 GeV	154	162
22 GeV	154	162
T18/12	155	136
To LEP	139	131

Supercycle 924
Prepare p+2 -> p+1

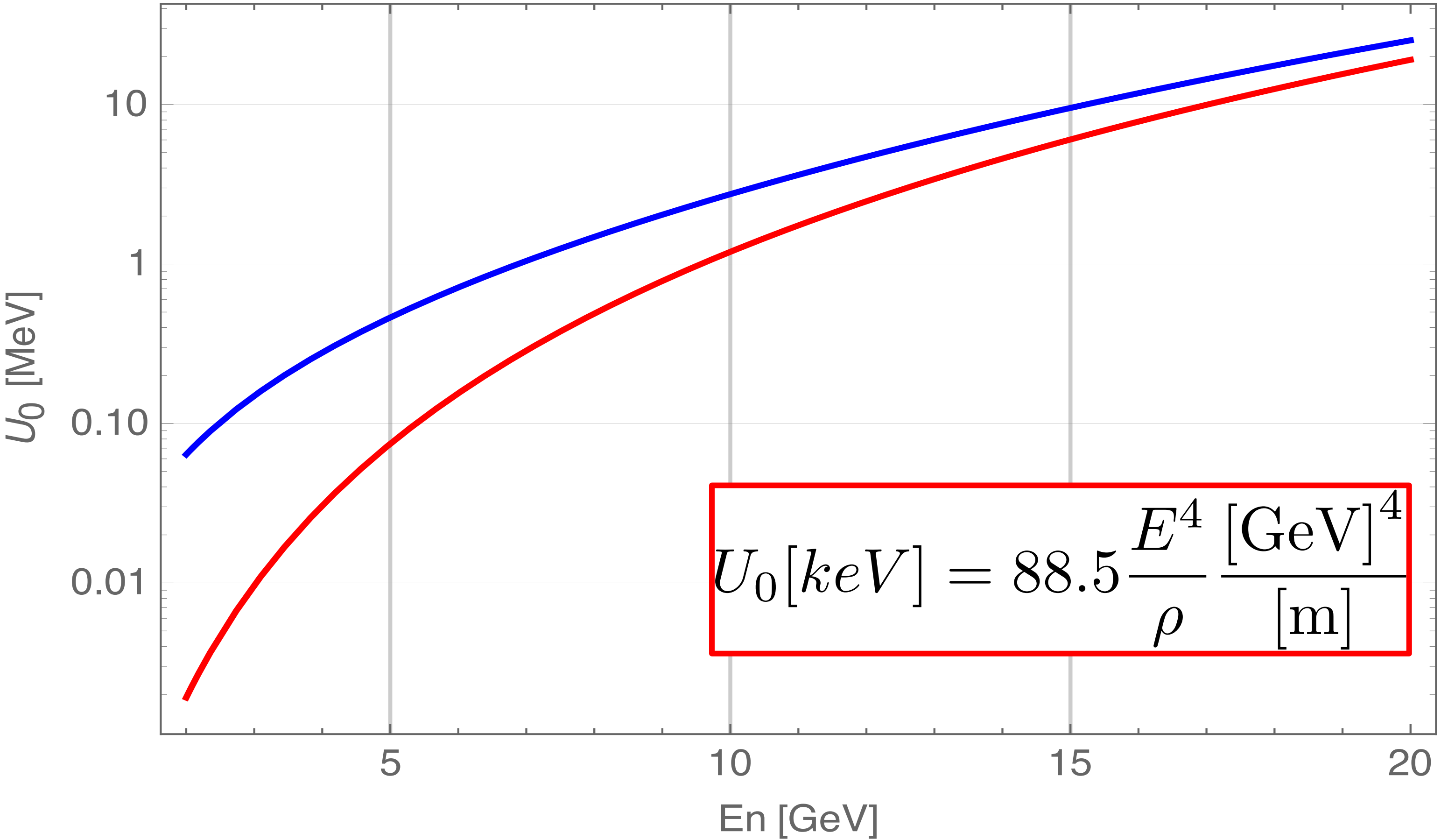
Prepare p+2 -> p+1
13470 – 14400ms (930ms)

- LEP filling interleaved with proton operation
- 4 cycles with 4 bunches ($2e^+$, $2e^-$) evolved to 2 cycles with 8 bunches (~**2.5×10^{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

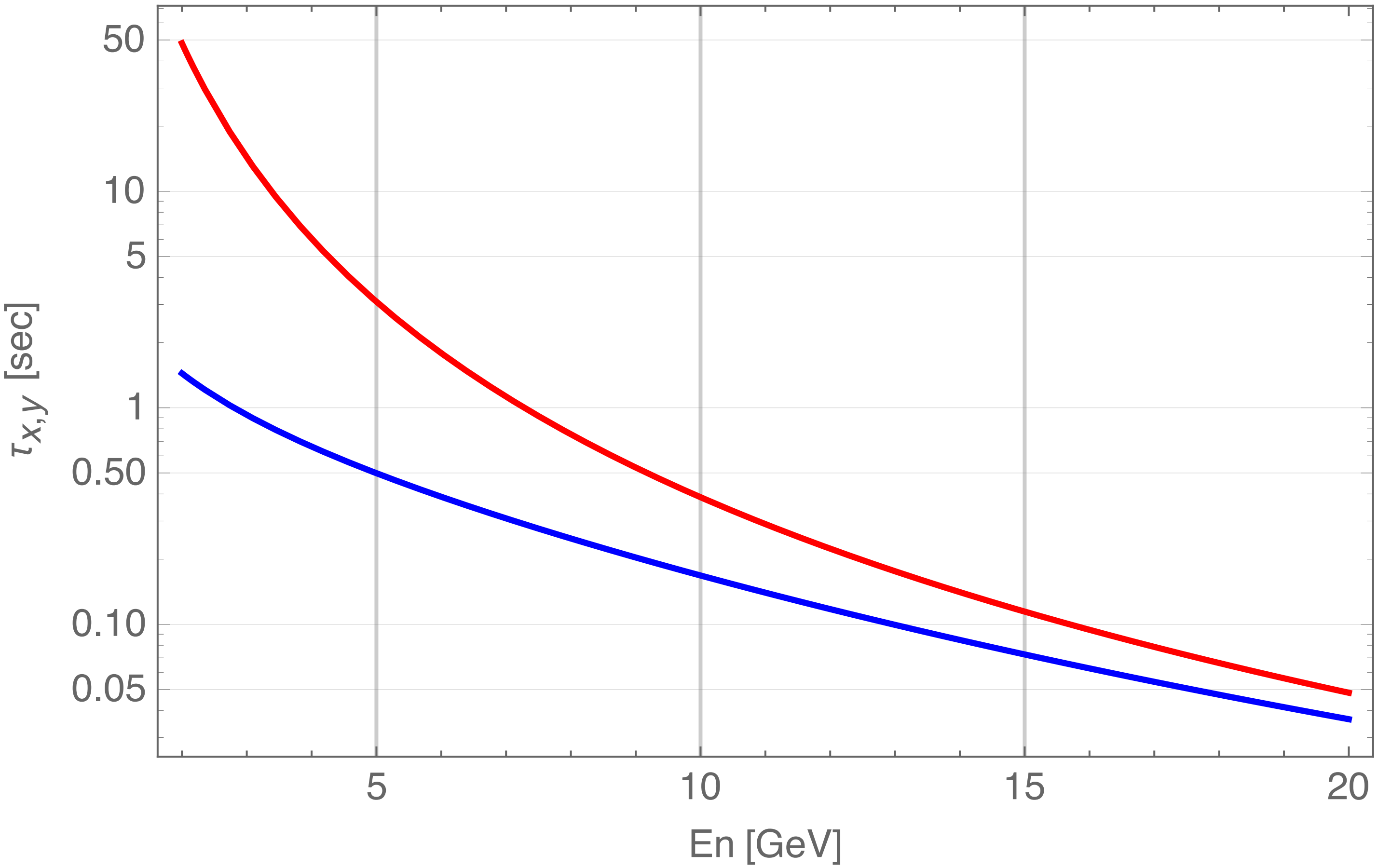
Energy loss/turn



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

- 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

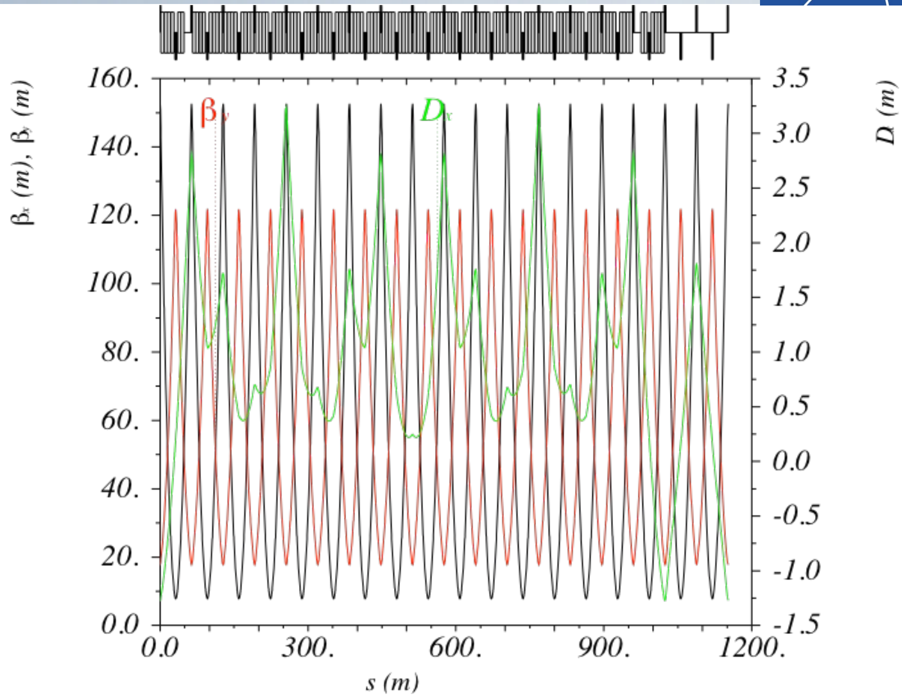
Damping time

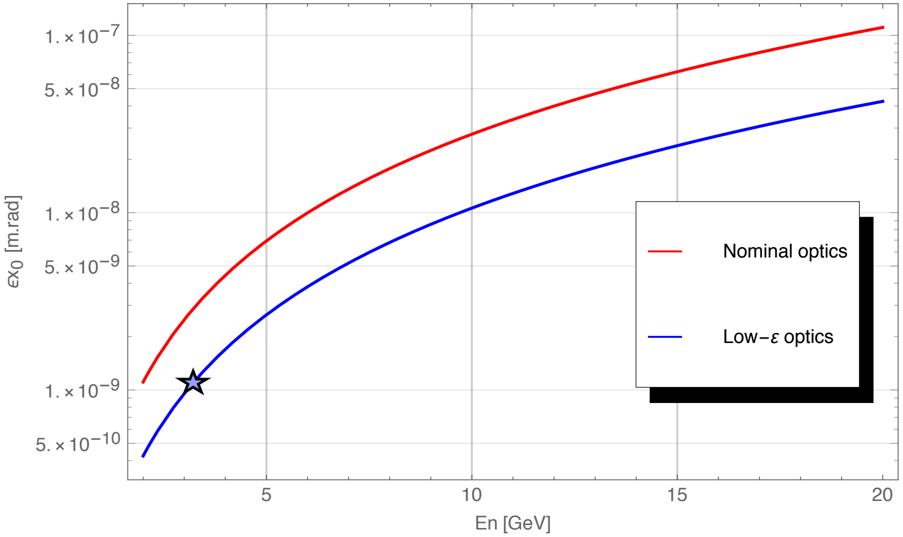


- **Damping time** at injection (3.5 GeV) **very large (9 s)**
- A 2-m **3.5T** **damping wiggler** could enhance damping for low energies to below 1 s (good for instabilities)

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, e-cloud
  - ☐ Electron/Positron beam dynamics
    - Equilibrium beam properties, energy loss/turn, damping time