Designing a synchrotron - A real life example

Yannis PAPAPHILIPPOU

Accelerator and Beam Physics

Beams Department
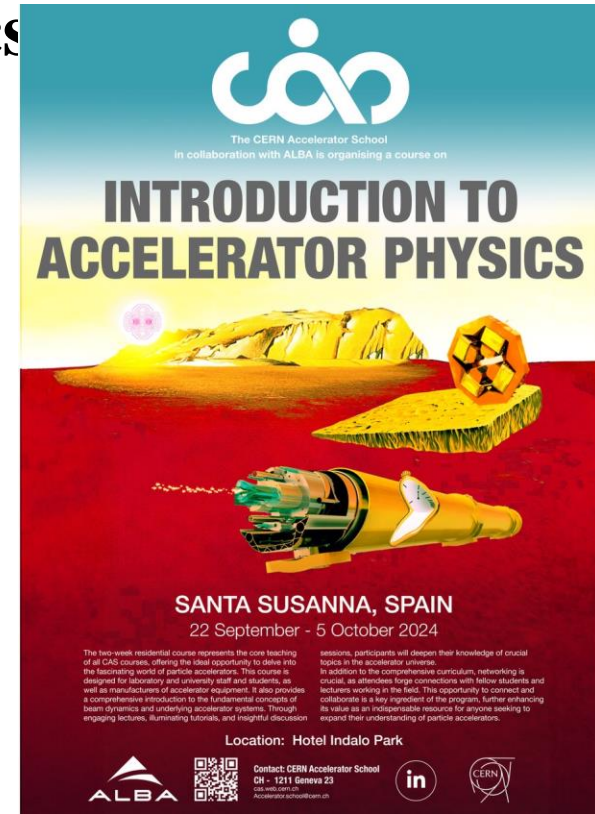
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CERN Accelerator School

Introduction to Accelerator Physics

Santa Susanna, Spain

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

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

- 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

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

- Consider **accelerator ring** for particles with **energy** E with N dipoles of **length** L or **effective length** l, i.e. measured on beam path
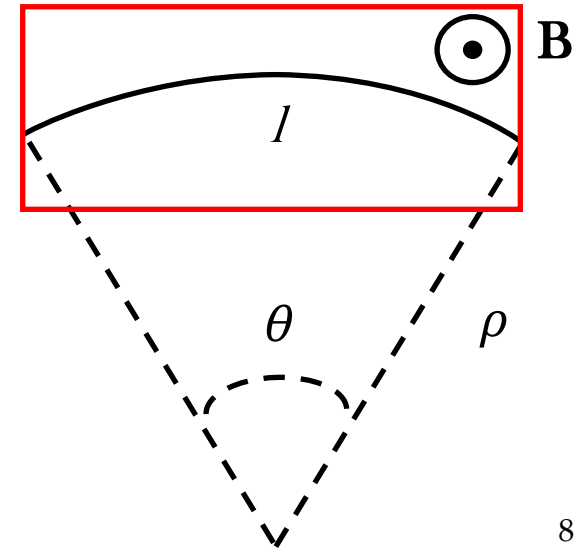
- Consider **accelerator ring** for particles with **energy** E with N dipoles of **length** L or **effective length** l, i.e. measured on beam path

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

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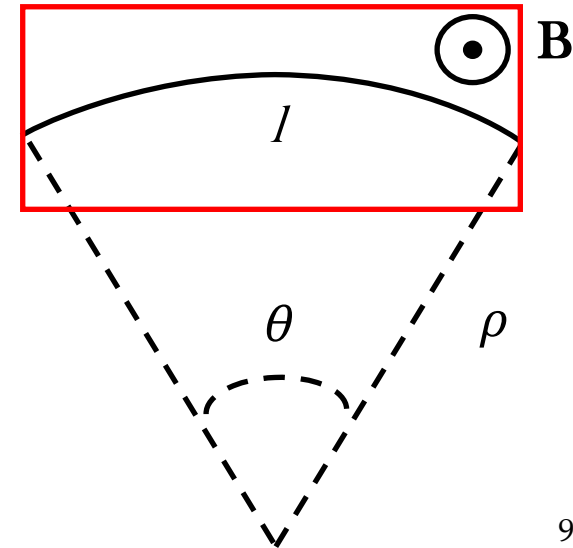
  - **Bending angle** $\theta = \dfrac{2\pi}{N}$

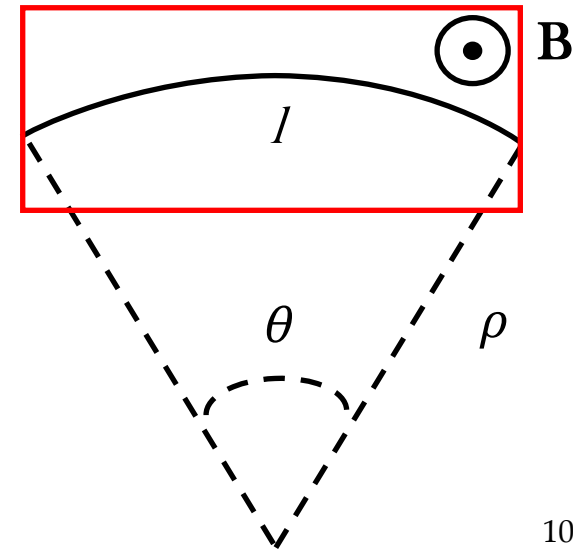 - **Bending radius** $\rho = \dfrac{l}{\theta}$

  - The **magnetic rigidity** is $B\rho = \dfrac{\beta E}{q}$

  - The **integrated dipole strength** is
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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

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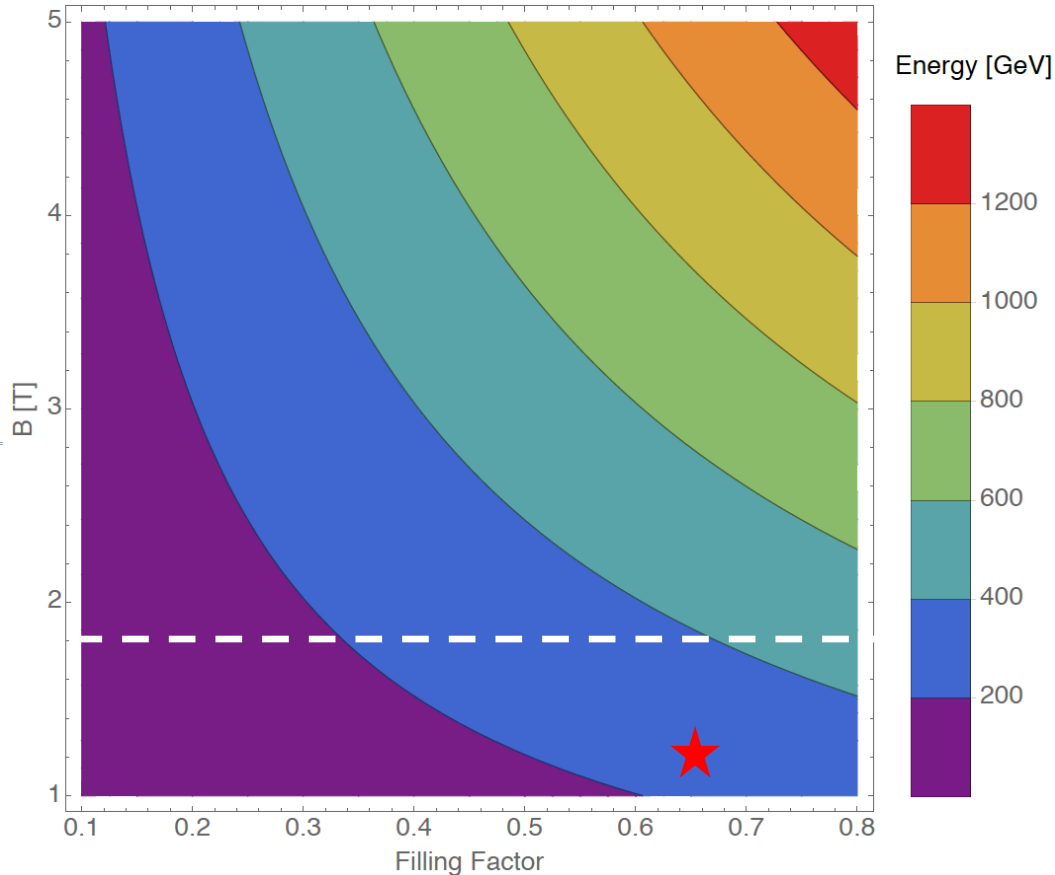
$$k_f = \frac{Nl}{C}$$

- 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)

- The **maximum** possible **circumference** between the CERN I (Meyrin) and CERN II (Prevessin) site was
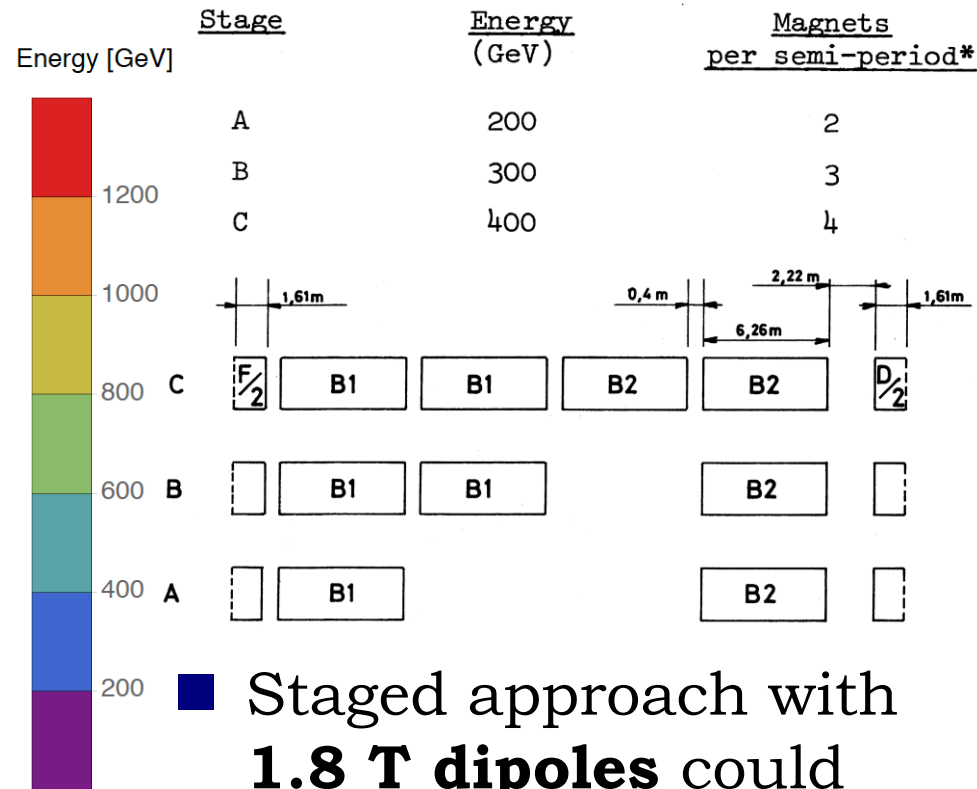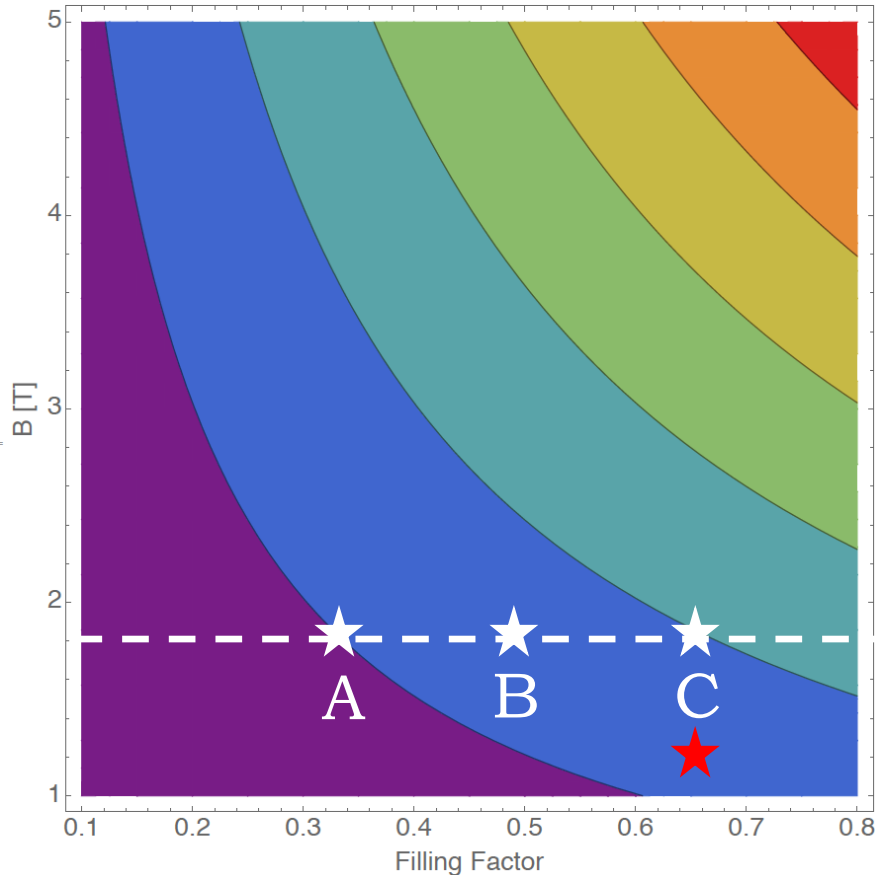
$$C_{\mathrm{SPS}} = 11 C_{\mathrm{PS}} = 2\pi \times 1100 \text{ m} \approx 6912 \text{ m}$$

- 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

13

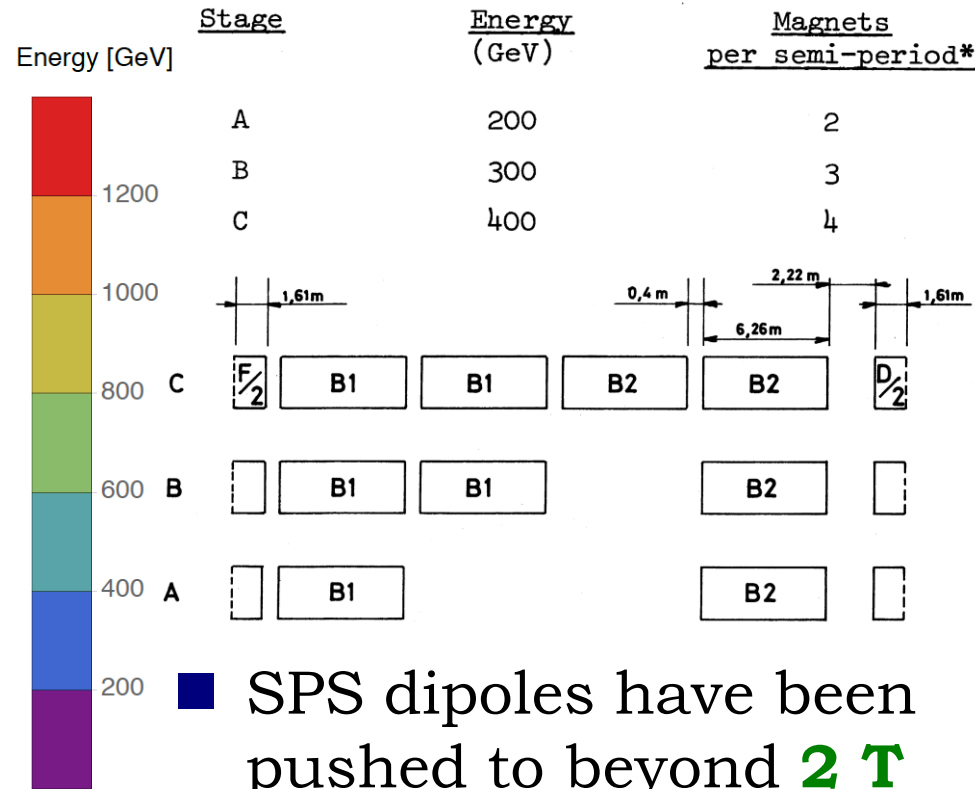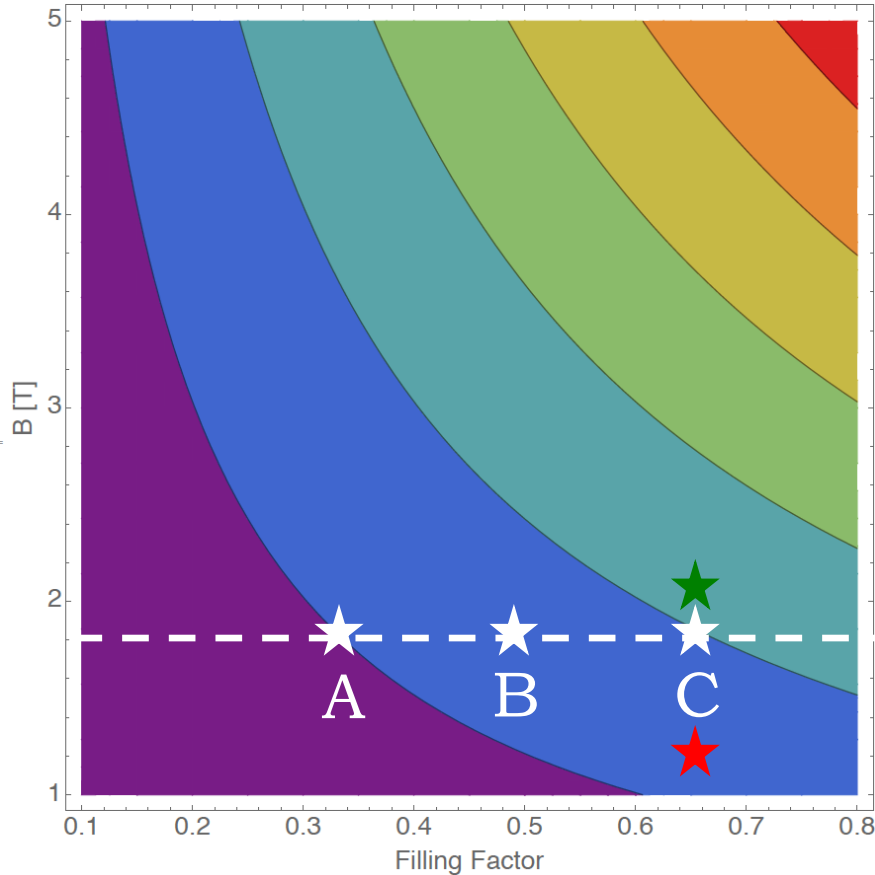The **maximum** possible **circumference** between the CERN I (Meyrin) and CERN II (Prevessin) site was

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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 maximum possible circumference between the CERN I (Meyrin) and CERN II (Prevessin) site was
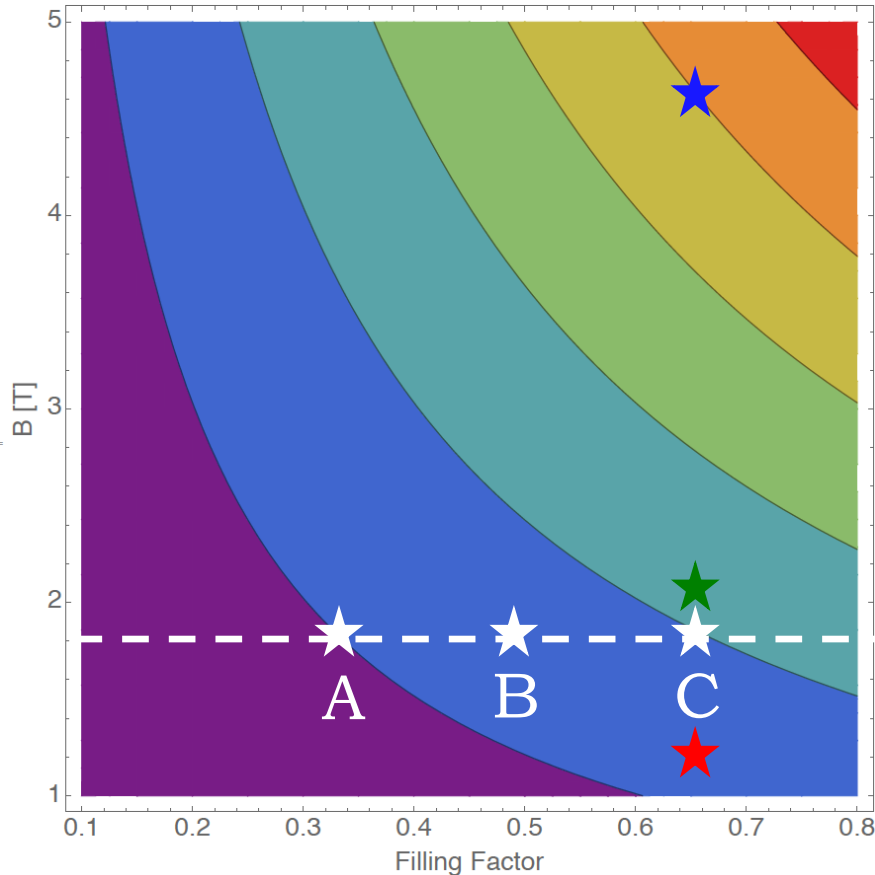
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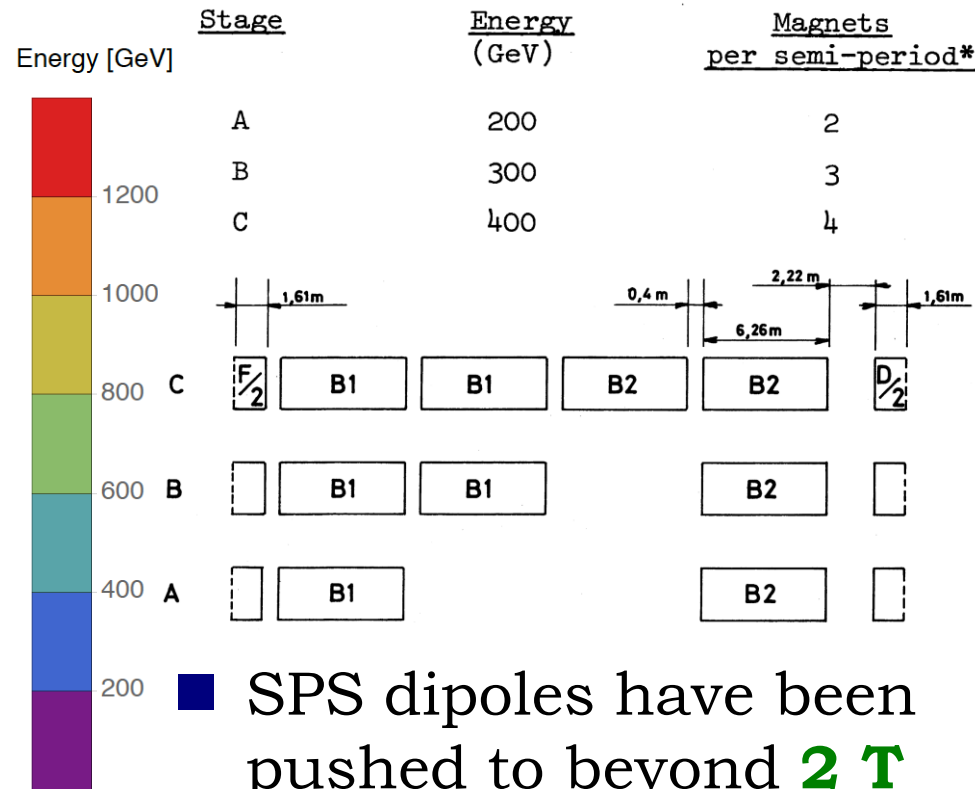
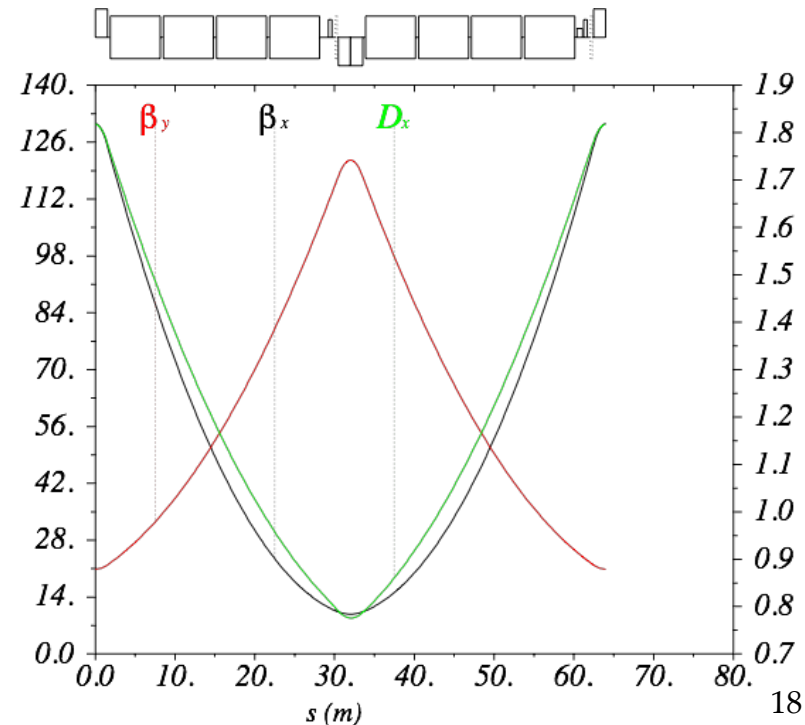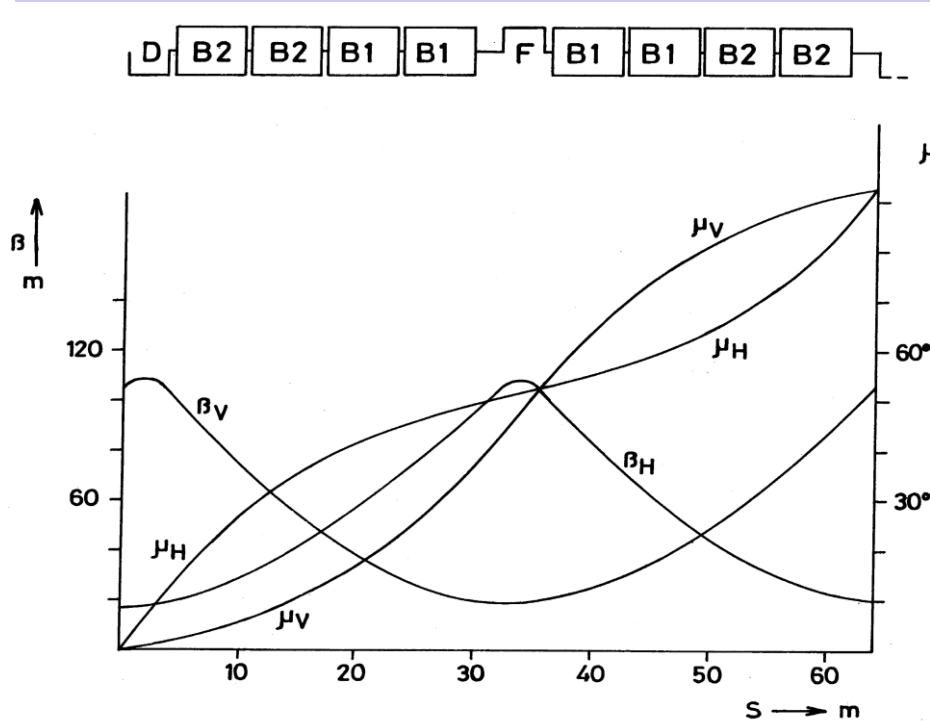■ SPS dipoles have been pushed to beyond **2 T** to reach **450 GeV**

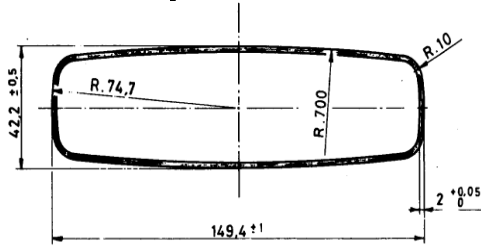■ **Super-conducting** option could raise the energy to **1 TeV**

Optics design and Magnet system

- **FODO cell** of around **65 m** long with phase advances of **π/2**

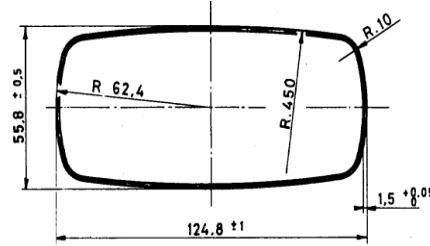- **Beta** function **maxima** slightly above **100 m**
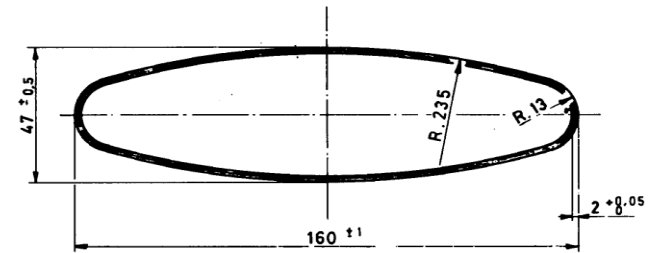
The 300 GeV Program, CERN/1050, 14/01/1972

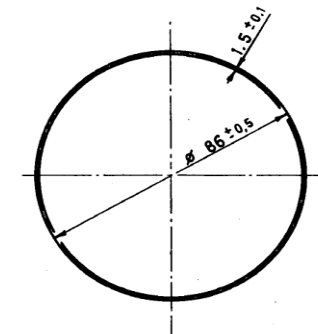- Magnet apertures follow beta function and dispersion evolution

Dipole B1

Dipole B2

Quadrupole F

Quadrupole D

The 300 GeV Program, CERN/1050, 14/01/1972
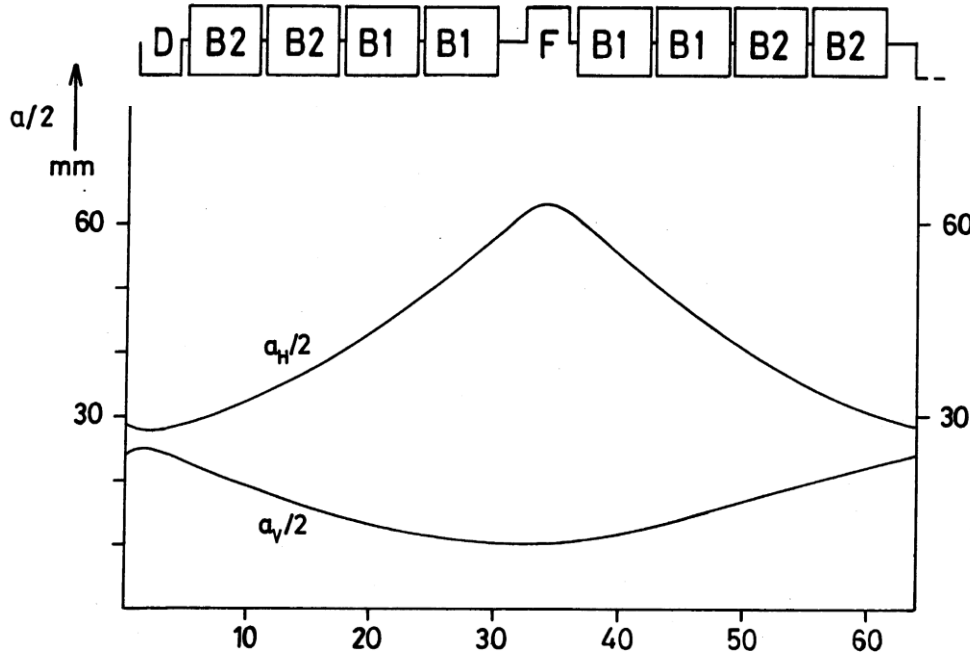
- **744 dipoles** (MBAs and MBBs) with 6.26 m length and different gaps

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

- **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

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

22

Dispersion suppression
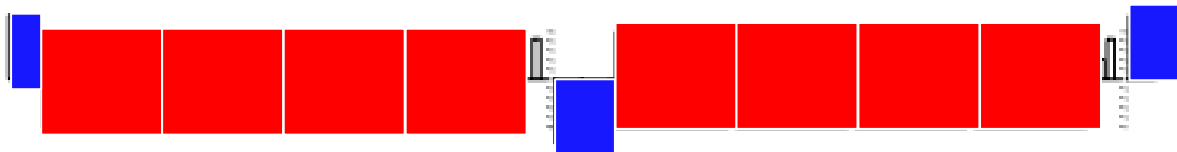
- **Dispersion** has to be **eliminated** in **special areas** like injection, extraction or interaction points (orbit independent to momentum spread)

- Use **dispersion suppressors**

- Methods for suppressing dispersion

  - **Eliminate two dipoles** in a FODO cell (missing dipole)

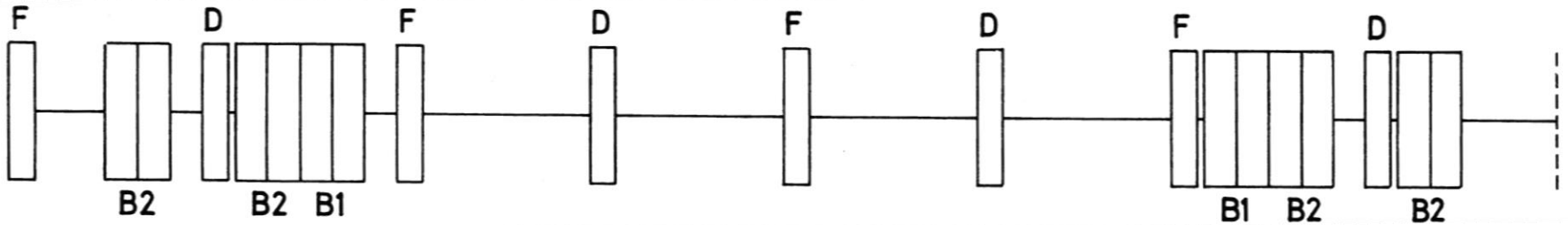 - Set last dipoles with **different bending angles**

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

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

 - For **equal bending angle** dipoles, the FODO phase advance should be equal to **π/2**
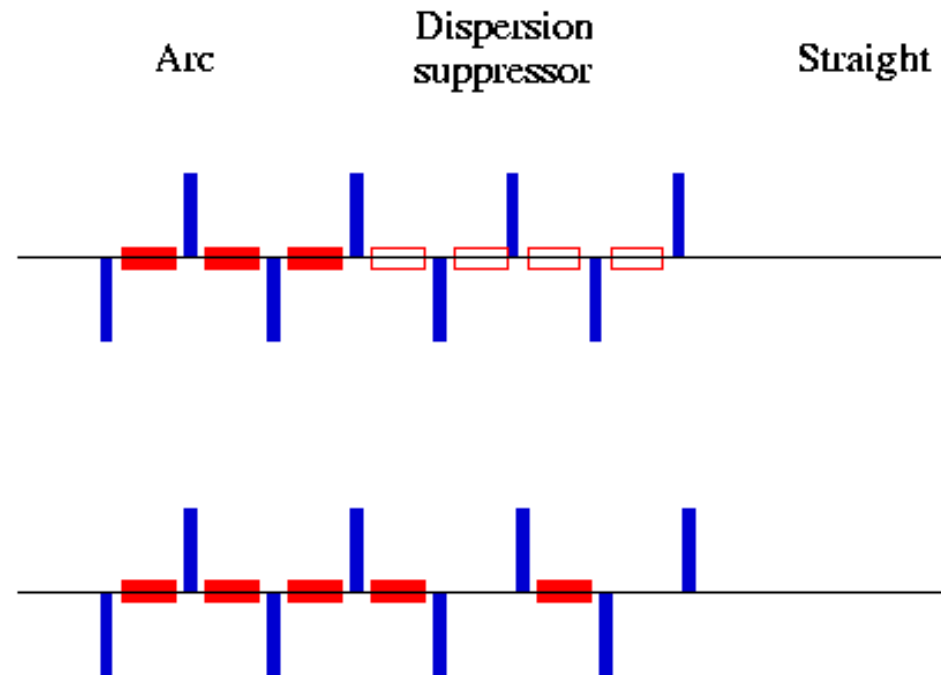
- In the SPS, all **dipoles** are powered in **series**, i.e. dispersion suppressor cells looks like a missing dipole, but they are not!

- 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
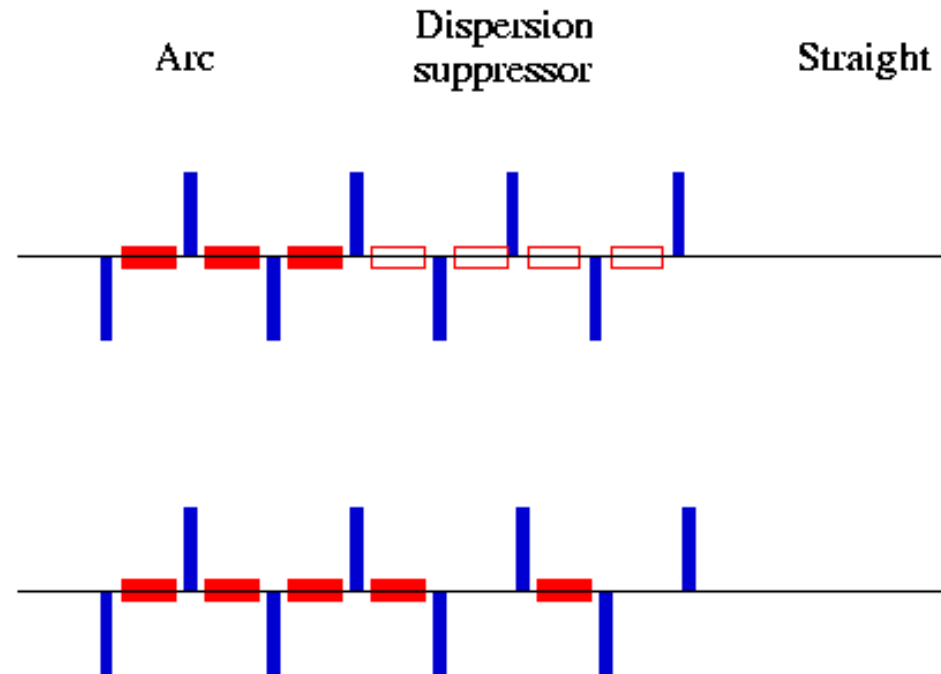
- Ring is composed by **6 identical sectors** ("sextants") with **16 arc cells** and **2 cells** in the **straight sections**

- The cell phase advance of π/2 brings the tunes between 26-27 (**Q26**)
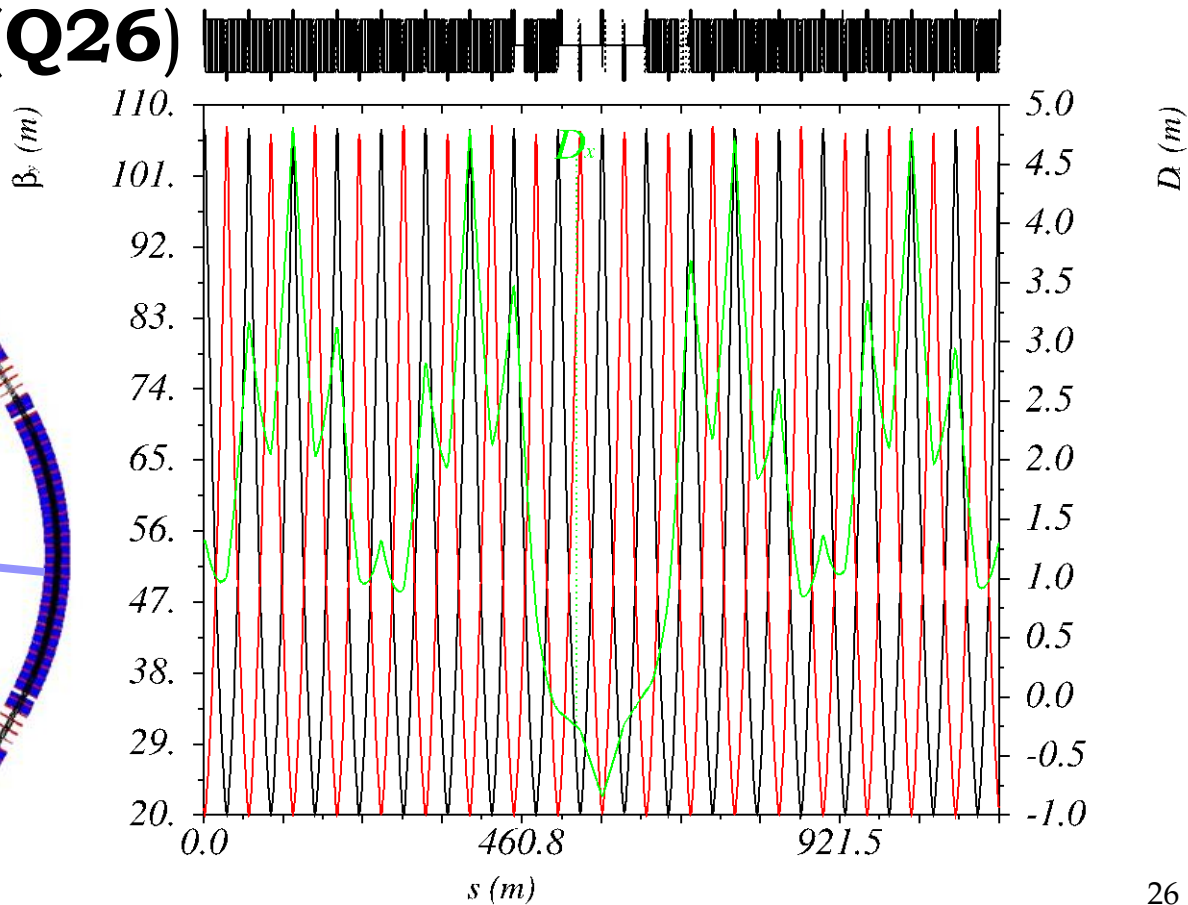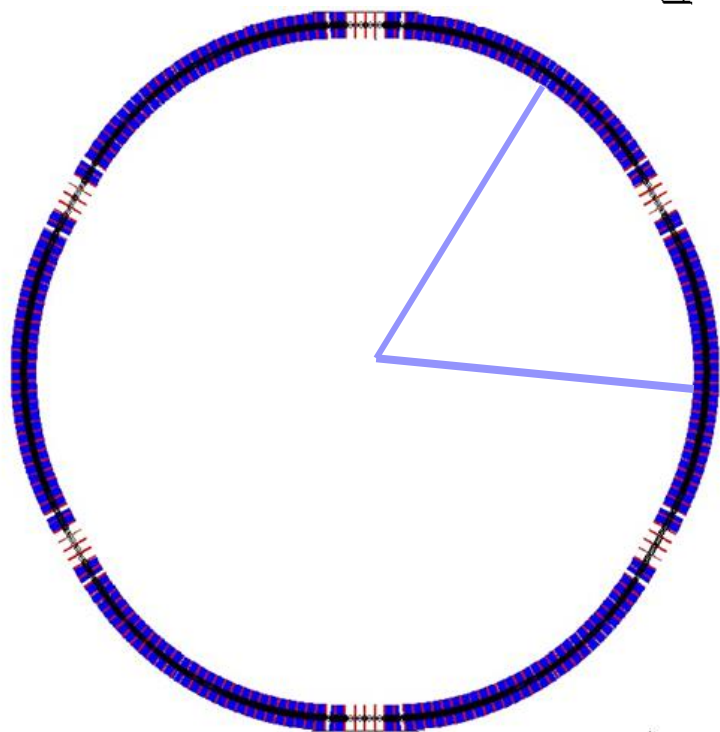
- Replace two straight section quadrupoles with **2 doublets** (4 quadrupoles)
- Equip adjacent **left/right quadrupoles** with individual bipolar **power convertors**
- Achieved **low β*** of 1.3/0.65 m
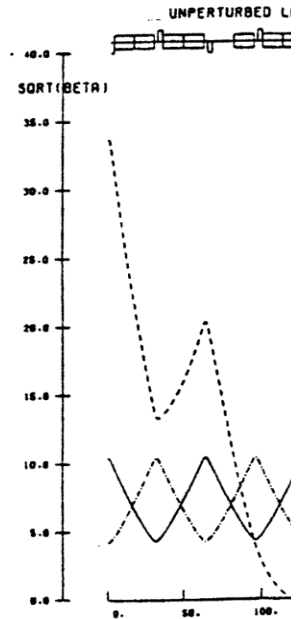
P. Faugeras et al., CERN-SPS-80/11, CERN-SPS-83/29
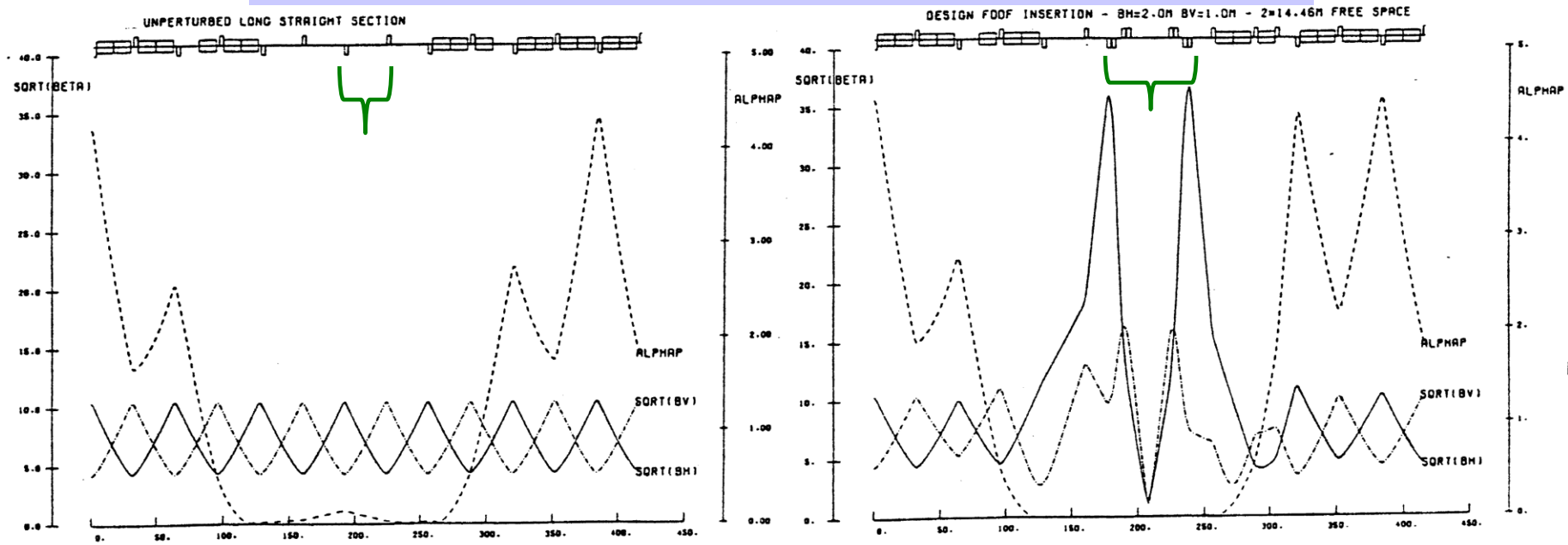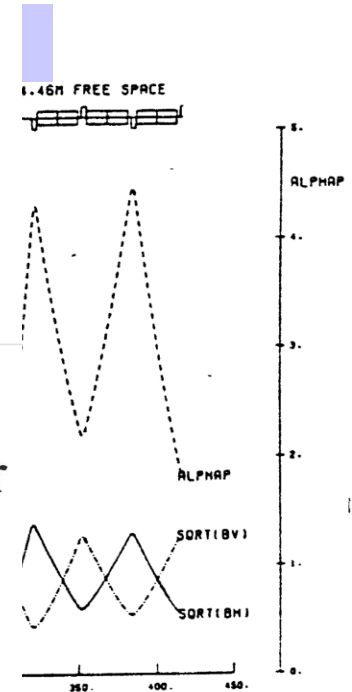
Photo from the Nobel Foundation archive.
Carlo Rubbia
Prize share: 1/2

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"

Designing a Synchrotron, CERN Accelerator School, September 2024

Transition energy and slippage factor

■ 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
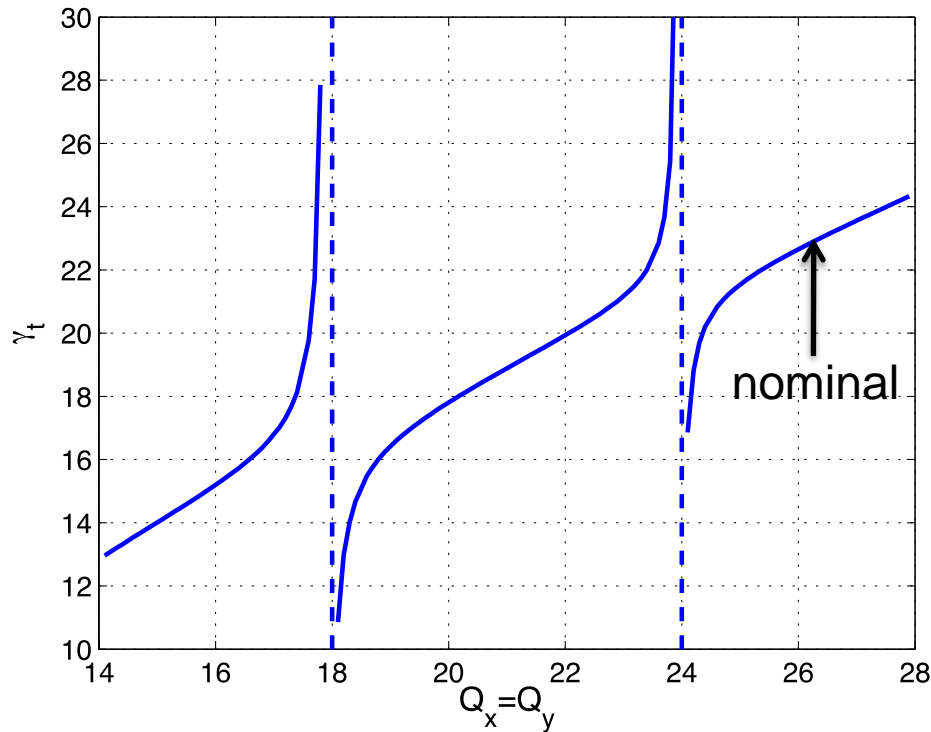
31

γ_t in the SPS

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

32
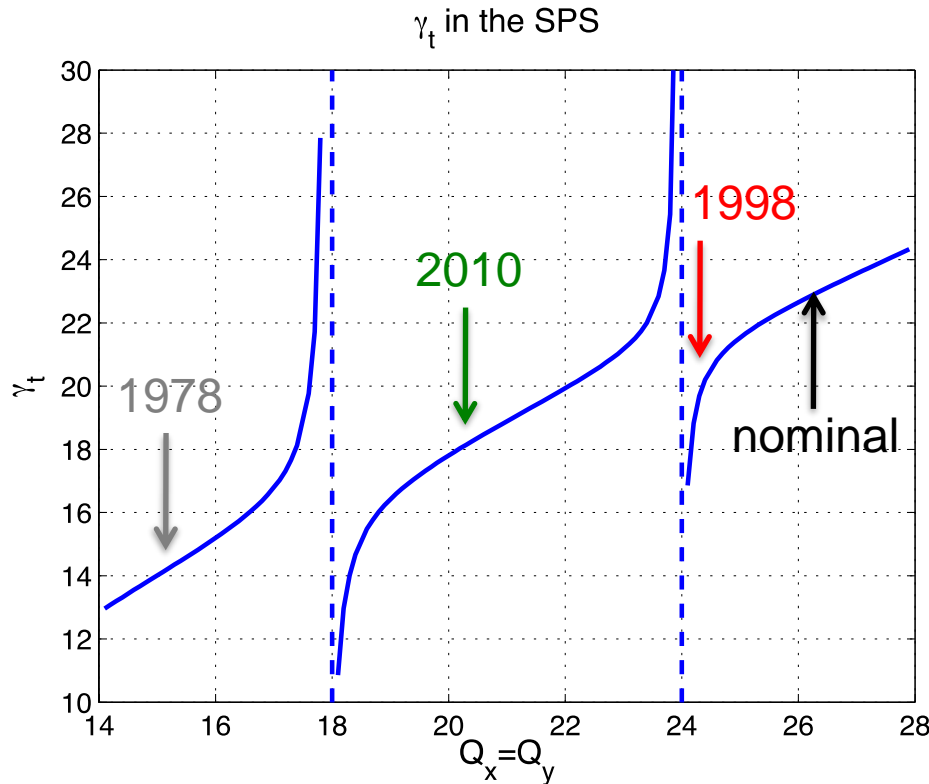
- **Resonant oscillation of dispersion function close to the "Resonant integer tunes" (multiples of super-periodicity 6) → asymptotic behavior of γ_t, (difficult for routine operation)**
- γ_t is a linear function of horizontal tune Q_x elsewhere

- Nominal SPS working point for LHC proton beams ($\gamma_t\sim$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\sim$14)

- G. Arduini et al., CERN/SL-Note 98-001, 1998; "Resonant tune" ($\gamma_t\sim$20)

- YP, H. Bartosik et al., Low γ_t, 2010 - "Resonant arc" with small dispersion in long straight sections ($\gamma_t\sim$18)

33

- 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 ($\gamma_t \sim 14$)

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

34
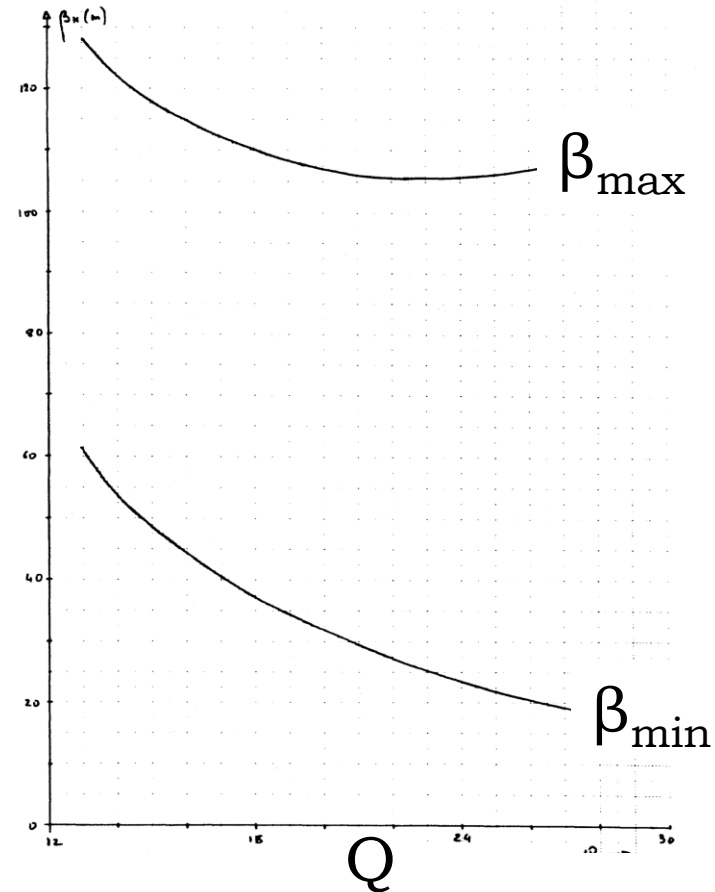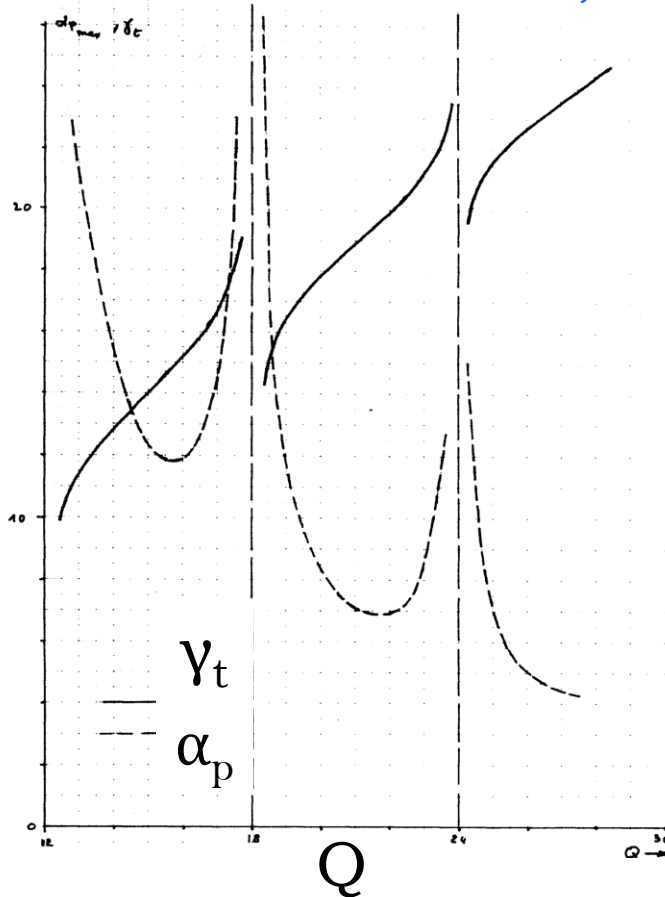
Manipulating optics for curing instabilities

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

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

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

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

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

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

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

$Q_x, Q_y = 26.13, 26.18$

$Q_x, Q_y = 20.13, 20.18$

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

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

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

Q20

Nominal optics Q26
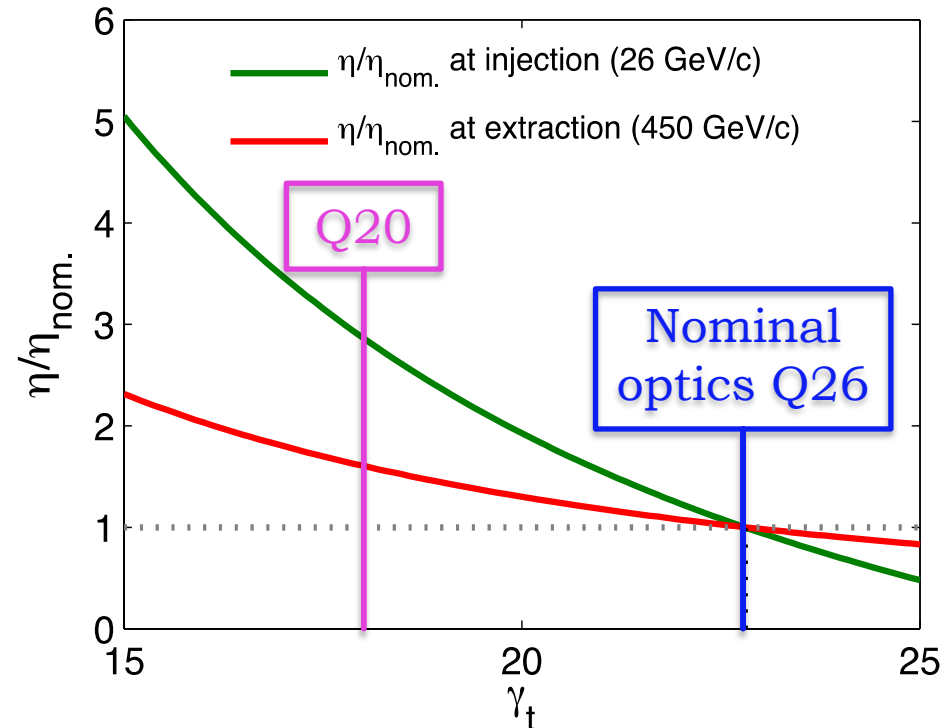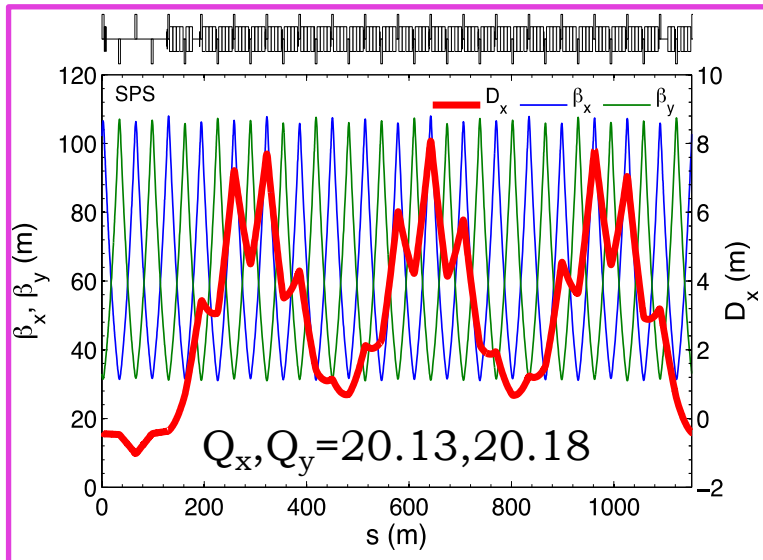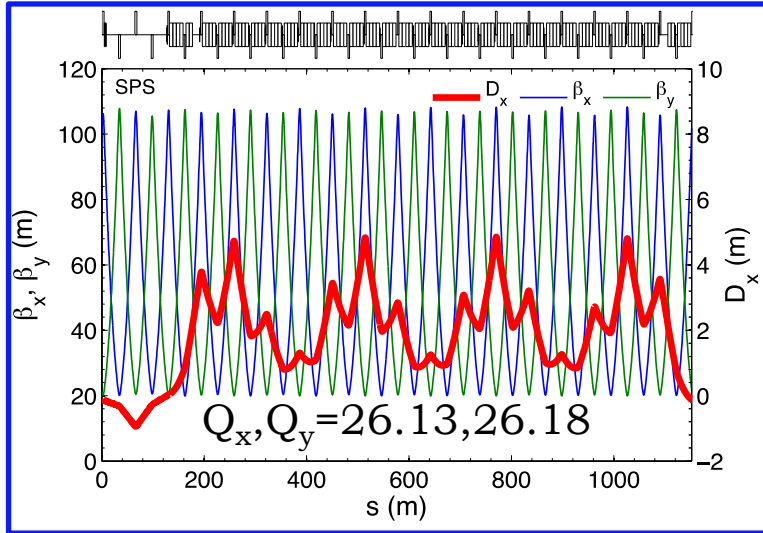
Slip factor relative to nominal SPS optics [37]
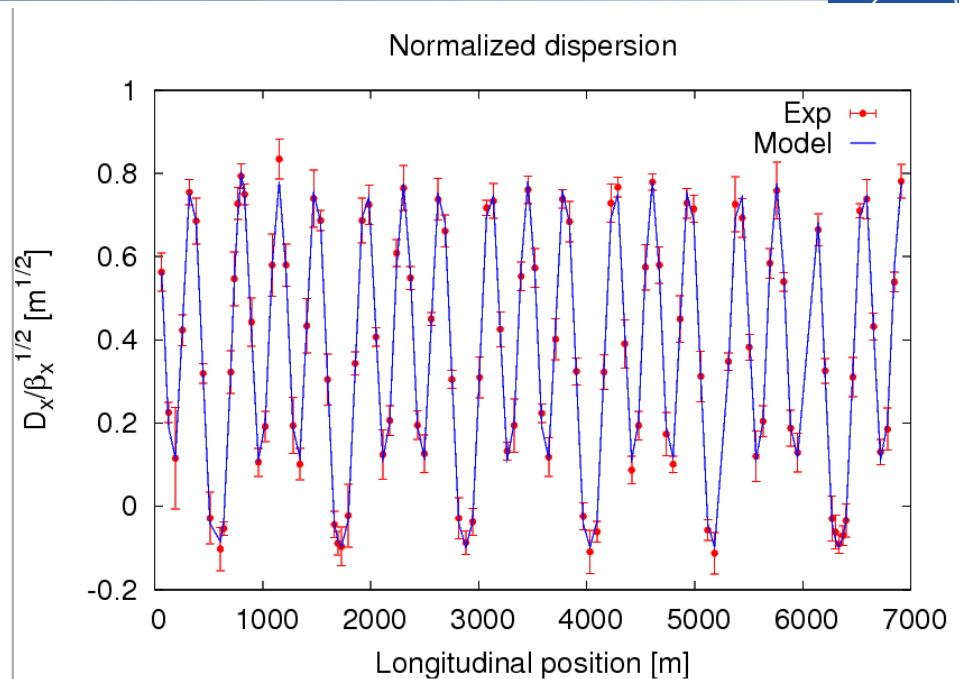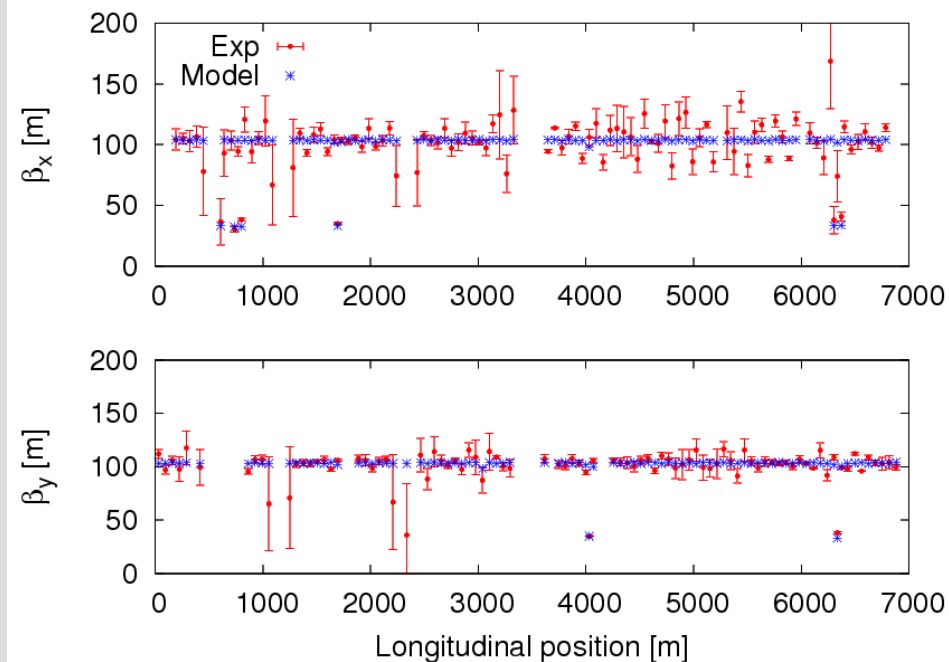
□ **Measurement** of the optics functions of the new lattice

  □ **Beta beating** around 20% in horizontal and 10% in vertical plane

  □ Normalized **dispersion** in striking agreement with the model

38

- ❑ 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)
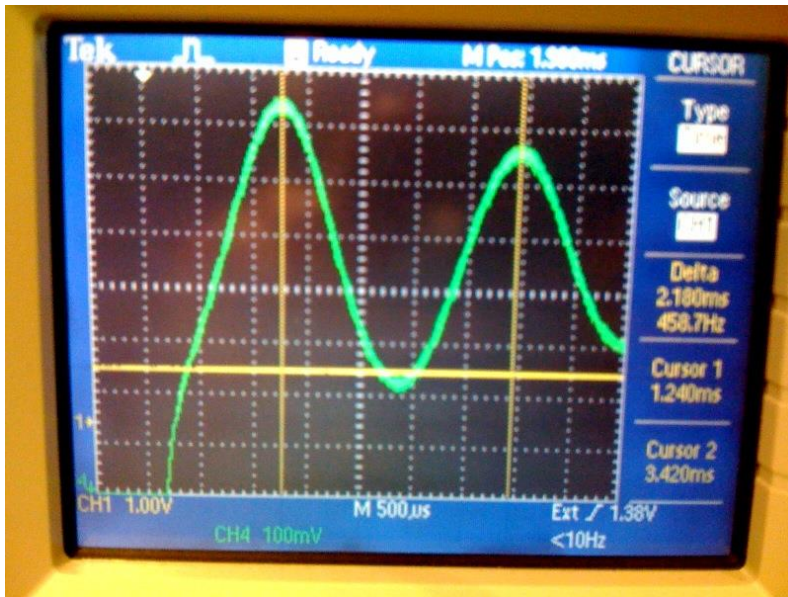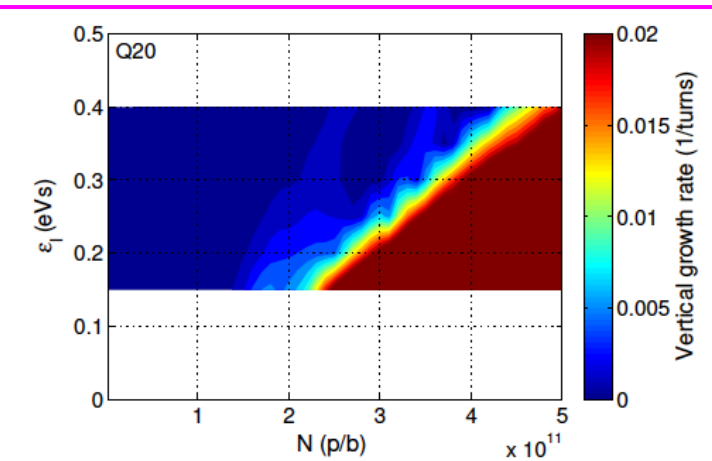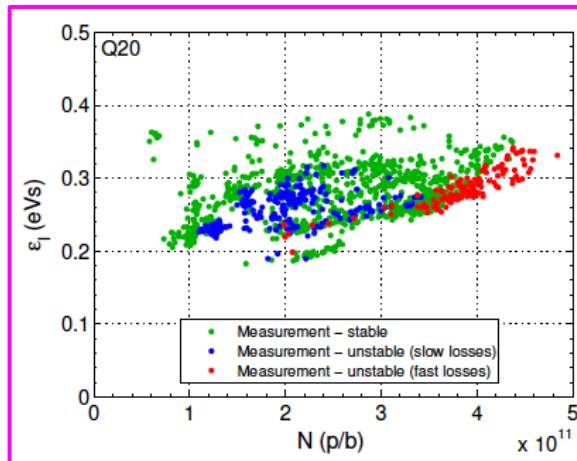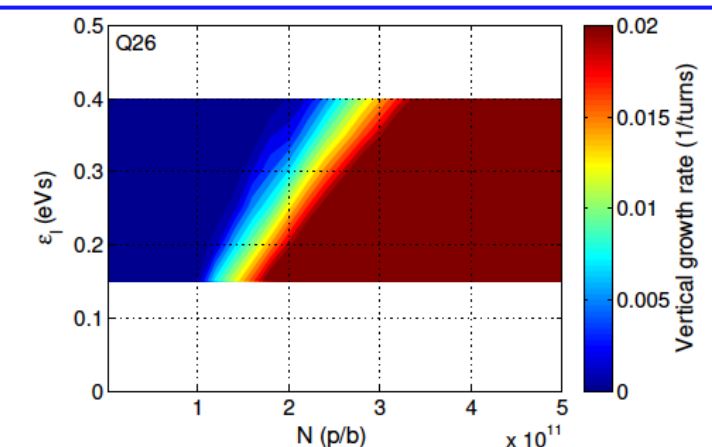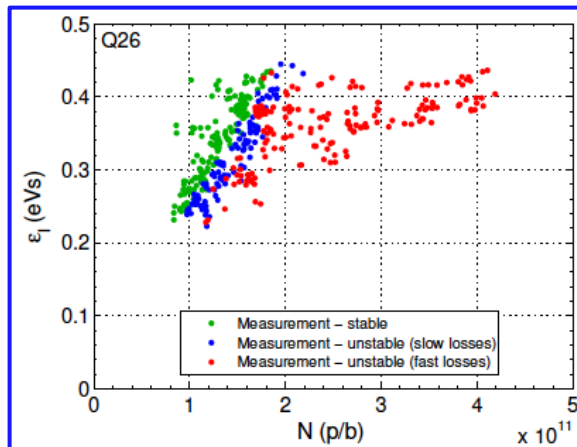

Q26: Fs=458/2=229Hz,
    Qs=0.0106/2=0.0053
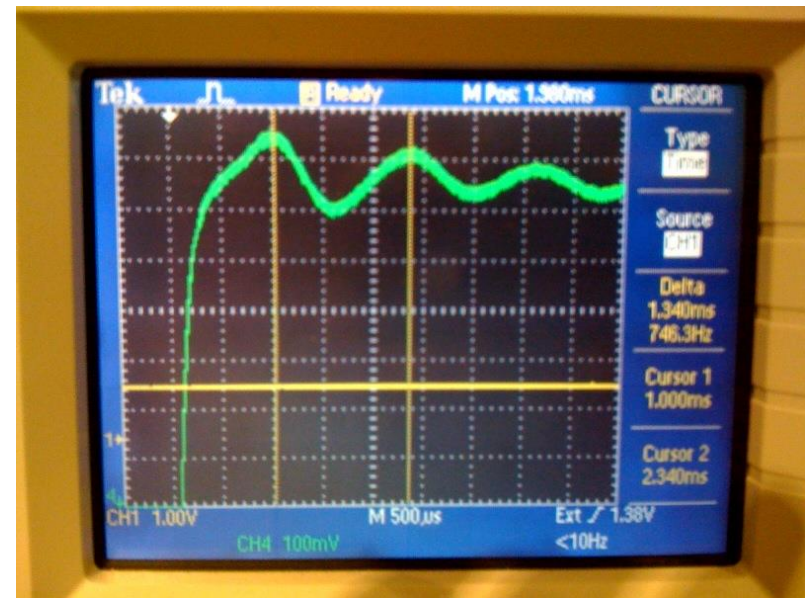
Q20: Fs=746/2=373Hz,
    Qs=0.0172/2=0.0086
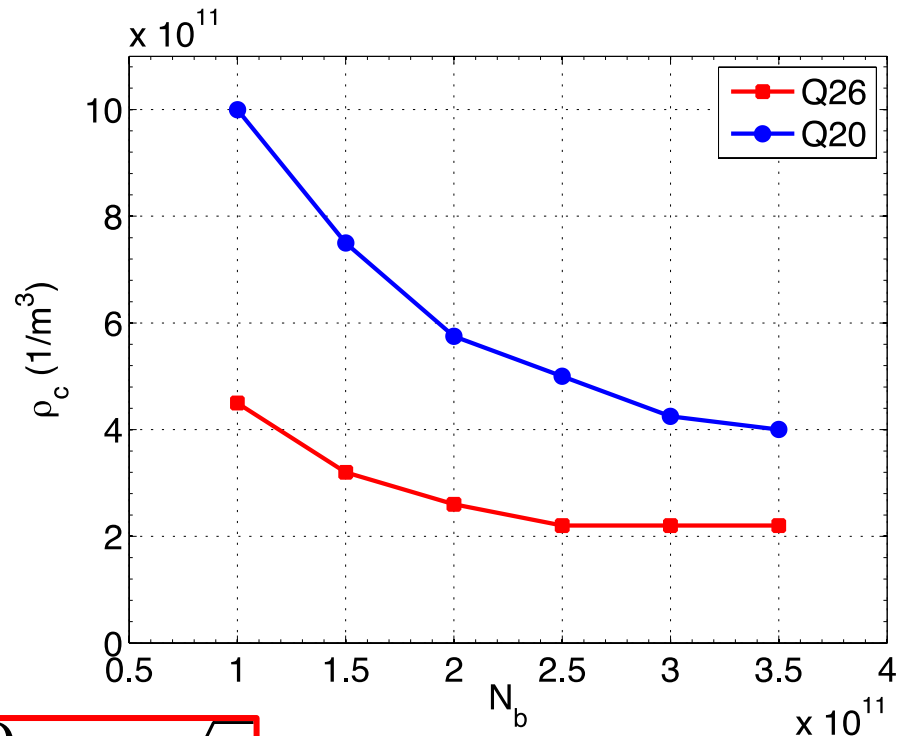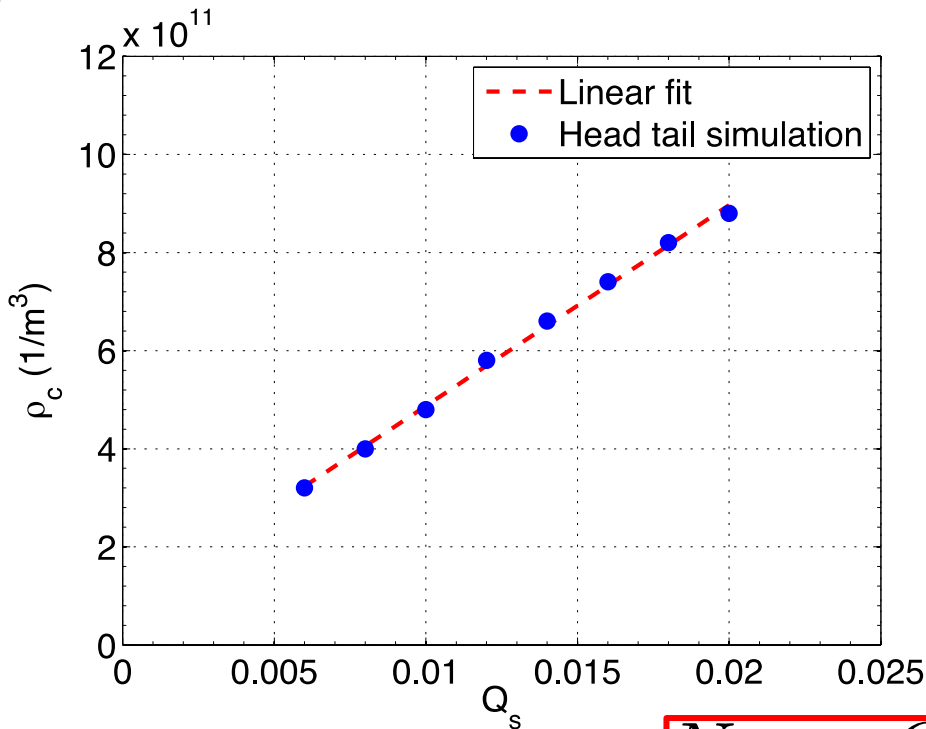
❑ In **nominal optics**, measured/simulated threshold at **1.6x10^{11}p/b** for low chromaticity

   ❑ High-chromaticity helps increasing threshold, but also losses along the cycle become excessive

❑ Measured/simulated threshold in **Q20** > **4x10^{11}p/b!!!**

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


H. Bartosik et al, IPAC 2014

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

❑ 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**
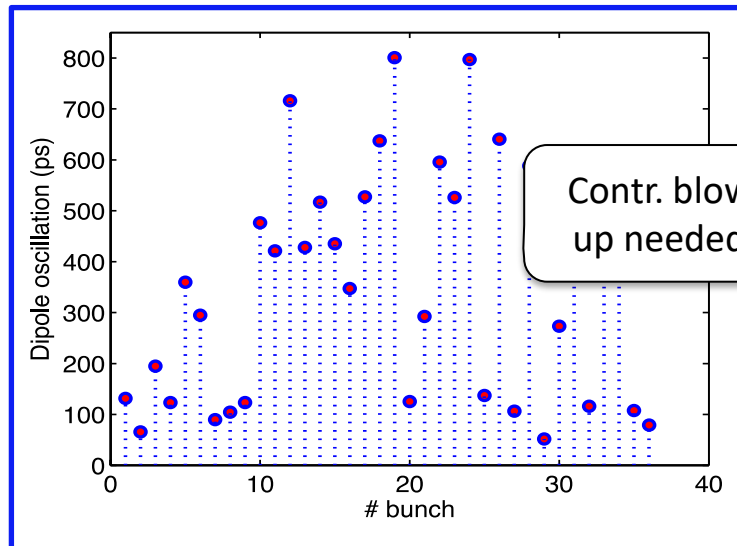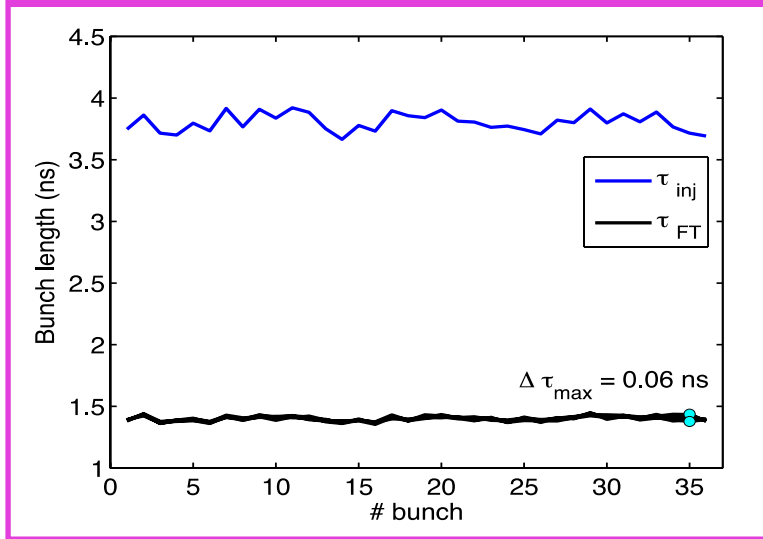
More margin with Q20 if e-cloud becomes issue for high intensity
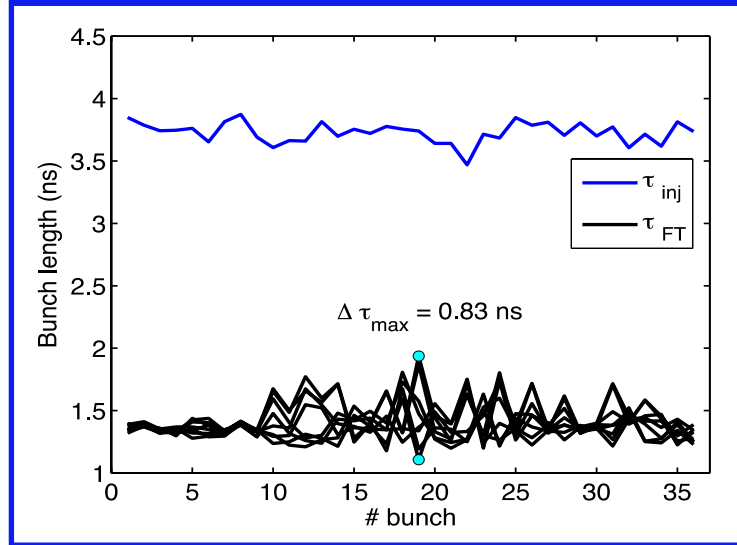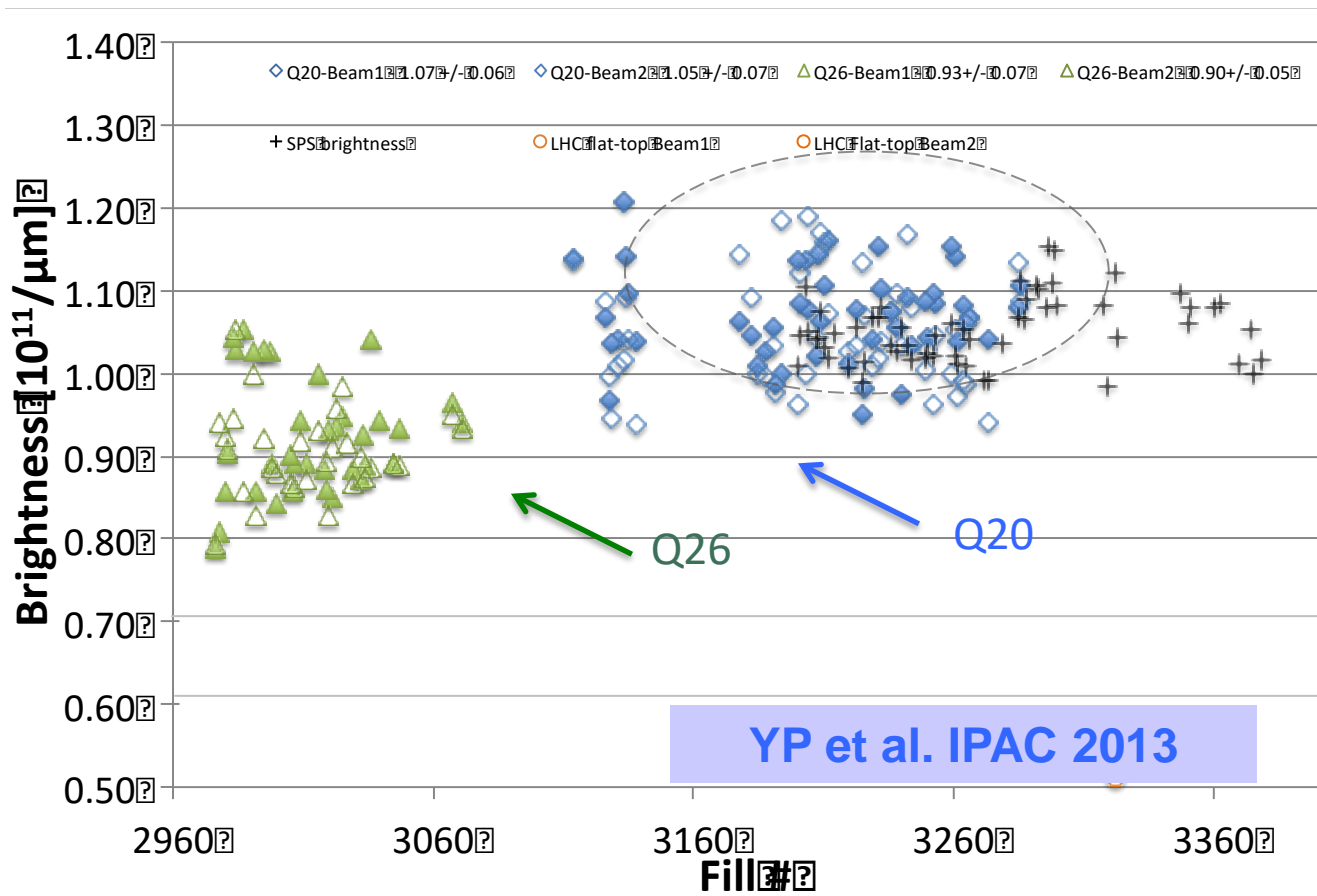
H. Bartosik et al, IPAC2011

T. Argyropoulos et al.

Stable beam

Contr. blow-up needed!
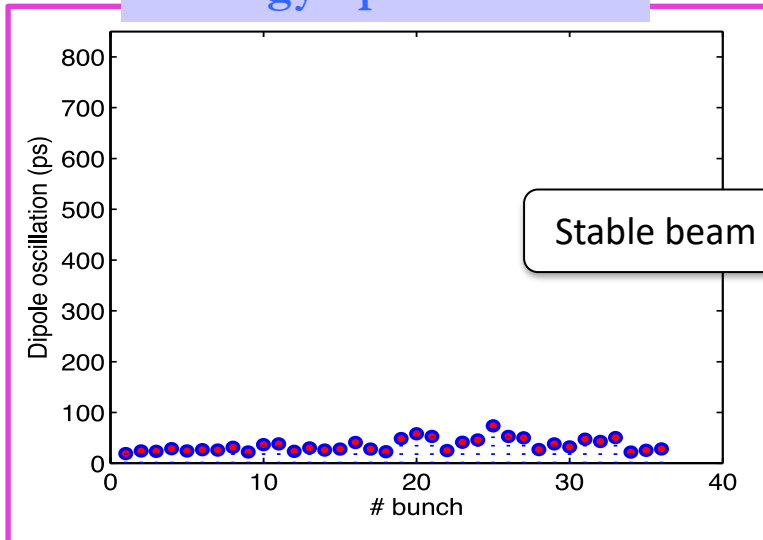
SPS-Q20 (1.6×10^{11} p/b)
double harmonic RF

SPS-Q26 (1.6×10^{11} p/b)
double harmonic RF

$\Delta \tau_{max} = 0.06$ ns

$\Delta \tau_{max} = 0.83$ ns

42

- ❑ 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
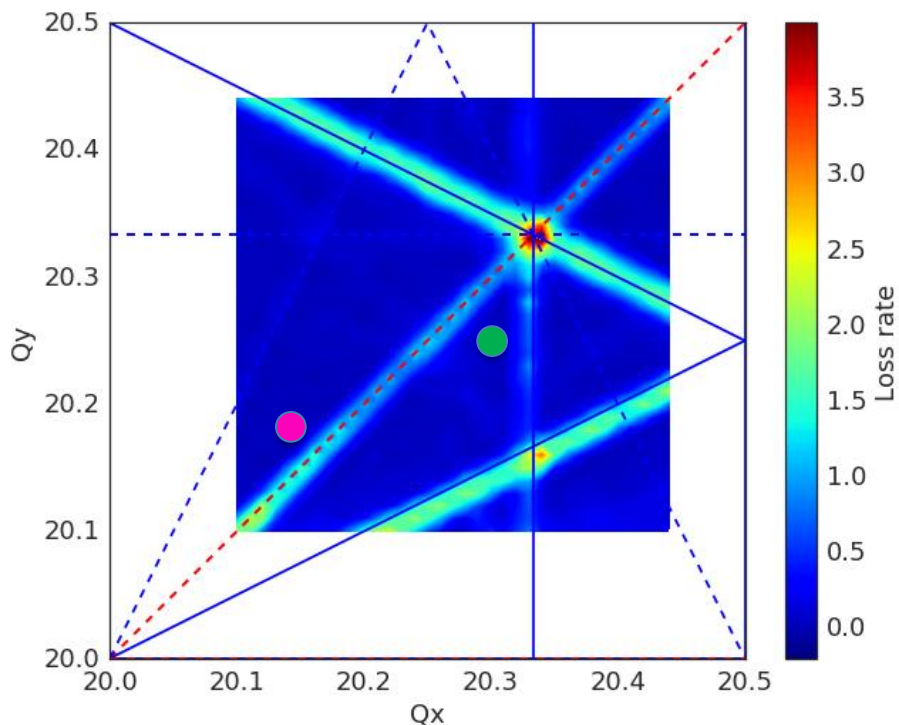
- proton working point
- ion working point

resonances:
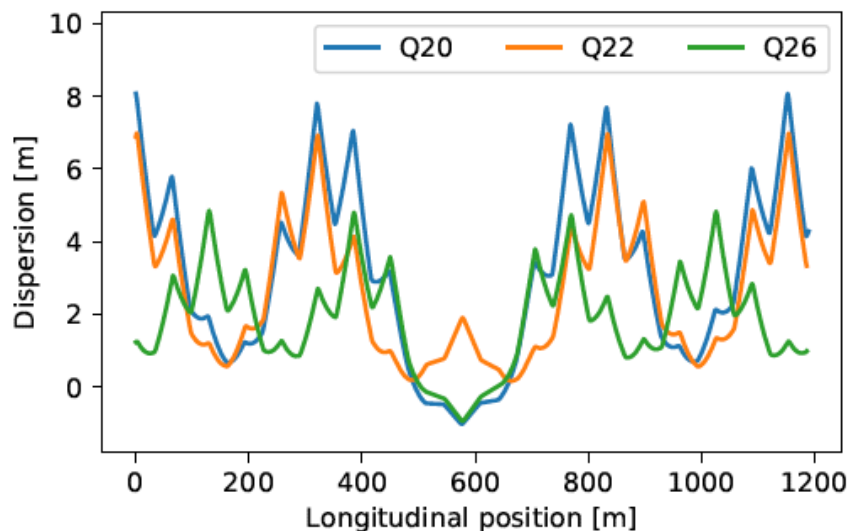
red: systematic
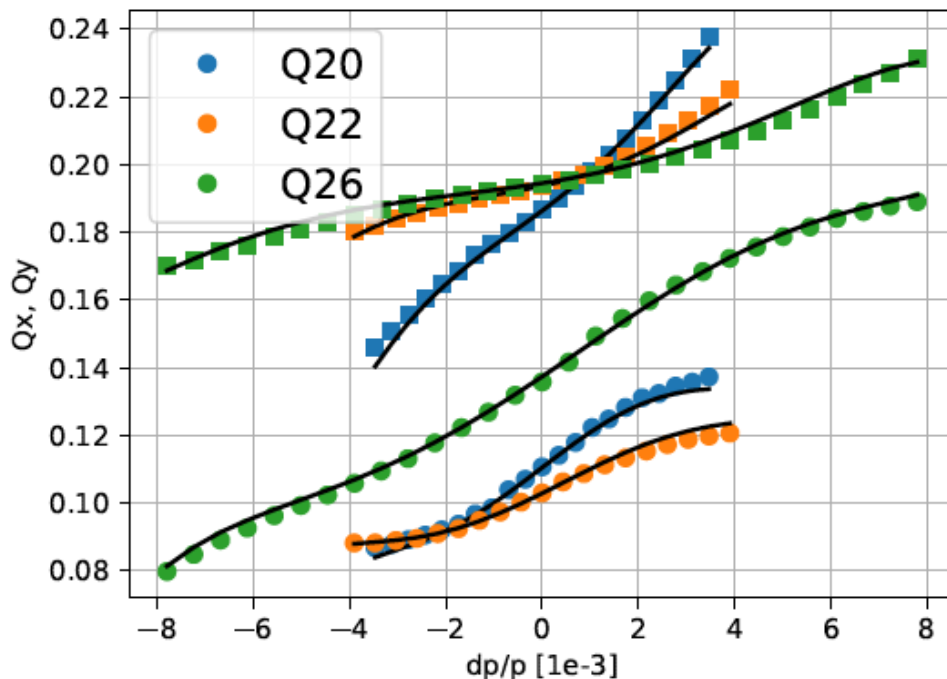blue: non-systematic
– upright
- - skew

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)
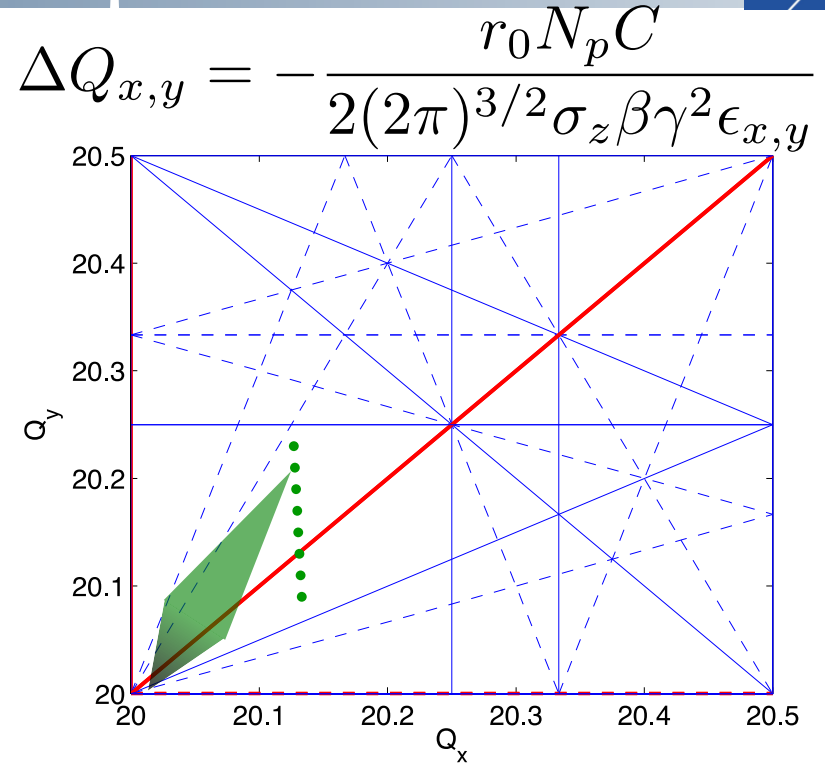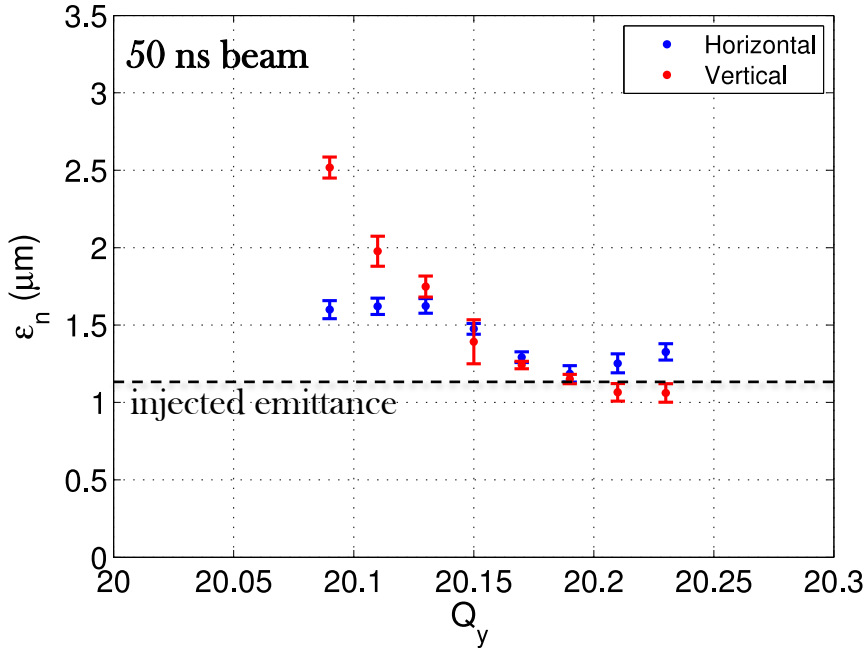
M. Carla' et al. IPAC2018

Sextupoles

$$Q = Q_0 + Q'(\frac{\delta p}{p}) + Q''(\frac{\delta p}{p})^2 + Q'''(\frac{\delta p}{p})^3 + \ldots$$

Quadrupoles   Octupoles   Decapoles

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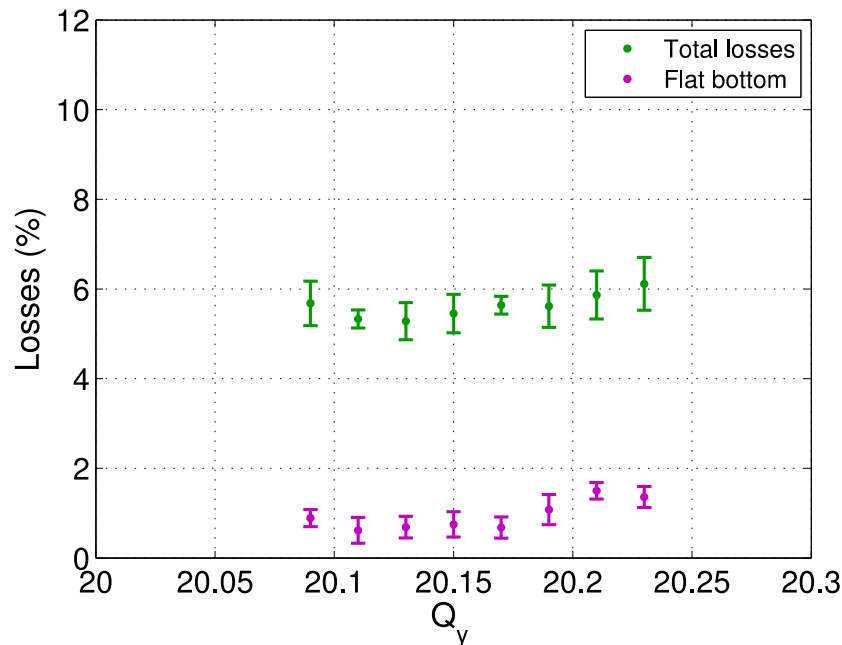
Space-charge

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

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

  - ❏ 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)

H. Bartosik et al. 2018

emittance at end of flat bottom

- **Vertical tune scan** with high brightness beam for 10 s storage time
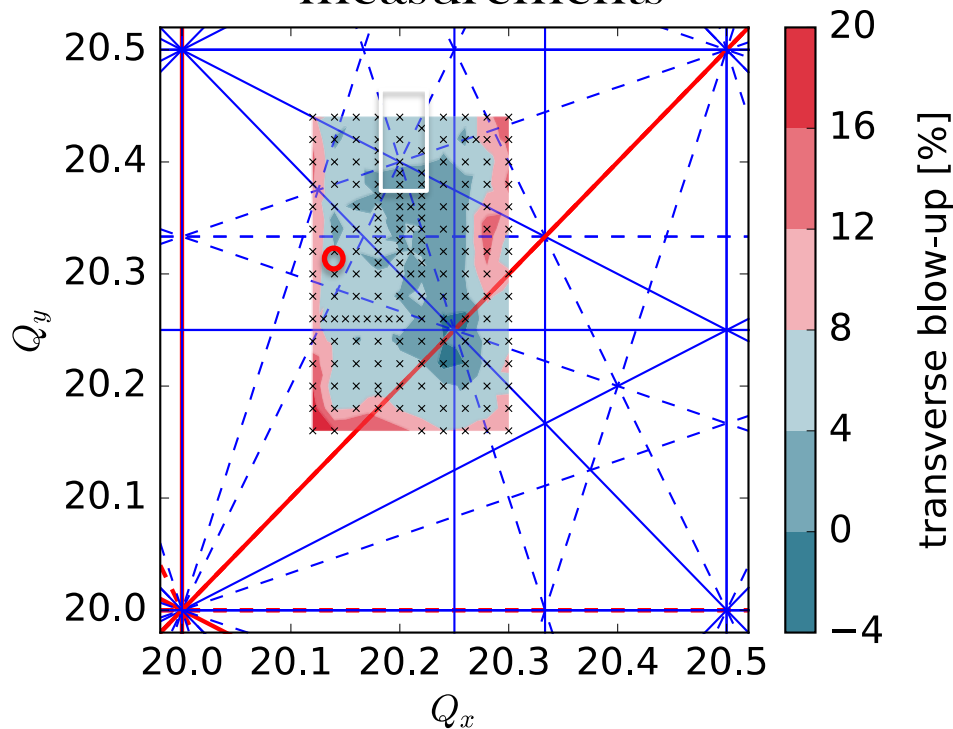 - N = 1.95x10^{11} p/b (at injection)
  - ε ~ 1.1 μm (at injection)
  - Transmission to flat top around 94% (very small losses on flat bottom)

ΔQ$_x$/ΔQ$_y$ ~ 0.10/0.20

H. Bartosik et al. 2018

49

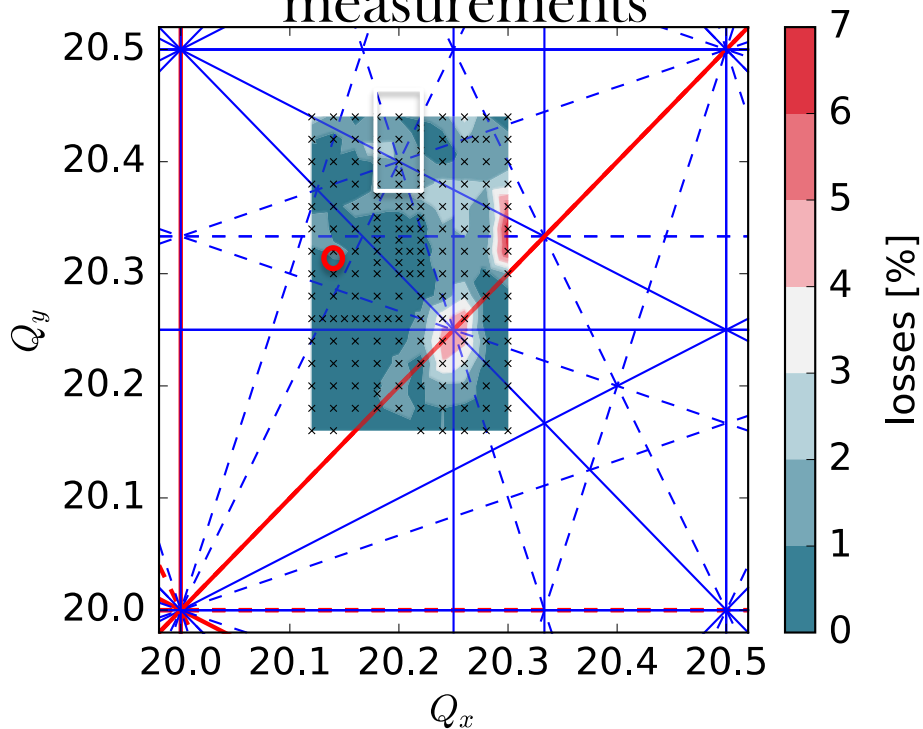Designing a Synchrotron, CERN Accelerator School, September 2024
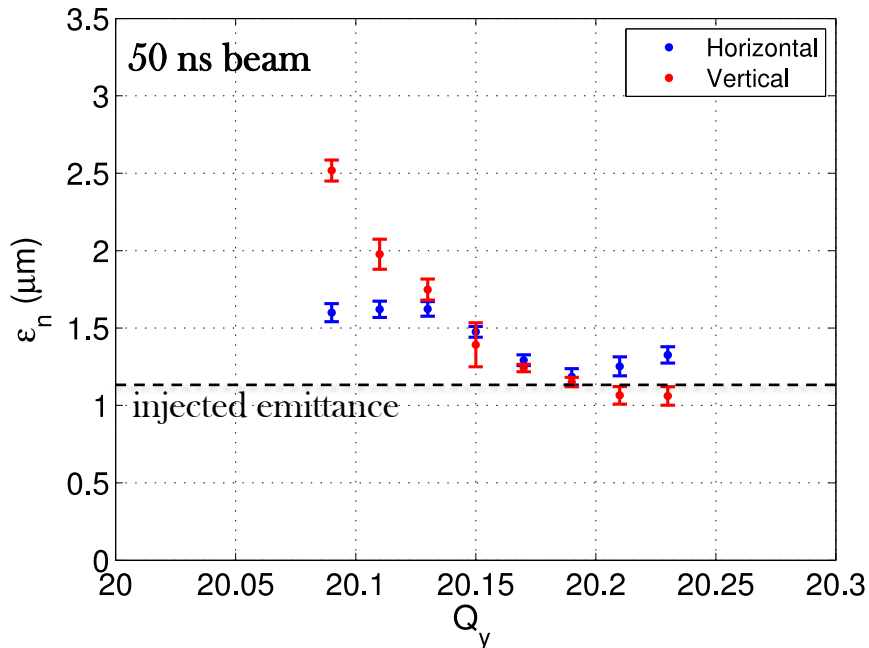
- Tune scan with high brightness single bunch beam for **3 s storage time**
  - ☐ Blow-up at integer resonances as expected (tune spread ΔQx, ΔQy ~ 0.10,0.19)
  - ☐ **Margin for higher brightness for working points in white box** (enhanced losses only close to Qx + 2Qy = 61 normal 3rd order resonance and around 4Qx = 81 normal 4th order resonance)
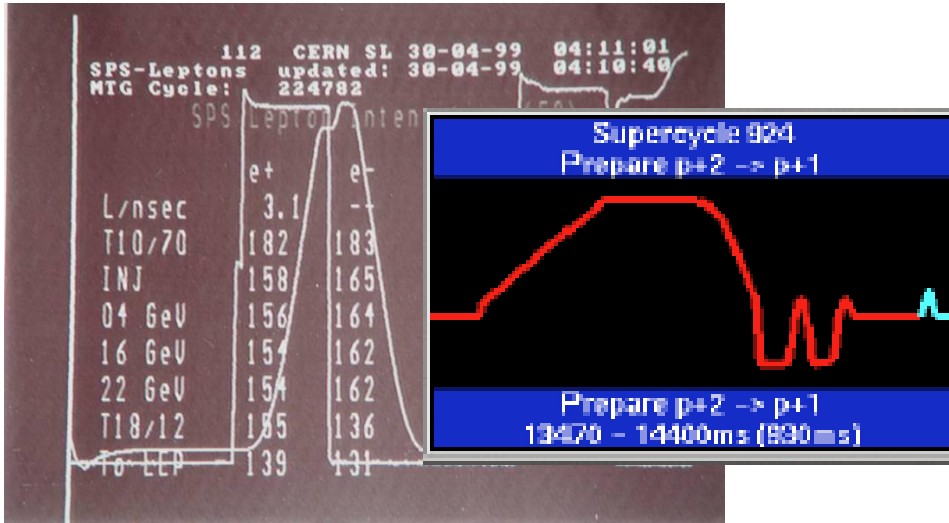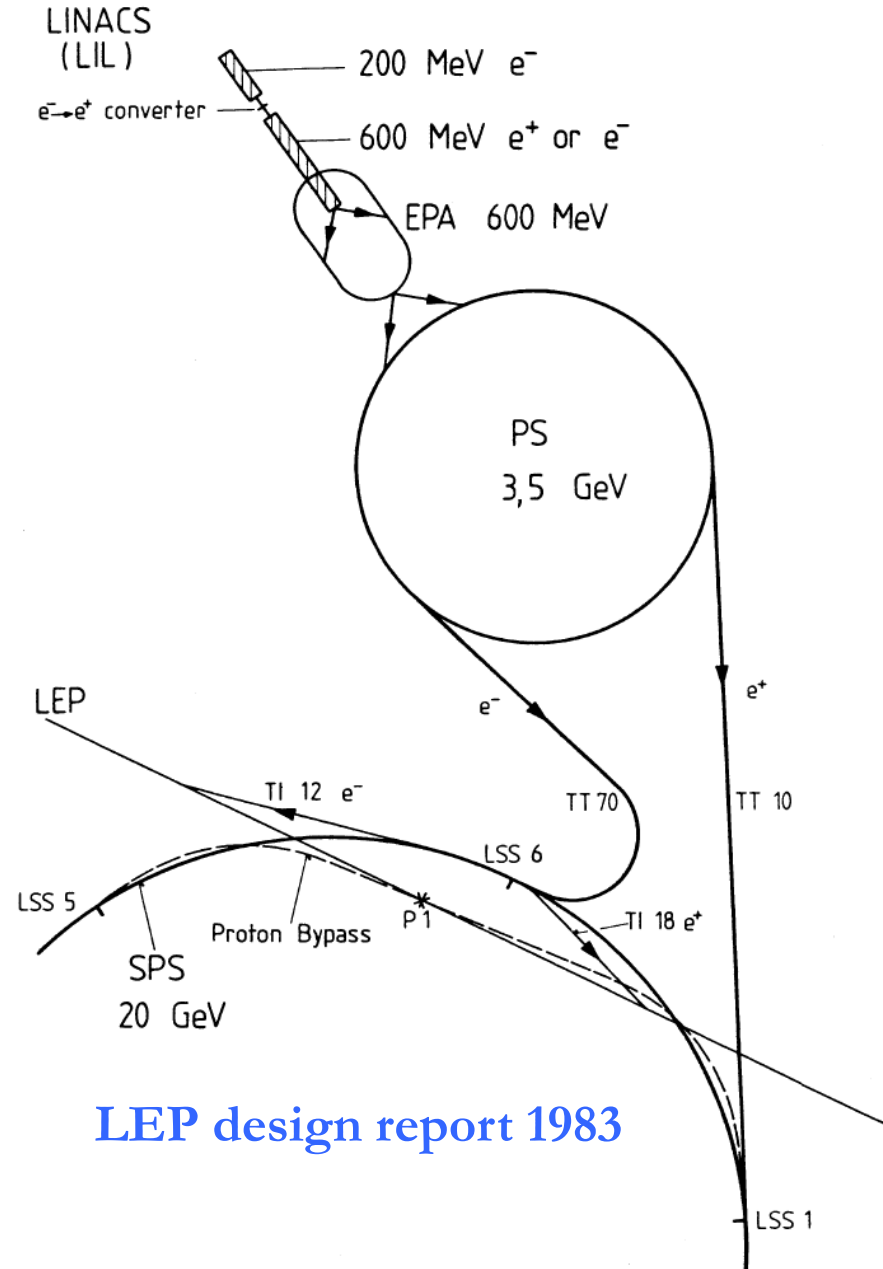
H. Bartosik et al. 2018


measurements

Electron-positron dynamics

P. Collier – Academic Training 2005

LINACS (LIL)
- 200 MeV e⁻
- $e^- \to e^+$ converter
- 600 MeV e⁺ or e⁻
- EPA 600 MeV
- PS 3,5 GeV

- LEP
- TI 12 e⁻
- Proton Bypass
- LSS 5
- SPS 20 GeV
- LSS 6
- P 1
- TI 18 e⁺
- e⁻
- e⁺
- TT 70
- TT 10
- LSS 1

■ LEP filling interleaved with proton operation

■ 4 cycles with 4 bunches (2e⁺, 2e⁻) evolved to 2 cycles with 8 bunches (~**2.5x10¹⁰** 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

The CERN Accelerator School

U_0 [MeV]

En [GeV]

$$U_0[keV] = 88.5 \frac{E^4}{\rho} \frac{[\text{GeV}]^4}{[\text{m}]}$$
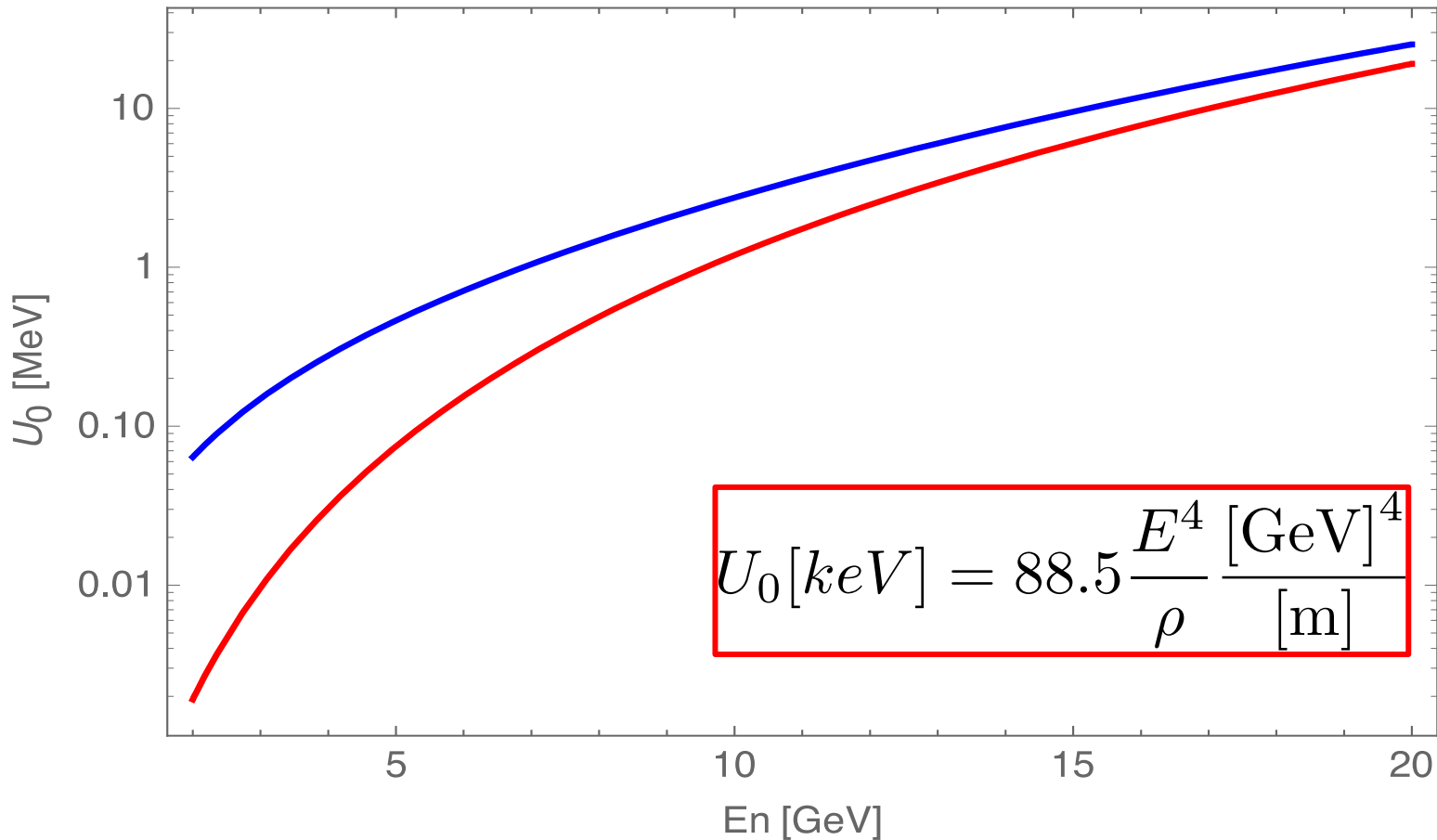
- Energy loss/turn necessitate **large RF voltage** (30 MV) at high energy
- Impact of a 2-m **3.5T** **damping wiggler** is mild at high energies

53
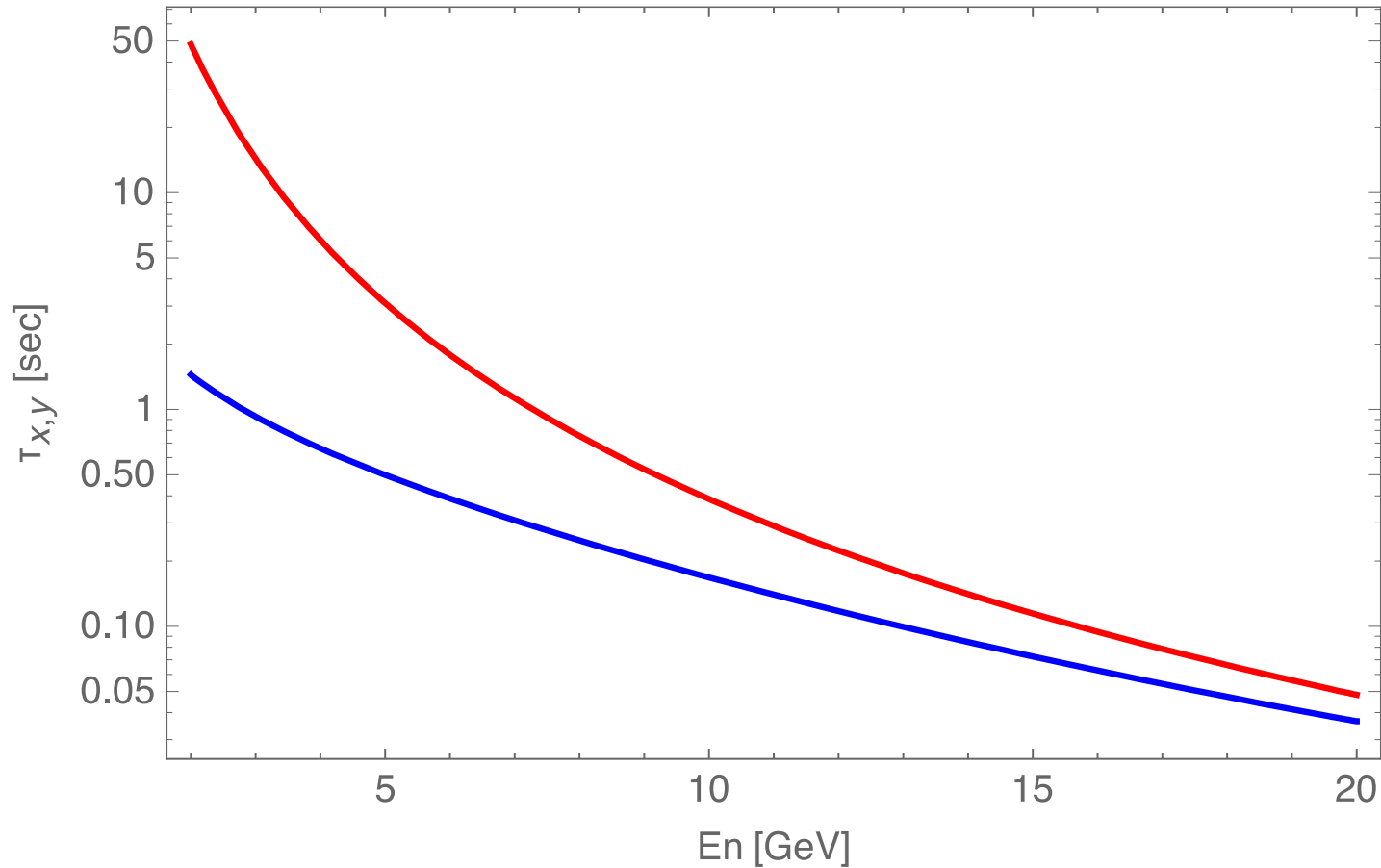
- **Damping time** at injection (3.5 GeV) **very large (9 s)**
- A 2-m **3.5T** **damping wiggler** could enhance damping for low energies to below 1 s (good for instabilities)

54

- 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
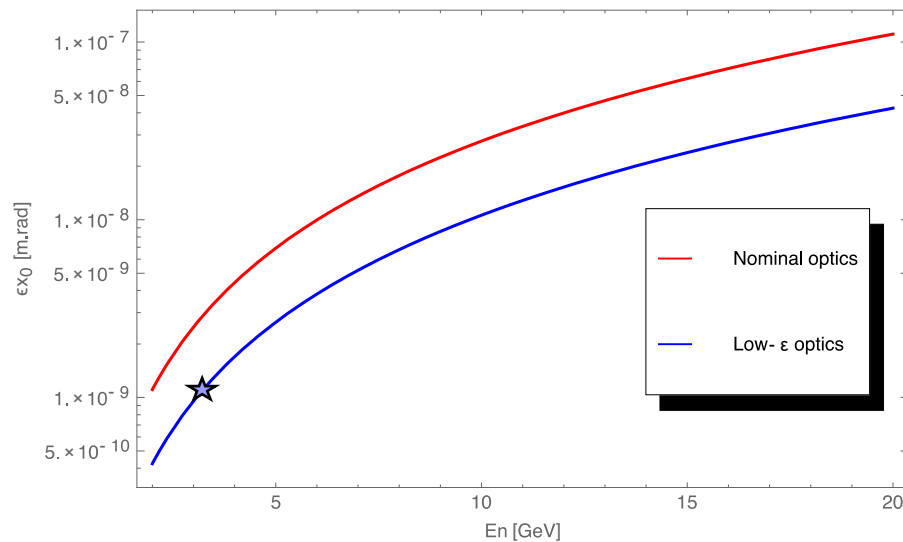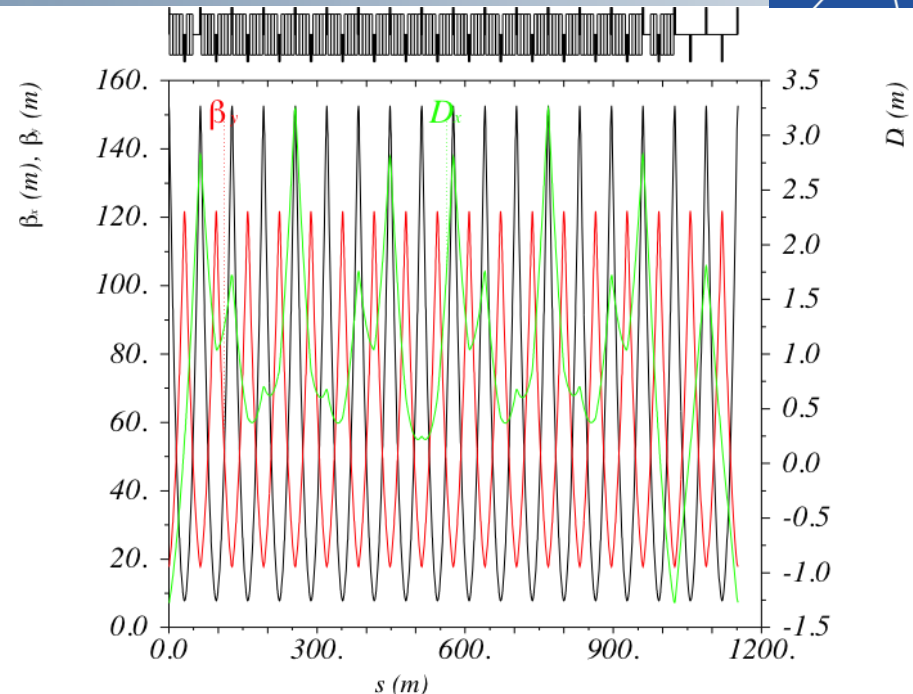
- Using the ~**50 years experience** since the design and operation of the Super Proton Synchrotron (SPS), reviewed **several beam dynamics concepts**

  - ❏ 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