

Designing a synchrotron - A real life example

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Introduction to Accelerator Physics
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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**

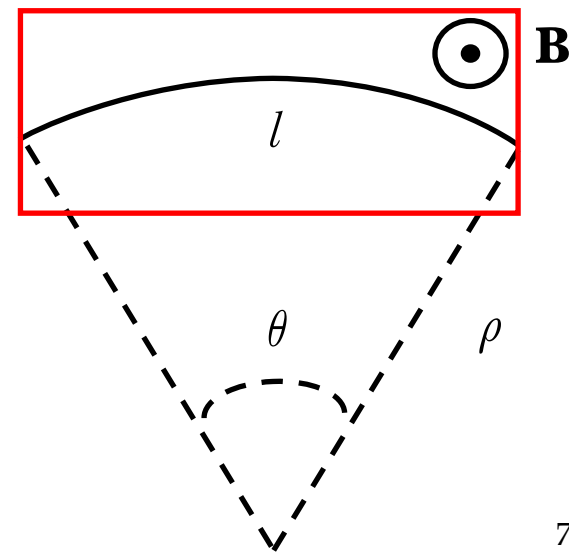
- Review several **aspects of beam dynamics** (mostly) presented in the introductory CAS lectures, applied to the **design and operation of a real synchrotron**
 - Choice of **basic parameters**
 - Energy, bending field and circumference
 - **Optics design**
 - Cell optics, insertions, transition energy
 - **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

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- 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



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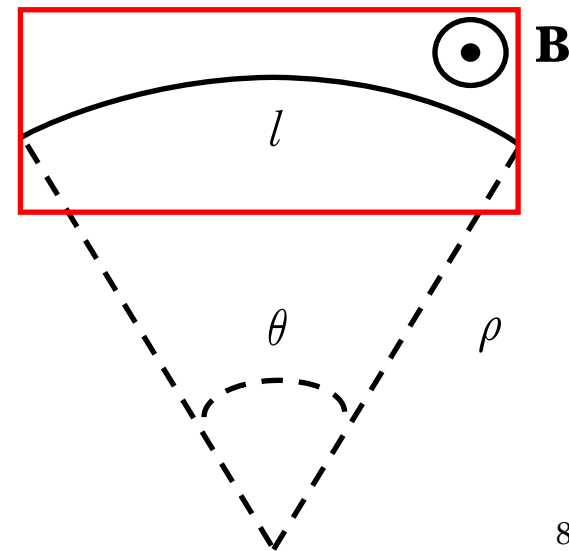
- **Bending angle** $\theta = \frac{2\pi}{N}$

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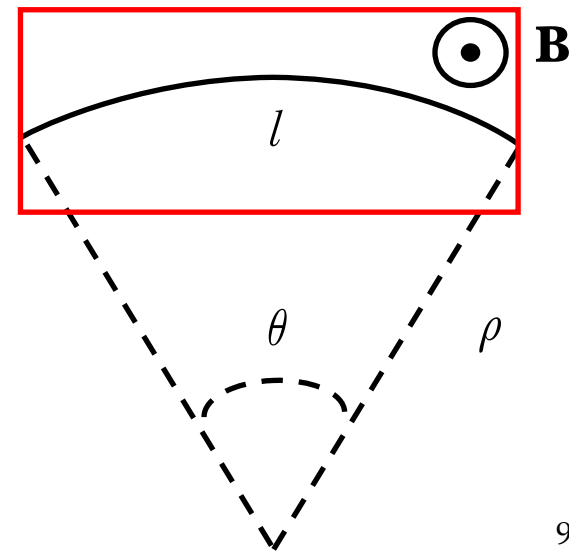
- The **magnetic rigidity** is $B\rho = \frac{\beta E}{q}$

- 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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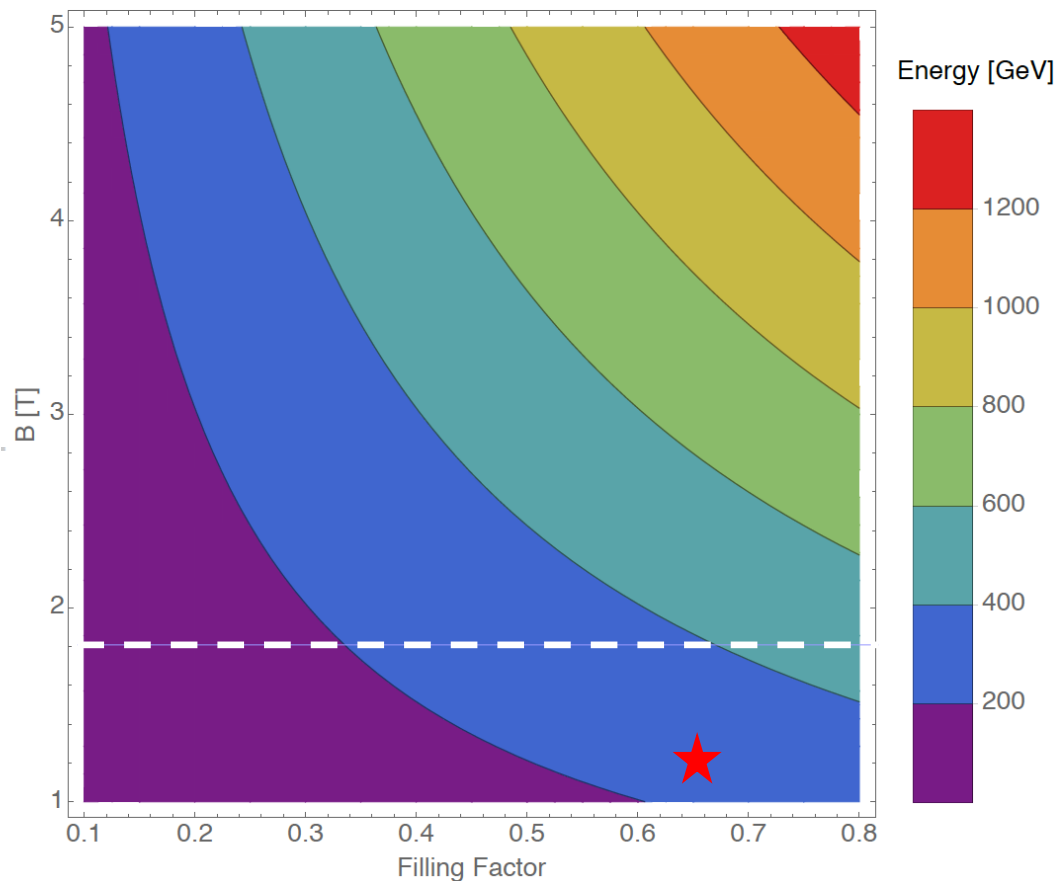
- The ring **circumference** becomes

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

- 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

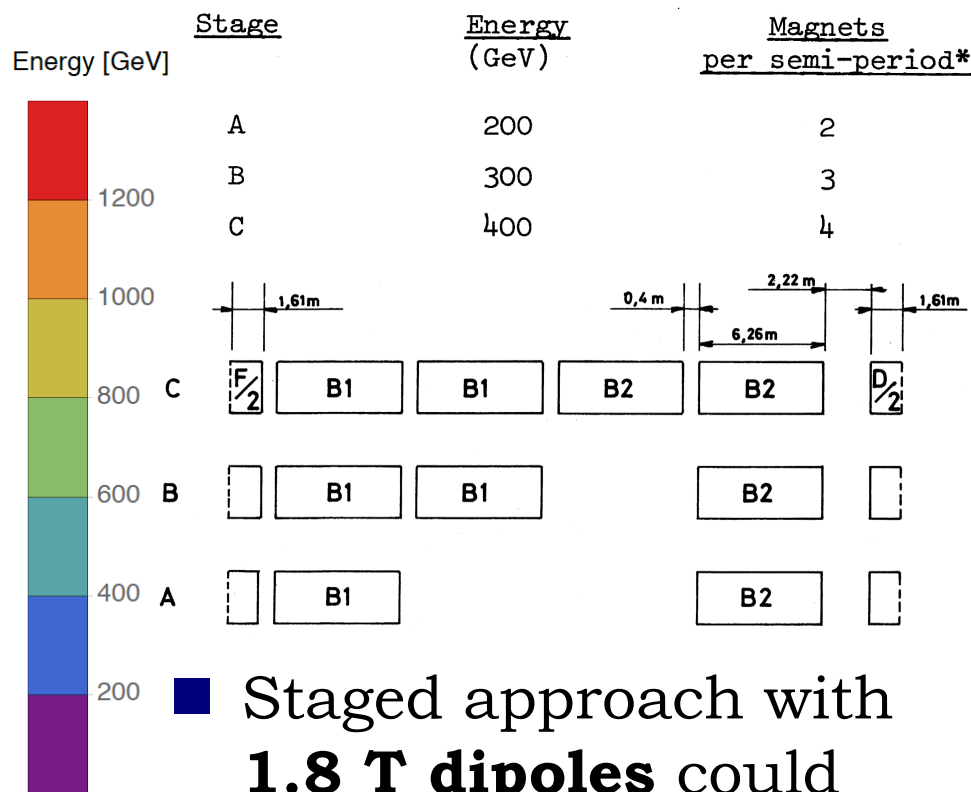
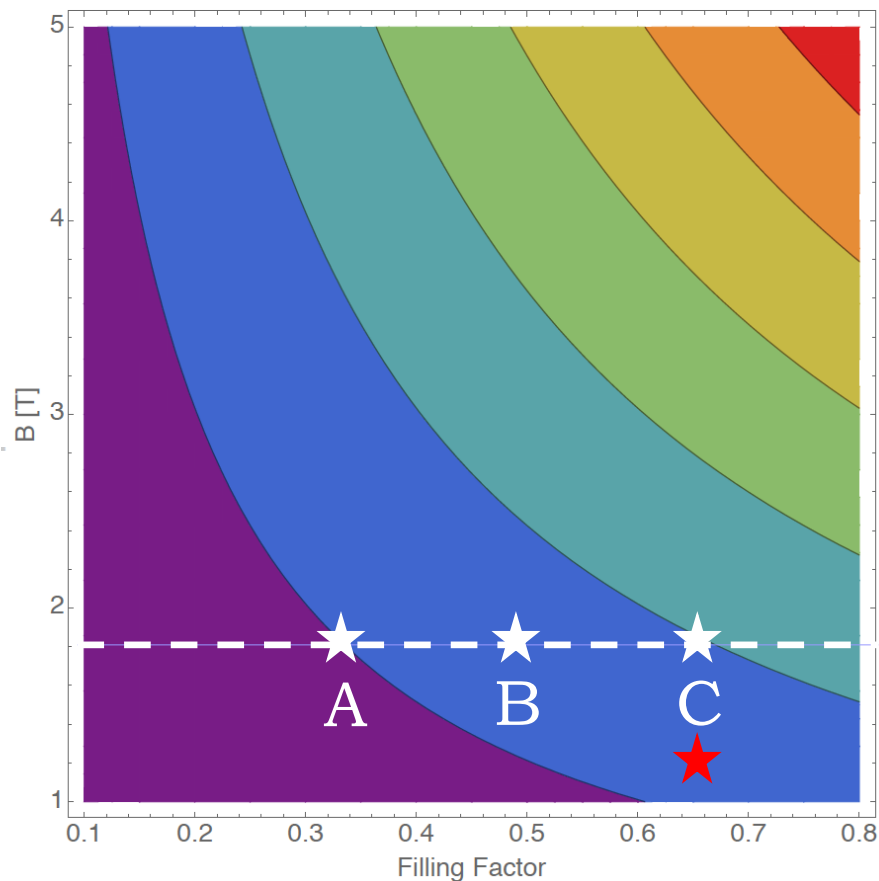
$$C_{\text{SPS}} = 11C_{\text{PS}} = 2\pi \times 1100 \text{ m} \approx 6912 \text{ m}$$



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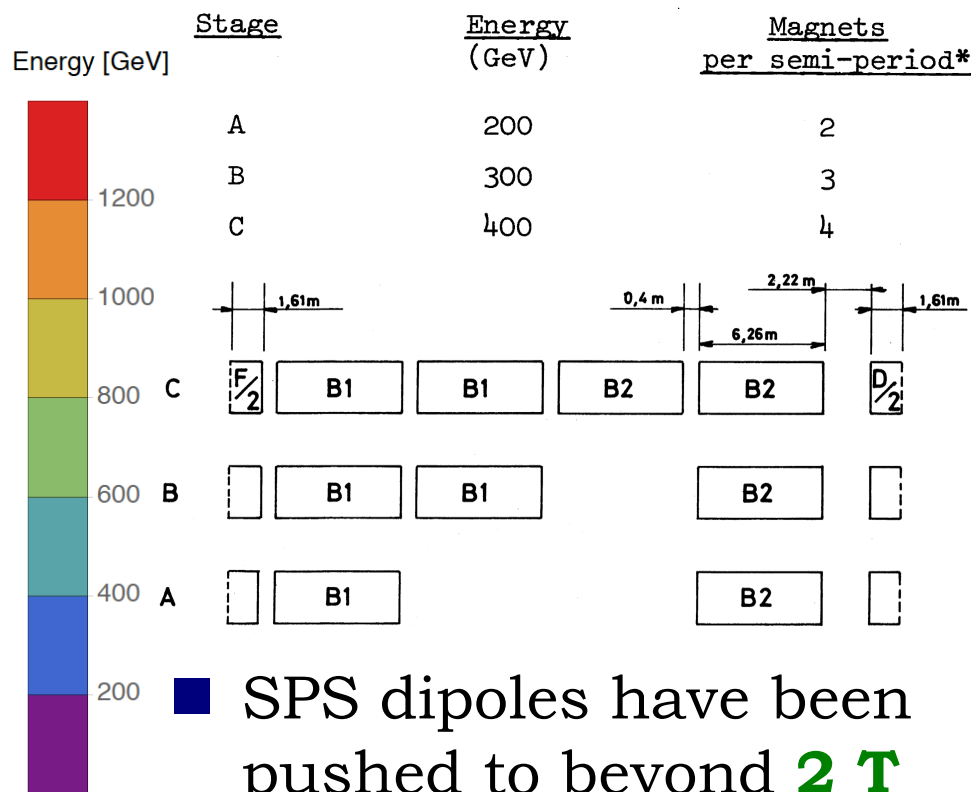
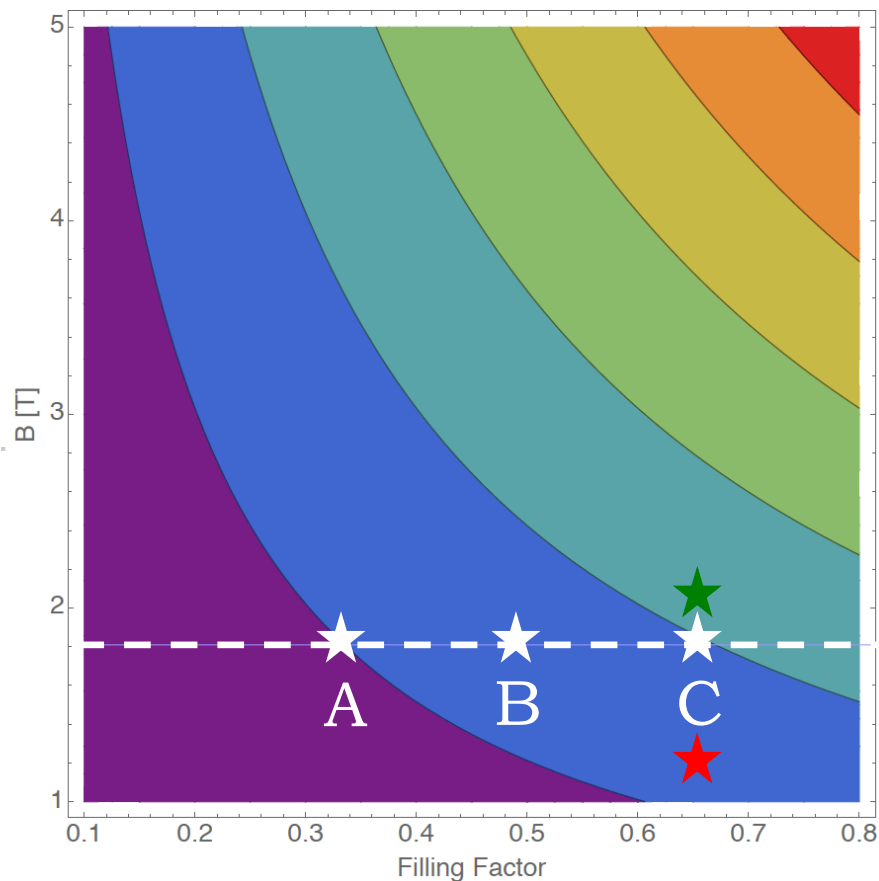
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- Staged approach with **1.8 T dipoles** could reach from 200 to 400 GeV

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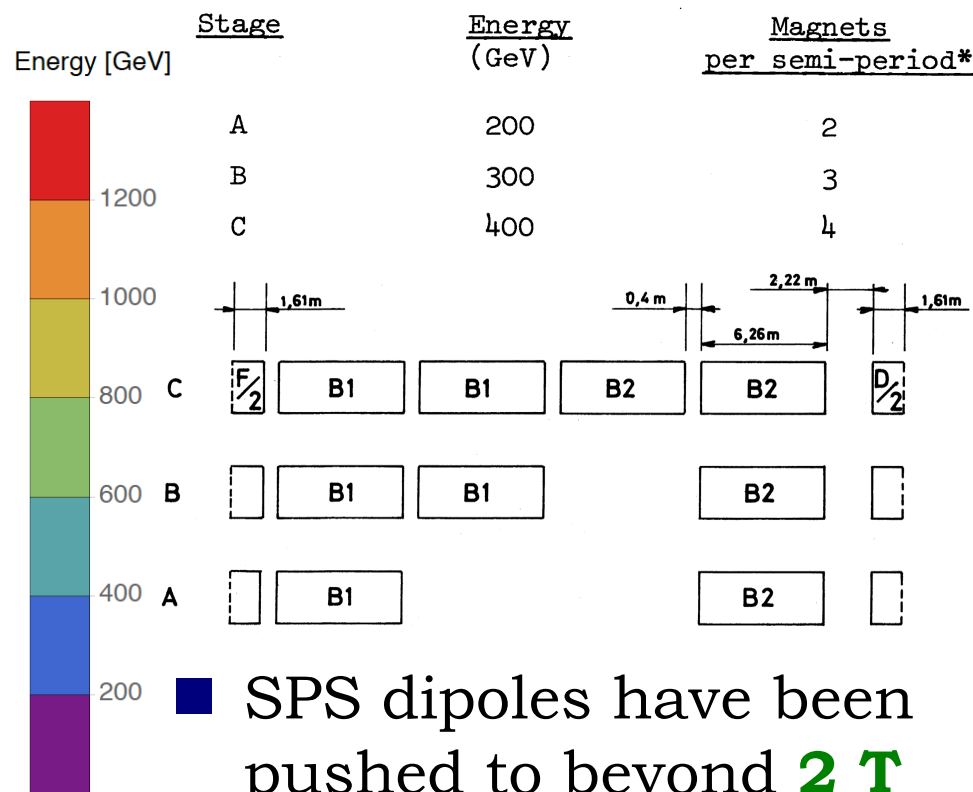
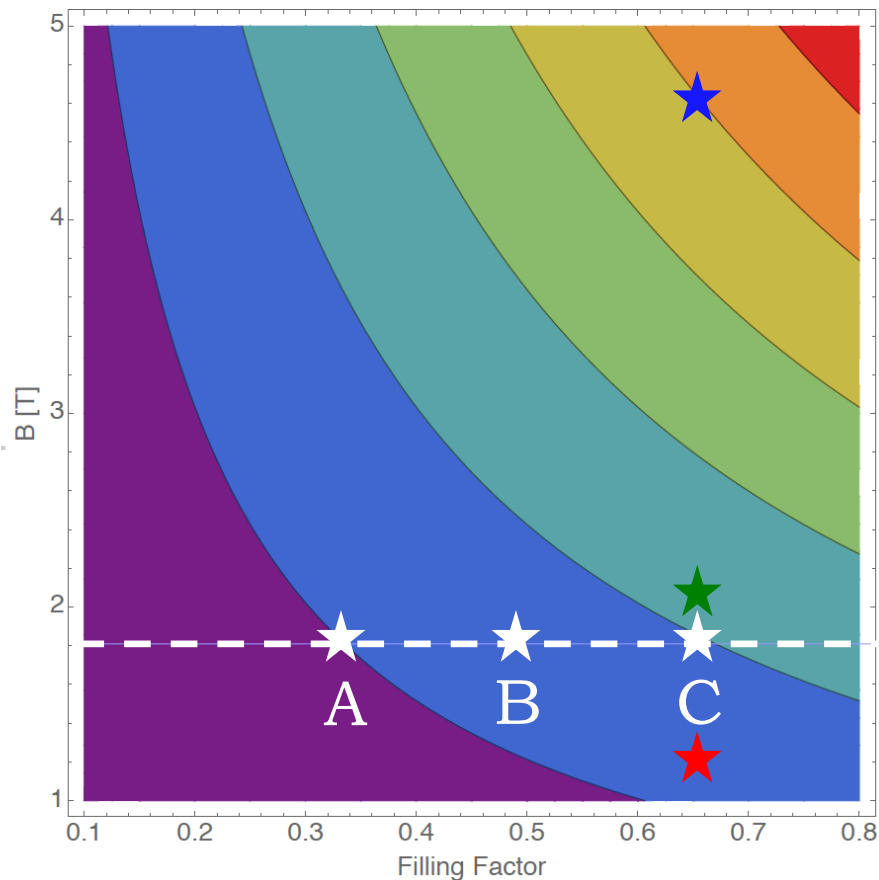
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- SPS dipoles have been pushed to beyond **2 T** to reach **450 GeV**

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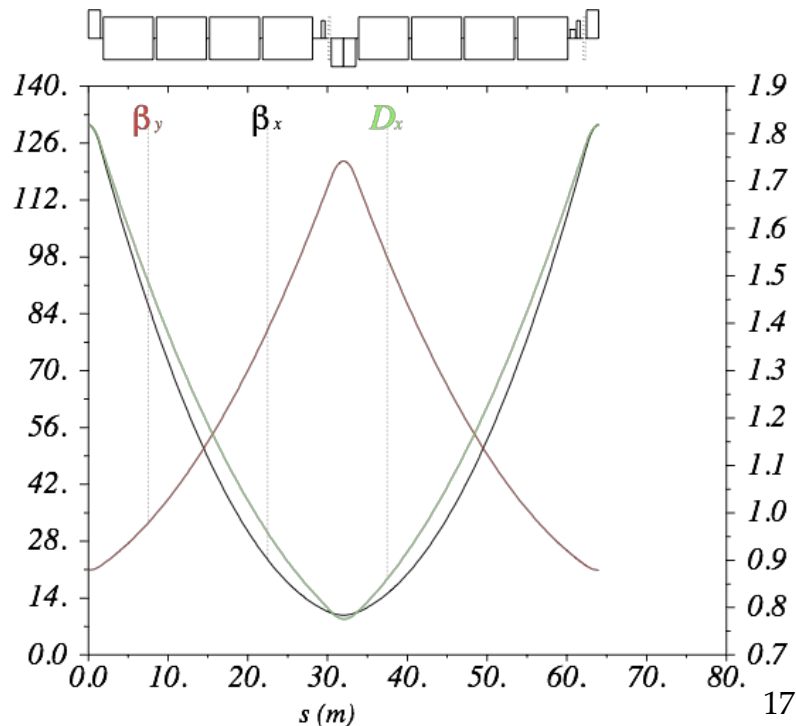
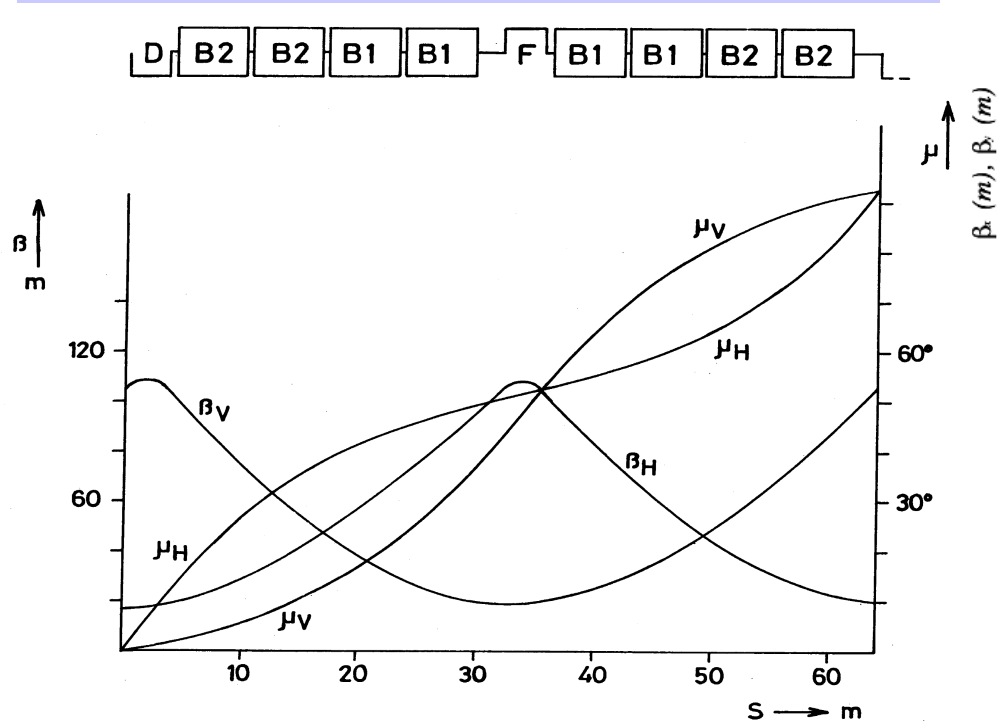
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- Super-conducting** option could raise the energy to **1 TeV**

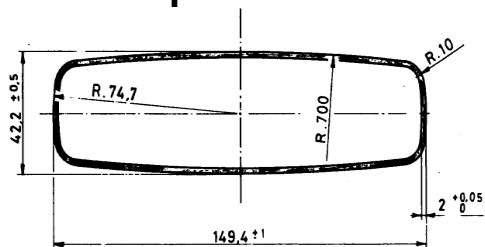
Optics design

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

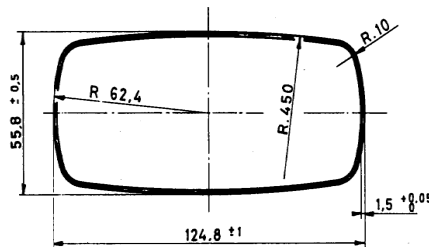
The 300 GeV Program, CERN/1050, 14/01/1972



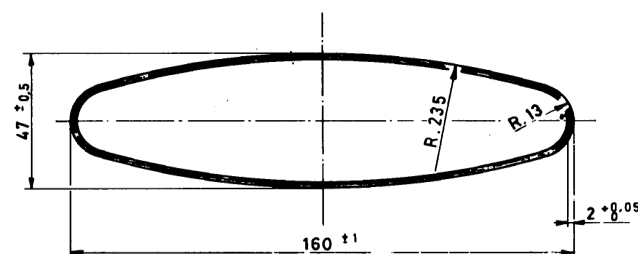
- Magnet apertures follow beta function and dispersion evolution



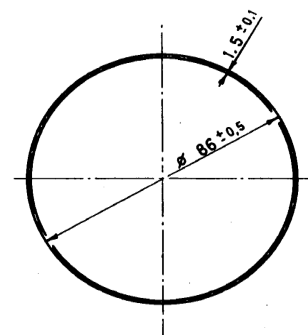
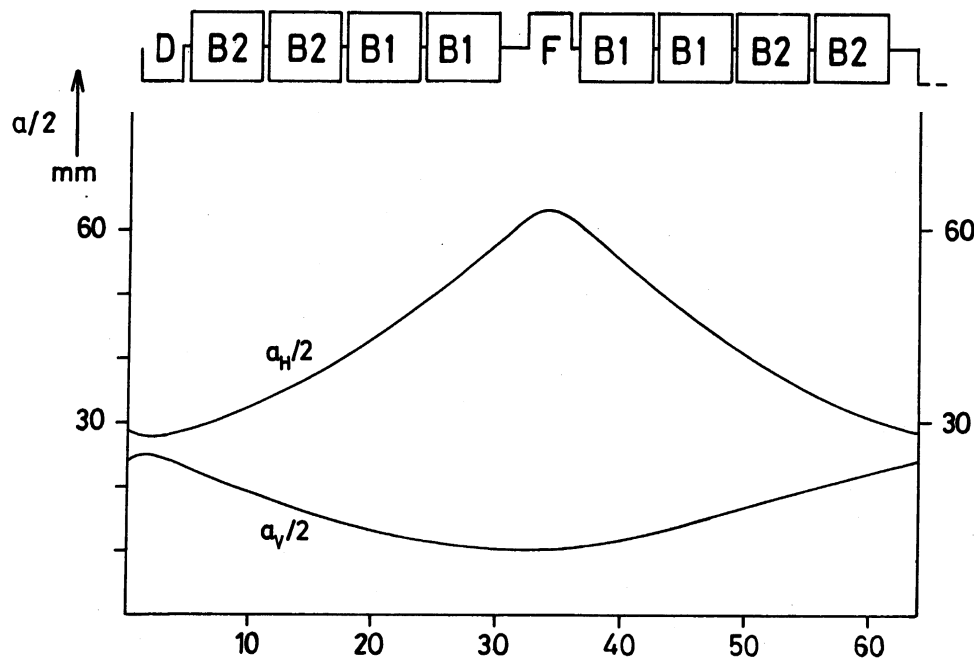
Dipole B1



Dipole B2



Quadrupole F



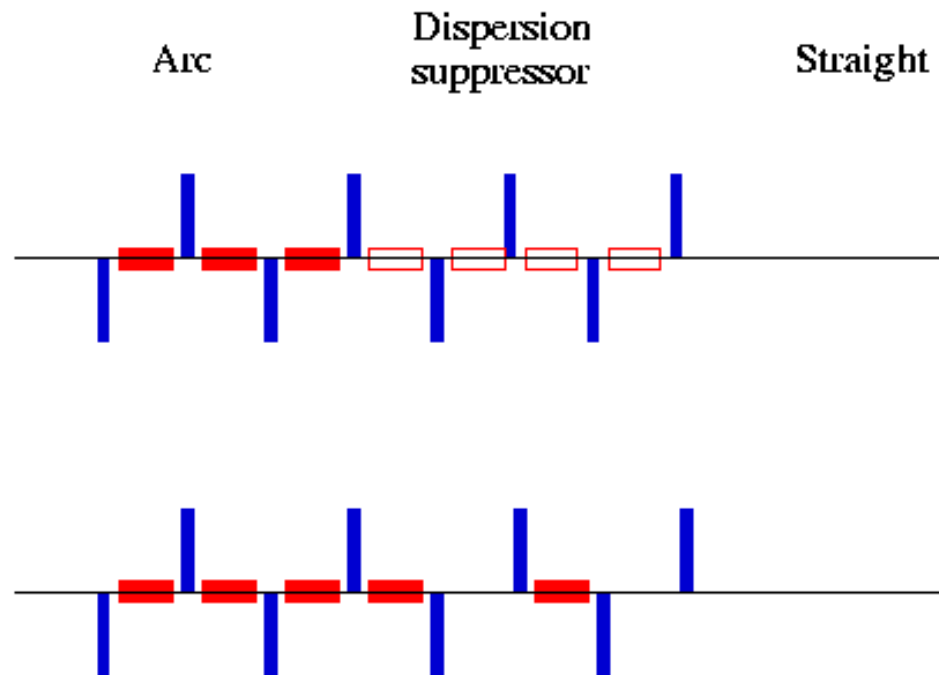
Quadrupole D

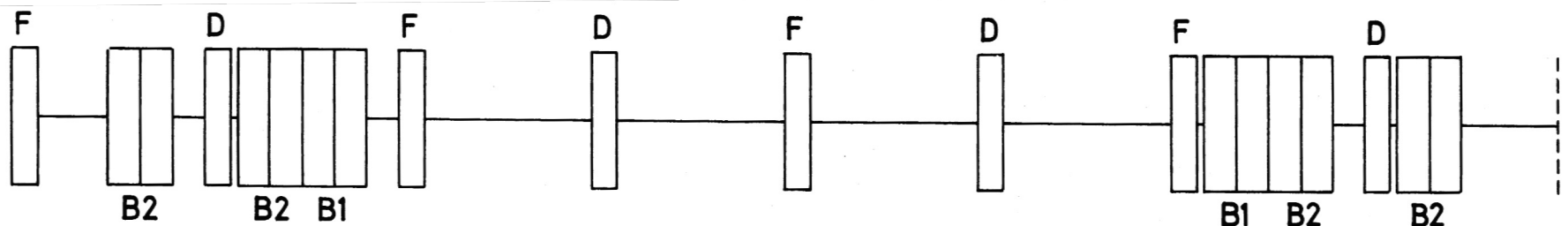
- **Dispersion** has to be **eliminated** in **special areas** like injection, extraction or interaction points (orbit independent to momentum spread)
- Use **dispersion suppressors**
- Methods for suppressing dispersion
 - **Eliminate two dipoles** in a FODO cell (missing dipole)
 - Set last dipoles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

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

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

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

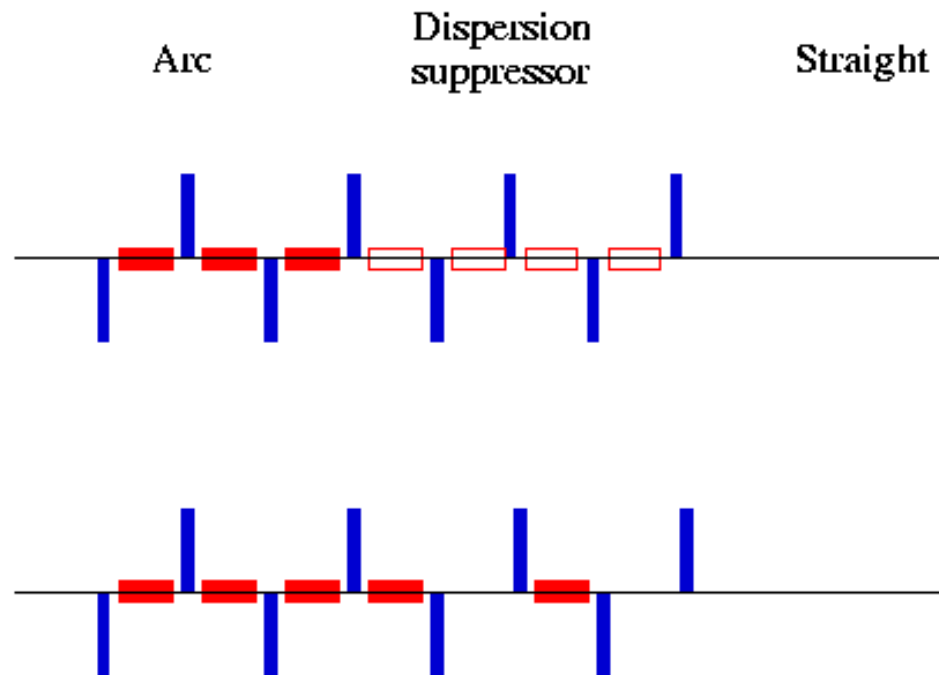




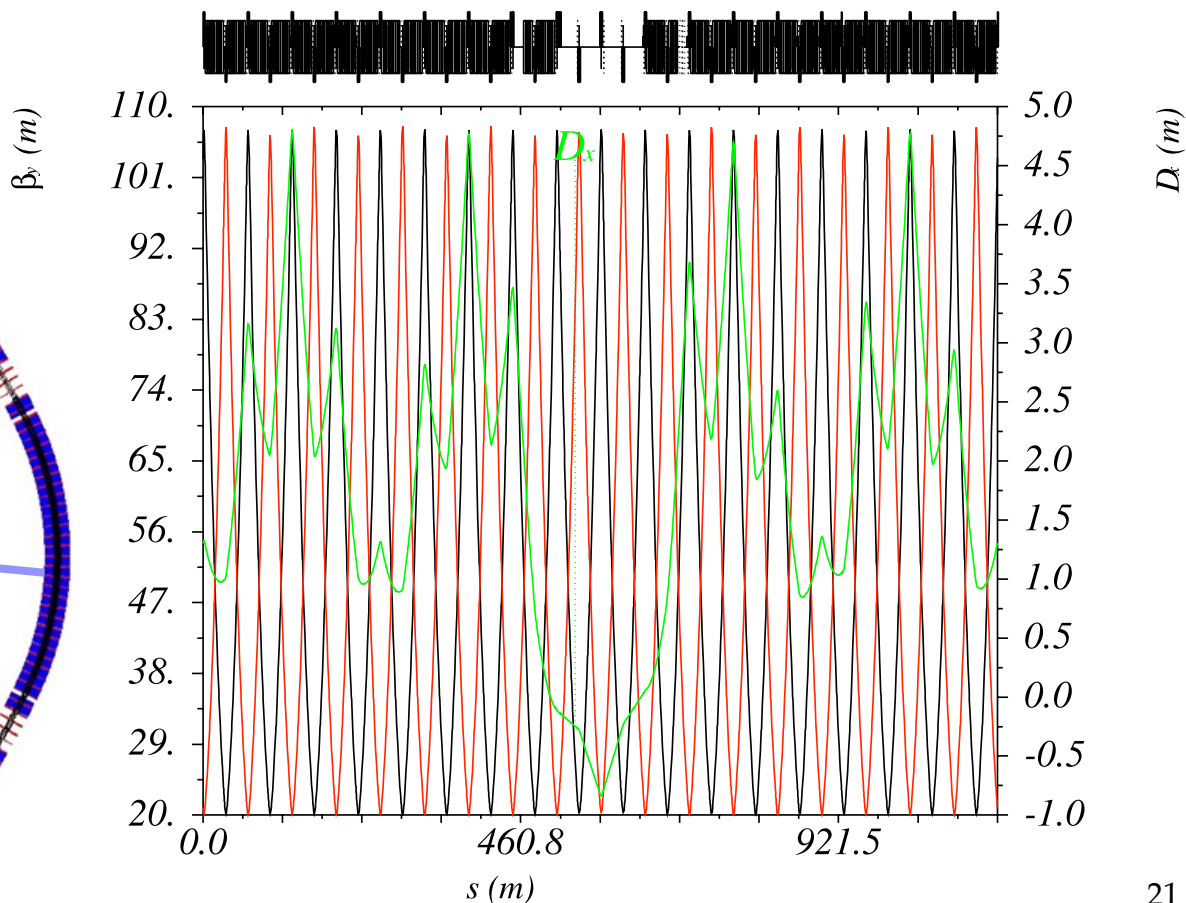
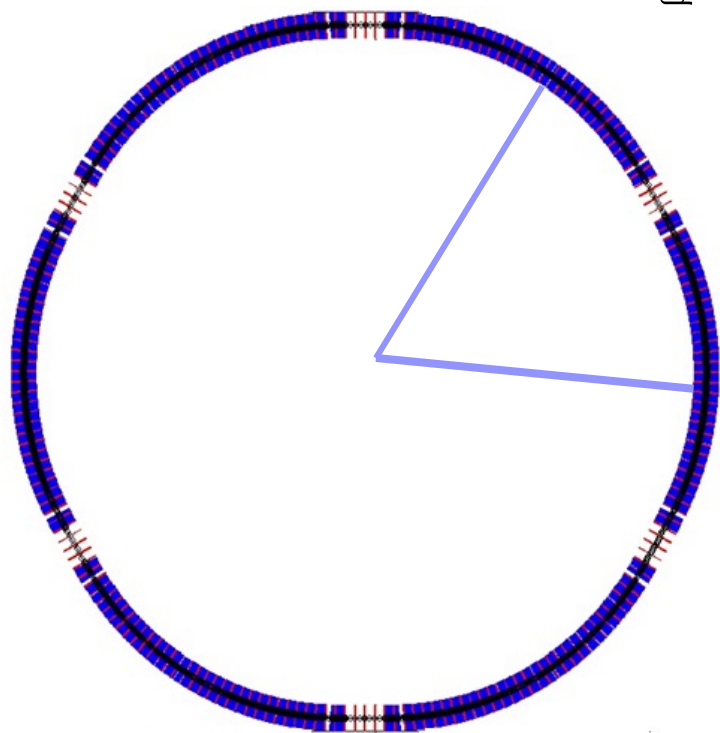
■ In the SPS, all **dipoles** are powered in **series**, i.e. dispersion suppressor cells looks like a missing dipole, but they are not!

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

■ **Dispersion oscillates** through the arc and vanishes at the edges

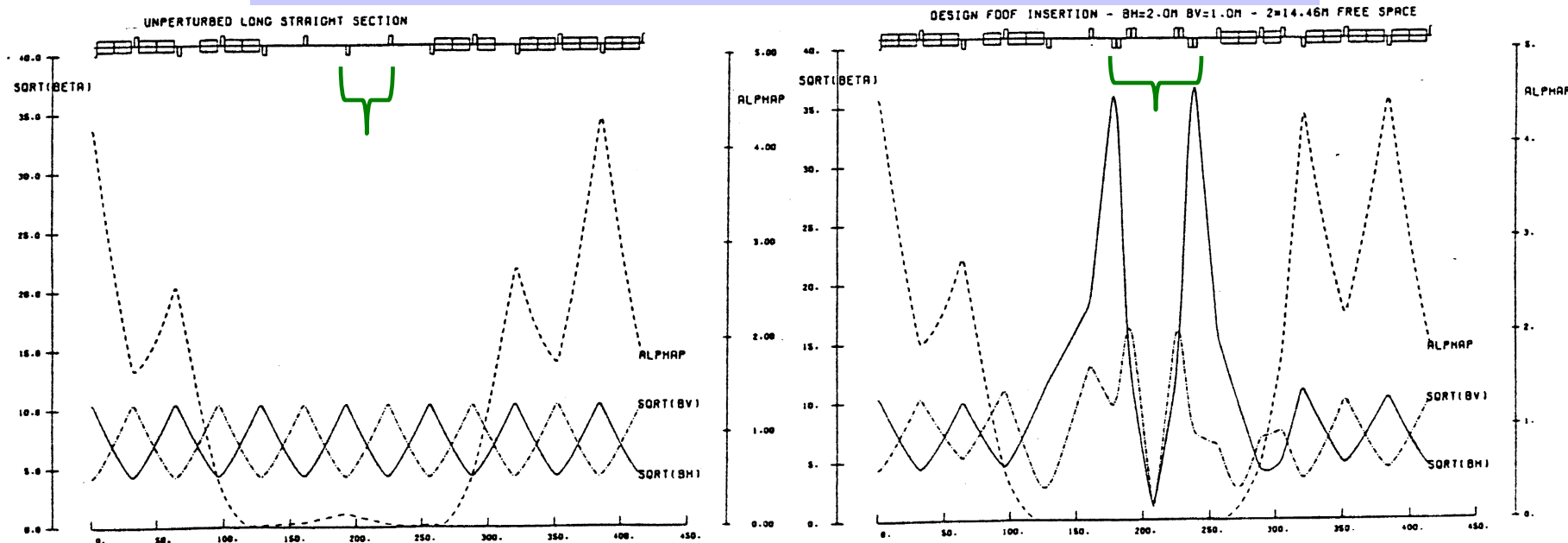


- Ring is composed by **6 identical sectors** (“sextants”) with **16 arc cells** and **2 cells** in the **straight sections**
- The cell phase advance of $\pi/2$ brings the tunes to 26-27 (**Q26**)



- 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



Magnet system

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

Number of magnets	744
Year of 1 st 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 1 st 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

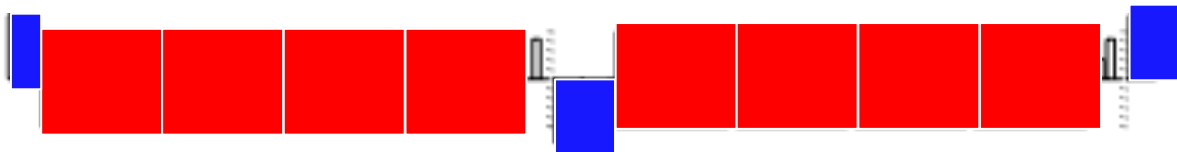


M. Giesch, CERN/SPS/80-3/AMS, 1980

MAIN PARAMETERS OF SEXTUPOL			LSFN	LSDN
Basic	: Nominal rms current	[A]	350	350
	Peak Current	[A]	500	450
	* Strength at peak current			
	1) Sextup. $\int a_3 dl$ ($a_3 = B''/r_2 = B''/2$)	[T/m]	85.8	176.6
		n^2		
	* 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



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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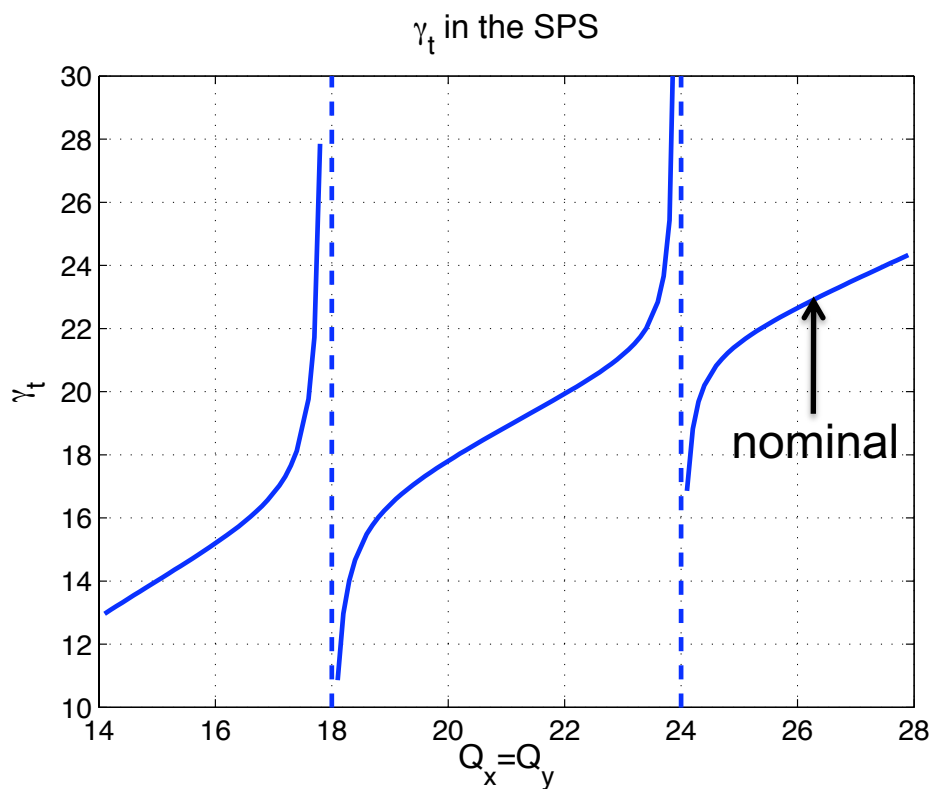
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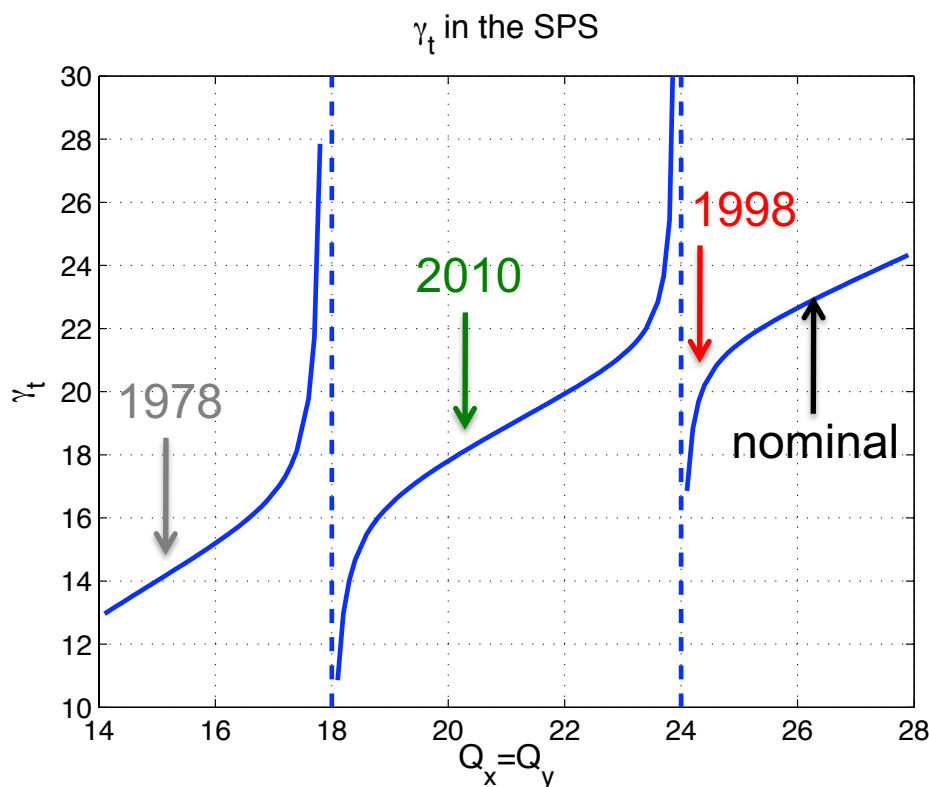


Quadrupoles

- 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



- 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

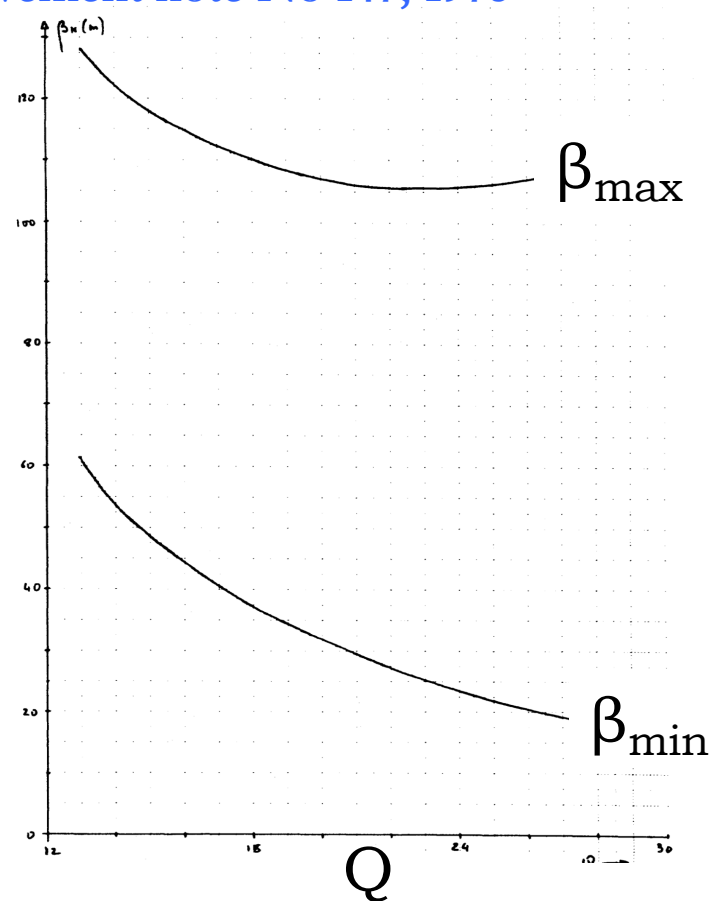
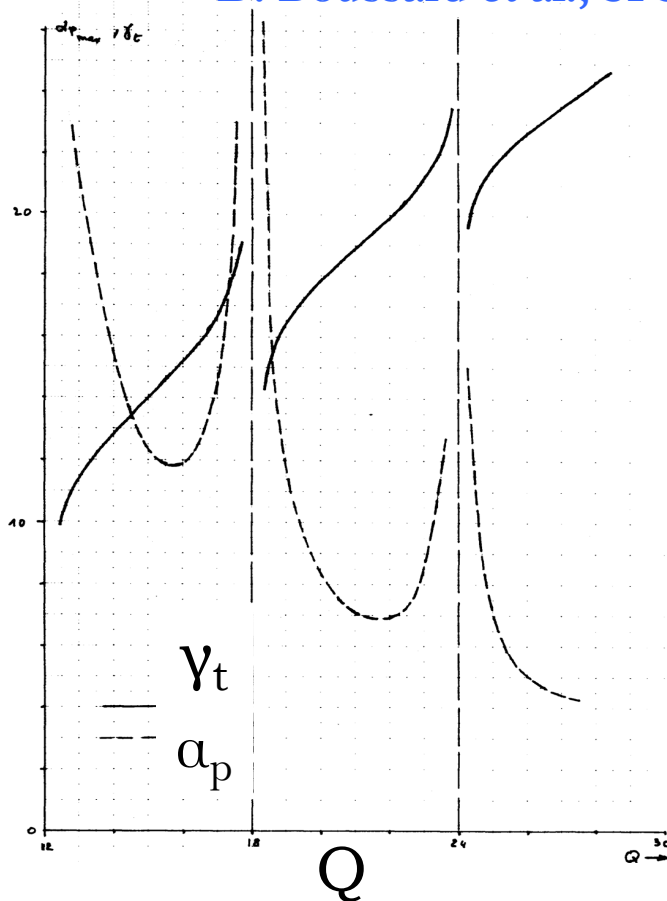


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- Nominal SPS working point for LHC proton beams ($\gamma_t \sim 23$)
- D. Boussard et al., SPS improvement note No 147, 1978; Injection above transition as TT10 was not ready for 26 GeV/c ($\gamma_t \sim 14$)
- G. Arduini et al., CERN/SL-Note 98-001,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

- 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



Manipulating optics for curing instabilities

❑ **Transverse** instabilities

❑ **TMCI** at injection - single bunch instability in vertical plane

- ❑ Threshold at 1.6×10^{11} p/b ($\epsilon_l = 0.35$ eVs, $\tau = 3.8$ ns) with low vertical chromaticity

$$N_{th} \propto \frac{\epsilon_l}{\beta_y} \eta$$

❑ **E-cloud** vertical instability for 25 ns beam

- ❑ Threshold higher than 1.2×10^{11} p/b

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

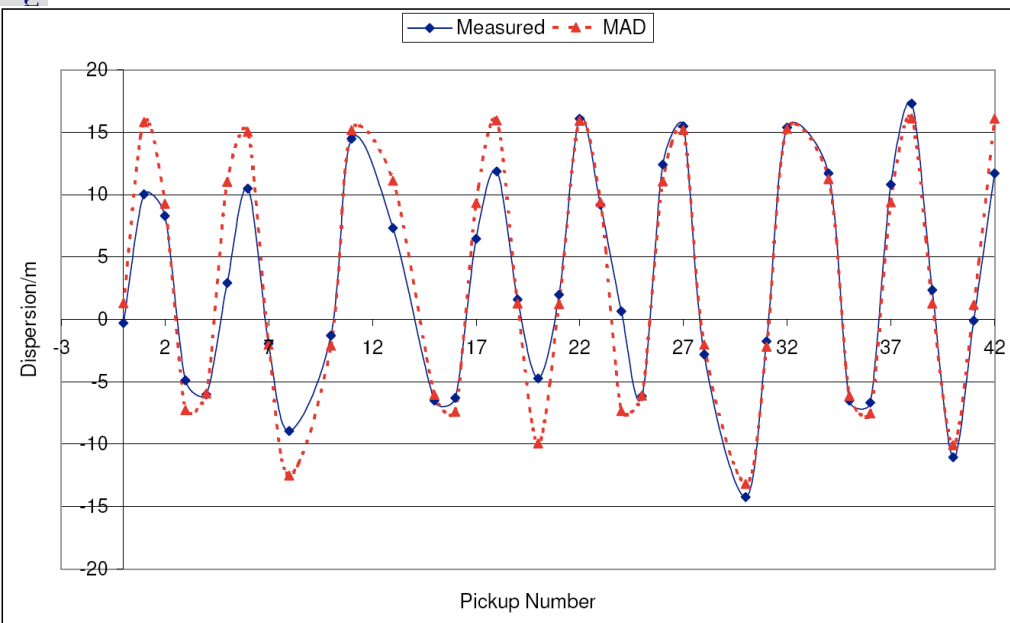
❑ **Longitudinal** instabilities

❑ Single bunch and coupled bunch

- ❑ Threshold at 2×10^{10} p/b for single harmonic RF (800 MHz cavity use is mandatory)

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

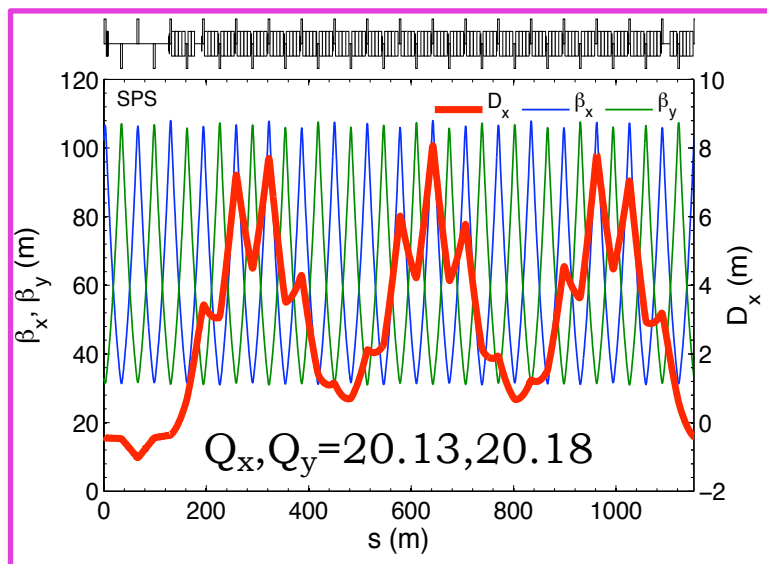
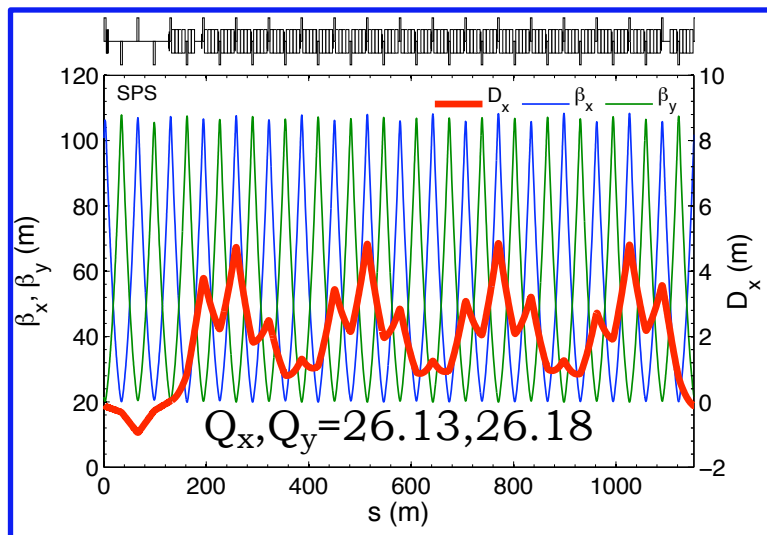
- By setting the SPS **integer tune** to a multiple of 6, large dispersion wave can be introduced (dispersion becomes even negative) by overall reducing transition energy
- Successfully establishing cycle in the SPS and measuring dispersion very close to the one of MAD
- 3-fold increase of the slippage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



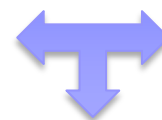
G. Arduini et al., CERN/SL-Note 98-001 (MD), 1998

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

Moving FODO phase advance from $4/16 \cdot 2\pi$ ($\pi/2$) to **$3/16 \cdot 2\pi$ ($3\pi/8$)**

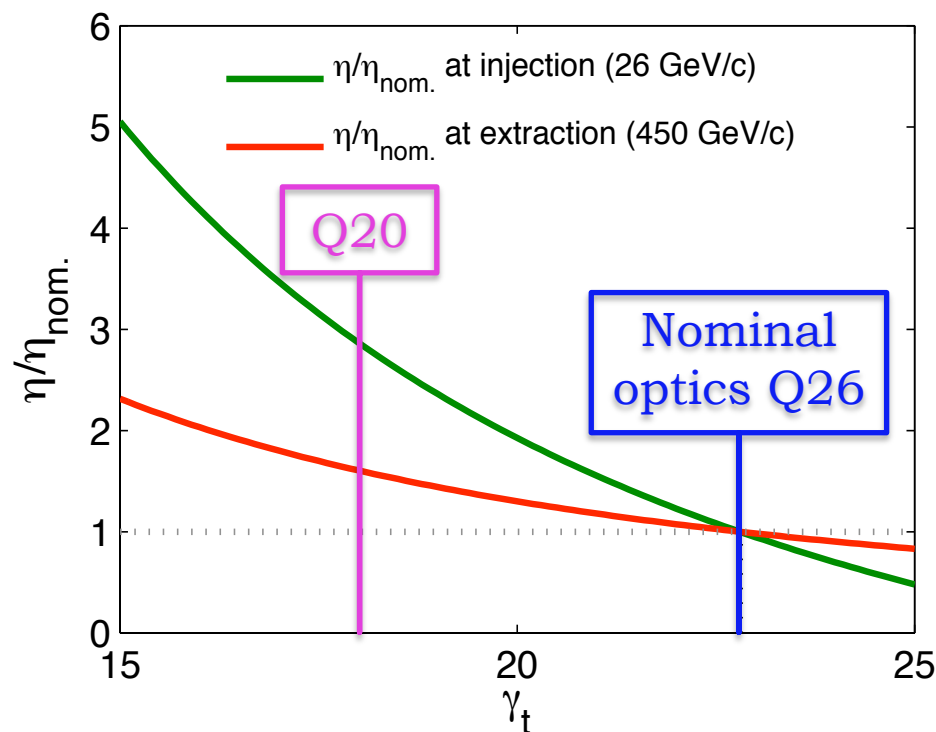


$$\eta = \frac{1}{\gamma_t^2} - \frac{1}{\gamma^2}$$

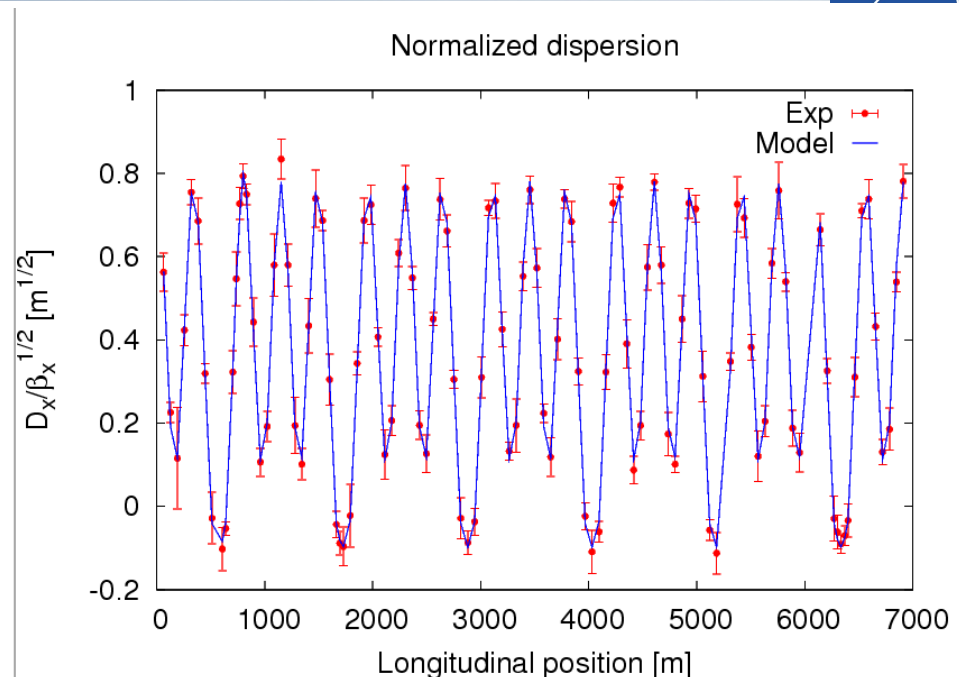
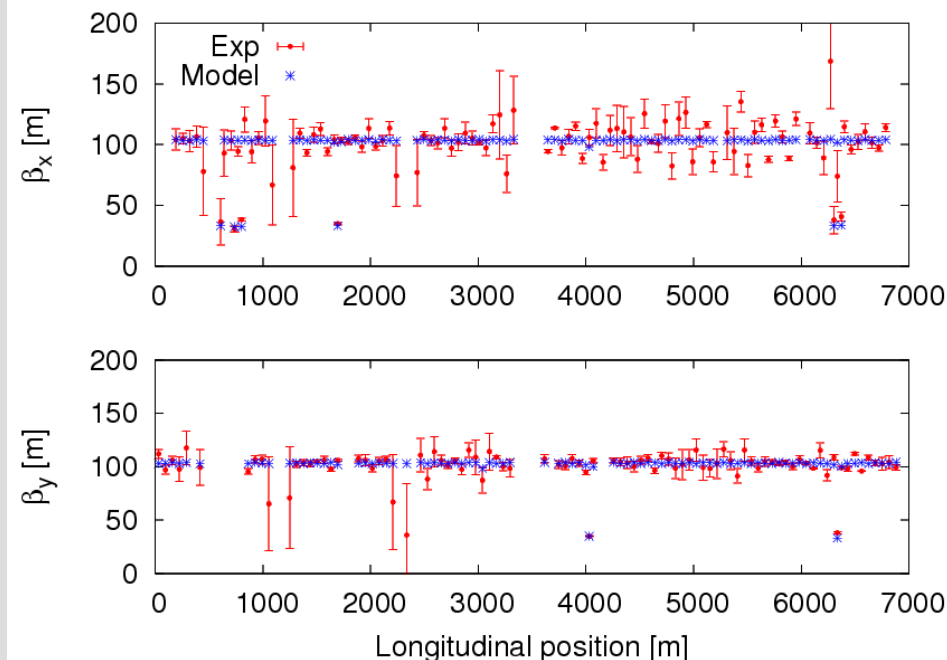


$$\gamma_{tFODO} \approx Q_x$$

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



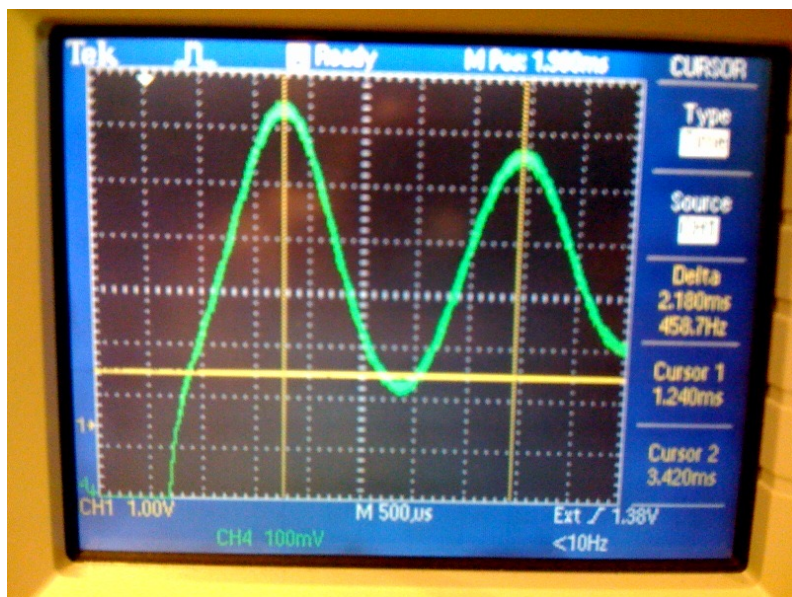
Slip factor relative to nominal SPS optics⁵⁷



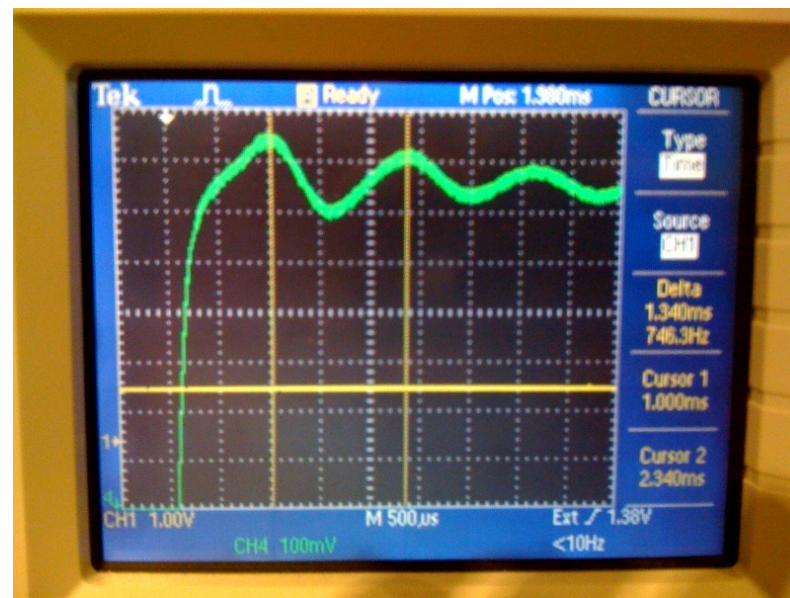
Measurement of the optics functions of the new lattice

- **Beta beating** around 20% in horizontal and 10% in vertical plane
- Normalized **dispersion** in striking agreement with the model

- ❑ 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: $F_s = 458/2 = 229\text{Hz}$,
 $Q_s = 0.0106/2 = 0.0053$

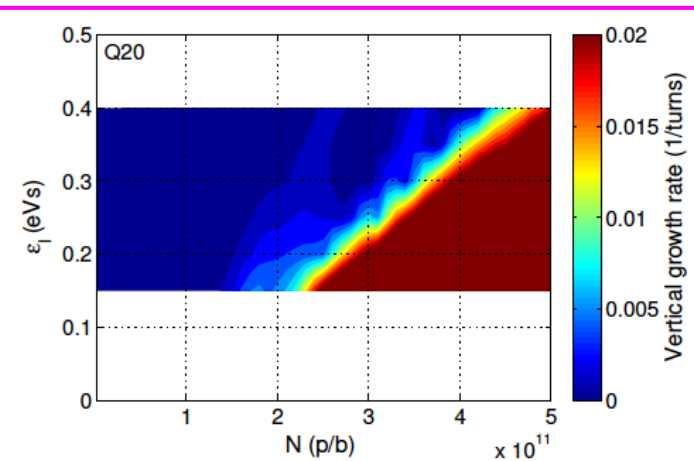
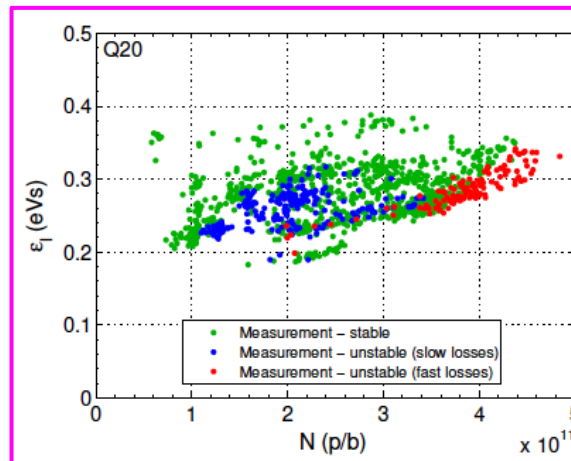
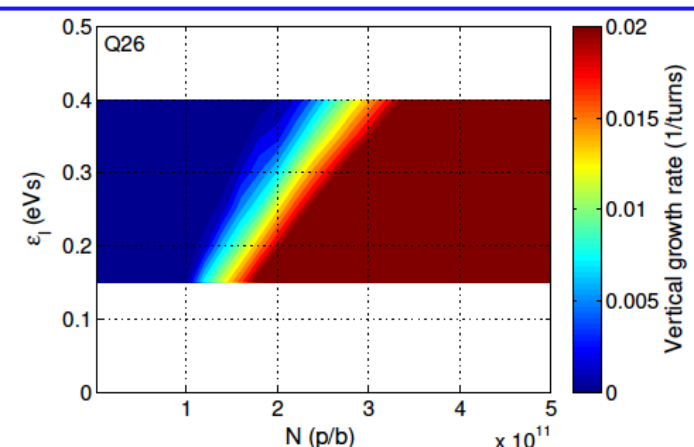
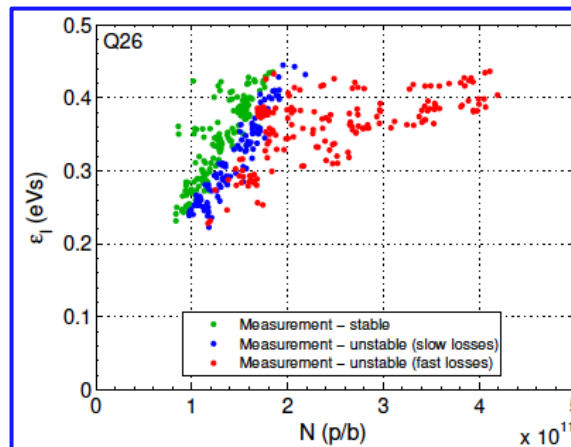


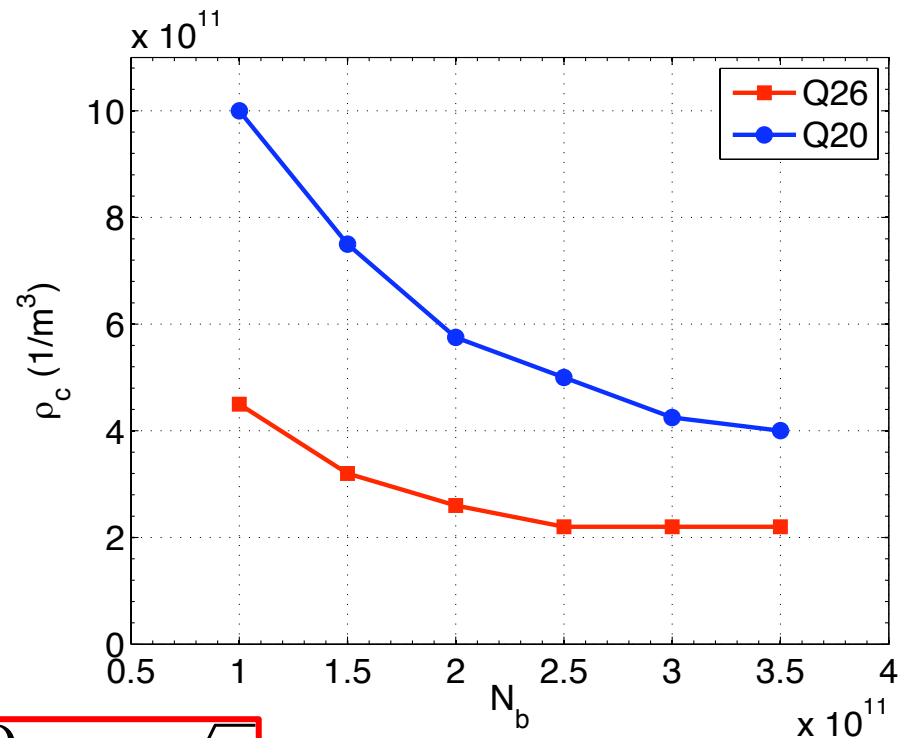
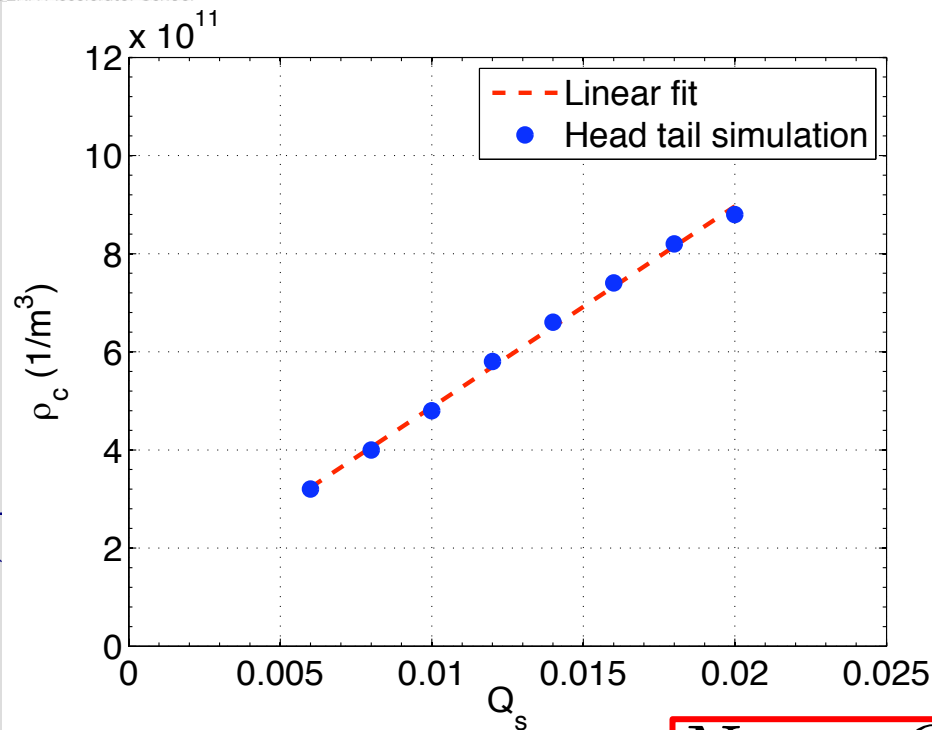
Q20: $F_s = 746/2 = 373\text{Hz}$,
 $Q_s = 0.0172/2 = 0.0086$

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

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

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**

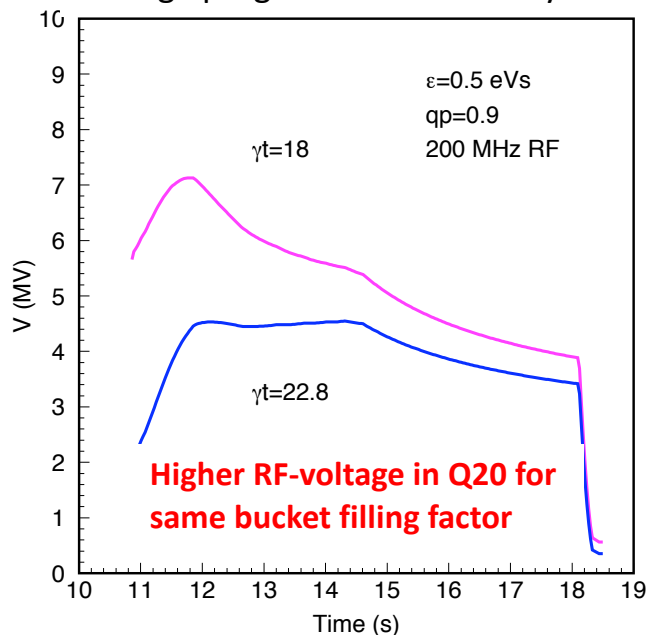
More margin with Q20 if e-cloud becomes issue for high intensity

H. Bartosik et al, IPAC2011

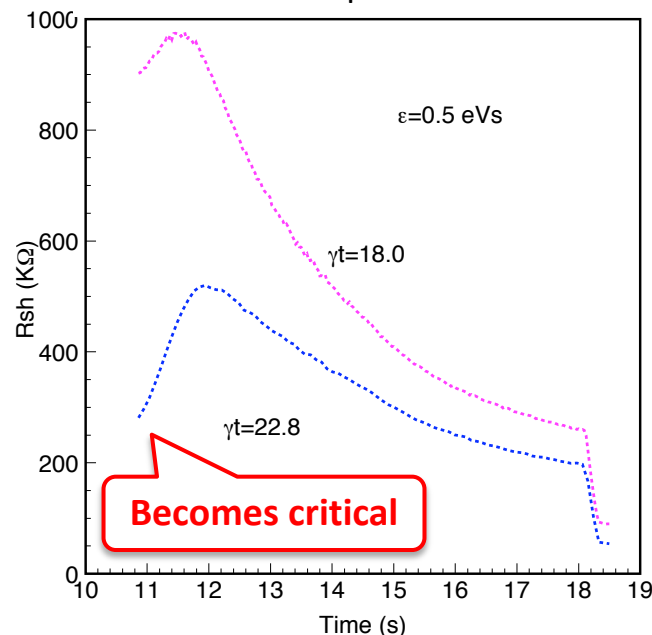
$$N_{th} \propto \epsilon_l^{5/2} \eta$$

E. Shaposhnikova

Voltage program 200 MHz RF system



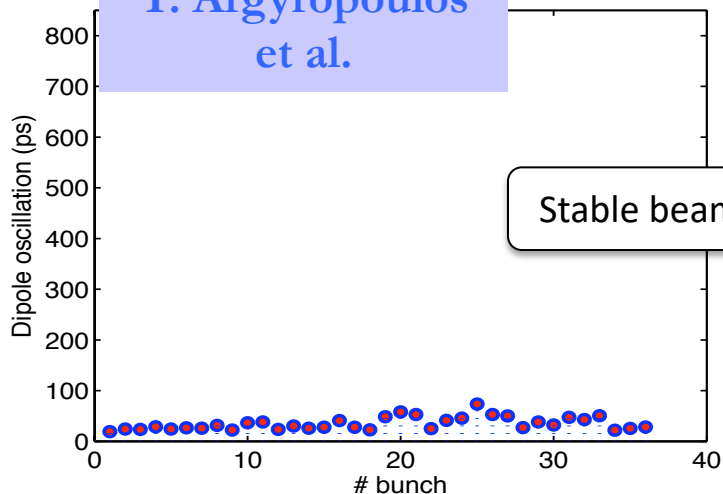
Narrow band impedance threshold



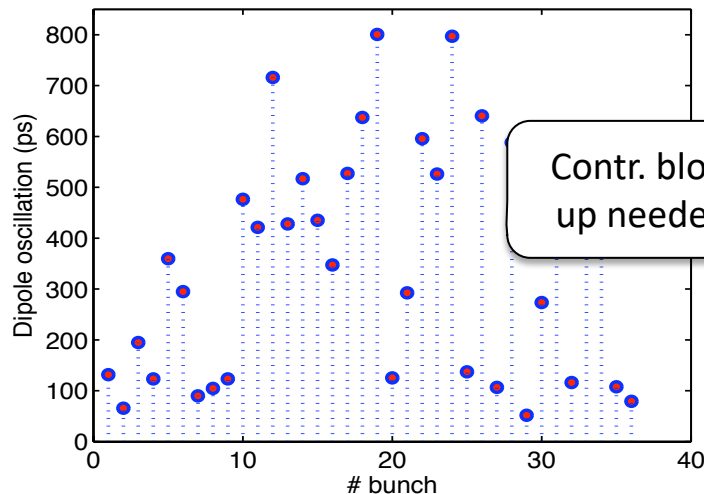
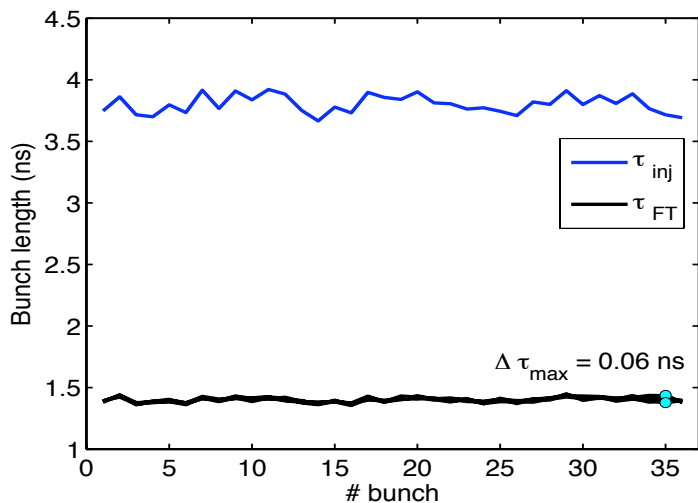
- ❑ Impedance threshold has minimum at flat top
 - ❑ Controlled longitudinal emittance blow-up during ramp for **Q26**
 - ❑ Less (or no) longitudinal emittance blow-up needed in **Q20**
- ❑ Instability limit at flat bottom
 - ❑ Critical with **Q26** when pushing intensity
 - ❑ Big margin with **Q20**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

T. Argyropoulos
et al.

Stable beam

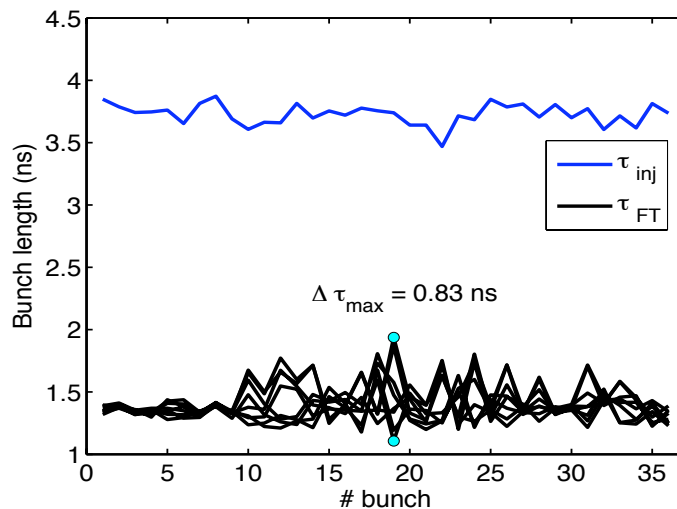


SPS-Q20 (1.6×10^{11} p/b)
double harmonic RF

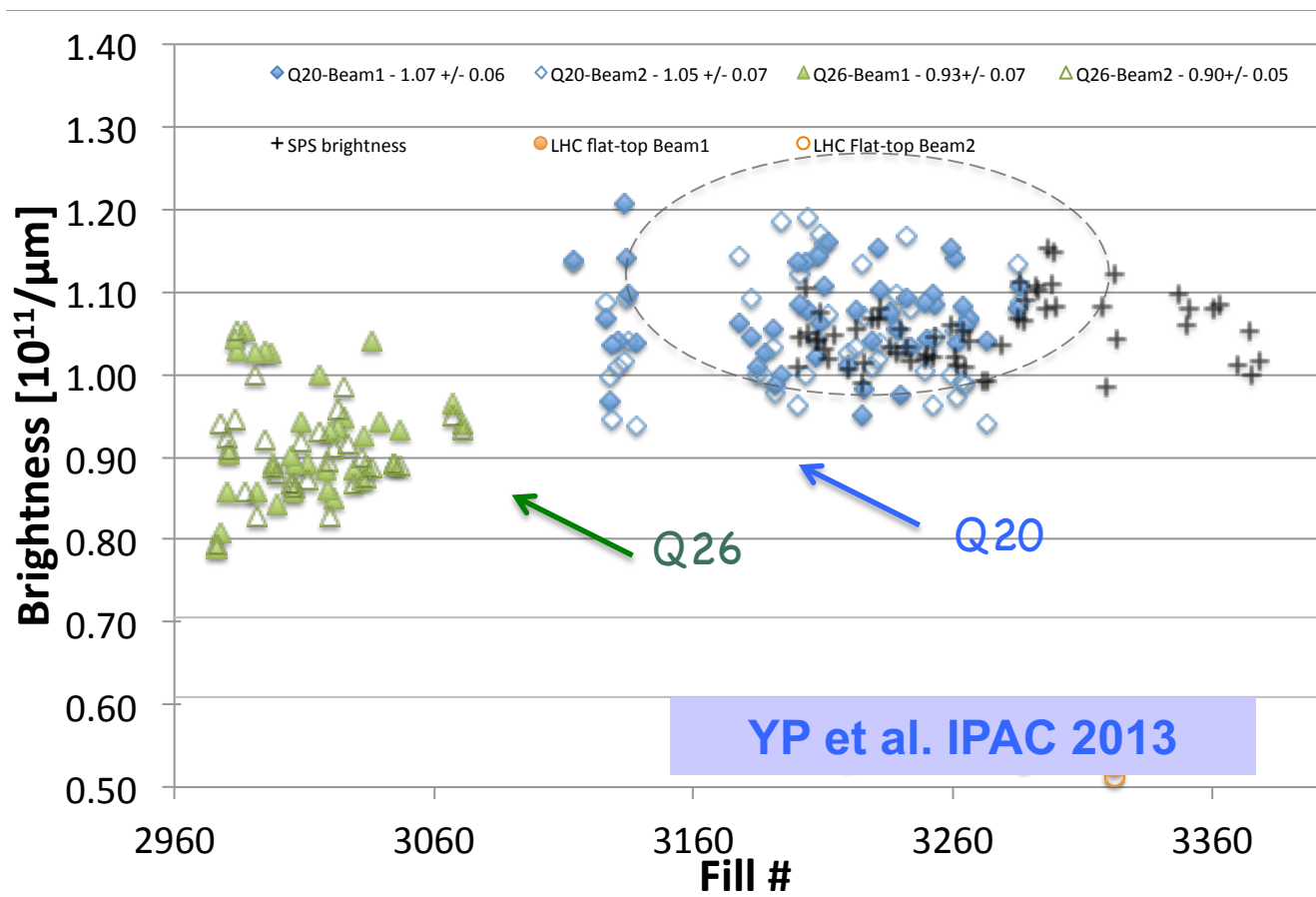


Contr. blow-up
needed!

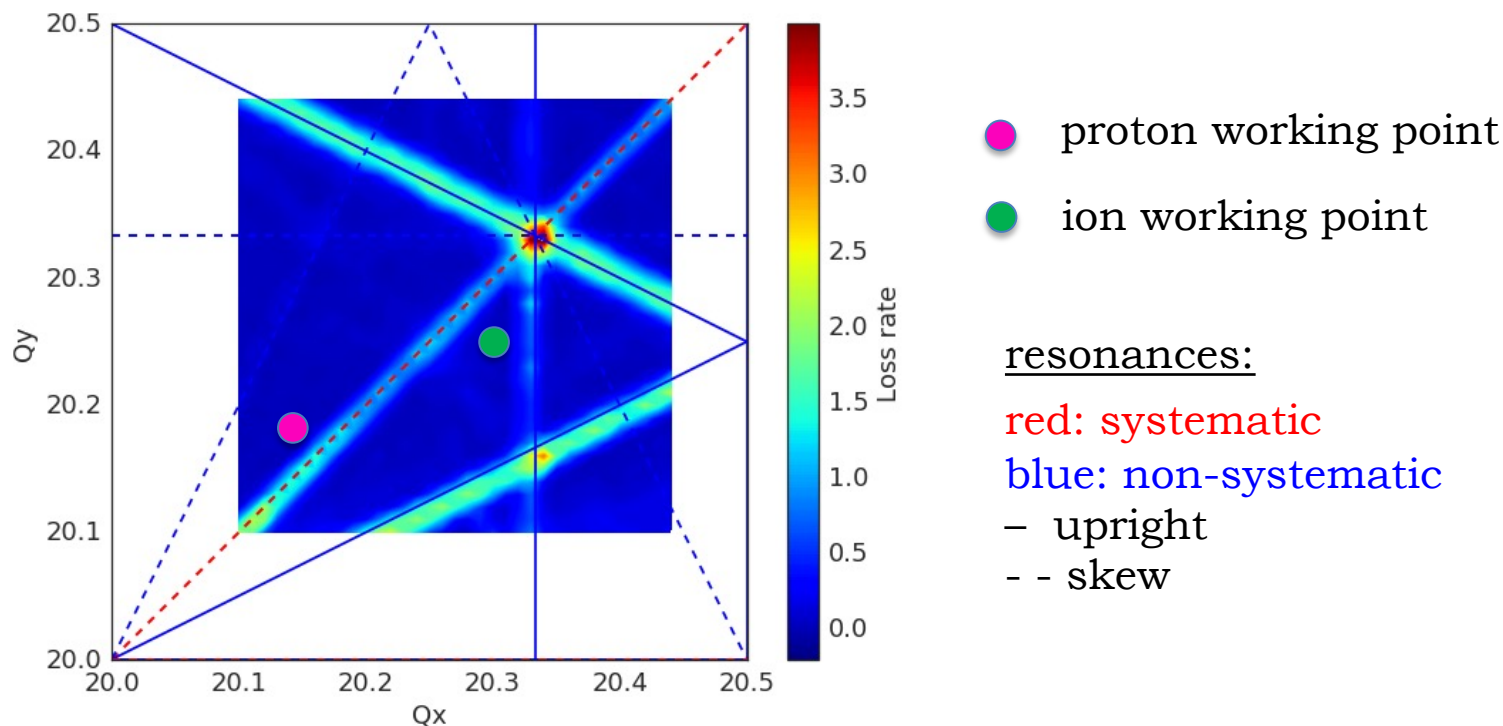
SPS-Q26 (1.6×10^{11} p/b)
double harmonic RF



- 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

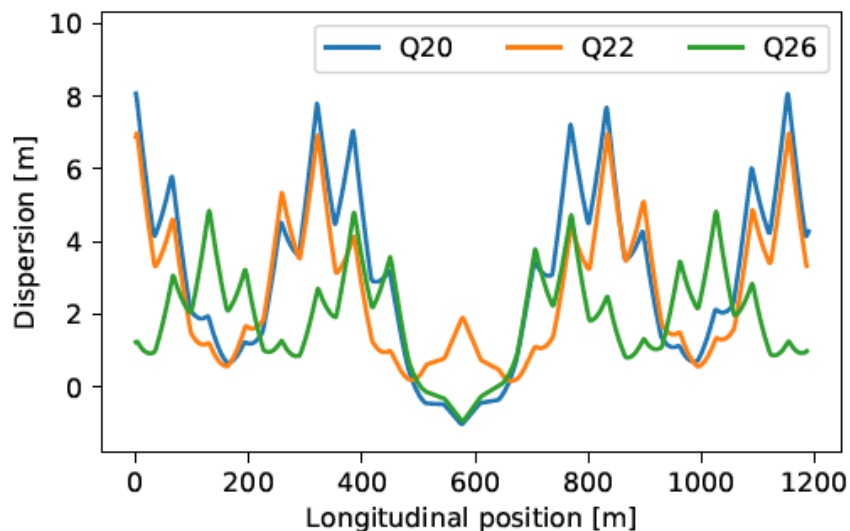


Non-linear dynamics

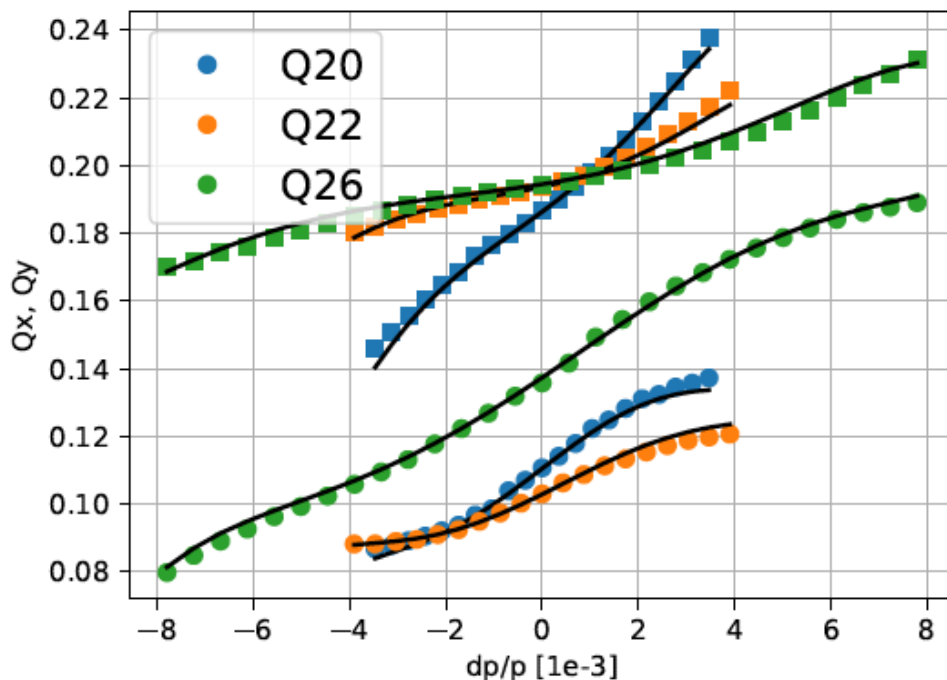


H. Bartosik et al. HB2018

- 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. Cartla' et al. IPAC2018



Sextupoles

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

Quadrupoles

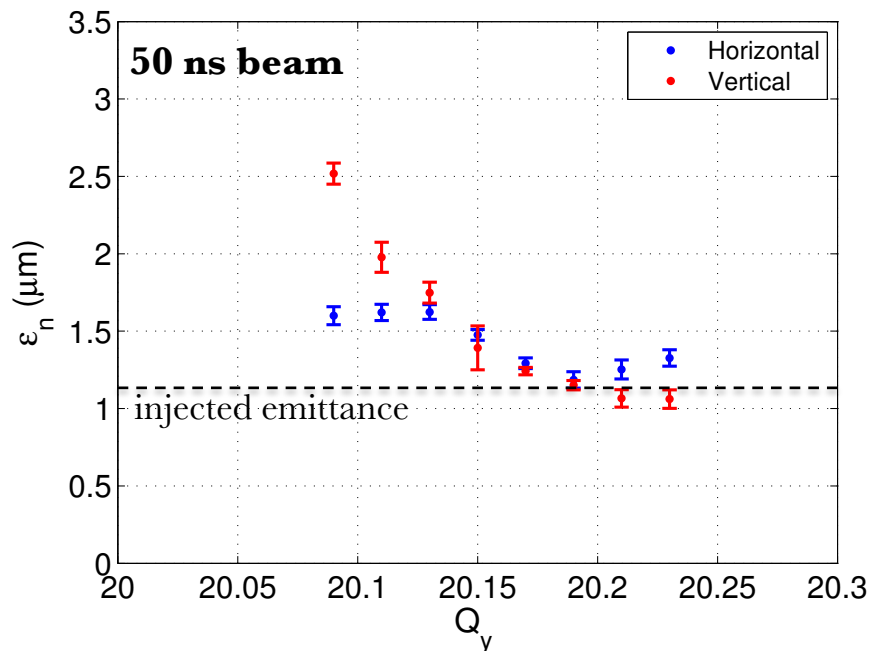
Octupoles

Decapoles

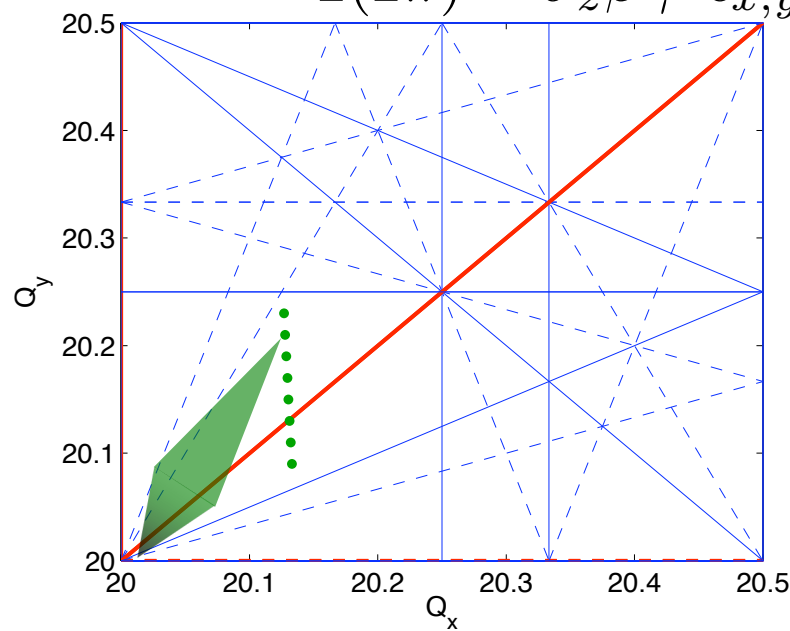
- Estimate “effective” magnet **multi-poles** that reproduce non-linear chromaticity measurement for three different optics

Space-charge

emittance at end of flat bottom

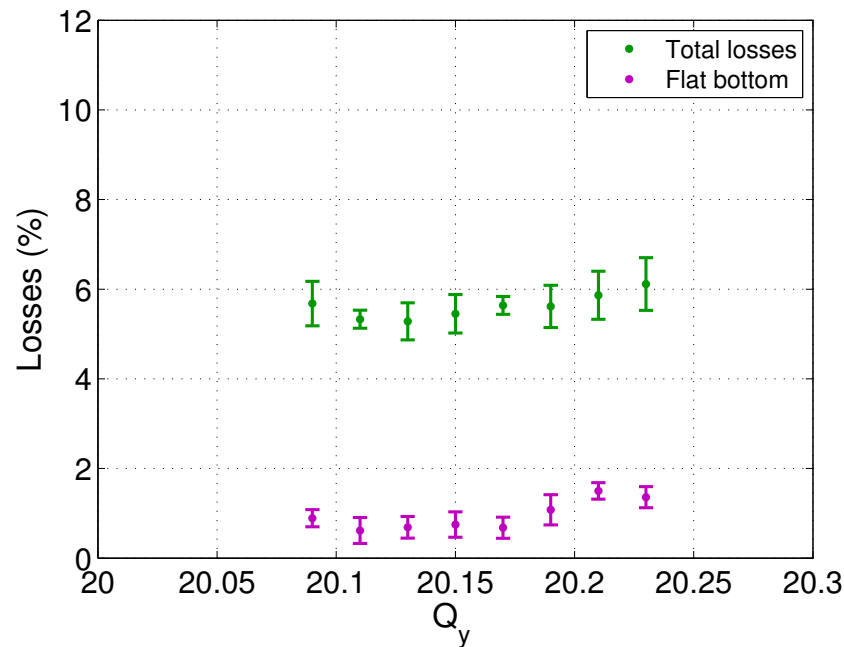
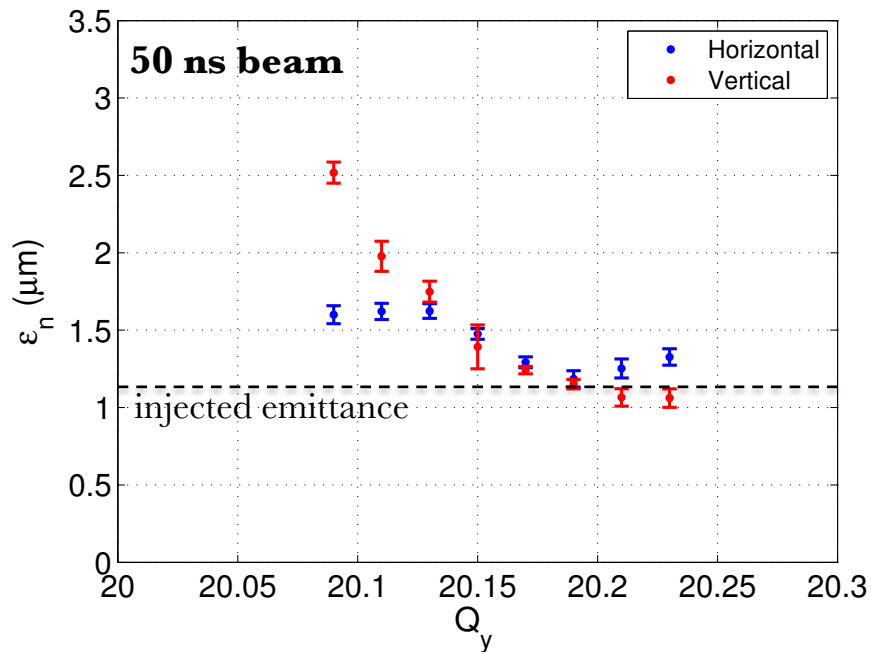


$$\Delta Q_{x,y} = - \frac{r_0 N_p C}{2(2\pi)^{3/2} \sigma_z \beta \gamma^2 \epsilon_{x,y}}$$



- **Vertical tune scan** with high brightness beam for **10 s storage time**
 - $N = 1.95 \times 10^{11}$ p/b (at injection)
 - $\epsilon \sim 1.1 \mu\text{m}$ (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 $\Delta Q_y = 0.21$
- $\Delta Q_x / \Delta Q_y \sim 0.10 / 0.20$

emittance at end of flat bottom

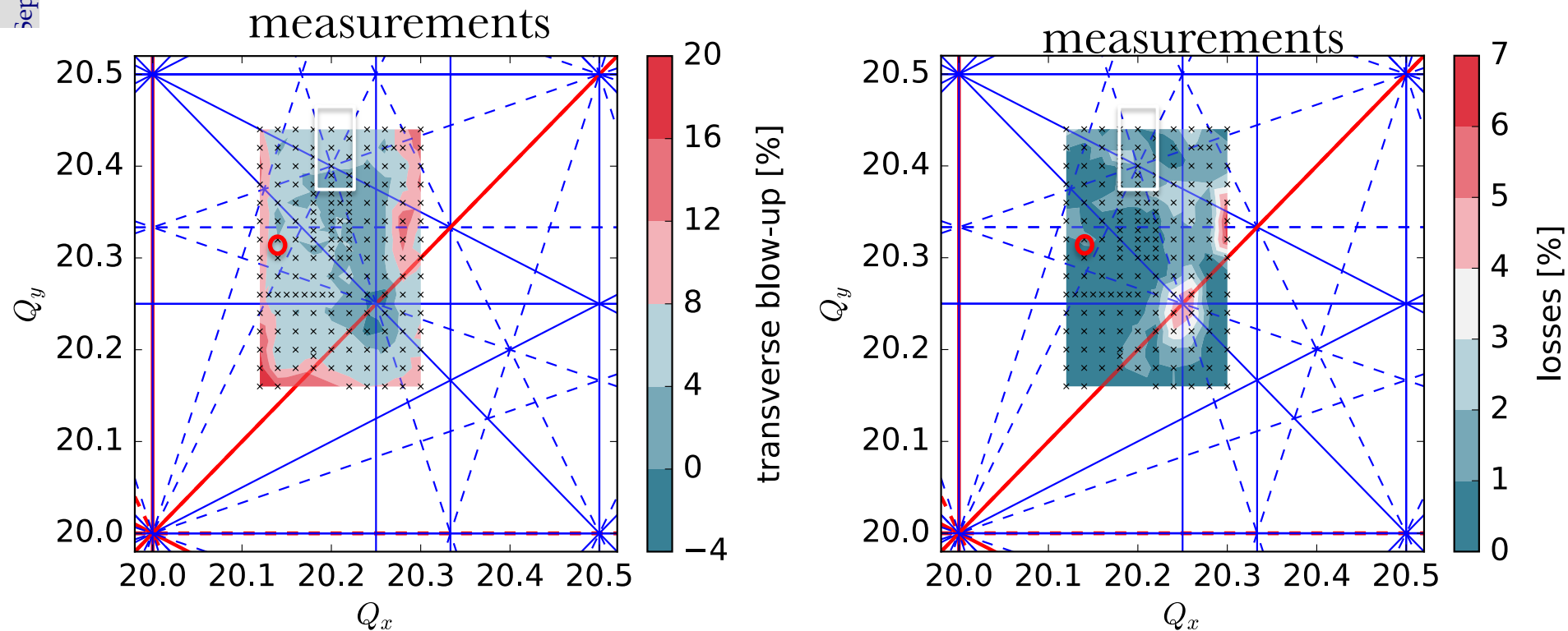


■ Vertical tune scan with high brightness beam for 10 s storage time

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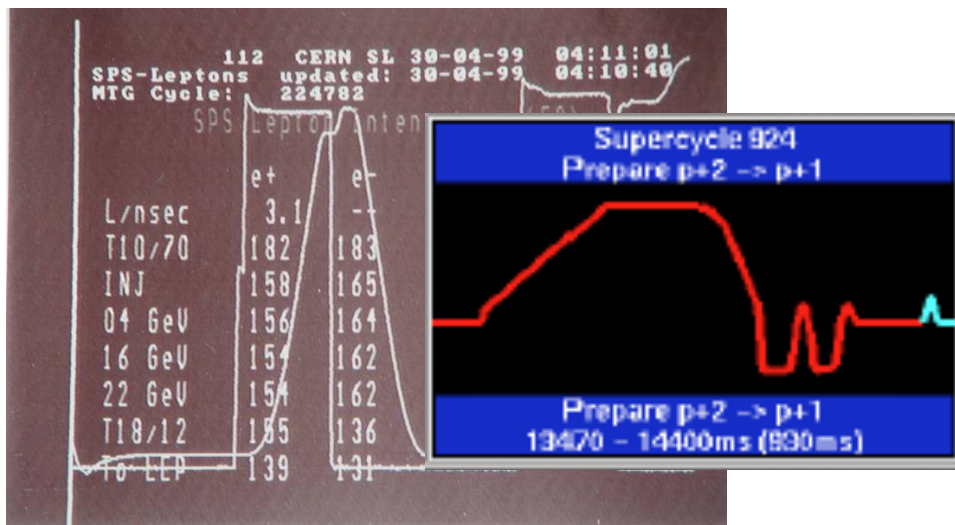
- Tune scan with high brightness single bunch beam for **3 s storage time**
 - Blow-up at integer resonances as expected (tune spread $\Delta Q_x, \Delta Q_y \sim 0.10, 0.19$)
 - **Margin for higher brightness for working points in white box** (enhanced losses only close to $Q_x + 2Q_y = 61$ normal 3rd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

September 2022

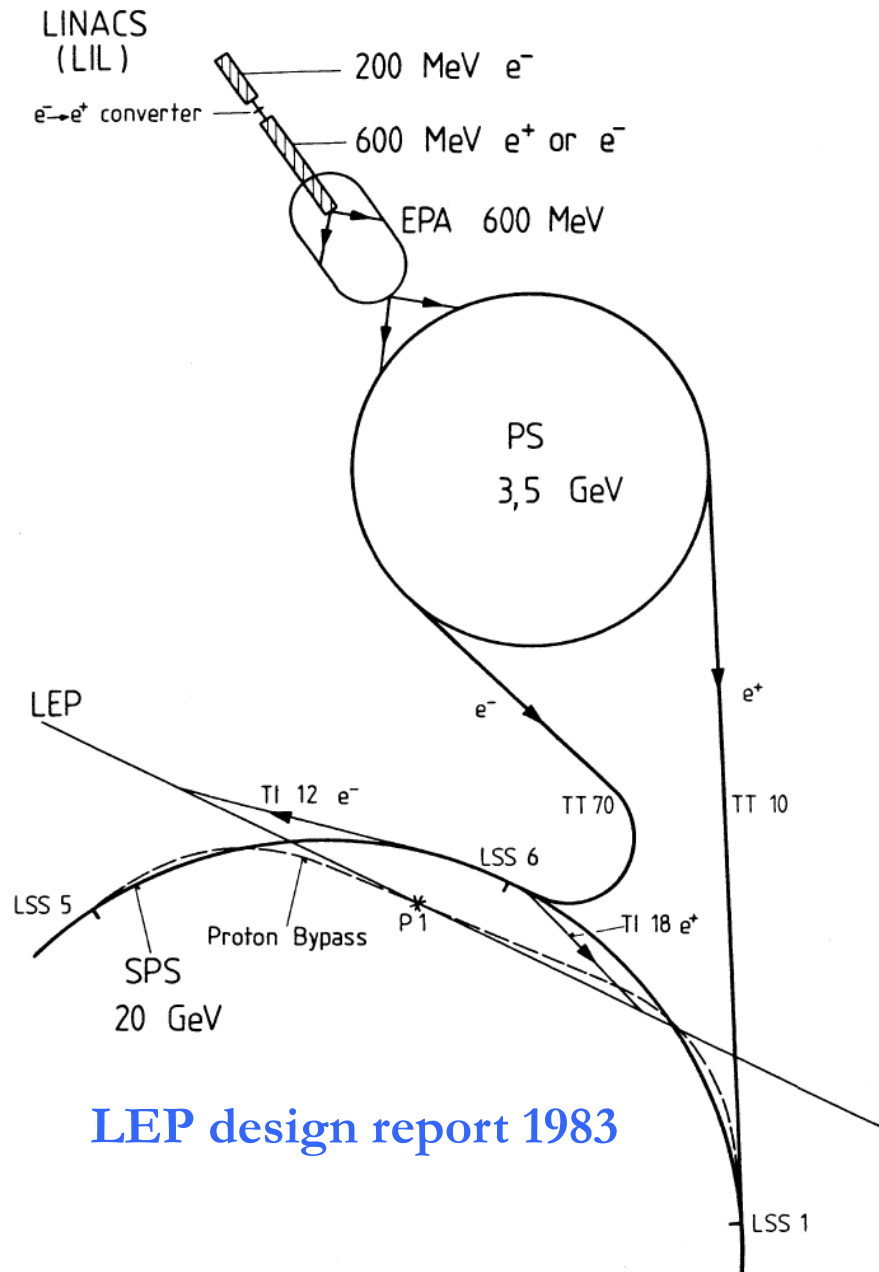


Electron-positron dynamics

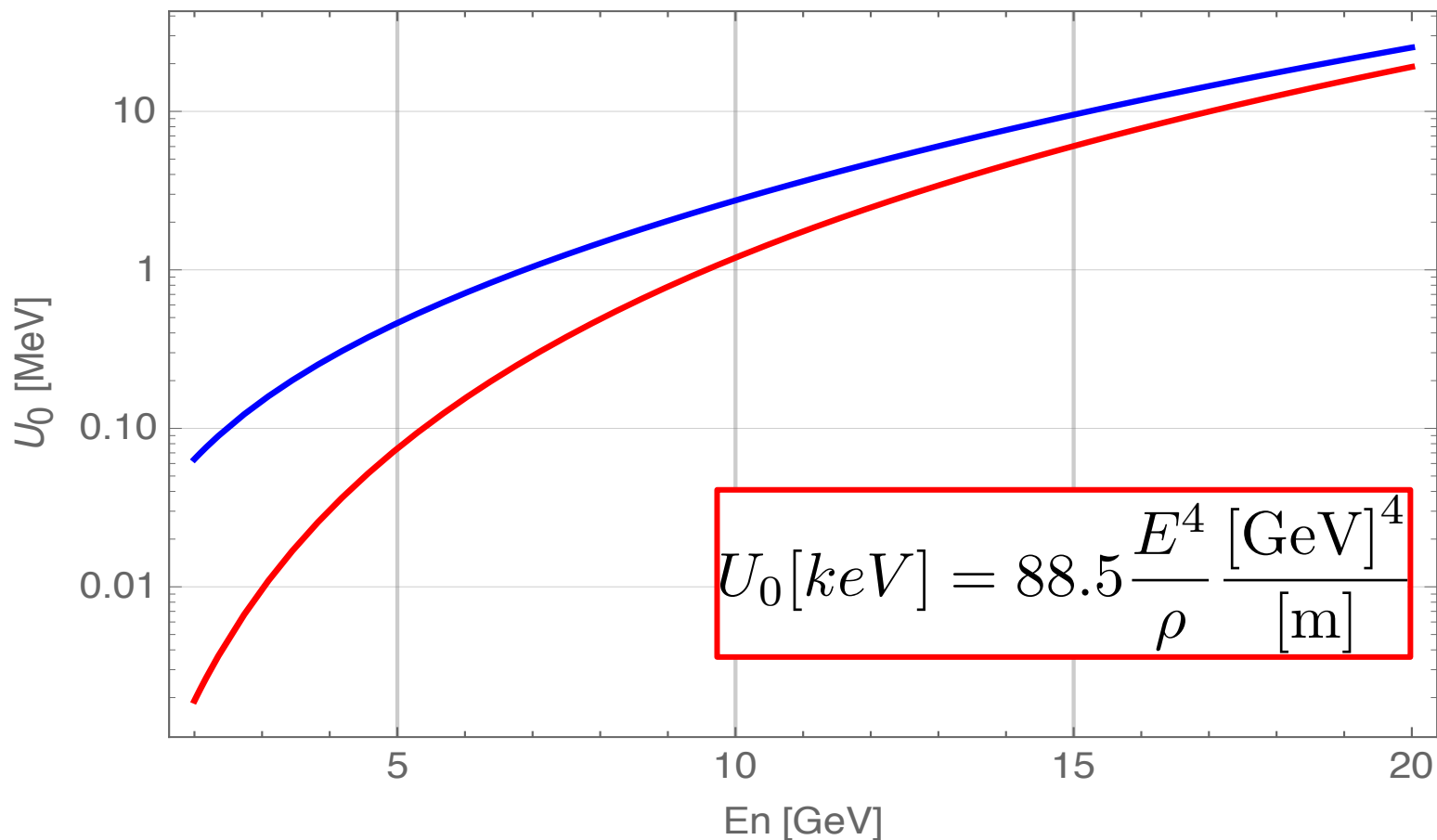
P. Collier – Academic Training 2005



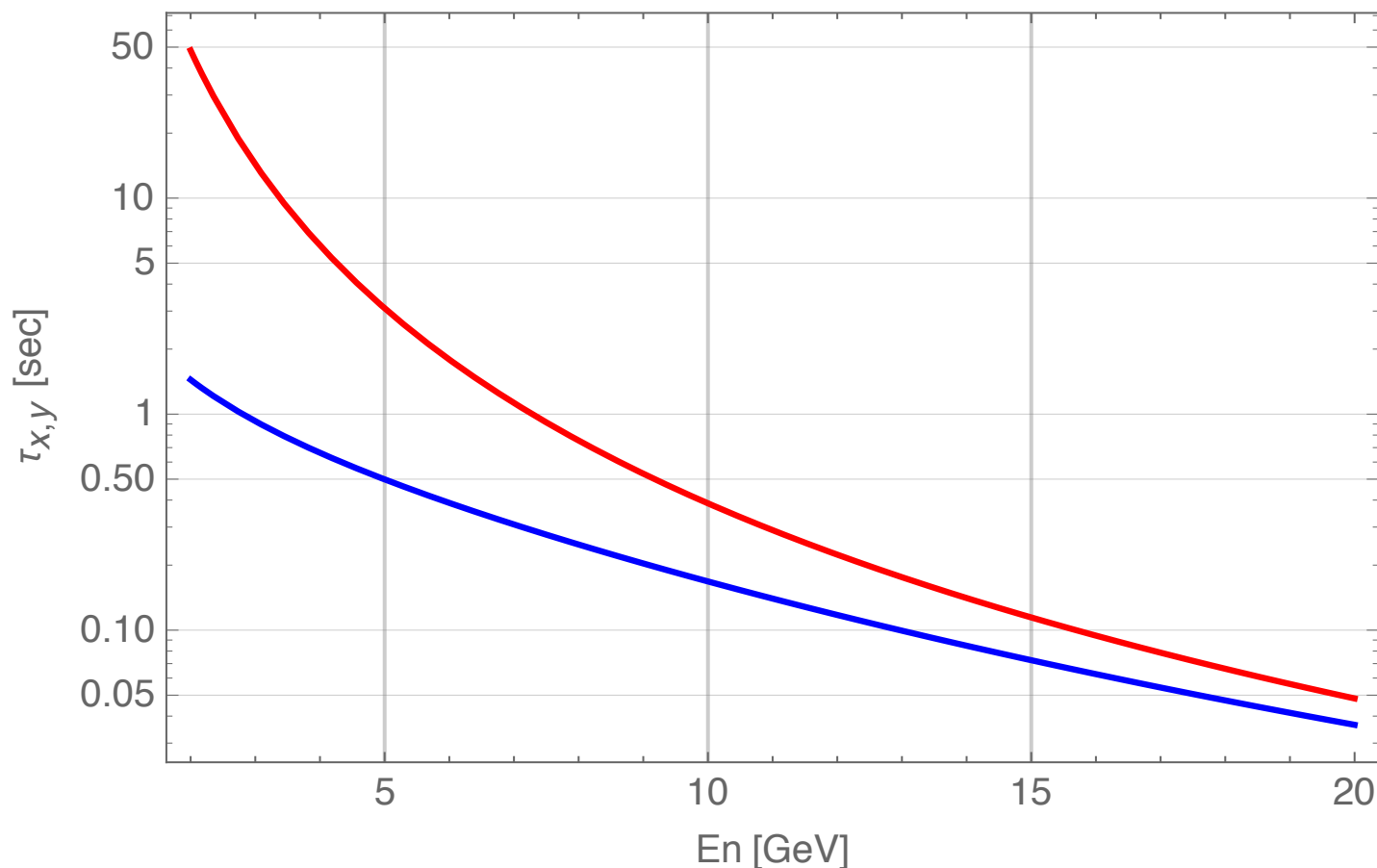
- LEP filling interleaved with proton operation
- 4 cycles with 4 bunches (2e⁺, 2e⁻) evolved to 2 cycles with 8 bunches (~2.5x10¹⁰ p/b)
- Energy to LEP: 18 → 20 → 22 GeV
- Lots of RF for leptons (200MHz SWC, 100MHz SWC, 352MHz SC),
- 2 Extractions in Point 6 towards LEP



LEP design report 1983

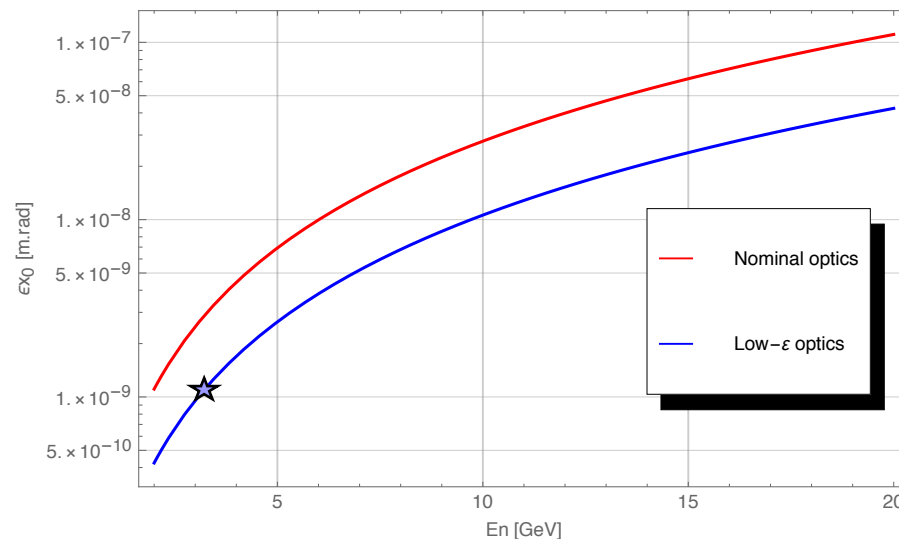
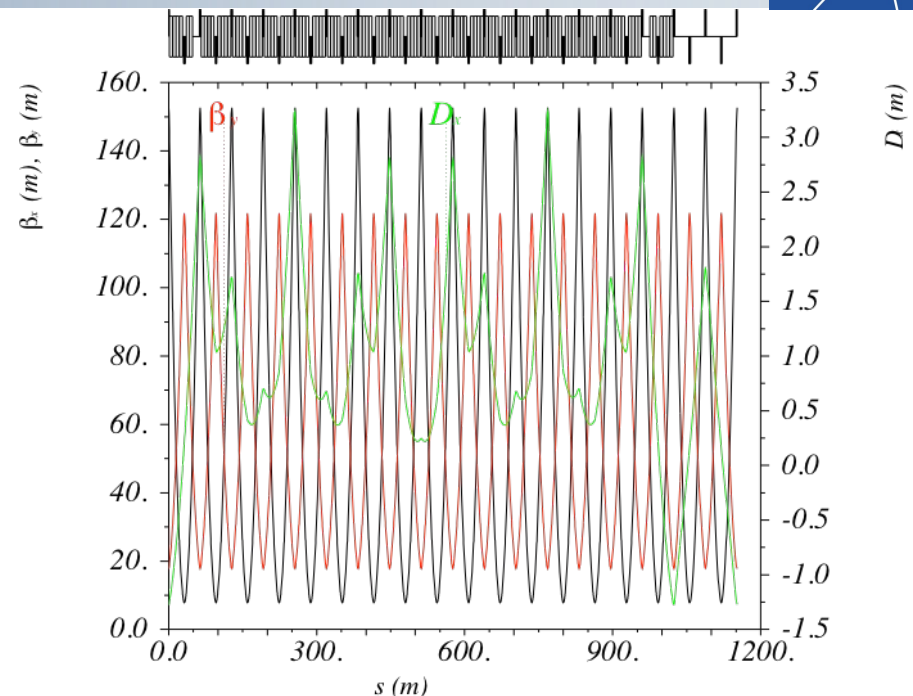


- Energy loss/turn necessitate **large RF voltage** (30 MV) at high energy
- Impact of a 2-m 3.5T **damping wiggler** is mild at high energies



- Damping time 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)

- 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 **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