OPTICS OPTIMIZATION FOR REDUCING COLLECTIVE EFFECTS AND RAISING INSTABILITY THRESHOLDS IN LEPTON AND HADRON RINGS

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CERN

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Outline

- Motivation for using optics to reduce collective effects
  - Ring performance parameters
- Optics quantities affecting collective beam behavior
  - Energy, beam sizes, slippage factor
- Concrete examples for rings in **design** or **operation**
  - High intensity and/or high-power rings
    - Negative momentum compaction factor – **PS2 ring**
  - Ultra-low emittance damping rings
    - Optics design of IBS dominated rings – **CLIC damping rings**
  - High-brightness hadron injectors
    - Raising instability thresholds – LHC beams at **SPS**

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Ring performance parameters

Colliders (and their injectors)	• Luminosity (brightness) $$\mathcal{L} = \frac{N_1 N_2 f n_b}{4\pi\sigma_x\sigma_y}$$
High-power rings	• Beam power $$P = \bar{I} E_k$$
X-ray storage rings	• Photon brilliance $$B = \frac{N_p}{4\pi^2 \bar{\epsilon_x} \bar{\epsilon_y}}$$

Extreme intensity within ultra-low beam dimensions

Collective effects become predominant

Linear optics for reducing collective effects

- An unconventional approach
  - Already large amount of single-particle constraints to be satisfied, including non-linear dynamics
  - Parameter space becomes larger and difficult to control
  - For operating rings, changing the optics is subject to restrictions
    - Existing magnets and powering scheme
    - Critical systems as RF and beam transfer elements

Analytical and numerical methods for obtaining global parameterization

A cost effective solution if successful

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"Optics" knobs I

- **Beam energy** (not a real optics constraint…)
  - Depends on users needs, pre-injectors' reach, cost…
  - Almost all collective effect (e-cloud is one exception) are reduced with increased energy
  - In e^+/e^- rings, $\epsilon_x \propto \gamma^2$ and optimum needs to be found for reaching high-brightness
- **Transverse beam sizes**
  - Larger beam sizes can reduce collective effects due to self-induced fields (space-charge, IBS)
  - High-brightness targets low emittances, thus optics functions are only handle for increasing beam sizes

"Optics" knobs II

- **Phase slip factor** $\eta = \alpha_p - \frac{1}{\gamma^2}$ with the momentum compaction factor $\alpha_p = \frac{1}{C} \oint \frac{D_x(s)}{\rho(s)} ds$
- Depends on energy and transverse beam sizes
- Connects transverse and longitudinal motion
  - Synchrotron frequency (or bunch length) proportional to $\sqrt{\eta}$
- Instability intensity thresholds (TMCI, microwave, coupled bunch,...) $N_{\mathrm{th}} \propto \eta$

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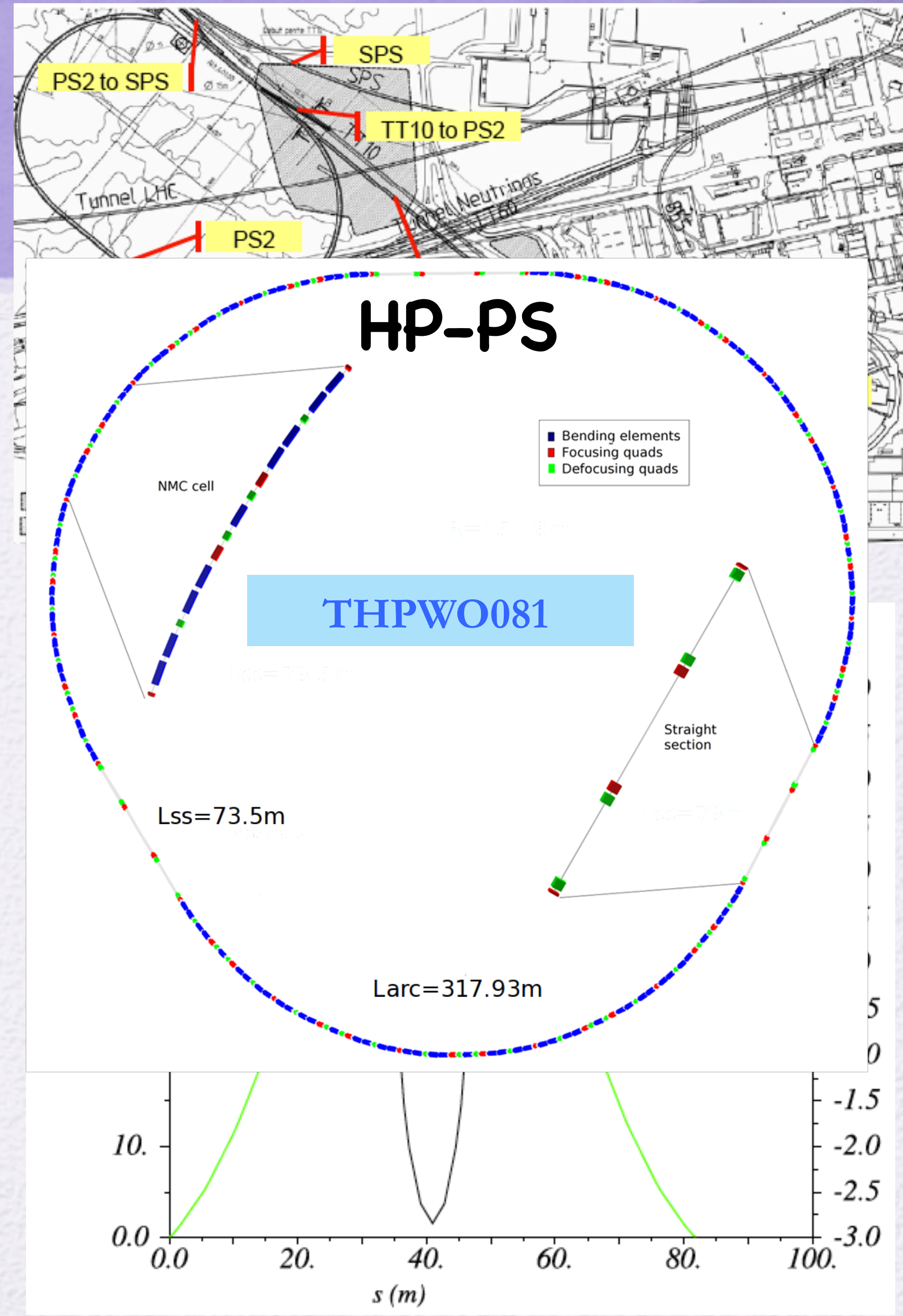
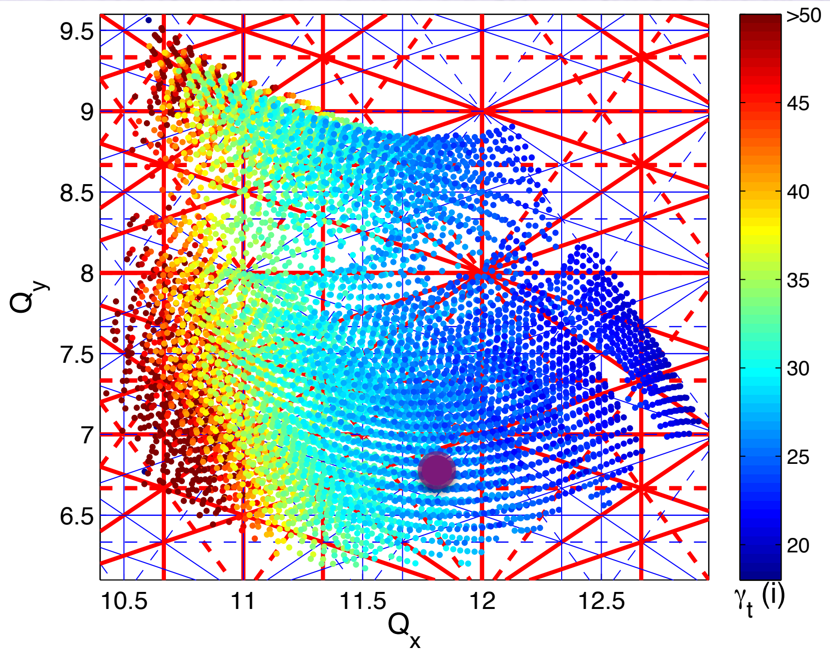
PS2 ring

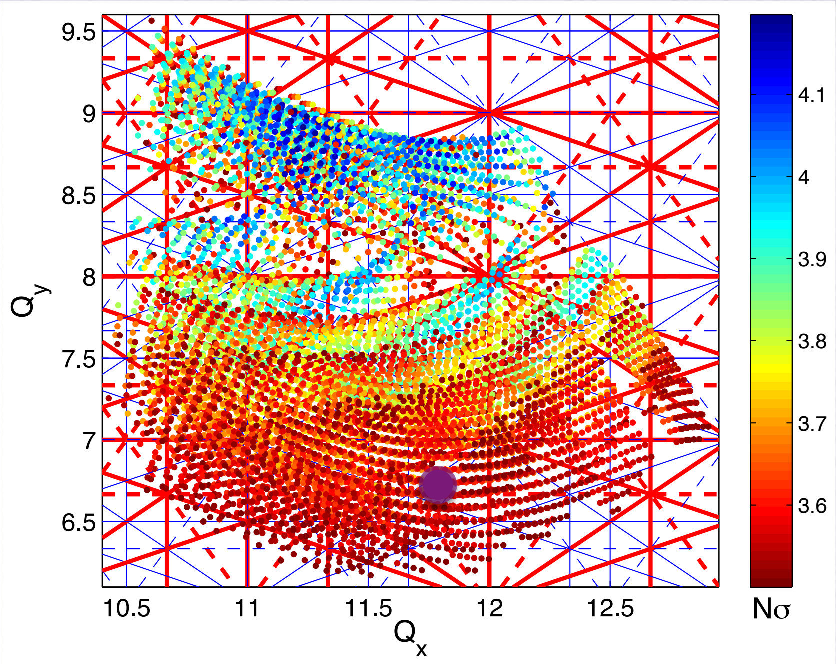
- ❑ Studied until 2010, as a possible upgrade scenario of the LHC injector complex
- ❑ Beam injected at 4 GeV/c from the LP-SPL and extracted at 50 GeV/c
- ❑ High-intensity ring with **negative momentum compaction** arc cells (avoid transition) and doublet straights
- ❑ Most of the design concepts currently adapted to a study of a **High-Power PS** (2MW) for neutrinos (LAGUNA-LBNO)



Optics optimization for PS2

H. Bartosik et al., THPE022, IPAC 2010





- Applying GLASS method (see D. Robin et al., PRST-AB 11, 024002, 2008)
- Global view of the "imaginary" transition gamma and geometrical acceptance dependence on tunes
  - Low transition energy for reducing collective effects (large horizontal tune)
  - Large acceptance (high vertical tune) for losses and magnet constraints (but small beam sizes)
- **Working point** chosen based on this analysis and non-linear dynamics optimization

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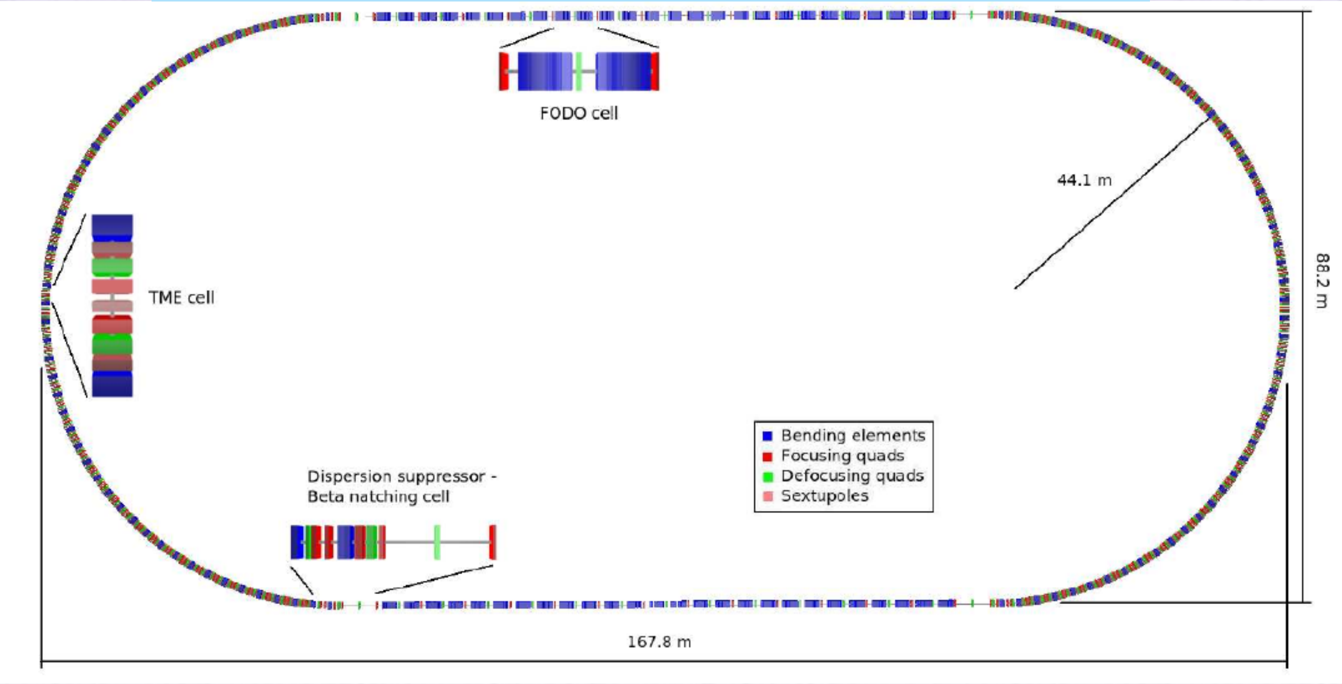
CLIC damping rings

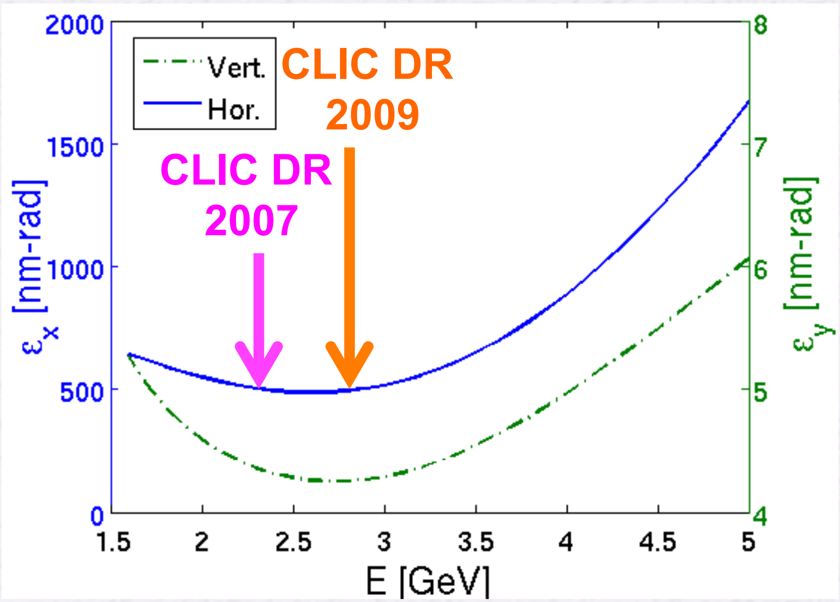
F. Antoniou, PhD thesis, NTUA, 2013

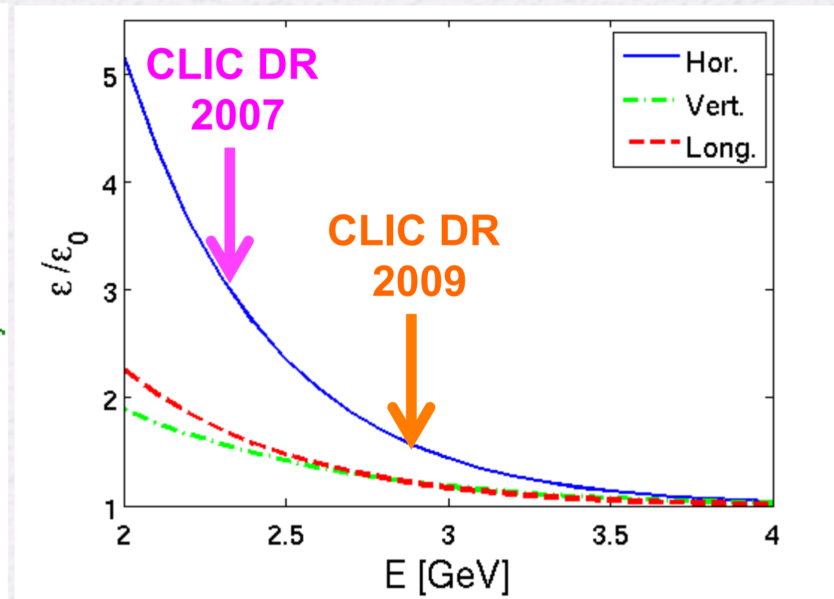


- Ultra low-emittance bunches with high bunch charge trigger several collective effects
  - Emittance dominated by IBS (significant blow up)
  - Large vertical space charge tune-shift
  - Single and multi-bunch instabilities (TMCI, microwave, e-cloud, fast-ion, coupled bunch,...)

→ Optics parameter optimization for reducing collective effects

Optimal energy





- Steady state emittance as a function of the energy (including IBS)
- Broad minimum at around 2.5 GeV
- Strong horizontal beam blow-up for lower energies
- Increased energy from **2.42** to **2.86** GeV resulted in reduction of horizontal emittance blow-up by a **factor of 2**

Parameterization of TME cells

$$f_1 = \frac{s_2(4s_1 l_d + l_d^2 + 8D_{xc}\rho)}{4s_1 l_d + 4s_2 l_d + l_d^2 - 8D_s\rho + 8D_{xc}\rho}$$

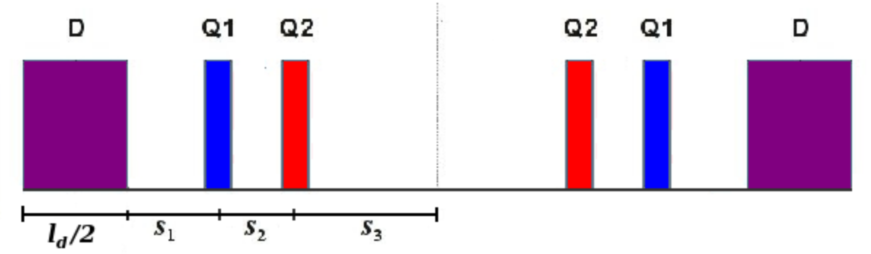
$$= \frac{l_d s_2 \left(12 s_1 + l_d \left(D_r + 3\right)\right)}{12 l_d \left(s_1 + s_2\right) + l_d^2 \left(D_r + 3\right) - 24 D_s \rho}$$

$$f_2 = \frac{8 s_2 D_s \rho}{-4 s_1 l_d - l_d^2 + 8 D_s \rho - 8 D_{xc} \rho}$$

$$= \frac{24 s_2 D_s \rho}{12 l_d s_1 + l_d^2 \left(D_r + 3\right) - 24 D_s \rho}$$

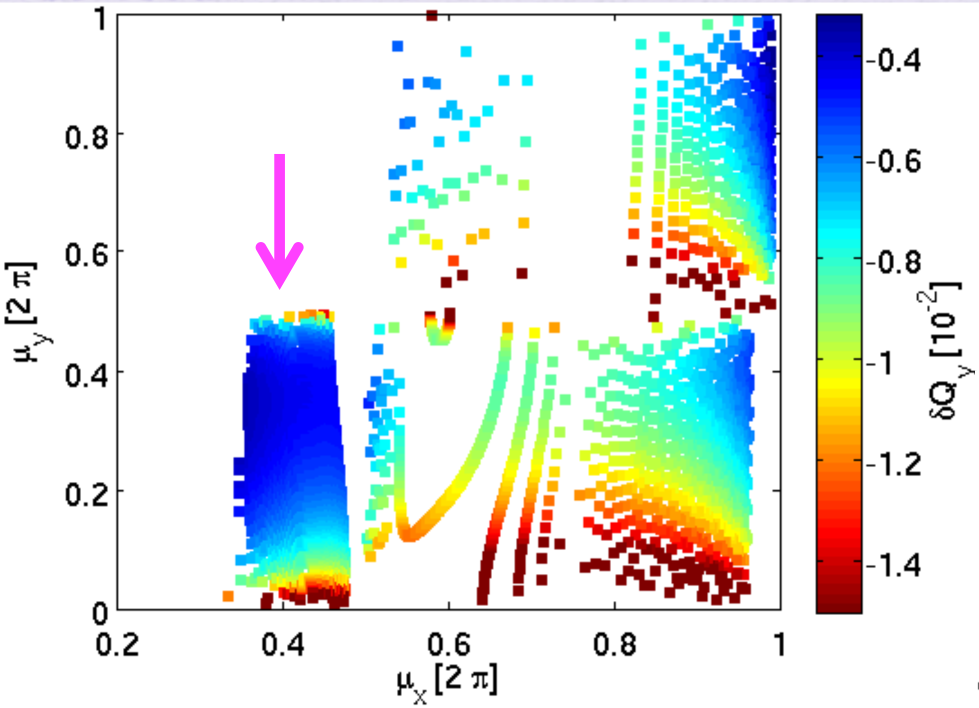
$$D_r = \frac{D_{xc}}{D_{xc}^{\min}}, \beta_r = \frac{\beta_{xc}}{\beta_{xc}^{\min}}, \varepsilon_r = \frac{\varepsilon_{xc}}{\varepsilon_{xc}^{\min}}$$

$$D_s = g(s_1, s_2, s_2, l_d, \beta_r, D_r)$$



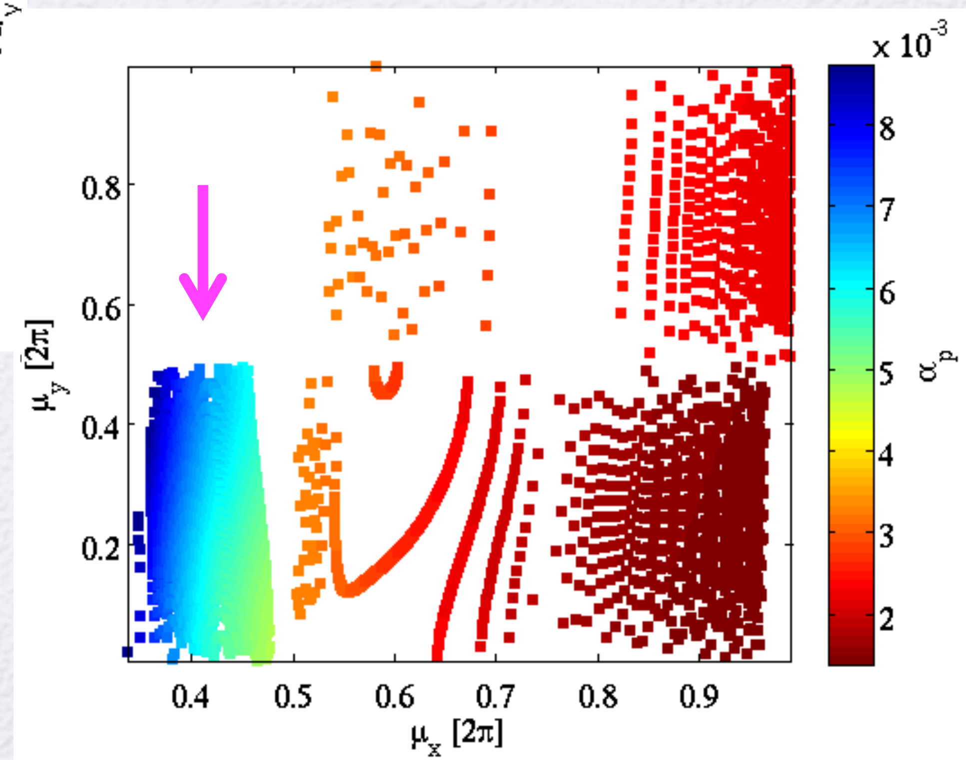
- Analytical representation of TME quadrupole focal lengths (thin lens)
  - Depending on horizontal optics conditions at dipole center (horizontal emittance) and drift lengths
  - Multi-parametric space for applying optics stability criteria, magnet constraints, non-linear optimization, **IBS reduction,…**

TME optimization for reducing IBS

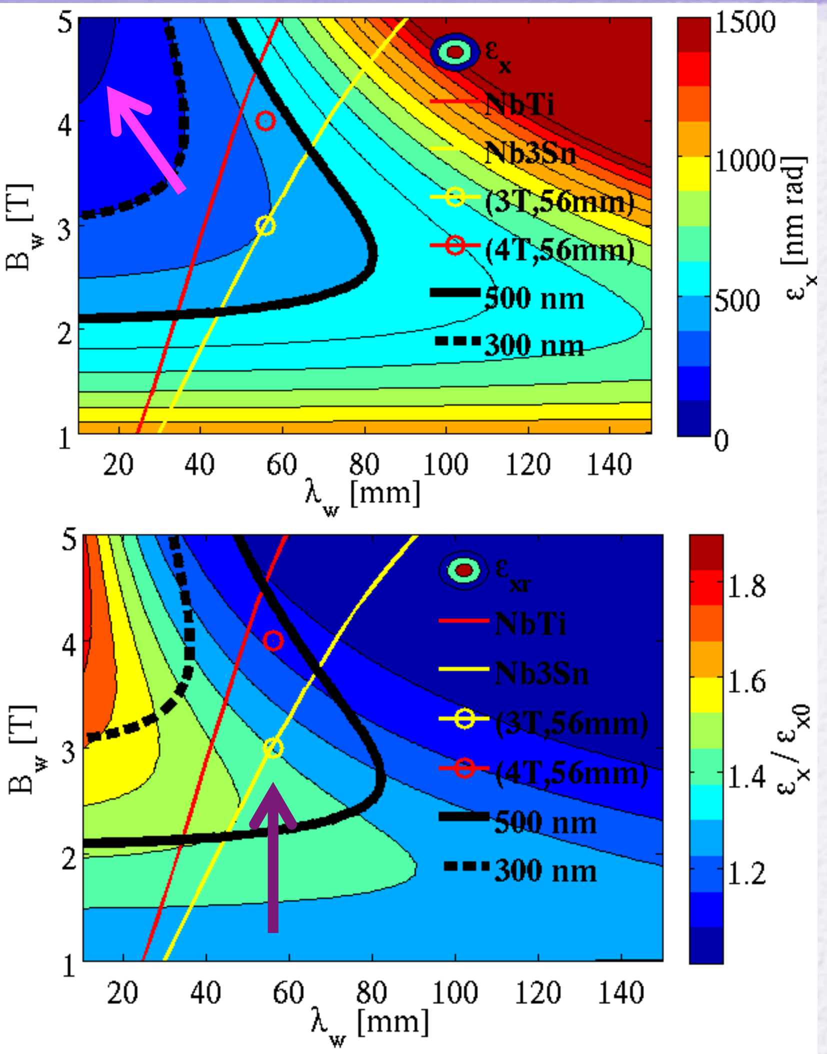


- **Low cell phase advances** can minimize **IBS growth rates**
- Correspond to large **deviation** from absolute theoretical emittance minimum

- Optimal also for minimizing **space-charge** tuneshift and increase **momentum compaction factor**



Wiggler parameter choice



- The **highest field** and **smallest period** provide the smallest emittance
- Lower emittance blow-up due to IBS for **high-field** but **moderate period** (within CLIC emittance targets)
- Wiggler prototype in NbTi with these specs, built at BINP, for installation to ANKA (KIT)
  - Serving X-ray user community but also beam tests
- Development of higher-field short models in Nb3Sn at CERN

D. Schoerling et al., PRST-AB 15, 042401, 2012

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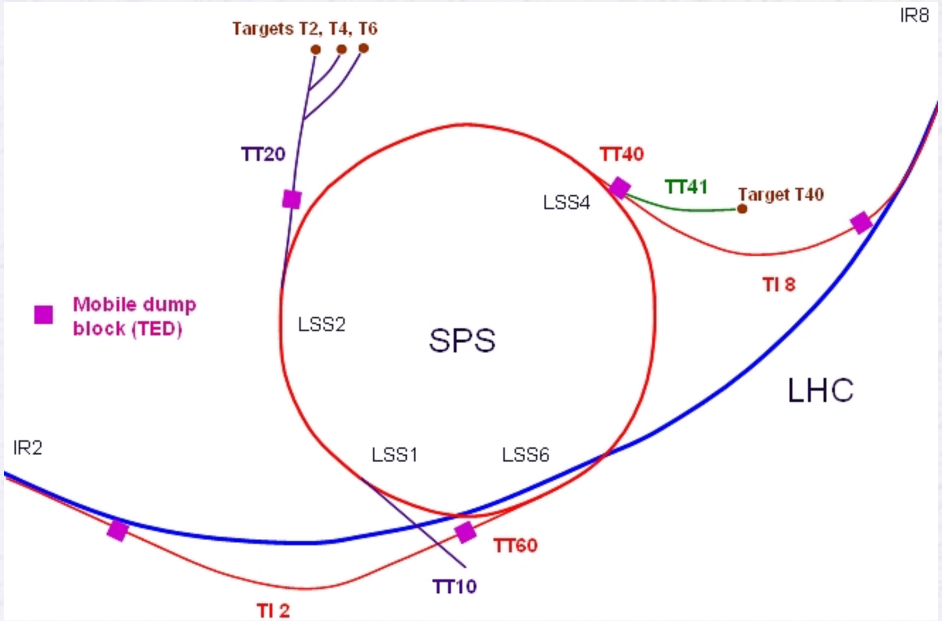
Injectors for high brightness – CERN SPS



- ❑ LHC injectors upgrade (LIU project) for High Luminosity LHC (HL-LHC)
  - ❑ Significantly higher intensity and brightness is required from injectors, including the SPS

R. Garoby et al. THPWO077

B. Godard et al. WEPEA053

- ❑ Intensity limitations of SPS

WG chaired by E. Shaposhnikova

  - ❑ Beam loading in 200MHz and 800MHz RF system – RF upgrade
  - ❑ Transverse mode coupling instability at injection (TMCI)
  - ❑ Longitudinal instabilities (single and multi-bunch)
  - ❑ Electron cloud for 25ns – coating?

Instability thresholds and slippage factor

- 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

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

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

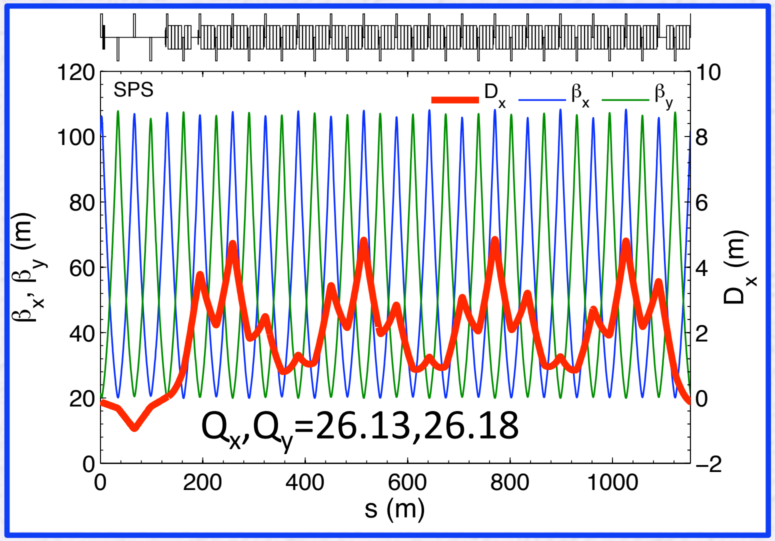
$$\boxed{N_{\mathrm{th}} \propto Q_s \propto \sqrt{\eta}}$$

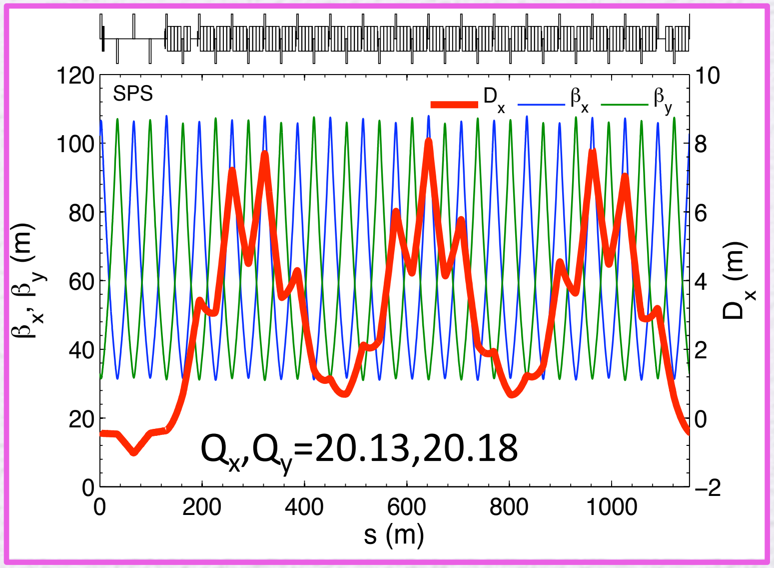
- Longitudinal instabilities
  - Single bunch and coupled bunch due to loss of Landau damping
    - Threshold at 2×10^{10}p/b for single harmonic RF (800 MHz cavity use is mandatory)

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

T. Argyropoulos et al, TUPWA039, TUPWA040

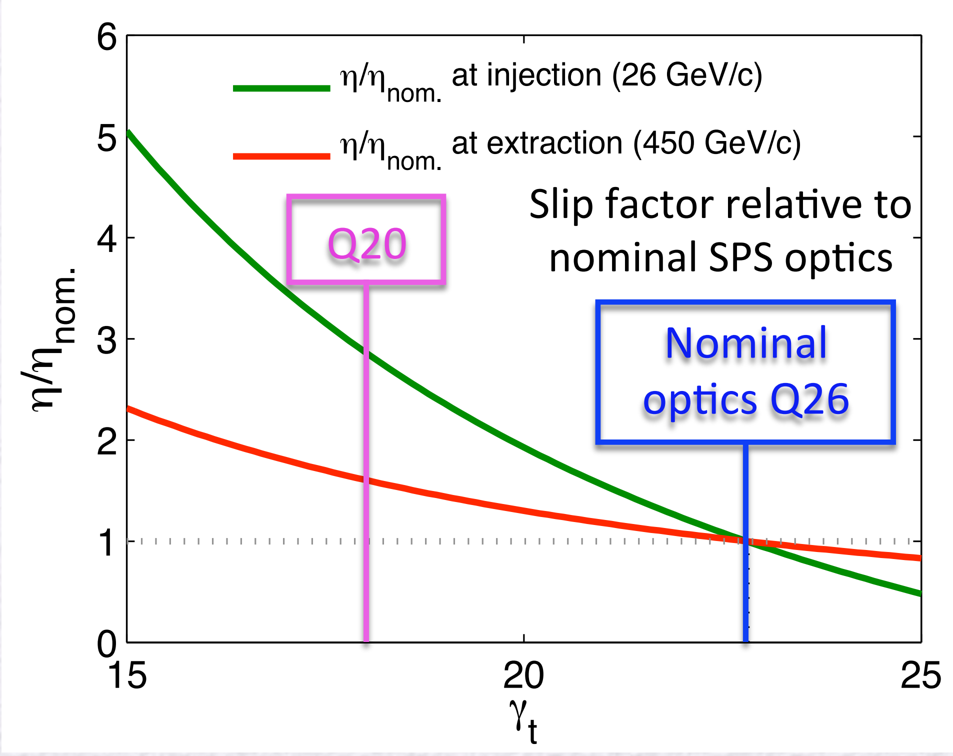
Increasing slip factor (lowering γ_t)





$$\eta = \frac{1}{\gamma_t^2} - \frac{1}{\gamma^2} \quad \Leftrightarrow \quad \gamma_{t_{FODO}} \approx Q_x$$

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

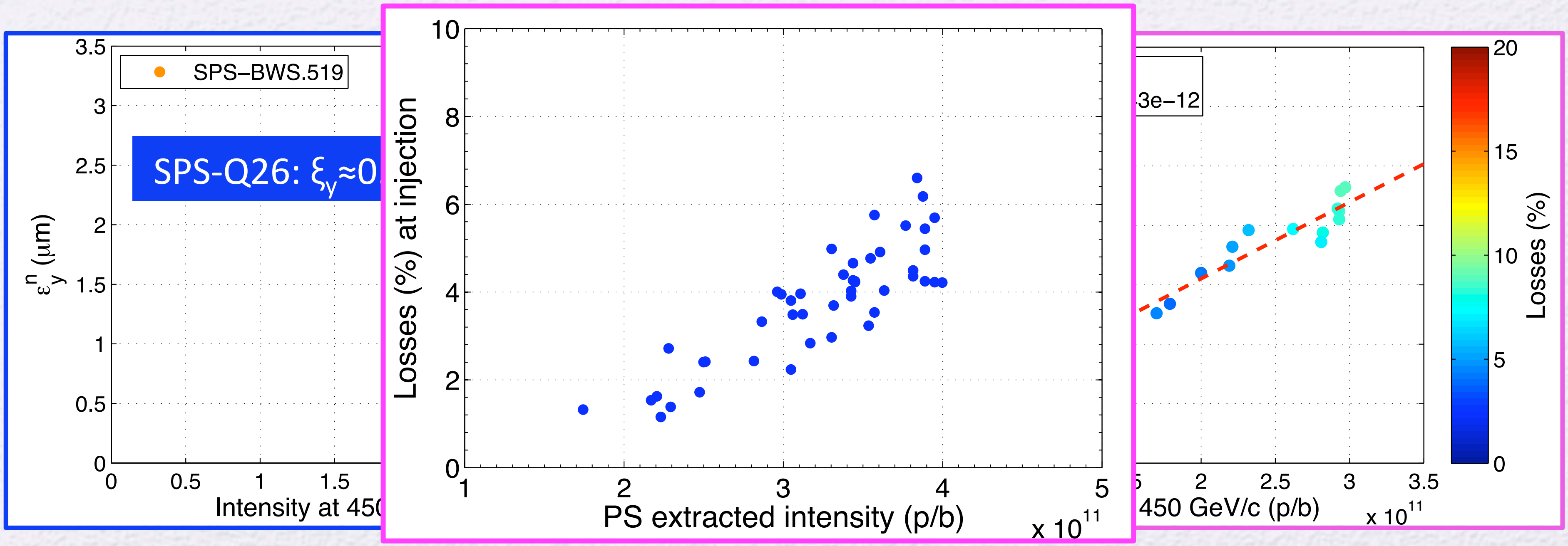


TMCI threshold

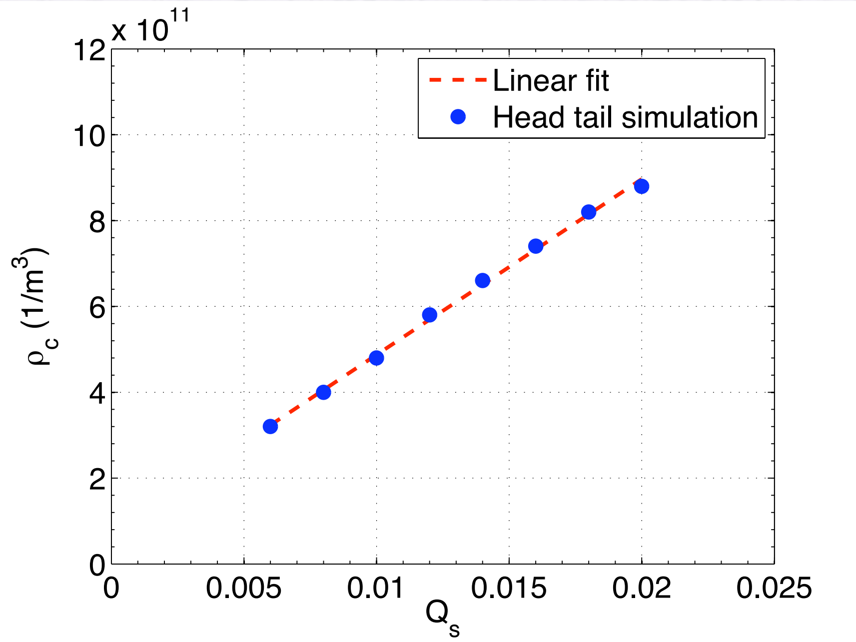
H. Bartosik et al, HB2012 and TUPME034

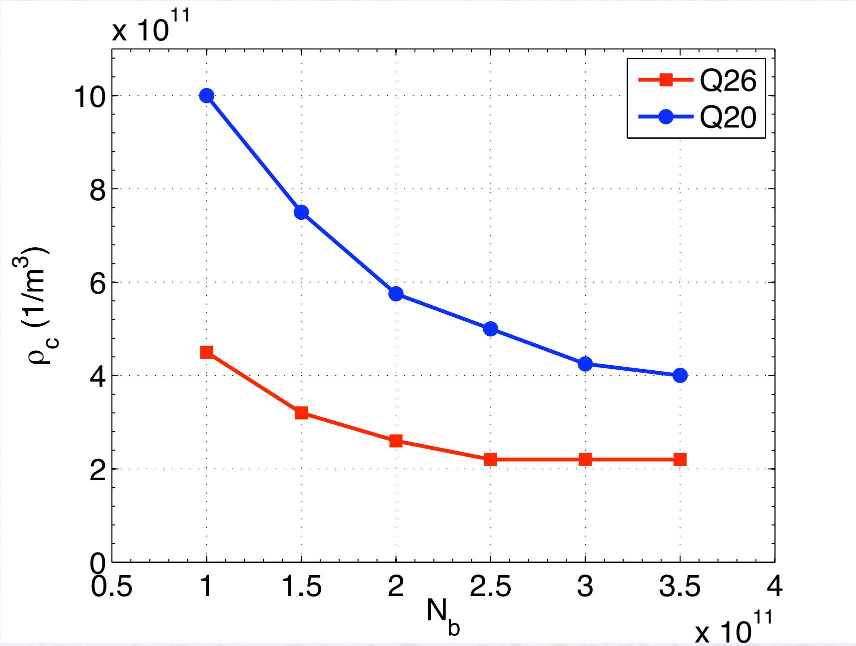
- In nominal optics, measured threshold at 1.6×10^{11}p/b for low chromaticity
  - High-chromaticity helps increasing threshold, but also losses along the cycle become excessive
- Measured threshold in Q20 > 4×10^{11}p/b!!!
  - Injected single bunches of 3×10^{11}p/b in the LHC for machine studies

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



E-cloud instability threshold





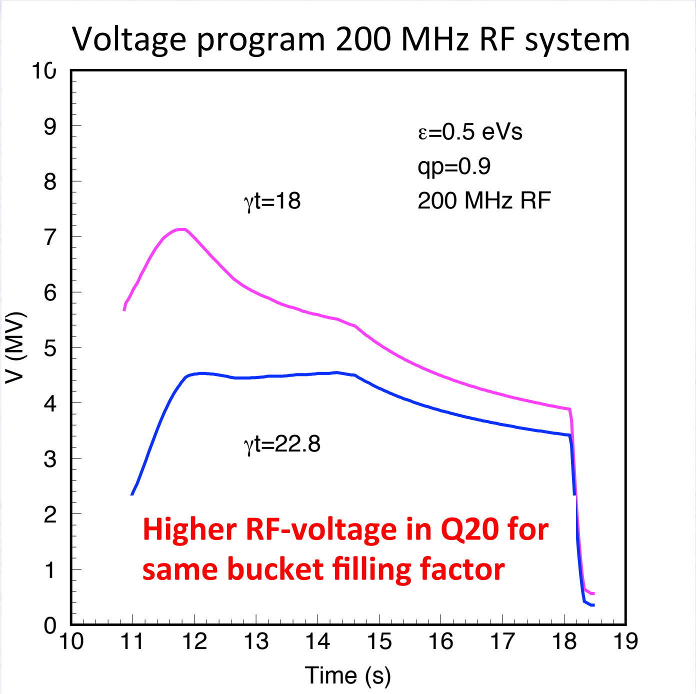
- Simulations with HEADTAIL code
  - Injection energy, uniform cloud distribution, located in dipole regions
- Linear scaling with Synchrotron tune demonstrated
- Clearly higher thresholds predicted for **Q20**

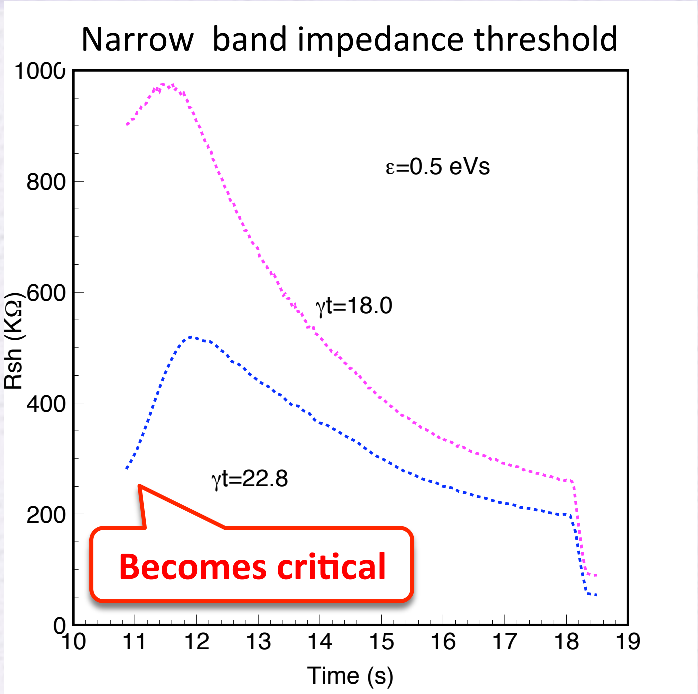
More margin with Q20 if e-cloud becomes issue for high intensity

H. Bartosik et al, IPAC2011

Longitudinal impedance threshold

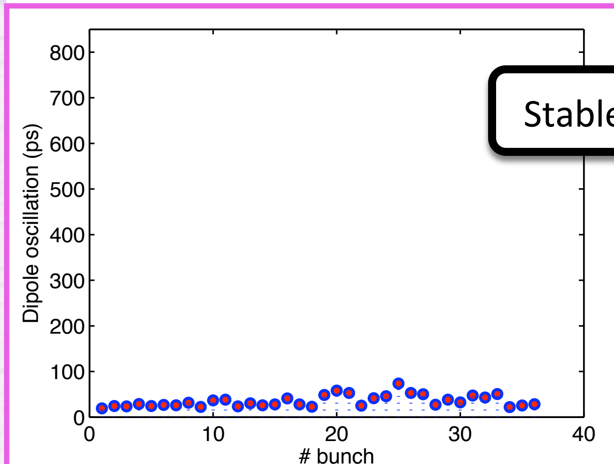
E. Shaposhnikova



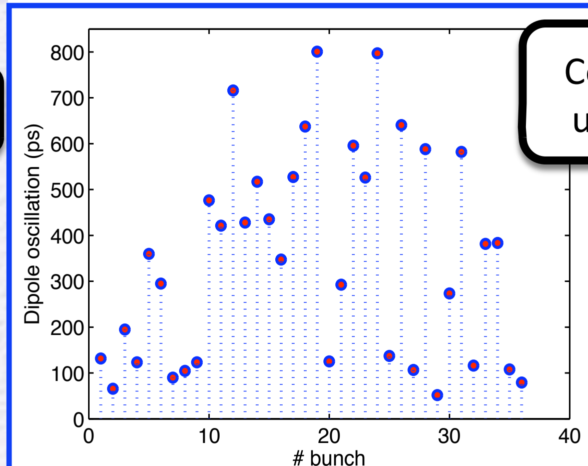


- Impedance threshold has minimum at flat top
  - Controlled longitudinal emittance blow-up during ramp for **Q26**
  - Less (or no) longitudinal emittance blow-up needed in **Q20**
- Instability limit at flat bottom
  - Crtitical with **Q26** when pushing intensity
  - Big margin with **Q20** (factor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

Stability without longitudinal blow-up



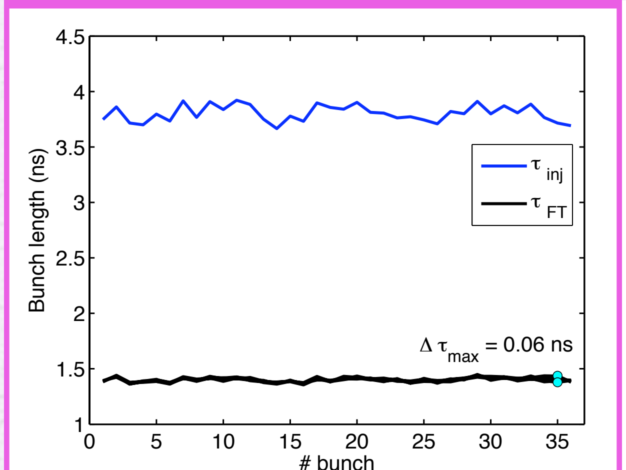
Stable beam

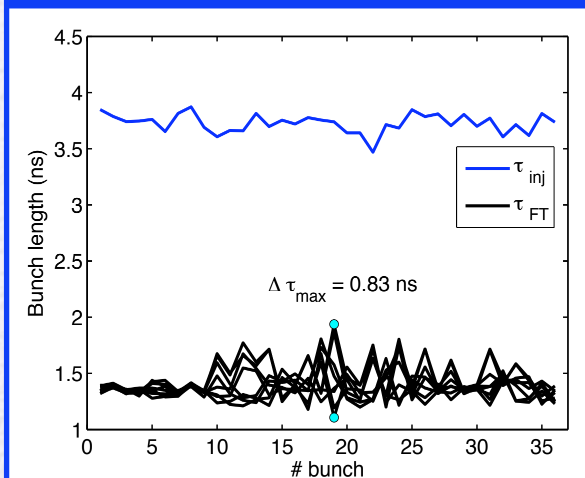


Contr. blow-up needed!

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

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



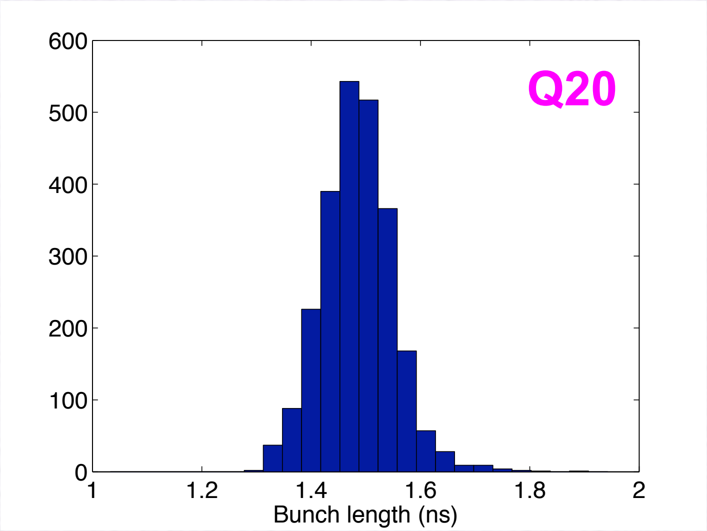


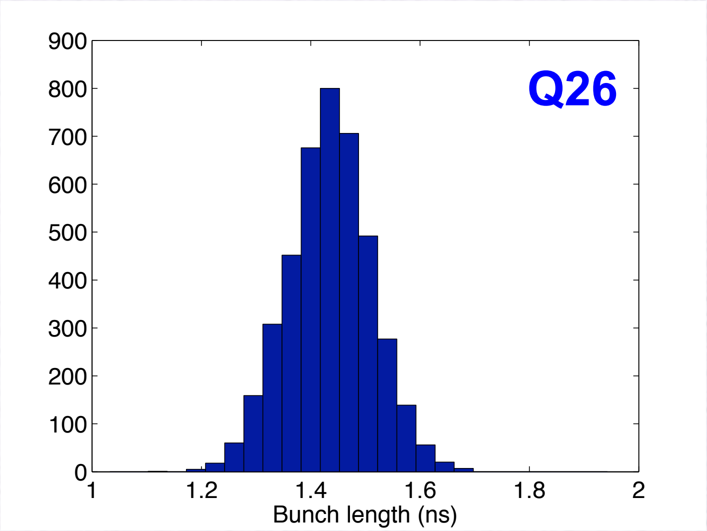
T. Argyropoulos et al.

Extraction to the LHC

- Bunches need to be shortened at flat top to fit LHC bucket
  - Maximum voltage already used in **Q26** (RF system upgrade)
  - Beam with same longitudinal emittance would have larger bunch length in **Q20**
- Similar bunch length at flat top in both optics for same longitudinal stability
  - Smaller longitudinal emittance in **Q20**
  - Smaller rms spread in bunch length at extraction with Q20
- **Ready for delivery to LHC**

T. Argyropoulos et al.

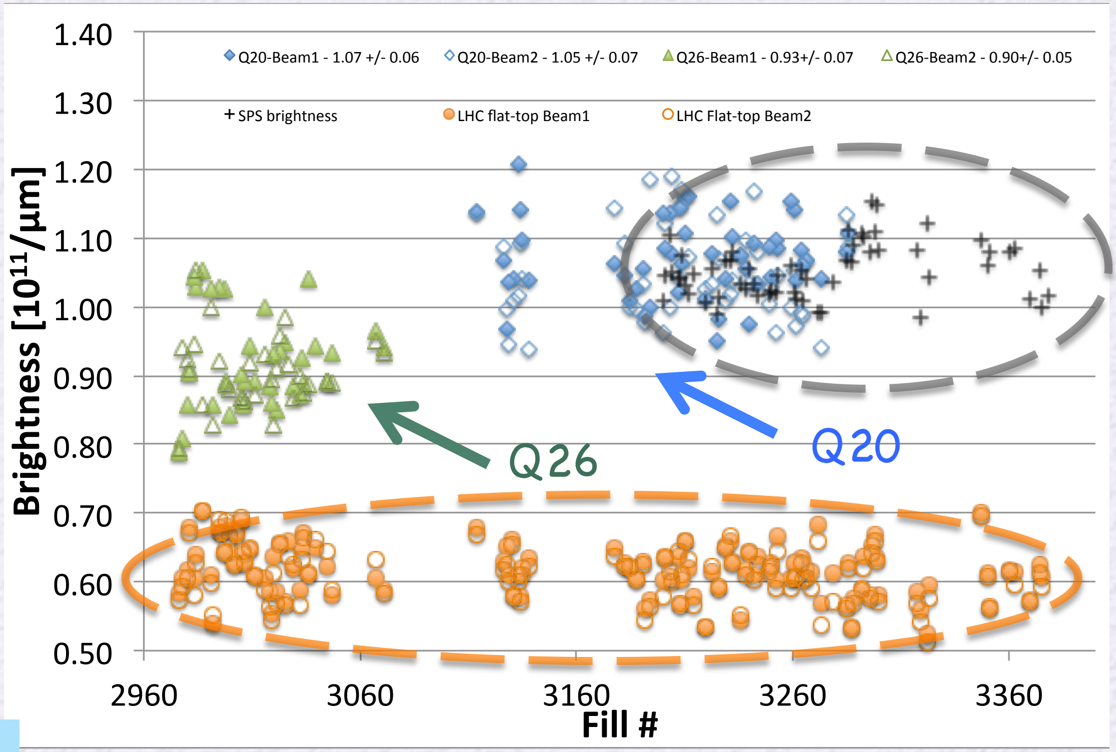




LHC brightness with SPS Q20

THPWO080

- Operational deployment of Q20 optics for LHC beams
- Very smooth switch (09/12), allowing around **20% brighter beams on LHC flat bottom**
- Excellent brightness preservation between **SPS flat bottom** and **LHC flat-bottom**
- Opened way for **ultra-high brightness beams** of HL-LHC era
- Delivered also with Q20
  - **25ns** beams for **LHC scrubbing run** (12/12)
  - LHC ion beam during **p-Pb run** (01-02/13)



F. Antoniou et al., TUPME046

- Work to be done in the LHC for digesting ultra high-brightness beams

Summary

- Optimization of linear optics parameters with direct impact to collective effects
  - Using analytical and numerical methods
  - NMC cell design and working point choice in high-intensity (or high-power) rings
  - Conceptual design of ultra-low emittance damping rings
  - Break intensity limitations in operating LHC injector, without any cost impact or hardware change
- Optics design needs to go beyond single-particle dynamics and include collective effects for reaching optimal performance

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(CERN)

H. Braun (PSI)

感谢您的关注

Thank you for your attention