ICFA mini-Workshop on "Mitigation of Coherent Beam Instabilities in particle accelerators" - MCBI 2019

23-27/09/2019

Mitigation of collective effects (coherent beam instabilities) by optics optimization

Y. Papaphilippou, CERN

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 rings
    - Optics design of IBS dominated rings – **CLIC damping rings**
    - Negative-α operation -> **SUPER-ACO, VSOR, DAFNE, KEKB,…**
  - High-brightness hadron injectors and colliders
    - Increasing impact of Landau octupole with optics – **HL-LHC**
    - 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

- **Unconventional** approach
  - Already large amount of **single-particle constraints** to be satisfied, including non-linear dynamics
  - Parameter space becomes **entangled** and difficult to control and optimise
  - 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

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 optics functions**
  - Larger beam sizes can reduce collective effects due to self-induced fields (space-charge, IBS)
  - High-brightness requires low emittances, thus optics functions are only handle for increasing beam sizes
  - Beta functions can also be manipulated to enhance impact of magnets used for Landau damping

"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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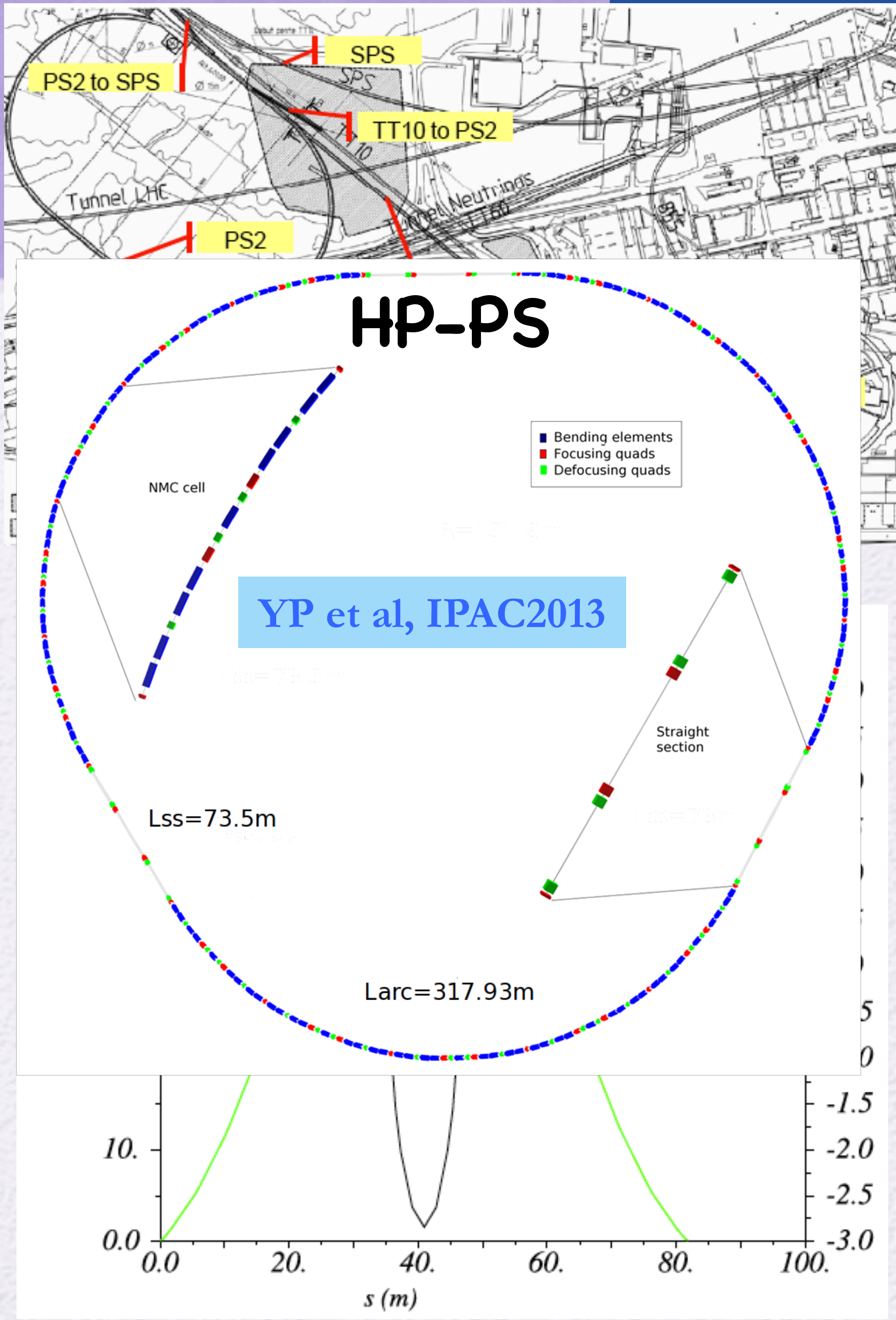
PS2 ring

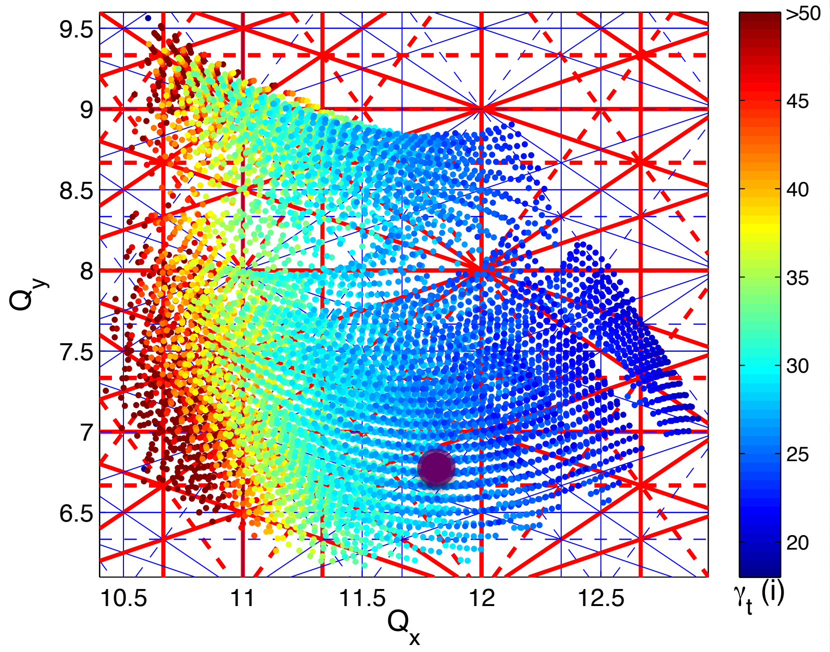
- Studied until 2010, as a possible upgrade scenario of the LHC injector complex
- Beam injected at 4 GeV/c from the LP-SPL and extracted at 50 GeV/c
- High-intensity ring with **negative momentum compaction** arc cells (avoid transition) and doublet straights
- Most of the design concepts adapted to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

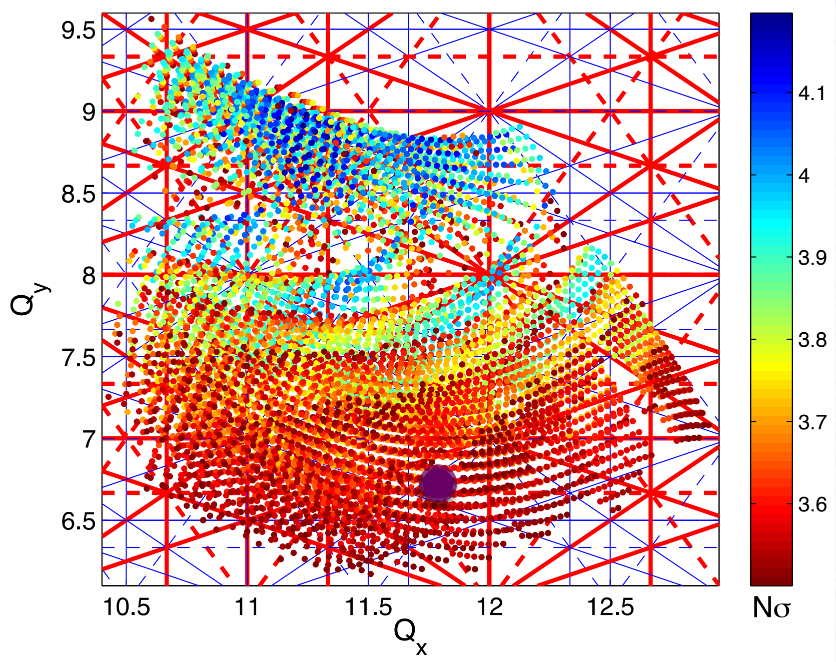


YP et al, IPAC2013

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 (vertical tune) for losses and magnet constraints (but small beam sizes)
- ❑ **Working point** choice based on this analysis and non-linear dynamics optimization

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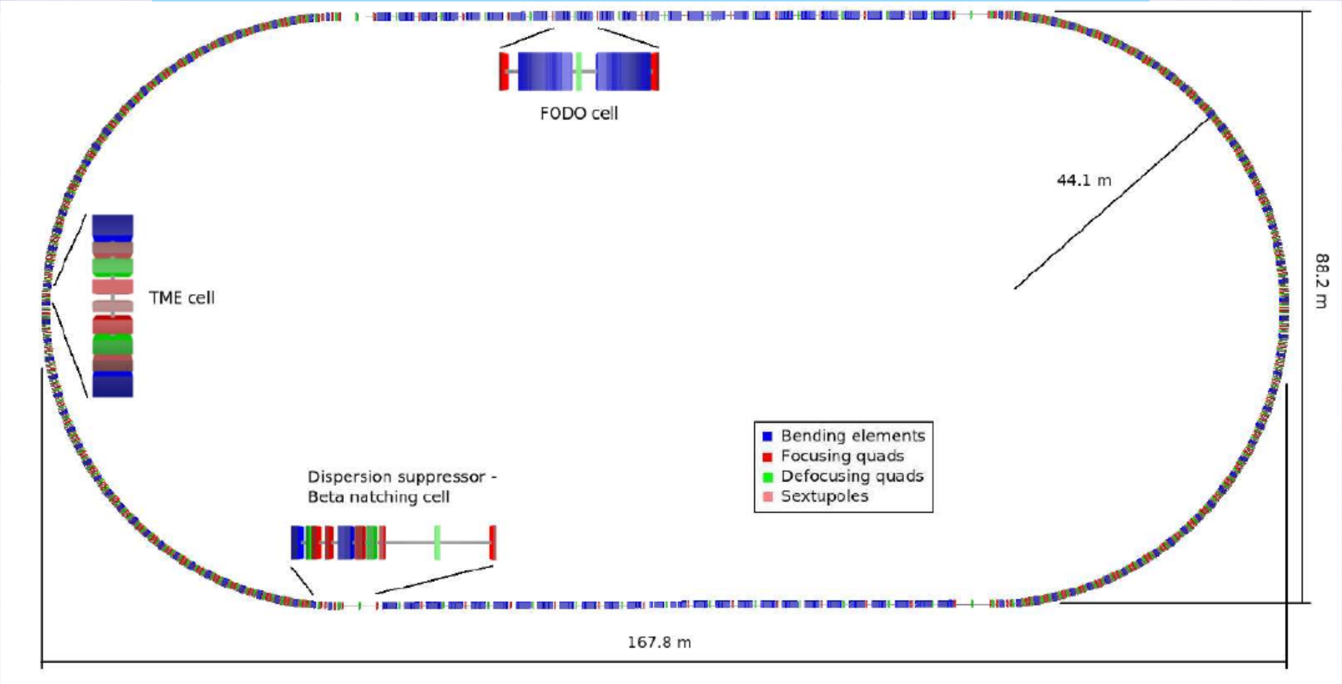
CLIC damping rings

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

Parameterization of TME cells

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

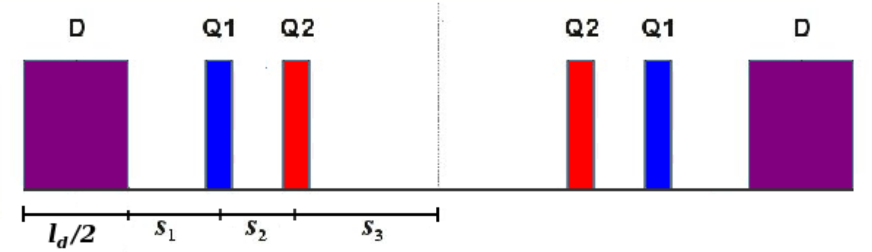
$$= \frac{l_d s_2\left(12s_1 + l_d\left(D_r + 3\right)\right)}{12 l_d\left(s_1 + s_2\right) + l_d^2\left(D_r + 3\right) - 24D_s\rho}$$

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

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

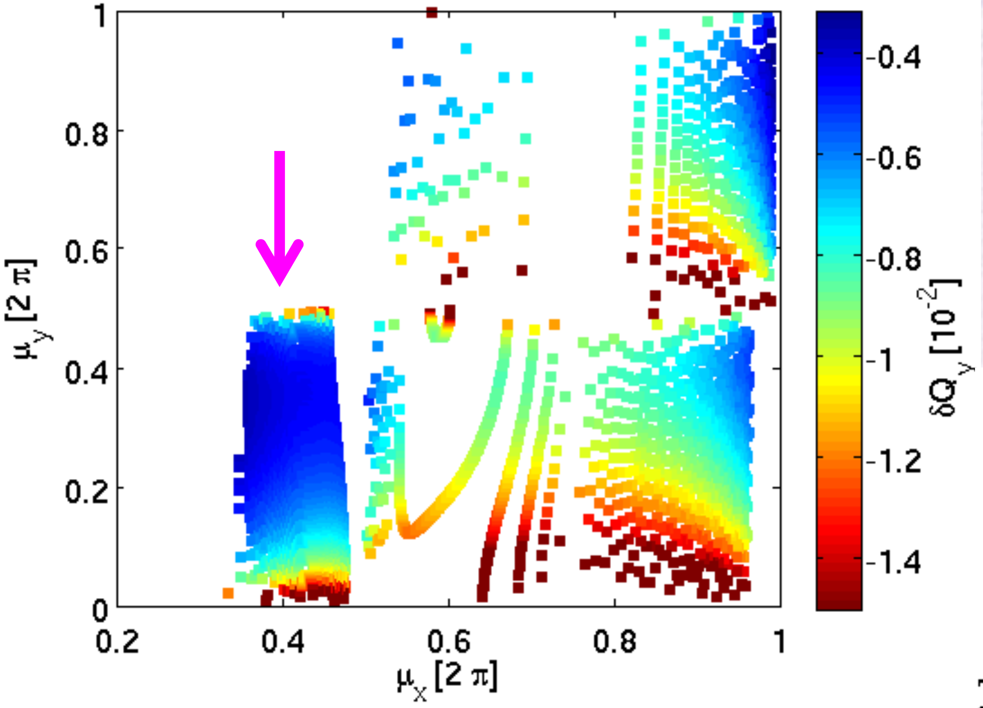
$$D_r = \frac{D_{xc}}{D_{xc}^{\min}}, \beta_r = \frac{\beta_{xc}}{\beta_{xc}^{\min}}, \varepsilon_r = \frac{\varepsilon_{xc}}{\varepsilon_{xc}^{\min}}$$

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

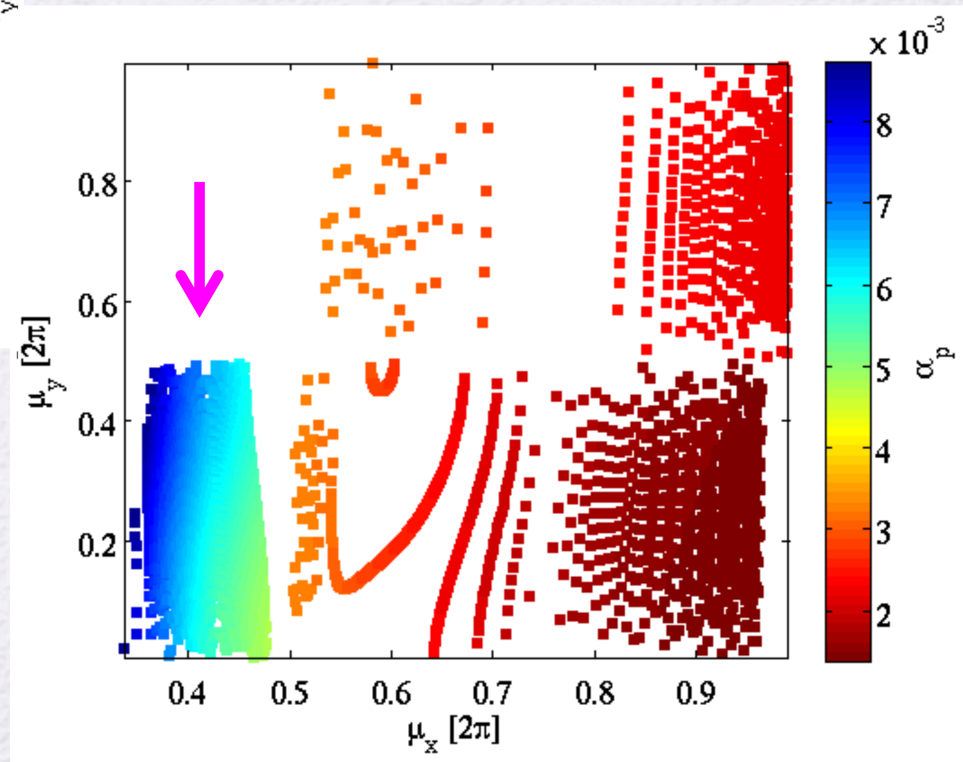


- ❑ **Analytical representation** of **TME** quadrupole **focal lengths** (thin lens)
  - ❑ Depending on horizontal optics conditions at dipole center (horizontal emittance) and drift lengths
  - ❑ Multi-parametric space for applying optics stability criteria, magnet constraints, non-linear optimization,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

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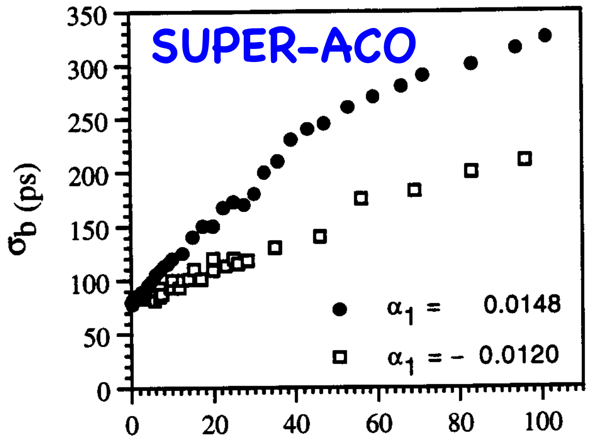
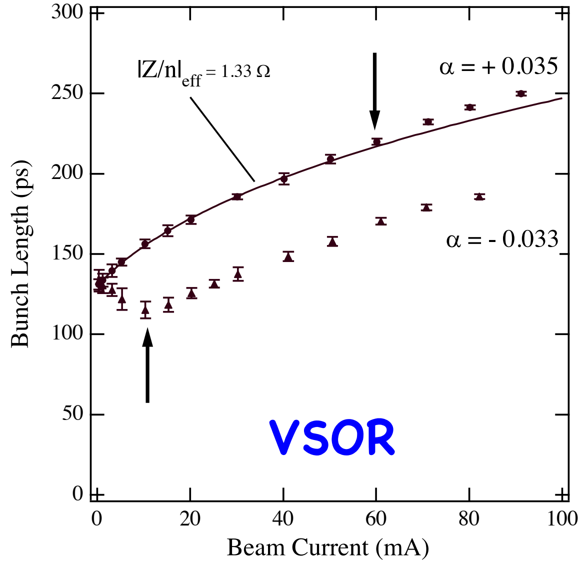
Negative-α operation

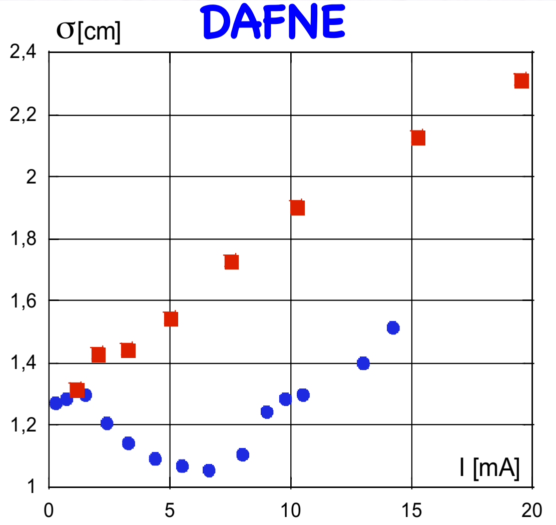
- ❑ (Low) **Negative-α** in low emittance rings for reaching **shorter bunches** (short X-ray pulses for light sources or luminosity in e+/e- colliders)
- ❑ Interesting regime to study and possibly mitigate **instabilities**
    - ❑ **Head-tail** damping and **TMCI** threshold increase with natural (negative) chromaticity (zero sextupole current)

A. Nadji et al., EPAC96

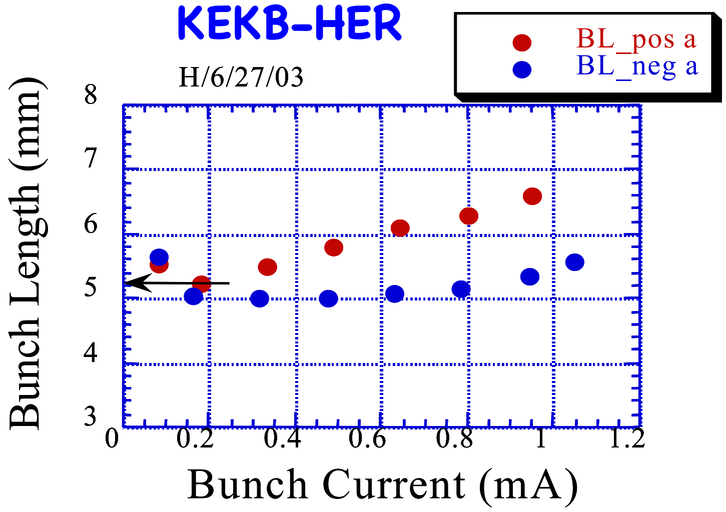




M. Hosaka et al., APAC98



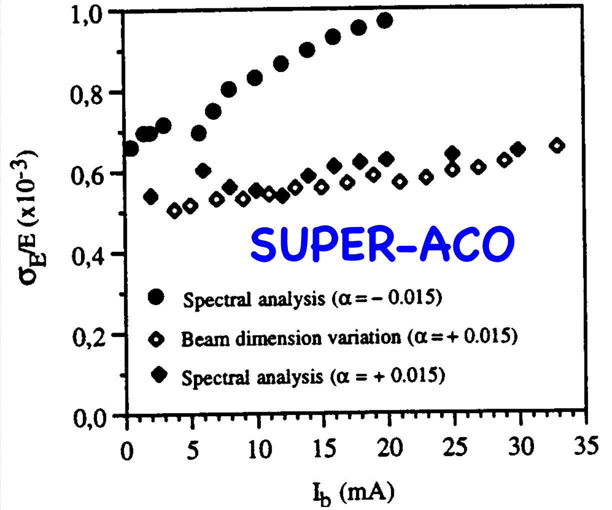
M. Zobov, et al. EPAC06

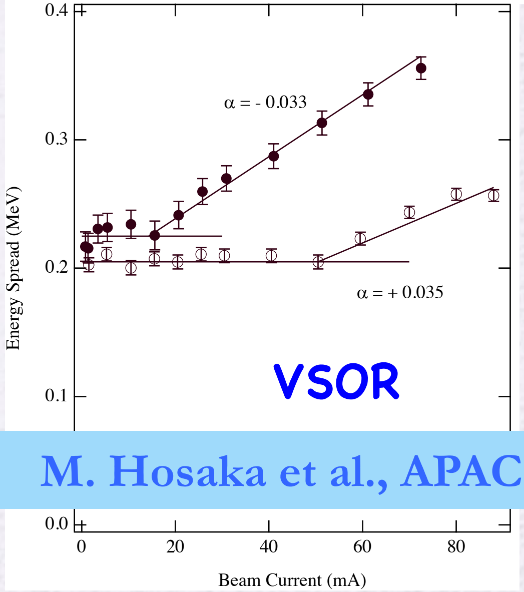


H. Ikeda, et al. Arxiv 2004

Negative-α operation

A. Nadji et al., EPAC96

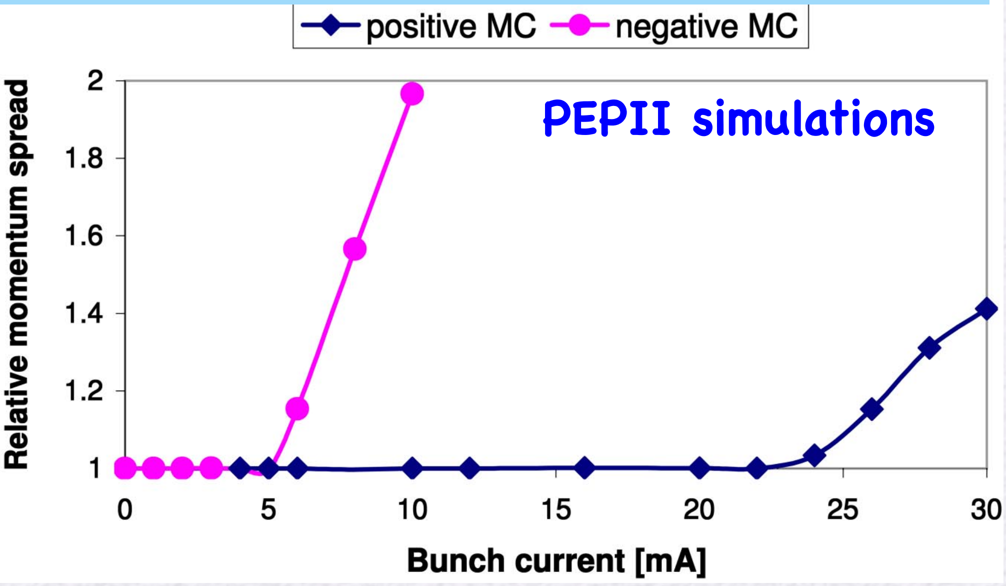




M. Hosaka et al., APAC98

- **Drawbacks**:
  - ☐ Difficult **optics conditions** to achieve in operating rings (in particular for low-α values)
  - ☐ Energy spread dependence w.r.t. current shows stronger increase for negative-α due to **microwave instability**

S. Heifets and A. Novokhatski, PRAB 2006



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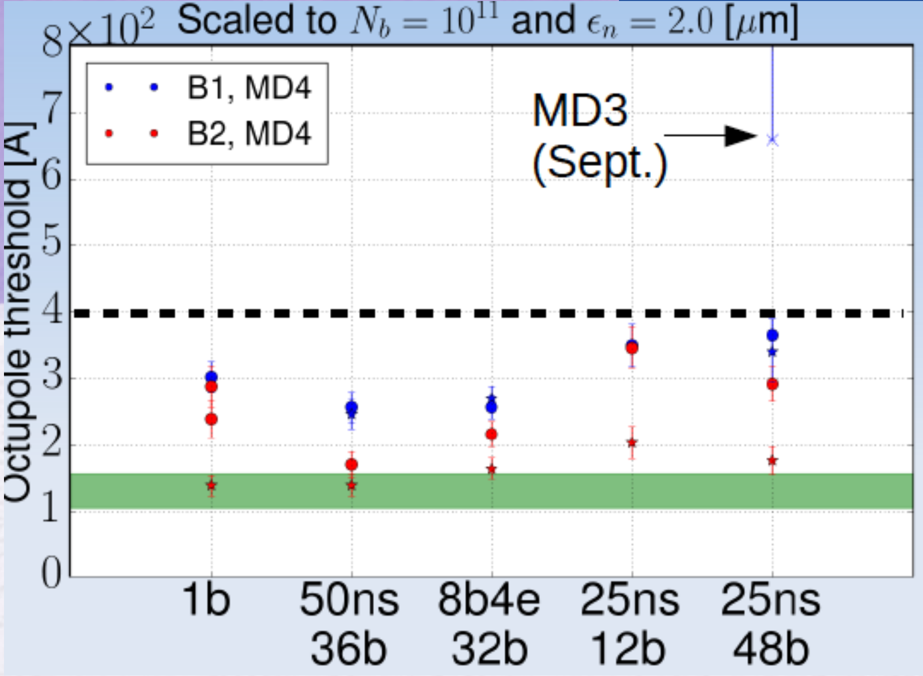
Instabilities in the LHC

- Instabilities mitigated with **high octupoles, chromaticity** and **ADT gain** (need well-corrected coupling)
- **Octupole** settings based on measurements
  - **Within reach** for **BCMS**
  - **Out of reach** for **BCS** (higher brightness)
  - Similar **needs** for **HL-LHC** beams

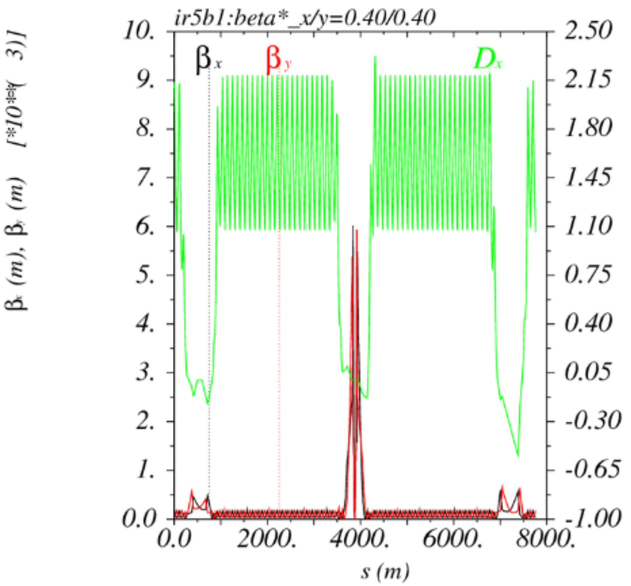


X. Buffat et al. Evian 2017

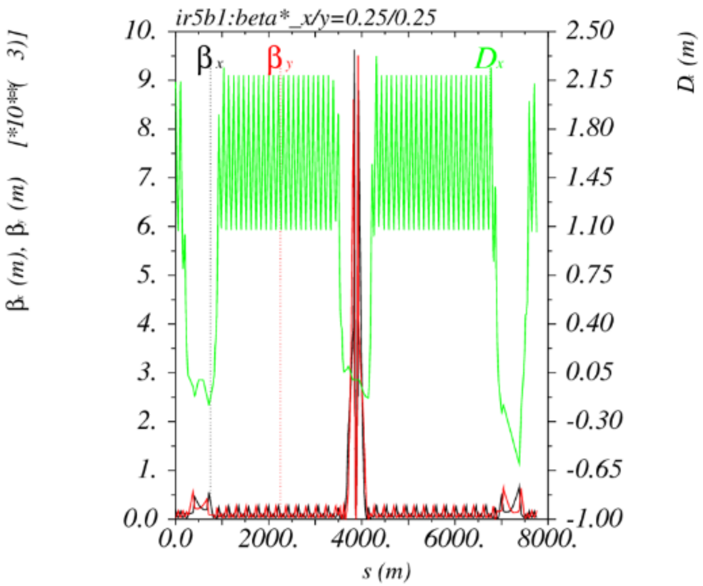
	Intensity [1e11 p/b]	Emittance [um]	pattern	Octupole current [A] 2017/ 2018a 6.5σ	2018b 6.0σ
25 ns standard (like 2017)	1.15	2.5 (2.4)	1-4 x 72 → 288	317	381
25 ns standard (high intensity)	1.30	2.8 (2.7)	1-4 x 72 → 288	325	390
25 ns BCMS (like 2017)	1.15	1.7 (1.4)	1-3 x 48 → 144	484	581
25 ns BCMS (high intensity)	1.30	1.9 (1.6)	1-3 x 48 → 144	495	594
25ns BCS (like 2017)	1.25	1.15 (1.0)	1-4 x 32 → 128	666	800
25ns BCS (high intensity)	1.30	1.20 (1.0)	1-4 x 32 → 128	693	832

From ATS to ATS

S. Fartoukh



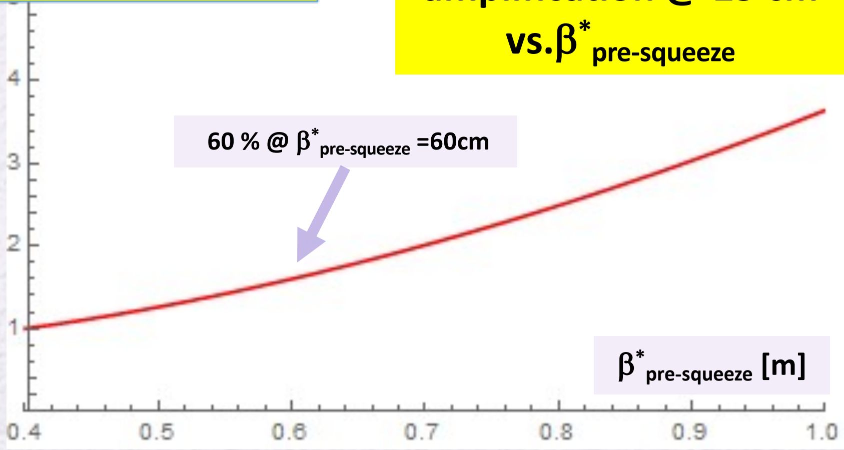
40 cm: *Tele-index = 1.0*



25 cm: *Tele-index = 1.6*
→ β_{max} ~ 10 km !

- ☐ **Telescope** of **ATS optics** employed to **enhance** β **at octupoles' location** and thereby achieve **more Landau damping** for maximum current (**HL-LHC** operational scenario)s

MO tune spread amplification @ 25 cm vs.$\beta^*_{\text{pre-squeeze}}$



60 % @ $\beta^*_{\text{pre-squeeze}}$ =60cm

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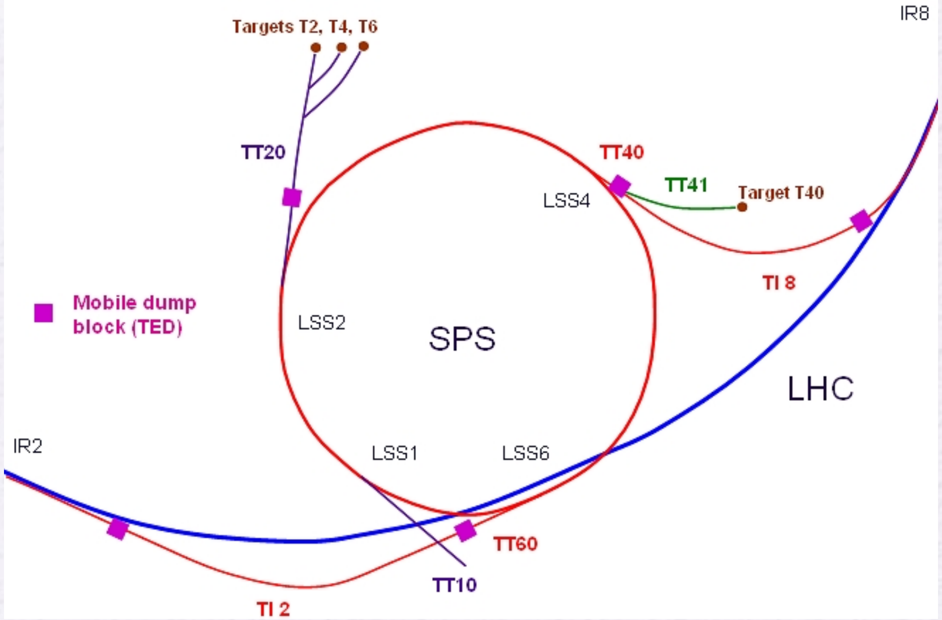
Injectors for high brightness – CERN SPS



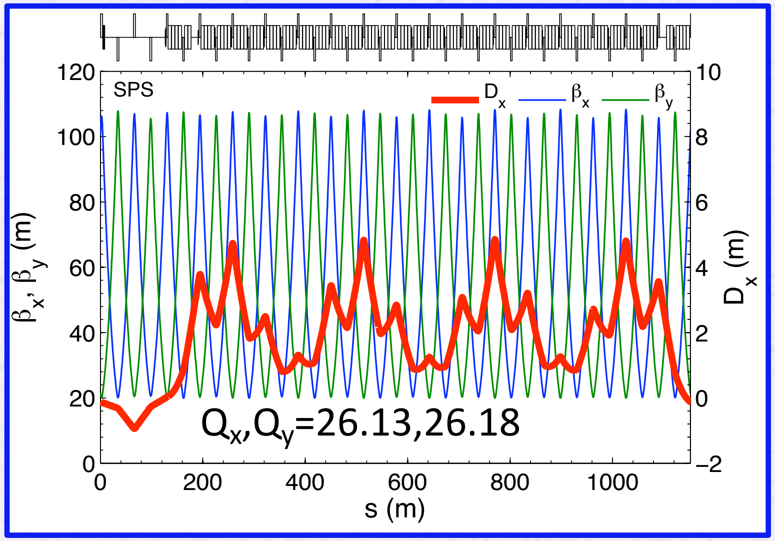
- LHC injectors upgrade (LIU project) for High Luminosity LHC (HL-LHC)
  - Significantly higher intensity and brightness is required from injectors, including the SPS

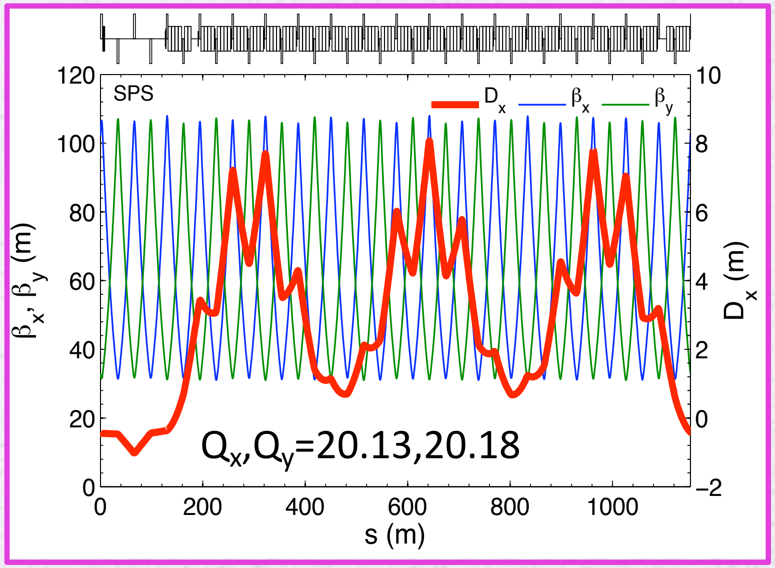
M. Medahi et al. IPAC 2019

- Intensity limitations of SPS
  - 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

WG chaired by E. Shaposhnikova

Increasing slip factor (lowering γ_t)

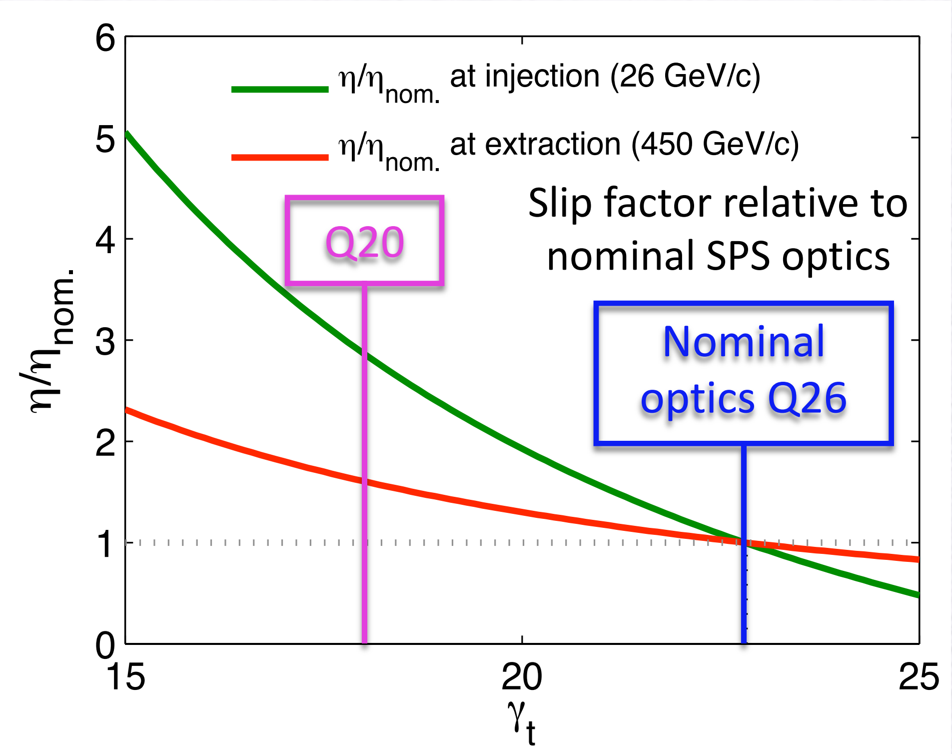




$$\eta = \frac{1}{\gamma_t^2} - \frac{1}{\gamma^2}$$

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

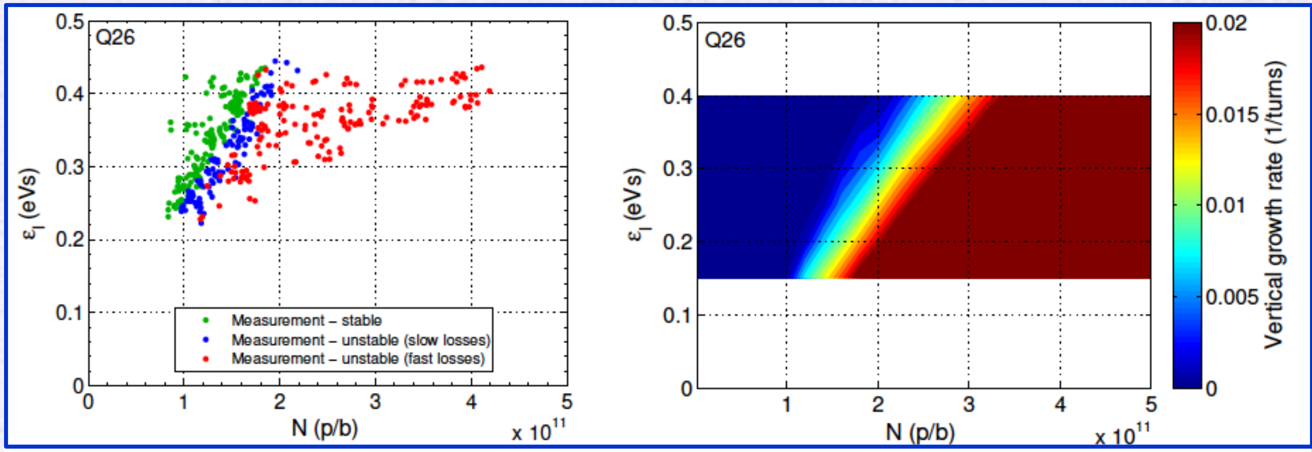
Slippage factor increased by a factor of **2.8** at **injection** and **1.6** at **flat top**

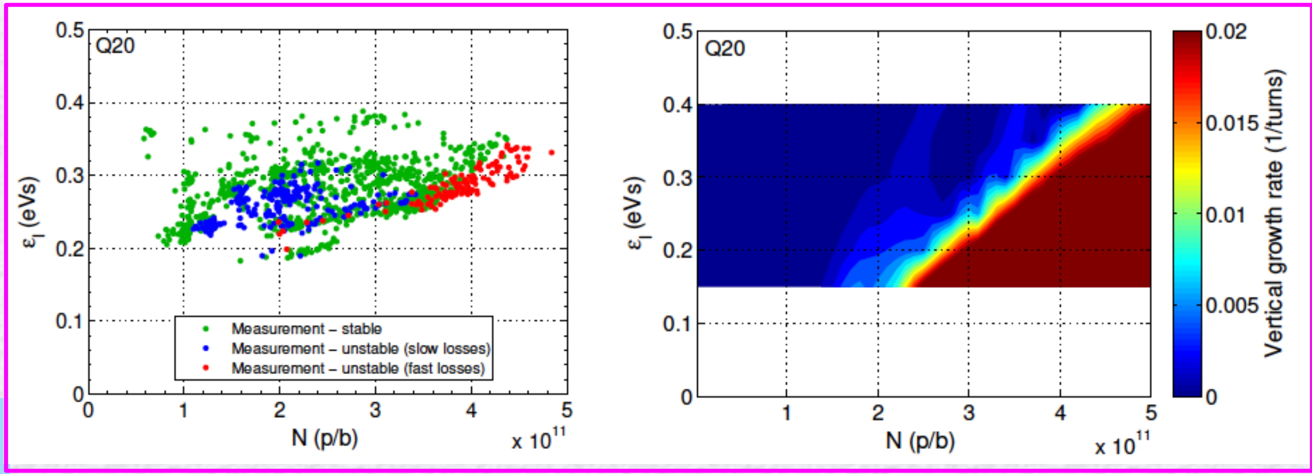


TMCI threshold

- ☐ In **nominal optics**, measured/simulated threshold at **1.6x10^{11}p/b** for low chromaticity
  - High-chromaticity increases threshold, but for high losses

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

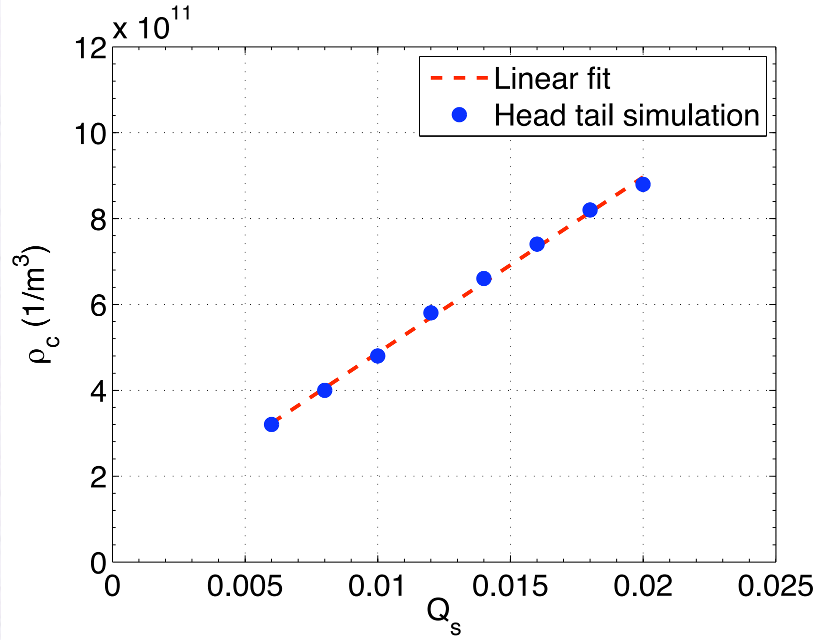


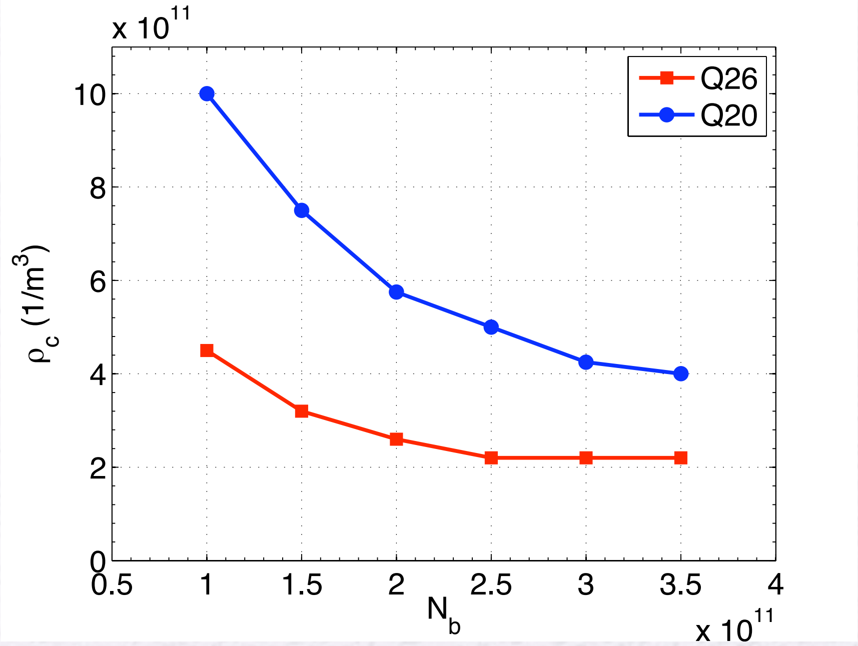


- ☐ Measured/simulated threshold in **Q20** > **4x10^{11}p/b!!!**

H. Bartosik et al, IPAC 2014

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**

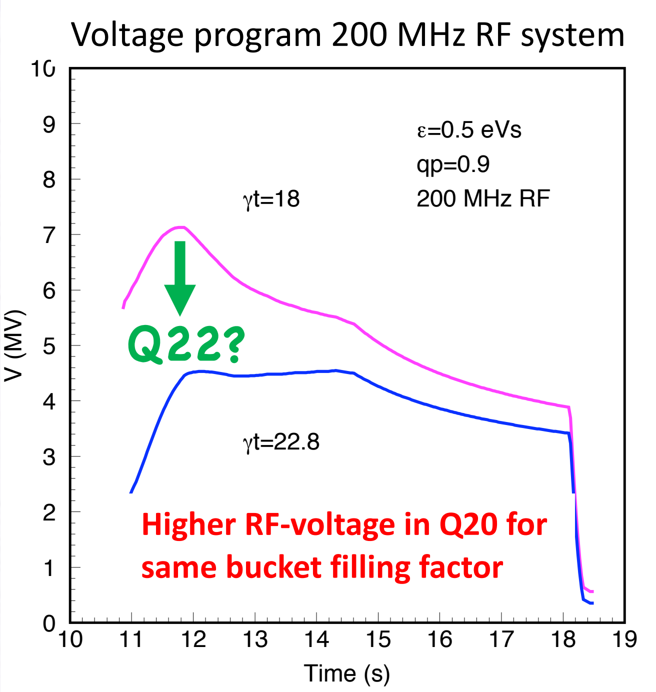
$$\boxed{N_{\mathrm{th}} \propto Q_s \propto \sqrt{\eta}}$$

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

H. Bartosik et al, IPAC2011

Longitudinal impedance threshold

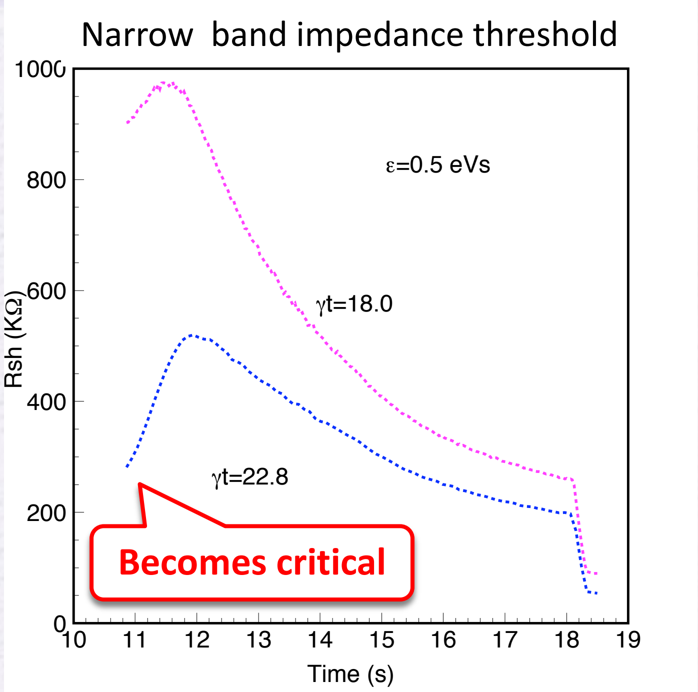
E. Shaposhnikova



Voltage program 200 MHz RF system

Q22?

Higher RF-voltage in Q20 for same bucket filling factor



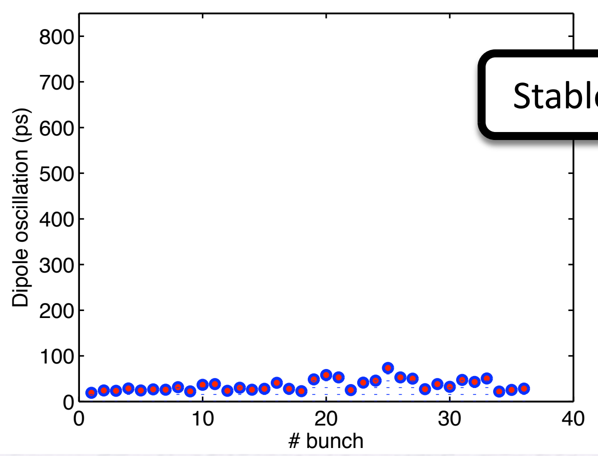
Narrow band impedance threshold

Becomes critical

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

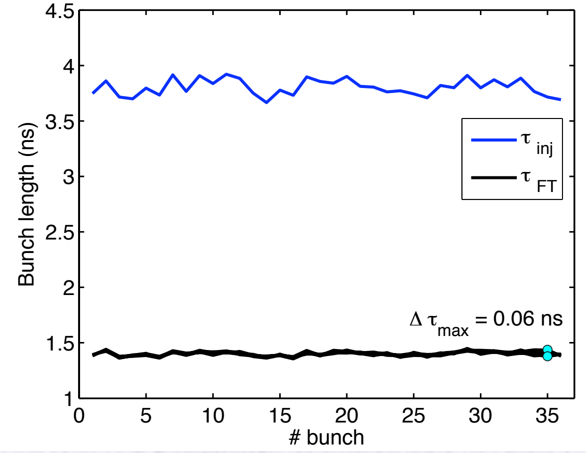
- Impedance threshold has minimum at flat top
  - Controlled longitudinal emittance blow-up during ramp for **Q26**
  - Less (or no) longitudinal emittance blow-up needed in **Q20**
- Instability limit at flat bottom
  - Crtitical with **Q26** when pushing intensity
  - Big margin with **Q20** (factor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

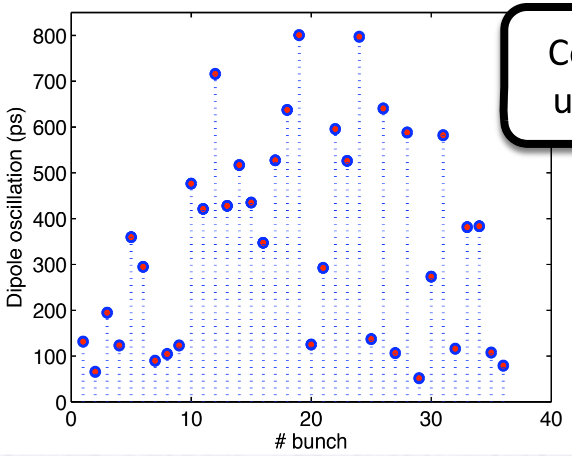
Stability without longitudinal blow-up



Stable beam

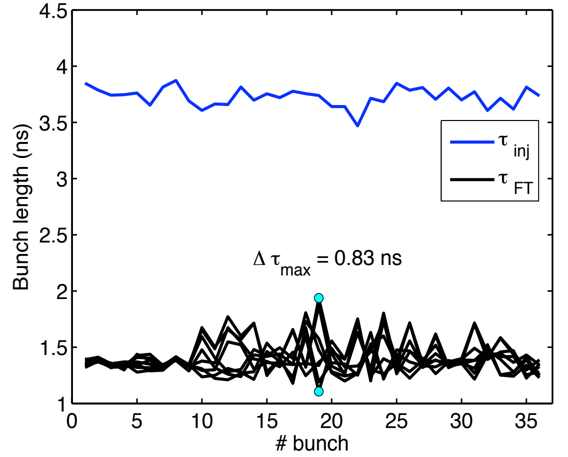
SPS-Q20 (1.6x10^{11} p/b) double harmonic RF





Contr. blow-up needed!

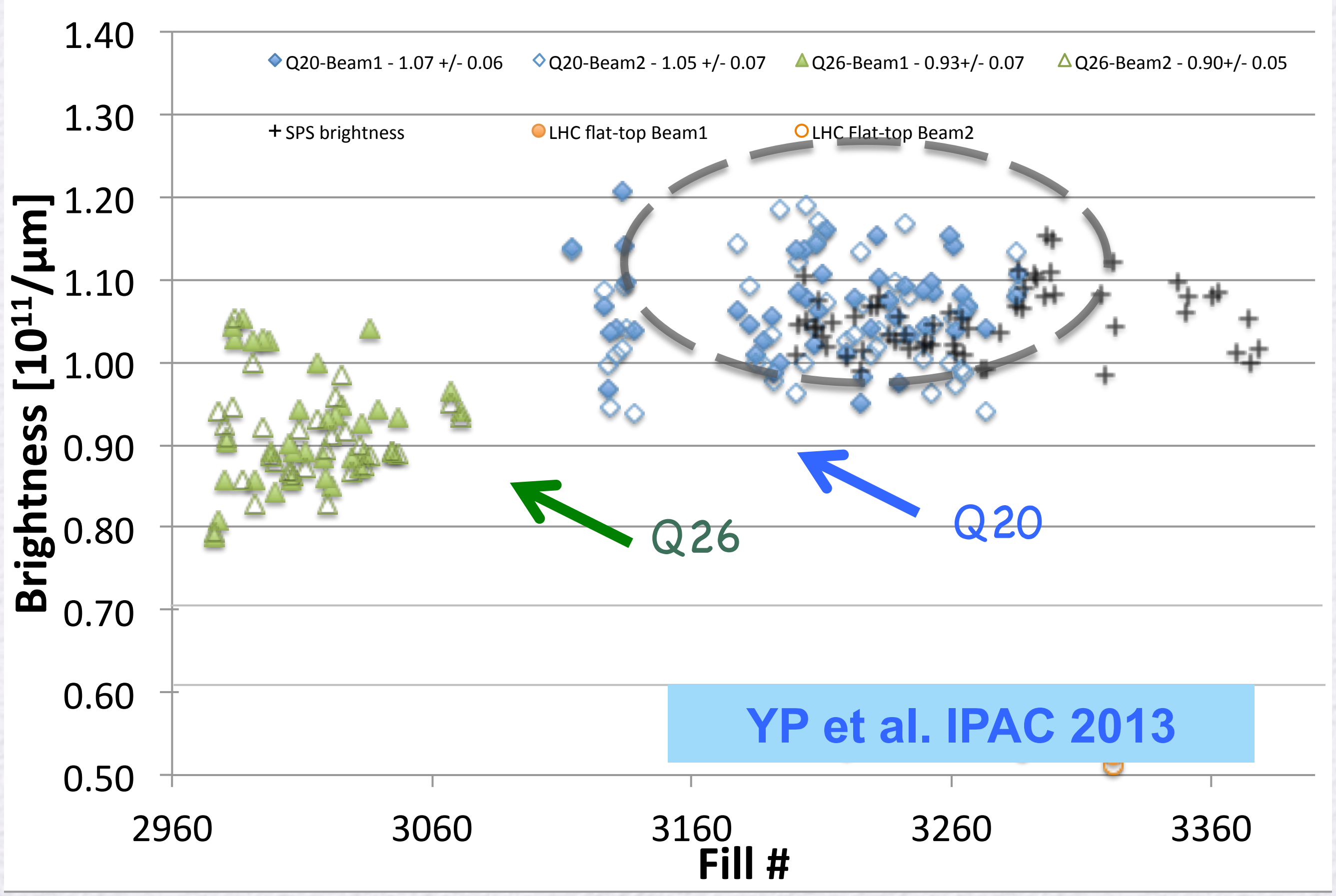
SPS-Q26 (1.6x10^{11} p/b) double harmonic RF



T. Argyropoulos, PhD thesis 2015

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

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 rings**
  - **Negative-α optics** for instability mitigation
  - **Enhance Landau damping** with optics manipulation
  - Break **intensity limitations** in operating LHC injectors, 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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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

T. Argyropoulos, PhD thesis, 2015

  - 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)