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

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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
Motivation for using optics to reduce collective effects

- Ring performance parameters

Optics quantities affecting collective beam behavior

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Concrete examples for rings in design or operation at CERN*

- High intensity and/or high-power rings
  - Negative momentum compaction factor - PS2 ring
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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
  \[ \alpha_p = \frac{1}{C} \int \frac{D_x(s)}{\rho(s)} ds \]

- 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,...)
  \[ N_{th} \propto \eta \]
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    - Negative momentum compaction factor – **PS2 ring**
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  - Raising instability thresholds – **LHC beams at SPS**
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

- 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

\[ f_1 = \frac{s_2(4s_1l_d + l_d^2 + 8D_{xc}\rho)}{4s_1l_d + 4s_2l_d + l_d^2 - 8D_s\rho + 8D_{xc}\rho} \]
\[ = \frac{l_d s_2 \left(12s_1 + l_d(D_r + 3)\right)}{12l_d(s_1 + s_2) + l_d^2(D_r + 3) - 24D_s\rho} \]

\[ f_2 = \frac{8s_2D_s\rho}{-4s_1l_d - l_d^2 + 8D_s\rho - 8D_{xc}\rho} \]
\[ = \frac{24s_2D_s\rho}{12l_ds_1 + l_d^2(D_r + 3) - 24D_s\rho} \]

\[ D_r = \frac{D_{xc}}{D_{xc}^{\text{min}}}, \beta_r = \frac{\beta_{xc}}{\beta_{xc}^{\text{min}}}, \epsilon_r = \frac{\epsilon_{xc}}{\epsilon_{xc}^{\text{min}}} \]
\[ D_s = g(s_1, s_2, s_2, l_d, \beta_r, D_r) \]

- 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
Motivation for using optics to reduce collective effects

Ring performance parameters

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Concrete examples for rings in design or operation

High intensity and/or high-power rings

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High-brightness hadron injectors

- Raising instability thresholds – LHC beams at SPS
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
  - 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?

WG chaired by E. Shaposhnikova
Instability thresholds and slippage factor

Transverse instabilities

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

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

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

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

Longitudinal instabilities

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

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

T. Argyropoulos et al, TUPWA039, TUPWA040
Increasing slip factor (lowering $\gamma_t$)

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

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

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

Slip factor relative to nominal SPS optics

Nominal optics Q26
TMCI threshold

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

\[ N_{th} \propto \frac{\varepsilon_l}{\beta_y} \eta \]

- SPS-BWS.519
- SPS-Q26: $\xi_y \approx 0$

\begin{align*}
S & \text{PS extracted intensity (p/b)} \\
L & \text{Losses (%) at injection} \\
I & \text{Intensity at 450 GeV/c (p/b)}
\end{align*}
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

- 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)
Stability without longitudinal blow-up

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

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

\[ \Delta \tau_{\text{max}} = 0.06 \text{ ns} \]

\[ \Delta \tau_{\text{max}} = 0.83 \text{ ns} \]

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
LHC brightness with SPS Q20

- 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)

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F. Antoniou et al., TUPME046

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- 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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