PETRA IV.
NEW DIMENSIONS

Touschek Lifetime and IBS effects in extremely low emittance rings

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IPAC, June 13th 2022

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

DESY.

Outline

- Motivation and landscape of ultra-low emittance rings
- Touschek lifetime
  - short review of theory
  - impact on ultra-low emittance ring and countermeasures
- Intrabeam scattering
  - short review of theory
  - impact on ultra-low emittance ring and countermeasures
- Conclusions and perspectives

Ultra-low emittance rings are needed for high brightness light source and high luminosity colliders

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Brilliance and coherent fraction are key performance parameter for **light sources**

$$\text{brilliance} = \frac{\text{flux}}{4\pi^2 \Sigma_x \Sigma_{x'} \Sigma_y \Sigma_{y'}} \qquad F = \frac{\lambda^2/(4\pi)^2}{\Sigma_x \Sigma_{x'} \Sigma_y \Sigma_{y'}}$$

$$\Sigma_{x,y} = \sqrt{\sigma^2_{x,y;e} + \sigma^2_{ph}}$$

$$\Sigma_{x',y';e} = \sqrt{\sigma^2_{x',y';e} + \sigma'^2_{ph}}$$

They are maximised for smaller electron beam emittances until the **diffraction limit** is reached

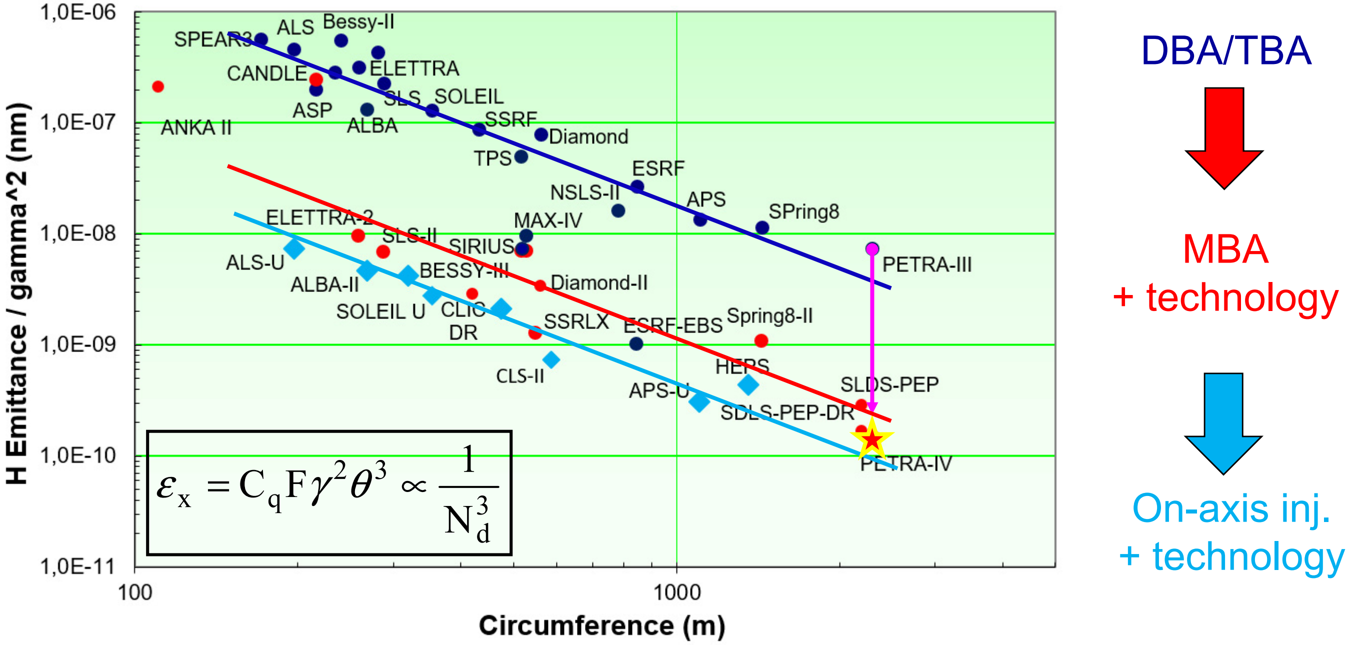
$$\varepsilon_{e^-} \le \varepsilon_{ph} = \frac{\lambda}{4\pi}$$

~10 pm for diffraction limit at ~1 Angstron (12.4 keV)
~100 pm for diffraction limit at ~ 1nm (1.24 keV)

Low emittance is required in colliders (or damping rings for linear colliders) to increase the luminosity

$$\text{luminosity} = \frac{n_b f_{rev} N_1 N_2}{4\pi \sigma_x \sigma_y} S = \frac{n_b f_{rev} N_1 N_2}{4\pi \varepsilon_x k \beta^*} S$$

Landscape of low emittance rings



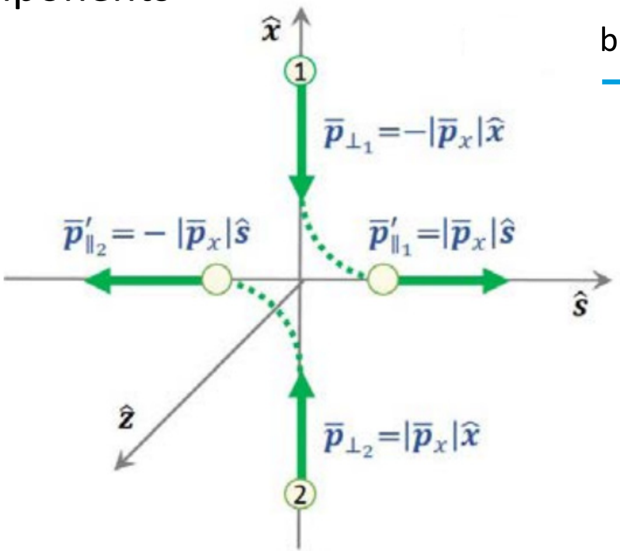
Multibend achromat technology underpins the development of diffraction limited light sources

HEPS <60 pm; APS-U 42 pm; PETRA IV 20 pm;

Ultra-low emittance rings provide high brightness and coherence up to high photon energies

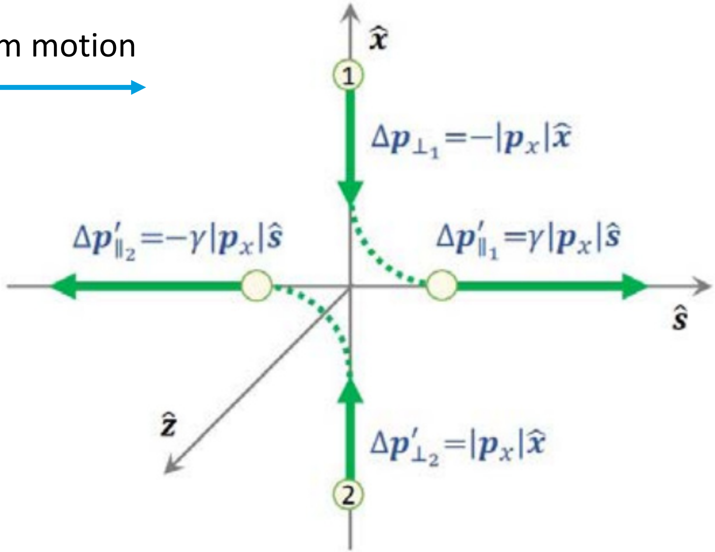
Touschek and intrabeam scattering originate from electron-electron scattering

Both Touschek effect and intrabeam scattering (IBS) originate from electron-electron scattering in a bunch as the electrons perform betatron oscillations. The scattering produces changes in the momenta of the electrons with possible large variation of the longitudinal components



centre of mass frame

beam motion



LAB frame

momentum change in lab frame

$\Delta p_{||} = \gamma p_x$

Figure courtesy M. Martini

Touschek and intrabeam scattering can limit the performance of low emittance rings

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There are two possibilities:

- particle longitudinal momentum outside the momentum aperture $\gamma\sigma_{x'} > \varepsilon_{acc}$

  the particles (generally both) are lost. This is the Touschek effect: one of the major particle loss mechanism in synchrotron light sources $\rightarrow$ Touschek lifetime

- particle longitudinal momentum inside the momentum aperture $\gamma\sigma_{x'} < \varepsilon_{acc}$

  intrabeam scattering excites particle oscillations: beam dimensions are increased in all three planes of motion and energy spread increases $\rightarrow$ IBS growth rates and equilibrium emittances

These effects are a source of concern for the operation of ultra low emittance rings where high charge bunches with reduced dimensions (high charge density) have to be stored.

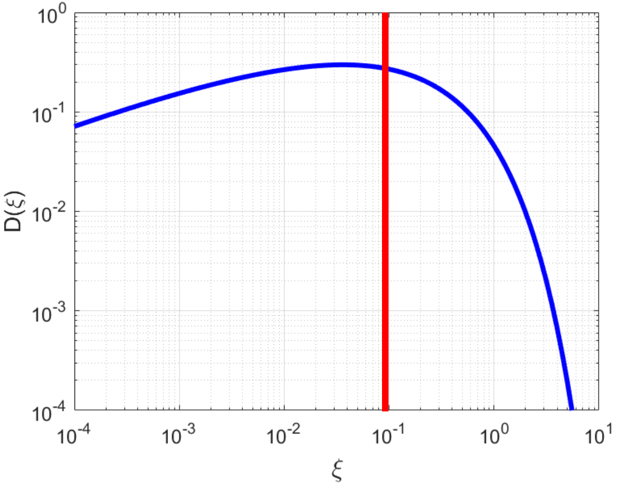
Touschek lifetime

Computing the cross section for events with change in momentum exceeding the momentum aperture, integrating over the particles distribution and averaging along the position in the ring we get the Touschek loss rate [Bruck (flat beam), Piwinski (coupled beam)]

$$\frac{1}{\tau} = \frac{N r_0^2 c}{8\pi\sigma_x\sigma_y\sigma_s} \frac{1}{\gamma^2 \varepsilon_{acc}^3} D(\xi)$$

$$D(\xi) = \sqrt{\xi}\left[-\frac{3}{2}e^{-\xi} + \frac{\xi}{2}\int_\xi^\infty \frac{\ln u}{u} e^{-u} du + \frac{1}{2}(3\xi - \xi\ln\xi + 2)\int_\xi^\infty \frac{e^{-u}}{u} du \right]$$

$$\xi = \left[\varepsilon_{acc} / \gamma\sigma'_x\right]^2 \approx \frac{\varepsilon_{acc}^2}{\gamma^2}\frac{\beta_x}{\varepsilon_x}$$



3rd generation light sources operate in the region where D(ξ) is flat (ε_{acc} = 3%; beta 10 m; 3 GeV; ε_x = 3 nm) **ξ ~ 0.09**

Touschek lifetime is increased by

- increasing momentum aperture
- bunch lengthening cavities
- operation with large coupling
- (high energy rings are favoured)
- (lower charge)

Touschek lifetime and ultra-low emittance

Computing the cross section for events with change in momentum exceeding the momentum aperture, integrating over the particles distribution and averaging along the position in the ring we get the Touschek loss rate [Bruck (flat beam), Piwinski (coupled beam)]

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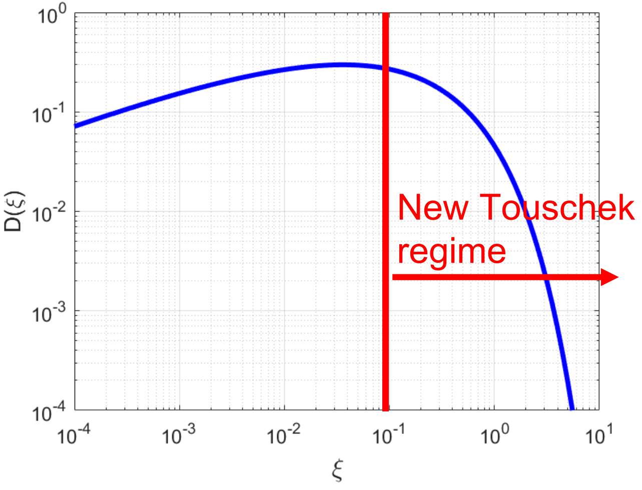
$$\xi = \left[\varepsilon_{acc}/\gamma\sigma_x'\right]^2 \approx \frac{\varepsilon_{acc}^2}{\gamma^2}\frac{\beta_x}{\varepsilon_x}$$



3rd generation light sources operate in the region where $D(\xi)$ is flat (ε_{acc} = 3%; beta 10 m; 3 GeV; ε_x = 3 nm) **~ ξ ~ 0.09**

New upgrades will probe the new Touschek regime

MAX-IV – like (ε_{acc} = 4%; beta 5 m; 3 GeV; ε_x = 0.3 nm) **ξ ~ 0.77**

PETRA IV – like (ε_{acc} = 3%; beta 5 m; 6 GeV; ε_x = 20 pm) **ξ ~ 1.6**

lower emittance → small transverse momentum σ_x' → $\gamma\sigma_x' < \varepsilon_{acc}$

A new Touschek lifetime regime for ultra low emittance rings: Touschek lifetime increase with decreasing emittance

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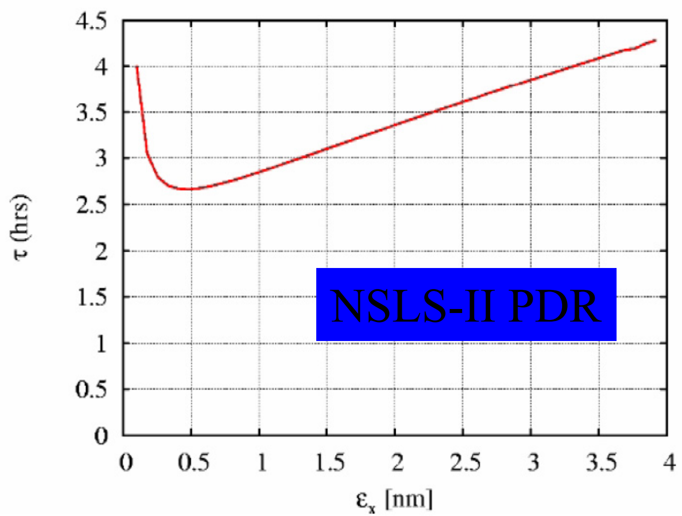
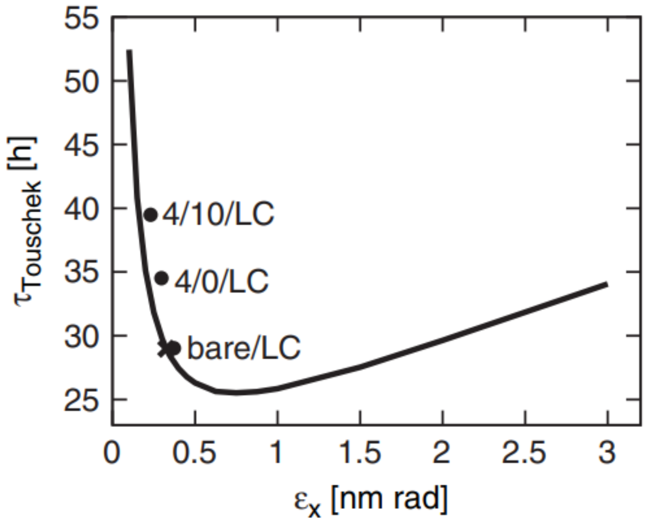
The new Touschek lifetime regime with low emittance was already highlighted in the NSLS-II and MAX IV designs



B. Podobedov, in LER14 (and PAC07)



S. C. Leemann et al., PRST-AB 12, 120701 (2009)

NSLS-II emittance (2 nm bare - 0.9 nm) still not in the new Touschek regime mode.

MAX IV emittance (330 pm bare - 200 pm) at the threshold of the new Touschek lifetime regime

The SLAC-SSRLX proposed design

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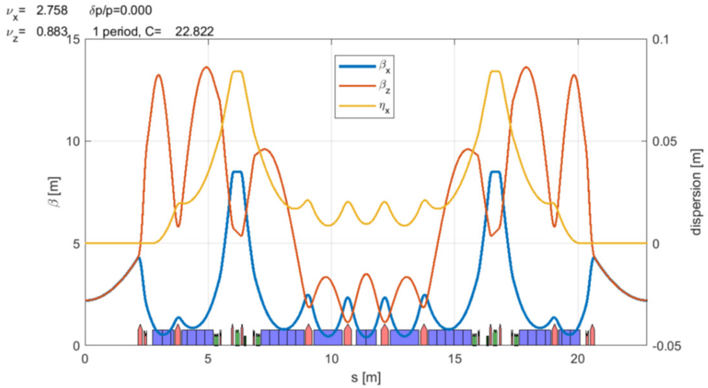
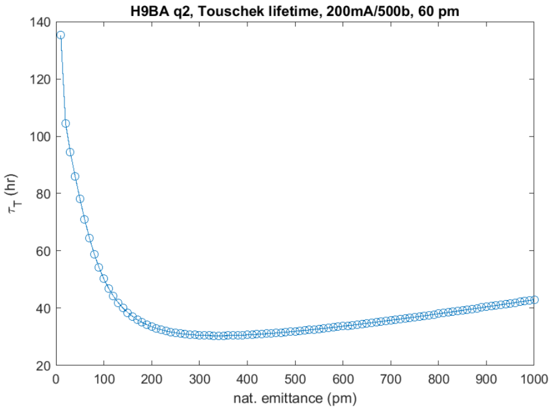
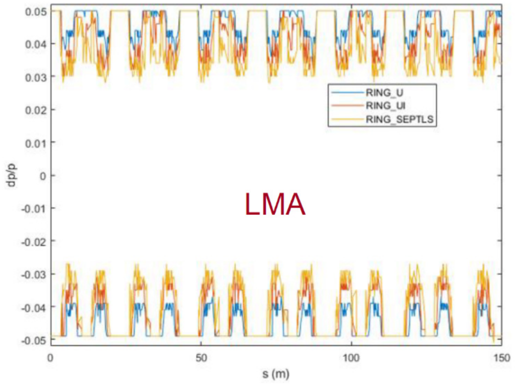
New H9BA lattice, 3.5 GeV (P. Raimondi): 60 pm emittance and damping wigglers to reduced the emittance to 30 pm







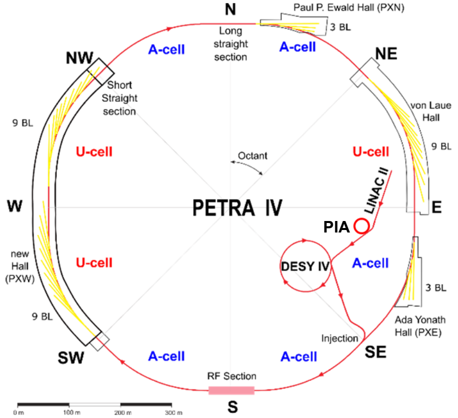
24 arcs, 24 straight sections (SS), 570 m
1 SS for injection
1 SS dedicated to the RF
5 SS for wigglers – 6 m long
17 SS for IDs (beamlines) – 4.3 m long

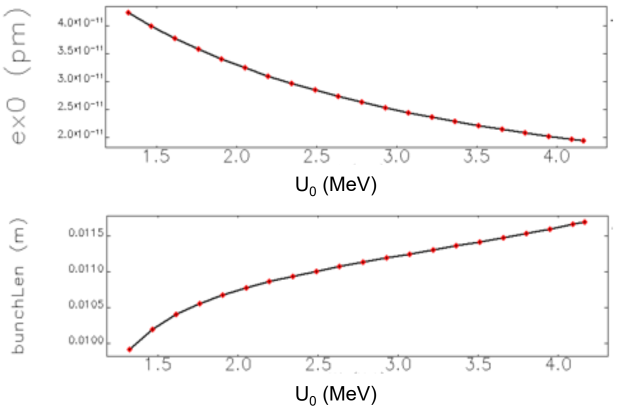
60 pm lattice 200 mA in 500 bunches can operate with Touschek lifetime in excess of ~50 h lifetime
LMA reduction with injection SS and wiggler SS gives 20 h (@200 mA)
Larger than present operational lifetime in SSRL at 7 nm

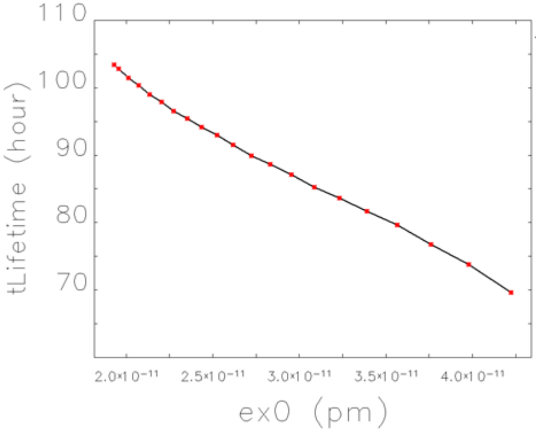
P. Raimondi „Design challenges for 4th generation light sources“ slides in Extreme Storage Ring Workshop (I-FAST) https://indico.cern.ch/event/1096767/

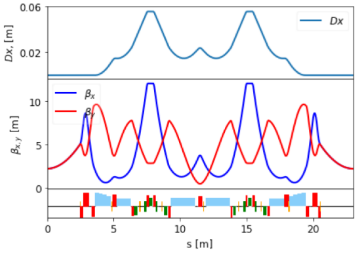
The PETRA IV upgrade – the ring with the lowest ε_x/γ^2

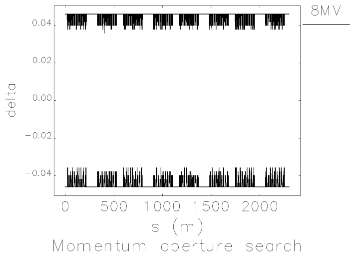
H6BA lattice, 6 GeV, 20 pm emittance with damping wigglers (43 pm no damping wiggler)











200 mA in 1600 bunches - 20 pm lattice

local momentum aperture ~4% (no errors) TLT ~100h

Reducing the emittance from 43pm to 20pm with damping wiggler by increasing U_0 from 1.2 MeV/turn to 4.2 MeV/Turn

Increase in lifetime of ~52%

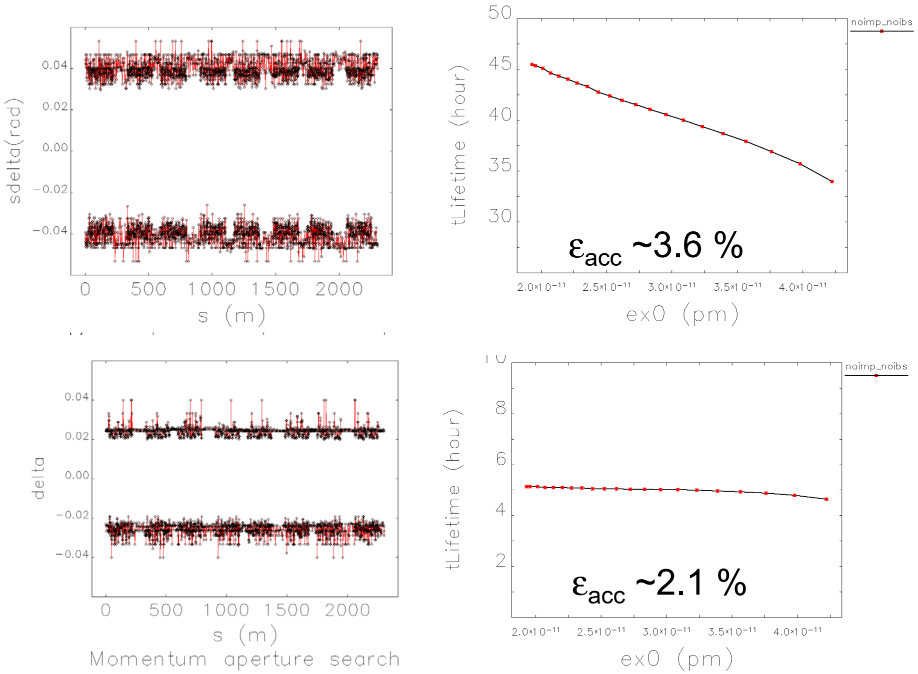
(small contribution from bunch lengthening)

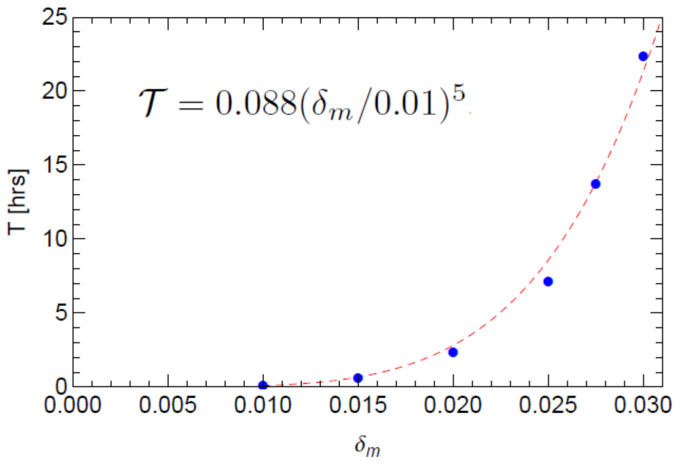
However significant reduction of MA with errors reduce lifetime

Touschek lifetime sensitivity to momentum aperture

Lifetime increase with emittance is very sensitive to the momentum aperture

With errors seeds providing a residual ~5% beta beating or poor MA the Touschek lifetime is quickly reduced





Lifetime calculations as a function of momentum aperture predict a dependence more rapid than ε_{acc}^3
Example from PEP-X (Cai, PRSTAB 2012)

SDLS in the PEP tunnel: optimised momentum aperture

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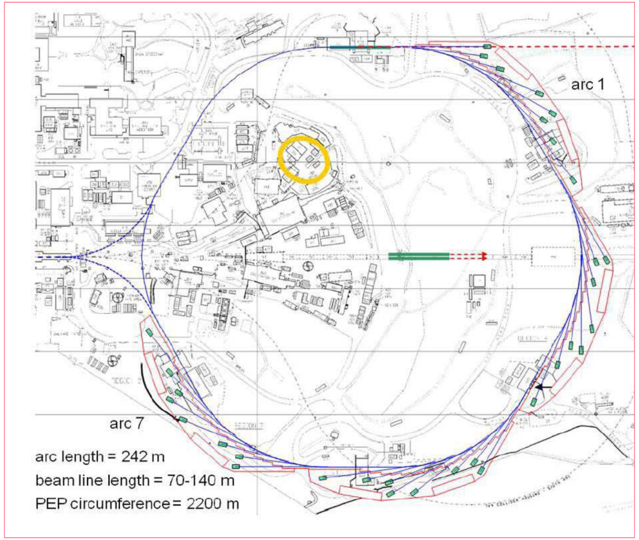
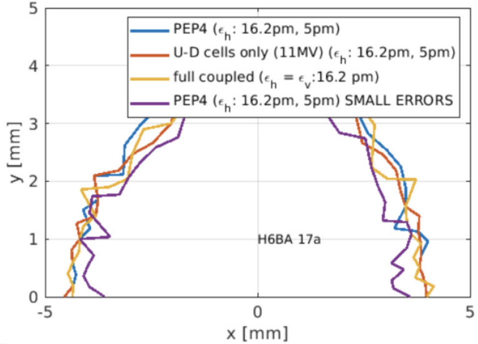
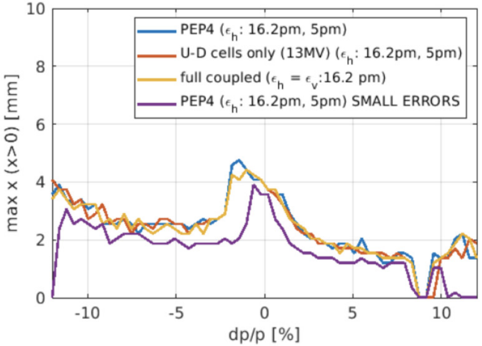
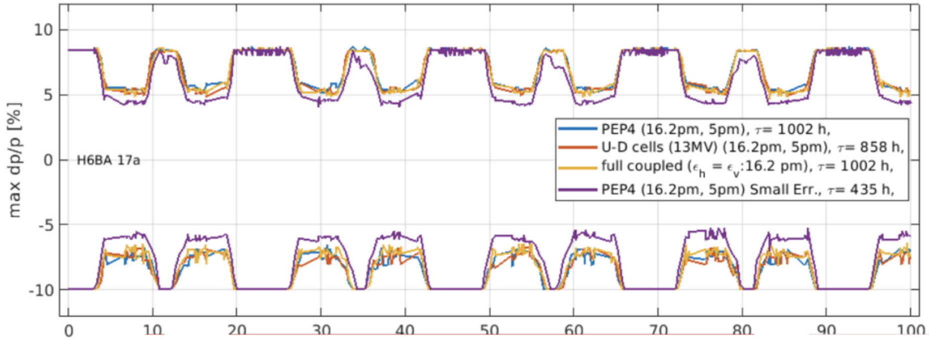
H6BA lattice in the PEP tunnel ε_x = 16pm @ 5 GeV (P. Raimondi) with damping wigglers









The momentum aperture is of the order of ±8%
The Touschek lifetime is of the order of 500hrs.
The drop in performances due to errors is very moderate, given the very moderate detunings

Courtesy P. Raimondi, S. Liuzzo

A new Touschek lifetime regime for ultra low emittance rings: Touschek lifetime increase with decreasing emittance

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The new Touschek regime gives the possibility of operating ring with ultra low emittance and large Touschek lifetime well within the usual operating requirements (e.g. 10 h Touschek lifetime $\rightarrow$ beam lifetime is limited by gas scattering).

However the dependence with the emittance and momentum aperture is sharp with a quick roll off. Impact on Touschek lifetime can be severe and pose operation difficulties.
It is essential:

- achieve and control the nominal emittance (errors, effect of IDs, collective effects, IBS)
- achieve and control the nominal MA (linear/nonlinear lattice tuning in presence of errors)

both conspire to push the operational parameters outside the large Touschek lifetime.
Additional countermeasures are

- Use of bunch lengthening cavities
- Increase coupling – operation with round beams

Landau Cavities for Touschek lifetime

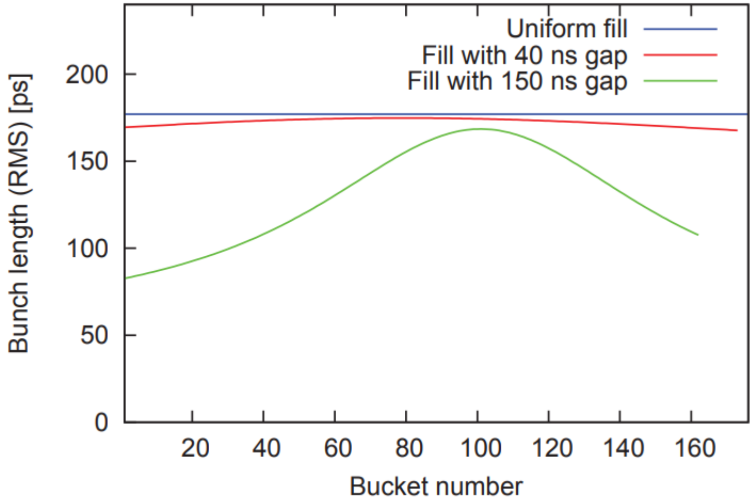
Harmonic cavities are used to lengthen the bunch and have been used in many light sources (SLS, ELETTRA, BESSY, ALS, MAX IV, …). They are integral part of the ultra low emittance upgrades

Decreases the charge density →
bunch lengthening factors ~5 at MAX IV

- Touschek lifetime increase by the same factor
- introduce synchrotron tune spread in the bunch (Landau Damping)

- no major problems except operation difficulties
  - transient beam loading and fill pattern dependence
  - current dependence in passive RF system

Effective way not only of increasing the Touschek lifetime but counteracting all collective instabilities



Transient beam loading evaluated at MAX IV with a 5 HC. Without HC the bunch length is 34 ps

Touschek lifetime for ESRF-EBS (6 GeV, ε_x = 135 pm, ξ ~ 0.4)

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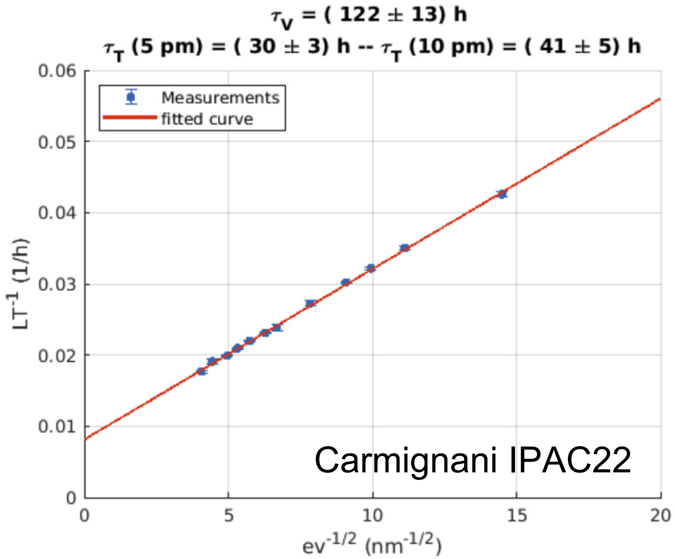
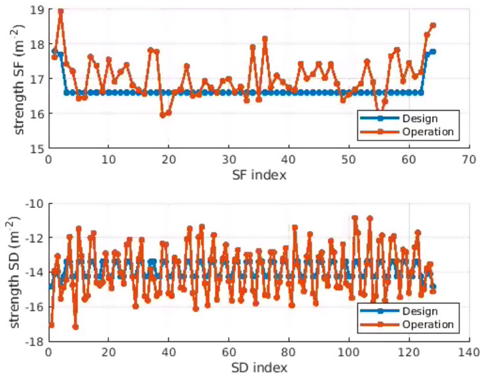
Lifetime measured at 200 mA, (4 mA in single bunch) $\rightarrow$ 30 h at 5 pm; vacuum lifetime 120 h

simulations with expected alignment error ~22 h at 5 pm

Touschek lifetime exceeded design values with errors (Liuzzo, IPAC15):



single sextupoles and octupoles scans with constant vertical emittance very effective to improve machine



The resulting sextupole setting is not periodic: variation of about 10% of the design value

Excellent lifetime due to alignment better than assumed and online optimization procedures of nonlinear dynamics

4th harmonic cavity foreseen to improve lifetime in timing modes (40 mA in 4 bunches)

Intrabeam scattering: review of theory

Particle surviving the electron-electron scattering acquire large longitudinal momentum.

The increases in longitudinal momentum is transferred through the dispersion function to the transverse planes. All bunch dimension and energy spread increase. In low emittance rings IBS increases the steady state beam dimension. It limits the emittance at the design current.

Piwinksi (1974), Bjorken-Mtingwa (1983), Kubo and Oide (2001) computed the rate of change of the invariants and beam properties. Math involved is complicated.

Bane (2002) provided simplified formulae in the high energy approximation and proved the equivalence of Piwinski and Bjorken-Mtingwa results

Piwinski and Bjorken-Mtingwa IBS growth rates

Piwinksi (1974) classical Rutherford scattering – weak focussing (extended in the CIMP)

Bjorken-Mtingwa (1983) quantum relativistic cross section: expressions look rather different!

$$\frac{1}{T_p} \equiv \frac{1}{\sigma_p}\frac{d\sigma_p}{dt}$$

$$\frac{1}{T_h} \equiv \frac{1}{\varepsilon_h^{1/2}}\frac{d\varepsilon_h^{1/2}}{dt}$$

$$\frac{1}{T_v} \equiv \frac{1}{\varepsilon_v^{1/2}}\frac{d\varepsilon_v^{1/2}}{dt}$$

$$\frac{1}{T_\delta} \approx 2\pi^{3/2}(\log)A\left\langle \frac{\sigma_H^2}{\sigma_\delta^2}\left(\frac{1}{a}g\left(\tfrac{b}{a}\right)+\frac{1}{b}g\left(\tfrac{a}{b}\right)\right)\right\rangle$$

$$\frac{1}{T_x} \approx 2\pi^{3/2}(\log)A\left\langle \frac{\mathcal{H}_x\sigma_H^2}{\varepsilon_x}\left(\frac{1}{a}g\left(\tfrac{b}{a}\right)+\frac{1}{b}g\left(\tfrac{a}{b}\right)\right)-a\,g\left(\tfrac{b}{a}\right)\right\rangle$$

$$\frac{1}{T_y} \approx 2\pi^{3/2}(\log)A\left\langle \frac{\mathcal{H}_y\sigma_H^2}{\varepsilon_y}\left(\frac{1}{a}g\left(\tfrac{b}{a}\right)+\frac{1}{b}g\left(\tfrac{a}{b}\right)\right)-b\,g\left(\tfrac{a}{b}\right)\right\rangle$$

$$\mathcal{H}_x = \gamma_x\eta_x^2 + 2\alpha_x\eta_x\eta_{px} + \beta_x\eta_{px}^2$$

$$\frac{1}{\sigma_H^2} = \frac{1}{\sigma_\delta^2} + \frac{\mathcal{H}_x}{\varepsilon_x} + \frac{\mathcal{H}_y}{\varepsilon_y}$$

$$a = \frac{\sigma_H}{\gamma}\sqrt{\frac{\beta_x}{\varepsilon_x}} \qquad b = \frac{\sigma_H}{\gamma}\sqrt{\frac{\beta_y}{\varepsilon_y}}$$

$$g(\omega) = \sqrt{\frac{\pi}{\omega}}\left[P^0_{-1/2}\left(\frac{\omega^2+1}{2\omega}\right) \pm \frac{3}{2}P^{-1}_{-1/2}\left(\frac{\omega^2+1}{2\omega}\right)\right]$$

$$(\log) \approx \ln\left(\frac{\gamma^2\sigma_y\varepsilon_x}{r_e\beta_x}\right)$$

CIMP

$$\frac{1}{T_i} = 4\pi A(\log)\left\langle \int_0^\infty d\lambda \frac{\lambda^{1/2}}{[\det(L+\lambda I)]^{1/2}} \times \left\{ \mathrm{Tr}L^i\,\mathrm{Tr}\left(\frac{1}{L+\lambda I}\right) - 3\,\mathrm{Tr}\left[L^i\left(\frac{1}{L+\lambda I}\right)\right]\right\}\right\rangle$$

$$L = L^{(p)} + L^{(h)} + L^{(v)} \qquad L^{(p)} = \frac{\gamma^2}{\sigma_p^2}\begin{pmatrix}0&0&0\\0&1&0\\0&0&0\end{pmatrix}$$

$$L^{(h)} = \frac{\beta_h}{\varepsilon_h}\begin{pmatrix}1&-\gamma\phi_h&0\\-\gamma\phi_h&\frac{\gamma^2\mathcal{H}_h}{\beta_h}&0\\0&0&0\end{pmatrix} \quad L^{(v)} = \frac{\beta_v}{\varepsilon_v}\begin{pmatrix}0&0&0\\0&\frac{\gamma^2\mathcal{H}_v}{\beta_v}&-\gamma\phi_v\\0&-\gamma\phi_v&1\end{pmatrix}$$

$$\mathcal{H}_h = [\eta_h^2 + (\beta_h\eta'_h - \tfrac{1}{2}\beta'_h\eta_h)^2]/\beta_h$$
$$\phi_h = \eta'_h - \tfrac{1}{2}\beta'_h\eta_h/\beta_h$$

BM

$$A = \frac{r_0^2 cN}{64\pi^2\beta^3\gamma^4\varepsilon_h\varepsilon_v\sigma_s\sigma_p}$$

(log) is the Coulomb log factor
log (b_{max}/b_{min})
typically ~8-16

Growth rates are obtained from integrals of local growth rates along the ring

Bane IBS growth rates

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Bane (2002) has proven that the Piwinski and BM IBS growth rates can be cast in the same way in the limit of high energy beams

Longitudinal IBS growth rate: $$\frac{1}{T_p} \approx \frac{r_e^2 c N_b (\log)}{16\gamma^3 \epsilon_x^{3/4} \epsilon_y^{3/4} \sigma_z \sigma_p^3} \left\langle \sigma_H \, g(a/b) \; (\beta_x \beta_y)^{-1/4} \right\rangle$$

Transverse IBS growth rate: $$\frac{1}{T_x} = \frac{\sigma_p^2}{\epsilon_x} \langle \mathcal{H}_x \delta(1/T_p) \rangle$$

$$\frac{1}{\sigma_H^2} = \frac{1}{\sigma_p^2} + \frac{\mathcal{H}_x}{\epsilon_x} + \frac{\mathcal{H}_y}{\epsilon_y} \qquad a = \frac{\sigma_H}{\gamma}\sqrt{\frac{\beta_x}{\epsilon_x}} \qquad b = \frac{\sigma_H}{\gamma}\sqrt{\frac{\beta_y}{\epsilon_y}} \qquad g(\alpha) = \alpha^{(0.021 - 0.044 \ln \alpha)}$$

In all cases the growth rates depend on the local optics functions and have to be averaged around the ring

Equilibrium emittance with IBS

The evolution of the emittance has an additional contribution due to IBS

The equations must be solved in a self consistent way as $T_{x,y,p} = T_{x,y,p}(\varepsilon_x, \varepsilon_y, \sigma_p)$

$$\frac{d\varepsilon_x}{dt} \equiv -\frac{2}{\tau_x}(\varepsilon_x - \varepsilon_{x0}) + \frac{2\varepsilon_x}{T_x} = 0$$

$$\frac{d\varepsilon_y}{dt} \equiv -\frac{2}{\tau_y}(\varepsilon_y - \varepsilon_{x0}) + \frac{2\varepsilon_y}{T_y} = 0$$

$$\frac{d(\sigma_p^2)}{dt} \equiv -\frac{2}{\tau_p}(\sigma_p^2 - \sigma_{p0}^2) + \frac{2\sigma_p^2}{T_p} = 0$$

Equilibrium solutions found for d/dt = 0

$$\varepsilon_x = \frac{\varepsilon_{x,0}}{1-\tau_x/T_x(\varepsilon_x,\varepsilon_y,\sigma_p)}$$

$$\varepsilon_y = \frac{\varepsilon_{y,0}}{1-\tau_y/T_y(\varepsilon_x,\varepsilon_y,\sigma_p)}$$

$$\sigma_p^2 = \frac{\sigma_{p,0}^2}{1-\tau_p/T_p(\varepsilon_x,\varepsilon_y,\sigma_p)}$$

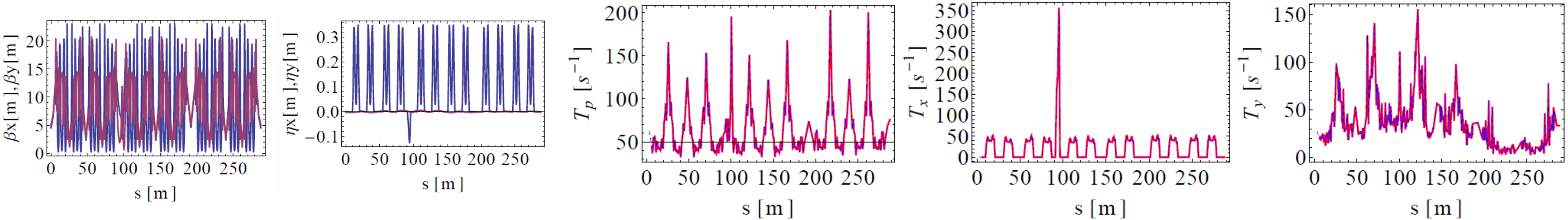
The IBS equilibrium emittance depends on

- charge density
- beam energy
- lattice optics and beam parameters (emittance, energy spread, bunch length)
- ratio τ_x/T_x the relative magnitude of IBS growth rates and radiation damping rates

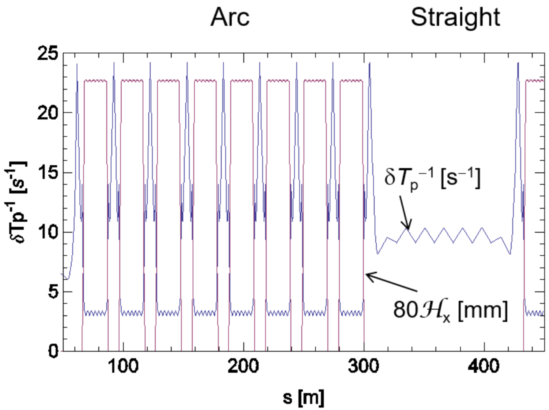
Linear optics for IBS

Computation of local scattering rates highlights regions where IBS is prevalent

IBS growth rate for the SLS lattice computed with MAD-X (Streun, Antoniu)



IBS growth rates and H_x for PEP-X lattice over one arc and one straight (Bane)

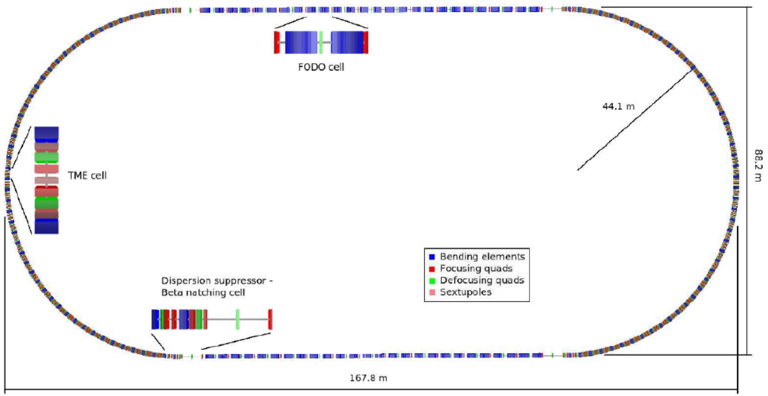


Minimisation of the IBS growth rates:

- avoid regions with local high charge density e.g. small β_x, β_y
- growth rates generally large when <Hx> large but the interplay with optic functions can be complex

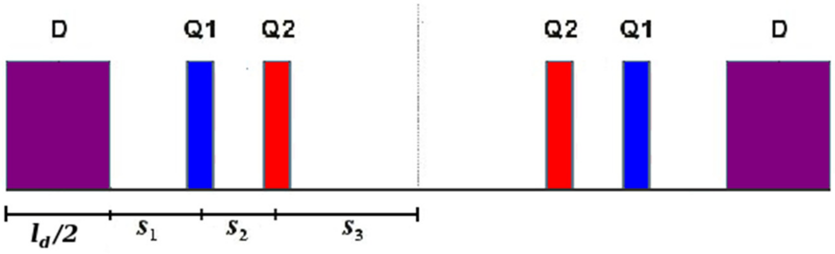
Linear optics (and energy choice) for IBS minimisation

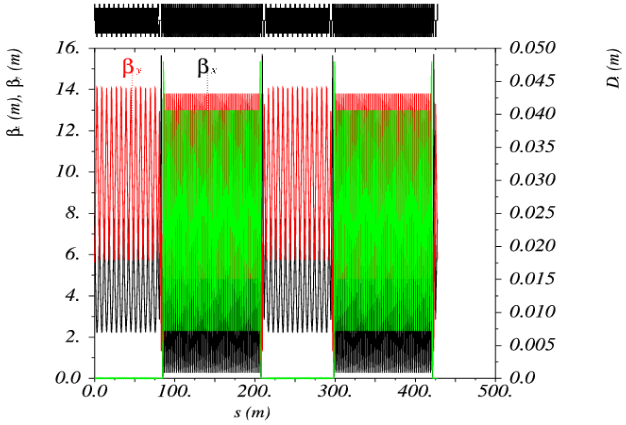
Efforts to control the IBS growth rates by tailoring the linear optics (and the energy choice) have been made in the context of ultra-low emittance ring for damping ring [Papahilippou, Antoniou, IPAC13]



CLIC damping ring layout – 90 pm @ 2.8 GeV

- Racetrack configuration – 420 m
- 2 arc sections filled with TME cells
- 2 long straight sections filled with FODO cells accommodating the damping wigglers

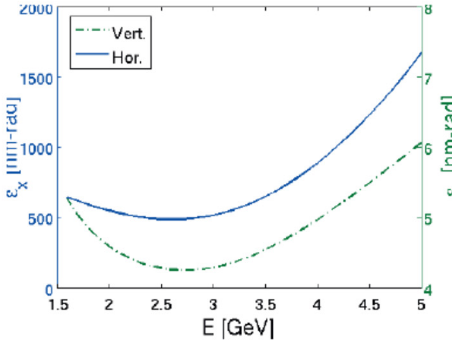


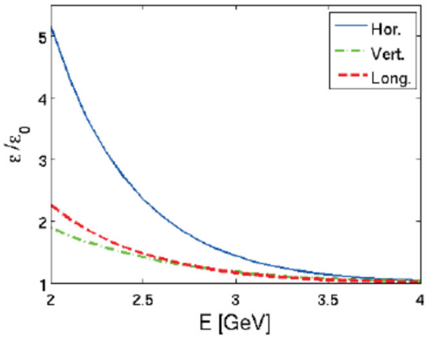


Linear optics (and energy choice) for IBS minimisation

PETRA IV. NEW DIMENSIONS

Systematic studies on the TME cells used for CLIC damping rings using Bane's formula



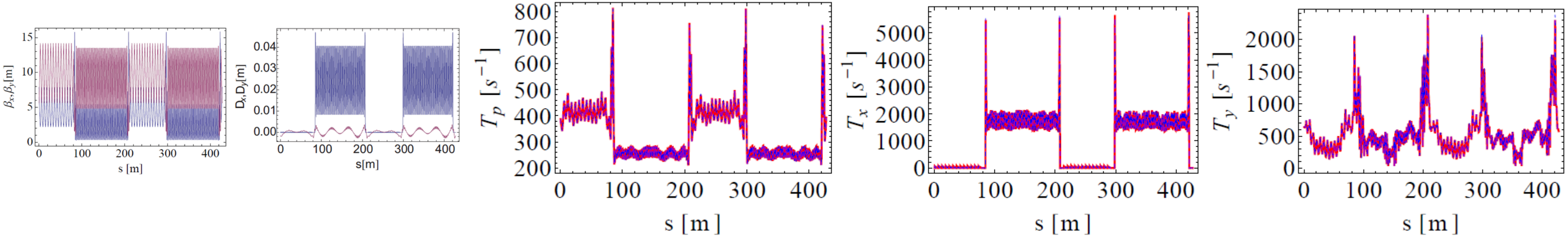


Minimum as a function of the energy
- natural emittance scales as γ^2

IBS blow up reduced at higher energy
- growth rates scale as $\sim 1/\gamma^4$

A best trade off minimum emittance is found

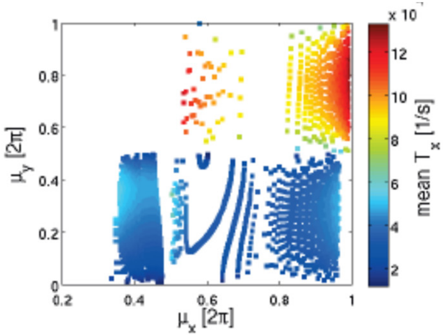
IBS growth rates can be studied as a function of the position along the CLIC Damping ring

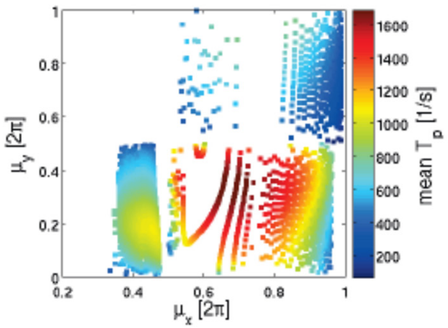


Linear optics for IBS: the CLIC damping ring example

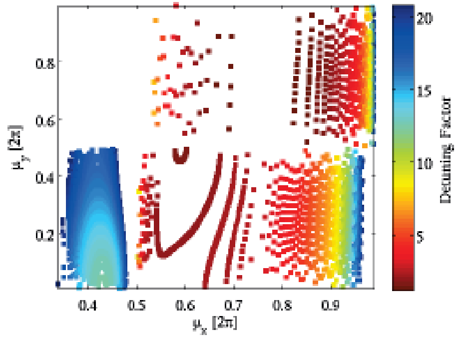
PETRA IV NEW DIMENSIONS

IBS growth rate as a function of the TME cell phase advance

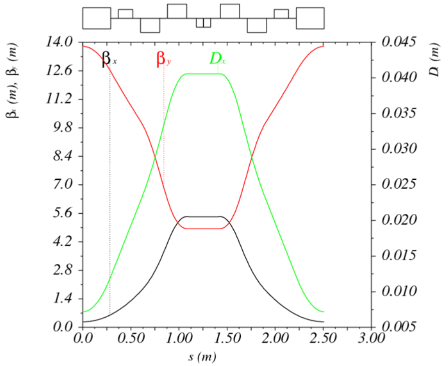


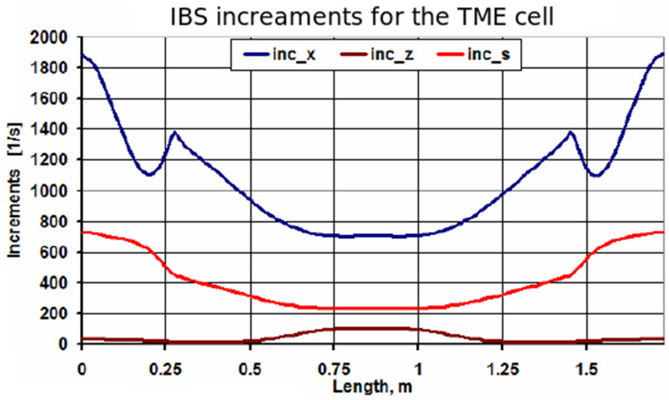


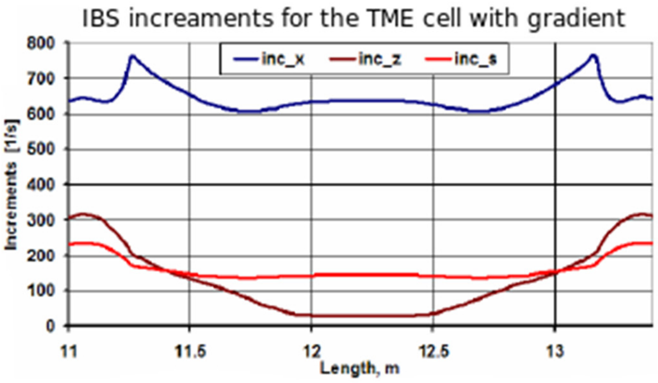
Minimisation of IBS requires a significant deviation from the TME condition (by a factor 15)



Introduction of gradient dipole allowed a reduction of factor ~3 of IBS damping rates for the same emittance







Using Damping Wigglers to reduce the emittance and the impact of IBS

Damping wigglers in **dispersion free straight sections** can be used to reduce the emittance

$$U_0 = \frac{e^2\gamma^4}{6\pi\varepsilon_0} I_2 \qquad U_{0,DW} = \frac{e^2\gamma^4}{6\pi\varepsilon_0}(I_2 + \Delta I_2)$$

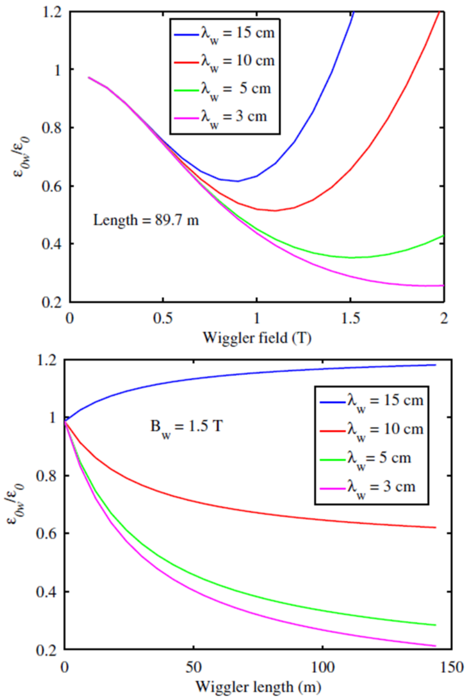
$$\tau_{x,0} = \frac{3}{r_0}\frac{T_0}{\gamma^3}\frac{1}{I_2 - I_4} \qquad \tau_{x,0} = \frac{3}{r_0}\frac{T_0}{\gamma^3}\frac{1}{I_2 + \Delta I_2 - (I_4 + \Delta I_4)}$$

$$\varepsilon_{x,0} = C_q\gamma^2\frac{I_5}{I_2 + I_4} \qquad \varepsilon_{x,DW} = C_q\gamma^2\frac{I_5 + \Delta I_5}{I_2 + \Delta I_2 + (I_4 - \Delta I_4)}$$

$$\sigma^2_{\varepsilon,0} = C_q\gamma^2\frac{I_3}{2I_2 + I_4} \qquad \sigma^2_{\varepsilon,DW} = C_q\gamma^2\frac{I_3 + \Delta I_3}{2(I_2 + \Delta I_2) + (I_4 - \Delta I_4)}$$

Most effective when the field in the main dipoles is smaller than the wiggler peak field (as in most MBA)

$$\frac{\epsilon_{0w}}{\epsilon_0} = \left(\frac{I_{x0}}{I_{xw}}\right)\frac{1 + \frac{4C_q}{15\pi I_{x0}} N_p \gamma^2 \frac{\langle\beta_{xw}\rangle\rho_o}{\epsilon_{x0}\rho_w^2}\theta_w^3}{1 + \frac{1}{2}N_p\frac{\rho_o}{\rho_w}\theta_w}$$



PEP-X parameters (Cai 2012)

Emittance reduction with damping wigglers

For wiggler field not too large (negligible self-dispersions), damping wigglers

reduce the emittance

increase the radiation damping rate

limited energy spread increase

$$U_{0,DW} = \frac{e^2\gamma^4}{6\pi\varepsilon_0}(I_2 + \Delta I_2)$$

$U_0 \sim I_2$

$$\tau_{x,DW} = \frac{3}{r_0}\frac{T_0}{\gamma^3}\frac{1}{I_2 + \Delta I_2 - (I_4 + \Delta I_4)}$$

$\tau_x \sim 1/I_2 \sim 1/U_0$

$$\varepsilon_{x,DW} = C_q\gamma^2 \frac{I_5 + \Delta I_5}{I_2 + \Delta I_2 + (I_4 - \Delta I_4)}$$

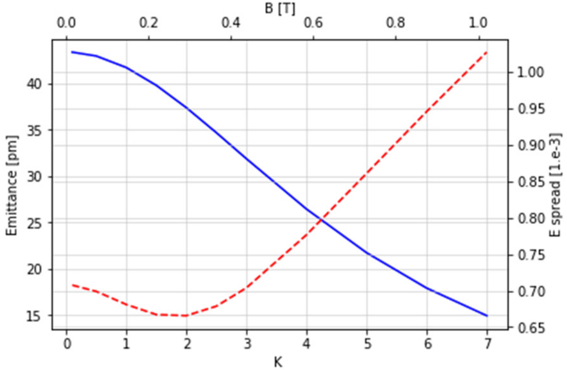
$\varepsilon_x \sim 1/I_2 \sim 1/U_0$

negligible self-dispersion

$$\sigma^2_{\varepsilon,DW} = C_q\gamma^2 \frac{I_3 + \Delta I_3}{2(I_2 + \Delta I_2) + (I_4 - \Delta I_4)}$$

σ_ε^2 increases with U_0

e.g. approx. $\sigma_\varepsilon^2 \sim U_0^a$



PETRA IV H6BA lattice (no Damping Wigglers)

ε_x = 43.5 pm*rad

σ_p = 0.71e-3

U_0 = 1.25 MeV/Turn

PETRA IV H6BA lattice with Damping Wigglers

ε_x = 19.3 pm*rad

σ_p = 0.90e-3

U_0 = 4.17 MeV/Turn

energy spread increases but still limited

IBS with damping wigglers

PETRA IV. NEW DIMENSIONS

Tx (IBS) also varies with the emittance (and with U_0) and in some conditions it scales approximately proportional to the emittance. From Bane formula

$$\frac{1}{T_x} = \frac{N r_0^2 c(\log)}{32\gamma^3 \varepsilon_x^{7/4} \varepsilon_y^{3/4} \sigma_s \sigma_p} \left\langle H_x \sigma_H g(a/b)(\beta_x \beta_y)^{-1/4} \right\rangle$$

σ_y ~ constant fixed at e.g. 8 pm

σ_H ~ $(\varepsilon_x/H_x)^{1/2}$

$\sigma_s\sigma_p$ grows with U_0

approximation $\rightarrow \sigma_s\sigma_p \sim U_0^{(1/4)} \sim \varepsilon_x^{(-1/4)}$

In this regime $T_x(\mathrm{IBS}) \sim \varepsilon_x \sim 1/U_0$

When the emittance is reduced with moderate field damping wigglers, the contribution to the equilibrium IBS emittance by IBS and radiation damping can compensate each other

$$\varepsilon_x = \frac{\varepsilon_{x,0}}{1 - \tau_x / T_x(\varepsilon_x, \varepsilon_y, \sigma_p)}$$

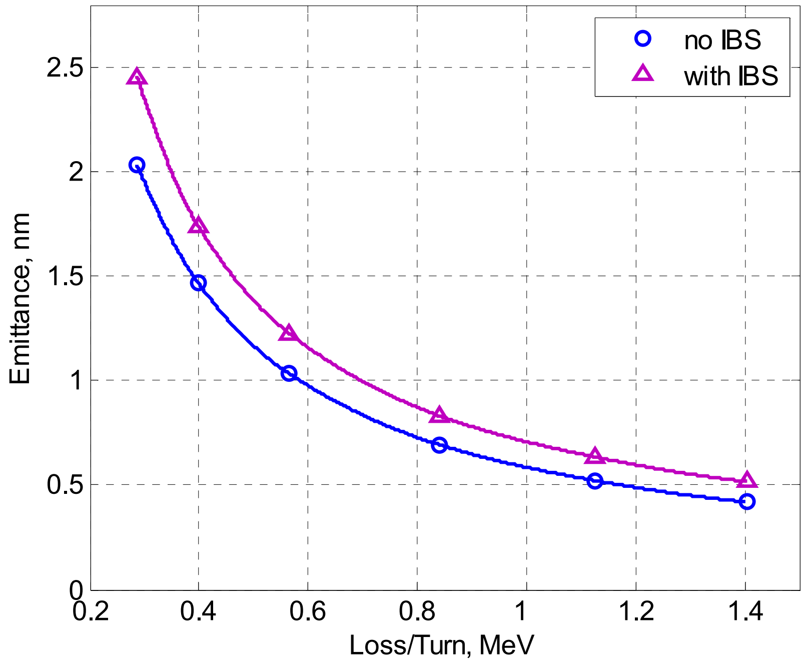
τ_x radiation damping $\rightarrow \tau_x \sim \varepsilon_x \sim 1/U_0$

T_x IBS growth rate $\rightarrow T_x(\mathrm{IBS}) \sim \varepsilon_x \sim 1/U_0$

Emittance and IBS with damping wigglers

PETRA IV. NEW DIMENSIONS

Example of calculation IBS equilibrium emittance for NSLS-II (Podobedov, LER14)



$$\varepsilon_x = \frac{\varepsilon_{x,0}}{1-\tau_x / T_x(\varepsilon_x, \varepsilon_y, \sigma_p)}$$

In a wiggler-dominated light source (emittance reduced by increasing I_2) IBS-induced emittance blow-up is approximately emittance-independent and small

If the emittance is reduced by reducing I5 (dispersion invariant in the arcs), the compensation effect will be lost and IBS equilibrium emittance will blow up

$$\tau_{x,0} = \frac{3}{r_0}\frac{T_0}{\gamma^3}\frac{1}{I_2+\Delta I_2-(I_4+\Delta I_4)}$$

while $T_x(IBS) \sim \varepsilon_x \sim I_5$

Emittance and IBS with damping wigglers: PETRA IV

Calculation of IBS equilibrium emittance for PETRA IV as a function of the energy loss per turn produced by the damping wigglers

H6BA lattice, 6 GeV, 20 pm emittance with damping wigglers (43 pm no damping wiggler)

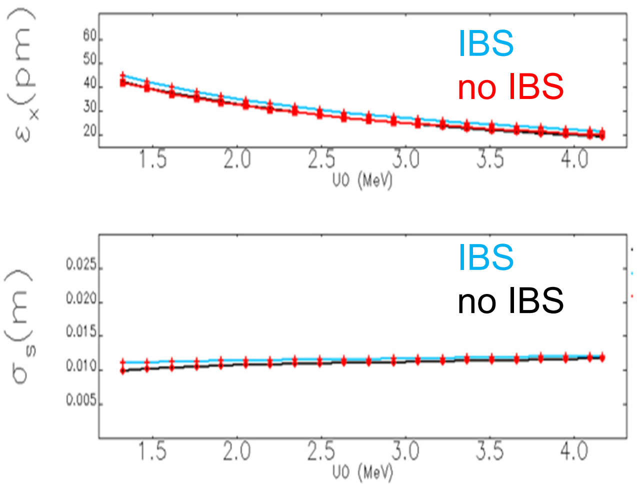
Brightness mode 200 mA in 1600 bunches (0.125 mA per bunch – 0.97 nC) (no errors)

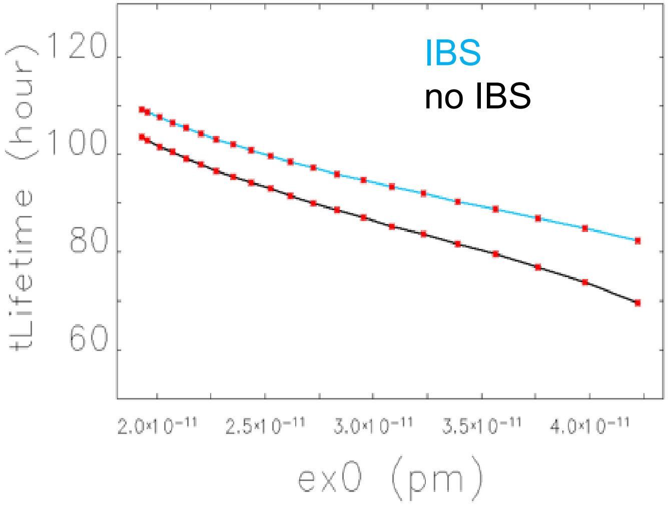
IBS emittance increase ~constant for all emittances and small

limited to 6% - 16%

(compared to 40% expected from the same emittance reduction without damping wigglers) via

$$\varepsilon_x = \frac{\varepsilon_{x,0}}{1-\tau_x / T_x(\varepsilon_x, \varepsilon_y, \sigma_p)}$$





Emittance and IBS with damping wigglers: PETRA IV

Calculation of IBS equilibrium emittance for PETRA IV as a function of the energy loss per turn produced by the damping wigglers

H6BA lattice, 6 GeV, 20 pm emittance with damping wigglers (43 pm no damping wiggler)

Timing mode 80 mA in 80 bunches (1.0 mA per bunch – 7.7 nC) (no errors)

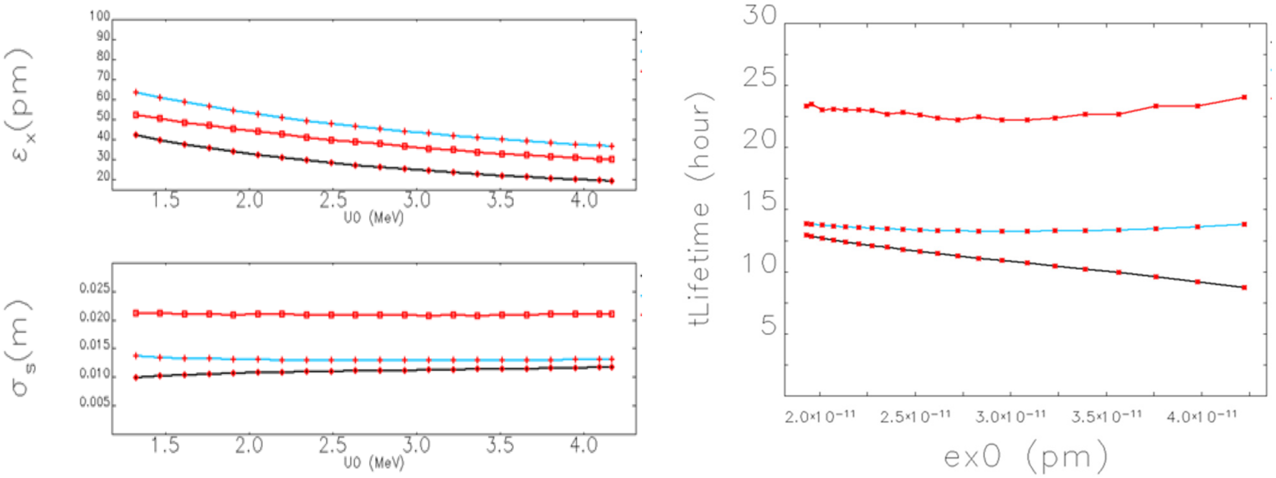
The beam dynamic is dominated by collective effects not by IBS

Strong bunch lengthening reduces the IBS emittance increase

The IBS emittance increase is ~constant for all emittances

Relative emittance increase IBS + IMPEDANCE 20%-110%

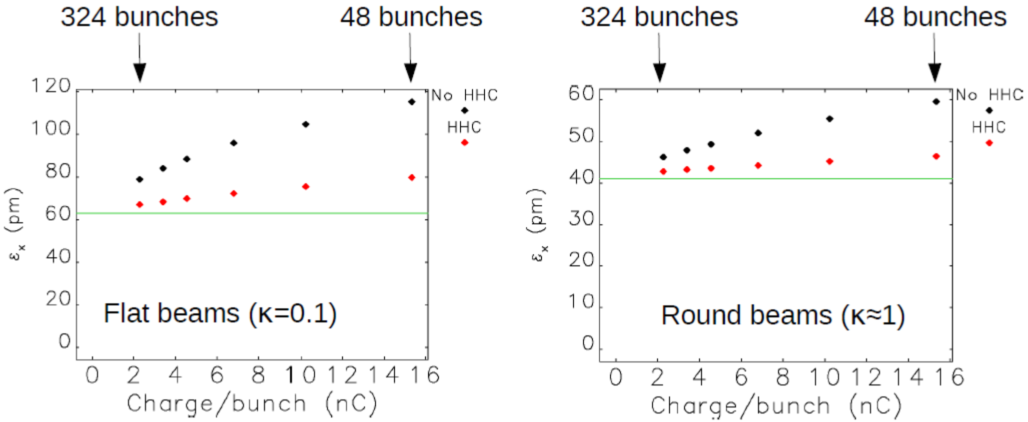
no IBS; with IBS; with IBS + Impedance



Countermeasures for reducing IBS emittance growth in ultra low emittance rings

- reduce emittance with damping wigglers to increase radiation damping (within limits)
- decreases the charge density to reduce the IBS growth rates

  run fill patterns with many bunches
  harmonic cavities for bunch lengthening
  round beam k = $\varepsilon_y / \varepsilon_x = 1$

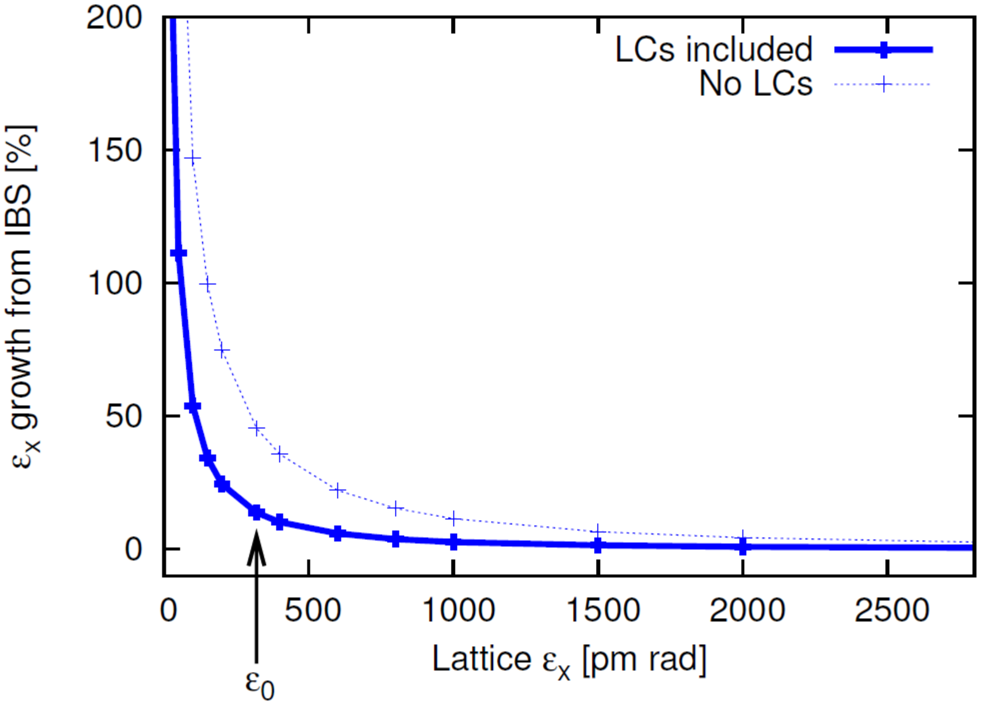


Example:
Operating modes in APS-U

IBS with reducing the emittance via I_5 and harmonic cavities

PETRA IV. NEW DIMENSIONS

Bunch lengthening cavities reduce the IBS growth. Simulation at MAX IV:



MAX IV 3GeV
I = 500 mA
δ_{RF} = 4.5%
$\sigma_\delta \approx$ const
ε_y = 8 pm rad

Simulations studies predict
IBS increase with emittance ~45%
S. Leemann PRST---AB, **17**, 050705, (2014)

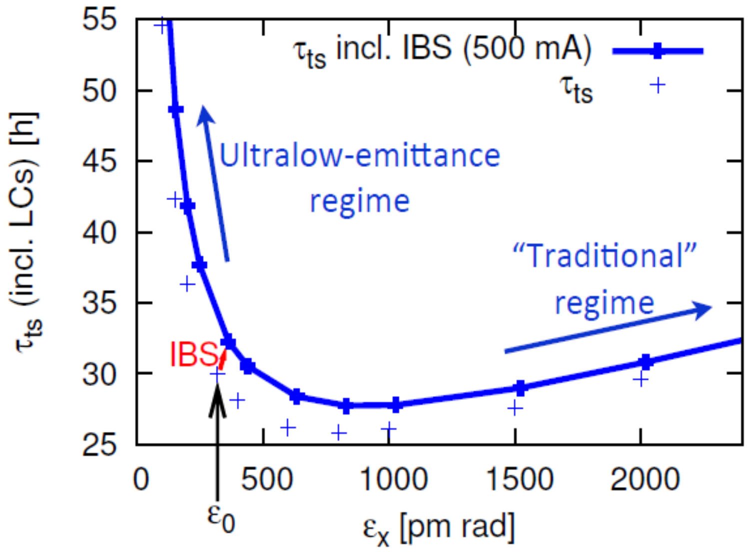
Bunch lengthening cavities reduce the
IBS increase with emittance ~13%

but below 100 pm the IBS equilibrium increases signifincanty even with Landau cavities

Handling emittance variations

Touschek lifetime and IBS equilibrium emittance vary significantly with the zero current emittance. Operational difficulties in stabilising the emittance can harm the machine performance – beside the impact on the brightness.

- Careful tuning of the optics to achieve the nominal emittance (LOCA, BB-methods)
- Careful tuning of the nonlinear optics guarantees the required momentum aperture
- Compensating ID impact to maintain the emittance constant in presence of gap movement
  - using damping wiggler to readjust ε_x (feed forward tables)
  - emittance blow up with striplines (concept tested at ESRF)
  - dispersion leaks in straight section (Tanaka, PRAB, 2022)
- Correct setting of HC to guarantee the required bunch lengthening to contain the emittance increase



Experimental tests of IBS emittance growth: SLS

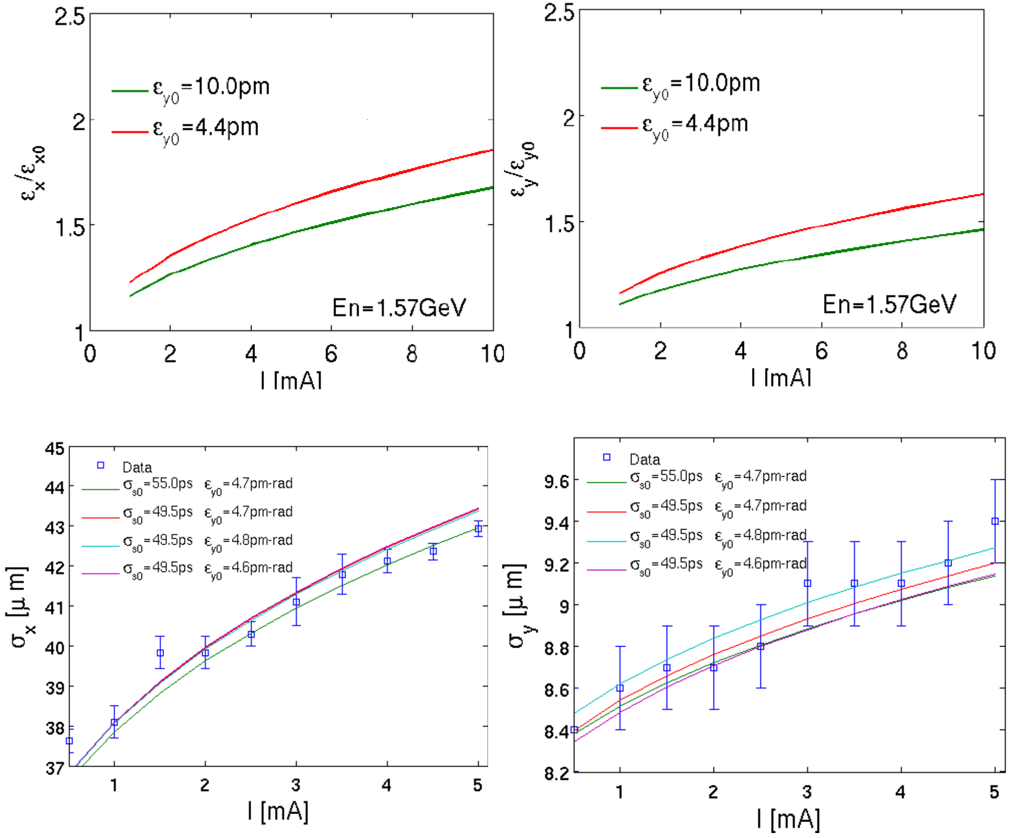
PETRA IV. NEW DIMENSIONS

The SLS is an ideal test facility for IBS studies:

- Record vertical emittance of 1 pm-rad at nominal energy (2.4 GeV)
- Availability of emittance monitoring diagnostics (hor./vert. beam size monitors)
- Ability to run at lower energies

The IBS effect at nominal energy is weak even at high bunch currents while at low energy is strongly enhanced and can be measured even at low bunch currents

Good agreement with CIMP theory found in transverse plane (longitudinal not measured)



Experimental tests of IBS emittance growth: NSLS-II

NSLS-II – 3 GeV at 0.7-0.9 nm emittance with 3 DW; 3 MV RF;
A. Blednykh et al. (LER 2020 and IPAC21)

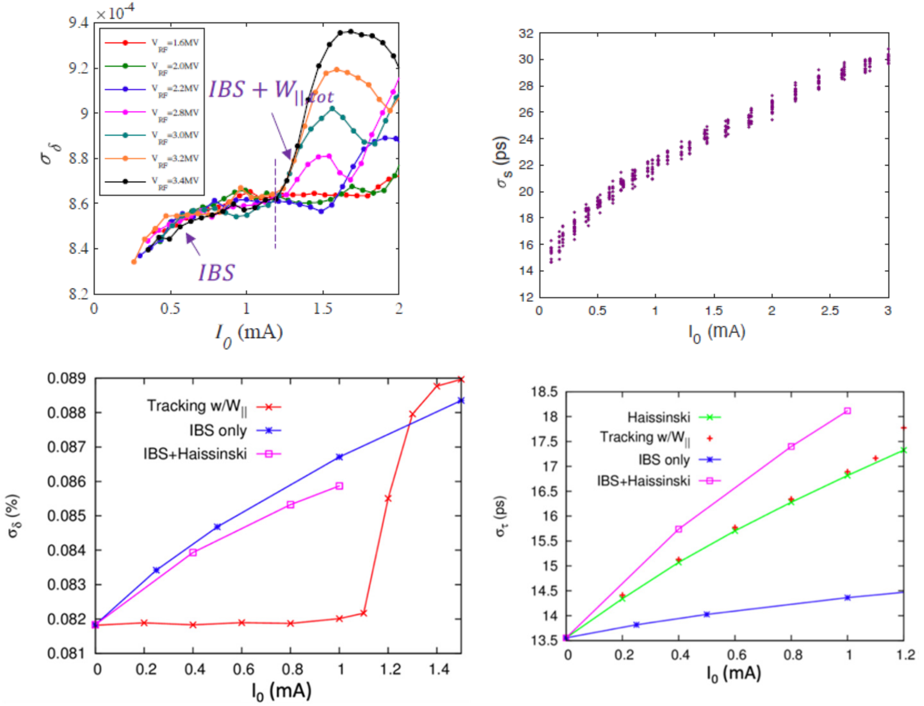
IBS investigation via bunch length, beam size and energy spread measurements

Significant interplay with other collective effects. Experimental difficulties in disentangle IBS effect from collective effect (PWD, MI)

An IBS dominated increase of energy spread could be disentangled from longitudinal collective effects at single bunch current below the MWI threshold.

IBS and Wakefield need to be simulated together

Energy spread vs single bunch current
Experimental data vs simulations

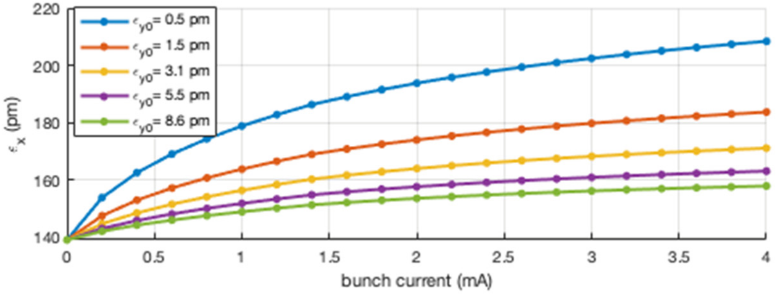


Experiments: IBS simulations and first tests at the ESRF-EBS

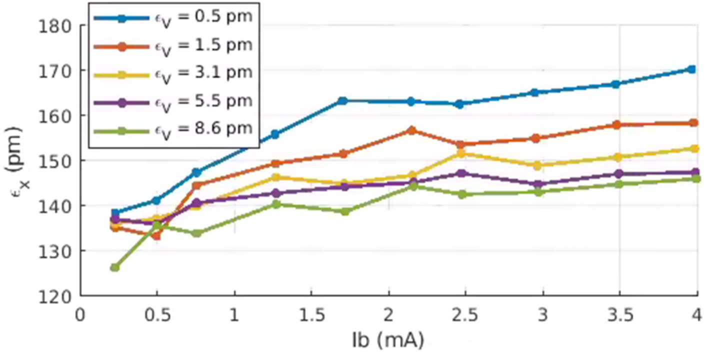
PETRA IV. NEW DIMENSIONS

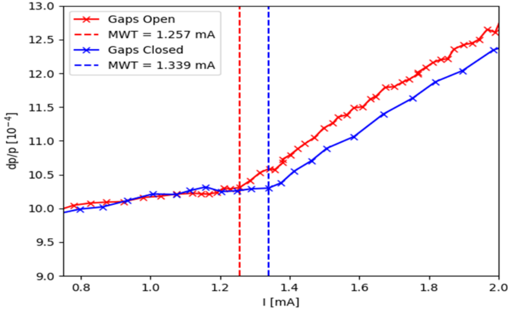
About 10% H emittance growth at 4 mA and 10 pm expected from IBS. Measurements are noisy, but the **measured effect is smaller in transverse and much smaller in longitudinal**.

Elegant simulations of IBS emittance and bunch lengthening



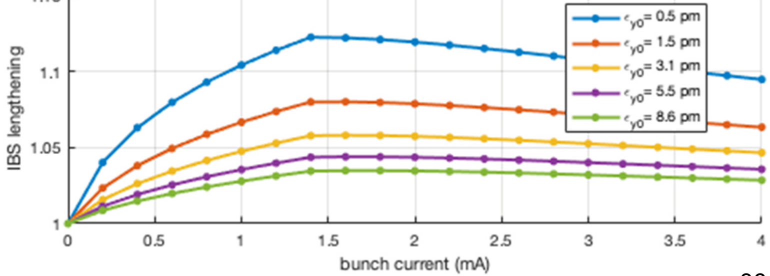
Measurements





Courtesy N. Carmignani (ESRF)

Bunch lengthening computed with IBS and impedance effect (MIW threshold ~1.3 mA)



Conclusions and perspectives

- Vast and complex theory has been developed for Touschek and IBS phenomena
- Ultra-low emittance rings provide new operating conditions with very large Touschek lifetime.
- Moderate field damping wiggler are a viable tool to reduce emittance and control IBS emittance growth.
- Landau cavities are effective tool to reduce the emittance growth due to collective effects. An essential tool in ultra low emittance lattices
- Special timing modes (high charge per bunch) will unavoidably compromise the ultra-low design emittance

Experiments so far have shown good agreement with the available models. More experimental studies are needed at the new facilities that will operate with ultra low emittance lattices

Thanks to many colleagues that provided material for this summary,

in particular
S.C. Leemann (ALS-U), B. Podobedov (NSLS_II), Y. Papaphilippou and F. Antoniu (CERN), N. Carmignani and S. Liuzzo (ESRF), P. Raimondi (SLAC), C. Li and I. Agapov (DESY)

Thank you for your attention!