Overview of instabilities in (storage ring) light sources

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ESRF | The European Synchrotron

OUTLINE

Low emittance rings lattice design

Collective effects and instabilities in low emittance rings

Impact of short bunches

BRILLIANCE

Brilliance is the main performance parameter for storage ring light source:

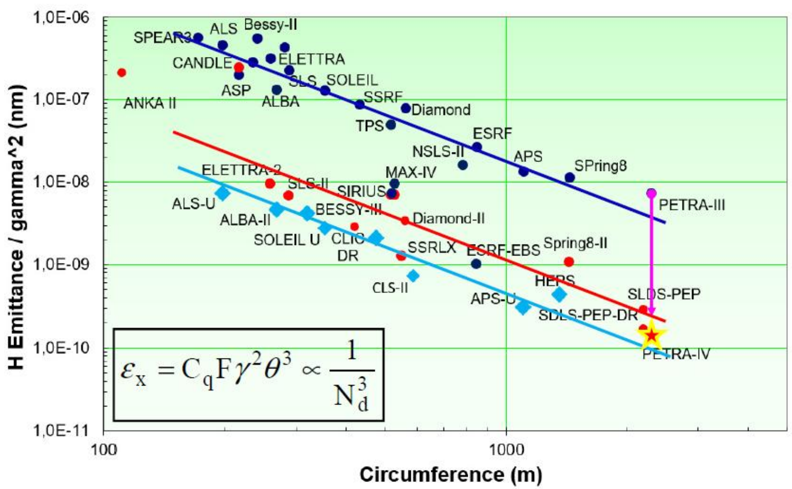
$$B_n = \frac{F_n}{4\pi^2\left(\varepsilon_x + \frac{\lambda_n}{4\pi}\right)\left(\varepsilon_y + \frac{\lambda_n}{4\pi}\right)}, F_n \propto I$$ High current and low emittance

$$\varepsilon_{x,y} < \frac{\lambda}{4\pi}$$ Diffraction limit at λ_n~0.1nm (~12keV) is ~10 pmrad

Low emittance lattice designs maximize the brilliance by reducing the emittance until the diffraction limit is reached:

- ε_y: coupling correction
- $\varepsilon_x = C_q \frac{\gamma^2 I_5}{J_x I_2} \propto \frac{\beta_x D_x}{\rho}, \varepsilon_x^{DBA} \approx 5.036e^{-13} E^2 \theta^3$
- Beam/photon energy
- Optics tuning
- Bending angle / number of dipoles / space / €
- Partition number: combined function magnets
- Beam current: RF power and collective effects

R. Bartolini, “Touschek lifetime and IBS effect in extremely low emittance rings”



LOW EMITTANCE RINGS LATTICE DESIGN

Starting from MAXIV in 2015 many facilities world-wide have upgraded to 4th generation storage ring design:

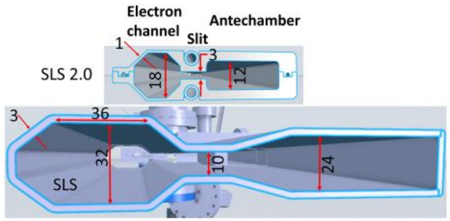
- Application of MBA concept
- 1-2 order of magnitude reduction of emittance
- **Increased charge density**

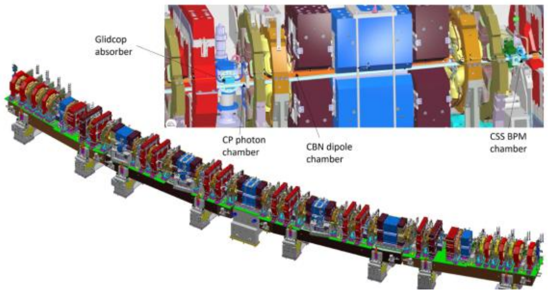
Common trends arise in all recent lattice designs:

- Increased number of dipoles
- Strong distributed focusing and sextupoles
- Reduction of the magnets, vacuum chambers aperture and ID gaps
- **Overall densification and miniaturization of accelerator components and reduction of transverse and momentum acceptances**

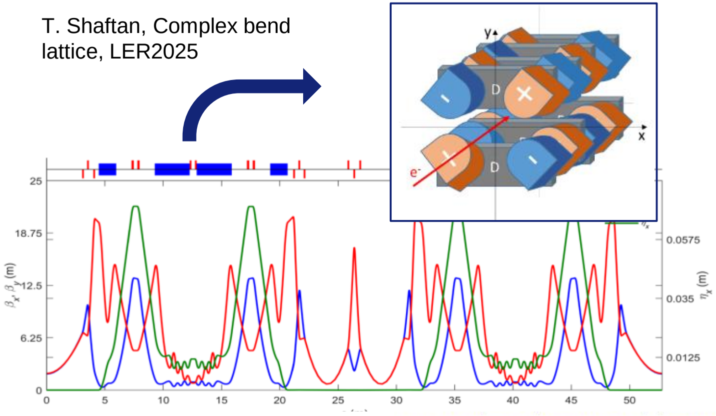
Collective effects and their consequences enhanced

R. Ganter et al., Vacuum chambers for the Swiss light source, PRAB 27, 053201





T. Shaftan, Complex bend lattice, LER2025



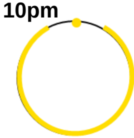
PARAMETERS AND OPERATING MODES

Modern light sources cover a wide range of parameters on which collective effect and instabilities strongly depend:

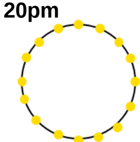
- **Energy, dimension:** radiation damping, instability growth rate
- **Optics / beam manipulation:** low or negative α, coupling, blow-up, bunch lengthening
- **Time structure:** multiple bunches low current, few bunches high current, hybrid
- **Motivated by performance (brilliance, photon spectrum, operation): collective effects studies nevertheless required to ensure design goals in all modes are achievable**

Uniform:
992 bunches
200mA total
10pm

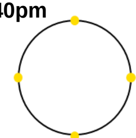
7/8+1:
868+1 bunches
200mA total
8mA single
10pm



16 bunches:
90mA total
~6mA per bunch
20pm

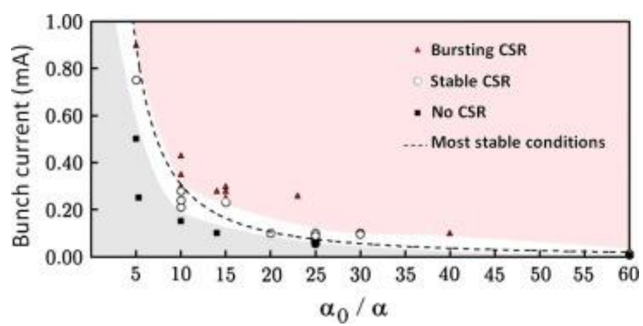


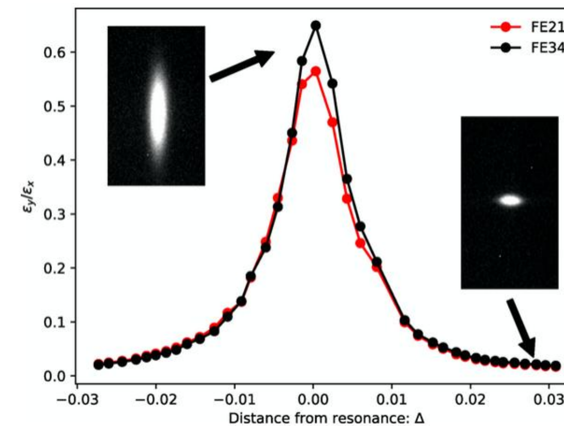
4 bunches:
40mA total
10mA per bunch
40pm



Main ESRF filling modes

J. Barros et al. "Characteristics and development of the coherent synchrotron radiation sources for THz spectroscopy" (SOLEIL)





M. Carla et al. "Methods for full coupling operation in a synchrotron light source" (ALBA)

INTRA-BEAM SCATTERING AND TOUSCHEK EFFECT

Particles inside a bunch can collide and result in a transfer of transverse to longitudinal momentum:

- **Energy deviation < MA :** IBS, beam size increase (3 planes)
- **Energy deviation > MA :** Touschek effect, lifetime reduction
- **More severe 4th generation light source:** increased charge density, reduced MA

➢ To preserve operating conditions these effects are generally **mitigated by increasing the transverse and / or the longitudinal beam size**

➢ **Strong interplay with other collective effects: need to modeled together**

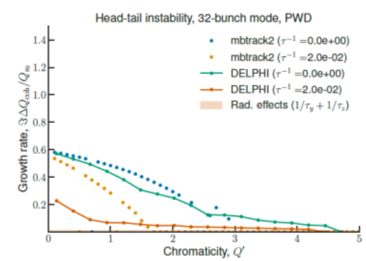
IBS growth rate:

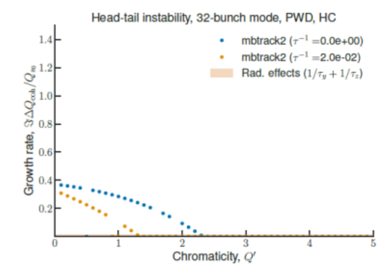
$$\frac{1}{T_{x,y,z}} \propto \frac{r_e^2 c N}{\gamma^4 \varepsilon_x \varepsilon_y \boxed{\sigma_z} \sigma_\delta}$$

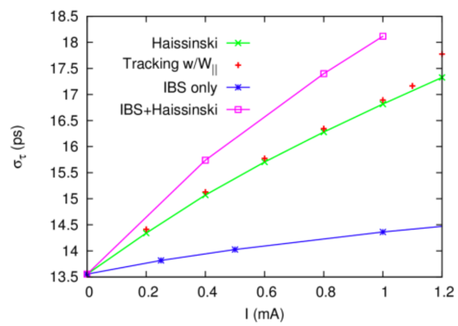
Touschek lifetime:

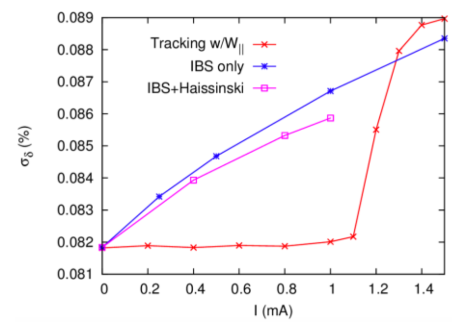
$$\frac{1}{T_\tau} \propto \frac{r_e^2 c N}{\gamma^2 \sqrt{\varepsilon_x} \sqrt{\varepsilon_y} \boxed{\sigma_z} \delta_{acc}^3}$$

V. Gubaidulin et al., “Transverse instabilities in SOLEIL II storage ring in the presence of a harmonic cavity” (SOLEIL)









A. Blednykh et al., “Combined Effect of IBS and Impedance on the Longitudinal Beam Dynamics” (NSLS)

BEAM COUPLING IMPEDANCE

Beam coupling impedance is the main source of instabilities in storage ring light source, it can be separated in 2 components:

- Resistive wall impedance
- Geometric impedance

➢ **Depends on the vacuum vessels shape and materials:** minimized during the design and mechanical engineering phase of accelerator components

➢ **Can be short range or long-range: single or multi-bunch**

➢ **Acts on longitudinal and transverse planes: kick, tune shift**

➢ **Sets limits on the maximum bunch and beam current: brilliance**

Resistive wall impedance for a circular chamber:

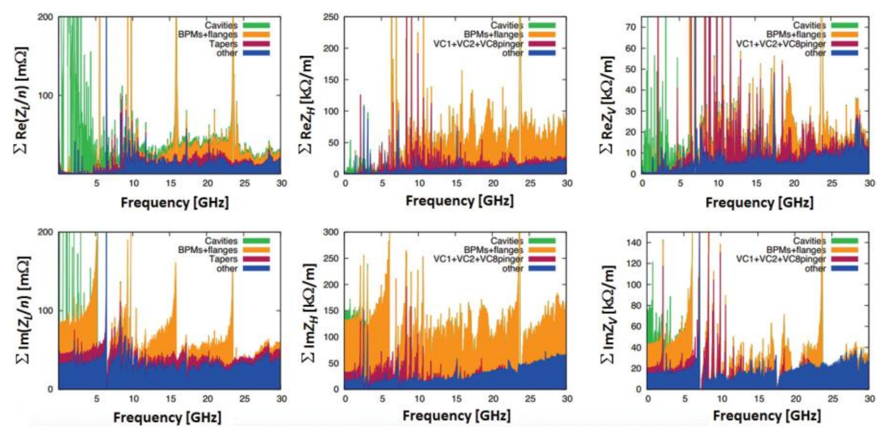
$$\frac{Z_{\parallel}^{\mathrm{RW}}(\omega)}{L} = \frac{\exp(-i\pi/4)}{2\pi}\frac{1}{b}\left(\frac{Z_0\rho_r\omega}{c}\right)^{1/2} \qquad [\Omega\,\mathrm{m}^{-1}]$$

and

$$\frac{Z_{\perp}^{\mathrm{RW}}(\omega)}{L} = \frac{\exp(-i\pi/4)}{2\pi}\frac{2}{b^3}\left(\frac{cZ_0\rho_r}{\omega}\right)^{1/2} \qquad [\Omega\,\mathrm{m}^{-2}]$$

Chamber radius

Material resistivity



M. Klein et al., "Study of collective beam instabilities for the MAX IV 3 GeV ring" (MAX IV)

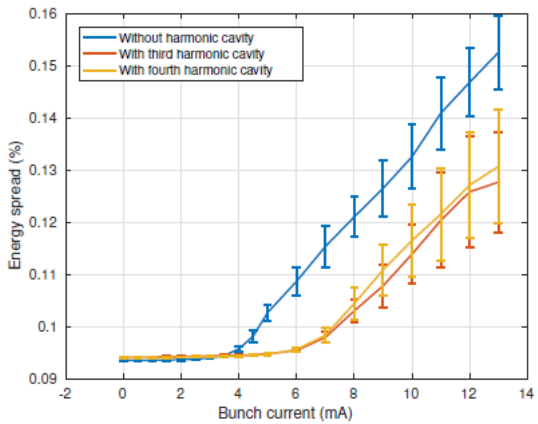
LONGITUDINAL SINGLE BUNCH INSTABILITIES

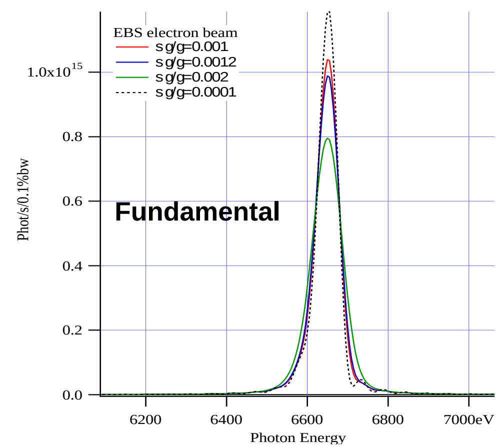
Longitudinal impedance mainly has two single bunch effects:

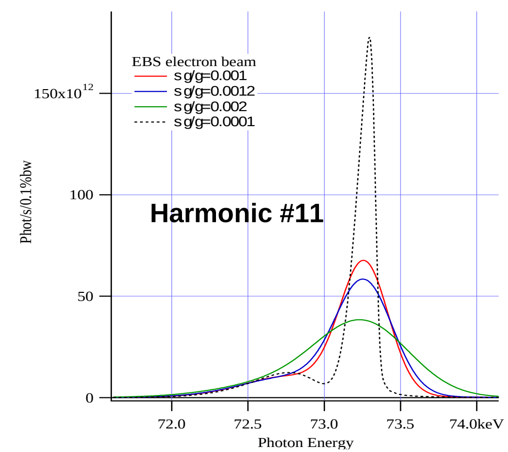
- **Bunch lengthening:** due to the potential well distortion
- **Microwave instability:**
    - Threshold effect resulting in increase in energy spread
    - Driven by longitudinal impedance or coherent synchrotron radiation (CSR)
    - Generally relevant for high current/bunch modes (threshold ~several mA) or special low α modes (threshold lower for short bunches)
    - ➢ **Affects the performance of beam lines using higher harmonics of undulators spectra**

Boussard criterion: $$\left|\frac{Z_{\parallel}}{n}\right| < \sqrt{\frac{\pi}{2}} Z_0 \frac{\gamma \alpha_p \sigma_\delta^2 \sigma_z}{r_e N_0}$$

N. Carmignani et al., "Harmonic RF systems for ESRF-EBS"







Undulator:
Period [mm]: 16
Length [m]: 2
K []: 2.1

Collecting aperture:
0.6 mm (H)
0.4 mm (V)
Distance from source: 30 m

Calculation by J. Chavanne for ESRF parameters

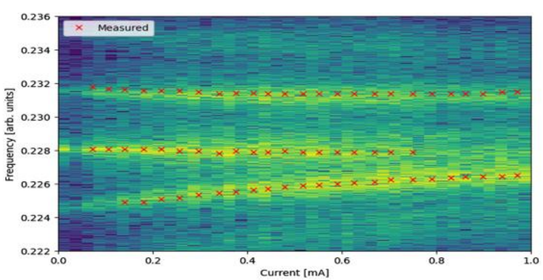
TRANSVERSE SINGLE BUNCH INSTABILITIES

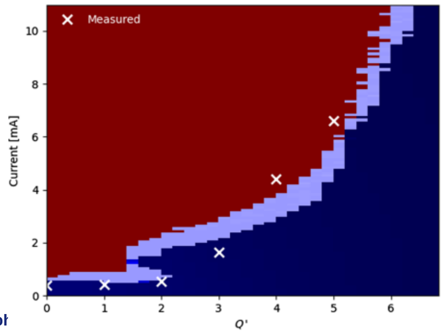
Short range wake field couple the head and the tail of the bunches:

- **Multi-bunch modes (low bunch current):** below TMCI threshold
- **Timing modes (high bunch current):** (well) above TMCI threshold
- **Example of ESRF:** TMCI threshold 0.5mA, multi-bunch mode min. current/bunch 0.2mA, max. current/bunch 10mA

➢ **Results in beam loss or emittance blow-up at high chromaticity**

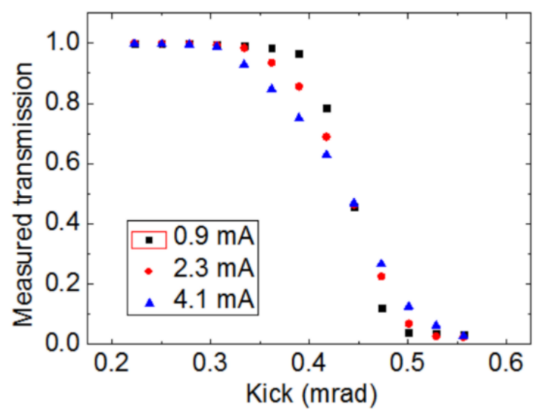
➢ **Injection can also be impacted:** injection saturation of high current bunches (ESRF), reduction of injection efficiency with small DA (APS-U)

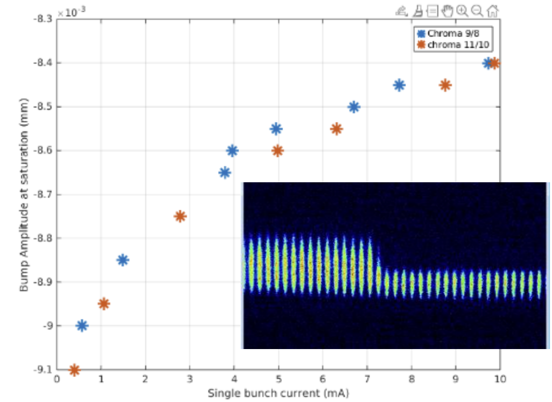




L. Carver et al., "Beam based characterization of the ESRF-EBS Source short range wakefield model"

R. Lindberg, "Collective effects in APS-U injection"



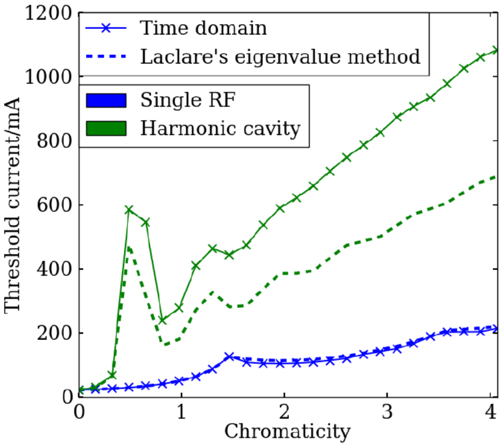


T. Perron et al., "measurement of injection saturation at ESRF"

MULTI-BUNCH INSTABILITIES

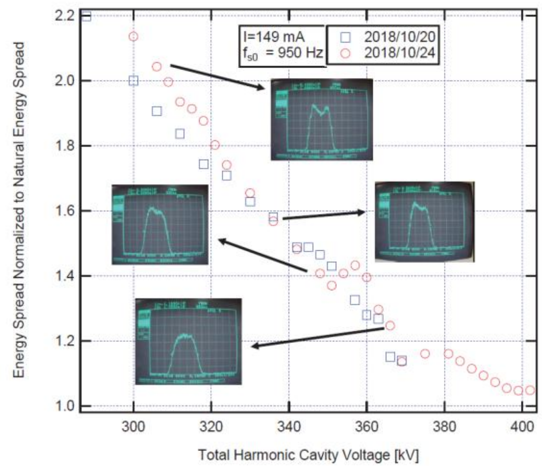
Long range wake fields couple the bunches together:

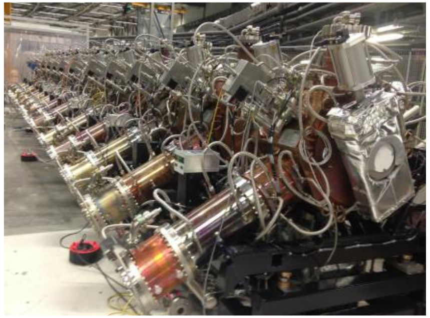
- **Transverse coupled bunch instabilities:** generally driven by resistive wall impedance, often not the limiting factor in light sources
- **Longitudinal coupled bunch instability:** generally driven by cavities HOMs, **can result in total beam current limitation**



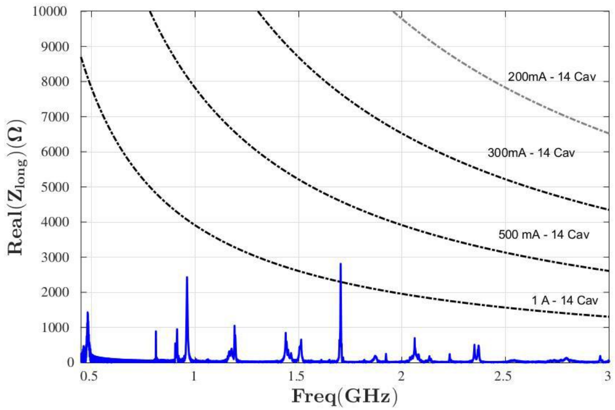
Resistive wall MB instability thresholds with harmonic cavity (R. Cullinan et al., IPAC16)

P. Tavares, "Commissioning and first-year operational results of the MAX IV 3 GeV ring"





A. D'Elia: ESLS-RF (2018)



ION INSTABILITIES

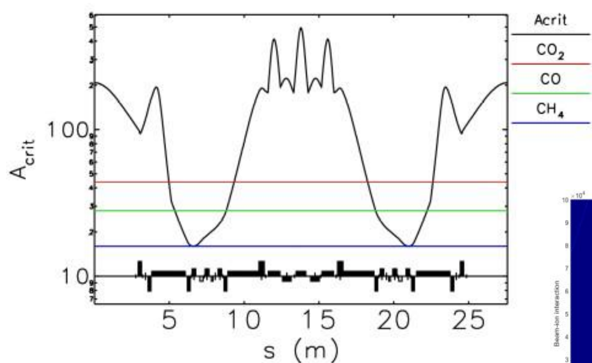
The electron beam ionizes the residual rest gas in the vacuum chambers:

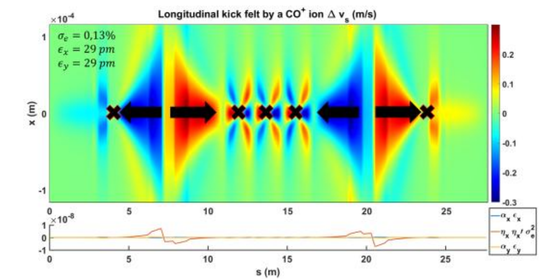
- These ions can be in the potential of the beam if their mass is larger than the critical mass $A_{crit}=\max(A_x, A_y)$
- Trapped ions can couple to the beam motion and drive a coherent (usually vertical) instability
- Instability growth depends on vacuum, current and beam size
- Classified in 2 type:
    - Trapped ion instability growth over many turns
    - Fast ion instability grow along a single bunch train
- **Both can result in beam loss or emittance growth**
- **Most severe during vacuum conditioning period:** temporarily mitigate by Q', gaps, feedback, rarely a limit for operation once vacuum is conditioned

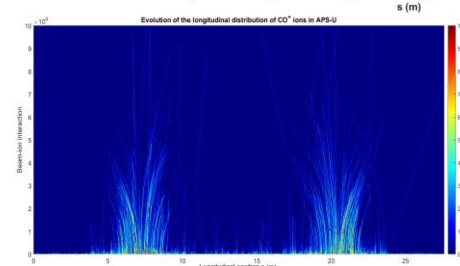
$$A_{x,y} = \frac{N_e\, r_p\, S_b\, Q}{2\sigma_{x,y}(\sigma_x + \sigma_y)}$$

$N_e \equiv$ bunch population
$r_p \equiv 1.5 \times 10^{-18}$ m
$S_b \equiv$ bunch spacing
$\sigma_x, \sigma_y \equiv$ beam size

J. Calvey, "Critical mass along APS-U cell"







A. Gamelin, "Ion trapping simulation for APS-U cell"

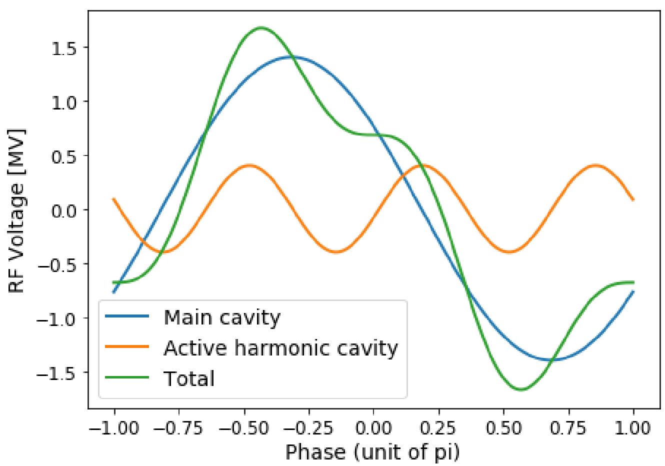
MITIGATIONS

Collective instabilities need to be mitigated to achieve design parameters:

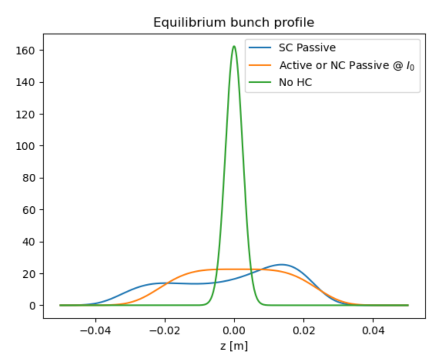
- **Impedance optimization at design stage of vacuum components:** smooth transitions, HOM damped cavities, material conductivity
- **Transverse:** Q', bunch-by-bunch feedback, coupling
- **Longitudinal**: bunch-by-bunch feedback, mode feedback, cavity temperature, bunch-by-bunch fluctuation

Optimization of touschek lifetime using bunch lengthening cavity widely adopted in 4th generation light sources:

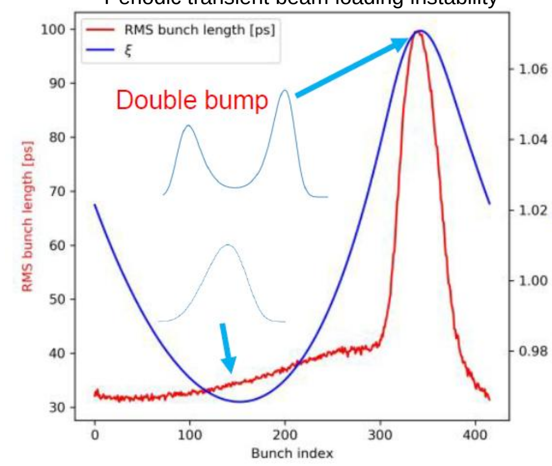
  - Indirect mitigation of all single bunch effects
  - Some benefits observed in some case for multi-bunch effects
  - ➢ **HC itself can drive longitudinal coupled bunch instabilities**



A. Gamelin, "Harmonic cavity studies for the SOLEIL Upgrade"



Periodic transient beam loading instability



TEMPORAL COHERENCE IN A STORAGE RING?

4th generation light sources tend to have lower lifetime and more severe IBS and collective instabilities: trend is to lengthen the bunches using HHC

This is obviously not the desired direction to achieve temporally coherent ring based light source. Compromise need to be found on:

- Bunch / beam current
- Bunch length, transverse emittance and energy spread
- ➢ **Brilliance would most certainly be reduced:** how much can we recover with optics and insertion device designs?

Can storage ring light source light sources bridge the gap between present 4th gen. rings and FELS? Special “coherent mode” may feature:

- Many bunches with low current
- Large(r) transverse emittance
- Special optics and undulators, low ID gaps
- On-axis injection
- ➢ **Flexibility integrated at design stage**

“Sacrificial” bunches have been considered:

- Lost for other beam lines
- How much do they perturb high brilliance set-ups?

How short do the bunches need to be?

MANY THANKS FOR YOUR ATTENTION