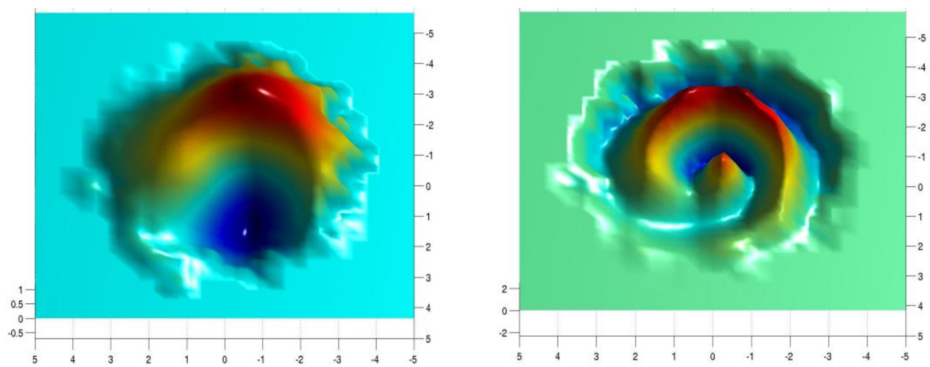
Collective Beam Instabilities and Methods of their Suppression



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U.S. DEPARTMENT OF ENERGY | Office of Science

SOLEIL SYNCHROTRON

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Acknowledgement :

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1. Introduction

◊ Figure of merit and target performance of High Brightness Light Sources (HBSLS):

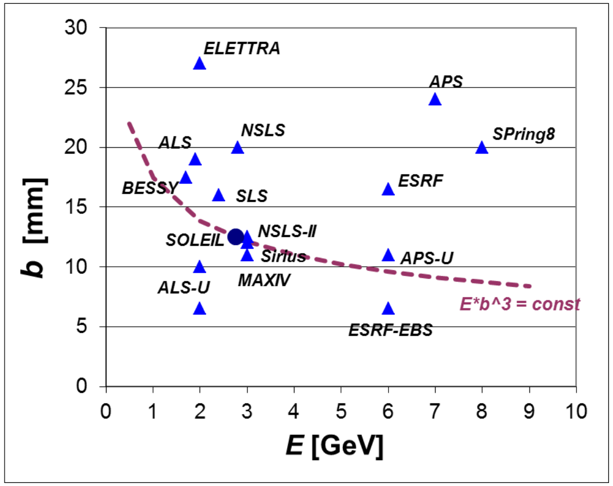
$$Brilliance = \frac{Photons}{Second \cdot mrad^2 \cdot mm^2 \cdot 0.1\% BW} \propto \frac{I}{\varepsilon_x \varepsilon_y}$$

N_i : Number of particles in a bunch, f : Revolution frequency, n_b : Number of bunches,
σ_u : Transverse beam size ($u = x, y$), I : Beam current, ε_u : Transverse emittance

- ***Total beam intensity*** constitutes one of the major two axes in raising the performance of HBSLSs
- For time-resolved experiments, ***high intensity bunches*** in specific beam fillings (e.g. hybrid and *N*-bunch modes) are also requested

◊ Reasons for collective effects becoming serious for HBSLSs:

- Stronger focusing needed for ultra-low emittance lattice
  - $\Rightarrow$ Reduced vacuum chamber aperture
  - $\Rightarrow$ Increased coupling impedance



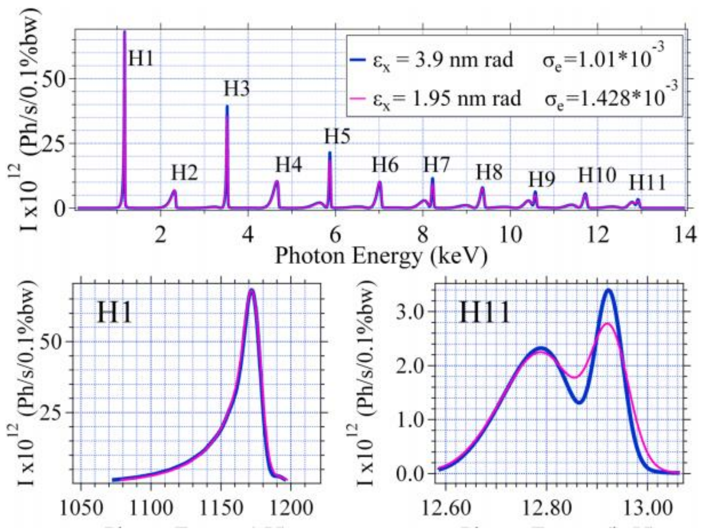
Local vertical half aperture b adopted in several existing and future light sources versus their machine energies

- Ultra-low-emittance optics

  $\Rightarrow$ Small horizontal dispersion $\Rightarrow$ Lower momentum compaction (even to $\alpha < 0$)

  $\Rightarrow$ Enhanced sensitivity to collective instability

  - Potentially dangerous collective beam instabilities: *Transverse single bunch, microwave, Resistive-wall (RW) instability in multibunch, ions-induced* (see more details later)



Degradation of undulator higher-harmonic spectra with beam energy spread widening (H. Abualrob et al., IPAC 2012)

A melted RF finger (SOLEIL)

  - Equally prominent: *Bunch lengthening* (though this may only be beneficial) and *beam-induced heating*

- Higher transverse phase space density due to ultra-low-emittance beam

  $\Rightarrow$ Intensity-dependent intra-beam Coulomb scattering

  - Perhaps the most constraining and inevitable "collective effects" in HBSLS: *IBS* and *Touschek*

2. Instability driving impedances Z

◊ General dependence of Z on the chamber (half) aperture b:

- Longitudinal impedance (roughly) $\propto b^{-1}$ + higher
- Transverse geometric impedance (roughly) $\propto b^{-2}$ + higher
- Transverse RW impedance $\propto b^{-3}$

cf) Impedance of a hole on the chamber: (S. Kurennoy, EPAC94)

$$Z_{//}(\omega) = -iZ_0 \frac{\omega}{c} \frac{(\alpha_m + \alpha_e)}{4\pi^2 b^2}, \qquad \vec{Z}_{\perp}(\omega) = -iZ_0 \frac{(\alpha_m + \alpha_e)}{\pi^2 b^4} \vec{a}_h \cdot \cos(\varphi_h - \varphi_b)$$

$\Rightarrow$
- Due to reduced b, larger relative contributions of tiny slits, holes, steps, …
- Tapers for low gap IDs may have relatively reduced contributions due to overall reduced aperture b
- An enhanced contribution of Z_{RW} is inevitable

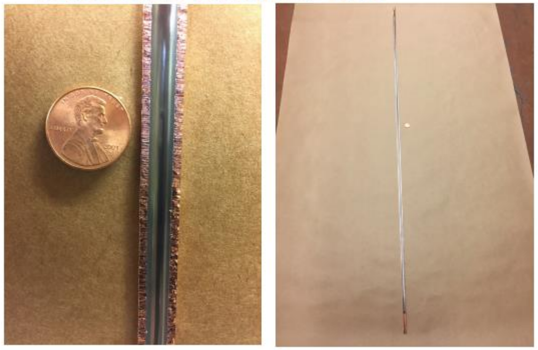
◊ General contributors:

- Tapers, BPMs, shielded bellows, flanges, cavities, kickers, absorbers, resistive-wall (RW), …

◊ Dependence on the chamber cross section:

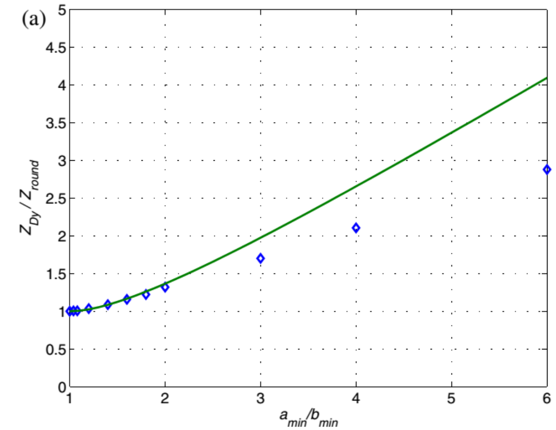
- Circular geometry (in MAXIV, SIRIUS, ALS-U, …) is in favor of reducing Z_V and suppressing incoherent tune shifts, …)

Very small NEG coated vacuum chambers



Coated 6 mm chamber (world record)

(*D. Robin, LER2016, SOLEIL*)

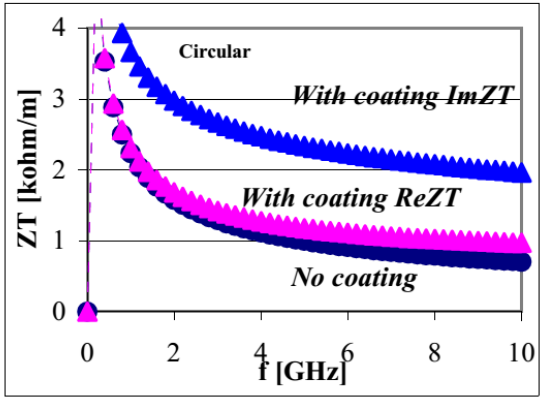


Dependence of taper inductance on the chamber cross section (B. Podobedov, S. Krinsky, PRSTAB ***10****, 074402 (2007))*

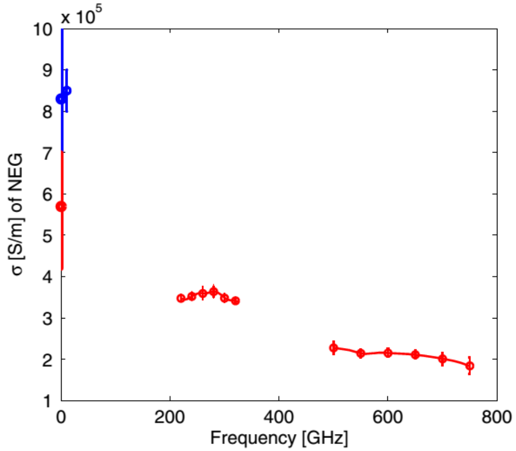
◊ Impedance of NEG coated chambers:

- For HBSLSs that require narrow beam pipes, vacuum pumping with NEG is very helpful
  $\Rightarrow$ Successfully applied to ESRF, ELETTRA, SOLEIL, MAXIV, ...
  $\Rightarrow$ Characteristics of Z_{NEG} must be well understood

- Early studies indicated that ~1 μm thick NEG coating has an effect;
  $$(\mathrm{Re}Z)_{NEG} \approx (\mathrm{Re}Z)_{substrate}, \qquad (\mathrm{Im}Z)_{NEG} \approx 2\times(\mathrm{Im}Z)_{substrate}$$
  in the frequency range below ~20 GHz, when the resistivity $\rho_{NEG} > \rho_{substrate}$
  $\Rightarrow$ Instability thresholds would not be directly affected by NEG
  - Bunch lengthening, coherent and incoherent tune shifts may be enhanced
  - Measurement made at ELETTRA and SOLEIL are in (qualitative) agreement with theory



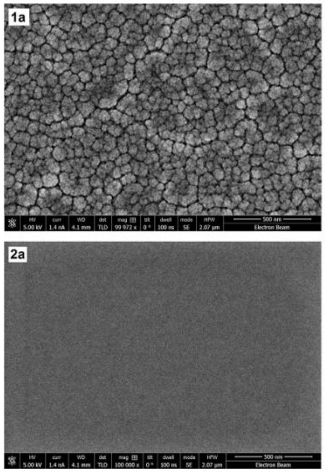
Analytical study of NEG Impedance (R. Nagaoka, EPAC 2004, Lucerne)



Experimental study of NEG electric conductivity versus frequency (E. Koukovivi-Platia et al., PRAB ***20****,011002 (2017))*

"columnar"

"dense"

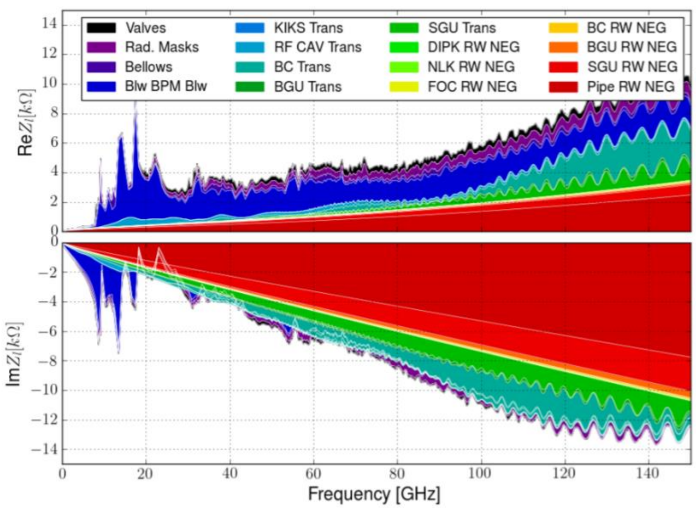


Experimental study of surface resistivity of two types of NEG (O. B. Malyshev et al., NIM ***A844*** *(2017) 99–107)*

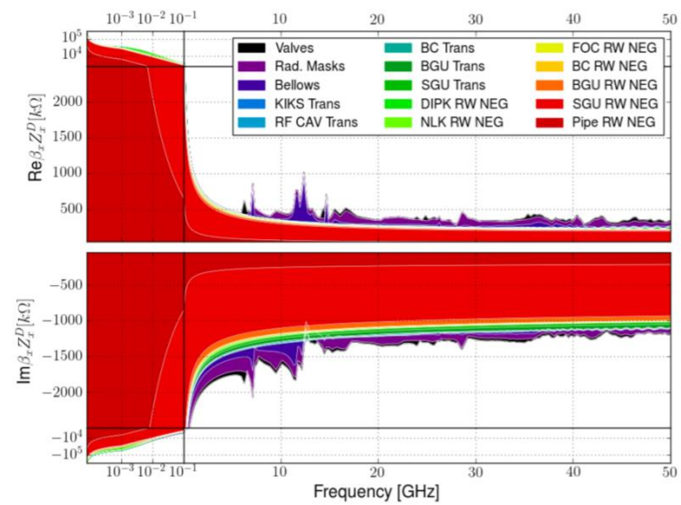
◊ Numerical evaluation of impedances/Construction of impedance budget:

- Using 3D EM solvers (*CST microwave studio*, *GdfidL*, *ECHO3D*, …)
- Analytical methods for resistive-wall and di-electric (ceramic) chambers
- Multi-layer RW (non-circular) chambers → *ImpedanceWake2D* (*IW2D*) developed at CERN

ex) Impedance budget evaluated for SIRIUS:



Element	Quant.	Bx [m]	By [m]
Pipe RW NEG	1	6.0	11.0
SGU RW NEG	14	2.2	2.2
BGU RW NEG	4	17.8	5.0
BC RW NEG	20	0.4	5.2
FOC RW NEG	80	7.2	6.5
NLK RW NEG	1	18.2	7.3
DIPK RW NEG	1	18.0	6.7
SGU Trans	14	2.4	2.4
BGU Trans	4	17.8	5.0
BC Trans	20	0.4	5.2
RF CAV Trans	1	7.3	7.3
KIKS Trans	1	18.2	7.1
Blw BPM Blw	160	6.6	8.8
Bellows	80	6.6	8.8
Rad. Masks	350	6.6	11.0
Valves	40	6.6	11.0



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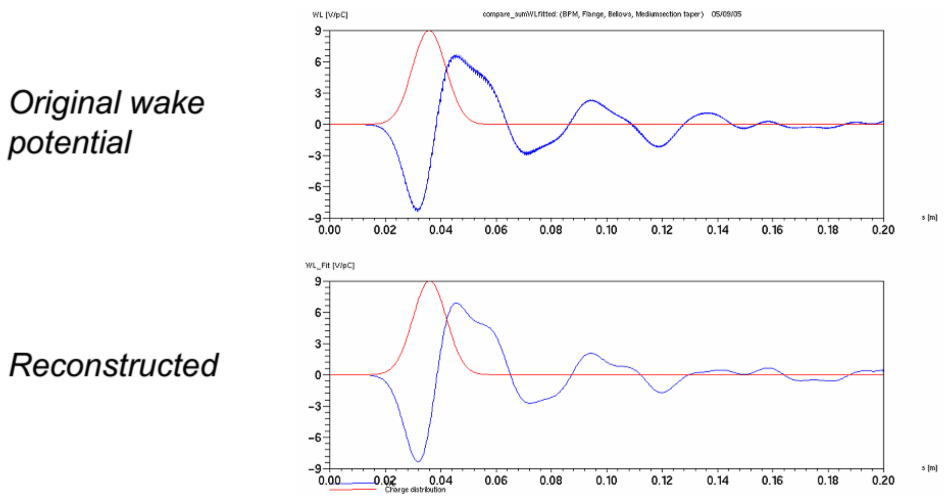
Impedance budget obtained for (the future machine) SIRIUS (left: longitudinal, right: transverse) (F.-E. De Sà, LER2016)

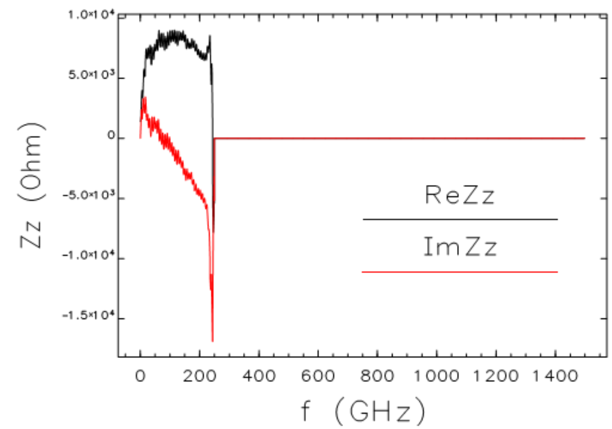
- Dominance of RW impedance (as compared to older machines)
- $\mathrm{Im}Z > 2\times\mathrm{Re}Z$ in practically the entire range due to NEG coating
- Machine is inductive (as always) at low frequencies

◊ Impedance modelling and comparison with reality:

- Ideally, the constructed $(Z)_{budget}$ should be used to perform simulations of collective effects
- For instability simulations, numerical wake potentials need be processed to wake functions
- Comparisons with reality often result in underestimating the impedance (inductive and/or resistive parts) by as much as a factor of ~2
- At APS, such discrepancy was compensated by re-performing the wake potential computations with a shorter bunch (σ = 5 → 1 mm) (Y.-C. Chae, PAC2007)
- AT SOLEIL, a study launched to re-examine the dependence of the calculated wake potentials on the mesh size



BPM impedance decomposition and reconstruction of a wake potential (R. Nagaoka, EPAC 2006, Edinburgh)



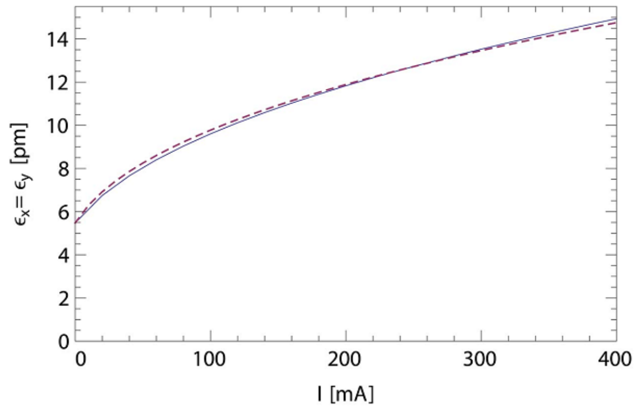
Re-calculation of the impedance database carried out at APS with a shorter bunch (σ = 1~2 mm), Y.-C. Chae, PAC2007)

3. Concerned collective effects/instabilities and their mitigations

3. 1 Instabilities and collective effects

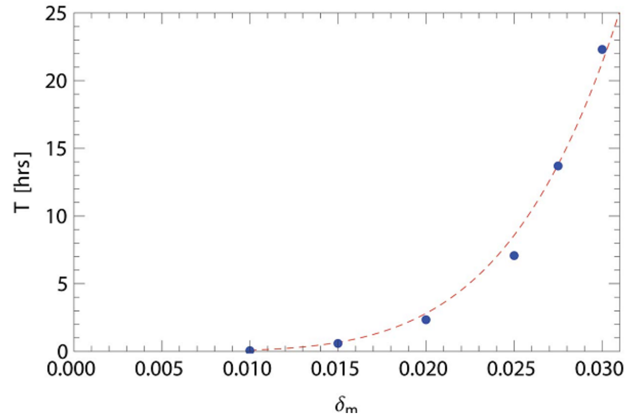
1) Intensity-dependent particle scatterings

- IBS is a multiple Coulomb scattering among electrons in a bunch leading to a beamsize increase in *all* directions
- Effect is enhanced for a low energy/emittance HBSLSs storing high (bunch) current.
- Many future HBSLSs consider making a beam ***round*** and/or ***long*** (via harmonic cavities) to minimize the effect.



Steady-state emittances as a function of beam current in PEP-X

- Touschek scattering is a large angle single Coulomb scattering. Energy transfer from transverse to longitudinal → may induce immediate particle losses. For HBSLSs, it sets a severe constraint on beam lifetime.
- Lower ε → Lower $\tau_{Touschek}$. However, below a certain emittance, $\tau_{Touschek}$ starts to increase as the scattering event decreases for a "well-aligned" electrons.
- Like IBS, $\tau_{Touschek}$ depends on local lattice functions and $(\Delta p/p)_{accep}$, and must be averaged around the ring, taking account of asymmetry on $(\Delta p/p)_{accep}$.



Touschek lifetime T for PEP-X versus(global) $(\Delta p/p)_{accep}$ parameter, δ_m (blue symbols). The dashed curve gives the fit: $T = 0.088(\delta_m/0.01)^5$.

(*Y. Cai et al., SLAC-PUB-14785*)

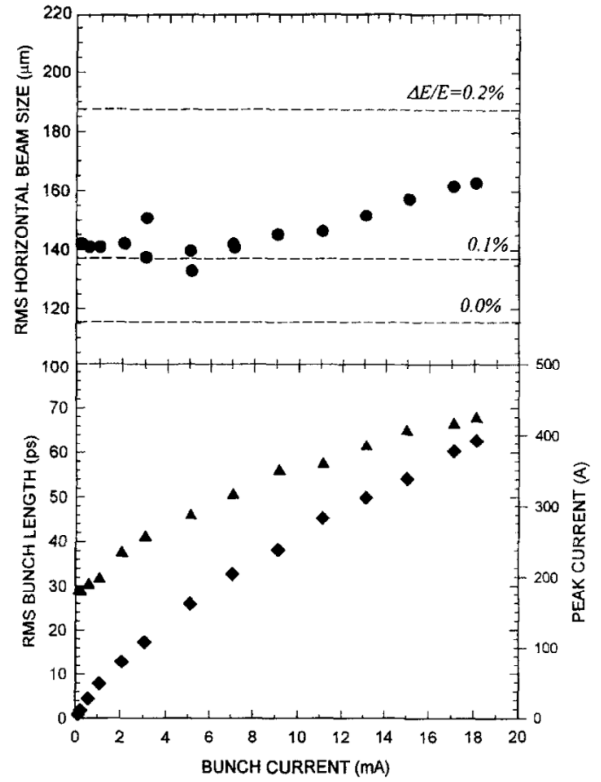
2) Bunch lengthening

- Most machines have predominant inductive impedance $Z_{inductive}$ at low frequencies, with which
- Longitudinal bunch profile deforms in the so-called PWD regime without changing the $\Delta p/p$ profile:

$$\left(\frac{\sigma_l}{\sigma_{l0}}\right)^3 - \left(\frac{\sigma_l}{\sigma_{l0}}\right) = \frac{1}{4\sqrt{\pi}} \cdot \frac{-2\pi i I\left[\frac{Z_{//}(\omega)}{n}\right]_{eff}}{V_{rf} h \cos\phi_s \left(\frac{\omega_0 \alpha}{\omega_{s0}} \sigma_\varepsilon\right)^3}$$

σ_{l0}, σ_ε, ω_{s0}: Zero current bunch length, energy spread and synchrotron (angular) frequency, I: Bunch current, h: Harmonic number, ω_0: Revolution (angular) frequency, φ_s: Synchronous phase

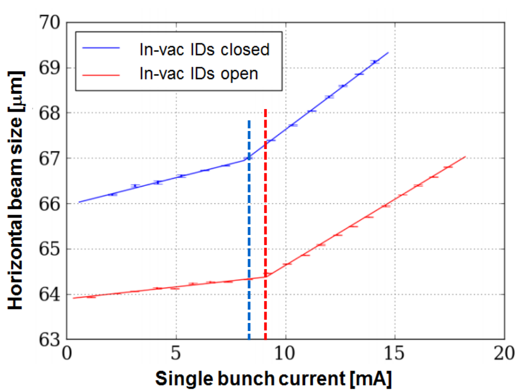
- If (above transition &) $\alpha > 0$, $Z_{inductive}$ lengthens the bunch
- If (above transition &) $\alpha < 0$, $Z_{inductive}$ shortens the bunch
- As many HBSLSs are interested in lengthening the bunch, the wake-induced lengthening should be beneficial
- Impact of PWD on microwave, head-tail, RW must be well understood, especially for HBSLSs that have small α or α < 0 due to antibends



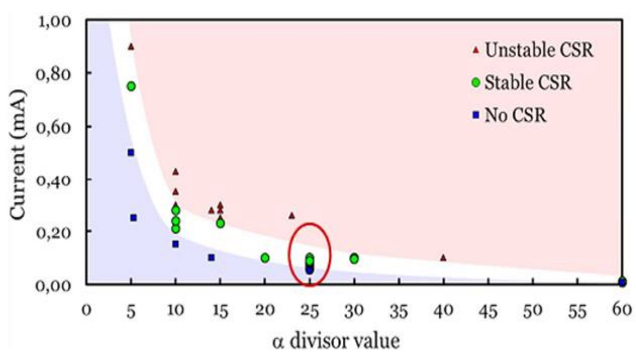
Bunch length and energy spread measured as a function of bunch current at APS (A. Lumpkin et al., NIM ***A393****, (1997) 50)*

3) Microwave and CSR instabilities

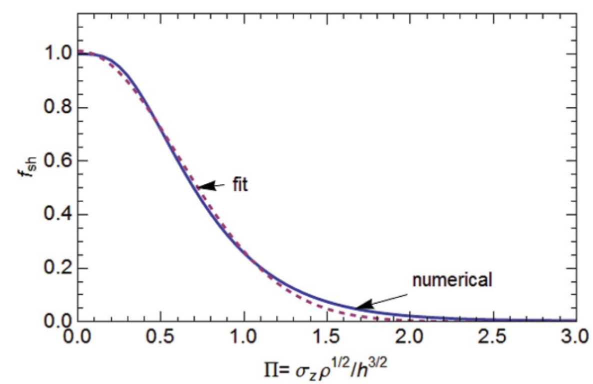
- Microwave instability is a longitudinal single bunch instability involving both energy spread widening and bunch lengthening (without beam losses)
- High frequency $\mathrm{Re}Z_{//}$ is considered responsible, which could either be $Z_{machine}$ and/or Z_{CSR}
- The instability must be avoided in HBSLSs that make use of higher harmonics of undulator spectra
- Threshold due to CSR lowers as α decreases
- Some of the running HBSLSs operate in low-α mode to produce CSR for users, but for future HBSLSs, such optics tuning may be difficult
- For HBSLSs in which *shielding* effectively works better (bending radius $\rho \rightarrow$ larger & vertical aperture $h \rightarrow$ smaller), the CSR instability should not be a big concern



Threshold measured (at SOLEIL) is considered to be due to CSR



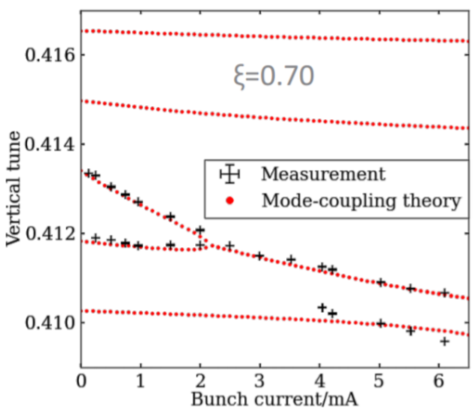
Single bunch CSR threshold versus α measured at SOLEIL (*Courtesy M.-A. Tordeux*)



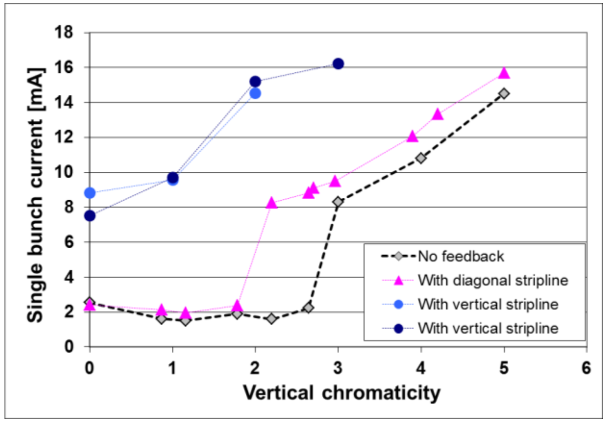
CSR-induced power (normalized) versus shielding parameter Π (K.L. Bane, TWIICE workshop, 2014)

5) TMCI, head-tail instabilities

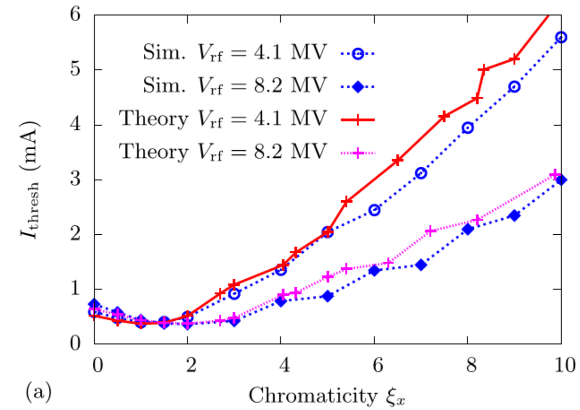
- For most HBSLSs, the TMCI threshold is fairly low
  - Strong detuning of mode 0 due to large $Z_{inductive}$ and $Z_{resistive}$ that couples modes 0 and -1
  - Origin of no coupling observed at MAXIV must be further investigated
- Shifting of the chromaticity ξ to larger positive values generally increases the threshold of head-tail instability (at the cost of losing the dynamic acceptance in most cases)
- Collective beam dynamics at high chromaticity and bunch current is more involved than the classical head-tail
  - Post head-tail theory developed at the ESRF (*Ph. Kernel et al., EPAC 2000*)
  - Recent study in the Fokker-Planck formalism (*R. Lindberg, PRAB **19**,124402 (2016)*)
  - For a HBSLS with $\alpha < 0$, the role of $\xi > 0$ and $\xi < 0$ changes



TMCI measurement at MAXIV, (G. Skripka et al, LER2016)



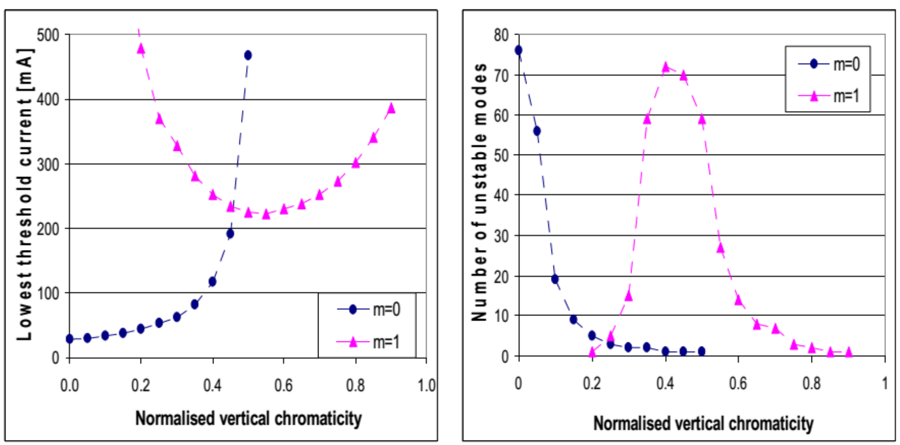
Threshold current versus ξ measured at SOLEIL



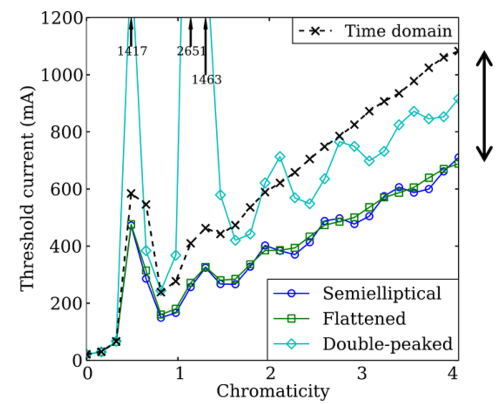
Study of high single current regime for APS-U by R. Lindberg

6) Resistive-wall (RW) instability

- A transverse multibunch instability driven essentially by Z_{RW} due to the long-range nature of Z_{RW}
- As the chamber aperture b tends to diminish for HBSLSs and $Z_{RW} \propto b^{-3}$, most HBSLSs are seriously impacted by this instability ($I_{threshold}$ usually very low)
- Thanks to the head-tail damping induced by Z_{BBR}, the instability (driven by lower-order head-tail modes) may be damped by shifting ξ to positive
- Bunch-by-bunch feedback generally works well in suppressing the instability
- Bunch lengthening by Harmonic Cavities (HC)s also appears effective in stabilizing the instability
  → Studies ongoing to clarify the physical mechanisms



Threshold and the number of unstable modes versus chromaticity estimated for SOLEIL (R. Nagaoka, EPAC 2006)

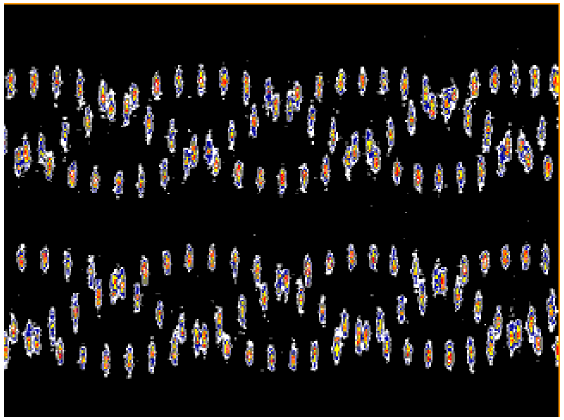


Time domain results give ~50% higher thresholds

Studies of the stabilising effect of HC lengthening on RW instability (F. Cullinan et al., PRAB ***19****,124401 (2016))*

7) Cavity HOM-induced instability

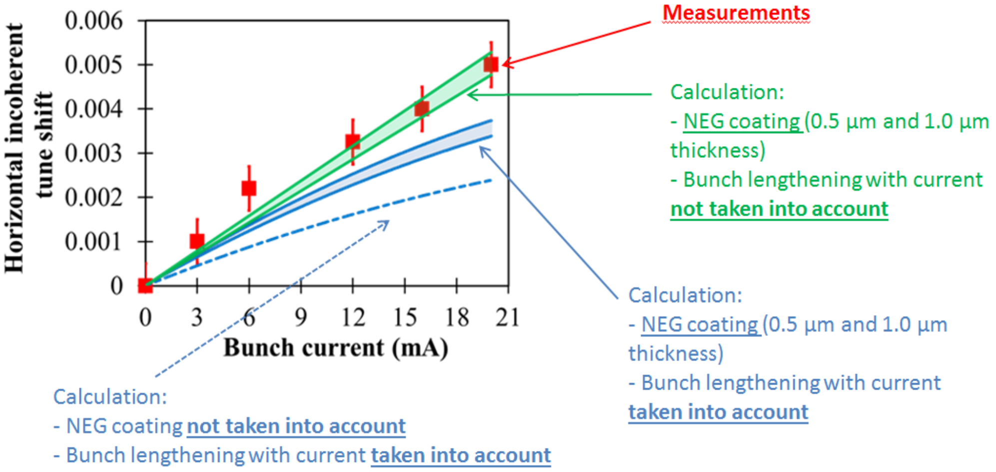
- Generally multibunch due to their long-range (High Q) nature
- Exist in both transverse & longitudinal planes and could induce beam losses
- Bench measurement of HOMs could give good predictions
- Temperature tuning of cavities, bunch-by-bunch feedback and bunch lengthening with HCs are known to be effective in suppressing the instability



Longitudinal coupled-bunch instability measured with a stream camera at the ESRF

8) Incoherent tune shifts due to non-circular RW chambers

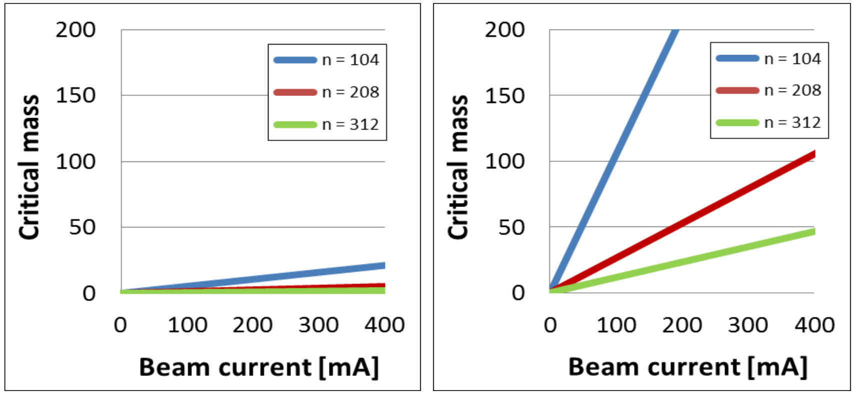
- Non-circular (flat) chambers induce quadrupole wakes
- Introduce non-negligible current-dependent optics distortions
- Studies made at SOLEIL indicate that the betatron tune shifts in an intense bunch of 20 mA attain nearly ***20 times larger*** tune shift than in multibunch at 500 mA
- NEG coating likely enhances tune shifts



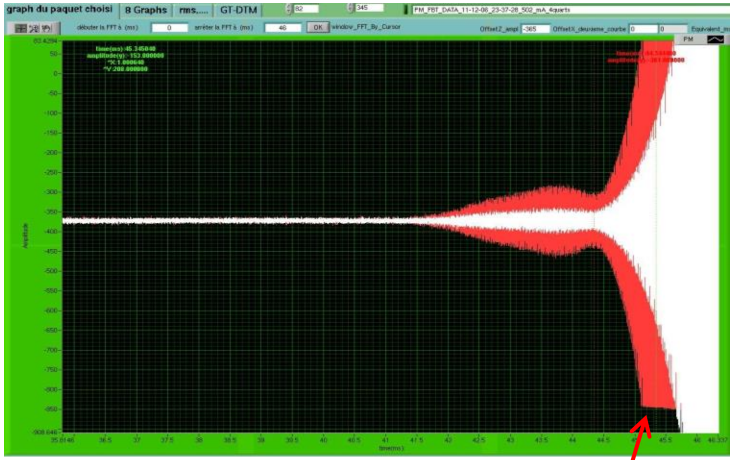
*(P. Brunelle et al., PRAB **19**,044401 (2016))*

9) Ion-induced instability

- Many 2nd generation SLSs (such as PF-KEK, NSLS-VUV ring, SuperACO, Aladin …) suffered from ion-trapping
- Ion trapping could induce beam blow-up, beam pulsation, reduction of lifetime, …
- Positron operation was considered (SuperACO, PF-KEK, APS, …) to avoid ion trapping
- Modern HBSLSs seem to suffer much less from ion trapping, due presumably to improved vacuum pressure and lower emittance
- For HBSLSs storing a high intensity and low emittance beam, however, a “single pass” interaction (FBII) between the two beams may become strong enough to jeopardise the performance.
- At SOLEIL, FBII arises due to local outgassing produced by beam-induced heating of vacuum components and provokes beam losses



Critical mass calculated for SOLEIL.
Left: ε_H = 4 nm. Right: ε_H = 200 pm.



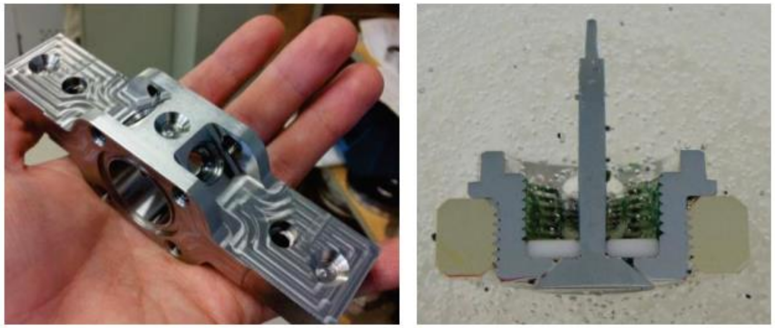
Measured beam loss at 500 mA
***White**: Beam,* ***Red**: TFB kick*

feedback saturation

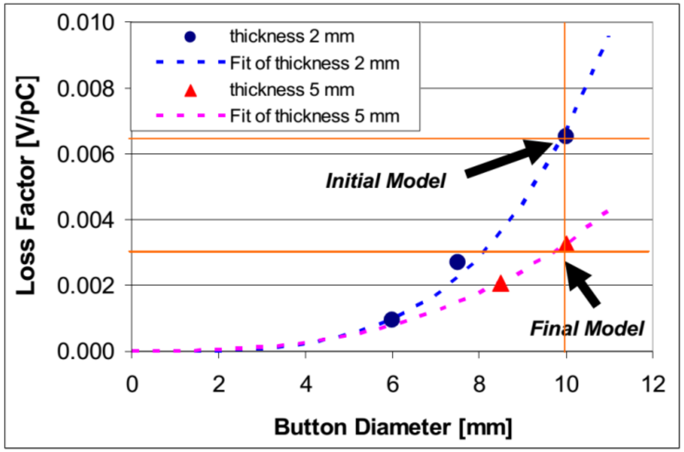
3. 2 Mitigations

1) Minimization of coupling impedance

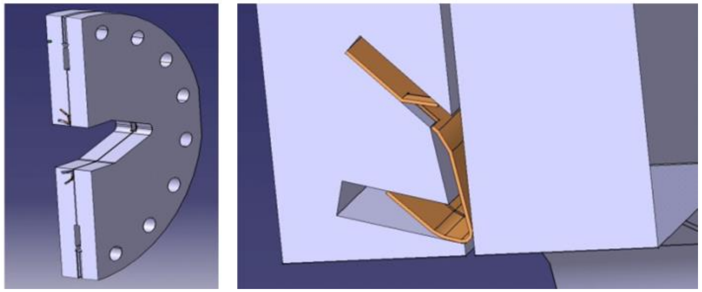
Some typical examples:



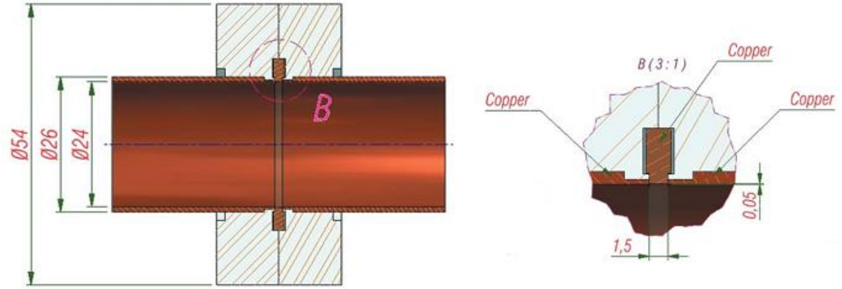
Bell-shaped BPM button developed at SIRIUS, optimized to increase the button cut-off frequency without losing the button sensitivity (A.R.D Rodrigues et al., IPAC2015).



Original design (at SOLEIL) created a too large k_{loss} due to trapped modes → Button thickness was increased to reduce k_{loss} by a factor of 2, instead of reducing the button diameter (R. Nagaoka et al., EPAC2006)



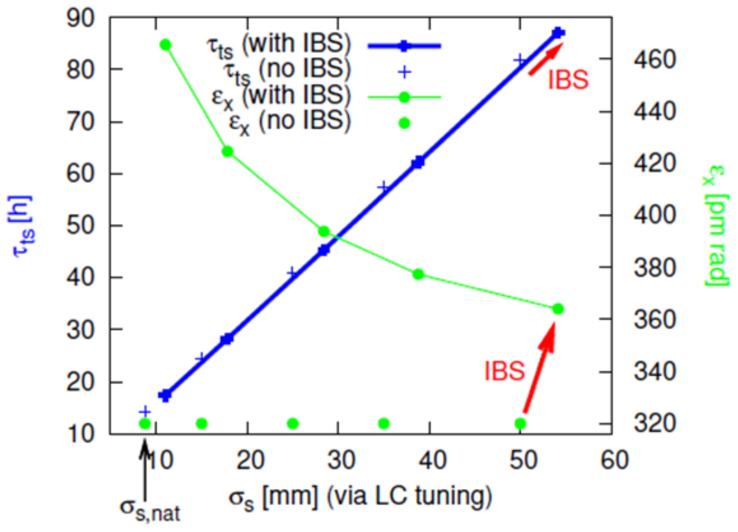
Short-circuited flange developed at SOLEIL. The metallic sheet (green) inserted between the two plates effectively shields the cavity-like structure (R. Nagaoka et al., EPAC2004).



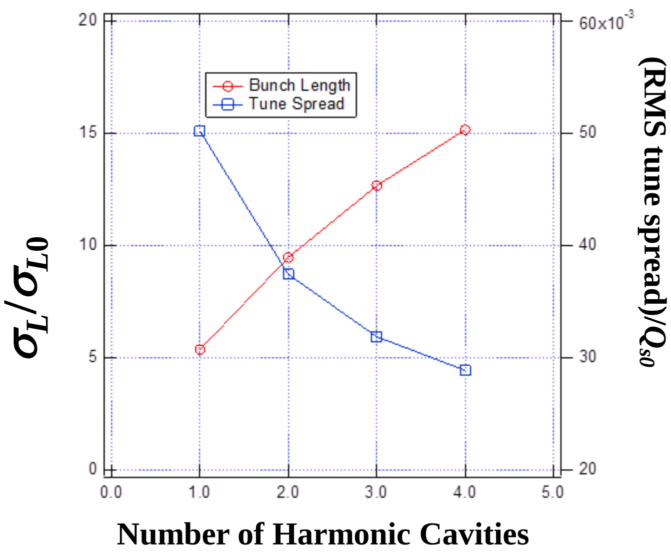
"Zero-impedance" flange developed at SIRIUS (R.M. Seraphim et al., IPAC2015)

2) Bunch lengthening cavities

- For ultra-low emittance HBSLSs, this seems to be the only way to fight against IBS
- Helps increase Touschek lifetime simultaneously in many situations
- Longitudinal tune spread and bunch lengthening appear to have significant stabilizing effects against instabilities → Studies ongoing
- Unsymmetrical beam fillings necessary for certain operations (e.g. ion clearing gap) may not be compatible with passive HCs due to transient beam loading
- Studies ongoing to pursue the limit of bunch lengthening factor beyond 5 aimed by MAXIV



IBS in the present MAXIV ring, plot by S.Leemann,MAX-lab Internal Note 201211071 (P. Tavares, LERD2016)

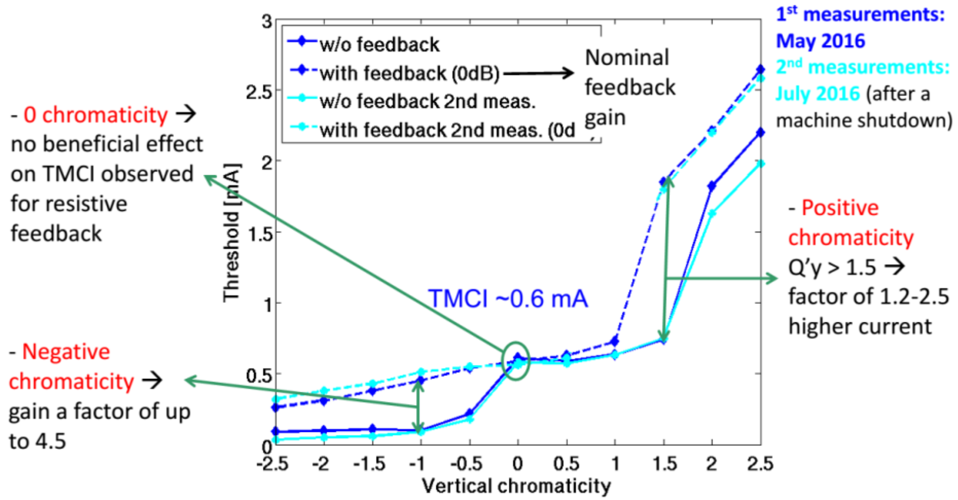


Studies of bunch lengthening factor beyond the factor of 5 at MAXIV, (P. Tavares, LERD2016)

3) Bunch-by-bunch feedback

- One of the efficient methods in suppressing beam instabilities driven by dipolar CM motions:
  - Longitudinal: HOM-driven coupled-bunch
  - Transverse: TMCI, head-tail (low-order), RW, HOM-driven coupled-bunch, beam-ion, …
- Technology is well established in fast detection of CM, signal processing (processors available on the market), and deflection
- Feedback performance appears to be generally satisfactory against RW instability at high current multibunch:
- In single bunch, the performance appears to depend much on the nature of instability
  → More studies required

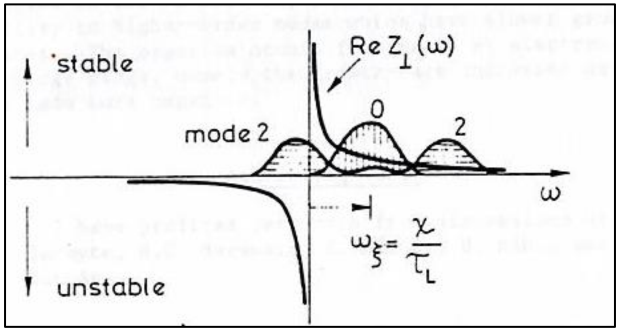
Vertical single bunch instability thresholds



Recent experimental/numerical studies made at DIAMOND (E. Koukovini-Platia et al., LER2016)

4) Chromaticity shifting

Positive effects	Negative effects
Damps lower-order head-tail modes (m = 0, -1, …)	Excites higher-order headtail modes Reduces dynamic acceptances → · Poorer injection rate · Touschek lifetime drops
Promotes Landau damping due to tune spreads $\Delta\nu = \xi\cdot(\Delta p/p)$	Loss of CM motions →
Increases certain instability thresholds	Reduces of feedback efficiency

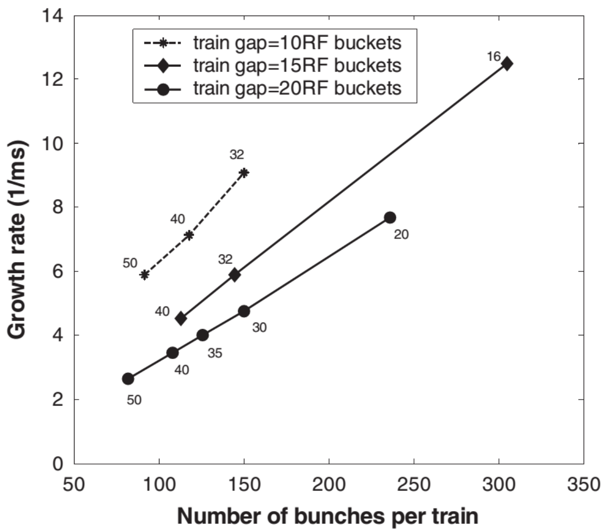


(Laclare, J. L. "Bunched Beam Coherent Instabilities",CERN 87–03)

If $\alpha < 0$ → $\xi < 0$ gives head-tail damping

5) Beam filling with gaps

- A large enough gap clears trapped ions
- Division of a bunch train into many short pieces with a certain gap in between suppresses Fast Beam-Ion Instability (FBII) (*cf. right figure*)
- With passive Harmonic Cavities (HC)s, unsymmetrical fills may induce transient beam loading and may not be compatible with bunch lengthening constraints



Simulation studies of FBII
(*L. Wang et al., PRSTAB* ***14****, 084401 (2011)*)

4. Summary

- There are clear reasons for which, the efforts of lowering the beam emittance to diffraction-limited regime enhance the beam sensitivity to collective effects.

  $\Rightarrow$ Mastering the concerned physical mechanisms and taking the countermeasures becomes of critical importance already from the design stage

- Specifically, the following collective effects are likely to be particularly threatening:
  - IBS/Touschek
  - Beam-induced heating
  - Microwave instability
  - Transverse single- and multibunch instabilities

- Bunch lengthening with HCs, bunch-by-bunch feedback appear to be indispensable mitigating methods, along with continued efforts of minimizing the coupling impedance.

- Associated with more stringent conditions imposed in raising the machine performance, especially in terms of beam properties and the machine impedance, different collective effects tend to appear simultaneously and create complicated combined effects (*both positive and negative*), and even possibly a new type of instability.