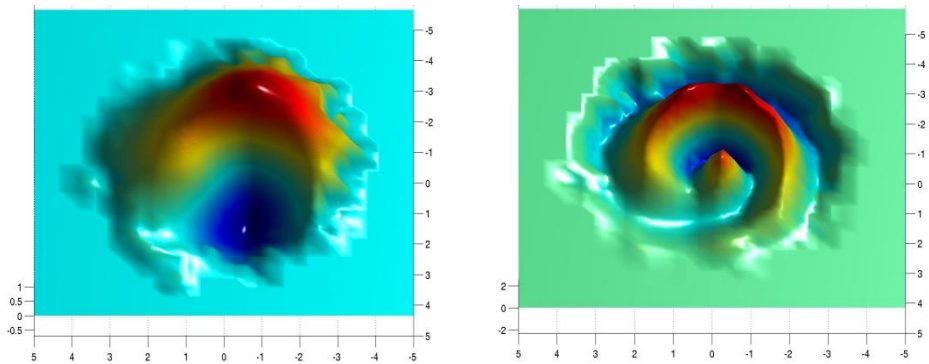
Collective Instabilities in Low Emittance Rings



Joint Workshop on Future Tau-Charm Factory
4-7 December 2018, LAL, Orsay, France

Ryutaro Nagaoka (Synchrotron SOLEIL)

Content:

1. **Introduction: Low emittance rings and collective effects**
2. **Instability driving impedances**
3. **Concerned collective effects/instabilities and their mitigations**
4. **Summary**

Acknowledgement :

RN thanks Marica Biagini (INFN) and Eugene B. Levichev (BINP) for the opportunity to give this talk at the Joint Workshop on Tau-Charm Factory at LAL. He thanks his colleagues in the accelerator physics group at SOLEIL, Christian Herbeaux, Amor Nadji, Alex Chao, Karl Bane, Francis Cullinan, Galina Skripka, Pedro Tavares, Eirini Koukovini and Naoto Yamamoto for helpful discussions.

1. Introduction: Low emittance rings (LERs) and collective effects

Whether it is a storage ring for beam collision in high energy physics or for synchrotron radiation, the beam intensity generally constitutes one of the main axes in raising its performance:

$$Luminosity = \frac{N_1 \cdot N_2 \cdot f \cdot n_b}{4\pi \ \sigma_x \sigma_y}$$

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

N_i : Number of particles in a bunch, f : Revolution frequency, n_b : Number of bunches, σ_u : Transverse beam size, I : Beam current, ε_u : Transverse emittance

- Inversely proportional to the product of e-beam transverse emittances
- Linearly proportional to the e-beam intensity

➔ **We want (ultra-) low emittance & high stored beam intensity**

⇒ Constant desire for higher beam intensities → Effectively beam instabilities issues persist endlessly. Besides, recent efforts to lower further the beam emittance effectively enhance beam sensitivity to collective instabilities.

Impact of LER designs on collective effects

- Basic principle for low emittance: $\left(\varepsilon_H\right)_{Minimum}^{Theoretical} \propto 1/N^3$

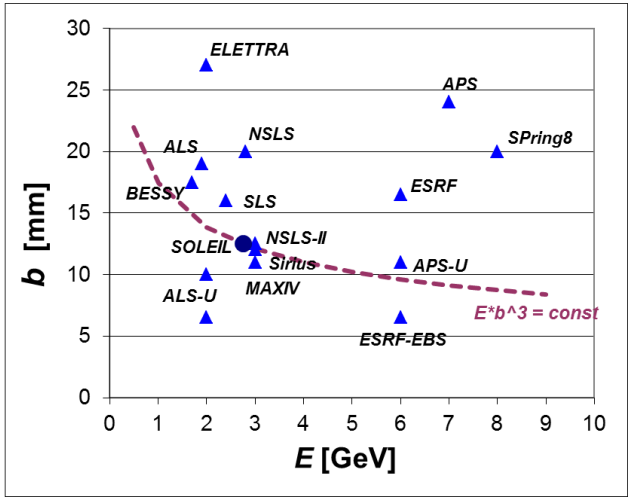
  → MBA (Multiple Bend Achromat) instead of DBA, TBA (trend in light sources)

- Need to approach the TME condition in every dipoles

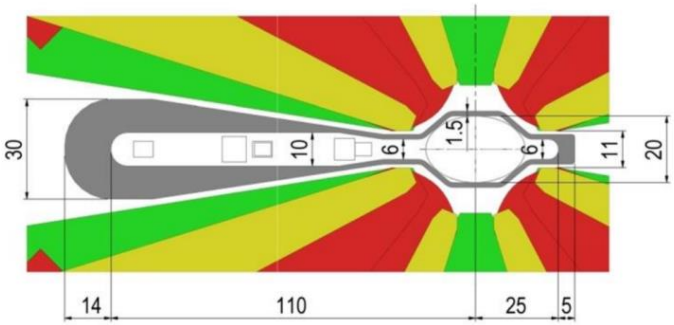
  → Strong distributed quad focusing (in the range of **100 T/m**)

  → Reduced magnet bore radii → Small beam duct half aperture b

  → Poorer vacuum conductance → NEG coating



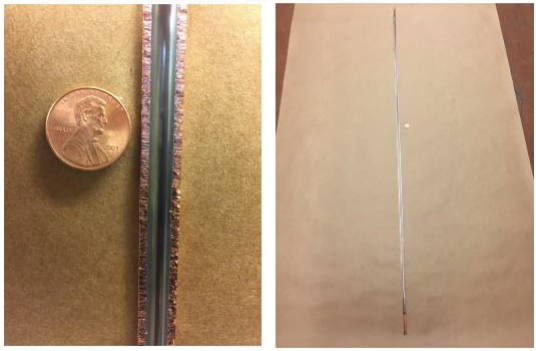
Local vertical half aperture b adopted in several existing and future light sources versus their machine energies



*For ESRF-EBS, the imposed 11mm pole to pole distance for all magnets **optimized for synchrotron radiation handling***

(from P. Raimondi, LER2016, Oct. 2016)

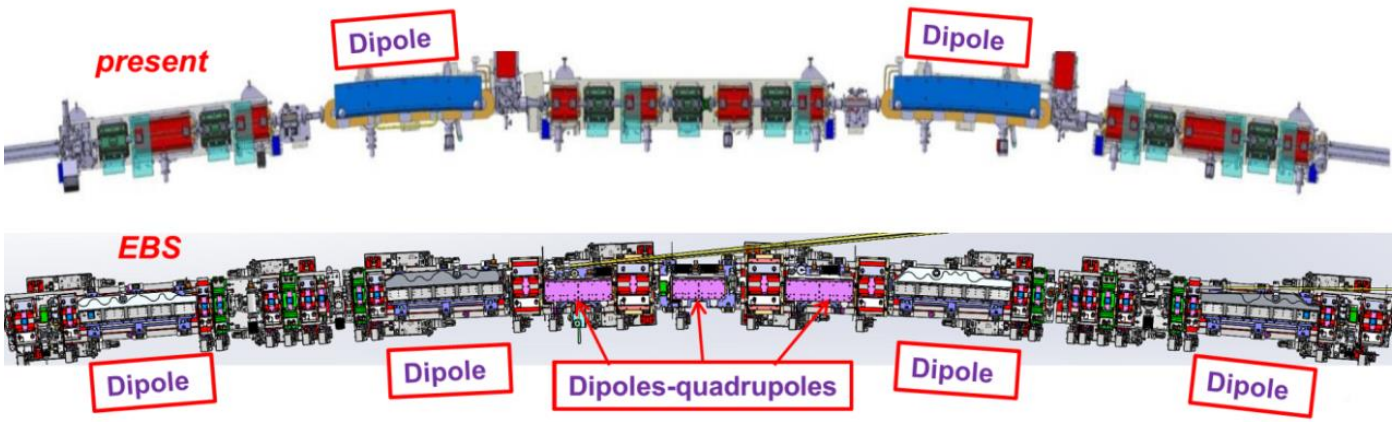
Very small NEG coated vacuum chambers



Coated 6 mm chamber (world record)

(*D. Robin, LER2016, SOLEIL*)

◊ LERs generally requires the magnet lattice to be tightly packed with dipoles, quadrupoles, sextupoles and plus all other standard elements such as flanges, BPMs, …



Comparison between ESRF and ESRF-EBS, (M. Hahn, 3ème Rencontres Nationales du Réseau Technologies du Vide, Oct. 2016)

◊ Chain of consequences and tendencies on stored beam dynamics:

- Approaching TME → low D_H, α, J_x, J_s, high *chromaticities*, … → Strong sextupoles → Small DA → On-axis injection, Swap-out
- Low emittance → Significant IBS, Touschek effects → Bunch lengthening with Harmonic Cavities (HCs)

◊ Likely impact on collective effects:

- Enhanced impedance Z due to smaller b's and to NEG coating (to be addressed again later)
- HC potential on coherent instabilities
- Transient beam loading effect of HCs on low-emittance beam
- Longer L-radiation damping time $(\tau_L)_{damping}$ if J_x is manipulated to increase

2. Characteristics of the resultant impedances

◊ 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)

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

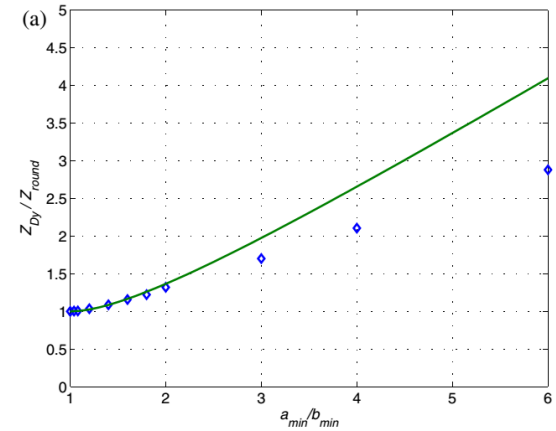
⇒
- Due to reduced b, larger relative contributions of tiny slits, holes, steps, …
- Tapers for low gap IDs may have relatively reduced contributions due to overall reduced aperture b
- An enhanced contribution of Z_{RW} is inevitable

◊ 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, …)



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

Impedance model summary for APS-U

Impedance source	Number	$\Im(Z_{\parallel})/n$ (Ω)	$k_{\rm loss}(\sigma_t = 50$ ps) (V/pC)
BPM-bellows	560	0.048	0.090
In-line absorber	760	0.060	0.045
Gate valve	160	0.020	0.002
Flange	1880	0.011	$< 10^{-3}$
ID transition	40	0.0018	$< 10^{-3}$
Crotch absorber	80	0.0070	0.002
Pumping cross	200	0.0015	$< 10^{-3}$
Inj/ext kickers	8	0.0075	0.94
Small-gap ID BPM	30	0.0013	0.008
352 MHz rf-cavity	10	0.001	3.8
Rf transitions	3	0.018	0.84
Resistive wall	NA	NA	2.18
Total	NA	0.18	7.9

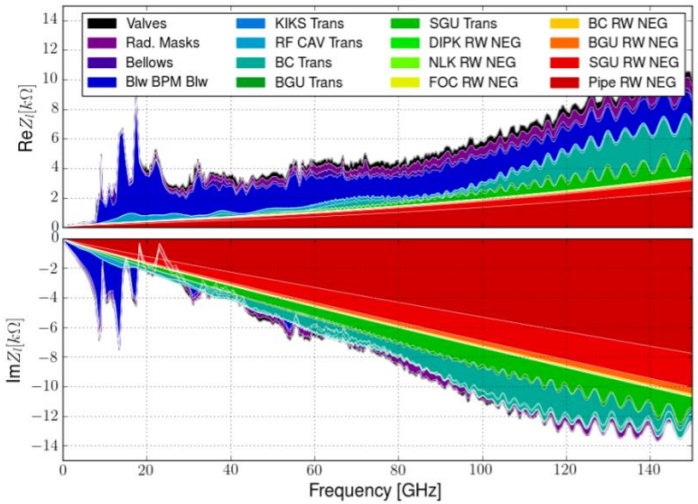
- Dominant source of transverse impedance is from the resistive wall of the narrow-gap ID chambers
- In-line photon absorbers are the second largest transverse impedance source

R. Lindberg, LER2018, CERN

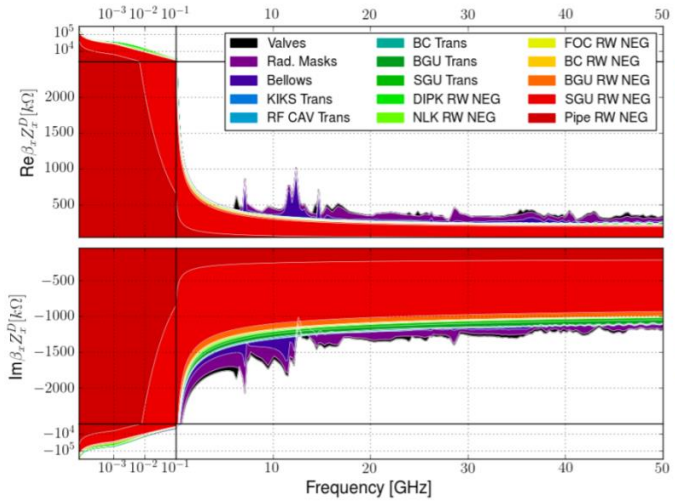
◊ Numerical evaluation of impedances /Construction of impedance budget:

- 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 (*Campinas, Brazil*):



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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Bellows	80	6.6	8.8
Rad. Masks	350	6.6	11.0
Valves	40	6.6	11.0

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

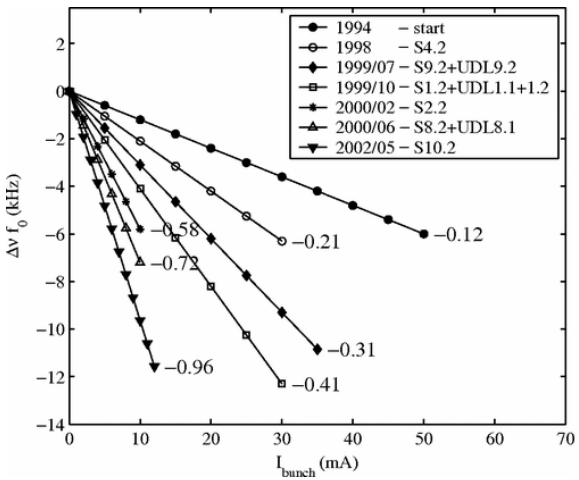
◊ Impedance of NEG coated chambers:

- For LERs that require narrow beam pipes, vacuum pumping with NEG is very helpful
  ⇒ Successfully applied to ESRF, ELETTRA, SOLEIL, MAXIV, …
  ⇒ Characteristics of Z_{NEG} must be well understood

- Early studies indicated that ~1 μm thick NEG coating has an effect;

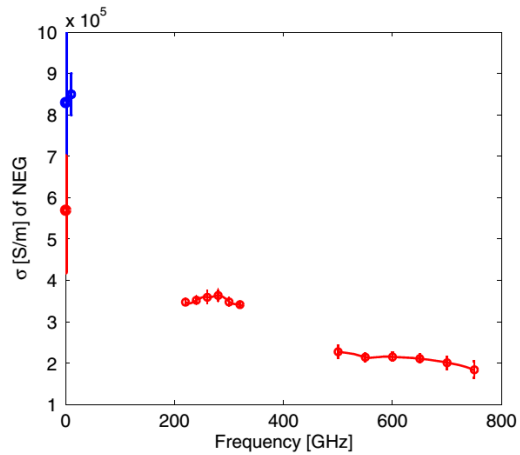
$$(\mathrm{Re}Z)_{NEG} \approx (\mathrm{Re}Z)_{substrate}, \qquad (\mathrm{Im}Z)_{NEG} \approx 2\times(\mathrm{Im}Z)_{substrate}$$

  in the frequency range below ~20 GHz, when the resistivity $\rho_{NEG} > \rho_{substrate}$
  ⇒ 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



Measured increase of $Z_{\perp}$ with NEG coated chambers

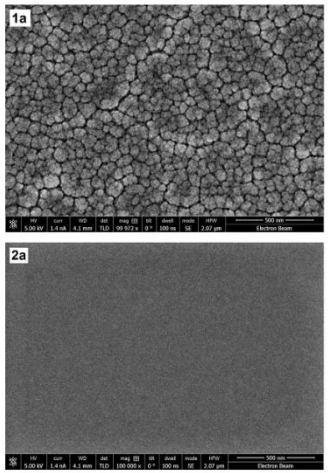
*E. Karantzoulis et al., PRSTAB **6**, 030703*



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

"columnar"

"dense"



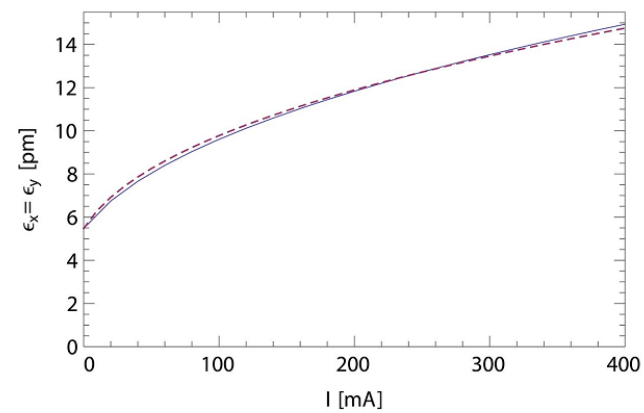
*Experimental study of surface resistivity of two types of NEG (O. B. Malyshev et al., NIM **A844** (2017) 99–107)*

3. Concerned collective effects/instabilities and their mitigations

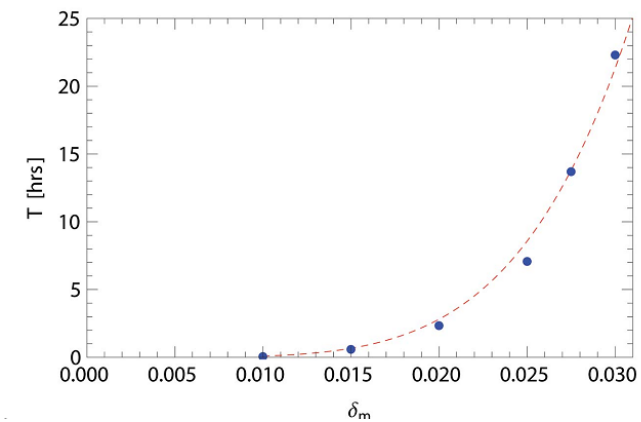
3. 1 Instabilities and collective effects

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 LERs storing high (bunch) current.
- Many future LERs consider making a beam ***round*** and/or ***long*** (via harmonic cavities) to minimize the effect (*as well as that of Touschek*).
- Touschek scattering is a large angle single Coulomb scattering. Energy transfer from transverse to longitudinal → may induce immediate particle losses. For LERs, 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 $(\Delta p/p)_{accep}$.



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



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*)

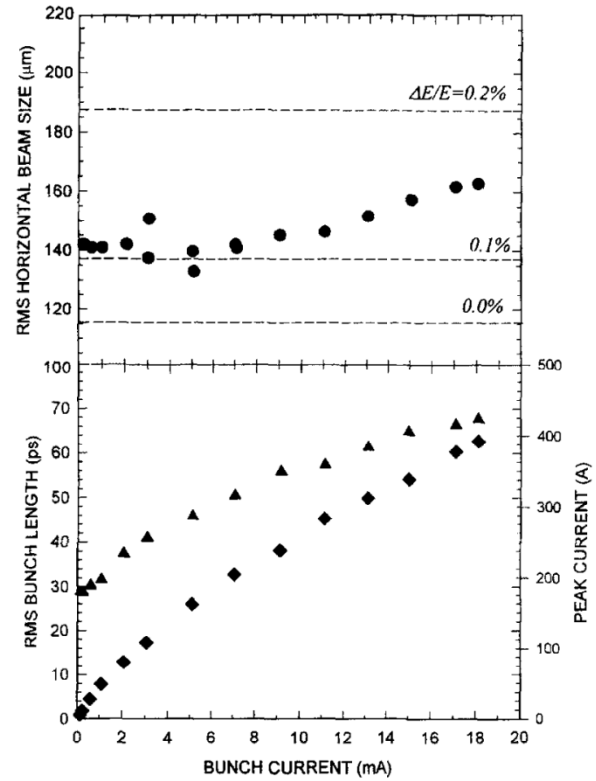
2) Bunch lengthening

- 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

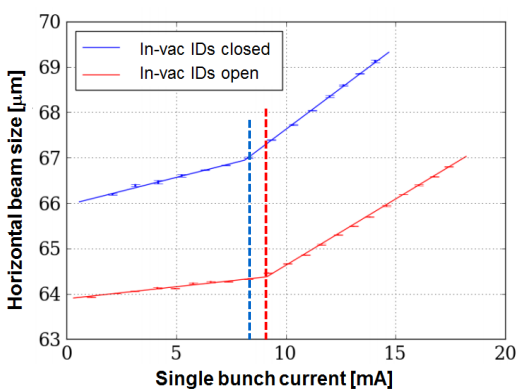
- If (above transition &) $\alpha > 0$, $Z_{inductive}$ lengthens the bunch
- If (above transition &) $\alpha < 0$, $Z_{inductive}$ shortens the bunch
- As many LERs are interested in lengthening the bunch, the wake-induced lengthening should be beneficial
- Impact of PWD on microwave, head-tail, RW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



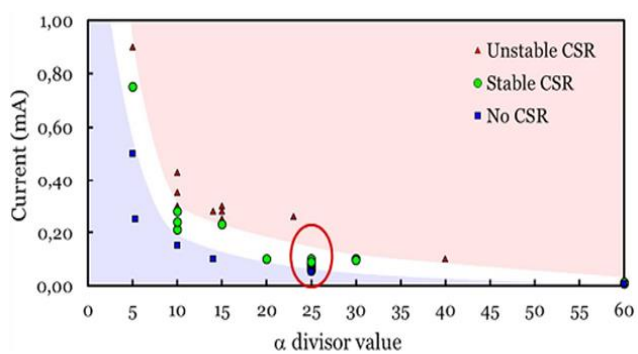
*Bunch length and energy spread measured as a function of bunch current at APS (A. Lumpkin et al., NIM **A393**, (1997) 50)*

3) Microwave and CSR instabilities

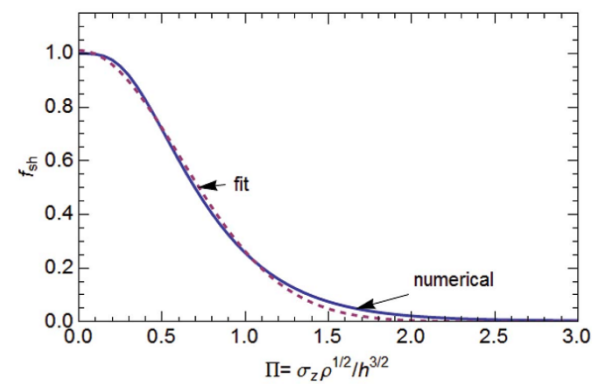
- Microwave instability is a longitudinal single bunch instability involving both energy spread widening and bunch lengthening (without beam losses)
- High frequency $\mathrm{Re}Z_{//}$ is considered responsible, which could either be $Z_{machine}$ and/or Z_{CSR}
- The instability must be avoided in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



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



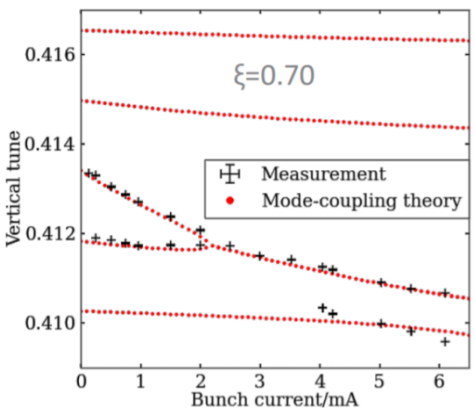
Single bunch CSR threshold versus α measured at SOLEIL (*Courtesy M.-A. Tordeux*)



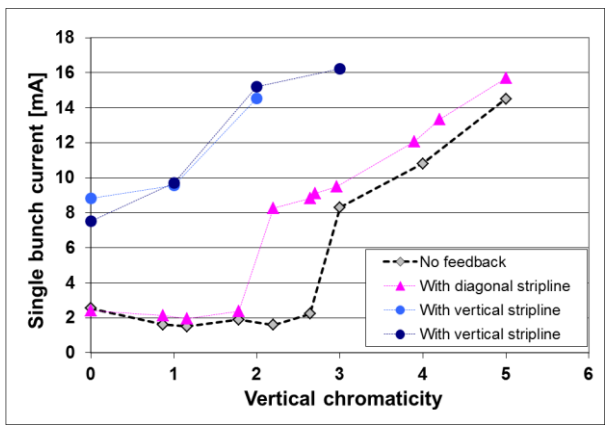
CSR-induced power (normalized) versus shielding parameter Π (K.L. Bane, TWIICE workshop, 2014)

5) TMCI, head-tail instabilities

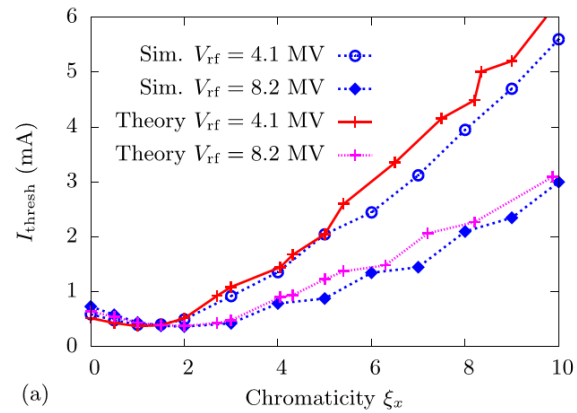
- For most LERs, the TMCI threshold is fairly low
  - Strong detuning of mode 0 due to large $Z_{inductive}$ and $Z_{resistive}$ that couples modes 0 and -1
  - Origin of no coupling observed at MAXIV must be further investigated
- Shifting of the chromaticity ξ to larger positive values generally increases 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 LER with $\alpha < 0$, the role of $\xi > 0$ and $\xi < 0$ changes



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



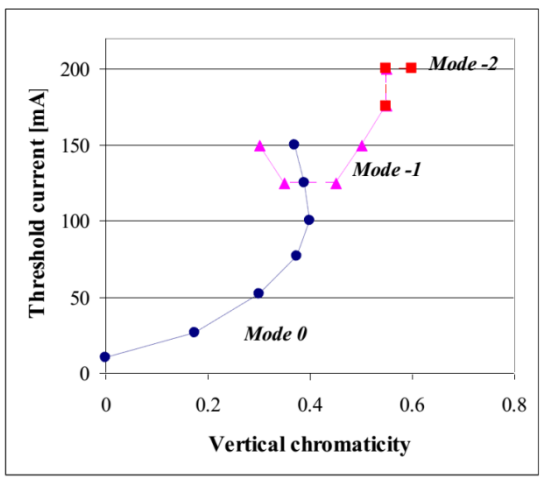
Threshold current versus ξ measured at SOLEIL



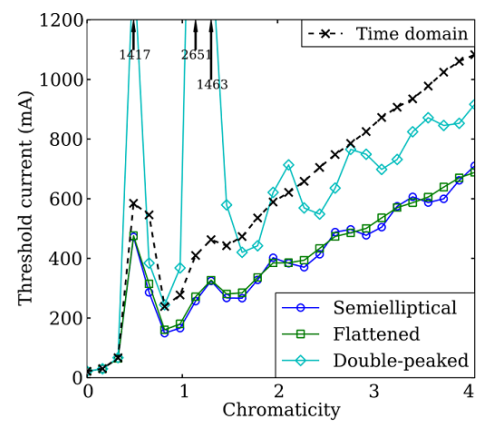
Study of high single current regime for APS-U by R. Lindberg

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 LERs and $Z_{RW} \propto b^{-3}$, most LERs 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



Measured vertical resistive-wall instability threshold versus chromaticity at the ESRF (R. Nagaoka, ESRF, 2002)

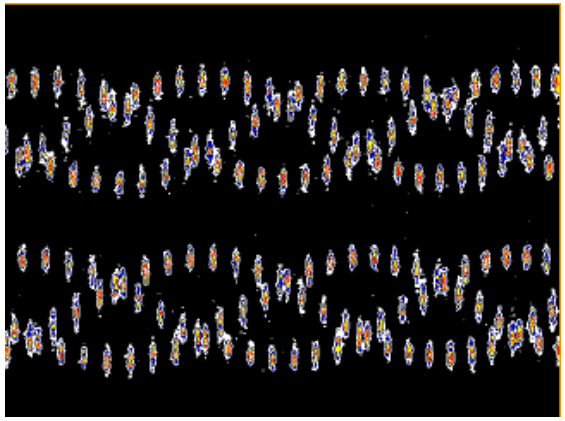


Time domain results give ~50% higher thresholds

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

7) Cavity HOM-induced instability

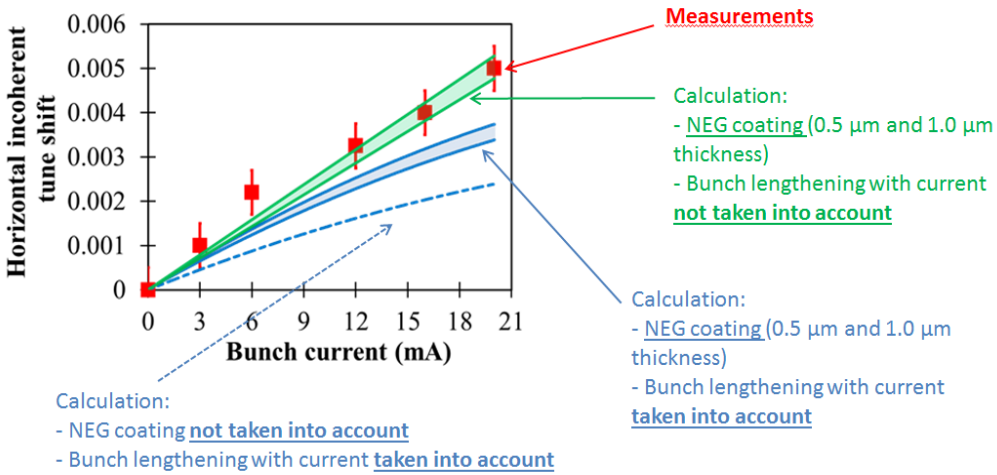
- Generally multibunch due to their long-range (High Q) nature
- Exist in both transverse & longitudinal planes and could induce beam losses
- Bench measurement of HOMs could give good predictions
- Temperature tuning of cavities, bunch-by-bunch feedback and bunch lengthening with HCs are known to be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

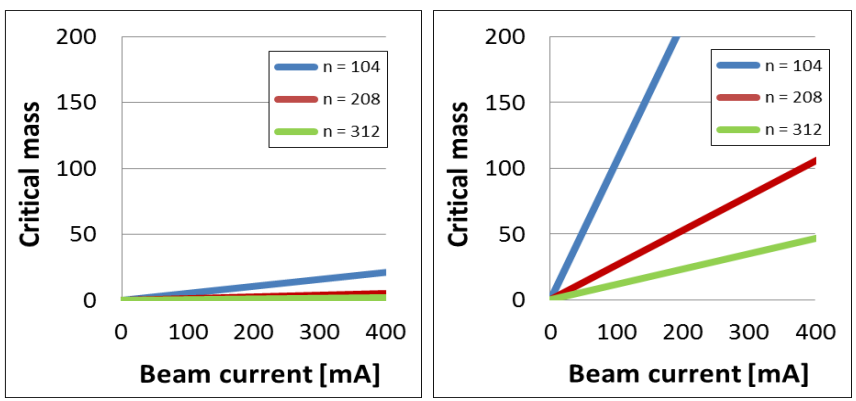
- Non-circular (flat) chambers induce quadrupole wakes
- Introduce non-negligible current-dependent optics distortions
- Studies made at SOLEIL indicate that the betatron tune shifts in an intense bunch of 20 mA attain nearly ***20 times larger*** tune shift than in multibunch at 500 mA
- NEG coating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



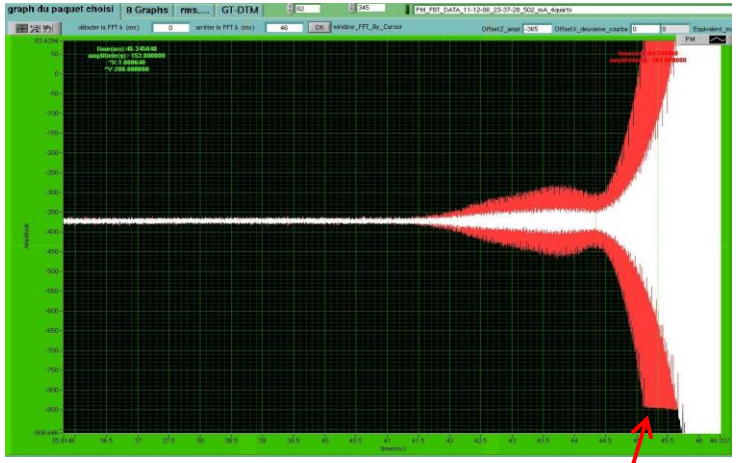
*(P. Brunelle et al., PRAB **19**,044401 (2016))*

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 LERs seem to suffer much less from ion trapping, due presumably to improved vacuum pressure and lower emittance
- For LERs 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.



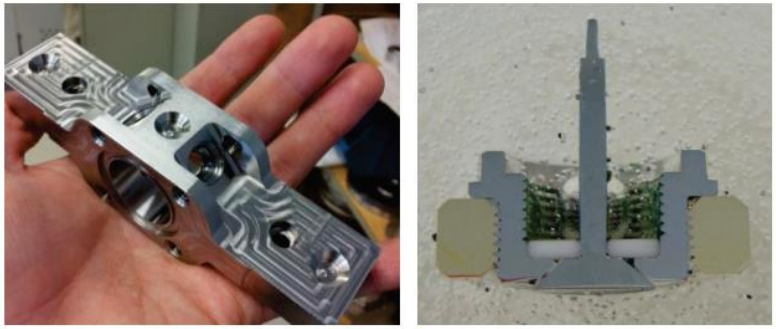
Measured beam loss at 500 mA
***White**: Beam,* ***Red**: TFB kick*

feedback saturation

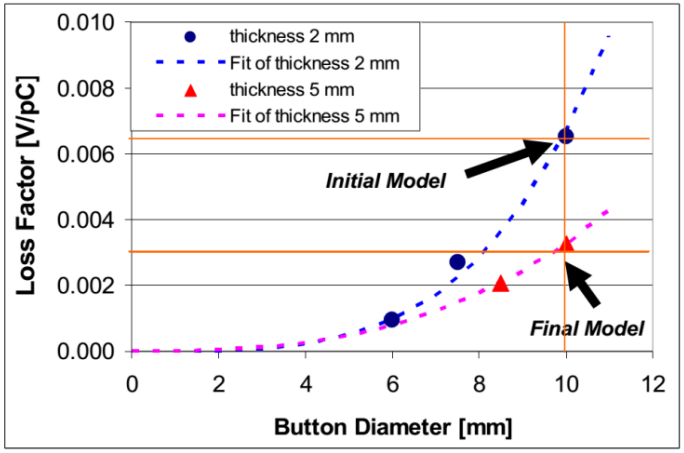
3. 2 Mitigations

1) Minimization of coupling impedance

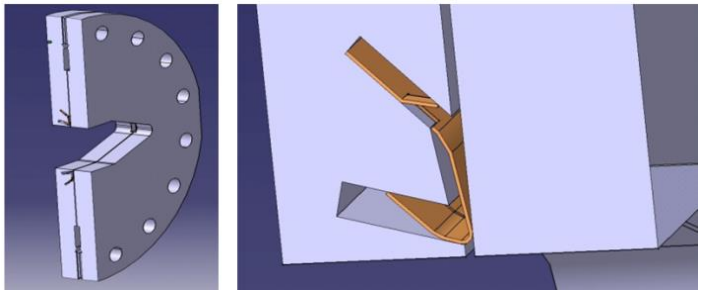
Some typical examples:



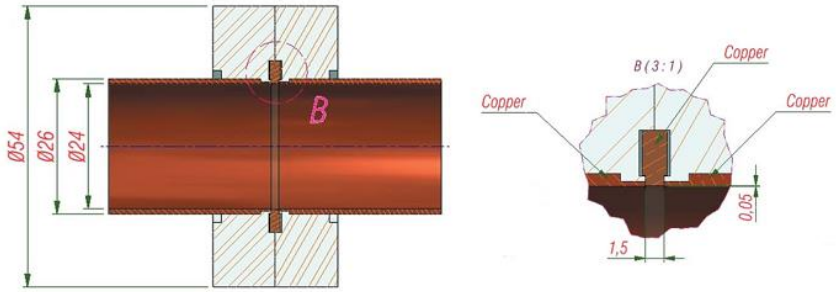
Bell-shaped BPM button developed at SIRIUS, optimized to increase the button cut-off frequency without losing the button sensitivity (A.R.D Rodrigues et al., IPAC2015).



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)



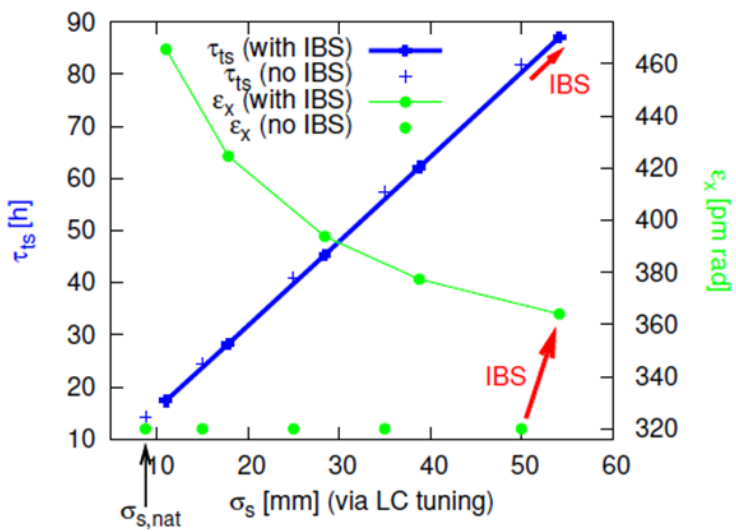
Short-circuited flange developed at SOLEIL. The metallic sheet (green) inserted between the two plates effectively shields the cavity-like structure (R. Nagaoka et al., EPAC2004).



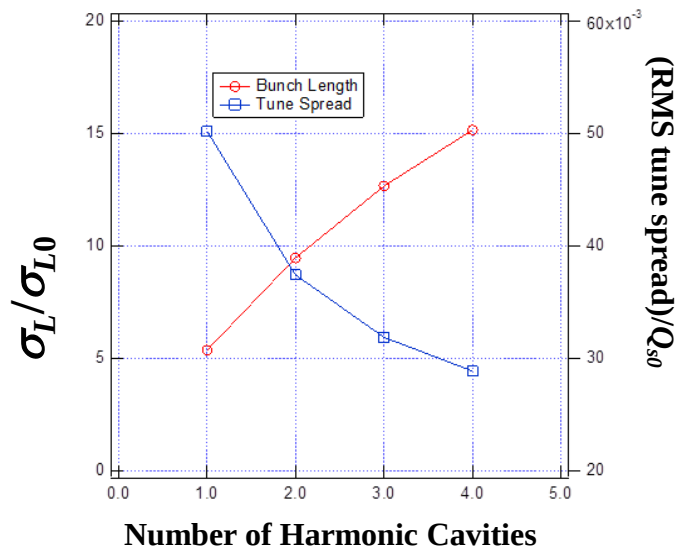
"Zero-impedance" flange developed at SIRIUS (R.M. Seraphim et al., IPAC2015)

2) Bunch lengthening cavities

- For ultra-low emittance LERs, 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 (especially passive) HCs due to transient beam loading
- Studies ongoing to pursue the limit of bunch lengthening factor beyond 5 aimed by MAXIV



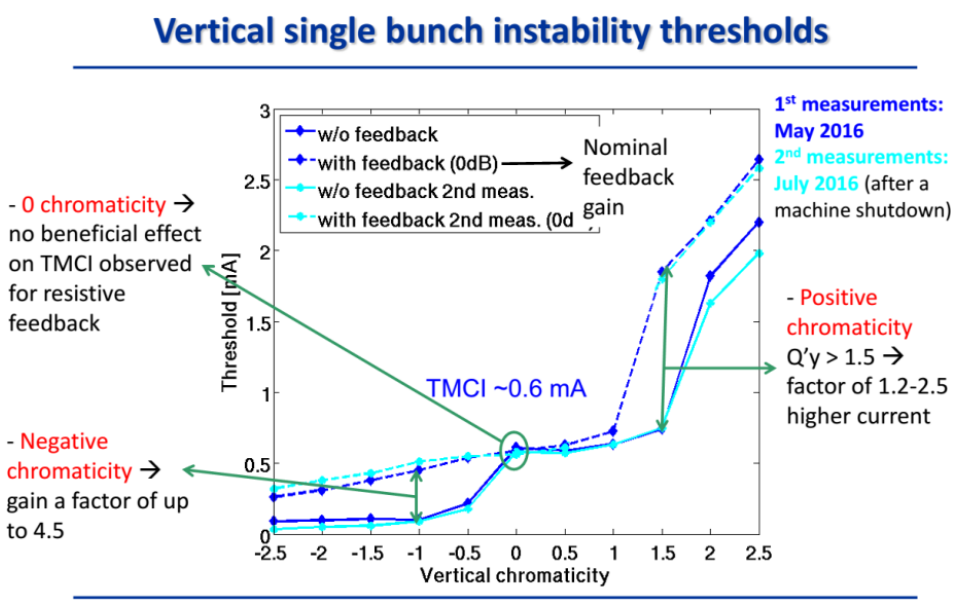
IBS in the present MAXIV ring, plot by S.Leemann,MAX-lab Internal Note 201211071 (P. Tavares, LERD2016)



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

3) Bunch-by-bunch feedback

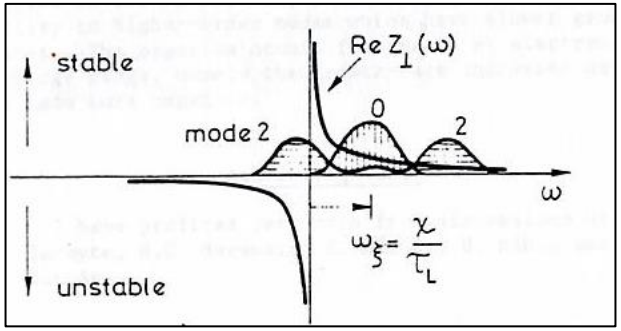
- One of the efficient methods in suppressing beam instabilities driven by dipolar CM motions:
  - Longitudinal: HOM-driven coupled-bunch
  - Transverse: TMCI, head-tail (low-order), RW, HOM-driven coupled-bunch, beam-ion, …
- Technology is well established in fast detection of CM, signal processing (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



Recent experimental/numerical studies made at DIAMOND (UK) (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 → Reduces of feedback efficiency
Increases certain instability thresholds	

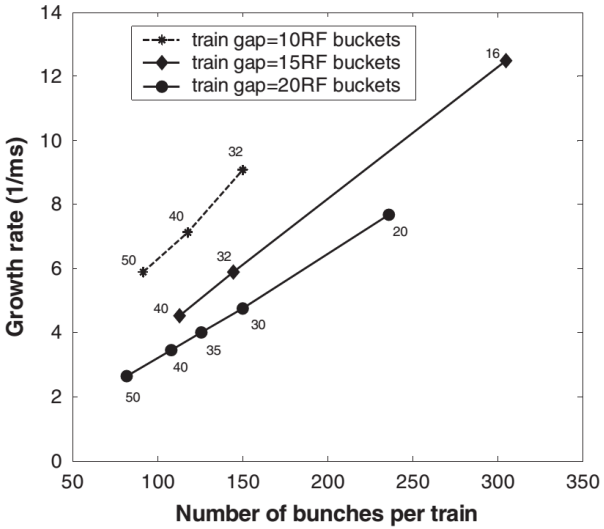


(Laclare, J. L. "Bunched Beam Coherent Instabilities",CERN 87–03)

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.