LEL Designs and Collective Effects

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<u>Content</u>:

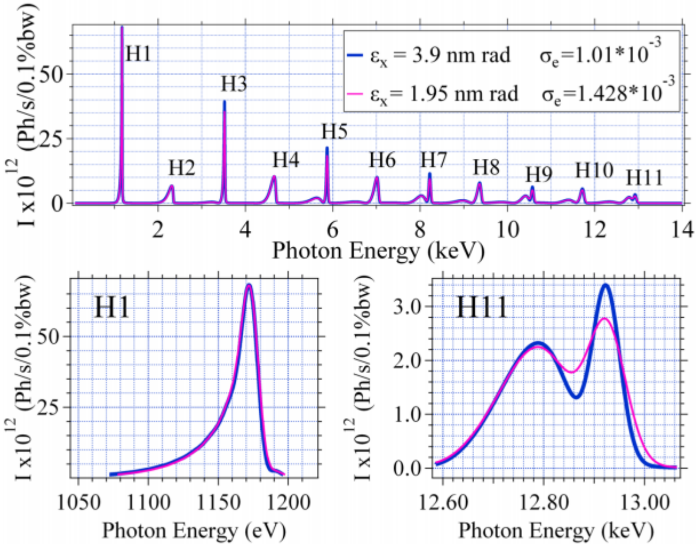
<u>Acknowledgement</u>:

RN thanks Pedro Tavares (MAXIV) for having provided his recent results on harmonic cavity bunch lengthening and K. Bane for his help.

1. Impact of LEL on Collective Effects and Impedance

◊ Impact of collective effects on a given machine may differ significantly from one to another depending on the machine parameters and the intended modes of operation:

- Energy dependence
  - Beam rigidity (instability growth rate $\propto 1/E$)
  - Radiation damping (effectively $1/\tau \propto E$)
  - IBS, Touschek scattering (stronger as E decreases)
- Machine scale dependence
  - Shorter total dipole length → smaller radius of curvature → stronger radiation damping
- Machine operational aspect
  - Multibunch versus high current per bunch oriented
  - Use of higher harmonics of undulator spectra
  - Short-bunch versus long bunch

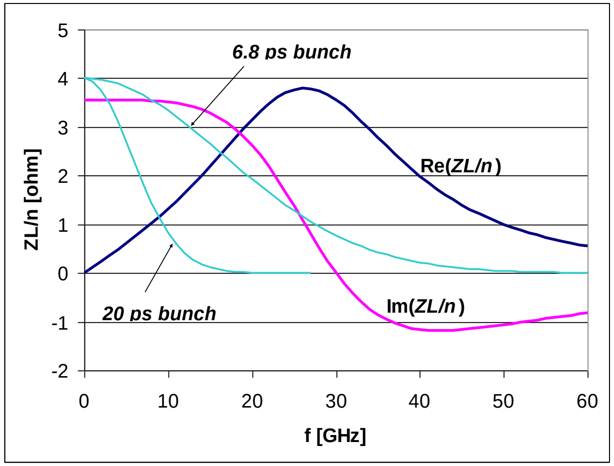


Flux calculation with SRW for U20 through an aperture 0.1×0.1 mm² located at 10 m from the source (H. Abualrob et al., IPAC 2012)

"Degradation of undulator higher-harmonic spectra with beam energy spread widening"

◊ LEL’s general influence on collective effects:

Lower emittance → MBA → Low dispersion → low alpha → shorter natural bunch length → higher sensitivity against wakes



Interaction of 6.8 ps and 20 ps bunches with 30 GHz BBR impedance

Ex). Transverse coherent detuning:

$$\frac{df_\beta}{dI} = -\frac{\beta}{8\pi^{3/2}\sigma_\tau E/e}\cdot \mathrm{Im}(Z_T)_{eff}$$

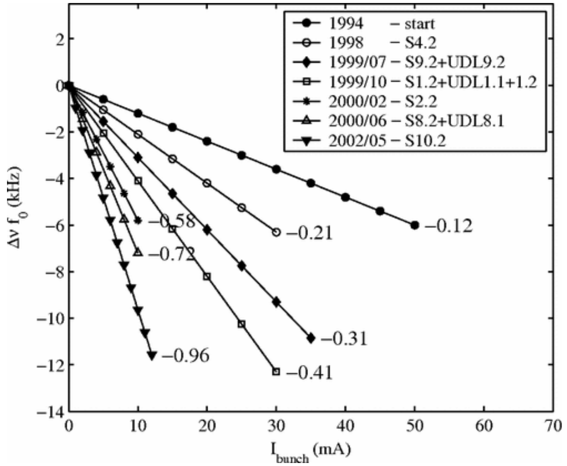
Additional likely MBA aspects:

- Weaker dipole fields → Larger bending radius → Weaker radiation damping
- Transverse gradient in dipoles → Increased damping partition J_e
  → Reduced longitudinal damping rate

Low emittance → Higher quadrupole and sextupole fields → Reduced bore radii
→ Reduced vacuum chamber half aperture b → Stronger wake fields (impedance)

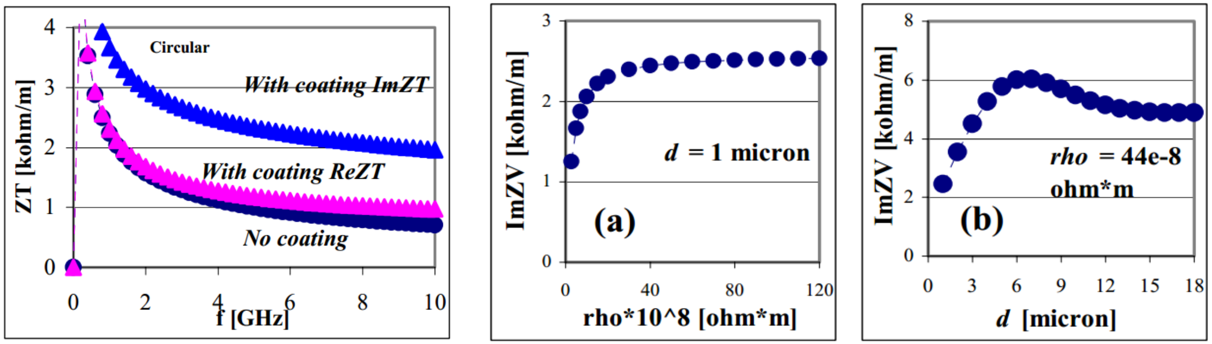
- Longitudinal impedance (roughly) $\propto\ b^{-1}$
- Transverse geometric impedance (roughly) $\propto\ b^{-2}$
- Transverse resistive-wall impedance $\propto\ b^{-3}$
- Minimization effort of geometric and resistive-wall impedance,
- Optimization of metallic coating of pulsed magnet (ceramic) chambers

→ NEG coating for efficient vacuum pumping → Increased impedance due to NEG



Observation of increased $Z_\perp$ with NEG coated chambers

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



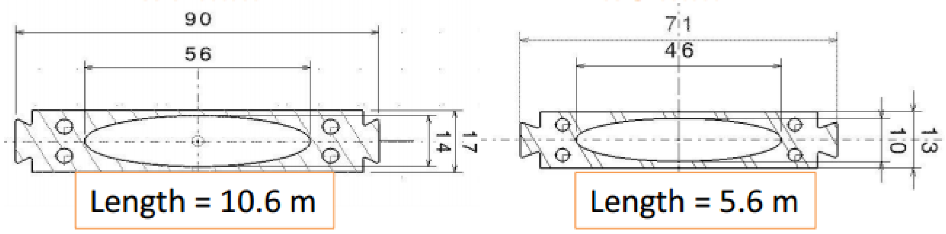
Analytical study of NEG Impedance (R. Nagaoka, EPAC 2004, Lucern)

Use of flat chambers such as for insertion devices (IDs) / Beta values at IDs:

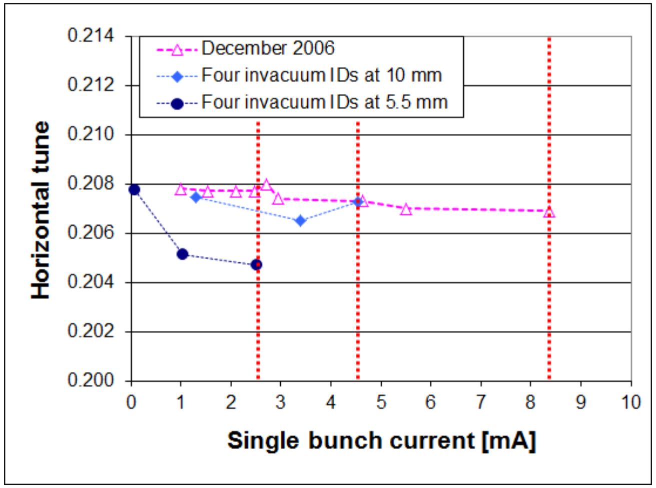
- Incoherent focusing
- Coupling of impedance to horizontal (even if there is no aperture limitation horizontally)
- Beam-induced heating due to low-gap sections and taper transitions

Long SS chambers
X = 2 x 28 mm
Z = 2 x 7 mm

Medium SS chambers
X = 2 x 23 mm
Z = 2 x 5 mm



ID low-gap chambers at SOLEIL



Reduction of horizontal TMCI threshold observed at SOLEIL

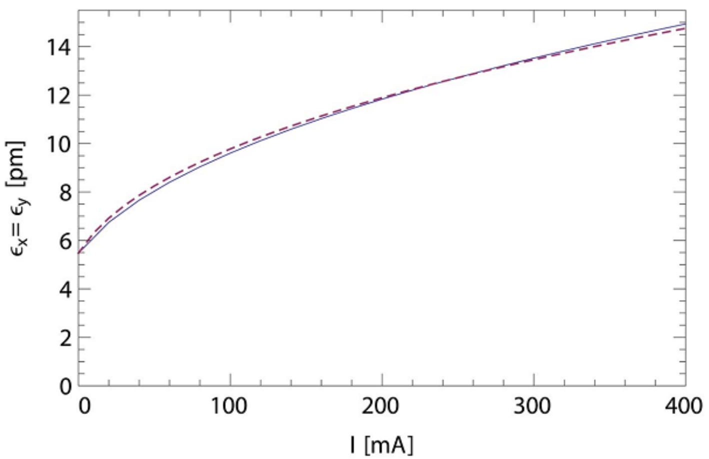
◊ Impact of Collective Effects on LEL

- To minimize transverse beam instabilities chromaticities are generally over-corrected to positive values, whereas
  Low emittance → High Quads gradient → High Natural Chromaticity → Difficulty correcting the chromaticities with small dispersion *H* → Dynamic Aperture limitations
  (Does chromaticity must always be over-compensated for beam instability ?)

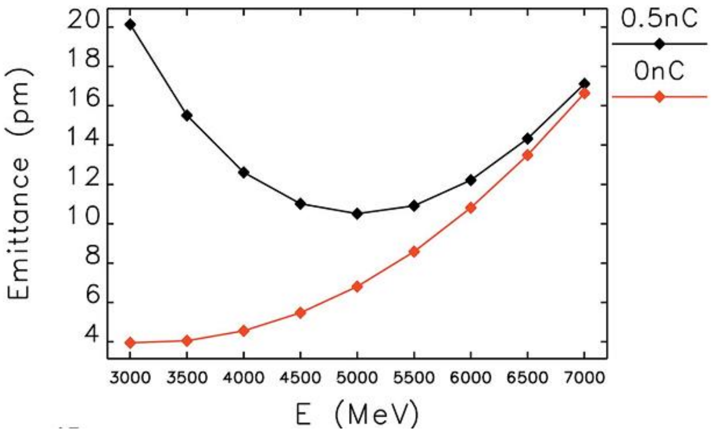
2. Concerned Collective Effects

2.1. IBS (Intra Beam Scattering)

- A multiple Coulomb scattering among electrons in a bunch that leads to an increase in all bunch directions including the energy spread → Harmful for LERs.
- Effect is most enhanced for a low energy LER storing high (bunch) current.
- Energy spread blow up is detrimental for the use of higher undulator harmonics in a light source
- IBS growth rates vary along the ring depending on the local lattice functions → Optimize lattice design to minimize IBS (*cf. talk by Fanouria*)
- Many future LERs consider making the beam round (best ways to do it may have to be studied), and/or a bunch long (via harmonic cavities) to minimize the IBS effects.



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

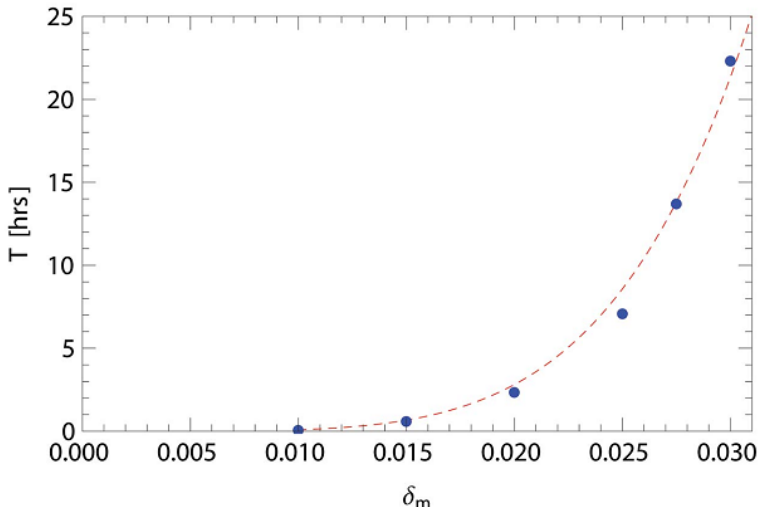


ε_x (= ε_y) versus E for the PEP-X lattice at nominal (black) and at zero (red) currents.

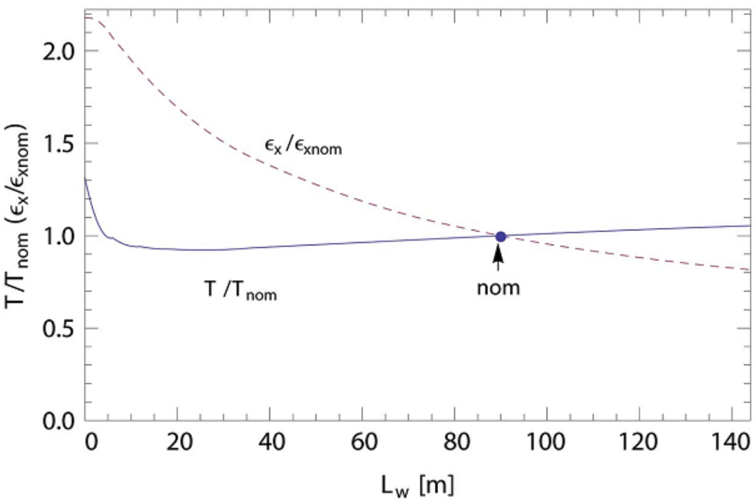
(*Y. Cai et al., SLAC-PUB-14785*)

2.2. Touschek Scattering

- Concerns large single Coulomb scattering where energy transfer from transverse to longitudinal leads to immediate particle loss. For LERs, it sets a severe constraint on beam lifetime.
- Lower emittance → Lower Touschek lifetime. However, below certain emittance, Touschek lifetime starts to increase since the scattering event decreases for a "well-aligned" electrons.
- Like IBS, Touschek lifetime depends on local lattice functions and momentum acceptance and must be averaged around the ring. In particular, the large asymmetry that a LER likely possesses on the momentum acceptance $\delta_{\pm}$ must be well taken into account.



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



ε_x (= ε_y) and Touschek lifetime T versus wiggler length L_w. These results are self-consistent calculations including IBS. The point labeled 'nom' represents the nominal case, with L_w = 90 m.

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

2.3. Collective Beam Instabilities

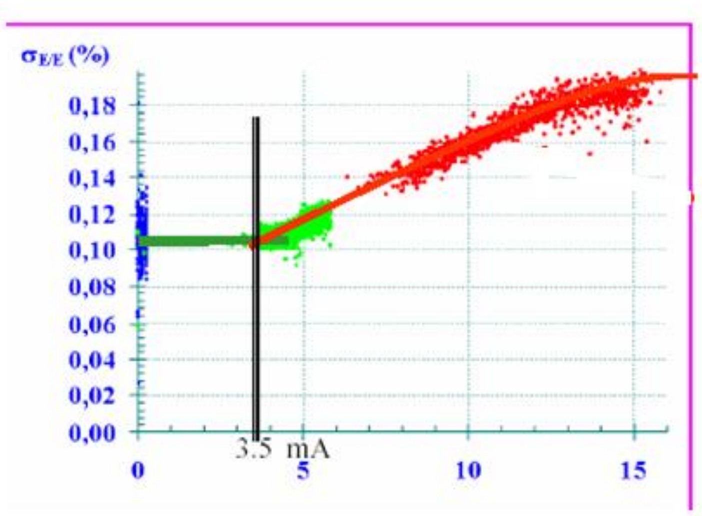
2.3.1. Single Bunch Instabilities

Longitudinal:

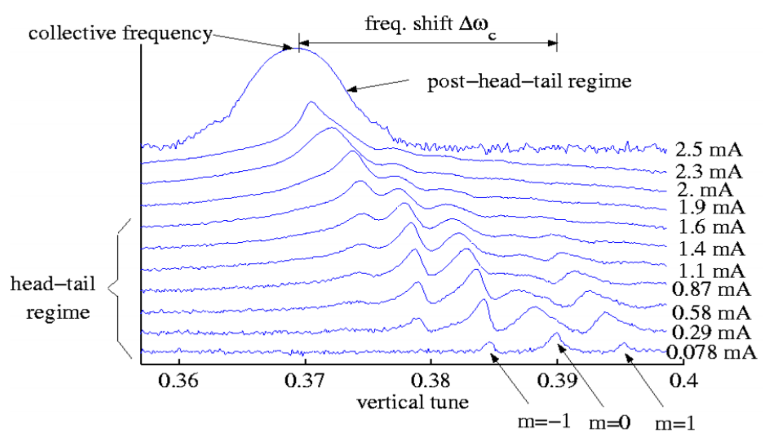
- **Bunch lengthening** (due to inductive nature of $Z_{//}$, the effect mostly beneficial)
- **Microwave instability** (energy spread widening and bunch lengthening)

Transverse:

- **TMCI** (Transverse Mode Coupling Instability, at $\xi = 0$)
- **Head-tail** and **post head-tail instabilities** (at $\xi \neq 0$)



Energy spread widening measured at ESRF



- *Headtail to post-headtail transition measured at the ESRF (P. Kernel et al., EPAC 2000, Vienna)*

2.3.2. Multibunch Instabilities

Resistive-wall Instability (transverse)

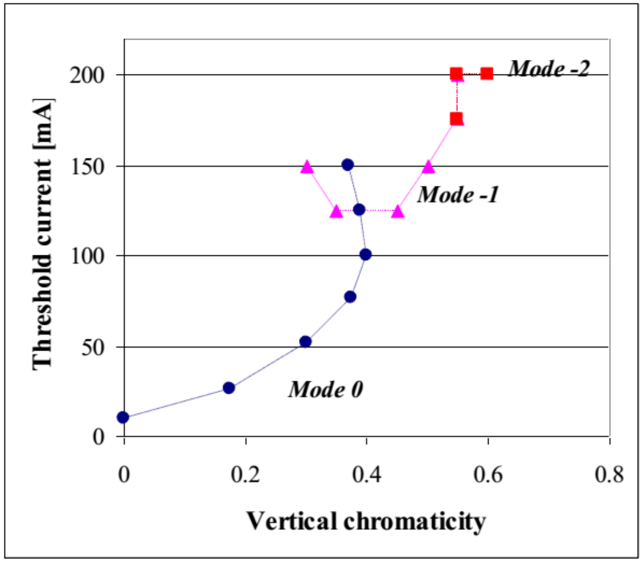
- Threshold at $\xi = 0$ is normally very low (~ a few tens of mA)
- May require a fairly large chromaticity to have a stable beam at the desired current

HOM-induced instability (transverse/longitudinal)

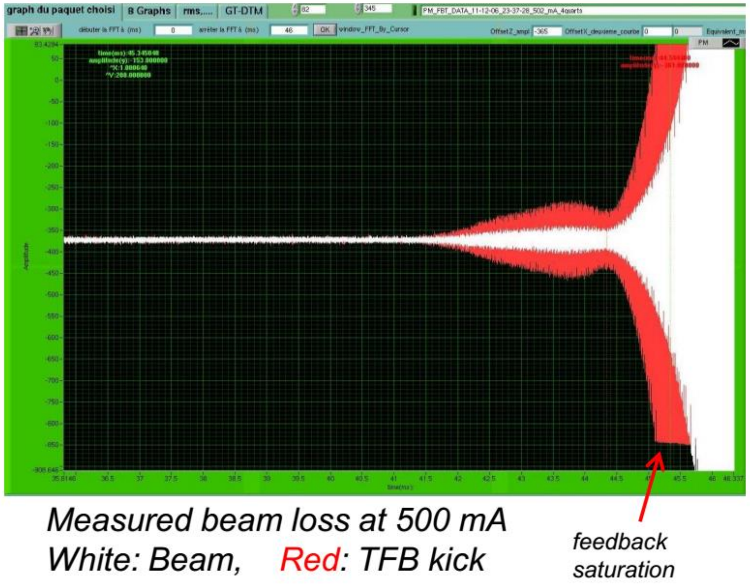
- Not only due to RF cavity HOMs, but trapped modes could induce instability

Ion instability (transverse)

- Not only due to increased vacuum pressure, but could be due to localized (beam-induced) outgassing



RW instability measured at the ESRF



Fast beam-ion instability measured at SOLEIL

2.4. Other Collective Effects

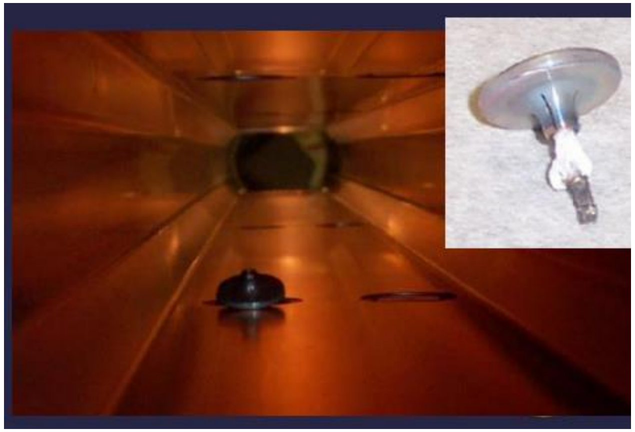
2.4.1. Beam-Induced Heating

- With reduced chamber aperture, beam-induced heating is likely to become yet an important issue for future LERs → May impose a severer constraint on the impedance than for beam instability.
- Vacuum components should not only be optimized at their ideal configuration, but their impedance degradation due to possible deformations and mis-positioning must be taken into account.

cf) Main motivations and conclusions from a mini workshop organized at Diamond (30 January 2013) on this topic:

- Simulations of wake losses using various 3D EM codes are used to calculate wake loss factor or wake impedance.
- We now know what power is lost from the beam, but where is it dissipated?

- **Please appeal to code developers to integrate changes or propose alternative!**

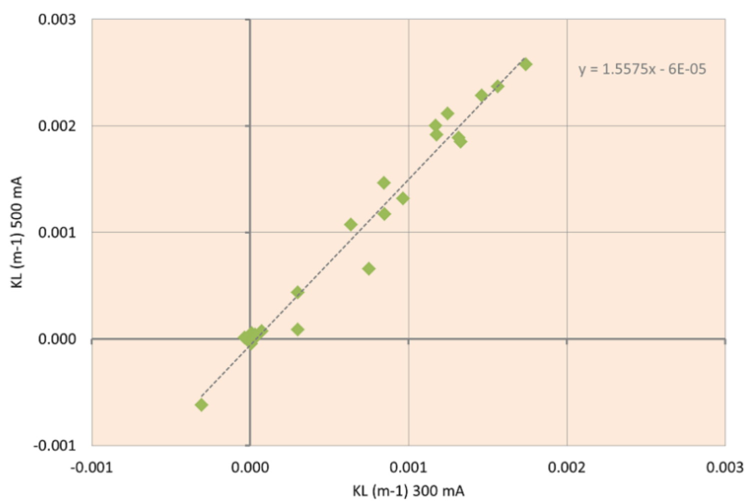


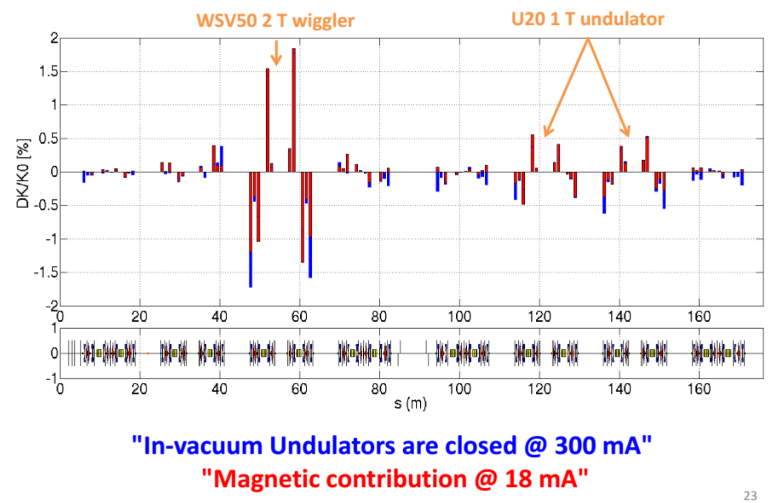
Melted BPM button in PEP-II

(*Guenther Rehm, Report from Mini-Workshop: Simulation of Power Dissipation and Heating from Wake Losses in Accelerator Structures, LER 2013 (Oxford)*)

2.4.2. Incoherent Focusing due to Flat Chambers and In-Vacuum IDs

- Beam passage in a flat (i.e. non-circular) resistive-wall (RW) chamber induces wake fields that give transverse ***incoherent*** focusing → The chamber effectively becomes a "*current-dependent quadrupole*".
- The effect is enhanced for
  - A high total current in multibunch due to extremely long-range RW fields that add up
  - A high intensity bunch due strong short-range RW field
- If a ring consists of many such chambers, the net additional focusing may destroy the delicate optimizations of a LER.



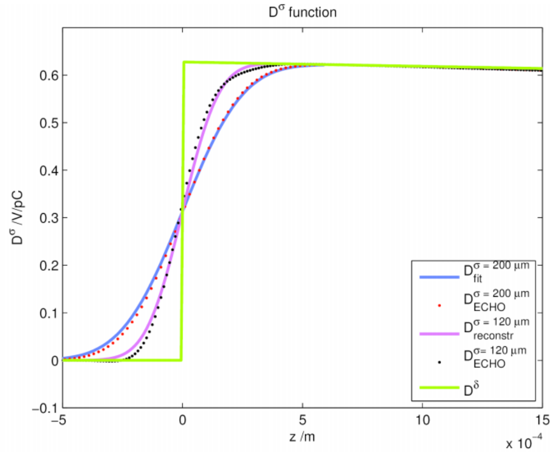


Effects measured at SOLEIL (P. Brunelle et al., TWIICE workshop)

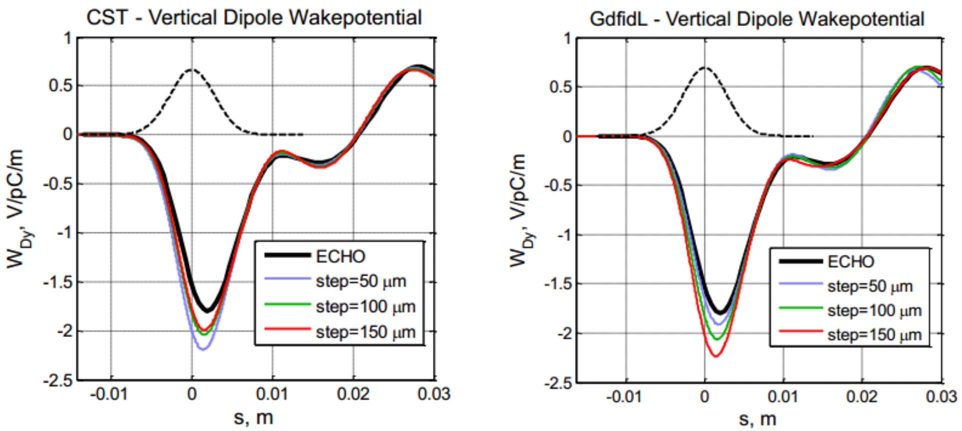
3. Mitigations

3.1. Impedance minimisation

- Continued studies of impedance itself are made in various directions by many experts in the field:
  - Numerical EM solutions of geometric impedance of 3D structures
  - Bench marking among different EM codes
  - Short range geometric and resistive-wall impedance
  - Impedance of coated chambers and up to very high frequencies



(G. Skripka, TWIICE workshop)



Comparison of CST, GdfidL and ECHO on a tapered cavity (H. de Oliveira Caiafa Duarte, LNLS, TWIICE workshop)

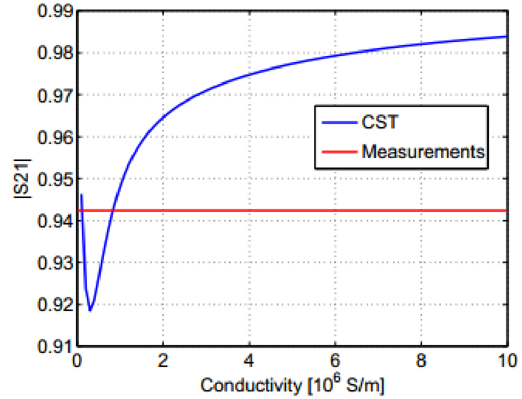
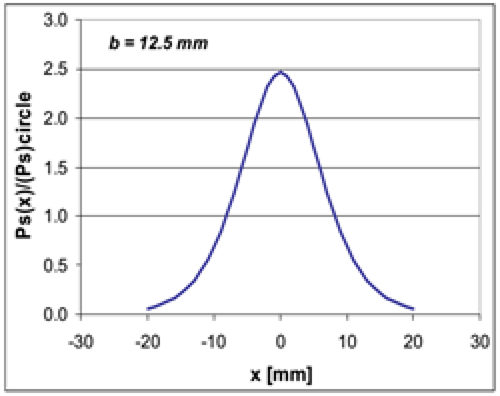


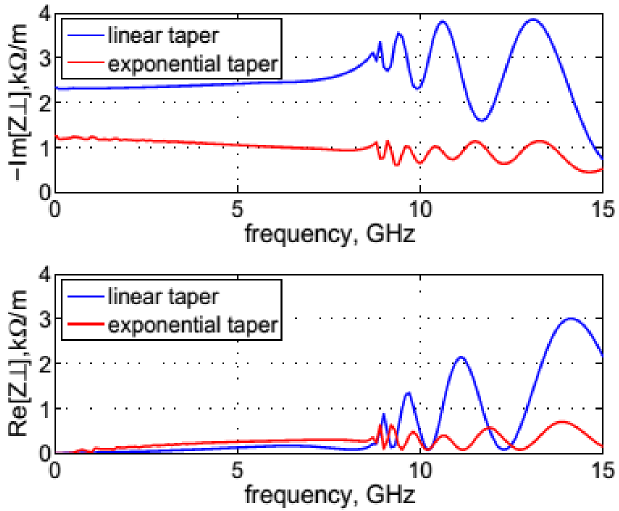
Figure: S21 at 12 GHz

Studies of the high frequency conductivity of NEG coating (E. Koukovini Platia, Ecole Polytech., Lausanne)

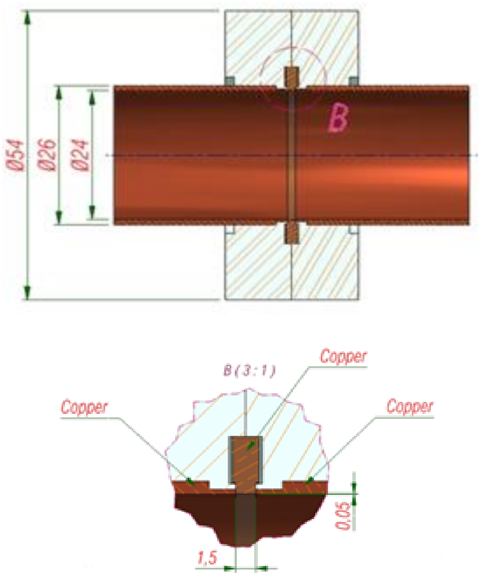
- Some examples of impedance minimizations studies made in LERs:
  - Taper transitions
  - BPM button profiles (avoid trapped mode without losing the button sensitivity)
  - RF fingers and shields in bellows and flanges
  - Zero impedance flange with no slit between the two plates
  - Optimization of thickness for NEG, copper coating, as well as titanium for ceramic chambers



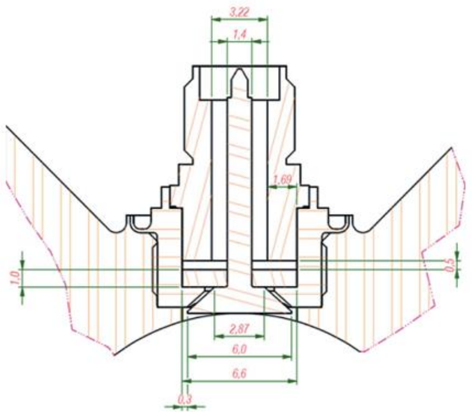
Power density distribution in a flat chamber



(Nonlinear taper studies, B. Podobedov, I. Zagorodnov, PAC2007, Albuquerque)



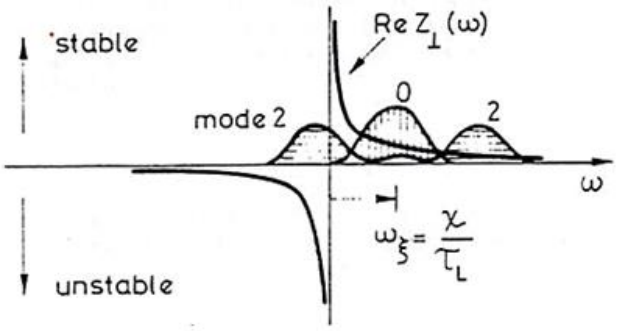
Zero impedance flange at Sirius (R. Seraphim)



A bell-shaped BPM button design studied at Sirius (H. Caiafa, TWIICE workshop)

3.2. Shifting of Chromaticity to a Positive Value

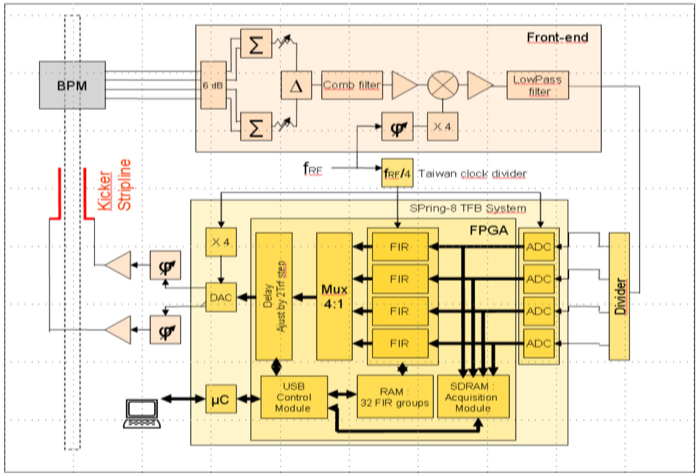
- May stabilize the beam both against single and multibunch instabilities
- Generally, however, it degrades the linear and nonlinear optics properties of a LER
- Has a risk of exciting higher-order headtail modes if they interact with high frequency impedance



$$\omega_\xi = \omega_0 \xi / \alpha$$

3.3. Bunch-by-Bunch Feedback

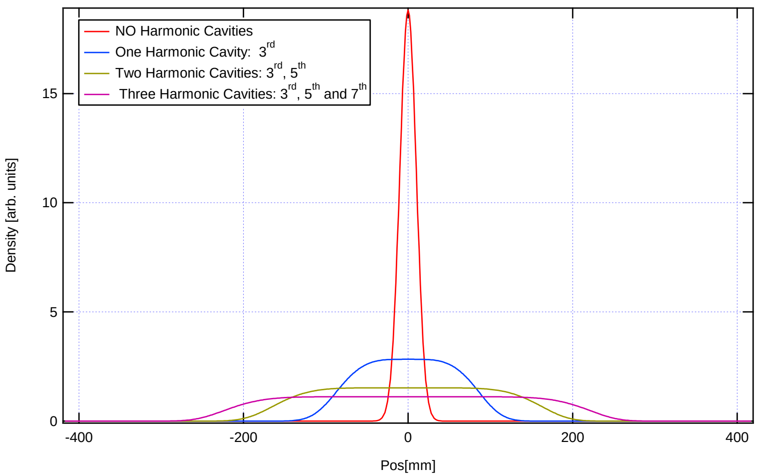
- FPGA-based systems available today are capable of stabilizing most of the machine impedance-induced (dipolar) coherent motions (TMCI, headtail, RW, HOM-driven, beam-ion, …).
- For future LERs, it may be considered as the most reliable means to fight against coherent instabilities along with Harmonic Cavity lengthening.
- At SOLEIL, transverse feedback is routinely running in both transverse planes in practically all modes.

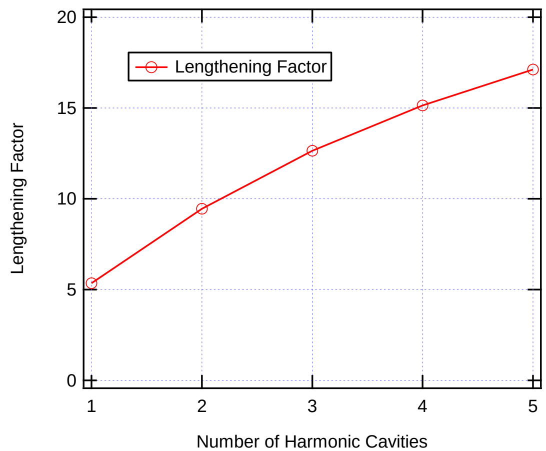


Layout of a feedback system (SOLEIL case)

3.4. Bunch Lengthening with Harmonic Cavities

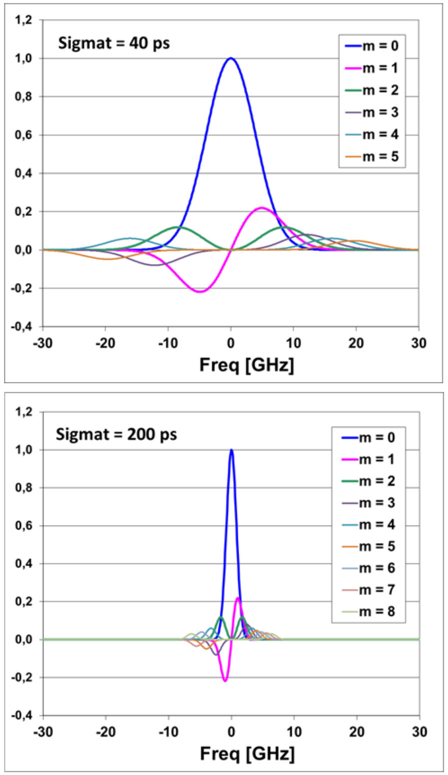
- Bunch lengthening via harmonic cavities (HCs), either passive or active, appears to be a very effective way in alleviating IBS and Touschek scattering, so long as short bunches are not required.
- Not only, but the scheme is expected to help stabilize coherent instabilities via
  - Landau damping due to tune spreads arising from flat potentials
  - Enhanced head-tail damping due to condensed mode spectra
- Numerical, theoretical and experimental studies must be made to quantitatively evaluate physically expected mechanisms.
- Extended HC schemes are being explored by groups of experts.





Courtesy Pedro Tavares (MAXLAB)

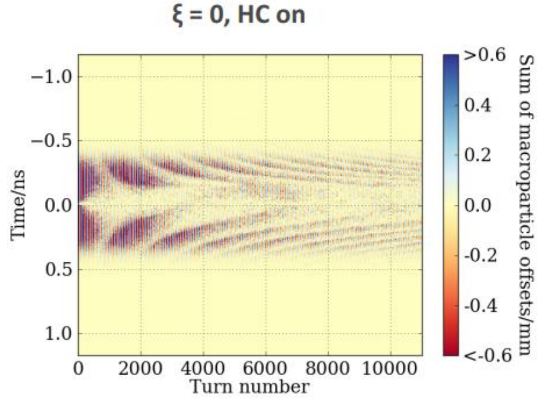
(*Å. Andersson, L. Malmgren, P. Tavares, Max-lab Internal Note 2015*)



Head-tail spectra of short and long bunches (MAXIV case)

3.5. Landau Damping due to Longitudinal and Transverse Tune Spreads

- An important byproduct of HC lengthening is the longitudinal tune spread created by a flat potential that may Landau damp longitudinal and headtail modes
- Likewise, transverse amplitude-dependent tune shifts may be beneficial against transverse instabilities, as demonstrated at Elettra (*L. Tosi et al., PRSTAB 6, 054401 (2003)*)

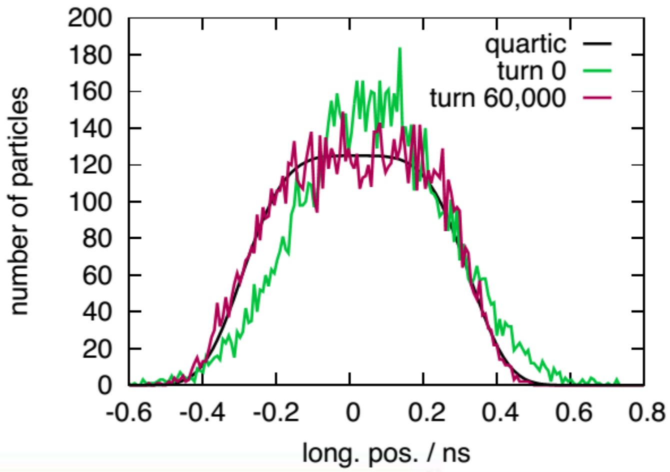


Simulation of the damping of a headtail mode due to longitudinal tune spread (G. Skripka et al., LER 2014)

3.6. Instability Simulations

- IBS is considered to be well predicted in general. However, there are still issues to be resolved, such as strong IBS regime, tail cuts and vertical coupling → Bench marking among different methods and experiments.
- Realistic impedance based on 3D models, RW fields and HC potential in arbitrary fillings including transient effects need be treated dynamically and simultaneously

  → Multiparticle tracking in time domain appears most effective. Bench marking becomes especially important



Longitudinal bunch distribution due to passive harmonic cavities, simulated by mbtrack for MAXIV (M. Klein et al., TWIICE, 2014)

4. Summary

- Design of a low emittance ring (LER) has clear reasons to enhance collective effects and beam instabilities, both in terms of beam properties and the machine impedance.
- Specifically, IBS may spoil the small horizontal emittance and Touschek scattering could significantly limit the beam lifetime above a given bunch current.
- Increased machine impedance due to smaller vacuum chamber aperture, along with wider bunch spectral bandwidth, tends to severely reduce the threshold of microwave, TMCI, headtail and resistive-wall instabilities.
- However, bunch lengthening with harmonic cavities and bunch-by-bunch feedback, in addition to chromaticity shifting, may turn out to be effective in reducing or suppressing many of the concerned collective effects and instabilities.
- Numerical, theoretical and experimental evaluations of the collective effects above in the presence of counter measures therefore become particularly important to guarantee the designed performance of future LERs.