Challenges of Synchrotron Light Sources against Collective Effects

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Content:

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1. Performance Goals and Characteristics of Light Sources

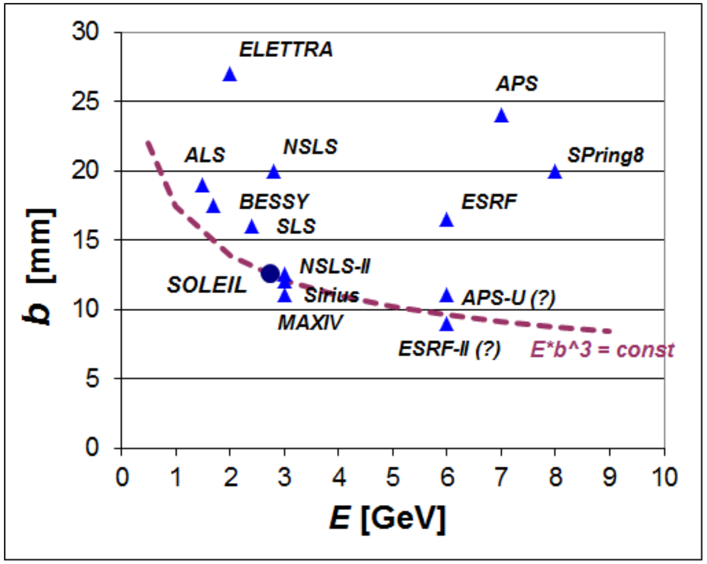
$$Brilliance = \frac{Photons}{Second \cdot mrad^2 \cdot mm^2 \cdot 0.1\%BW}$$

Two principal ways of increasing the brilliance:

- Lowering the beam tranverse emittance
- Increasing the beam intensity

However, they result in enhancing the problems of collective effects due to the following (entangled) reasons:

- $I_{operation} > I_{threshold}$
- Low emittance → stronger focusing → smaller bore radii → smaller chamber aperture → larger impedance



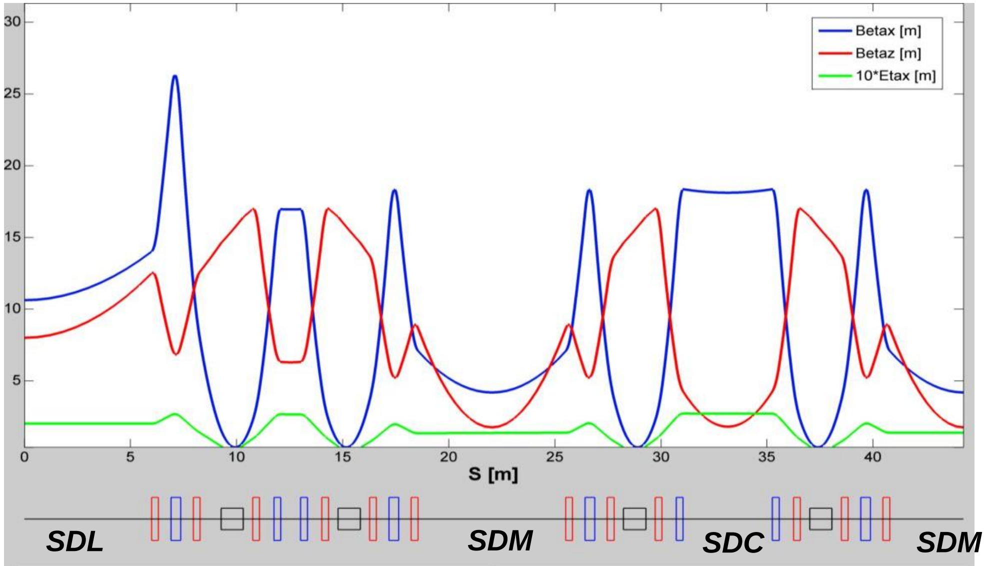
Vertical half aperture versus energy for several light source rings

- Low emittance → strong focusing → larger natural chromaticity → stronger sextupole → smaller dynamic aperture

- Light Source Rings (*LSR*s) require long lifetime with good injection efficiency
  → High cellular periodicity to maximize dynamic aperture
  → Distributed impedance (both Resistive-Wall (*RW*) and Broadband (*BB*) impedance)

- Low emittance → smaller momentum compaction α → shorter bunch → higher beam sensitivity to collective effects

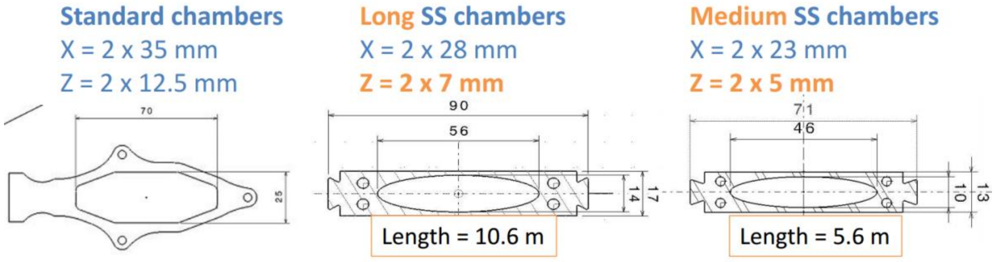
$$\alpha = \frac{1}{L_c}\oint \frac{D_H}{\rho_0} ds$$



Example of SOLEIL lattice and optics (1/8 ring)

- In addition, *LSR*s use insertion devices (*ID*s) as primary *LS*s, and thus are optimized to install many of them working at small magnetic gaps
  → Many transitions (tapers) and low gap chambers
  → Another source of impedance

Low gap chamber in a 12 m long straight section in SOLEIL



Three type of vacuum chambers in SOLEIL, P. Brunelle, TWIICE 2014)

- In addition to high photon flux users, there are users requesting high intensity/bunch for time-resolved exeriments, as well as Coherent Synchrotron Radiation (*CSR*) in the *IR* range
  → Delivery of different operation modes (multibunch, single bunch, multi-single bunch, hybrid, low α (*CSR*), …)
  → Different instability issues

- A big challenge is emerging today (due to progress, above all, in optics design and magnet technology): Ultimate Storage Rings (*USR*s) or Diffraction Limited Storage Rings (*DLSR*s), having the horizontal emittance ε_H nearly one order of magnitude smaller

  → Features described above are all far more amplified

  → Keeping the beam intensity as one of the two major performance is a big challenge

MAX IV	7BA	3 GeV	320 pm	500 mA	SS length 5m	DA 7mm w/errors
Sirius	5BA w/superbend	3	280	500	5m & 6m	5 mm w/errors
Spring-8	6BA	6	67.5	300	4.5m & 27m	3 mm w/errors
APS	7BA	6	147	100		
Pep-X	7BA	4.5	11	200	5 m	10 mm w/errors
ESRF Phase II	7BA	6	130	200	5m	10 mm
SOLEIL	QBA w/longit.. gradient dipole	2.75	980 (220)	500		Robins. Wiggler + beam adapter
Diamond	mod. 4BA, 5BA, 7BA	3	45-300	300	5m & 7 m	2 mm
ALS	5BA - 7BA	2	50-100	500	5 m	2-3 mm
BAPS	7BA-15BA	5	50	150	10m & 7m	10 mm w/errors
tUSR	7BA	9	3	100	TEV tunnel	0.8 mm

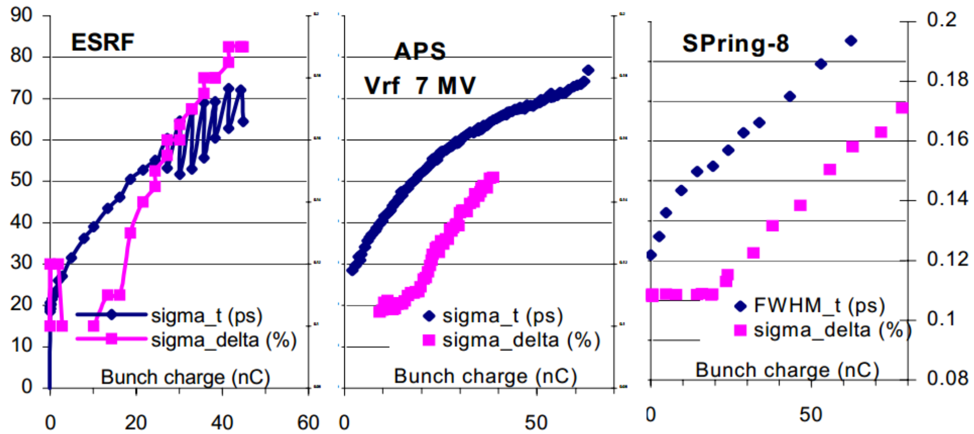
Survey of ultra-low-emittance lattices presented at USR workshop in Beijing, Nov. 2012
(R. Bartolini, Low Emittance Ring Workshop, Oxford, July 2013)

2. Collective Effects in Light Sources

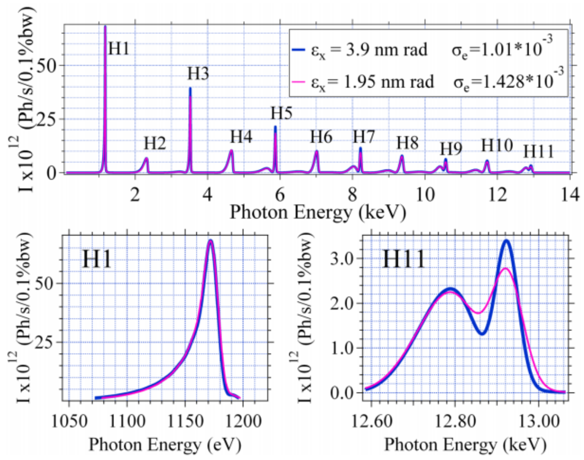
◊ **Single bunch instabilities**

- Generally, significant **bunch lengthening** in the inductive regime
  → However, beneficial in most cases

- **Energy spread blows** up in several *LSR*s before reaching $(I_{single})_{max}$ due to microwave instability



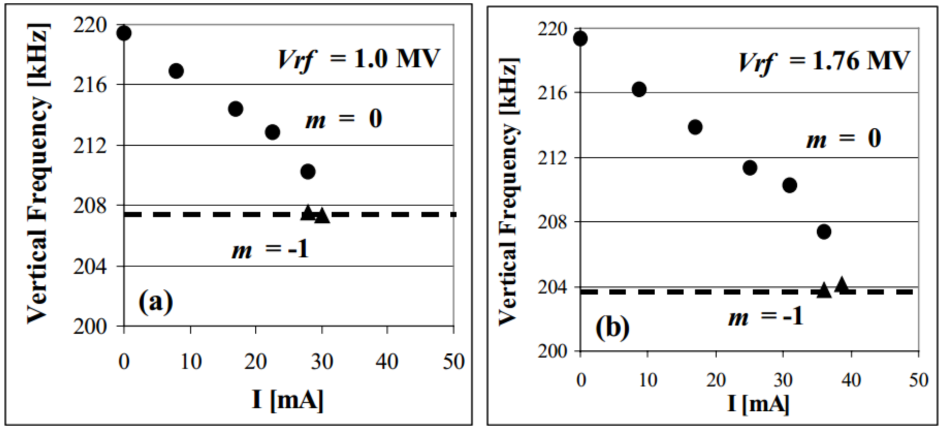
Comparison between ESRF, APS and SPring-8, K. Harkay et al., EPAC 2002, Paris, France



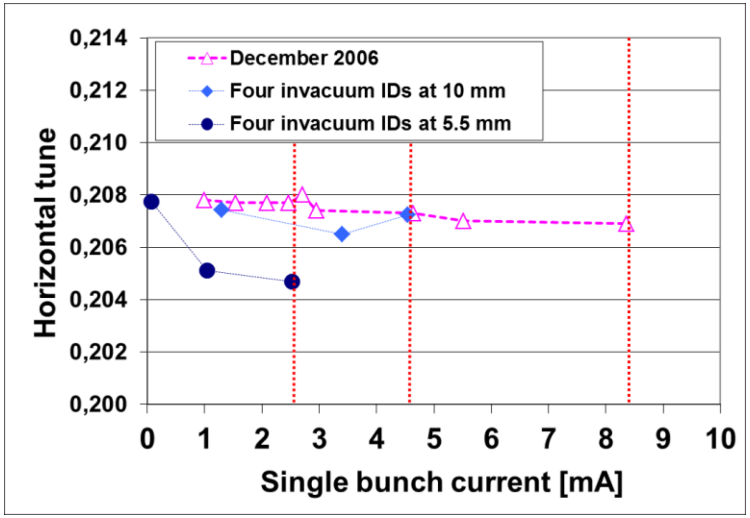
- For *LSR*s using high-harmonics undulator spectra (especially low to medium energy machines), the deterioration of the spectra due to energy spread widening must be avoided

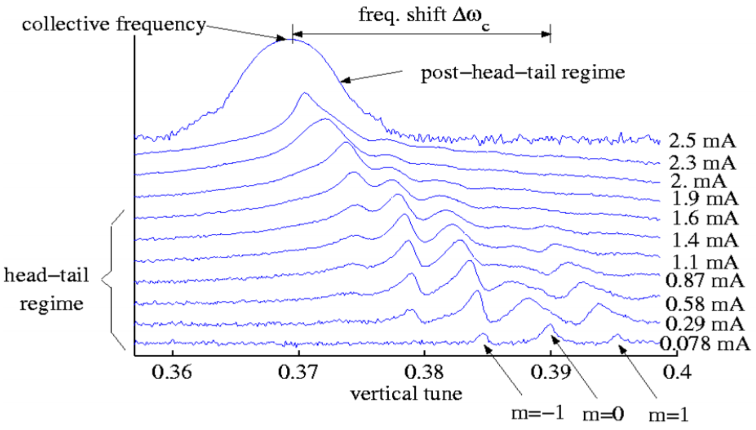
Flux calculation with SRW for U20 through an aperture 0.1×0.1 mm² located at 10 m from the source (H. Abualrob et al., IPAC 2012)

- **TMCI** between 0 and -1 modes are encountered in most *LSR*s. In many cases, the thresholds are significantly low as compared to $(I_{single})_{operation}$.



TMCI measured at ELETTRA (J.L. Revol et al.,EPAC2000,Vienna)

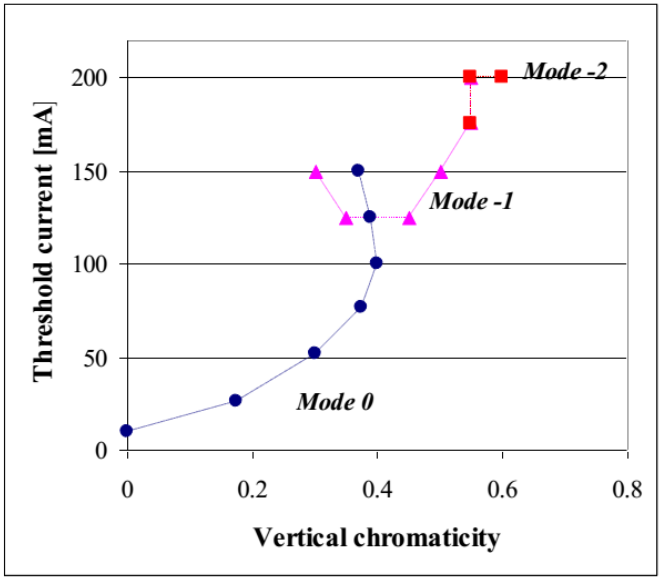




- At SOLEIL, installation of in-vacuum IDs rendered the horizontal TMCI threshold to be as low as the vertical

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

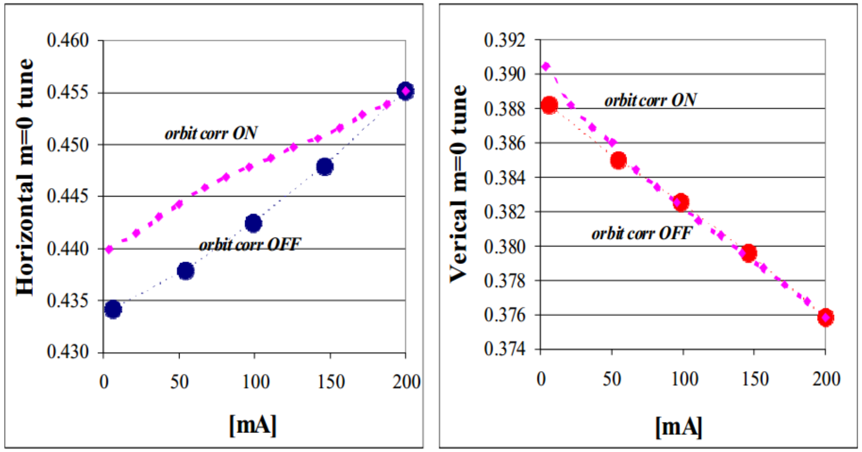
◊ Multibunch instabilities



*Measured vertical **RW instability** thresholds versus chromaticity in the uniform filling at the ESRF*

- In many *LSR*s, the **RW threshold** at zero chromaticity is significantly low as compared to $I_{operation}$.
- Chromaticity shifting helps raising the threshold, but may associate a series of higher-order headtail modes that drive the coupled-bunch instability

- **Incoherent tune shift** due to flat chambers is observed in many *LSR*s.
- Since *LSR*s are sensitive to optics (tunes/symmetry), compensation of the effect may be needed.

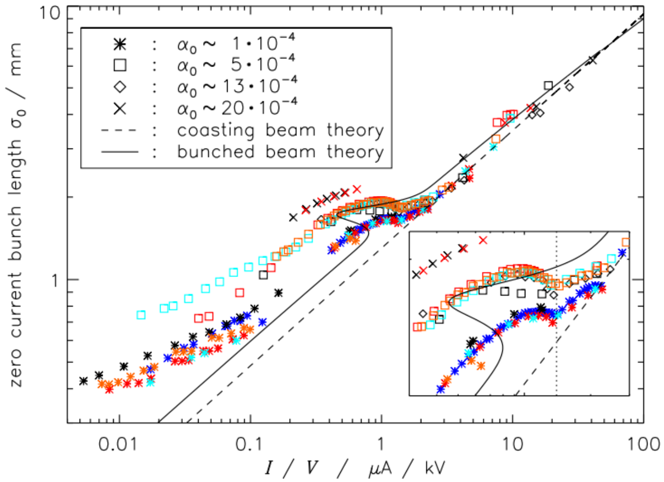


Meaured incoherent tune shifts in ESRF (R. Nagaoka et al., PAC 2001, Chicago)

◊ Other collective effects

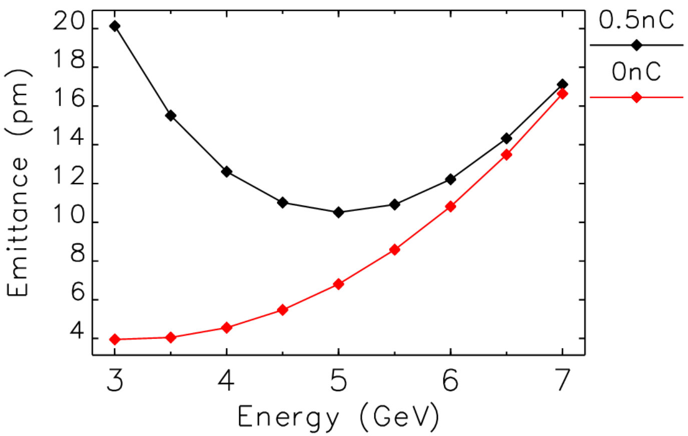
- **Beam-induced machine heating**
  (shielded-bellows, flanges, BPMs, tapers, ceramic chambers, …)

Melted RF finger at SOLEIL, Courtesy N. Béchu



Scaled values of measured bursting thresholds in MLS. (M. Ries et al., IPAC 2012, Louisiana)

- **CSR instability**
  Many studies are on-going to characterize the instability as a function of machine parameters, impedance models, and beam filling, …

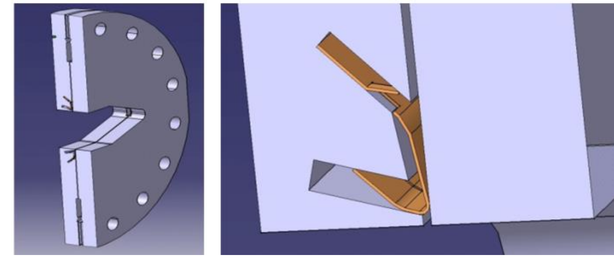


Calculated emittance $\varepsilon_x = \varepsilon_y$ vs energy for a round beam in PEP-X (Y. Cai et al., Phys. Rev. ST Accel. Beams15,054002 (2012)).

- **IBS and Touschek scattering**
  The issues are particularly important for future ultra-low emittance LSRs

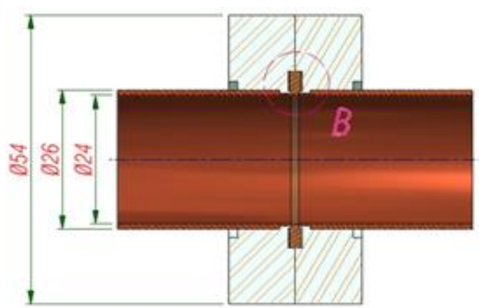
3. Specific Impedance Issues and Studies in Light Sources

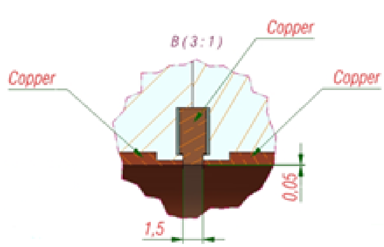
◊ **Flange impedance**



- At SOLEIL, a flange having a longitudinal slit of 0.4 mm and radial depth of 50 mm turned out to create critically strong trapped modes

→ Unacceptably low instability thresholds and high loss factor
→ A thin shielding metallic foil introduced drastically improved the impedance
→ Occasional deformation of the foil creating a serious heating problem in reality confirms the correctness of the impedance calculation (done with *GdfidL*)

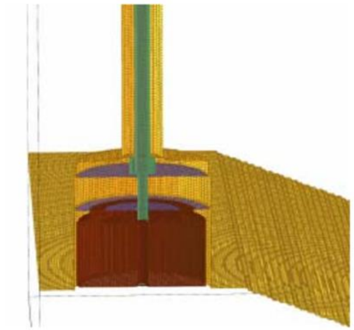


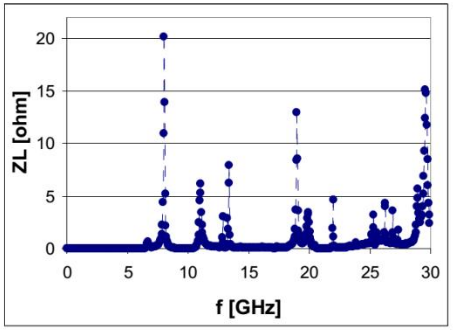


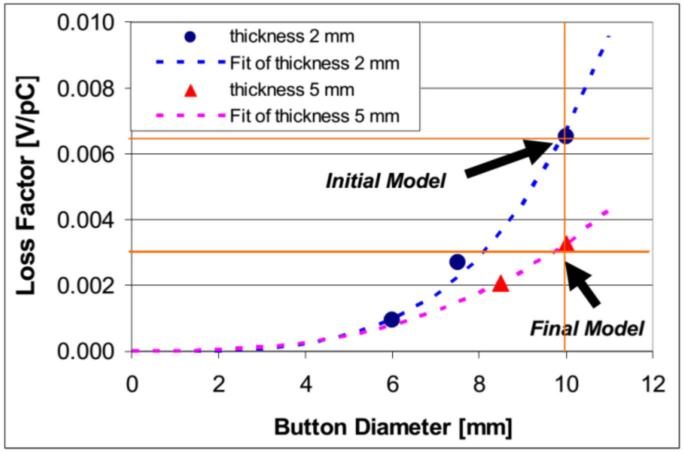
- A "zero impedance" flange with no slit between the two plates developed at Sirius, Brazil *(R. Seraphim, Sirius 2014)*, on the basis of the model developed at KEK *(Matsumoto et al., EPAC 2006)*.
- An additional effort is made for an electron to sees only one material (copper) across a flange.

→ Likely to be a promising solution for future DLSRs

◊ BPM impedance



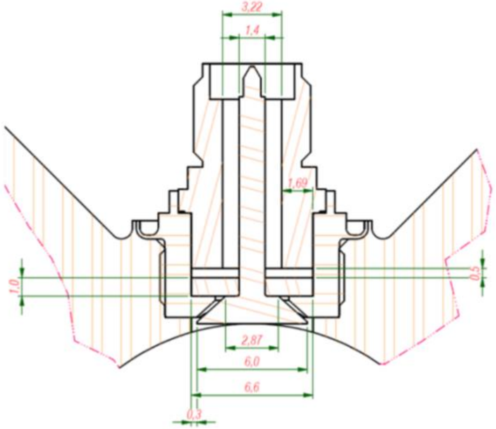




(R. Nagaoka et al., EPAC 2006, Edinburgh)

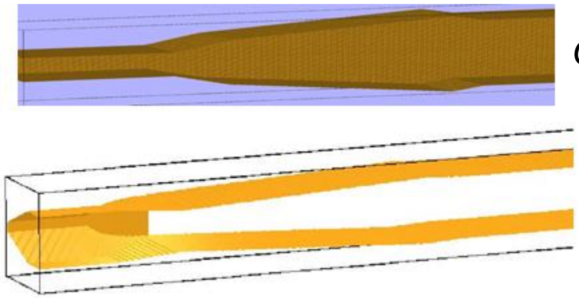
- At SOLEIL, the original BPM design created a too large k_{loss} due to the trapped mode
  → Since keeping the high reading accuracy is vital for a *LSR*, the button thickness was increased to reduce k_{loss} (by a factor of 2) instead of reducing the button diameter
  → Heat distribution was also studied with the surface integral of $H_{//}^2/(2\kappa\delta)$ (*GdfidL*)
  → Coupled-bunch nature of k_{loss} was also evaluated

- Interesting studies are underway at Sirius (Brazil) optimising the button shape, such as a bell-shape, so to increase the trapped mode frequency without losing the button sensitivity *(H. Caiafa, at TWIICE 2014)*.



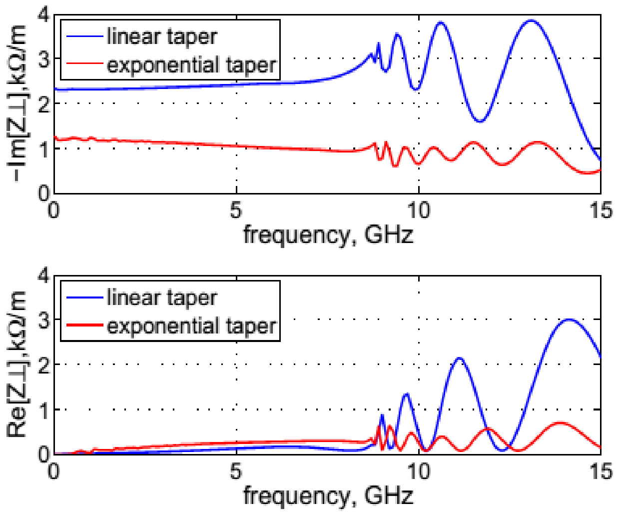
◊ Taper impedance

- In *LSR*s, taper transitions are inevitable between magnet chambers to IDs and RF cavities etc.
- Tapers are inductive at low frequencies, but become also resistive at high frequencies and may create problems of heating and instabilities (*cf. problems encountered at SOLEIL*).



Variable in-vacuum ID tapers at SOLEIL

- As we want to minimize the lengths taken by tapers, minimization of taper impedance for a given length is a particularly important issue for *LSR*s.



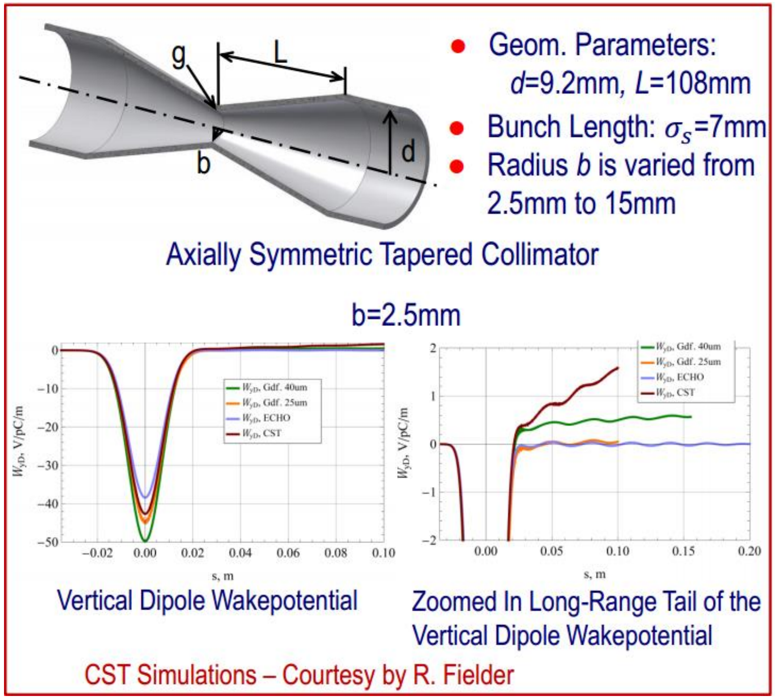
(B. Podobedov, I. Zagorodnov, PAC2007, Albuquerque)

- Taper impedance minimization via nonlinear taper geometry, as well as studies of short-range taper wake fields (*B. Podobedov, PAC 2012, Louisiana*), recently made by B. Podobedov and his collaborators.

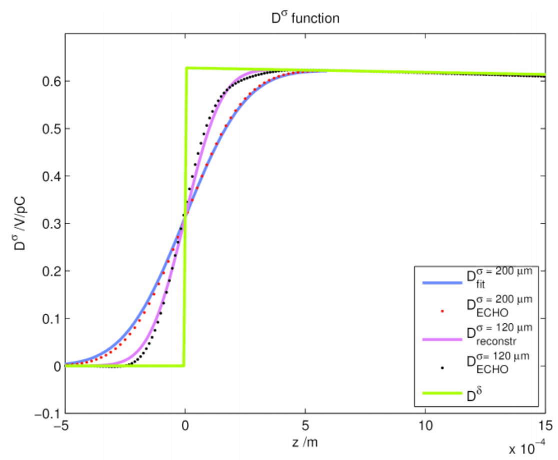
  → Should be ways to follow for future *LSR*s

◊ EM solver comparison/New approach to short-range wakes

- Numerical 3D *EM* solutions are effectively the only way to obtain the wanted wake fields
- It is therefore of great importance to bench mark different codes available
- Two groups in the *LS* community (Sirius & NSLS-II) made a systematic comparison of widely used 3D codes (cf. *TWIICE workshop*, *2014*), using *ECHO* (2D code) as a reference.



(A. Blednykh, TWIICE workshop, 2014)

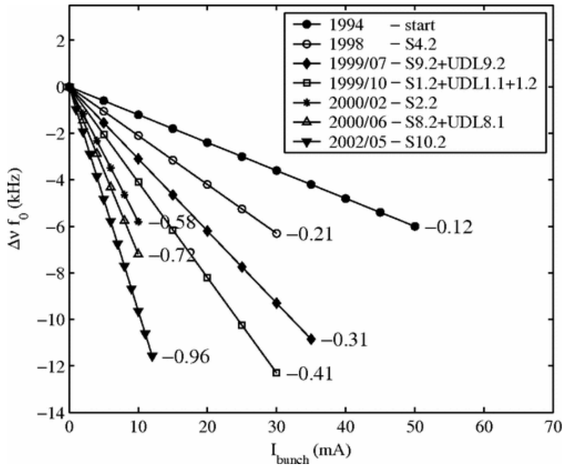


(G. Skripka, TWIICE workshop, 2014)

- Semi-analytical method developed by Podobedov & Stupakov (*Phys. Rev. ST Accel. Beams* ***16***, *024401*) to obtain short-range (high frequency) wakes, and its application to *LS*s as initiated by G. Skripka (Univ. Lund) may be a promising complementary approach.

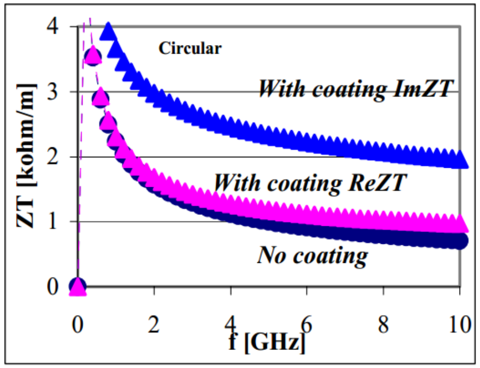
◊ NEG coating in *LSR*s

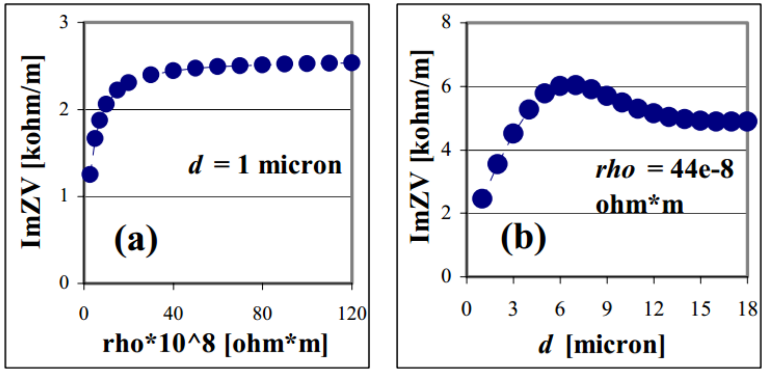
- NEG coating, which turned out to be very effective in pumping the residual gases without pumping ports, is more and more used in *LSR*s.
- SOLEIL is the 1st *LSR*s that has as much as nearly half of the entire chamber NEG coated.
- Observation made at Elettra, however, had raised some concern on the impedance.



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

- Analytical studies made showed an increase in *ImZ*, but had to assume high resistivity & coating thickness to explain quantitatively the Elettra result





R. Nagaoka, EPAC 2004, Lucern

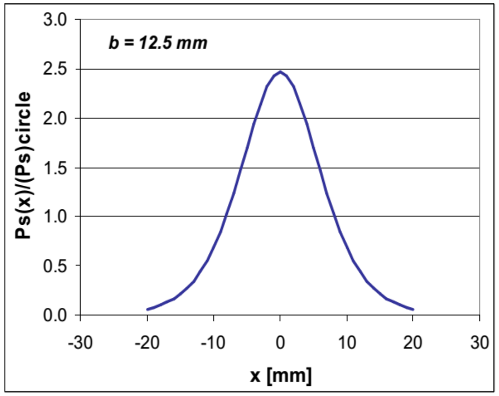
- For future *DLSR*s, NEG coating is expected to be an indispensable technology.

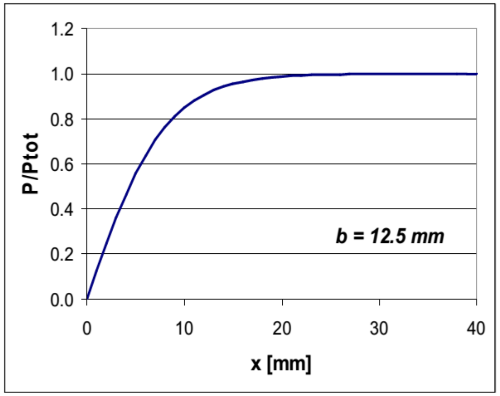
◊ Ceramic chamber coating and heating

- Ceramic chambers are used for pulsed magnets such as injection kickers.
- Optimization of the metallic (e.g. Titanium) coating is critically important as a compromise between performance and image current heating
- Analytical studies are made of EM fields involving di-electric materials

$$P_s(x) = \frac{\pi^2}{4\cosh^2(\frac{\pi}{2b}x)} \cdot (P_s)_{circle}$$

(R. Nagaoka et al., EPAC 2006, Edinburgh)





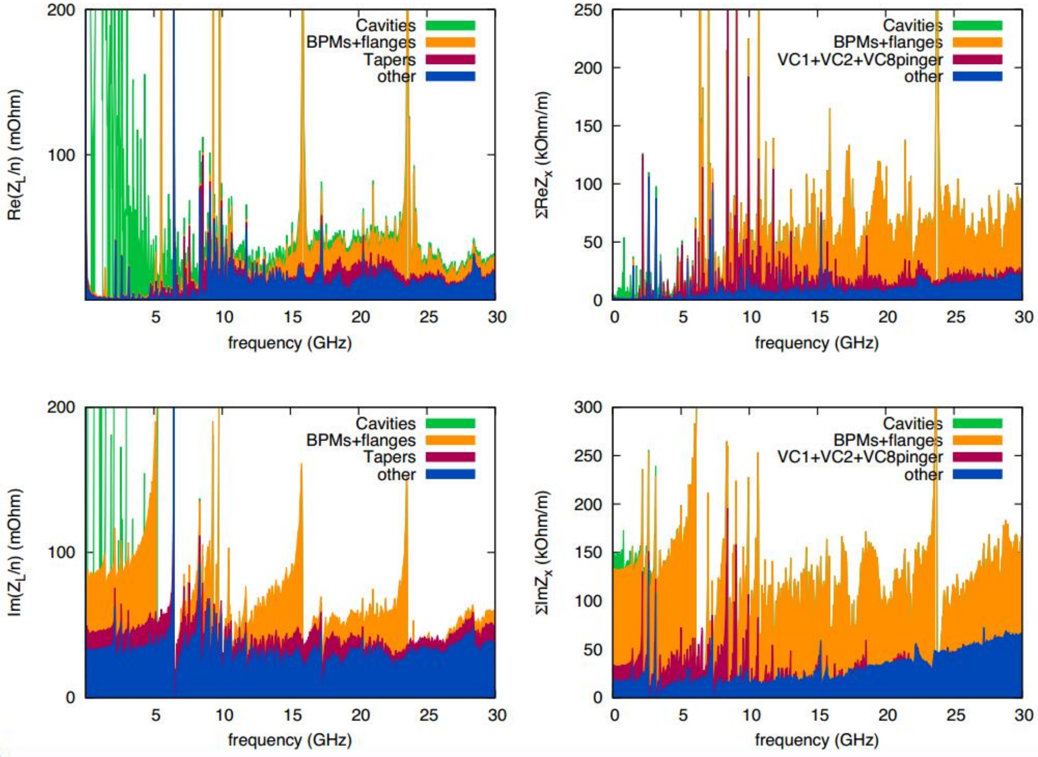
- Not only the dissipated power, but the power density distribution is important in determining the required cooling capacity
- Peak power density is particularly enhanced for low gap flat chambers, and is thus expected to be important for future *DLSR*s

4. Simulation Studies and Cures of Collective Effects

◊ **Construction of numerically calculated impedance model**

- Instead of using a simplified analytical model, wake potentials numerically computed by an EM solver are used to construct the ring impedance. RW impedance is superimposed on the geometric one.

- Frequency range is limited by the mesh size used. Usually limited to ~30 GHz.
- For resonators found in geometric computations, only *R/Q* dependence is followed
- For transverse impedance, the removal of “monopole” contributions is made for non-circular chambers



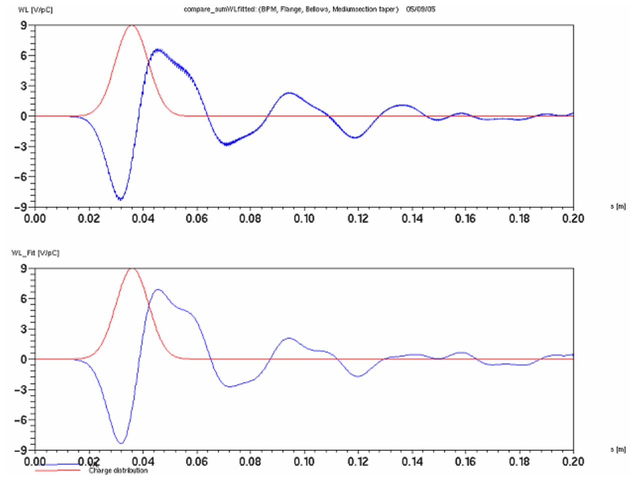
Total impedance calculated for MAXIV 3 GeV using GdfidL, (M. Klein et al., TWIICE, 2014)

◊ Use of numerically calculated impedance model in simulations

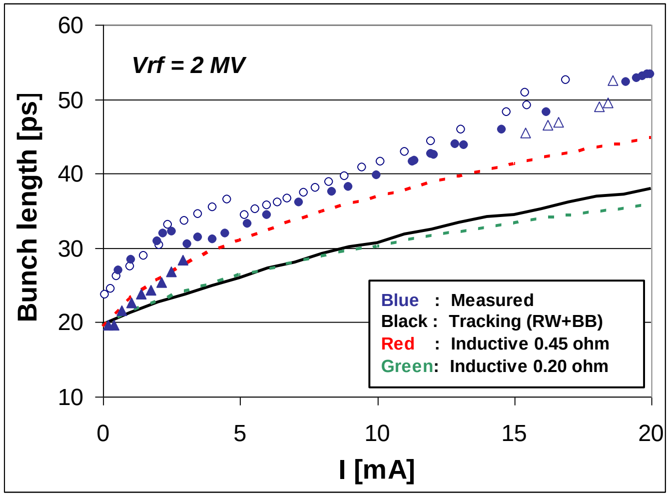
- Several approaches are known on the way to use numerically obtained wake potentials in simulations, as ideally, what is required is the Green's functions.
- The approach taken at SOLEIL is to fit the impedance with mathematically known impedance functions (resonators, inductance, capacitance, resistance, …)

Original wake potential

Reconstructed



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

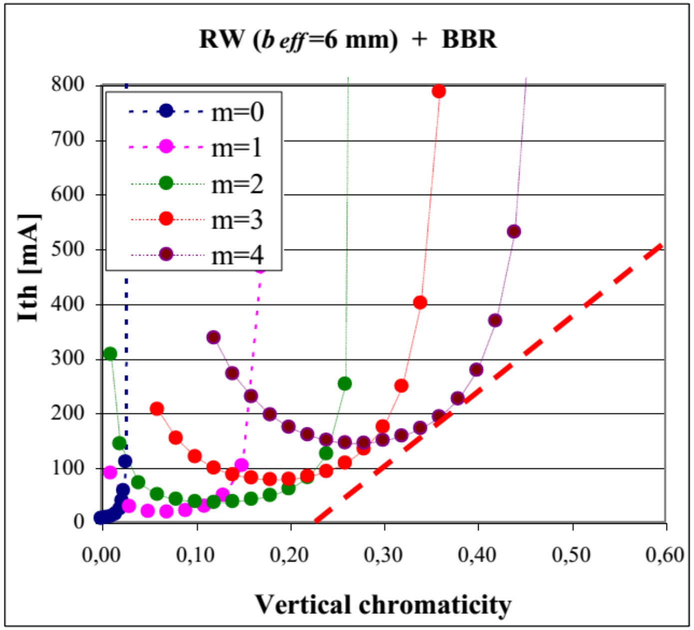


Measured bunch lengthening versus predicted (SOLEIL)

- At SOLEIL, the use of numerically obtained impedance model underestimated the bunch lengthening, vertical and horizontal coherent detuning by nearly a factor of ~2, the reason of which is not understood (*R. Nagaoka, PAC 2007, Albuquerque*).

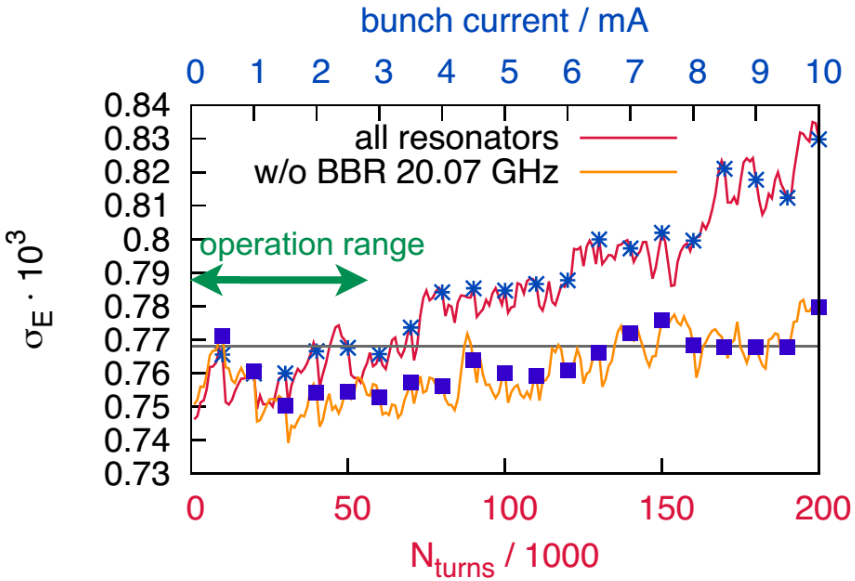
◊ Frequency domain and time domain simulations

- *MOSES* is used in many *LSR*s to study TMCI and headtail instability. At SOLEIL, a frequency domain solver (*rwmbi*) was developed to study RW instability in multibunch.



RW instability study using rwmbi, R. Nagaoka, ESRF 05-02/Theory, 2002

- Several multiparticle tracking codes have been developed in the light source community (*elegant*, *OASIS*, *sbtrack*, *mbtrack*, …)

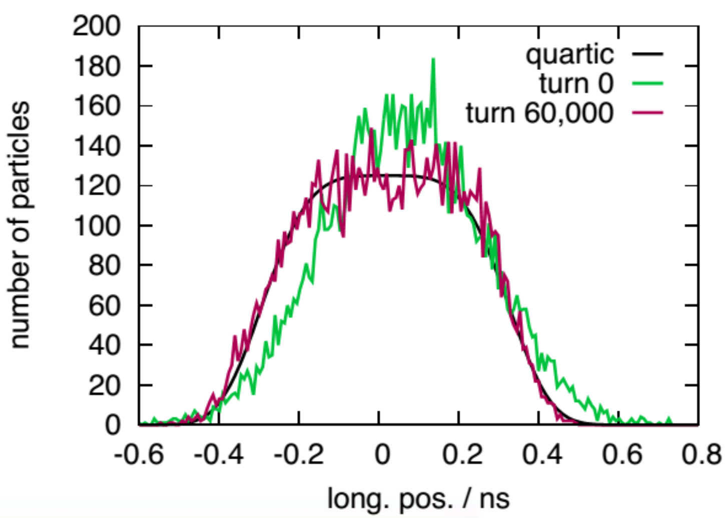


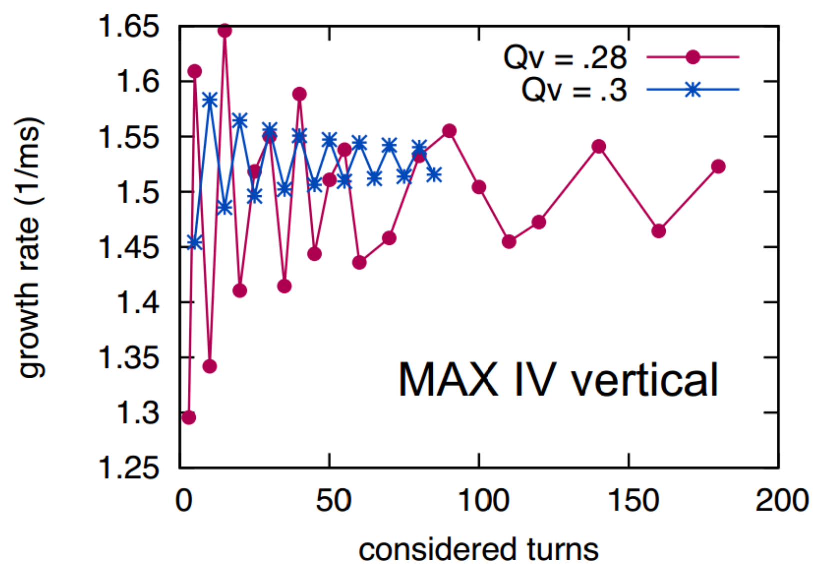
Energy spread widening versus bunch current simulated by mbtrack (M. Klein et al., TWIICE, 2014)

◊ **Development of macro-particle single bunch and multibunch tracking codes**

- With the marked enhancement of computing power today, we are able to simulate the complicated beam-ring system with multi-particle/multi-bunch tracking.
- Specifically, the following effects are considered particularly important to study:

  - Intra-bunch and coupled-bunch motions (short-range and long-range RW fields)
  - Chromaticity shifting
  - Beam filling dependence
  - Long-range harmonic cavity fields (including transient beam-loading)
  - Landau damping due to tune spreads (longitudinal/transverse)



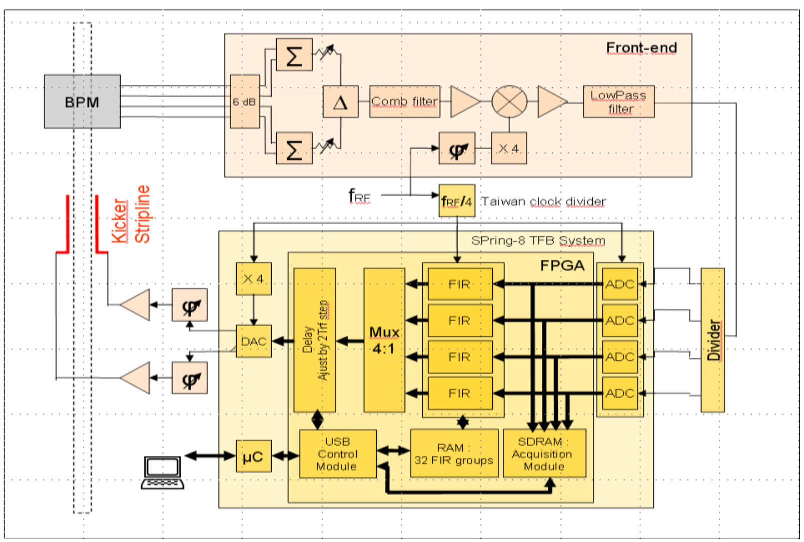


Evolution of longitudinal bunch distribution due to passive harmonic cavities (left), and RW instability growth rate versus multi-turn effects (right) simulated by mbtrack for MAXIV (M. Klein et al., TWIICE, 2014)

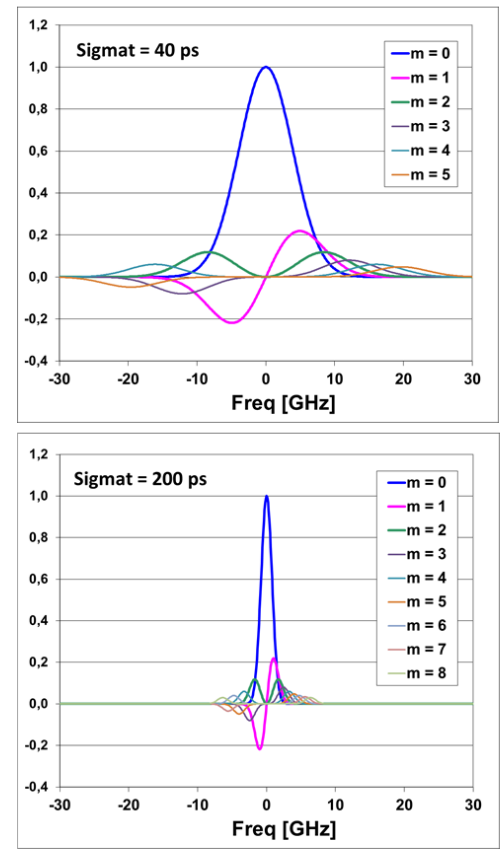
◊ Cures of collective effects in light sources

- Traditionally chromaticity shifting to positive (head-tail damping)
  → Efficiency quite limited (excitation of higher-order modes/reduction of dynamic acceptance)

- Feedback system (for instabilities associating dipolar CM motions: RW instability, HOM-driven, ion instability, …)
- Bunch lengthening with harmonic cavities (to be combined with chromaticity shifting, induced tune spreads, …)



Bunch-by-bunch digital (FPGA-based) feedback system (SOLEIL case)

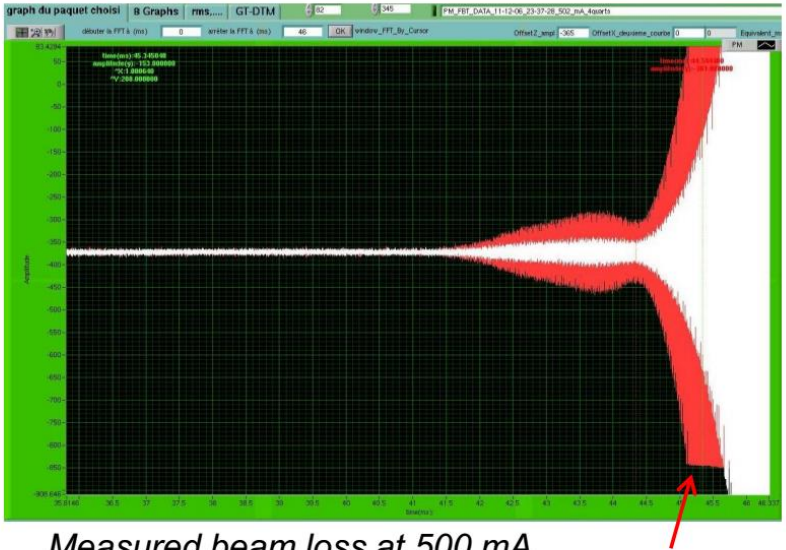


Head-tail spectra of short and long bunches (MAXIV case)

◊ **Fast beam-ion instability encountered at SOLEIL:**
… arising from different collective effects and correction scheme combined

- At SOLEIL, the operation at the highest multibunch current of 500 mA is hampered by the FBII
- The instability occurs some ~10 minutes after accumulating the beam, often ending in complete beam losses. Until then, the beam is kept completely stable with transverse feedback
- The instability is understood to be due to a combined effect of;

  RW instability, beam-induced heating (i.e. wake effect), local out-gassing, FBII, bad reaction of transverse feedback



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

- Similar phenomenon was observed at SSRF (Shanghai) with the following aspects in common: Presence of in-vacuum IDs, transverse feedback running against RW instability
- Such instability may become more serious for future *LSR*s.
- Sophisticated simulation taking different effects into account is required

(R. Nagaoka et al., TWIICE, 2014)

5. Summary

- For light sources, the effort to lower the emittance tends to make the ring more sensitive to collective effects both impedance-wise and beam property-wise.
  → For *DLSR*s, this trend will be particularly serious
  → Impedance minimization becomes of high importance

- Consequently, the information on the impedance is becoming more and more demanding:
  - Over 3D objects possessing fine structures (slits, slots, steps, tapers, …)
  - Short-range/high frequency → A point charge wakes
  - High *Q* resonators with realistic values of *Q* (finite conductivity material calculations)
  - Surface roughness wakes
  - Refined RW impedance models (multi-layered, finite thickness wall, short-range, …)
  - CSR wake models for more realistic chambers

- Beam-induced machine heating is likely to become a serious issue for future *LSR*s
  → Necessity of advanced studies of conversion into heat as well.

- Wake field induced FBII encountered at SOLEIL and SSRF may become more serious for future *LS*s