Review on Beam Instabilities in Circular Accelerators

LNF mini-workshop series

December 14th 2015

Bruno Touschek Auditorium

In honour of Theo Demma

Ryutaro Nagaoka (Synchrotron SOLEIL)

Istituto Nazionale di Fisica Nucleare

Content:

RN thanks Manuela Boscolo, Marica Biagini, Alessandro Variola and their colleagues at INFN-LNF for the occasion created.

1. Introduction: Why beam instabilities in storage rings

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

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

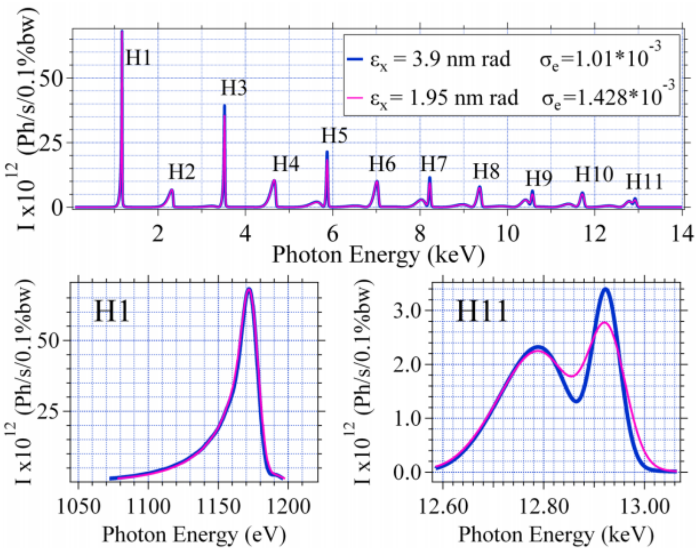
$$Brilliance = \frac{Photons}{Second \cdot mrad^2 \cdot mm^2 \cdot 0.1\%BW} \propto \frac{I}{\varepsilon_x \varepsilon_y}$$

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

$\Rightarrow$ Permanent wishes for higher beam intensities, and so effectively, endless beam instabilities issues to pursue. Recent efforts to lower further the beam emittance, for example, have explicit correlations with enhanced beam instabilities.

Specifically, the impact of collective effects differs 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"

More globally, the types and the physical content of beam instabilities much depend upon,

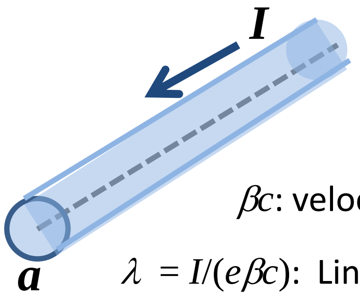
- Mass of the stored particles
  - Non-relativistic versus relativistic particles
  - Hadron versus leptons (the degree of radiation damping)
- Sign of the particle's electric charge
  - Negative versus positive
- Bunch length and the degree of bunching
  - Bunched beams versus coasting-like beams

$\Rightarrow$ A review given here only covers a part of the entire subject, due to the limited experience and the knowledge of the presenter

2. Collective Effects and Coherent Beam Instabilities in Storage Rings

2.1 Space Charge Effects

Historically, space charge effects were studied since early times as they were important in low energy proton (hadron) rings.



βc: velocity

$\lambda = I/(e\beta c)$: Line density

◊ Direct Space Charge Force

$$E_r = \begin{cases} \dfrac{e\lambda}{2\pi\varepsilon_0}\dfrac{r}{a^2} & (0 < r < a) \\ \dfrac{e\lambda}{2\pi\varepsilon_0}\dfrac{1}{r} & (a < r) \end{cases} \qquad B_\varphi = \begin{cases} \dfrac{\mu_0 I}{2\pi a^2}\cdot r & (0 < r < a) \\ \dfrac{\mu_0 I}{2\pi r} & (a < r) \end{cases}$$

$$\rightarrow \quad F_r = eE_r - evB_\varphi = \frac{e^2\lambda}{2\pi\varepsilon_0 a^2}\frac{r}{\gamma^2} \quad (r < a)$$

$$\rightarrow \quad \Delta\nu = \frac{1}{4\pi}\oint \beta(s)\cdot\Delta k(s)\, ds \approx -\frac{N r_0 \beta_{av}}{2\pi a^2\beta^2\gamma^3} \approx -\frac{N r_0 R}{2\pi a^2 \nu\beta^2\gamma^3}$$

N : Number of stored particles

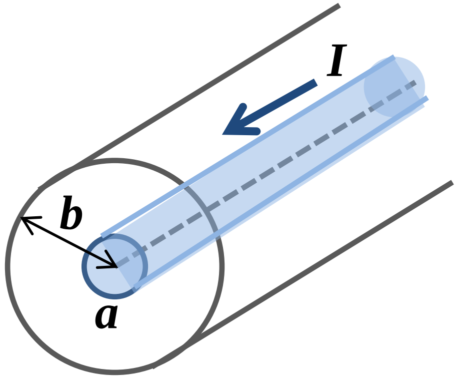
r_0 : Classical radius of the particle

ν : Betatron tune

R : Machine radius

$\Rightarrow$ A tune shift to a half-integer resonance gives the direct space charge limit N

◊ Indirect Space Charge Force



- Transverse space charge force taking into account the image current studied by L.J. Laslett → "Laslett tune shift"

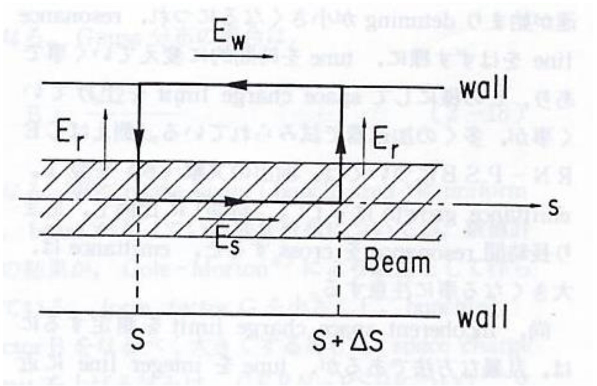
- Longitudinal phase stability limit

$$E_s = -\frac{e g_0}{4\pi\varepsilon_0\gamma^2}\frac{\partial\lambda}{\partial s} + E_w \qquad \left[\, g_0 = 1 + 2\ln(b/a) \,\right]$$

If the chamber wall is inductive, $E_w = e(\beta c)^2 L \dfrac{\partial\lambda}{\partial s}$

a particle loses the energy per turn by

$$U = \left(\frac{e g_0 R}{2\varepsilon_0\gamma^2} - e\beta^2 c^2 L\right)\cdot\frac{\partial\lambda}{\partial s}$$



(image taken from OHO '86, KEK)

$\Rightarrow$ Particles under the RF potential $V_{RF} = V_0 \sin\varphi$ reaches the longitudinal stability limit when the N reaches the limit

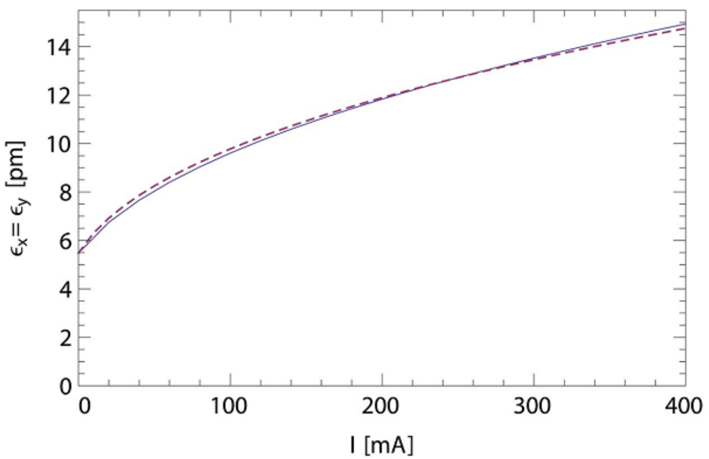
$$N_{sp} = \frac{2V_0 h l^3 \cos\phi_s}{3e\beta c R^2\left(\dfrac{g_0 Z_0}{2\beta\gamma^2} - \omega_0 L\right)}$$

where h: Harmonic number, l: Bunch half length, and a parabolic distribution assumed for $\lambda(s)$

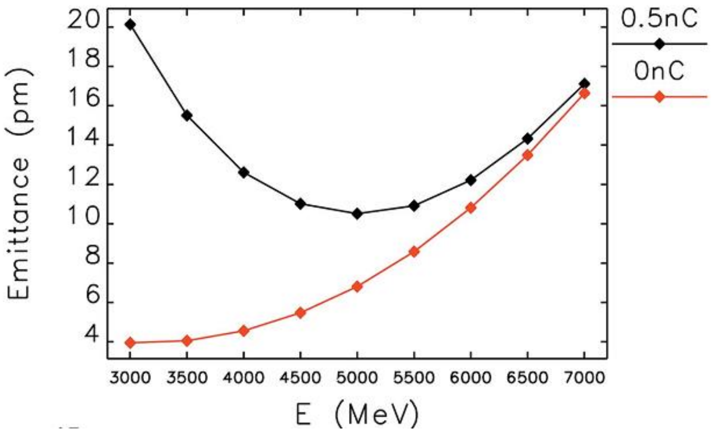
2.3 Scattering Effects

◊ IBS (Intra Beam Scattering)

- A multiple Coulomb scattering among electrons in a bunch leads to an increase in all bunch directions including the energy spread.
- Effect is enhanced for a low energy LER (Low Emittance Rings) 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.
- Many future light source LERs consider making a 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*)

Summary of a review talk given by Theo on IBS at the TWIICE workshop (SOLEIL, January 2014)

Summary

SIRE and C-MAD/IBS-TRACK?

Apparently a new improved kinetic scheme for IBS

- The effect is well understood for the core particles or if the effect is a perturbation
- We don't know what is the effect on the tails
- Interesting aspects of the IBS such as its impact on damping process and on generation of non Gaussian tails may be investigated with a multiparticle algorithm.
- Two codes implementing the Zenkevich-Bolshakov algorithm to investigate IBS effects have been developed at LNF and at CERN:
  – Benchmarking with conventional IBS theories gave good results (both codes).
  – Evolution of the particle distribution shows deviations from Gaussian behaviour due to IBS effect (SIRE, CLIC-DR).
  –Comparison of the code results with measurements would provide the possibility of
  •Benchmarking with real data
  •Tuning code parameters (number of cells, number of interactions, etc.)
  •Revision of the theory or theory parameters (Coulomb log, approximations used, etc.)

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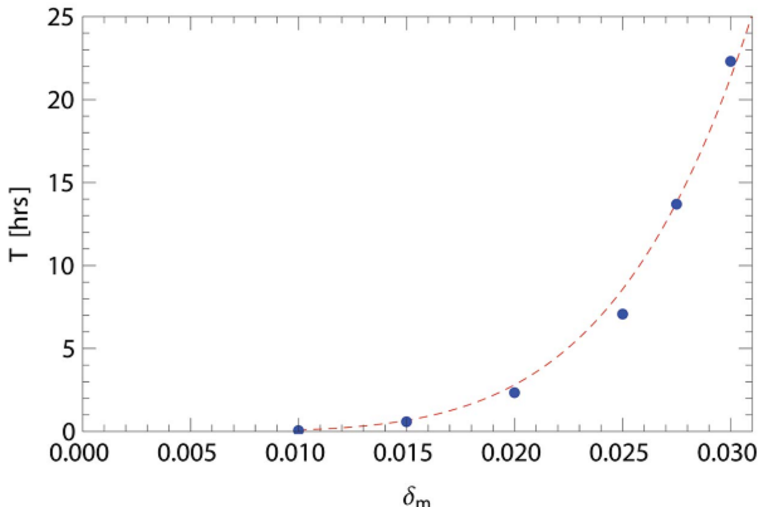
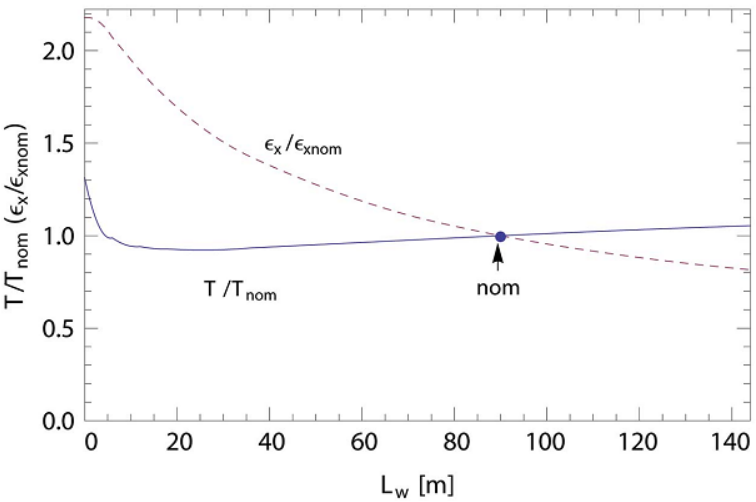
◊ Touschek Scattering

- 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: $T = 0.088(\delta_m/0.01)^5$.

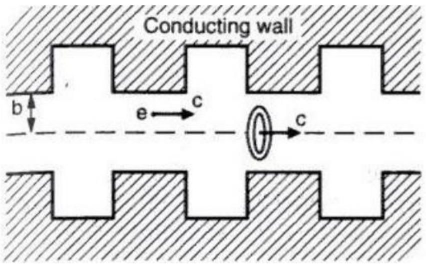


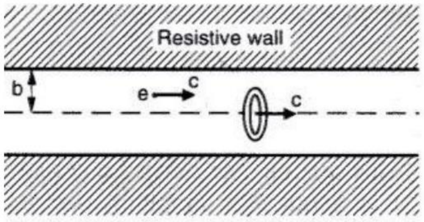
ε_x (= ε_y) and Touschek lifetime T versus wiggler length L_w. These results are self-consistent calculations including IBS. The point labeled ‘nom’ represents the nominal case, with L_w = 90 m.

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

2.4 Impedance Issues

Since there is no way of constructing a ring with superconducting chambers everywhere with no cross section changes, the coupling impedance has always been and would continue to be the dominating source of beam instabilities.





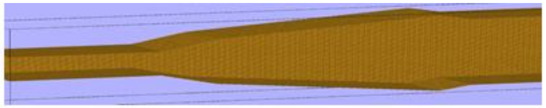
Images taken from Alex Chao textbook

As the chamber apertures tend to diminish and beam profiles evolve in modern rings
→ Advanced (extended) impedance studies always of great importance.

◊ **Geometric impedance**

Vacuum elements usually making large contributions:

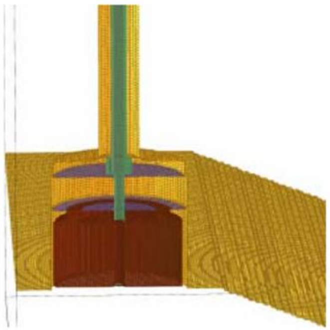
- Tapers, collimators, scrapers
- Cavities
- Flanges
- Bellows
- BPMs
- Striplines

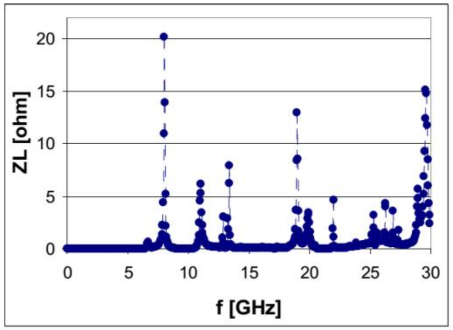


Original

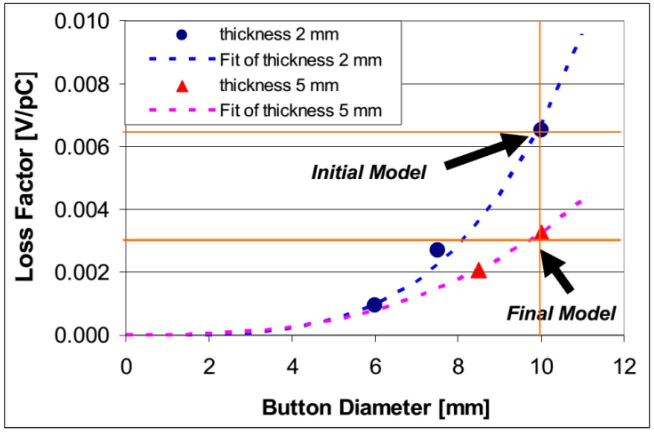
New

In-vacuum insertion device tapers at SOLEIL



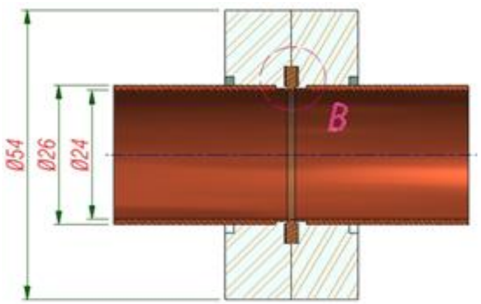


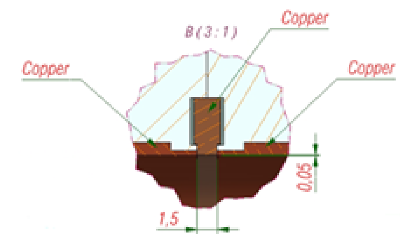
Optimisation of a BPM button (SOLEIL, 2004)

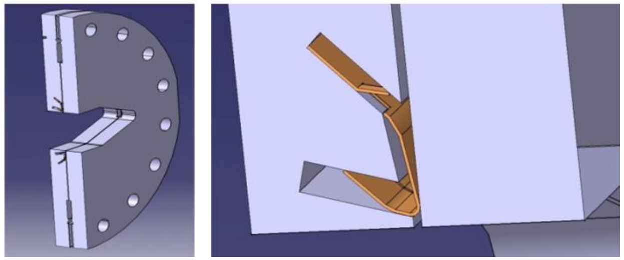


<u>Challenging aspects</u>:

- Modelling of complicated & fine 3D structures
- Evaluation of short-range wakes (high frequency impedance)
- Evaluation of high Q (long-range) resonators
- Evaluation of power dissipation (heat generation)







RF shielding of a flange (SOLEIL, 2004)

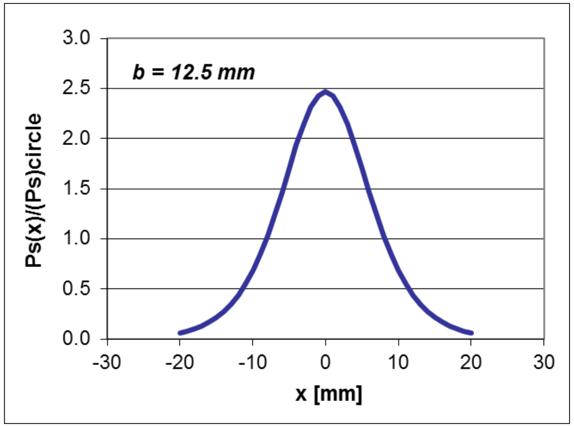
“Impedance free” flange developed at Sirius (Brazil)

◊ Resistive-wall impedance and impedance of dielectric materials

Challenging aspects:

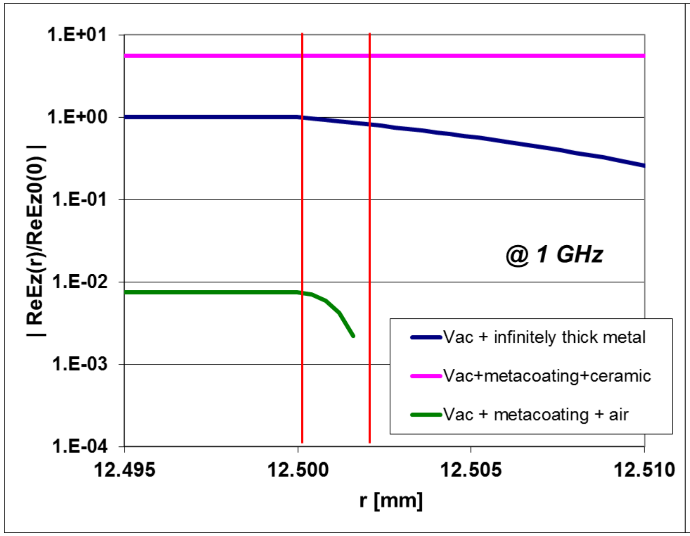
Explore the dependence of impedance on;

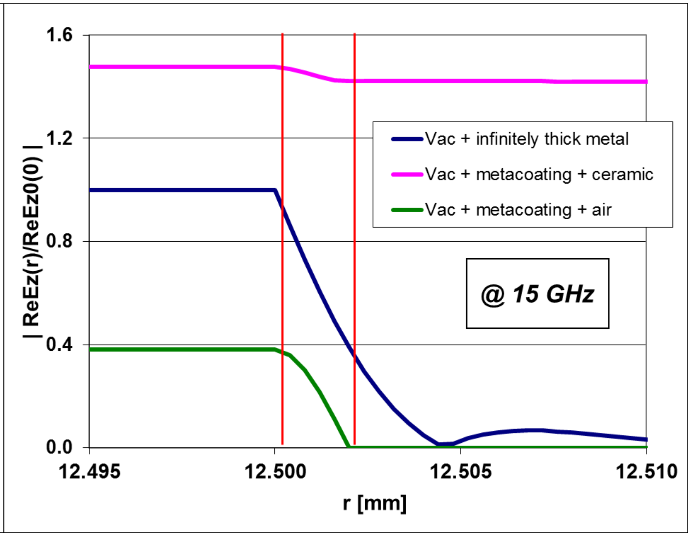
- Short-range (high frequency) regimes
- Layers of various materials including air
- Arbitrary chamber cross section
- Effects combined with geometric impedance



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

Above: horizontal distribution of power density on the flat chamber wall





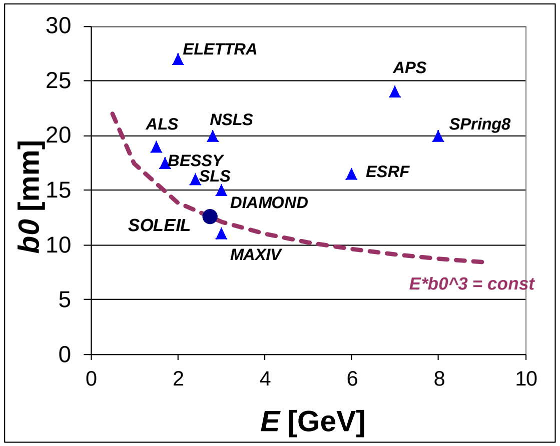
Left: $E_z(r)$ for different material layers to study the image current flow

2.5 Impedance-Induced Collective Effects

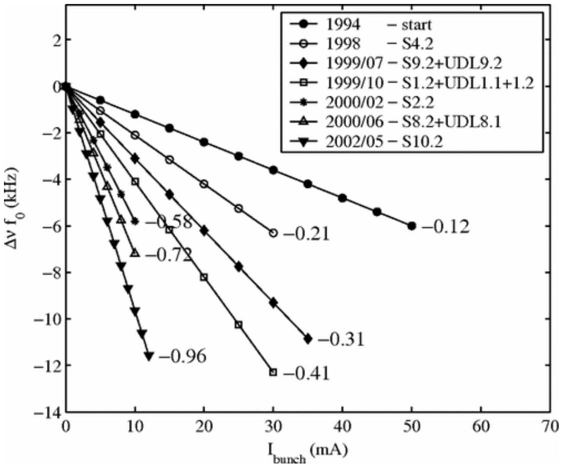
◊ Correlation between low emittance and impedance-induced collective effects

- 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 $\propto\ b^{-3}$

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

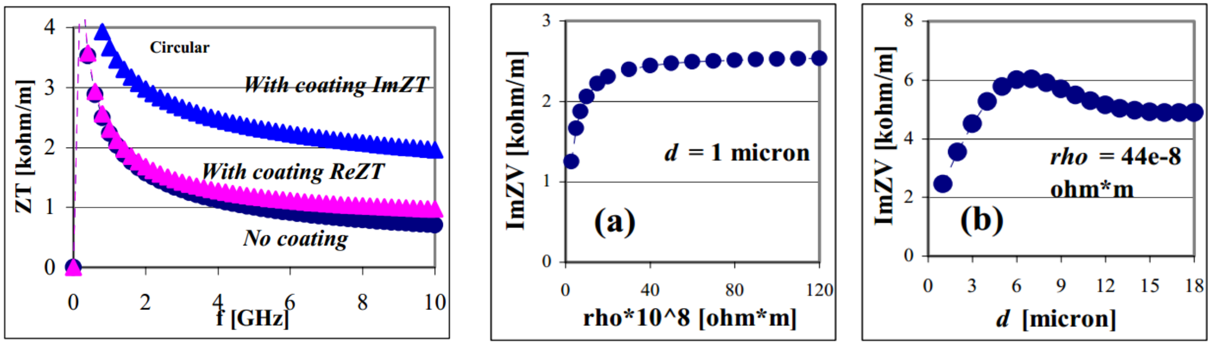


Vertical half aperture versus machine energy in several light sources



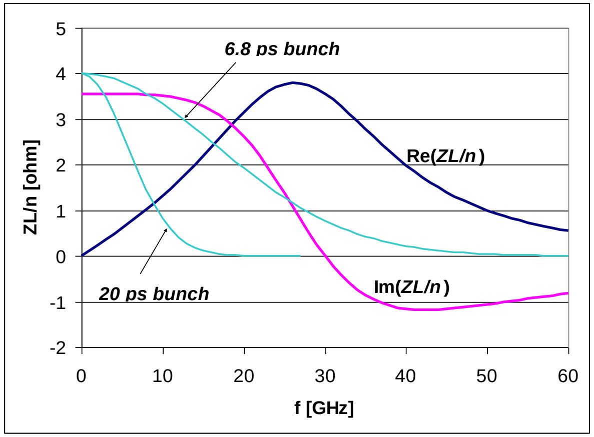
Observation of increased $Z_\perp$ with NEG coated chambers

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



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

- Lower emittance → Low horizontal dispersion → Low momentum compaction → Shorter natural bunch length → Higher sensitivity against wakes



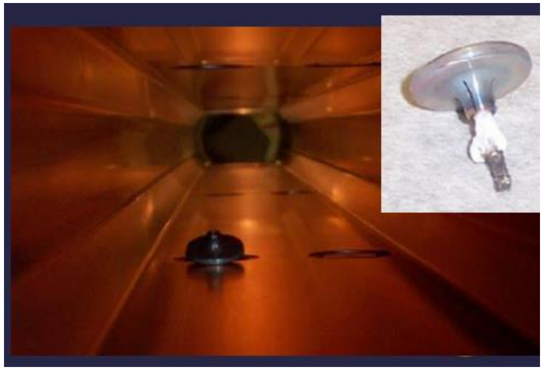
Interaction of 6.8 ps and 20 ps bunches with 30 GHz BBR impedance

ex). Transverse coherent detuning:

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

◊ Beam-Induced Heating

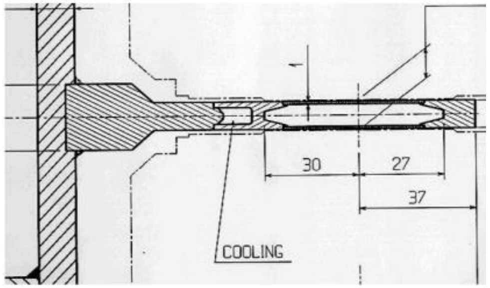
With reduced vacuum chamber aperture, the enhanced longitudinal impedance brings about beam-induced heating → In reality this may create severer problems in running a ring than due to beam instability.



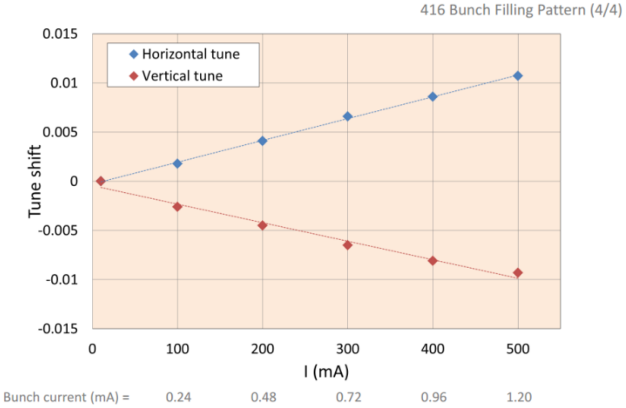
Melted BPM button in PEP-II

A melted RF finger (SOLEIL)

◊ Vertically narrow (i.e. non-circular) chambers inducing incoherent tune shifts



ESRF 10 mm chamber



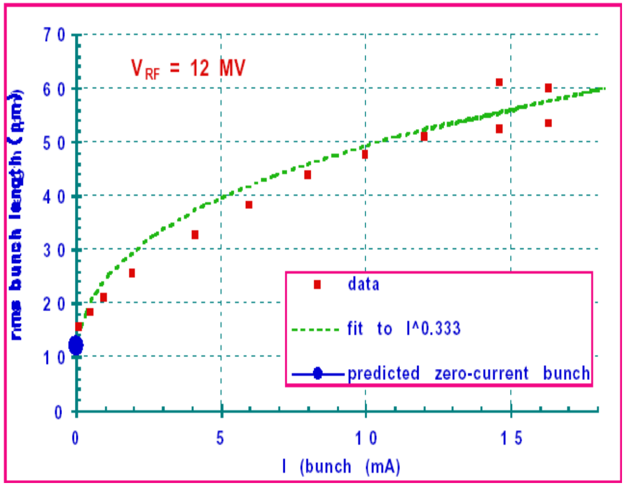
Incoherent tune shifts measured at SOLEIL

(P. Brunelle et al., TWIICE, 2014)

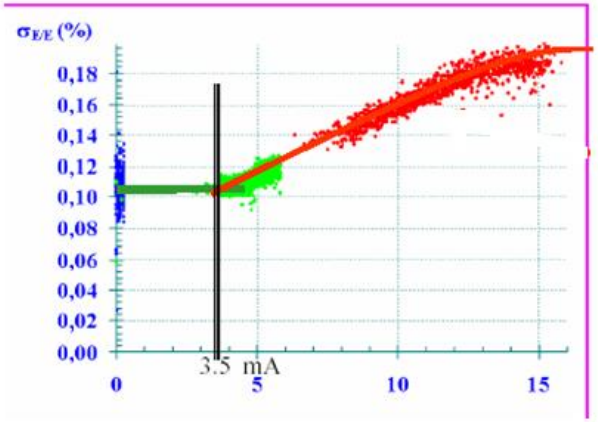
◊ Single bunch instabilities

Longitudinal:

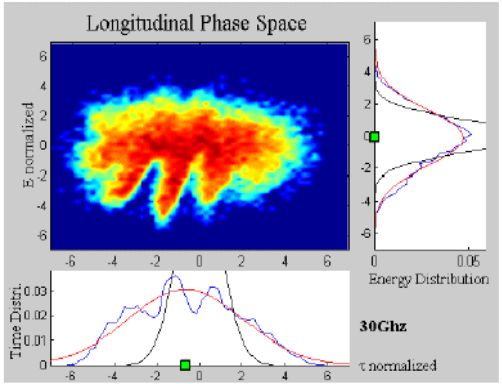
- Bunch lengthening in the potential well regime (due generally to inductive nature of $Z_{//}$)
- Microwave instability (energy spread widening and bunch lengthening)



Comparison of measured and calculated bunch lengthening



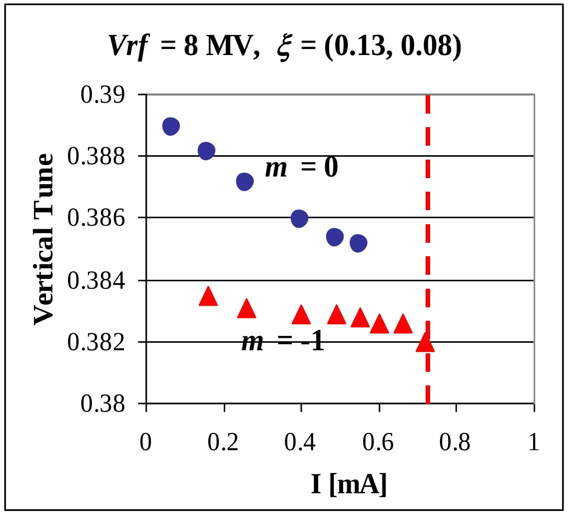
Measured microwave threshold at the ESRF



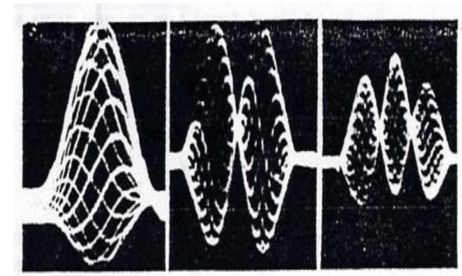
Tracking simulation of microwave instability

<u>Transverse</u>:

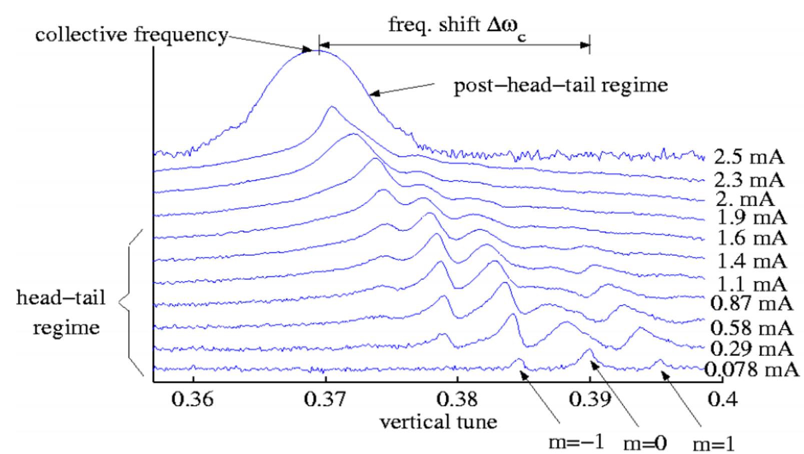
- Coherent detuning (due beam interaction with the low frequency inductive $Z_\perp$)
- Transverse Mode-Coupling Instability (TMCI)
- Headtail and Post-Headtail Instabilities



Measured vertical coherent detuning and TMCI threshold at the ESRF



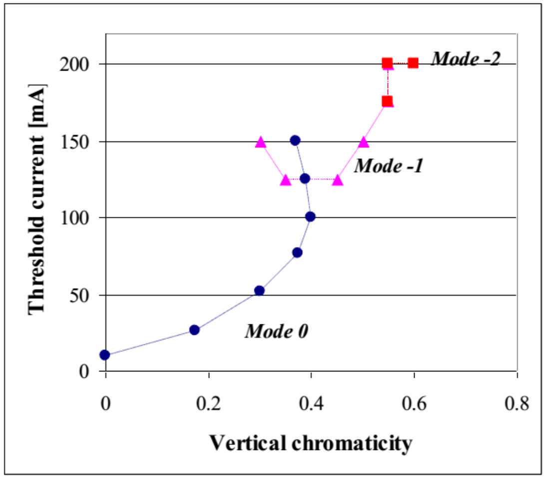
Famous measured headtail motions in F. Sacherer's paper



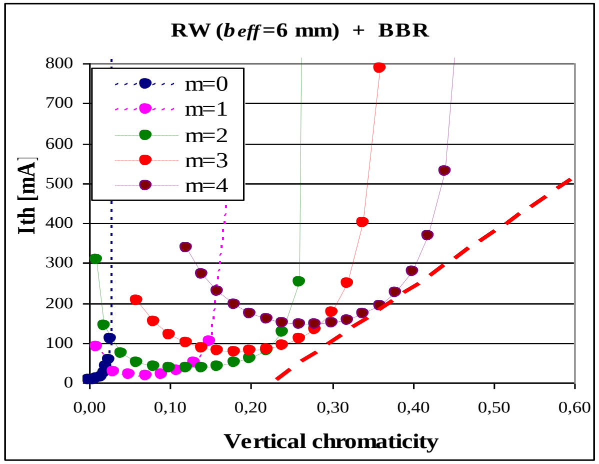
- *Headtail to post-headtail transition measured at the ESRF (P. Kernel et al., EPAC 2000, Vienna)*

◊ Multibunch instabilities

- Resistive-wall instabilities in the transverse planes

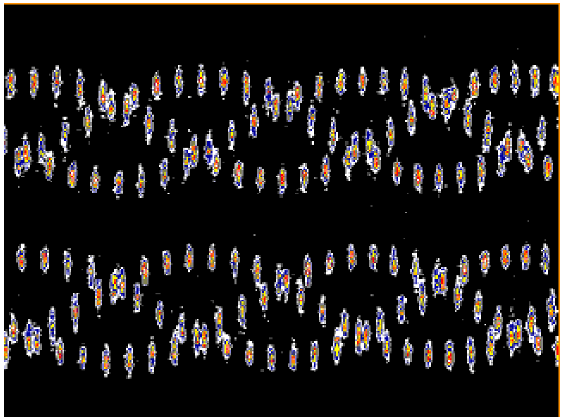


RW instability measured at the ESRF



Simulation of resistive-wall instability versus chromaticity (*R. Nagaoka, "Ultimate storage ring studies", ESRF 2002*)

- High Q resonances (typically HOMs of the RF cavities) in whichever planes (L/H/V)



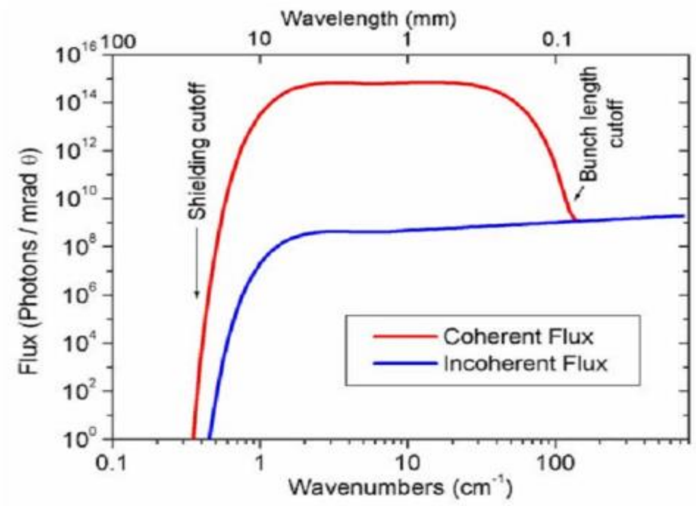
Longitudinal coupled-bunch instability measured with a stream camera at the ESRF

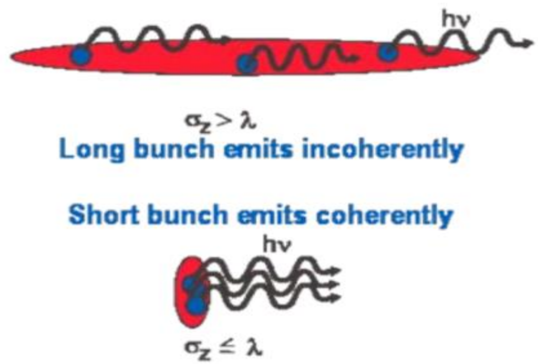
To fully understand the nature of resistive-wall instabilities, one **needs to follow both** the **single** bunch and the **coupled-bunch** dynamics.

→ Full numerical tracking (such as *mbtrack*)

2.6 CSR-Induced Instability

- Electrons in a bunch radiate photons coherently for waves that are $\lambda >> \sigma_L$



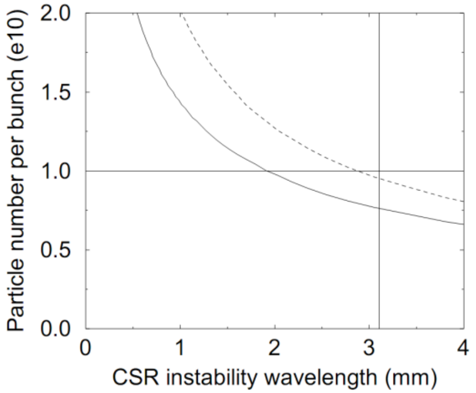


(*From J. Byrd, "CSR studies at ALS", 2006*)

- With a long bunch, however, a wave λ that fulfills the coherence condition may be shielded by the vacuum chamber.
  → In low-emittance rings, bunch length $(\sigma_L)_{zero\text{-}current}$ tends to be small and CSR may appear

- Since the photon flux $\propto N^2$ (N : number of electrons/bunch), a big interest of its use for the SR community as an Infrared THz source.
  → The ring is operated in low-α optics to further lower the bunch length.
  → Efforts made to enhance CSR without falling into the bursting mode.

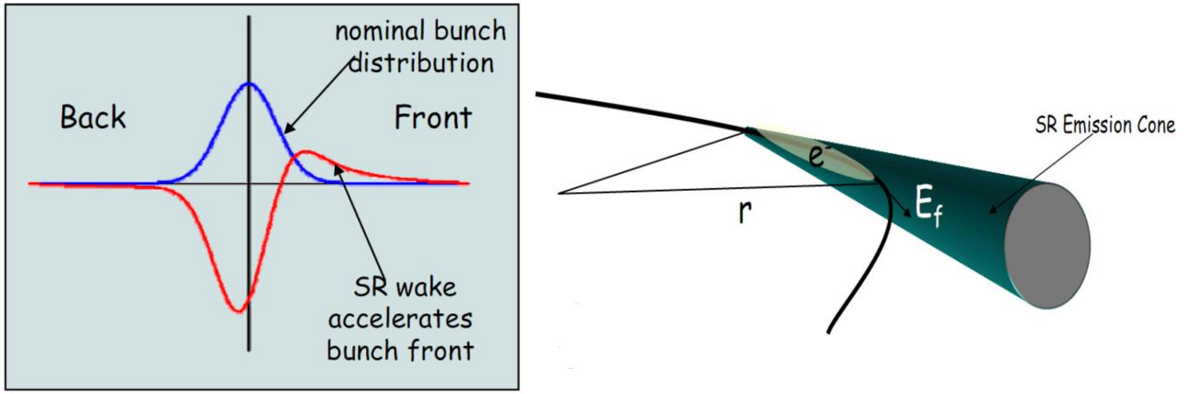
- For damping rings, on the contrary, CSR is undesired as it may induce ***single bunch longitudinal instability*** (micro-bunching and energy-spread widening).



CSR instability threshold as a function of λ calculated for KEK ATF damping ring (*T. Raubenheimer et al., PAC03*)

→ For both communities, study of CSR wakes and its impact on the beam is highly important.

◊ CSR wake fields



(*From J. Byrd, "CSR studies at ALS", 2006*)

- (In free space) particles in the *tail* excite fields felt by particles in the *head* of a bunch

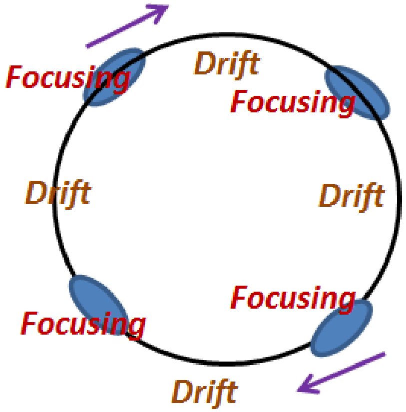
2.7 Two-Beam Instabilities

A stored beam could be perturbed by the presence of a group (cloud/beam) of other particles in the beam duct.

◊ Electron cloud → Mauro's talk

◊ Ions

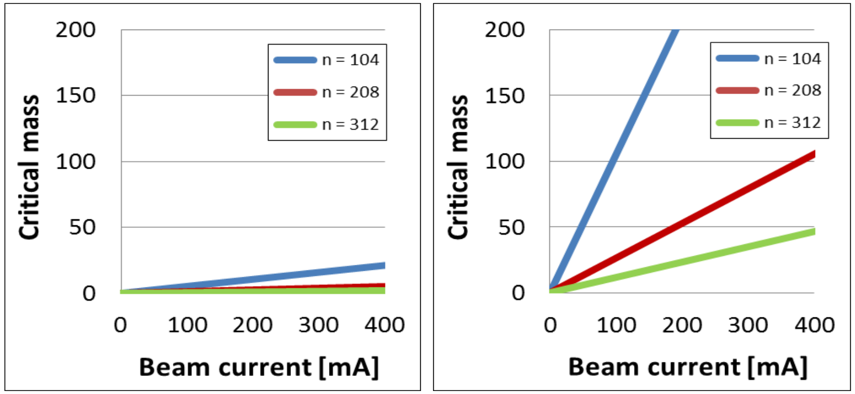
- Residual gases could be ionised via collision and be attracted by the electro-static potential of a stored beam.
- In the linear approximation, a "critical mass" gives a criterion for **ion trapping**:

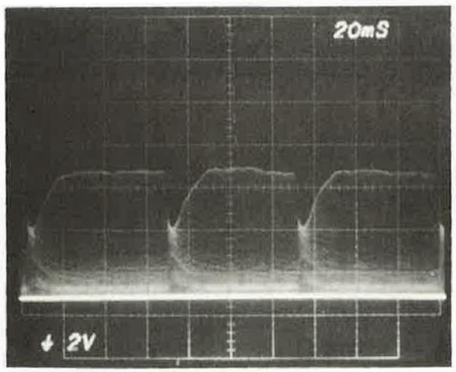


$$A \geq A_c \equiv \frac{N}{n_b} \frac{r_p}{n_b} \frac{\pi R}{\beta^2 \sigma_y (\sigma_x + \sigma_y)}$$

(A_c: Critical mass)

N : Total number of stored electrons
n_b : Number of bunches
r_p : Classical proton radius (= $e^2/4\pi\varepsilon_0 m_p c^2$)
R : Machine radius

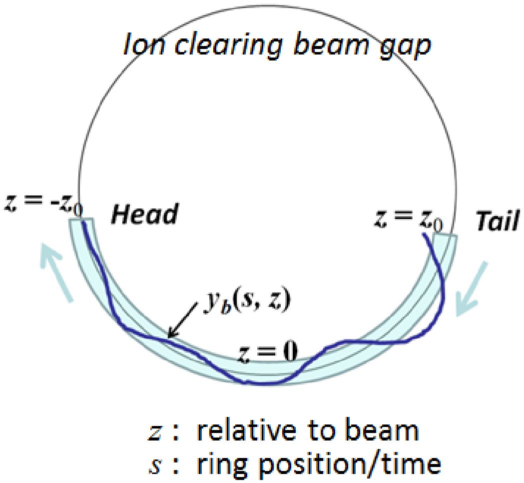




Beam pulsation observed at KEK-Photon Factory due to trapped ions (*S. Sakanaka, OHO 1986*)

- For low emittance machines, ion trapping tends not to be an issue (cf. *example calc. for SOLEIL*).

- For modern and future rings storing a high intensity and low emittance beam, a "single pass" interaction between the two beams may become strong enough to jeopardise the performance.



- This type of two-beam interaction, named "**Fast Beam-Ion Instability** (**FBII**)" resembles "beam breakup in linacs" and does not involve ion trapping, and an ion clearing beam gap may not be helpful.

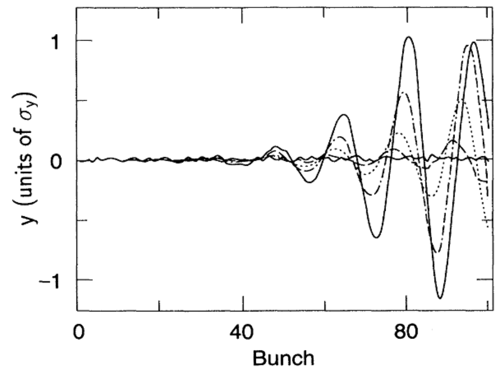
(*Raubenheimer and Zimmermann, Phys. Rev. E***52***, 5487, 1995*)

- Asymptotic growth rate at the tail of a bunch train:

$$\tau_{aymp}^{-1}(s^{-1}) \approx \frac{N_e^{3/2} n_b^2}{\gamma} \times \left[5 p_{gas}(\mathrm{Torr}) \frac{r_e r_p^{1/2} L_{sep}^{1/2} c}{\sigma_y^{3/2}(\sigma_x+\sigma_y)^{3/2} A^{1/2} \omega_\beta} \right]$$

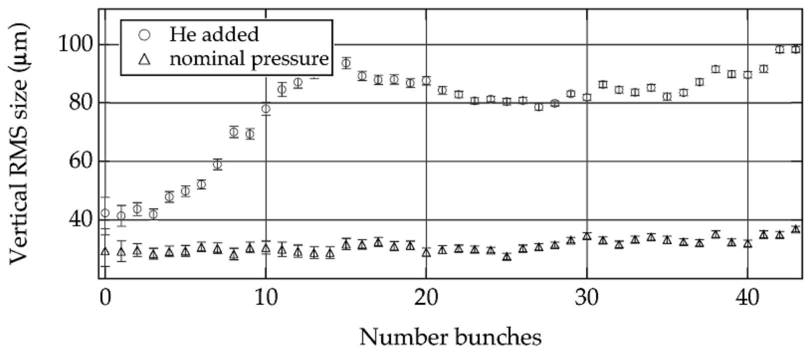
depends strongly on

- Number of bunches $\propto n_b^2$
- Number of particles per bunch $\propto N_e^{3/2}$
- Beam size $\propto \sigma_y^{-3/2} \cdot (\sigma_x+\sigma_y)^{-3/2}$

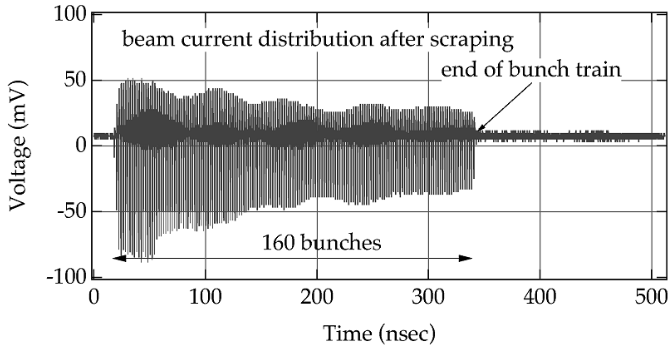


Simulated vertical oscillation y_b vs bunch number at several different instants

- FBII was experimentally demonstrated in ALS, PLS and KEK by artificially increasing the vacuum pressure.



Measured vertical beam size as a function of the length of bunch train



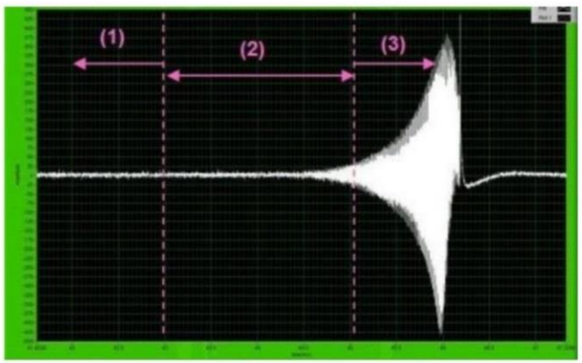
Measured vertical amplitude along the bunch train after insertion of a vertical scraper

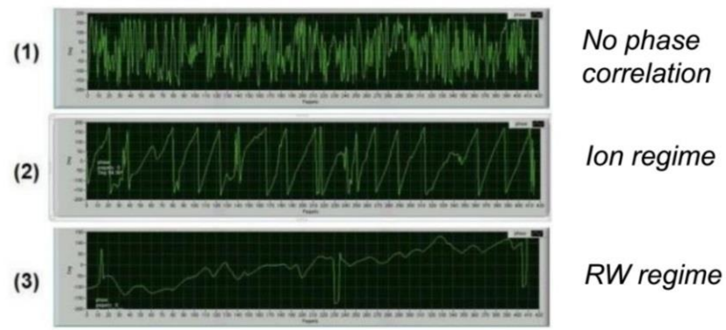
(*J. Byrd et al., PRL **79**, 79, 1997*)

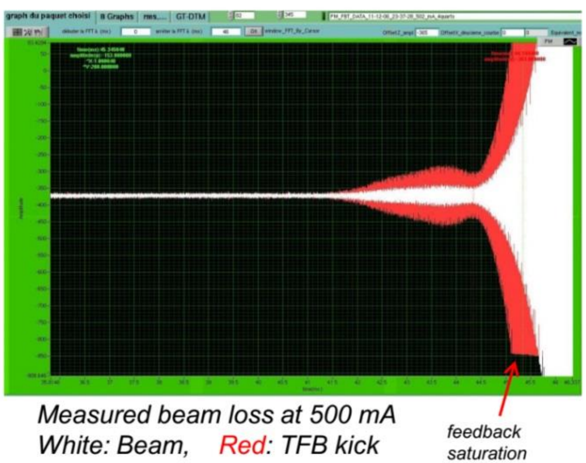
◊ Beam losses encountered at SOLEIL and considered to be due to FBII:

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

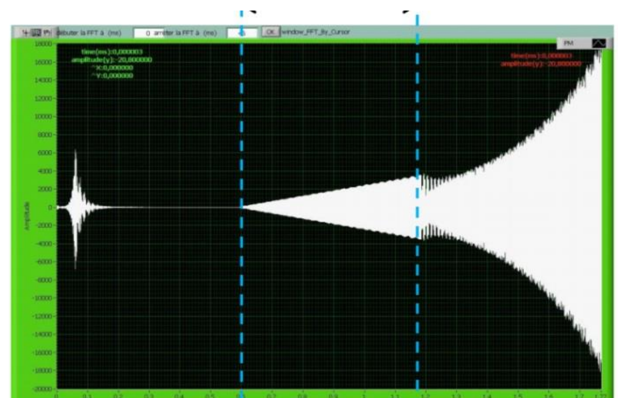
- At SOLEIL, transverse bunch-by-bunch feedback is routinely used to suppress resistive-wall (RW) instability.
- However, depending upon the beam filling and intensity, beam-induced heating could trigger FBII via outgassing and leads to ***total beam losses***.
- Usually the beam is lost some 10 minutes ***after*** reaching the final current (500 mA)
- The above interval of time as well as the ***total beam loss*** due to FBII remained as a big puzzle







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



Simulation: RW with temporal "shaker" excitation at F_{ion}

Experimental and numerical analyses lead us to conclude that over the time interval, the ***local pressure keeps rising*** up to the point when feedback hits its limit and becomes ***destructive***

3. Conclusions

- Beam instabilities in storage rings are a subject on which many accelerator physicists and engineers are actively working today in order to fight against them and raise further the storage ring performance.

- We have quite good physical insights into the mechanisms of various known instabilities today, and the large advance in the numerical computing power in the last decades has enabled us to elucidate quantitatively complicated effects in more realistic models.

- However, 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, and even a new type of instability.

- We should continue along the passion and the enthusiasm that Theo always had in confronting the challenging collective beam physics issues to pursue the ultimate storage ring performance.