Review of Collective Effects for Low Emittance Rings

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Outline:

1. Introduction
2. Impedance induced effects
3. CSR induced effects
4. IBS
5. Two-beam Instabilities
6. Summary

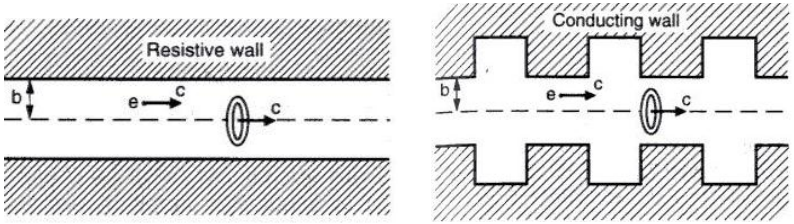
1. Introduction

◊ Low-emittance high current beam is the common goal for many damping rings and light sources, to increase respectively the luminosity and the brilliance.

◊ However, the smallness of the emittance tends to enhance the sensitivity of high current beams against various collective effects.

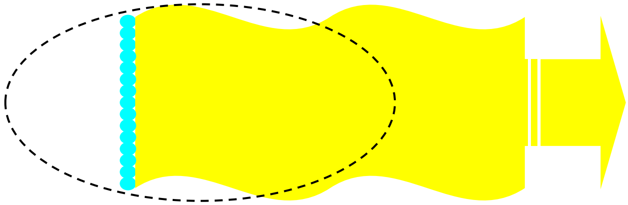
➔ ***See F. Antoniou (CERN)***

◊ Collective effects reviewed hereafter:

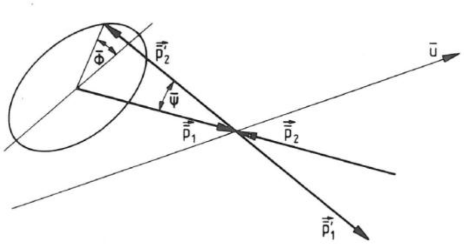


(from AW Chao, "Physics of collective beam instabilities…")

Vacuum chamber wakes

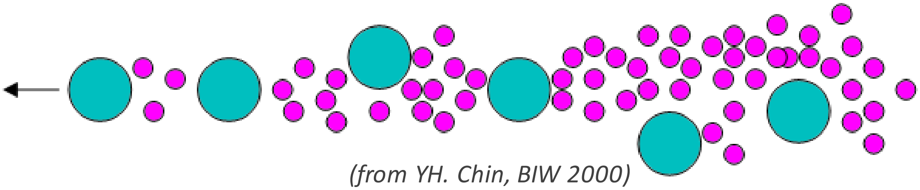


CSR wakes



(from A. Piwinski, Tech. Rep. HEAC 74, 1974)

Intra-beam scattering



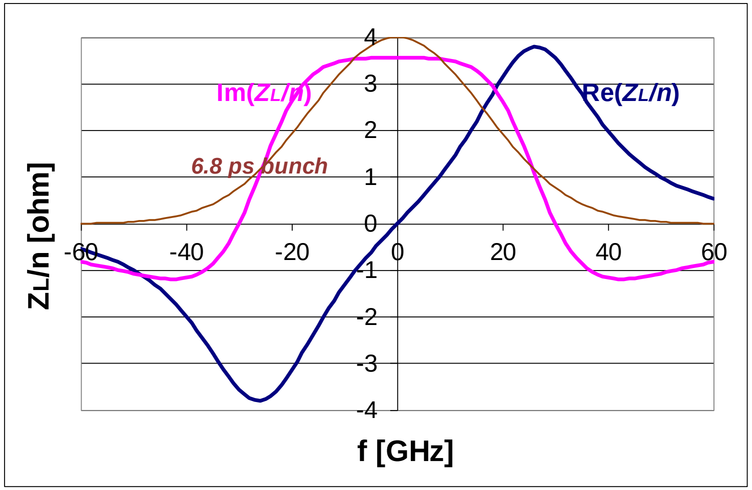
(from YH. Chin, BIW 2000)

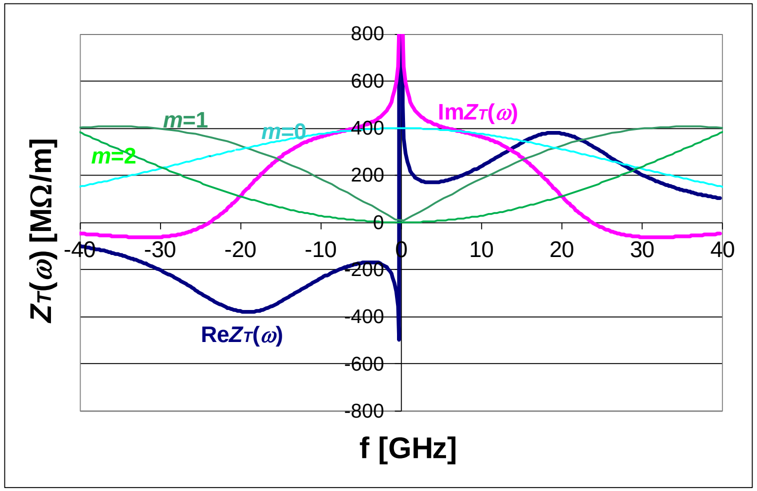
Two-beam interactions

2. Impedance-Induced Effects

◊ Impact on a low-emittance beam

Low emittance optics → Low momentum compaction factor α → Shorter bunch length → Stronger interaction with high frequency wakes





- Interaction with low frequency wakes (inductive nature):
  - Bunch lengthening/Coherent detuning

- Interaction with high frequency wakes:
  - Microwave instability (single bunch longitudinal):
    Energy spread blow-up/bunch lengthening
  - Headtail/TMCI (single bunch transverse):
    Transverse beam blow ups and losses

- Beam-induced heating
- Coupled-bunch instability due to resonant (trapped) modes

  Beam blow ups, losses, filamentation, …

A melted RF finger (SOLEIL)

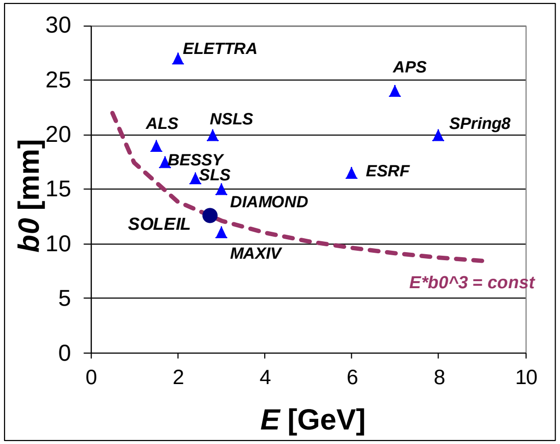
◊ Sources of Impedance in Low Emittance Rings

RF cavities, injection/extraction kickers, resistive-wall, BPMs, flanges, RF shielded bellows, tapers, ante-chamber slots, pumping slots, …

➔ ***See E. Koukovini-Platia (CERN)***

- Light sources tend to have small gap chambers everywhere and very low gaps (< 10 mm) for insertions devices with tapers in between.

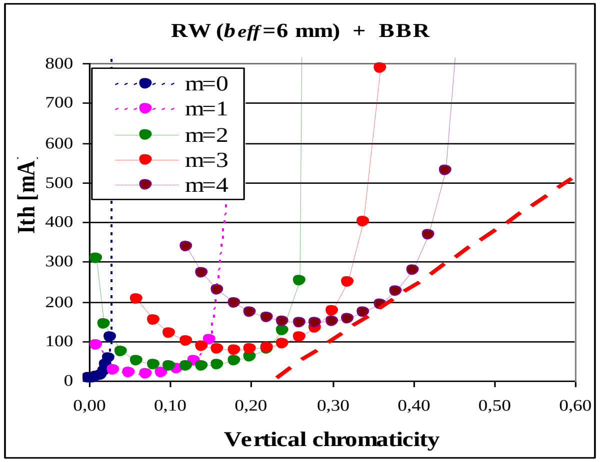
10 mm gap chamber at SOLEIL



Vertical half aperture versus machine energy in several light sources

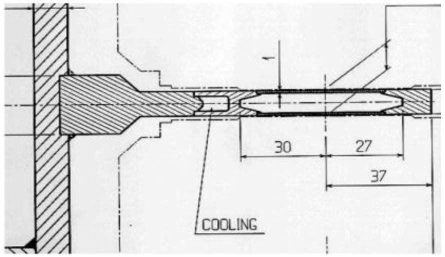
➔ Resistive-wall instability (coupled-bunch transverse) becomes important

➔ Chromaticity-shifting does not always work due to short bunches interacting with high frequency wakes

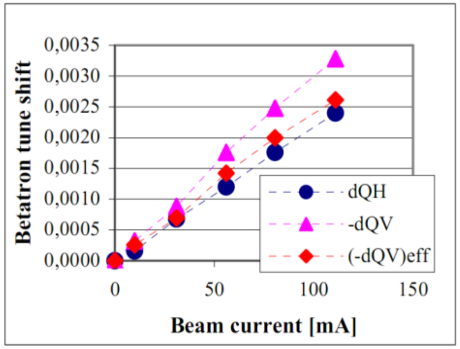


Resistive-wall instability versus chromaticity
(*R. Nagaoka, "Ultimate storage ring studies", ESRF 2002*)

- Vertically narrow (i.e. non-circular) chambers induce current-dependent incoherent tune shifts



ESRF 10 mm chamber



Left: Measured tune shift in BESSY II

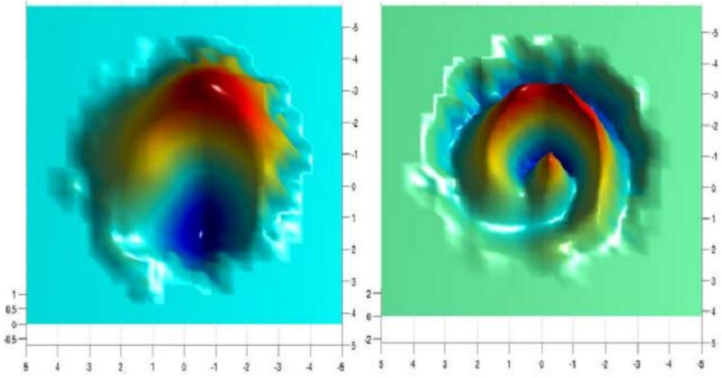
(*R. Nagaoka et al., EPAC02*)

➔ In some light sources, the tune shifts at high current amounts to several synchrotron tunes
➔ Closure of in-vacuum insertions may induce large coherent & incoherent tune shifts

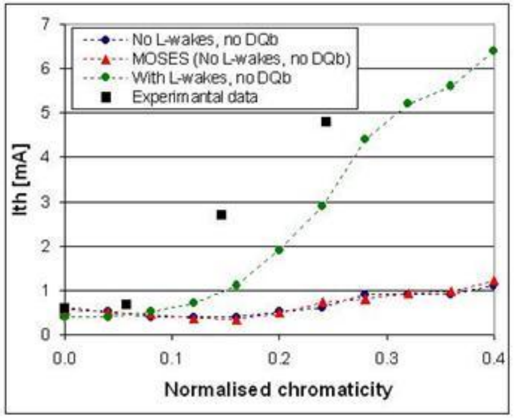
◊ Wake field studies/calculations

- Numerical calculations taking into account 3D geometry/fine-meshing (0.1 mm order)/short-bunch (1 mm order)/valid impedance calculations up to tens of GHz
- Continuous development on EM-field solvers (low-dispersion, parallelization, …)
- Analytical wake field studies (short-range resistive-wall, surface roughness, 3D taper wakes, …)

➔ *See B. Podobedov (BNL)*



Simulation of headtail instabilities (*R. Nagaoka, EPAC02*)



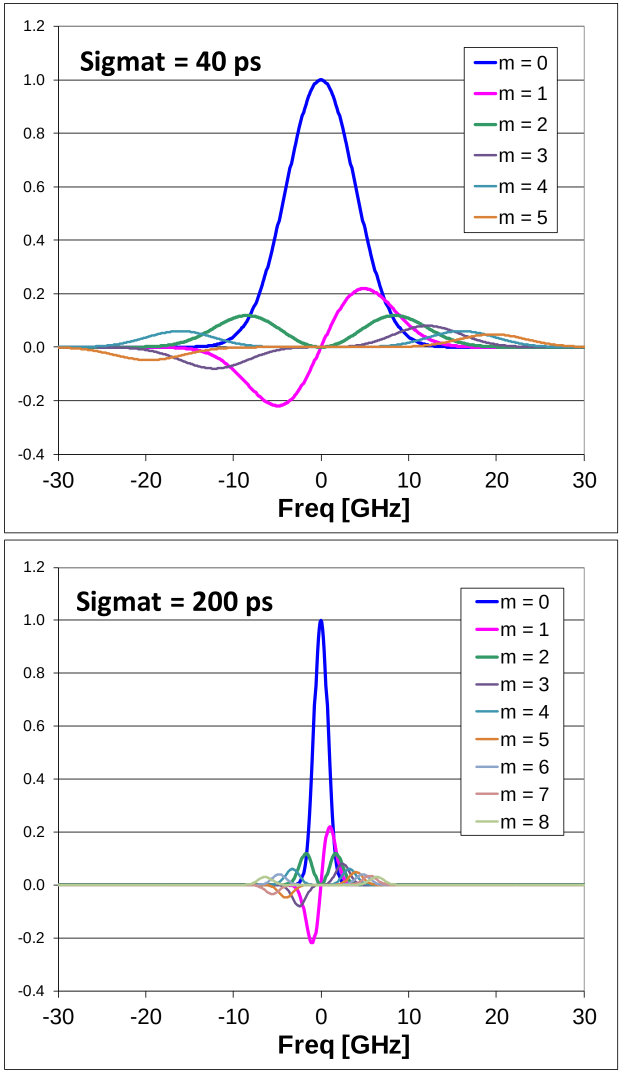
Impact of longitudinal-vertical coupling
(*R. Nagaoka et al., PAC09*)

◊ Simulation studies/calculations

- Linearised Vlasov equation (eigenvalue calculations) in frequency domain
- Multiparticle tracking/Vlasov-Fokker-Planck calculation in time domain
- Use of numerically obtained wake fields/CSR wakes
- Coupling between different planes/inclusion of optics non-linearity

◊ Counter measures

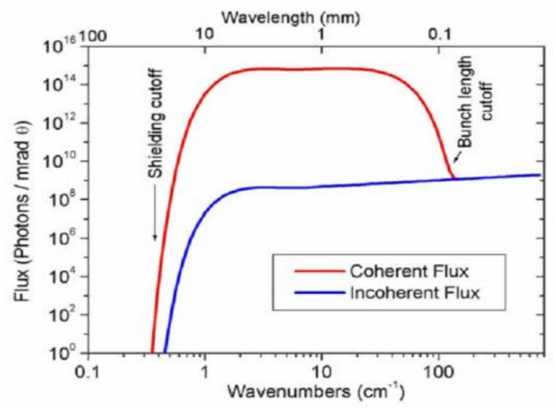
- Application of positive chromaticity
- Bunch by bunch feedback ➔ ***See T. Nakamura (SPring-8)***
- Bunch lengthening with harmonic cavities

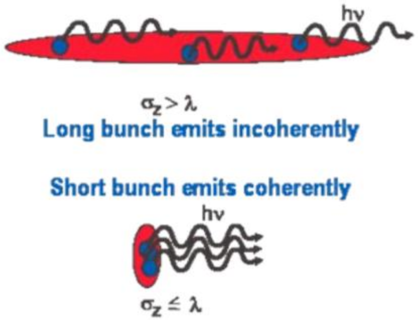


Distribution of headtail modes as a function of bunch length (MAXLAB-SOLEIL, 2011)

3. CSR Induced Effects

◊ Electrons in a short bunch radiate photons coherently



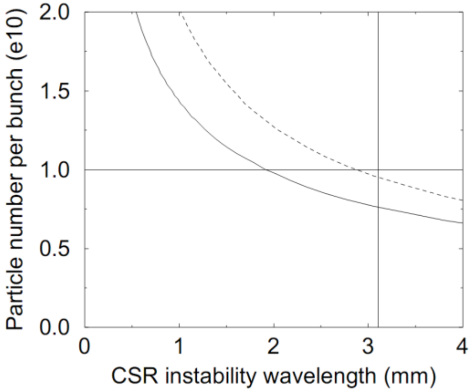


(*From J. Byrd, "CSR studies at ALS", 2006*)

- 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 (ALS, BESSY II, UVSOR, ANKA, MLS, DIAMOND, SOLEIL, …).
  ➔ The ring is operated in low-α optics to further lower the bunch length.
  ➔ Efforts made to enhance CSR without falling in the bursting mode.

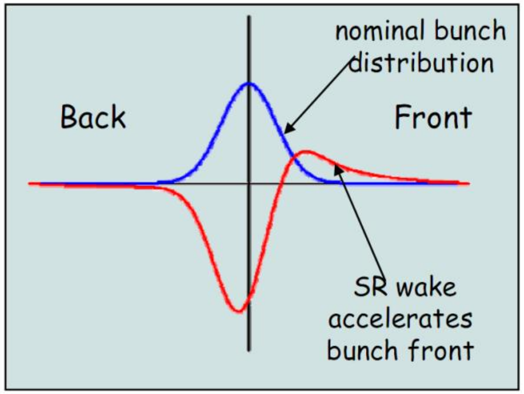
- For damping rings, on the other hand, CSR is undesired as it may induce single bunch longitudinal instability (micro-bunching and energy-spread widening).

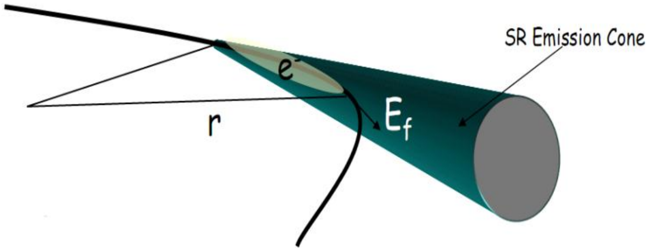


CSR instability threshold as a function of λ calculated for KEK ATF damping ring (*T. Raubenheimer et al., PAC03*)

➔ In both rings, study of CSR wakes and its impact on the beam is highly important.

◊ CSR wake field





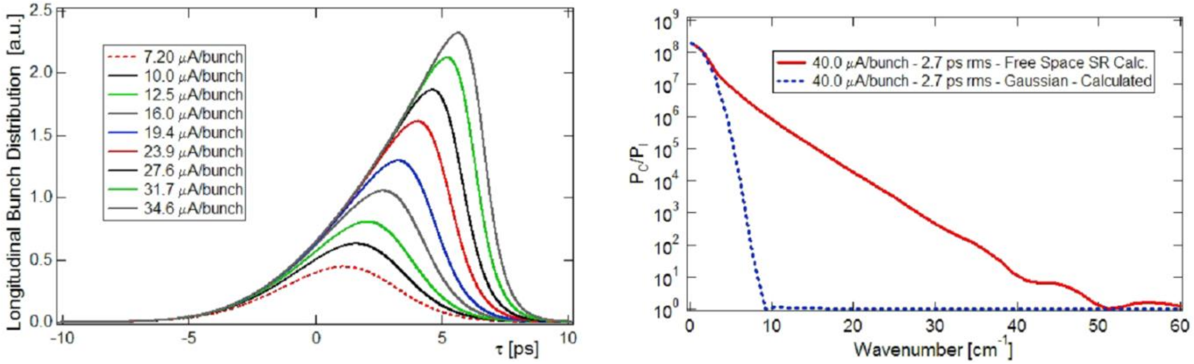
(*From J. Byrd, "CSR studies at ALS", 2006*)

- Particles in the tail excite fields felt by particles in the head of a bunch

- Pioneering studies on CSR wakes (in free space, two metal plates):

  (*J.M. Murphy et al, Part. Accel.* ***57***, *9* (*1997*) ; *Y. S. Derbenev et al., DESY Report No. TESLA-FEL 95-05, 1995*)

- CSR wake tends to distort the Gaussian distribution so as to enhance CSR up to higher frequencies



(*From F. Sannibale et al., PAC03*)

◊ Studies on CSR instability

- It was theoretically shown that CSR may enhance an initial density fluctuation leading to instability

  (*G. Stupakov, S. Heifets, PRSTAB* ***5***, *054401, 2002*)

- Conventional microwave instabilities due to machine impedance may excite CSR instability (often in the bursting regime).

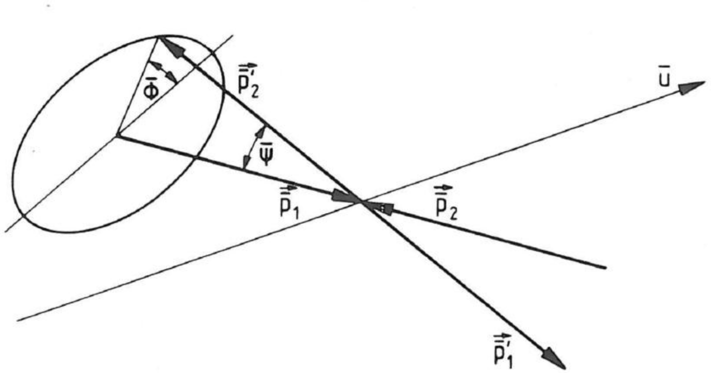
- Simulation studies (Multiparticle tracking/Linearised-Vlasov/Vlasov-Fokker-Planck)
  Pioneering study by R. Warnock,
  Recent theoretical progress (*K.L.F. Bane, Y. Cai, G. Stupakov, PRSTAB* ***13***, *104402, 2010*)

➔ ***A. Novokhatski (SLAC); V. Judin (ANKA); M. Ries (MLS)***

4. IBS (Intra Beam Scattering)

◊ IBS and its impact on a low-emittance beam

- IBS is a multiple Coulomb scattering between charged particles within a bunch.
- IBS is a “collective” effect as it depends (linearly) on the bunch current.
- IBS induces momentum transfer from transverse to longitudinal and is similar to Touschek scattering, but the latter refers to particle losses longitudinally.



Change of momenta in a two-particle collision in the centre-of-mass coordinate system
(*Taken from A. Piwinski, Tech. Rep. HEAC 74, Stanford, 1974*)

- However, a non-zero dispersion excites betatron oscillations and increases transverse momenta.
- IBS is a big concern to low-emittance rings as it may spoil the small emittance

Emittance growth rate ~ (Number of particles/bunch) / (ε_H*ε_V*σ_L * γ^3)

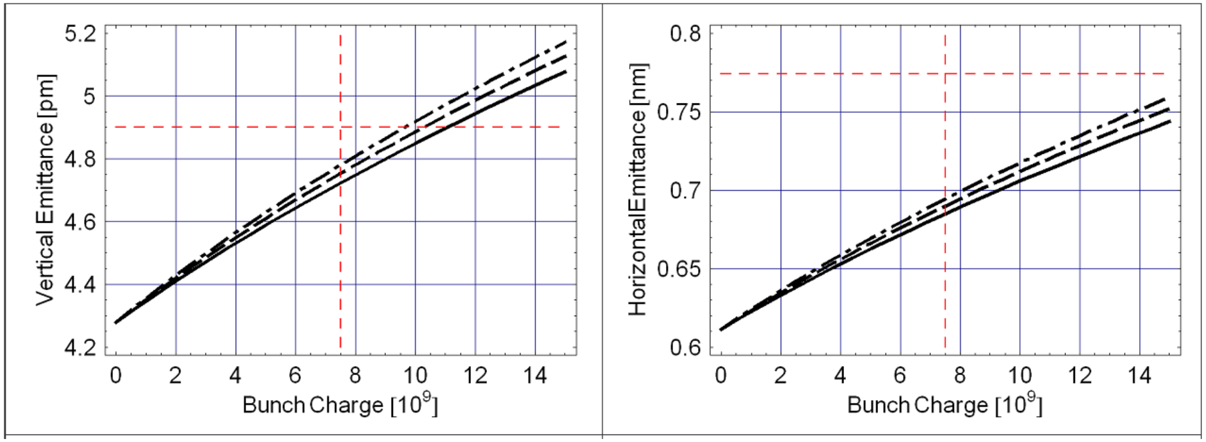
◊ Theoretical studies of IBS

- Pioneering works by A. Piwinski (*Tech. Rep. HEAC 74, Stanford, 1974*), and by J. Bjorken, S. Mtingwa (*Part. Accel., 13 (1983) 115*).

- Evaluation of the derived expressions not simple, as they involve numerical integrations all around a ring (average over the lattice)
  ➔ "High energy (γ >> 1) approximations" sought to derive integrated formulae:

- T. Raubenheimer, SLAC-R-387, PhD thesis, 1991
- K. Bane, EPAC 2002
*- K. Kubo et al., PRSTAB **8**, 081001 (2005)*

➔ ***See K. Bane (SLAC); T. Dema (INFN-LNF); K. Kubo (KEK)***



Bane's approximation to Bjorken-Mtingwa theory applied to NLS damping ring: (*Taken from A. Wolski, LBNL-59525, LCC-0147, CBP Tech Note-319, 2004*)

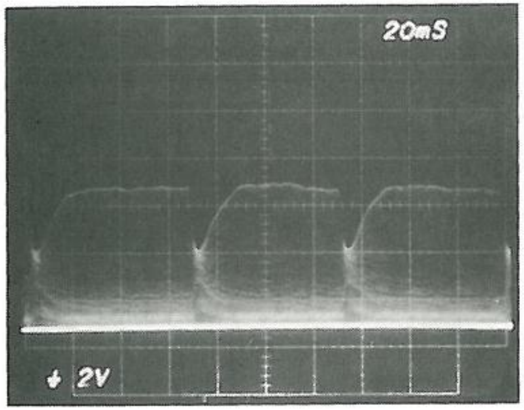
Cf) "Active" bunch lengthening as a solution to suppressing IBS

5. Two-Beam Instabilities

◊ Ion trapping

- Even in ultra-vacuum, circulating electrons collide with the residual gas and ions created.
- Ions may be trapped in the electrostatic potential of the electrons.
- Detrimental effects of ion trapping: Emittance blowup/current limitation/lifetime reduction/tune shifts/two-beam instability.

  ➔ Observed in many early light sources (DCI, ACO, SRS, KEK-PF, UVSOR, NSLS, Aladdin, …)



Two-beam instability observed at KEK-PF
(Taken from S. Sakanaka, OHO Lecture note 1986)

- Counter measures:
  Beam gaps/clearing electrodes/beam shaking/chromaticity/octupoles/use of positron beams

◊ Fast Beam-Ion Instability (FBII)

- Even if ions are not trapped, they may render a beam unstable in a single beam passage.
- This is particularly true with modern rings aiming to achieve

  - Low emittance → Small beam sizes

  - High brightness/luminosity → Large number of bunches

Growth rate $$\tau^{-1}_{aymp,e^-}(s^{-1}) \approx \frac{N_b^{3/2} n_b^2}{\gamma} \times \left[5 p_{gas}(\mathrm{Torr}) \frac{\beta_y r_e r_p^{1/2} L_{sep}^{1/2} c}{\sigma_y^{3/2} (\sigma_x + \sigma_y)^{3/2} A^{1/2}} \right]$$

N_b: Number of electrons/bunch

n_b: Number of bunches

(*Linear model of T. Raubenheimer and F. Zimmermann*)

- Early experimental studies of FBII in ALS/PLS/ESRF, …
- FBIIs observed in light sources, but do not seem to affect seriously high current operations.

  ➔ Presence of strong stabilizing effects (e.g. tune spreads)?

  ➔ Recent experimental observations and analysis made at SPring-8/SPEAR-III, …

  ➔ See L. Wang (SLAC)

- Persistent FBII encountered at SOLEIL in high current operations.
- FBII is considered to be one of the serious performance limitations in future damping rings.
    - ➔ Tracking simulations performed including transverse feedback
    - ➔ Good vacuum & use of many truncated trains of bunches found as important mitigators

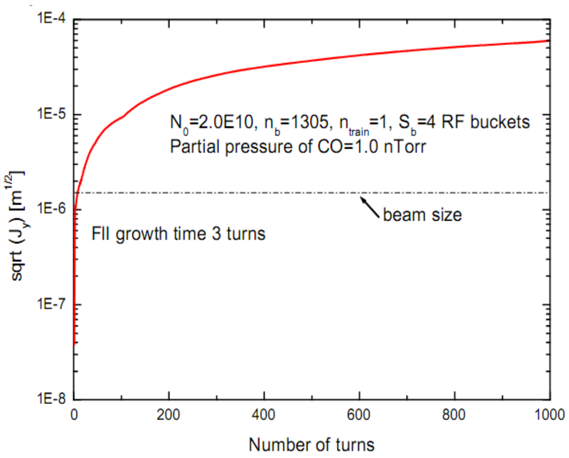


Figure 1: Beam oscillation amplitude *vs*. number of turns for 1305 bunches in a single train at 1.0 nTorr CO.

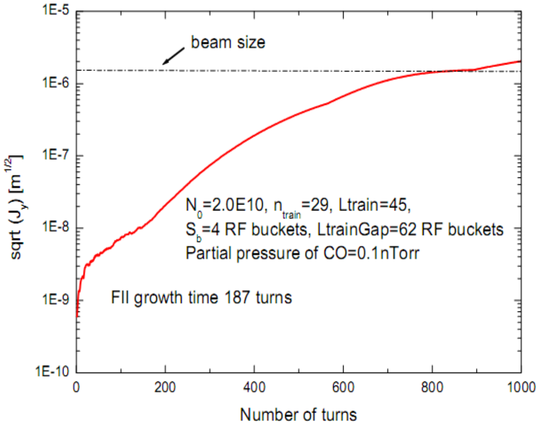


Figure 7: Beam oscillation amplitude *vs*. number of turns for 29 bunch trains, with each consisting 45 bunches at 0.1 nTorr CO.

(*Taken from "FBII studies for the 3 km long ILC damping ring", G. Xia, PAC 2011*)

◊ Electron Cloud Instability (ECI)

(*cf. Review by M.A. Furman, http://mafurman.lbl.gov/ecloud_awc_30nov01.pdf*)

- Electron-Cloud Instability (ECI) was first observed at PF-KEK in the early 90’s as vertical coupled-bunch instability when the ring was operated in the positron mode.
- Unlike ion instability, ECI in PF persisted even with large beam gaps, with spectra being qualitatively different from the former.
- First experimental and theoretical studies identifying the instability as ECI:
  - *M. Izawa, Y. Sato and T. Toyomasu, PRL **74**, (1995), 5044*
  - *K. Ohmi, PRL **75** (1995), 1526*; *S. Heifets, Proc. CEIBA95 (1995)*

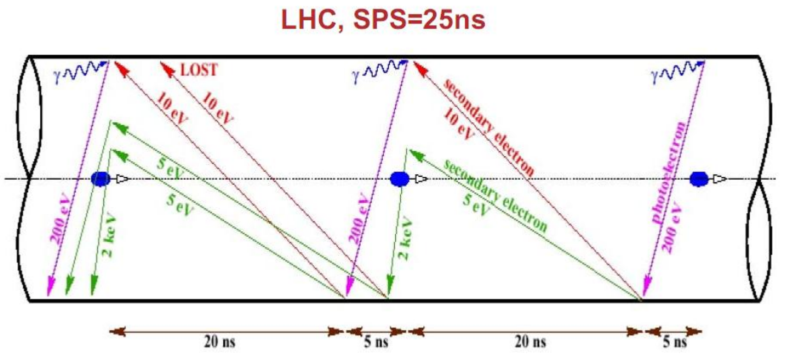


Fig. courtesy of F. Ruggiero, G. Arduini

(*Taken from K. Harkay, “Observation and Modeling of Electron Cloud Instabilities”, EPAC 2006*)

- ECI is deeply linked to beam-induced multipacting.
- ECI was later observed in BEPC, APS, PEP-II, KEKB, SPS, PS, PSR, CESR, ...

◊ Impact of Electron Cloud on the Beam

- Range of an effective wake function induced by EC is short (several to tens of RF buckets), and EC can excite coupled-bunch instabilities of a wide spectrum.
- EC could also induce single bunch headtail/beam-breakup instabilities, tune shifts along a bunch train, intra-beam tune spreads, emittance blowups (transverse/longitudinal) and beam losses.
- An intense EC could bring about localized pressure rise, heating of the vacuum system and even malfunctioning of a diagnostic system (a shielding effect).

➔ Great efforts made by the people concerned to study EC buildup and its impact on the beam

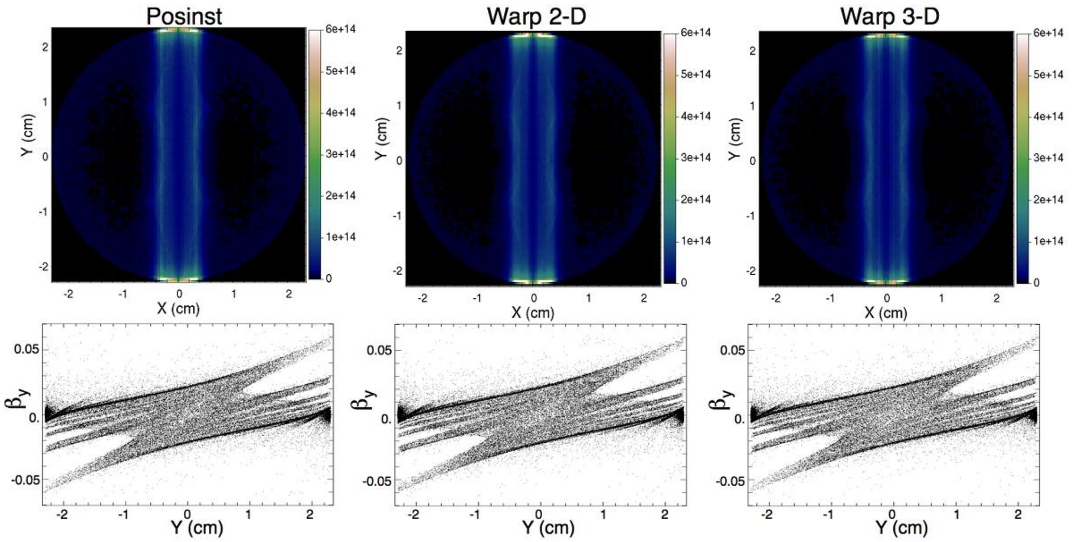


Figure 3: Snapshots of electron density and vertical phase space from build-up simulations using (left) POSINST, (middle) Warp in 2-D, (right) Warp in 3-D.

Benchmarking the EC buildup between different codes (Taken from J.L. Vay et al, PAC2007)

◊ Simulation code development:

POSINST, ECLOUD, HEADTAIL, Quick-PIC, CLOUDLAND, ORBIT, PEHTS, Best, WARP, CSEC, PARSEC, …

◊ EC and ECI Mitigating Methods

➔ ***See R. Cimino (INFN-LNF)***

- Reduction of photoelectric yield *Y*, secondary electron emission (SEY) δ and photon reflectivity *R* by introducing grooves on the vacuum chamber surface

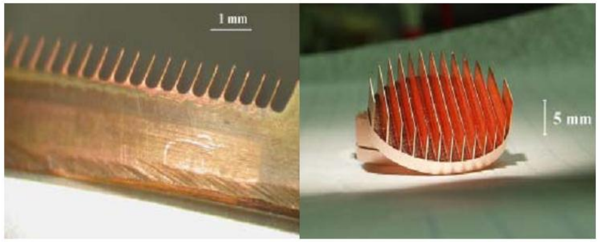
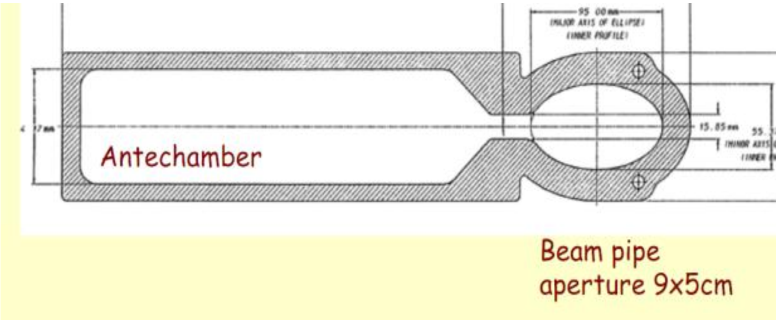


Figure 7. Samples with two different rectangular groove profiles, 1 mm or 5mm depth.

(*Taken from M. Pivi et al., PAC 2005*)



(*Taken from U. Wienands et al., ICFA WS BNL*)

- Introduction of ante-chamber to let high energy photons escape from the beam chamber
- TiN coating (~0.1 micron thick)
- Active means: Chromaticity, octupole, solenoidal field wrapping, beam filling, parasitic bunches, transverse feedback, …

➔ ***See M. Palmer (Cornell)***

6. Summary

◊ Achieving both ultra-low emittance and a high intensity beam is indeed a great challenge in view of the severe limitations arising from different collective effects.

◊ However, thanks to remarkable progress made in the last decades in theoretical, experimental, numerical studies and technologies, we generally have a high level of understanding on most of the critical issues and means to evaluate and control them.

➔ ***N. Terunuma (KEK)***

◊ Importance of inter-disciplinary studies should be stressed in order to obtain fully quantitative evaluation of collective effects.

◊ Alleviation of collective effects due to bunch lengthening may be pursued wherever possible *à la* MAX IV strategy.