Beam Dynamics and Collective Effects in "Ultimate" Storage Rings

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JASRI/SPring-8

Outline

- Introduction
- Intra-beam scattering
- Touschek lifetime
- Fast ion instability
- Microwave instability

Ultimate Storage Rings

- **Diffraction limited light source for 1 Å-wavelength**

Brilliance of a Light Source

$$B = \frac{\Phi}{4\pi\Sigma_x\Sigma'_x\Sigma_y\Sigma'_y}$$

Φ : total photon flux,

$$\Sigma_{x,y} = \sqrt{\sigma_{x,y}^2 + \sigma_p^2},$$

$$\Sigma'_{x,y} = \sqrt{\sigma'^2_{x,y} + \sigma'^2_p}$$

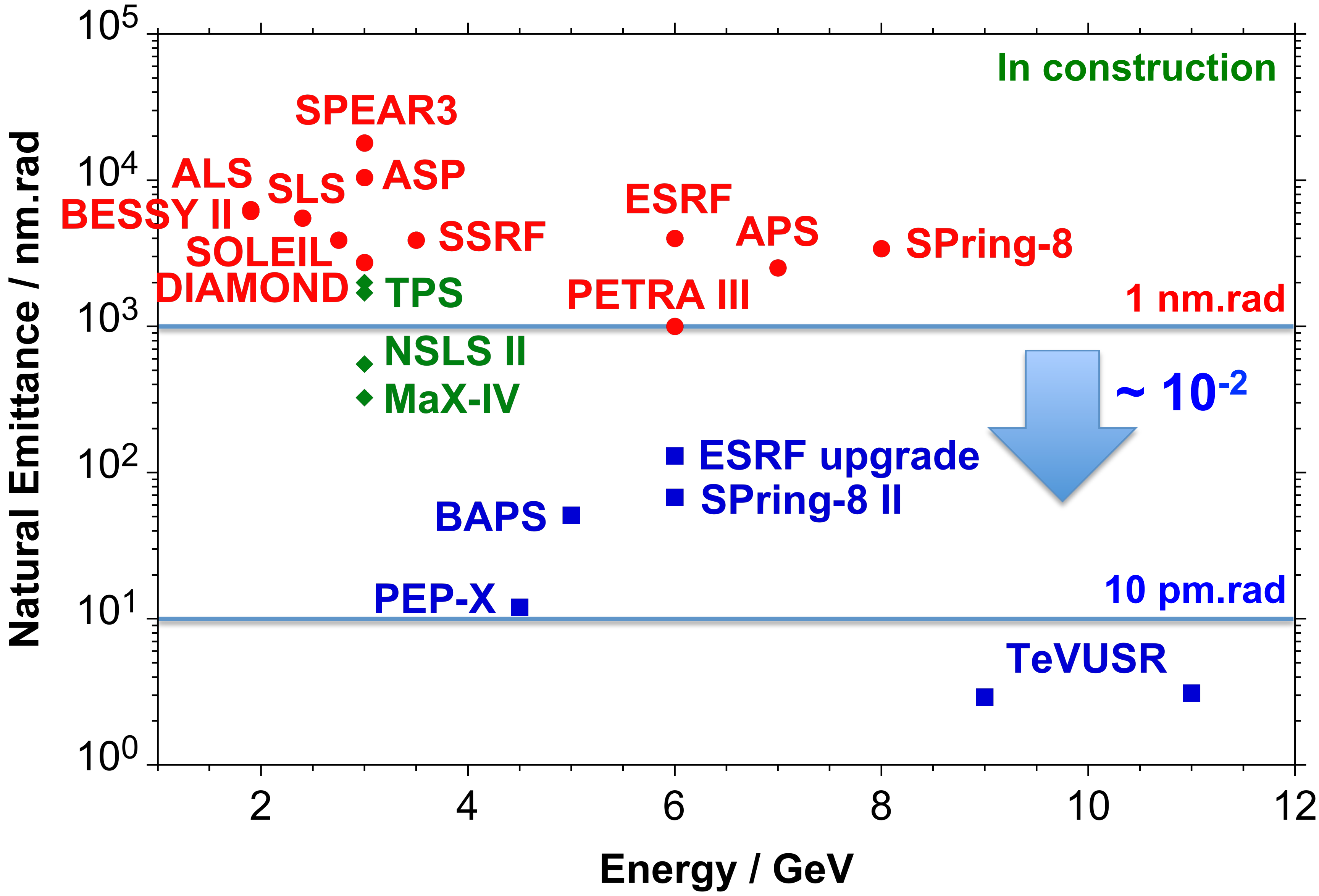
Diffraction limited operation

Electron beam emittance

$$\varepsilon_{x,y} < \frac{\lambda}{4\pi}$$ **= 10 pm.rad at 1 Å-wavelength**

Emittances of Present and Future LS

As of USR Workshop @ Beijing Oct. 2012



Traditional Impedances

- Traditional impedances don’t change with the beam emittance, which are not included in this talk.
- Smaller radius of vacuum chamber and gap of insertion device (ID) required by USR enhance the impedances, so stronger feedback may be needed.
- Shortening of bunch length due to lower emittance also enhances the impedance effects, but they could be relaxed by stretching bunch, e.g. by higher harmonic cavity.

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Intra-beam Scattering

- **Multiple Coulomb scattering in bunch gives statistical excitation as well as quantum radiation.**

IBS growth rate

$$\frac{1}{T_p} = \frac{1}{\sigma_p}\frac{d\sigma_p}{dt} \qquad \frac{1}{T_x} = \frac{1}{\varepsilon_x^{1/2}}\frac{d\varepsilon_x^{1/2}}{dt} \qquad \frac{1}{T_y} = \frac{1}{\varepsilon_y^{1/2}}\frac{d\varepsilon_y^{1/2}}{dt}$$

Calculated by

1) Piwinski w/ using classical theory
2) Bjorken-Mtingwa w/ using quantum filed theory

Bane's high energy approximation formula

Intra-beam Scattering

Steady state beam properties

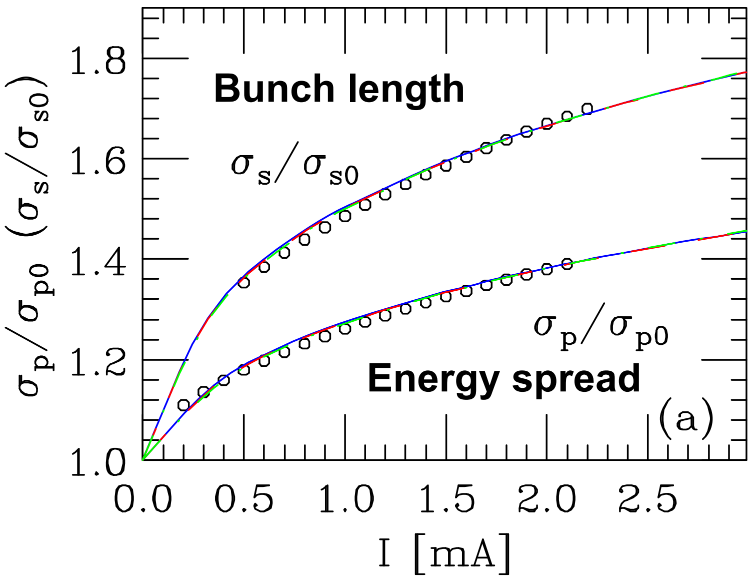
$$\sigma_p = \frac{\sigma_{p0}}{1-\tau_p/T_p}, \qquad \varepsilon_x = \frac{\varepsilon_{x0}}{1-\tau_x/T_x}, \qquad \varepsilon_y = \frac{\varepsilon_{y0}}{1-\tau_y/T_y}$$

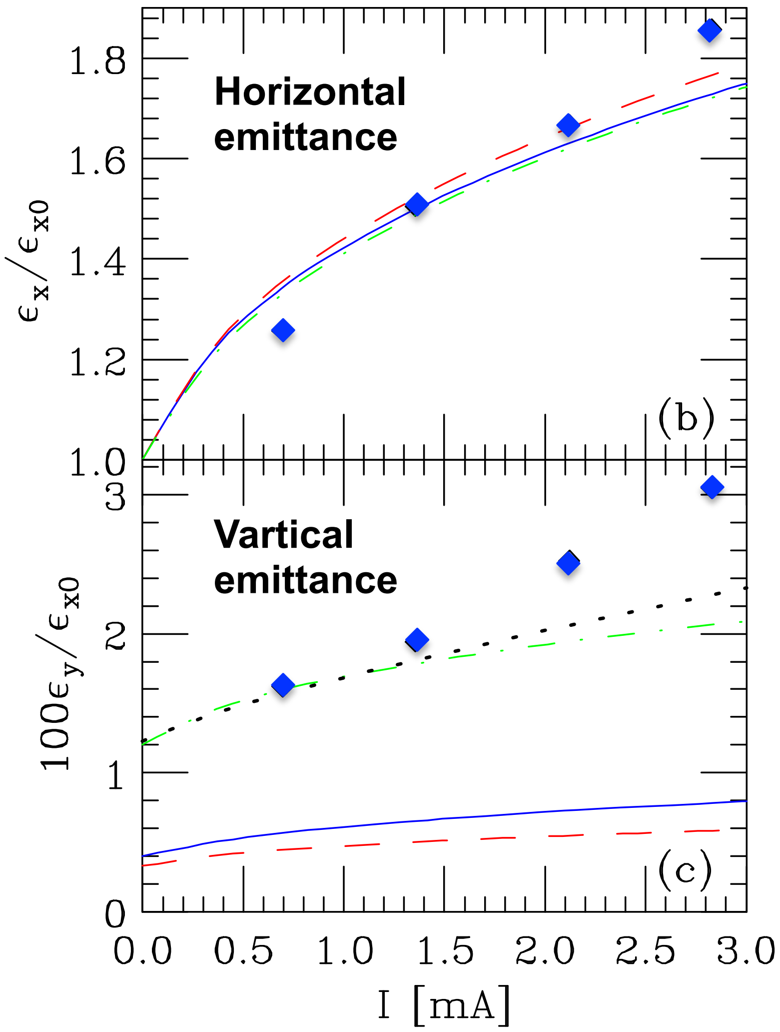
τ_i: radiation damping times
σ_{p0}, $\varepsilon_{x,y0}$: beam properties w/o IBS

- **Steady state beam properties are included in IBS growth rates $T_{p,x,y}$, so they are solved iteratively.**
- **Local growth rates are function of lattice parameters, so calculation of total growth rates requires average around the ring.**
- **Agreement of Piwinski and Bjorken-Mtingwa formulae and validity of Bane's approximation are well confirmed by numerical study for ATF.**

Intra-beam Scattering at ATF

- **Comparison of calculation with measurement at ATF**





Energy	1.28 GeV
Nominal energy spread	0.0544 %
Nominal h. emittance	1.05 nm.rad
Nominal bunch length	5.06 mm

Courtesy of Karl Bane, SLAC

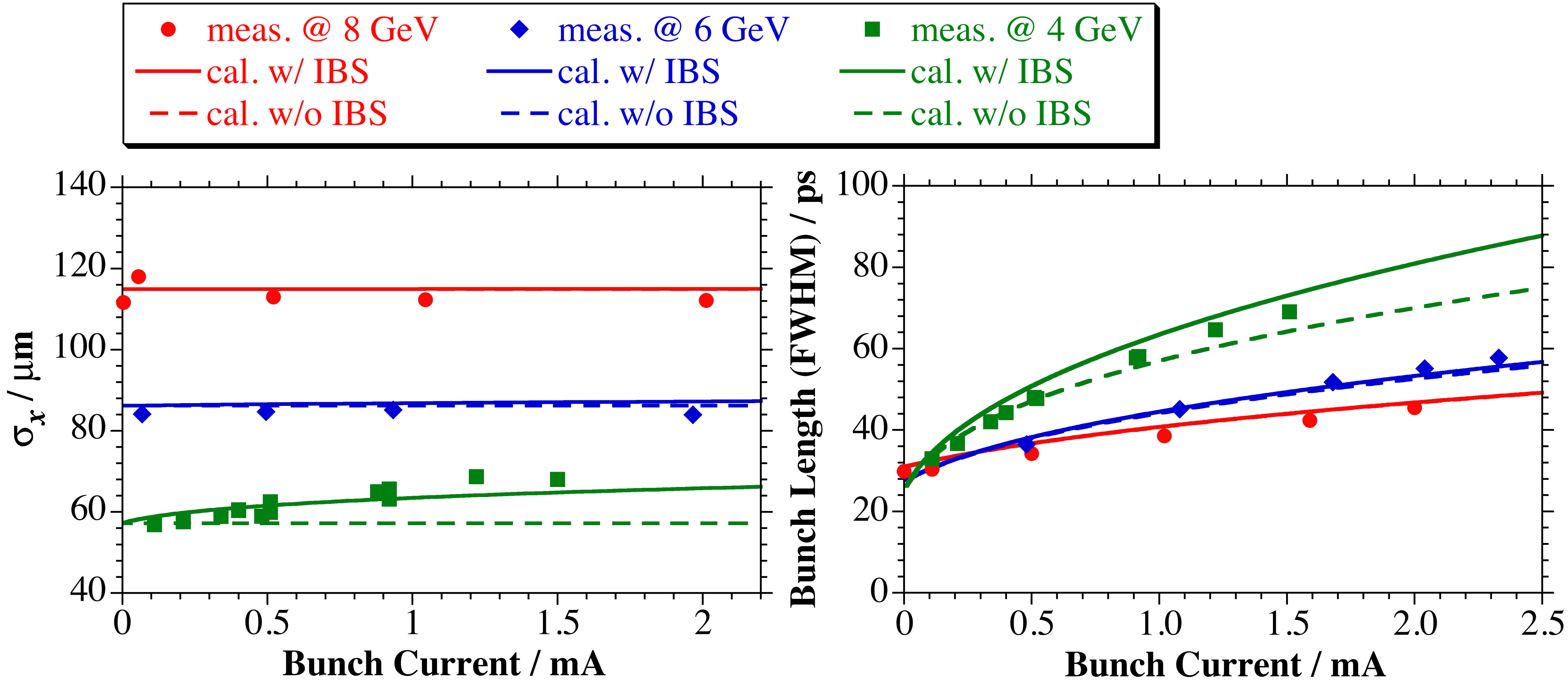
Parameters for SPring-8 / SPring-8 II

	SPring-8	SPring-8 II	unit
Energy	8 GeV	6 GeV	GeV
Circumference	1435.95	1435.95	m
Total stored current	100	300	mA
Natural emittance	3500	67	pm.rad
Relative rms energy spread	0.109	0.096	%
Natural rms bunch length	13	5.4	ps
Momentum compaction	1.67×10^{-4}	1.55×10^{-5}	
Synchrotron tune	0.01	0.004	
Transverse radiation damping time	8.3	14.4	ms
Longitudinal radiation damping time	4.15	7.2	ms

As of USR Workshop @ Beijing Oct. 2012

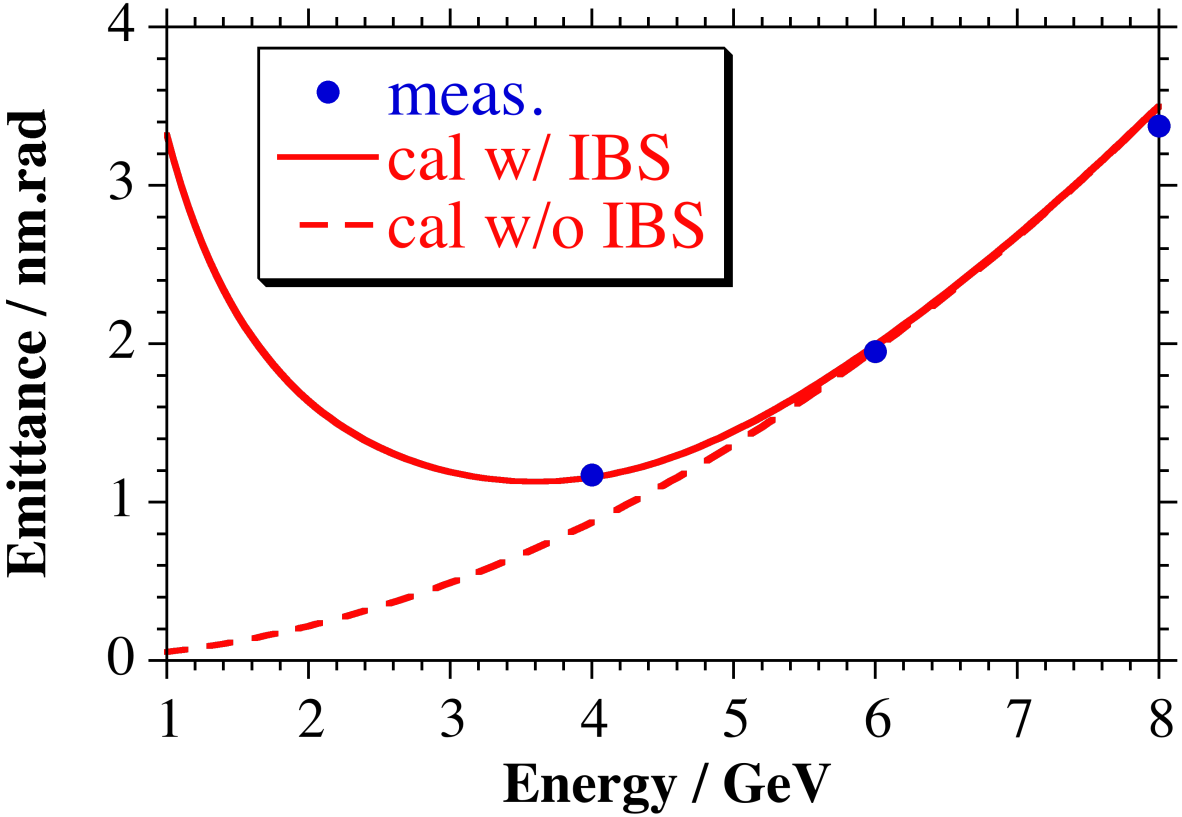
Intra-beam Scattering at SPring-8

- **Beam size, bunch length measurement for beam energy 8 GeV, 6 GeV, 4 GeV**



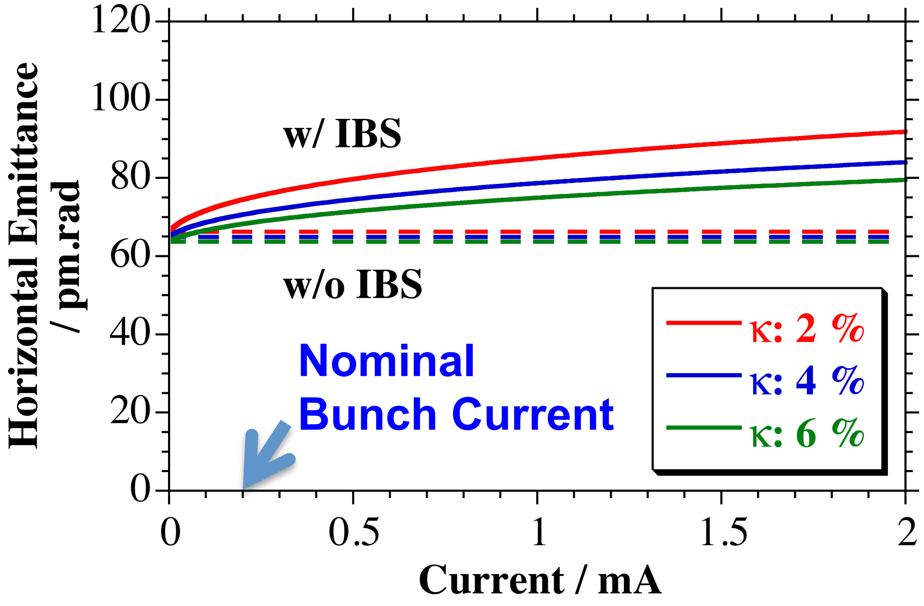
Energy dependence of IBS at SPring-8

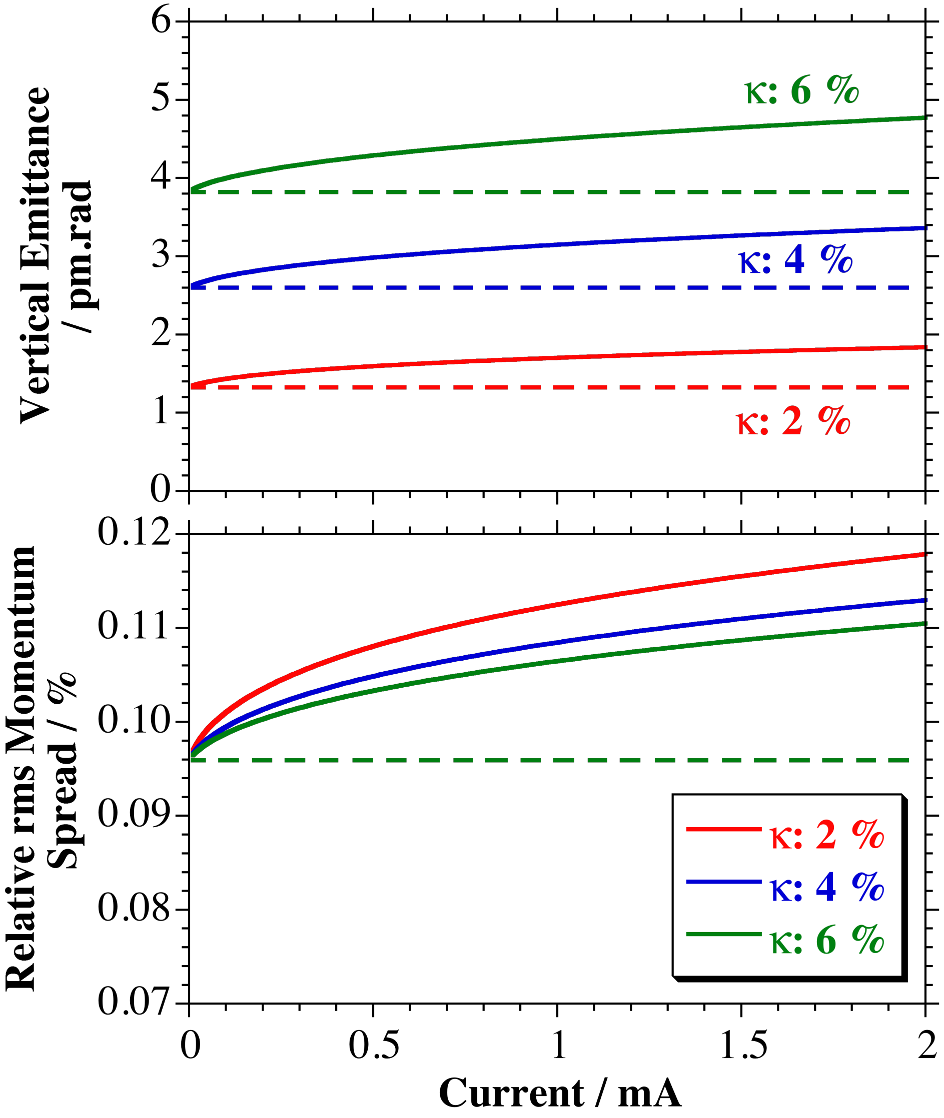
- Horizontal emittance for I_b = 1 mA vs. electron energy



Intra-beam Scattering at SPring-8 II

- Current dependence of IBS at SP-8 II





Though electron beam energy is 6 GeV, the significant effect of IBS is observed.
IBS could be reduced at the cost of vertical emittance.
Lengthening bunch can also reduces IBS, suitable for brilliance.

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Touschek Lifetime

- **Large Coulomb scattering, transfering transverse momenta to logitudinal, leading to beam loss.**

Full (2-dim) Touschek lifetime formula by Piwinski

$$\frac{1}{\tau}=\frac{r_0^2 cN_b}{8\sqrt{\pi}\gamma^4\varepsilon_x\varepsilon_y\sigma_p\sigma_\ell}\left\langle \sigma_H\int_{\delta_m^2}^{\infty}\frac{du}{u^{3/2}}\left(\frac{u}{\delta_m^2}-1-\frac{1}{2}\ln\frac{u}{\delta_m^2}\right)e^{-B_1 u}I_0\left(B_2 u\right)\right\rangle$$

$\varepsilon_{x,y}$: transverse emittance, σ_p : relative momentum spread,

σ_ℓ : bunch length, δ_m : momentum acc., I_0 : modefied Bessel func.

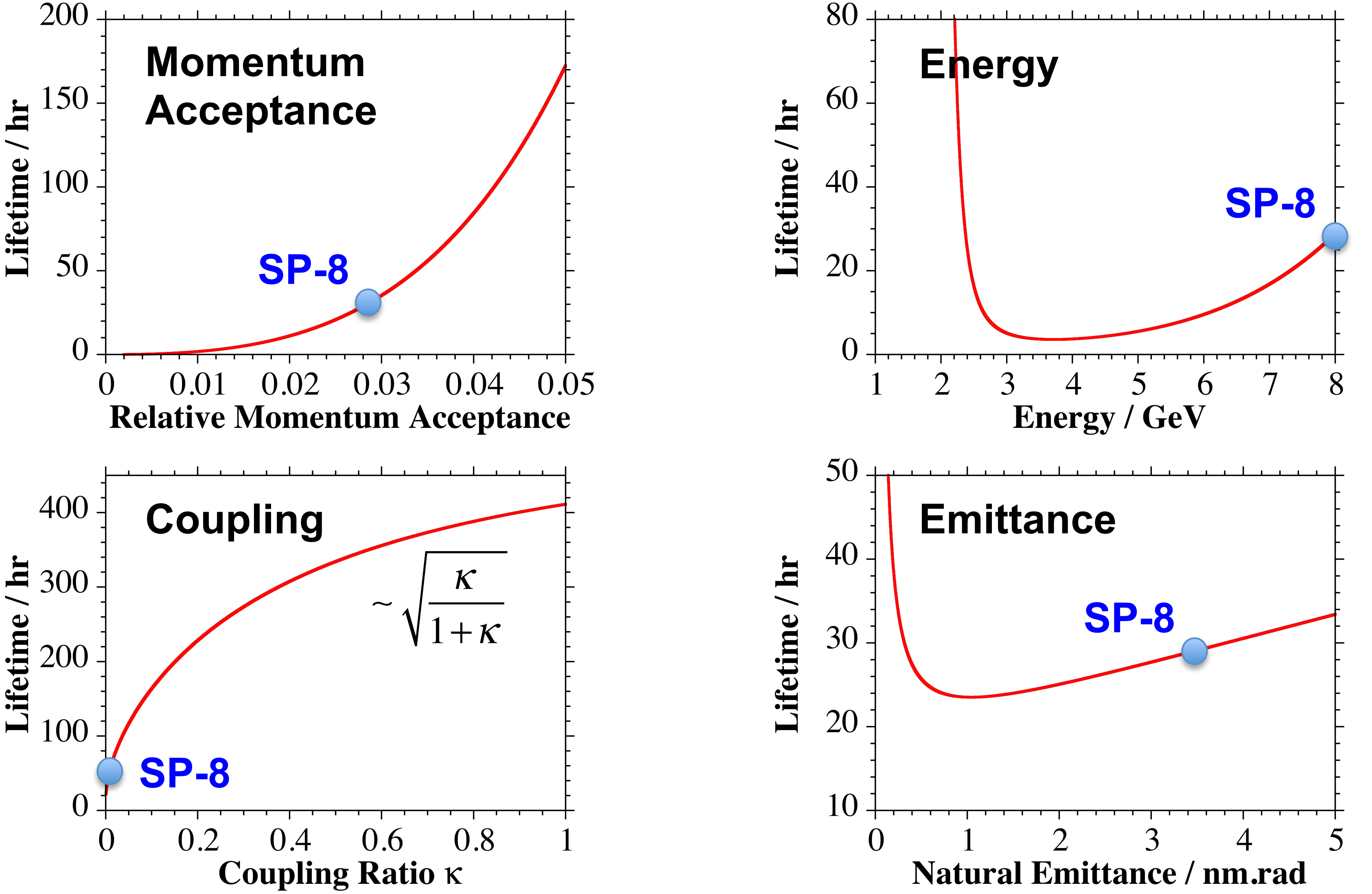
$$B_1=\frac{1}{\gamma^2}\left[\frac{\beta_x}{\varepsilon_x}+\frac{\beta_y}{\varepsilon_y}-\sigma_H^2\left(\frac{\phi_x^2}{\varepsilon_x^2}+\frac{\phi_y^2}{\varepsilon_y^2}\right)\right]/2,\ B_2=\sqrt{B_1^2-\frac{\sigma_H^2\beta_x\beta_y}{\gamma^4\varepsilon_x\varepsilon_y}\left(\frac{1}{\sigma_p^2}+\frac{\eta_x^2}{\varepsilon_x\beta_x}+\frac{\eta_y^2}{\varepsilon_y\beta_y}\right)}$$

$$\frac{1}{\sigma_H^2}=\frac{1}{\sigma_p^2}+\frac{H_x}{\varepsilon_x}+\frac{H_y}{\varepsilon_y},\ H_{x,y}=\gamma_{x,y}\eta_{x,y}^2+2\alpha_{x,y}\eta_{x,y}\eta'_{x,y}+\beta_{x,y}\eta'^2_{x,y}$$

$$\phi_{x,y}=\alpha_{x,y}\eta_{x,y}+\beta_{x,y}\eta'_{x,y}$$

Touschek Lifetime on Beam Properties

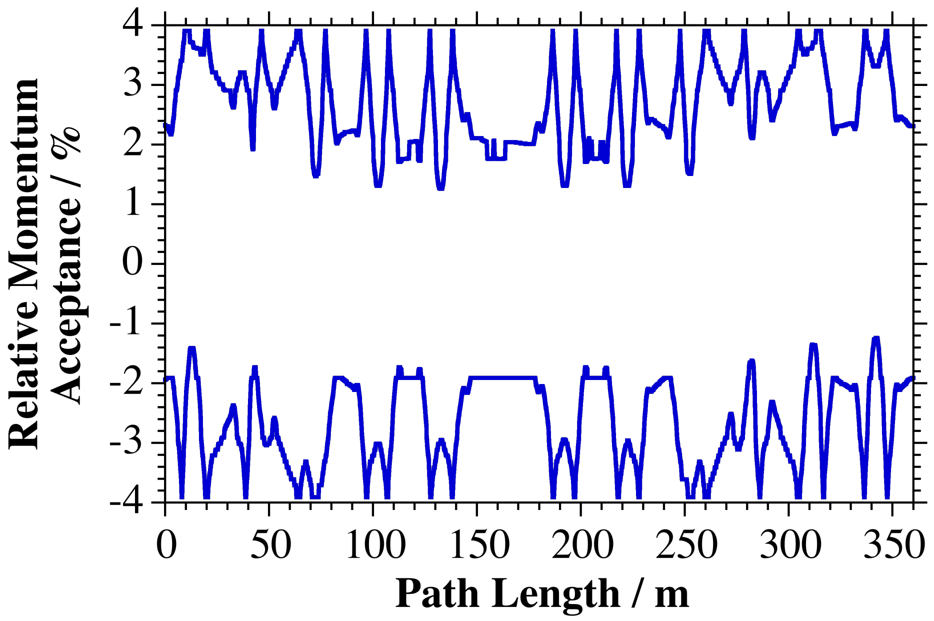
- **Lifetime for 1 mA / bunch** @ SPring-8



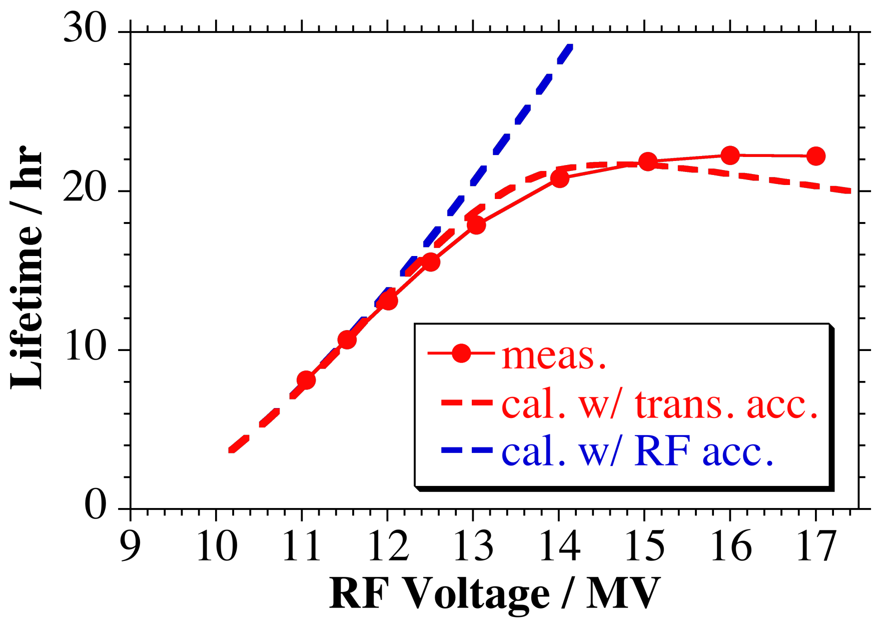
Touschek Lifetime at SPring-8

- In practical, momentum acceptance is also limited by transverse dynamics, since particles scattered at nonzero dispersion start to oscillate around dispersion with a large amplitude.

Estimated momentum acceptance over 1/4 SPring-8



Touschek lifetime at SPring-8 as a function of RF voltage



Improving Momentum Acceptance

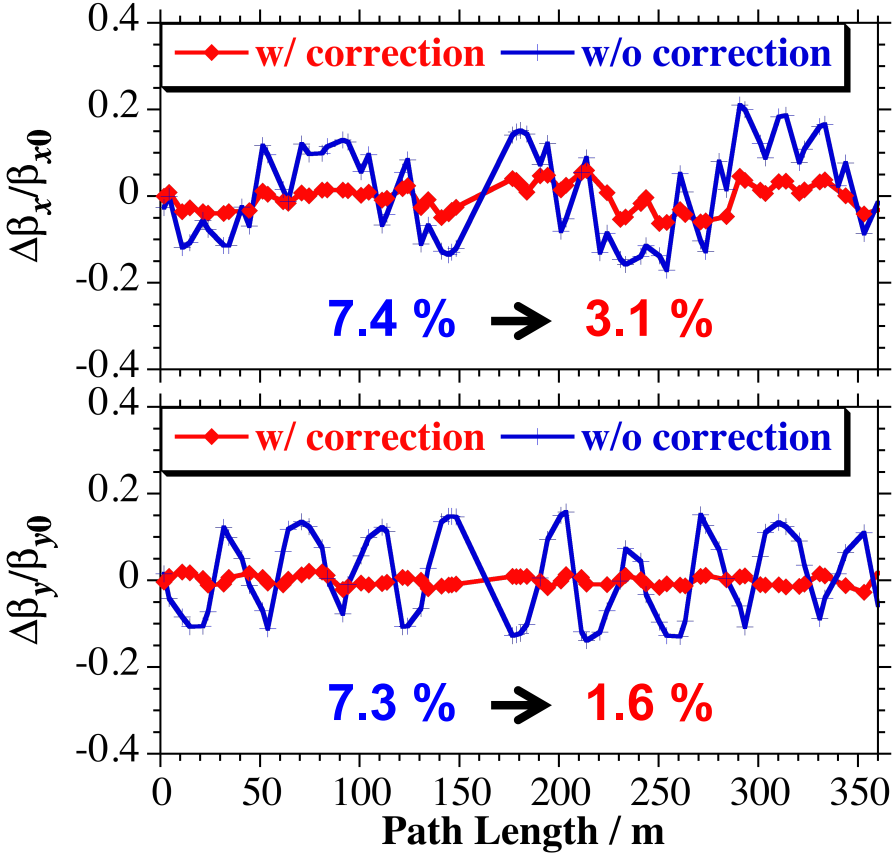
- Linear optics
  - Analysis of orbit response matrix, e.g. LOCO program
    - β-beating correction
    - β-coupling correction
- Non-linear optics
  - Resonance driving term correction
  - Frequency map analysis
  - Genetic algorithms

Effect of Optics Correction

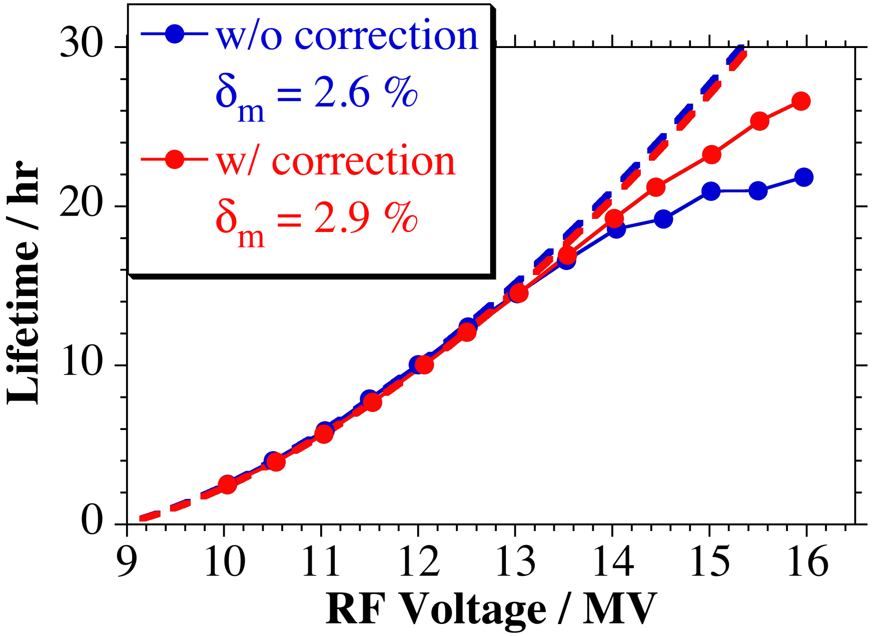
- **Linear optics correction at SPring-8**

  based on analysis of orbit respose matrix

Measured distortion of β-func



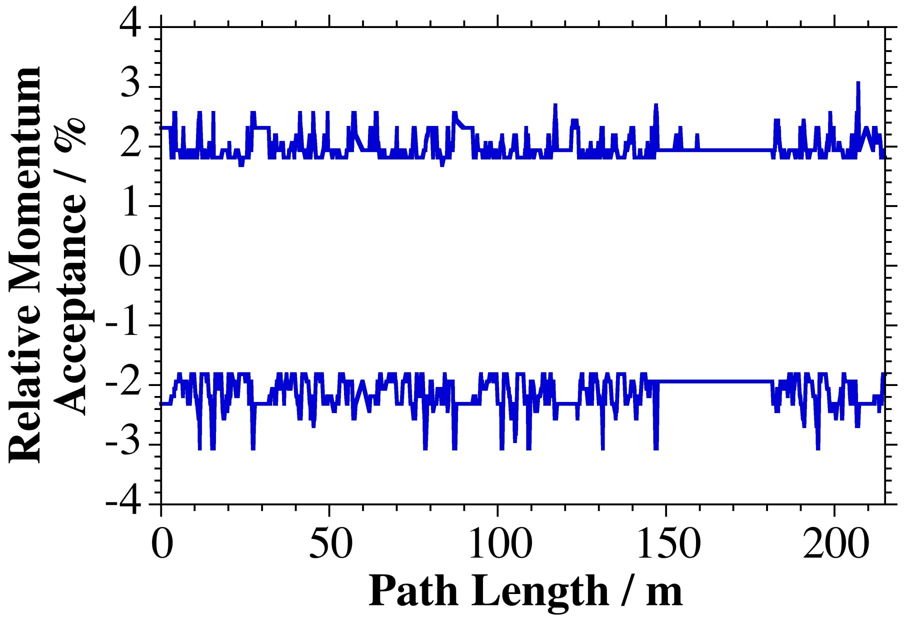
Touschek lifetime (meas.) as a function of RF voltage

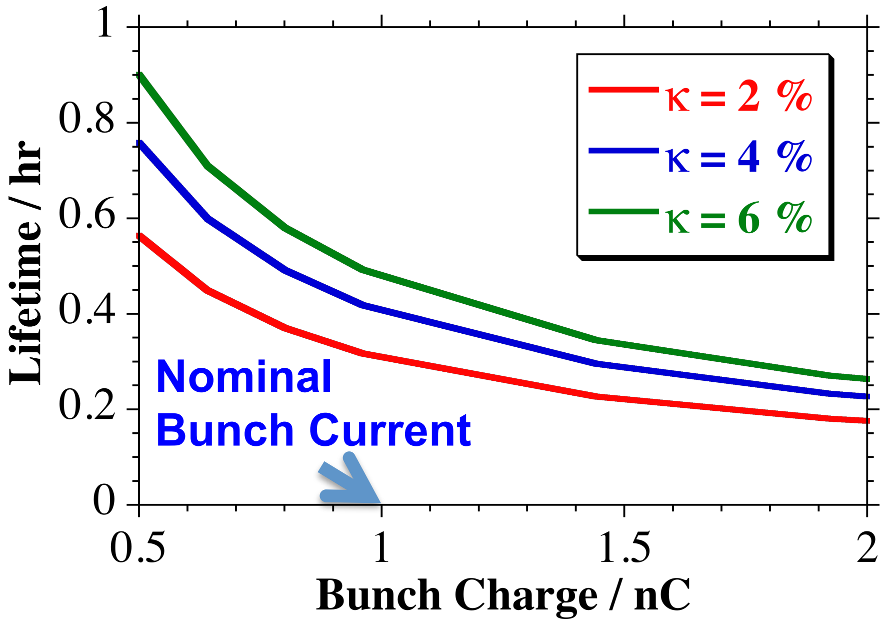


Touschek Lifetime of SPring-8 II

- **Momentum acceptance w/ Sx alignment error (σ = 10 μm, 2 σ cut)**
- **Touschek lifetime w/ intra-beam scattering**

- **Stable Top-up operation needs lifetime over 0.5 hour.**
- **Bunch lengthening by higher harmonic cavity or/and coupling increase: essential for practical operation.**





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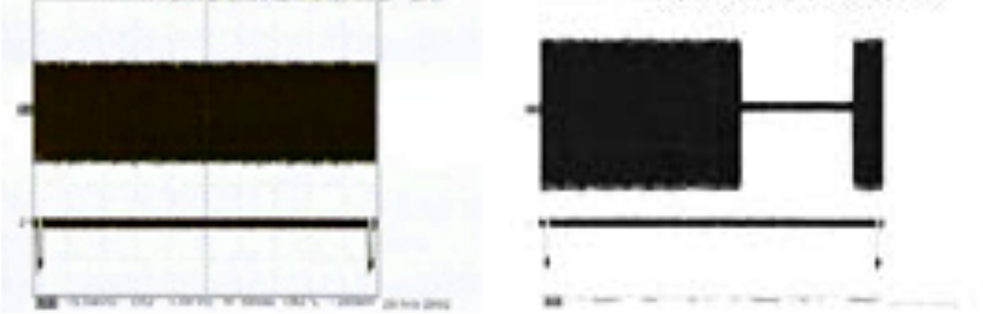
Ion Trapping

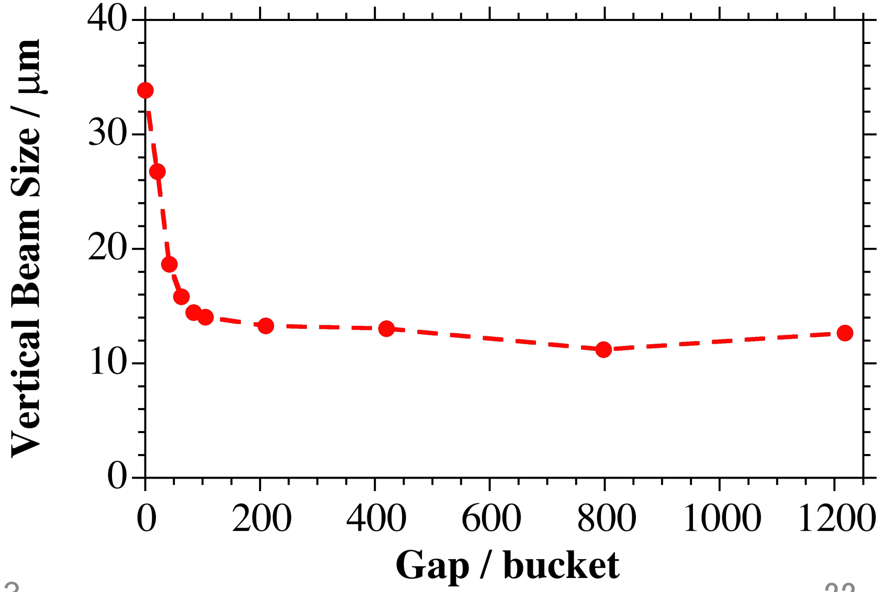
- **Ion generated by beam-gas ionization trapped by electron beam.**
- **Trapped ion causes instabilities, vertical emittance blow-up.**
- **To avoid ion trapping, light source rings use a long bunch train filling pattern followed by a long gap.**

Beam filling pattern



Full filling **2/3 filling**

σ_y vs. Ion clearing gap @ SP-8

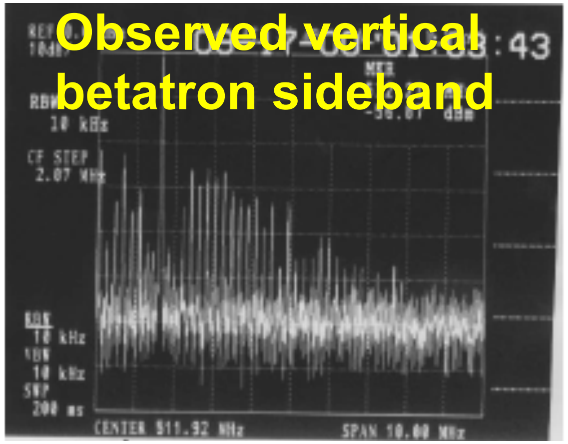


Fast Ion Instability

- **Ion clearing gap can't exclude ion from accumulating during one passage of single bunch train.**
- **Those ions can still cause Fast Ion Instability (FII).**

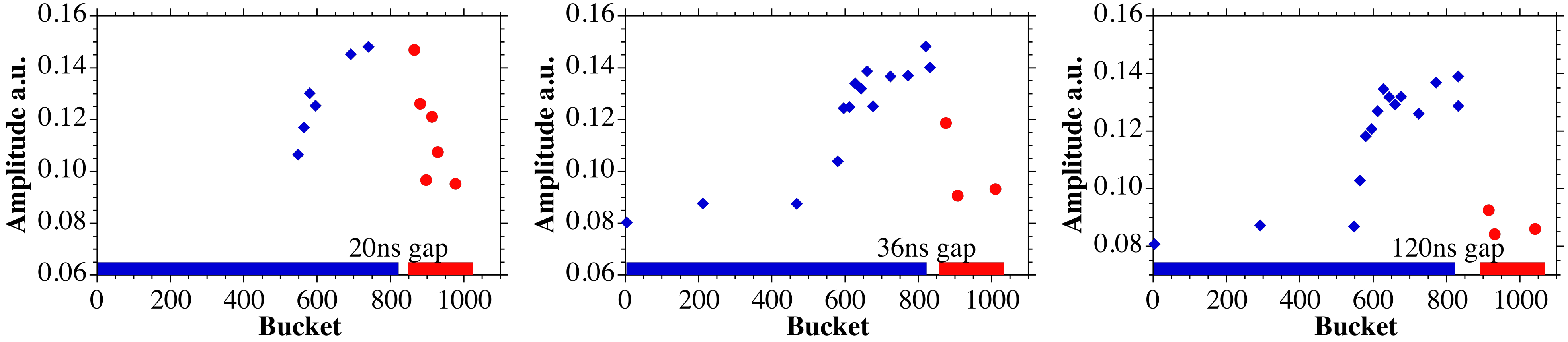
  by Raubenheimer and Zimmermann
- **Under bad vacuum condition FII is observed in many light sources: ALS, PLS, SOLEIL, SSRF, …**
- **At SP-8, after reconstruction of ¼ of ring to introduce 30m long magnet-free straight sections, FII occurred Sep-2000, and disappeared**

  as vacuum improving.

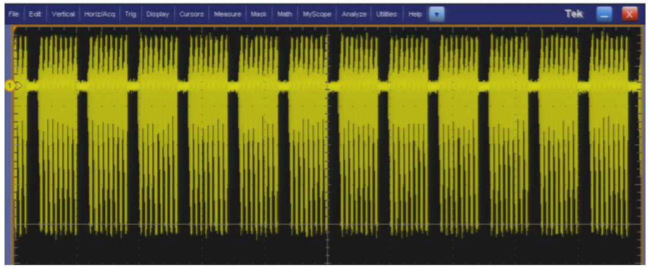

Observed vertical betatron sideband

Observation of FII at SP-8

- Experimental condition:
  - 820 buckets (1/3 of ring) filled with 1-st bunch train.
  - 2-nd train of 160 buckets stored with gap 20ns, 36ns, 120ns.
- Results:
  - Bunch oscillation in 1-st train rises at ~500 bucket.
  - No bunch oscillation in 2-nd train with 120ns gap.



Multi bunch filling pattern of SP-8:
160 bunch train x 12



FII at USR

- **Small beam sizes enhance the growth rate of FII.**

Growth rate of FII

$$\frac{1}{\tau}=\frac{cr_e\beta_y N_b n_b}{2}\frac{W}{\gamma}$$

N_b : # of electron per bunch, n_b : # of bunches

W: Coupling force between electron bunch and ions

$$W=\frac{8\sigma_i P}{3\sqrt{3kT}}\left(\frac{r_p}{A}\right)^{1/2}\frac{\left(N_b s_b\right)^{1/2} n_b}{\boxed{\sigma_y^{3/2}\left(\sigma_y+\sigma_x\right)^{3/2}}}$$

σ_i : ionization cross section, r_p : proton classical radius,

A : mass nummber of ion, s_b : bunch spacing

Coupling force of SP-8 II is several tens or more larger than SP-8, so FII may occur at nominal pressure.

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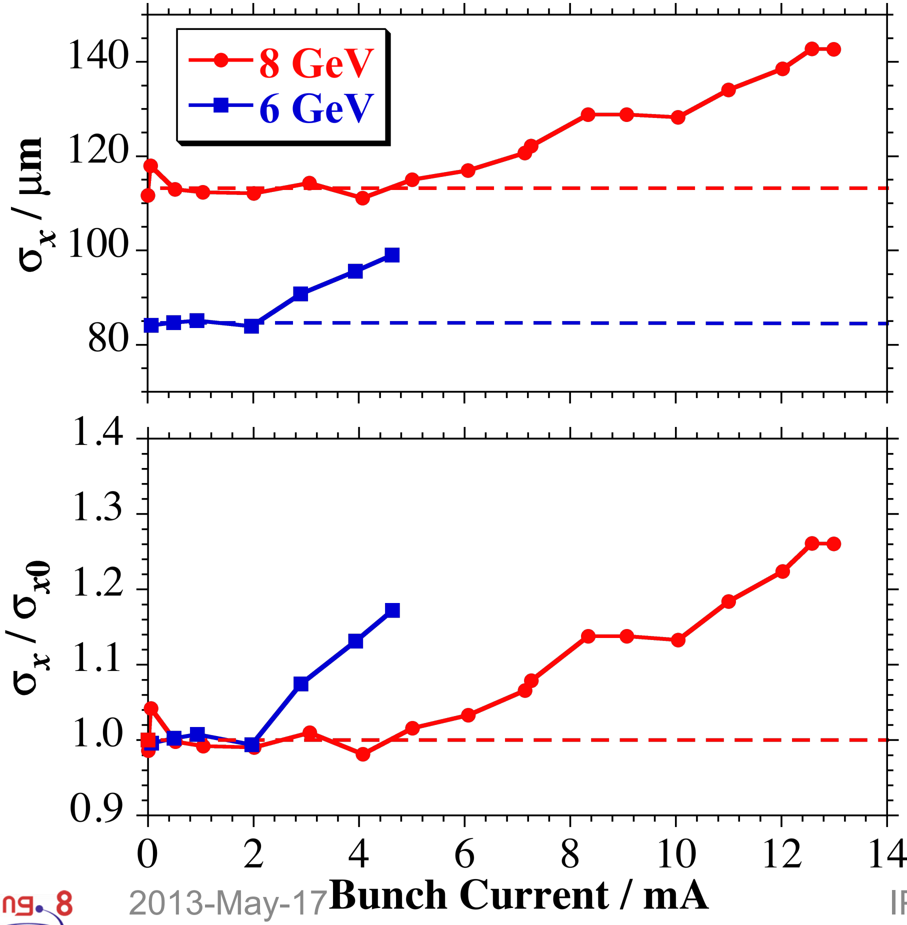
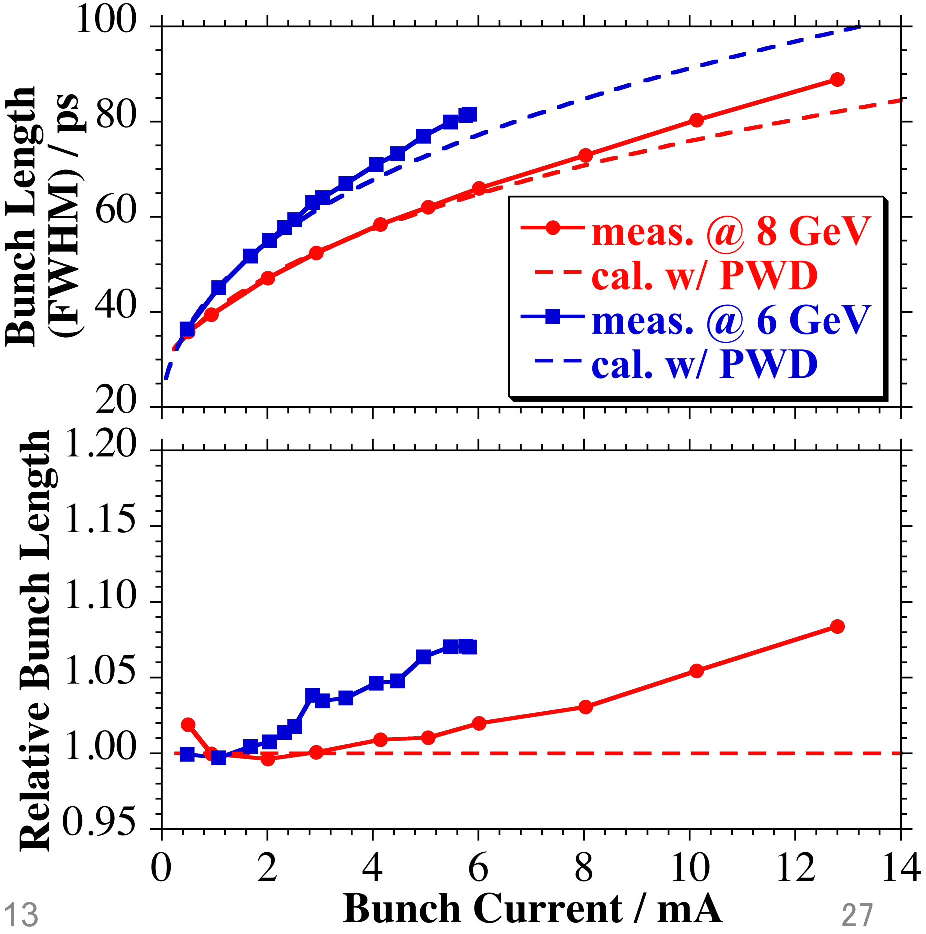
Microwave Instability

- **Microwave (single bunch longitudinal) instability causes anomalous energy spread blow-up and bunch lengthening above threshold current.**



σ_x vs Bunch Current



Bunch Length vs Bunch Current

Microwave Instability

- **Threshold current of MWI (Boussard criterion)**

$$I_{th} \leq \frac{2\pi\alpha E\sigma_p^2\sigma_\ell}{e\left|Z(n)/n\right|L}$$

α : momentum compaction, σ_p : energy spread, σ_ℓ : bunch length

$Z(n)$: broad band impedance, L : circumference

	α	σ_p	σ_l	I_{th}
SPring-8 (6 GeV)	**1.67×10^{-4}**	**0.082**	**10 ps**	**2 mA**
SPring-8 II	**1.55×10^{-5}**	**0.096**	**5.5 ps**	**~ 0.14 mA**

c.f. 300 mA / 2436 = 0.12 mA

Small momentum compaction lowers threshold current of MWI, which becomes important for USR.

Summary

- Higher harmonic cavity is necessary for USR to reduce IBS and Touschek effects.
- Coupling control is also important for USR.
- Momentum acceptance should be extended as large as possible by optimization of non-linear dynamics.
- Microwave instability and Fast ion instability may occur at nominal condition of USR.