Issues on ILC Damping Rings

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Outline

Part I	Overview of CERN DR meeting
Part II	Fast Beam Ion Instability (FBII)
Part III	Summary and Future Plan

Part I Overview of CERN DR meeting

- 2.5 days of intensive meeting
- ~34 participants
- Issues on every aspects of damping rings
- Formed the Baseline Configuration Recommendation (BCD) for GDE
- 6km and 2×6km rings as the candidates of ILC electron and position damping rings, respectively

http://www.desy.de/~awolski/ILCDR/

Reports at the meeting

- Task force 1: Acceptance Issues
- Task force 2: Vertical Emittance Tunning
- Task force 3: Classical Instabilities
- Task force 4: Space-Charge Effects
- Task force 5: Kicker Technology
- Task force 6: Electron Cloud
- Task force 7: Fast-Ion Instability
- Task force 8:Cost Estimates
- Task force 9: Reliability and Operability
- Task force 10: Polarization

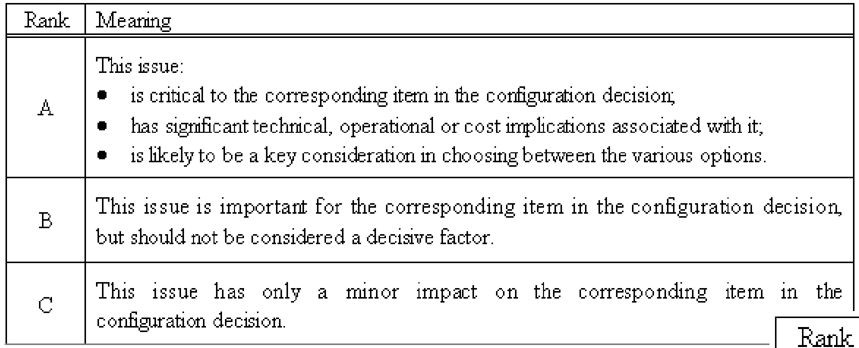
Special session: CESR damping ring test facility

Issues on ILC damping rings

- Circumference
- Beam energy
- Injected emittance and energy spread
- Bunch train length and bunch charge
- Extracted bunch length
- Injection and extraction kickers
- Damping wiggler
- Multipole magnets
- RF system technology
- Vacuum chamber aperture
- Feedback systems, instrumentation and controls

	Circumference	Beam energy	Injected emittance/energy spread	Bunch train length/bunch charge	Extracted bunch length	Injection/extraction kickers	Damping wiggler	Multipole magnets	RF system technology	RF frequency	Vacuum chamber aperture
Circumference	▨	•	•	•	•	•	•				
Beam energy	•	▨	•	•	•		•				
Injected emittance/energy spread	•	•	▨				•				•
Bunch train length/bunch charge	•	•		▨	•	•				•	
Extracted bunch length	•	•		•	▨						
Injection/extraction kickers	•			•		▨					
Damping wiggler	•	•	•				▨				•
Multipole magnets								▨			
RF system technology									▨		
RF frequency				•						▨	
Vacuum chamber aperture			•				•				▨

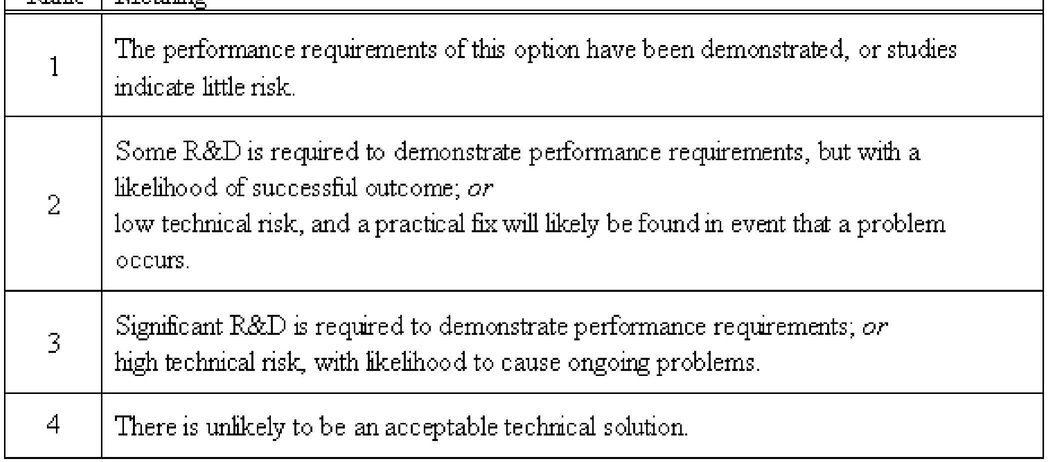
Issues on ILC damping rings (cont')



Rank	Meaning
A	This issue: • is critical to the corresponding item in the configuration decision; • has significant technical, operational or cost implications associated with it; • is likely to be a key consideration in choosing between the various options.
B	This issue is important for the corresponding item in the configuration decision, but should not be considered a decisive factor.
C	This issue has only a minor impact on the corresponding item in the configuration decision.

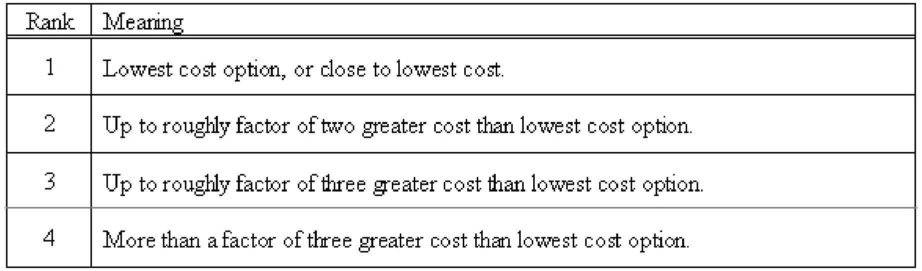
The significance of the issues relevant to each configuration item

The risk associated with the various options are ranked



Rank	Meaning
1	The performance requirements of this option have been demonstrated, or studies indicate little risk.
2	Some R&D is required to demonstrate performance requirements, but with a likelihood of successful outcome; *or* low technical risk, and a practical fix will likely be found in event that a problem occurs.
3	Significant R&D is required to demonstrate performance requirements; *or* high technical risk, with likelihood to cause ongoing problems.
4	There is unlikely to be an acceptable technical solution.

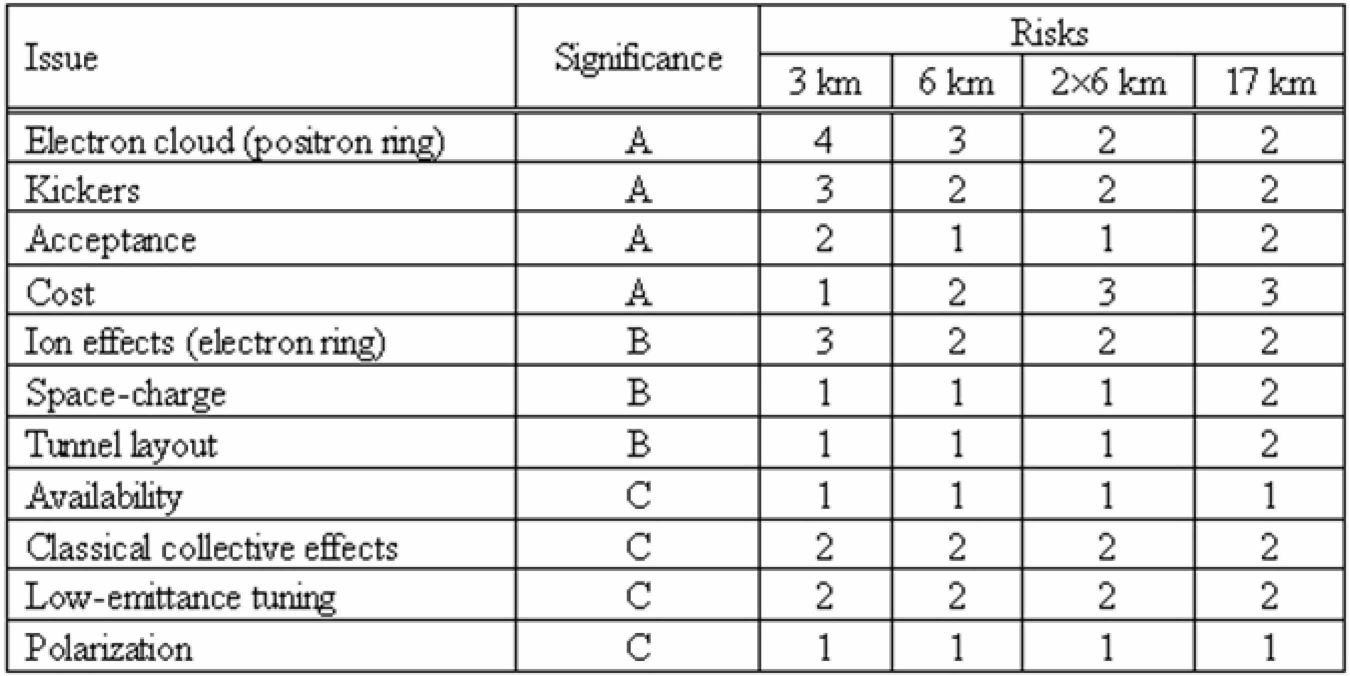
The cost impacts of the various options are ranked



Rank	Meaning
1	Lowest cost option, or close to lowest cost.
2	Up to roughly factor of two greater cost than lowest cost option.
3	Up to roughly factor of three greater cost than lowest cost option.
4	More than a factor of three greater cost than lowest cost option.

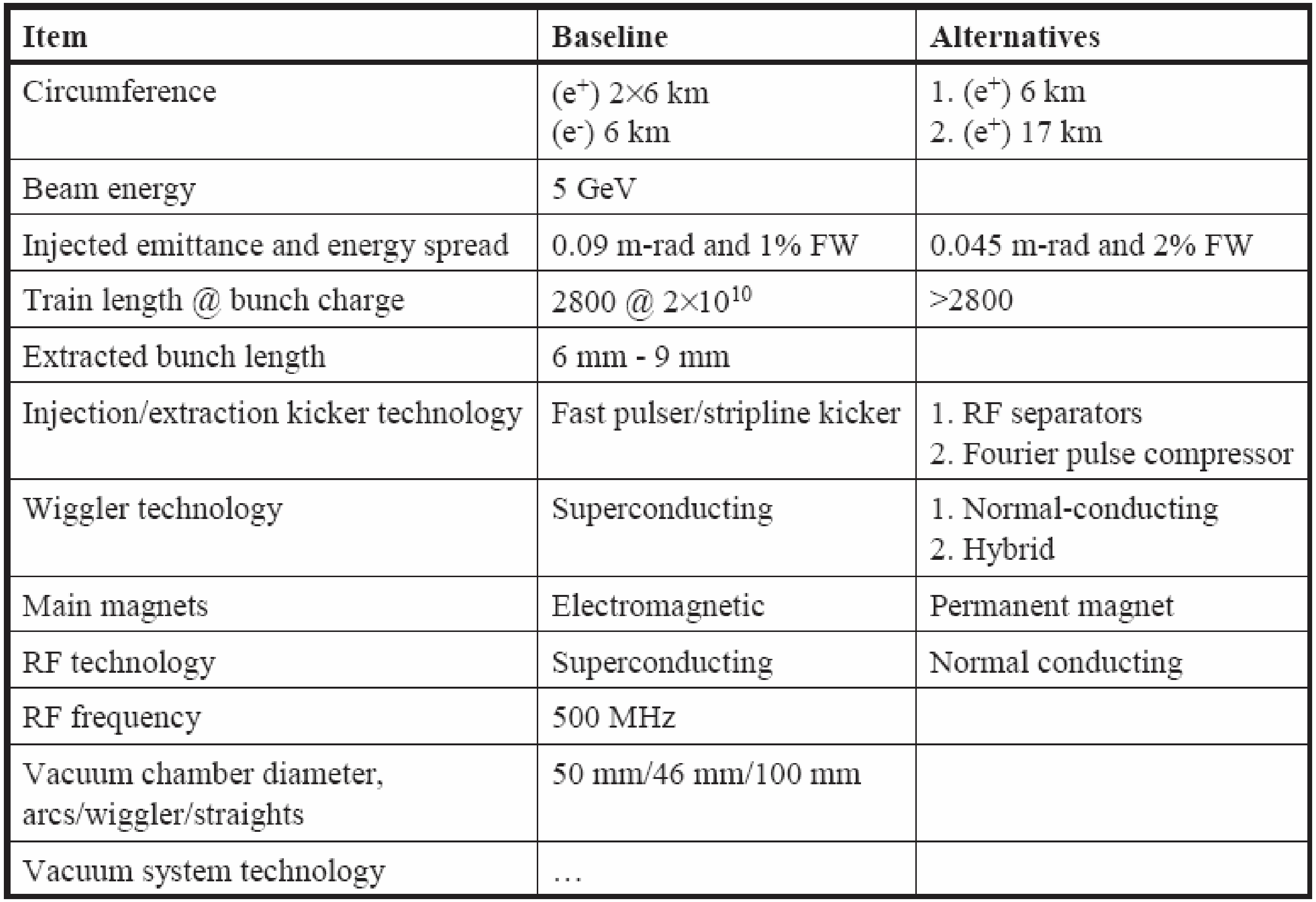
Issues on ILC damping rings (cont')

Issues Ranking



Issue	Significance	Risks			
		3 km	6 km	2×6 km	17 km
Electron cloud (positron ring)	A	4	3	2	2
Kickers	A	3	2	2	2
Acceptance	A	2	1	1	2
Cost	A	1	2	3	3
Ion effects (electron ring)	B	3	2	2	2
Space-charge	B	1	1	1	2
Tunnel layout	B	1	1	1	2
Availability	C	1	1	1	1
Classical collective effects	C	2	2	2	2
Low-emittance tuning	C	2	2	2	2
Polarization	C	1	1	1	1

Recommendations summarized



Item	Baseline	Alternatives
Circumference	(e^+) 2×6 km (e^-) 6 km	1. (e^+) 6 km 2. (e^+) 17 km
Beam energy	5 GeV	
Injected emittance and energy spread	0.09 m-rad and 1% FW	0.045 m-rad and 2% FW
Train length @ bunch charge	2800 @ 2×10^{10}	>2800
Extracted bunch length	6 mm - 9 mm	
Injection/extraction kicker technology	Fast pulser/stripline kicker	1. RF separators 2. Fourier pulse compressor
Wiggler technology	Superconducting	1. Normal-conducting 2. Hybrid
Main magnets	Electromagnetic	Permanent magnet
RF technology	Superconducting	Normal conducting
RF frequency	500 MHz	
Vacuum chamber diameter, arcs/wiggler/straights	50 mm/46 mm/100 mm	
Vacuum system technology	…	

---- Excerpt from recent slides of Andy Wolski

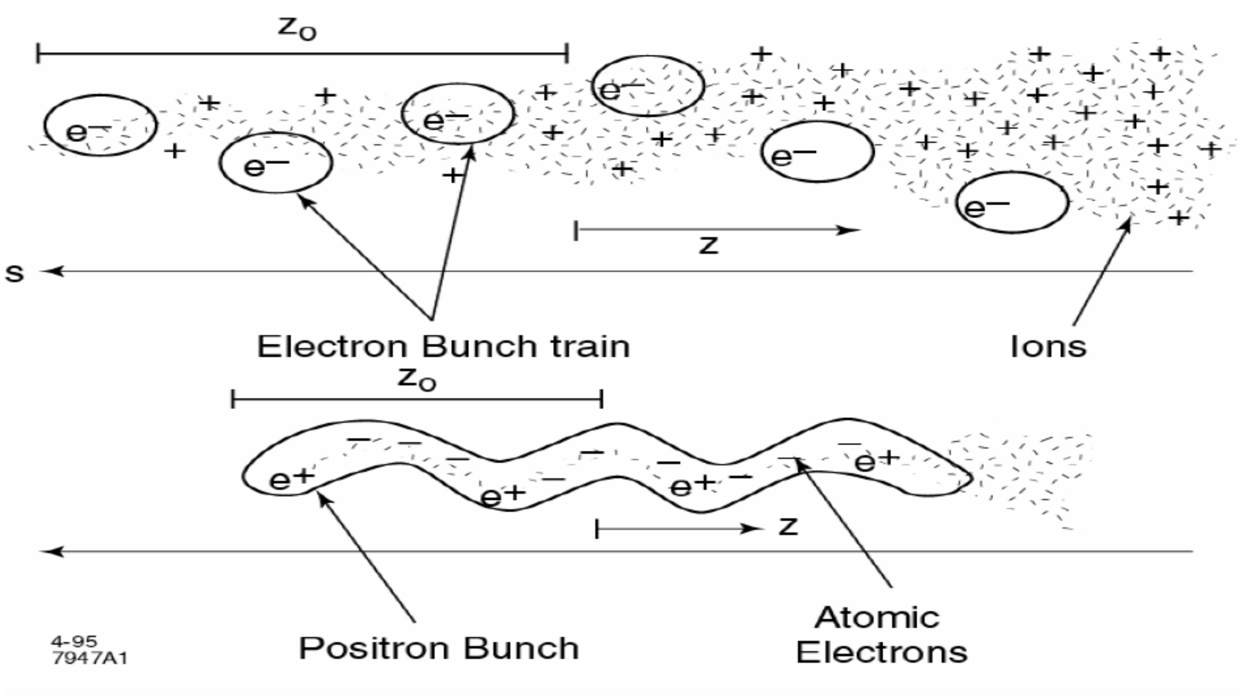
Part II Fast Beam Ion Instability

- Ion effects arise when ions are trapped in the potential well of the beam
- Ions accumulate until stabilized by neutralization, second ionization, etc
- In high current storage rings or linacs with long bunch trains, the ions accumulate during the passage of a single bunch train
- This leads to fast beam ion instability, which is noticeable in the damping rings for ILC

What is FBII ?

- FBII is due to residual gas ionization
- Beam bunches’ motion couples the ions’
- FBII is a single pass instability like BBU, unlike the classical trapped-ion instability

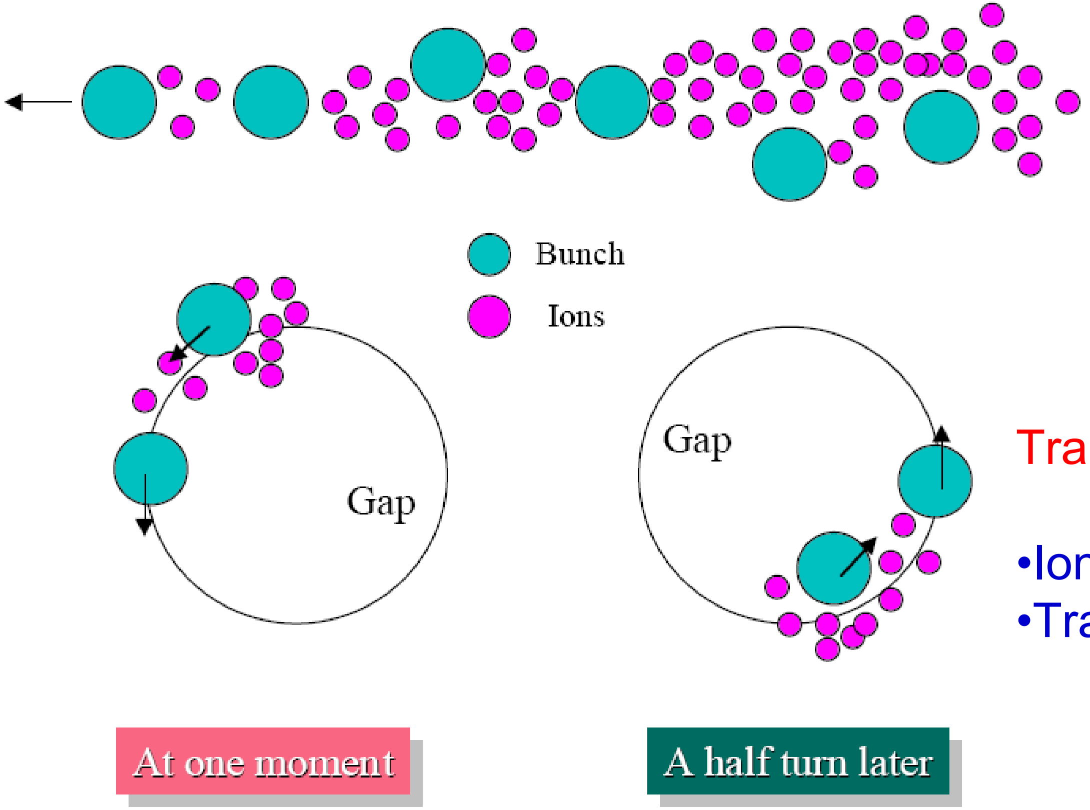
What is FBII (cont')?



FBII can arise ions in an electron beam or

electrons in a positron (proton) beam

What is FBII? (cont')



Transient effect !

- Ions are cleared out by a gap
- Transient (single pass) phenomenon

Linear theory of FBII

$$\frac{d^2 y_b(s,z)}{ds^2} + \omega_\beta^2 y_b(s,z) = K[y_i(s,s+z) - y_b(s,z)] \int_{-\infty}^{z} \rho dz'$$

$$\frac{d^2 \tilde{y}_i(s,t)}{dt^2} + \omega_i^2(z)[\tilde{y}_i(s,t) - y_b(s,z)] = 0$$

$$y_i(s,t) = \frac{\int_{-\infty}^{z} dz' \rho \tilde{y}_i(s,t)}{\int_{-\infty}^{z} dz' \rho}$$

$$K \equiv \frac{2\lambda_{ion} e_e}{\gamma \Sigma_y (\Sigma_x + \Sigma_y)} \qquad \omega_i(z) \equiv \sqrt{\frac{2 N_b r_p}{L_{sep} A \Sigma_y (\Sigma_x + \Sigma_y)}}$$

- ✓ Ions generated in the beam by collision ionization
- ✓ Assume the trapped particles are stable in train and have small initial velocities

---- Excerpt from SLAC-PUB-6740

Linear theory of FBII (cont')

Linear theory assuming collisional ionization and stable ions in the beam

$$\lambda = 6N_{tot}P[\mathrm{Torr}] \qquad y_b \sim \frac{y_0 e^{\sqrt{t/\tau_c}}}{(t/\tau_c)^{1/4}}$$

(quasi-exponential growth)

$$\frac{1}{\tau_c} = \frac{4d_{gas}\sigma_{ion}\beta_y N_b^{3/2} n_b^2 r_e r_p^{1/2} L_{sep}^{1/2} c}{3\sqrt{3}\gamma\sigma_y^{3/2}(\sigma_x+\sigma_y)^{3/2} A^{1/2}}$$

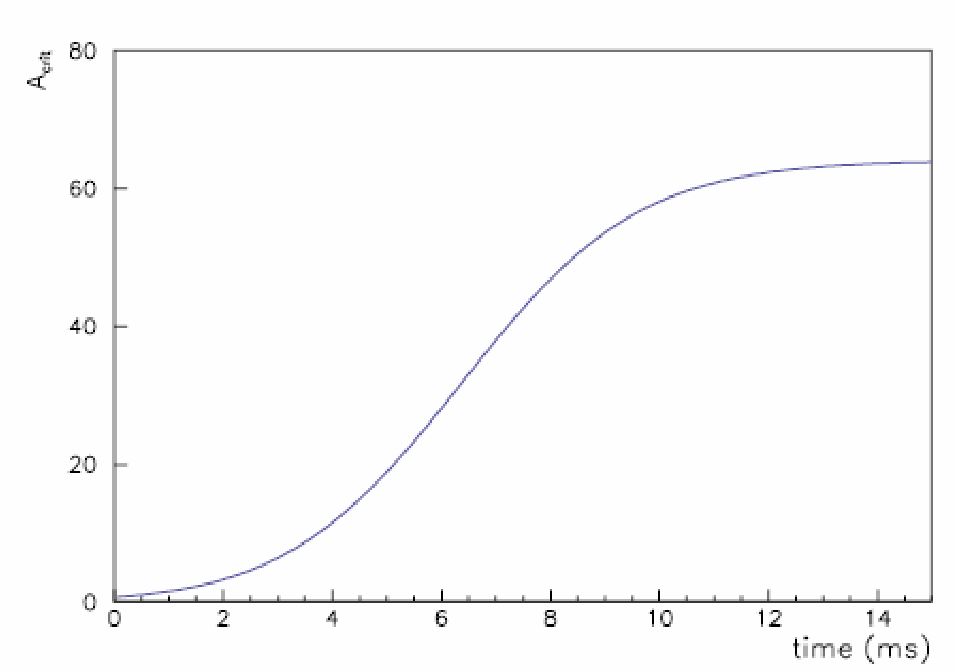
$$\omega_i = \left(\frac{4N_b r_p c^2}{3AL_{sep}\sigma_y(\sigma_x+\sigma_y)}\right)^{1/2}$$

By considering the decoherence of ions, the growth time will become as

$$y \sim \exp(t/\tau_e) \qquad \frac{1}{\tau_e} = \frac{1}{\tau_c}\frac{c}{2\sqrt{2}l_{train}(\Delta\omega_i)_{rms}}$$

Exponential growth !

Trapping mass



$$A_{crit} = \frac{N_{tot} C r_p Q}{n_b^2 \, 2\sigma_y \left(\sigma_x + \sigma_y\right)}$$

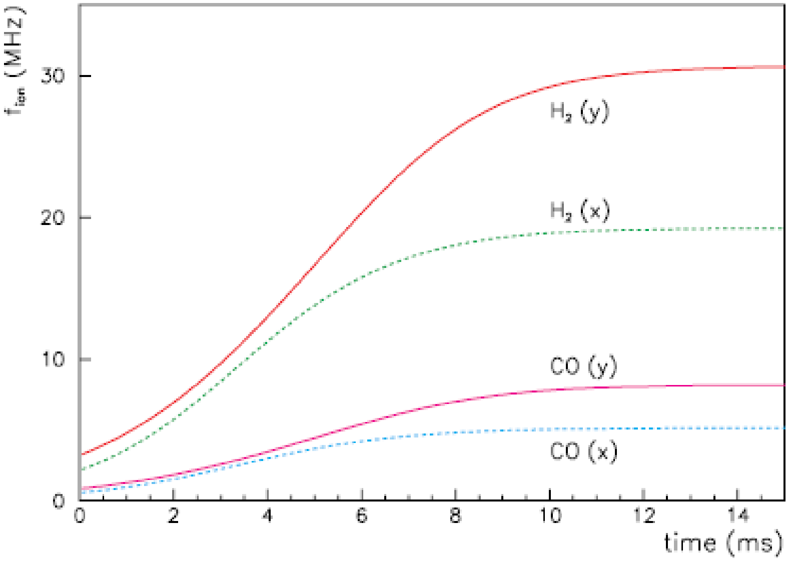
$$N_{tot} = n_b N_b$$

The critical ion mass (a.m.u) above which ions can be trapped, increases during the store as the beam size shrinks (SLC damping ring)

---- Excerpt from SLAC-PUB-7546

Ion frequency

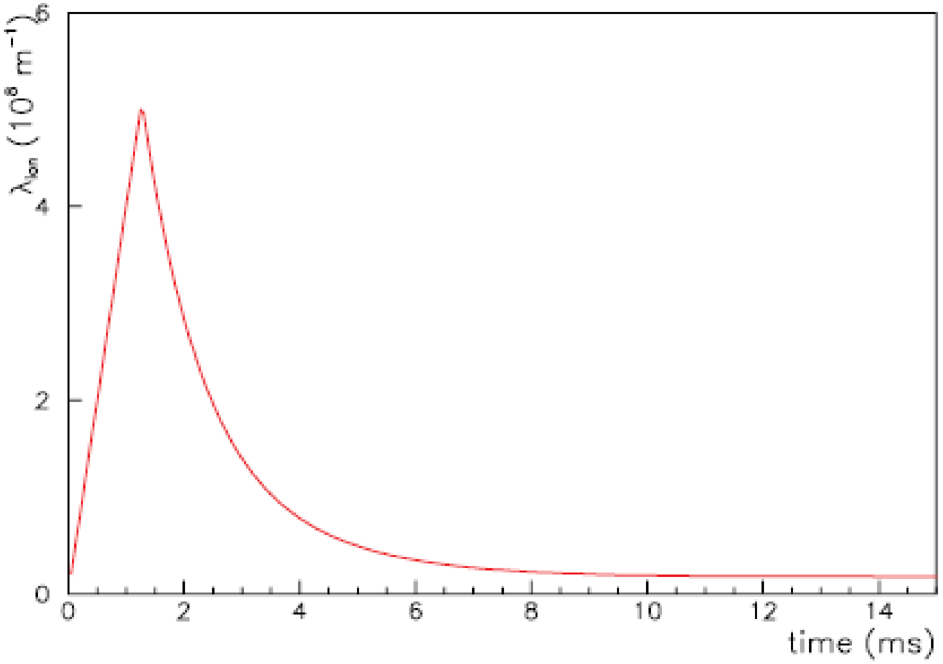
$$f_{ion,x,y} = \frac{c}{2\pi}\left(\frac{2N_{tot} r_p Q}{C\sigma_{x,y}\left(\sigma_x + \sigma_y\right)A}\right)^{1/2}$$



The oscillation frequencies for two different ion species as a function of store time during which the beam shrinks

---- Excerpt from SLAC-PUB-7546

Ion linear density



Predicted ion linear density, increase linearly with time then decreasing with the beam size (SLC damping ring)

---- Excerpt from SLAC-PUB-7546

Effects due to FBII

- The vertical beam size blow-up
- Growth of vertical emittance
- Tune shifts due to FBII
- Beam lifetime ?

Experimental study of FBII

- First observation of FBII at ALS

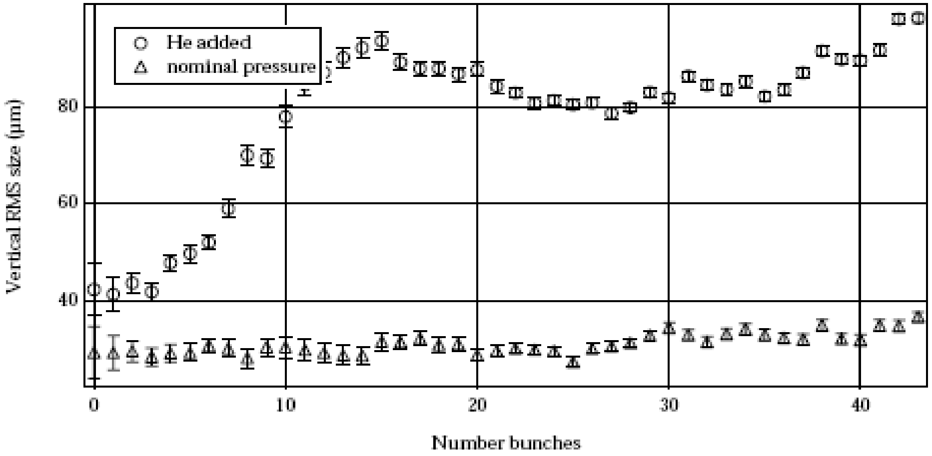


Figure 5: RMS vertical beam size versus the number of bunches for nominal and elevated pressure conditions.

---- Excerpt from J.Byrd et al., PAC97

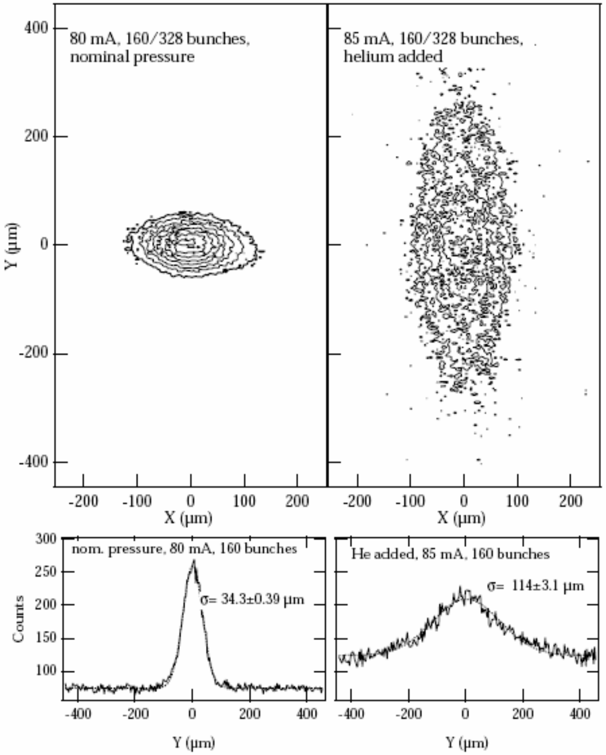


Figure 4: Transverse profile images (shown as contour plots) of the beam for nominal pressure and with helium added; the vertical profile for each image is also shown along with a fit to a gaussian distribution.

Effects due to FBII (cont')

Tune shift due to FBII (ion-induced incoherent tune shift)

$$\Delta Q_y = \frac{r_e \beta_y \lambda_{ion} C}{\gamma 2\pi \sigma_y \left(\sigma_x + \sigma_y\right)}$$

β_y is the average vertical beta function, λ_{ion} the ion line density, *C* the ring circumference

Ion-induced coherent tune shift is half of incoherent tune shift

Growth time of FBII (cont')

Ring	PPA	OTW	OCS	BRU	MCH	DAS	TESLA
Wiggler	127	225	350	824	721	592	609
ARC	2697	898	4722	3180	3455	3052	2015
Long straight	0	2101	1040	2329	11759	13370	14376

Growth time and tune shifts in different damping rings for CO+

Ring	PPA	OTW	OCS	2OCS	BRU	MCH	DAS	TESLA
$\tau_{wiggler}$ (μs)	0.6	0.8	0.8	1.6	0.7	1.75	2.67	2.4
τ_{arc} (μs)	25	4.2	3.6	6.9	3.56	9.43	12.7	13.5
$\tau_{straight}$ (μs)		43	19	38	46	52	54	53
τ_{ring} (μs)	2.6	8.7	4.4	8.3	3.2	20.5	40.2	43
τ_{ring} in turns	0.28	0.81	0.22	0.2	0.15	0.39	0.71	0.76
Tune shift	0.33	0.2	1.05	1.0	0.5	0.69	0.72	0.9

Pwiggler=2.0nTorr;

Plong_straight =0.1nTorr

P_arc=0.5nTorr

Conclusion: **17km Rings (DAS/MCH/TESLA) have a longer growth time**

Growth time of FBII (cont')

$$\tau^{-1}_{asym,e^+} \approx 7\,p(\mathrm{Torr})\frac{N_b^{3/2} r_e^{3/2} \sigma_z^{1/2} c}{\gamma \sigma_y^{3/2} \left(\sigma_x + \sigma_y\right)^{3/2} \omega_\beta}$$

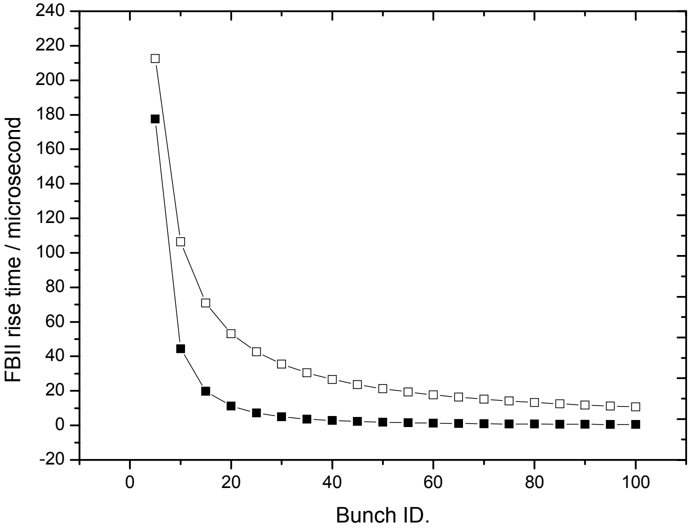
Asymptotic growth times due to FBII in positron damping rings in 0.1nTorr

Damping Rings	PPA	OTW	OCS	BRU	MCH	DAS	TESLA
Growth time (ms)	1.2978	1.5282	1.4863	1.7712	7.7502	8.0797	2.3356
Growth time (turns)	137.9	142.2	72.9	83.9	145.9	142.5	41.2

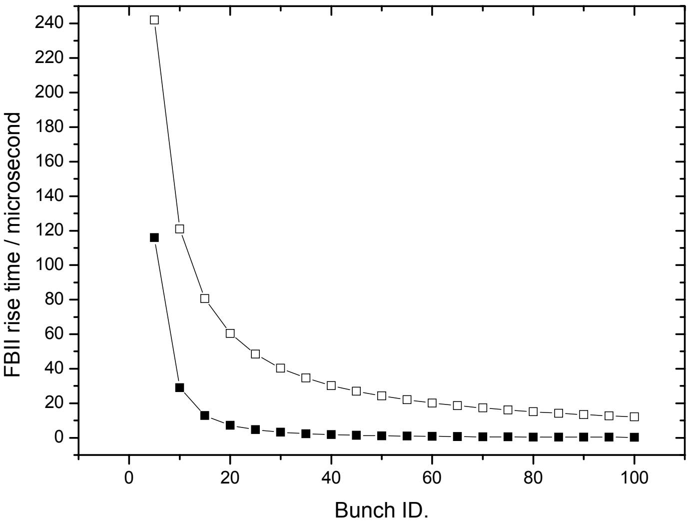
Conclusion: the expected instability rise time for the positron damping ring is a few ms, which is long enough and comparable to the synchrotron period, hence the synchrotron motion will prevent the build-up of the instability.

Growth time of FBII (cont')

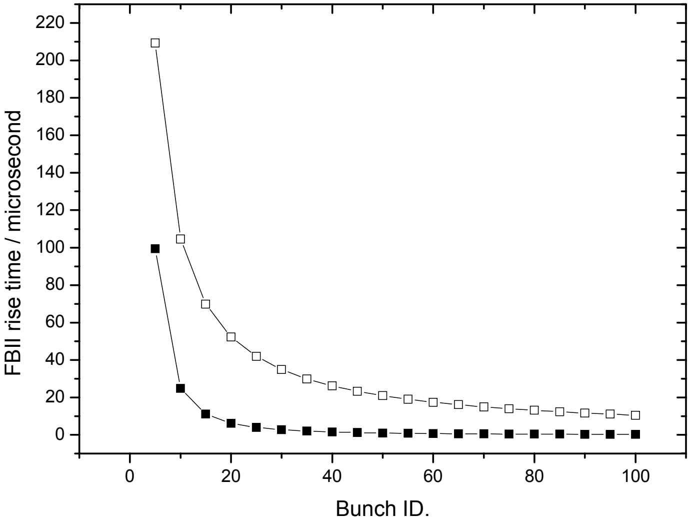
OTW



OCS



TESLA



The FBII rise time variation versus bunch ID for the straight section of 3 damping rings

■— without ion frequency spread

□— 10% ion frequency spread

Potential cures

- Upgrade the vacuum pressure (source of ions production)
- Increase the ion frequencies spread using an optical lattice, so that the ion frequencies varies significantly with the time, and no coherent oscillation can therefore develop
- Introduce the gaps in the bunch train in order to clear the ions or make beam shaking
- Bunch by bunch feedback system to realign the trailing bunch

Simulations of FBII

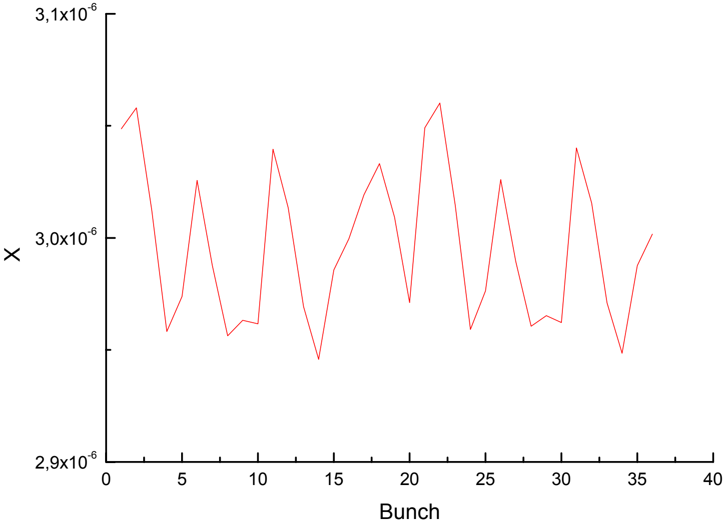
Simulations: Ion_MAD (lattice tracking PIC code)

- Beam and ions are represented by macro-particles
- Track through lattice as defined in MAD deck
- Beam is assumed Gaussian when calculating forces
- Ion fields are calculated using 2-D FFT
- Fields are mapped onto grid $\pm 5\sigma_{x,y}$
- Ions are generated at rest and are assumed non-relativistic
- Synchrotron motion is included but no longitudinal motion of ions
- Ions are discarded after bunch train

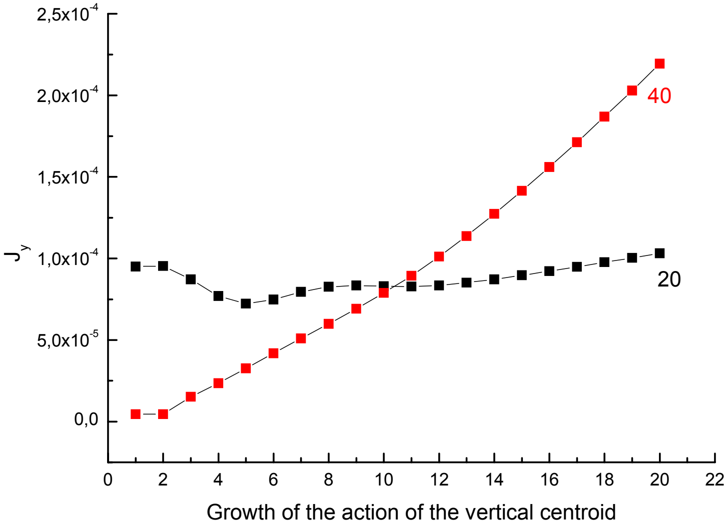
Simulation of FBII (cont')

- By using Strong-Strong model developed by T. Raubenheimer
- The blow-up of vertical oscillation amplitude
- The growth of vertical emittance

$$J_y = \frac{1}{2}\left[\frac{1+\alpha^2}{\beta}\langle y\rangle^2 + 2\alpha\langle y\rangle\langle y'\rangle + \beta\langle y'\rangle^2\right]$$

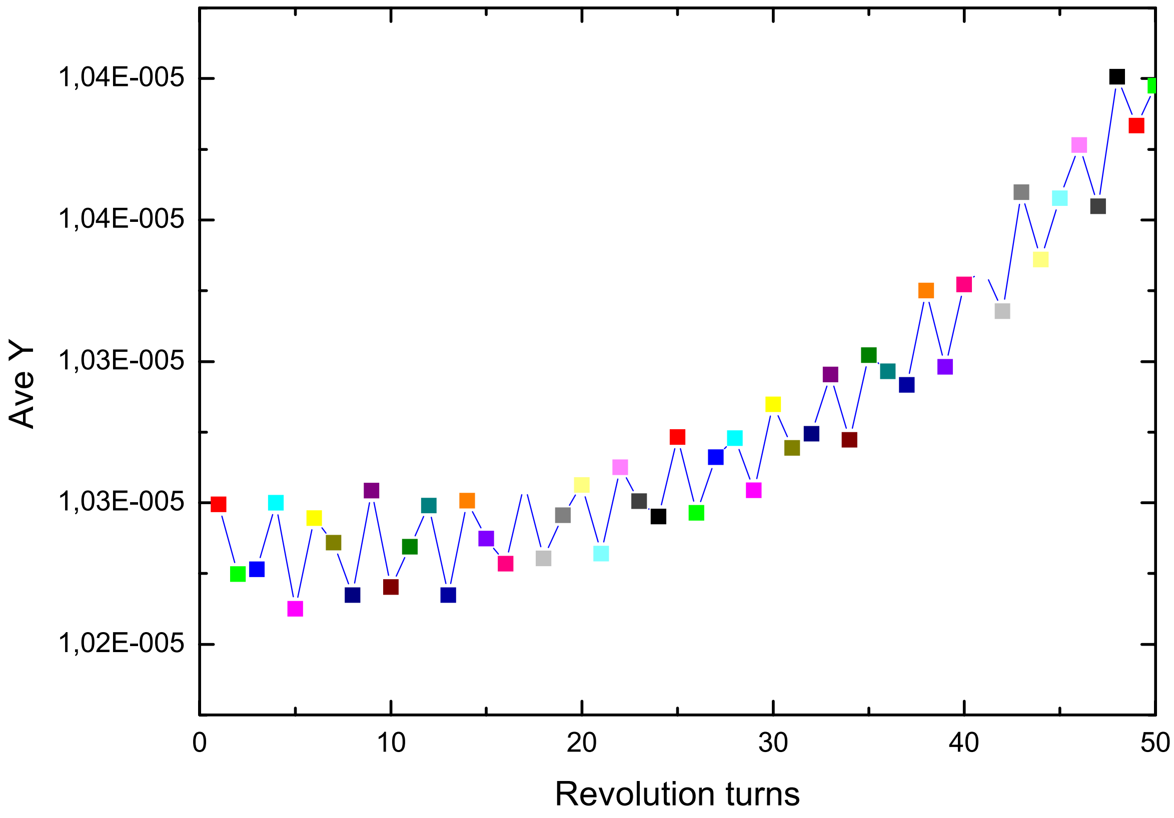


Beam oscillation amplitude along the bunch train



Growth of the action of the vertical centroid in ATF for carbon monoxide (atomic mass 28), in a pressure 1×10^{-8} Torr.

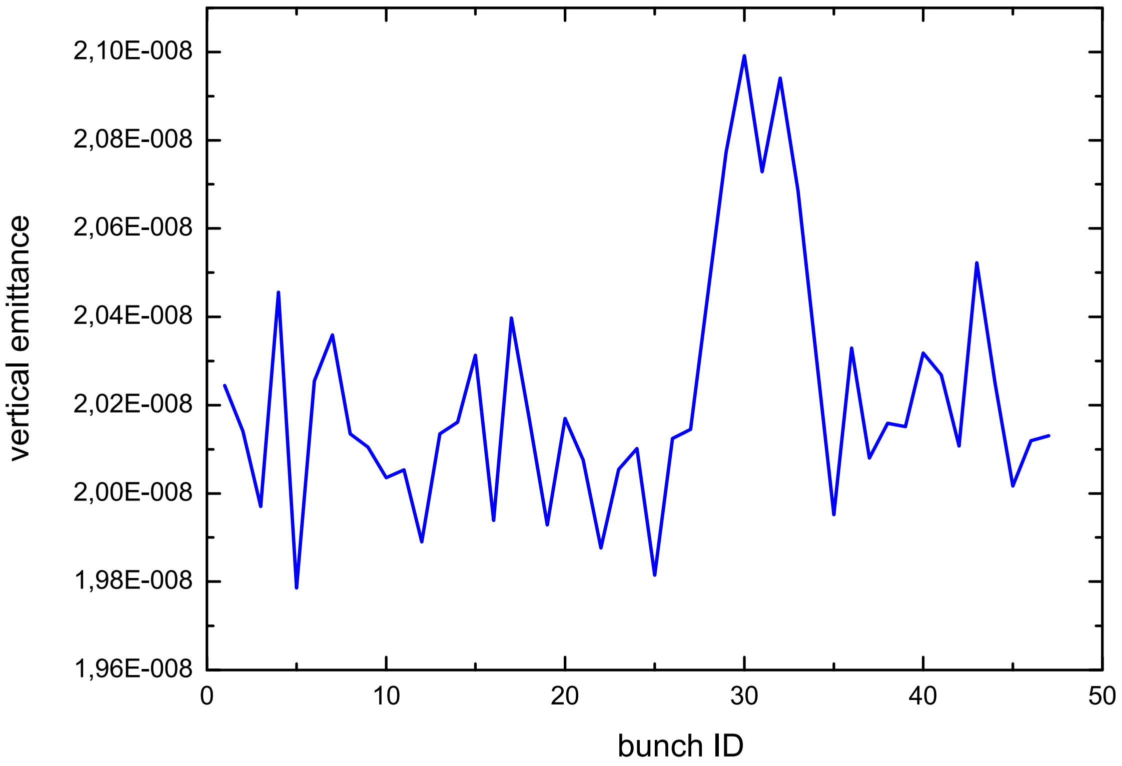
Simulation of FBII (cont')



OCS DR, E=5.066 GeV, Vacuum pressure 1E-9 Torr,

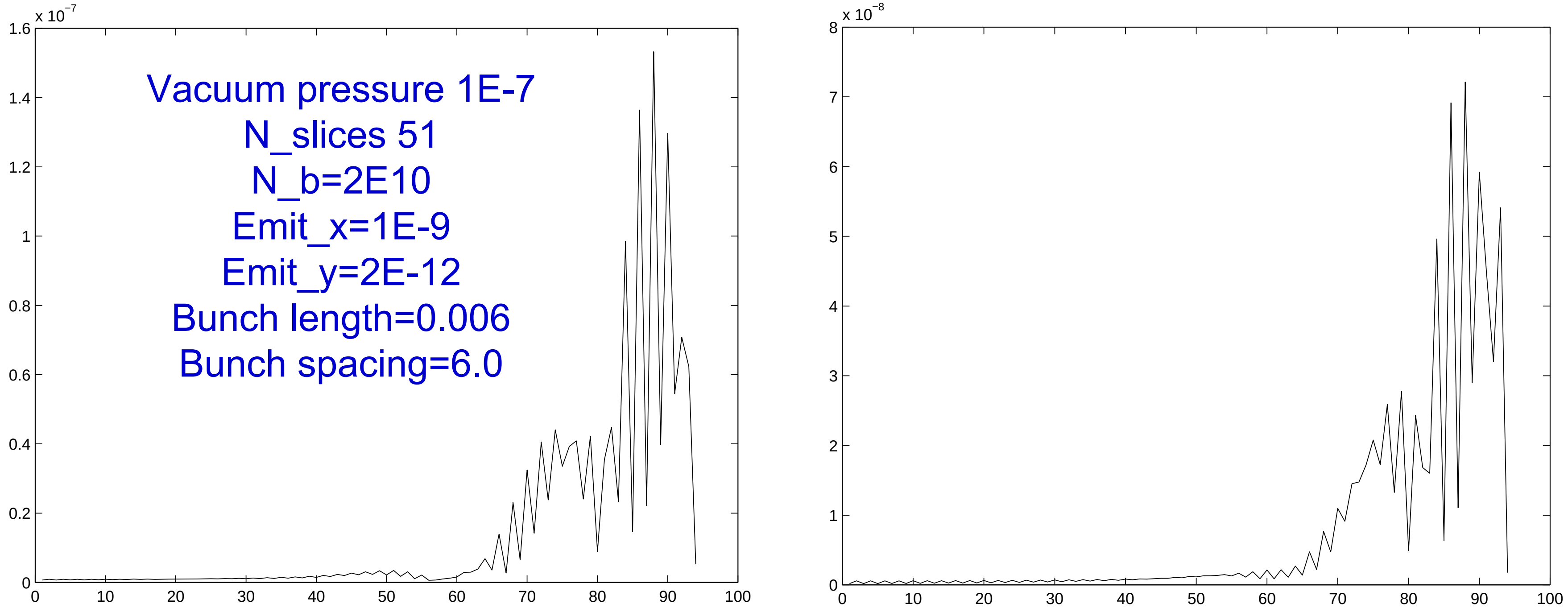
no radiation damping rate, no feedback damping

Simulation of FBII (cont')



OCS DR, E=5.066 GeV, Vacuum pressure 1E-9Torr, no radiation damping rate, no feedback damping (50th turn)

Simulation of FBII (cont')

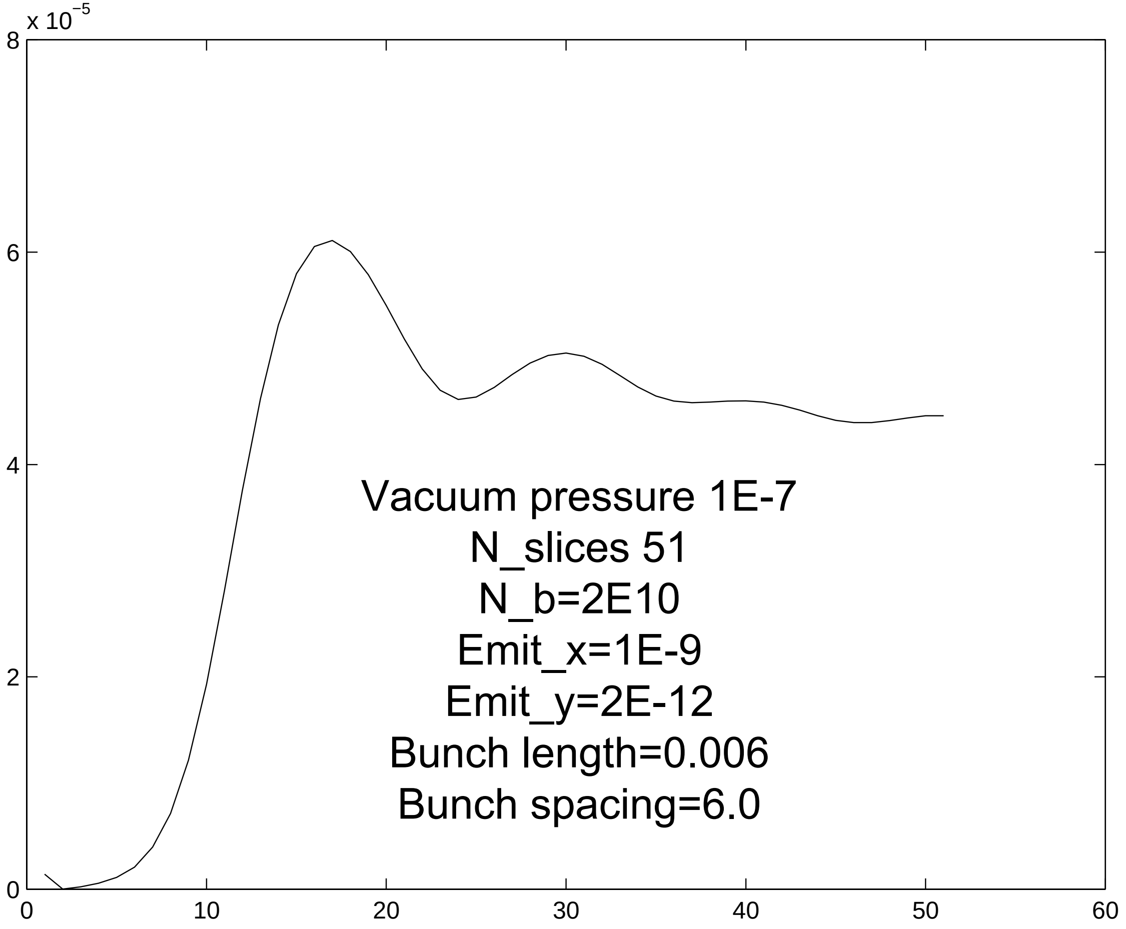


Vacuum pressure 1E-7
N_slices 51
N_b=2E10
Emit_x=1E-9
Emit_y=2E-12
Bunch length=0.006
Bunch spacing=6.0

Beam emittance variations due to FBII in

TESLA Damping Ring

Simulation of FBII (cont')



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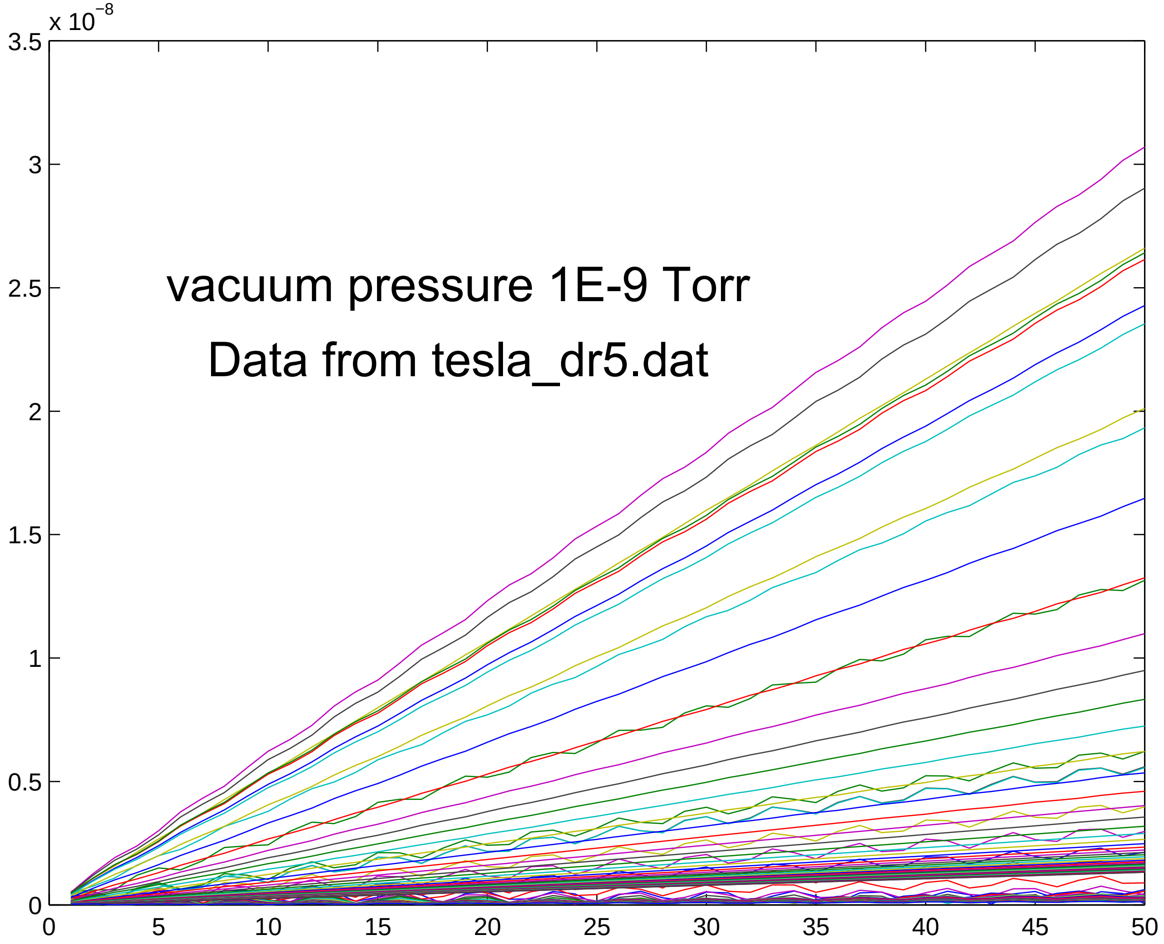
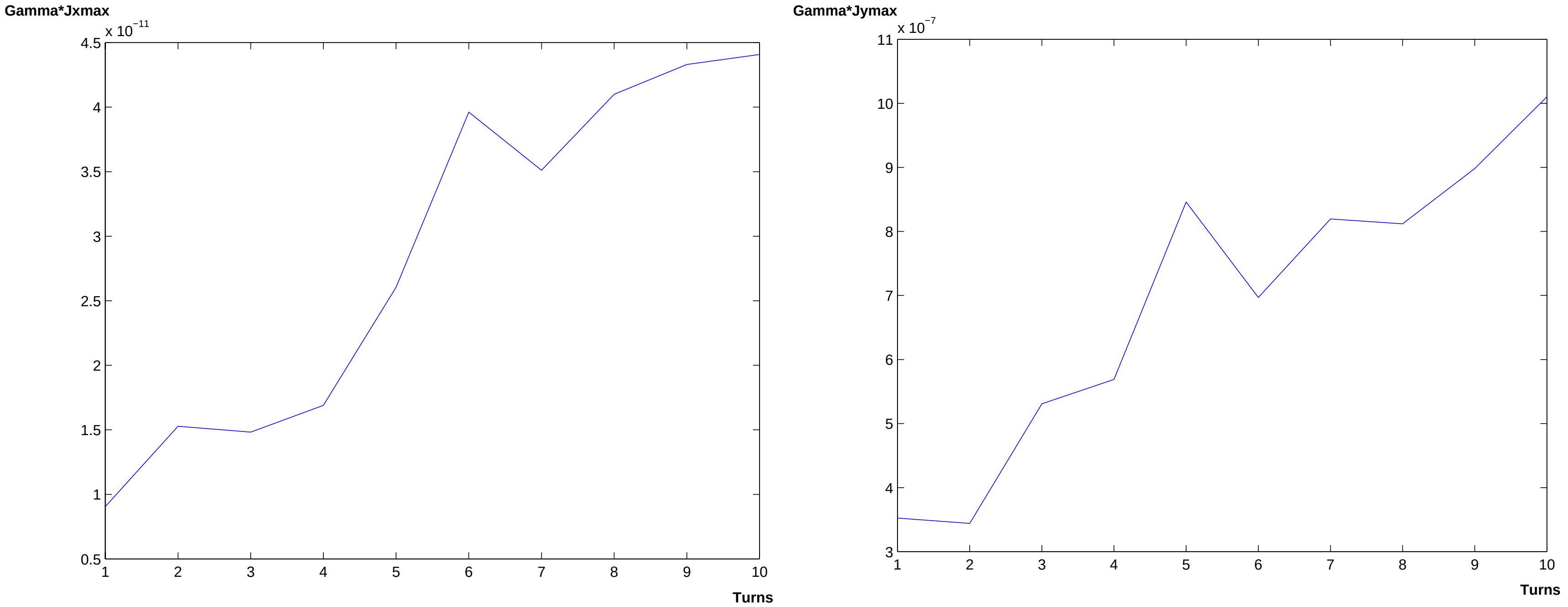
Simulation of FBII (cont’)



Beam offset in Tesla damping ring due to FBII

Simulation of FBII (cont’)

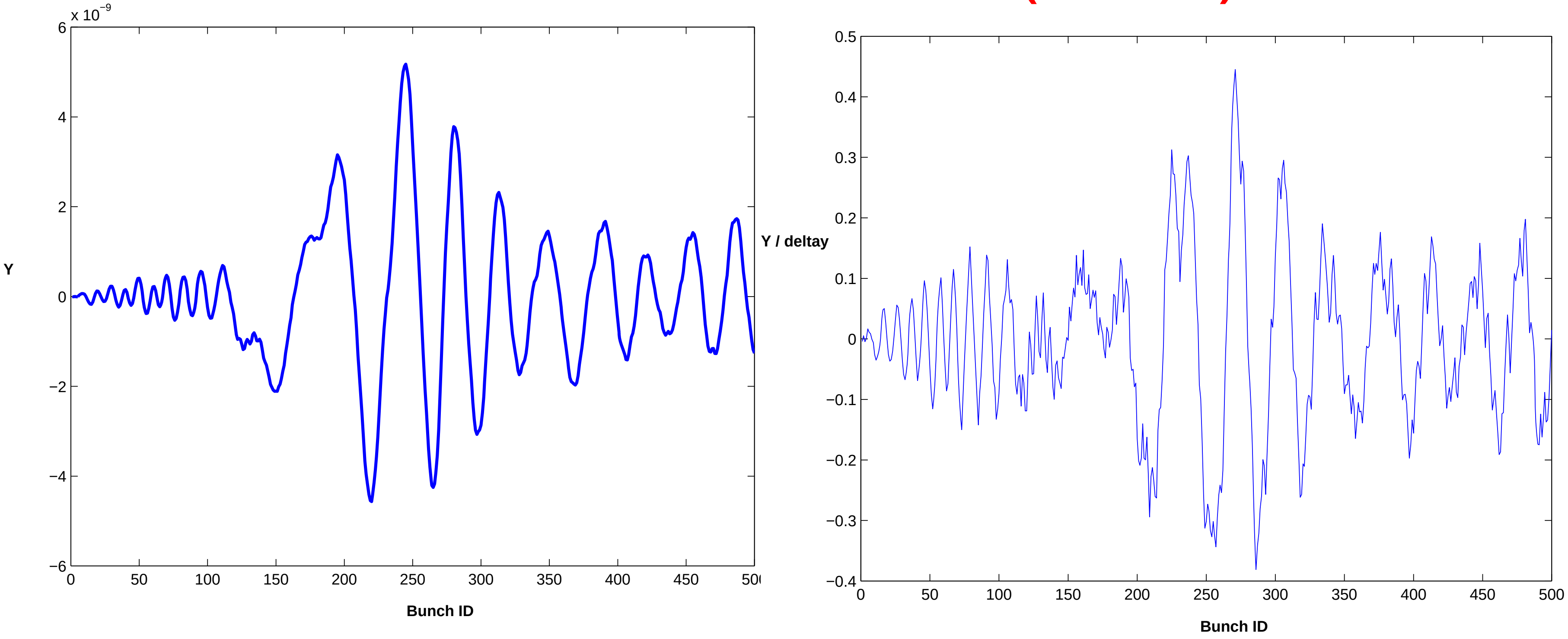


Action of Betatron oscillation *vs*. revolution turns

Simulation of fast ion instability in KEKB

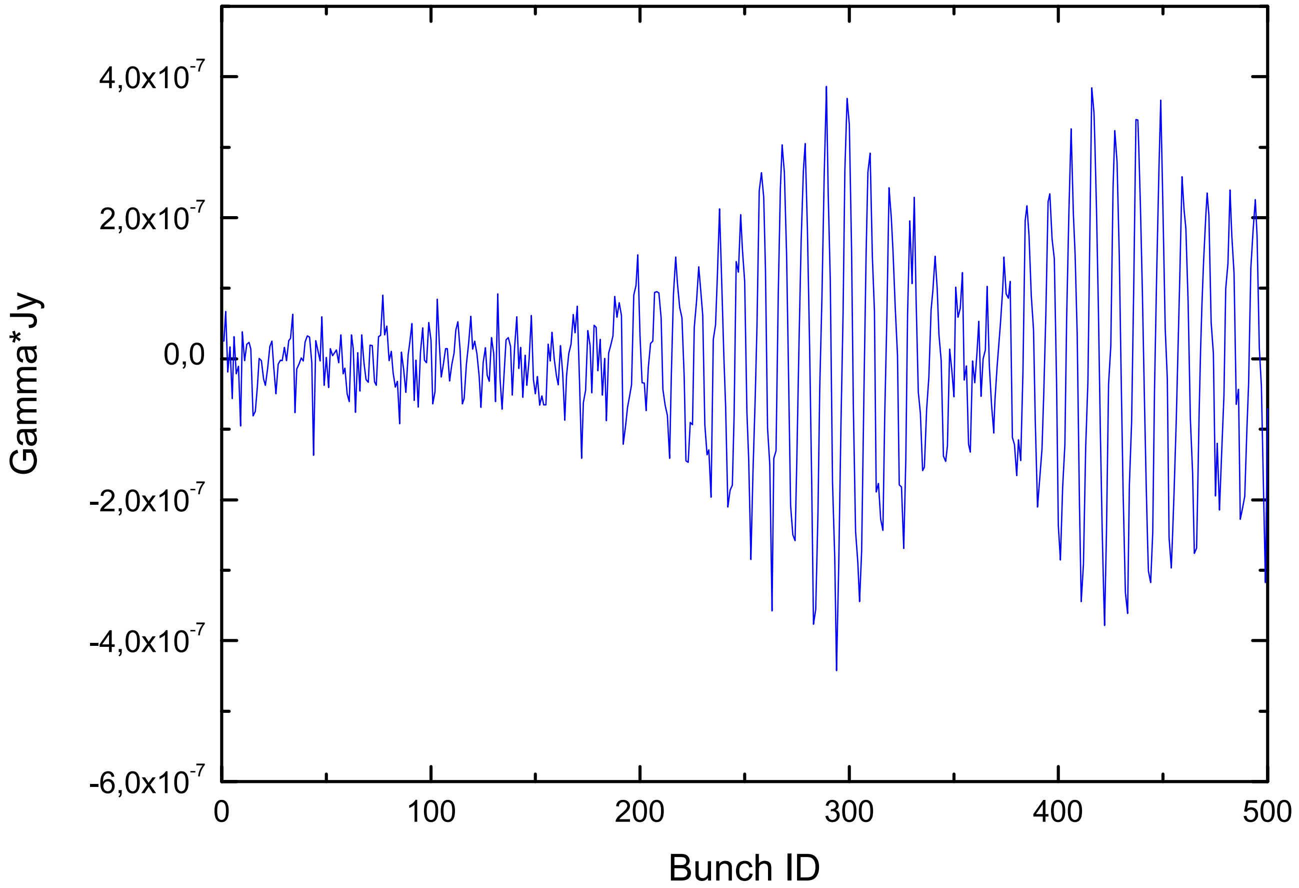
Weak-Strong model developed by K. Ohmi (The ions are represented as marco-particles while the beam bunch is rigid (only the barycenter motion of beam is considered))

Simulation of FBII (cont')



Coupled bunch pattern due to FBII in KEKB, the vacuum pressure is assumed to be 1nTorr. Oscillation amplitude *vs*. bunch ID

Simulation of FBII (cont')



Simulation of fast ion instability in KEKB

Part III Summary and Future Plan

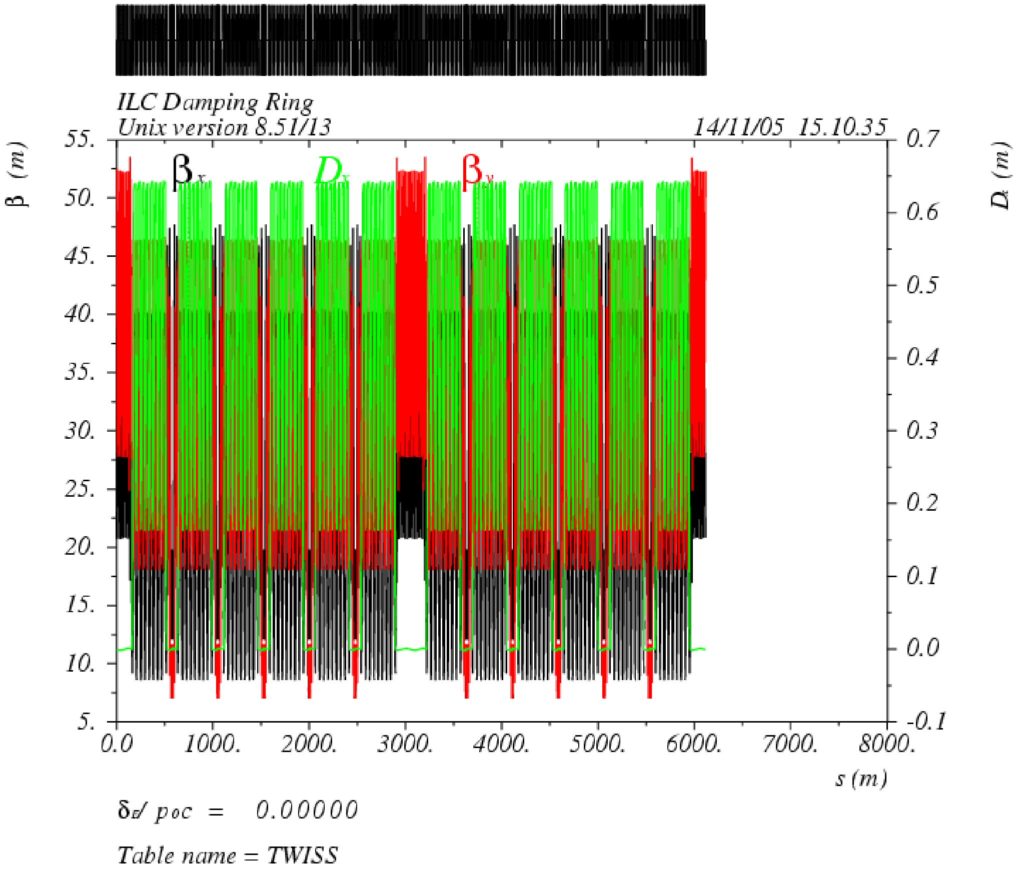
- FBII is a potential limitation for many multi-bunch small emittance storage rings as damping rings of ILC
- FBII should be studied further and experimental verification
- Benchmarking simulation work should be done further

Future Plan

- Simulate the fast beam ion instability in OCS damping ring
- Compare the FBII results from Weak-Strong model and Strong-Strong model
- Code development for ion effects

Also

- Mini-gap in the bunch train to mitigate the ion effects
- Ion induced pressure instabilities in the positron ring
- And so on…



OCS lattice optimization

Fast ion instability in OCS electron damping ring

Thanks !

Appendix I
(emittance and energy spread damping)

$$\sigma_x(t)=\sqrt{\varepsilon_x(t)\beta_x+\eta_x^2\sigma_\delta^2(t)}$$

$$\sigma_y(t)=\sqrt{\varepsilon_y(t)\beta_y+\eta_y^2\sigma_\delta^2(t)} \qquad \eta_y\approx 0$$

$$\varepsilon_x(t)=\varepsilon_{x,0}e^{-2t/\tau_x}+\left(1-e^{-2t/\tau_x}\right)\varepsilon_{x,\infty}$$

$$\varepsilon_y(t)=\varepsilon_{y,0}e^{-2t/\tau_y}+\left(1-e^{-2t/\tau_y}\right)\varepsilon_{y,\infty}$$

$$\sigma_\delta(t)=\sigma_{\delta,0}e^{-t/\tau_\delta}+\left(1-e^{-t/\tau_\delta}\right)\sigma_{\delta,\infty}$$

Here, $\varepsilon_x(t),\varepsilon_y(t)$ are horizontal and vertical emittance, respectively

$\varepsilon_{x,0},\varepsilon_{y,0}$ are initial H. and V. emittance, respectively

$\varepsilon_{x,\infty}(t),\varepsilon_{y,\infty}(t)$ are equilibrium H. and V. emittance respectively

σ_δ the rms energy spread; ‘0’ and ‘∞’ refer to initial and equilibrium value

Appendix II

- Growth rate scales as $(\sigma_y \sigma_x)^{-3/2}$,namely $(\beta_x \beta_y)^{-3/4}$
- Important for low emittance beams in linear collider