Fast Ion Instability Study at DESY

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Outline

- Ions production
- Ion trapping instability
- Fast ion instability (FII)
- Simulation study of FII
- Recent experiment on FII
- Summary

Ions production

Sources of ions production

- The main source of ions comes from the inelastic collisions of the electron beam with the molecules of residual gas in vacuum pipe
- Tunneling ionization due to the collective electric field of the bunch
- Compton scattering of the synchrotron radiation on the electrons of residual gas molecules

Ions production

The cross section of the collisional ionization,

$$\sigma_i = 4\pi\left(\frac{\hbar}{mc}\right)^2\left[C_1\left(\frac{1}{\beta^2}\ln(\frac{\beta^2}{1-\beta^2})-1\right)+\frac{C_2}{\beta^2}\right]$$

the molecular density

$$n_m = 3.22\times10^{22}P_m$$

And the time it takes for one circulating particle to create one ion is given by

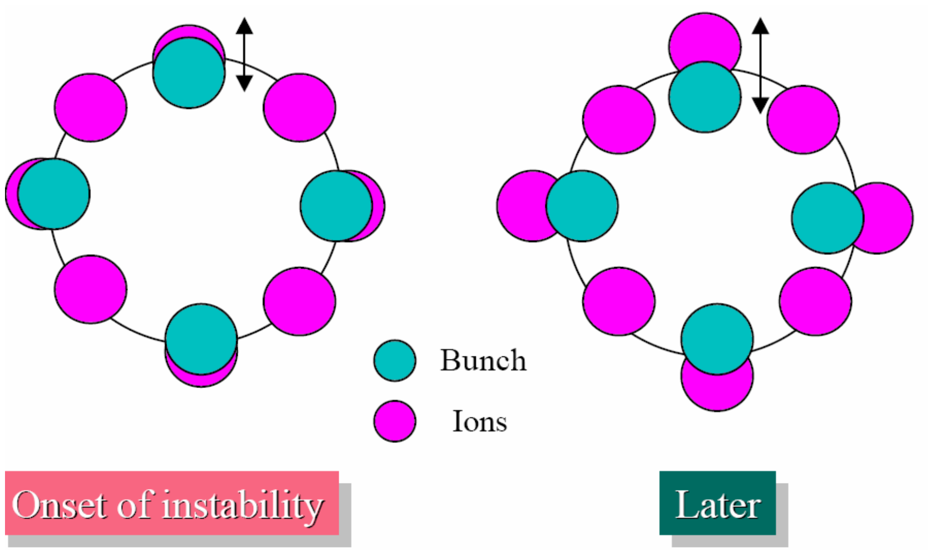
$$\tau_{col} = \frac{1}{n_m c\beta\sigma_i}$$

Cross sections of collision ionization for ILC damping rings
(nominal beam energy: 5GeV)

Molecule	A	C_1	C_2	**σ_i [10^{-22}m^2]**	P_m [10^{-9} Torr]	n_m [10^{12}m^3]	τ_m [sec]
H_2	2	0.50	8.1	**0.31**	0.75	24.15	4.39
CO	28	3.70	35.1	**1.86**	0.14	4.51	3.97
CO_2	44	5.75	55.9	**2.92**	0.07	2.25	5.06
CH_4	16	4.23	41.85	**2.16**	0.04	1.29	11.97

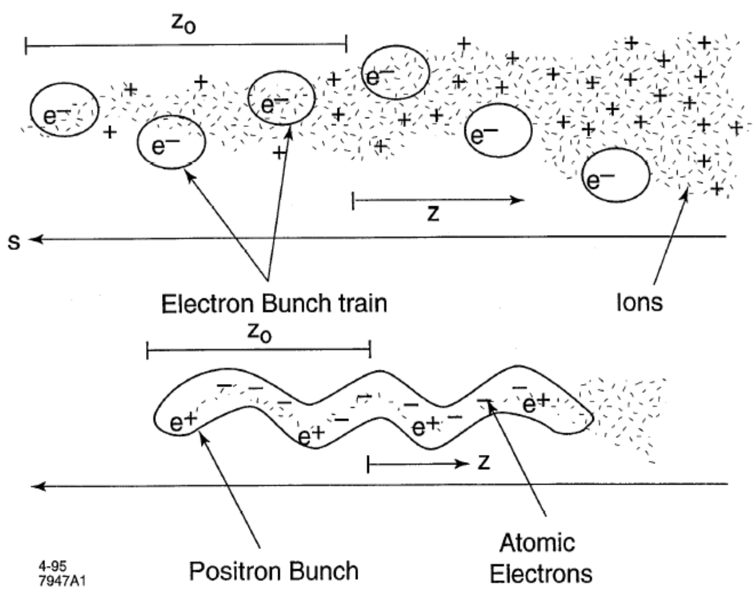
Ion trapping instability

- Ion trapping occurs when ions are trapped turns by turn in the potential well of the beam
- Ions accumulate until stabilized by neutralization, second ionization, etc.
- The adverse effects of ions include the beam emittance growth, beam lifetime reduction, tune shift and tune spread etc
- These phenomena have been observed in many existing machines (ALS, PLS,KEK-PF,SRRC,NSLS-VUV, PEPII, BEPC etc.)
- Ion trapping can be cured by introduction of a gap in the bunch trains.

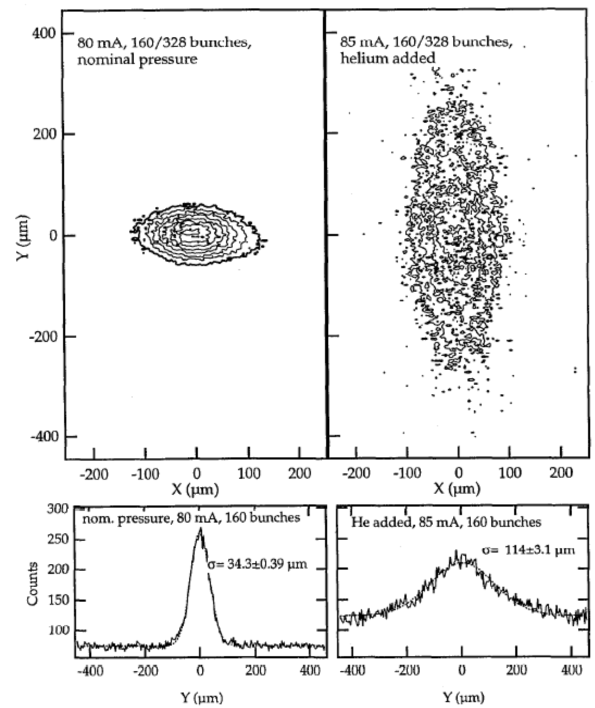


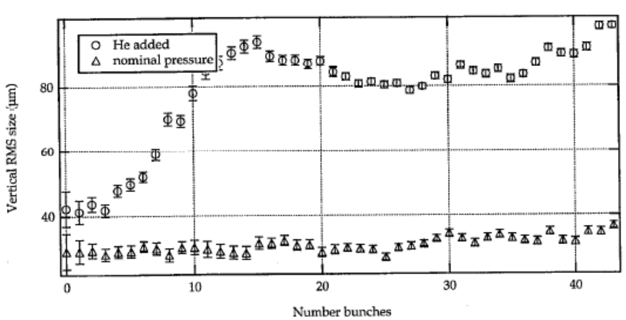
Fast ion instability

- In high current storage rings or linacs with long bunch trains, the ions accumulation during a single passage of bunch train is significant.
- This leads to fast ion instability (FII), which is noticeable in the ultra-low emittance (2pm) and high current damping ring operation for the ILC.
- Linear theory of FII was developed by Raubenheimer, Zimmermann, Stupakov, etc.
- This instability has been confirmed experimentally in some facilities such as ALS, TRISTAN AR, PLS, Spring-8, KEKB HER, ATF DR, PEP II, etc.



Fast ion instability





ALS (1997)

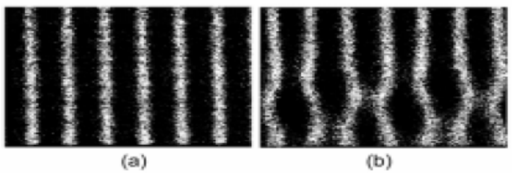


Figure 2. Snapshots taken every 4 µsec before and after the turn-off of the ion pumps. Total time span in horizontal direction is 25 µsec (6.4 mm in spatial unit), and 500 nsec in vertical direction. a) Snapshots taken at nominal condition. Very weak oscillation was observed at the very tail of the bunch train. b) After ion pumps were turned off, the snake-tail oscillation at the tail is clear.

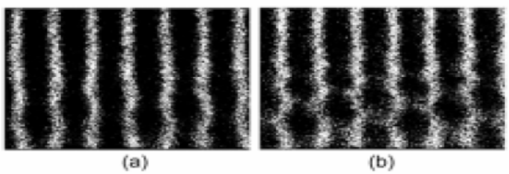


Figure 3. Two series of snapshots taken after He injection. a) Snapshots for 0.2 nTorr He, and b) for 3.34 nTorr He. The increase of the ion frequency from Figure 2b is manifest. The beam size blow-up at the tail is also clearly shown.

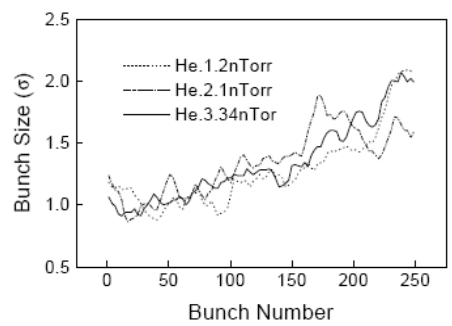
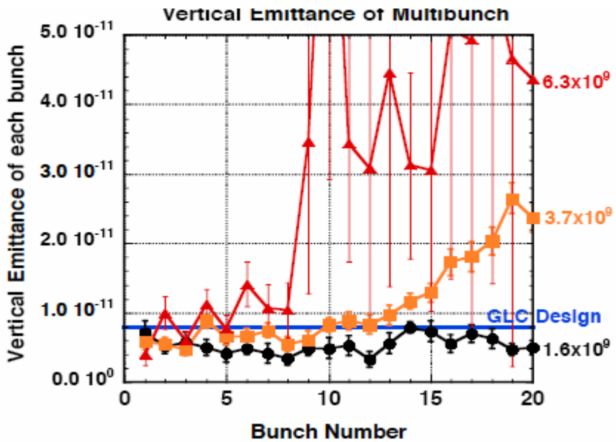


Figure 5. Bunch size measured along the bunch train for three different cases of 1.2 nTorr, 2.1 nTorr, and 3.34 nTorr showing the same growth pattern. Bunch sizes are normalized to the initial bunch size.

PLS (1998)



ATF

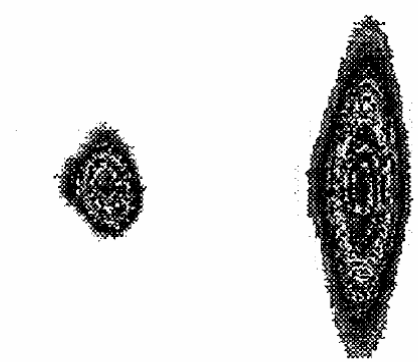


Figure 4. Synchrotron radiation profile just before and after the vertical beam blow-up threshold.

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Fast ion instability

FII characteristics:

- FII is due to residual gas ionization
- Beam bunches' motion couple the ions' motion
- FII is a single pass instability like BBU, unlike the classical trapped-ion instability
- FII can arise in storage rings, linacs, and beam transport line.
- It can cause coupled bunch instability, beam size blow-up, emittance growth and tune shifts etc

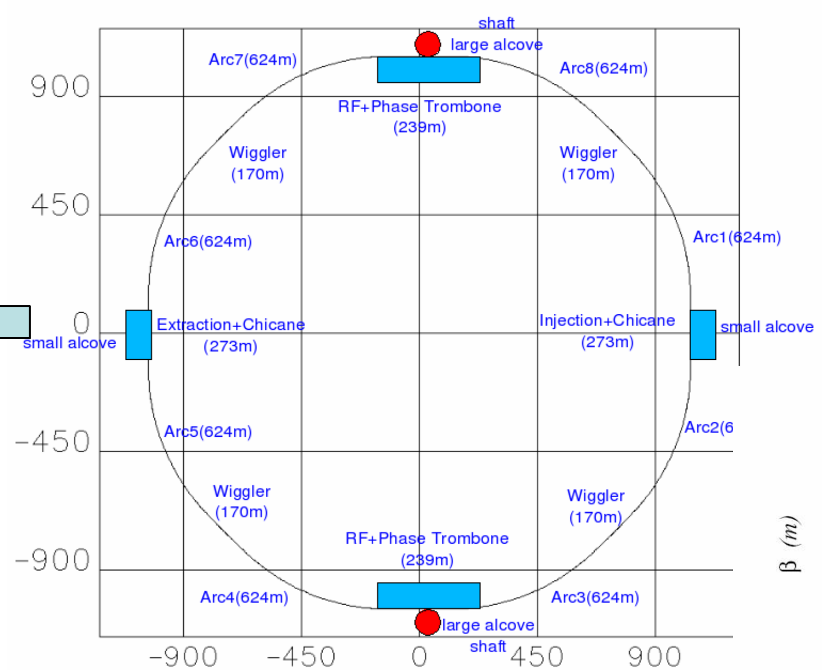
Potential cures:

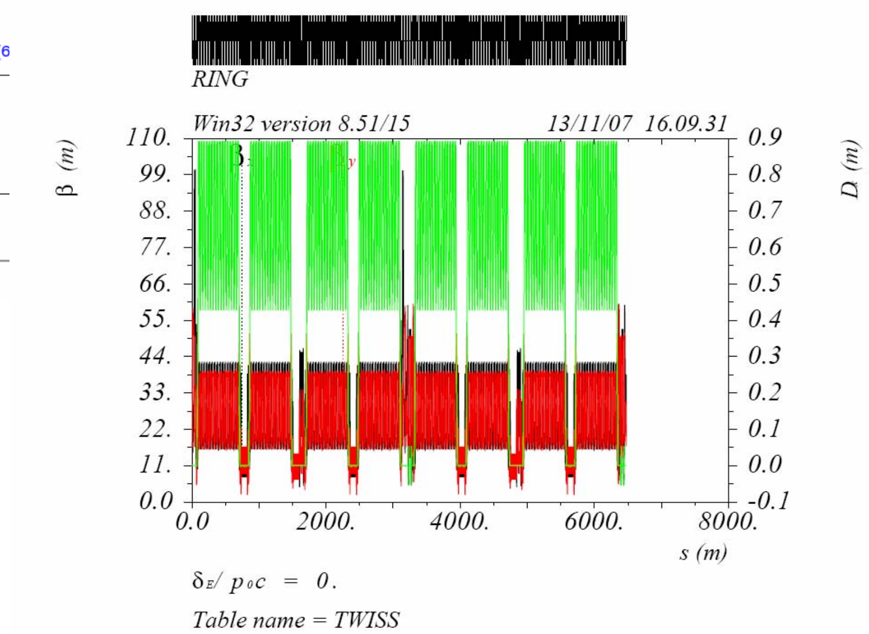
- Upgrade the vacuum condition
- Increase the ion frequencies spread using an optical lattice, so that the ion frequencies vary significantly with the time, and no coherent oscillation can therefore develop
- Introduce the gap between the bunch trains in order to clear the ions or make ions unstable
- Bunch by bunch feedback system to realign the trailing bunches

The baseline lattice OCS8

extraction

injection





Layout and optics of ILC damping rings

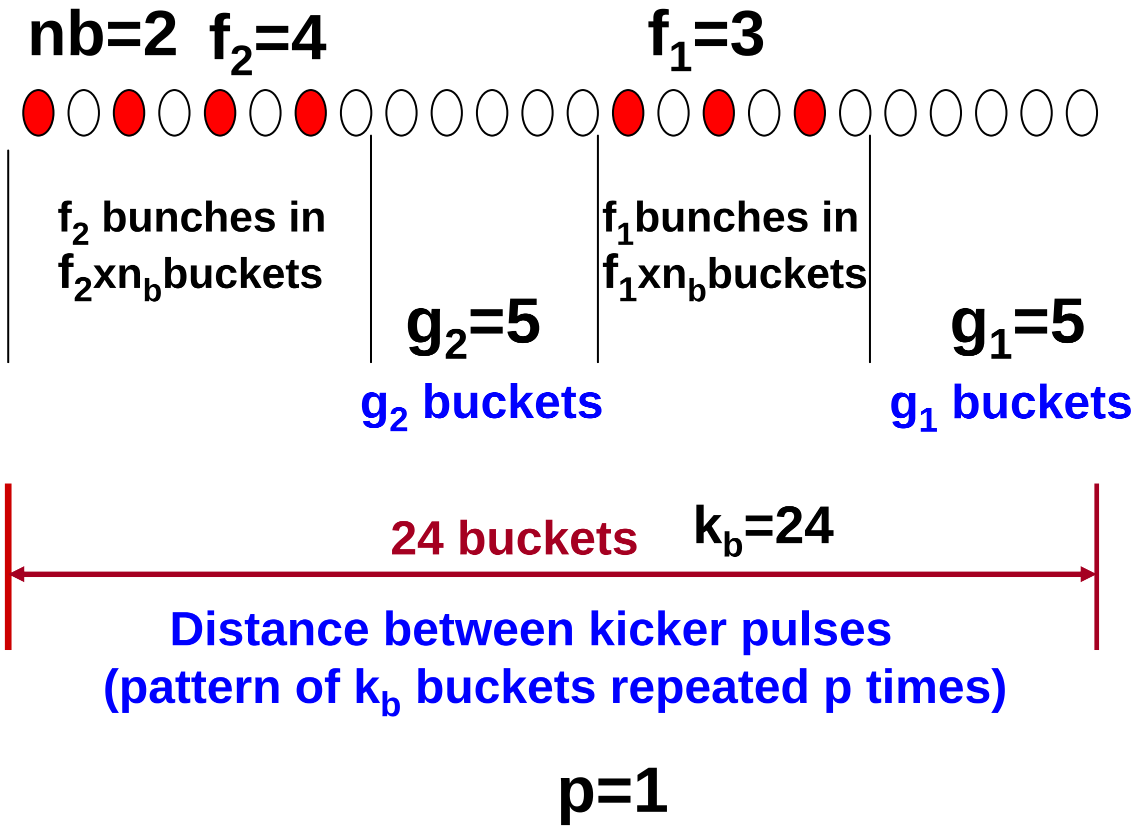
Parameters and fill patterns

Energy	5 GeV
Circumference	6476.4395 m
Harmonic number	14042
Betatron tunes	49.23, 53.34
Chromaticity	-63.7, -63.3
Momentum compaction	3.96×10^{-4}
Natural emittance	4.95 μm
Damping time	25 ms
RF voltage	21.2 MV
Energy loss per turn	8.7 MeV
Momentum acceptance	1.48%
Synchrotron tune	0.06
Equilibrium bunch length	9 mm
Equilibrium energy spread	0.128%

Fill patterns	***A***	***B***	***C***
Bunch spacing, [bucket]	2	2	4
Number of trains, p	117	78	58
Bunches per even-numbered minitrain, f_2	0	0	23
Gaps per even-numbered minitrain, g_2	0	0	30
Bunches per odd-numbered minitrain, f_1	45	45	22
Gaps per odd-numbered minitrain, g_1	30	90	30
DR average current, mA	405	405	401
Total number of bunches	5265	3510	2610
Bunch population [$\times 10^{10}$]	1.04	1.56	2.07

Basic beam parameters and fill patterns of ILC damping ring

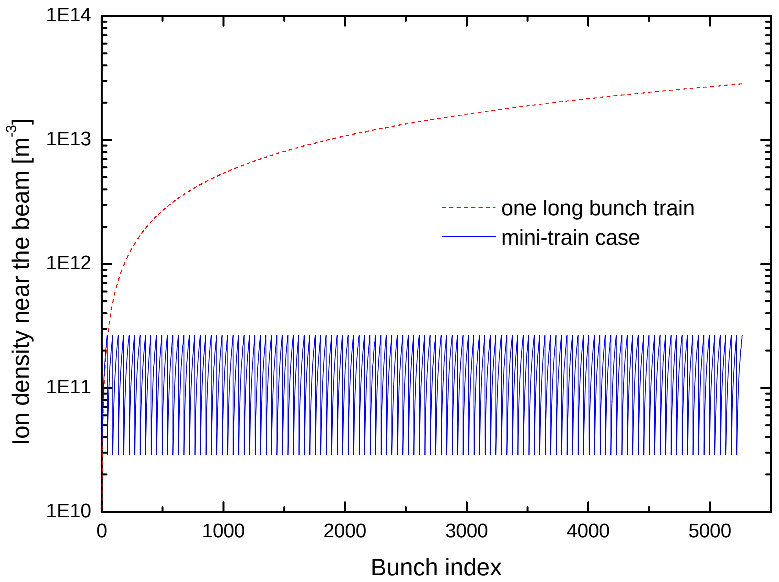
A fill pattern case



Ion density

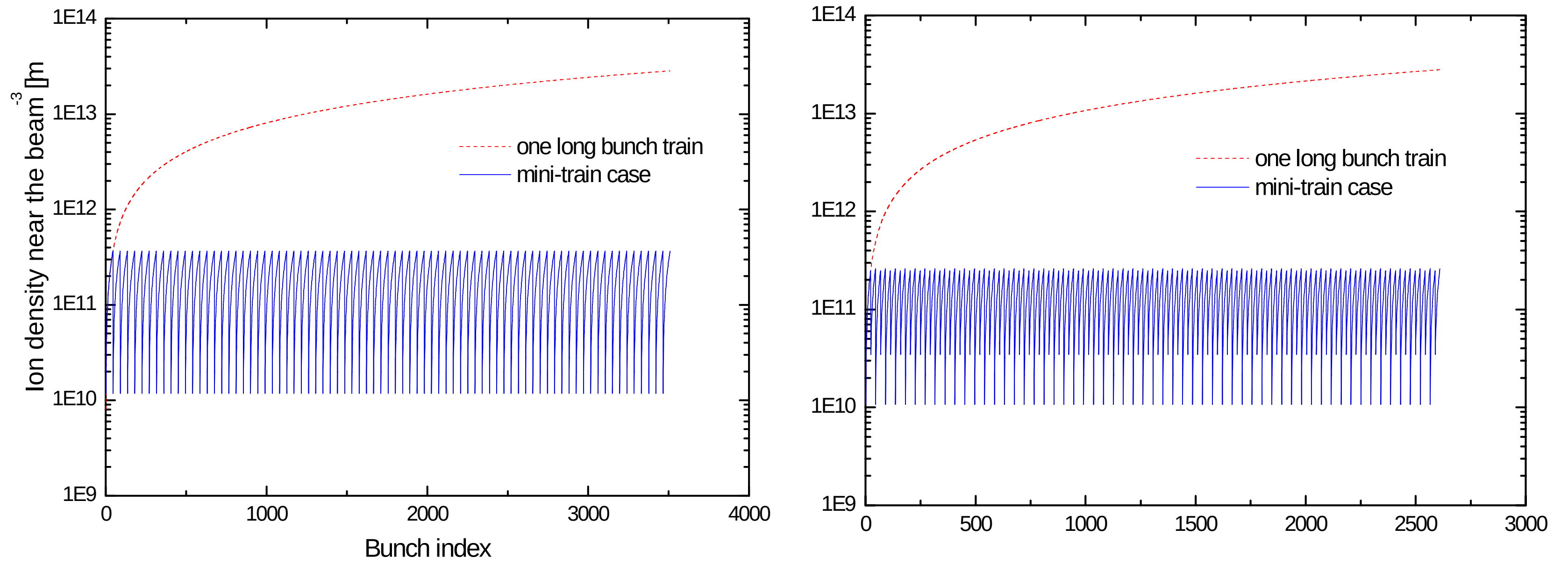
$$\rho_i \approx \frac{\rho_{i0}}{\sqrt{\left(1+L_{gap}^2\omega_x^2\right)\left(1+L_{gap}^2\omega_y^2\right)}}$$

$$\omega_{x,y}^2 = \frac{2N_0 r_p}{L_{sep} A \sigma_{x,y}\left(\sigma_x+\sigma_y\right)}$$



Ion density near the beam for one long bunch train case (dash) and for fill pattern *A* in mini-train case (solid) in ILC damping ring OCS8.

Ion density



Ion density near the beam for one long bunch train case (dash) and for fill pattern *B and C* in mini-train case (solid) in ILC damping rings.

Mini-train can reduce the ion density by a factor of 100 compared to one long bunch train case !

Simulation study of FII

- A weak-strong code is developed
- Electron bunch is a rigid Gaussian beam
- Ions are regarded as macro-particles
- The interaction of ions and beam particles is based on Bassetti-Erskine formula
- Beam motion between ionization points can be linked *via* linear transfer matrix
- Many interaction points are taken into account

Simulation study of FII

- Kicks between electrons and ions (based on Bassetti-Erskine formula)

$$\Delta v_{y,i} + i\Delta v_{x,i} = -2N_0 r_e c \frac{m_e}{M_i} f(x_{ie}, y_{ie})$$

$$\Delta y' + i\Delta x' = \frac{2r_e}{\gamma} \sum_i N_i f(x_{ie}, y_{ie})$$

$$f(x,y) = -\sqrt{\frac{\pi}{2(\sigma_x^2 - \sigma_y^2)}} \left[w\left(\frac{x+iy}{\sqrt{2(\sigma_x^2 - \sigma_y^2)}} \right) - \exp\left(-\frac{x^2}{2\sigma_x^2} - \frac{y^2}{2\sigma_y^2} \right) w\left(\frac{x\frac{\sigma_y}{\sigma_x} + iy\frac{\sigma_x}{\sigma_y}}{\sqrt{2(\sigma_x^2 - \sigma_y^2)}} \right) \right]$$

$$w(z) = \exp(-z^2)[1 - \mathrm{erf}(-iz)]$$

Simulation study of FII

- Beam motion between ionization points can be linked *via* linear optics

$$\begin{pmatrix} z_2 \\ z'_2 \end{pmatrix} = \begin{bmatrix} \sqrt{\frac{\beta_2}{\beta_1}}(\cos\psi + \alpha_1 \sin\psi) & \sqrt{\beta_2\beta_1}\sin\psi \\ \frac{\alpha_1 - \alpha_2}{\sqrt{\beta_2\beta_1}}\cos\psi - \frac{1+\alpha_1\alpha_2}{\sqrt{\beta_2\beta_1}}\sin\psi & \sqrt{\frac{\beta_1}{\beta_2}}(\cos\psi + \alpha_2 \sin\psi) \end{bmatrix} \begin{pmatrix} z_1 \\ z'_1 \end{pmatrix}$$

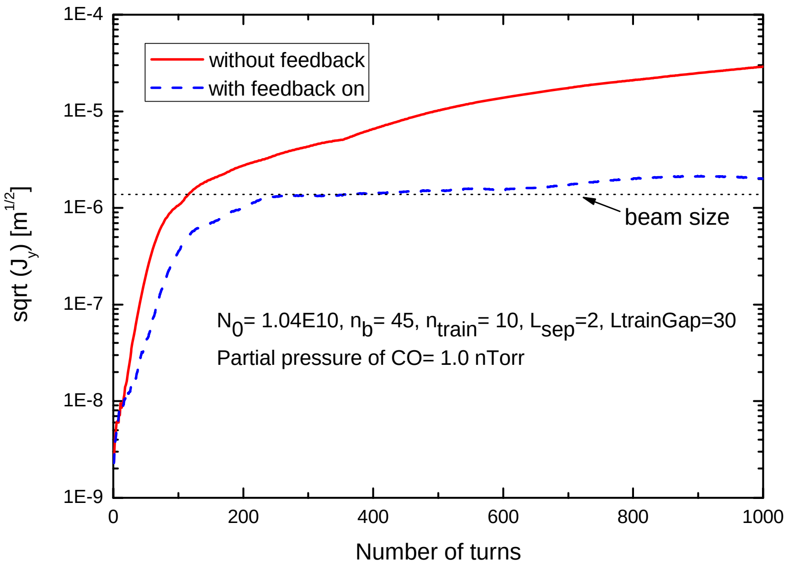
$$z = (x, y)$$

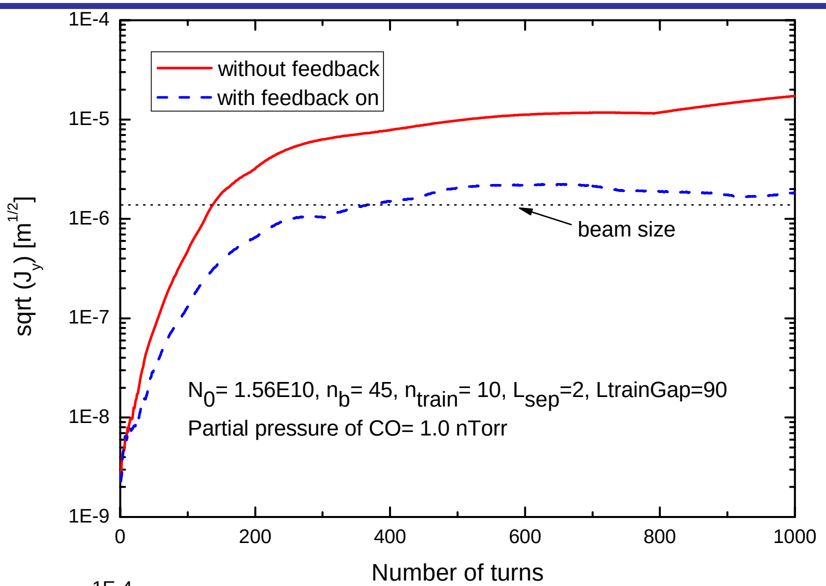
- For the flat beam, we mainly care about the vertical direction (y direction)

OCS8 damping ring

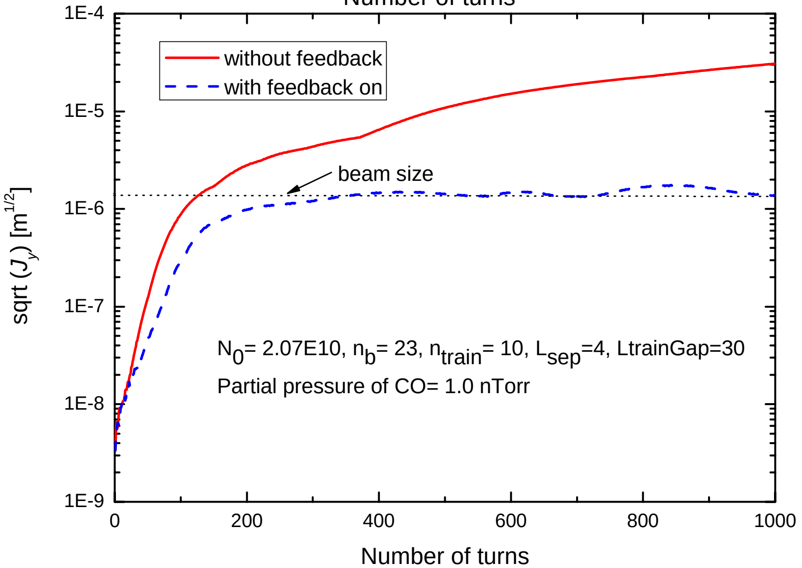
- One octant of the ring lattice is chosen
- Number of elements is the same as the number of interaction points
- The interaction between the beam and ions is based on Bassetti-Erskine formula
- The linear transfer matrix are used to connect each interaction point
- The beam centroid motion is recorded turn by turn
- The feedback is also applied in the code

Simulation results

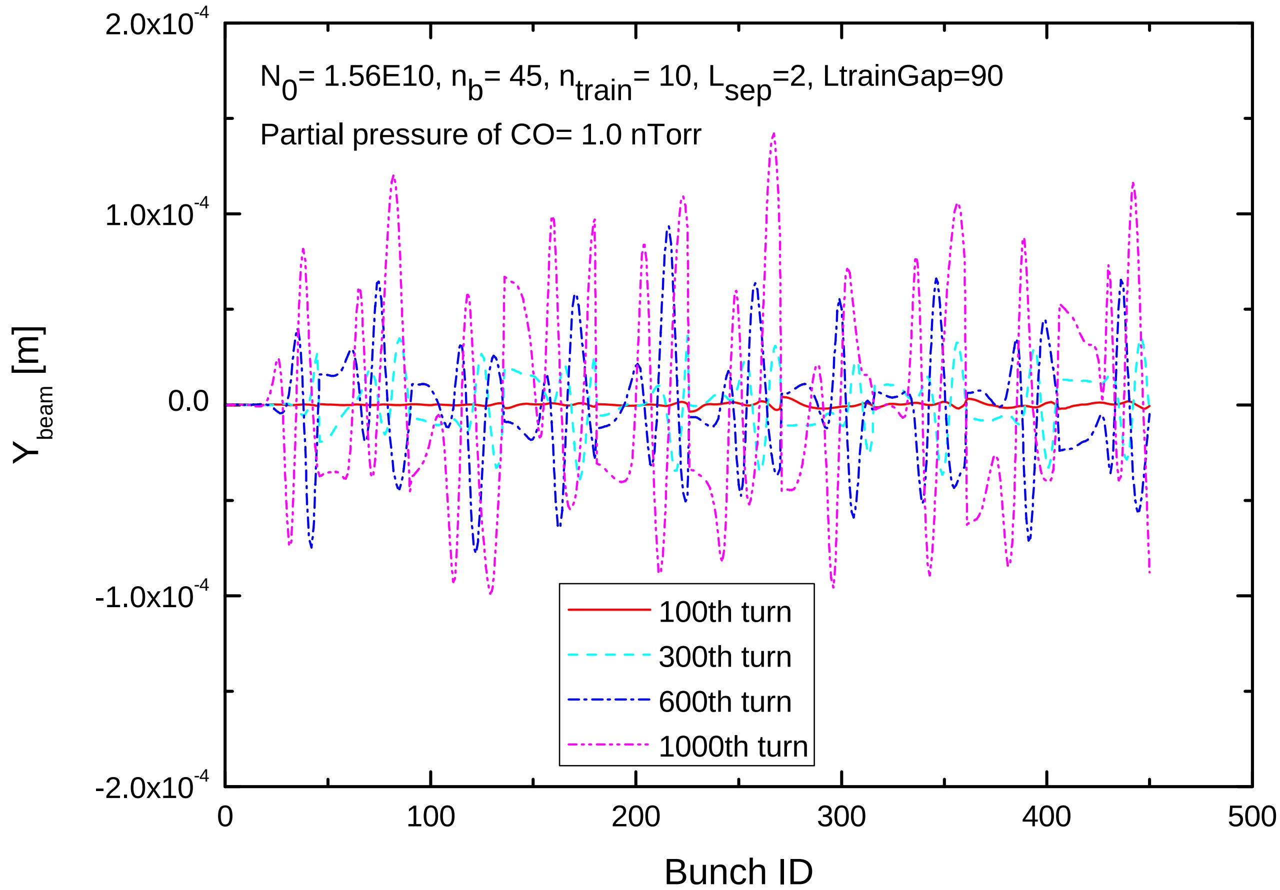




Evolution of maximum amplitude with respect to number of turns for fill pattern *A, B* and *C* without and with feedback damping. The damping time of feedback is 50 turns.

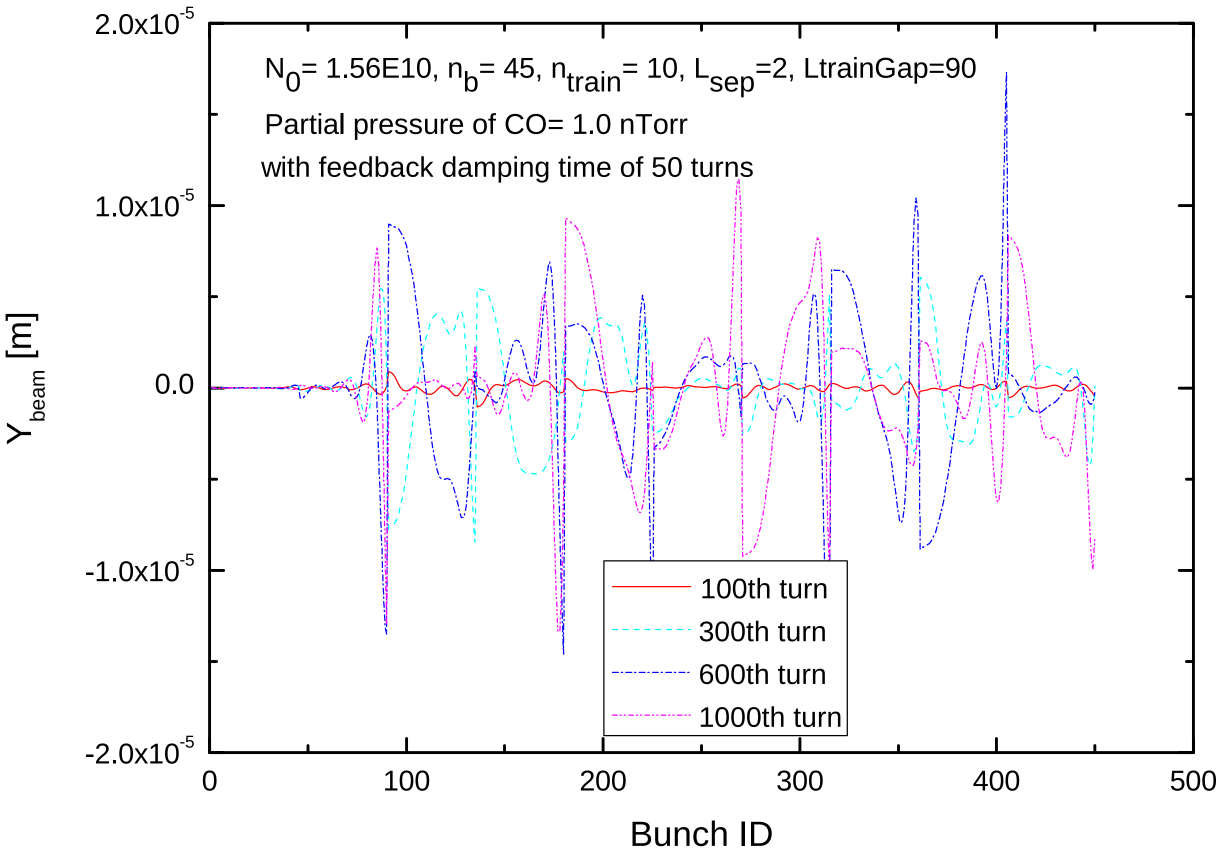


Beam oscillation



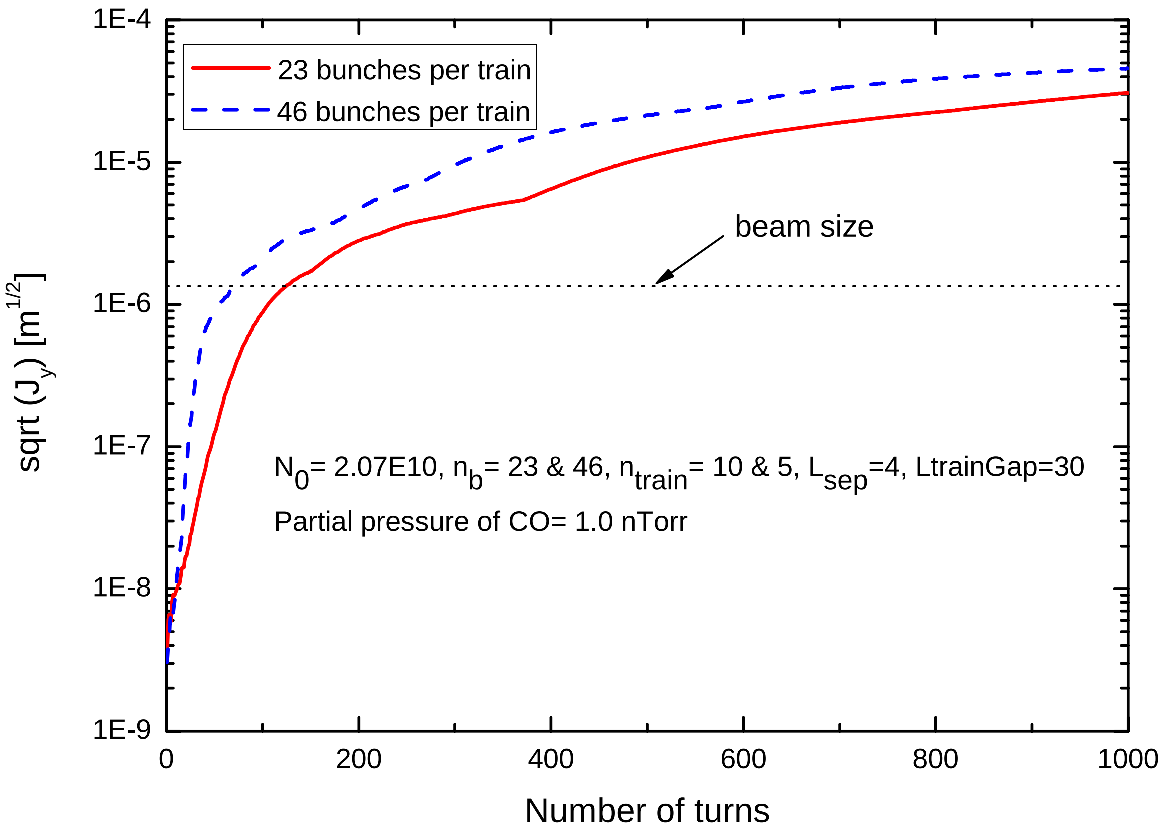
Bunch oscillation amplitude for fill pattern B *vs*. bunch ID in different turns, w/o feedback damping

Beam oscillation



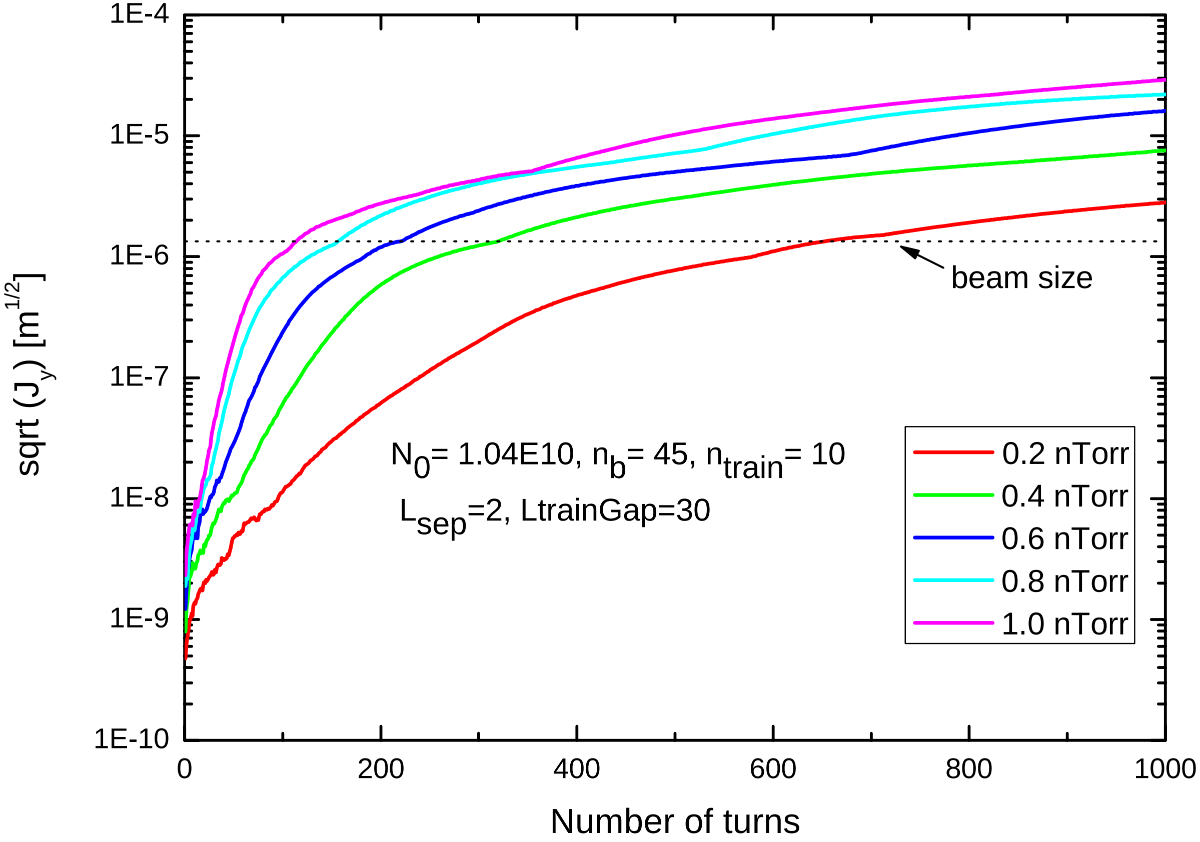
Bunch oscillation amplitude for fill pattern B *vs*. bunch ID in different turns, with feedback damping time of 50 turns

Mini-train Effect



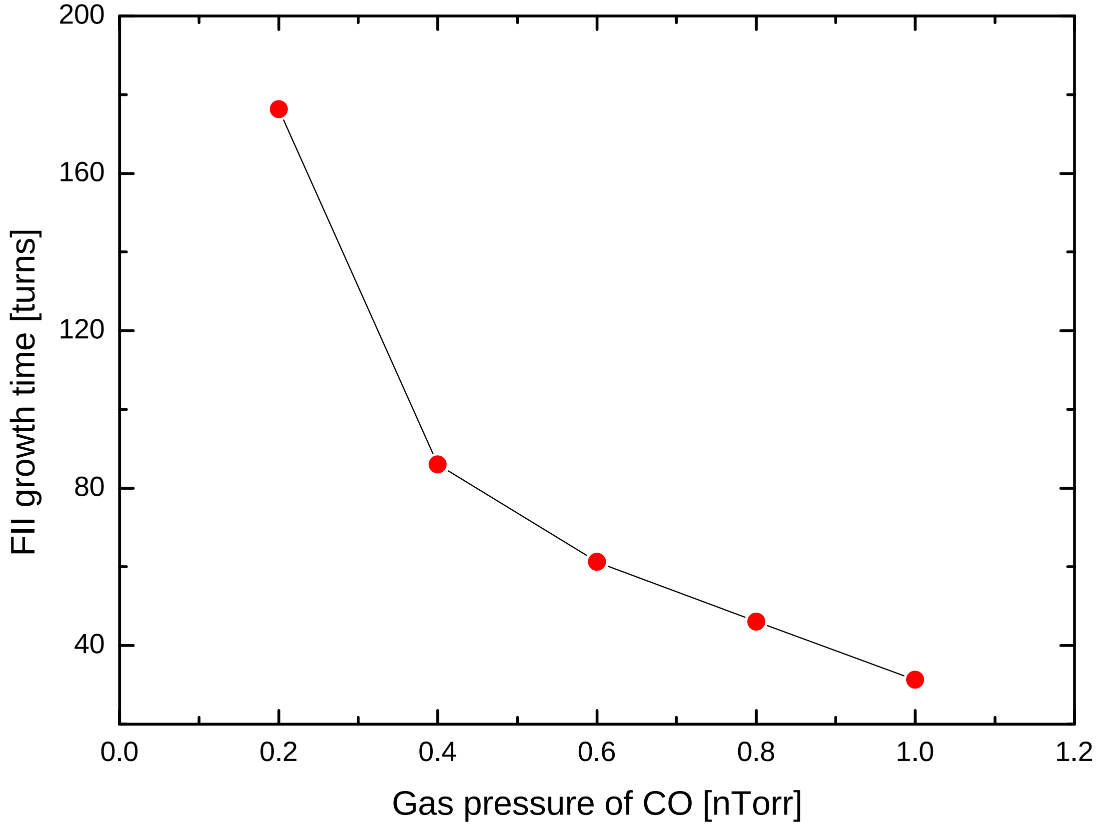
Evolution of maximum amplitude with respect to number of turns for fill pattern *C* for short bunch train and long bunch train

Vacuum pressure



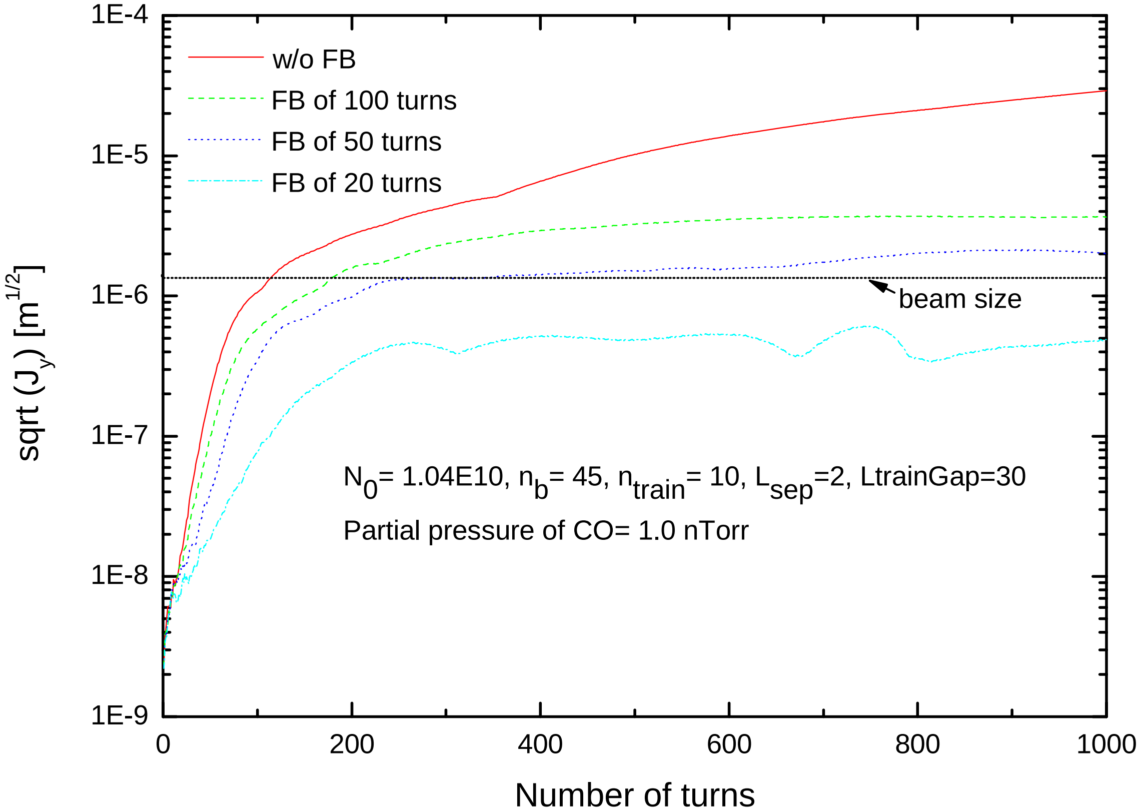
Evolution of maximum amplitude with respect to number of turns for fill pattern *A* in different CO pressures

Growth time



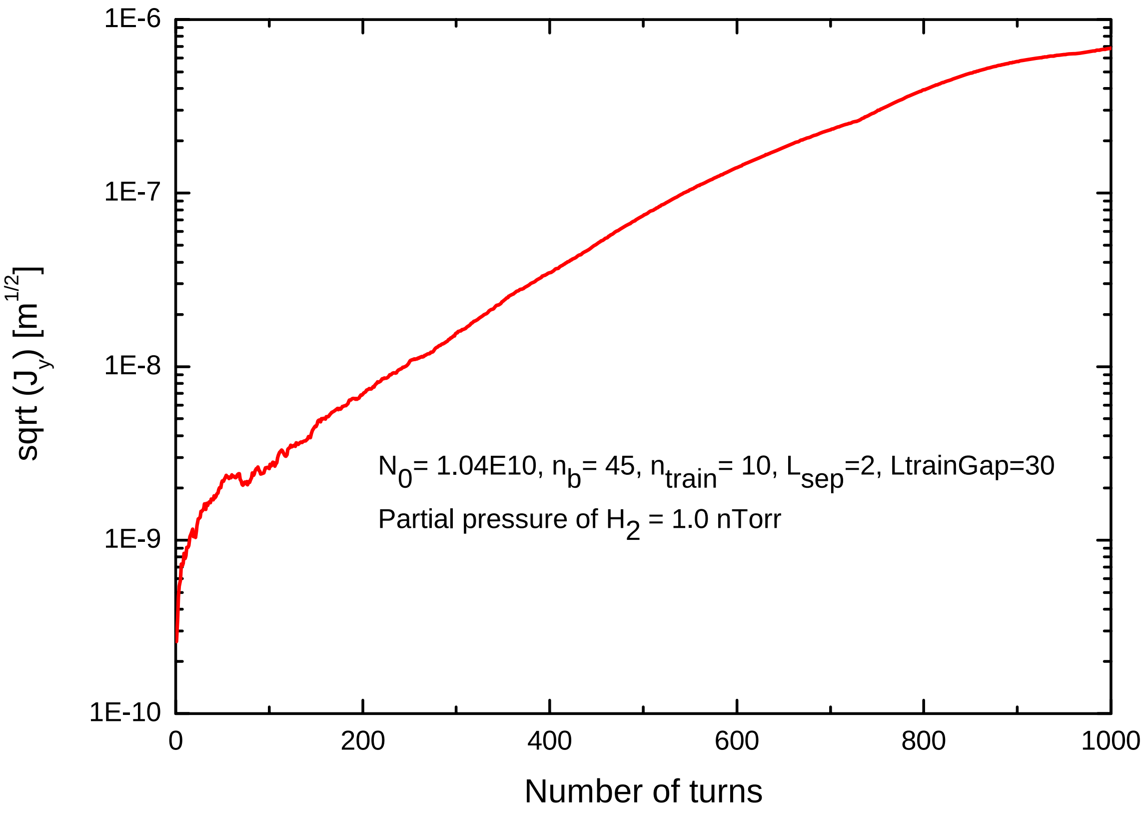
FII growth time *vs*. vacuum pressures of CO for fill pattern *A* without feedback

Feedback



Evolution of maximum amplitude with respect to number of turns for fill pattern case *A* in various feedback damping times

Other gas species



Evolution of maximum amplitude with respect to number of turns for fill pattern case *A* in H_2 gas pressure of 1 nTorr.

Conclusion of simulation results

- With the introduction of mini-trains the ion density near the beam can reduce significantly.
- For the three typical fill patterns of the ILC damping ring, the ion density in the mini-train case is about a factor of 100 less than that of the single long bunch train case.
- The simulation results show for three fill patterns *A*, *B* and *C*, the fast ion instability can not be totally damped by a fast feedback system with the damping time of 50 turns if the gas pressure of CO is larger than 1nTorr.
- Therefore, a better vacuum pressure (< 1nTorr) and a more advanced feedback system with damping time shorter than 50 turns are crucial to overcome FII.
- Comparing to one long bunch train case, the mini-train can reduce the growth of FII significantly

Recent experiment on FII at ATF

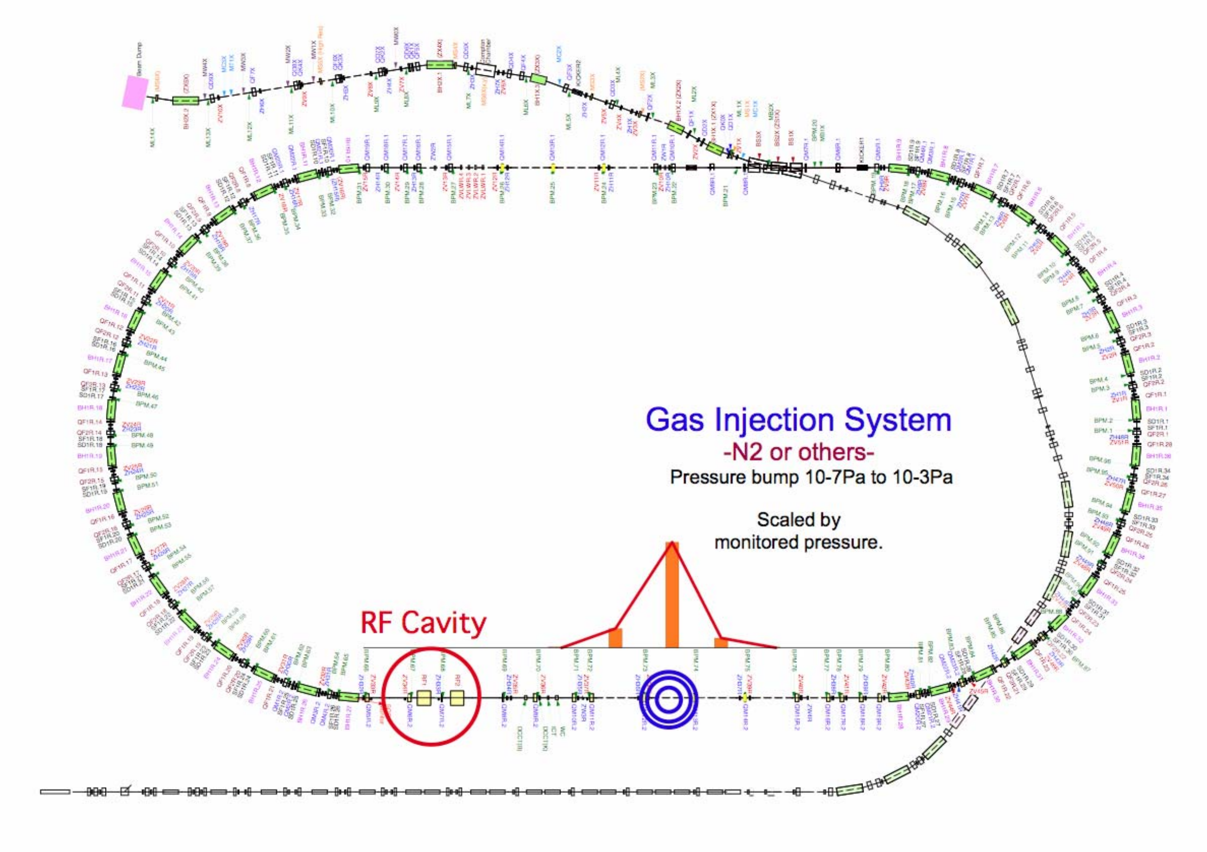
Motivation:

- To understand FII in low emittance, high intensity and multi-bunch operation machine
- To see in which parameter set can trigger the FII
- To extrapolate FII in ILC electron damping ring

Experiment setup:

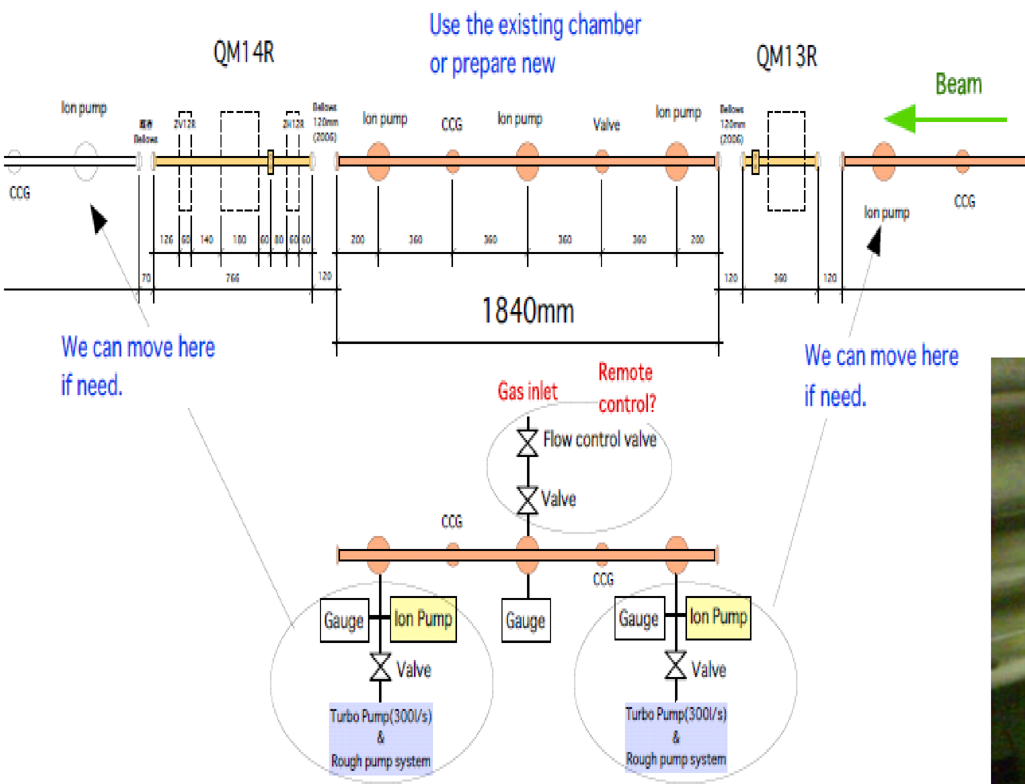
- Newly designed gas inlet system in south straight of ATF DR with additional vacuum gauges (CCGs)
- Gas flow controller can elevate local gas pressure up to two orders of magnitude
- Some diagnostics instruments such as X-ray synchrotron radiation monitor (XSR), streak camera, turn by turn BPM and laser wire system…

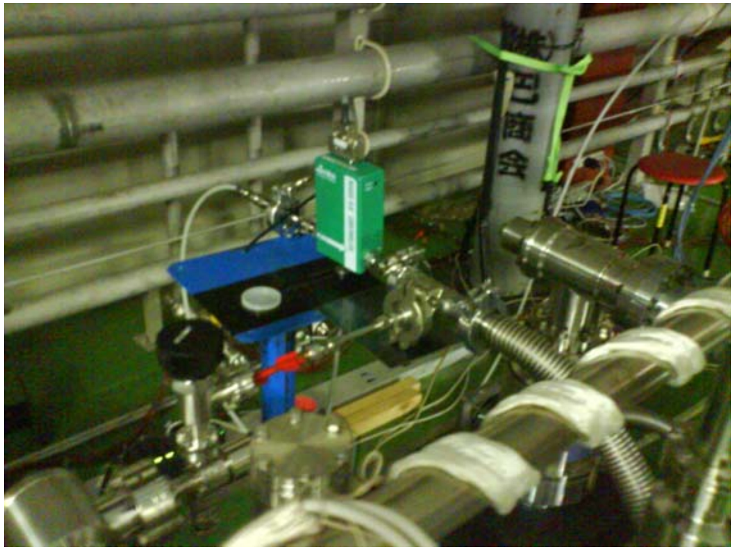
ATF damping ring



Newly setup gas inlet system in ATF damping ring

Schematics of gas inlet system

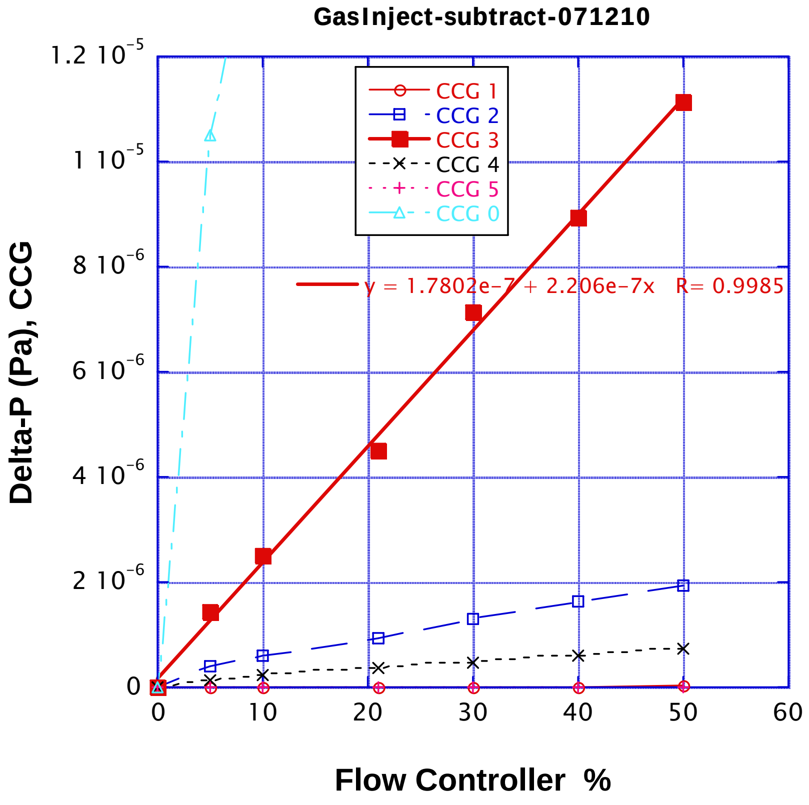


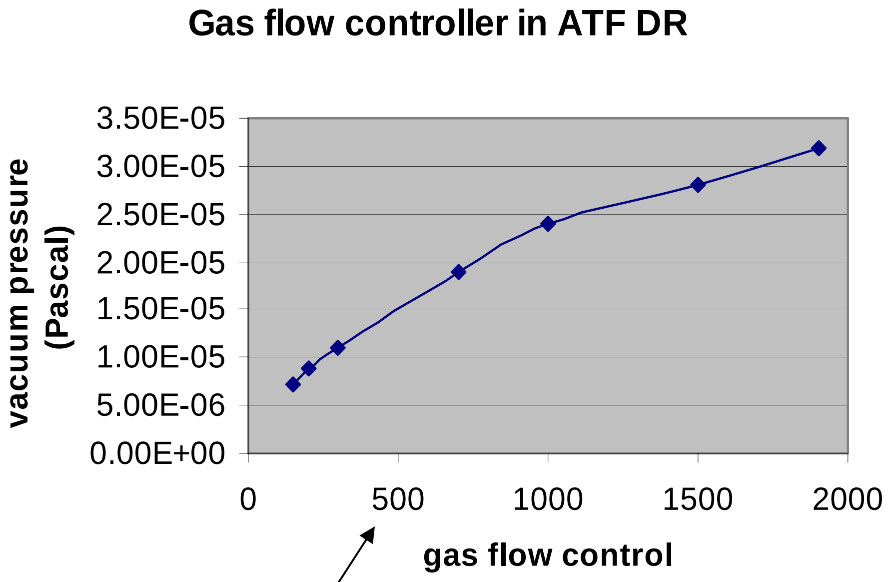


Gas inlet system with gas flow controller

Gas flow control

Data come from measurement on Dec 10, 2007

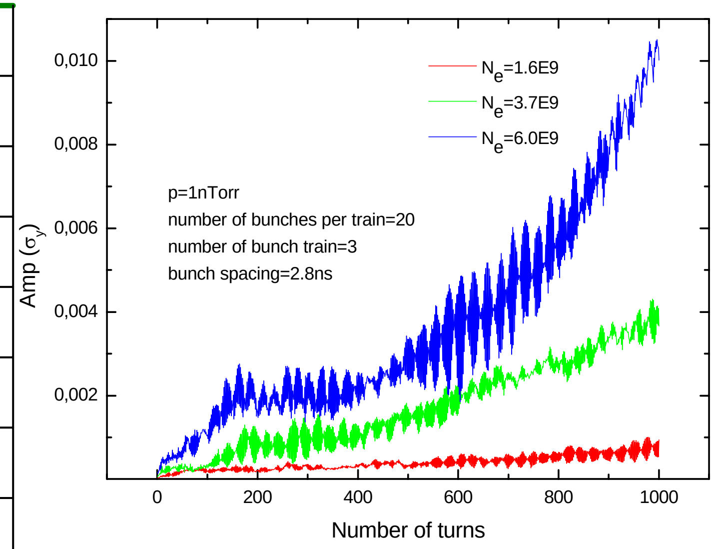


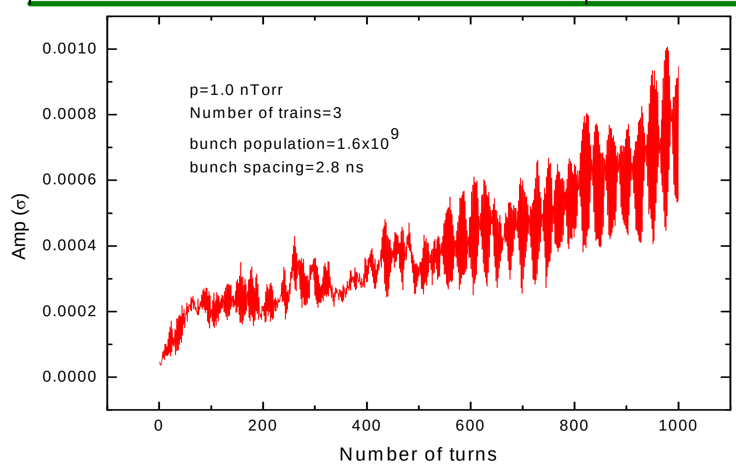


Change the flow controller (Data come from measurement on Dec 14, 2007)

ATF DR parameters

Beam energy [GeV]	1.28
Circumference [m]	138.6
Harmonic number	330
Momentum compaction	2.14E-3
Bunch population [$\times 10^{10}$]	2.0
Bunch length [mm]	3
Energy spread	0.06%
Horizontal emittance [mrad]	1.5E-9
Vertical emittance [mrad]	5E-12



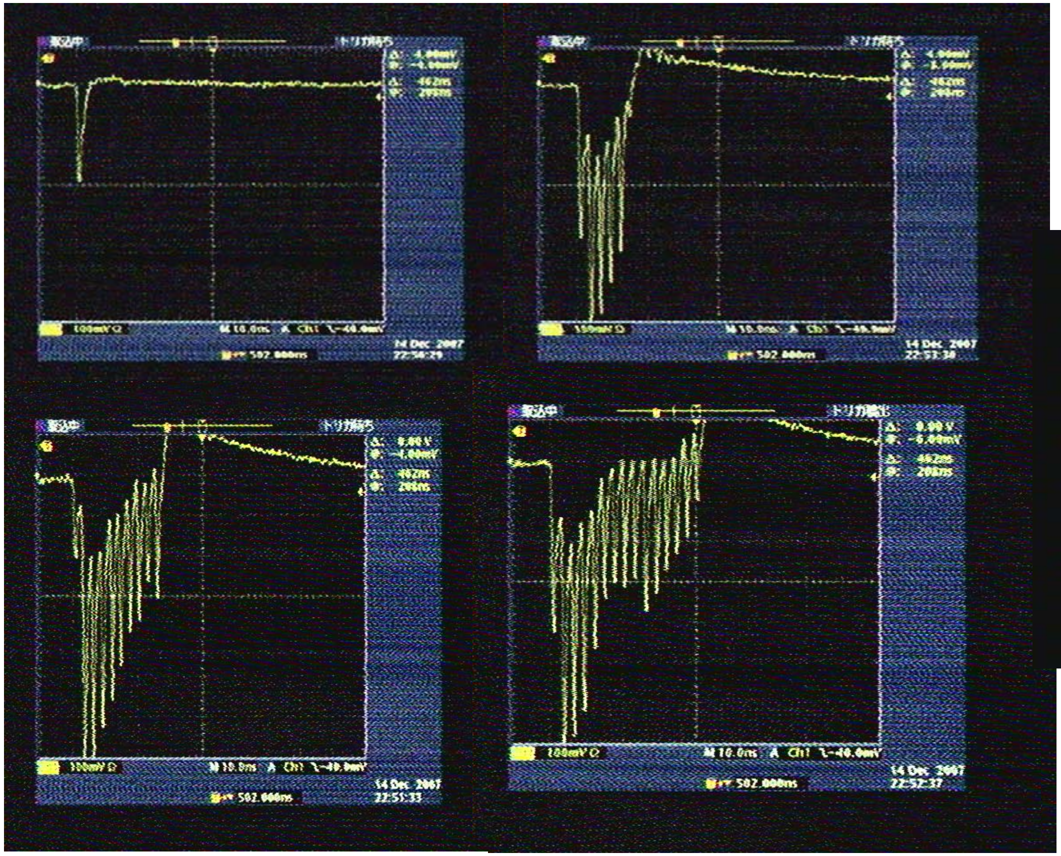


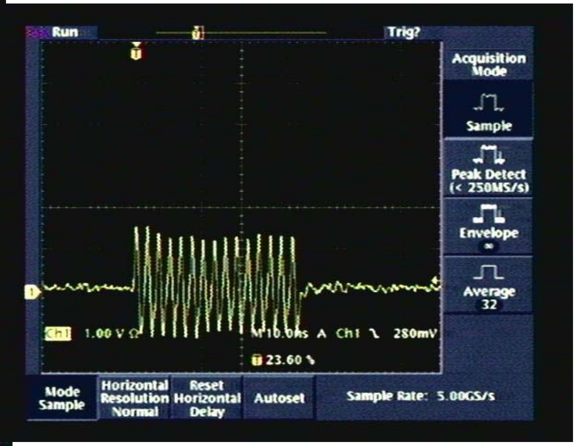
Fast beam ion insatbility in ATF Damping Ring

Since the vertical emittance of DR is very large, it is difficult to identify the fast ion instability this time.

However we indeed observed the beam profile blowup for multi-bunch operation and at high vacuum pressure case.

Tuning the machine

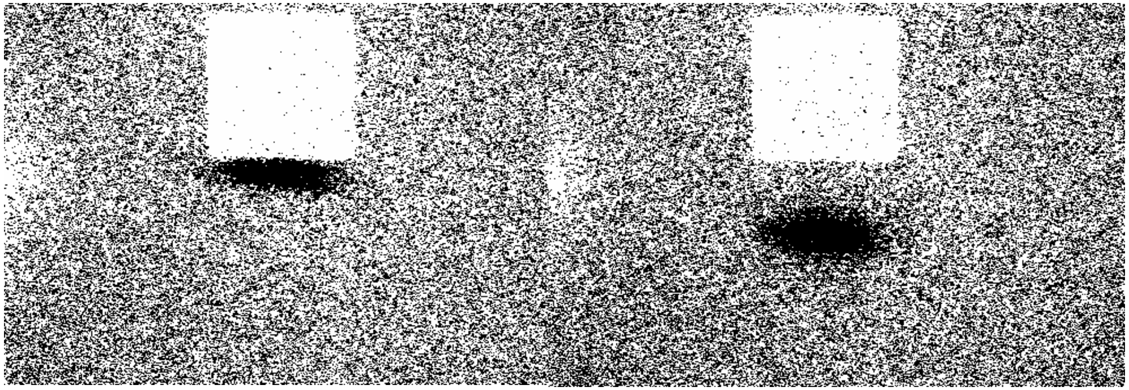




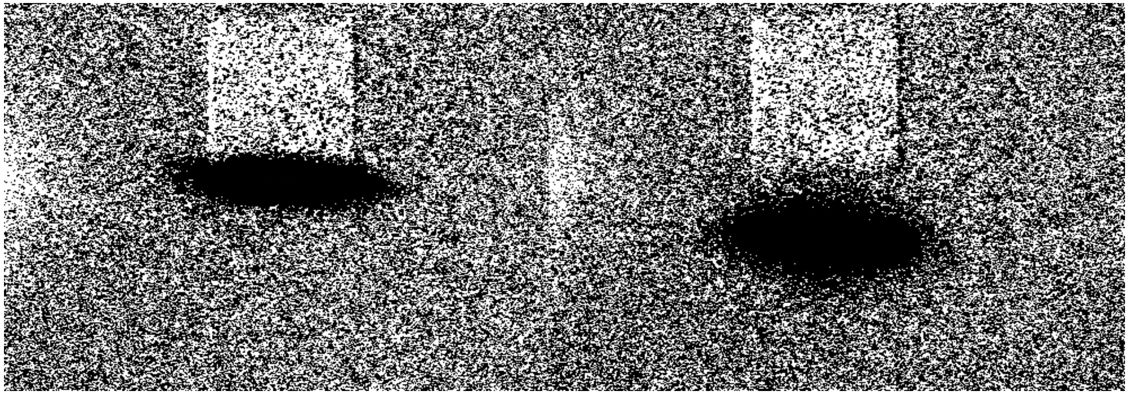
Tune the ATF damping ring to multi bunch operation

1~15 bunches per train

Preliminary results (1)

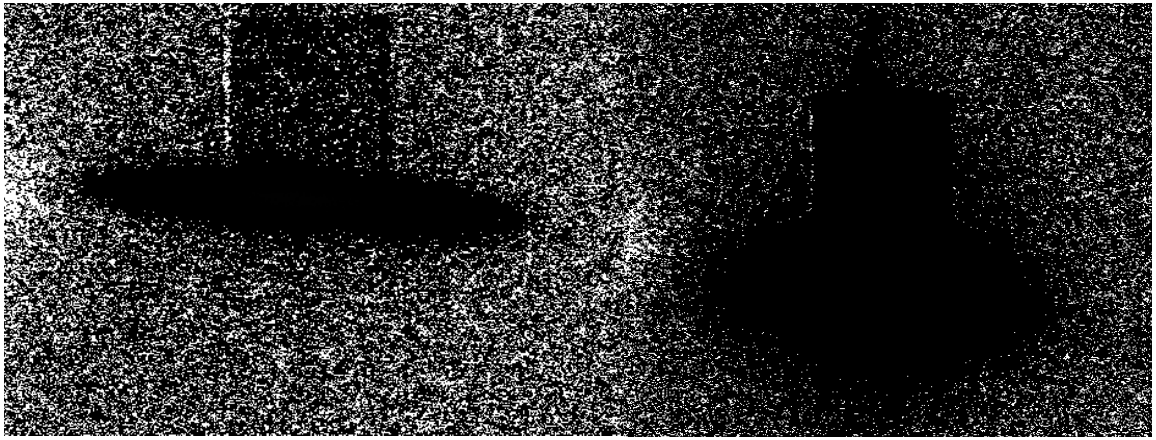


0.3E10_2.92E-5Pa_1bunch_1train (normal operation)   0.39E10_9.15E-4Pa_1bunch_2train

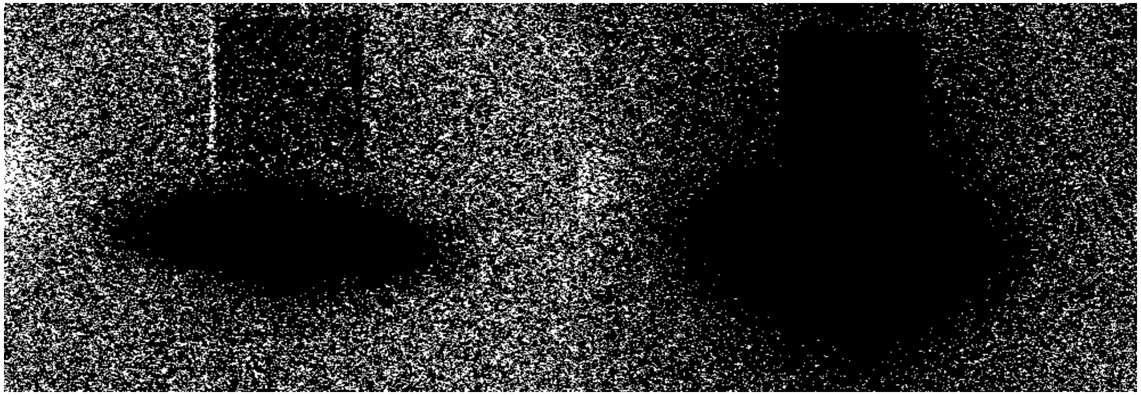


2.2E10_2.98E-5Pa_5bunches_1train   2.39E10_9.27E-4Pa_5bunches_2train

Preliminary results (2)

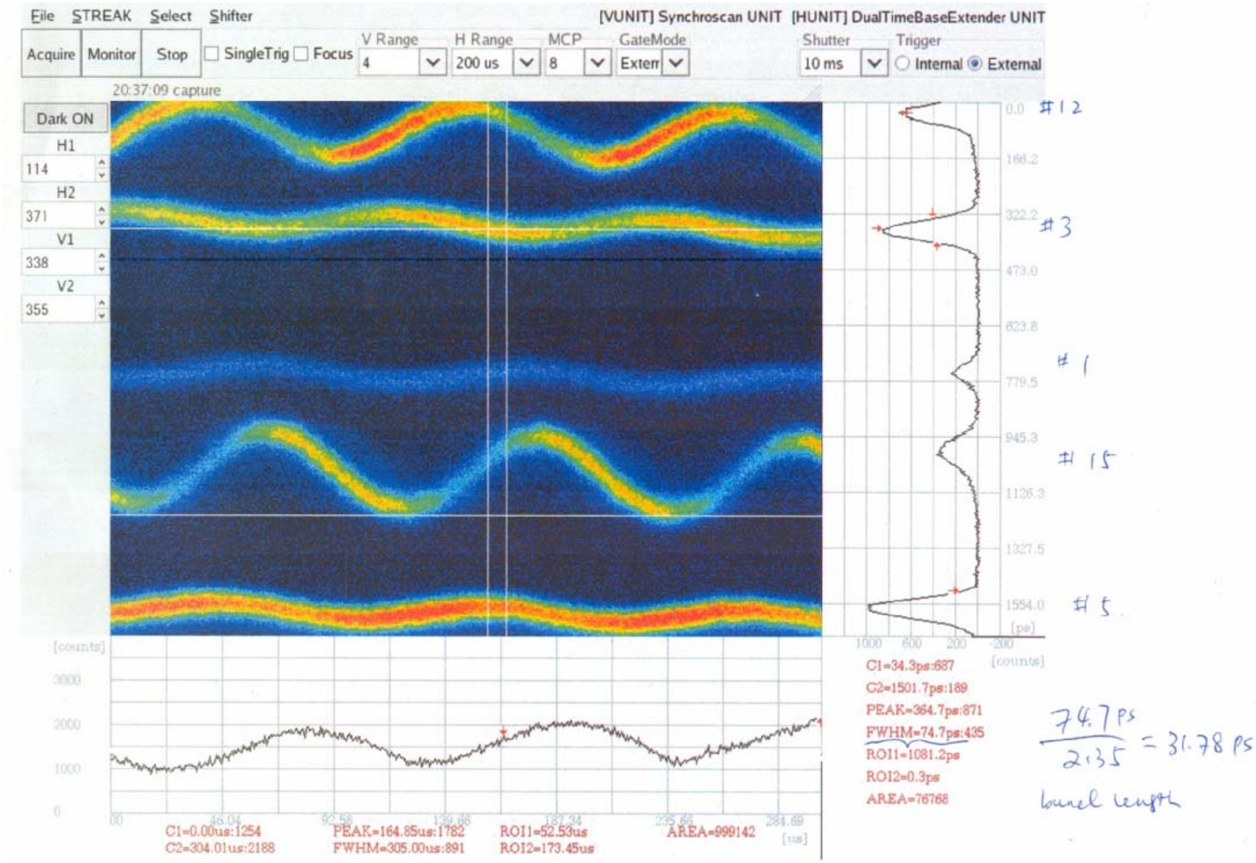


5.3E10_1.87E-4Pa_15bunches_1train **5.9E10_9.4E-4Pa_15bunches_2train (sudden blowup)**



11.10E10_9.27E-4Pa_15bunches_1 train **11.10E10_9.27E-4Pa_15bunches_2 train (sudden blowup)**

Preliminary results (3)



The bunch oscillation information from streak camera

Conclusion of the experiment

- A sudden beam profile blow up was observed for multi bunch operation.
- If we increase the number of trains, the beam profile increases a lot.
- Further study of this instability is necessary. In that case, the machine will have to be tuned to a low emittance mode (less than 10pm for example).
- To optimize the machine to multi bunch mode operation (Energy Compensation System will be ready). The beam size and emittance can be measured at that time. In addition, streak camera, turn by turn BPM can be used to diagnose the beam in the ring.
- The residual gas species will be analyzed via newly-setup RGAs, then the different ion species effect on FII can be investigated.

Summary

- The ion effects in the ILC electron damping ring is extensively studied.
- For the current design of the ILC damping rings, the partial pressure of CO less than 1ntorr is required to mitigate FII.
- The mini-train is proven to be effective both from the theory and simulation aspects.
- Fast feedback system with the damping time shorter than 50 turns is crucial.
- Further experimental study of FII is necessary to bench-mark the simulation results against experimental data.

➢ Several publications concerning FII study: EUROTeV-Reports 2006-003, 2006-004, 2006-047, 2007-012, 2007-013, 2008-004, 2008-005. Nucl. Instr. and Meth. A 593,183(2008).

Acknowledgement

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