MAX-PLANCK-GESELLSCHAFT

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Evaluation of fast ion instability in ILC 3 km damping ring

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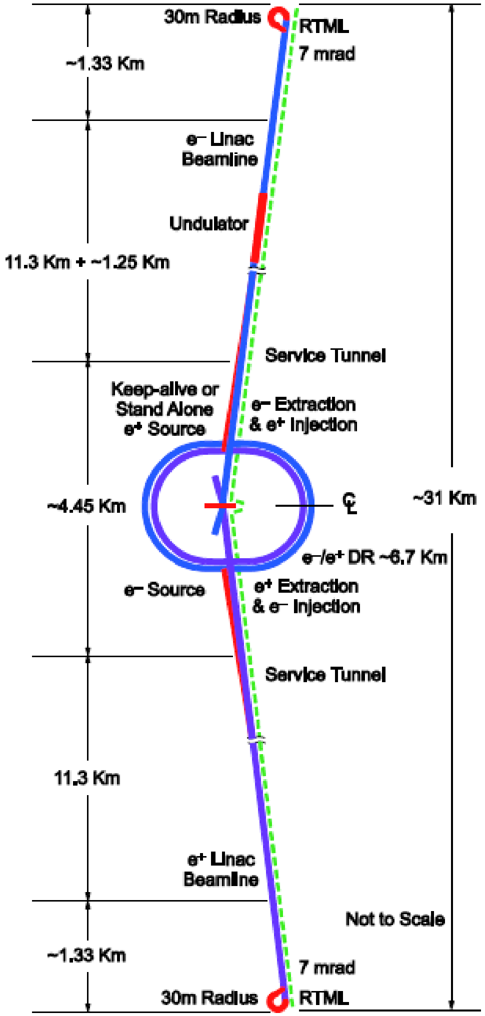
Outline

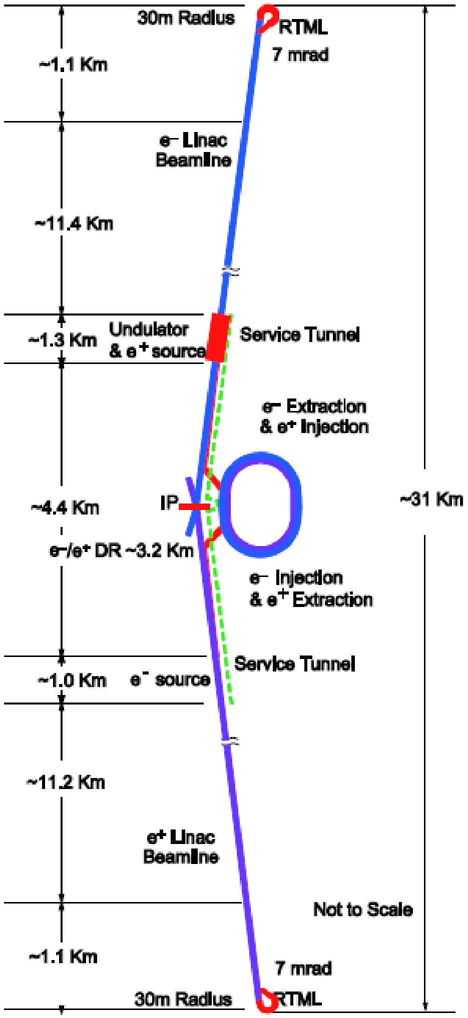
- ☐ ILC damping ring
- ☐ Ion instability, introduction
- ☐ Simulation study of fast ion instability
- ☐ Some cures for fast ion instability
- ☐ Summary

Towards the TDR in 2012

RDR

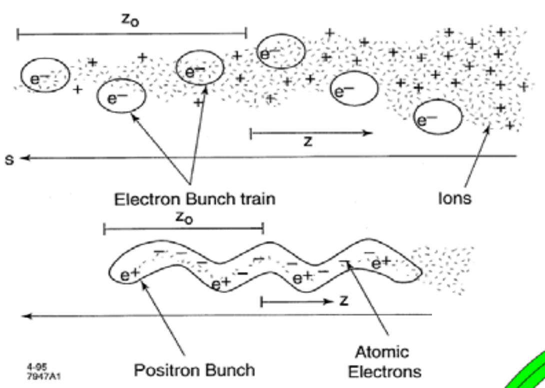


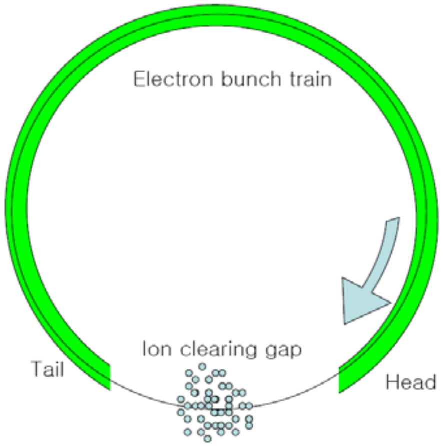
SB2009



- **Single Tunnel for main linac**
- **Move positron source to end of linac**
- **Reduce number of bunches factor of two (lower power)**
- **Reduce size of damping rings (3.2 km)**
- **Integrate central region**
- **Single stage bunch compressor ?**

Ion instability, introduction





- The adverse effects of ions include the beam emittance growth, beam lifetime reduction, tune shift and tune spread
- Ion trapping can be cured by introduction of a gap in the bunch trains.
- 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.
- This phenomena were already observed in many existing machines ALS, PLS, KEK-PF,SRRC, NSLS-VUV, PEPII, BEPC etc.

Sources of Ions

- Inelastic collisions with the gas
- Tunneling ionization
- Synchrotron radiation ionization

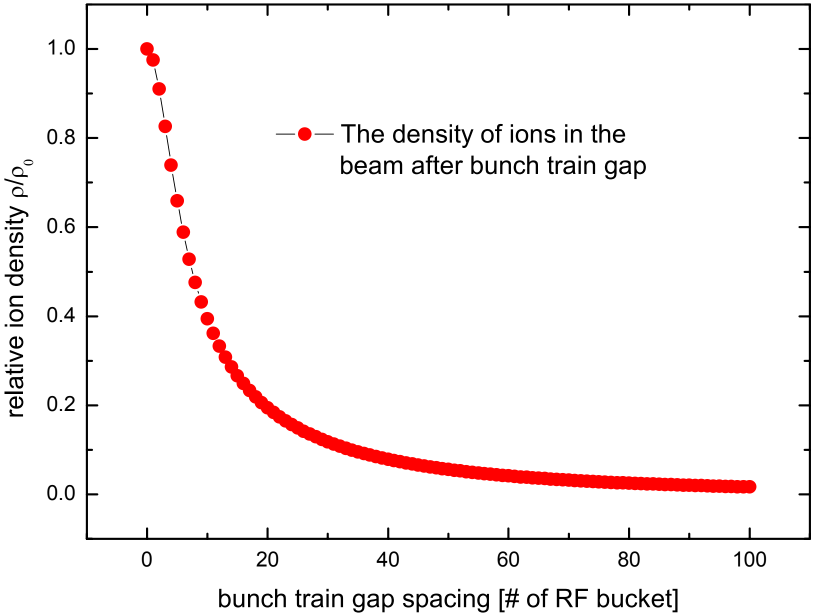
Gap effects

- If a gap is introduced in the bunch train, one can estimate the density of the ions in the beam after the clearing gap

$$\lambda_{ion}[m^{-1}] = \sigma_{ion} n_b N_0 p / k_b T \approx 6.4 N_0 n_b p[\mathrm{torr}]$$

$$\rho \approx \frac{\rho_0}{\sqrt{\left(1+L_{gap}^2\omega_x^2\right)\left(1+L_{gap}^2\omega_y^2\right)}}$$

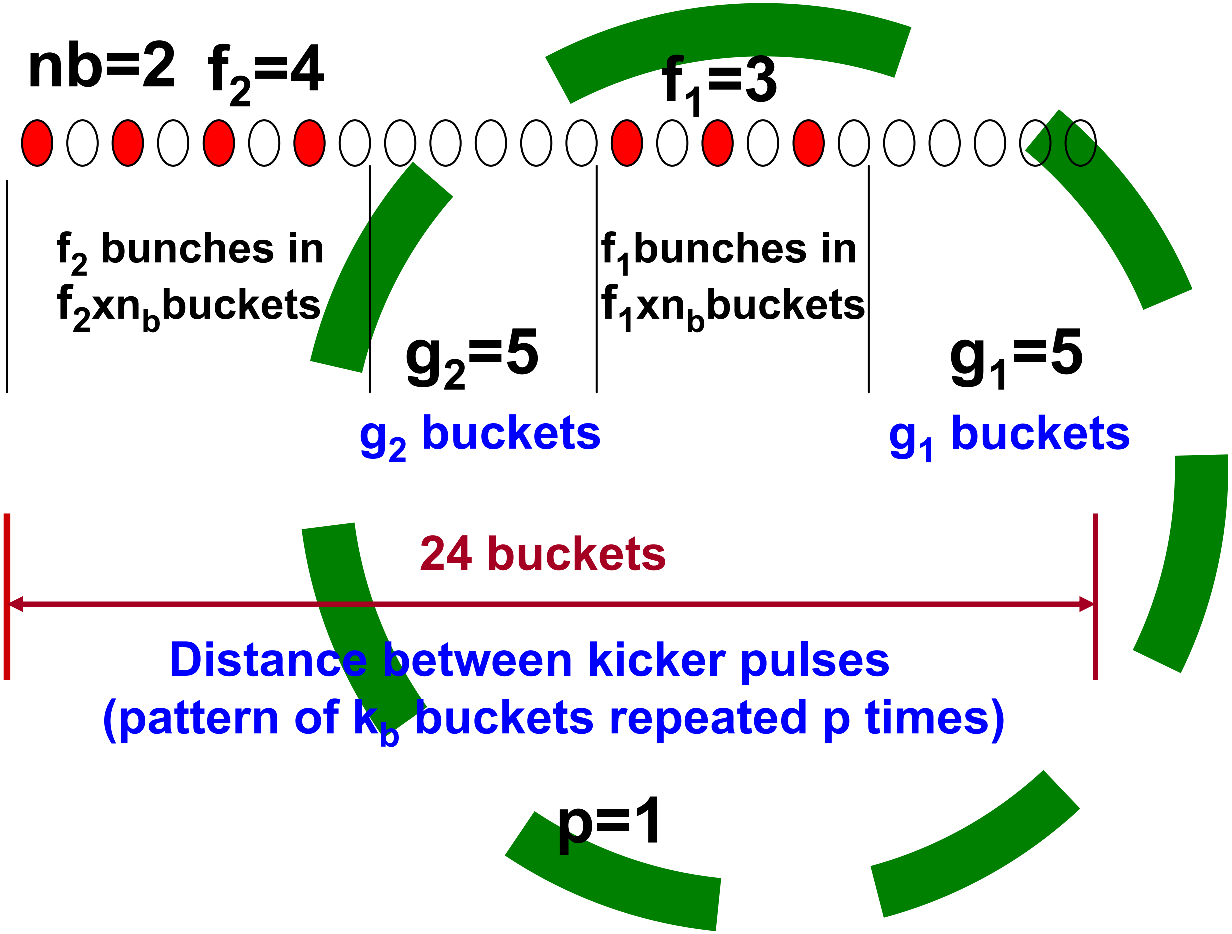
$$\omega_{x,y}^2 = \frac{2N_0 r_p}{L_{sep} A \sigma_{x,y}\left(\sigma_x+\sigma_y\right)}$$



The density of the residual ions in the beam after the clearing gap

where ρ_0 is the ion density at the end of the bunch train and $\omega_{x,y}$ are the ion oscillation frequencies

A fill pattern case



$nb=2$ $f_2=4$

$f_1=3$

f_2 bunches in $f_2 x n_b$ buckets

$g_2=5$

f_1 bunches in $f_1 x n_b$ buckets

$g_1=5$

g_2 buckets

g_1 buckets

24 buckets

Distance between kicker pulses
(pattern of k_b buckets repeated p times)

$p=1$

Simulation study of FII

- A weak-strong code has been 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)

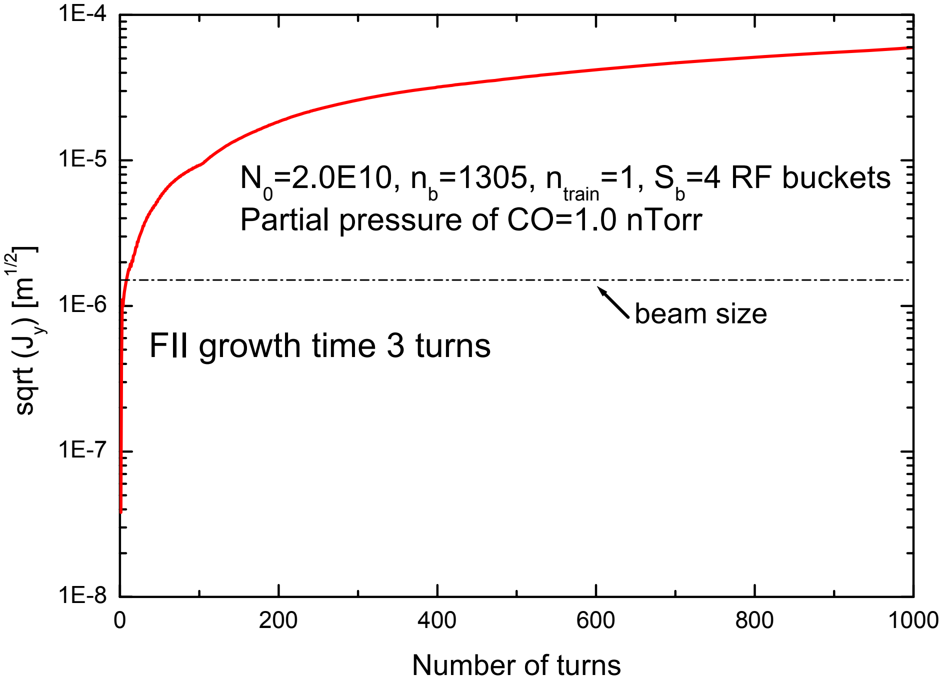
Parameters of SB2009 DR

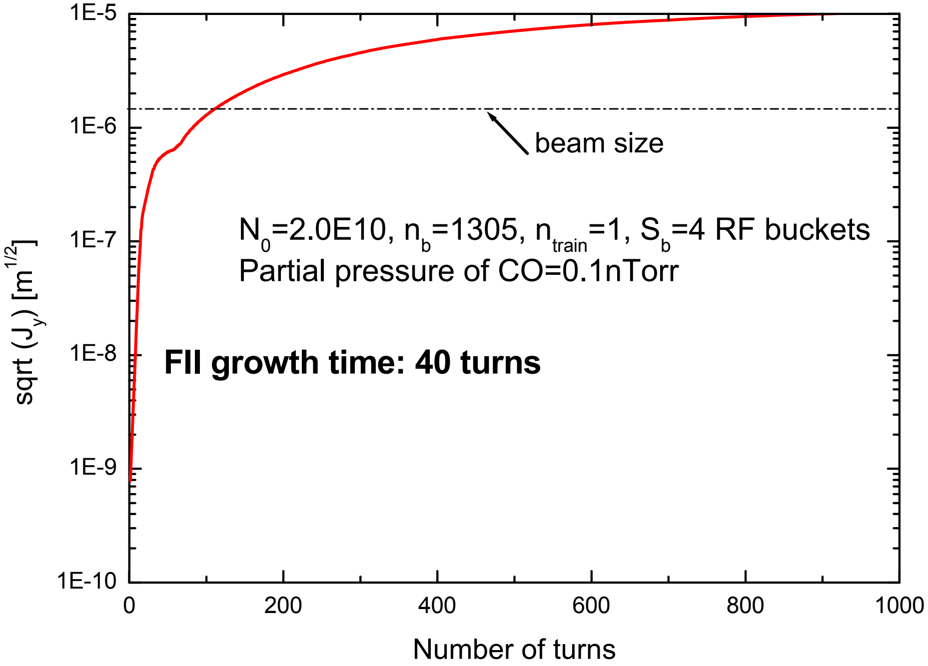
Energy (GeV)	5.0
Circumference (m)	3238
Harmonic number	7021
Bunch number	2610-1305
Bunch spacing (buckets)	2-4
Number of particles/bunch	2×10^{10}
Damping time τ_x (ms)	24
Emittance ε_x (nm)	0.66
Emittance ε_y (pm)	2
Momentum compaction α	1.5×10^{-4}
Synchrotron tune	0.059
Energy spread	1.2×10^{-3}
Bunch length (mm)	6
RF frequency (MHz)	650
RF voltage (MV)	7.5

Simulation results (SB2009)

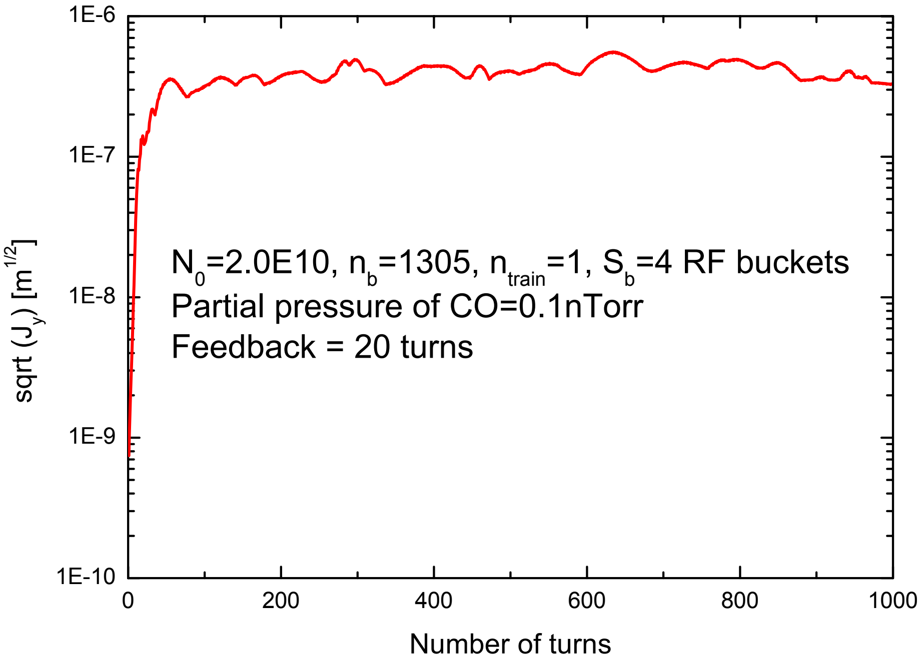
Evolution of maximum amplitude with respect to number of turns for various gas pressures and feedback damping rates

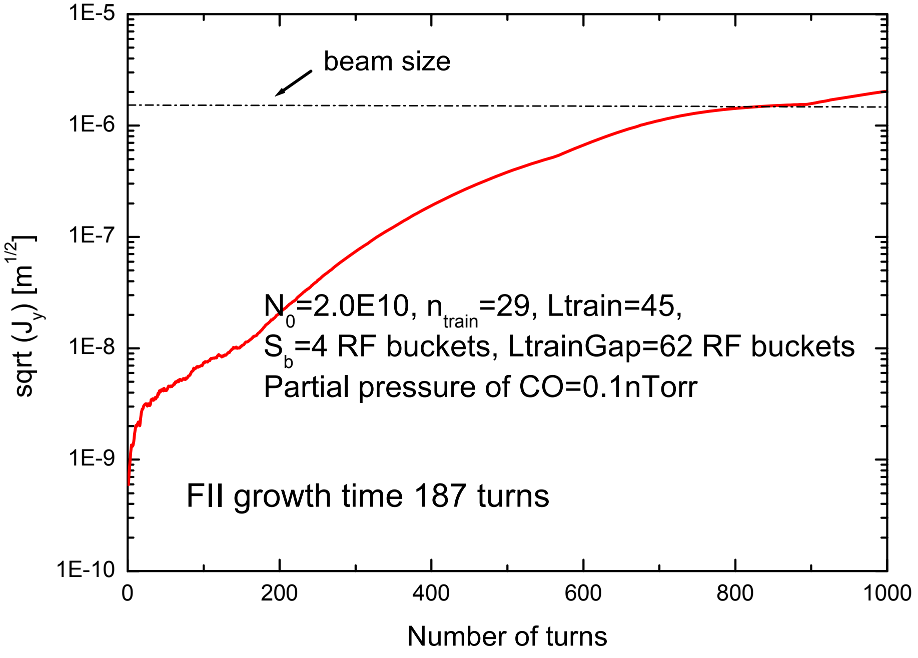
$$J_y = \frac{1}{2}\left[\gamma y^2 + 2\alpha y y' + \beta y'^2\right]$$





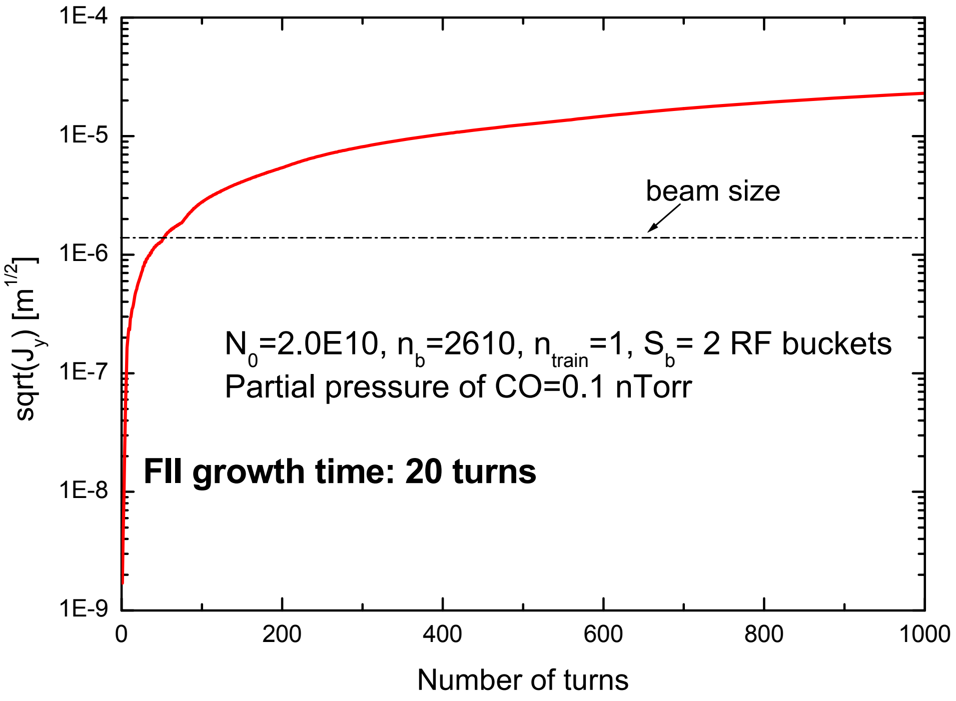
Simulation results (SB2009)


N_0=2.0E10, n_b=1305, n_{train}=1, S_b=4 RF buckets
Partial pressure of CO=0.1nTorr
Feedback = 20 turns


N_0=2.0E10, n_{train}=29, Ltrain=45,
S_b=4 RF buckets, LtrainGap=62 RF buckets
Partial pressure of CO=0.1nTorr

FII growth time 187 turns

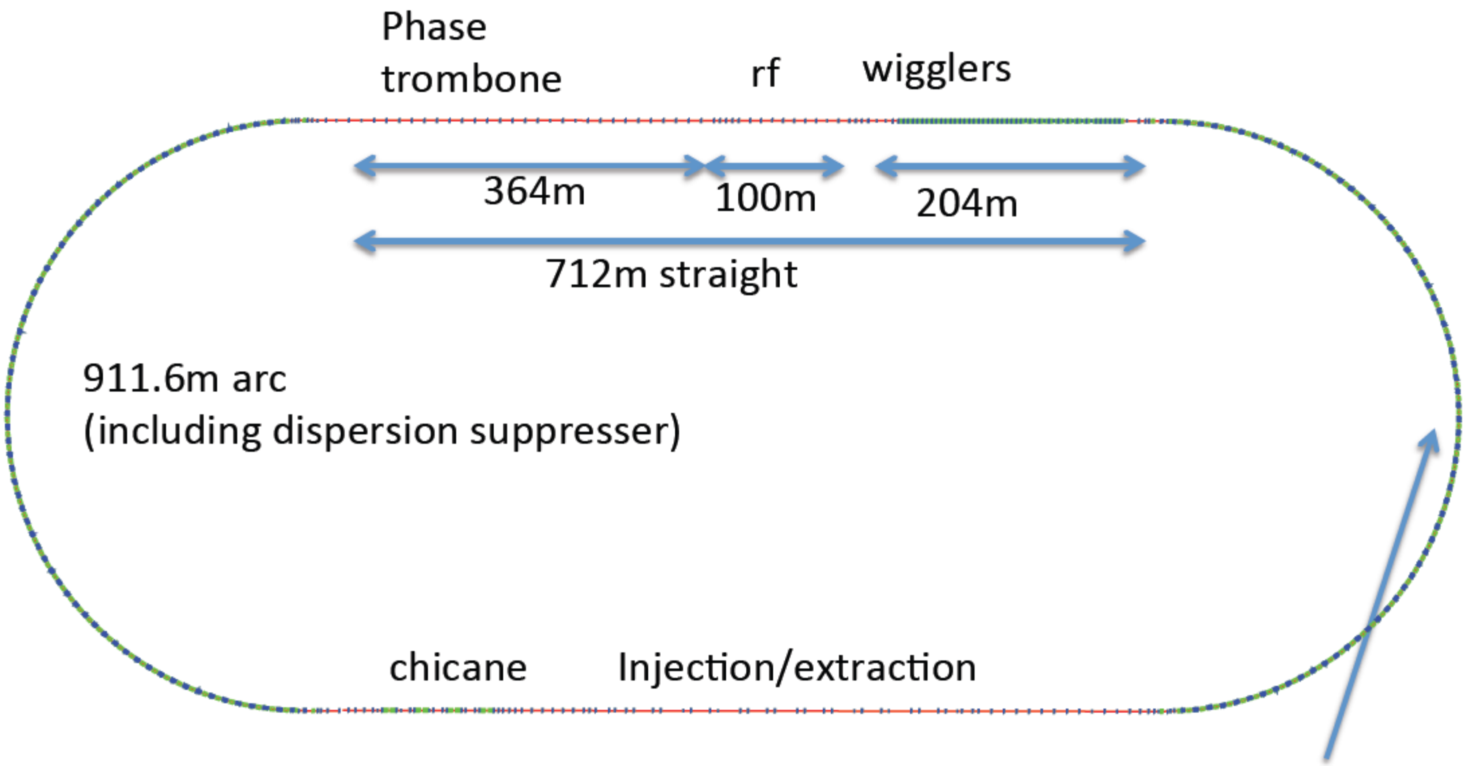
Simulation results (SB2009)



N_0=2.0E10, n_b=2610, n_{train}=1, S_b= 2 RF buckets
Partial pressure of CO=0.1 nTorr

FII growth time: 20 turns

3.2 km DTC01 damping ring



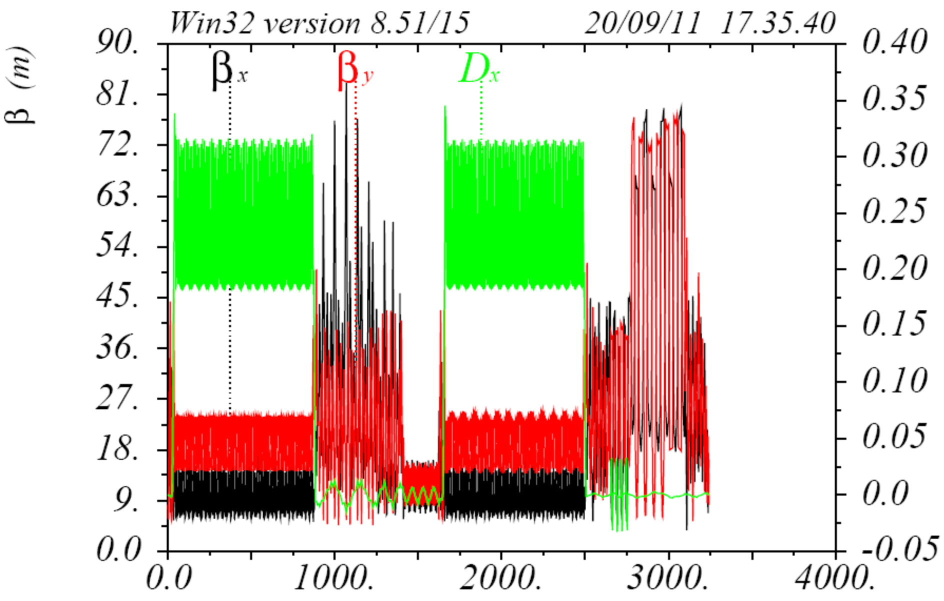
The arc is assembled from 75 FDBDF (focus/defocus/bend/defocus/focus) "TME variant" arc cells.

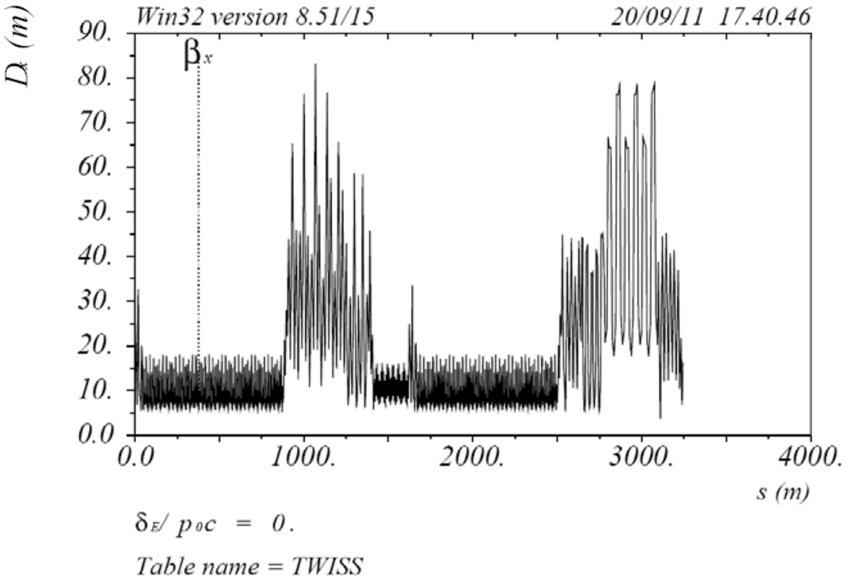
Cell length = 10.931m

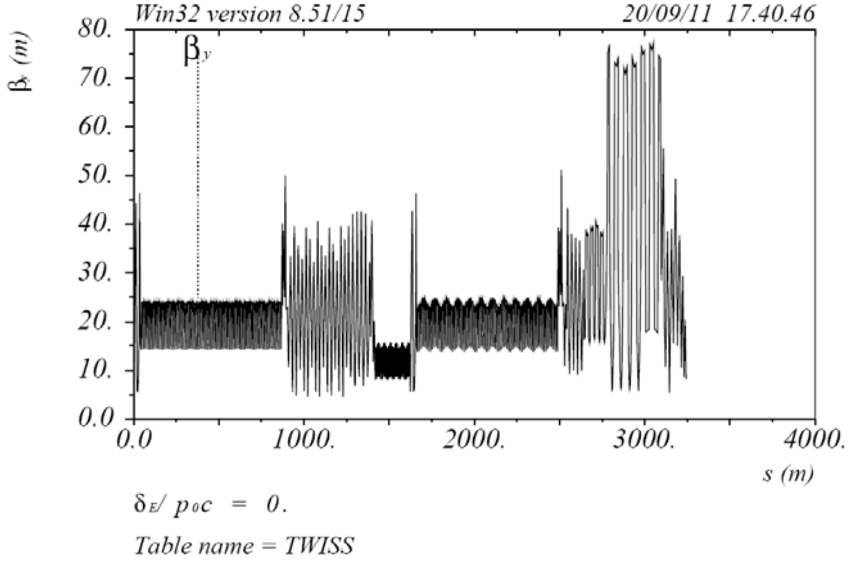
Bend length = 3m

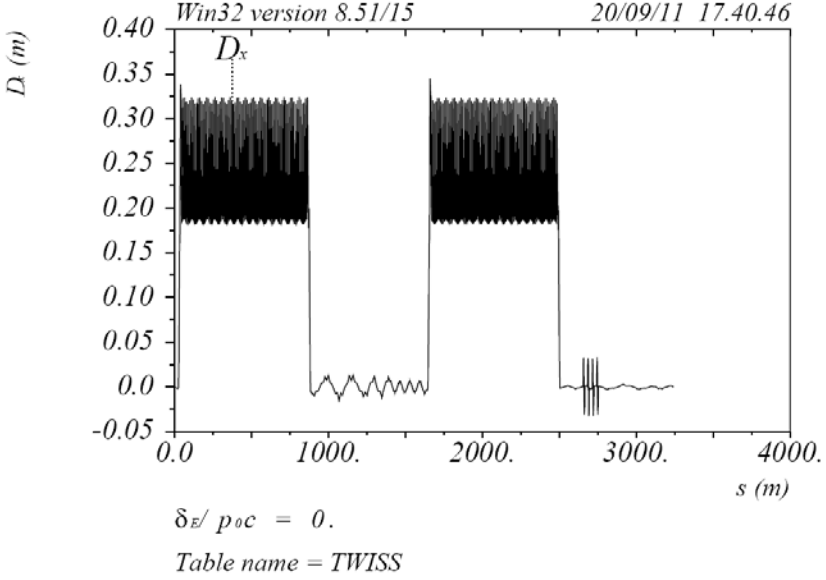
D. Rubin

DTC01 optical functions





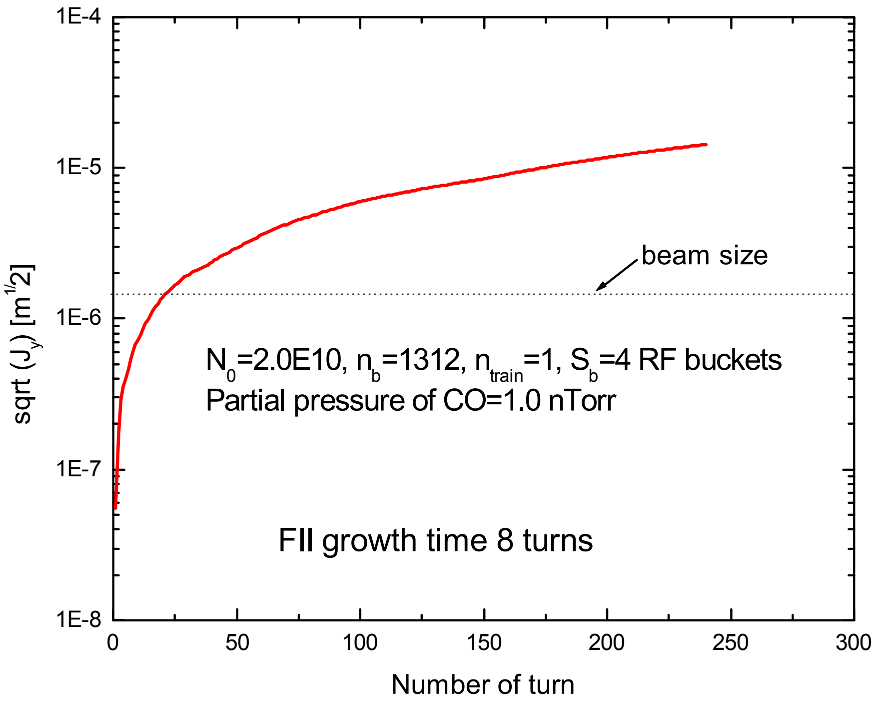




Parameters of DTC01 DR

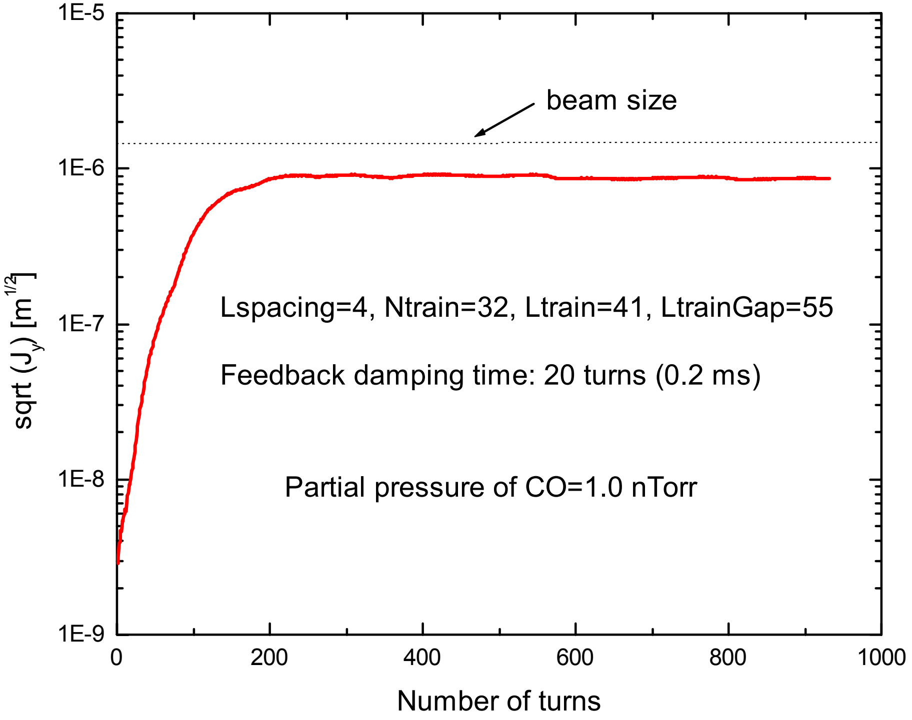
Energy (GeV)	5.0
Circumference (m)	3242.90
Harmonic number	7026
Bunch number	2625-1312
Bunch spacing (buckets)	2-4
Number of particles/bunch	2×10^{10}
Damping time τ_x (ms)	24
Emittance ε_x (nm)	0.66
Emittance ε_y (pm)	2
Momentum compaction α	1.5×10^{-4}
Synchrotron tune	0.059
Energy spread	1.1×10^{-3}
Bunch length (mm)	6
RF frequency (MHz)	650

Simulation results (DTC01)



N_0=2.0E10, n_b=1312, n_{train}=1, S_b=4 RF buckets
Partial pressure of CO=1.0 nTorr

FII growth time 8 turns



Lspacing=4, Ntrain=32, Ltrain=41, LtrainGap=55

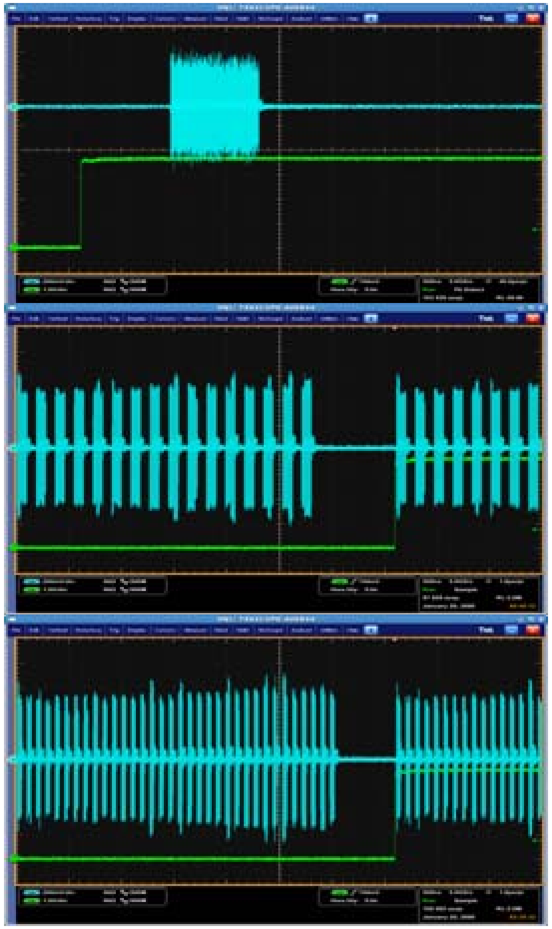
Feedback damping time: 20 turns (0.2 ms)

Partial pressure of CO=1.0 nTorr

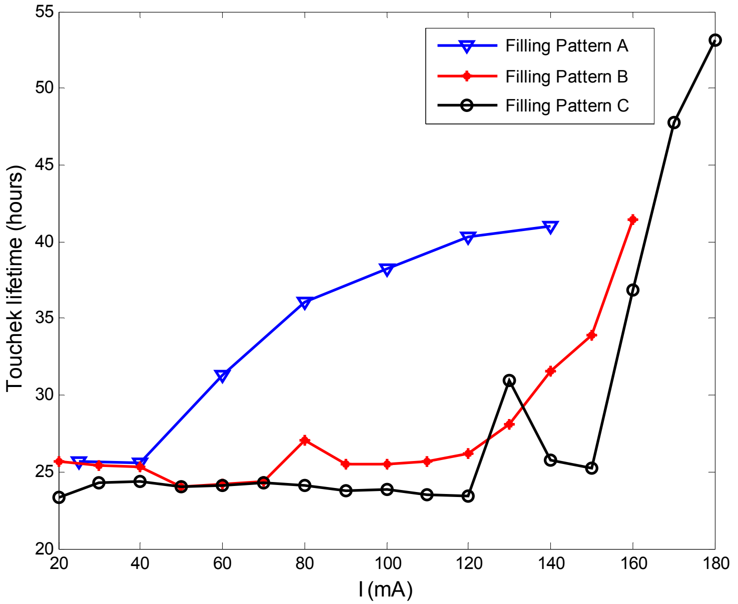
Possible cures

- Upgrade the vacuum condition below the threshold of onset of FII
- Introduce the gap between the bunch trains (mini-trains) in order to clear the ions or make ions unstable
- Bunch by bunch feedback system to realign the trailing bunches
- Increase chromaticity to a large value to suppress the growth of FII (verified in ALS and SSRF)
- Clearing electrodes, others

Mini-train effect



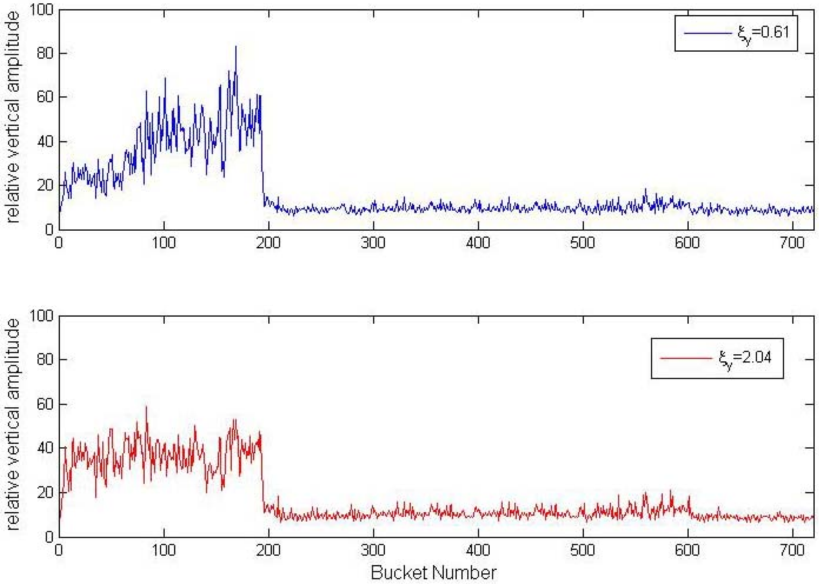
SSRF (2009)



In this experiment, the RF voltage and the bunch charge keep constant. The change of the Touchek lifetime reveals the information of the bunch size variation caused by the FII. There are three filling patterns for comparing, filling pattern A is a long bunch train with bunch current 0.5mA, B is mini-train with 20 bunches with bunch current 0.5mA separated by 16 buckets gap, C is mini-train with 10 bunches (bunch current 0.5mA) separated by 8 buckets gap.

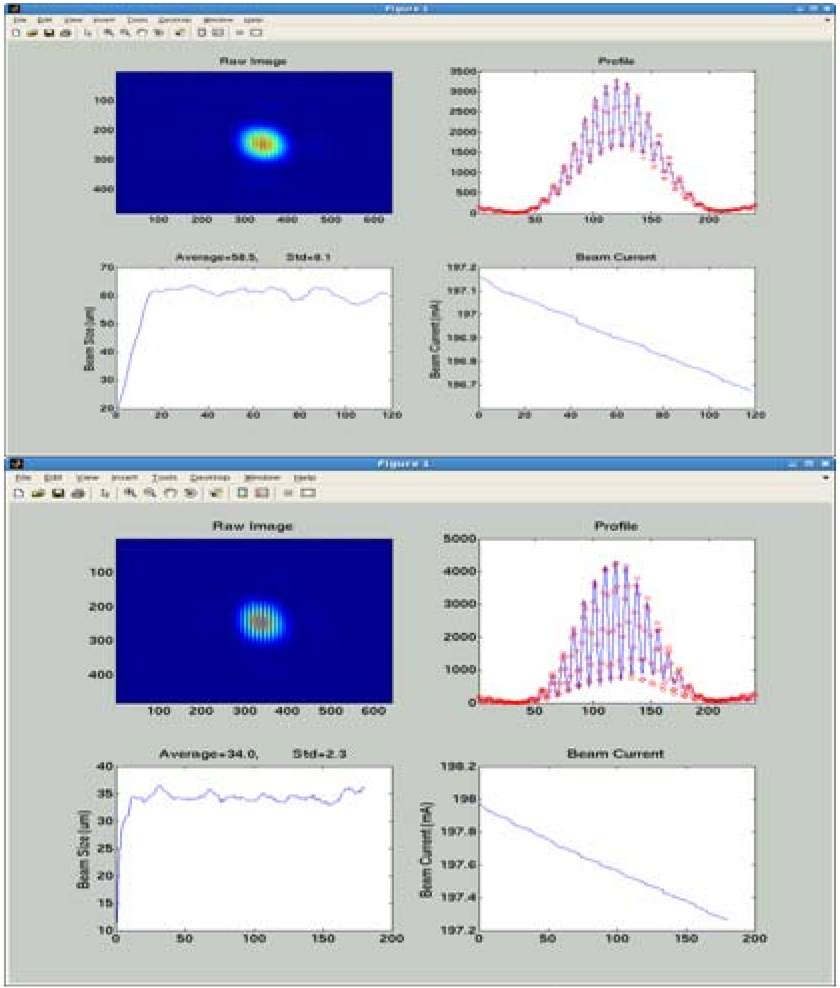
B. Jiang et al., Nucl. Instr. And Meth. A 614, 331 (2010)

Chromaticity effect



SSRF (2009)

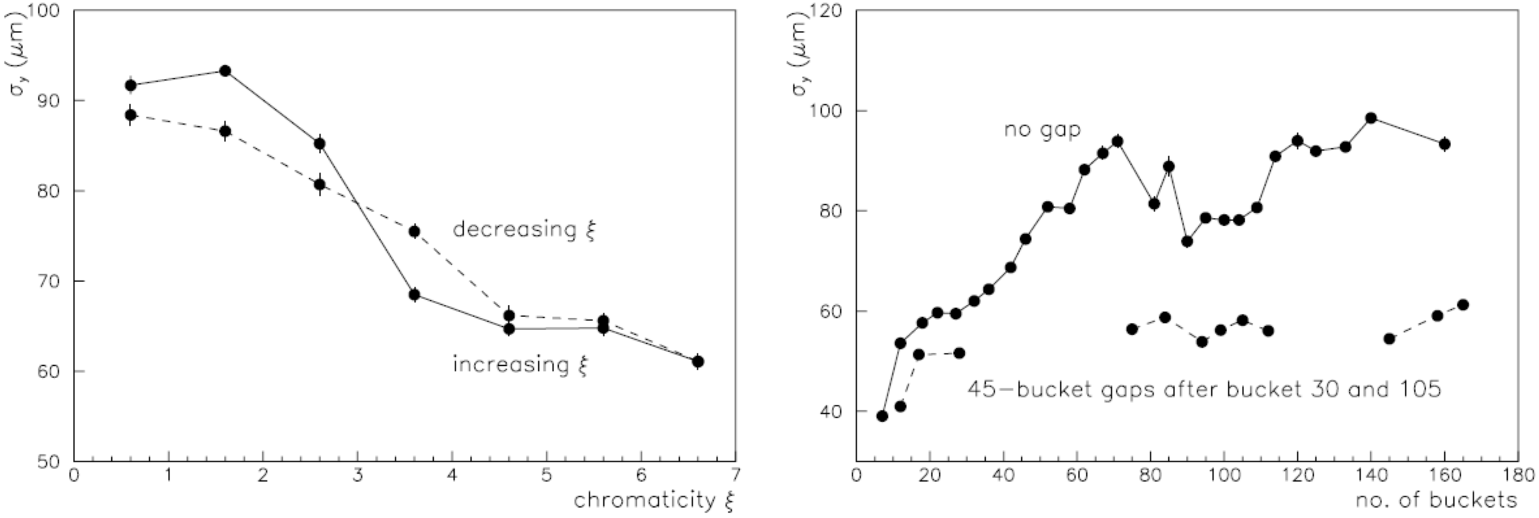
Bunch oscillation data taken from a bunch-by-bunch TFB system. It is clearly shown that high chromaticity suppresses the tail bunch oscillation amplitude (the average pressure is 0.42 nTorr, beam current of 197mA).



Vertical beam size measured from the interferometer. Beam lifetime for ξy = 2.04 case is 26 hours (below), beam lifetime for ξy = 0.61 case is 38 hours (upper).

B. Jiang et al., Nucl. Instr. And Meth. A 614, 331 (2010)

Chromaticity effect



RMS vertical beam size: (left) versus the vertical chromaticity ξy (the horizontal chromaticity ξx=1.5 was held constant, the helium pressure was about 30 nTorr, and the total current of the 160-bunch train was 75 mA); (right) versus the number of bunches, in the train with and without two additional gaps of 45 empty buckets each; the helium pressure during this measurement was about 30 nTorr, and the bunch current about 0.5 mA.

F. Zimmermann et al., SLAC-PUB-7736 (1998).

ALS (1998)

Summary

- For the current design of the ILC 3 km damping rings, the partial pressure of CO less than 1ntorr is required to mitigate FII.
- The mini-train is proven to be very effective for alleviating the FII.
- Fast feedback system with the damping time as short as 20 turns can be used to damp the FII.
- Further experimental study of FII is necessary to bench-mark the simulation results against experimental data.

Acknowledgement

Thanks to Dr. David Rubin and Dr. Mark Palmer for providing the MAD file of DTC01 lattice

Thanks for your attention !