Status of Fast Ion Instability Studies

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presented by E. Elsen

Ion effects overview

- Collision ionization of residual gas in the vacuum chamber is the main source of ion production
- Ion effects will arise when ions are trapped in the potential well of the beam
- Ions will be accumulated 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 ion instability (FII), which is a concern for the ultra-low emittance (2pm) damping ring of the International Linear Collider (ILC)

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
- External charge effects can arise due to ionized ions in an electron beam or similarly for electrons in a positron (proton) beam
- It can cause coupled bunch instability, beam size blow-up, emittance growth, tune spread and tune shifts etc

Potential cures:

- Improved vacuum
- Increase of ion frequencies spread using an optical lattice, so that the ion frequencies varies significantly with the time, and no coherent oscillation develops
- Introduce gaps in the bunch trains in order to clear the ions or render ions unstable
- Bunch by bunch feedback system to realign the trailing bunch

Collision ionization

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

$$n_m = 3.22\times 10^{22} P_m$$

And the mean 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 collisional ionization for ILC damping rings
(for nominal beam energy: 5 GeV)

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

Linear theory

Critical mass, ion density, FII growth time, ion oscillation frequency, ion angular frequency, FII growth time in presence of ion angular frequency variation, and the coherent tune shift due to ions

$$A_c = \frac{N_b r_p L_{sep}}{2\sigma_y(\sigma_x+\sigma_y)}$$

$$\lambda_{ion}[m^{-1}] = \sigma_{ion} n_b N_b p / k_b T$$

$$y \sim \exp(t/\tau_e)$$

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

$$f_i = \frac{c}{2\pi}\times\left(\frac{2N_b r_p}{A L_{sep}\sigma_y(\sigma_x+\sigma_y)}\right)^{1/2}$$

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

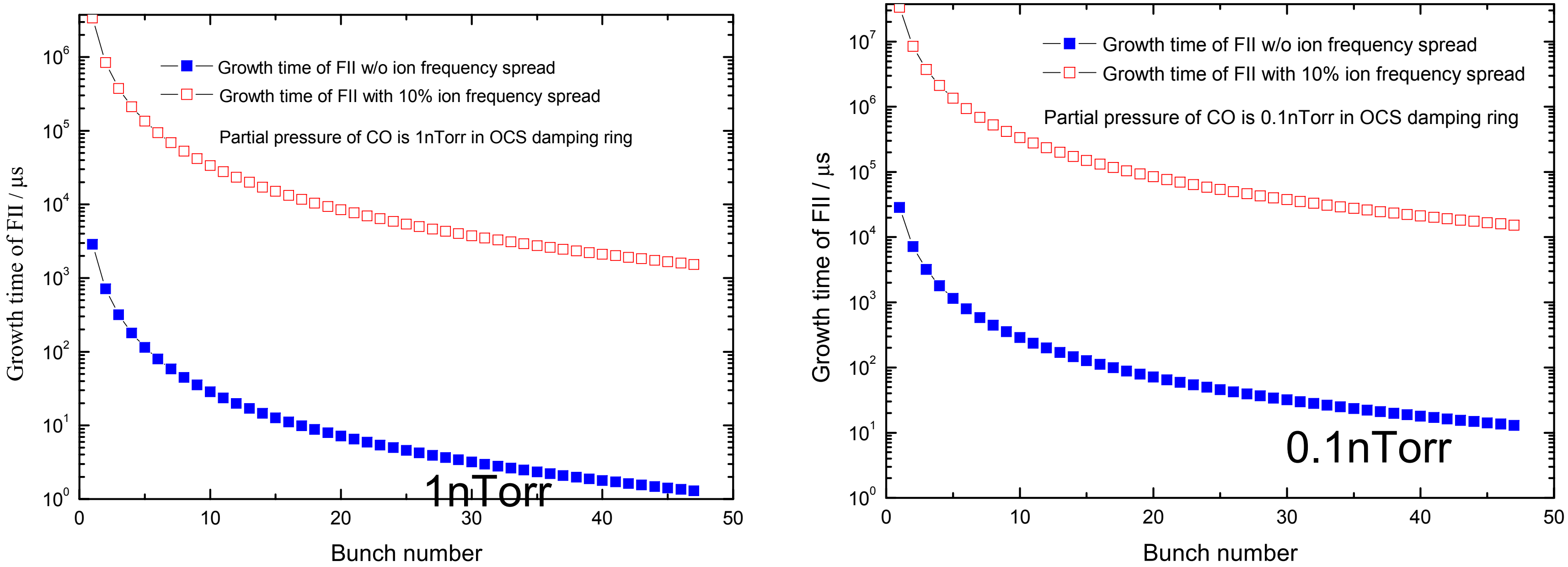
$$\frac{1}{\tau_e} = \frac{1}{\tau_c}\frac{c}{2\sqrt{2}\, l_{train}(\Delta\omega_i)_{rms}}$$

$$\Delta Q_{x,y;coh} = \frac{\beta_{x,y} r_e \lambda_{ion} C}{\gamma\, 4\pi\sigma_{x,y}(\sigma_x+\sigma_y)}$$

The growth time of FII is closely related to the beam sizes, the larger the value $\sigma_y^{3/2}(\sigma_x+\sigma_y)^{3/2}$, the larger the characteristic FII growth time. It is possible to use the up-to-date feedback system (~0.5 ms) to damp the FII growth.

Estimation of growth time of FII

- The growth time of FII in OCS straight sections.

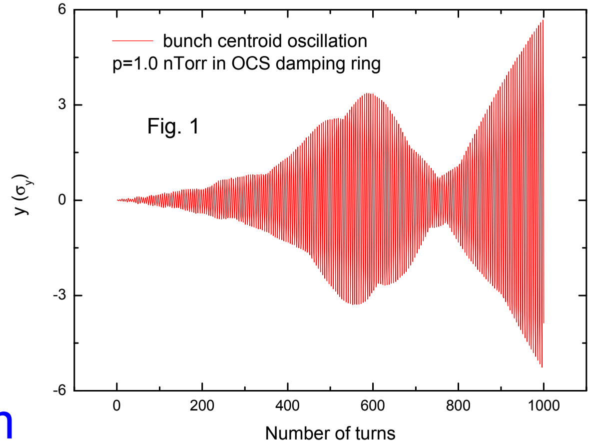


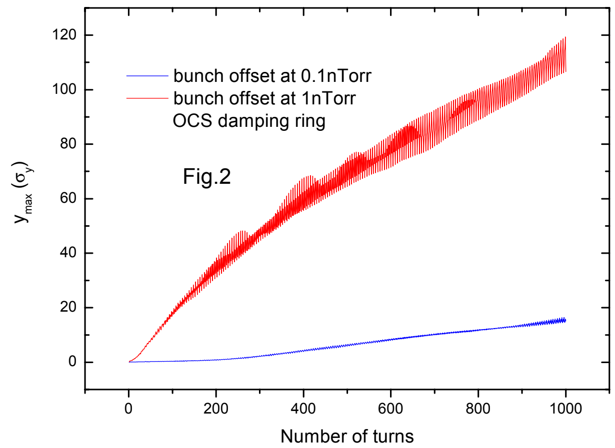
FII growth time versus bunch number in CO^+ for 47 bunches per train.

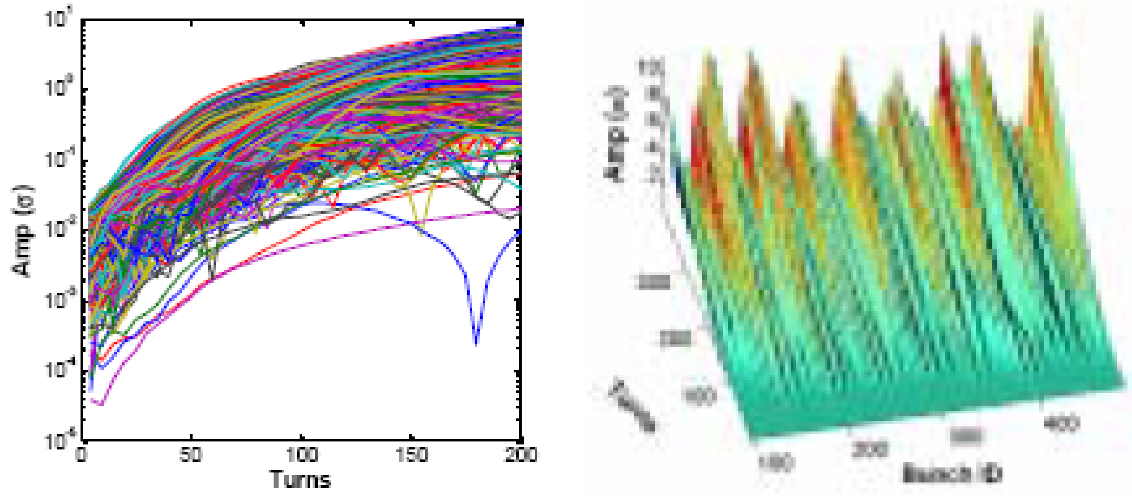
- Potentially dangerous for train end according to analytical estimate.

Simulation results

- Fig.1. Oscillation of vertical beam centroid *vs.* number of turns in OCS damping ring (p=0.1nTorr).
- Fig.2. Bunch maximum offset *vs.* number of turns in OCS damping ring (p=1.0nTorr and 0.1nTorr).
- Fig.3. Growth of vertical oscillation amplitude in the beam driven by ions







(a) Fig.3 (b)

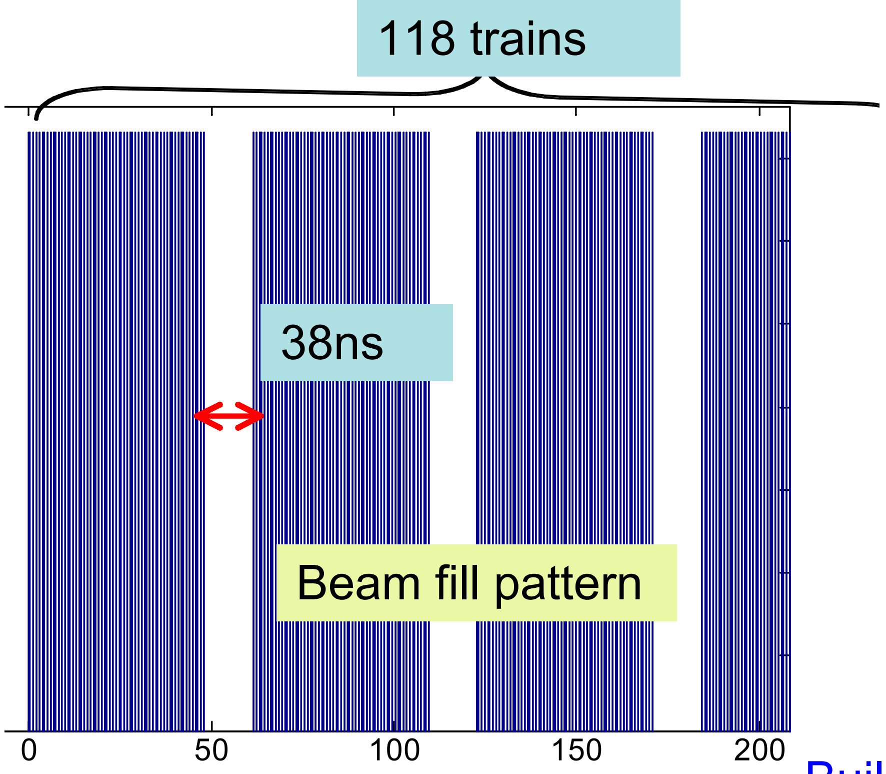
G.Xia et al, EPAC06, L.Wang et al, EPAC06

Effect of train gaps (ILC)

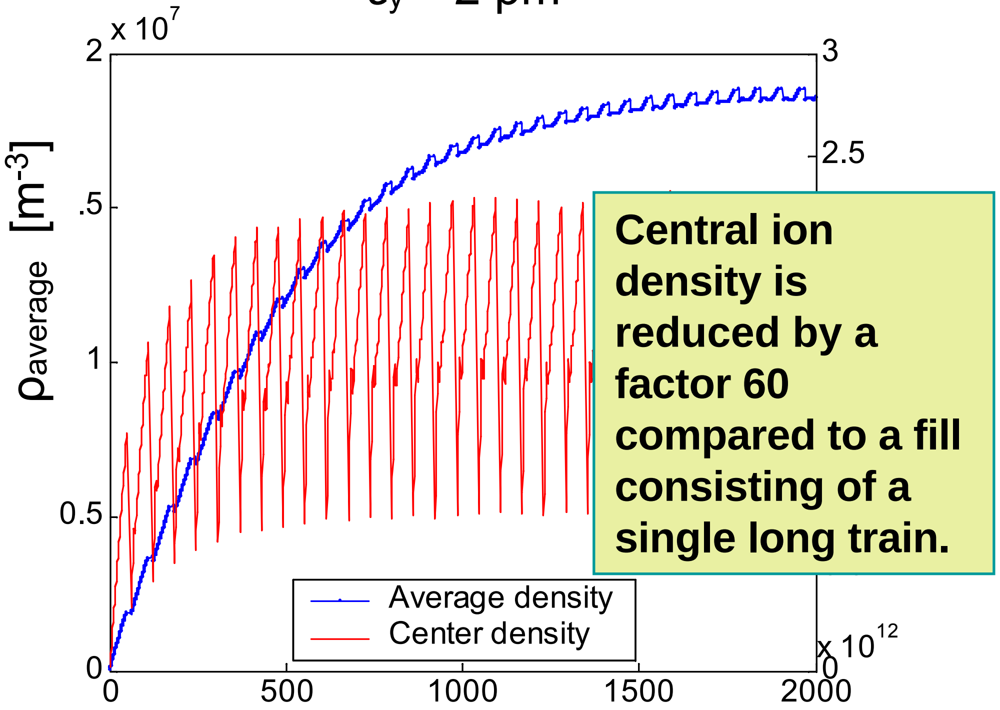
(Wang, et al. EPAC06)

Ion-density Reduction Factor (IRF)

$$\mathrm{IRF} = \frac{1}{N_{train}} \frac{1}{1-\exp(-\tau_{gap}/\tau_{ions})}$$



with equilibrium emittance
$\varepsilon_x = 0.5$ nm
$\varepsilon_y = 2$ pm

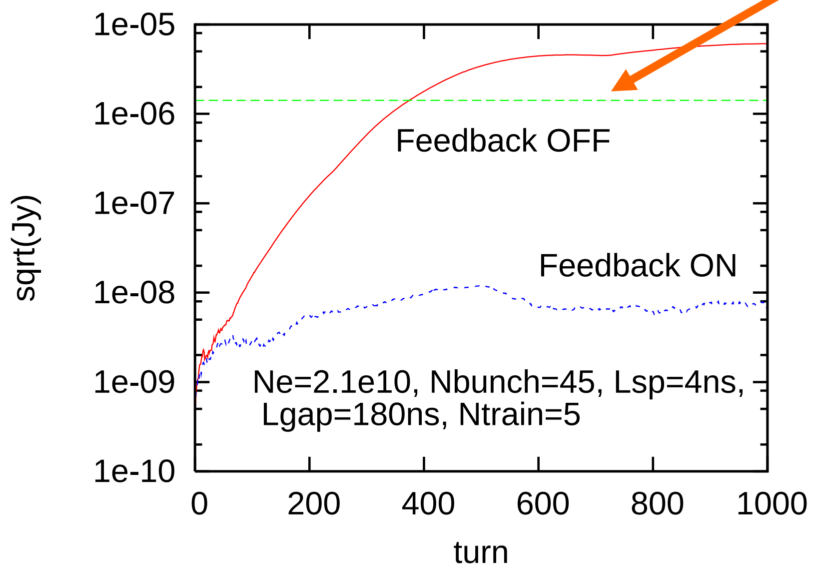


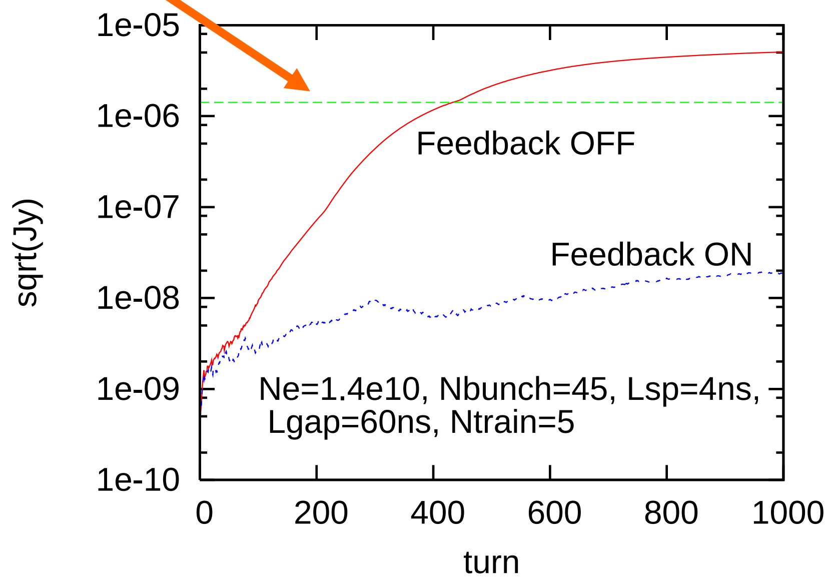
Build-up of CO+ ion cloud at extraction (with equilibrium emittance). The total number of bunches is 5782, P=1 nTorr.

Beam size blow up

Beam size

(K.Ohmi)





Base line

Low Q

- Feedback gain, 50 turn, is sufficient to suppress the instability. Amplitude is $0.01\sigma_y$.
- Nbunch: number of bunch in a train, Lsp: bunch spacing, Lgap: Gap between trains, Ntrain: number of train (model).

FII experimental studies in ATF DR

- A proposal has been submitted to KEK on experimental studies of FII in ATF DR
- The ATF beam has small emittance, 4 pm have been achieved (ILC damping ring:2 pm).
- Eventually the accurate turn-by-turn and bunch-by-bunch beam position monitors of ATF can record the beam position for a train of bunches.
- The laser wire can provide precise bunch-by-bunch beam size measurement

What can be tested at ATF DR ?

- The main effects of ion cloud include emittance blow-up, fast dipole instability and tune shift. ATF FII experiment can distinguish the two ion effects: beam size blow-up and dipole instability using its very precise diagnostic system.
- The dipole oscillation could be suppressed by a feedback system while there are no efficient ways to suppress the emittance blow-up.

Goals of the experiment

- Distinguish the two ion effects: beam size blow-up and dipole instability.
- Quantify the beam instability growth time, tune shift and vertical emittance growth. Based on the linear model, the growth rate is proportional to the ion density (the related parameters include vacuum pressure, average beam line density, emittance, betatron function and beam fill pattern). Sensitivity to vertical emittance should be largest.
- Quantify the bunch train gap effect
- Beam shaking effect
- Provide detailed data to benchmark simulations with experiment. Relate understanding to other measurements (e.g. ALS, PLS and KEKB).

Detailed experiment

- Measurement of vacuum pressure and the main components of gas species.
- Effects of pressure and bunch current, e.g.
  - Vary pressure (5, 10, 20 nTorr) by injecting hydrogen/nitrogen gas or turn off the vacuum pumps
  - Vary beam: 1 train, N= 2, 4, 6, 10, 20×10^9
  - Change optical function to adjust the level of flatness of the beam (Junji's proposal)
    - introduce a vertical dispersion or
    - local coupling of the horizontal and vertical betatron motion
  - Vary train gap
- Repeat with 2 and 3 bunch trains, if possible including length of gaps.
- repeat above with a different emittance
- Beam shaking effect (intermediate plan, 2008?)
- Apply feedback system to damp the beam oscillation; study its performance
- …

Requirements

- Diagnostics:

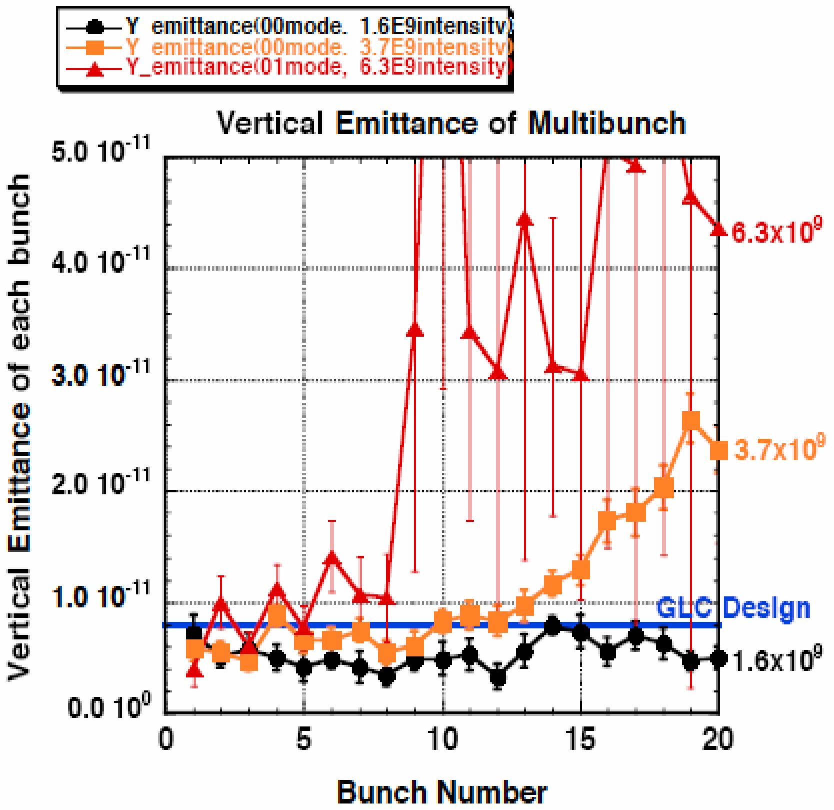
  BPMs, streak camera, fast gated camera, SR interferometers, feedback systems, CCDs, laserwire and other diagnostic equipments

- Manpower for experiments:

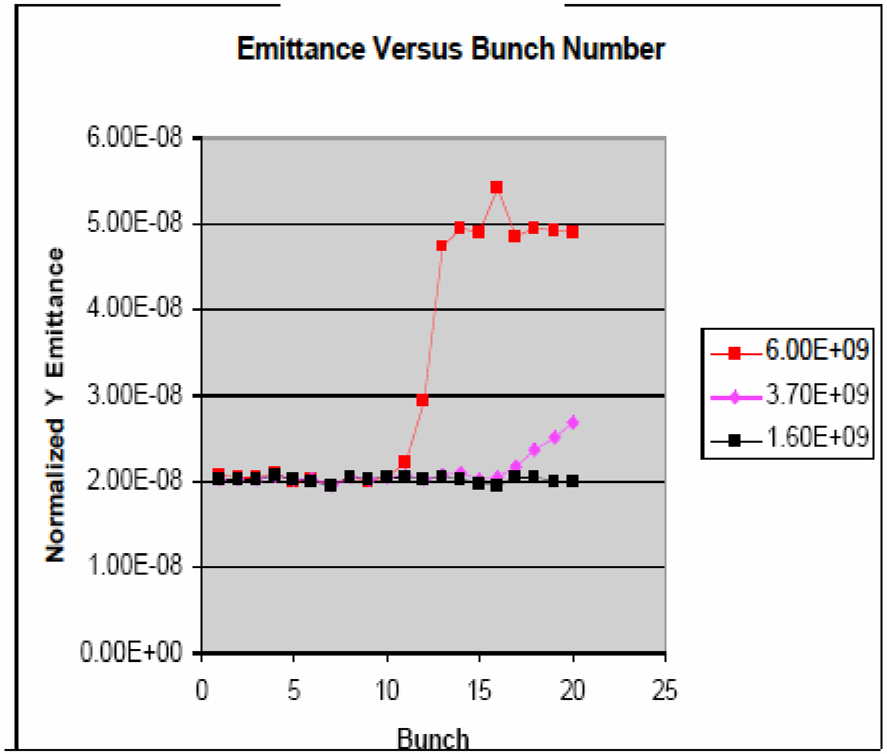
  Junji Urakawa et al. (KEK), Lanfa Wang, Tor Raubenheimer (SLAC), Guoxing Xia, Eckhard Elsen (DESY), Andy Wolski (CCLRC) and possibly colleagues from CERN, FNAL, KNU etc.

Tor Raubenheimer

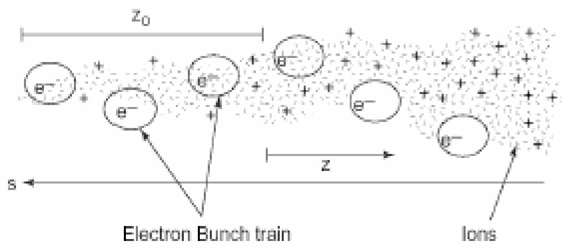
Preliminary result of Fast Ion Instability simulation



simulation



Behavior of Y emittance is very similar.



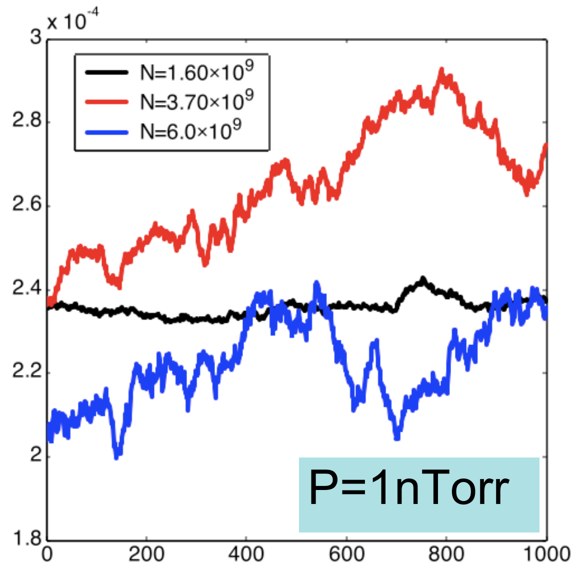
Schematic of the Fast-Beam Ion Instability

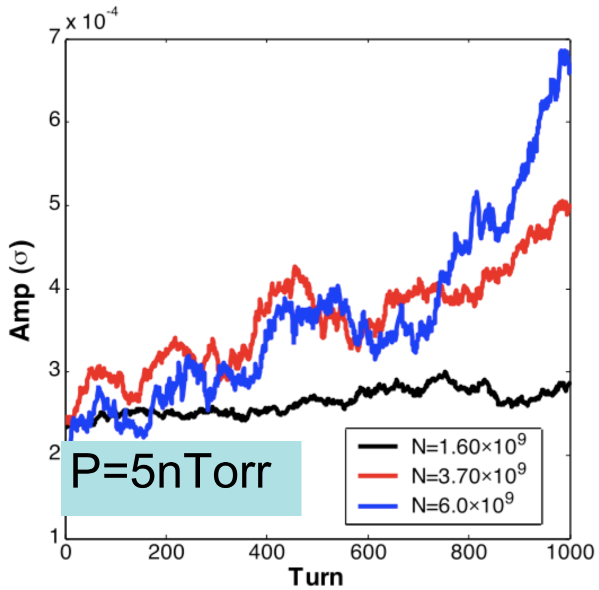
ATF FII experiment in the year 2004

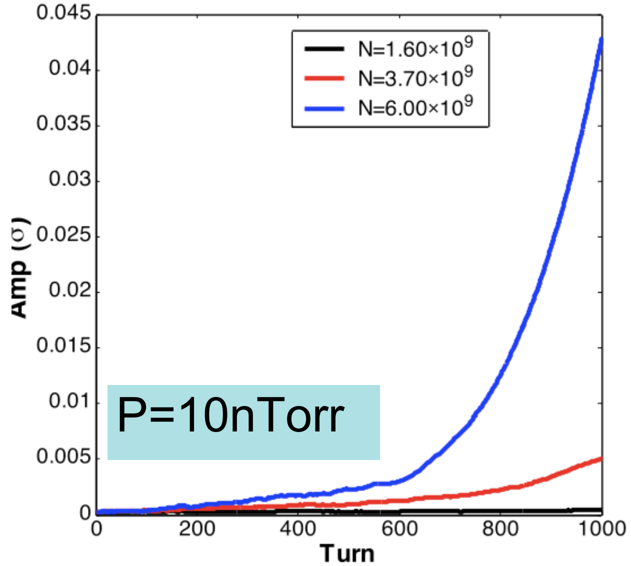
FII at ATF

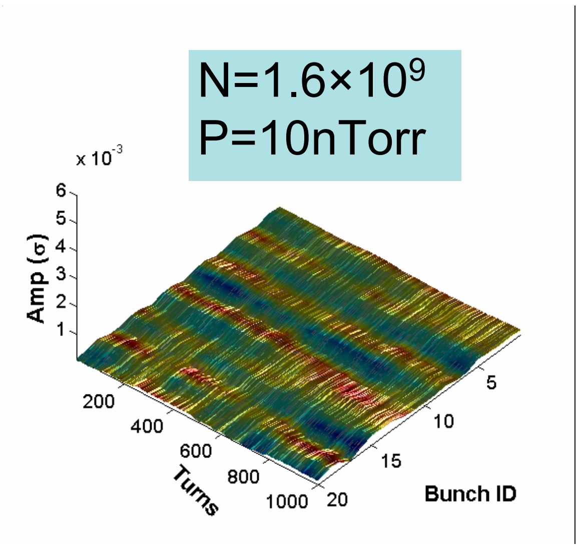
Lanfa Wang

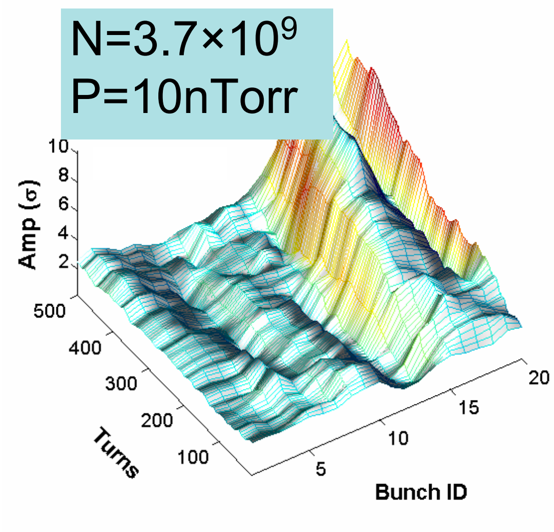
Using strong-strong and weak strong model

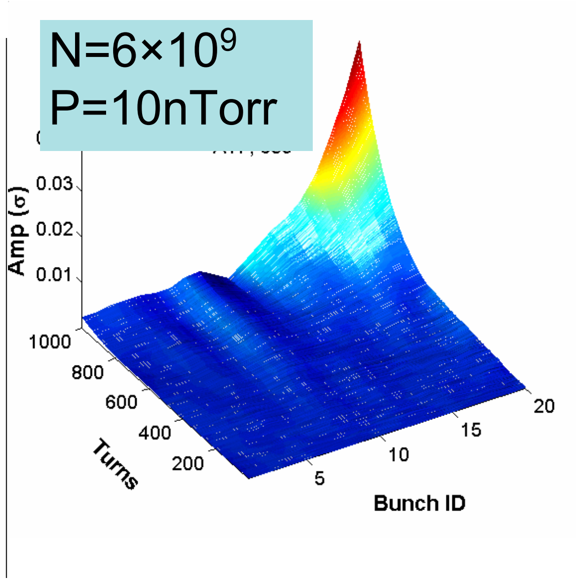












Simulation model (G.Xia)

- Weak-strong approximation
- Electron beam is a rigid Gaussian
- Ions are macro-particles
- The interaction is described by Bassetti-Erskine formula
- Typically 6 collision points in the ring (more points can be chosen manually)

Simulation model (2)

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

$$
\begin{aligned}
\Delta v_{y,i} + i\Delta v_{y,i} &= -2N_b r_e c \frac{m_e}{M_i} f(x_{ie}, y_{ie}) \\
\Delta y' + i\Delta x' &= \frac{2r_e}{\gamma} \sum_i N_i f(x_{ie}, y_{ie})
\end{aligned}
$$

$$
\begin{aligned}
f(x,y) &= -\sqrt{\frac{\pi}{2(\sigma_x^2-\sigma_y^2)}}\left[w\left(\frac{x+iy}{\sqrt{2(\sigma_x^2-\sigma_y^2)}}\right) - e^{-\frac{x^2}{2\sigma_x^2}-\frac{y^2}{2\sigma_y^2}}\, w\left(\frac{x\frac{\sigma_y}{\sigma_x}+iy\frac{\sigma_x}{\sigma_y}}{\sqrt{2(\sigma_x^2-\sigma_y^2)}}\right)\right] \\
w(z) &= e^{-z^2}\left(1-\mathrm{erf}(-\mathrm{iz})\right)
\end{aligned}
$$

Simulation model (3)

- Beam motion between ionization points is linked *via* linear optics

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

$$z = (x, y)$$

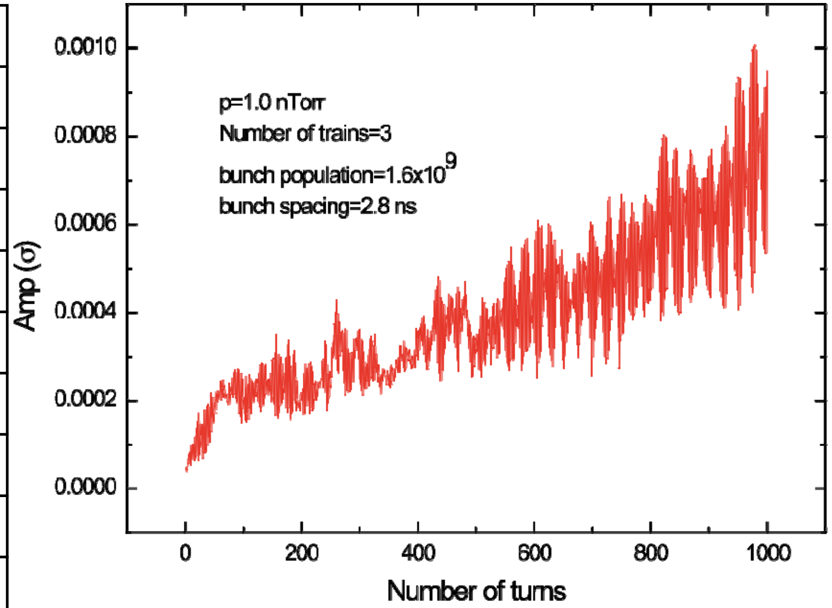
- For a flat beam, we mainly care about the vertical direction (y direction)

Simulation results (1)

Parameters of ATF damping ring

Beam energy [GeV]	1.28
Circumference [m]	138.6
Harmonic number	330
Momentum compaction	2.14E-3
Bunch population [$\times 10^9$]	1.6, 3.7 and 6.0
Bunch length [mm]	6
Energy spread	0.06%
Horizontal emittance [mrad]	1.4E-9
Vertical emittance [mrad]	1.5E-11
Vacuum pressure [nTorr]	1 and 5

Weak strong approximation



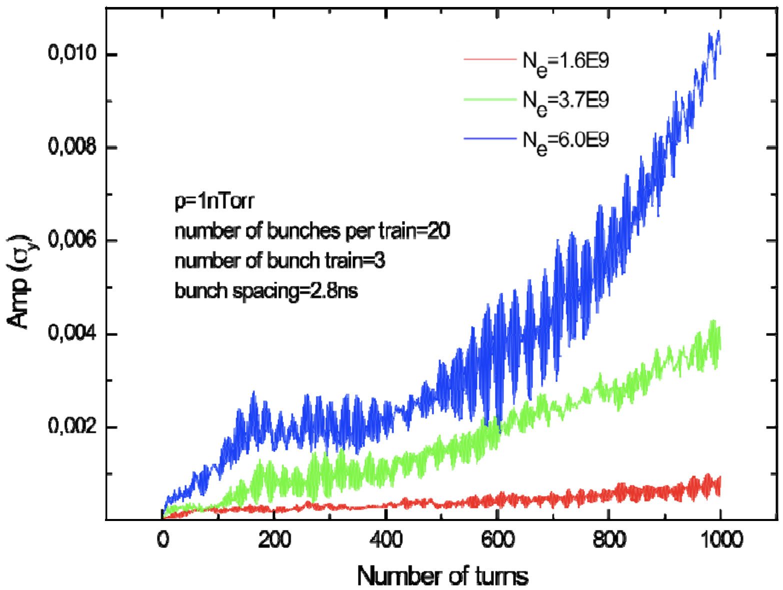
Fast beam ion insatbility in ATF Damping Ring

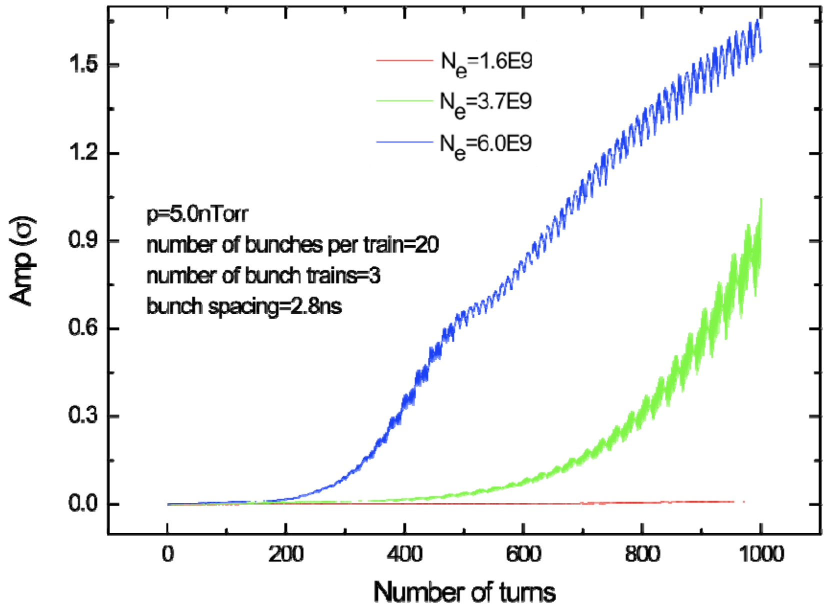
One long bunch train is used in simulation !

The 60th bunch is recorded here

Beam centroid oscillation amplitude with respect to number of turns

Simulation results (2)





Beam centroid oscillation amplitude with respect to number of turns

If we introduce gaps between the bunch trains,

the growth rate is reduced by a factor of 100 !

Calculated results

Ion effects in ATF damping ring

Bunch population	1.6E9			2.0E10		
Vacuum pressure [nTorr]	1	5	10	1	5	10
Ion density [m^{-1}]	309	1545	3090	3862	19312	38625
Critical mass	1.28	1.28	1.28	16	16	16
Ion oscillation frequency	2.4E7	2.4E7	2.4E7	8.6E7	8.6E7	8.6E7
FII growth time [s]	6.8E-5	1.4E-5	6.8E-6	1.5E-6	3.1E-7	1.5E-7
FII grow. time (10% ion freq. spread) [s]	4.0E-4	8.1E-5	4.0E-5	3.2E-5	6.5E-6	3.2E-6
Tune shift	1.9E-5	9.5E-5	1.9E-4	2.3E-4	1.2E-3	2.4E-3

Summary

- Fast ion instability (FII) is still one of the most critical issues for R&D of ILC DR
- FII became very high priority after Cornell DR workshop'06
- Simulation results show it will affect the DR' s performance
- There is an excellent opportunity to characterize FII systematically at ATF and to compare to the simulation results
- FII mitigation should be studied further