Numerical study of FII in the ILC Damping Ring

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SLAC

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Outline

- Introduction
- Simulation
- Wake of ion cloud
- Bunch train effect
- Optics effect
- Emittance effect
- Feedback
- Summary

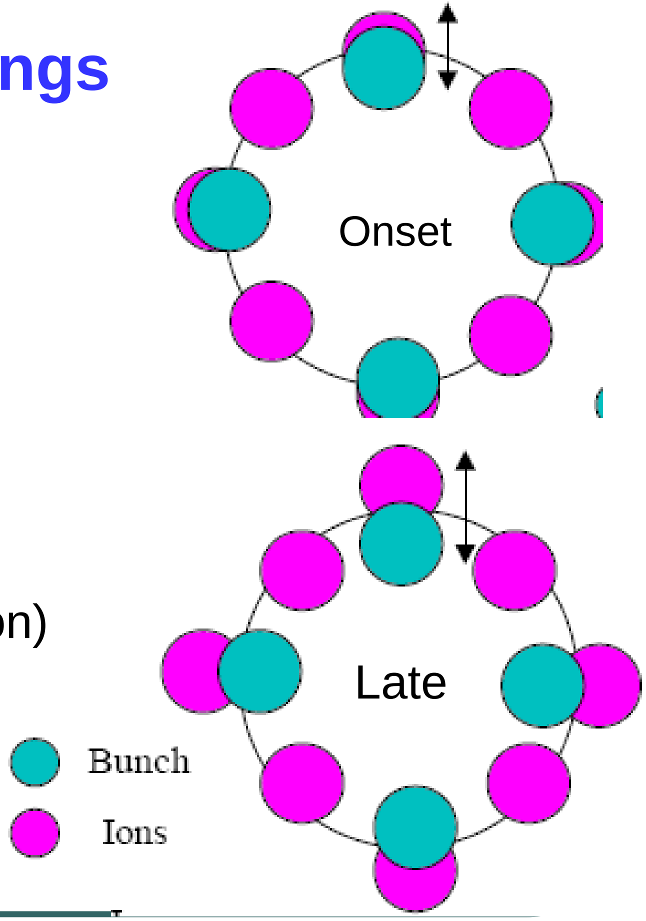
Introduction

Ion-related instabilities at electron rings

- ☐ Ion trapping
- ☐ Fast Beam-Ion Instability (FBII)

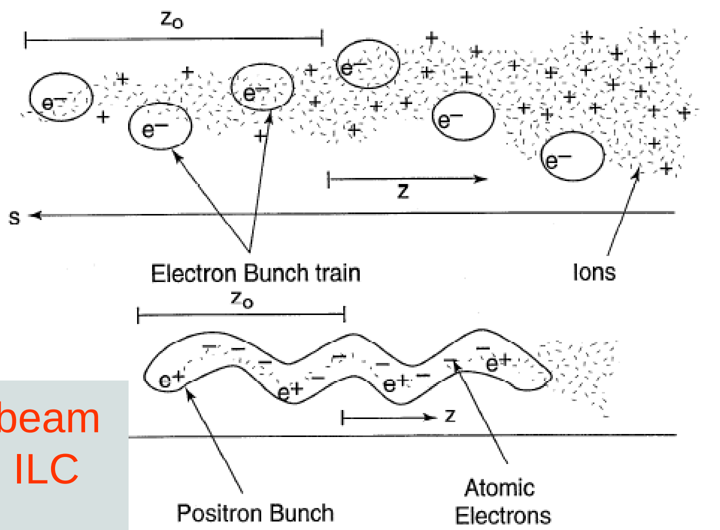
Traditional Ion trapping

- Uniform filling of a beam
- Occur in storage rings
- No clearing of ions (saturation of ion population)
- Stationary state (even though unstable)
- Existence of threshold for onset of instability
- Narrow-band spectrum



Fast Beam Ion Instability (FBII)

- Ions are cleared out by gaps
- The ions created by the head of the bunch train perturb the bunches that follow.
- A gap in the bunch train does not inhibit the instability.
- Transient (single pass) phenomenon
- Occur in rings, linacs or beam transport lines
- Broad-band spectrum



T. Raubenheimer

Small beam spot in ILC DR!!!

$$\frac{1}{\tau_e} \approx \frac{c r_e \lambda_i \beta_y}{3\sqrt{2}\gamma \sigma_y (\sigma_x + \sigma_y)} \frac{1}{(\Delta\Omega_i)_{rms}}$$

$$\lambda_i = \sigma_i P N n_b /(kT)$$

Phys. Rev. E52, No. 5, p. 5487 (1995)

KEK Proceedings 96-6, p. 243 (1996)

Ion trapping with/without gap

Stability of an ion (linear motion)

$$\begin{pmatrix} y \\ \dot{y} \end{pmatrix}_{n+1} = M \cdot \begin{pmatrix} y \\ \dot{y} \end{pmatrix}_{n}$$

y : ion coordinate

n : turn of a bunch train

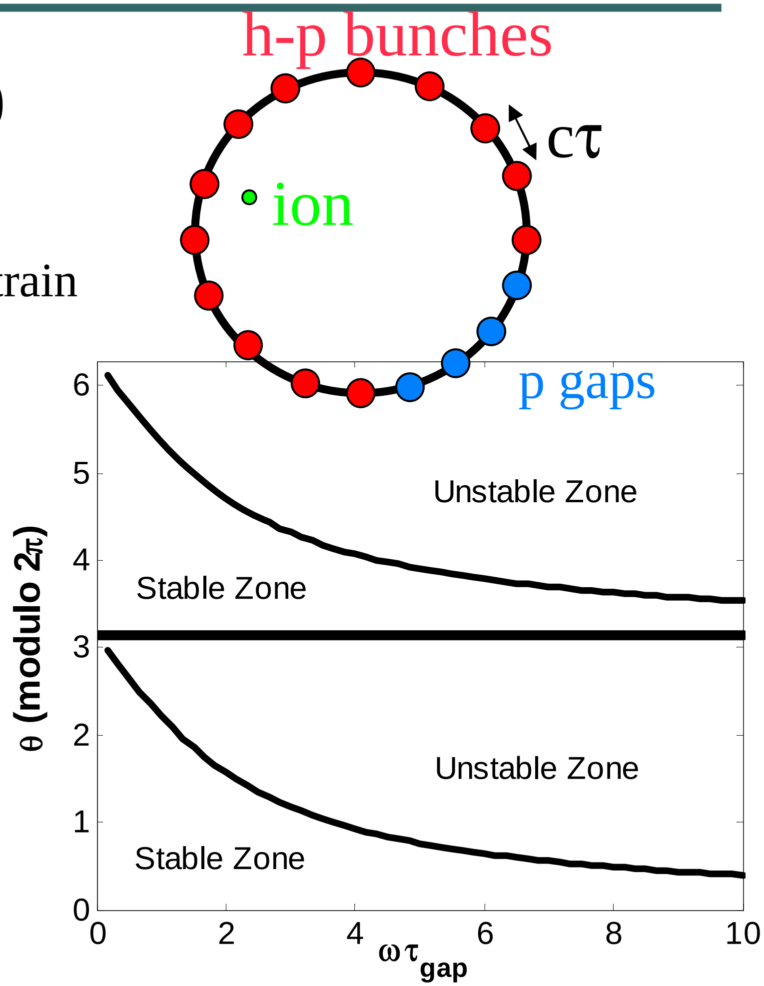
$$M = \left\{ \begin{pmatrix} 1 & \tau \\ 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 \\ -K & 1 \end{pmatrix} \right\}^{p} \begin{pmatrix} 1 & (h-p)\tau \\ 0 & 1 \end{pmatrix}$$

$$K = \frac{2N_b r_e mc}{M_{ion}\sigma_y(\sigma_x + \sigma_y)}$$

kick by a bunch

N_b : number of electrons / bunch,
m, M_{ion} : electron and ion mass,
$\sigma_{x,y}$: beam size of electron bunch,

Stability condition $Tr|M| < 2$



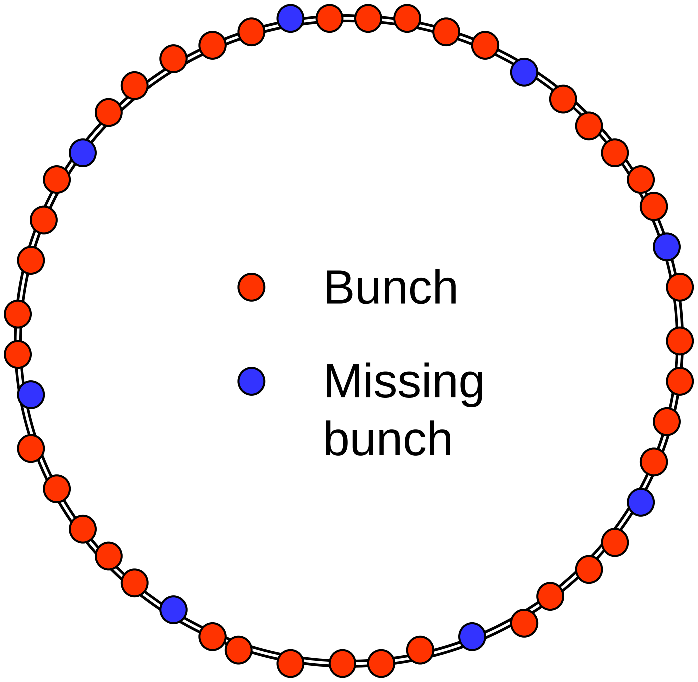
Beam-Ion instability in ILC DR

Mitigations of FBII

- Multi-bunch-train filling pattern (most light sources using one long gap filling pattern)
- Bunch–by-bunch Feedback
- More

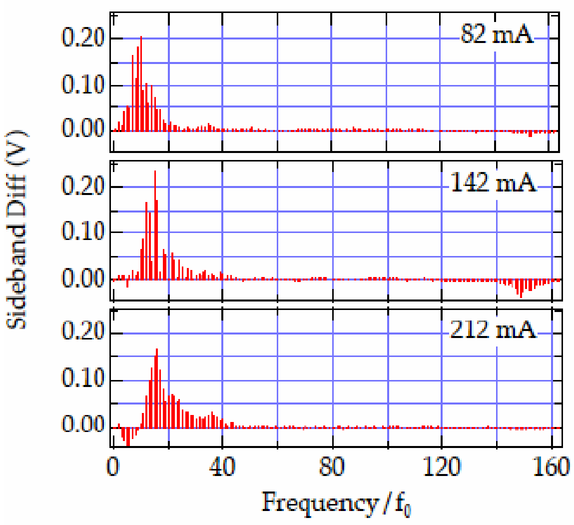
Characters of ion instability in ILC DR

Combination of traditional ion trapping instability and Fast Ion Instability



FBII Observations

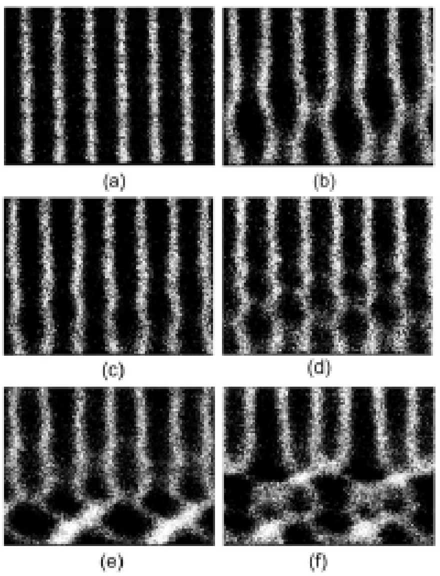
- The instability has been observed at many laboratories (ALS, PLS, KEK AR, ATF) by artificially increasing the vacuum pressure.
- For present day light sources it does not pose a problem. May become a problem for lower emittances and damping rings.



ALS

σ_y~30µm

J. Byrd, Phys.Rev.Lett.79:79-82,1997.



0.2nTorr

3.34nTorr →

PLS

σ_y~100µm

FIG. 1. Snapshots taken at (a) normal condition (0.7 mA/bunch), (b) ion pumps turned off (0.64 mA/bunch), (c) 0.2 nTorr He (0.61 mA/bunch), and (d) 3.34 nTorr He (0.52 mA/bunch). Two snapshots showing (e) a sharp triangular waveform (3.34 nTorr He, 0.6 mA/bunch), and (f) a turbulent centroid oscillation at the tail (3.34 nTorr He, 0.6 mA/bunch). All snapshots are taken every 4 μsec (4 turns). Horizontal span is 25 μsec (6.4 mm in spatial unit), and vertically 500 nsec from top to bottom.

Phys. Rev. Lett. 81, 4388–4391 (1998)

FBII at ATF
Observation & simulation

Preliminary result of Fast Ion Instability simulation

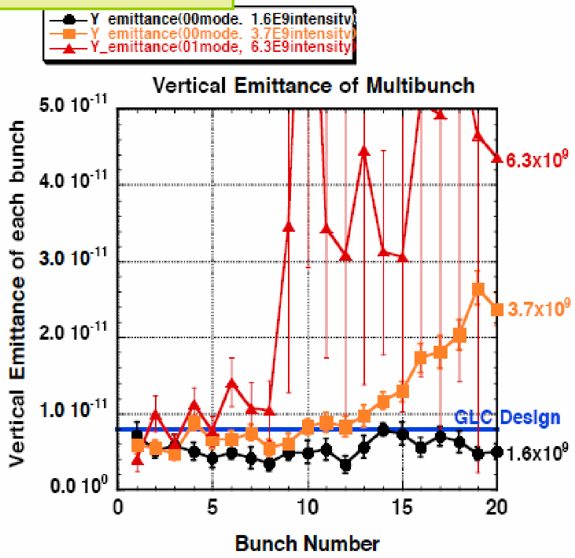
Experiment

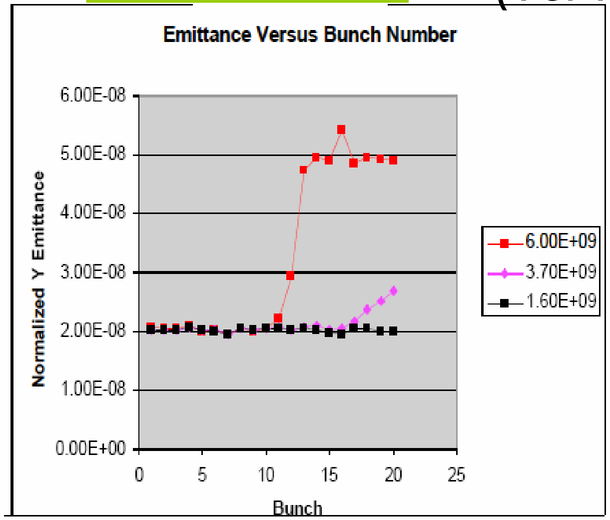
Simulation

(Tor Raubenheimer)

ATF

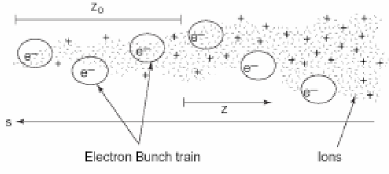
σ_y<10μm





Behavior of Y emittance is very similar.

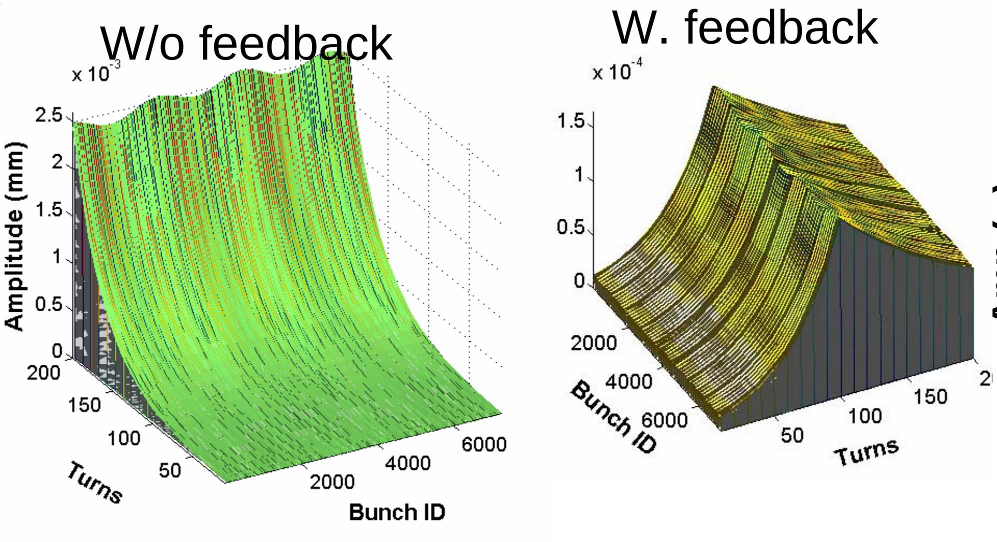
(Junji Urakawa)



Schematic of the Fast-Beam Ion Instability

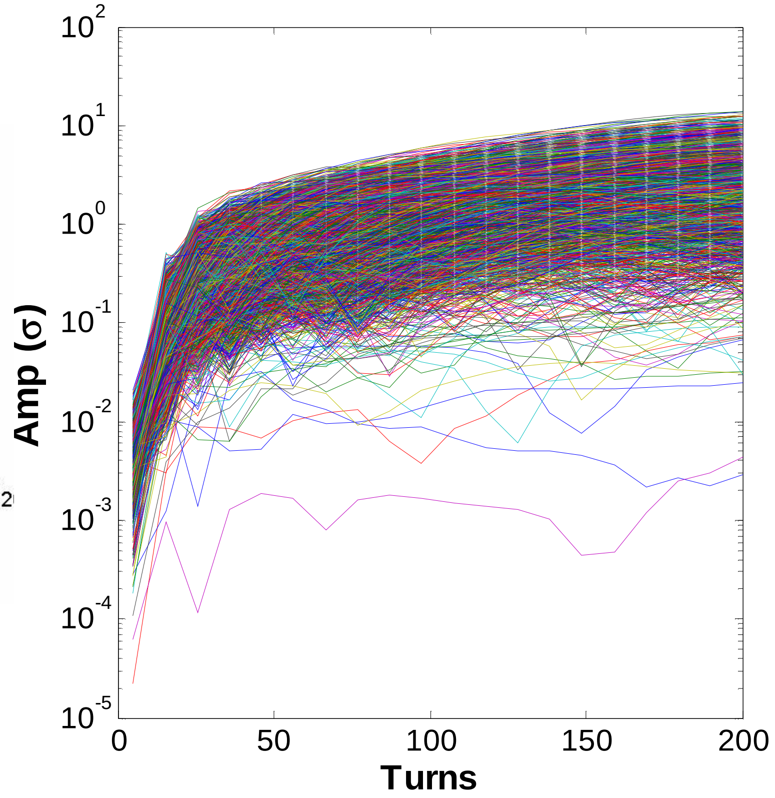
Comparison with Impedance effect

Resistive wall instability in ILC DR



Instability Modes with feedback gain 30turns/0.67*ms;* Growth time=36turns

FBII



Beam Fill patterns (example)

5782 bunches :

118 trains

49 bunches per train

Bunch spacing 2 RF buckets =3ns

Train gap: 25RF buckets=38ns

Bunch intensity : 0.97E10

2767 bunches :

1 short train with 22 bunches + 61 long train with two short train in each long train (23 bunches per train+ 22 bunches per train)

Bunch spacing: 4 buckets =6ns

Train gap: 28 buckets=43ns

Bunch intensity : 2.02E10

Description	Value
Beam energy	5.0 GeV
Circumference	6695 km
Harmonic number	14516
RF frequency	650 MHz
Tunes	52.28/47.40
Momentum compaction	0.40×10^{-3}
Number of bunches	2767~5782
Bunch intensity	$0.97\sim2.02\times10^{10}$
Emittance at injection	5.0×10^{-10}m
Vacuum	1nTorr

Effect of train gaps (ILC)

(Wang, et al. EPAC06)

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

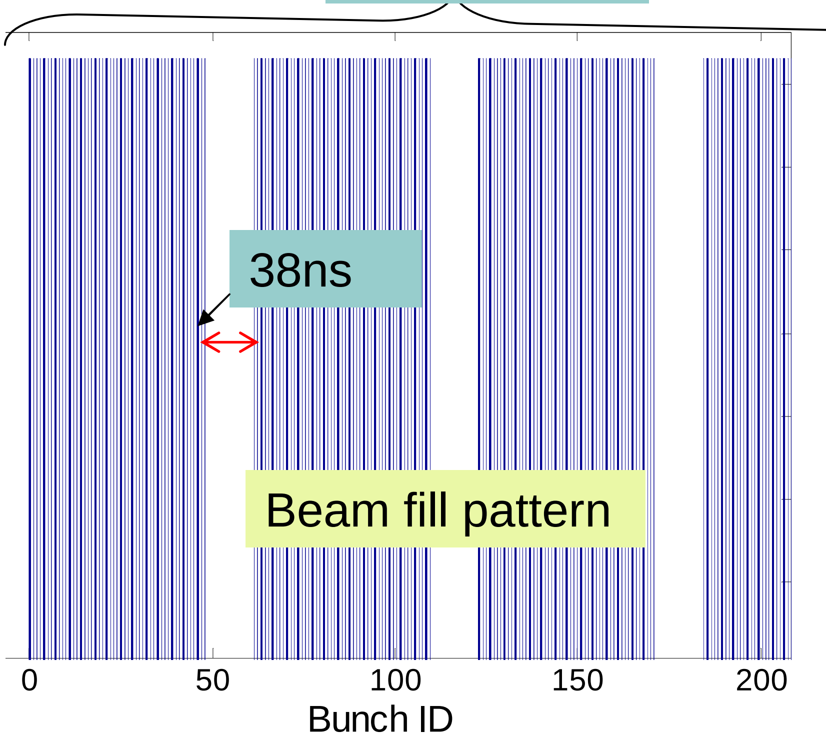
Lager number of trains, longer gap and a smaller emittance help!

with equilibrium emittance

Ex=0.5 nm

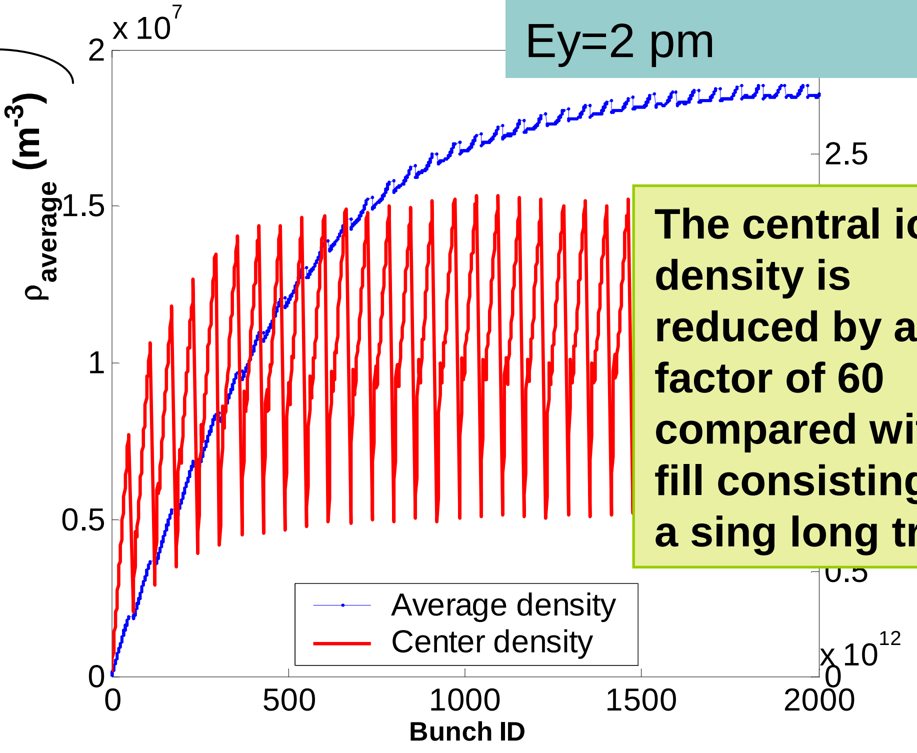
Ey=2 pm

118 trains



38ns

Beam fill pattern



The central ion density is reduced by a factor of 60 compared with a fill consisting of a sing long train

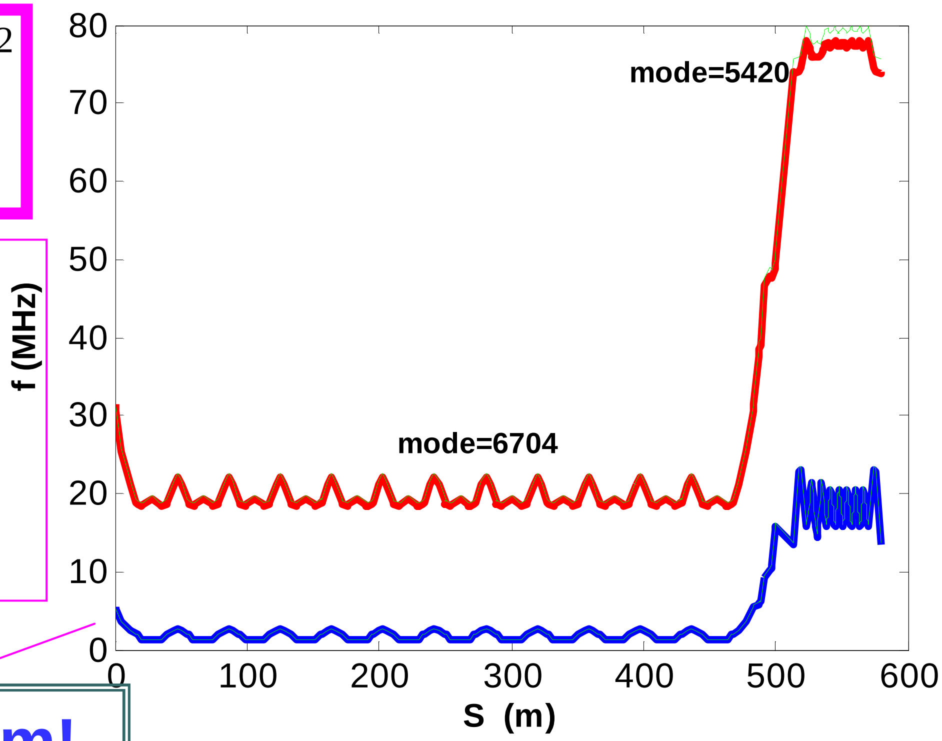
Build-up of CO+ ion cloud at extraction (with equilibrium emittance). The total number of bunches is 5782, P=1 nTorr.

Ion oscillation frequency

$$f_{x(y)} = \frac{c}{2\pi}\left(\frac{4Nr_p}{3AS_b(\sigma_x+\sigma_y)\sigma_{x(y)}}\right)^{1/2}$$

where
N=number of electrons in a bunch
S_b=distance between bunches
$\sigma x(y)$ =horizontal/vertical beam sizes
rp=classical proton radius
A=ion mass number

Wide-band beam spectrum!



CO+ frequency at OCS

Why Simulation

Analysis can estimate the FBII in the exponential growth region (small amplitude), while

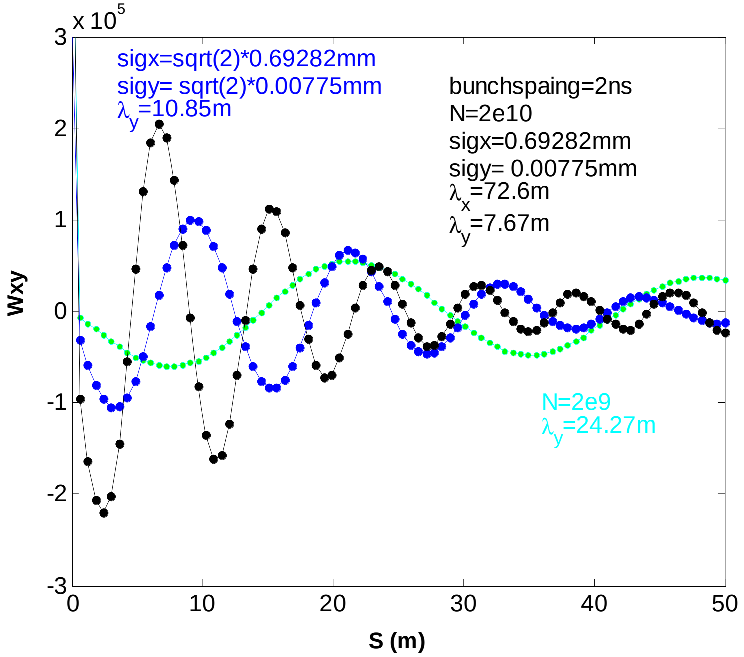
Simulation has many advantages

- Traditional instability & FBII
- Optics effect
- Nonlinear effect
- Gap effect
- Multi gas species effect
- Feedback
- ……

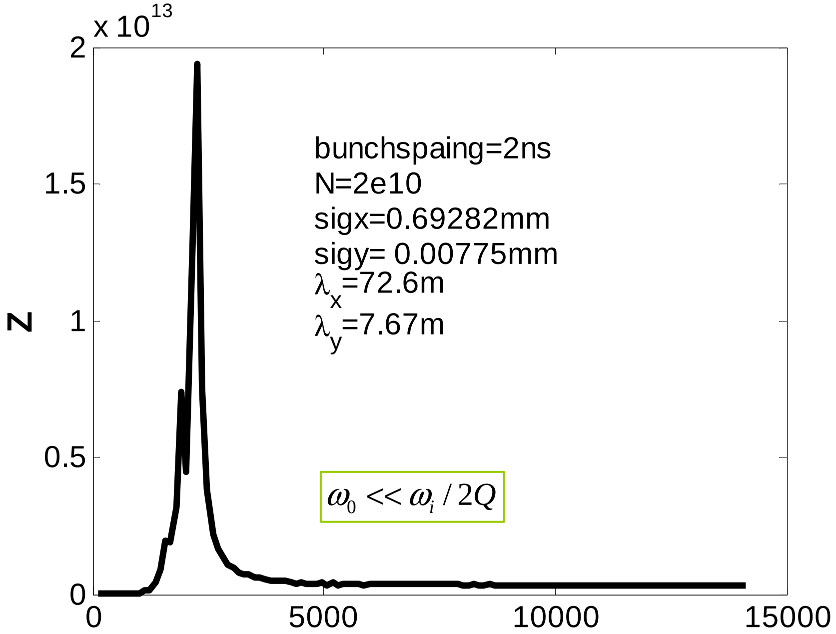
Semi-analytical method---Wake of the ion cloud

- **The Wake has low Q**
- **There are always some unstable modes, independent of the tune**

$$\omega_i / \omega_0 = 870 \; for \; \text{vertical}$$



Wake for different beam



FTT of the wake

Effect of interaction points 1/2
Nb=5782, 1 IP

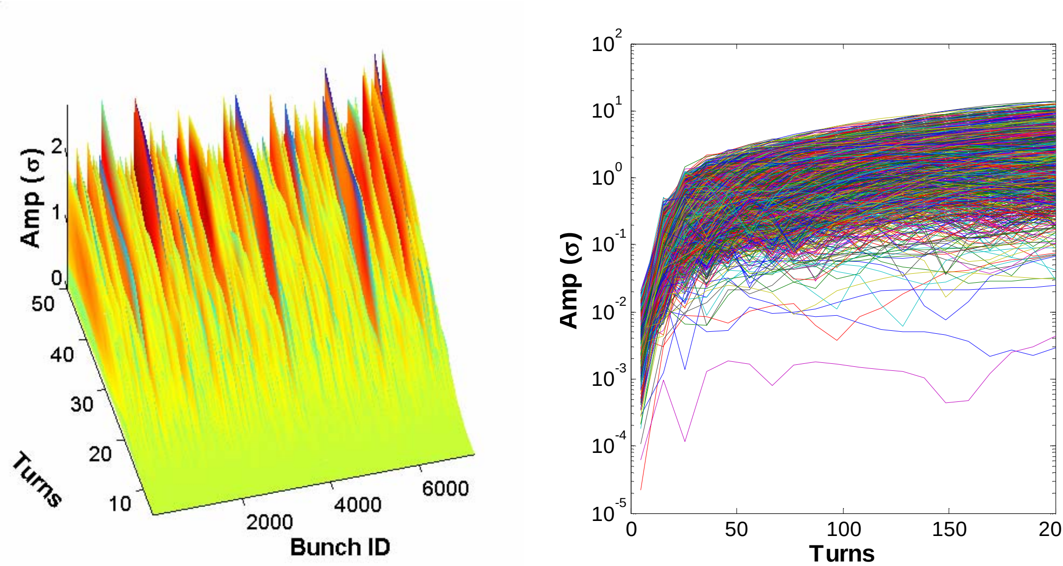
Average Co+ frequency fx/fy=12.36/ 53.97 [MHz]

Growth time in vertical =4turns

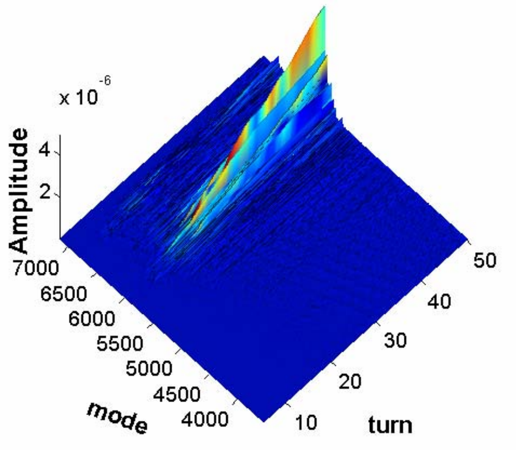
Growth time in horizontal =70turns

$$\frac{1}{\tau_e} \approx \frac{c r_e \lambda_i \beta_y}{3\sqrt{2}\gamma\sigma_y\left(\sigma_x+\sigma_y\right)} \frac{1}{\left(\Delta\Omega_i\right)_{rms}}$$

Gennady Stupakov,et.al, KEK Proceedings 96-6, p. 243 (1996)



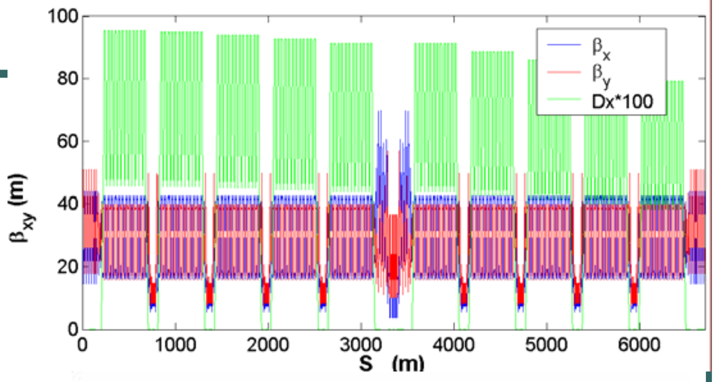
Bunch Vertical oscillation amplitude



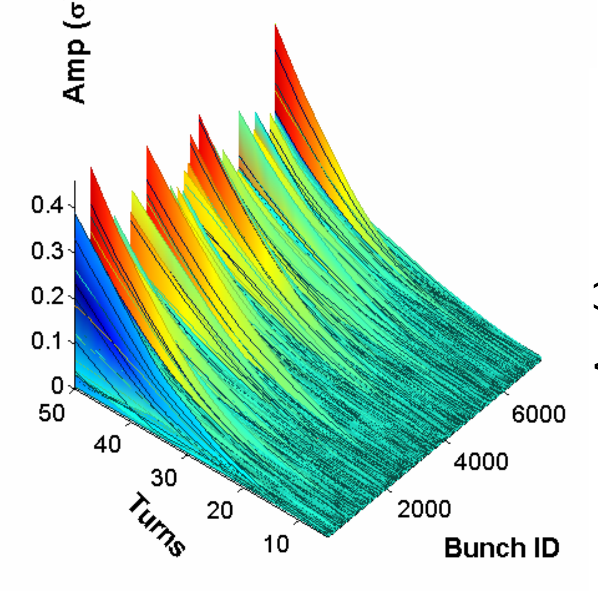
Instability modes

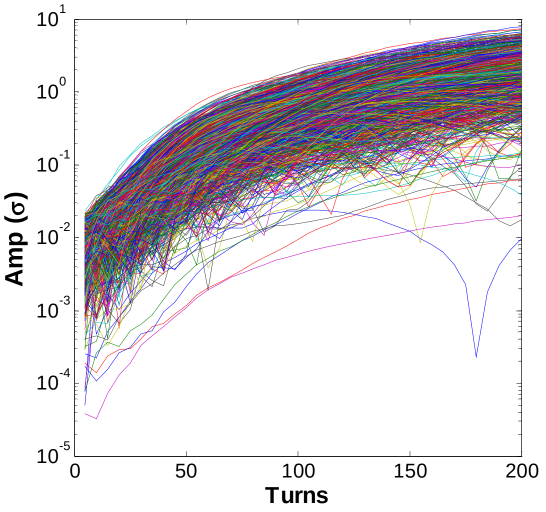
Effect of interaction points 2/2

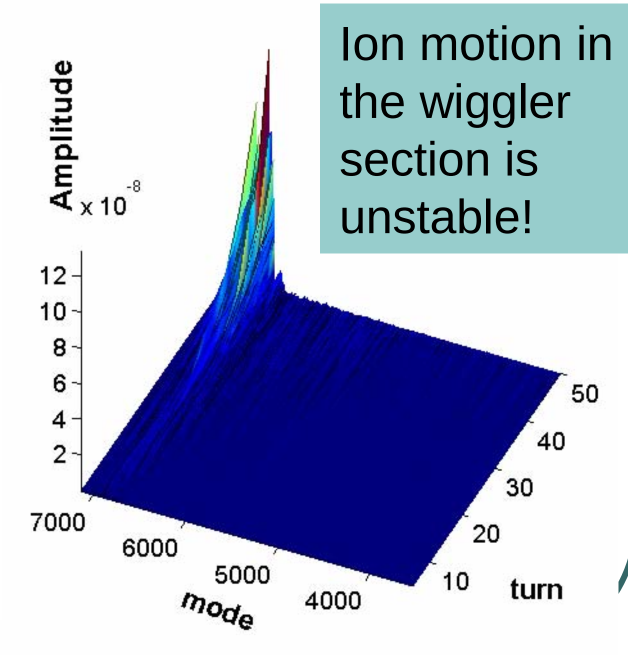
Nb=5782, N IPs



- Optics is included in the simulation
- Growth time in vertical Plane=13turns
- Simulation gives $\boxed{(\Delta\Omega_i)_{rms} \approx 0.3}$







Ion motion in the wiggler section is unstable!

Emittance effect 1/3

Emittance dependence

❑**Trapping condition**

$$A_{x(y)} = \frac{N r_p S_b}{2(\sigma_x + \sigma_y)\sigma_{x(y)}}$$

Ions with a relative molecular mass greater than *Ax(y)* will be trapped

❑ **Gap effect**

$$\boxed{\mathrm{IRF} = \frac{1}{N_{train}} \frac{1}{1 - \exp(-\tau_{gap} / \tau_{ions})}} \quad \tau^{ion}_{x(y)} \sim \frac{2\pi}{c} \left(\frac{(\sigma_x + \sigma_y)\sigma_{x(y)}}{4 N r_p} \right)^{1/2}$$

More ions are trapped with a larger emittance

❑**Instability**

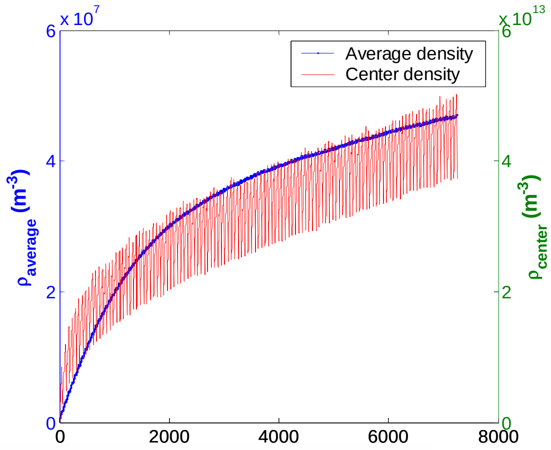
$$\boxed{\frac{1}{\tau_e} \approx \frac{c r_e \lambda_i \beta_y}{3\sqrt{2}\gamma\sigma_y\left(\sigma_x + \sigma_y\right)} \frac{1}{(\Delta\Omega_i)_{rms}}}$$

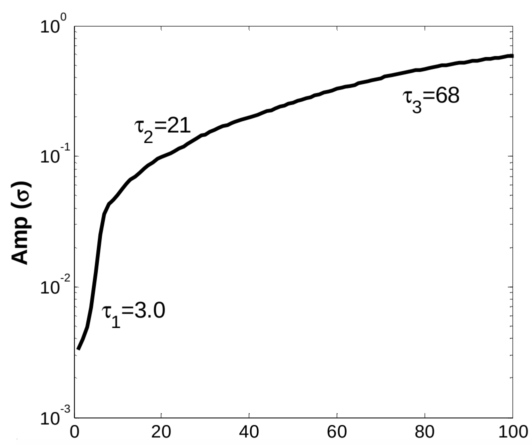
Lower instability rate with a larger emittance

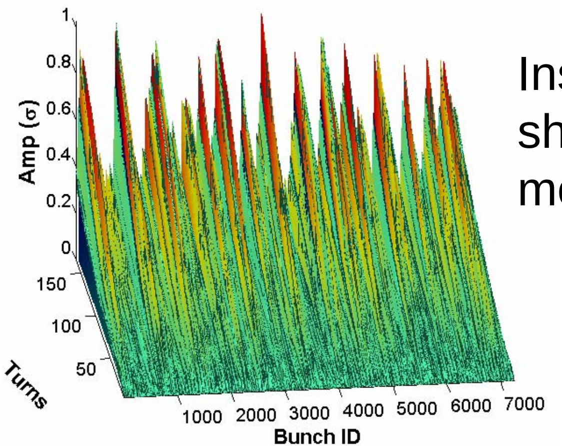
Emittance effect 2/3

5782nb 4rd damping time

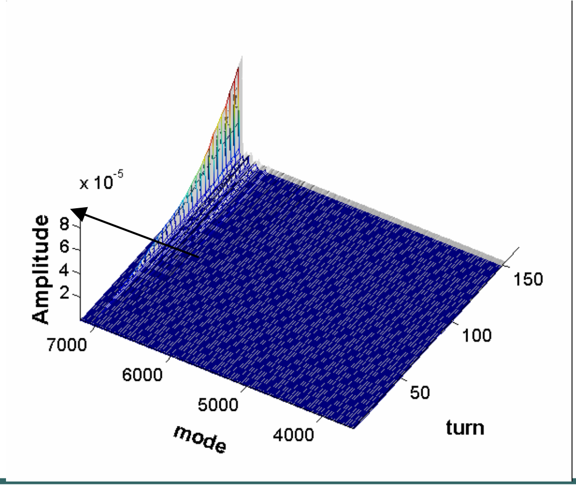
Long term of ion accumulation comparing with equilibrium emittance





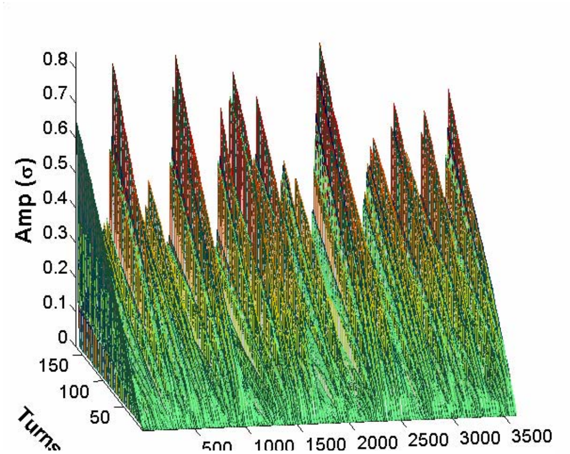


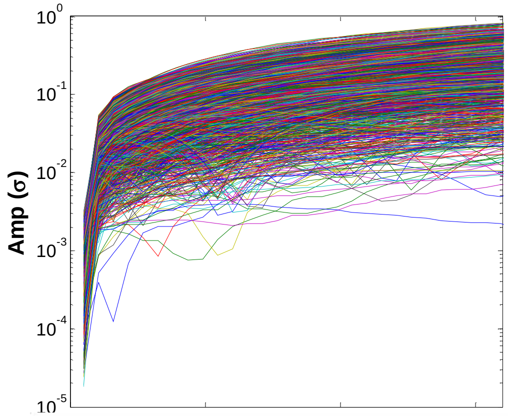
Instability shifts to low modes



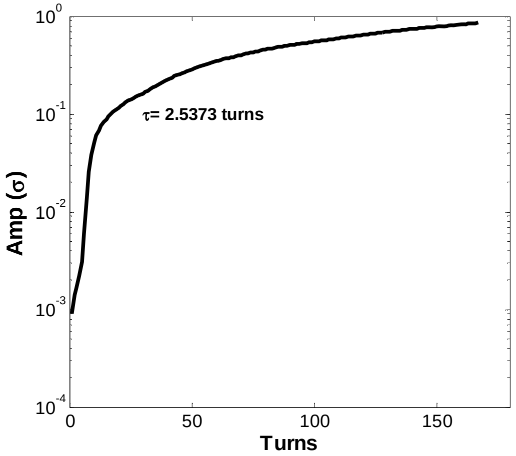
Emittance effect 3/3

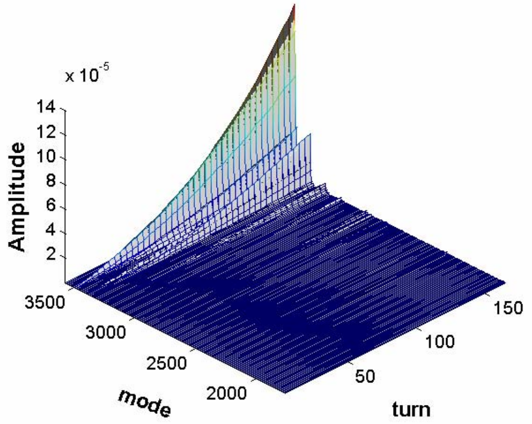
2767nb pattern 3rd damping time



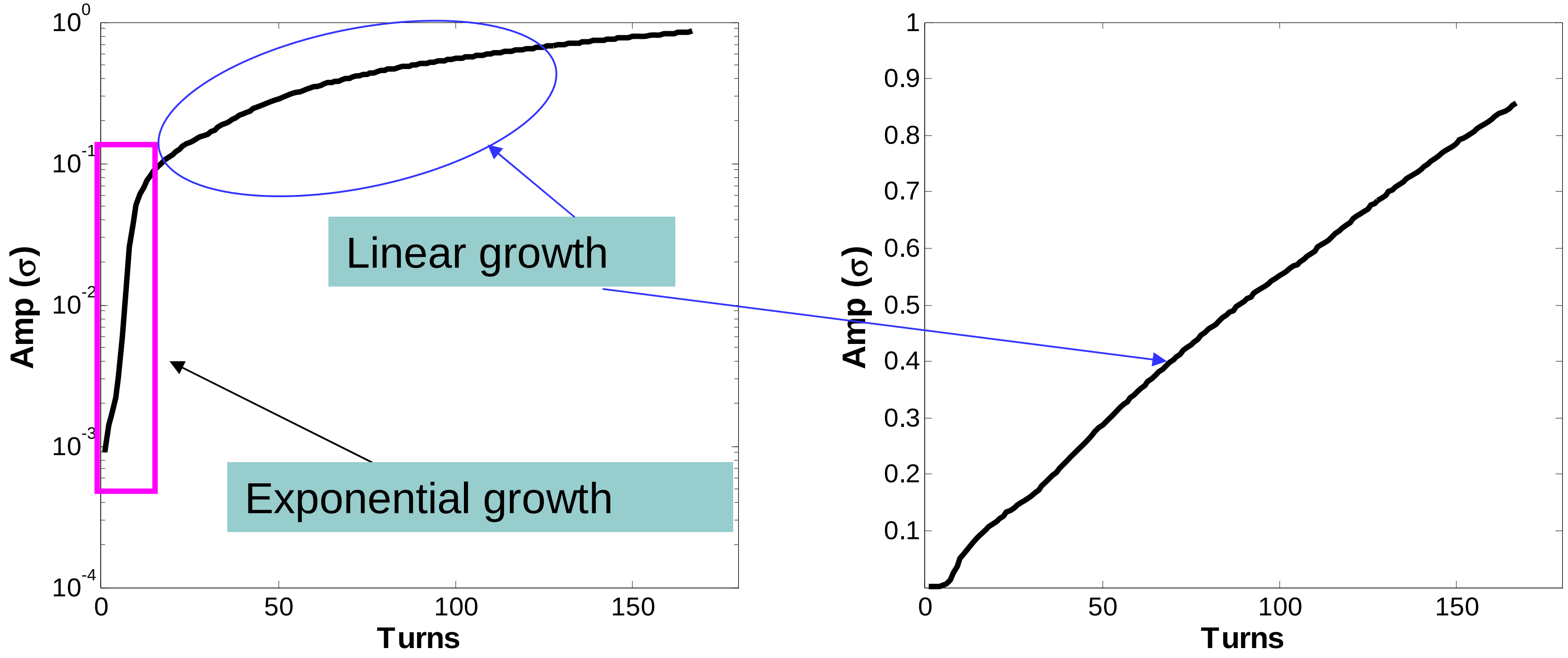


Tau~3 turn





Exponential & linear growth



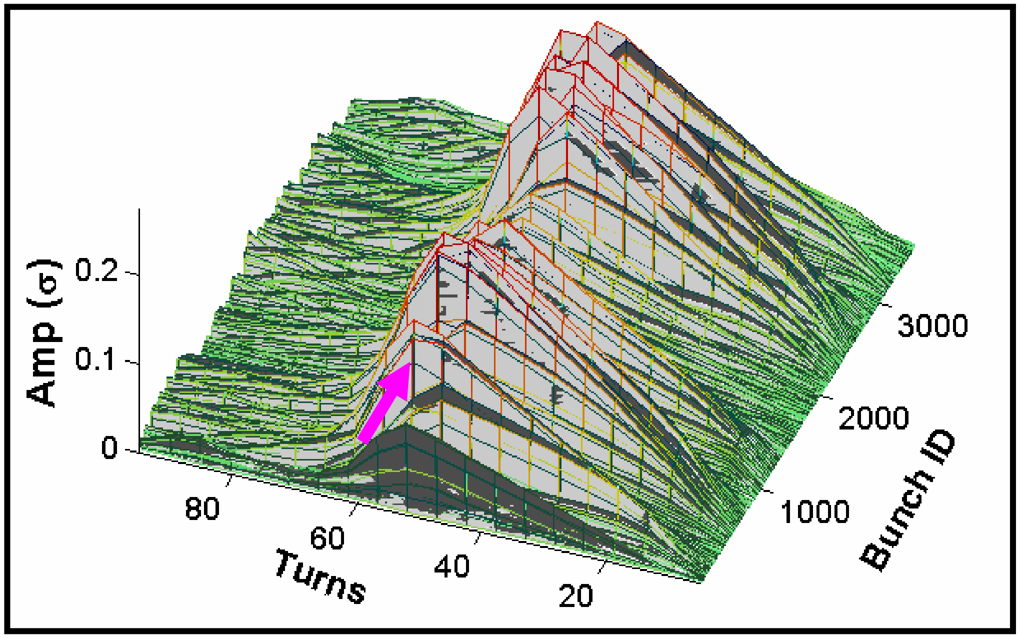
Linear growth

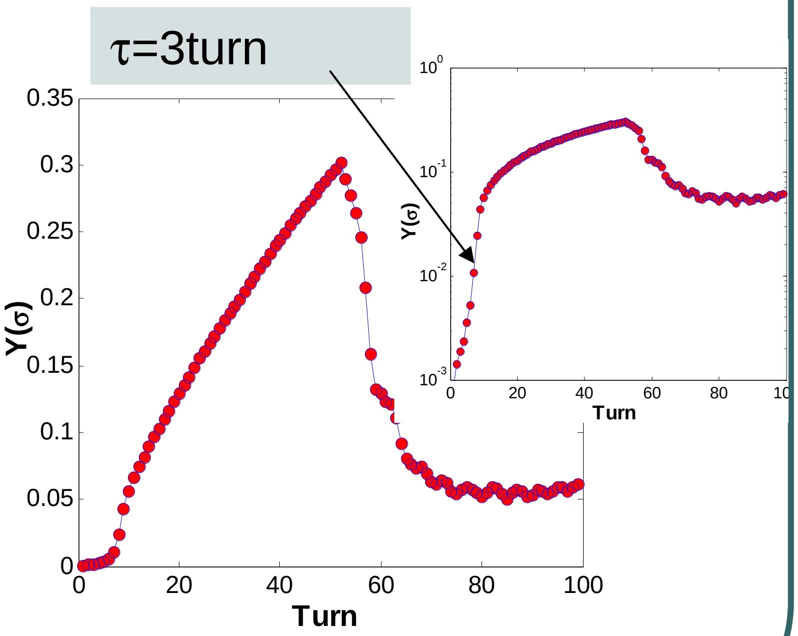
Exponential growth

fileampmax_ocs_2767nb3d5g

Can a slower feedback suppress the instability?

- A bunch-by-bunch feedback with a damping rate slower than the exponential growth rate may limit the oscillation amplitude in the exponential growth region (0.1~1sigma) by suppressing the linear oscillation.

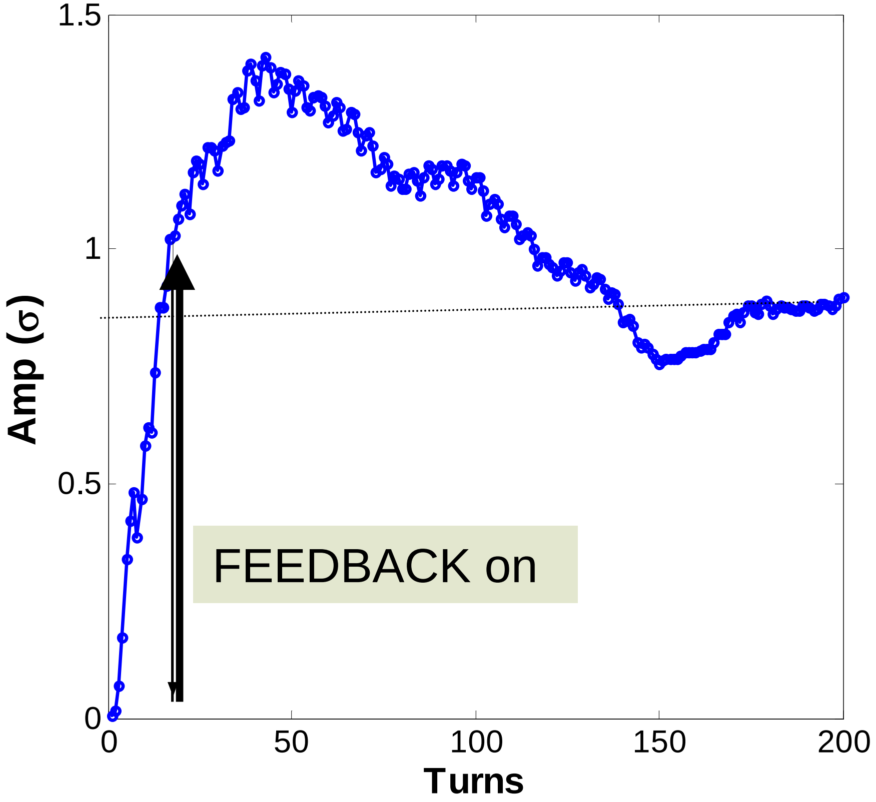



τ=3turn

Feedback damping time 10 turn. It is turned on around 50th turn when the instability is already developed. (file:ocs_2767nb3devefdbk_amp)

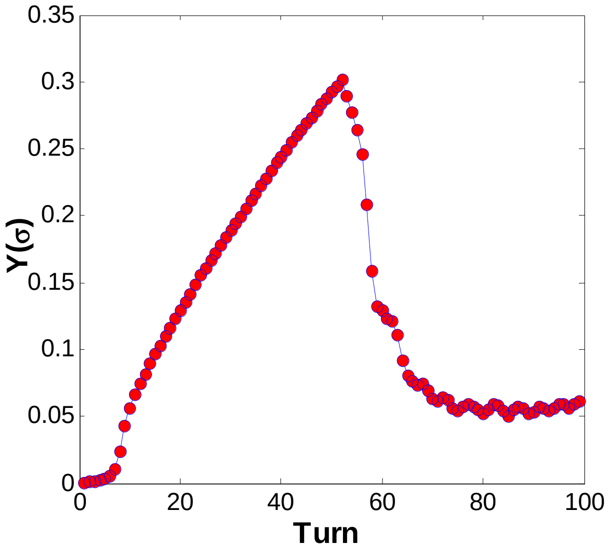
Feedback effect; Example 2

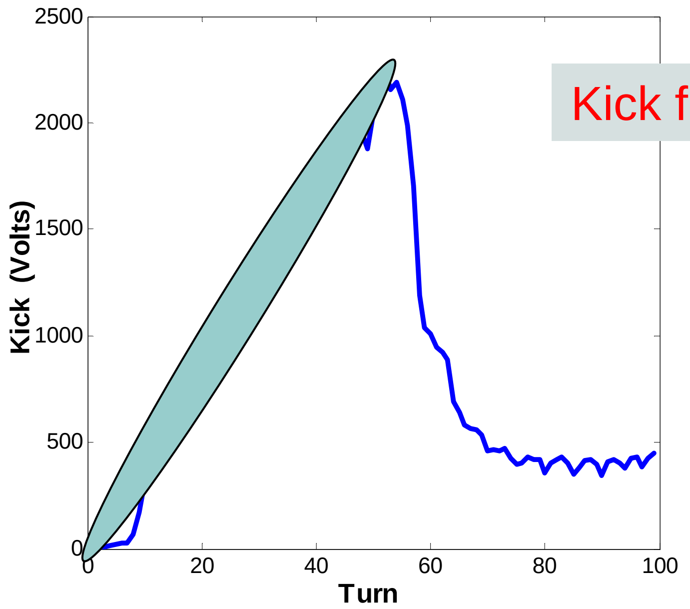
- ➢Feedback damping time 10 turns
- ➢FII instability growth time <10 turns
- ➢The saturation level depends on the instability character and feedback gain



Bunch-by-bunch Feedback System

- **Required Bandwidth: 325MHz**
- **Design Feedback damping time: 0.2ms(10 turns) (FII can be faster)**
- **Maximum voltage: >20kV! (*required from resistive wall instability with τ> 30turns; injected emittance 100nm, beta function=40m, injection offset = 1mm*)**





Kick for ion instability

Possibility to increase gain limit?

H. Fukuma

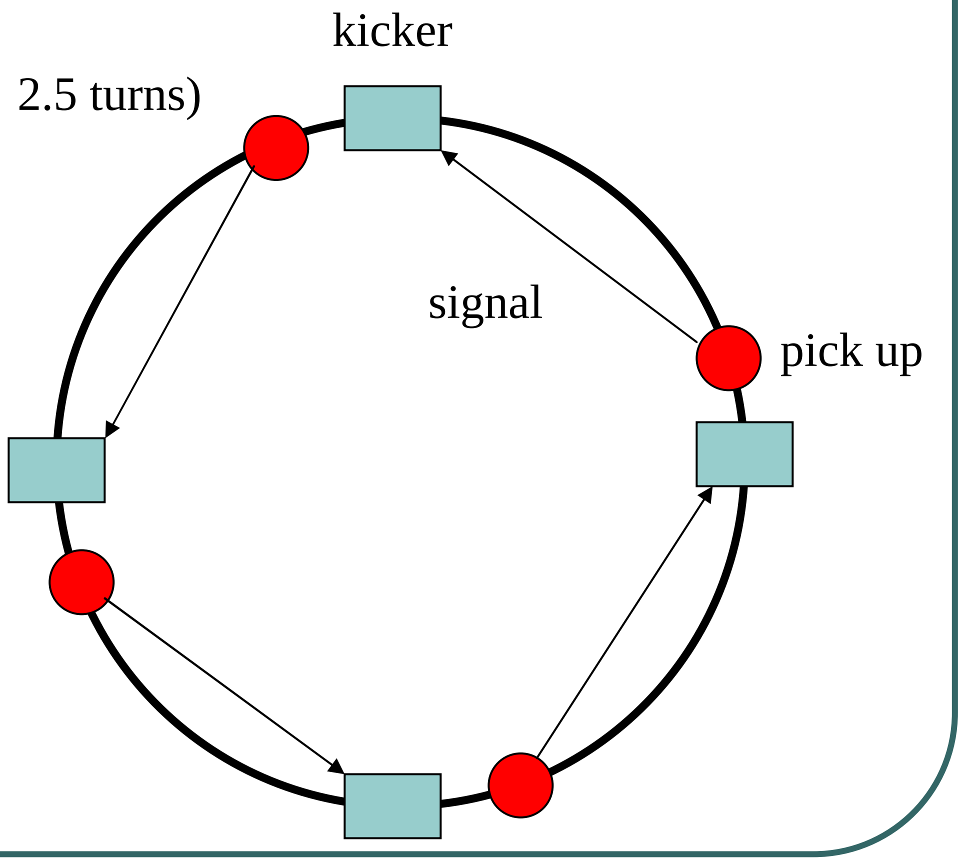
4 systems with feedback delays of a quarter of a turn

(10 turns → 2.5 turns)

→ 4 times faster damping time

Straight signal paths cutting across the arcs must be provided to match the beam flight time.

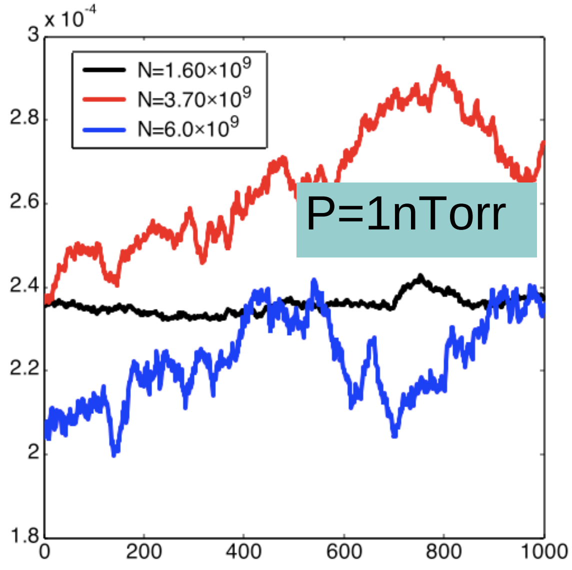
How many kickers can be installed in the ring theoretically and technically ?



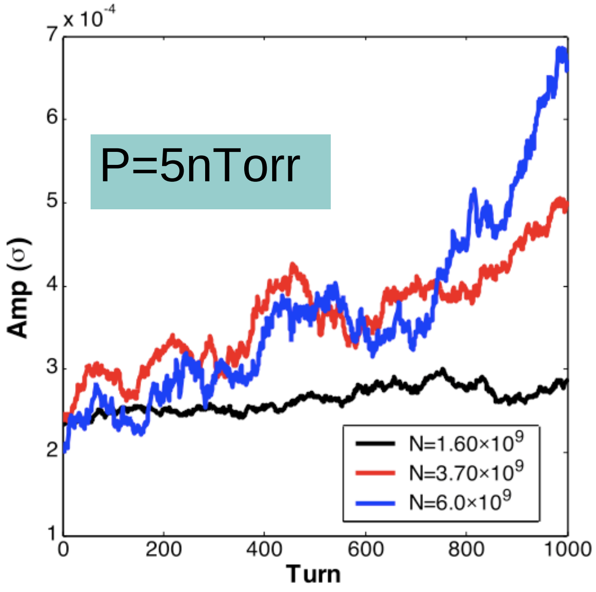
Outlook

- Work with vacuum experts to specify the vacuum
- Work with feedback experts to study the feedback effect. (e.g. including err/noise in the modeling; increasing damping rate by multi-kick per turn? ...)
- Study of the emittance blow-up
- Study other mitigations
- Program update (Adaptive simulation…)
- Benchmark the program (1st ATF experiment data available; and some data from CESR)
- ……

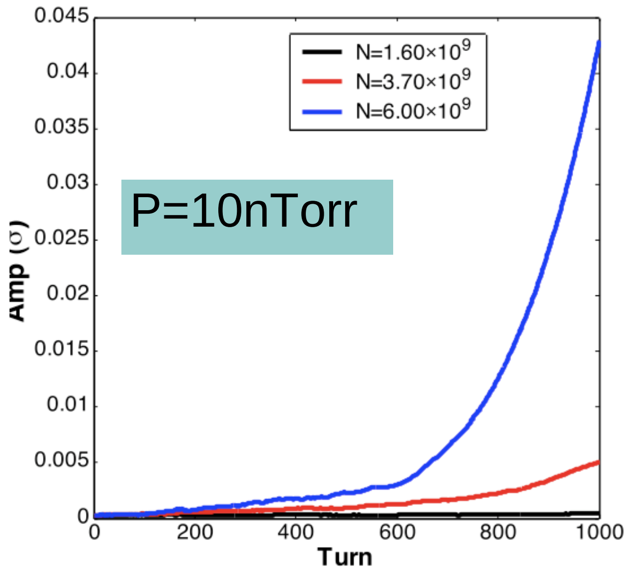
FII at ATF (simulation)



P=1nTorr

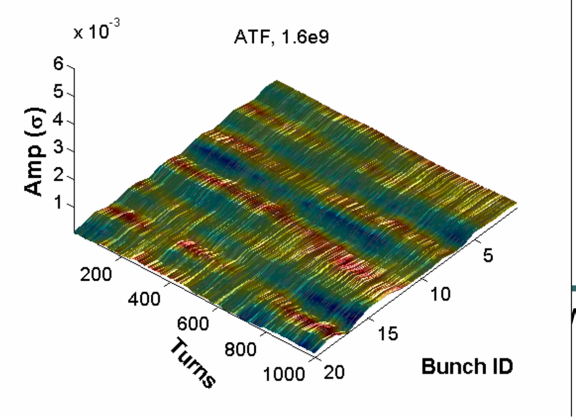


P=5nTorr

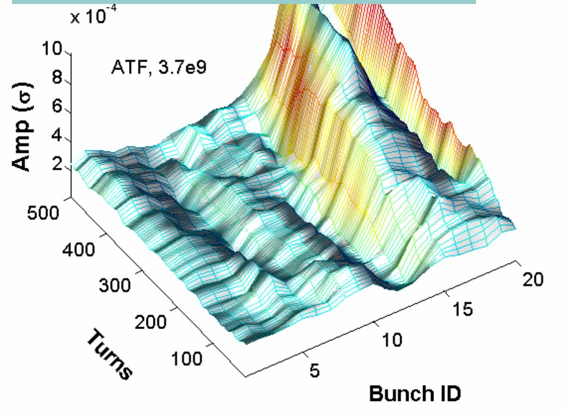


P=10nTorr

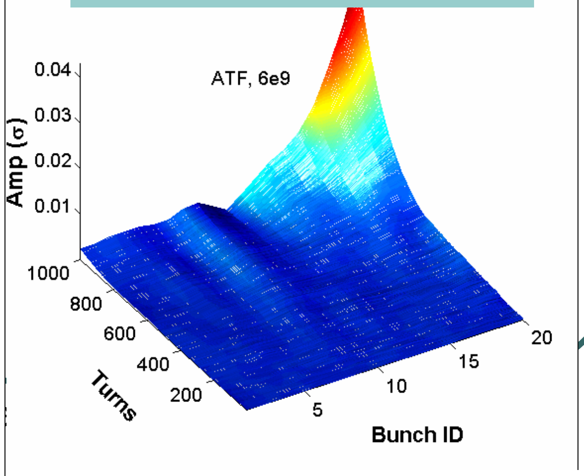
P=10nTorr, N=1.6E9



P=10nTorr, N=3.7E9



P=10nTorr, N=6E9



Summary

- Ion instability was simulated with different conditions.
- Gaps between bunch trains can significantly lower the ion density.
- The fastest vertical instability Growth time at 1nTorr < 10 turns (rapid growth region); Instability in Horizontal is weak.
- A bunch-by-bunch feedback with damping time 10 turn can damp the beam oscillation to a amplitude at the order of the beam size. Therefore, the ion instability may not cause a beam loss. However, the remained dipole oscillation may lead to a loss of luminosity.
- Many qualitative experimental verifications of dipole instability, quantitative verification is not done yet.
- Besides train gap (longer gap help, but we lose luminosity), vacuum and feedback (difficult?), other cures also should be investigated

Acknowledgement

- **Thank your all !**
- Thanks to A.Wolski, Y. Cai, M. Venturini and G. Xia for their efforts to arrange this talk
- Thanks to A. Chao, G. Stupakov, S. Heifets, H. Fukuma, K. Ohmi, G. Xia, E. Kim, A. Wolski …… for many useful discussions
- Thanks to the enormous efforts of Juni Urakawa and their team for the beam study