An Accurate Model of Beam Ion instability & its application to ILC DR and SPEAR3*

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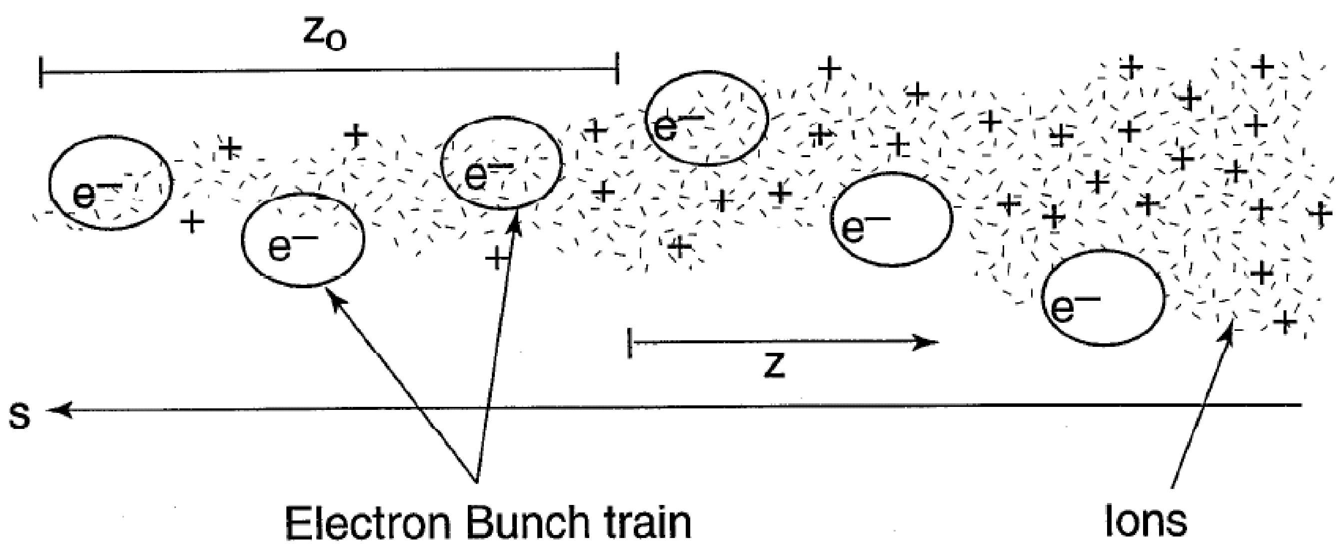
Contents

Introduction

- **Ions generated by beam-gas ionization**
- **Ions are trapped along the electron-bunch train;**
- **The ions created by the head of the bunch train perturb the bunches that follow.**
- **Occur in rings, linacs or beam transport lines;**
- **Broad-band spectrum**
- **Normally only in vertical direction due to the small vertical beam size**



Observations-Beam Size Blow-up

- The instability has been observed at many laboratories when vacuum is not good
  - Artificially increasing the vacuum pressure (ALS, PLS, ATF)
  - At commissioing times or restart after a long shutdown (ESRF, DIAMOND,…)
  - After installation of new (insertion device) chambers (SPring-8, ESRF, …)

ELETTRA

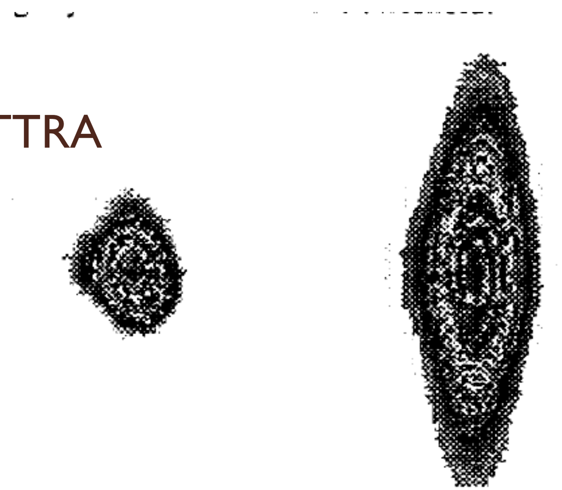
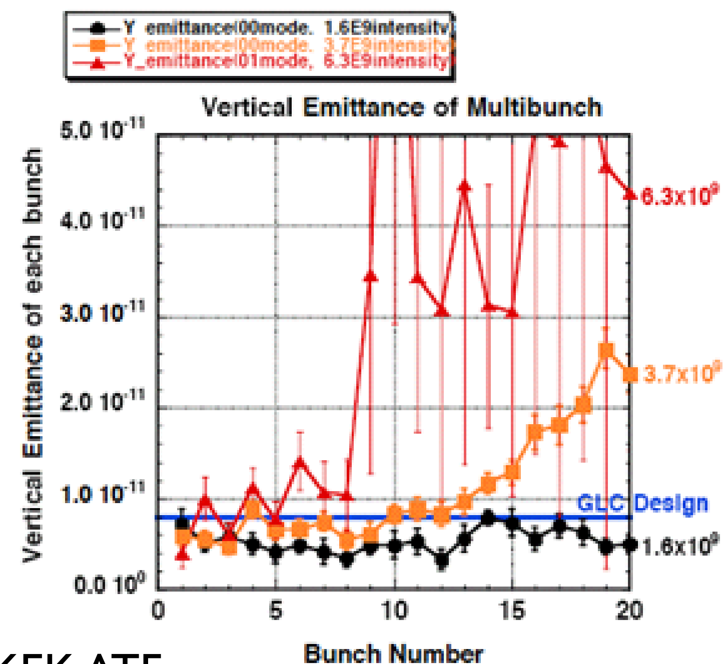


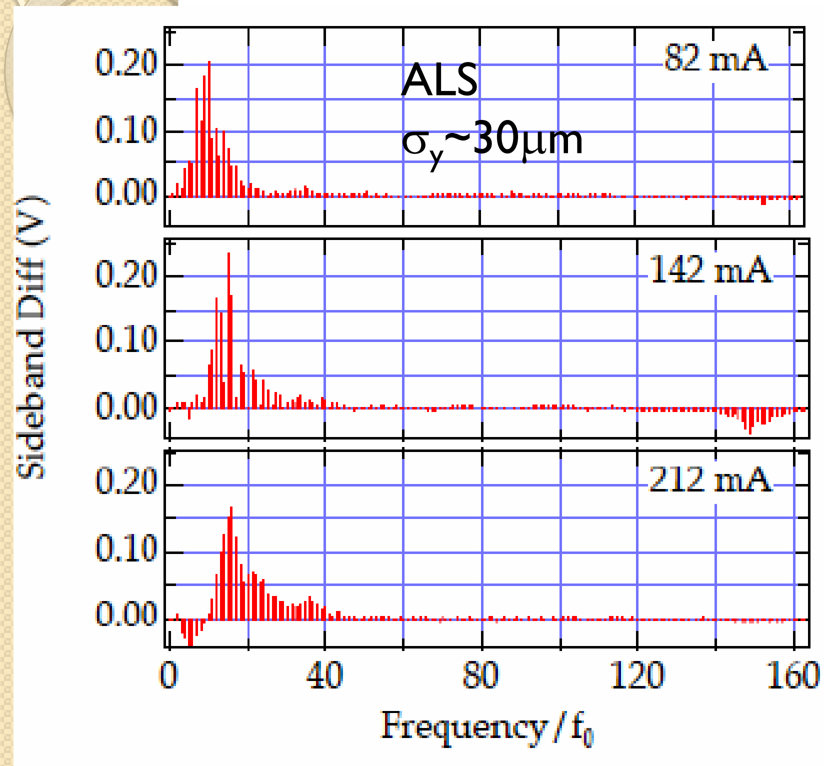
Figure 4. Synchrotron radiation profile just before and after the vertical beam blow-up threshold.

C. J. Bocchetta, et. al. 1994



KEK ATF

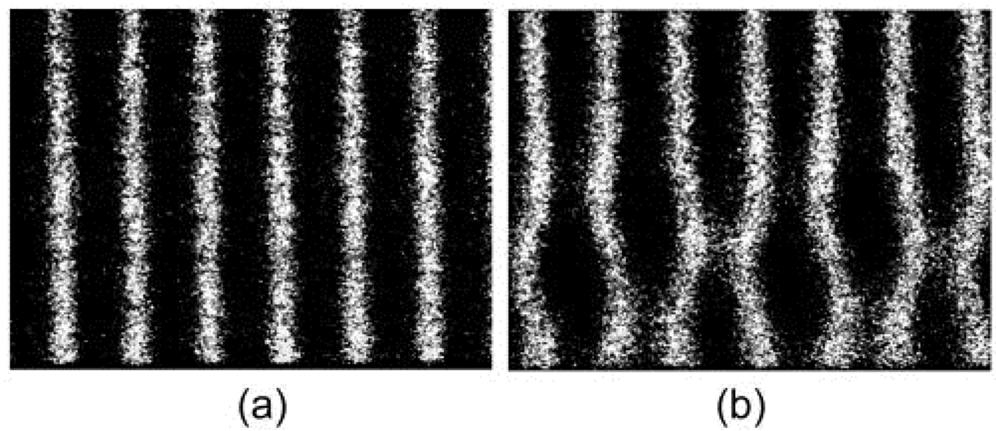
Observations---Coupled bunch instability



ALS

Beam spectrum at different beam current

(J. Byrd et al., PRL, ***79*** *(1997) 79)*



P=0.4nTorr (normal)

P=1nTorr w/o He injection

Dual sweep streak camera image of a bunch train

(M. Kwon et al., Phys. Rev. ***E57*** *(1998) 6016)*

FII at SSRF with nominal vacuum

(Bocheng Jiang, et. al. NIMA 614, 2010)

Single bunch train with bunch Number 450, 37.5% gap (0.54μs)
Beam current: 200mA
Vertical emiittance: 27.3pm
Horizontal emittance 3.9nm

Table 1
Main parameters of the SSRF storage ring.

Beam energy (GeV)	3.5
Circumference (m)	432
Harmonic number	720
Natural emittance (nm rad)	3.9
Transverse coupling	0.7%
Beam current (mA)	≥ 200
Betatron tunes Q_x/Q_y	22.22/11.
Synchrotron tune Q_s	7.2×10^{-3}
Momentum compaction α	4.27×10
Natural chromaticity ξ_x/ξ_y	$-55.7/-$
Relative energy spread	9.7×10^{-4}
RF frequency (MHz)	499.654
Damping times $\tau_x/\tau_y/\tau_s$ (ms)	7.35/7.36

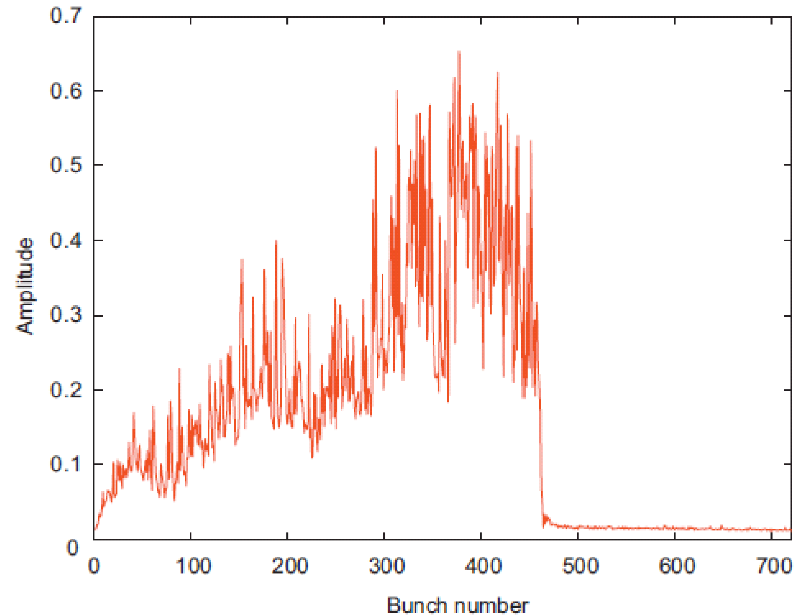
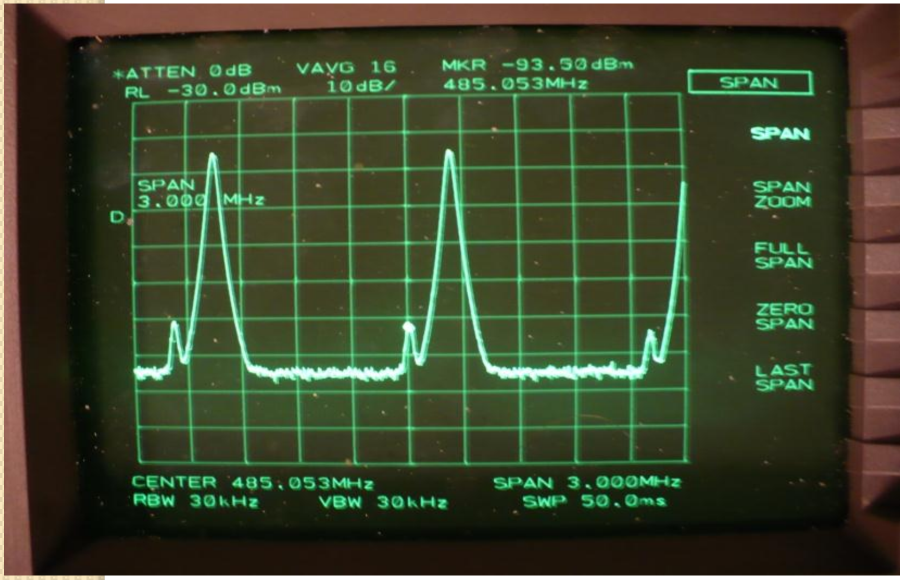


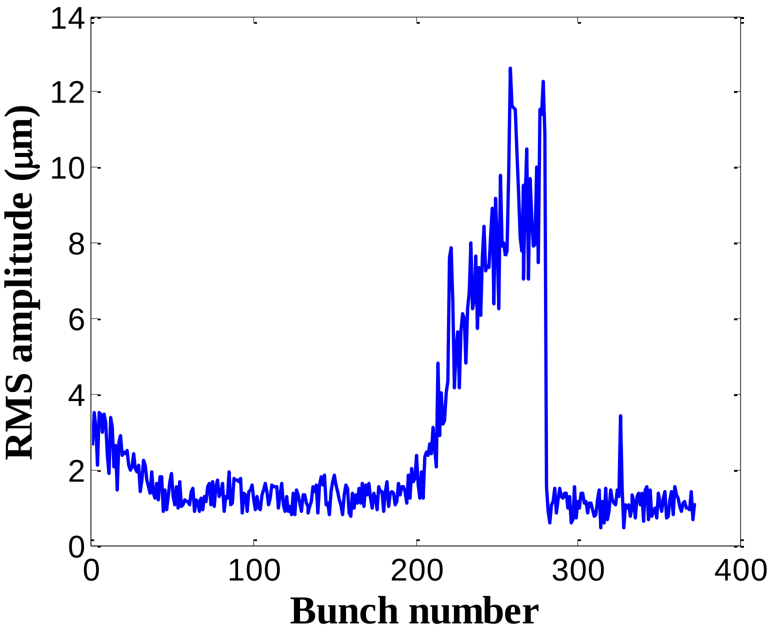
Fig. 1. The relative oscillation amplitude of bunch centroid versus the bunch number (data taken from the bunch-by-bunch BPM).

FII@SPEAR3

Small vertical oscillation (~10 μm) has been observed when a single bunch train beam filling pattern is used



Beam spectrum at 200 *mA* with a single bunch train filling pattern



Measured vertical amplitude along the bunch train (200mA)

Main Parameters of SPEAR3 and the ILC DTC02 damping Ring

Physics	Symbol/Unit	SPEAR3	ILC DTC damping ring
Beam Energy	E_0 [GeV]	3	5
Circumference	C [m]	234	3238.76
Horizontal Emittance	ε_x [nm]	10	0.637
Vertical Emittance	**ε_y [pm]**	**14**	**2**
Beam Current	**I [mA]**	**200-500**	**389/779**
Bunch Number	M	280	1312/2625
Harmonic Number	h	372	7022
Bunch Spacing	*ns*	2.1	6.2/3.1
RF Frequency	f_{RF} [MHz]	476.315	650
Revolution Frequency	f_0 [MHz]	1.280	0.09
Tune	n_x / n_y / n_s	14.1/6.18/0.01	48.36/27.22/ 0.03
Momentum Compaction Factor	**α**	**1.6×10^{-3}**	**3.36×10^{-4}**
Energy Spread	σ_e	9.8×10^{-4}	1.0×10^{-3}
Bunch Length	σ_l [mm]	6	6
Radiation Damping Time	$\tau_x/\tau_y/\tau_z$ [ms]	4.0/5.3/3.2	22/22/11
Total Vacuum Pressure	P [nTorr]	0.1~0.5	0.5

Beam filing patterns of ILC DTC02 damping ring

Parameter	KCS	DRFS	FP upgrade
Energy[GeV]	**5.0**	**5.0**	**5.0**
Circumference[m]	**3238.76**	**3238.76**	**3238.76**
Emittance $\varepsilon_x/\varepsilon_y$ [pm]	**637/2**	**637/2**	**637/2**
Harmonic number	**7022**	**7022**	**7022**
Number of bunches	**1312**	**1312**	**2625**
Beam current[mA]	**389**	**389**	**779**
Bunch spacing [λ_{RF}]	**4**	**4**	**2**
Beam Filling period	**19**	**14**	**29**
Fill pattern (1period)			
Train [bunch number]	**34**	**22**	**44**
Gap [in λ_{RF}]	**45**	**33**	**31**
Train [bunch number]	**34**	**22**	**45**
Gap [in λ_{RF}]	**49**	**33**	**31**
Train [bunch number]		**22**	
Gap [in λ_{RF}]		**33**	
		23	
		33	
Bunch length[mm]	**6**	**6**	**6**
Energy spread, σ_δ	**1×10^{-3}**	**1×10^{-3}**	**1×10^{-3}**
Mom. compaction, α	**3.36×10^{-4}**	**3.36×10^{-4}**	**3.36×10^{-4}**
Tunes, ν_x / ν_y / ν_s	**48.36 /27.22 /0.03**	**48.36/27.22 / 0.03**	**48.36/27.22 /0.03**
Damp times τ_x /τ_y /τ_s [ms]	**22 / 22 / 11**	**22 / 22 / 11**	**22 / 22 / 11**
E loss/turn, U_0 [MeV]	**4.87**	**4.87**	**4.87**
RF voltage, V_{RF} [MV]	**12.83**	**12.83**	**12.83**

Summary of beam-ion instability Theory

- **FII (single bunch train with long gap)**
  - **(I)** Quasi-exponential growth (linear force)

(T. O. Raubenheimer and Frank Zimmermann, PRE,51,5487,1995)

$$\frac{1}{\tau_c}=\frac{1}{2}\frac{cr_e\beta_y Nn_b}{\gamma}\hat{W}(l)=\frac{r_e c\beta_y\rho_{i,eff}}{\gamma}\frac{\omega_i Z}{c}\qquad \rho_{i,eff}=\frac{2\lambda_i}{3\sigma_y(\sigma_y+\sigma_x)}\qquad \omega_{i,x,y}=c\left(\frac{2\lambda_e r_p}{A\sigma_{x,y}\sigma_{x,y}(\sigma_y+\sigma_x)}\right)^{1/2}$$

  - **(II)** Exponential growth (includes nonlinear space charge force)

(E. Kim and K. Ohmi, Japanese Journal of Applied Physics 48 (2009) 086501)

$$\frac{1}{\tau_{kim\_Ohmi}}=\frac{1}{2}\frac{r_e c\beta_y\rho_{i,eff}Q_0 3}{\gamma\quad 2}$$

(only when time is small?)

  - **(III)** Exponential growth (Linear space charge + Optics with **large frequency spread)**

(Gennady Stupakov, KEK Proceedings 96-6)

$$\frac{1}{\tau_e}\approx\frac{r_e c\beta_y\lambda_i}{3\gamma\sigma_y(\sigma_y+\sigma_x)}\frac{1}{(\Delta\omega_i/\omega_i)_{rms}}=\frac{1}{2}\frac{r_e c\beta_y\rho_{i,eff}Q^{G.S}_{optics}}{\gamma}\qquad Q^{GS}_{optics}=(\omega_i/\Delta\omega_i)_{rms}/\sqrt{2}$$

  - **(IV)** Nonlinear regime (nonlinear space charge regime) (S. Heifets, PEP-II AP note, 95-20)

- **Uniform/Multi-bunch train filling** (*Includes both nonlinear space charge and optics*)

(L. Wang, et. al. PRSTAB 14, 084401, 2011)

$$\frac{1}{\tau}\approx\frac{r_e c\beta_y\rho_\infty Q}{\gamma}\qquad \frac{1}{Q}=\frac{1}{Q_0}+\frac{1}{Q_{optics}}$$

Growth rate is proportional to the ion density and Q of the wake!!

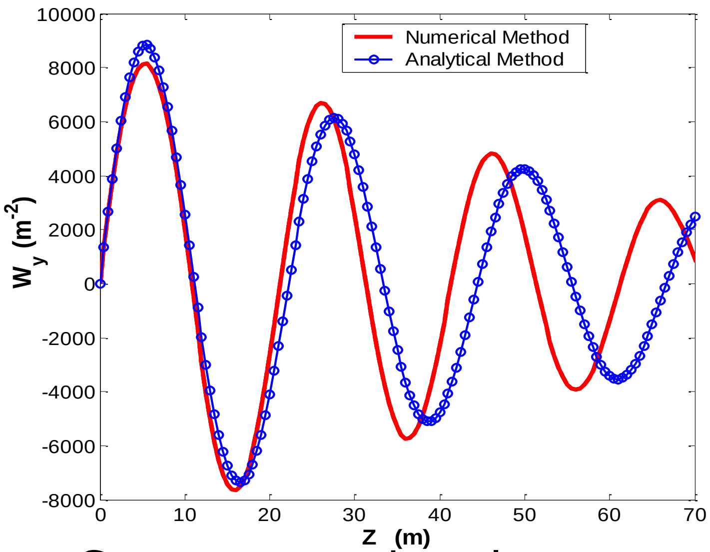
Can we include all effects together?
Nonlinear space charge;
Arbitrary Beam optics;
Arbitrary Multiple gas species vacuum

Our method: Wake function

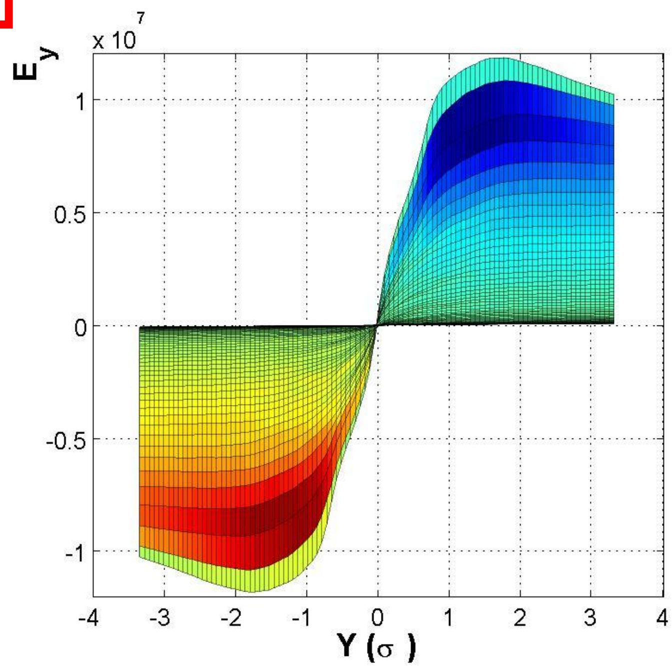
- **The nonlinear space charge force is included. The Q of the wake represents the nonlinearity of the E-force. Typically, it is below 10.**
- **The wake has good linearity when the bunch offset is smaller than the beam size where the fastest instability occurs**

$$W(s)=\frac{4}{3}\frac{\omega_i}{c}\frac{\lambda_i}{\lambda_e}\frac{1}{\sigma_y(\sigma_y+\sigma_x)}e^{-\frac{\omega_i s}{2Qc}}\sin(\frac{\omega_i s}{c})$$

(L. Wang, et. al. PRSTAB 14, 084401, 2011)



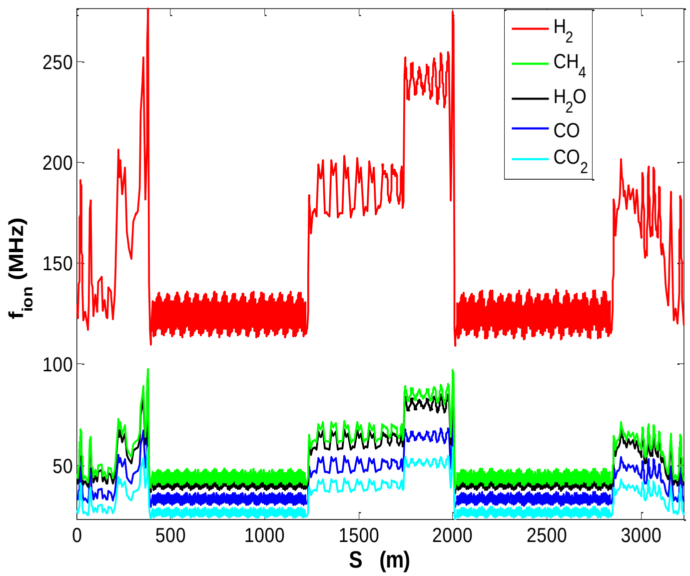
Comparison with analysis



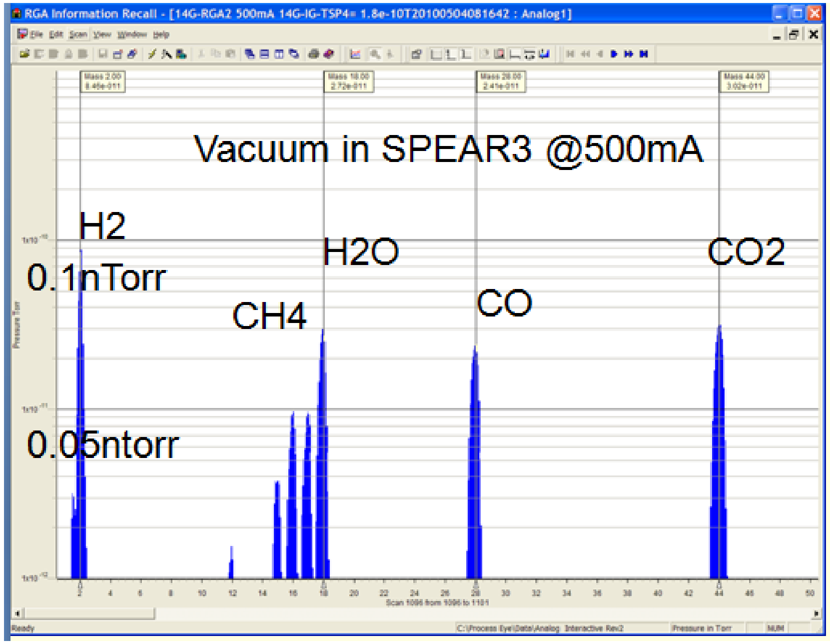
E-field of ion cloud

Effects of Optics & multiple gas species

- Beam size varies along the ring, this frequency spread due to optics provide damping to the instability. How to accurately model it?
- There are multiple gas species in the real vacuum. Does the superposition rule apply?



Ion frequency along the ILC damping ring with the KCS beam



Wake and impedance with arbitrary Optics and Vacuum

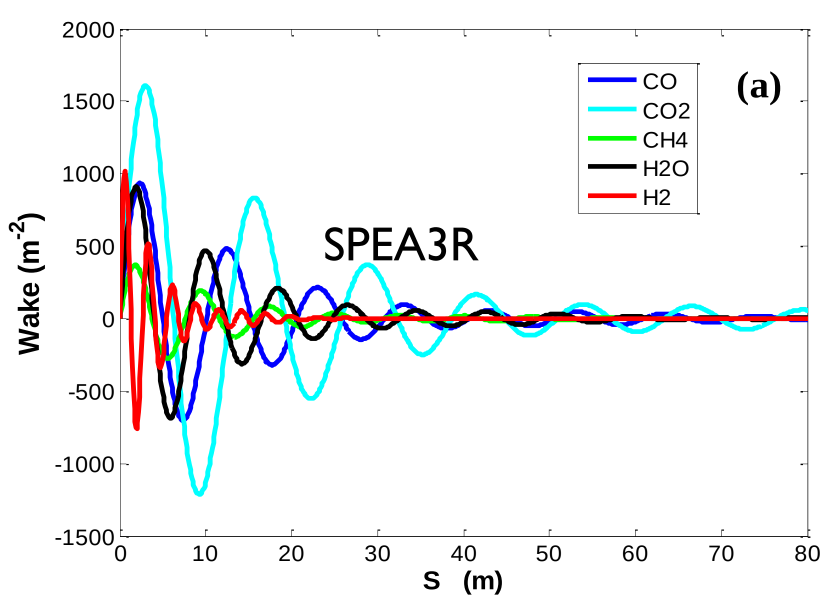
The total wake function of ions along the whole ring

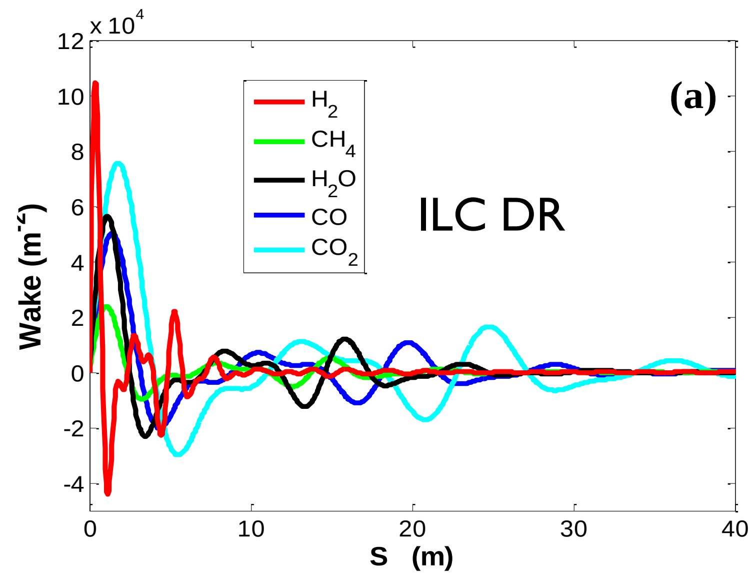
$$W_{ring}(z) = \int_0^C \frac{4}{3}\frac{\omega_{i,y}(s)}{c}\frac{\lambda_i(s)}{\lambda_e}\frac{1}{\sigma_y(s)(\sigma_y(s)+\sigma_x(s))} e^{-\frac{\omega_i(s)z}{2Q_0 c}} \sin(\frac{\omega_i(s)z}{c})ds$$

Ion Frequency:

$$f_{i,y} \approx \frac{c}{2\pi}\left(\frac{4\lambda_e r_p}{3A(\sigma_x+\sigma_y)\sigma_y}\right)^{1/2}$$

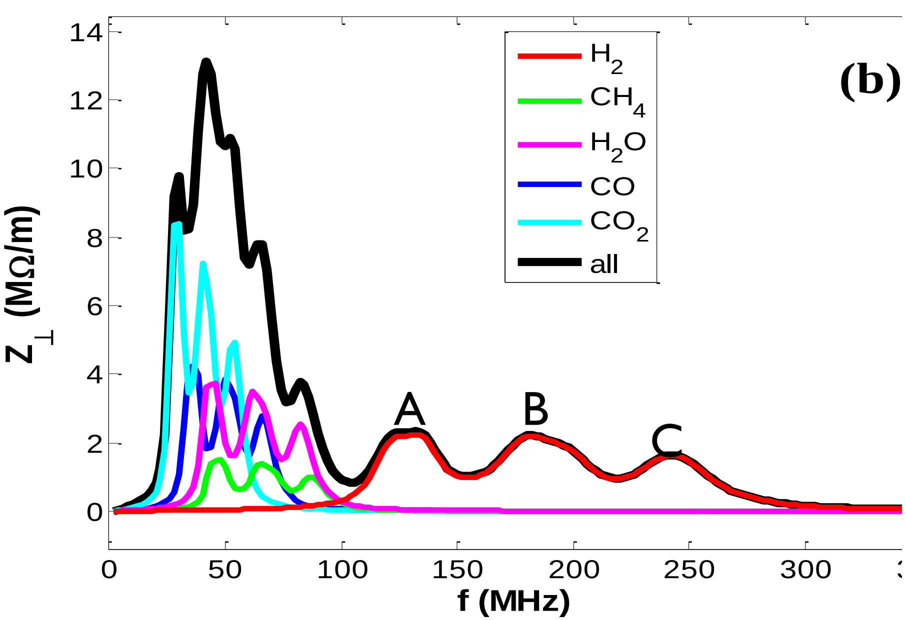
A is the mass number of ion; so the wake is ion species dependent.

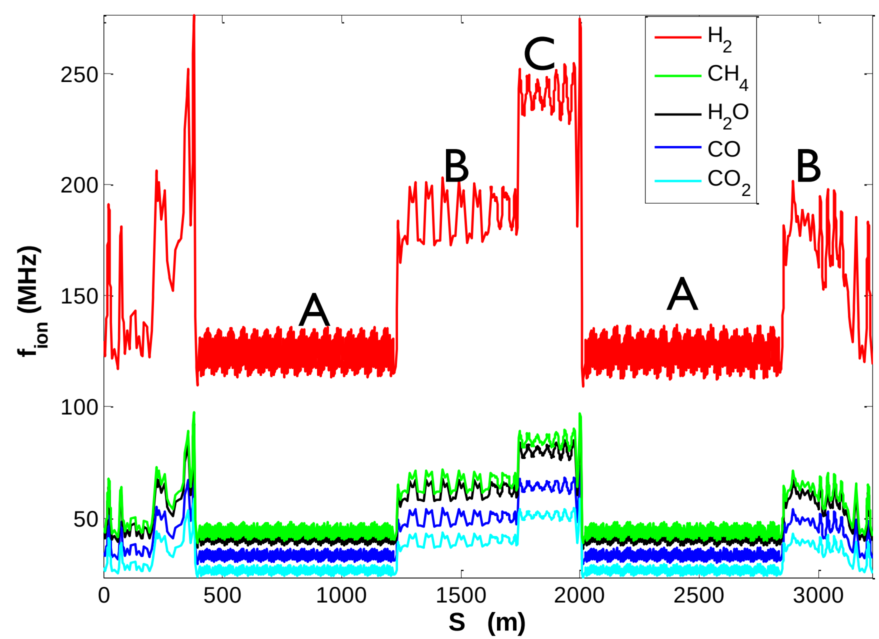




Impedance of ion cloud

Impedance ***provides a rich*** **source of** ***information:***
Easy to know the contributions from individual gas species and also from ions at different location along the accelerator.
Instability growth rate is directly related to impedance(next page)





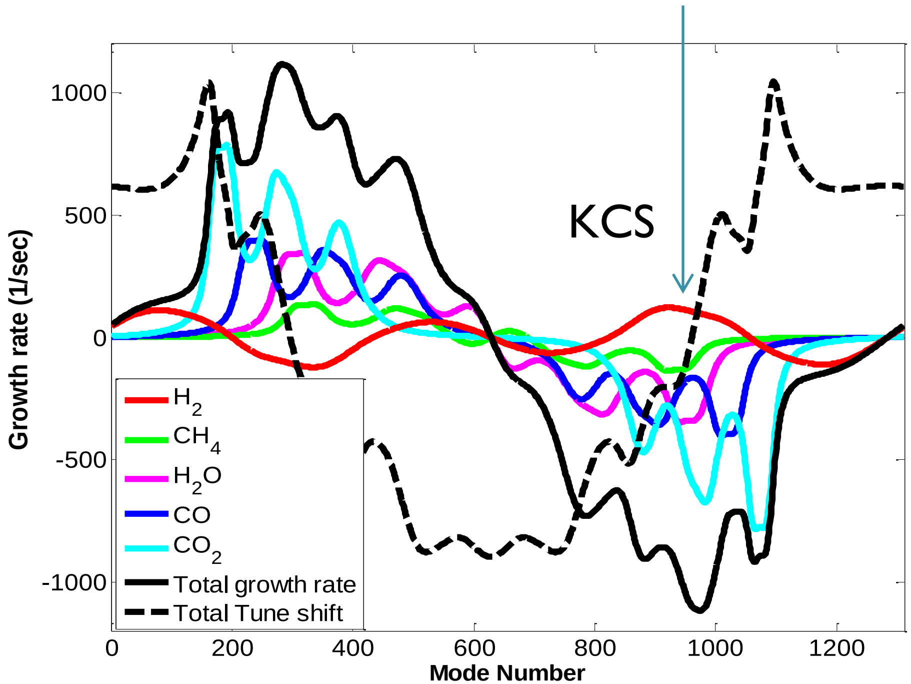
Impedance of ion cloud in ILC DR with KCS configuration. The total pressure is 0.5nTorr. The partial pressure is 48%, 5%, 16%, 14% and 17% for H2, CH4, H2O, CO and CO2 gas, respectively.

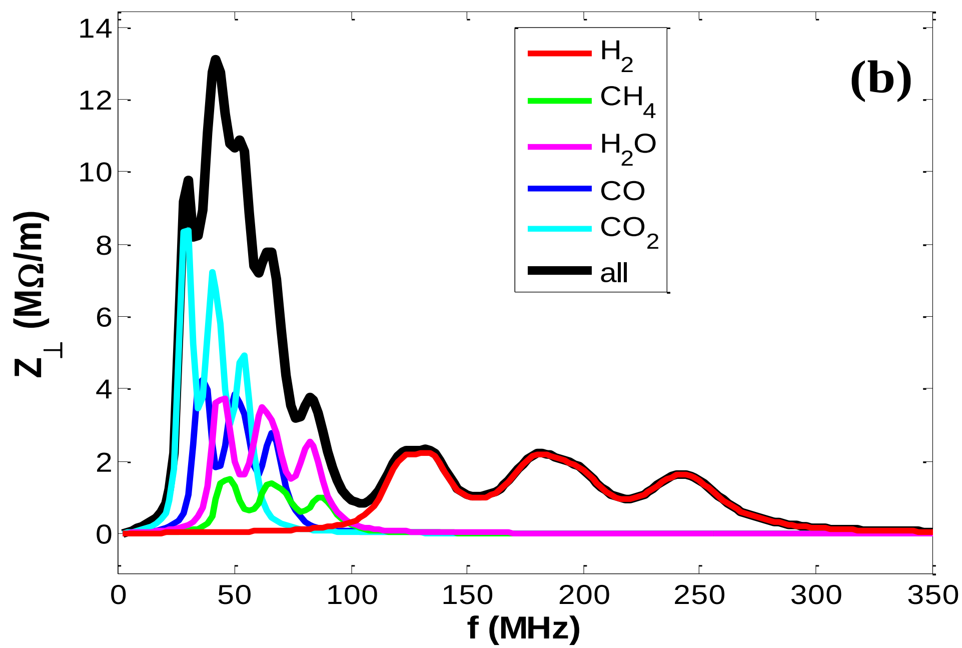
Analysis Beam ion instability in ILC DR

When the beam is evenly filled along the ring, the coherent frequency shift for mode number μ is

$$\Omega_\mu - \omega_\beta = -i \frac{N_e M r_e c}{2\gamma T_0^2 \omega_\beta} \sum_{p=-\infty}^{\infty} Z_\perp((pM + \nu_y + \mu)\omega_0)$$

Damping effect of H2 ion on the most unstable modes





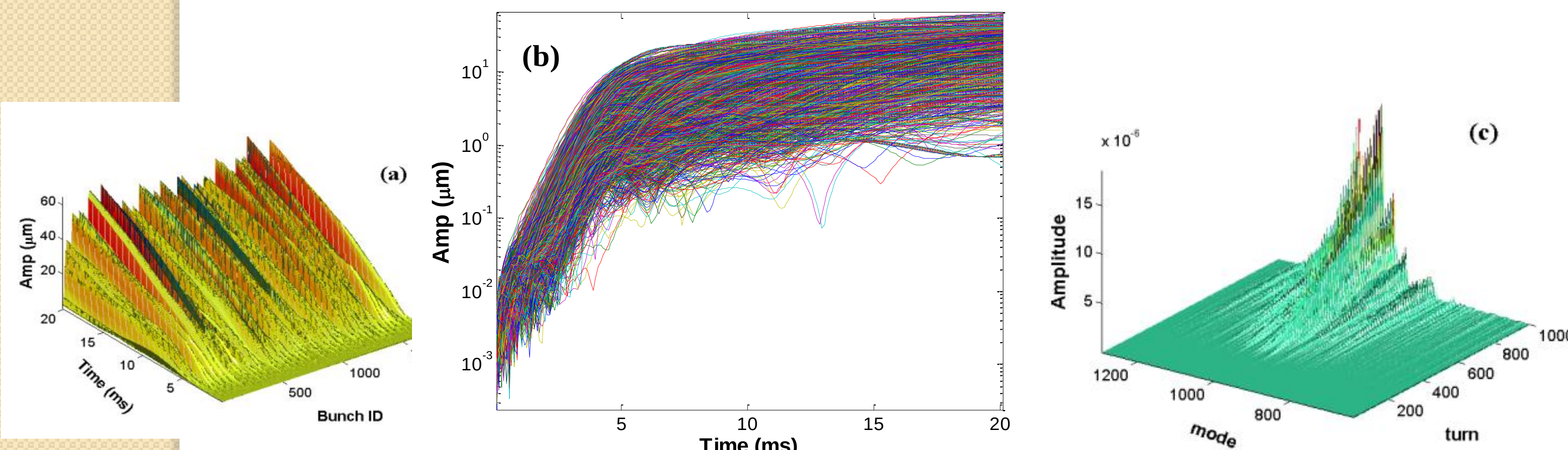
The unstable modes driven by various types of ions for the ILC KCS (Left) and FP upgrade (right) configuration. The total vacuum pressure is 0.5 *nTorr*

Simulation of FII in ILC DR

Simulation is done with PIC code (L. Wang, et. al. PRSTAB 14, 084401, 2011)

The simulation is expensive , >100 CPU hrs

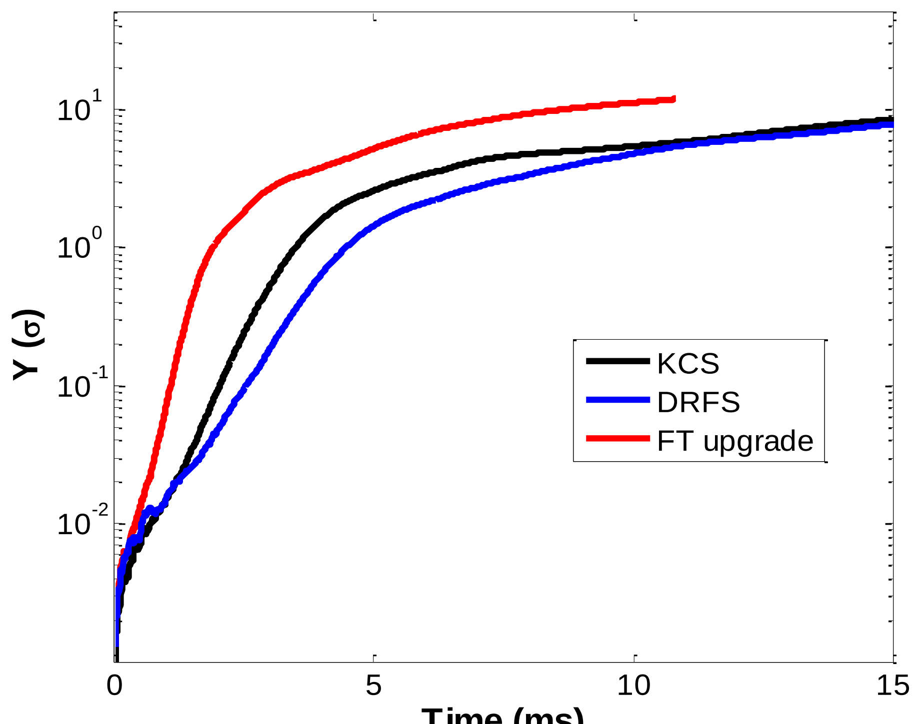
The fastest exponential growth times for the three configurations shown in Table are 0.61 *ms*, 0.91 *ms* and 0.40 *ms*, respectively. Again the simulations agree with our analyses (0.89ms, 1.2ms, 0.7ms)



Simulated vertical beam ion instability in the ILC damping ring with KCS configuration: 3D plot (a) and 2D plot (b) of the growth of vertical amplitude; growth of unstable modes(c) Total pressure 0.5nTorr

FII at ILC DR with DCT04

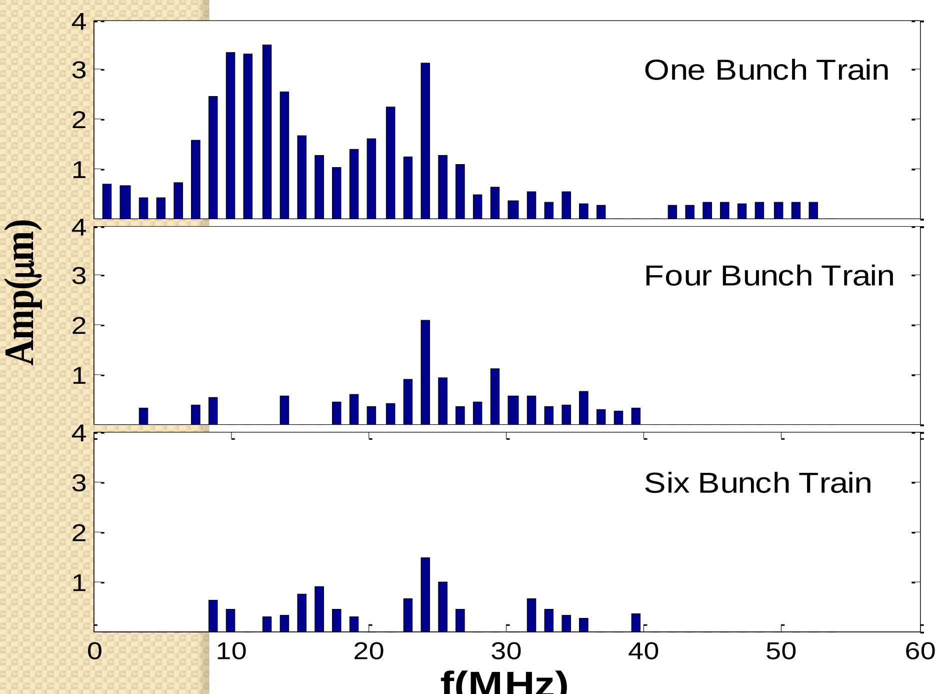
The optics of DCT is recently updated. There is a smaller vertical emittance of 1.2pm in DCT04 design compared with 2pm as in DCT02. Therefore the growth time becomes shorter: they are 0.59*ms*, 0.80*ms* and 0.29 *ms* for KCS, DRFS and FP upgrade beam, respectively (**SLAC-PUB-15268)**



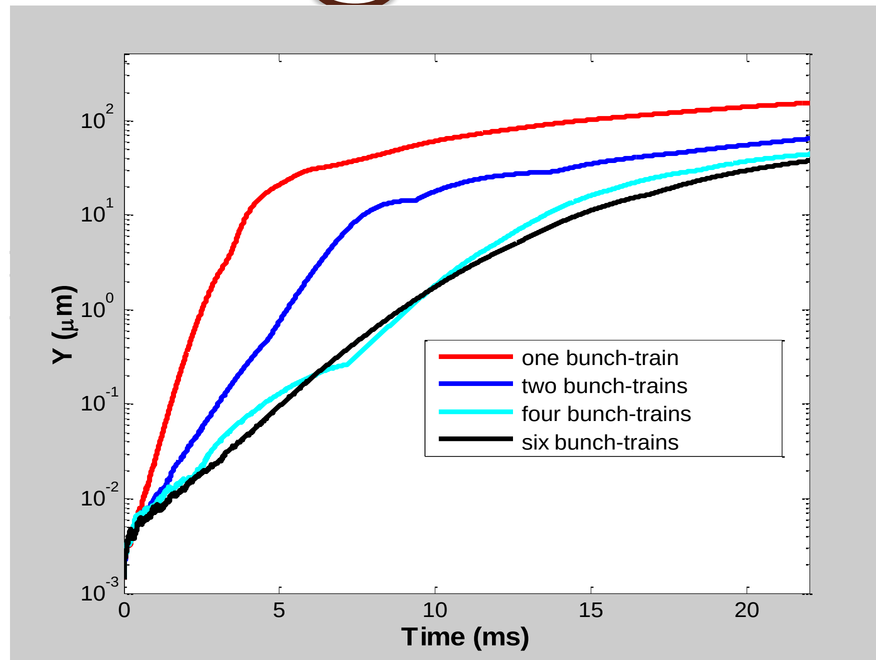
Simulated vertical beam ion instability with DCT04 lattice for various beam configurations

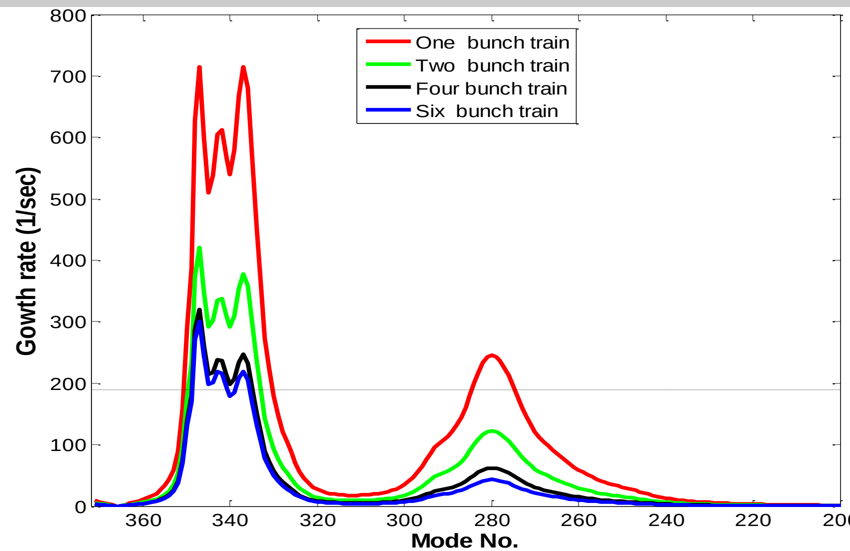
Beam filling patter effect@SPEAR3

Multiple bunch train can mitigate the beam ion instability with high intensity beam by reducing the ion density (Theory and simulation, see L. Wang, et. al. PRSTAB 14, 084401, 2011)

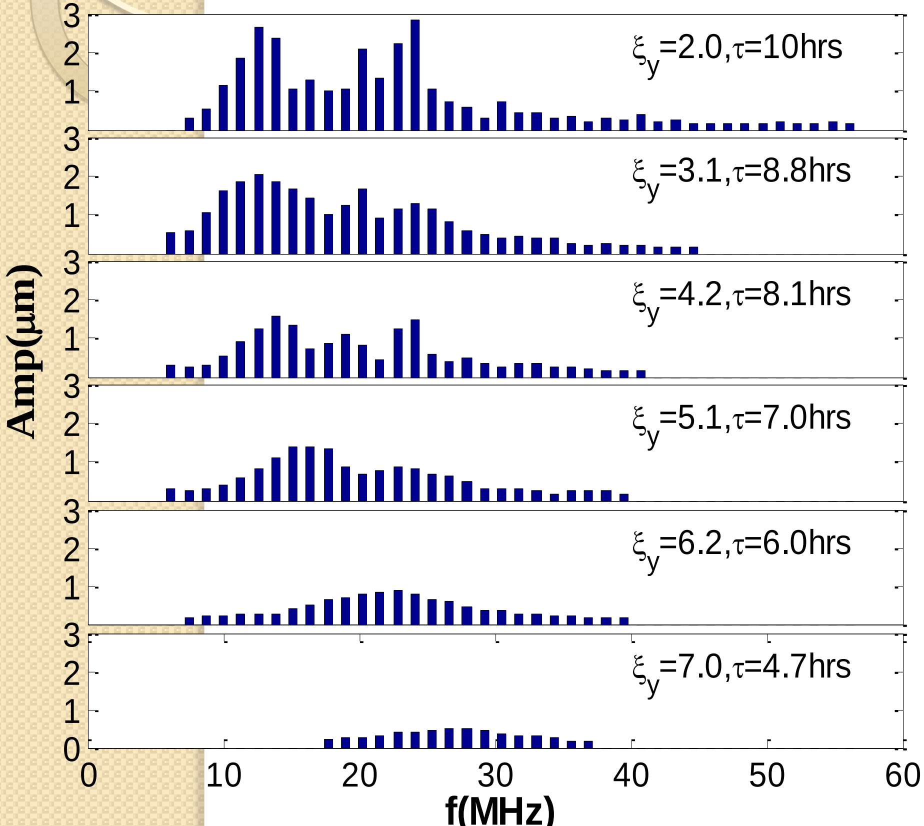


Observation

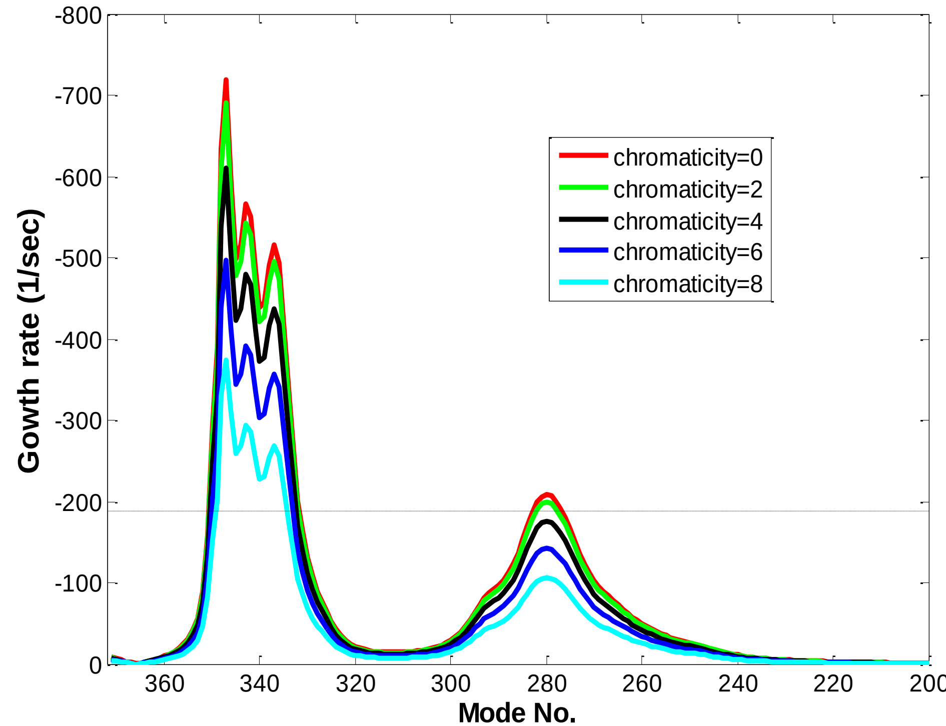




Mitigation with Chromaticity



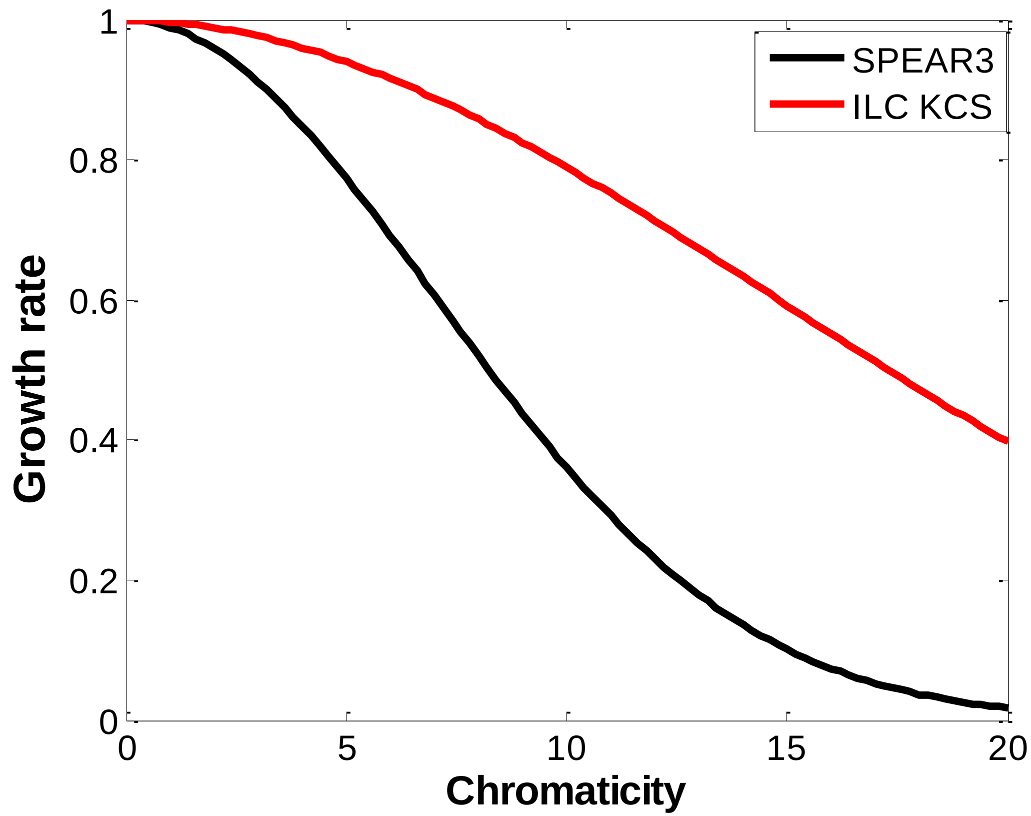
Observed oscillation amplitude of beam's vertical lower sidebands with varying vertical chromaticity in SPEAR3.



Calculated growth rate of the beam ion instability in SPEAR3 at different chromaticity, P=0.37nTorr. 1tr

Chromaticity effect

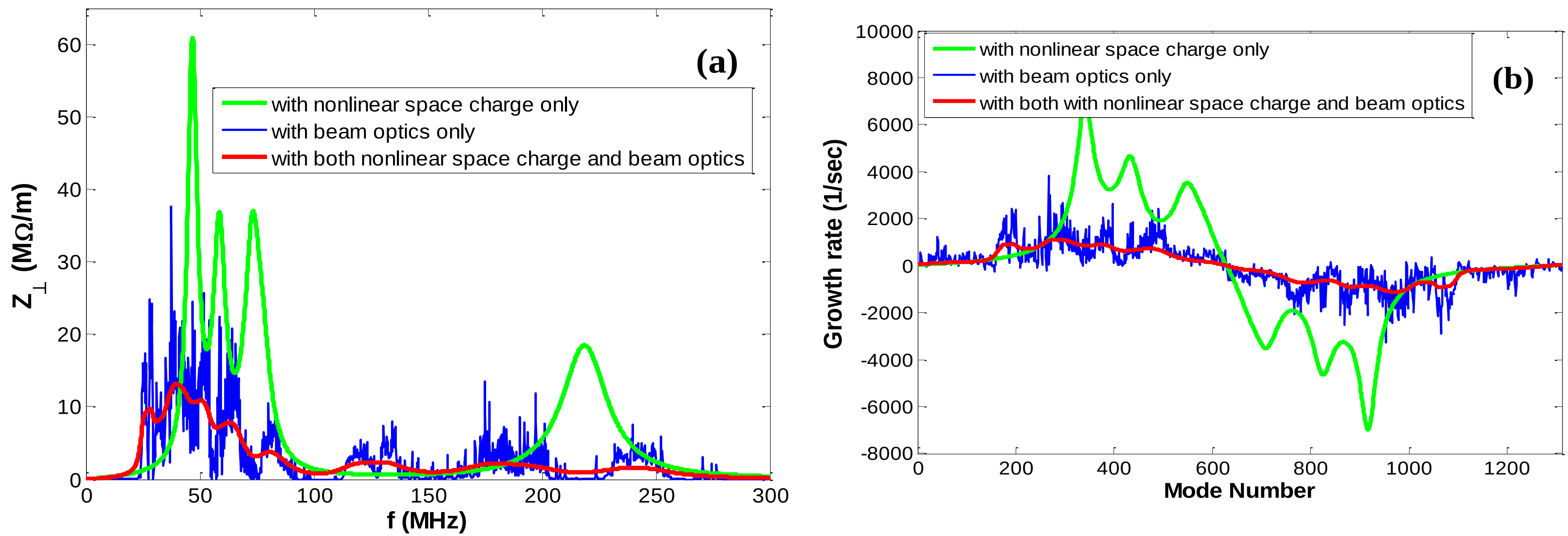
Chromaticity is more effective for machines with low momentum compaction factor, small ring and long bunch length



damping effect of chromaticity to the beam ion instability in SPEAR3 and the ILC damping ring. The vertical axis is the normalized growth rate

Comparison of the damping effect of nonlinear space charge force and beam optics

In SPEAR3, the two damping effects are similar
In ILC, beam optics provides stronger damping



The real part of the impedance (a) and growth rate of beam ion instability (b) in ILC damping ring with KCS configuration for various effects

Summary

- We analyze the multi-bunch train beam ion instabilities with **arbitrary** beam optics, multi-gas species vacuum, nonlinear space charge force and realistic beam filling pattern together. All these factors provide damping to the instability.
- Our analyses agree well with expensive simulation, and the observations in SPEAR3.
- It is critical to use multiple gas species….
- Both beam optics and nonlinear space charge provide strong damping effect to the instability;
- A large chromaticity can mitigate the instability at the expense of reduced lifetime

Acknowledge

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- Thanks the organizers of the working group on Damping Rings :

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