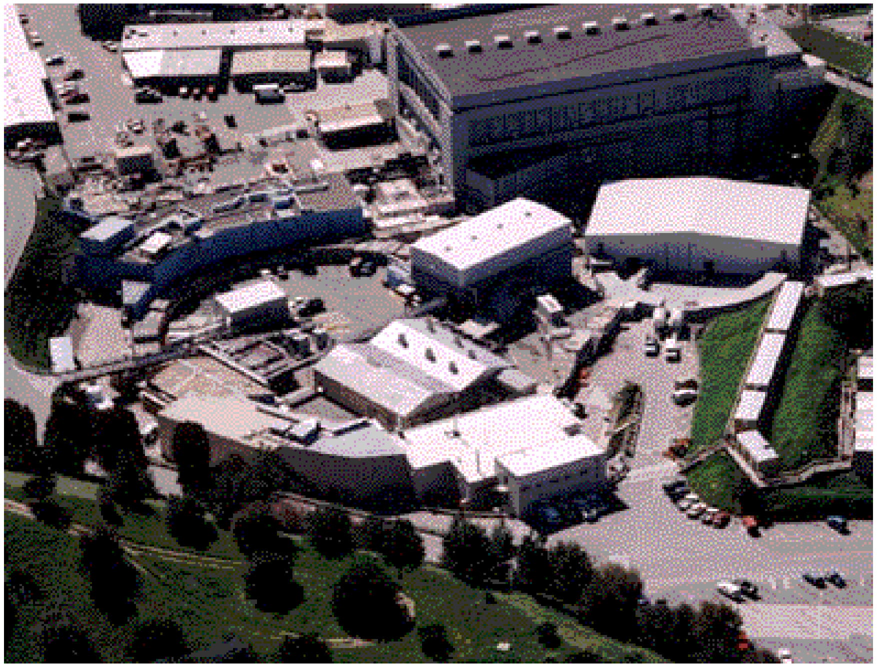
Beam-ion Instabilities in SPEAR3



KEK accelerator physics Seminar

2/15/2012

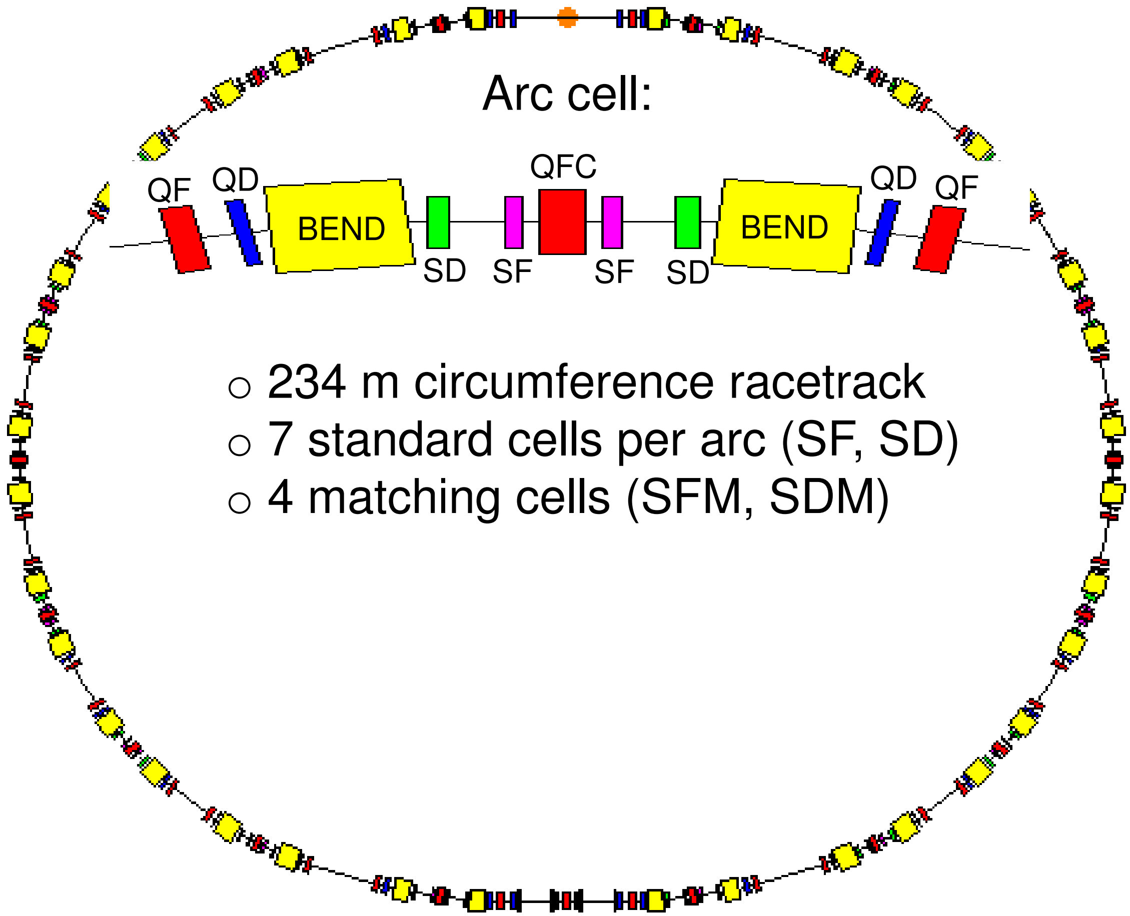
Lanfa Wang, SLAC

SLAC NATIONAL ACCELERATOR LABORATORY

Outline

- Introduction to SPEAR3
- Introduction to FII(Fast Ion Instability)
- Observations in SPEAR3
  - effect of emittance
  - Effect vacuum pressure
  - Effect of beam current
  - Effect of beam filling pattern
  - Effect of chromaticity
  - Effect of feedback
  - Effect Vacuum burst
- Summary

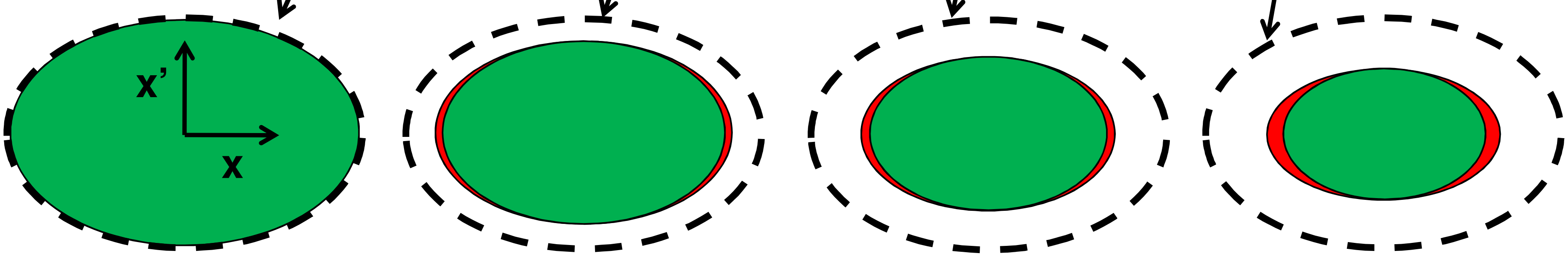
SPEAR3 Layout



- 234 m circumference racetrack
- 7 standard cells per arc (SF, SD)
- 4 matching cells (SFM, SDM)

Emittance of SPEAR3, ε_x

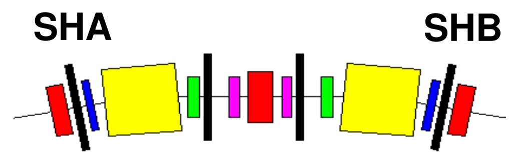
	Achromat	Low emittance	"Lower" emittance	Superconducting damping wigglers
	2004-2007	2007-now	Working in progress	Future
ε_{x0} (nm)	18.0	11.2	7.68	<5.0
ε_x, IDs (nm)	**14.6**	**9.6**	**6.76**	**4.9**
$\varepsilon_{x,eff}$ (nm)	**14.6**	**10.1**	**7.24**	**5.65**
η, ID (m)	0	0.1	0.1	0.1
σ_E (permil)	0.96	0.98	0.97	1.26
ν_x	14.13	14.13	15.13	15.11



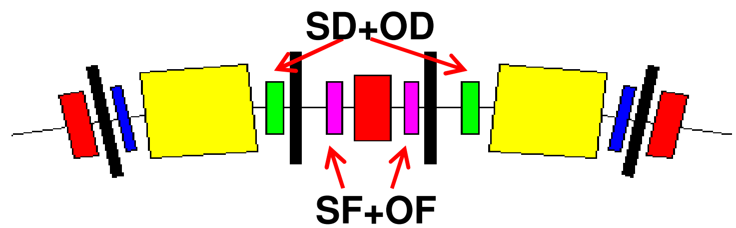
Effective emittance, $\varepsilon_{x,eff}$ includes η_x: $\varepsilon_{x,eff} = \sigma_x \sigma_{x'} = \sqrt{\varepsilon_x \beta_x + \eta^2 \sigma_E^2}\sqrt{\varepsilon_x / \beta_x}$

Adding nonlinear knobs (simulation)

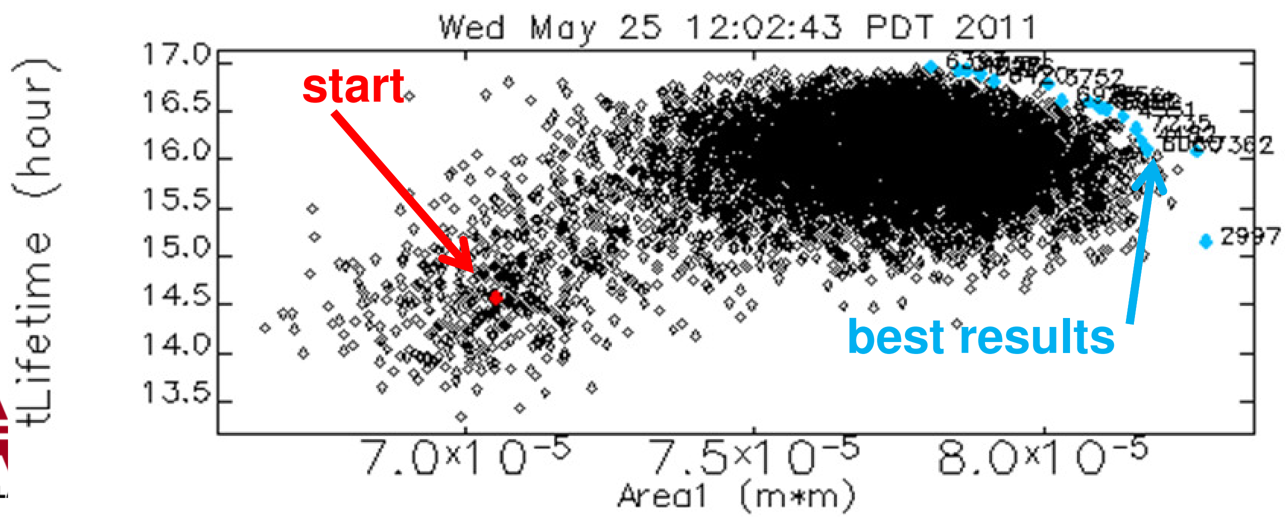
1. New sextupole magnets
   - Two families
   - On steering magnets



2. Octupole magnets



3. Independent power supply. MOGA (multi-objective Genetic Optimizer) elegant tracking, 6.7 nm lattice, with 21 sextupole families



Main parameters@SPEAR3

24.7% ion clearing gap
0.19μs

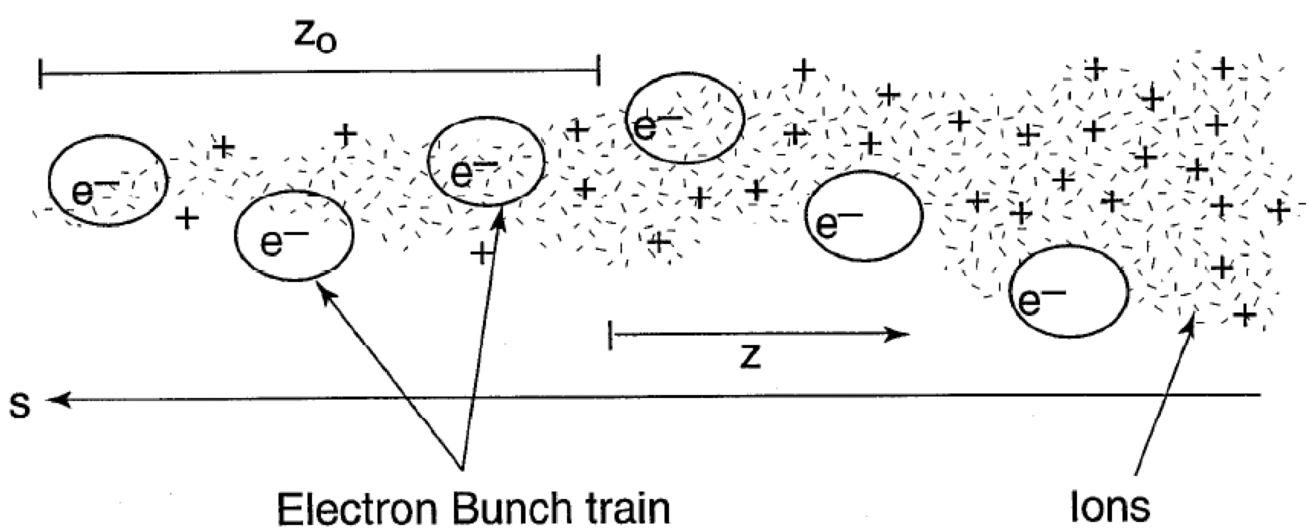
Physics	Symbol/Unit	
Horizontal Emittance	nm	10
Vertical Emittance	pm	14
Beam Current	mA	200 (500)
Bunch Number		280
Harmonic Number		372
Beam Energy	GeV	3
Circumference	m	234
Bunch spacing	ns	2.1
RF frequency	MHz	476.315
Revolution frequency	MHz	1.28038
Horizontal tune		14.1
Vertical tune		6.177
Momentum compaction factor		1.6×10^{-3}
Energy Spread		9.8×10^{-4}
Radiation Damping time	$\tau_x/\tau_y/\tau_z$ [ms]	4.0/5.3/3.2
Vacuum	nTorr	0.1~1

Introduction to FII(Fast Ion Instability)

- **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;**

Characteristic of ion instabilities

- **Broadband spectrum**
- **Normally only in vertical direction due to the small vertical beam size**
- **The amplitude saturated at order of beam sigma**



Coupled motion

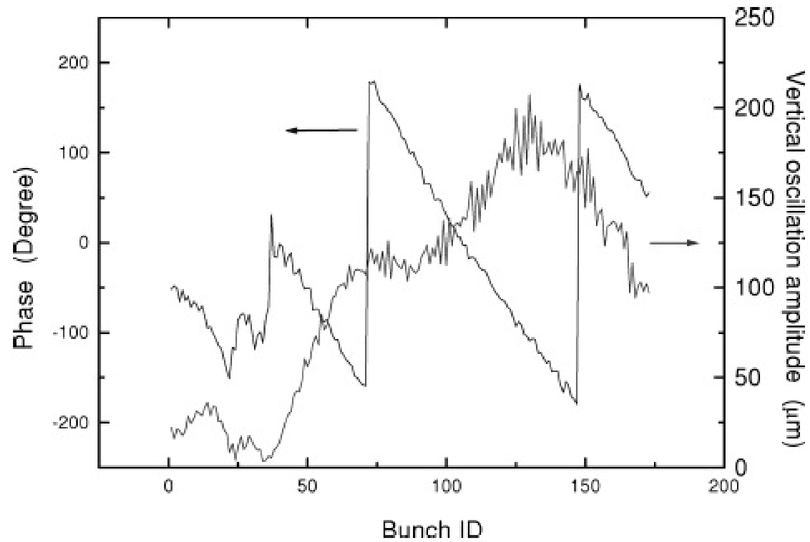
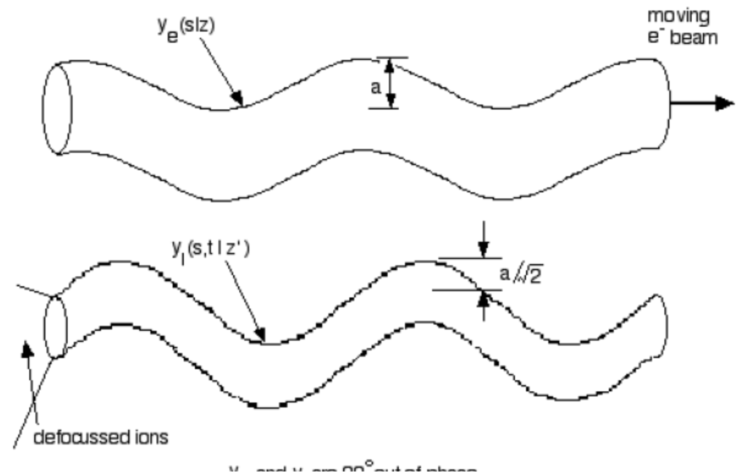
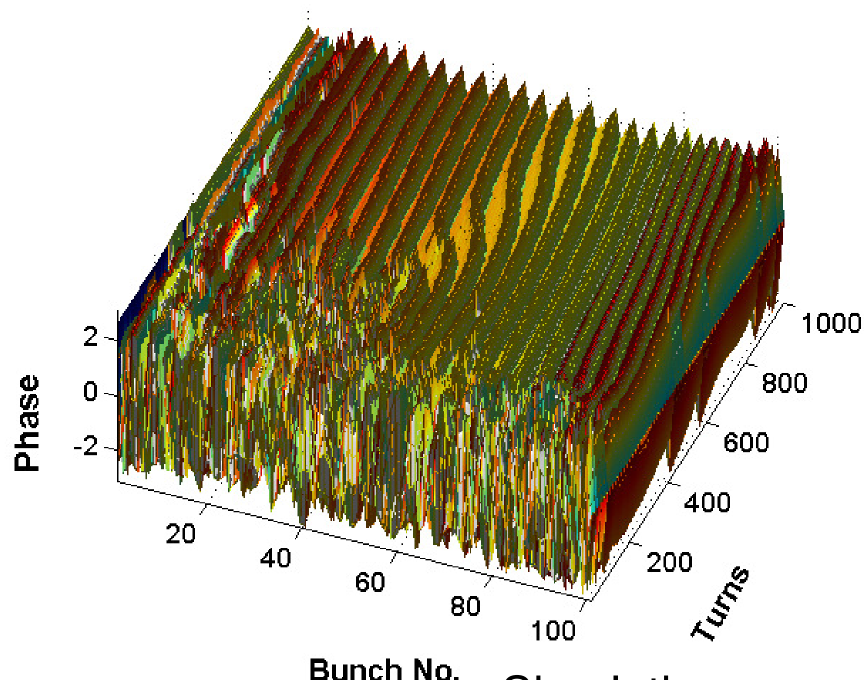


FIG. 4. A plot of the amplitude and phase of each bunch for a period of 200 turns. This was obtained by performing fast Fourier transform on the raw SBPM data over 200 turns.

M. Kwon, PRE Vol. 57,1998

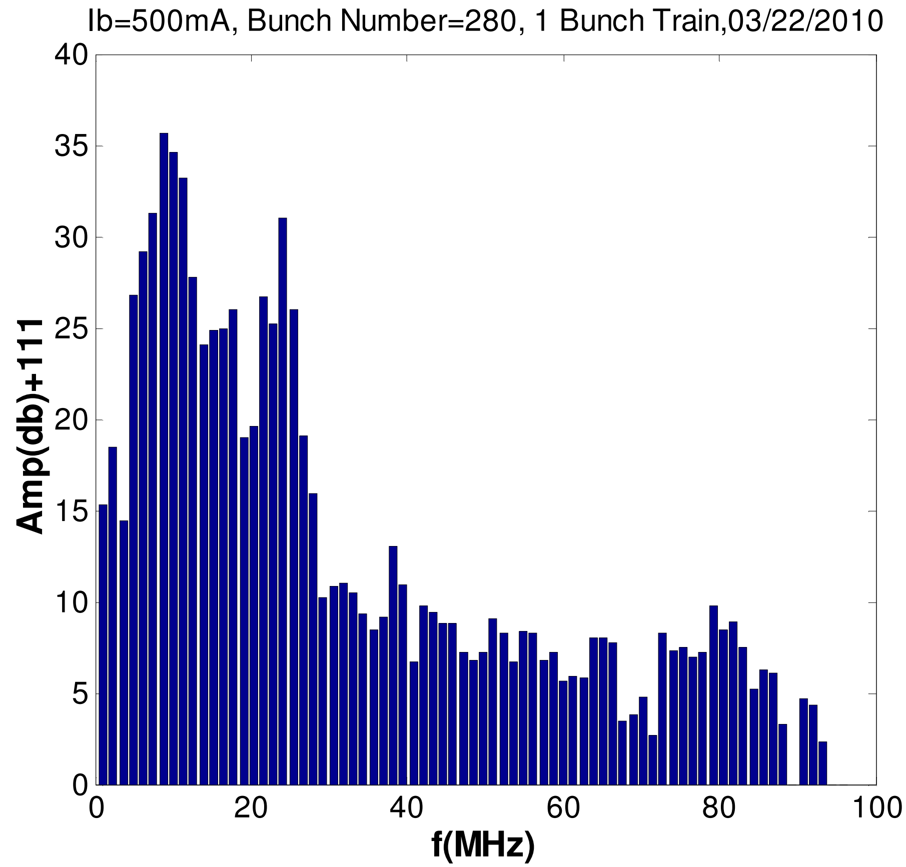




Simulation

Broad band Spectrum

Spectrum depends on the beam current, optics(emittance, betatron function), vacuum



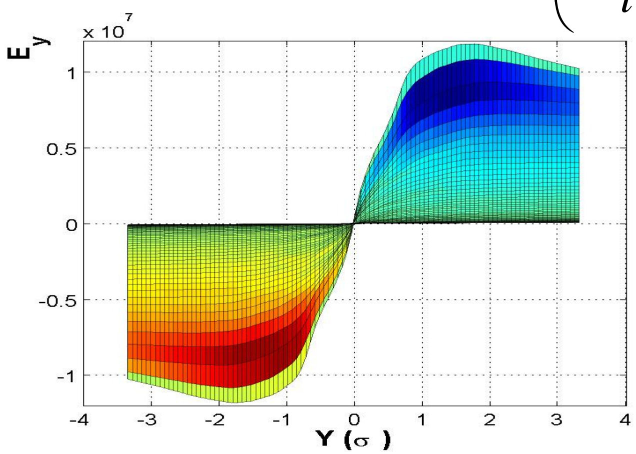
Experimental data @SPEAR3

Saturation of beam-ion instability

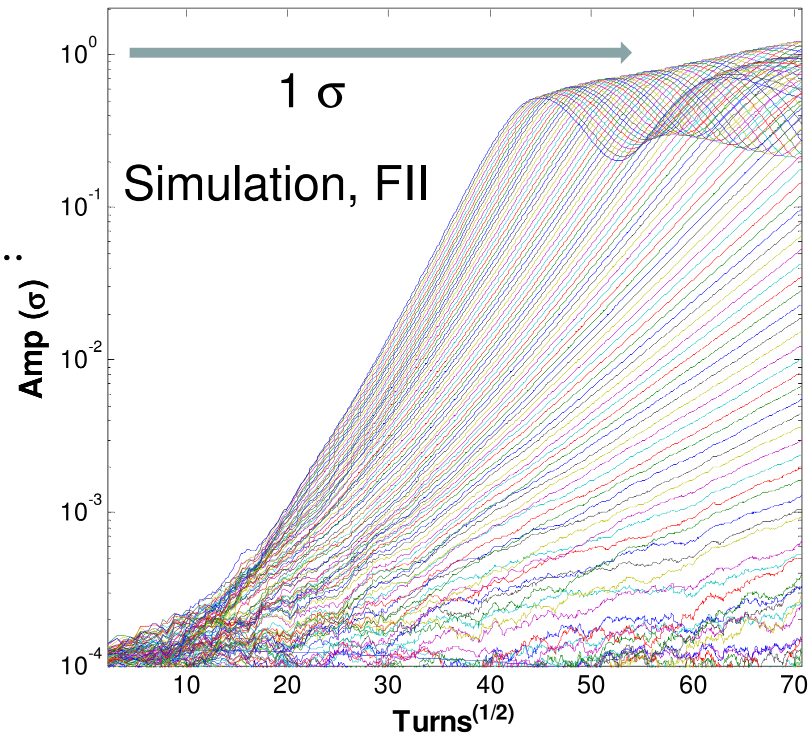
When the bunches' amplitude is larger (compare with beam size), the nonlinear force automatically slow down the instability!

Different from other instabilities, ions induced instability rarely causes beam loss.

(T.R & F.Z) $$\tilde{y}(s,z) \approx \exp\left(+\frac{z}{l}\sqrt{\frac{t}{\tau_c}}\right) * \ldots$$



Electric field vs. amplitude

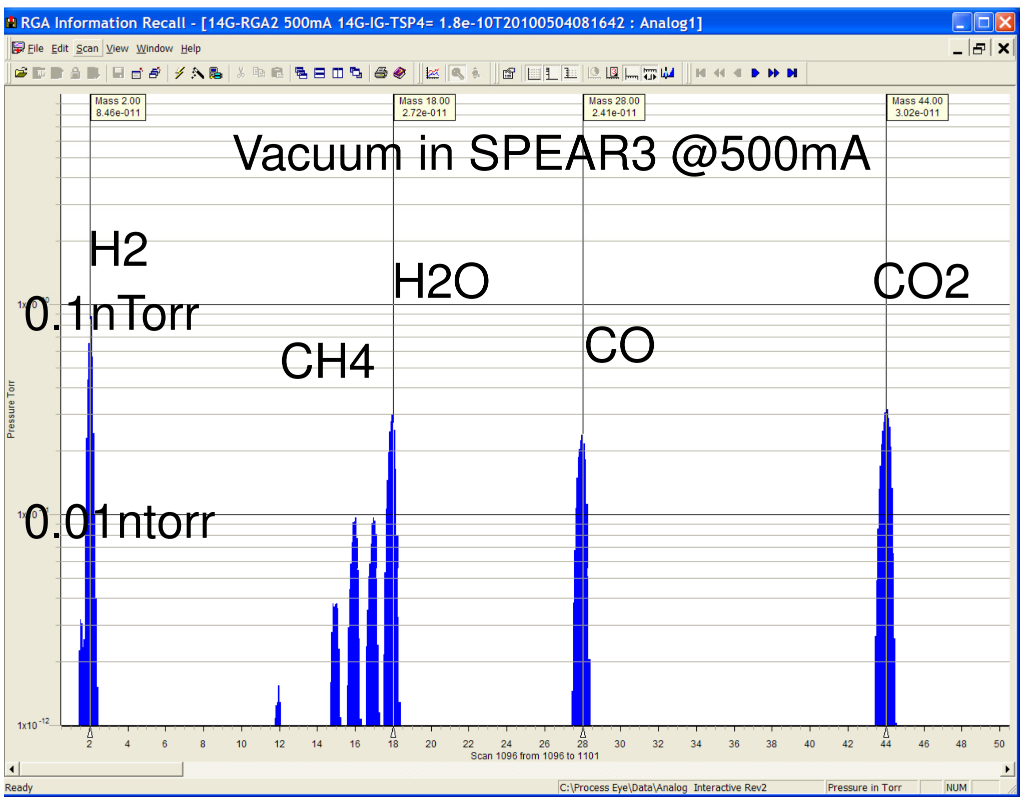


FII Theory: Phys. Rev. E52, No. 5, p. 5487 (1995))

Ion species in vacuum

$$\boxed{\lambda_i = \delta_i \frac{P}{kT} N_e n_b}$$

Here P is the vacuum pressure, δ_i is the ionization cross-section, N_e is the number of electrons per bunch, T is temperature and k is Boltzmann constant

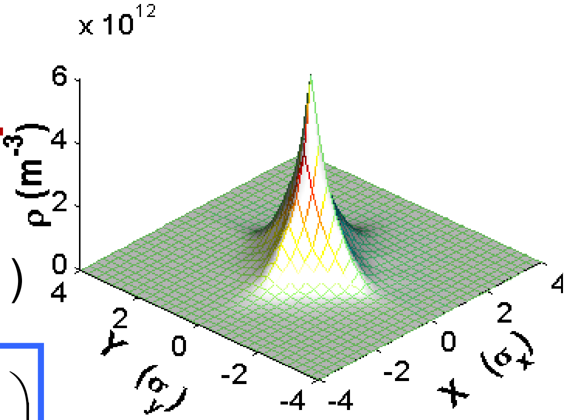


Total pressure <0.5 nTorr

Gas Species	Mass Number	Cross-section	Percentage in Vacuum
H2	2	0.35	48%
CH4	16	2.1	5%
CO	28	2.0	14%
CO2	44	2.92	17%
H2O	18	1.64	16%

Ion distribution (*steady status*)

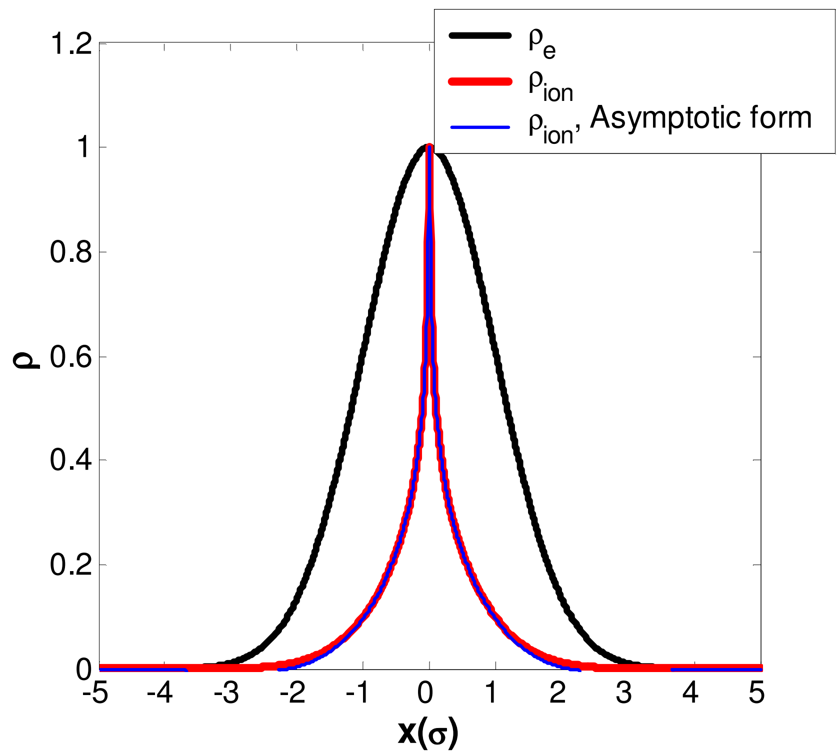
$$\rho(x) = \frac{1}{\pi\sqrt{2\pi}\sigma_x} e^{-\frac{x^2}{4\sigma_x^2}} K_0\left(\frac{x^2}{4\sigma_x^2}\right)$$ (P.F. Tavares, CERN PS/92-55)

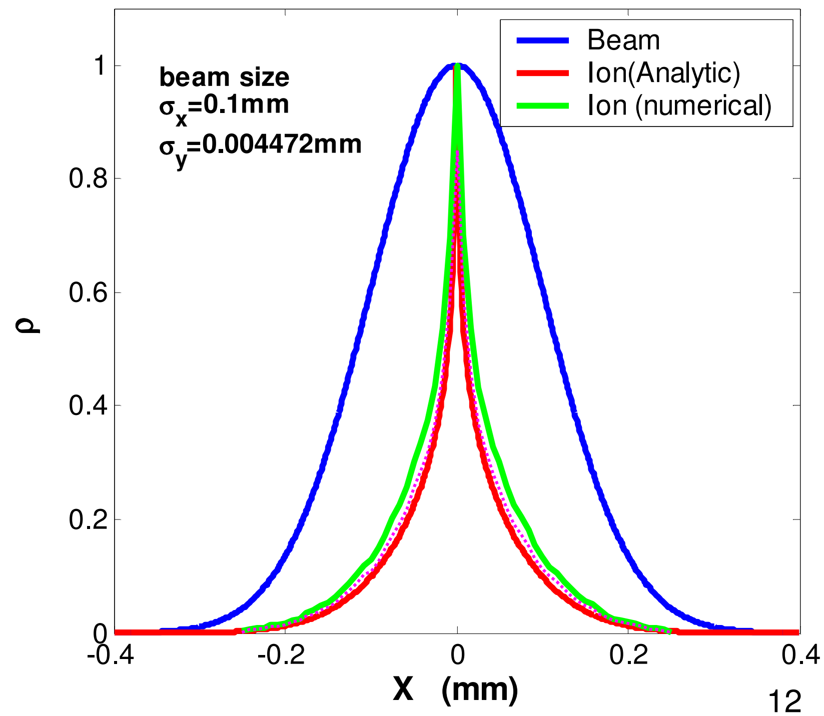


the distribution at x→0 is [1]

$$\boxed{\rho(x) \approx -\frac{1}{\pi\sqrt{2\pi}\sigma_x} e^{-\frac{x^2}{4\sigma_x^2}}\left(\log(\frac{x^2}{8\sigma_x^2}) + \gamma\right)}$$

γ=0.577215





Space Charge Wake from ion cloud

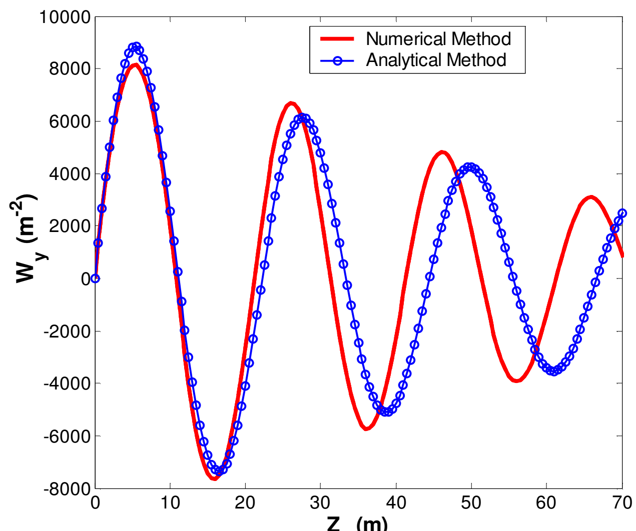
$$W(z) = N_i\left(\frac{r_p N}{AS_b}\right)^{1/2}\left[\frac{4}{3}\frac{1}{\sigma_y(\sigma_y+\sigma_x)}\right]^{3/2} e^{-\frac{2\pi f_{i,y} z}{2Q_0 c}}\sin\left(\frac{2\pi f_{i,y} z}{c}\right)$$

Where N_i is the ion number; N is e-beam population; Sb is bunch spacing

Frequency of the wake

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

Wake, Q=7.14, λ=21.1m



Comparison with analysis

- The wake is long range, which causes coupled bunch instability

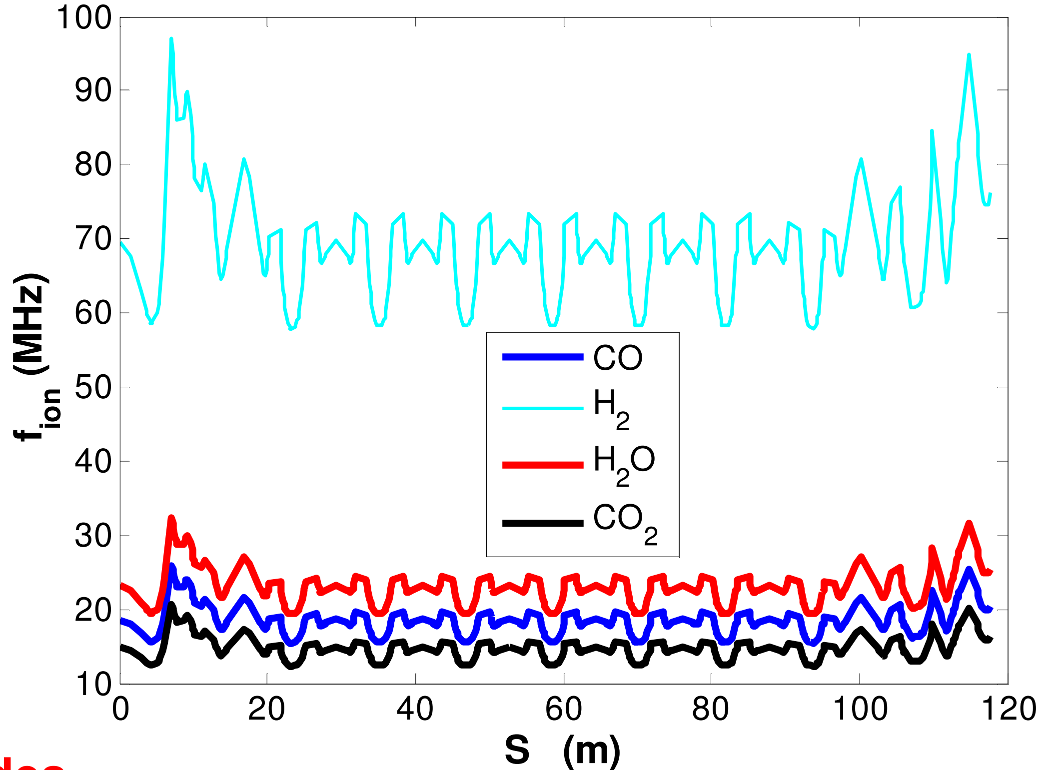
What we expect to be observed

When the beam is evenly filled along the ring, the exponential growth rate of the coupled bunch instability for mode $y_j^\mu \propto e^{2\pi\mu j/n_b}$ is [Alex Chao's book, for example]

$$\frac{1}{\tau^\mu} = \frac{N_e n_b r_e c}{2\gamma T_0^2 \omega_\beta} \sum_{p=-\infty}^{\infty} \mathrm{Re}\{Z_{ion}((pn_b + \nu_y + \mu)\omega_0)\}$$

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

The frequency of the unstable modes depends on the optics!



Calculated ion frequency along the ring for a beam current of 200mA

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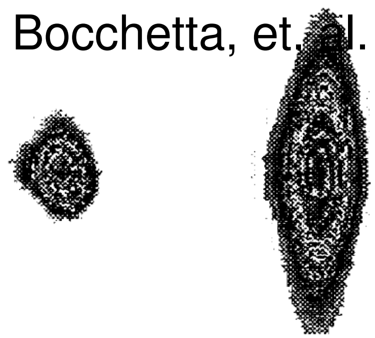
Observations with high pressure

(gas injection)

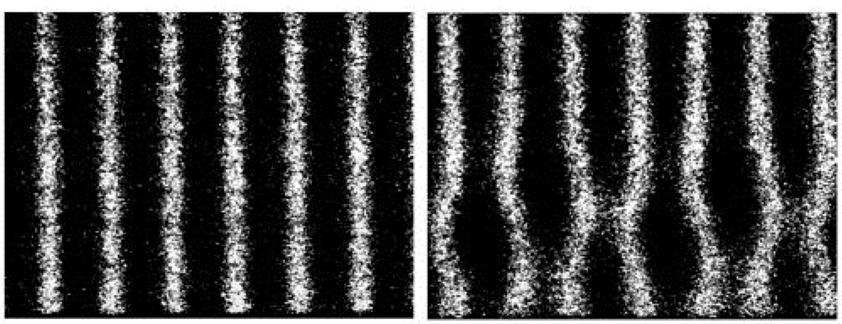
- Instability has been observed at many laboratories when vacuum is not good
  - Artificially increasing the vacuum pressure (ALS, PLS, ATF)
  - At commissioing times or restart after a long shutdown (ESRF, DIAMOND)
  - After installation of new (insertion device) chambers (SPring-8, ESRF)

C. J. Bocchetta, et. al. 1994



ELETTRA

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

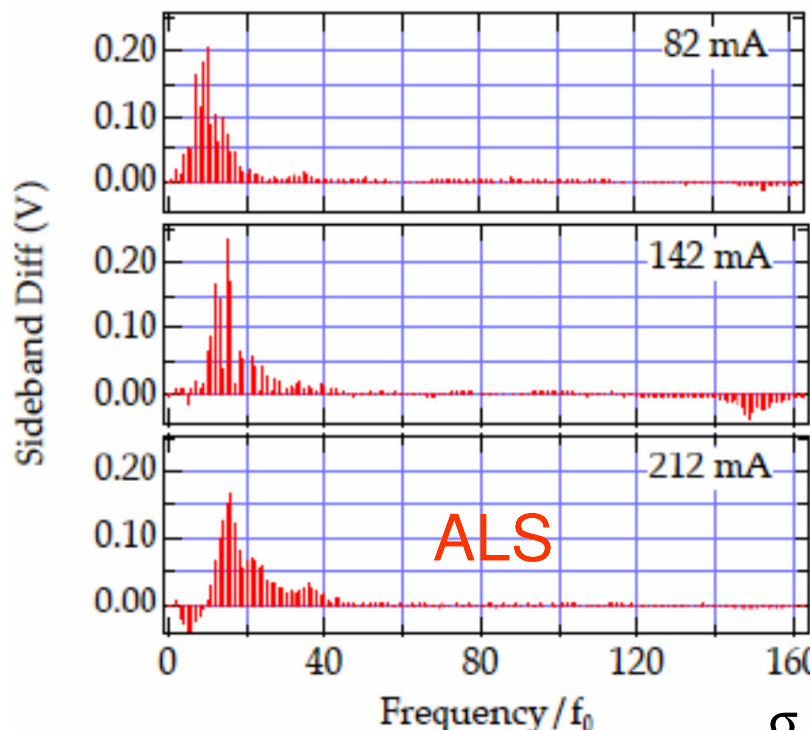


(a) (b)

PF P=0.4nTorr (normal)

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

P=1nTorr w/o He injection



ALS

σ_y~30μm

Observations at Nominal conditions

- 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)
- The instability also occurs at nominal condition (SOLEIL, SSRF, SPEAR3…)
- **For existing light sources it does not pose a problem. May become a problem for lower emittance rings**

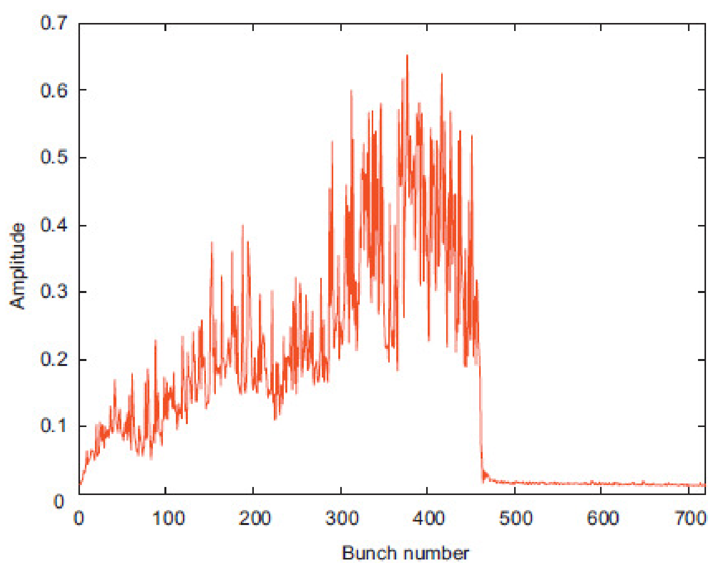


Fig. 1. The relative oscillation amplitude of bunch centroid versus the bunch number (data taken from the bunch-by-bunch BPM).

Vertical amplitude along the bunch train
SSRF, nominal vacuum

SSRF, B. Jiang, NIMA 614 (2010) 331–334

Observations in SPEAR3

- ❑Effect of emittance
- ❑Effect of vacuum pressure
- ❑Effect of beam current
- ❑Effect of beam filling pattern
- ❑Effect of chromaticity
- ❑Effect of feedback
- ❑Effect of vacuum burst

Ion instability at SPEAR3@200mA

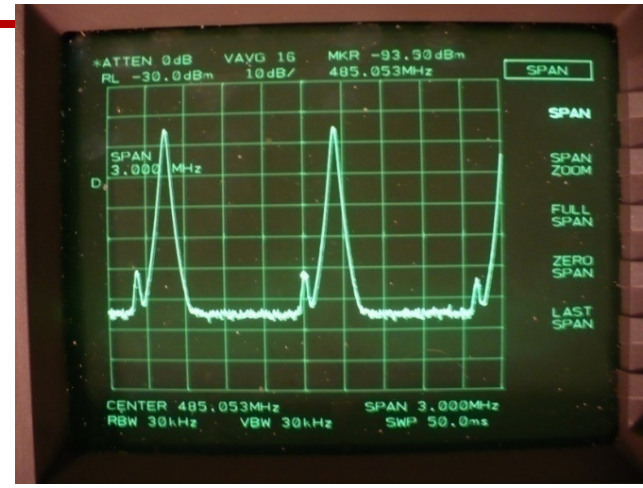
Experiment condition:

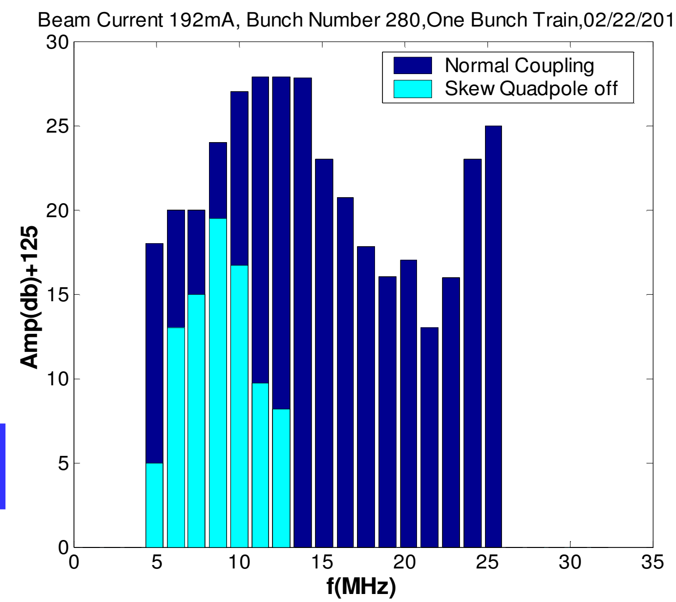
Beam Current: 192mA
Bunch Number: 280
1 Bunch Train

- ➢Vertical low sideband was observed at frequency from 5~26MHz , which agrees with the analysis
- ➢The sidebands move to low frequency region when the beam emittance increases, which agree with the theory , and confirms this is FII(fast ion instability)

$$f_{i,x,y} = \frac{c}{2\pi}\left(\frac{2N_e r_p}{AS_b k_{x,y}\sigma_{x,y}(\sigma_y+\sigma_x)}\right)^{1/2}$$

Lower instability rate with a larger emittance

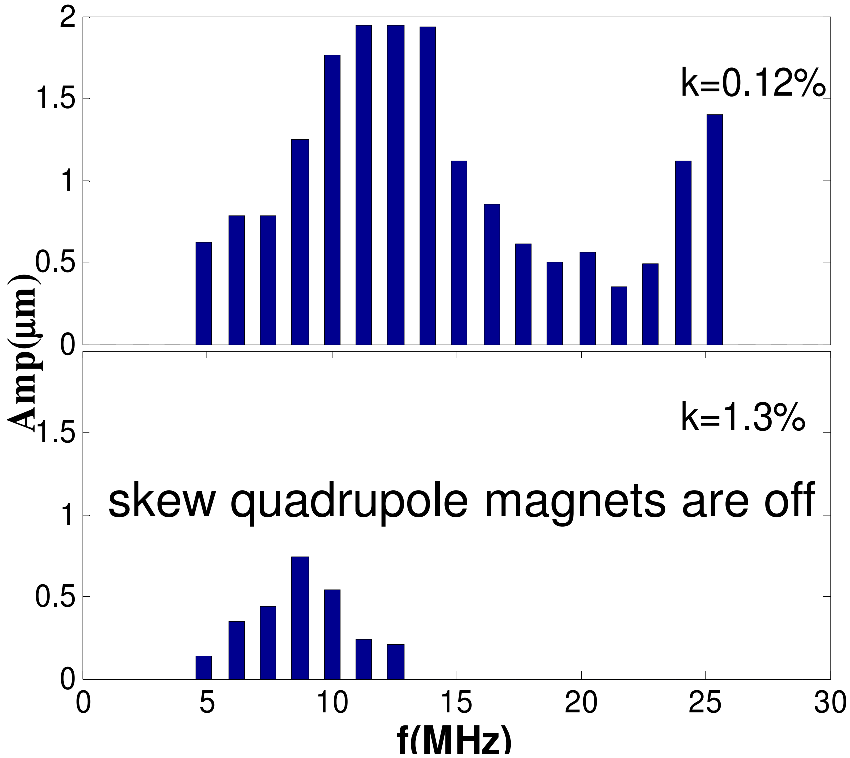




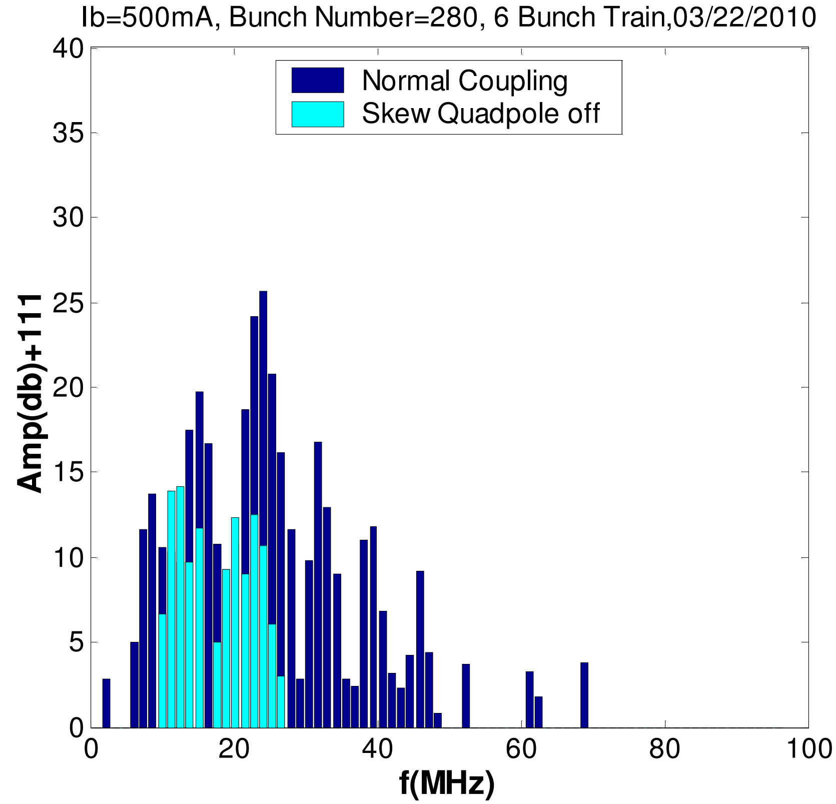
Vertical sideband

Effects of coupling

skew quadrupole magnets are on



190mA single bunch train

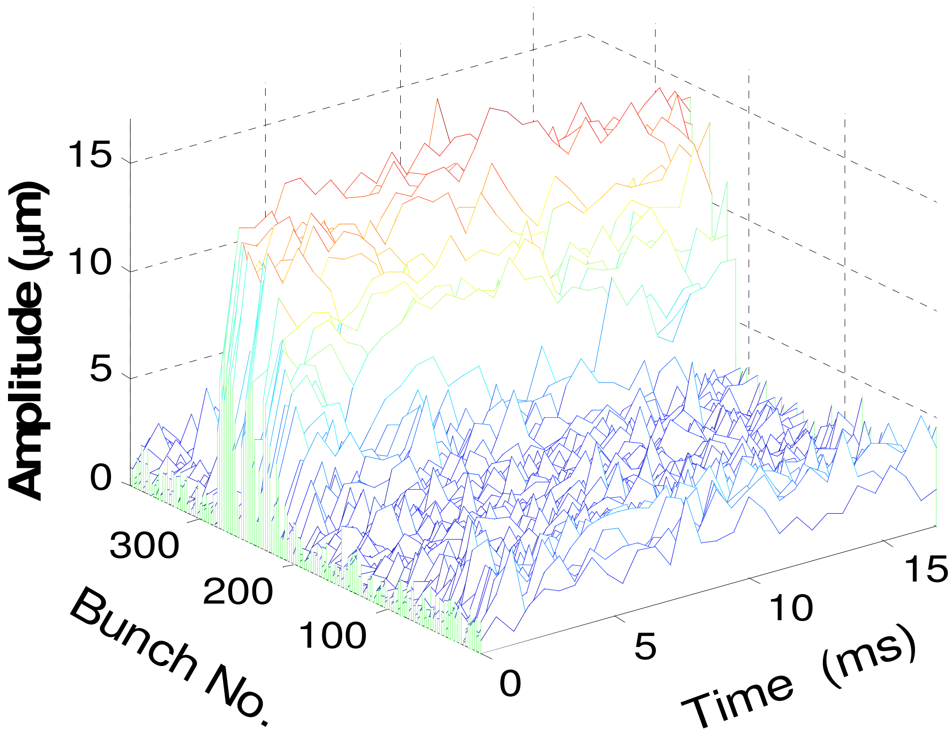


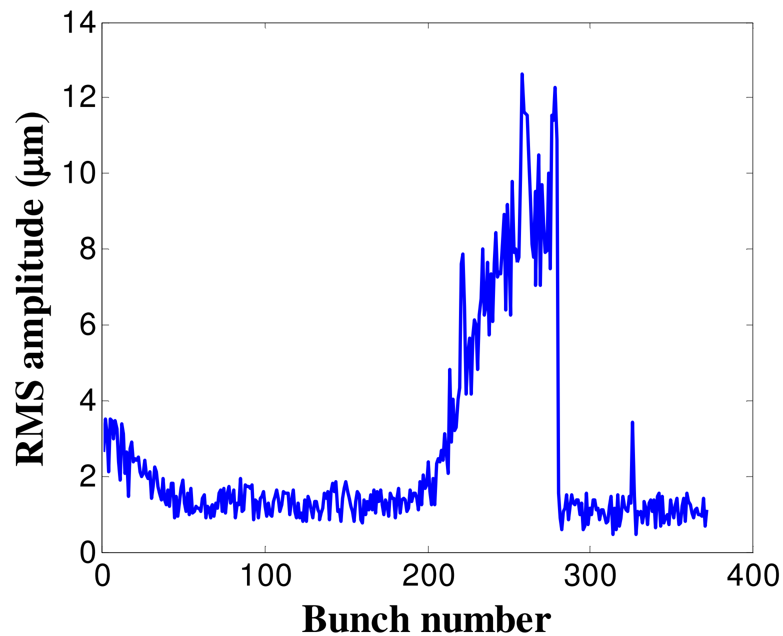
500mA Six bunch trains

Bunch oscillation along the bunch train

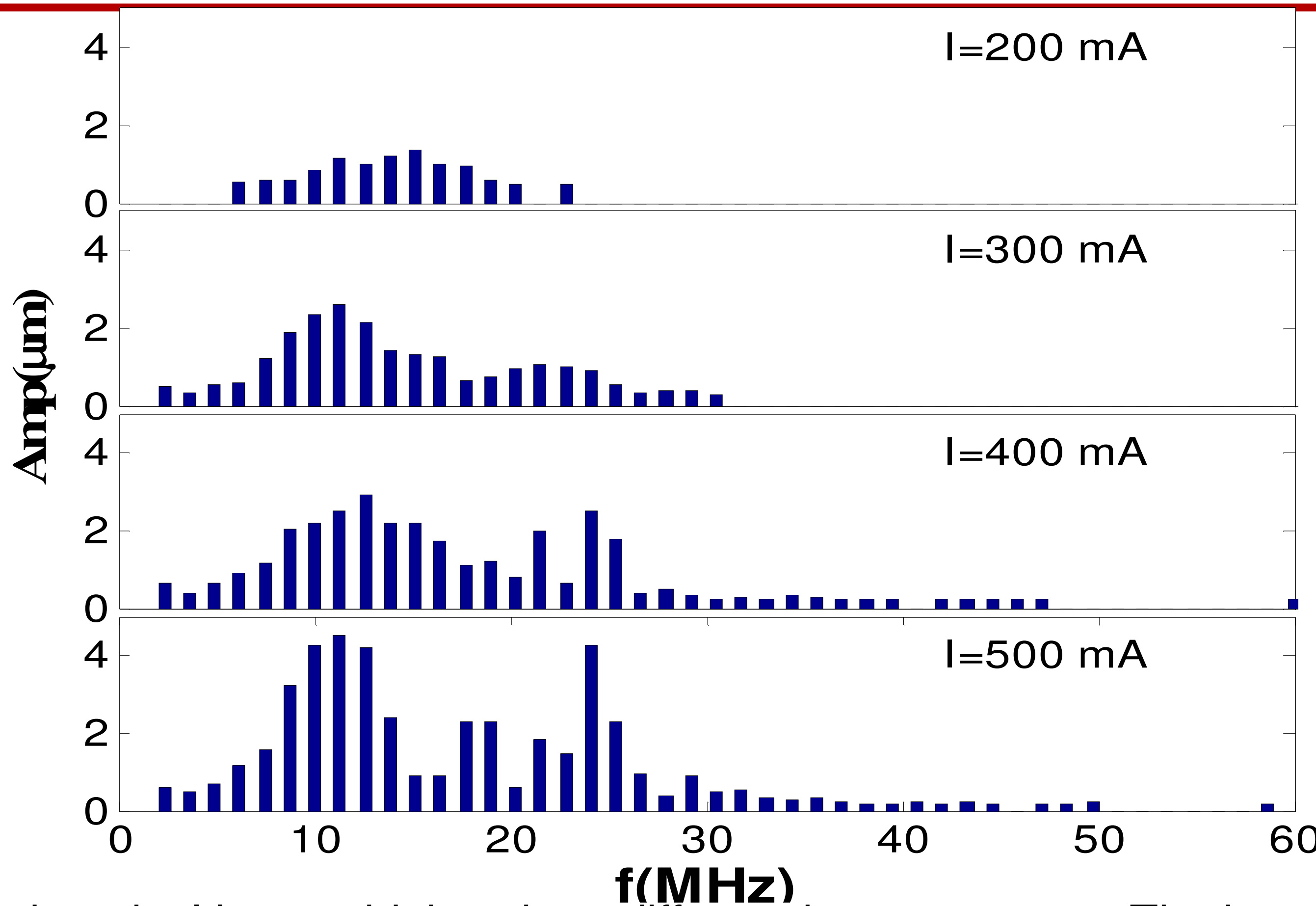
Single bunch train@200mA

Vertical bunch oscillation amplitude saturated at the amplitude around 1 sigma (12um)





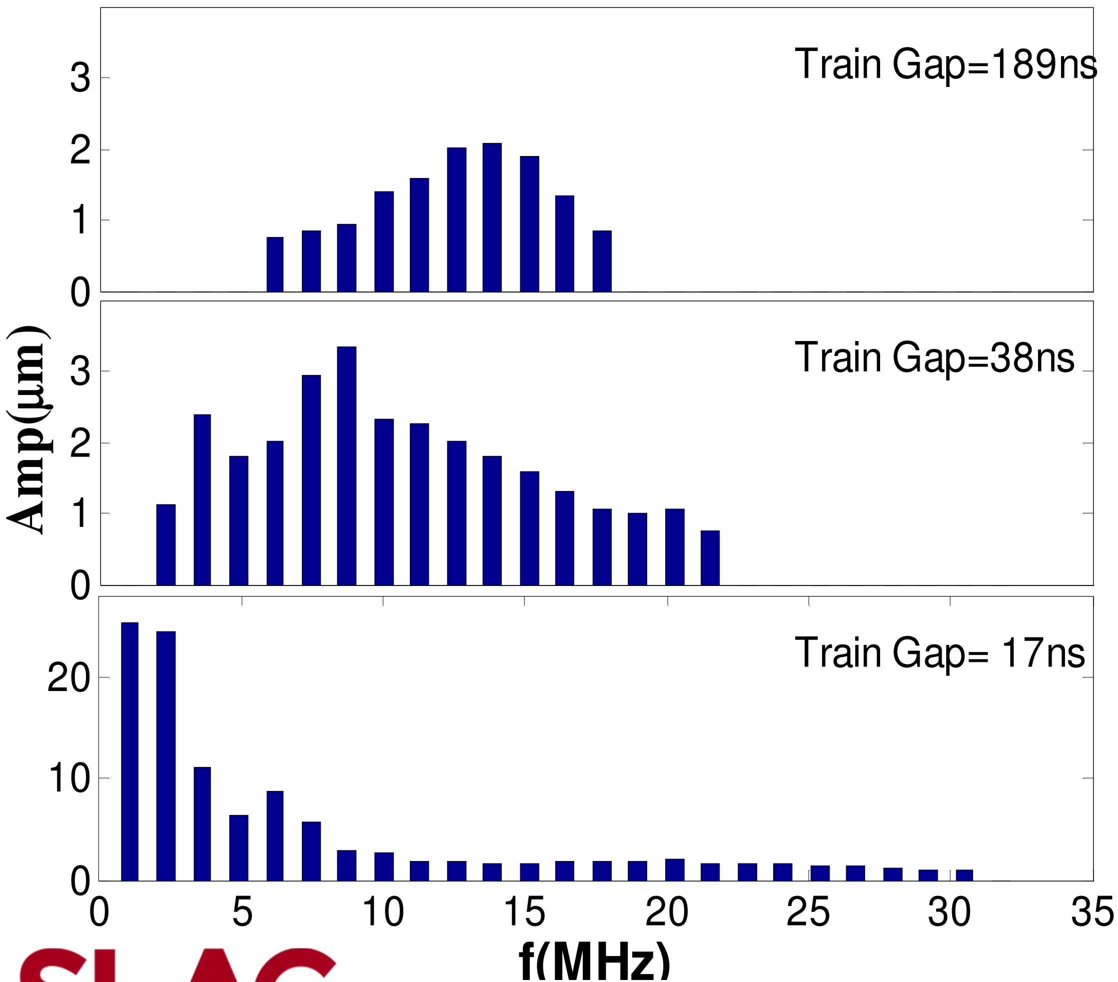
Effects of beam current

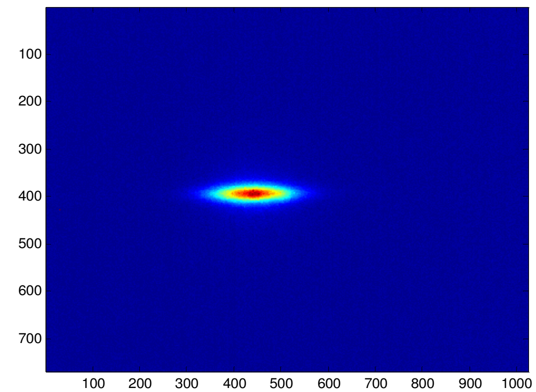


Observed vertical lower sidebands at different beam currents. The beam has single bunch train with 280 bunches

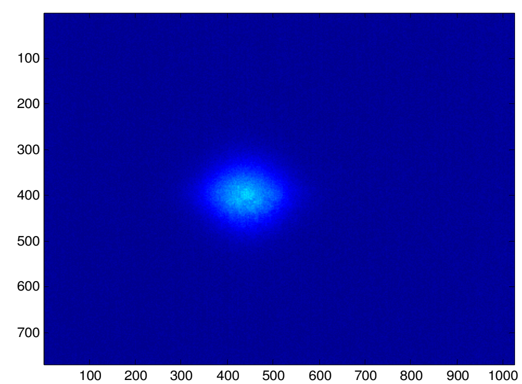
Effects of bunch train gap

Single bunch-train, 200mA



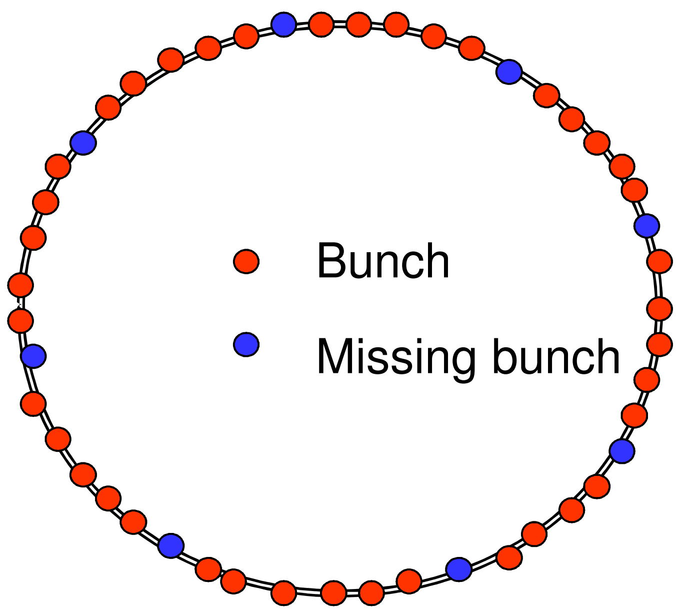


42ns gap



No gap

Mitigation with multi-bunch train beam filling

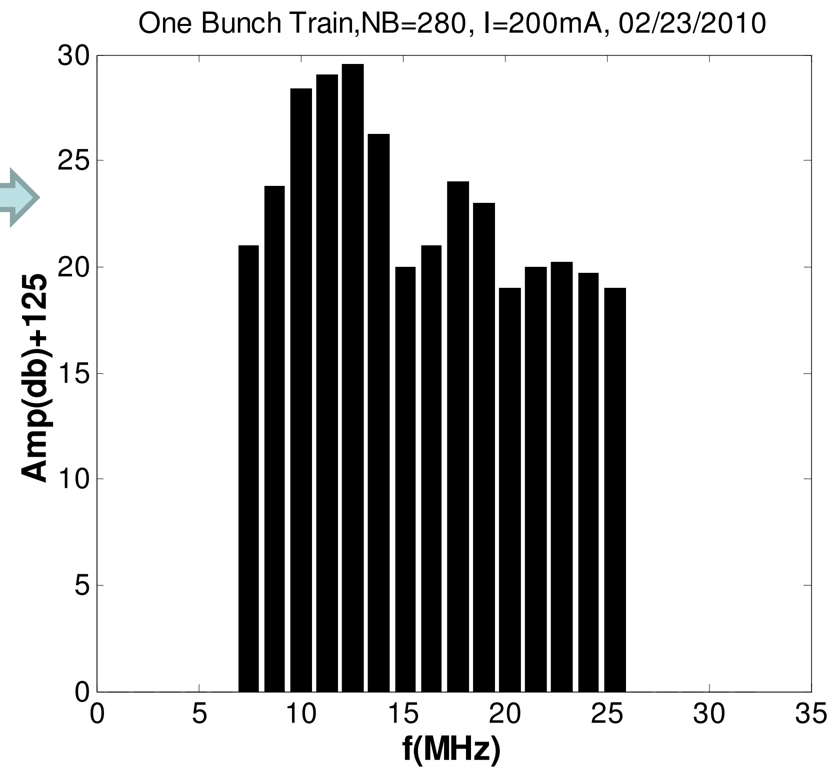


Effects of beam filling pattern@200mA

Filling 1: **1 Bunch Train** (3pm)

1 Bunch Train;
200 mA
280 Bunches

Sideband found



Filling 3: **2 Bunch Train** (4:15pm)

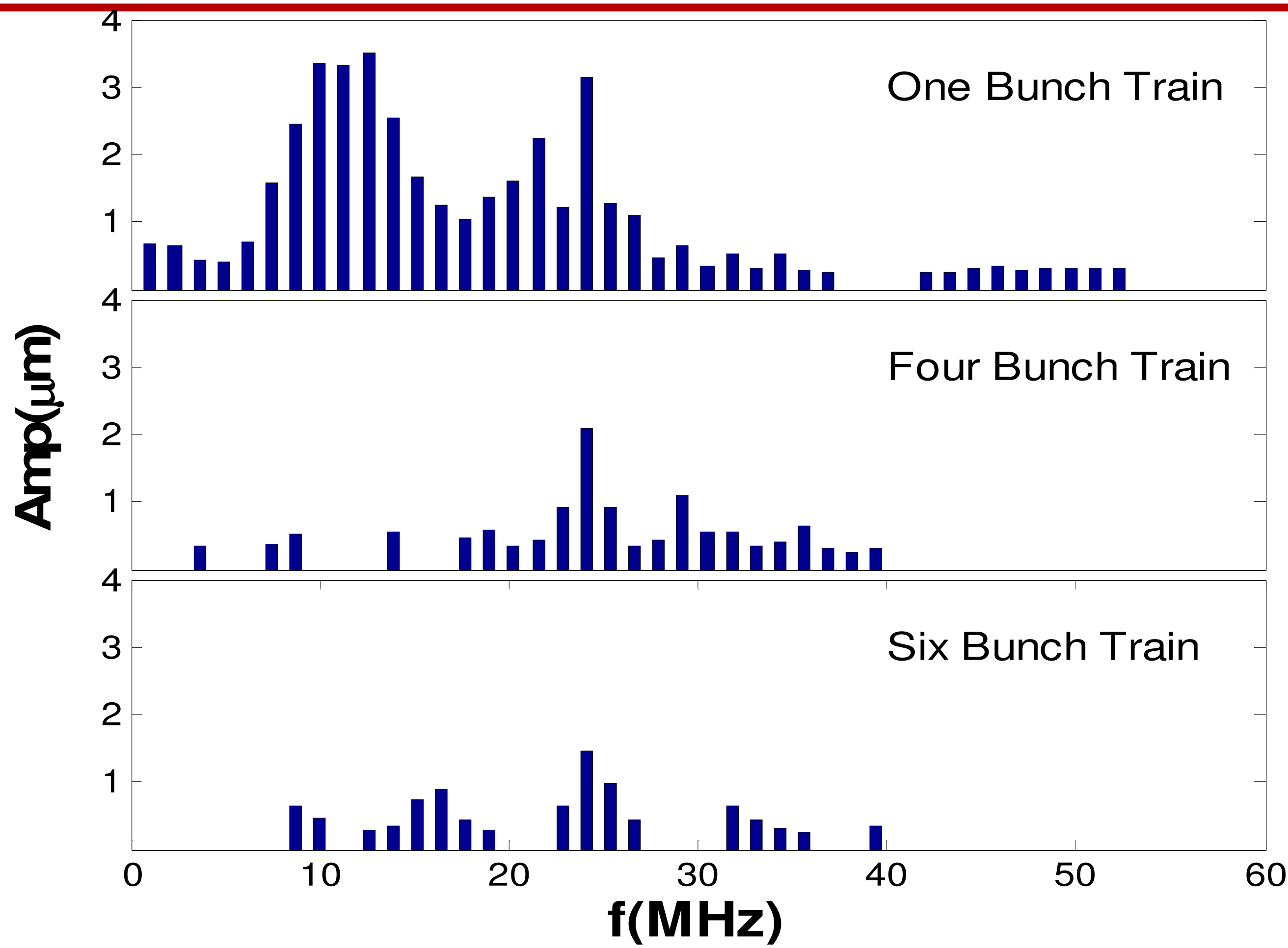
2 Bunch Train;
200 mA
280 Bunches

No sideband

Vertical sideband with 1 bunch train

Growth time about 2.5ms~5ms?

Effects of beam filling pattern@500mA



Beam current 500mA

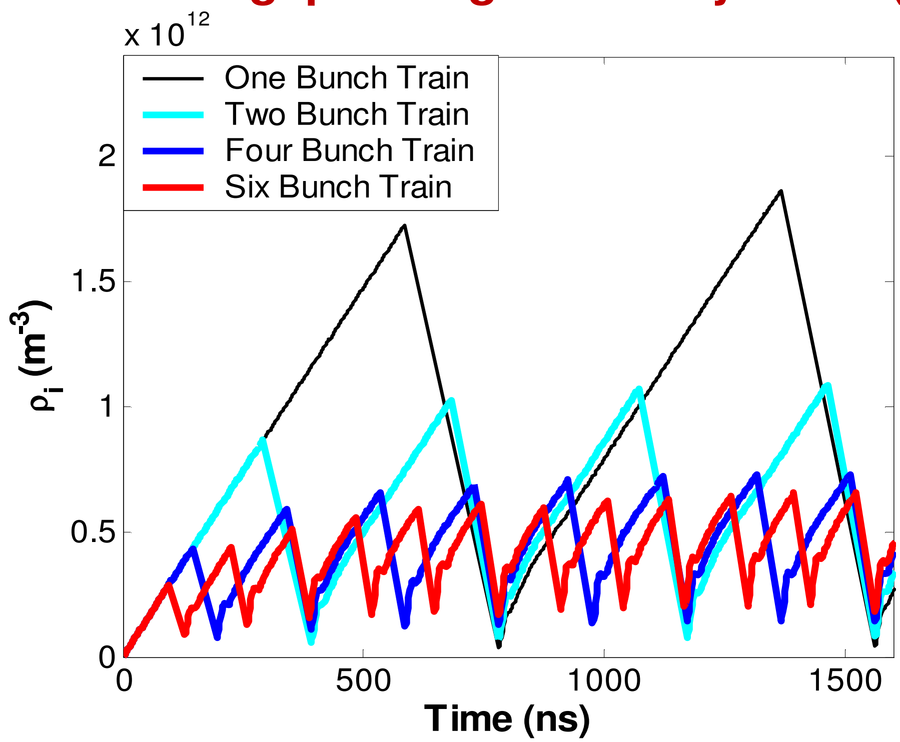
Simulation of ion cloud build-up

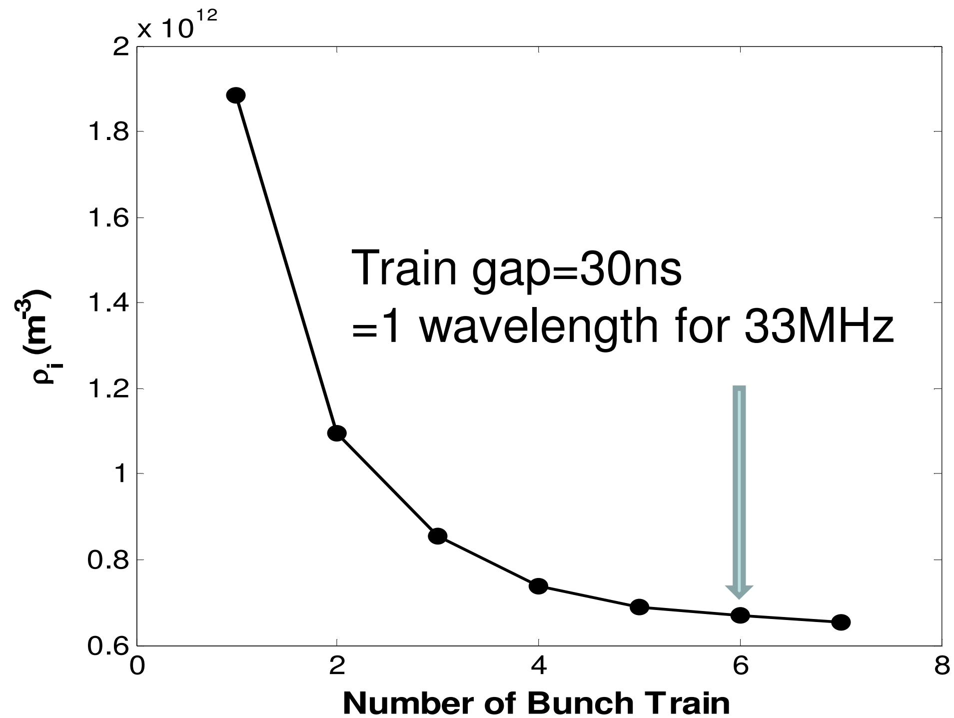
Ion density reduction due to multi-bunch train

$$f_{gap} = \frac{1}{N_{train}} \frac{1}{1 - e^{-\tau_{gap}/\tau_{diffusion}}}$$

The required train gap is only about 1 ion oscillation period.

A short gap for high intensity beam (PEPX uses more than 100 bunch trains)

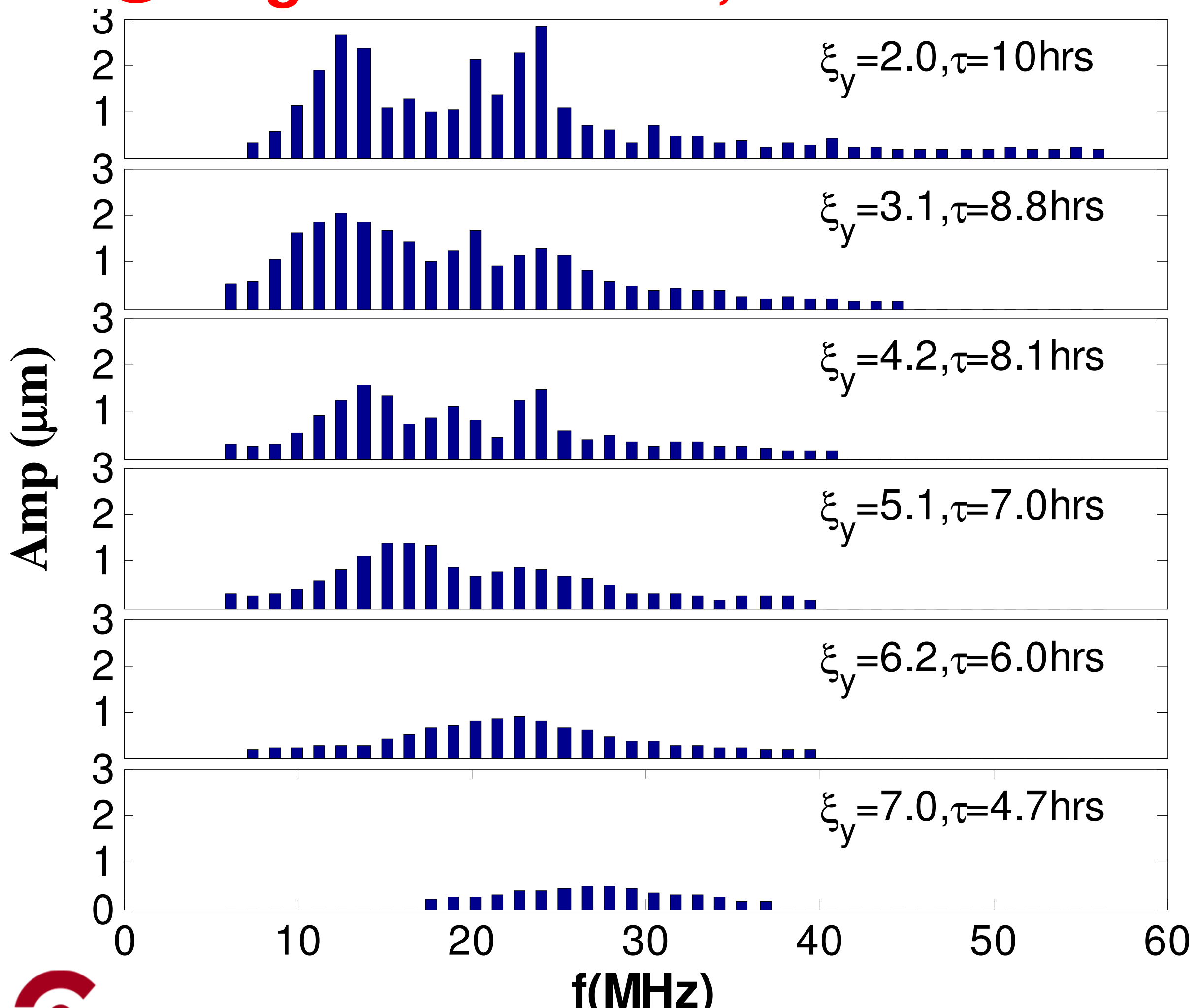




Build-up of ions with different beam filling pattern@500mA

Effect of chromaticity

@Single bunch train, 500mA



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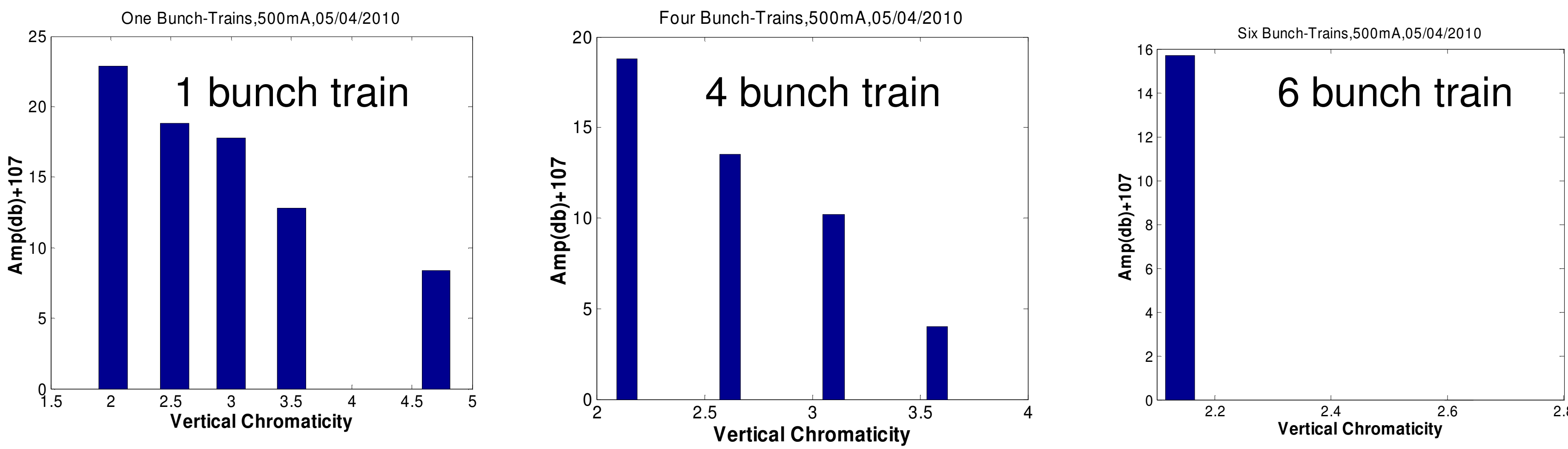
Effect of Chromaticity@500mA

1 bunch train
- Increase chromaticity, lifetime drop from 11hrs to 9.hrs
- With vertical chromaticity 4.6, the sideband still appear.

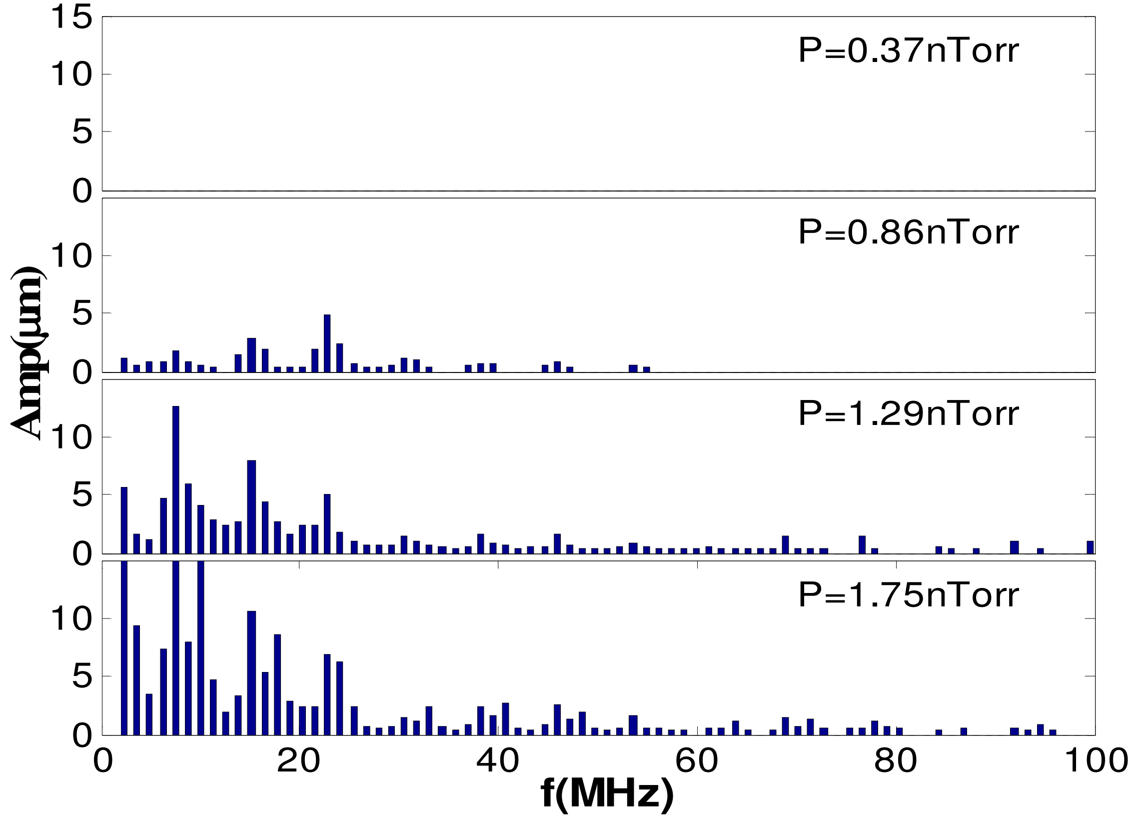
4 bunch train
- With vertical chromaticity 3.6, the sideband becomes weak.

6 bunch train
- With vertical chromaticity 2.6, the sideband disappear.



Effects of vacuum pressure

@300mA Six bunch train

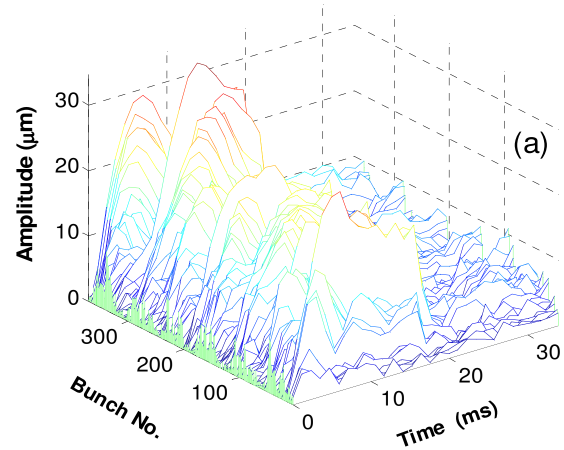


The beam consists of six bunch trains with total bunch number of 280. The beam current is 300 mA. There are no sidebands with the nominal pressure of 0.37nTorr. The vacuum pressure is increased by partially turning off the ion pumps.

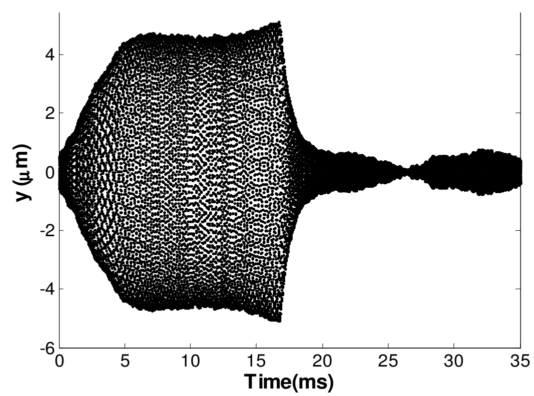
Preliminary feedback test

There is no bunch-by-bunch feedback in SPEAR3, we tested once of the feedback from Dimtel, Inc

Almost uniform filling pattern: 448mA, six bunch train, bunch number 366, (only 1 missing bunch in each train gap)



The oscillation amplitude has been reduced. Some bunches still have residual oscillations
Possible reasons:
(1) The bandwidth of the feedback kicker is not large enough
(2) The instability is too fast

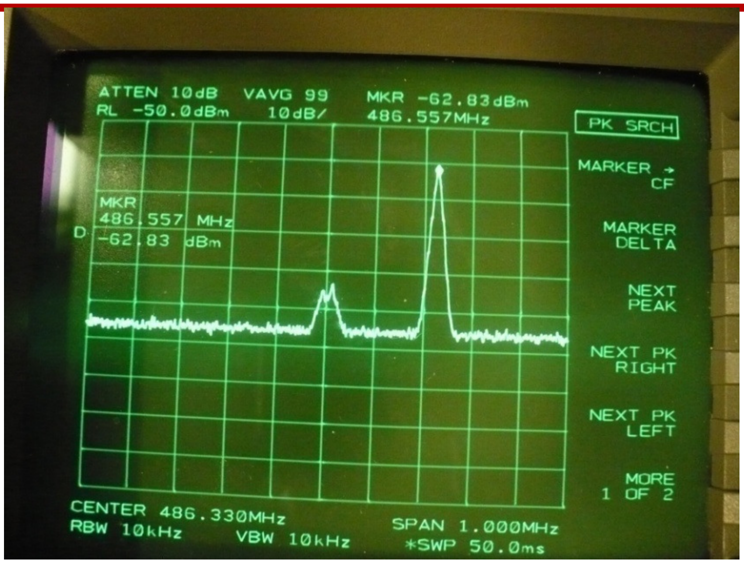


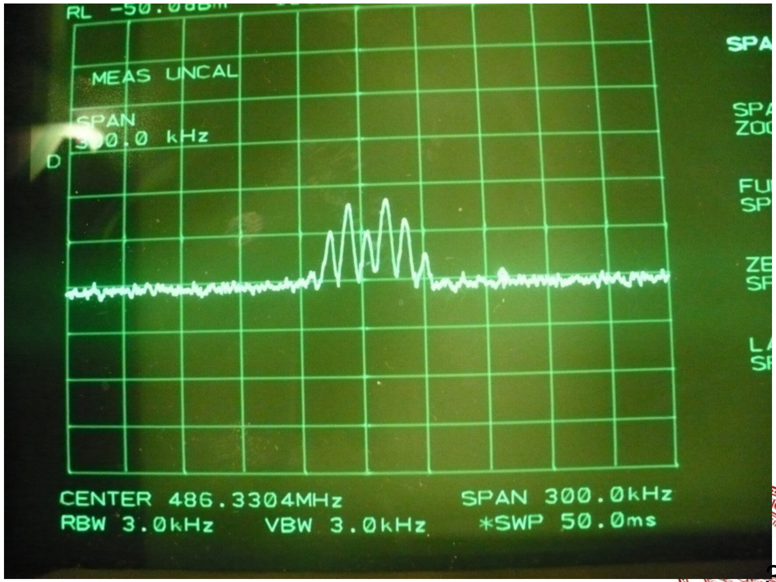
Measured beam's unstable mode 354 when the bunch-by-bunch feedback is on and off,

Effect of Vacuum burst

In nominal case, the beam ion instability can't case beam loss due to the saturation mechanism.

However, when there is a vacuum burst, partial beam loss and strong beam ion instability





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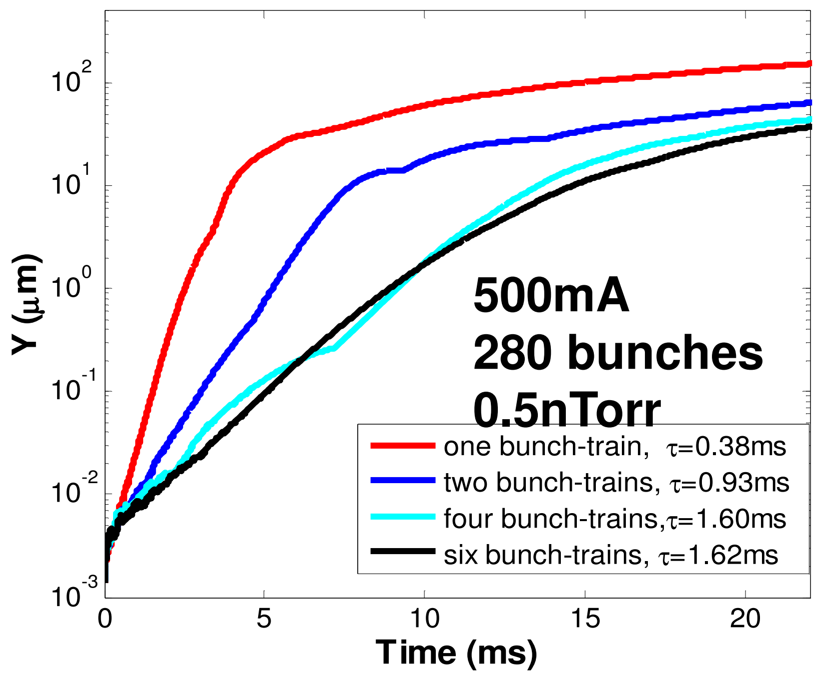
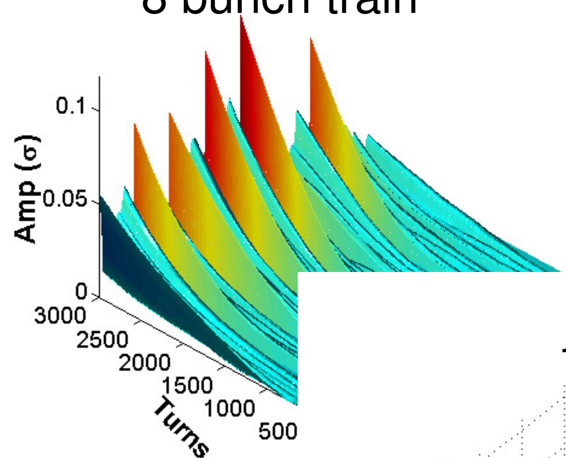
Comparison with simulation

- ✓0.5nTorr total pressure is used in the simulation(nominal pressure is order of 0.3ntorr)
- ✓Simulated growth time with 6 bunch-trains beam is 1.6ms(**2.7 ms** for 0.3nTorr pressure)
- ✓Simulation doesn't include chromaticity and radiation damping,
- ✓The vertical radiation damping times is 5.3ms.**The real growth time should be <5.3ms**

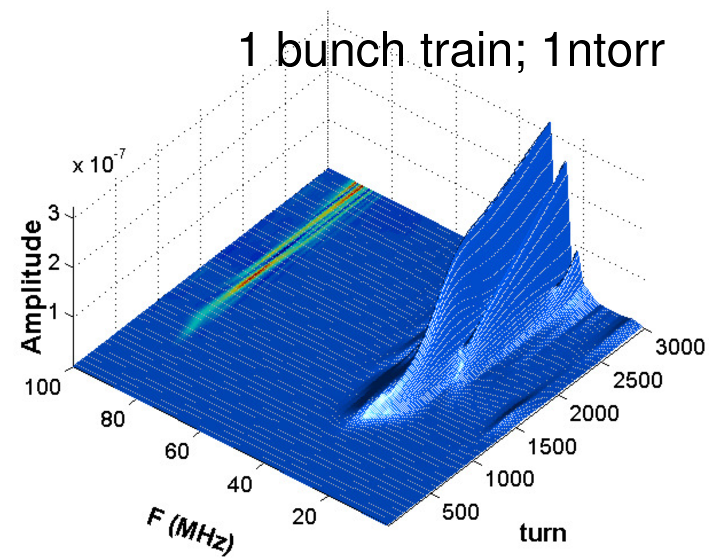


Simulated beam ion instability for different beam filling patterns

8 bunch train



1 bunch train; 1ntorr

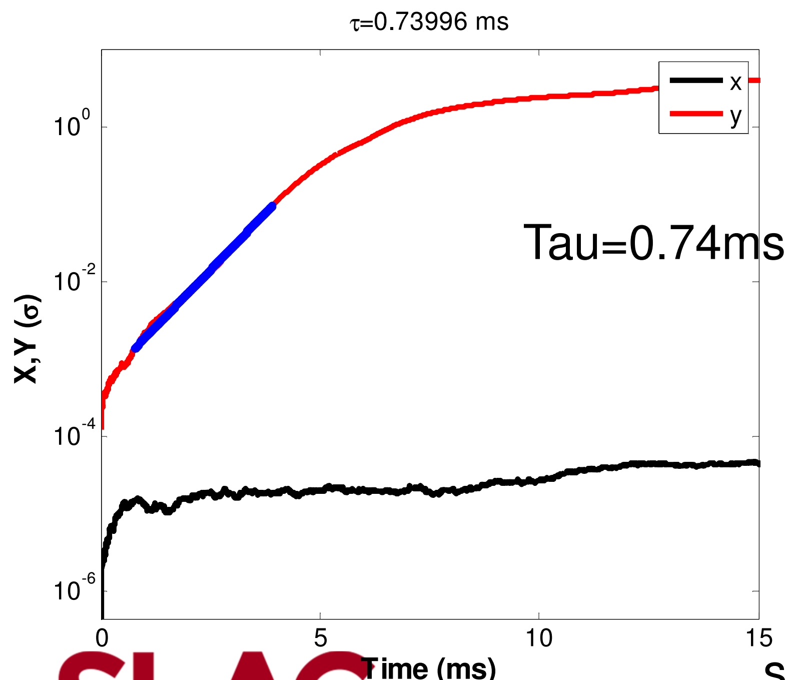


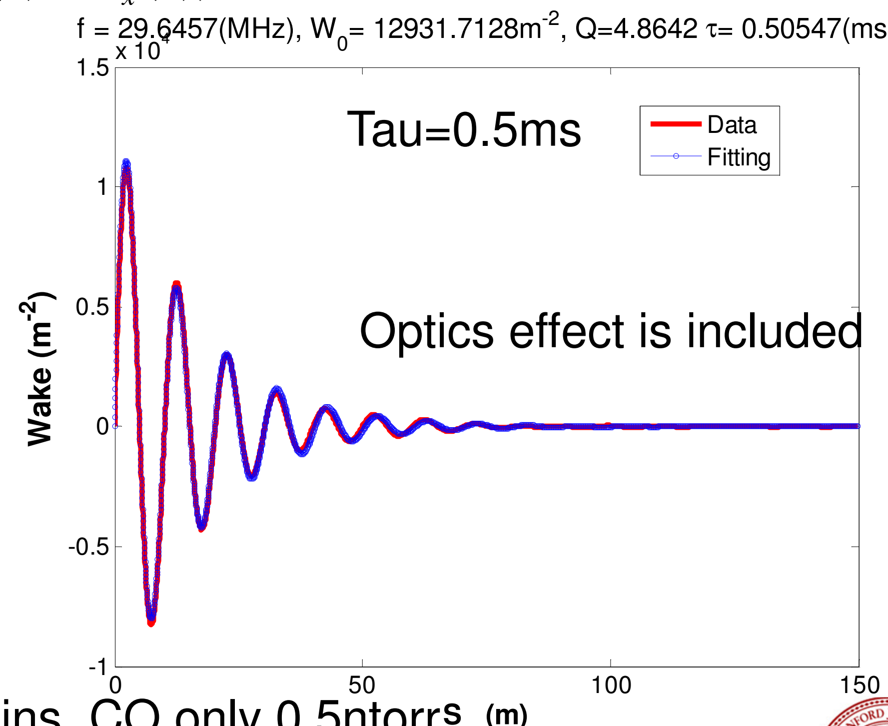
Comparison of simulation with analysis (6 bunch train)

Multi-bunch train Instability $\frac{1}{\tau} \approx \frac{r_e c \beta_y \bar{\rho} Q}{\gamma}$ $\hat{W}_t = \frac{2\omega_i}{c} \frac{L}{\lambda_e} \rho_{i,eff}$ (PRSTAB, e084401)

both nonlinear space-charge effect and optics are included

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

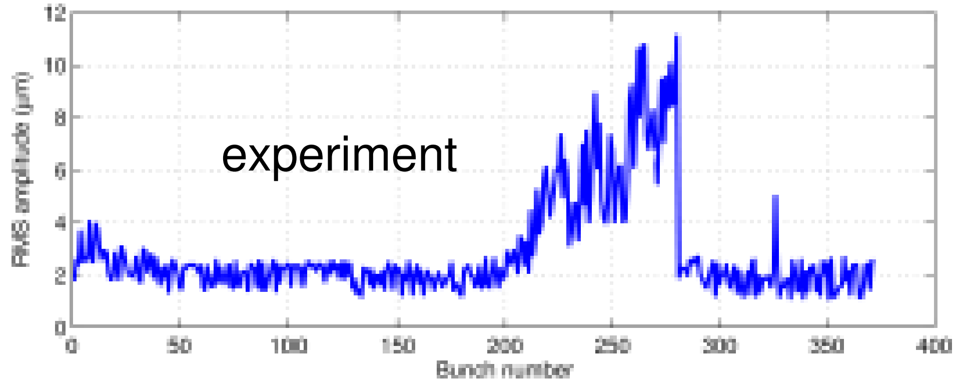


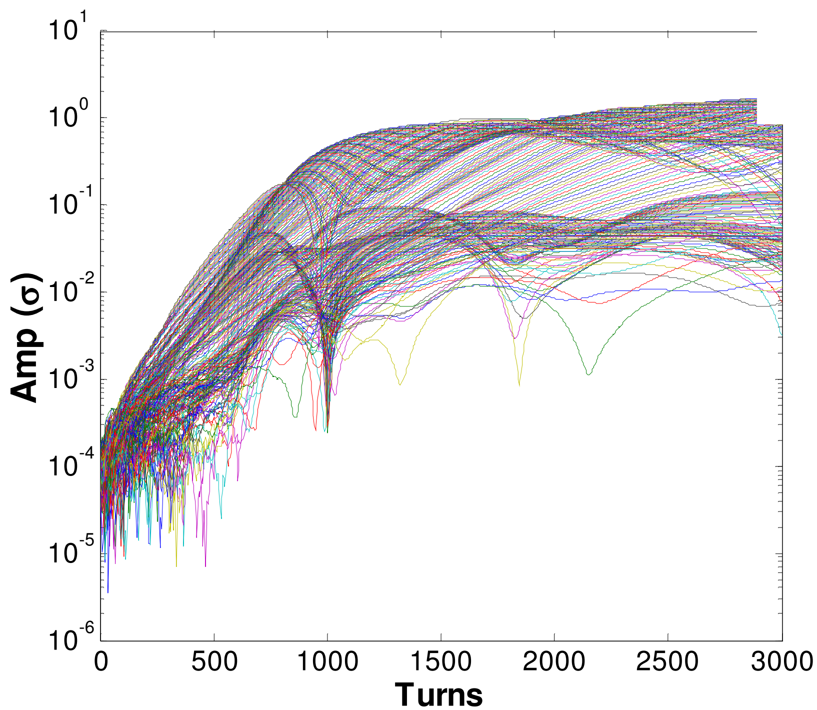


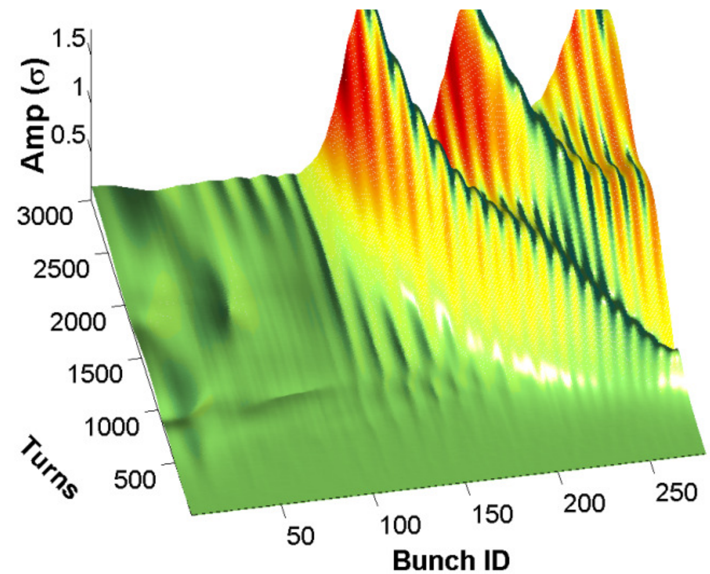
six trains, CO only 0.5ntorr

Beam ion instability at nonlinear region (y>σ)

- Strong nonlinearity
- Slow growth with amplitude beating







Beam-ion instability @500mA

Summary of Mitigations

- Better vacuum
- Clearing electrode

  (only practicable for small ring, add impedance)
- Multi-bunch-train

  (simple, cheap, very effective for high intensity beam)
- Chromaticity

  (useful with side-effects: lifetime & injection rate drop)
- Feedback System

  (very effective, need more R&D?)

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Summary

- The observations in SPEAR3 agree with theory & simulations
- This type of instability can be mitigated by multi-bunch train beam filling

  SPEAR3@500mA: 6 bunch-trains filling pattern

  200mA: 2 bunch trains

  Multi-bunch train is very effective for high intensity beam such as ILC, SuperKEKB, PEPX. (up to two orders of magnitude)
- Chromaticity can mitigate the instability at the cost of lifetime
- Bunch-by-bunch feedback is very effective(need more test? FII can be very fast although the amplitude is small)
- The beam ion instability is not a problem for SPEAR3 although we don't have feedback
- Beam-ion Instability can be important for future small emittance rings, such as ultimate storage ring light source ~pm, especially for collider.

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Acknowledgements

- Thanks James Safranek, Jeff Corbett, John Schmerge, Jim Sebek, Dmitry Teytelman, and other SSRL members for the data taking and discussions

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Thank You!

Backup slides

Comparison of FII in various electron rings (single bunch train mode is assumed)

- **For present day light sources/e-rings, FII does not pose a serious problem. It can be a problem for future low emittance light sources and damping rings.**

RING	E (GeV)	Cir(m)	n_b	I (mA)	L_{SP}(m)	E_X/σ_x nm·rad/µm	E_Y/σ_Y nm·rad/µm	$\rho_{i,eff}/\gamma$
PEPII	8.0	2199	1588	1550	1.26	31/660	1.4/144	1.1
KEKB	8.0	3016	1387	1200	2.1	24/500	0.49/75	1.0
ALS	1.5	196.8	320	400	0.6	6.3/160	0.06/23	1.2
APS	7.0	1104	24	100	45.9	3.0/276	0.025/11	0.4
PLS	2.0	280	180	360	0.6	12.1/350	0.12/35	0.3
ATF	1.3	138	20	64	0.77	1.2/70	0.0045/5	1.6
SPEAR3	3.0	234	280	500	0.63	10/200	0.014/10	1.6
NSLSII	3.0	792	1040	500	0.6	1.0/122	0.008/11	8.1
SUPERKEKBI	3.5	3016	5120	9400	0.6	24/600	0.24/60	18.7
SUPERKEKBII	7.0	3016	2500	2600	1.18	5.1/280	0.013/14	23.7
ILC	5.0	6000	3K/6K	400	0.5/1	0.8/120	0.002/6	55.3
PEPX	4.5	2199	3154	1500	0.6	0.08/18	0.0043/5.7	596

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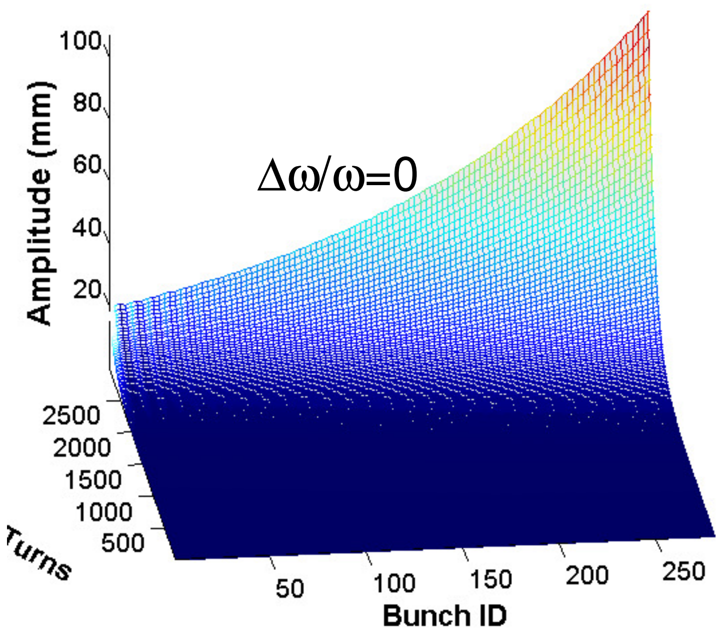
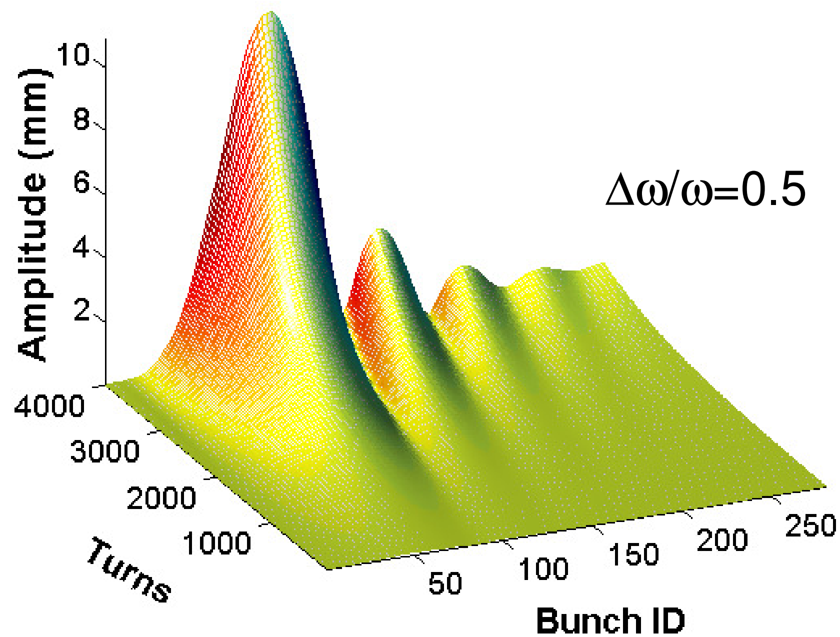
Effect of frequency spread of HOM (BBU)

- Constant Wake of ion-cloud

$$W(z) = W_0 e^{-\frac{\omega_i z}{2Qc}} \sin(\frac{\omega_i z}{c}) \qquad Z_t(\omega) = \frac{W_t}{\omega} \frac{Q}{1 + iQ\left(\frac{\omega_i}{\omega} - \frac{\omega}{\omega_i}\right)}$$

- Frequency spread model: 10 modes with equal frequency variation





[Yokoya, ?]

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Types of beam ion instability[1]

- Single bunch train: Fast ion Instability (FII)
  - **zero frequency spread** **(next page)**
  - **With large frequency spread**
- Uniform beam filling pattern $a = 0.5$
- Multi-bunch train beam filling pattern $a = 1.0$

$$(0.5 \le a \le 1)$$

The maximum exponential growth rate

$$\rho_{i,eff} = \frac{2\lambda_i}{3\sigma_y(\sigma_y + \sigma_x)}$$

$$\tilde{y}(t) \propto e^{\frac{t}{\tau}} \Rightarrow \frac{1}{\tau} \approx \frac{r_e c \beta_y Q}{\gamma}(a\rho_\infty) \quad a = \bar{\rho} / \rho_\infty$$

$\bar{\rho}$ Is the average ion density seen by all bunches

ρ_∞ Is the maximum ion density seen by all the bunches

Q : typically 1~8, can be smaller than 1

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Quasi-exponential growth Regime I
(FII, Zero Frequency spread case)

$$\frac{\Delta \omega_i l}{c} << \frac{1}{2}\sqrt{\frac{t}{\tau_c}}$$

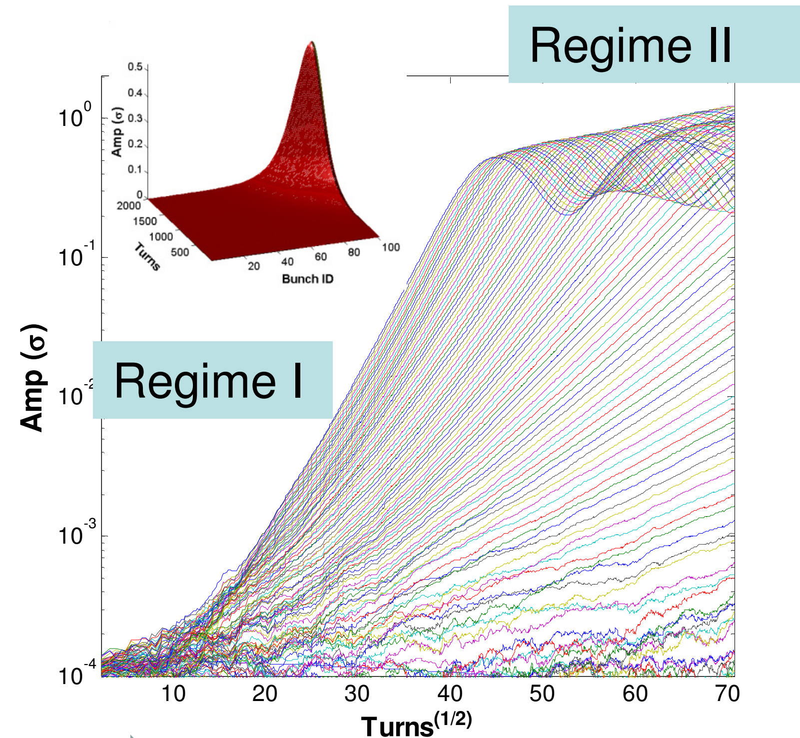
Region I

$$\frac{\partial^2}{\partial s \partial z}\tilde{y}(s,z) = \frac{\beta_y \Lambda}{4} z\tilde{y}(s,z)$$

$$\tilde{y}(s,z) = I_0\left(z\sqrt{\frac{\beta_y \Lambda}{2}s}\right) \approx \exp\left(z\sqrt{\frac{\beta_y \Lambda}{2}s}\right) = \exp\left(\frac{z}{l}\sqrt{\frac{t}{\tau_c}}\right)$$

$$\frac{1}{\tau_c} = \frac{1}{2}\frac{cr_e\beta_y N n_b}{\gamma}\hat{W}(l) = \frac{r_e c\beta_y \rho_{i,eff}}{\gamma}\frac{\omega_i z}{c}$$

Fast instability only when the amplitude is small than the beam size!



FII , simulation

(T. Raubenheimer, F. Zimmermann, PRE V51, 5487, 1995)

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Theory of FII

Single bunch train instability

Zero frequency spread (w.o optics), Quasi-exponential growth

(T. Raubenheimer, F. Zimmermann, PRE V51, 5487, 1995)

$$\tilde{y}(s,z) \propto \exp\left(\frac{z}{l}\sqrt{\frac{t}{\tau_c}}\right) \qquad \frac{1}{\tau_c} = \frac{1}{2}\frac{cr_e\beta_y N n_b}{\gamma}\hat{W}(l) = \frac{r_e c\beta_y \rho_{i,eff}}{\gamma}\frac{\omega_i z}{c}$$

With frequency spread due to optics, exponential growth

[G. Stupakov, KEK Proceedings 96-6, 243 (1996)]

$$\frac{1}{\tau_{e,FII}} \approx \frac{r_e c\beta_y \lambda_i}{3\sqrt{2}\gamma\sigma_y(\sigma_y+\sigma_x)}\frac{1}{\Delta\omega_i/\omega_i}$$

Multi-Bunch-train instability

$$\frac{1}{\tau} \approx \frac{r_e c\beta_y \bar{\rho} Q}{\gamma}$$

Both Optics effect beam

$$a = \bar{\rho}/\rho_\infty \quad (0.5 \le a \le 1)$$

a=1 for an even beam filling pattern;
a=0.5 for a single bunch train beam filling pattern

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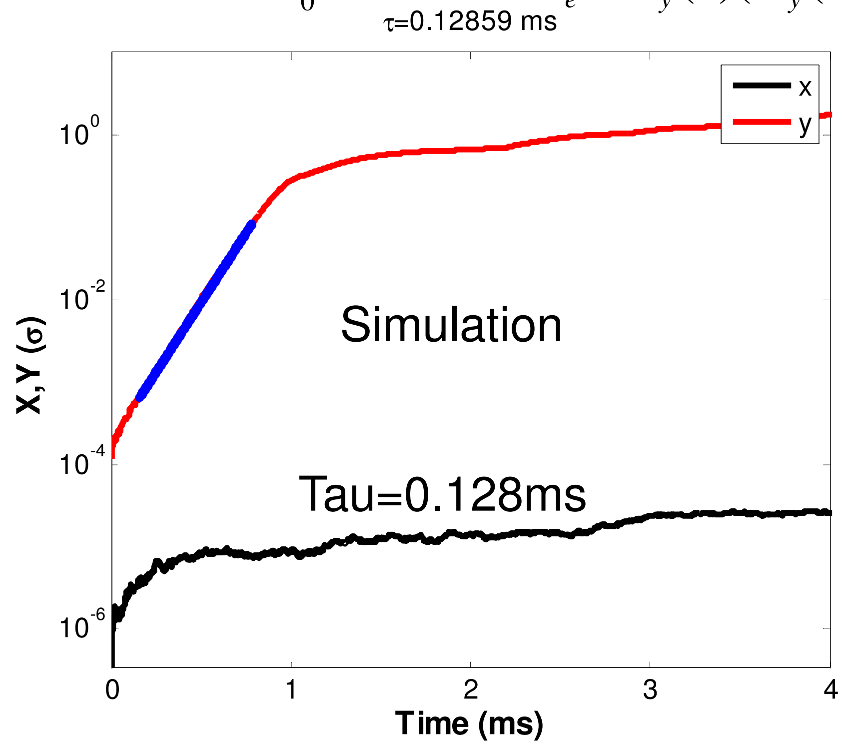
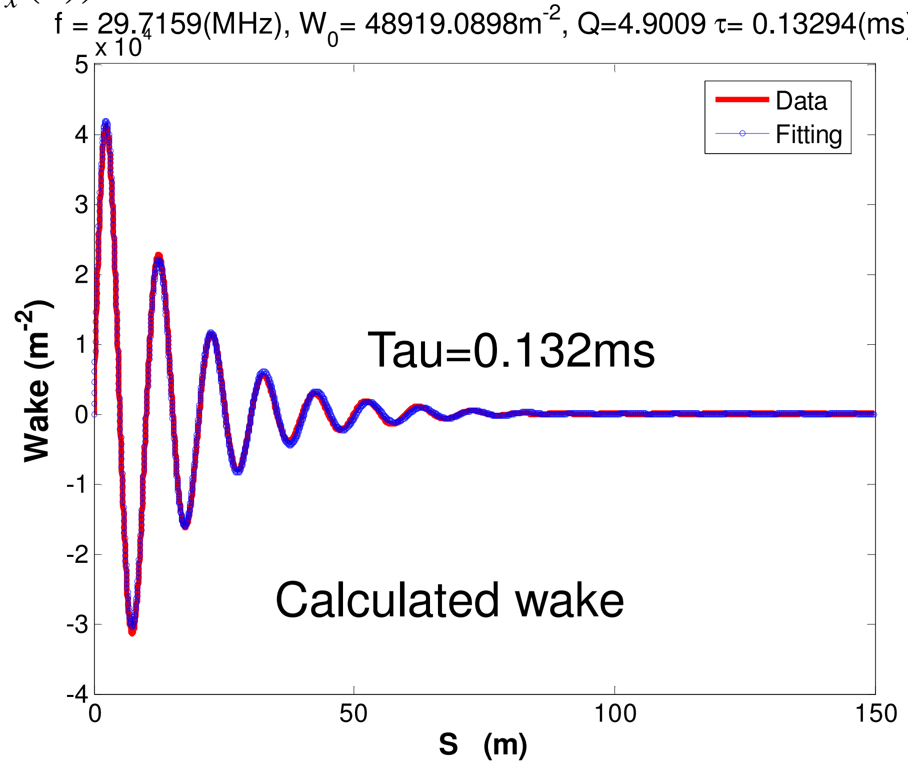
Comparison of simulation with analysis (1 bunch train)

Analysis Using the total wake (Q0=8)

Optics effect is included

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

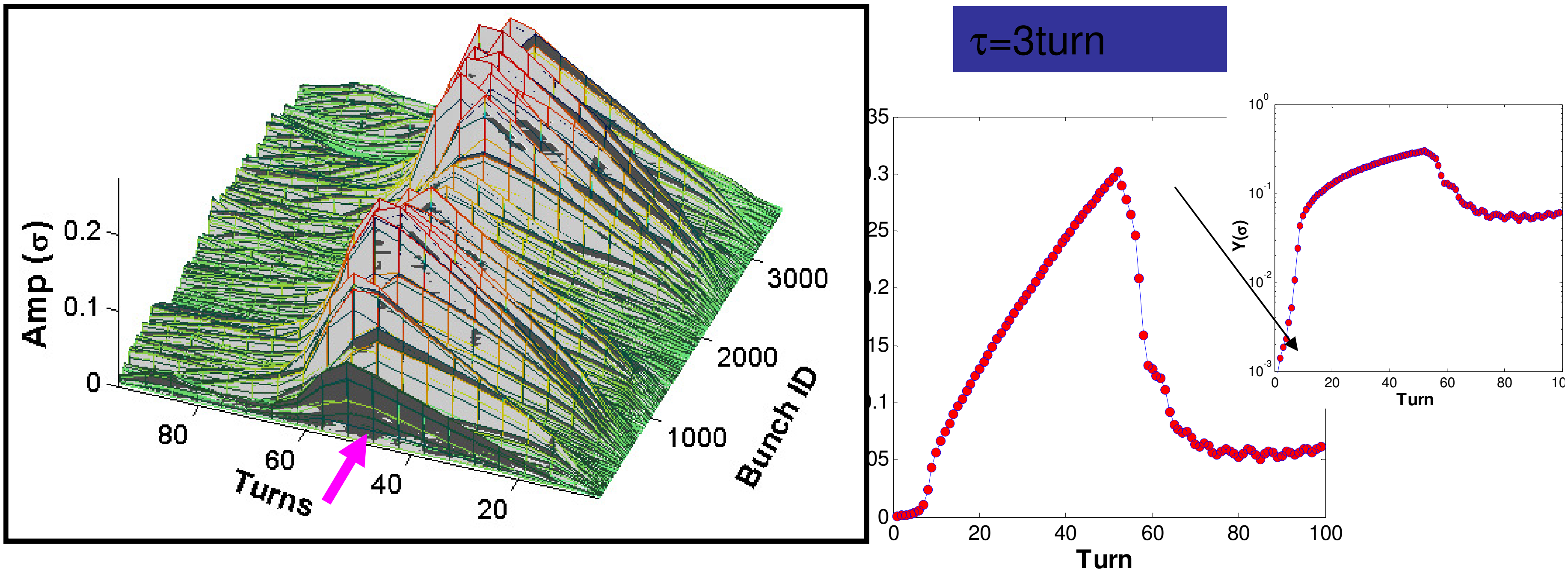




One train, 500mA, 280 bunches, CO only 0.5ntorr

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.



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