Suppression of Transverse Instabilities by Chromaticity Modulation

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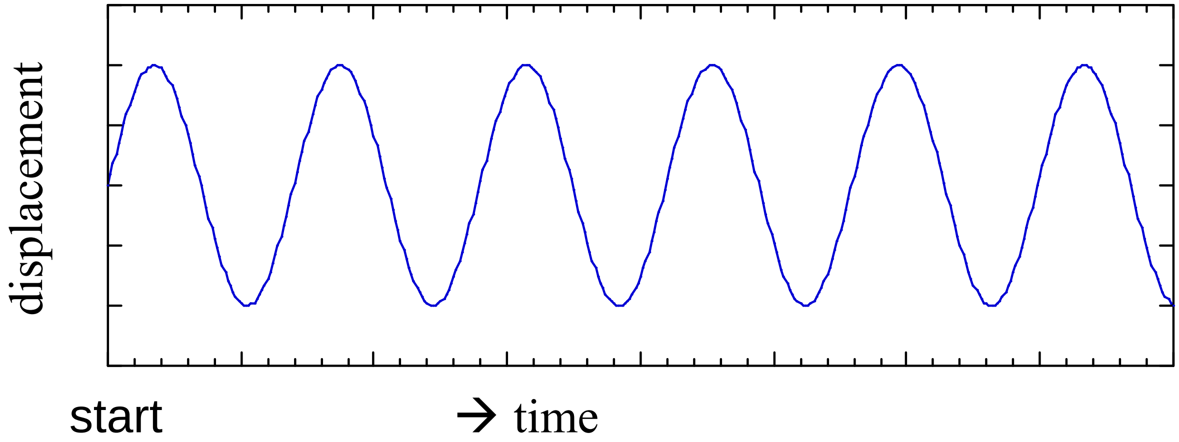
Landau damping of betatron motion

Suppose that particles in a bunch have tune variation (spread).

After many revolutions, they oscillate with different phases.

Then the oscillation amplitude of the average (coherent osci.) becomes smaller.



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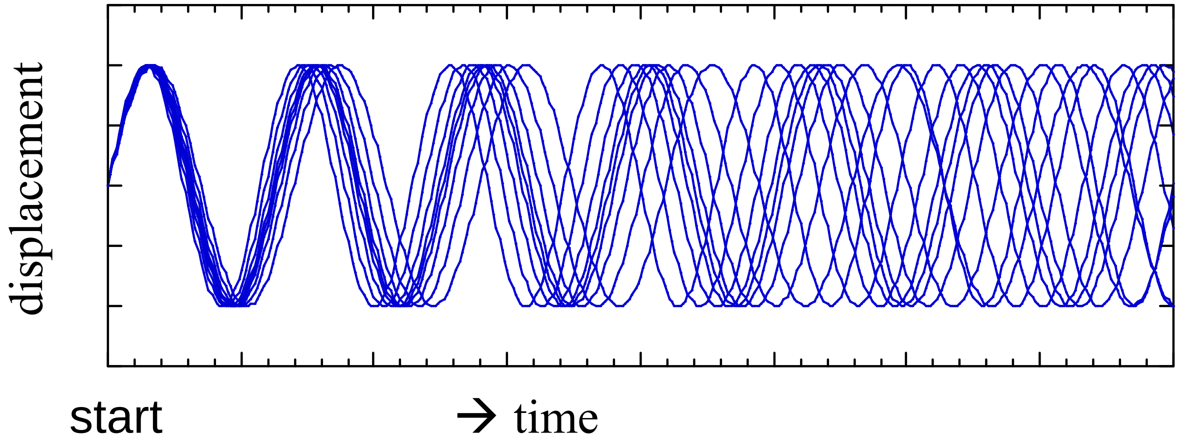

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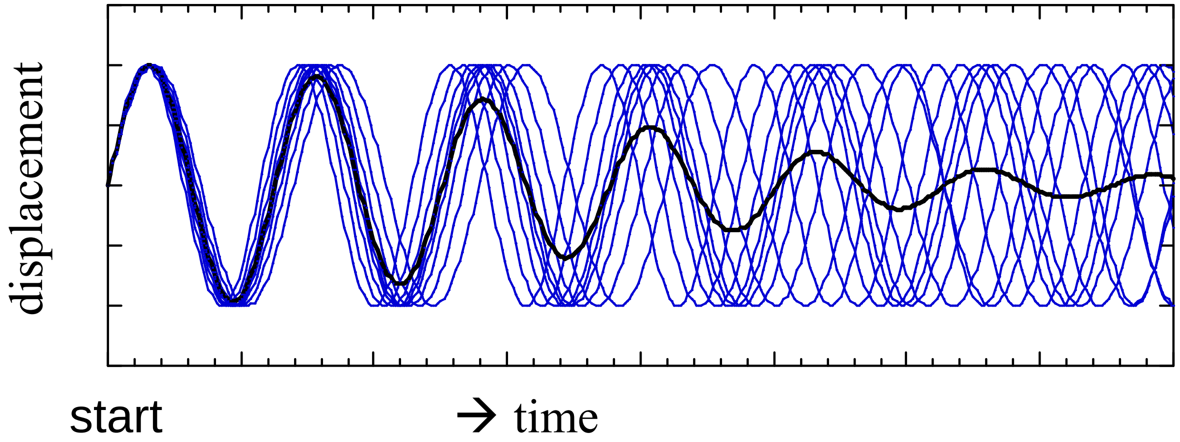

It suppresses the growth of the oscillation.

→ suppression of any transverse instability

Chromatic Tune Spread

Betatron tune shift with chromaticity $\Delta\nu = \xi_0 \delta$

With synchrotron oscillation $\delta = \delta_0 \cos\omega_S t + (\omega_S / \alpha_P)\tau_0 \sin\omega_S t$

Averaged tune shift over T_S $\langle \Delta\nu \rangle_{T_S} = \langle \xi_0 \delta \rangle_{T_S} = 0$

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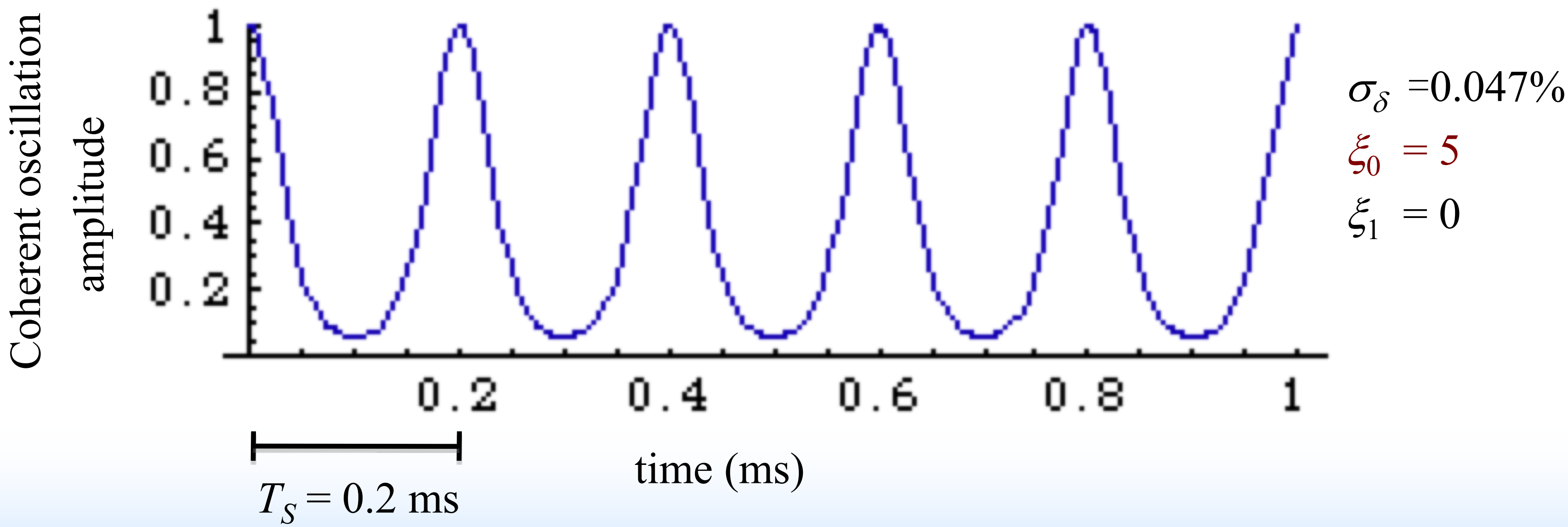
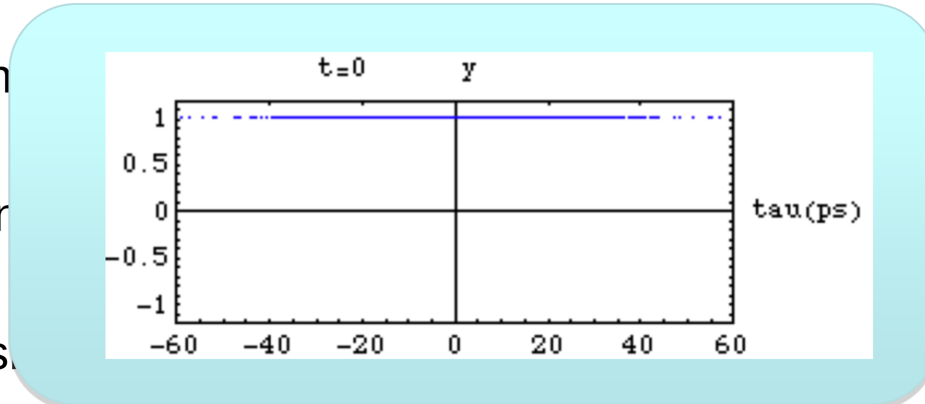


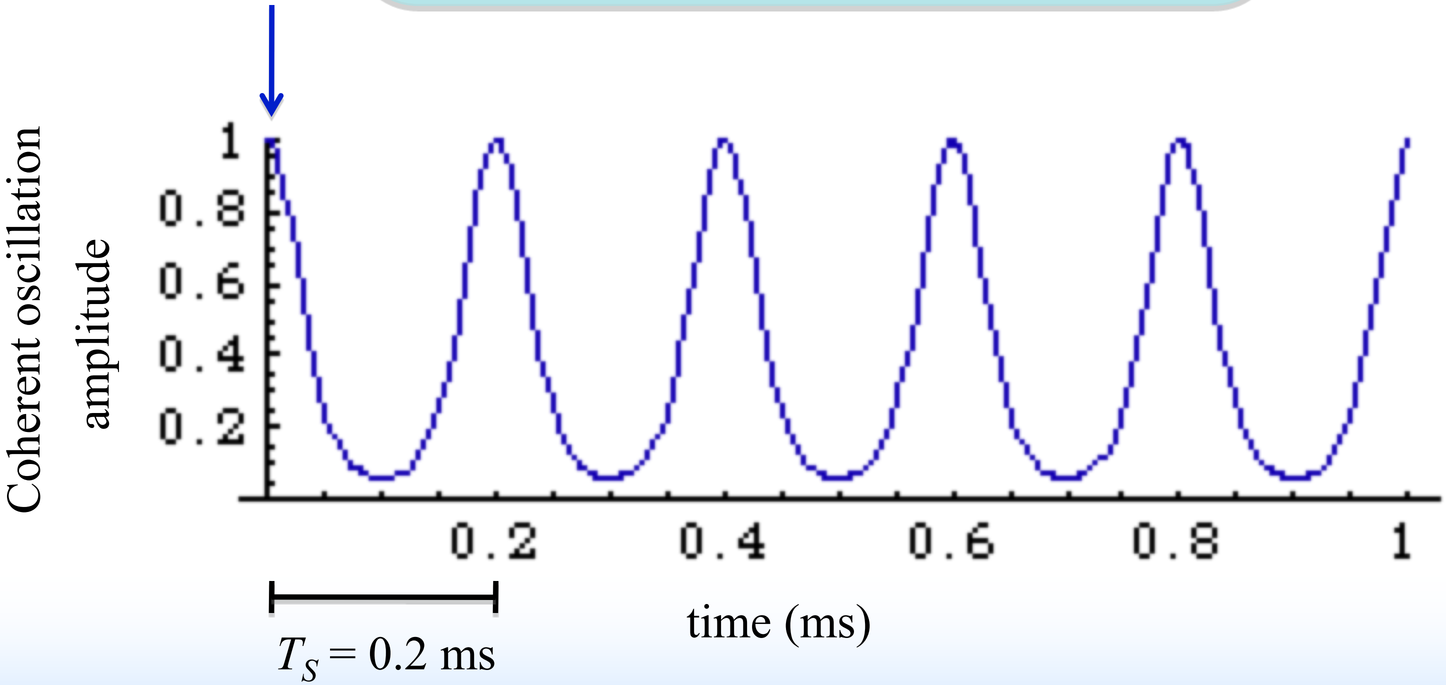
Chromatic Tune Spread

Betatron tune sh

With synchrotron $\ldots_P)\tau_0 \sin\omega_S t$

Averaged tune s





σ_δ =0.047%

$\xi_0 = 5$

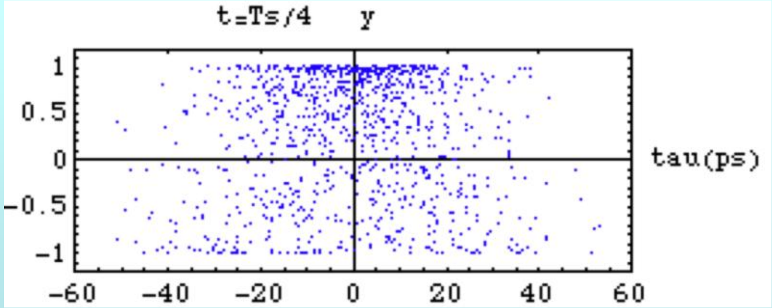
$\xi_1 = 0$

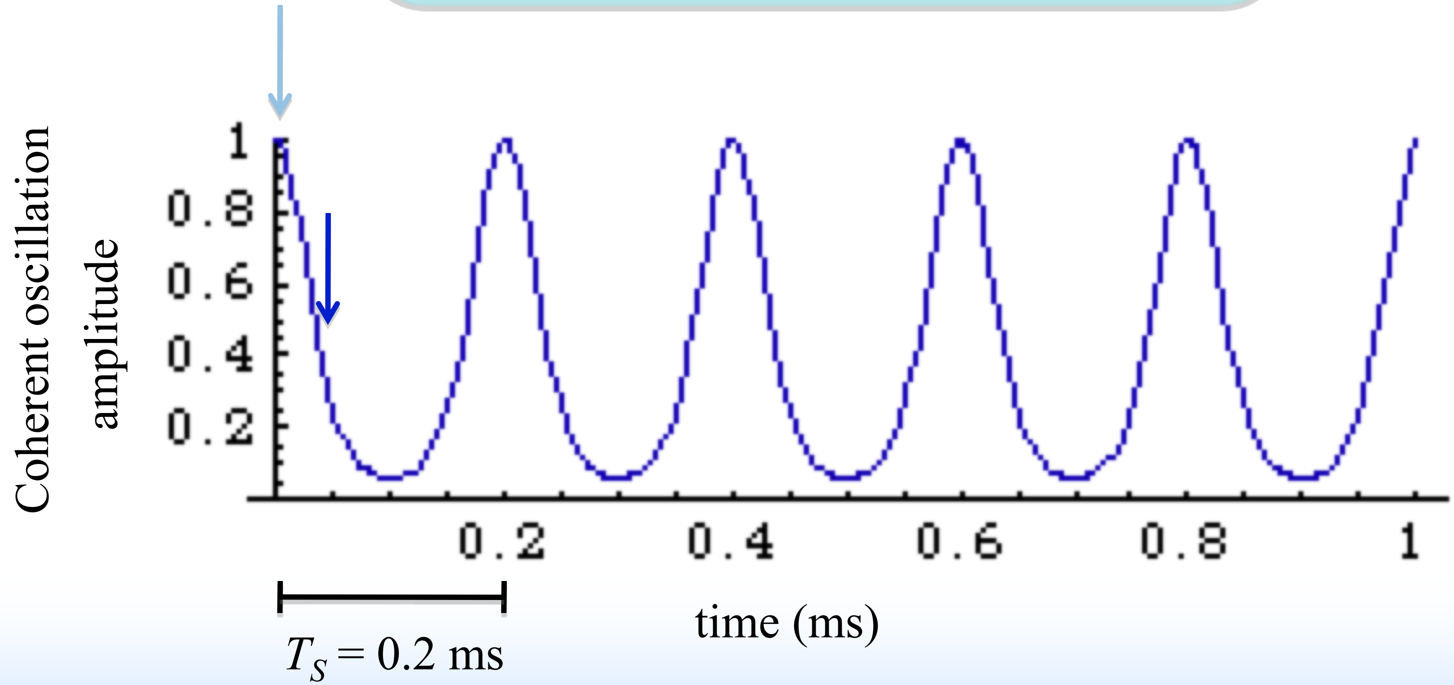
Chromatic Tune Spread

Betatron tune sh

With synchrotron $\ldots_P)\tau_0 \sin\omega_S t$

Averaged tune s





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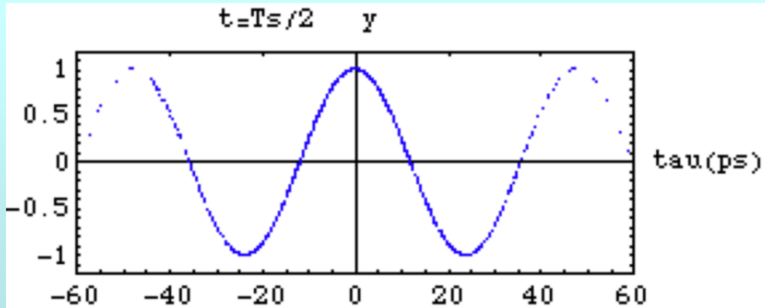
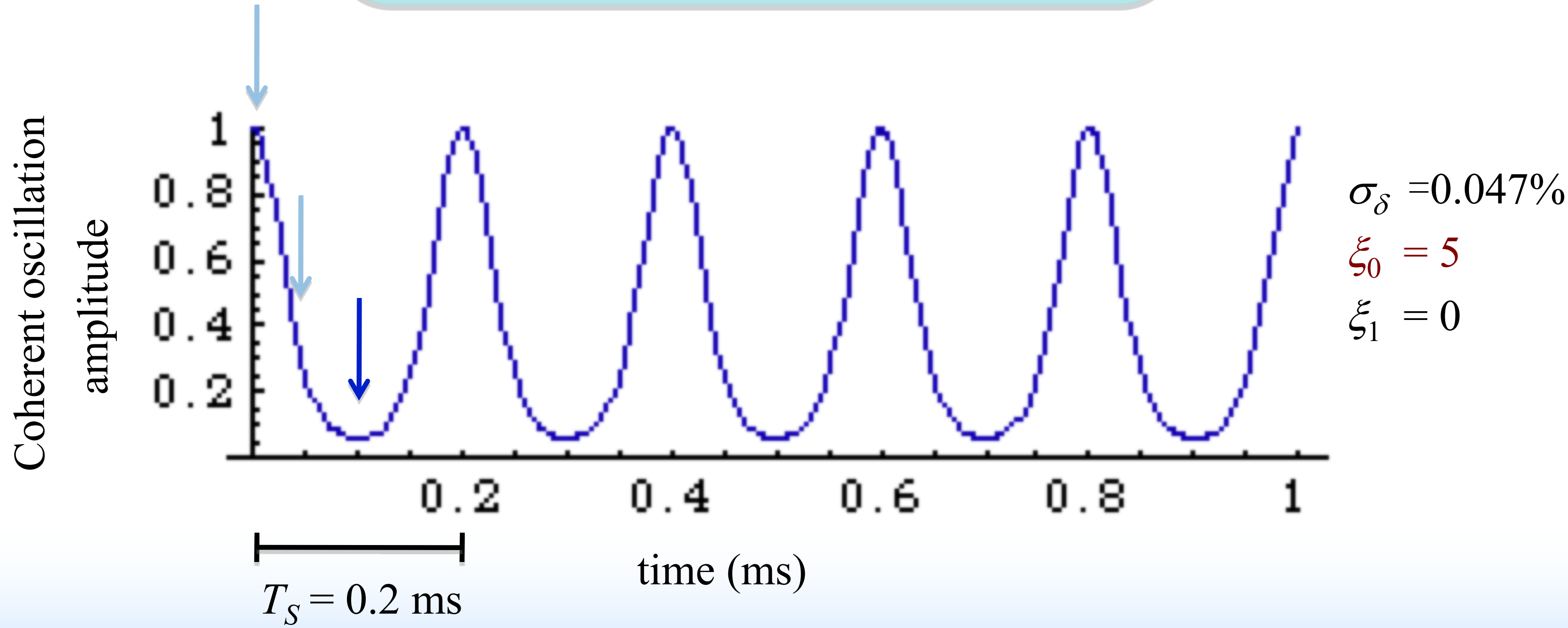


Averaged tune s

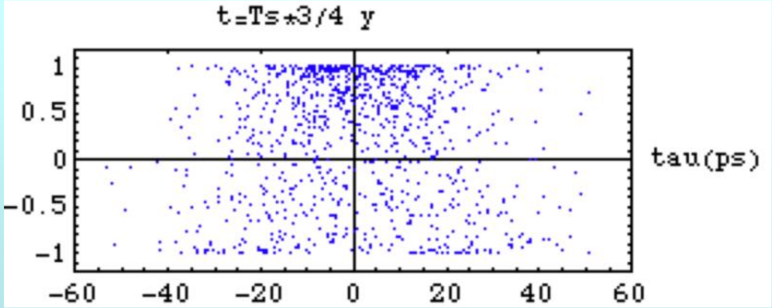


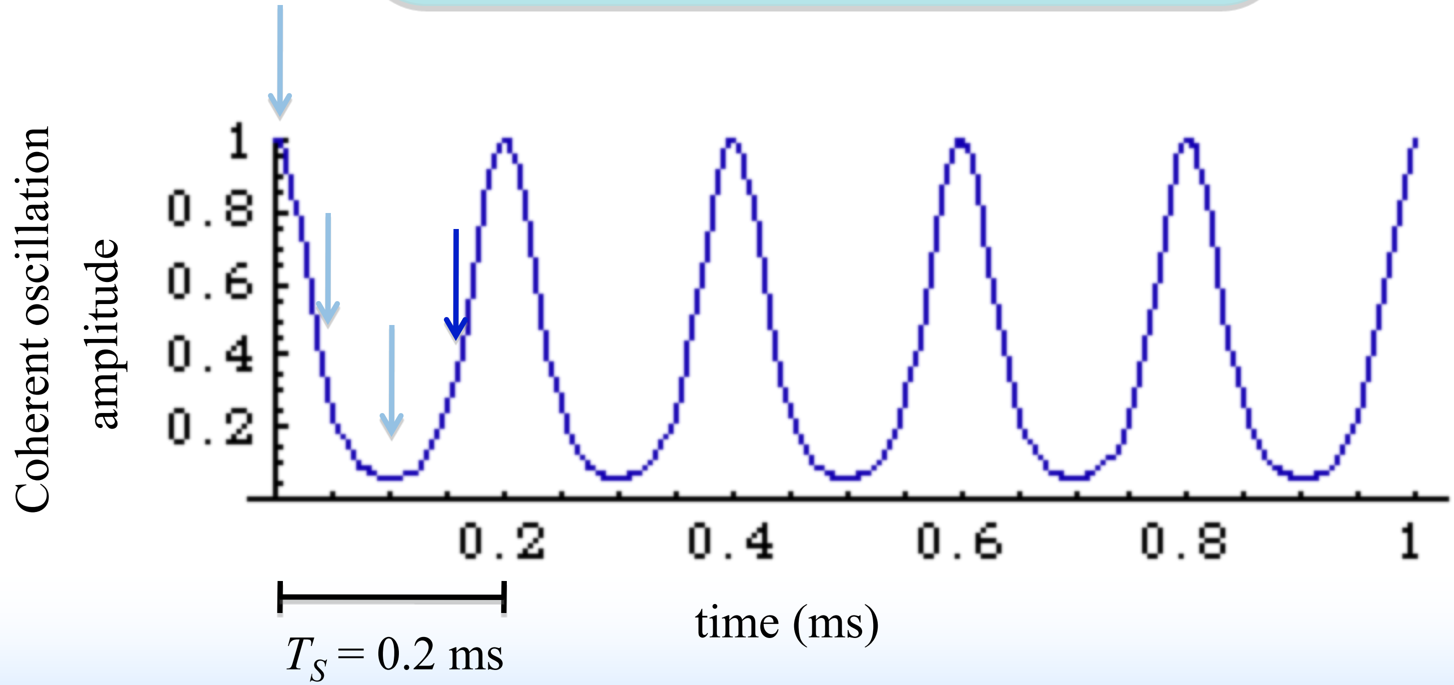
Chromatic Tune Spread

Betatron tune sh

With synchrotron $\;{}_P)\tau_0 \sin\omega_S t$

Averaged tune s





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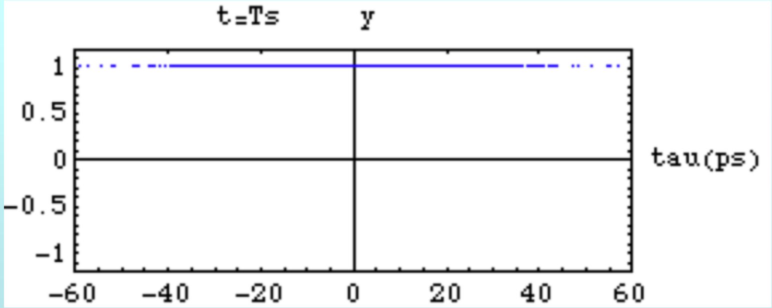
Chromatic Tune Spread

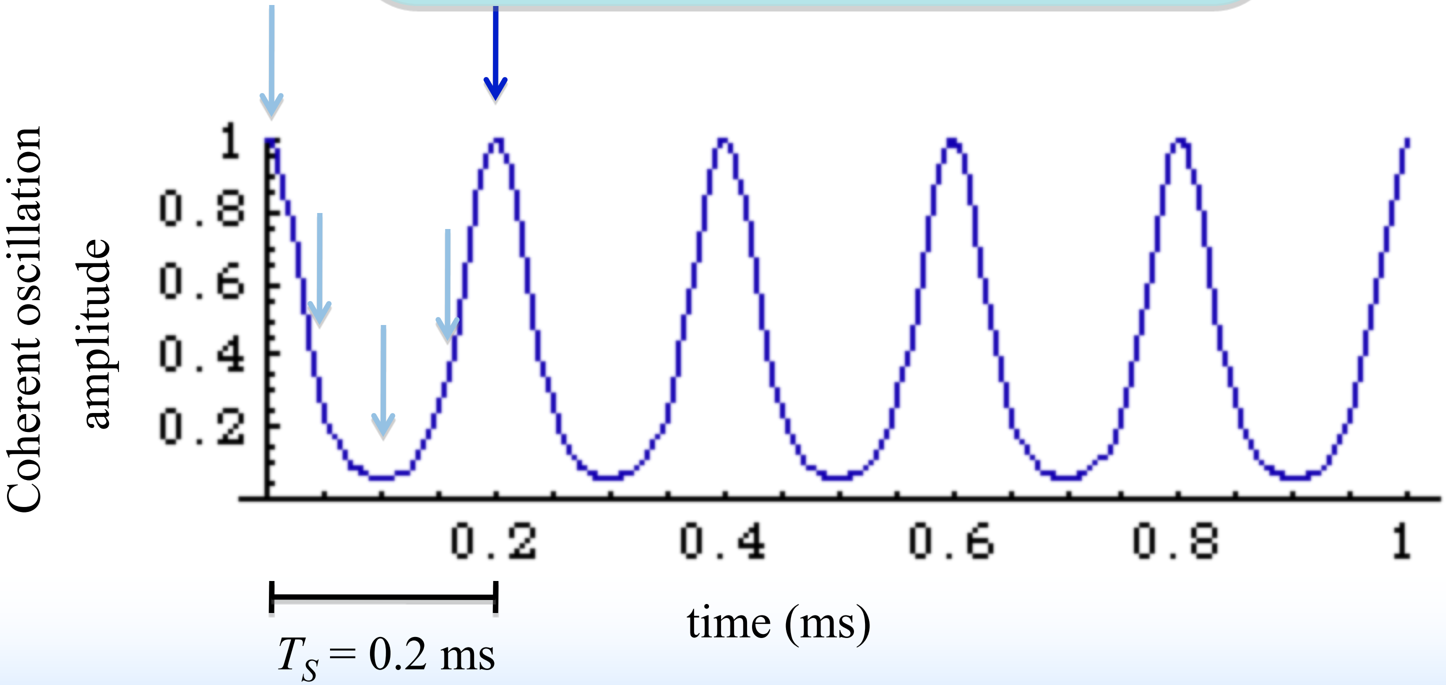
Betatron tune sh

With synchrotron



$_P)\tau_0 \sin\omega_S t$

Averaged tune s



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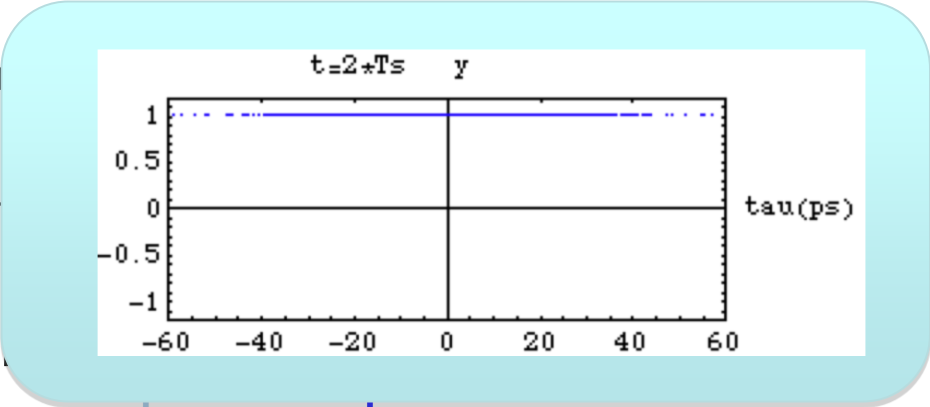

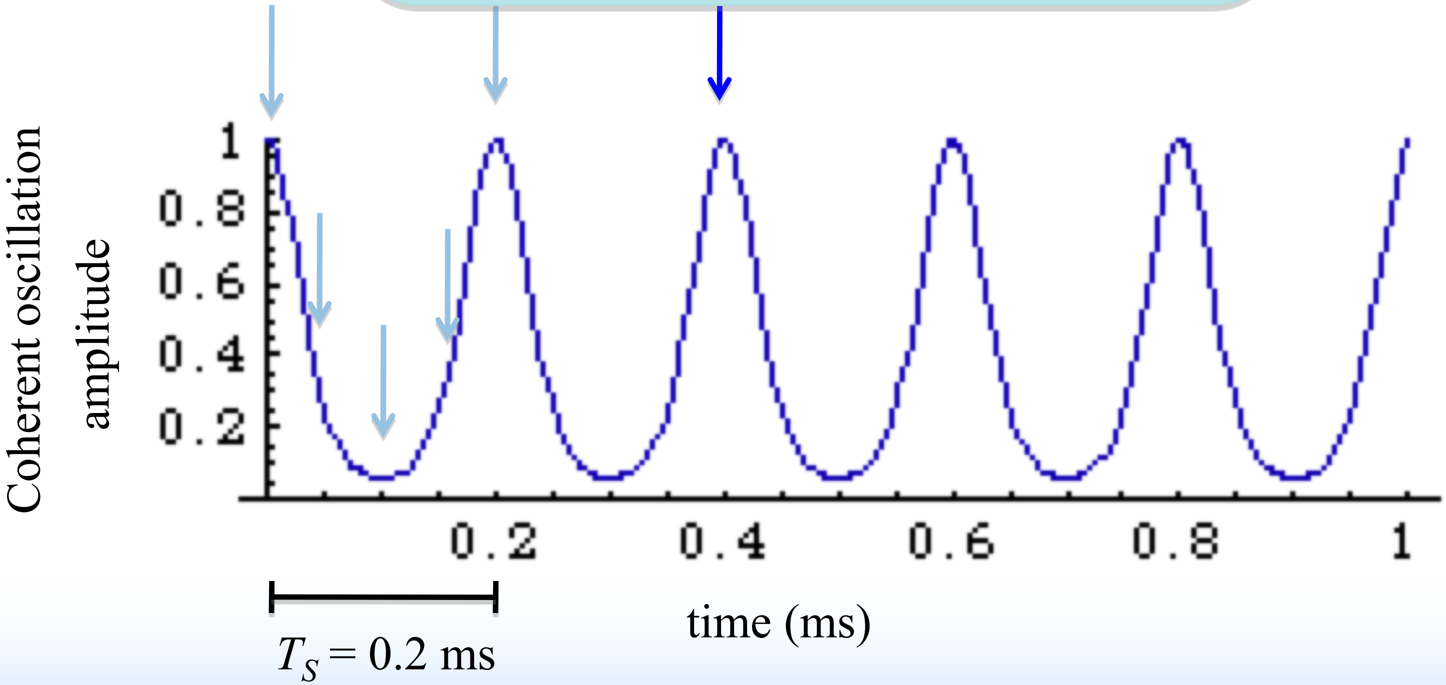

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$\xi_0 = 5$

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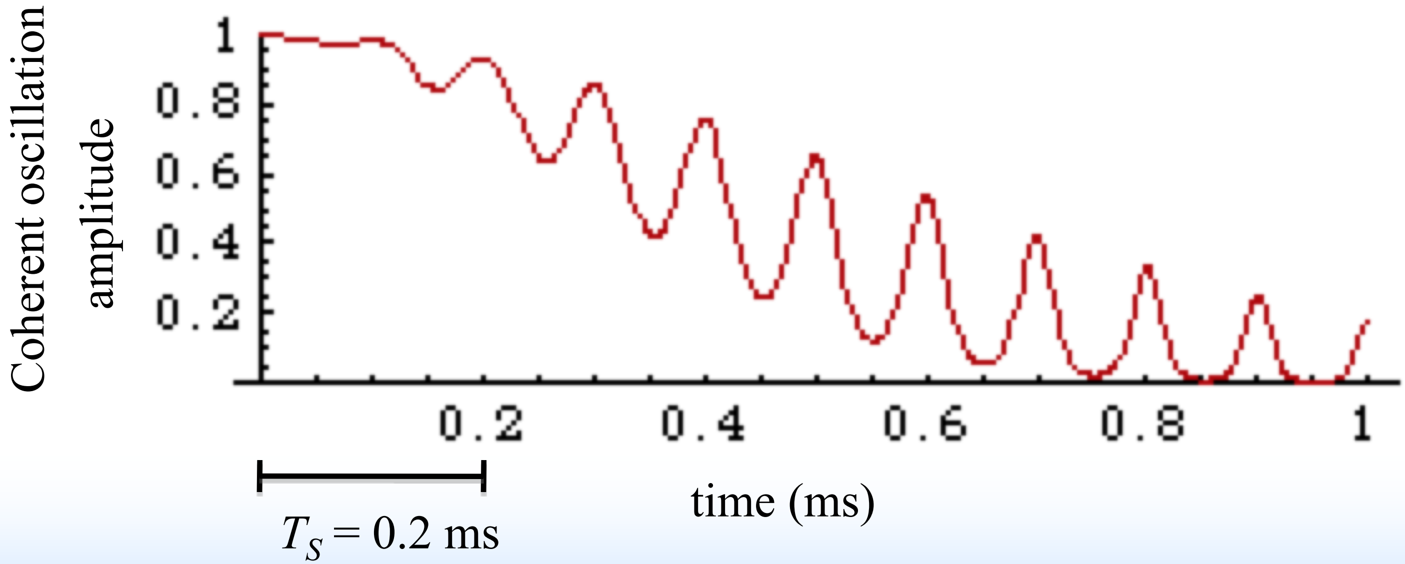
Chromatic Tune Spread

Chromaticity modulation $\Delta\nu = (\xi_0 + \xi_1 \cos\omega_S t)\delta$

With synchrotron oscillation $\delta = \delta_0 \cos\omega_S t + (\omega_S / \alpha_P)\tau_0 \sin\omega_S t$

Averaged tune shift over T_S $\langle \Delta\nu \rangle_{T_S} = \langle \xi\delta \rangle_{T_S} = \frac{1}{2}\xi_1\delta_0$

tune spread



σ_δ =0.047%

$\xi_0 = 0$

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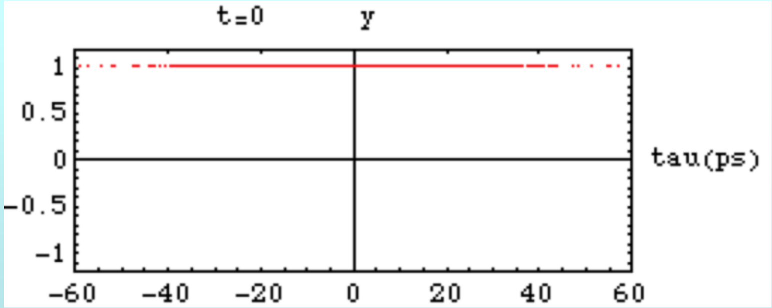
Chromatic Tune Spread

Chromaticity mo

With synchrotron

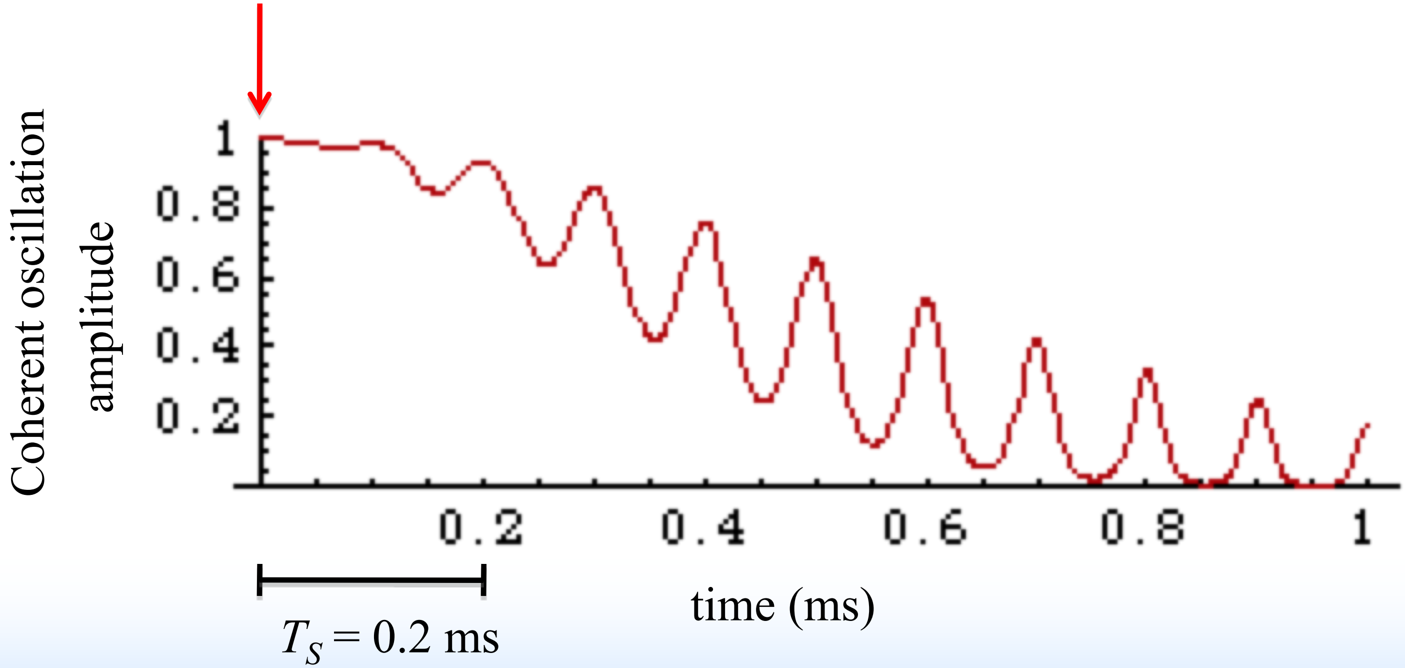
Averaged tune s



$\nu_P)\tau_0 \sin\omega_S t$

δ_0

2



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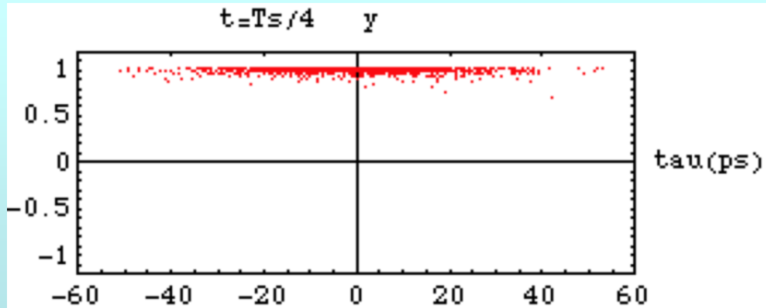
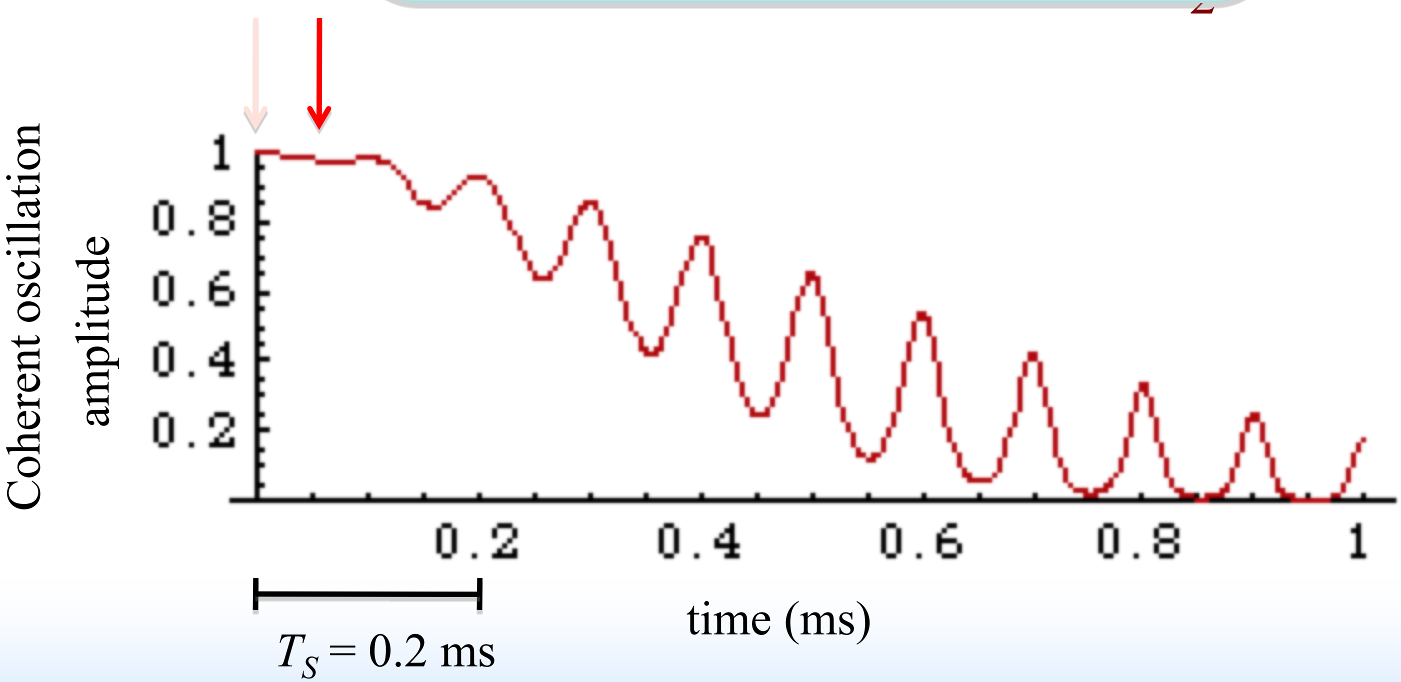
Chromatic Tune Spread

Chromaticity mo

With synchrotron ... $_P)\tau_0 \sin\omega_S t$

Averaged tune s... δ_0 ... 2





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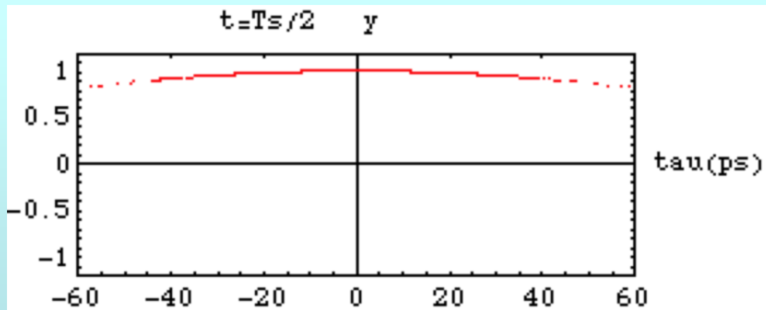
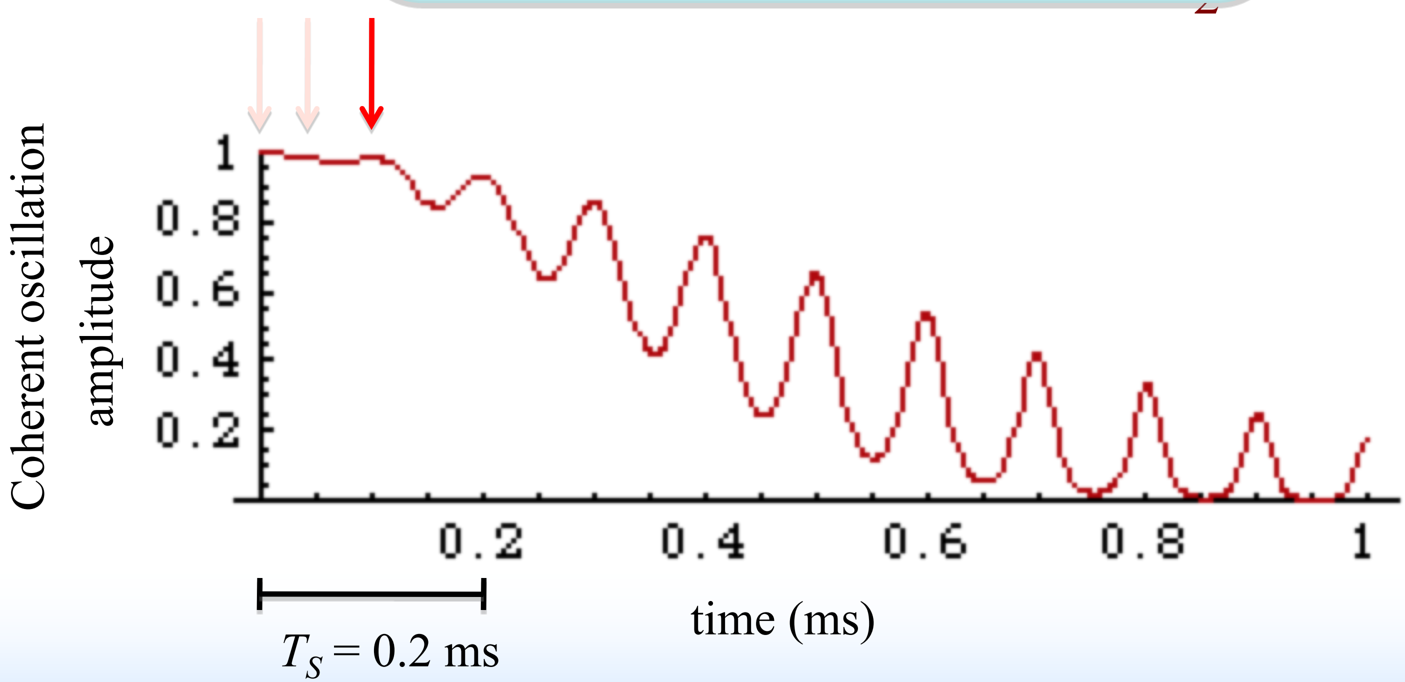
Chromatic Tune Spread

Chromaticity mo

With synchrotron $_P)\tau_0 \sin\omega_S t$

Averaged tune s δ_0





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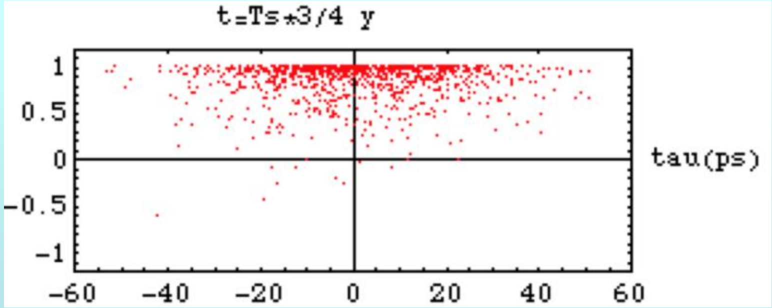

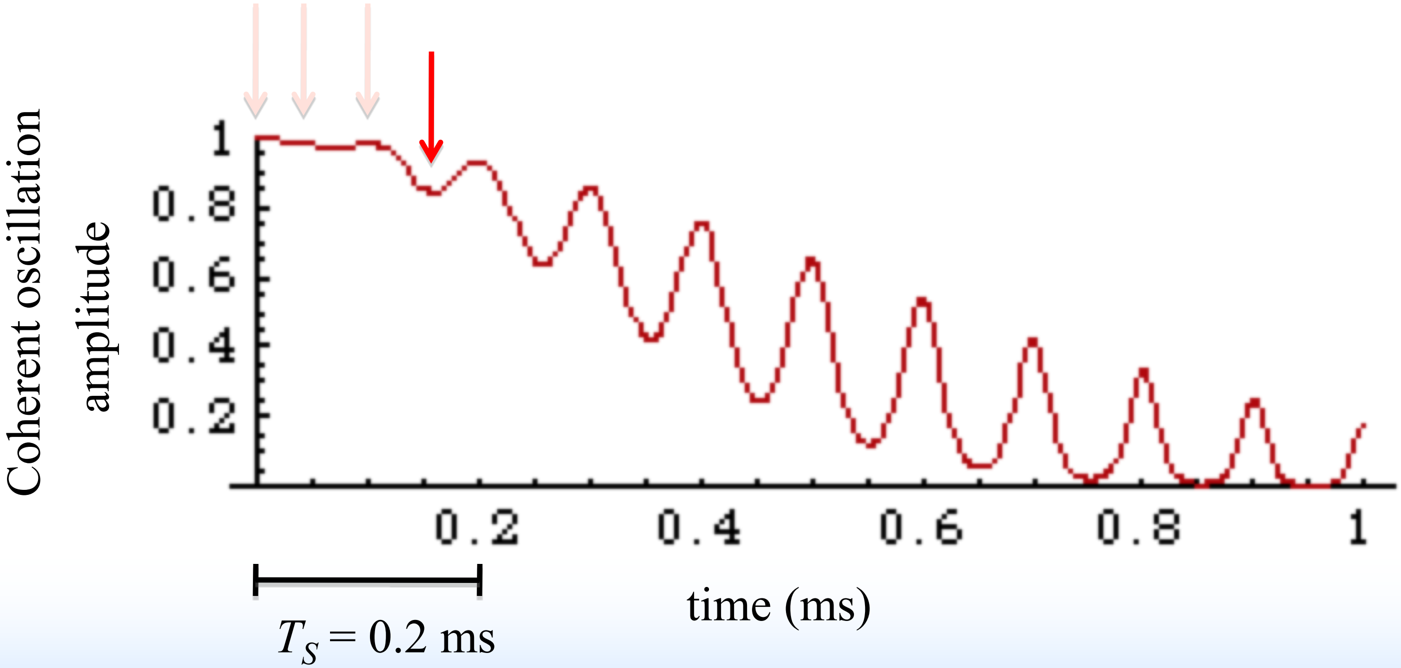

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Chromatic Tune Spread

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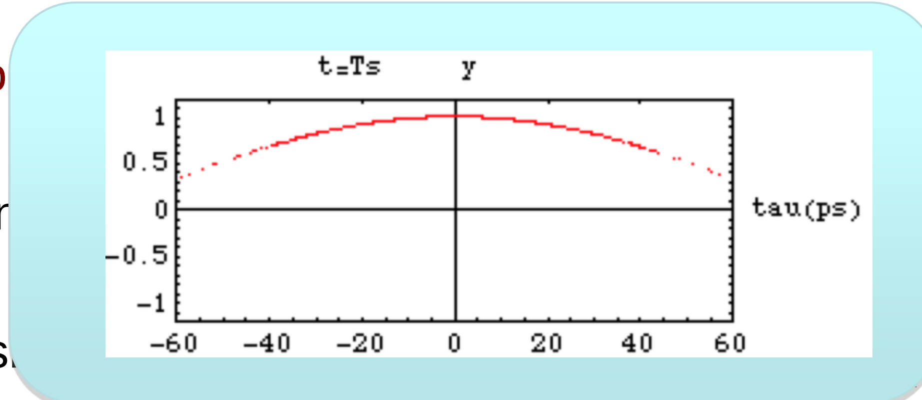
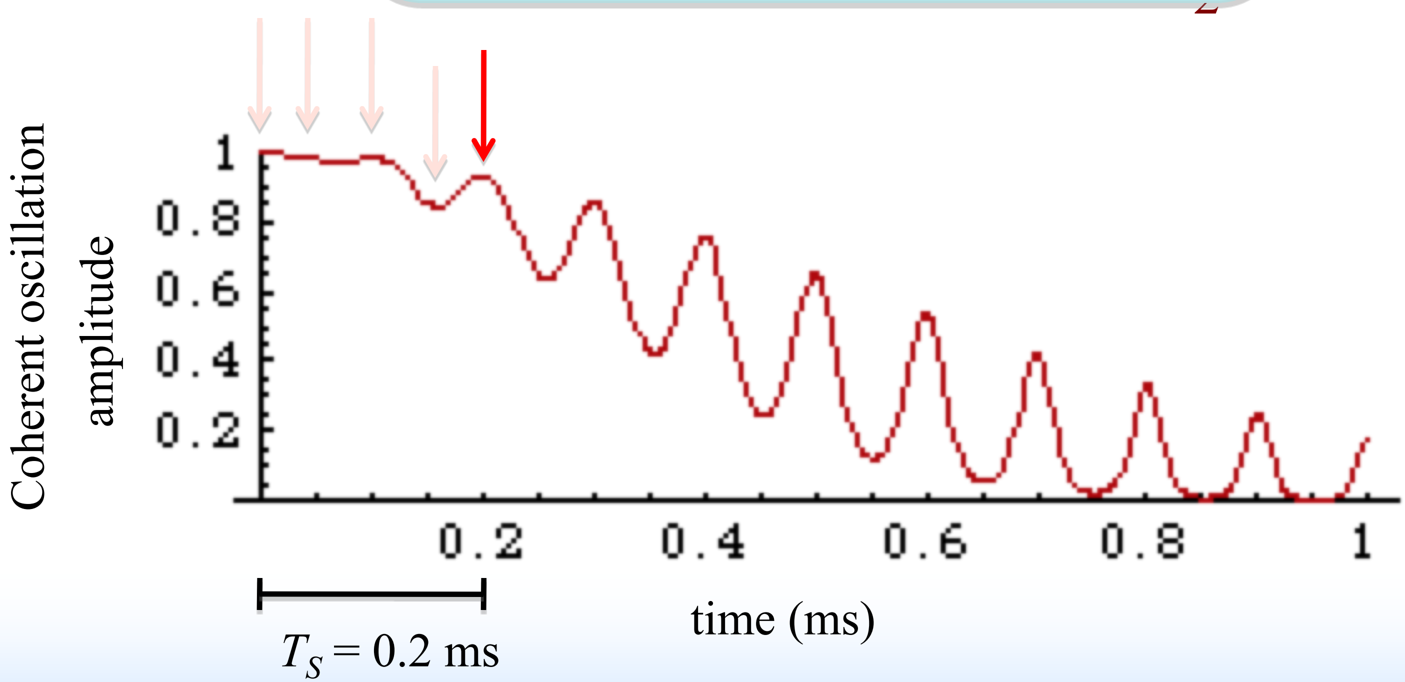


With synchrotron $)\tau_0 \sin\omega_S t$

Averaged tune s δ_0 2



$\sigma_\delta = 0.047\%$

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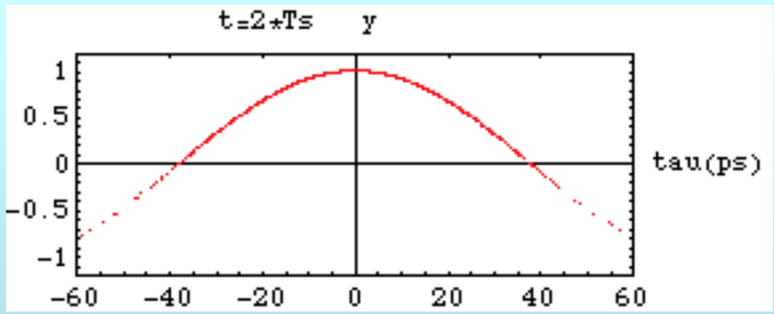
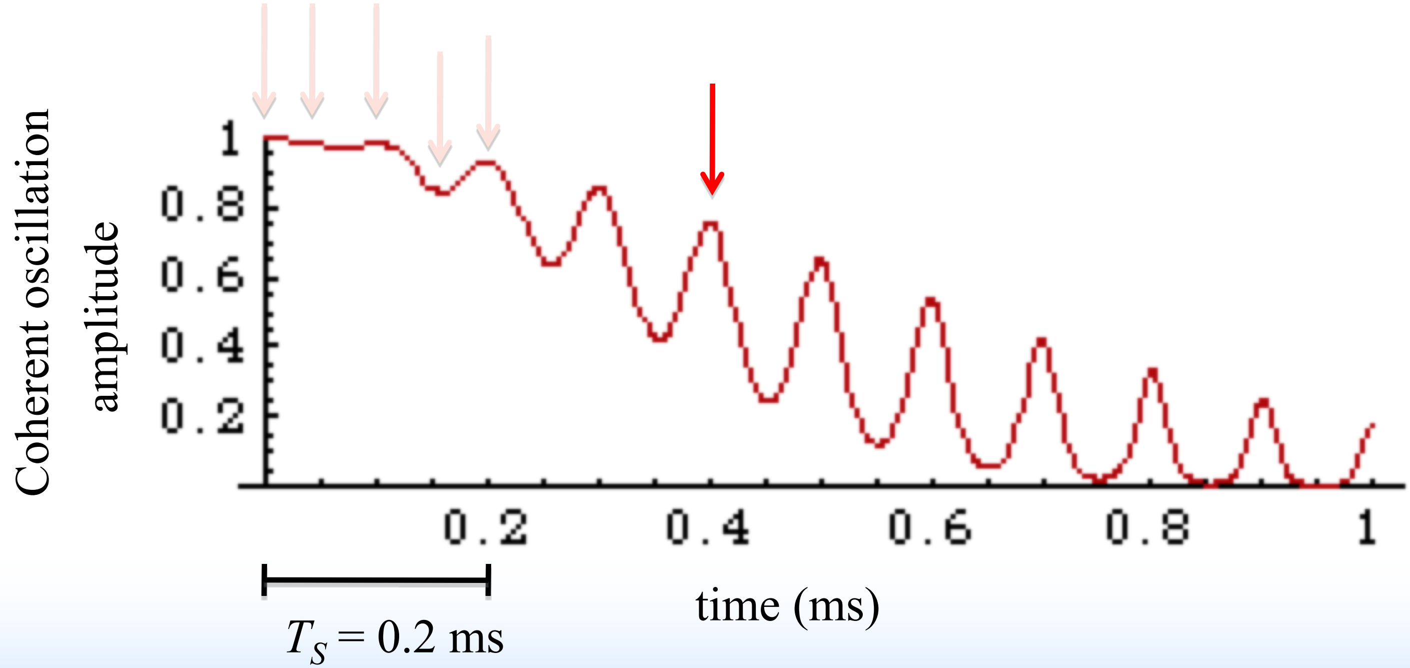
Chromatic Tune Spread

Chromaticity mo



With synchrotron ... $)\tau_0 \sin\omega_S t$

Averaged tune s... δ_0



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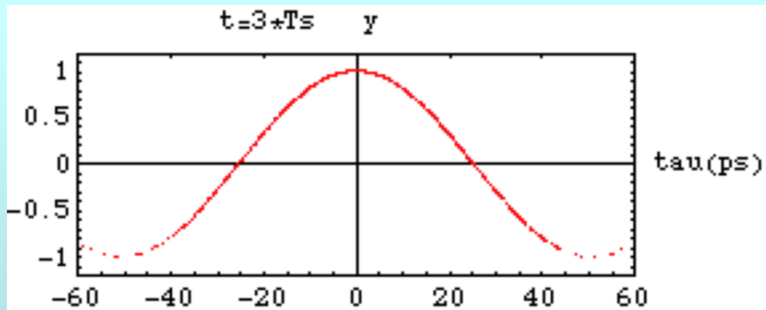

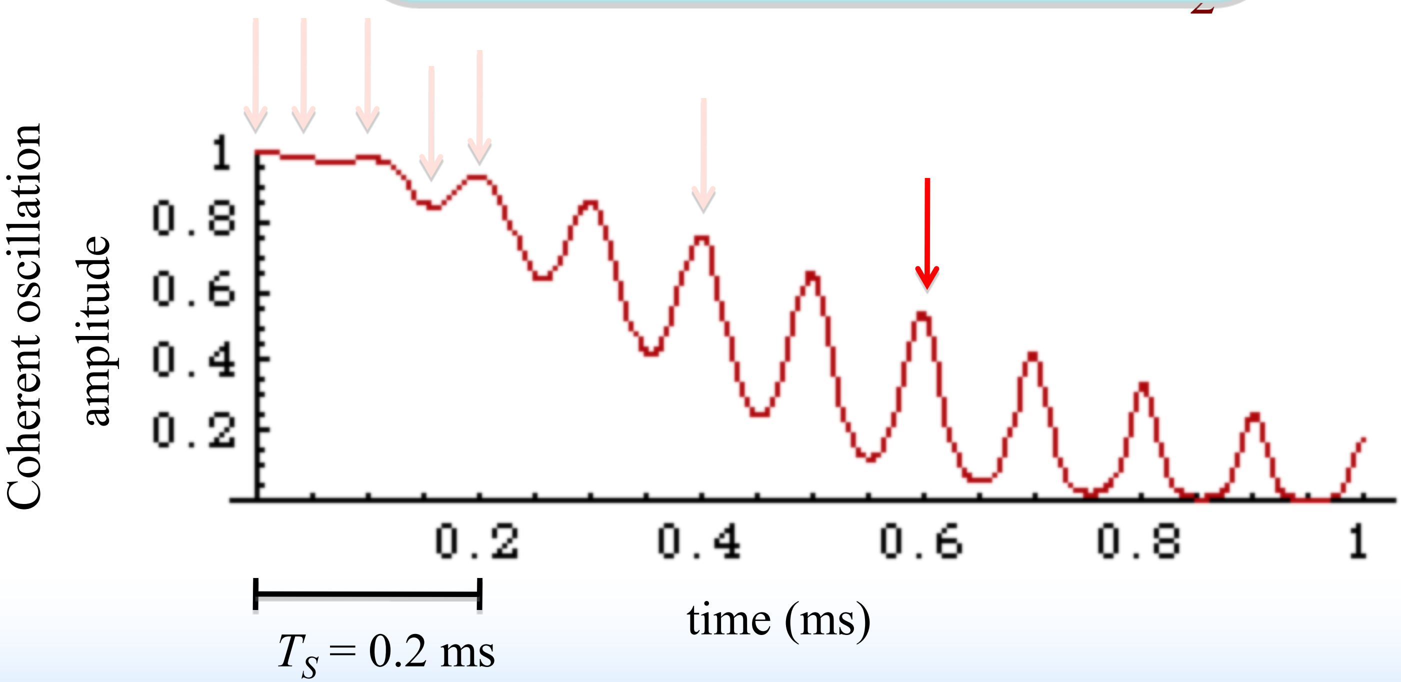

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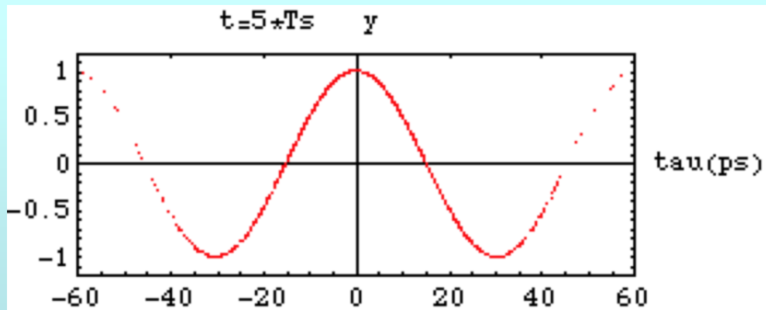

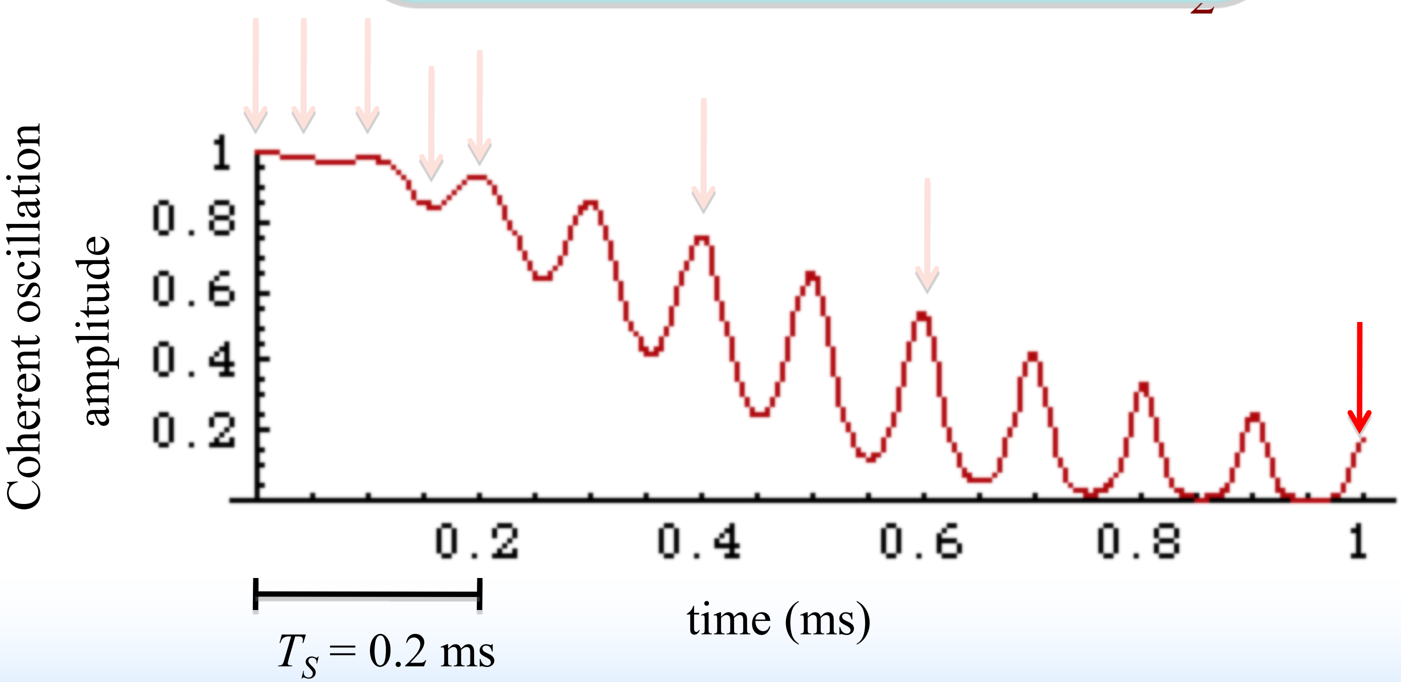

$\sigma_\delta = 0.047\%$

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Chromatic Tune Spread

Chromaticity modulation

$$\Delta\nu = (\xi_0 + \xi_1 \cos\omega_S t)\delta$$

With synchrotron oscillation

$$\delta = \delta_0 \cos\omega_S t + (\omega_S / \alpha_P)\tau_0 \sin\omega_S t$$

Averaged tune shift over T_S

$$\langle \Delta\nu \rangle_{T_S} = \langle \xi\delta \rangle_{T_S} = \frac{1}{2}\xi_1\delta_0$$

$$\sigma_\nu = \frac{1}{2}\xi_1\sigma_\delta$$ tune spread

Landau damping time
(for Gaussian)

$$\frac{1}{\tau_L} = \sqrt{\frac{2}{\pi}}\omega_0 \frac{1}{2}\xi_1\sigma_\delta$$

Brief History of chromaticity modulation

1995 T. Nakamura	The first proposal	(*PAC'95*)
1997 W. Cheng *et al*.	Theoretical analysis on single bunch instability	(*PRL78 & PR-E56*)
2005 V.H. Ranjbar	Report on the first try	(*PAC'05*)
2006 Nakamura *et al*.	Preliminary report on the first success	(*Annual Meeting of Particle Acc. Soc. of Japan*)

This is the first English report about the success of the instability suppression.

NewSUBARU

1.0 - 1.5GeV electron storage ring
(Top-up operation at 1GeV; energy during the experiment)
One AC sextupole magnet was installed for the experiment.

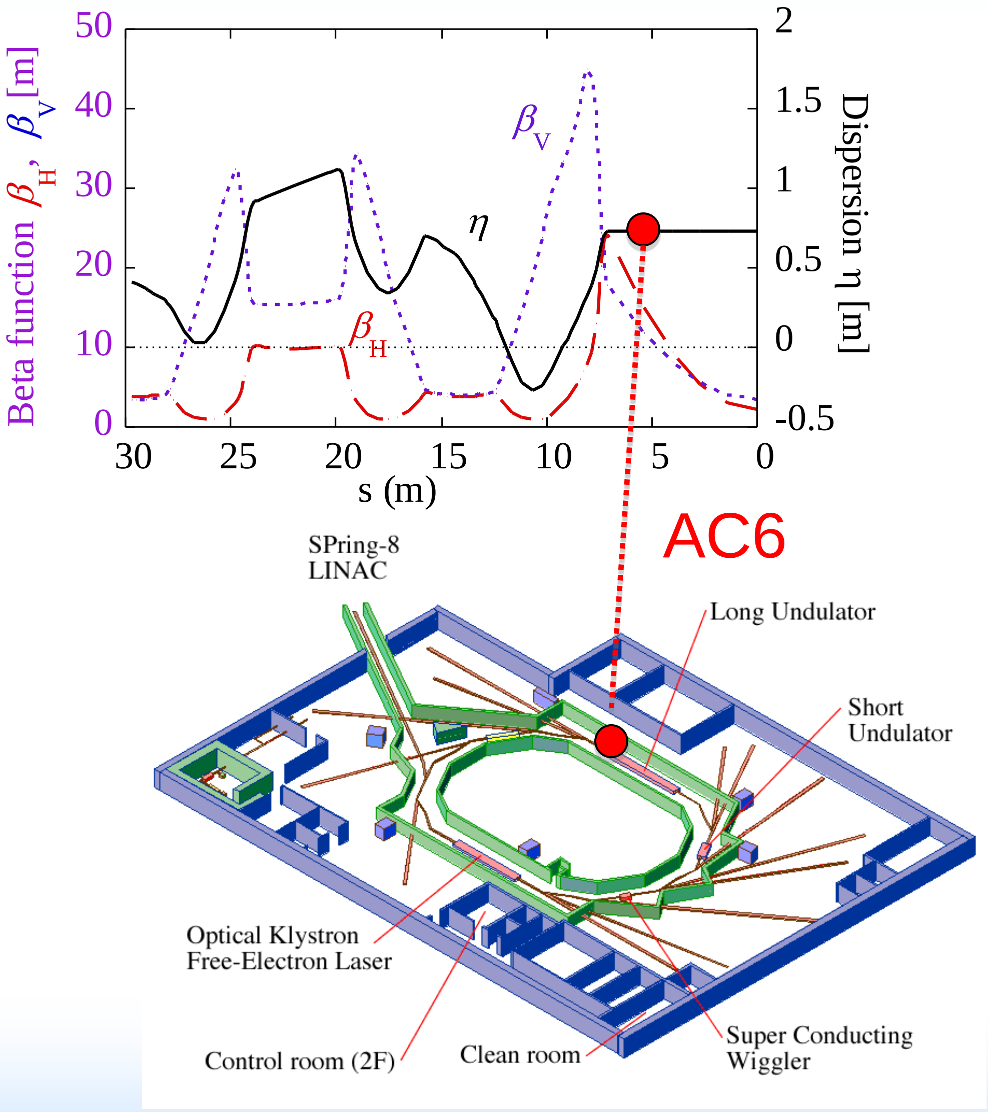
Lab. Tour at the end of IPAC'10

NewSUBARU

Non-achromatic lattice

(*Y. Shoji, 2005 Ann. Meeting of PASJ*)

Electron energy	1 GeV
Dispersion at AC6	0.73 m
Beta func. at AC6	17/13 m
Betatron tune	6.2, 2.2
DC chromaticity	33
Synch. osc. frequency	5 kHz
Natural energy spread	0.047%
Rad. damping time	22 ms

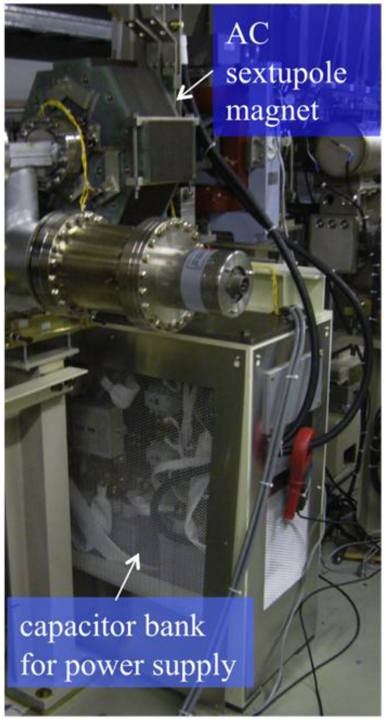


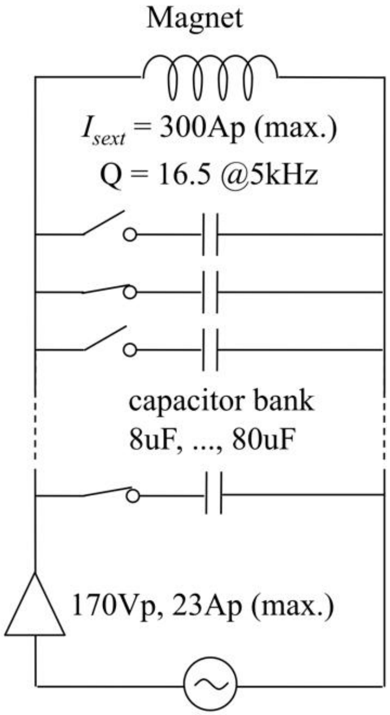
AC Sextupole Magnet

AC Sextupole magnet system

(*T. Nakamura, K. Kumagai, Y. Shoji, T. Ohshima, ...* *MT-20, 2007*)

Pole length	0.15m
Bore diameter	80 mm
Yoke material	0.35 mm Si steel
Coil turn	1 turn/pole
Operation frequency	4 – 6 kHz
Drive current	300A peak
Field strength	36 T/m^2
Modulation amplitude ξ_1	1.63/1.25
Damping time	0.21/0.27 ms
(Synchrotron osci. period	0.2ms)





Experiment

(1) Damping of coherent betatron oscillation amplitude

(2) Suppression of multi-bunch instability due to the cavity HOM

(3) Improvement of maximum single bunch current

= suppression of mode coupling instability

What we adjusted the parameters before the experiment.

(a) Beam position (setting accuracy < 0.5mm)

→ minimize beam oscillation driven by AC6 (induced osc. $\Delta\varepsilon$ <1 pm rad.)

(b) Modulation frequency (setting accuracy < 50 Hz)

→ maximize the suppression effect

The modulation frequency should be the incoherent synchrotron frequency.

Coherent Oscillation Damping

Oscillation source

H / V

ξ_0 =1.1 / 0.9

τ_L = 1.3 / 1.6 ms

τ_L =0.84 / 1.1 ms

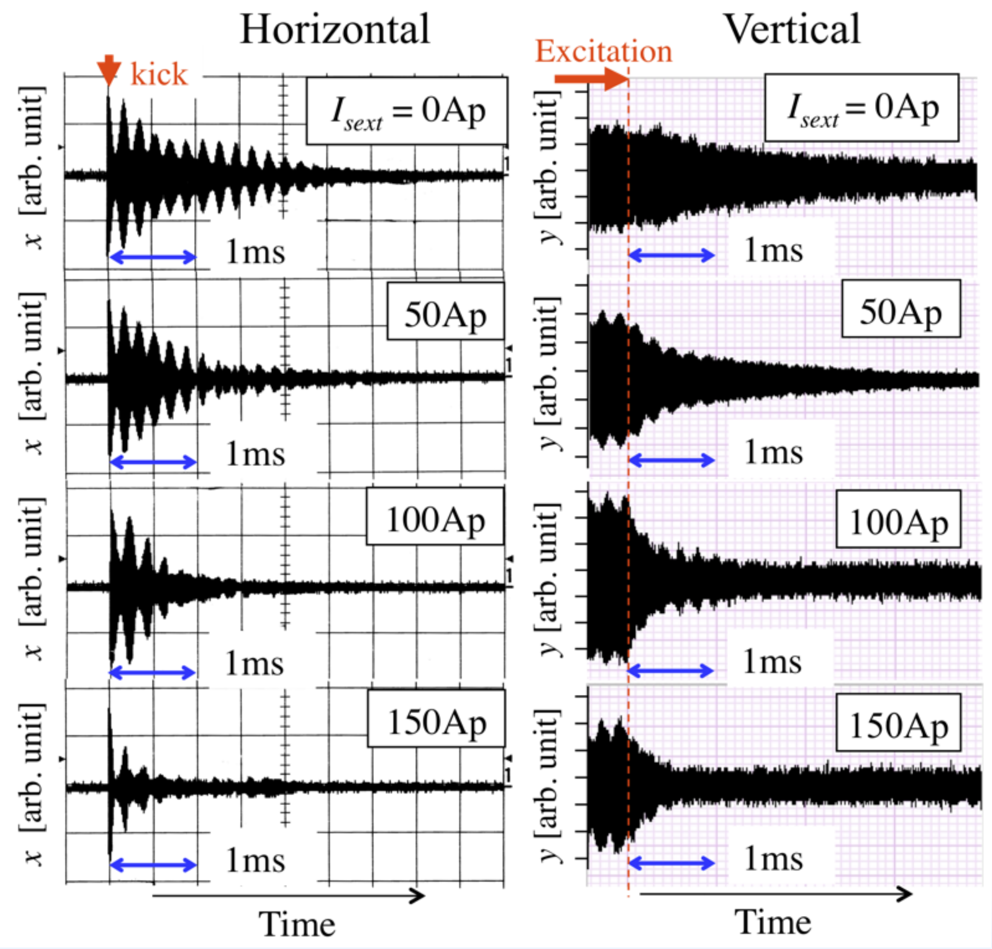
τ_L =0.42 / 0.54 ms

ξ_1 =0.82 / 0.63 ms

τ_{RAD} =22 ms; Ts=0.2 ms

single kick

sinusoidal deflection

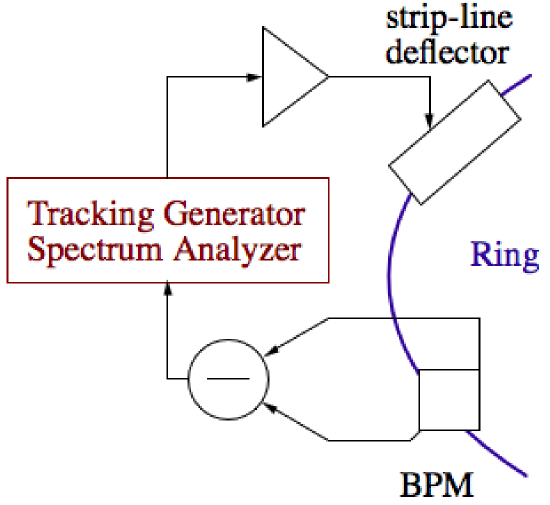


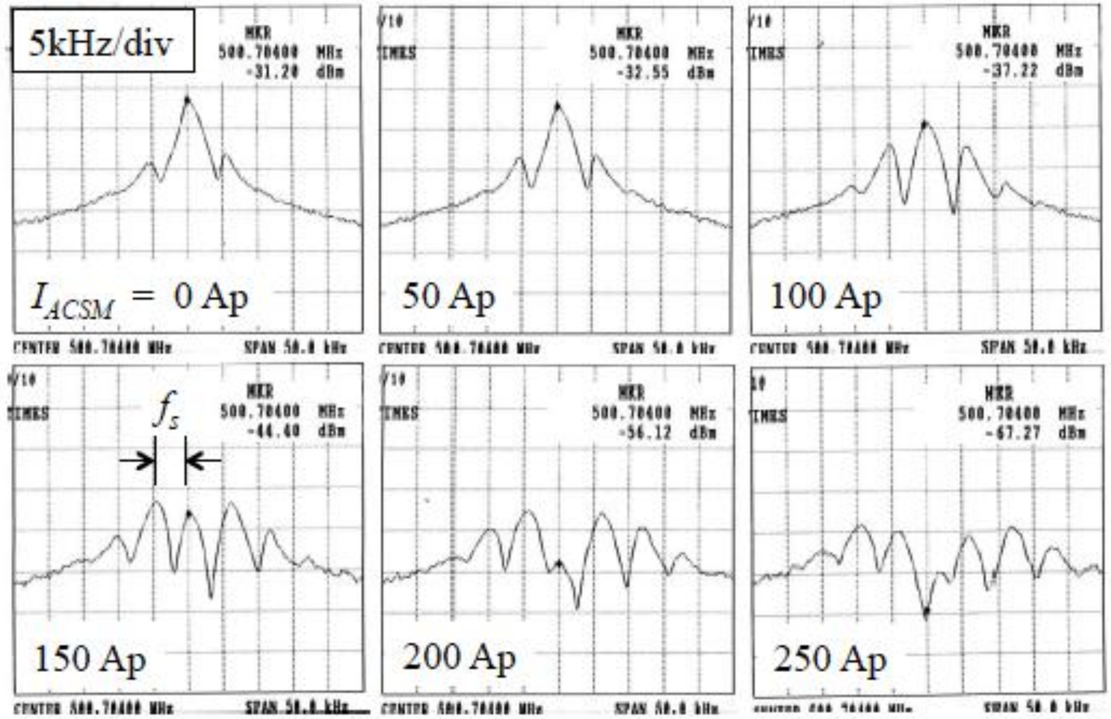
Coherent Oscillation Damping

Measurement of the beam response

(betatron resonance)

$\xi_{0x} = 1.8$





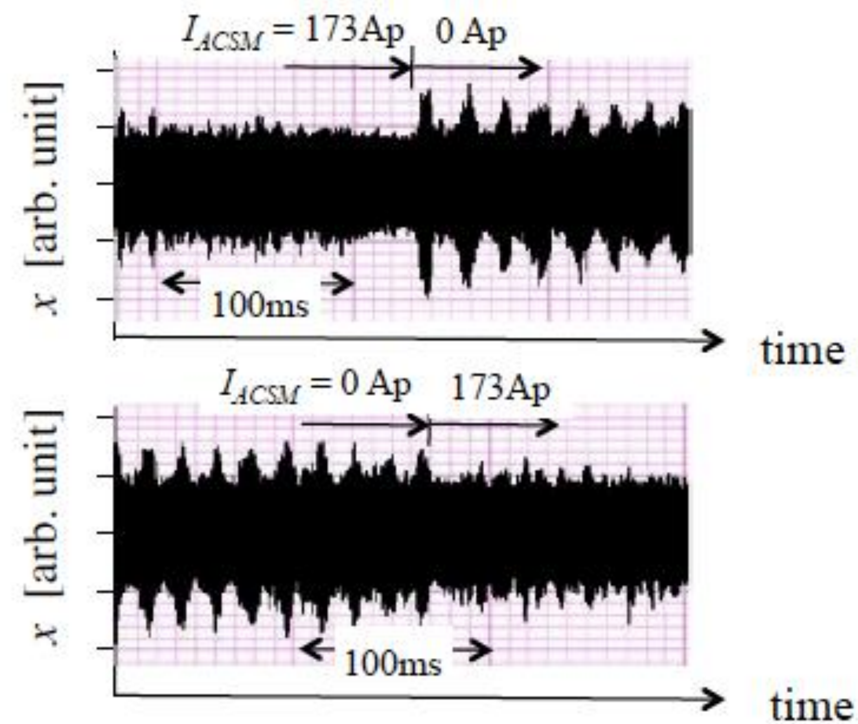
Multi-bunch Instability

Move RF tuner, then cavity HOM frequency to a resonant point.
(horizontal TM110; 792 MHz)

Excite AC6 and suppress the instability.

ξ_{0x} =1.1

ξ_{1x} =1.0 (τ_L =0.36ms) ON/OFF



saw teeth period ~ 20ms

Multi-bunch Instability

harmonics of revolution

horizontal betatron sidebands

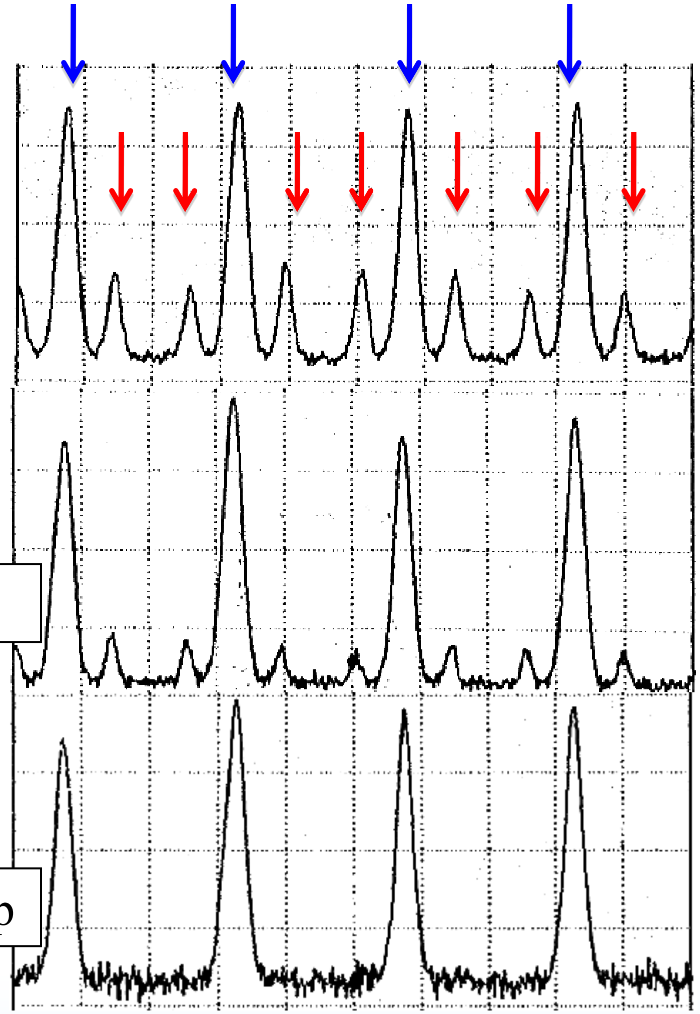
Frequency domain observation;

larger modulation
→ stronger instability suppression

$I_{ACSM} = 0$ Ap

$I_{ACSM} = 75$ Ap

$I_{ACSM} = 100$ Ap



$\xi_{0x} = 1.8$

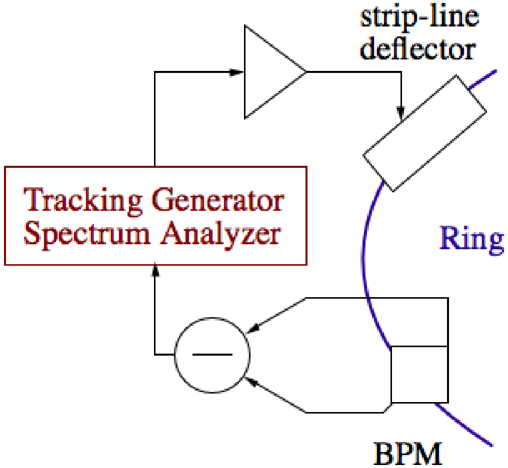
Single Bunch Instability

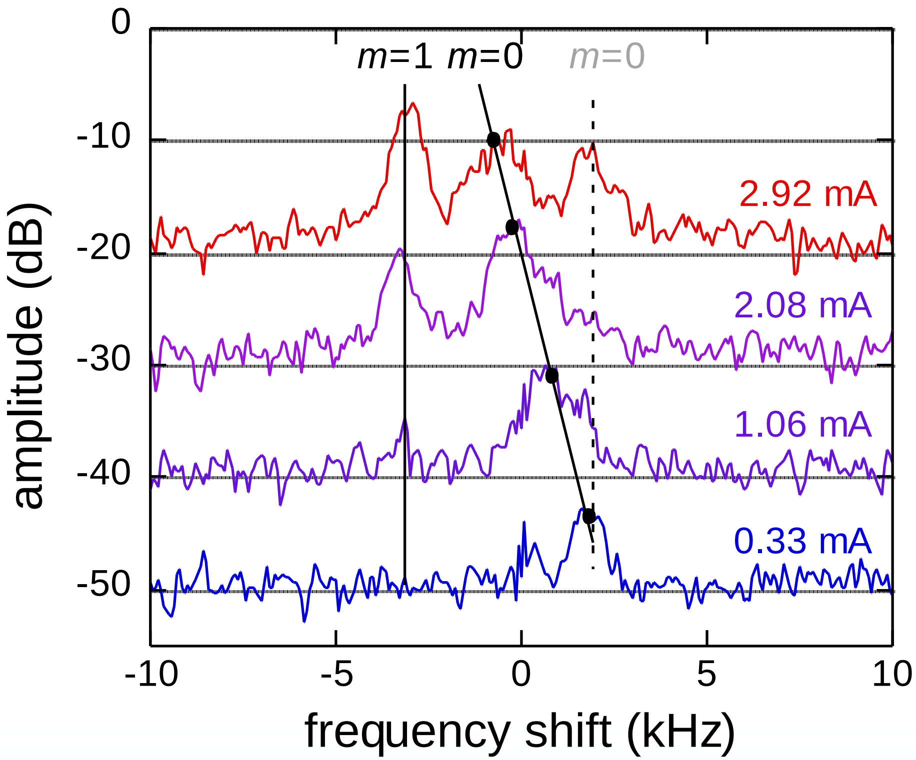
Single bunch instability (vertical mode coupling)

The oscillation modes shifted with the beam current.

$$\xi_{0y} = 0.6$$

$$\xi_{1y} = 0 \quad (I_{ACSM} = 0 \text{ Ap})$$

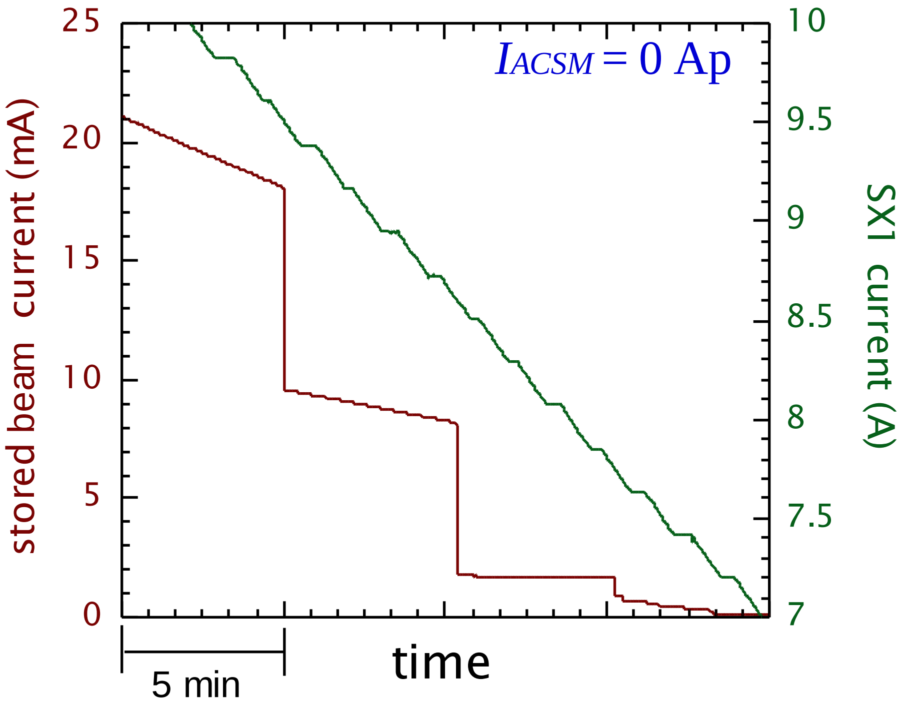




Single Bunch Instability

Suppression of the mode coupling instability

→ Enlarge the maximum bunch current



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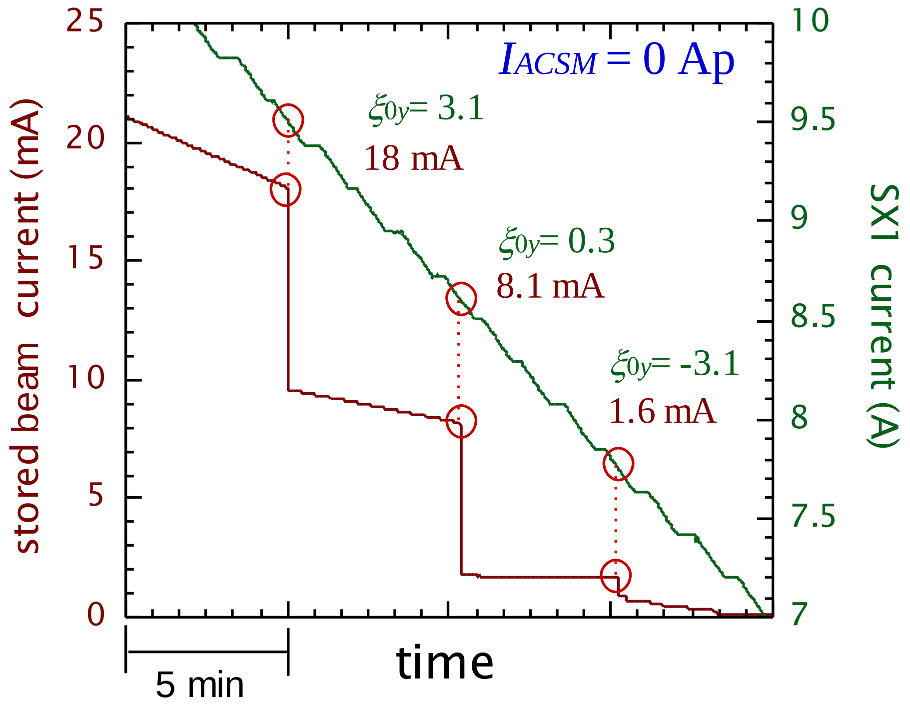

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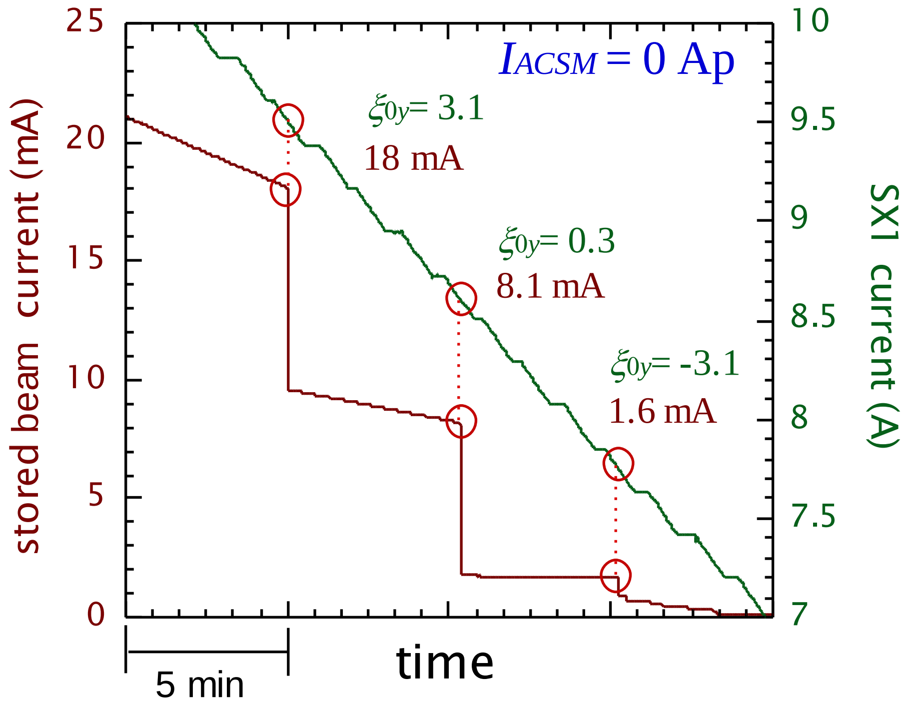

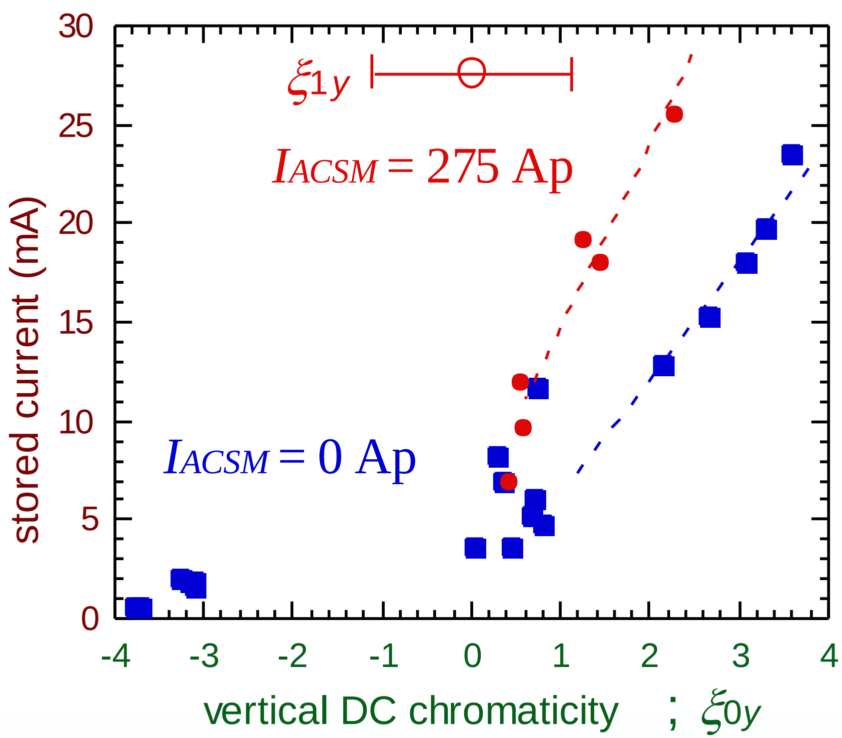

Comparison with Other Methods

Methods of instability suppression

Method	Landau damping	Bunch-by-bunch feedback
Tuning	easy	needs precise timing adjustment, Hadron ring impossible when f_0 changes with energy Electron ring difficult gain adjustment with different current bunches.
Instability	any transverse	works only for center of mass movement
Damping power	weak	strong

Comparison with Other Methods

Magnets for Landau damping

Magnet	AC sextupole	Octupole
Tune shift	chromatic $\Delta\nu \propto \delta$	amplitude dependent $\Delta\nu \propto x^2$
Dynamic aperture	better	worse
Magnet strength	AC magnet with ceramic duct weaker than DC sextupoles	DC magnet strong esp. at low ε ring

SUMMARY

We showed the first experimental demonstration
on the suppression of transverse beam instabilities
by means of the chromaticity modulation.

The multi-bunch instability (horizontal HOM) was suppressed.
The single bunch instability (vertical MCI) was suppressed.

This work was supported by the Grant-in-Aid for Scientific Research from Ministry of Education, Science, Sorts and Culture Government of Japan, kiban(B) 16360043 .