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Quasi-Isochronous (Low-Alpha) Operation and Observation of CSR at NewSUBARU

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Negative Alpha A. Ando, S. Hashimoto

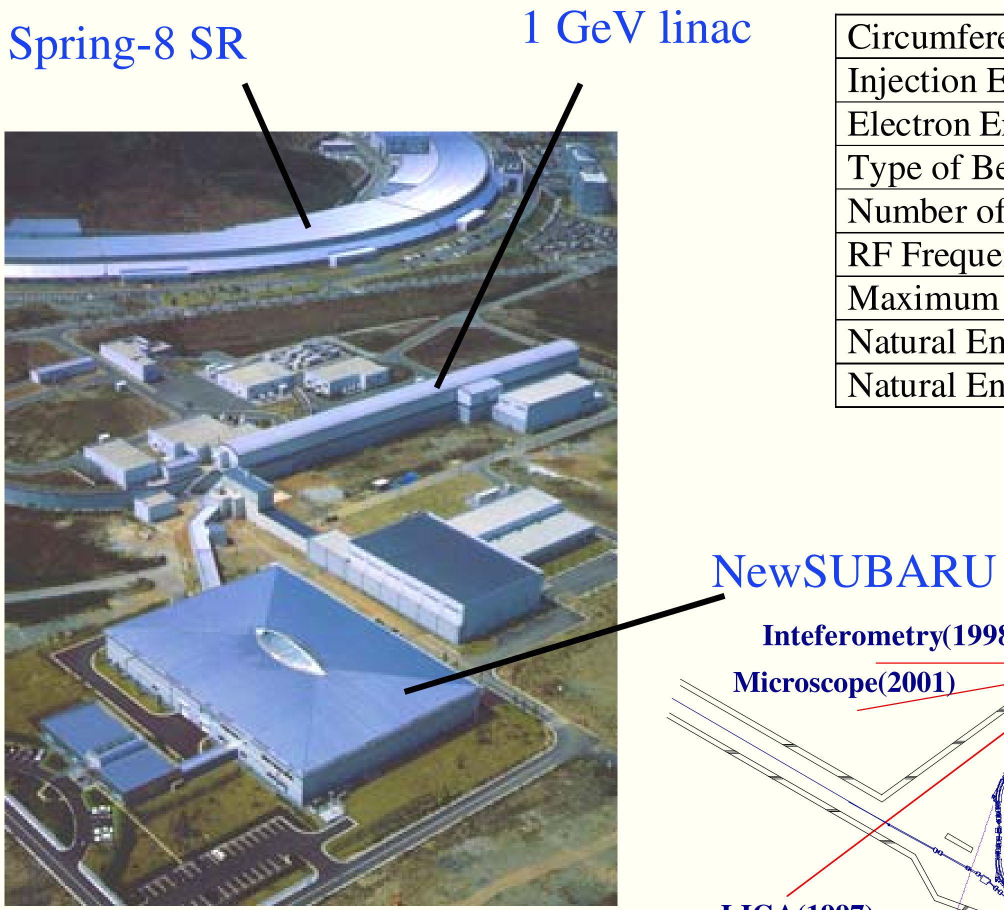
CSR Ando, Hashimoto, Shoji

T. Nakamura SPring-8 (Accelerator)

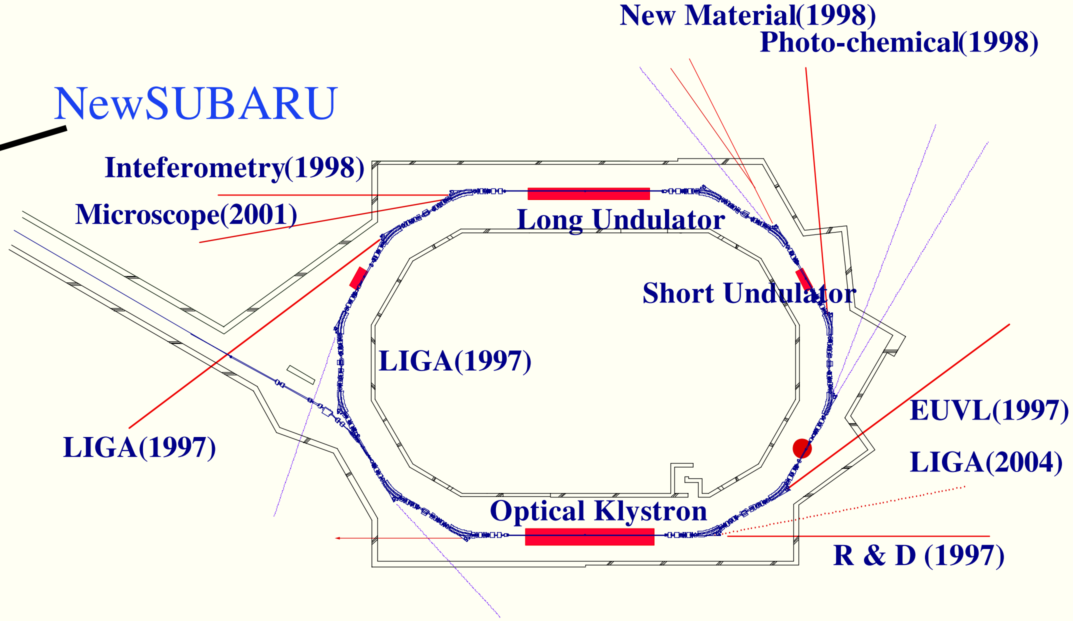
T. Takahashi Kyoto University

H.Kimura, T.Hirono, K.Tamasaku, M.Yabashi SPring-8 (Beam Line)

Where is NewSUBARU ?



Circumference	118.7 m
Injection Energy	1.0 GeV
Electron Energy	0.5 - 1.5 GeV
Type of Bending cell	DBA with Inv.B
Number of Bending Cell	6
RF Frequency	499.956 MHz
Maximum Stored Current	500 mA
Natural Emittance	38 nm (1GeV)
Natural Energy Spread	0.047% (1GeV)



Basic Idea of Low Alpha

* Quasi-isochronus = small momentum compaction factor (α)

  $L/Lo \equiv 1+\alpha_1\delta + \alpha_2\delta^2 + \alpha_3\delta^3 + \, ...$

  $\delta \equiv (E-E_0)/E_0$

* Small α_1 --> short bunch

  $f_S = \alpha_1^{1/2} (eV_{RF}^2 - U_0^2)^{1/4} (h/2\pi E)^{1/2} f_{REV}$

  $\sigma_T = \alpha_1^{1/2} (eV_{RF}^2 - U_0^2)^{-1/4} (E/h)^{1/2} (\sigma_E / f_{REV})$

  f_S is used to estimate α_1

* High V_{RF} is another way to compress the bunch

* Linear Factor α_1

  $\alpha_1 = (1/Lo) \int (\eta/\rho) ds$

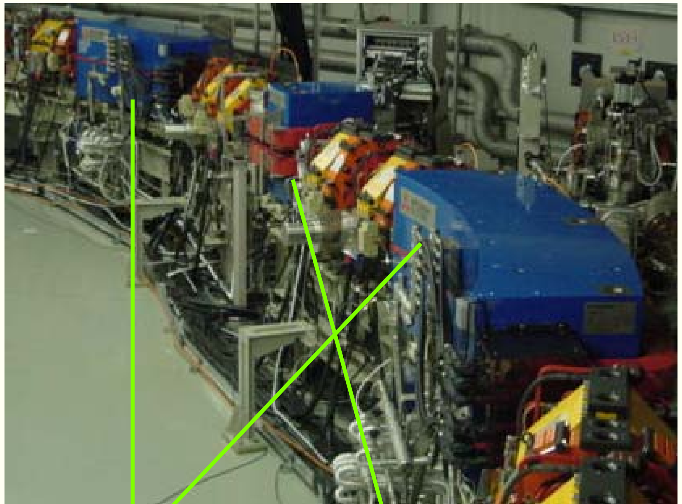
  $\alpha_1 \approx 0$ requires negative η section --- Break achromat

  or negative ρ section. --- Invert bend

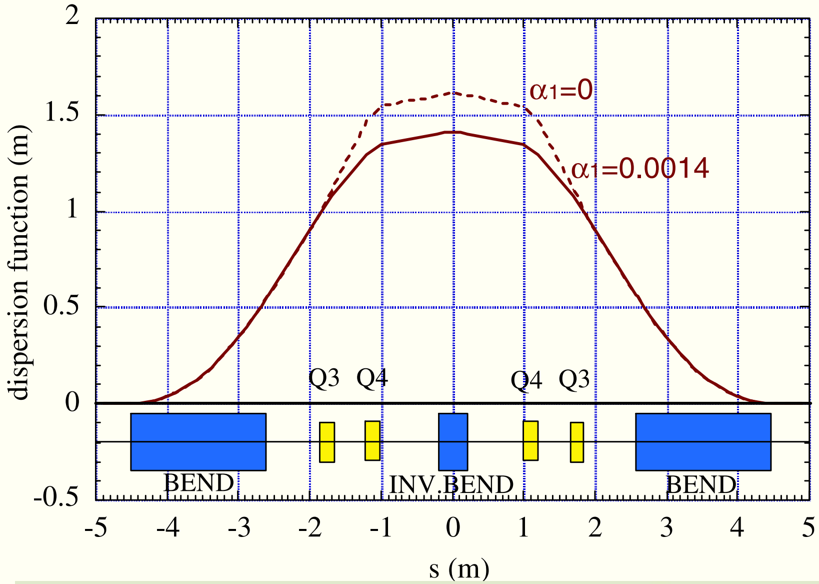
Control of α_1 ; Invert Bend

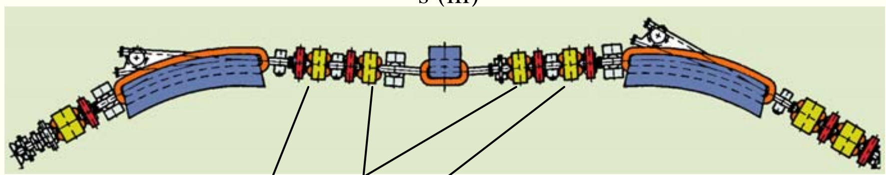
Change η in the invert bends --> change α_1
keeping achromatic condition

34^o -8^o $+34^o$ $=60^o$



Normal Bend   Invert Bend





Two Q-families are used

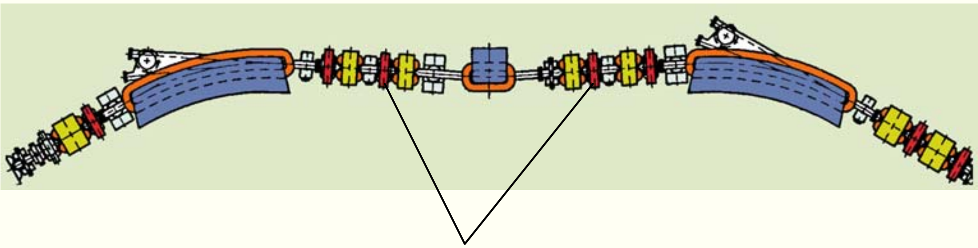
Second Order Factor α_2

Sextupole & chromaticities

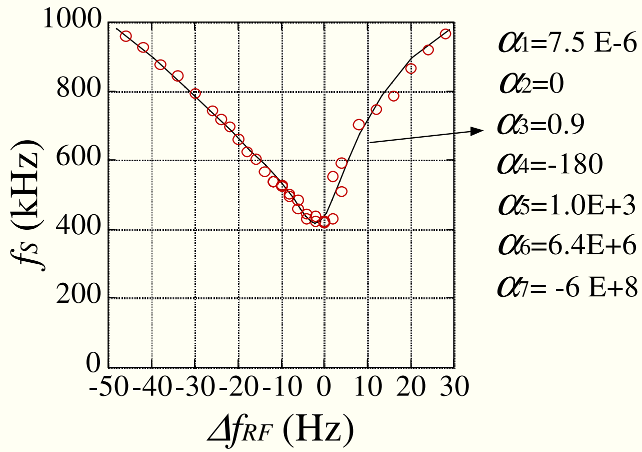
α_2 control is the essential part of $\alpha_1 \approx 0$ operation

$\Delta\alpha_2 = (1/2L_0) \int \eta_1^{\,3} \Delta K_2 ds$	synch. tune	$\alpha_2 = 0$
$\Delta\xi_x = -(1/4\pi) \int \eta_1 \beta_x \Delta K_2 ds$	horizontal tune	$\xi_X = -1.7$
$\Delta\xi_y = (1/4\pi) \int \eta_1 \beta_y \Delta K_2 ds$	vertical tune	$\xi_Y = -7.7$

$$K_2 = (1/B_0\rho_0)(\partial^2 B_y / \partial x^2)$$



This Sextupole family controls α_1



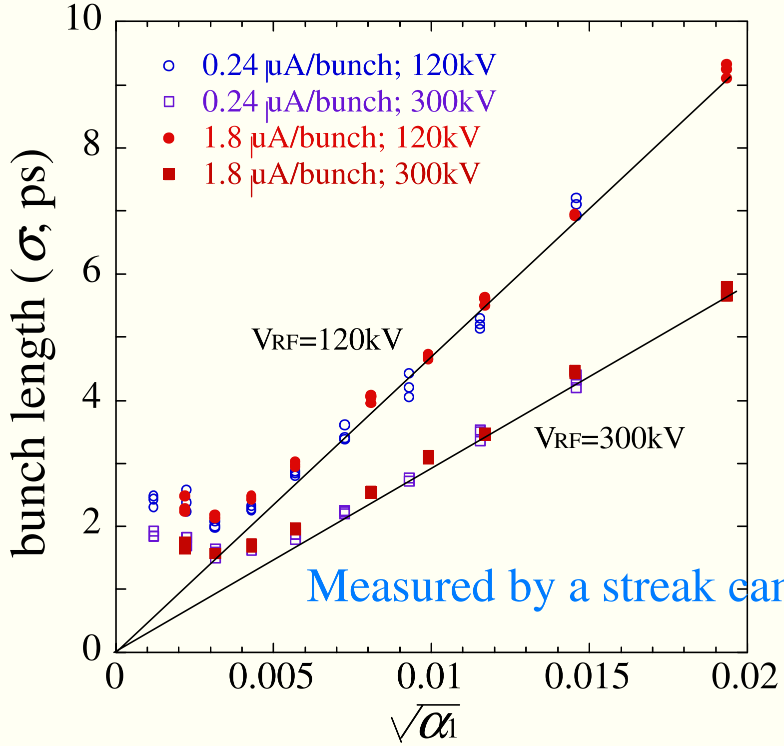
f_{RF} dependence of f_S is measured to confirm that $\alpha_2 = 0$

Result(1); Bunch Shortening

Reduce α_1

The σ_T is reduced according to $\sqrt{\alpha_1}$ scaling low ($\alpha_1 > 2x10^{-5}$)

Minimum length was 1.4ps



Measured by a streak camera

Low current

I_B < 2uA/bunch (0.4mA)

No current dependent lengthening

At $\alpha_1 < 2x10^{-5}$

Reduction of α_1 did not reduce σ_T.

Raise of V_{RF} reduced σ_T .

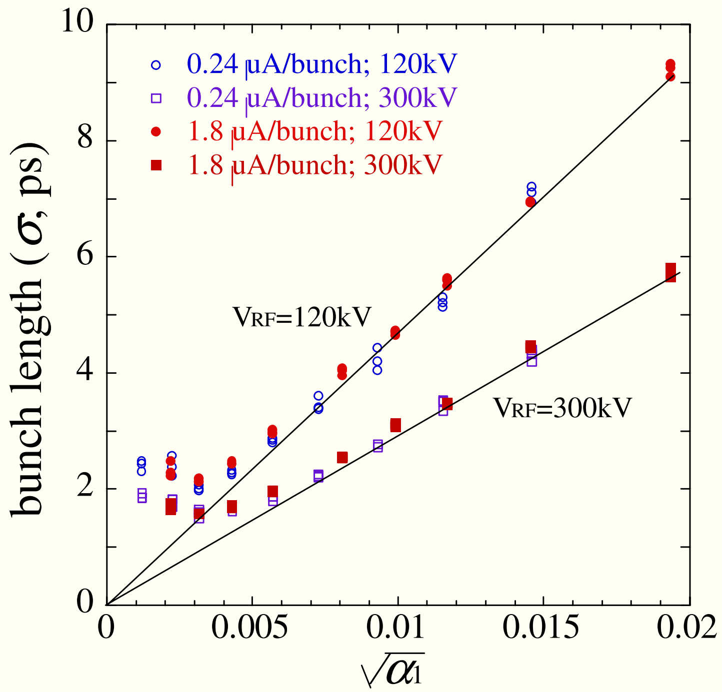
Resolution of the monitor was not the reason of the limitation.

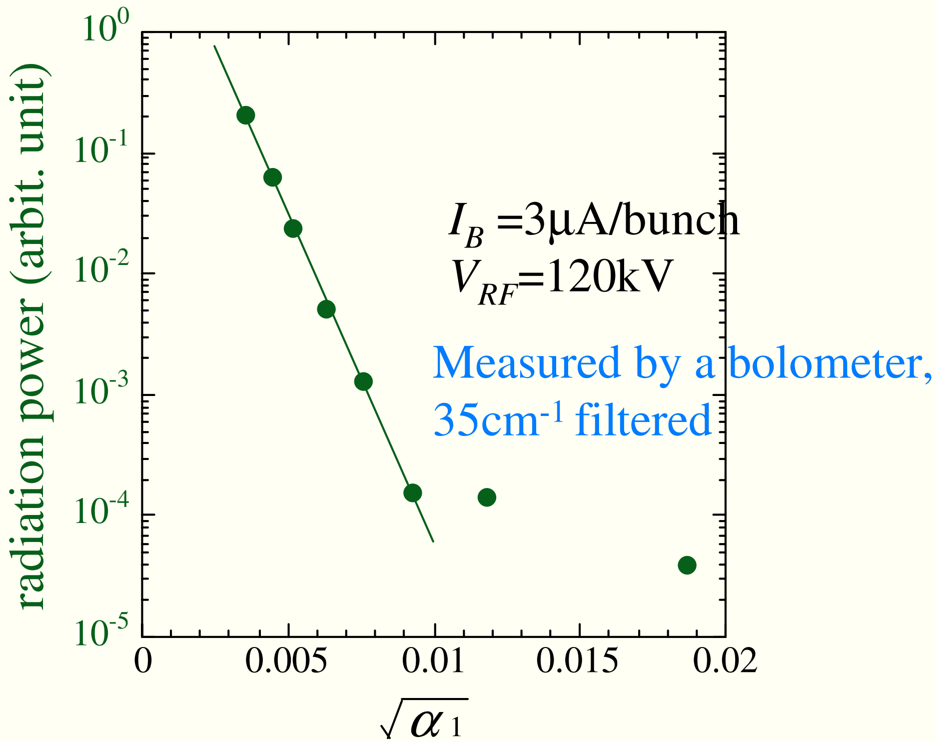
We will come back to this problem after some sheets

Result(2); CSR(Coherent Synchrotron Radiation)

Lower α_1 --- high radiation power

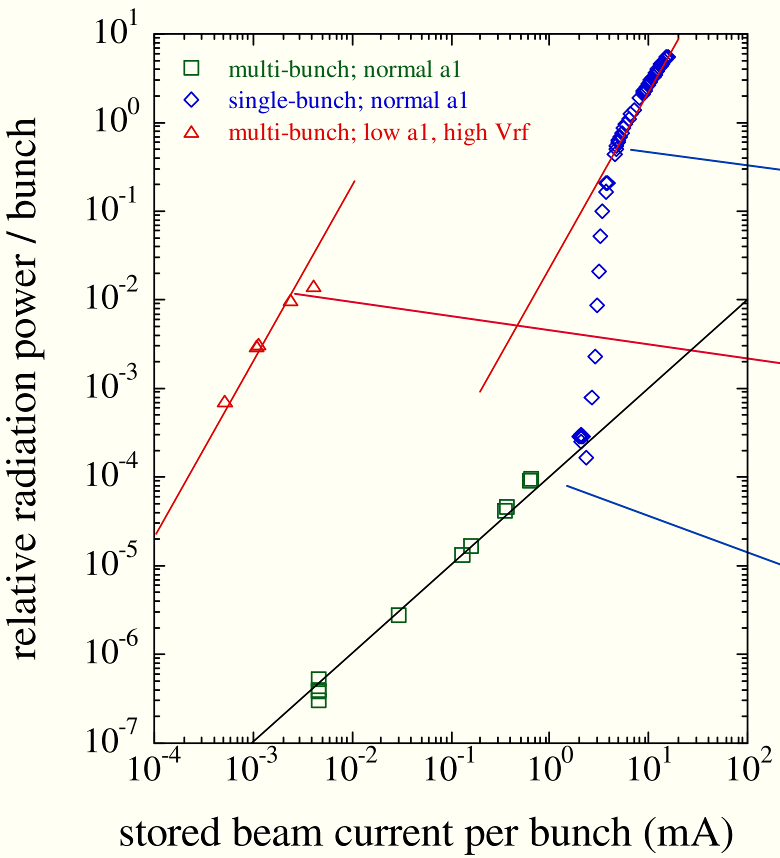
Did the power show the same saturation? NO, maybe.





Integration of power up to 35cm^{-1}

Result(3); CSR modes



THz radiation mode

measurement with bolometer ($35cm^{-1}$)

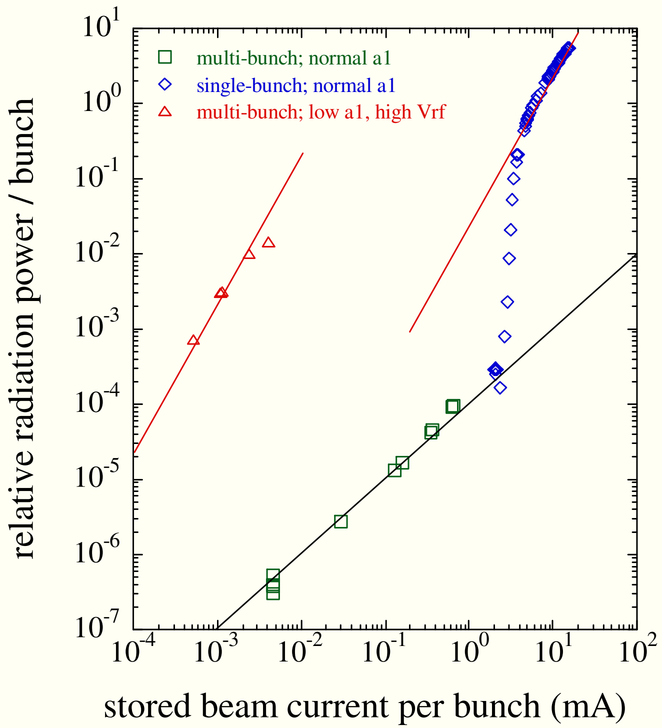
normal α_1, high current per bunch
-- burst mode CSR

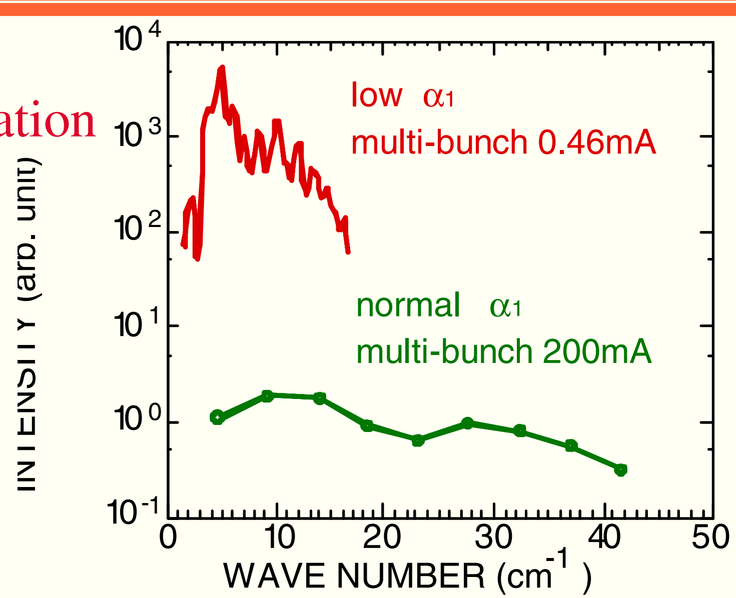
small α_1 -- staedy state CSR ?
Power $\propto I^2$

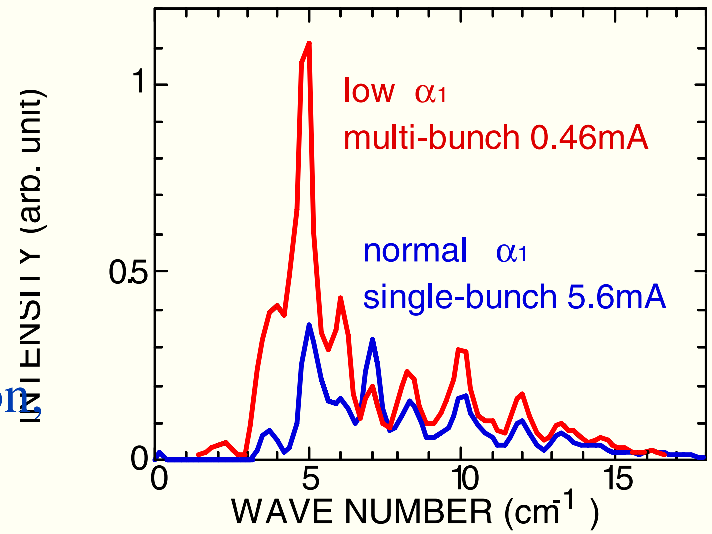
normal α_1, low current
-- normal radiation
Power $\propto I$

Result(4); CSR Spectrum

CSR-- strong long λ radiation







Burst mode had shorter λ radiation, although the bunch was long.

Result(5); Bunch compression by V_{RF}

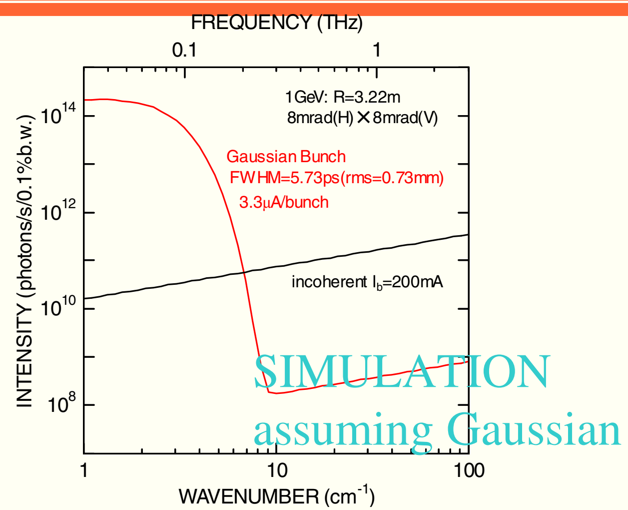
CSR spectrum

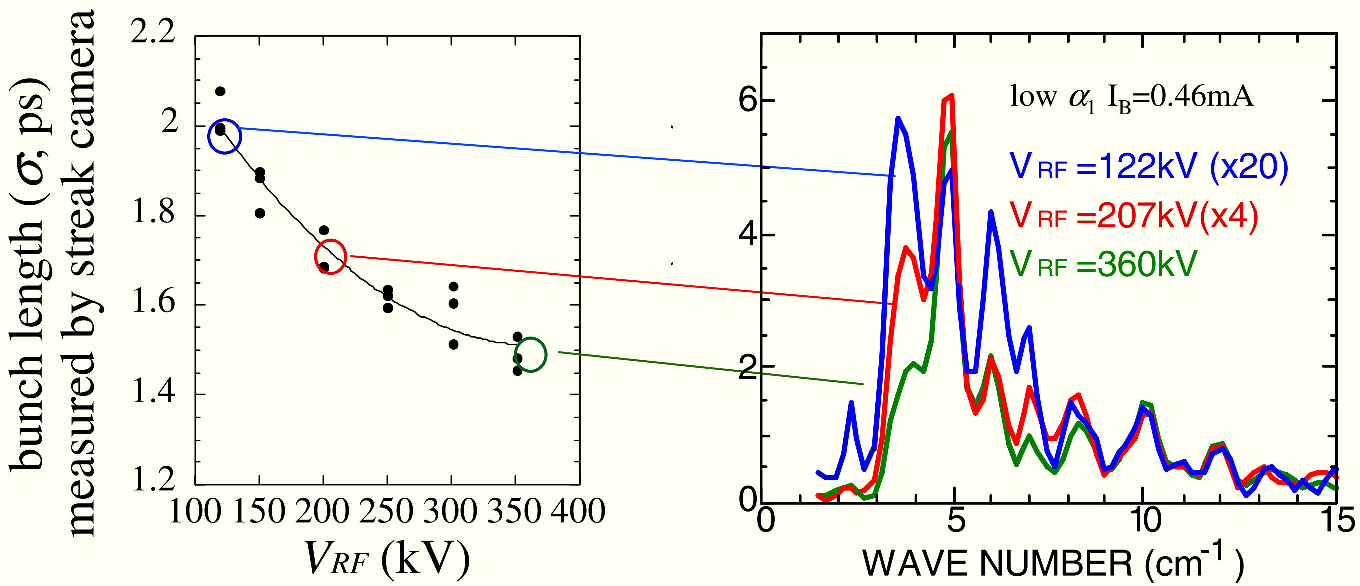
Power; $P=I^2$

Spectrum;

short bunch -> short wave length CSR

continuous spectrm ? the data is not clear





Shorter bunch emits shorter wavelength CSR

Beam Dynamics Interests

Two Main Subjects

Low Current --->		Quasi-isochronous limit (This presentation)	
Current Dependence -->		Instability	(MWI, CSR
		Form factor	(potential well distortion)

Some theoretical predictions on the limit

Limitation from the finite α_2		--- old and practical problem
Longitudinal Radiation Excitation		Y.Shoji *et al*., PR-E 0.06 ps
Synchro-beta coupling	Linear coupling	Y.Shoji, PR-STAB 0.2 ps
	Second order	E. Forest, $\Delta\delta = 0.7\ \sigma_{EN}$

. . . .

More practical problem --- stability

RF noise

Magnet ripple

. . . .

BESSY-II; Leading machine

* Achieved at BESSY II

shorted bunch 0.7 ps rms
steady state coherent radiation at low alpha

* What were their problems?

"The phase noise of the master oscillator and of the 250MHz fast sweep voltage … these noise sources add a random contribution of ≈2.4ps to the bunch length. " (M. Abo-Bakr, *et al.*, PAC03)

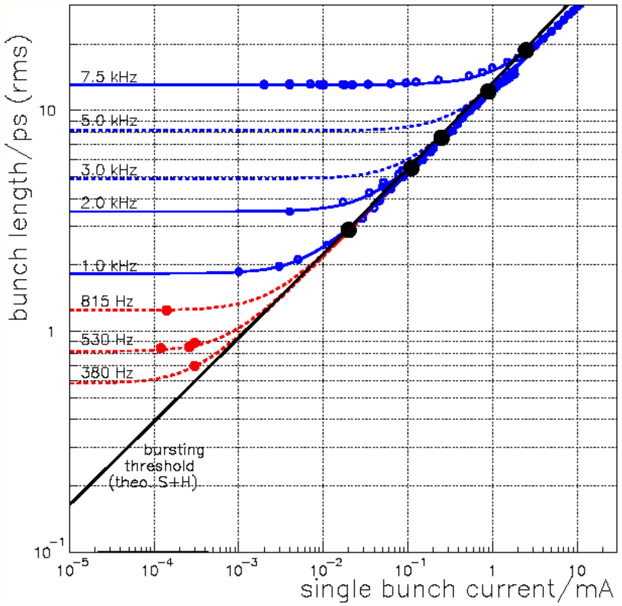
"Presently there is a limit by 300Hz noise, visible on the longitudinal beam signal,.. " (J. Feikes, *et al*,, EPAC2004)

".. a relative current change of the Q4-family .. of 10^{-4} produces a CSR power change of 25% "(J. Feikes, *et al*, Beam Dynamics News Letter 35)

"A tiny change of the sextupole, the last figure of the setting panel by just a few, destroys the beam condition" (G. Wuestwfeld)

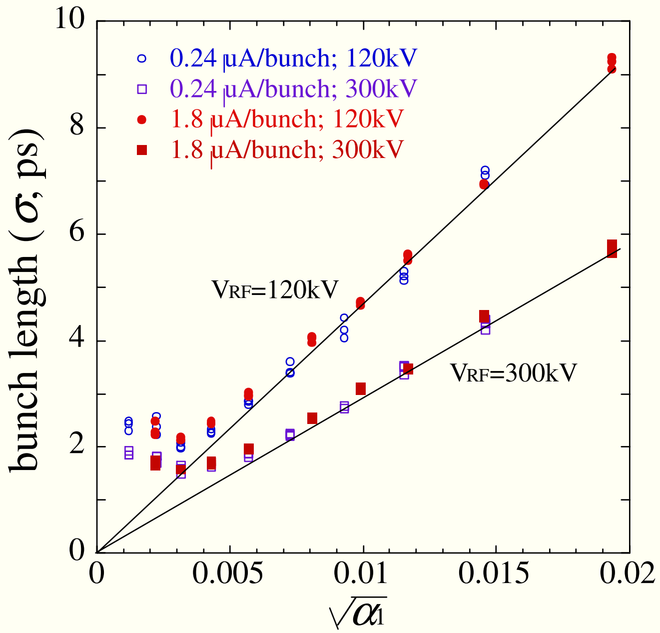
Parameters of BESSY II and NewSUBARU

	BESSY II	NewSUBARU
Natural Energy Spread	0.08%	0.047%
Natural Emittance (nm rad)	30π	30π
α_1	-1.4×10^{-6}	5×10^{-6}
α_3	-0.01	0.9
Damping time	8ms	12ms
Lattice	non-achromatic DB	DBA+IB
Time jittering at Streak C	2.4ps	0.4ps



BESSY II

J. Feikes et al., EPAC2004



(4) Practical limitations from the magnet

".. a relative current change of the Q4-family .. of 10^{-4} produces a CSR power change of 25% (J. Feikes, et al, BESSY, Beam Dynamics News Letter 35)

Setting resolution of Q-magnet (16 bit, stability=10^{-4}/8h)

Q4 Setting resolution = 1 bit --> $\Delta\alpha_1 = 4 \times 10^{-6}$

Fine adjustment is possible using other Q magnets

Setting resolution of Sext-F (12 bit, stability=10^{-3}/8h)

Setting resolution = 1 bit --> $\Delta\alpha_2 = 2.6 \times 10^{-3}$

Fine adjustment is possible using other S magnets

Large enough RF bucket α_3

$d[L/Lo]/d\delta > 0$ be satisfied for all δ

---> $\alpha_1 + 2\alpha_2\delta + 3\alpha_3\delta^2 > 0$ ---> $\alpha_2^2 - 3\alpha_3\alpha_1 < 0$

$\alpha_2 = 2.6 \times 10^{-3}$, $\alpha_3 = 0.9$ ---> $\alpha_1 > 2.5 \times 10^{-6}$ **(σ_τ>0.5ps)**

Field Ripple is also important

(5) The α_3-- Another essential part

LNSTI

The α_3 makes stable RF bucket for large δ

The α_1 and α_3 should have same signs. --> enough RF bucket

When α_1 and α_3 have opposite sign --> short life time

Large α_3 enlarges tolerance of α_2

Large α_3 with the energy spread effectively enlarge α_1

$$d[L/Lo]/d = \alpha_1 + 2\alpha_1\delta + 3\alpha_3\delta^2$$

$$\alpha_3 = 0.9$$

σ_{EN}=0.047% (natural spread) $\quad <3\alpha_3\delta^2> = 6\alpha_3\,\sigma_{EN}^2$

$\Delta\alpha_1$=1.2X10^{-6}

(6) Coherent Longitudinal Oscillation

Longitudinal oscillation $[\Delta\tau]/[\Delta\delta] \propto \alpha_1^{1/2}$

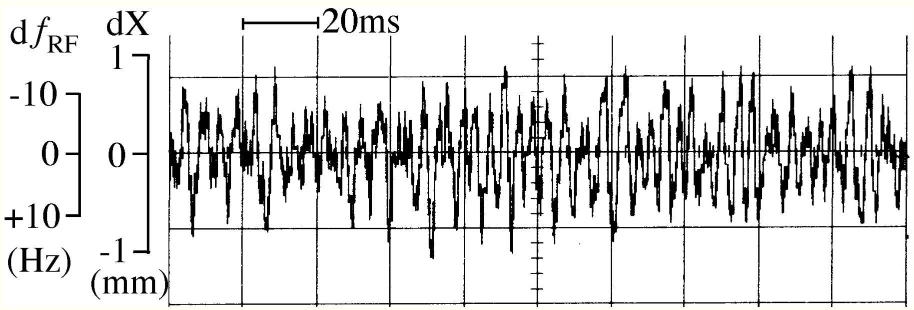
At low alpha, the energy deviation by the coherent oscillation becomes large.

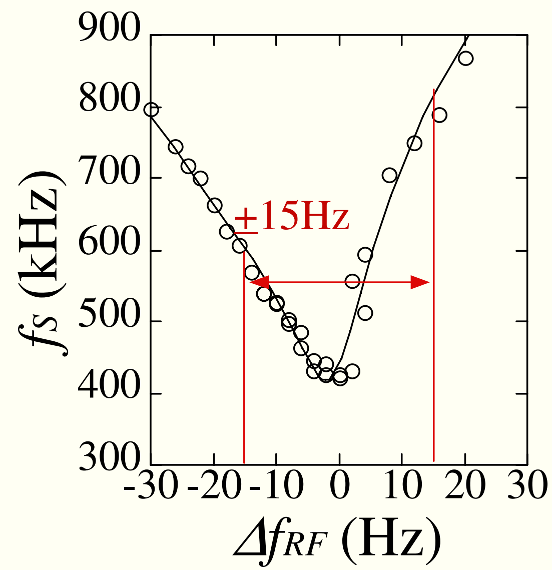
Two kinds of oscillation

on-resonance oscillation induced by a broad-band noise

out-of resonance oscillation at harmonic components of the primary line (60Hz)

Low frequency; dX signal





Effect of Slow Oscillation ; Simulation

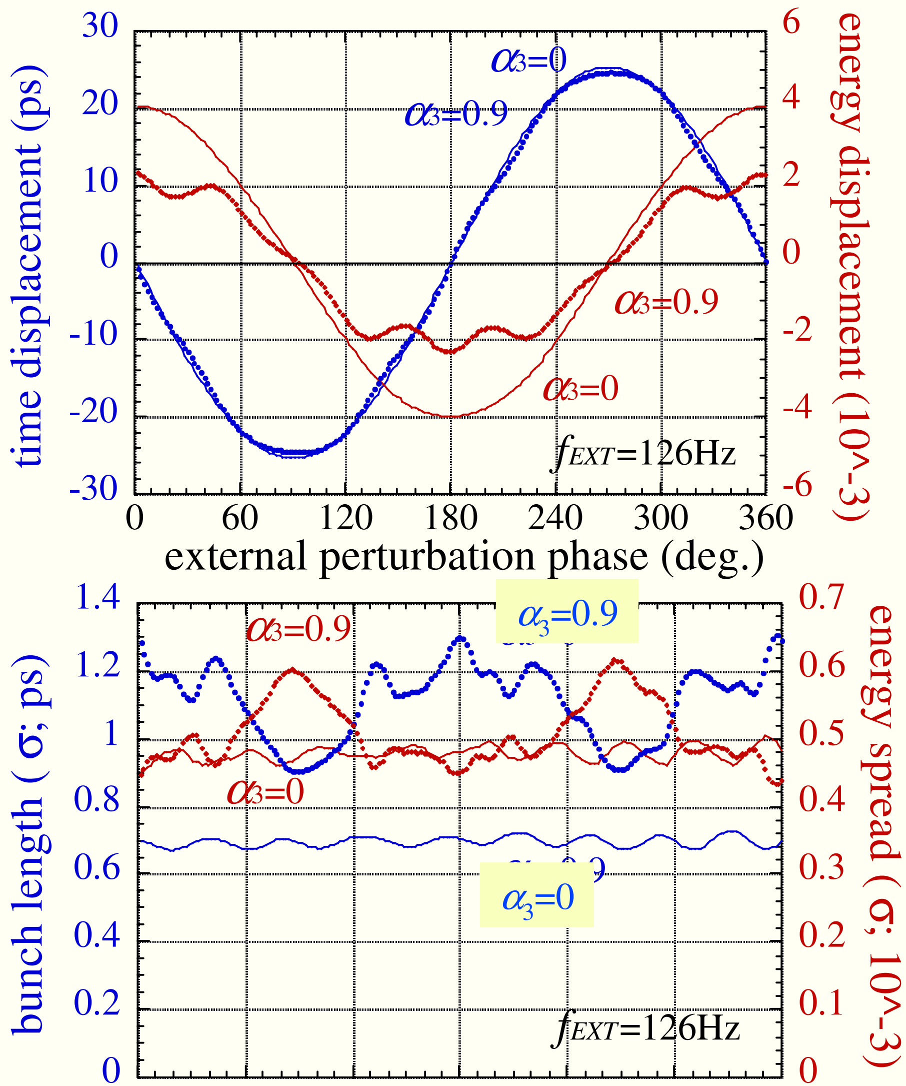
Beam parameters

E	1GeV
τ_ε	11.4 ms
α_1	$5x10^{-6}$
α_3	0.9
V_{RF}	300kV
f_S	547Hz
σ_E/E	$0.48x10^{-3}$
σ_T	0.69 ps

external perturbation

f_{EXT}	126Hz
amp	±10Hz (24ps)

number of particles 1000



Circumference Feed-Back

LASTI

A dipole error produces a longitudinal oscillation

Dipole error at dispersive sections changes circumference $\Delta L = \theta_{ERR}\ \eta_{ERR}$

The response of COD to θ_{ERR} is

$$x = [\sqrt{\beta}/2\sin\pi\nu]\ \sqrt{\beta_{ERR}}\ \theta_{ERR}\cos[\,|\psi-\psi_{ERR}|-\pi\nu] - (1/\alpha_1)\ (\Delta L/L_0)\ \eta$$

In small α_1 ring, the second term is dominant.

dX has high sensitivity -- good diagnostic of a longitudinal oscillation

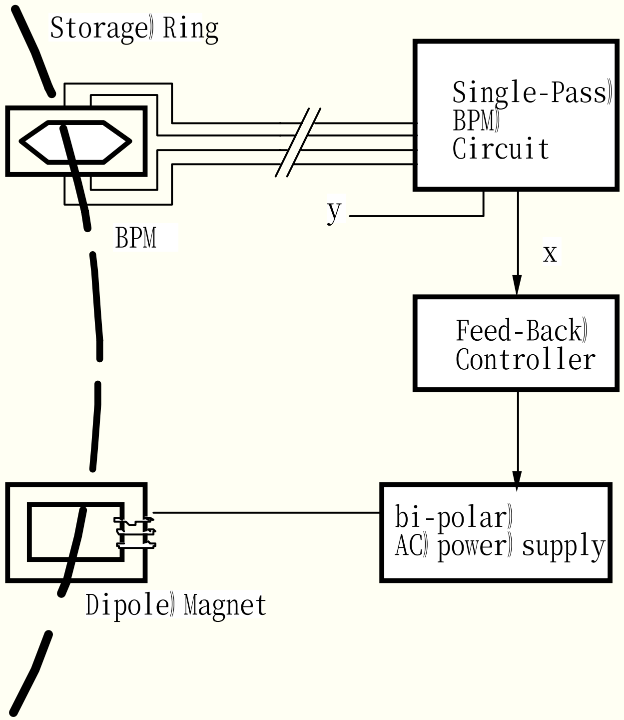
$$\tau = \frac{(2\alpha_E + j\omega)\Delta_C - \omega_S^2\Delta_P}{\omega_S^2 - \omega^2 + 2j\omega\alpha_E}e^{j\omega t} \qquad \varepsilon = \left(\frac{\omega_S^2}{\alpha}\right)\frac{\Delta_C + j\omega\Delta_P}{\omega_S^2 - \omega^2 + 2j\omega\alpha_E}e^{j\omega t}$$

Active feed back to the dipole magnet
reduces longitudinal oscillation-- good for a slow feed-back

Circumference Feed-Back; test

A dipole steering is used to reduce longitudinal oscillation

Dipole error at dispersive sections
changes circumference

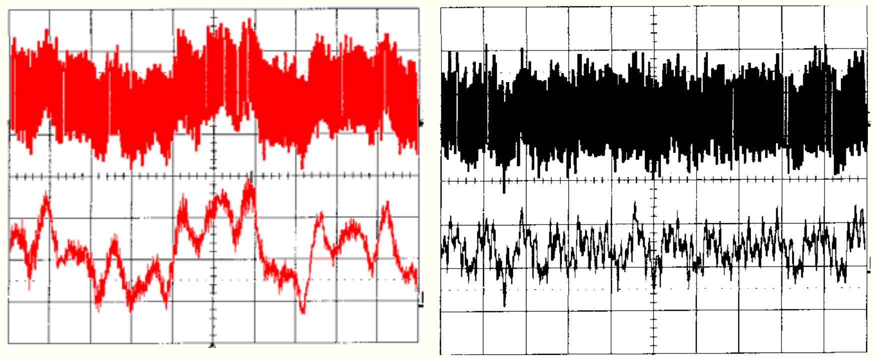


dX signal

(w. LPF; x2)

BPM signal (X)

Feed-back OFF ON



Resonant Oscillation

Reduce Oscillation by Low level phase feed-back

In operation at SPring-8 (T. Ohshima, PAC2001)

The similar effect also at NewSUBARU (Y. Kawashima, Y. Shoji)

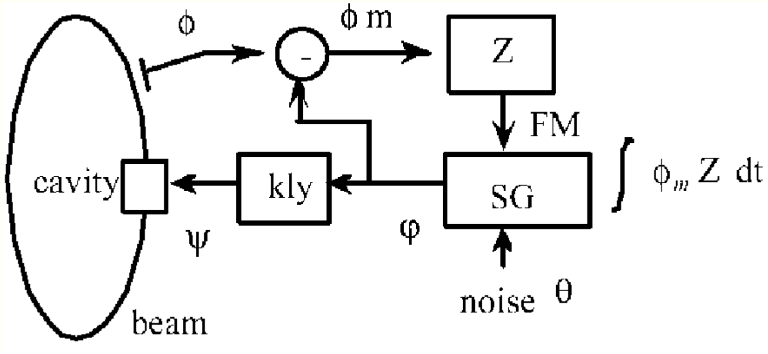


Figure 1: Beam phase and RF system.

T.Ohshima, PAC 2001

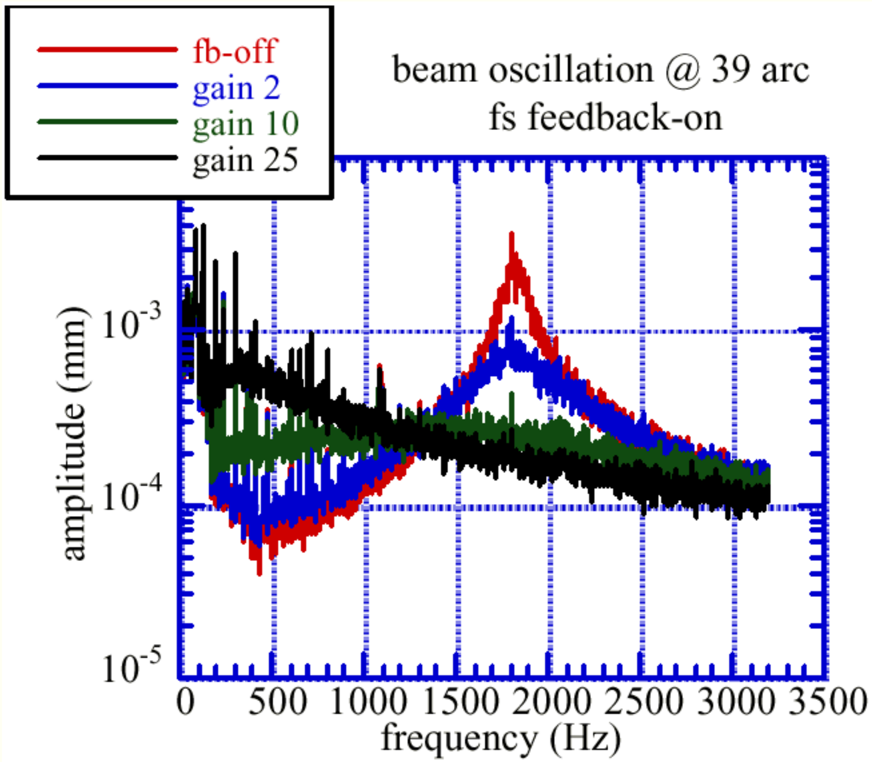
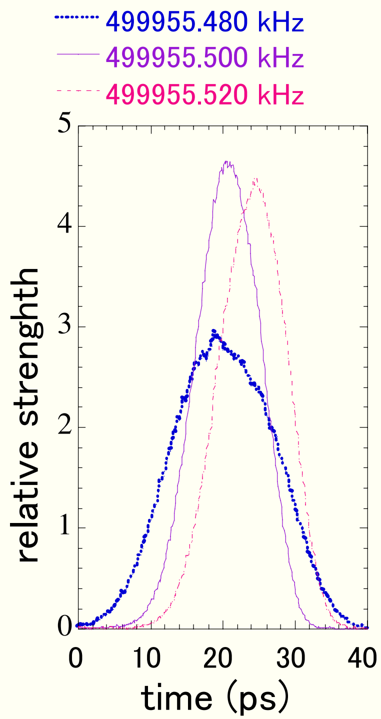


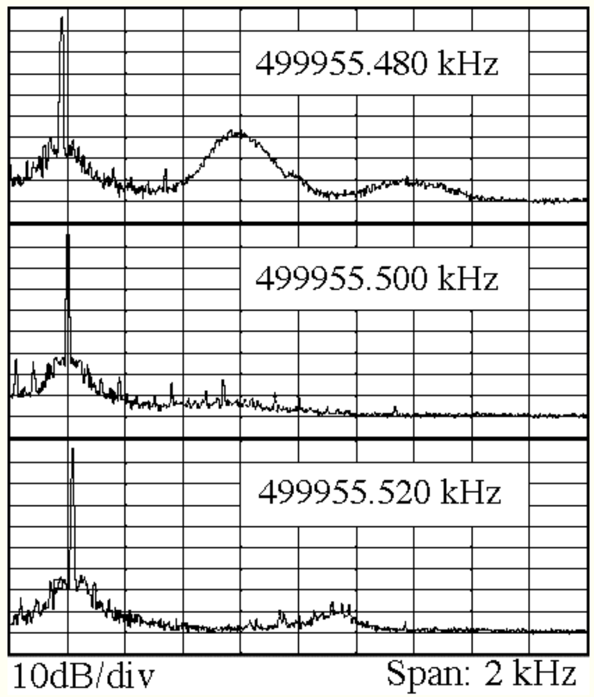
Figure 5: The measured beam position spectrum.

Unknown Process

Synchrotron Oscillation is enhanced at $\delta > 0$

The bunch length was not always shortest at where the f_S was the smallest.
It strongly depended on δ (or Δf_{RF}) at small α_1 ($\alpha_1 = 1\times10^{-5}$).





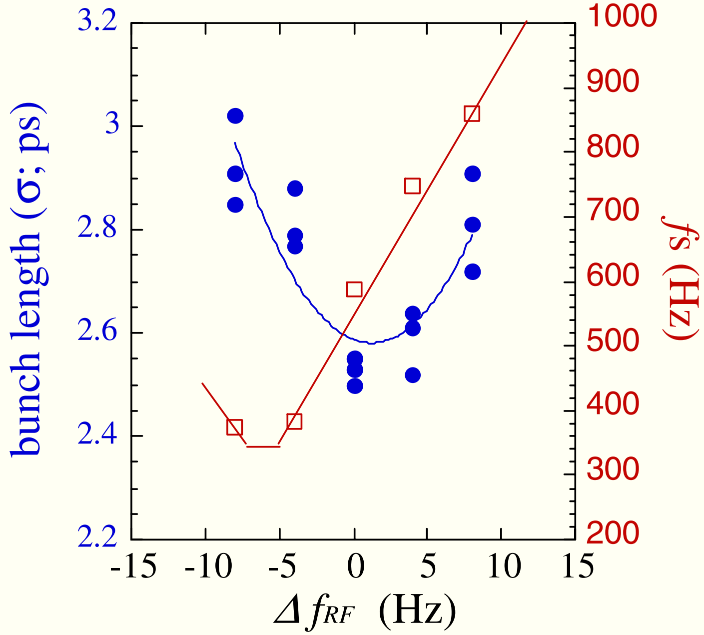
bunch shape. FFT spectrum of the beam signal

Measured bunch length and CSR

Bunch length vs *fs*

2004/06/13

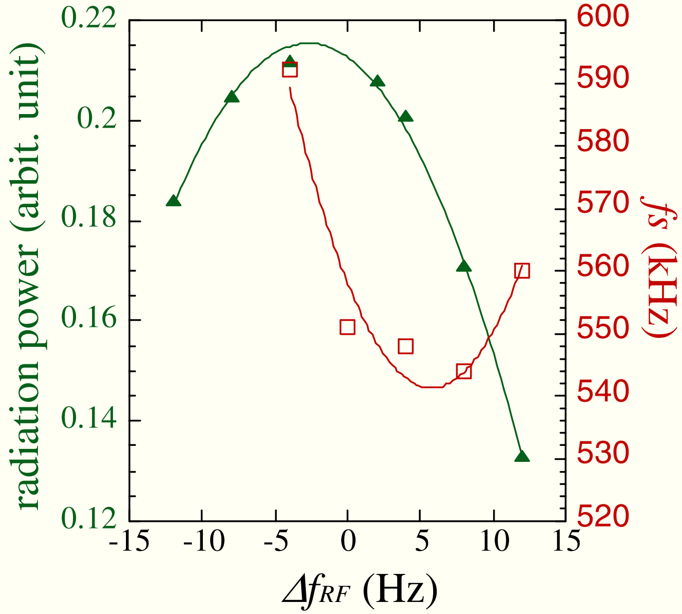
α_1=5x10^{-6}; I_B=40μA V_{RF}=120kV



CSR power vs *fs*

2004/12/14

α_1=1x10^{-5}; I_B=500μA; V_{RF}=120kV



Beam Dynamics Interests Again

Coupling of

Longitudinal Oscillation &		Transversal Oscillation
energy displacement δ	------>	horizontal displacement $dX = \eta\, \delta$
dispersion at RF cavity	------>	synchro-beta resonance
shift of circumference	<-------	c.o.d.
timing spread at H is not 0	<-------	betatron oscillation
spread of circumference	<------	chromatic tune spread

Requires High Stability& Low Noise

synchrotron frequency	300-800 Hz or less
damping time,	100Hz
harmonic noise of primary line	60Hz - 720Hz

Non-linearity of RF bucket

the linear part is extremely small,
the second order term is almost zero

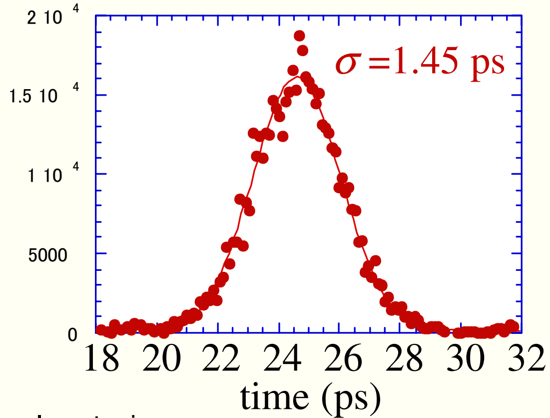
StreakCamera ; Bunch Length Measurement

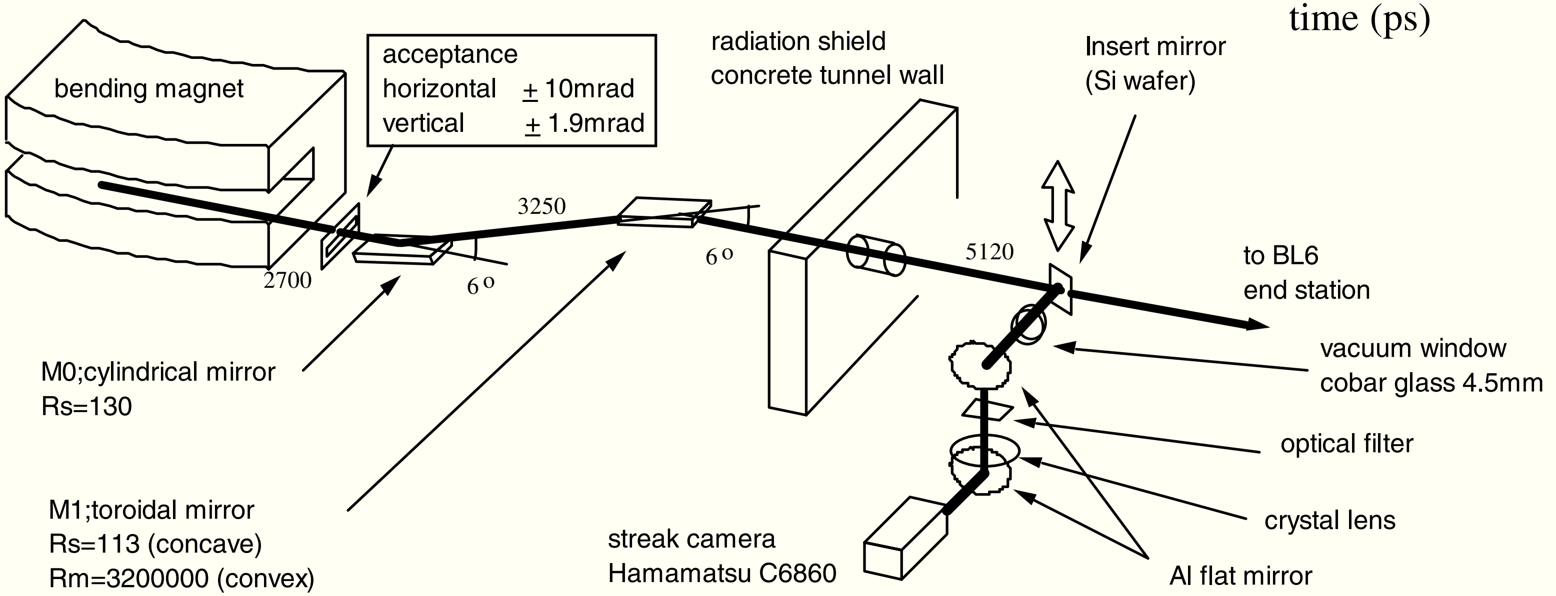
Hamamatsu C6860 is set at BL6

Time resolution 0.5ps

Scanning freq. 83.3MHz (f_{RF} /6)

1 measurement takes 1/30~1sec

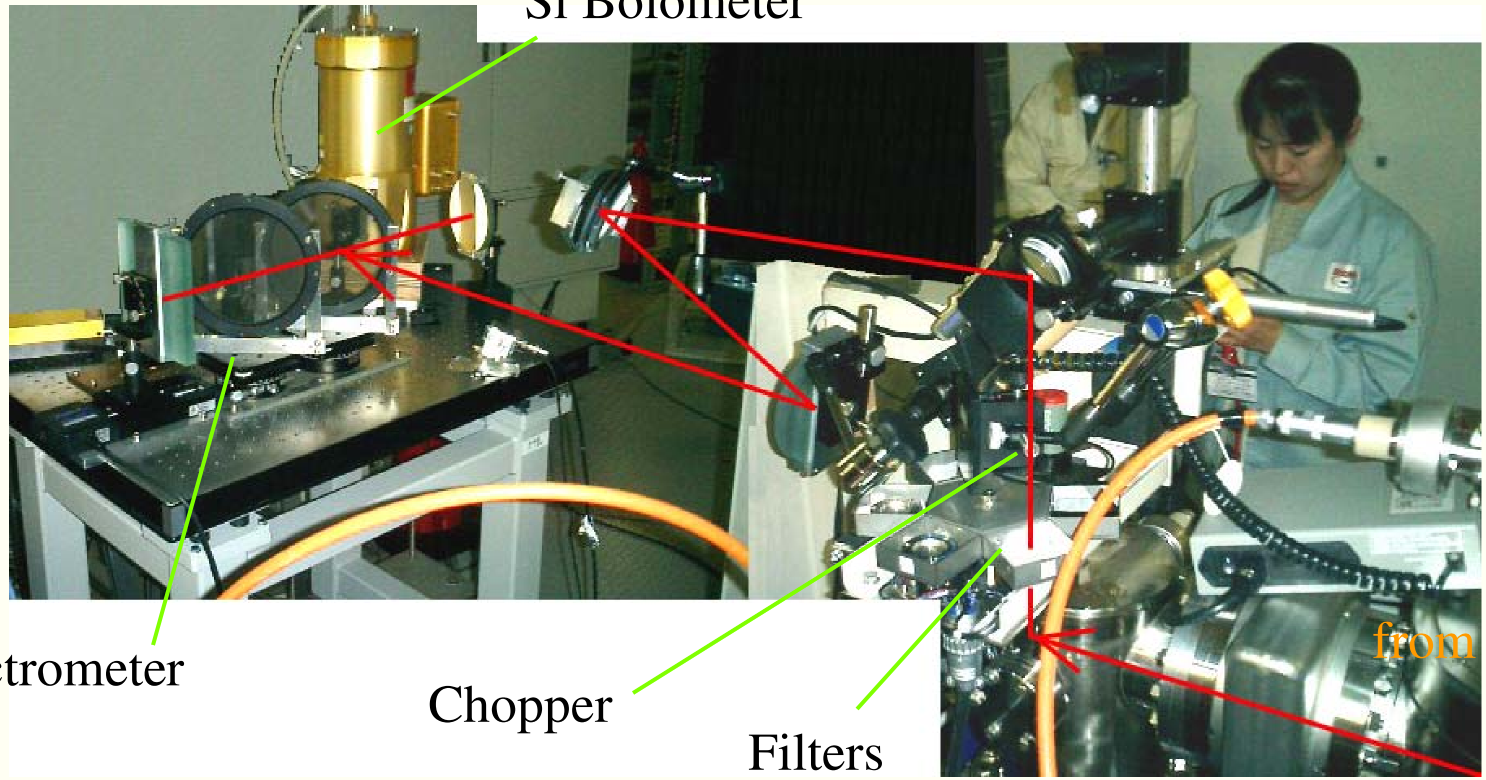




Observation of CSR ---Bolometer

A bolometer is set at the line for a beam diagnostics

chopping frequency 10Hz
Inside filter 35cm^{-1}
Spectrum -- interferometer



(1) Longitudinal Radiation Excitation

A stochastic fluctuation of where the photo-emission takes place produces a fluctuation of RF phase and enlarges the equilibrium bunch length. Because of this radiation excitation the bunch length cannot be larger than

$$\sigma_{TI} = T_0\, \sigma_{EN} \sqrt{I_\alpha}$$

at any locations of the ring. This is the intrinsic limit of a storage ring determined only by T_0 (revolution period), σ_{EN} (natural energy spread), and I_α (a variance of partial momentum compaction factor: α*).

$$I_\alpha = \langle [\alpha^*(s) - \langle \alpha^*(s) \rangle]^2 \rangle \;, \alpha^*(s) = (1/L) \int_s^L (\eta/\rho)\, \mathrm{d}s$$

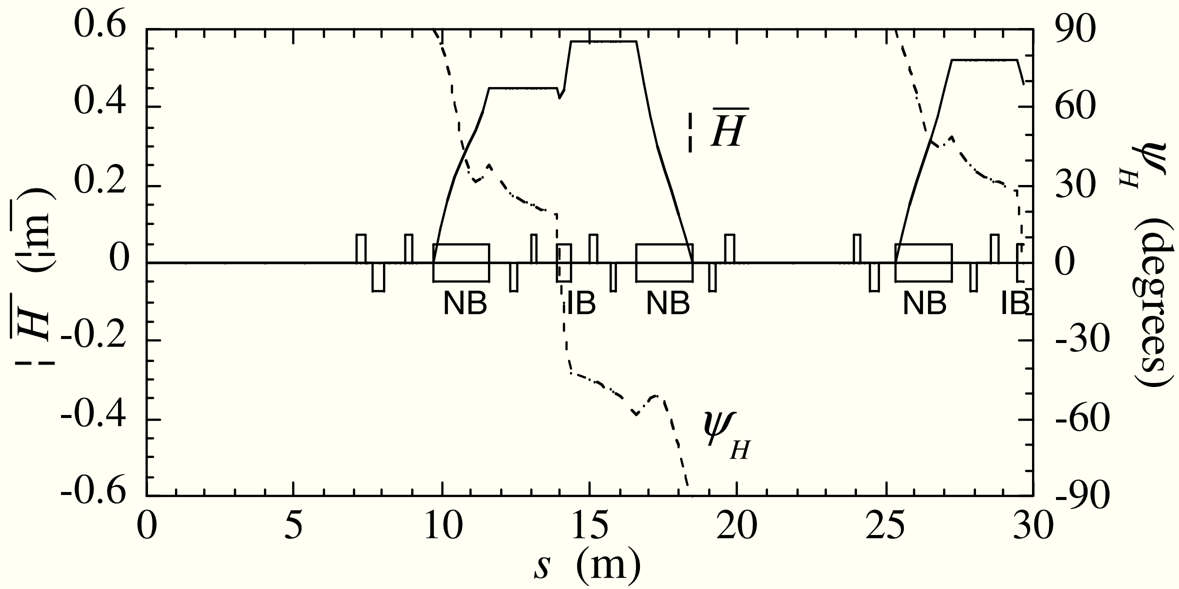
In NewSUBARU, at 1GeV σ_{TI} = 0.06 ps --- small

(2) Linear Coupling with Betatron Motion

An electron in a storage ring passing through bending magnets at the outer side or inner side of a central orbit according to its betatron oscillation amplitude and phase. It makes a deviation in the path length and produces a bunch lengthening.

$$\sigma_{B1} = \sqrt{\varepsilon H}$$

$$H = \gamma\eta^2 + 2\alpha\eta\eta' + \beta\eta'^2$$



In NewSUBARU
at the light source point for the streak camera. σ_{B1} =0.2 ps --- samll

(3) Higher Order Coupling

A contribution of betatron oscillation to the circumference

$\Delta L \approx \pi \varepsilon_X \xi_X$ (E. Forest)

This shift of $\Delta L/L$ is cancelled out by an energy shift δ

$(\Delta L/L) = -(\alpha_1 \delta + \alpha_3 \delta^3)$.

NewSUBARU

$\varepsilon_X = 3\times10^{-8}$m (natural emittance), ξ_X =-1.7, α_1=4 X 10^{-6}

$\Delta\delta$ = 0.033%= 0.7 σ_{EN}

--> ξ_X should be under control (accuracy is not required)

A shift of the synchronous phase ϕ_S

. $\Delta\phi_S = \tan\phi_S\,[k\, \beta_{RF} \varepsilon_{CSI}/4 - (2+D)\delta]$ --- negligibly small

Forced Longitudinal Oscillation

Forced Coherent Synchrotron Oscillation

$$\frac{d\tau}{dt} = -\alpha\varepsilon + \Delta_C e^{j\omega t}$$

$$\frac{d\varepsilon}{dt} = \frac{\omega_S^2}{\alpha}(\tau + \Delta_P e^{j\omega t}) - 2\alpha_E\varepsilon$$

$$\tau = \frac{(2\alpha_E + j\omega)\Delta_C - \omega_S^2\Delta_P}{\omega_S^2 - \omega^2 + 2j\omega\alpha_E} e^{j\omega t}$$

$$\varepsilon = \left(\frac{\omega_S^2}{\alpha}\right)\frac{\Delta_C + j\omega\Delta_P}{\omega_S^2 - \omega^2 + 2j\omega\alpha_E} e^{j\omega t}$$

Phase Noise Δ_P ; on resonance

$\tau_{MAX} = (\omega_S / 2\alpha_E)\Delta_P$ small for small ω_S

$\varepsilon_{MAX} = [\omega_S^2/\alpha)/(2\alpha_E)]\Delta_P$ no dependence on ω_S if V_{RF} is constant

Phase Noise Δ_P ; $\omega \ll \omega_S$

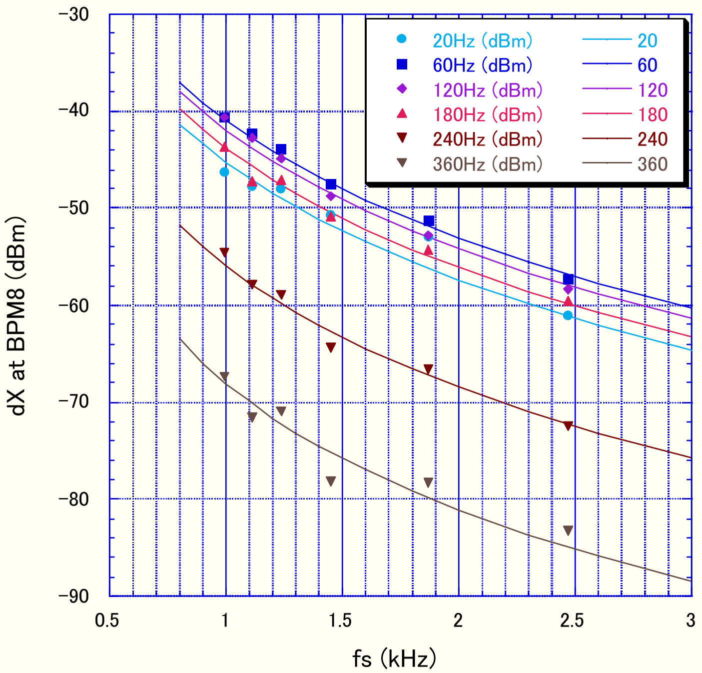
$|\tau| \approx \Delta_P$ no dependence on ω_S neither on α_1

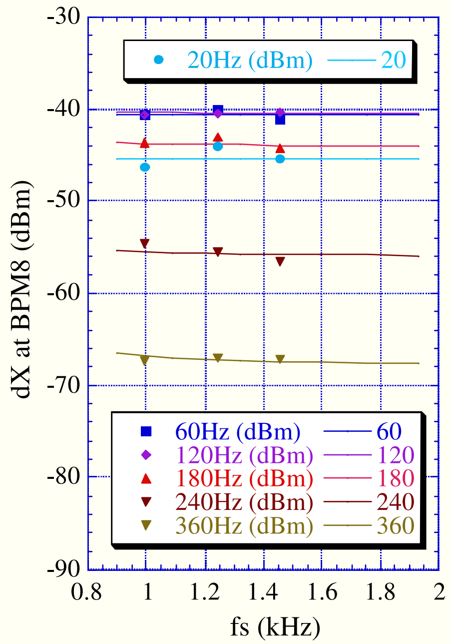
$|\varepsilon| \approx \omega/\alpha)\Delta_P$ large at low α_1(small ω_S)

Harmonic Oscillation

"Presently there is a limit by 300Hz noise, visible on the longitudinal beam signal,.. (BESSY, EPAC2004)"

Noise Source -- Phase noise of RF power?





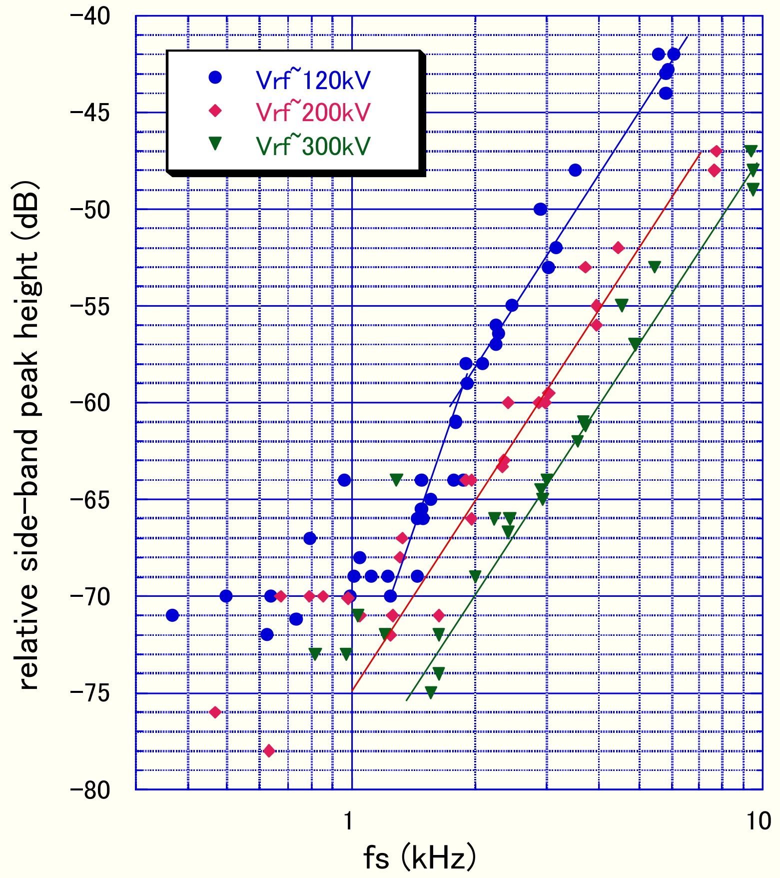
dX signal depends on a_1 -- longitudinal oscillation

Resonant Oscillation

Noise Source -- Phase noise of RF power

Relative height of the f_S side-band of RF frequency.

Width ; constant =80Hz



f_S dependence; 10dB/Oct

6dB/Oct from the basic eq.

4dB/Oct f dependence of the noise

V_{RF} dependence of phase noise

A noise of the phase detector has an input power dependence.

Is it correct that the main noise source is the phase detector?

Correction of Phase Jittering

"The phase noise of the master oscillator and of the 250MHz fast sweep voltage … these noise sources add a random contribution of ≈2.4ps to the bunch length. "
(BESSY; M. Abo-Bakr, et al., PAC03)

Effect of phase jitter

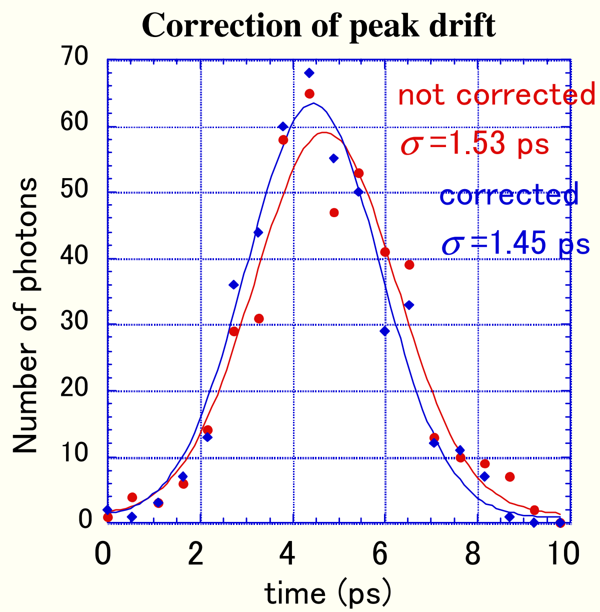
Compare the measurements in 1s and in 1/30s.

$\sqrt{(\sigma_{1S}^2 - \sigma_{1/30S}^2)}$, was 0.3

Correction of phase jitter

22 measurements with 0.1 ms gate.
(~20 photons/measurements)
Shift them by their peak positions
and make a sum of 22 profiles

$\sqrt{(1.48^2 - 1.53^2)} \approx 0.4$ ps.

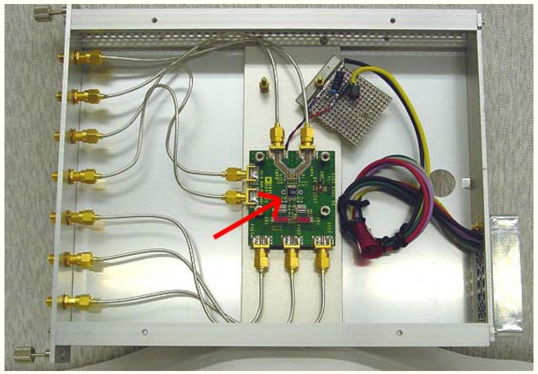


Testing New Phase Detector

Present System
3 NIM modules

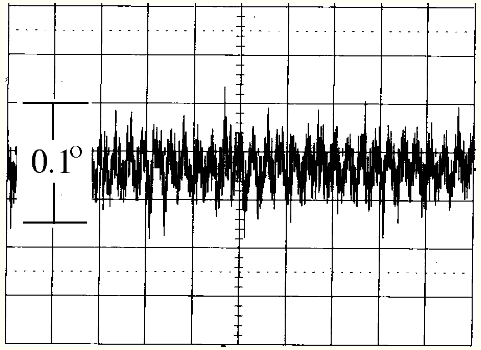
Hand-maid module

by Y. Kawashima (SPring-8)

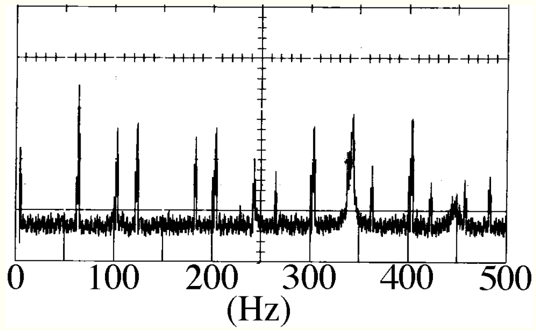


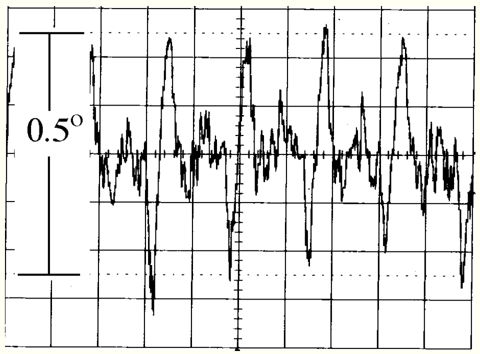
Noise Level of output signal

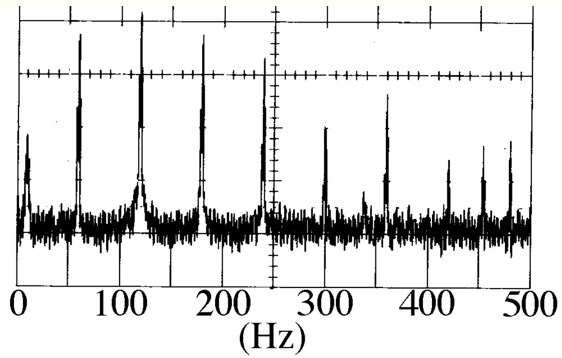
10ms/Div



10dB/div







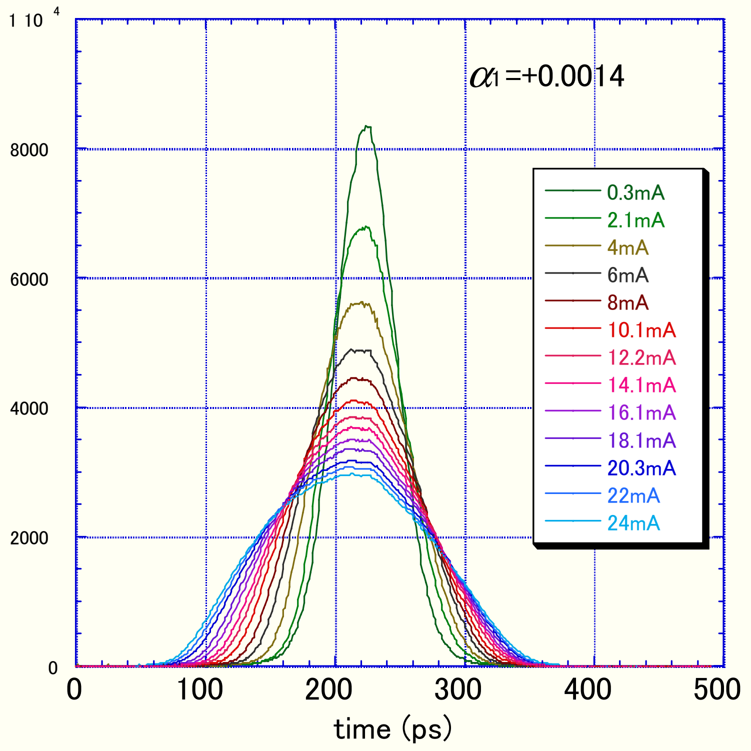
Negative α_1

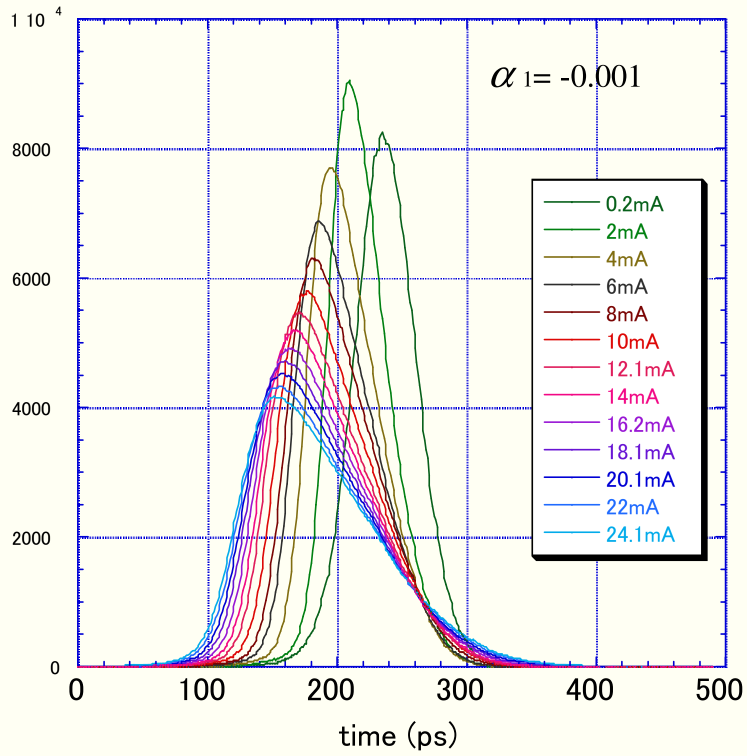
Potential well distortion --> deformation of bunch

α_1 >0; Gauss --> parabolic

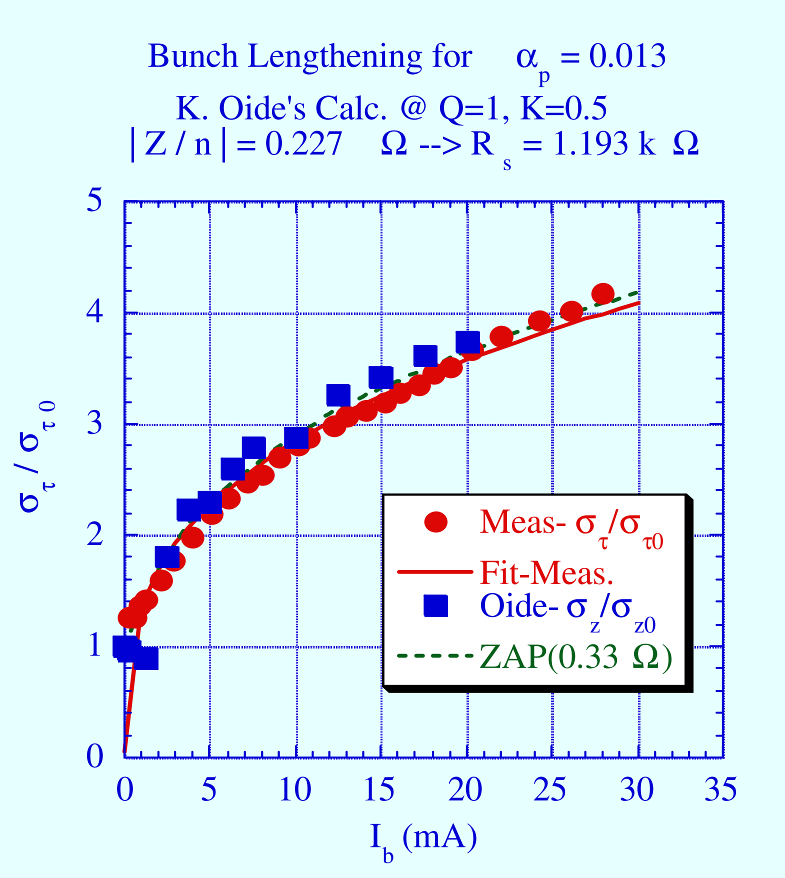
α_1 <0; Gauss --> rectangular (better form factor)

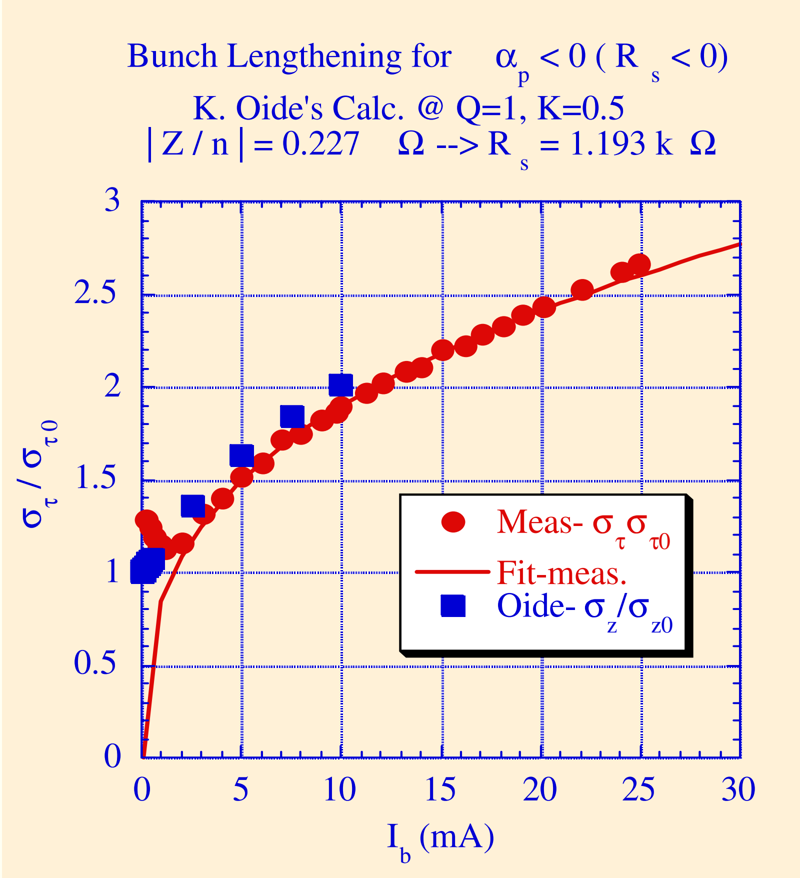
We could not see the threshold of CSR (~5mA).





Bunch length vs. current



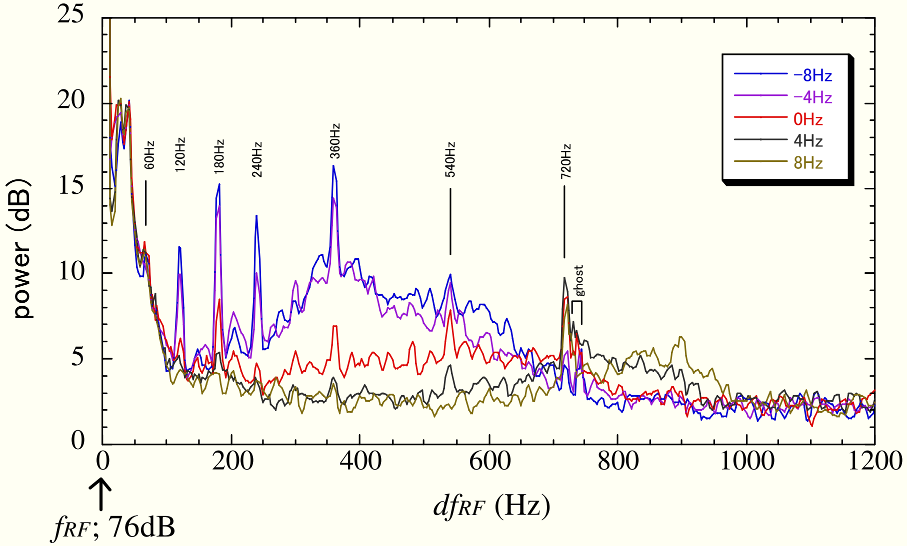


A. Ando, 2005 ann. meeting of Japanese Society for Synchrotron Radiation Research

power spectrum of longitudinal oscillation

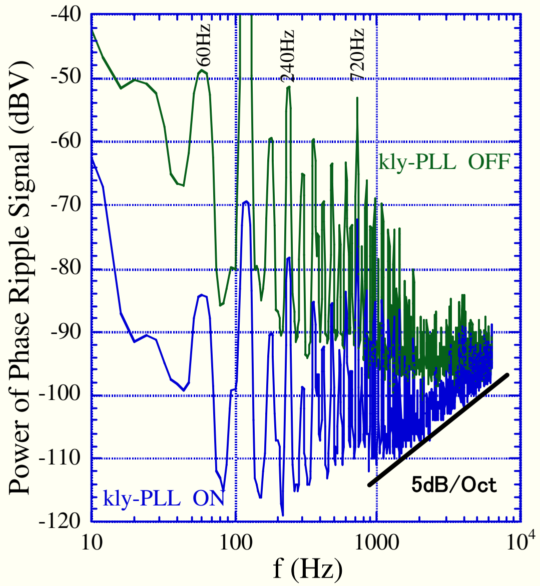
Beam Phase

(pick up electrode)



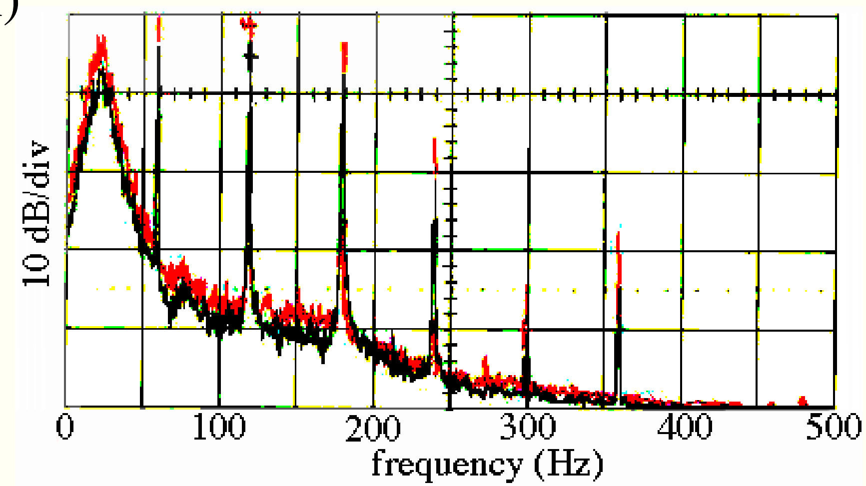
LLC phase

klystron noise
feedback



Energy

(BPM dX)



How to identify the noise source

LASTI

Forced Coherent Synchrotron Oscillation

$$\tau = \frac{(2\alpha_E + j\omega)\Delta_C - \omega_S^2 \Delta_P}{\omega_S^2 - \omega^2 + 2j\omega\alpha_E} e^{j\omega t} \qquad \varepsilon = \left(\frac{\omega_S^2}{\alpha}\right) \frac{\Delta_C + j\omega\Delta_P}{\omega_S^2 - \omega^2 + 2j\omega\alpha_E} e^{j\omega t}$$

The ratio, τ/ε is different for a different noise source

Phase noise; Δ_P $\qquad \tau/\varepsilon = j\alpha_1/\omega$

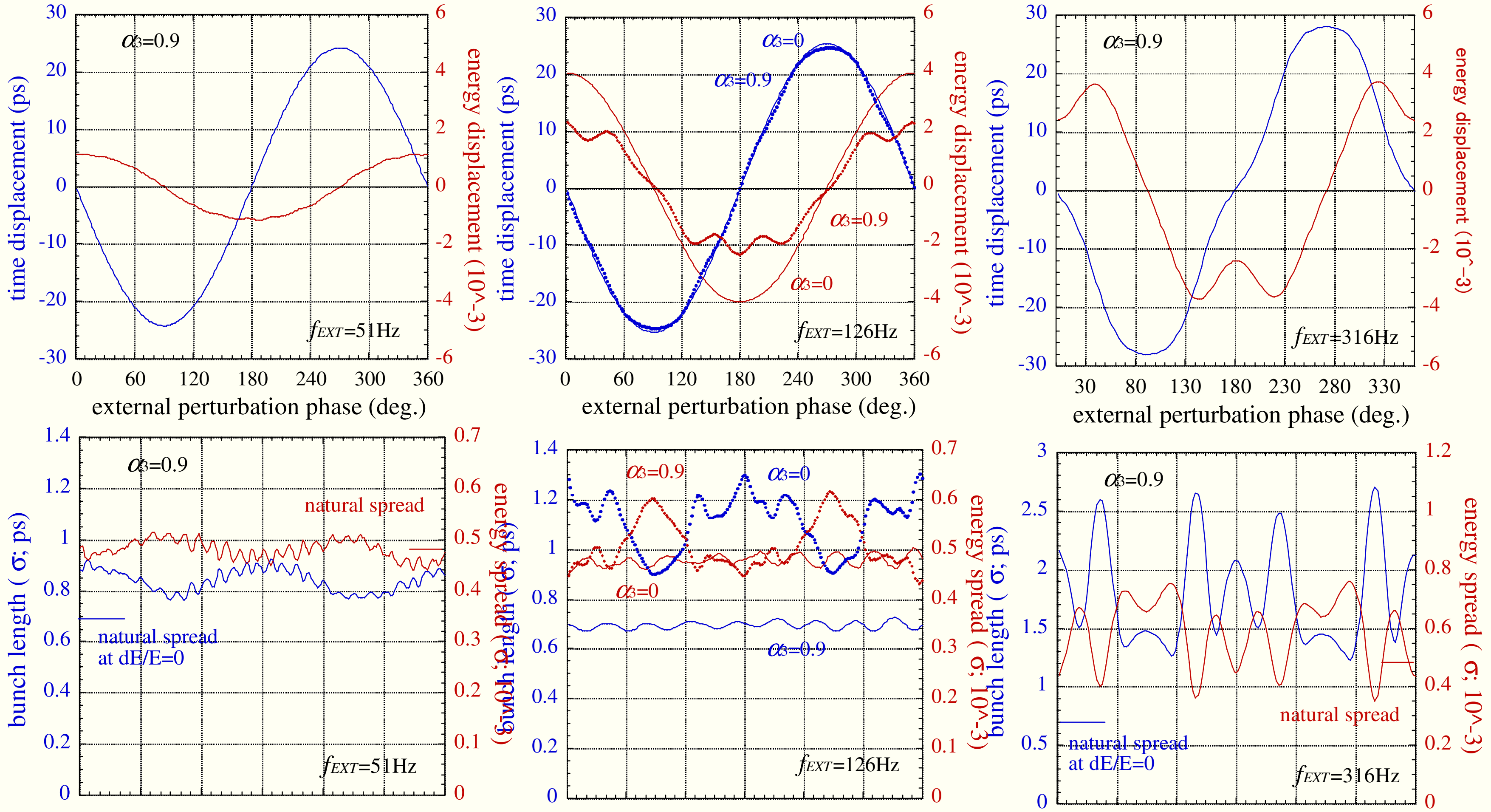
RF control

Circumference noise; Δ_C $\qquad \tau/\varepsilon = (2\alpha_E + j\omega)(\alpha_1/\omega_S^2)$

Magnet ripple $\qquad = (j\alpha_1/\omega)(\omega/\omega_S)^2 + 2\alpha_E\, \alpha_1/\omega_S^2$

By the measurement of τ and ε at the same time, we can identify the noise source.

Non-linear bucket with phase noise



SUMMARY

LASTI

Present Status at NewSUBARU

*The ring reaches to the bunch shortening limit at $\alpha_1 \approx 2 \times 10^{-5}$ (1.4ps)
*Burst mode and steady state CSR is observed.

Progressing R&D at NewSUBARU

*Mechanism which limited bunch shortening at NewSUBARU
*Negative α_1 (understand form factor, MWI)
*A beam line for the observation of CSR

More R&Ds

*Maximum current for users, Thresholds of instabilities
*Refinement of parameter (test of IB-in-gap sextupole)
*Make the machine more stable
*Low and High Energy Operation
. . . .