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

Y. Shoji
LASTI, University of Hyogo

Low Alpha       Y. Shoji, S. Hisao*, T. Matsubara*           *students
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?

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circumference</td>
<td>118.7 m</td>
</tr>
<tr>
<td>Injection Energy</td>
<td>1.0 GeV</td>
</tr>
<tr>
<td>Electron Energy</td>
<td>0.5 - 1.5 GeV</td>
</tr>
<tr>
<td>Type of Bending cell</td>
<td>DBA with Inv.B</td>
</tr>
<tr>
<td>Number of Bending Cell</td>
<td>6</td>
</tr>
<tr>
<td>RF Frequency</td>
<td>499.956 MHz</td>
</tr>
<tr>
<td>Maximum Stored Current</td>
<td>500 mA</td>
</tr>
<tr>
<td>Natural Emittance</td>
<td>38 nm (1 GeV)</td>
</tr>
<tr>
<td>Natural Energy Spread</td>
<td>0.047% (1 GeV)</td>
</tr>
</tbody>
</table>

New SUBARU

- 1 GeV linac
- Spring-8 SR
- New Material (1998)
- Photo-chemical (1998)
- Interferometry (1998)
- EUVL (1997)
- LIGA (1997)
- LIGA (2004)
- Microscope (2001)
- Optical Klystron
- Long Undulator
- Short Undulator
- R & D (1997)
Basic Idea of Low Alpha

* Quasi-isochronus = small momentum compaction factor ($\alpha$)

$$\frac{L}{L_0} \equiv 1 + \alpha_1 \delta + \alpha_2 \delta^2 + \alpha_3 \delta^3 + \ldots$$

$$\delta \equiv \frac{(E - E_0)}{E_0}$$

* Small $\alpha_1$ --> short bunch

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

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

$f_S$ is used to estimate $\alpha_1$

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

* Linear Factor $\alpha_1$

$$\alpha_1 = \frac{1}{L_0} \int \left( \frac{\eta}{\rho} \right) ds$$

$\alpha_1 \approx 0$ requires negative $\eta$ section --- Break achromat or negative $\rho$ section. --- Invert bend
Control of $\alpha_1$; Invert Bend

Change $\eta$ in the invert bends --> change $\alpha_1$
keeping achromatic condition

$34^\circ - 8^\circ + 34^\circ = 60^\circ$

Two Q-families are used
Second Order Factor $\alpha_2$

Sextupole & chromaticities

$\alpha_2$ control is the essential part of $\alpha_1 \approx 0$ operation

$$\Delta \alpha_2 = \frac{1}{2L_0} \int \eta_1^3 \Delta K_2 ds$$  \hspace{1cm} \text{synch. tune} \hspace{1cm} \alpha_2 = 0$$

$$\Delta \xi_x = -\frac{1}{4\pi} \int \eta_1 \beta_x \Delta K_2 ds$$  \hspace{1cm} \text{horizontal tune} \hspace{1cm} \xi_x = -1.7$$

$$\Delta \xi_y = \frac{1}{4\pi} \int \eta_1 \beta_y \Delta K_2 ds$$  \hspace{1cm} \text{vertical tune} \hspace{1cm} \xi_y = -7.7$$

$$K_2 = \frac{1}{B_0 \rho_0} \left( \frac{\partial^2 B_y}{\partial x^2} \right)$$

This Sextupole family controls $\alpha_1$

$f_{RF}$ dependence of $f_S$ is measured to confirm that $\alpha_2 = 0$
Result(1): Bunch Shortening

Reduce $\alpha_1$

The $\sigma_T$ is reduced according to $\sqrt{\alpha_1}$ scaling low ($\alpha_1 > 2 \times 10^{-5}$)
Minimum length was 1.4ps

Low current

$I_B < 2\mu\text{A}/\text{bunch} (0.4\text{mA})$
No current dependent lengthening

At $\alpha_1 < 2 \times 10^{-5}$

Reduction of $\alpha_1$ did not reduce $\sigma_T$.
Raise of $V_{RF}$ reduced $\sigma_T$.
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 $\alpha_1$ --- high radiation power

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

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

$I_B = 3\,\mu$A/bunch
$V_{RF} = 120\,kV$

Measured by a bolometer, 35\,cm$^{-1}$ filtered
Result(3); CSR modes

**THz radiation mode**
measurement with bolometer (35 cm⁻¹)

- normal $\alpha_1$, high current per bunch
  -- burst mode CSR

- small $\alpha_1$ -- steady state CSR? 
  \[ \text{Power} \propto I^2 \]

- normal $\alpha_1$, low current
  -- normal radiation
  \[ \text{Power} \propto I \]
**Result(4); CSR Spectrum**

CSR-- strong long $\lambda$ radiation

Burst mode had shorter $\lambda$ radiation although the bunch was long.
Result(5); Bunch compression by $V_{RF}$

CSR spectrum
Power; $P=I^2$
Spectrum;
short bunch $\rightarrow$ short wave length CSR
continuous spectrm $?$ the data is not clear

Shorter bunch emits shorter wavelength CSR

SIMULATION assuming Gaussian
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 $\alpha_2$ --- 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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>BESSY II</th>
<th>NewSUBARU</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural Energy Spread</td>
<td>0.08%</td>
<td>0.047%</td>
</tr>
<tr>
<td>Natural Emittance (nm rad)</td>
<td>30(\pi)</td>
<td>30(\pi)</td>
</tr>
<tr>
<td>(\alpha_1)</td>
<td>-1.4x10^{-6}</td>
<td>5x10^{-6}</td>
</tr>
<tr>
<td>(\alpha_3)</td>
<td>-0.01</td>
<td>0.9</td>
</tr>
<tr>
<td>Damping time</td>
<td>8ms</td>
<td>12ms</td>
</tr>
<tr>
<td>Lattice</td>
<td>non-achromatic DB</td>
<td>DBA+IB</td>
</tr>
<tr>
<td>Time jittering at Streak C</td>
<td>2.4ps</td>
<td>0.4ps</td>
</tr>
</tbody>
</table>

**BESSY II**

J. Feikes et al., EPAC2004

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**Graphs**

- Graph showing bunch length versus single bunch current for different voltages and currents.
- Graph showing bunch length versus \(\sqrt{\alpha_i}\) for different voltages and currents.

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(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 $\alpha_3$

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

$\Rightarrow \alpha_1 + 2 \alpha_2 \delta + 3 \alpha_3 \delta^2 > 0$ --> $\alpha_2^2 - 3 \alpha_3 \alpha_1 < 0$
$\alpha_2=2.6 \times 10^{-3}$, $\alpha_3=0.9$ --> $\alpha_1>2.5 \times 10^{-6}$ ($\sigma_t>0.5$ps)

Field Ripple is also important
(5) The $\alpha_3$-- Another essential part

The $\alpha_3$ makes stable RF bucket for large $\delta$

The $\alpha_1$ and $\alpha_3$ should have same signs. --> enough RF bucket
When $\alpha_1$ and $\alpha_3$ have opposite sign --> short life time

Large $\alpha_3$ enlarges tolerance of $\alpha_2$
Large $\alpha_3$ with the energy spread effectively enlarge $\alpha_1$

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

$\alpha_3 = 0.9$

$\sigma_{EN} = 0.047\%$ (natural spread) \hspace{1cm} \langle 3\alpha_3\delta \rangle = 6\alpha_3\sigma_{EN}^2$
$\Delta\alpha_1 = 1.2 \times 10^{-6}$
(6) Coherent Longitudinal Oscillation

Longitudinal oscillation \[ \frac{\Delta \tau}{\Delta \delta} \propto \alpha^{1/2} \]
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

- $E = 1\text{GeV}$
- $\tau_\varepsilon = 11.4\ \text{ms}$
- $\alpha_1 = 5 \times 10^{-6}$
- $\alpha_3 = 0.9$
- $V_{RF} = 300\ \text{kV}$
- $f_s = 547\ \text{Hz}$
- $\sigma_E/E = 0.48 \times 10^{-3}$
- $\sigma_T = 0.69\ \text{ps}$

external perturbation

- $f_{EXT} = 126\ \text{Hz}$
- amp $= \pm 10\ \text{Hz} (24\ \text{ps})$

number of particles 1000
A dipole error produces a longitudinal oscillation

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

The response of COD to \( \theta_{\text{ERR}} \) is

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

In small \( \alpha_1 \) ring, the second term is dominant.

\( dX \) has high sensitivity -- good diagnostic of a longitudinal oscillation

\[
\tau = \frac{(2\alpha_E + j\omega)\Delta_C - \omega_S^2 \Delta_P}{\omega_S^2 - \omega^2 + 2j\omega\alpha_E} e^{j\omega t} \quad \varepsilon = \frac{\omega_S^2}{\alpha} \frac{\Delta_C + j\omega\Delta_P}{\omega_S^2 - \omega^2 + 2j\omega\alpha_E} e^{j\omega t}
\]

Active feed back to the dipole magnet reduces longitudinal oscillation-- good for a slow feed-back
A dipole steering is used to reduce longitudinal oscillation

Dipole error at dispersive sections changes circumference

BPM signal (X)

Feed-back OFF ON

dX signal (w. LPF; x2)
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.
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 $\delta$ (or $\Delta f_{RF}$) at small $\alpha_1$ ($\alpha_1 = 1 \times 10^{-5}$).

bunch shape. FFT spectrum of the beam signal
Measured bunch length and CSR

**Bunch length vs $f_s$**
2004/06/13
$\alpha_1=5\times10^{-6}; \ I_B=40\mu\text{A} \ V_{RF}=120\text{kV}$

**CSR power vs $f_s$**
2004/12/14
$\alpha_1=1\times10^{-5}; \ I_B=500\mu\text{A}; \ V_{RF}=120\text{kV}$
Beam Dynamics Interests Again

Coupling of
Longitudinal Oscillation & Transversal Oscillation

energy displacement $\delta$ $\longrightarrow$ horizontal displacement $dX = \eta \delta$
dispersion at RF cavity $\longrightarrow$ synchro-beta resonance
shift of circumference $\leftarrow$ c.o.d.
timing spread at $H$ is not 0 $\leftarrow$ betatron oscillation
spread of circumference $\leftarrow$ 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
Hamamatsu C6860 is set at BL6
Time resolution 0.5 ps
Scanning freq. 83.3 MHz ($f_{RF}/6$)
1 measurement takes 1/30~1 sec

σ = 1.45 ps

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Observation of CSR --- Bolometer

A bolometer is set at the line for a beam diagnostics

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

Si Bolometer

Spectrometer
Chopper
Filters

from the ring
(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), $\sigma_{EN}$ (natural energy spread), and $I_\alpha$ (a variance of partial momentum compaction factor: $\alpha^*$).

$$I_\alpha = \langle [\alpha^*(s) - \langle \alpha^*(s) \rangle]^2 \rangle , \quad \alpha^*(s) = (1/L) \int_s^L (\eta/\rho) \, ds$$

In NewSUBARU, at 1GeV $\sigma_{TI} = 0.06 \text{ ps} \quad \text{--- small}$
(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.

\[ \sigma_{Bl} = \sqrt{\varepsilon H} \]

\[ H = \gamma \eta^2 + 2\alpha \eta \eta' + \beta \eta'^2 \]

In NewSUBARU at the light source point for the streak camera. \( \sigma_{Bl} = 0.2 \) 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 \( \delta \)

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

NewSUBARU
\( \varepsilon_X = 3 \times 10^{-8} \) m (natural emittance),  \( \xi = -1.7, \  \alpha_1 = 4 \times 10^{-6} \)
\( \Delta \delta = 0.033\% = 0.7 \ \sigma_{EN} \)

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

A shift of the synchronous phase \( \phi_S \)

\[ \Delta \phi_S = \tan \phi_S [k \beta_{RF} \varepsilon_{CSI} / 4 - (2+D)\delta] \text{ --- negligibly small} \]
Forced Longitudinal Oscillation

Forced Coherent Synchrotron Oscillation

\[
\frac{d\tau}{dt} = -\alpha \varepsilon + \Delta C e^{j\omega t}
\]

\[
\frac{d\varepsilon}{dt} = \frac{\omega_S^2}{\alpha} (\tau + \Delta P e^{j\omega t}) - 2\alpha \varepsilon
\]

\[
\tau = \frac{(2\alpha_E + j\omega)\Delta C - \omega_S^2 \Delta P}{\omega_S^2 - \omega^2 + 2j\omega \alpha_E} e^{j\omega t}
\]

\[
\varepsilon = \frac{\omega_S^2}{\alpha} \frac{\Delta C + j\omega \Delta P}{\omega_S^2 - \omega^2 + 2j\omega \alpha_E} e^{j\omega t}
\]

Phase Noise \(\Delta_P\); on resonance

\[
\tau_{\text{MAX}} = \left(\frac{\omega_S}{2\alpha_E}\right) \Delta P
\]

\[
\varepsilon_{\text{MAX}} = \left[\frac{\omega_S^2}{\alpha}\right] \frac{\Delta P}{2\alpha_E}
\]

small for small \(\omega_S\)

no dependence on \(\omega_S\) if \(V_{RF}\) is constant

Phase Noise \(\Delta_P\); \(\omega \ll \omega_S\)

\[
|\tau| \approx \Delta P
\]

no dependence on \(\omega_S\) neither on \(\alpha_1\)

\[
|\varepsilon| \approx \omega / \alpha \Delta_P
\]

large at low \(\alpha_1\) (small \(\omega_S\))
“Presently there is a limit by 300Hz noise, visible on the longitudinal beam signal,... (BESSY, EPAC2004)"

Noise Source -- Phase noise of RF power?

\[ \text{dX signal depends on } a_1 \text{ -- longitudinal oscillation} \]
Noise Source -- Phase noise of RF power
Relative height of the $f_S$ side-band of RF frequency.
Width; constant $=80$Hz

$f_S$ 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 \( \approx 2.4 \text{ps} \) to the bunch length. “ (BESSY; M. Abo-Bakr, et al., PAC03)

Effect of phase jitter

Compare the measurements in 1s and in 1/30s.
\[ \sqrt{\left( \sigma_{1S}^2 - \sigma_{1/30S}^2 \right)} \], was 0.3

Correction of phase jitter

22 measurements with 0.1 ms gate.
\(~20 \text{ photons/measurements}\)
Shift them by their peak positions
and make a sum of 22 profiles
\[ \sqrt{\left( 1.48^2 - 1.53^2 \right)} \approx 0.4 \text{ ps}. \]
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

(Hz)

(0 100 200 300 400 500)

(0 100 200 300 400 500)

(0.1°)

(0.5°)
**Negative $\alpha_1$**

Potential well distortion --> deformation of bunch

$\alpha_1 > 0$; Gauss --> parabolic

$\alpha_1 < 0$; Gauss --> rectangular (better form factor)

We could not see the threshold of CSR (~5mA).
Bunch length vs. current

Bunch Lengthening for $\alpha_p = 0.013$
K. Oide's Calc. @ Q=1, K=0.5
$|Z/n| = 0.227$ $\Omega \rightarrow R_s = 1.193 \Omega$

Bunch Lengthening for $\alpha_p < 0$ ($R_s < 0$)
K. Oide's Calc. @ Q=1, K=0.5
$|Z/n| = 0.227$ $\Omega \rightarrow R_s = 1.193 \Omega$

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

Forced Coherent Synchrotron Oscillation

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

\[ \varepsilon = \frac{(\omega_S^2)\Delta_C + j\omega\Delta_P}{\omega_S^2 - \omega^2 + 2j\omega\alpha_E} e^{j\omega t} \]

The ratio, \( \tau/\varepsilon \) is different for a different noise source

Phase noise; \( \Delta_P \)  
RF control  
\( \tau/\varepsilon = j\alpha_1/\omega \)

Circumference noise; \( \Delta_C \)  
Magnet ripple  
\( \tau/\varepsilon = (2\alpha_E + j\omega)(\alpha_1/\omega_S^2) \)

\[ = (j\alpha_1/\omega)(\omega/\omega_S)^2 + 2\alpha_E\alpha_1/\omega_S^2 \]

By the measurement of \( \tau \) and \( \varepsilon \) at the same time, we can identify the noise source.
Non-linear bucket with phase noise

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- Time displacement (ps)
- Energy displacement (10^-3)
- External perturbation phase (deg.)

\( \alpha_3 = 0.9 \)
\( f_{\text{EXT}} = 51 \text{Hz} \)

\( \alpha_3 = 0 \)
\( f_{\text{EXT}} = 126 \text{Hz} \)

\( \alpha_3 = 0.9 \)
\( f_{\text{EXT}} = 316 \text{Hz} \)

- Bunch length (\( \sigma \); ps)
- Energy spread (\( \sigma \); 10^-3)

natural spread
at \( dE/E = 0 \)
SUMMARY

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 $\alpha_1$ (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
    . . . .