Some Techniques for Producing Short SR Pulses in Storage Rings

- Utilizing head-tail oscillations
- Excitation of bunch-shape oscillations

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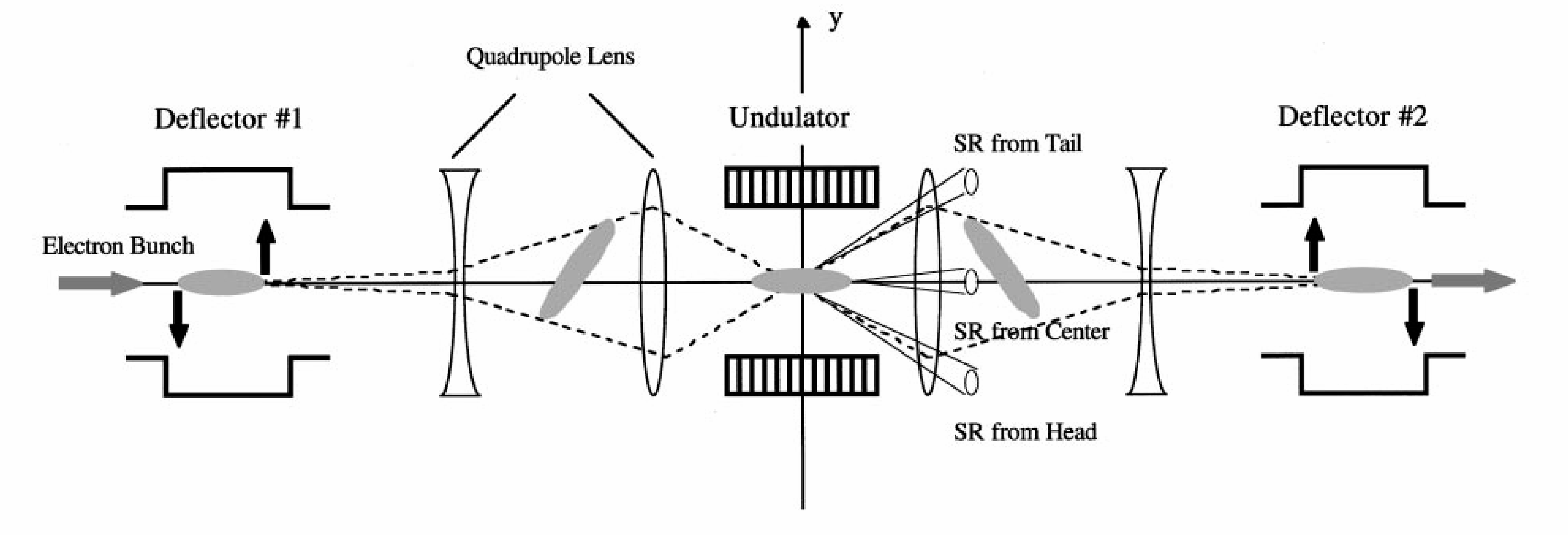
I. Utilizing Head-Tail Oscillations

Original RF orbit deflection method

A. Zholents et al., Nucl Instrum & Methods A**425** (1999) 385.
M. katoh: Jpn. J. Appl. Phys. **38** (1999) L547.



Cited from Katoh's paper.

Deflecting cavities are very expensive.

Using superconducting Crab cavity for KEKB: (~ 1.5 M$/cavity ?)

Transverse voltage $V_{\perp}$ ~ 1.44 MV

$$\theta = \frac{eV_{\perp}kz}{E} \simeq 40\ \mu\text{rad} \qquad E = 6.5\ \text{GeV},\ z = 1.7\ \text{cm}$$

Idea: apply multiple kicks of weaker strength

Normal conducting cavity (TM110 mode)

$$\theta \simeq 5\ \mu\text{rad} \qquad E = 6.5\ \text{GeV},\ z = 1.7\ \text{cm}$$

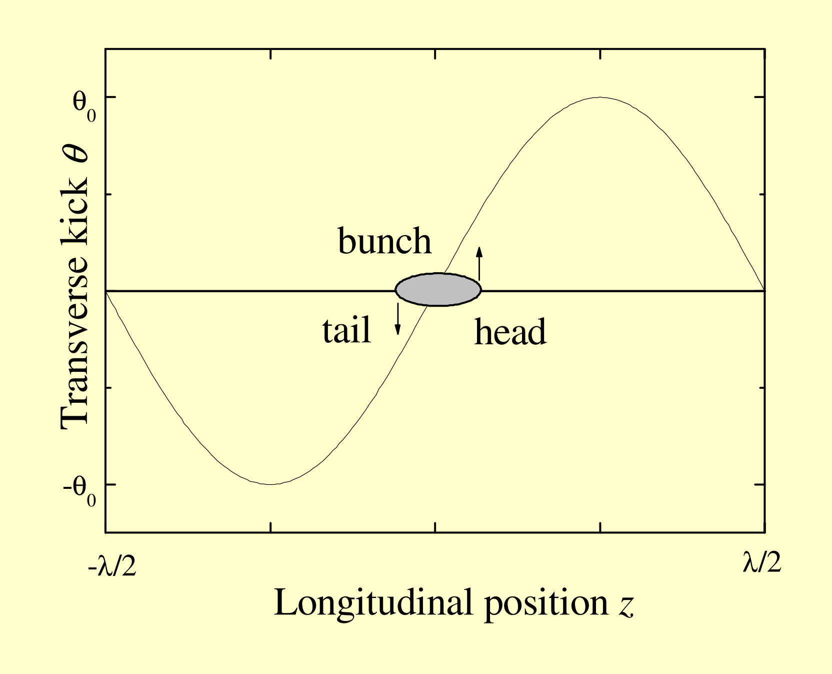
f = 508 MHz, Wall loss: 8.7 kW/cavity

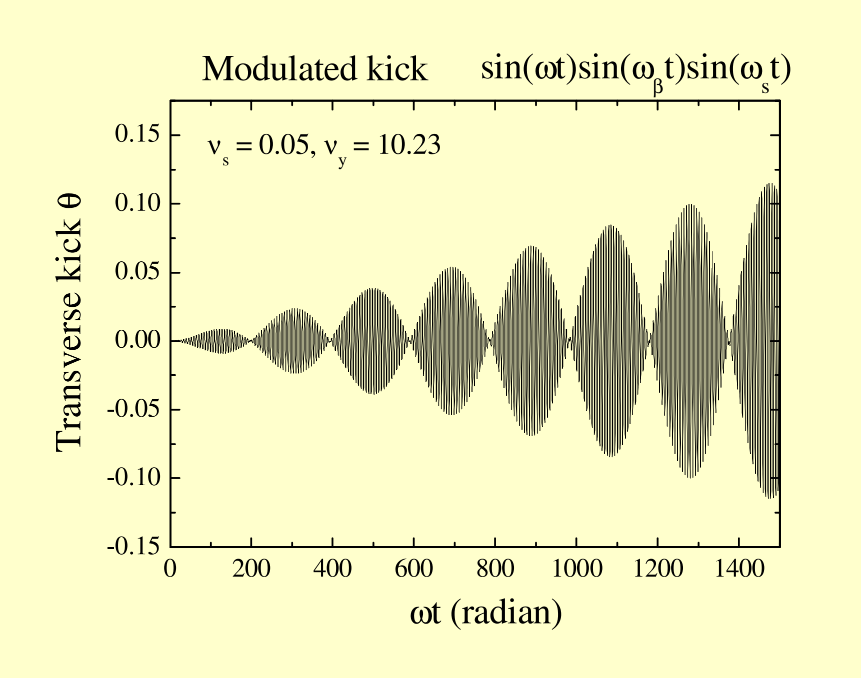
S. Sakanaka: Jpn. J. Appl. Phys. **43** (2004) 6457.

Excitation of head-tail oscillations

Modulate deflecting-rf by both frequencies of ω_β and ω_s

$$F_y = p_0 k_v z \cos(\omega_\beta t)\cos(\omega_s t)\delta_{T_0}(t)$$





Equations of motion

$$\frac{d^2y}{dt^2}+2\lambda\frac{dy}{dt}+\omega_\beta^2 y = ck_v z\cos(\omega_\beta t)\cos(\omega_s t)\delta_{T_0}(t) \qquad z = r_0\cos(\omega_s t+\psi_0)$$

Aporoximately: $$\frac{d^2y}{dt^2}+2\lambda\frac{dy}{dt}+\omega_\beta^2 y = \frac{ck_v r_0}{2T_0}\cos(\omega_\beta t)$$

Solution (assuming $y_0 = y'_0 = 0$)

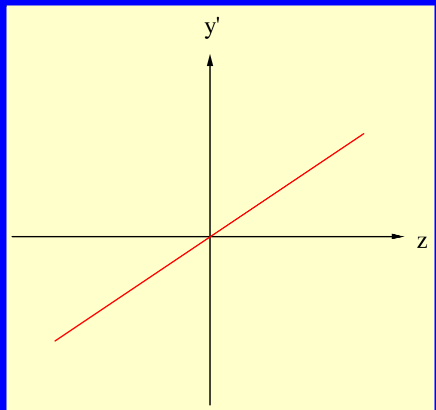
$$y(t)\approx\frac{ck_v z_0}{4\lambda_\beta T_0\omega_\beta}\left(1-e^{-\lambda_\beta t}\right)\sin(\omega_\beta t)$$

$$y'(t)\approx\frac{k_v z_0}{4\lambda_\beta T_0\omega_\beta}\left(1-e^{-\lambda_\beta t}\right)\cos(\omega_\beta t)$$

At certain time: $t_s = n\cdot T_s = m\cdot T_\beta$ (synchronous time)

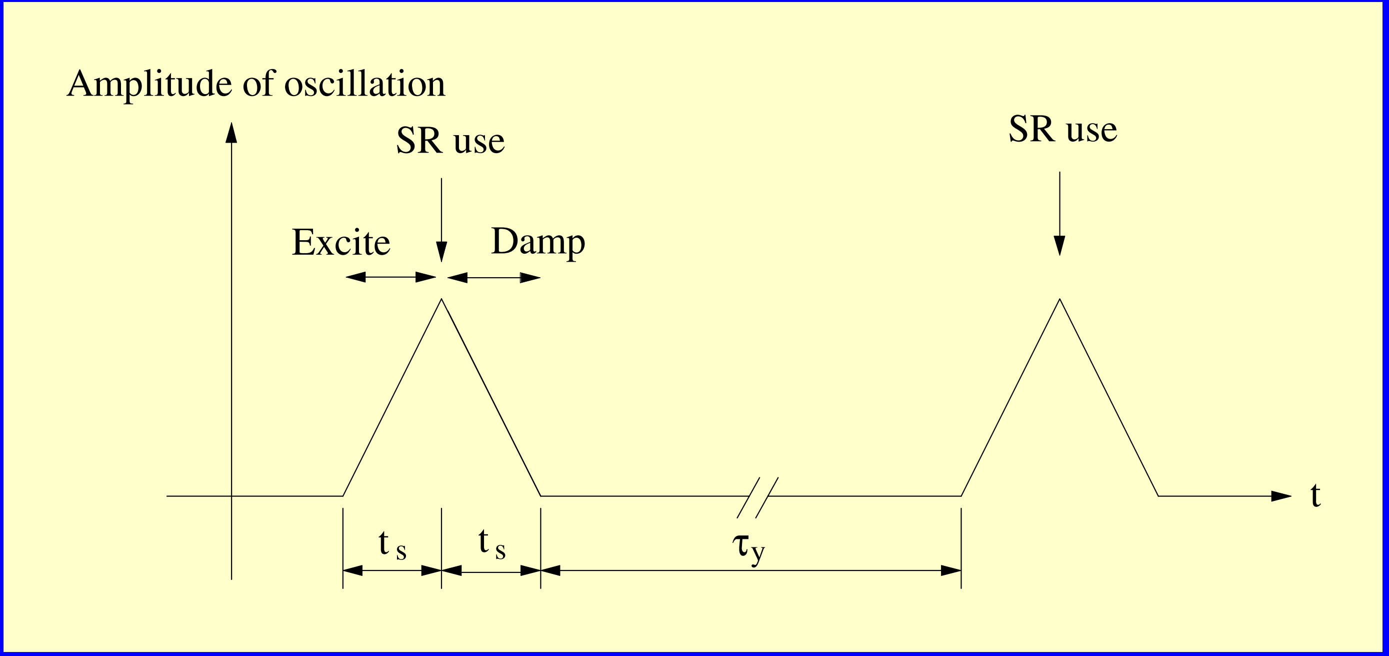
$$y(t_s)\approx 0$$

$$y'(t_s)\approx\frac{k_v z(t_s)}{4\lambda_\beta T_0}\left(1-e^{-\lambda_\beta t_s}\right)$$



Use of Short-Pulse SR

- After exciting the head-tail oscillation, short SR pulse is isolated using fast mechanical shutter.
- The head-tail oscillation is damped down by applying opposite kicks.



Example (simulation)

Machine parameters: PF-AR

$E = 6.5$ GeV

$\nu_y = 10.125$

$\nu_s = 0.05$

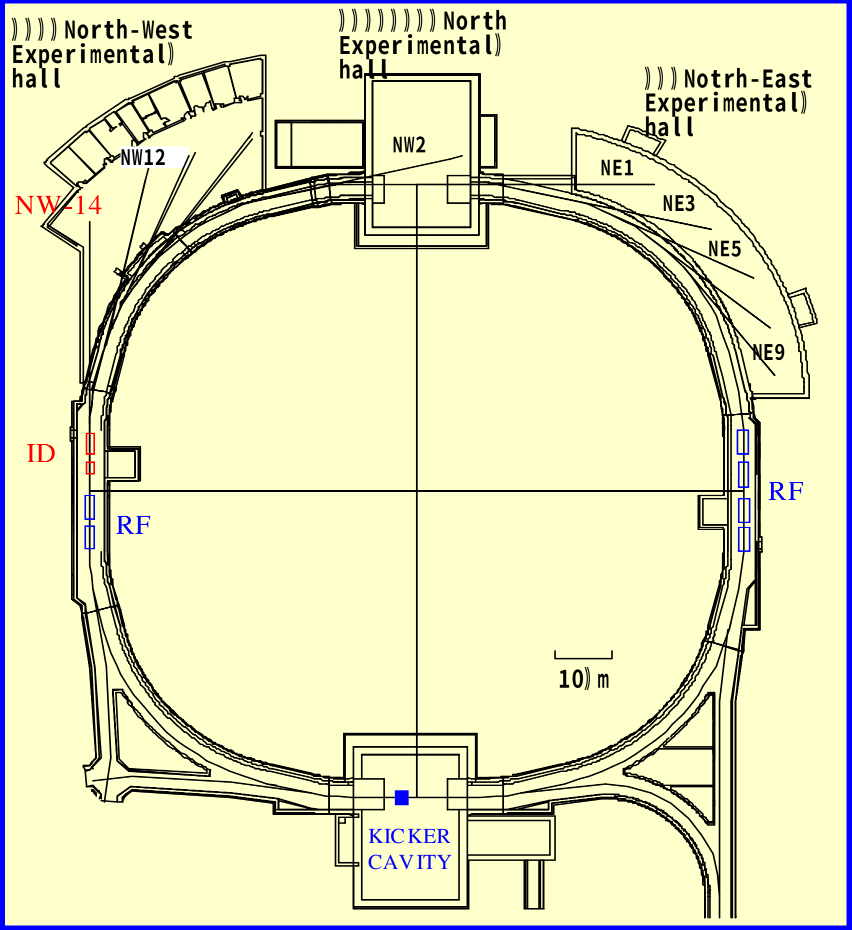
$\sigma_z = 17$ mm

$f_{rf} = 508.57$ MHz

$h = 640$

$\varepsilon_x = 300$ nm·rad

$\varepsilon_y = 0.3$ (3) nm·rad



Kicker cavity

kick strength: 5 μrad (at z = 17 mm)

frequency: 508.57 MHz

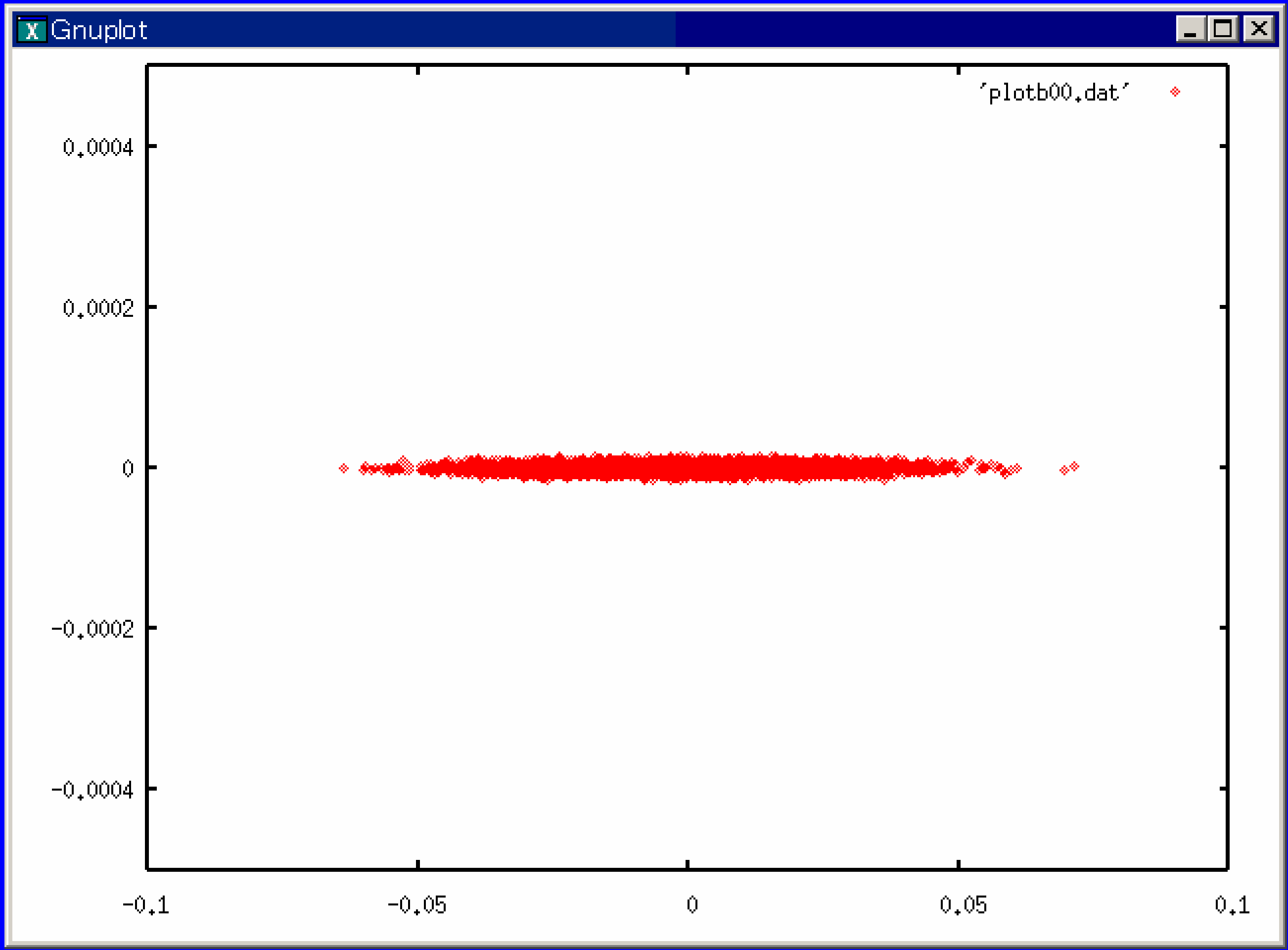
bandwidth: 140 kH

$\beta_y = 16$ m (at kicker cavity)

$= 4$ m (at undulator)

Growth of head-tail oscillation

Deflection: 5 μrad/kick (at σ_z)
XY-coupling: 0.1%
$\Delta\nu_y = 0.125$, $\nu_s = 0.05$



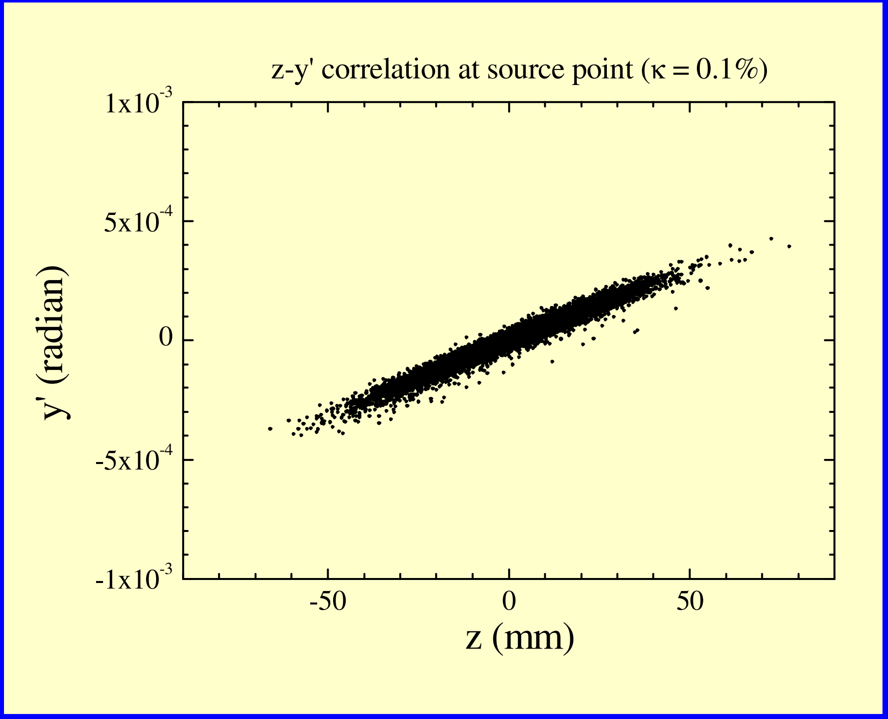
Vertical Slope at the kicker cavity
y' (rad)

Longitudinal position z (m)

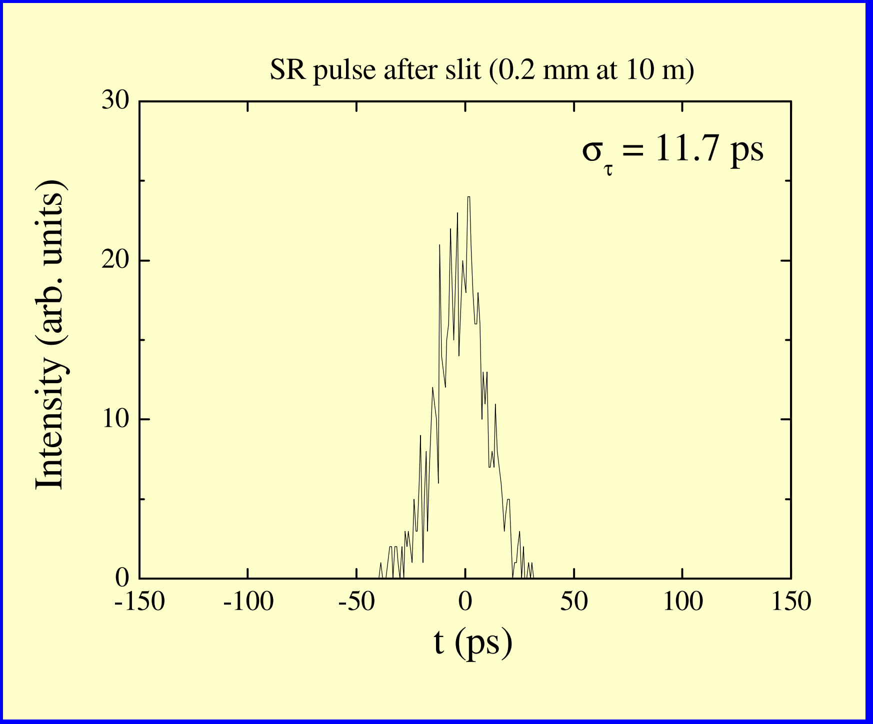
Simulation result

(X-Y coupling 0.1%)

RF deflection: 5 μrad (at $z = \sigma_z$)
β_{cav} = 16 m, β_{source} = 4m



Particle distribution at the undulator (after 41 turns)



X-ray pulse after the slit (width 0.2 mm; 10 m downstream from the undulator)

Summary: head-tail oscillation

- We can introduce y'-z correlation by exciting head-tail oscillations.

--- Benefit

- kicker-cavity is less expensive

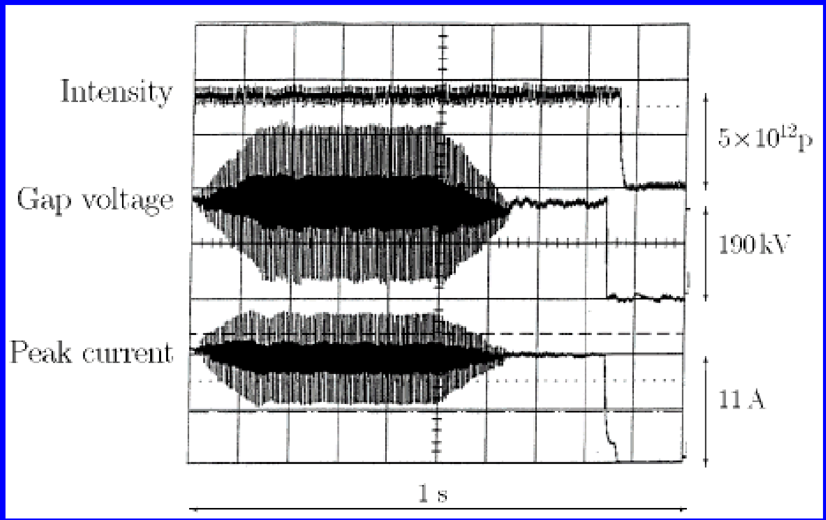
--- Drawbacks

- achievable pulse length cannot be very short at present
- repetition rate : ~ $1/\tau_y$ ~ 400 Hz

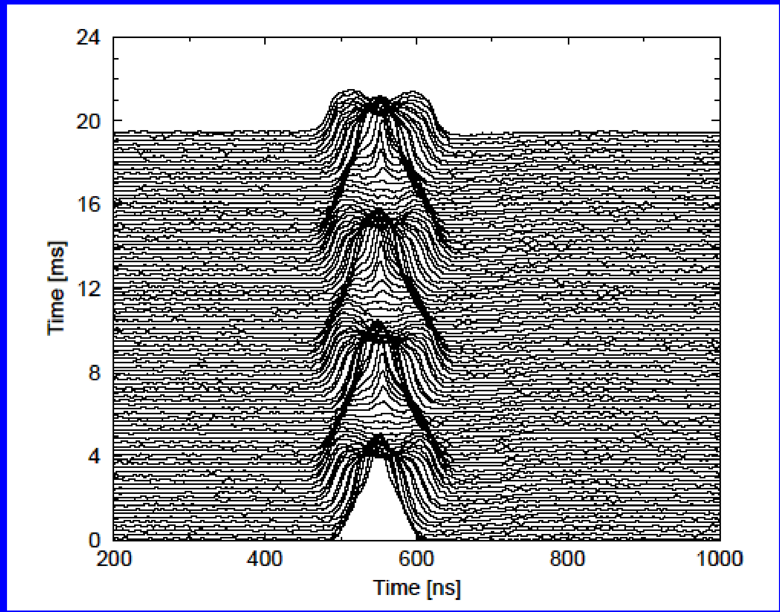
II. Excitation of bunch-shape oscillations

In the Bookhaven AGS, short proton bunches were successfully produced by adiabatic excitation of bunch-shape oscillations, using rf amplitude modulation (at $\omega \sim 2\omega_s$).

M. Bai et al., Phys. Rev. ST Accel. Beams **3** (2000) 064001.



Modulated rf voltage, the beam peak detector signal, and the beam current signal.



Bunch shape oscillation observed with a wall current monitor.

M. Bai et al., *ibid.*

Application to the electron storage ring

Initial idea:

Rise/fall times (T_{rise}) of the rf modulation should meet the requirements.

1) To excite the bunch-shape oscillation "adiabatically",
 the rise time should be much longer than the synchrotron period.

$$T_{\mathrm{rise}} \gg T_{\mathrm{s}}$$

2) To avoid to reach equilibrium distribution, the rise time should be shorter than the radiation-damping time.

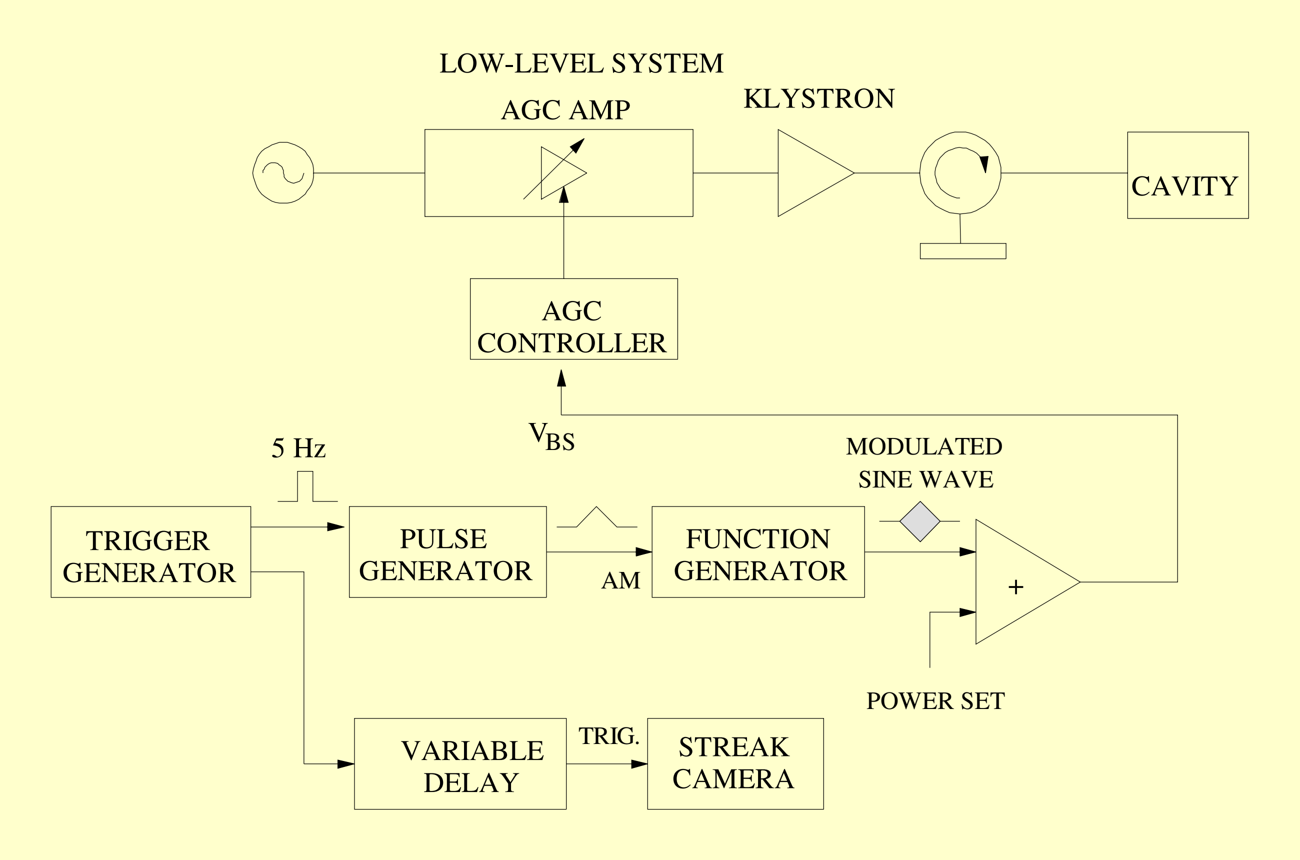
$$T_{\mathrm{rise}} \ll \tau_{\mathrm{rad}}$$

Experiment at the KEK Photon Factory

Beam energy	E	2.5 GeV
Synchrotron frequency	f_s	24 kHz
Longitudinal damping time	τ_z	3.9 ms
RF voltage	V_c	1.7 MV

Natural bunch length (rms): 33 ps

The rise time was chosen to be about 1.2 ms.

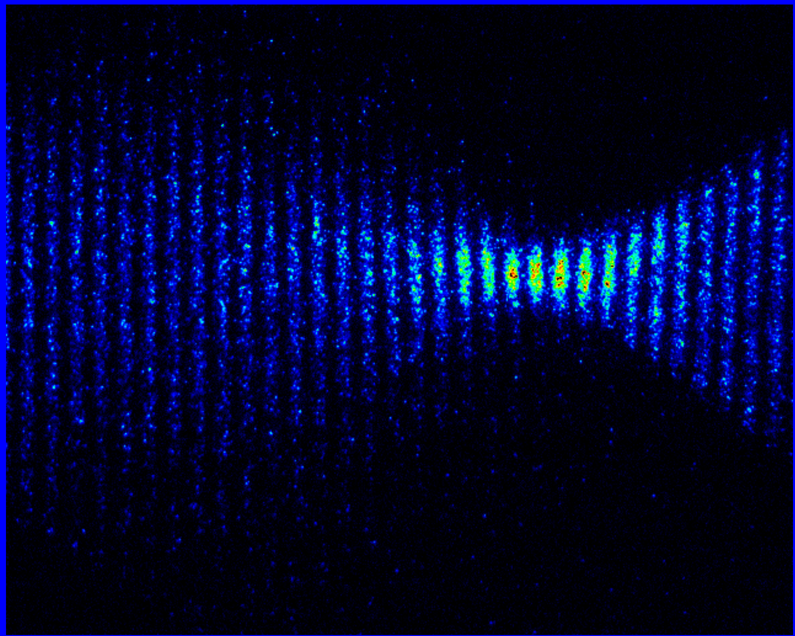


Setup for exciting bunch-shape oscillations.

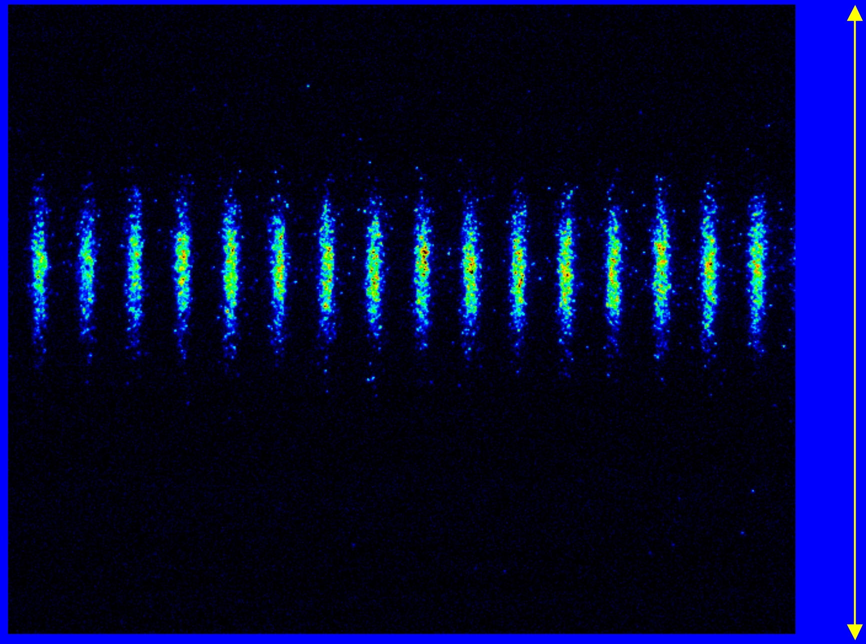
RF amplidudes of two rf stations (among four) were modulated.

Modulation frequency: 45.5 kHz (~ 2×f_s).

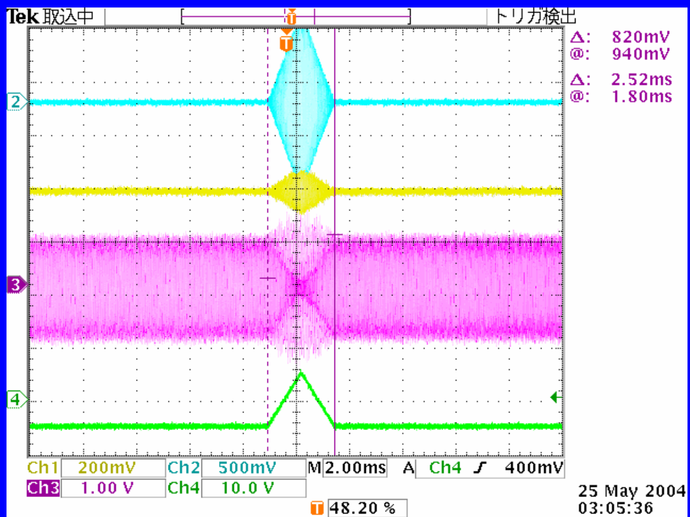
Observed bunch-shape oscillation with a streak camera



With rf modulation. 1.1 mA, singlebunch.



Without any modulations.



Signals of rf-modulation:

Ch2 (blue): modulation signal (45.5 kHz)

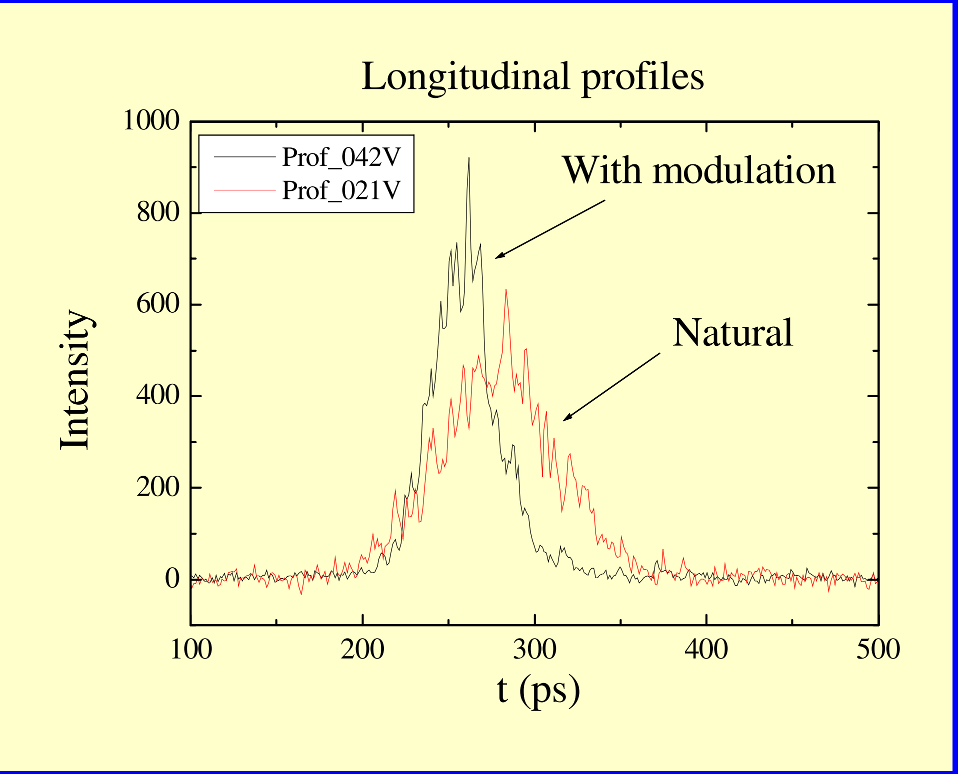
Ch1 (yellow): input to AGC controller.

Ch3 (red): Output rf signal from klystron
(station No. 4)

Ch4 (green): gate signal for the modulation.

(Abscissa: 2 ms/div.)

Longitudinal bunch profiles

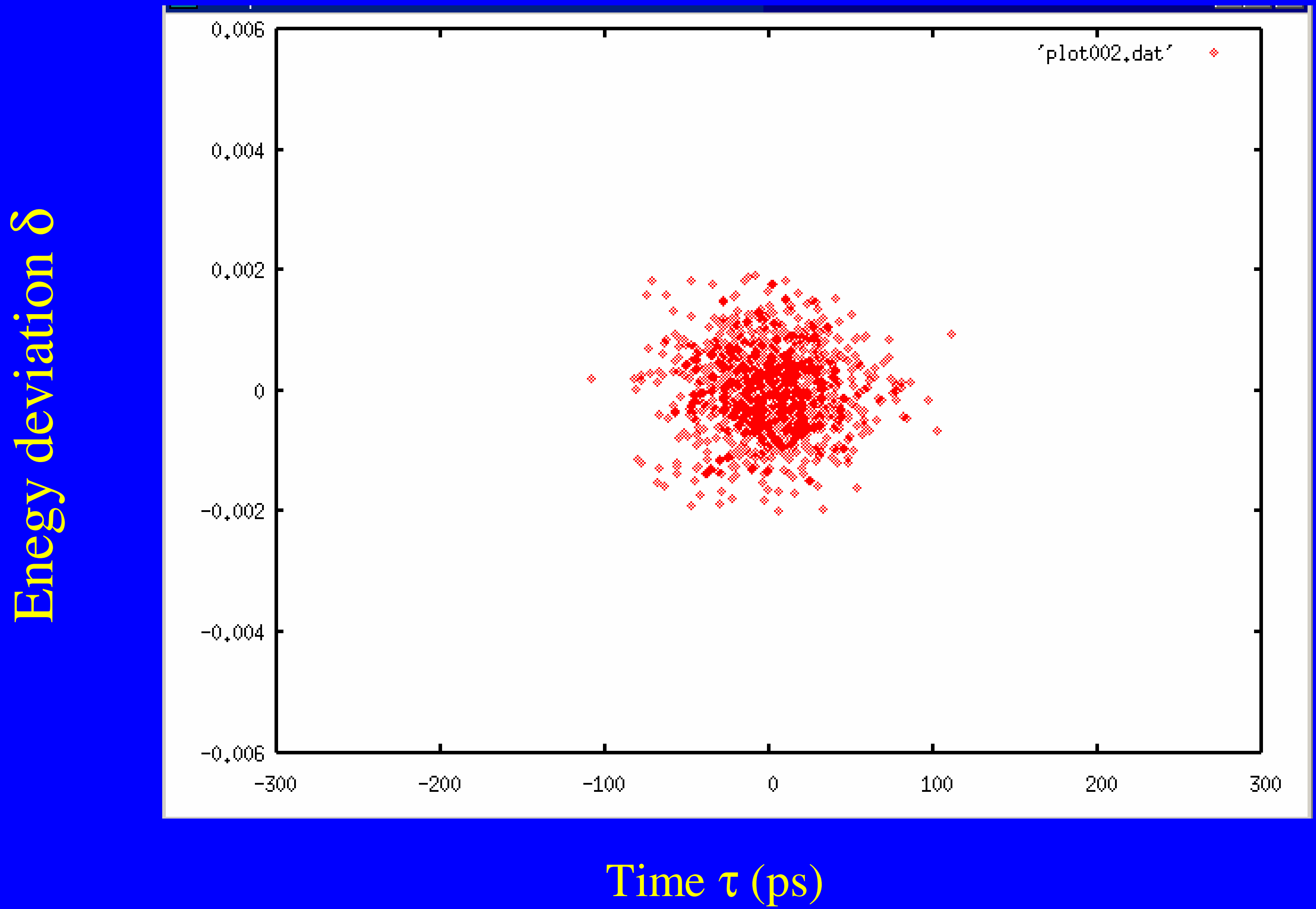


Natural: σ_τ ~ 33 ps

With modulation: σ_τ ~18 ps

At the shortest timing, the bunch length of ~18 ps (55% of natural bunch length) was obtained.

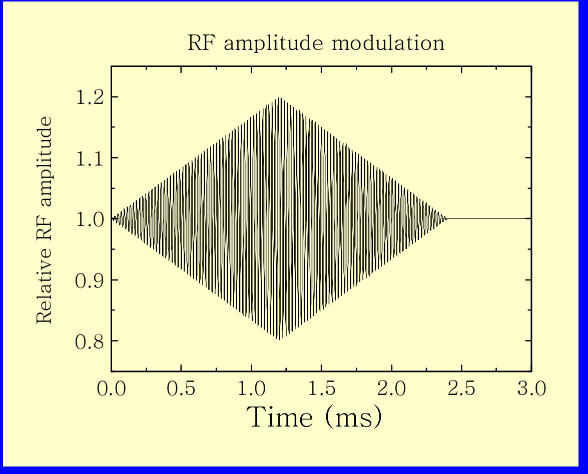
Growth of the bunch-shape oscillation (simulation)

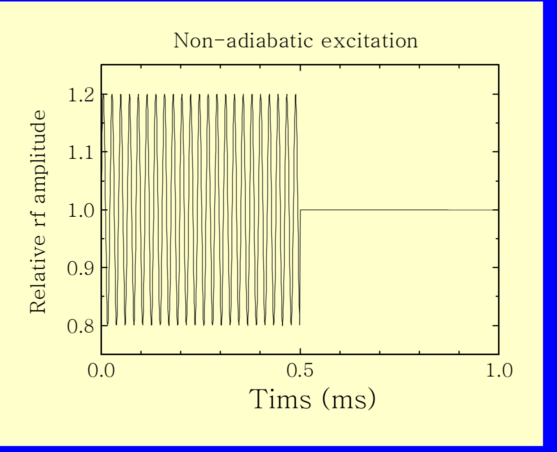


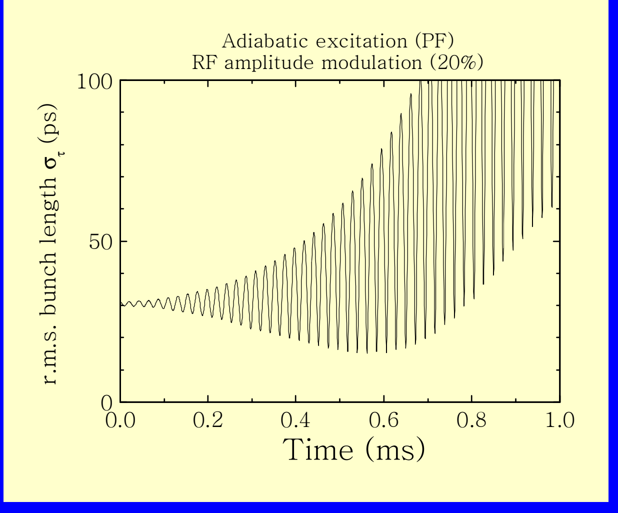
Longitudinal distributions at evey synchrotron period (from 26 to 5000 turns with a step of 70 turns).

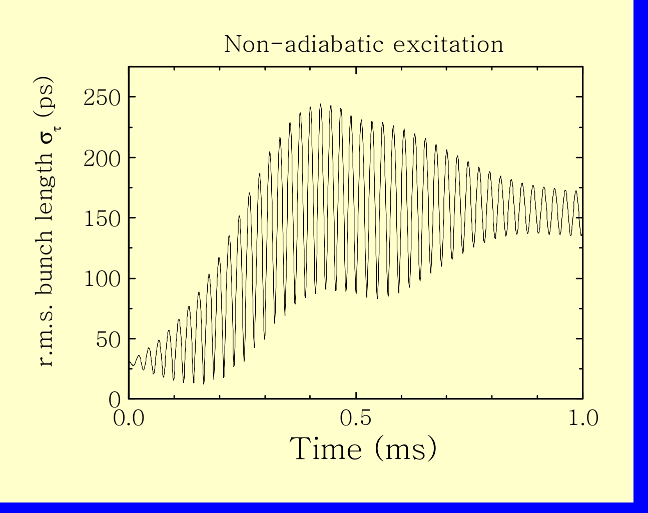
Simulations

Step-like rf modulation gives shorter bunches.









Shortest bunch length: 15.4 ps
(after 0.54 ms)

(rf modulation: 20 %)

Shortest bunch length: 12.3 ps
(after 0.54 ms)

Simulations suggested that ...

- Even when the rf modulation is applied slowly, the evolution of bunch-shape oscillation is not reversible.

  Proton beams: $\phi_s = \pi/2$

  $\rightarrow$ rf-amplitude modulation gives only gradient modulation

  Electron beams: $\phi_s \neq \pi/2$

  $\rightarrow$ rf-amplitude modulation gives both gradient and voltage modulations

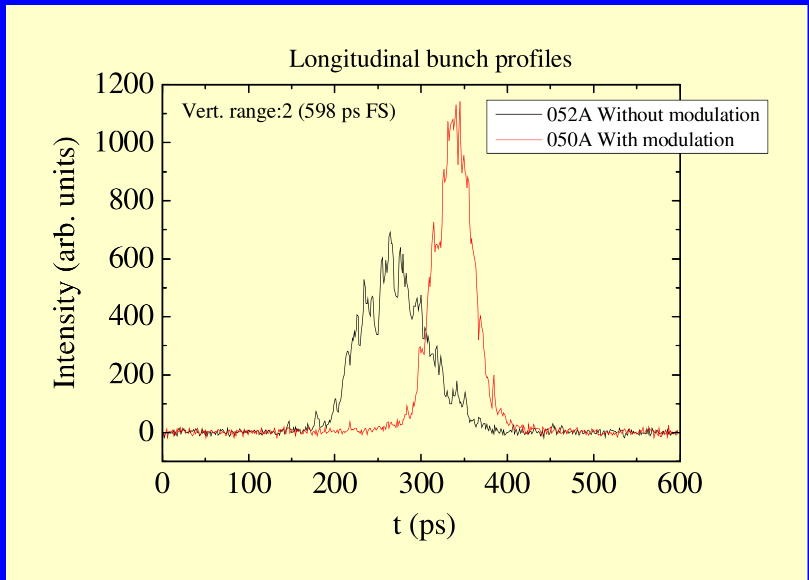
- Slow rise of the modulation is not essential for obtaining short bunch. Rather, step-like excitation is better.

Experiment at the Photon Factory

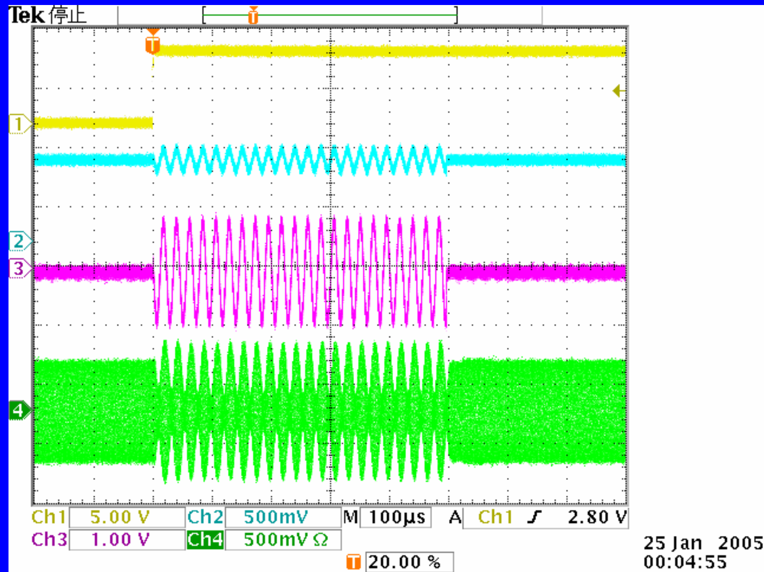
Step-like rf modulation

Minimum bunch length: 16 ps

Without modulation: 36 ps



Comparison of the longitudinal bunch shapes with/without rf modulation.



Signals of rf modulation.
ch1: trigger, ch3: rf modulation, ch4 klystron output signal.

Summary: bunch-shape oscillations

- By exciting bunch-shape oscillations, the bunch length could be shortened by a factor of about 50 %.

- This technique will be useful in some applications.

  -- combination with low-α optics (further shorter bunch), production of coherent THz radiation.