OBSERVATION OF TRANSVERSE-LONGITUDINAL COUPLING EFFECT AT UVSOR-II

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  - Observation of turn-by-turn CSR by Schottky THz diode detector
  - Transverse-longitudinal coupling
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- Summary

Subpicosecond dip structure created by laser bunch slicing

- Beam dynamics of subpicosecond electron bunch is interesting issue in several accelerator applications,
  - Energy recovery linac, ERL
  - Free electron laser, FEL
  - Short bunch electron beam in isochronous or low alpha storage ring
  - Electron-positron collider for high energy physics, such as International linear collider (ILC) etc.

- How to observe a behavior of such a short electron bunch in the second generation storage ring?

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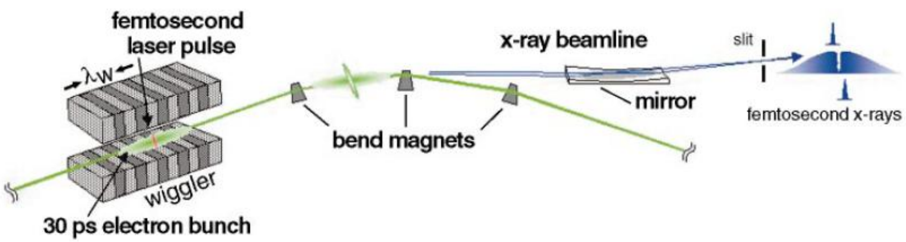
Laser bunch slicing



R. W. Schoenlein *et al*, Science. **287**, (2000) 2237.

We assumed

Behavior of dip structure

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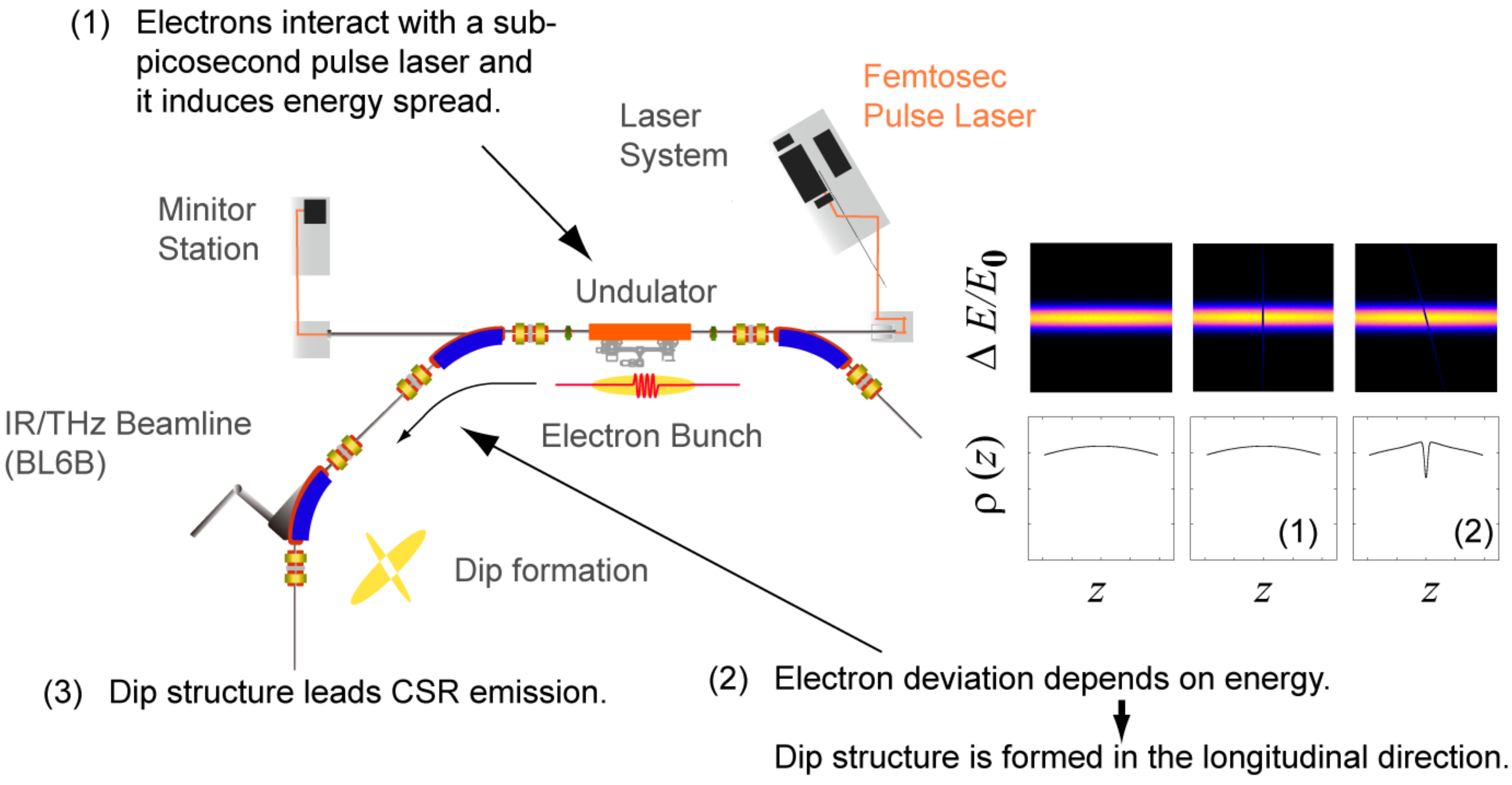
Behavior of sub-picosecond electron bunch

Laser bunch slicing at UVSOR-II

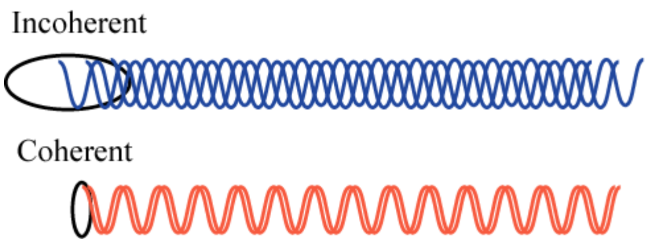


Coherent synchrotron radiation (CSR)

- First observation of CSR is reported at Tohoku university, on 300-MeV linac.

T. Nakazato *et al*, Phys. Rev. Lett. **63**, (1989) 1245

- Synchrotron radiation becomes coherent at wavelength longer than the bunch length.
- Radiation intensity has a quadratic dependency on the number of electron in a bunch.



$$P(k) = Np(k)$$

$$P(k) = N^2 p(k)$$

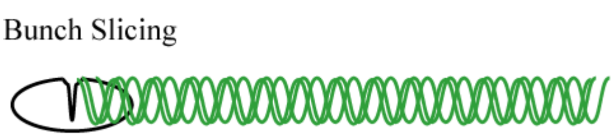
$P(k)$: Total radiation power

N : Number of electron in a bunch

$p(k)$: Radiation power per electron

Typical electron bunch contains 10^9-10^{10} electrons.

- A dip structure on an electron bunch, which is created by the technique of 'laser bunch slicing' , also emits CSR.



Total radiation power $P(k)$

Incoherent Coherent

$$P(k) = Np(k) + F(k)N(N-1)p(k)$$

J.S. Nodvick and D. S. Saxon, Phys. Rev. 96, (1954) 180.

$F(k)$: Form factor

Fraction of coherent synchrotron radiation

$$F(k) = \left| \int \rho(z) e^{ikz} dz \right|^2$$

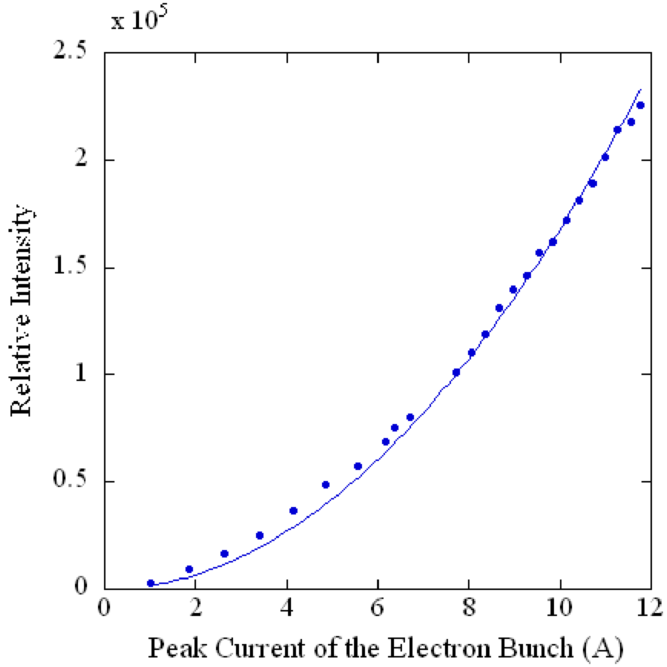
$\rho(z)$: Longitudinal electron density distribution

Dip structure with subpicosecond scale on the electron bunch can be measured via CSR spectrum at THz range

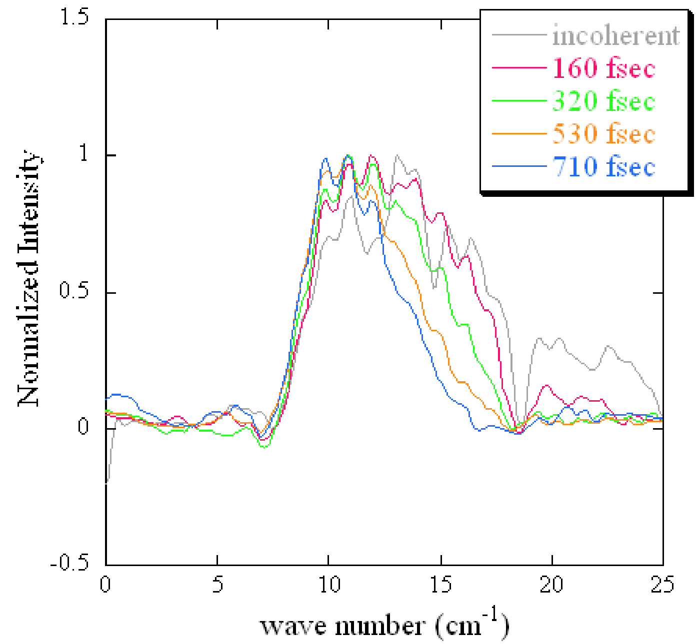
Experimental results at UVSOR-II

- First observation of laser bunch slicing at UVSOR-II

M.Shimada *et al*, Jpn. J. Appl. Phys. **46**, (2007) 7939.



Quadratic dependency on electron beam current

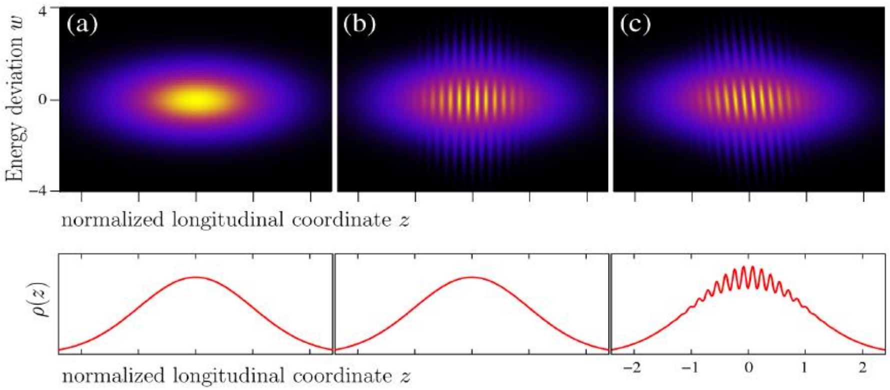


CSR spectra vs. laser pulse duration

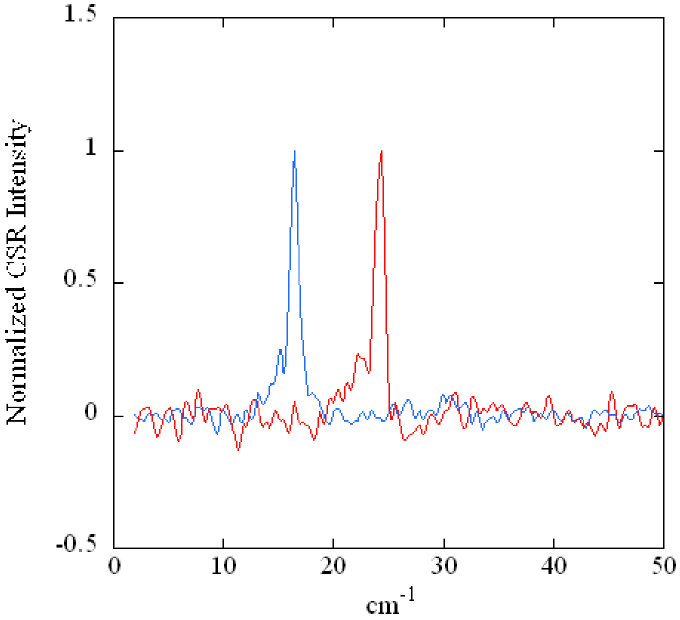
Experimental results at UVSOR-II

- Tunable quasi-monochromatic CSR by sinusoidal modulated laser pulse

S.Bielawski *et al*, Nature Phys. **4**,(2008) 390.

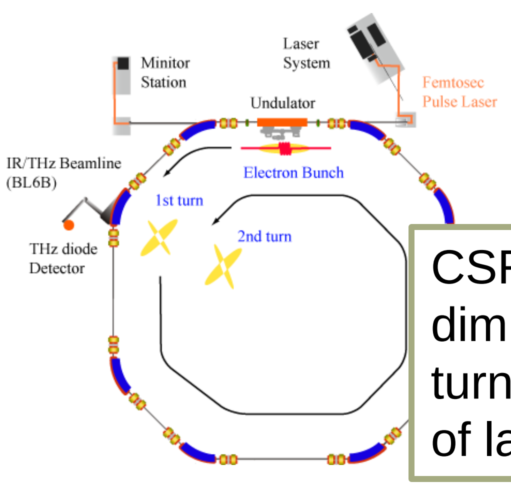


Longitudinal phase space and distribution of electron bunch



CSR spectra vs. frequency of pulse modulation

Evolution of the dip structure in low alpha operation mode



CSR signal strongly diminishes after a few turns at UVSOR because of large $\alpha_c = 0.028$.

Momentum compaction factor, α_c $\qquad \frac{\Delta L}{L} = \alpha_c \frac{\Delta E}{E}$

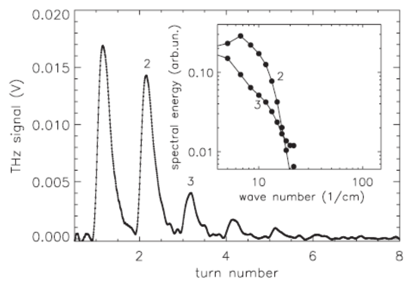
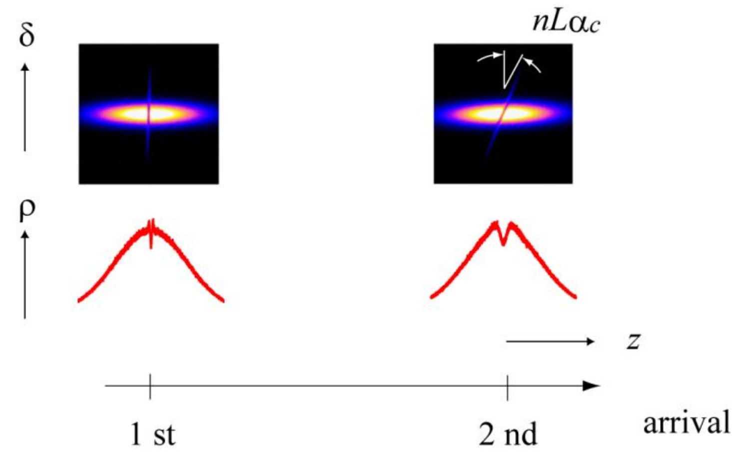


FIG. 3. THz radiation signal as measured over 8 storage ring turns using an InSb detector operated at 10 K and spectra from the 2nd and 3rd turn, respectively. The full spectrum from the first turn is not accessible by this detector type.

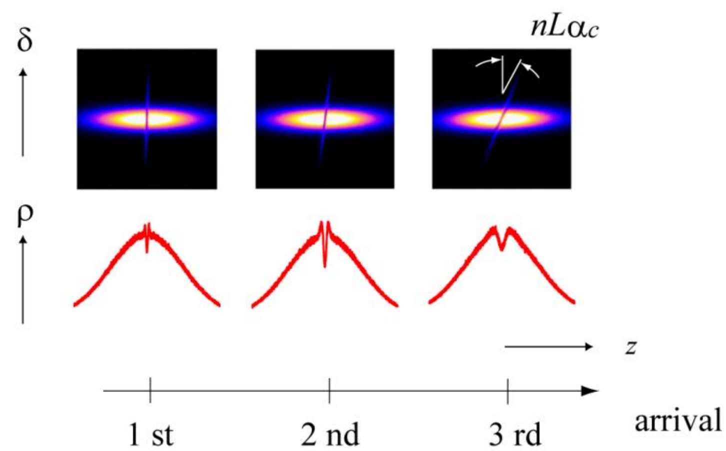
Turn-by-turn CSR measured at BESSY

K. Holldack *et al*, Phys. Rev. Lett. **96**, (2006) 054801

- Normal Optics (α_c=0.028)



- Low Alpha Optics



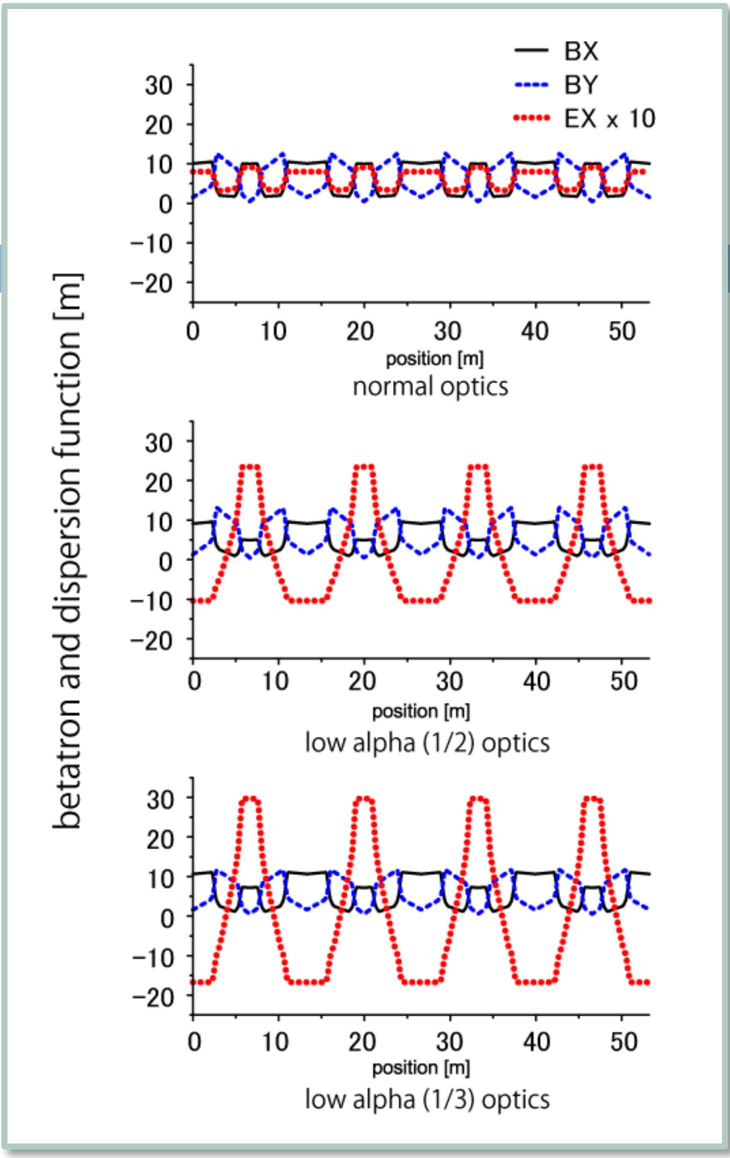
To maintain a dip structure during a long time, we use low alpha optics operation.

Low alpha optics of UVSOR-II

TABLE I: Main parameters of a normal and two low-alpha optics.

	Normal	low α_C (1/2)	low α_C (1/3)
α_C	0.028	0.00615	0.00471
ν_x	3.75	3.53	3.68
ε_x [μm-mrad]	15.6	139.2	176.8
η_x [m] [a]	0.800	-1.038	-1.671
η_x [m] [b]	0.248	0.430	0.560

[a] η_x is a dispersion function at the center of the undulator
[b] η_x is a dispersion function at the detector



- Two betatron tune ν_x
  - low α_c (1/2) : ν_x is around a half integer
  - low α_c (1/3) : ν_x is around a 1/3 of integer

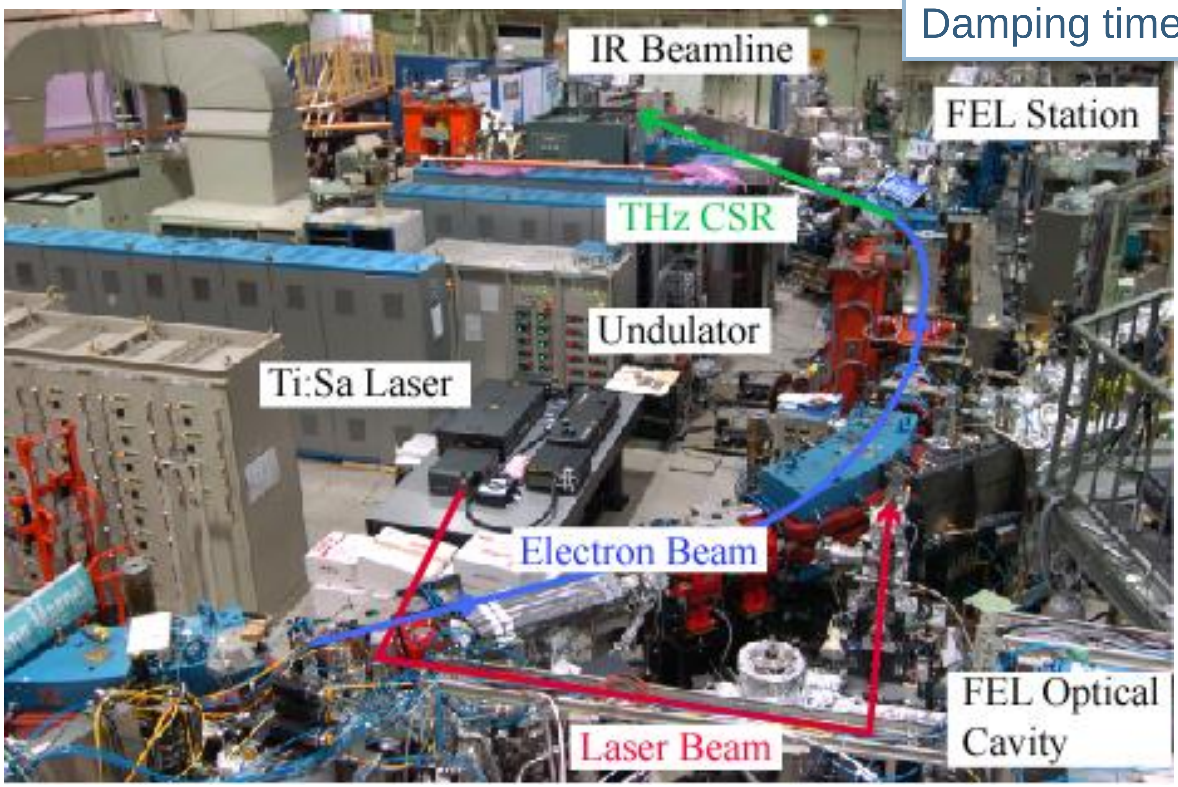
At low alpha optics,

- Vibration amplitude of dispersion function is larger,
- Transverse emittance ε_x is larger,

than that of normal optics.

Main parameter of UVSOR-II for laser bunch slicing

Electron Energy	600 MeV
Circumference	53.2 m
Undulater Length	2.31 m
Natural Emittance	17.4 nm-rad
Natural Energy Spread	3.4×10^{-4}
Natural Bunch Length	3.1 cm (~100psec)
RF Frequency	90.1 MHz
Revolution Frequency	14.4 kHz
Damping time	19 msec

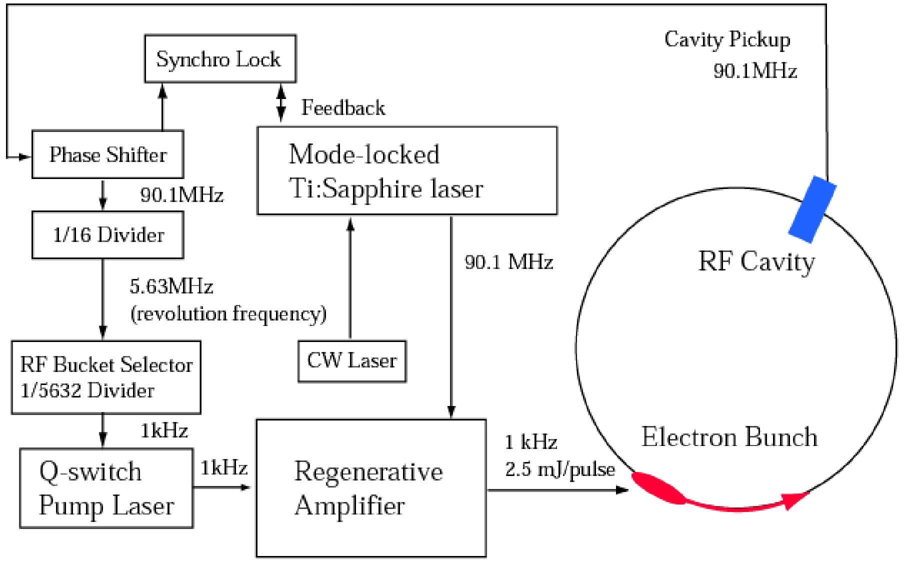


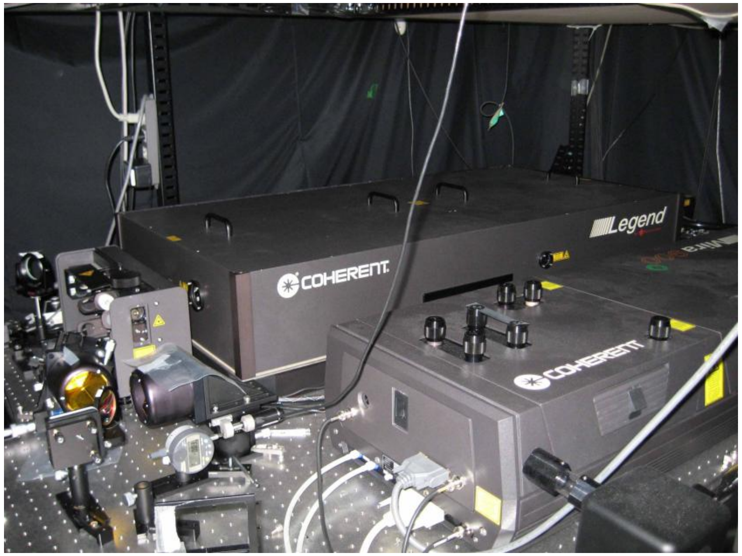
Titanium Sapphire femto-second laser and synchronization system

Laser parameters

Pulse Energy	2.5 mJ/pulse
Pulse Width	130 fs ~ 2 ps
Rep. Rate	1 kHz
(synchronized with 90.1 MHz)	
Wavelength	790 - 810 nm

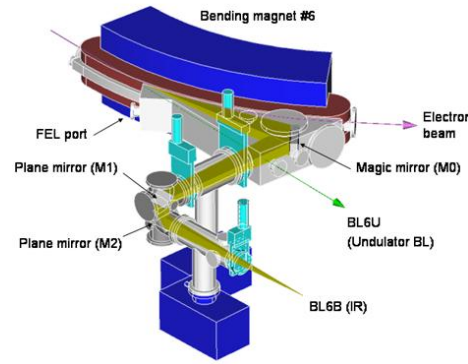
Synchronization system

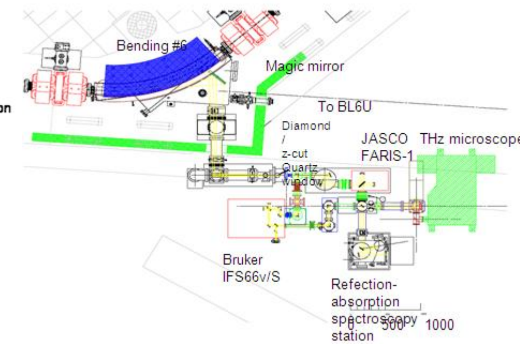




Schottky THz diode detector and beamline BL6B

- Schottky THz diode detector
  - Response time is a few 100 ps
  - Limited bandwidth
  - Operation at room temperature
  - Susceptibility to static electricity





- Beamline for infrared and THz region, BL6B
  - Magic mirror
    - large acceptance angle 215 x 80 [$mrad^2$]
    - Summation of optical path length and electron orbital length is the same for each position

	Frequency range	Mean value of responsivity
VDI ZBD2.2	$11cm^{-1}$~$16.6cm^{-1}$	2000 V/W
VDI ZBD3.4	$7.3cm^{-1}$~$11cm^{-1}$	2500 V/W
Millitech DXP-06	$3.7cm^{-1}$~$5.7cm^{-1}$	23.5 dBi

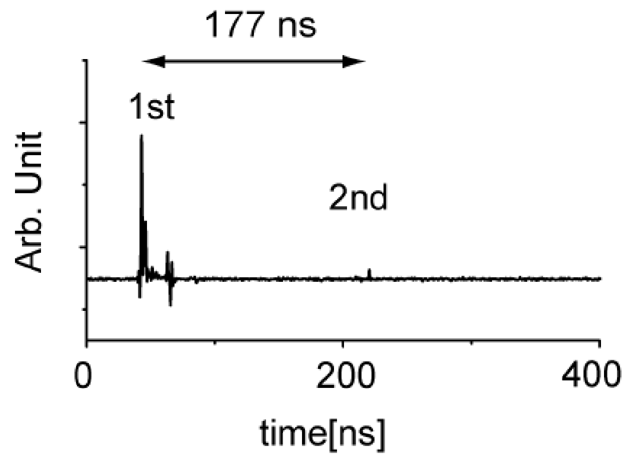
CSR: normal optics versus of low alpha optics

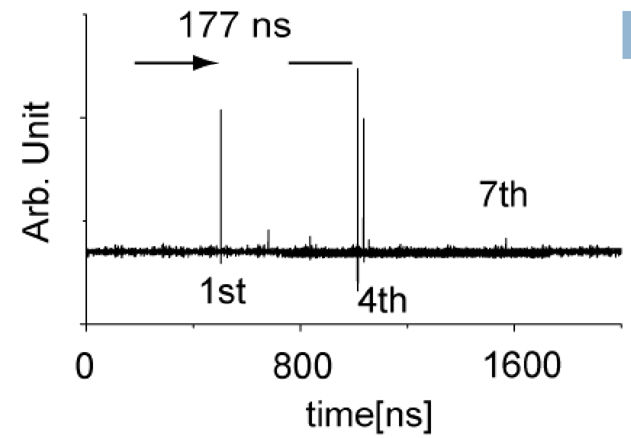
Frequency range

7.3 ~ 11.0 cm^{-1}

Revolution time

177 ns





Momentum Compaction Factor, αc
Betatron tune, νx

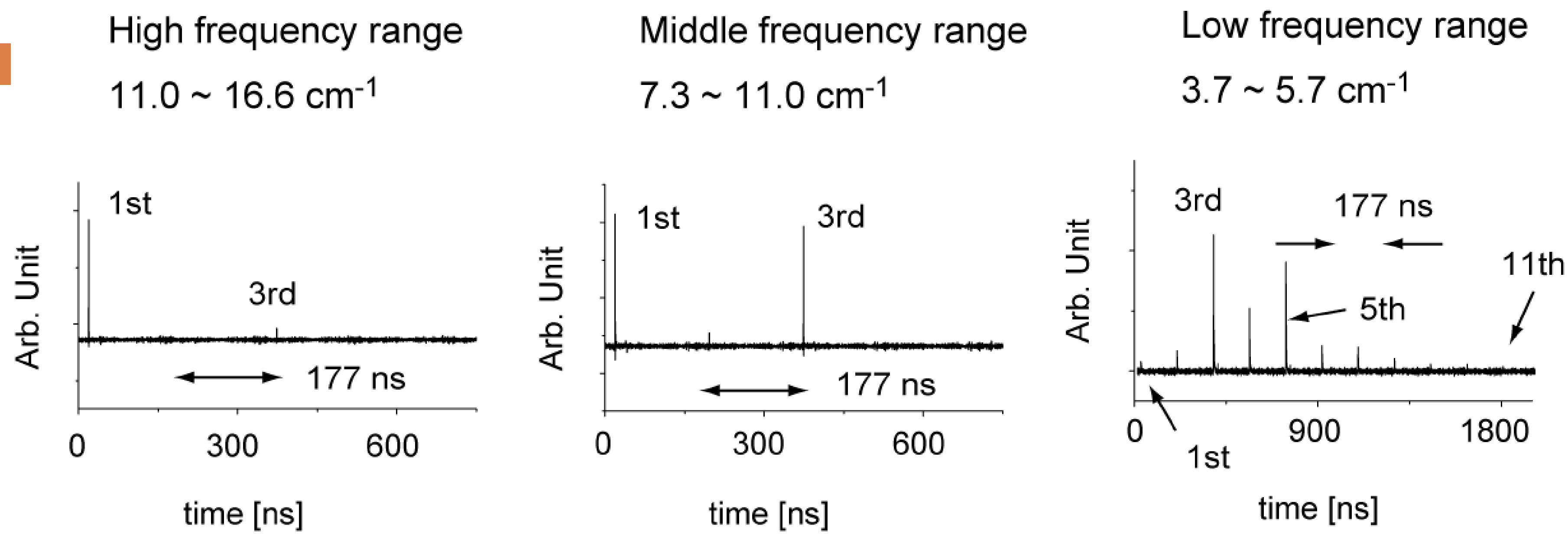
Normal Optics
αc : 0.028
νx : 3.75

Low Alpha Optics
αc : 0.0047
νx : 3.68

- Normal optics : Only two CSR signals are observed.
- Low alpha optics : CSR signal is observed up to 7 th arrival.
  - 1 st and 4 th CSR signal is stronger than others.
  - 7 th CSR signal is stronger than 5 th and 6 th ones.

Intense CSR is observed every three turns.
Is it linked to the fact that νx is close to 1/3 of integer ?

Low alpha optics with ν_x around a half integer



Low Alpha Optics

αc : 0.0061

νx : 3.53

- Arrival time of strong CSR signal depends on frequency range.
- Strong CSR signal is observed at every two turns because ν_x is around a half integer.

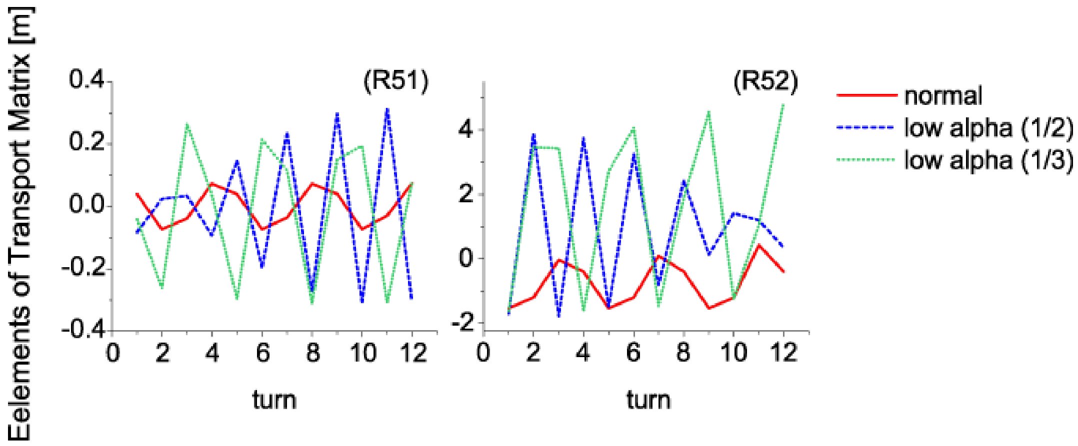
Temporal evolution seems linked to betatron tune.

Transverse-longitudinal coupling : theory

- Change in longitudinal position Δz can be described in linear beam dynamics

$$\Delta z = R_{51}x + R_{52}x' + R_{56}(\delta + \Delta\delta)$$

x : horizontal position
x' : derivation of horizontal position
z : longitudinal position
δ : deviation of energy
$\Delta\delta$: change in energy by laser bunch slicing



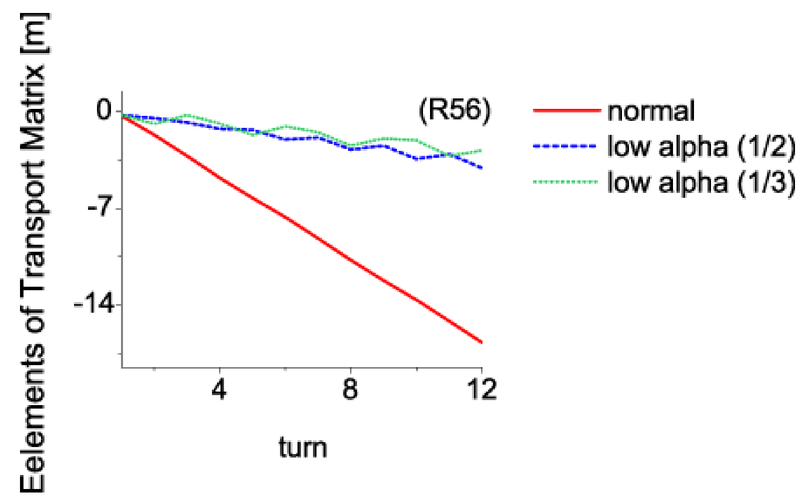
Development of elements transport matrix, (R51, R52)

- **Transverse-longitudinal coupling is significant at low alpha optics at UVSOR-II**
  - Increase in amplitude of oscillation of R_{51} and R_{52}. (Dispersion function η_x)
  - Large values of x and x'. (Large transverse emittance ε_x)

Relationship of R_{56} with α_c

$$\Delta z = R_{51}x + R_{52}x' + R_{56}(\delta + \Delta\delta)$$

Element of turn-by-turn transport matrix, R_{56} oscillates at betatron tune of ν_x.



Development of R56

The element of R_{56} is related to the momentum compaction factor α_c.

$$R_{56}^{rev} = \alpha_c L - [\eta_x R_{51}^{rev} + \eta'_x R_{52}^{rev}]$$

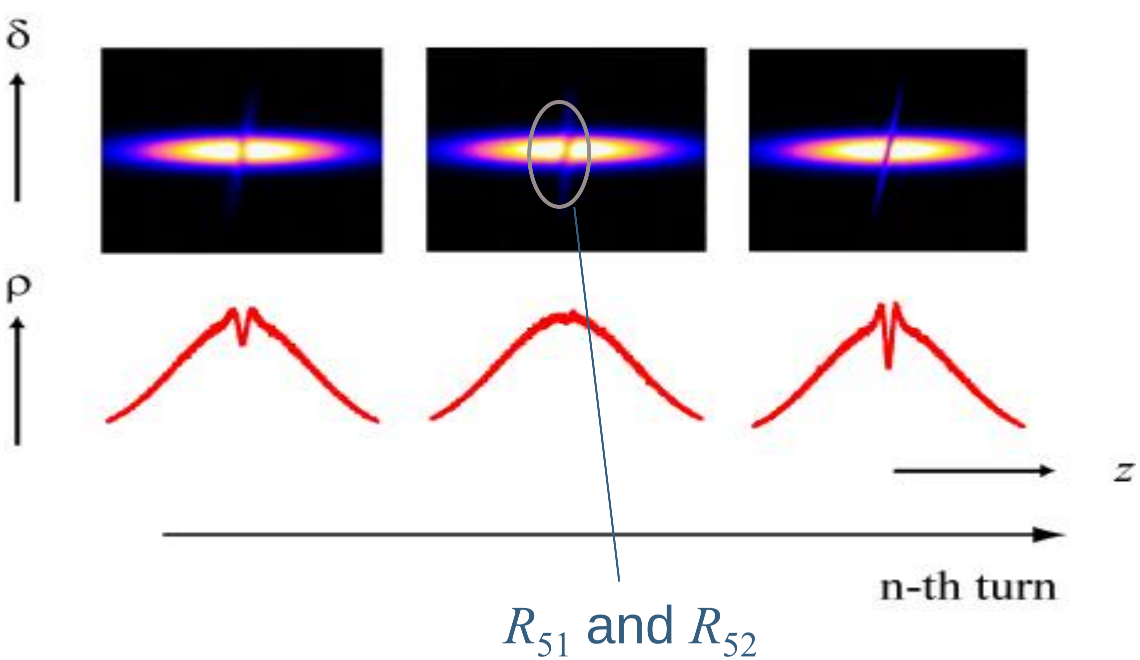
where dispersion function of η_x and η'_x at the start position of the transport matrix.

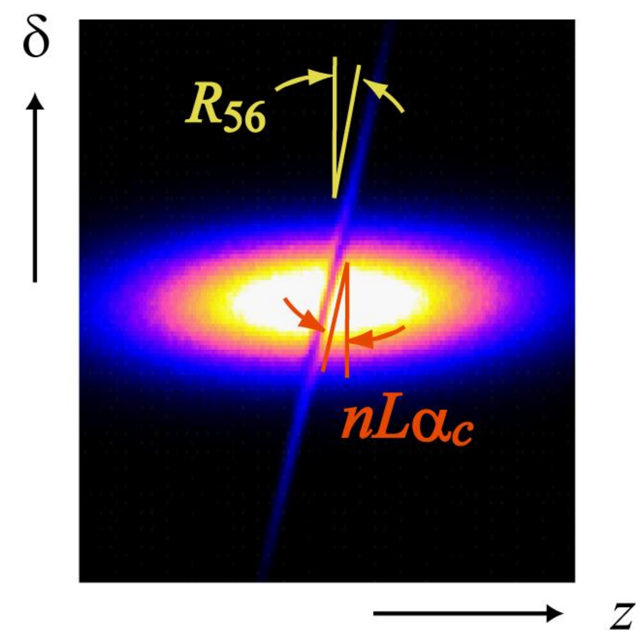
α_c	:	synchrotron oscillation
R_{51}, R_{52}	:	betatron oscillation
R_{56}	:	synchrotron & betatron oscillation

Three elements creating dip structure

1. Low density region is tilted by $nL\alpha_c$ (synchrotron oscillation).
2. Nearby low electron density region oscillates in longitudinal direction at betatron frequency (R_{51} and R_{52}).
3. Fragment oscillates according to R_{56}, which includes both synchrotron and betatron oscillation.

$$R_{56}^{rev} = \alpha_c L - [\eta_x R_{51}^{rev} + \eta_x' R_{52}^{rev}]$$



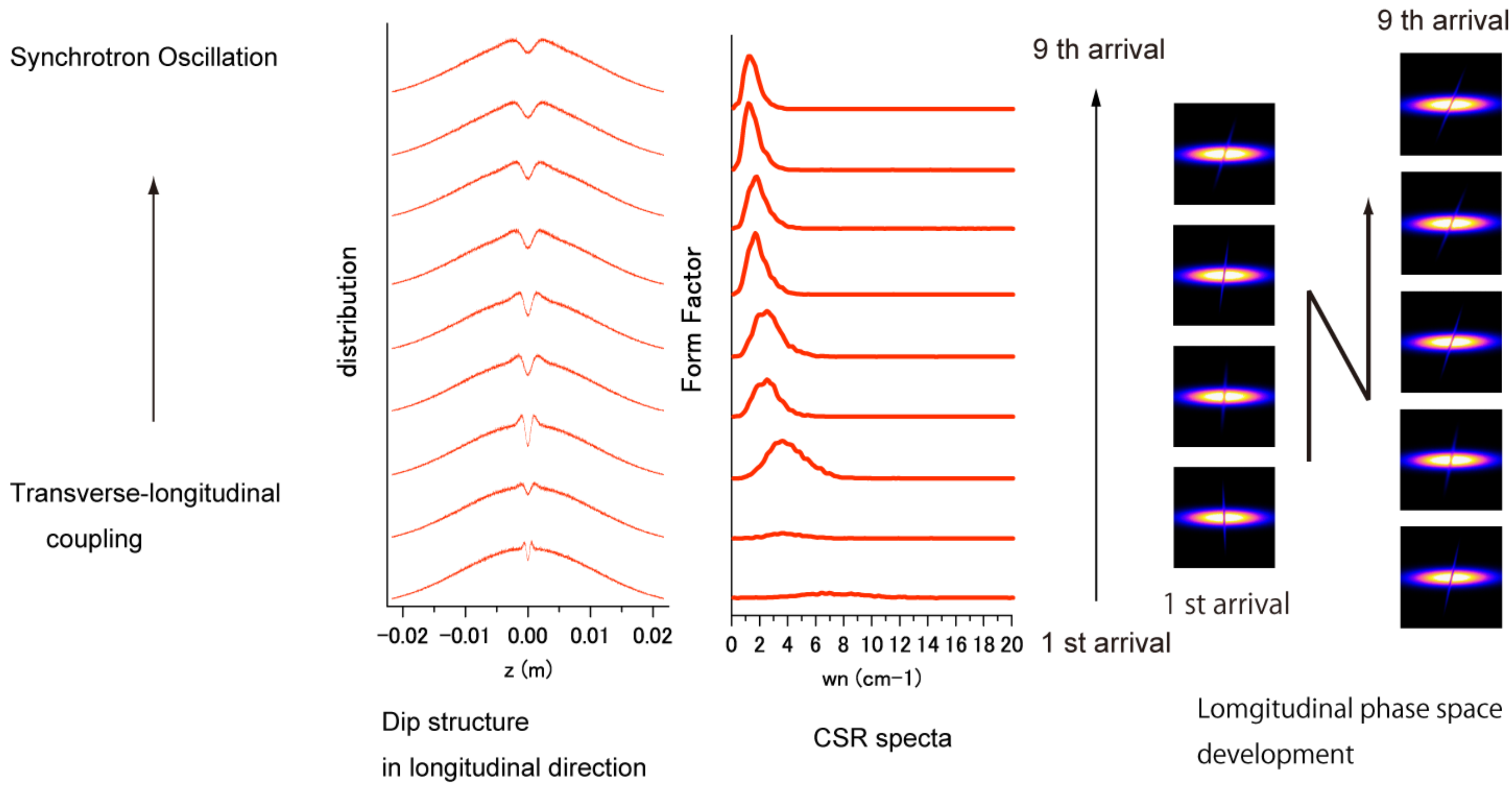


Evolution of longitudinal dip structure

Case of low α_c (1/2) Optics

$$\alpha_c = 0.0061$$

$$\nu_\beta = 3.53$$

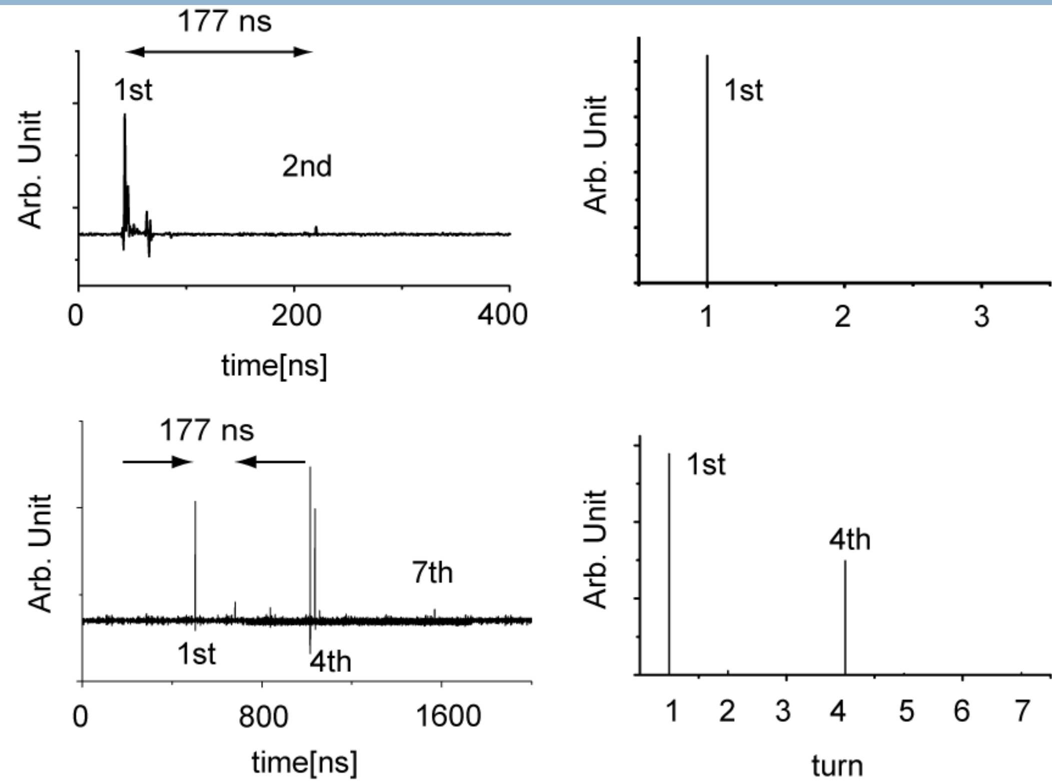


- Sharp dip structure appears every two turns up to fifth arrival.
- As number of turns increases, the dip spreads and its amplitude decreases because of synchrotron oscillation.

Comparison of experimental result with simulation
- Normal optics and low α_c (1/3) optics

Normal Optics
αc : 0.028
νx : 3.75

Low Alpha Optics
αc : 0.0047
νx : 3.68



Frequency range
7.3 ~ 11.0 cm^{-1}

Experimetal results

Simulation results

- Experimental results are in good agreement with theory, which are considered only linear beam dynamics

Comparison of experimental result with simulation - Normal optics and low α_c (1/2) optics

High frequency range

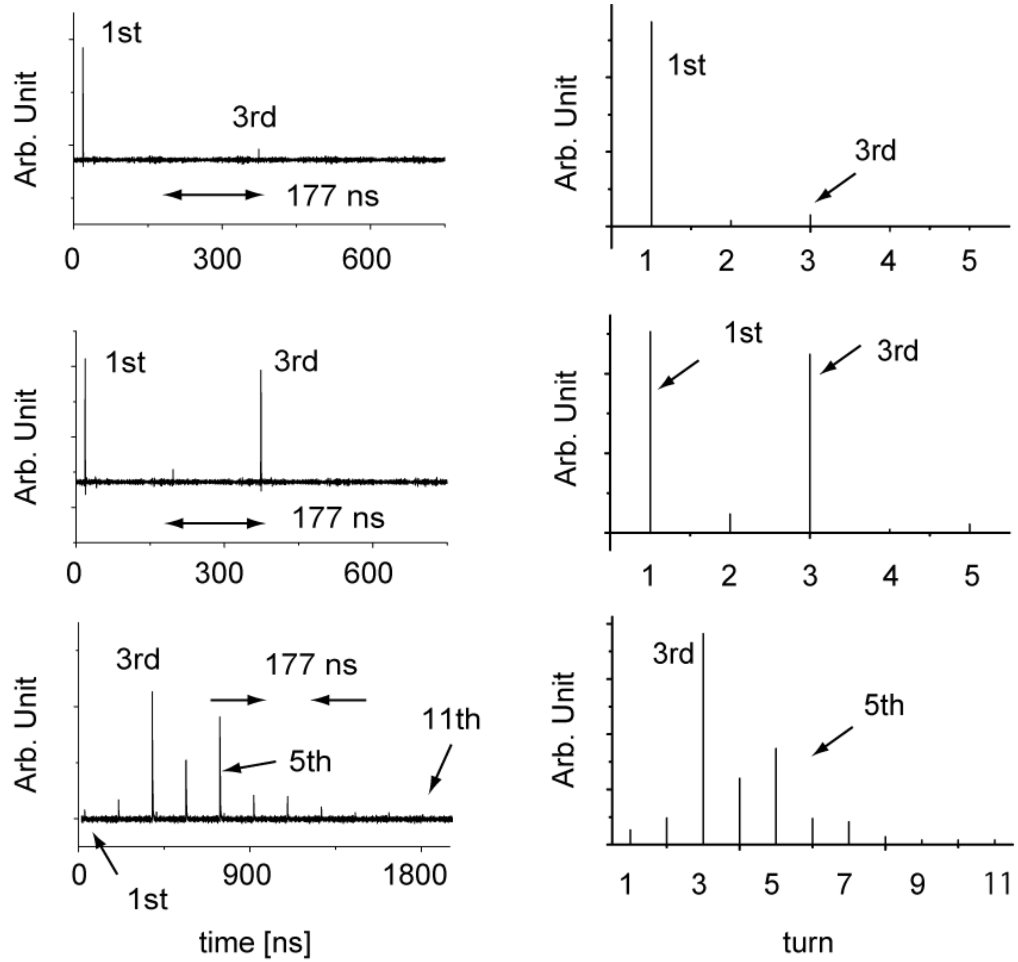
11.0 ~ 16.6 cm^{-1}

Middle frequency range

7.3 ~ 11.0 cm^{-1}

Low frequency range

3.7 ~ 5.7 cm^{-1}



Low Alpha Optics

αc : 0.0061

νx : 3.53

Experimetal results

Simulation results

- Experimental results are in good agreement with theory

Summary

- Schottky THz diode detector enabled us to observe turn-by-turn CSR signals of UVSOR-II, whose revolution time 177 ns.
- With the low α_c optics, CSR signal is observed up to11 th turn. On the other hand, with normal optics, strong CSR signal is observed only during first turn.
- We observed CSR signal depending on the betatron frequency. It clearly indicates the existence of the transverse-longitudinal coupling.
- Intensity of CSR signal is in good agreement with the simulation result considering only linear beam dynamics.
- This experiment also demonstrated that THz CSR signals with several frequency ranges are available for measurement of longitudinal micro-structure.

Acknowledgements

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