WECOYBS06

Demonstration of THz Oscillation via Resonant Coherent Diffraction Radiation

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- Supported by SRF accelerator application team in KEK and cERL collaboration.
- Financially supported by JSPS KAKENHI 16H05991 and 18H03473
- Phys. Rev. Lett. **121,** 184801 (2018), Phys. Rev. Accel. Beams **22,** 04073 (2019)

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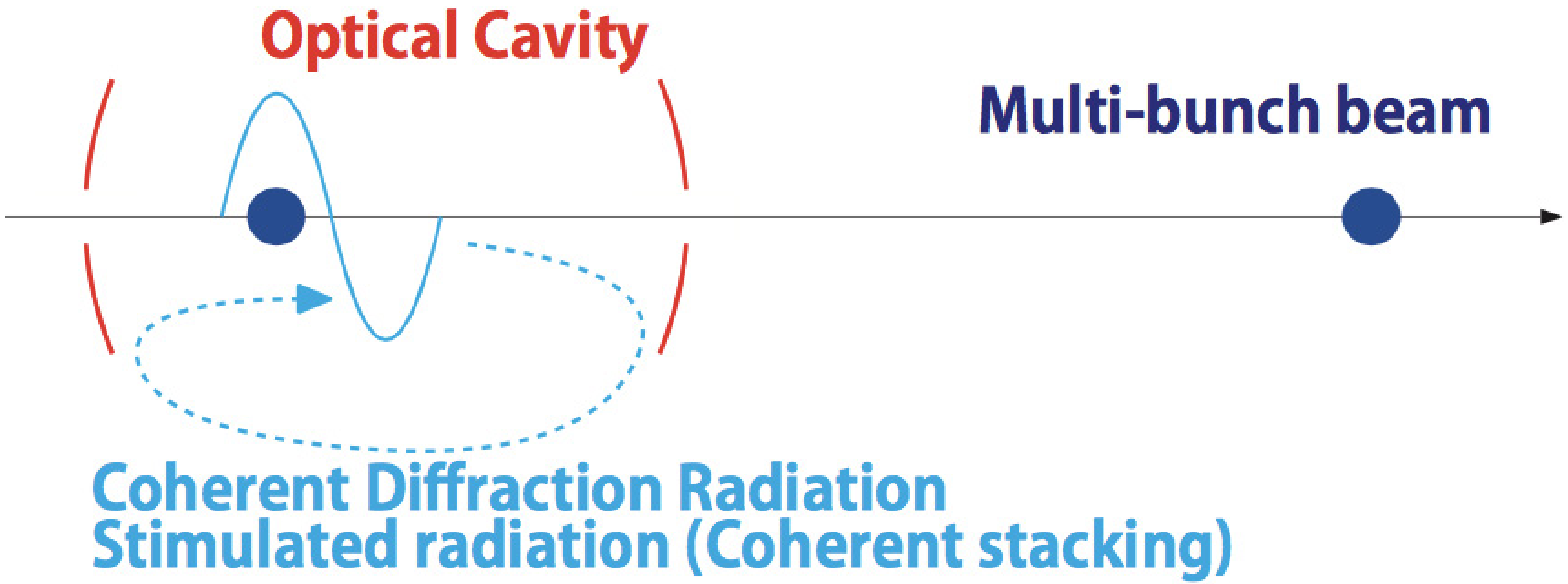
- Purpose
- Principle of stimulated radiation
- Broad-band excitation

Overview



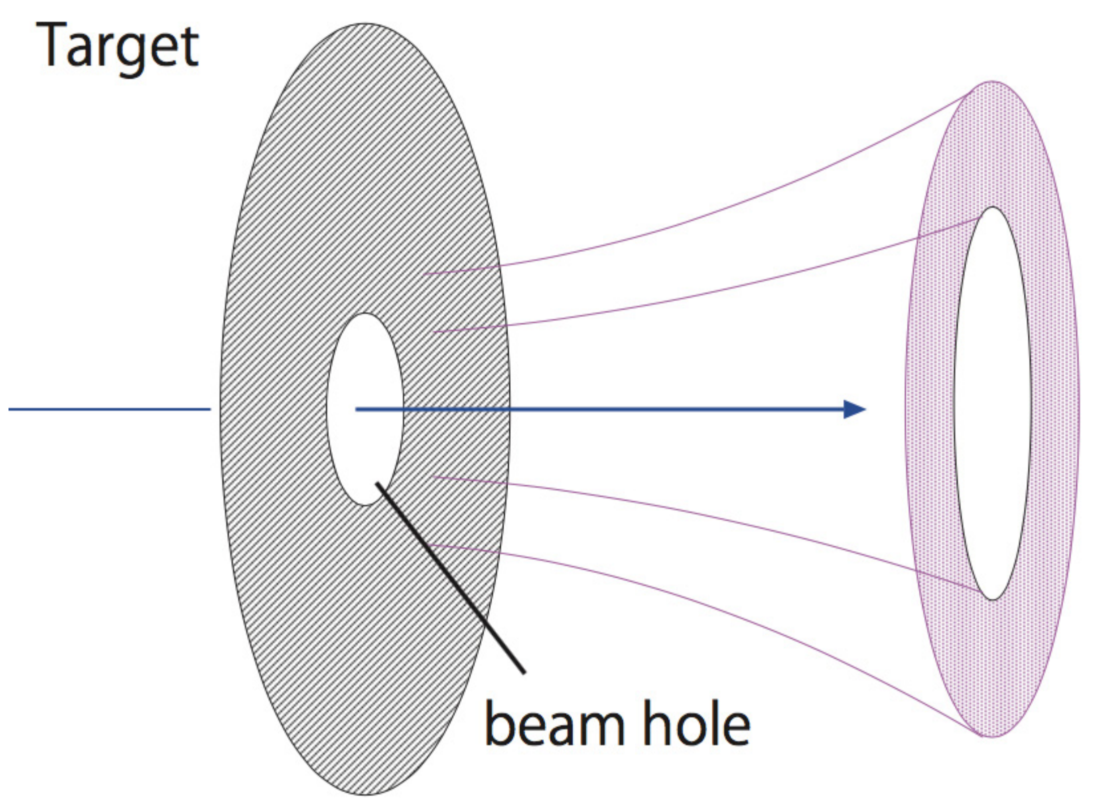
Possible layout only by modern linacs.

- low emittance ⇨ small aperture
- short bunch ⇨ THz coherent radiation
- high rep.rate ⇨ multi-bunch stacking

- What is this?
  - A mode-lock laser pumped by electron beam.
  - A pre-bunch seeded FEL (~1 THz radiation from 1.3 GHz modulation)
  - A broad-band FEL, compact and without an undulator.

Coherent Diffraction Radiation

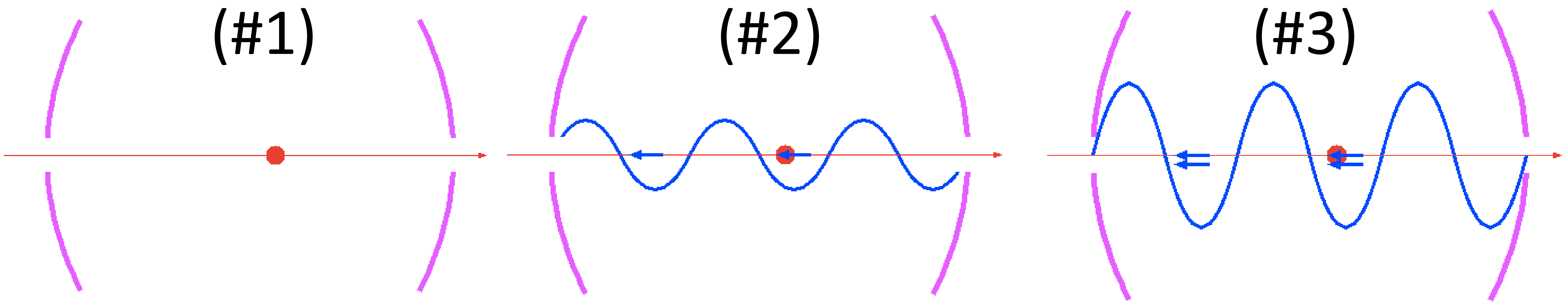
- Beam pass through a small hole on a metal target.
- Radiation is produced at the electromagnetic boundary.
  - Similar as transition radiation, but beam is not destroyed.
  - Coherent radiation if the bunch length < wavelength.



- Characteristics
  - $1/\gamma$ angular distribution
  - Radial polarization
  - Forward and backward direction
  - Flat spectrum (HF cut-off by hole)

Stimulated radiation

- Radiation produced in an optical cavity and by a multi-bunch beam
- Emit radiation in the existing field.
  - Coherent stacking by amplitude addition.
  - Extract more energy (Stimulated).



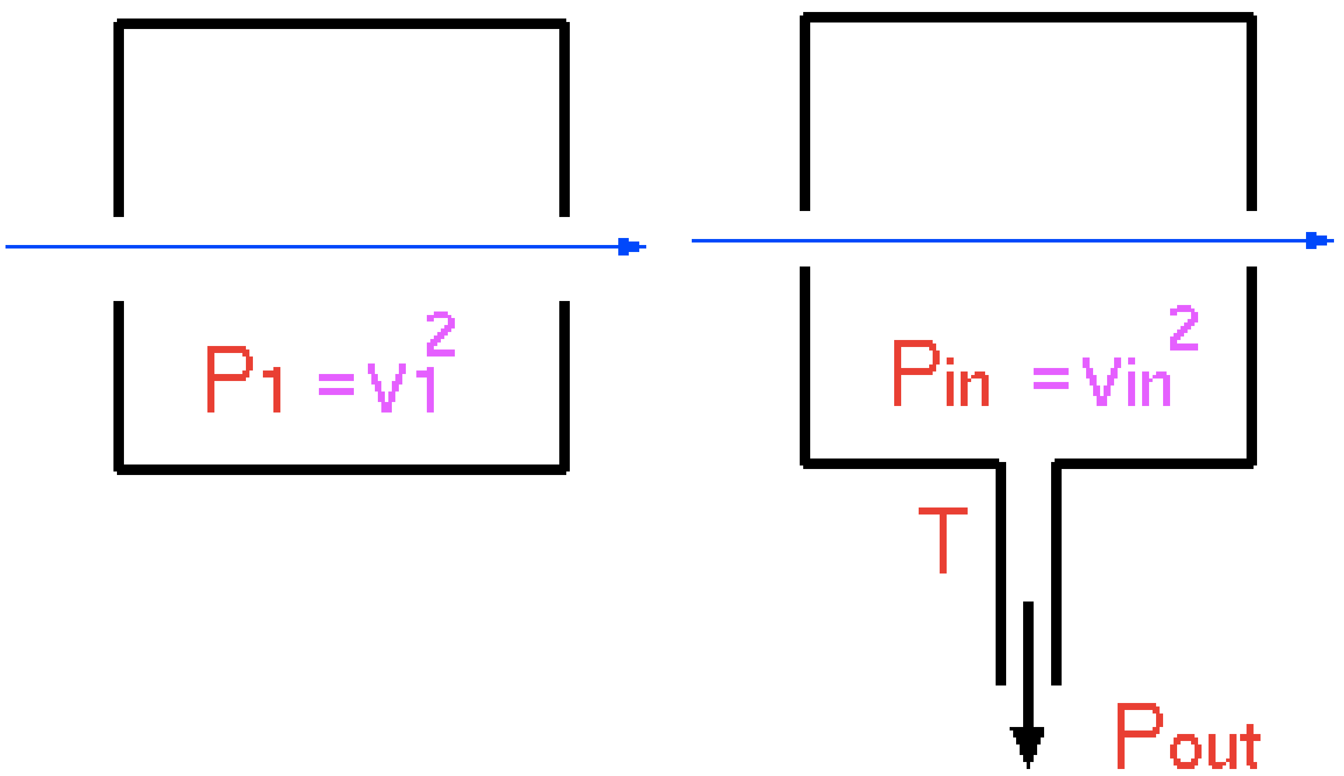
Coherent Stacking

(1) Incoherent stacking (add by Intensity)

$$P_{out} = TP_{in} = T[P_1 + P_1(1-T) + P_1(1-T)^2 + \cdots]$$
$$= P_1$$

(2) Coherent stacking (add by amplitude)

$$P_{out} = TP_{in} = T\left|v_1 + v_1\sqrt{1-T} + v_1(\sqrt{1-T})^2 + \cdots\right|^2$$
$$= \frac{4}{T}P_1$$

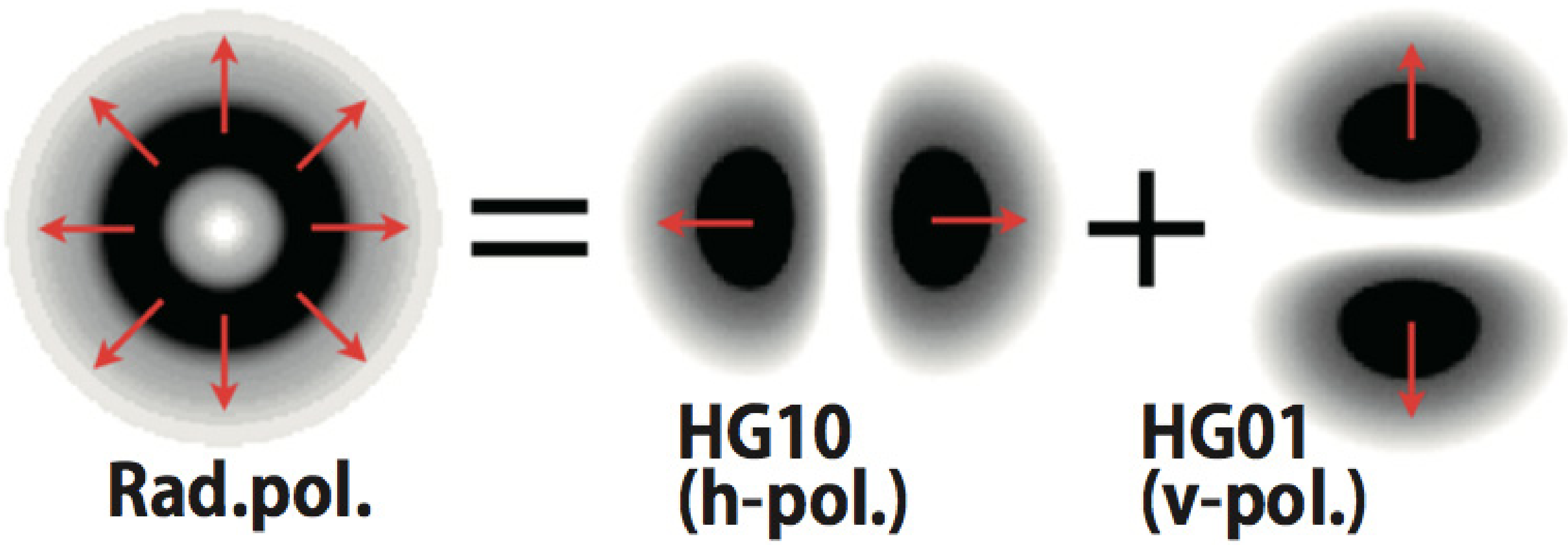


Gain by factor 4/T

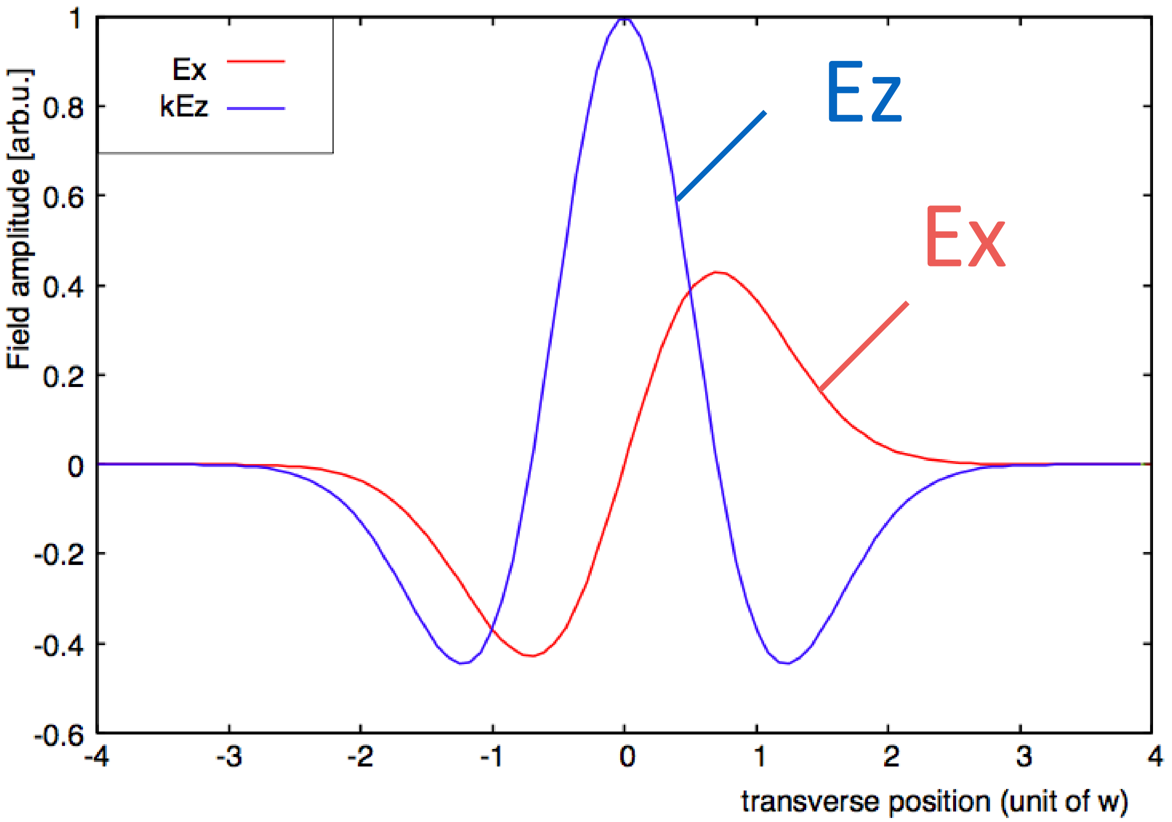
Extract more energy
(Stimulated radiation)

Longitudinal Field

- Extract energy by radiation ⇄ Beam deceleration
- Decelerating field exists in the radial polarization mode.



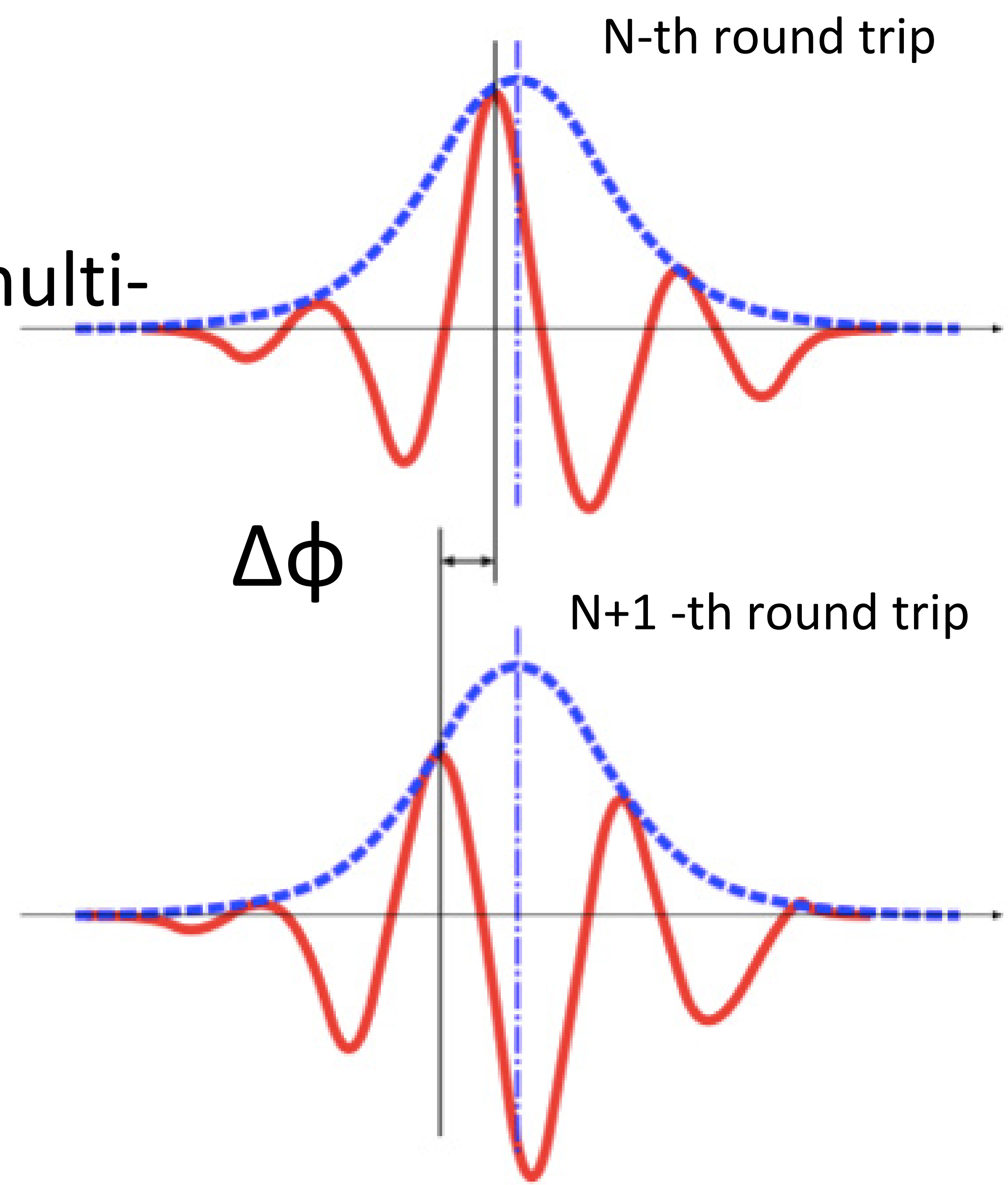
$$ikE_z = \frac{\partial E_x}{\partial x}$$



- Stacked field stimulate further radiation emission.

Mode-lock

- Wavelength << Cavity length
  - Many longitudinal modes (~1000)
  - CEP: carrier-envelope-phase



- Δϕ= 0 (Zero-CEP) is necessary for multi-bunch coherent stacking

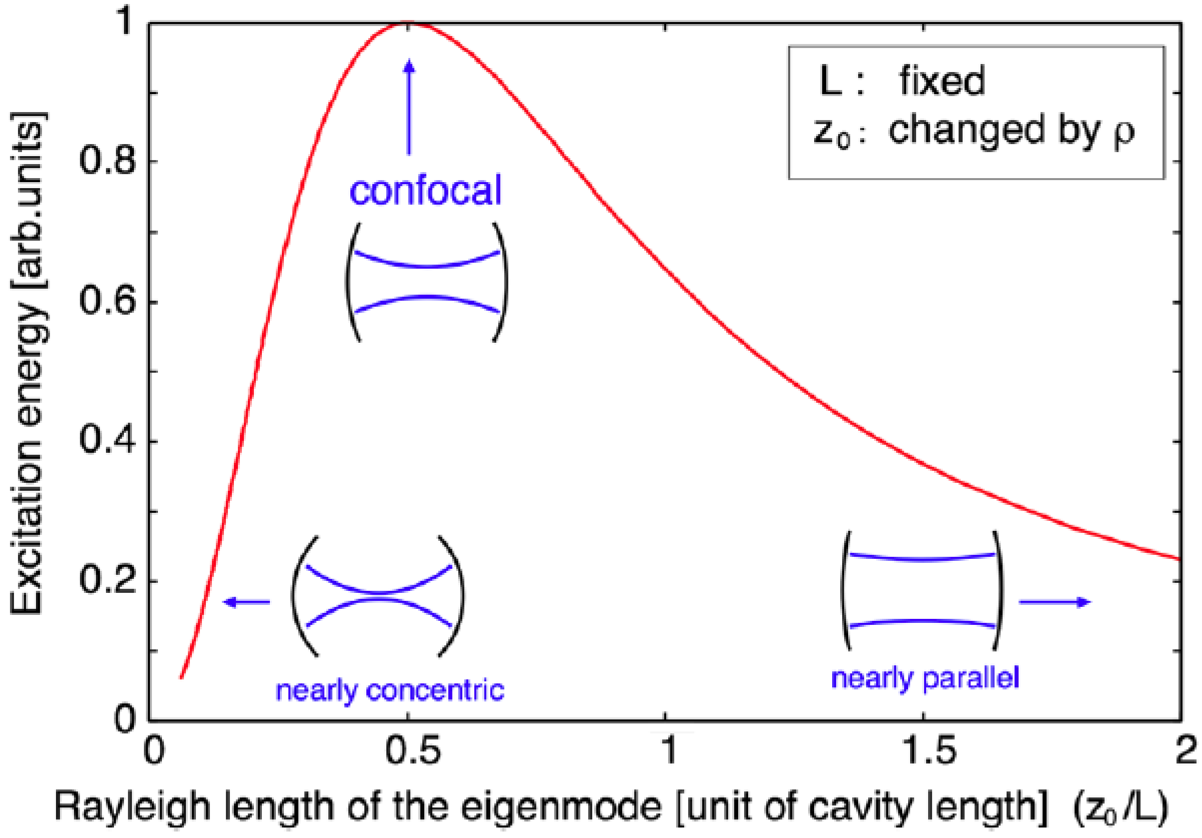
- CEP is determined by cavity design
  - R=L (confocal) → Zero-CEP

$$\Delta\phi = 8\tan^{-1}\left(\sqrt{\frac{L/R}{2-L/R}}\right)$$

Optical Cavity Design

- Phase shift between the two cavity mirror is important
- Optimum parameter is L = ρ
  - L: cavity length
  - ρ : curvature radius cavity mirror

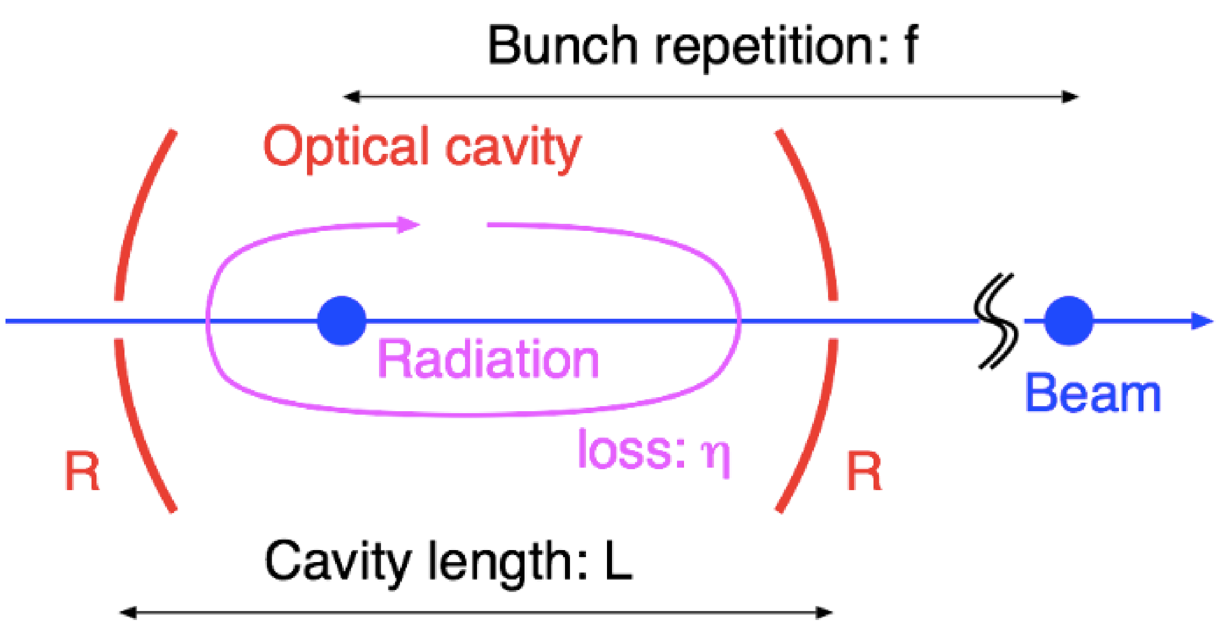
Cavity length (L)	115 mm
Range of L adjustment	±10 mm
Diameter of mirror	50 mm
Thickness of mirror	10 mm
Radius of curvature of mirror (ρ)	115 ± 3 mm
Diameter of mirror hole	3 mm (tapered to 6 mm)
Material of mirror	Au-coated Cu

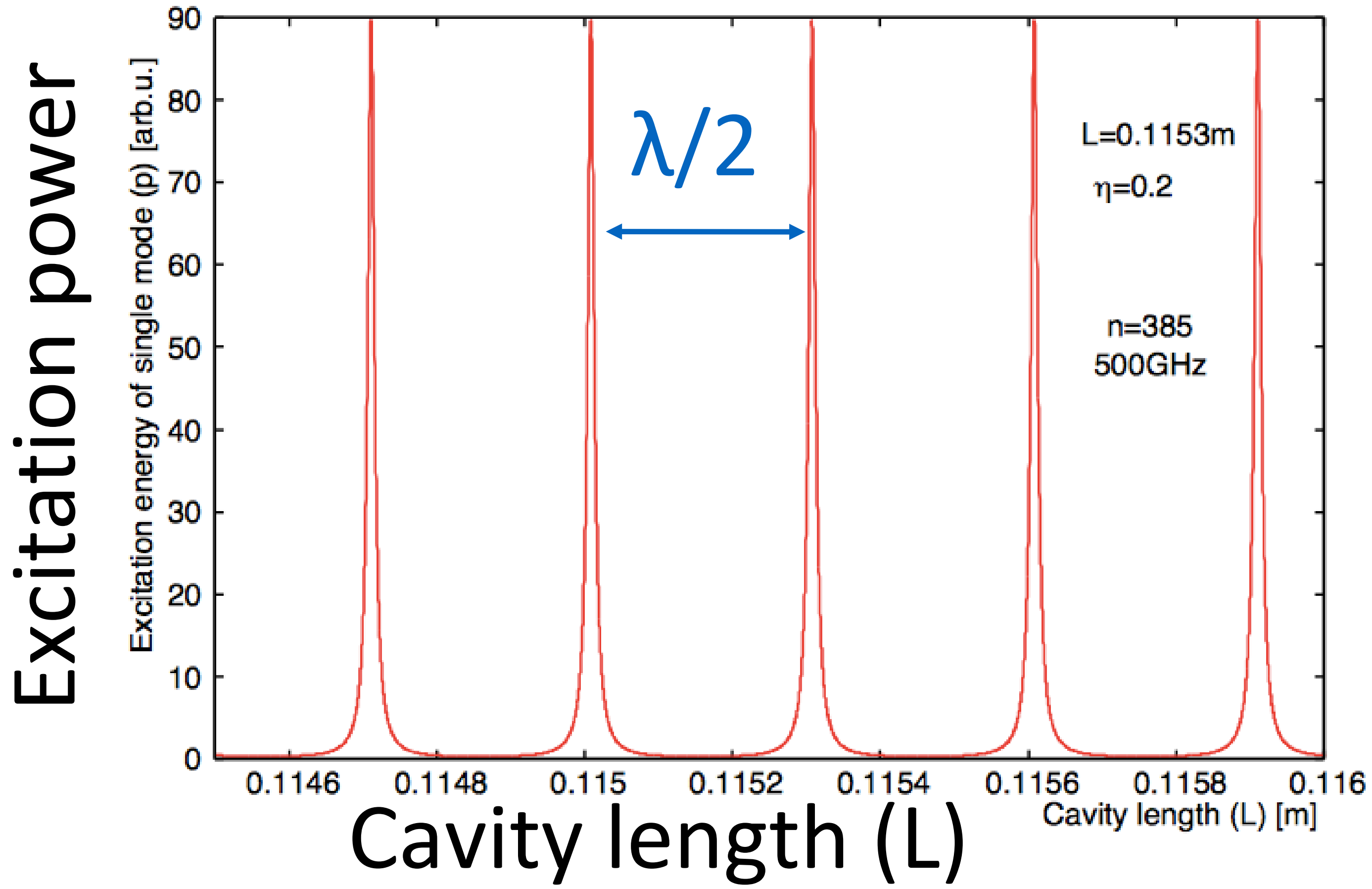


Simulation

- Situation in an experiment
  - Fixed beam repetition (f)
  - Measure radiation power while changing cavity length (L)
- This is a single mode calculation.
  - There are many modes of broad wavelength and the resonance conditions are different in general.

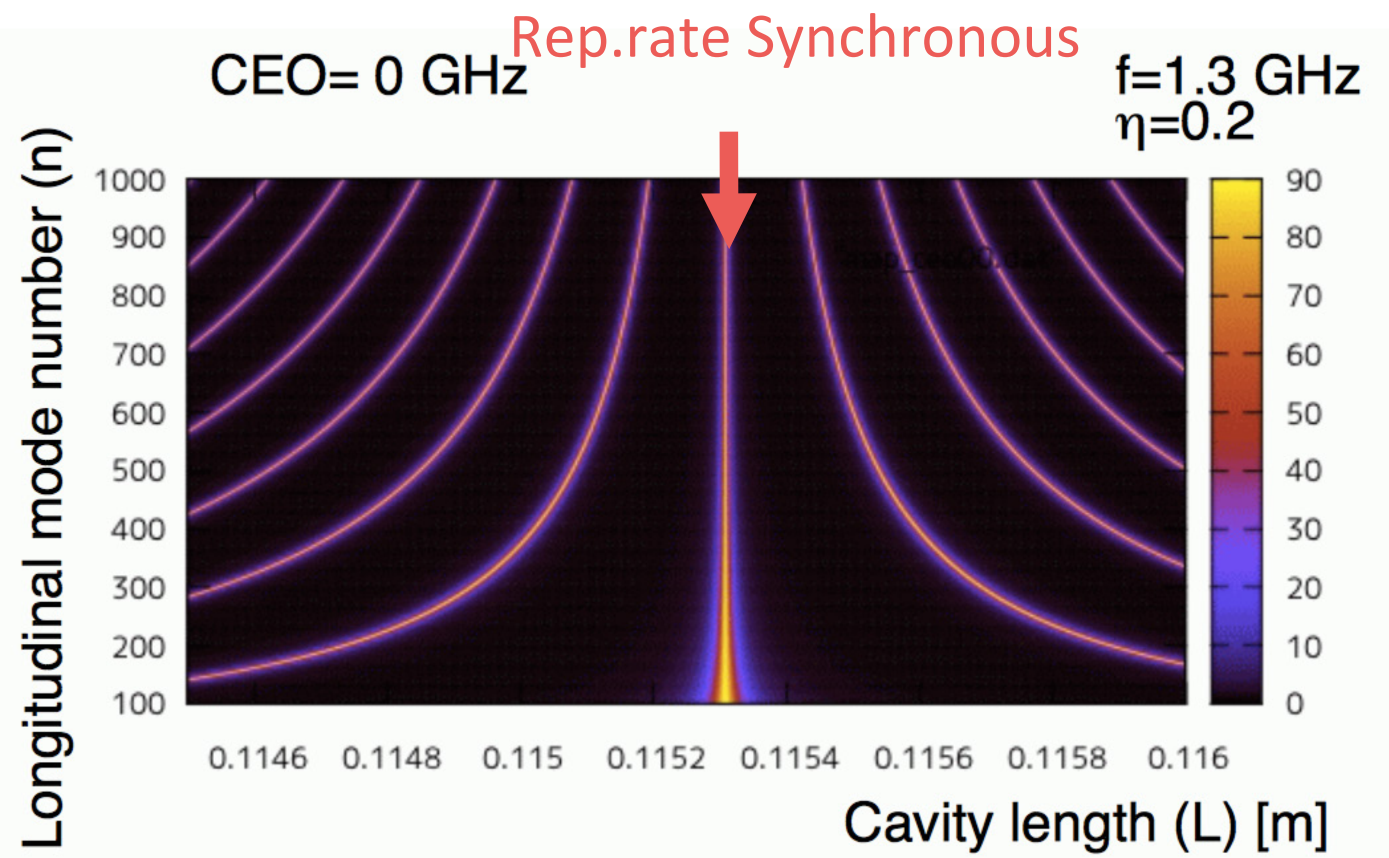
$$v_m = v_1 + v_1\sqrt{1-\eta}e^{i\theta} + v_1(\sqrt{1-\eta}e^{i\theta})^2 + \cdots + v_1(\sqrt{1-\eta}e^{i\theta})^{m-1}$$

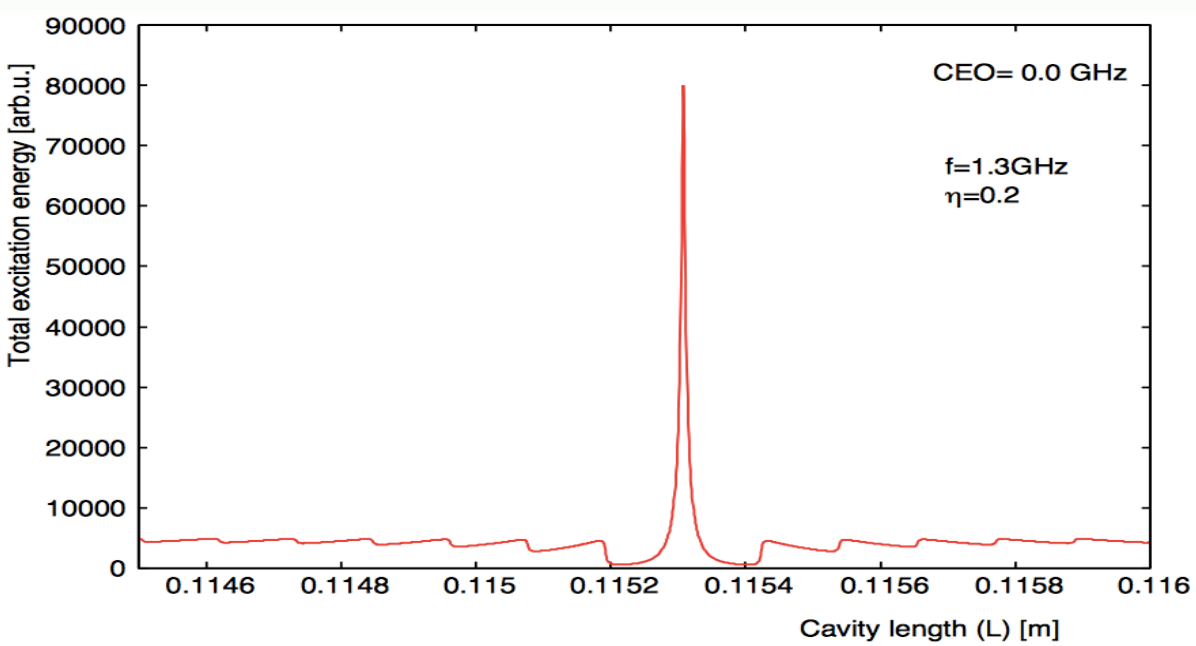




Broad spectrum

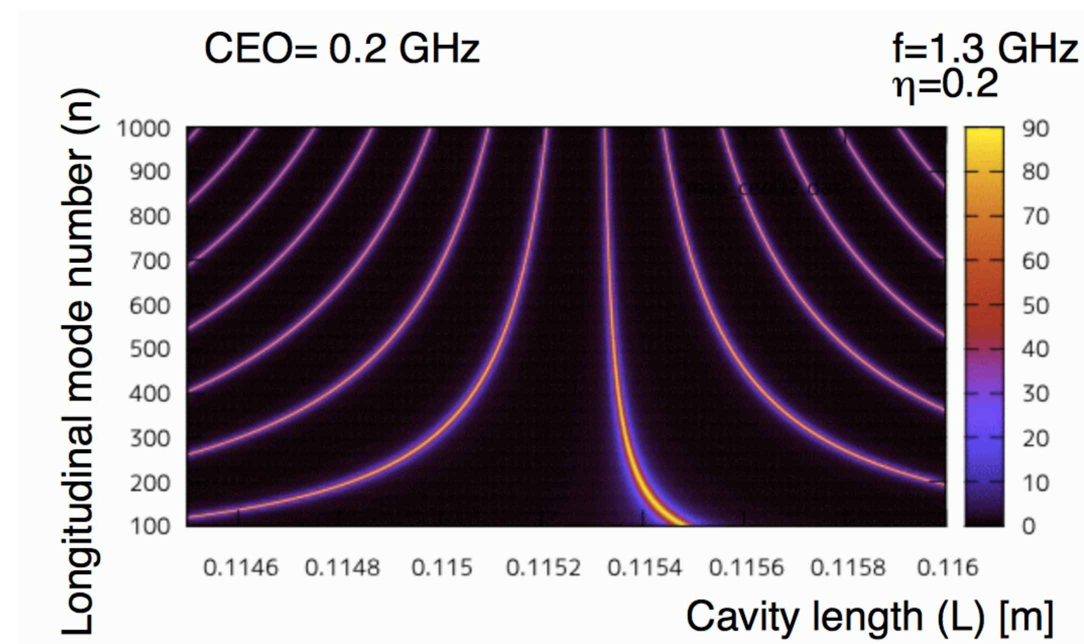
- Many longitudinl modes (1THz = ~700-th modes (f=1.3GHz))
- Generally, different wavelength → different resonance condition.
  - Exception: Zero-CEP case, a common resonance condition.





Non-zero-CEP case:

no such a condition



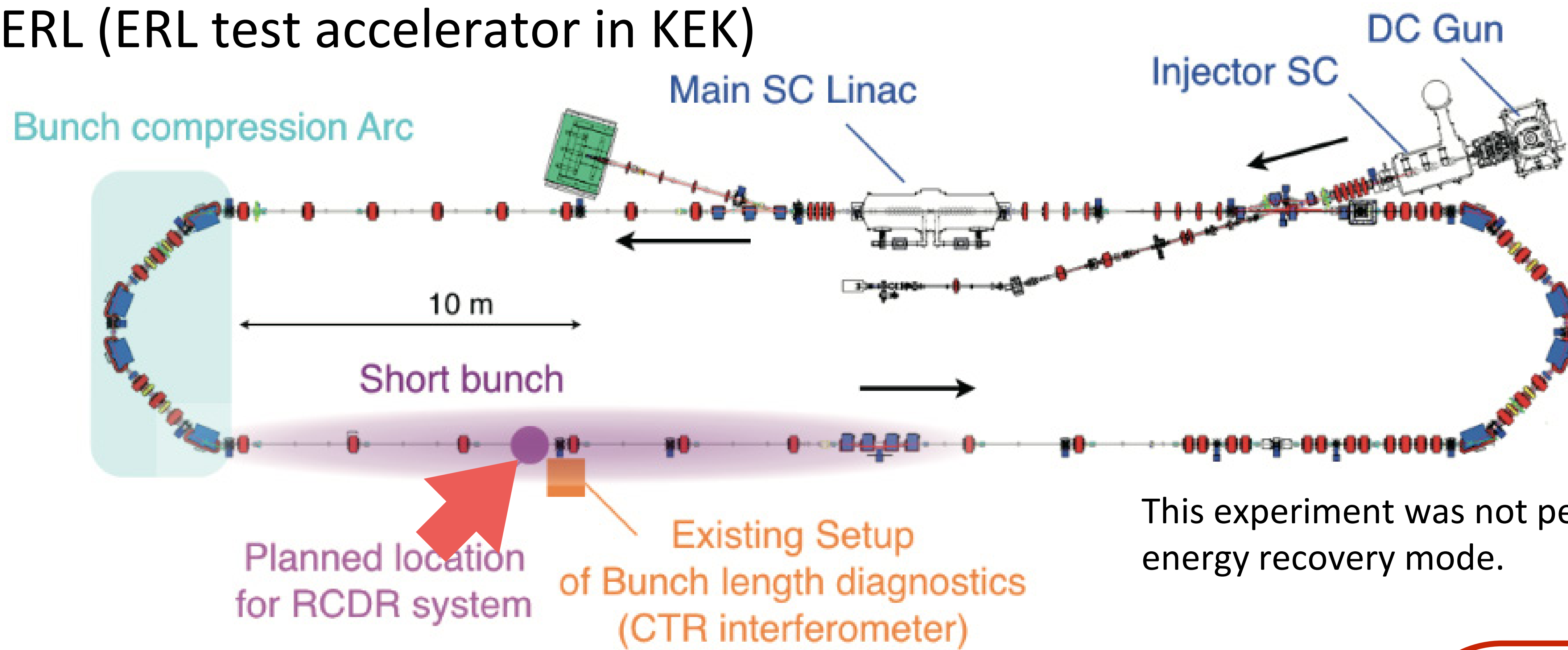
Zero-CEP is necessary for broad excitation

Experimental Setup

- Beam parameter
- Optical cavity
- Measurement system

Beam parameter

- cERL (ERL test accelerator in KEK)

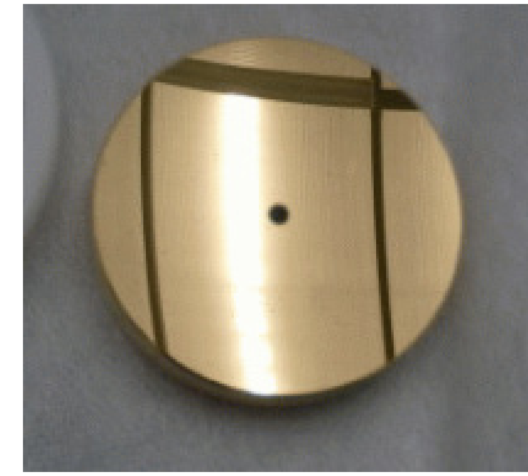


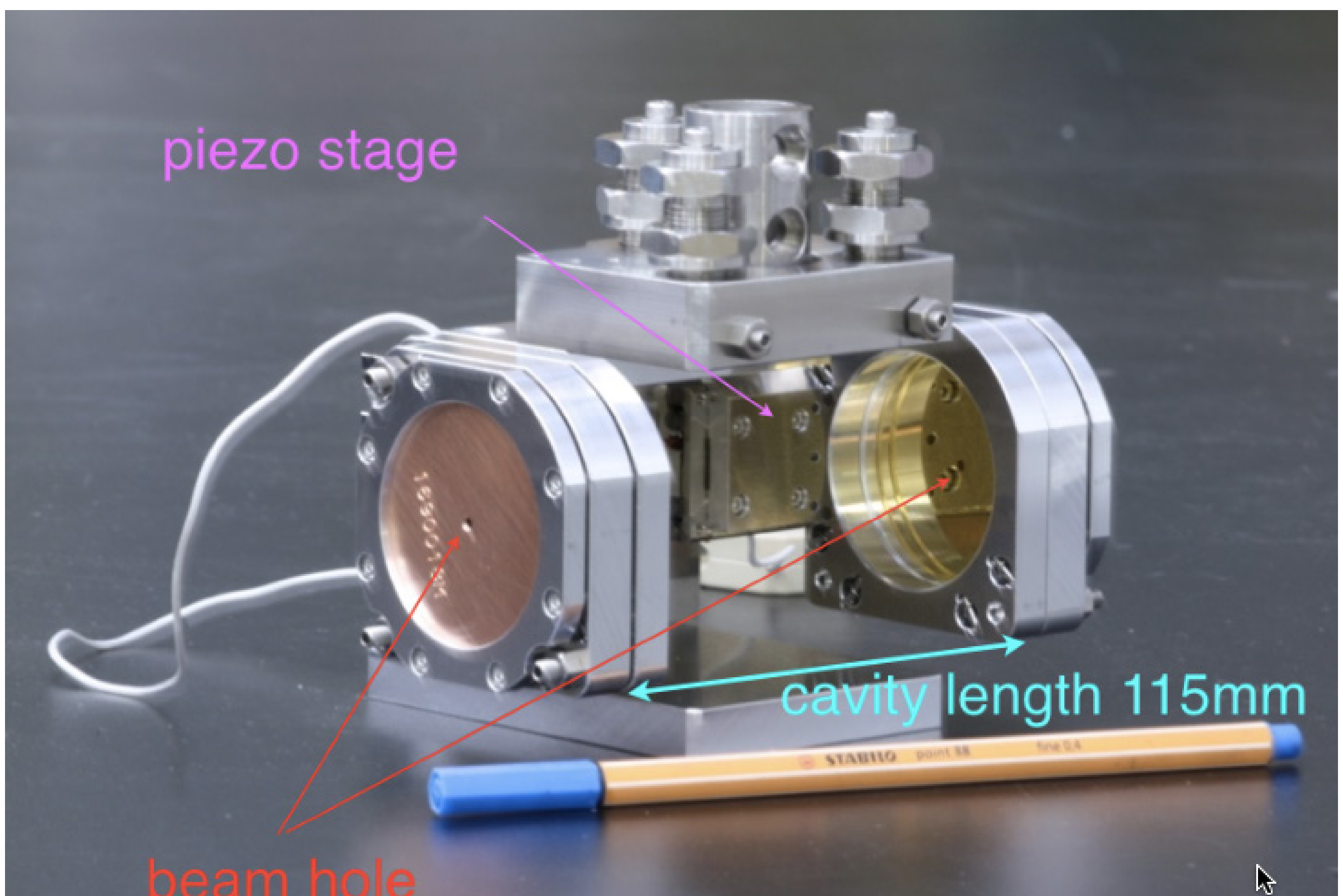
This experiment was not performed in energy recovery mode.

	target	established(2016.3)	this experiment
Beam energy	35 MeV	20 MeV	17.8 MeV
Average current	10 mA	1 mA	1μs burst
Bunch charge	77 pC/b	7.7 pC/b	1.2 pC/b
Bunch repetition	1.3 GHz	1.3 GHz, 162.5 MHz	1.3 GHz
Norm. emittance	0.3 mm•mrad	0.3 mm•mrad (0.5pC/b) 1.5 mm•mrad (7.7pC/b)	1.4 mm•mrad
Bunch length(RMS)	3 ps 100 fs (compressed)	3 ps 250 fs (compressed)	<200 fs

Optical cavity

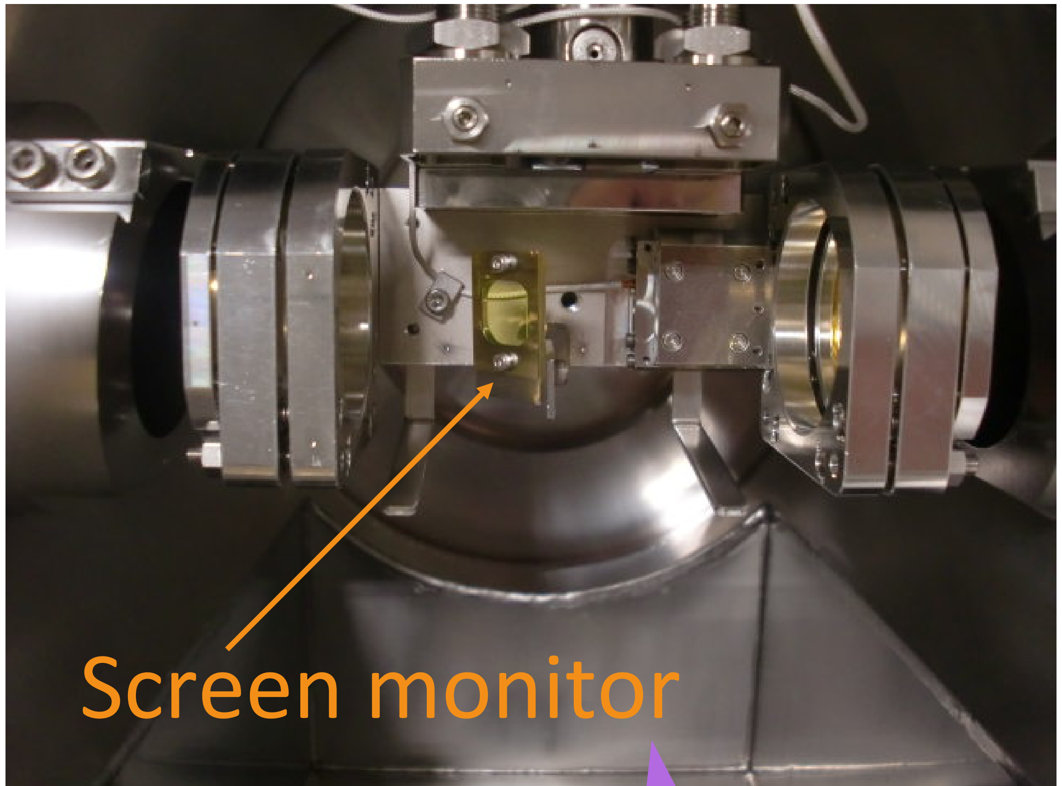
- L=115mm. (Rep.rate 1.3GHz)
- R=115mm (Designed to be Zero-CEP)
- Au-coated Copper mirror
- Beam hole diameter 3mm
- Cavity length can be scanned by a piezo stage.



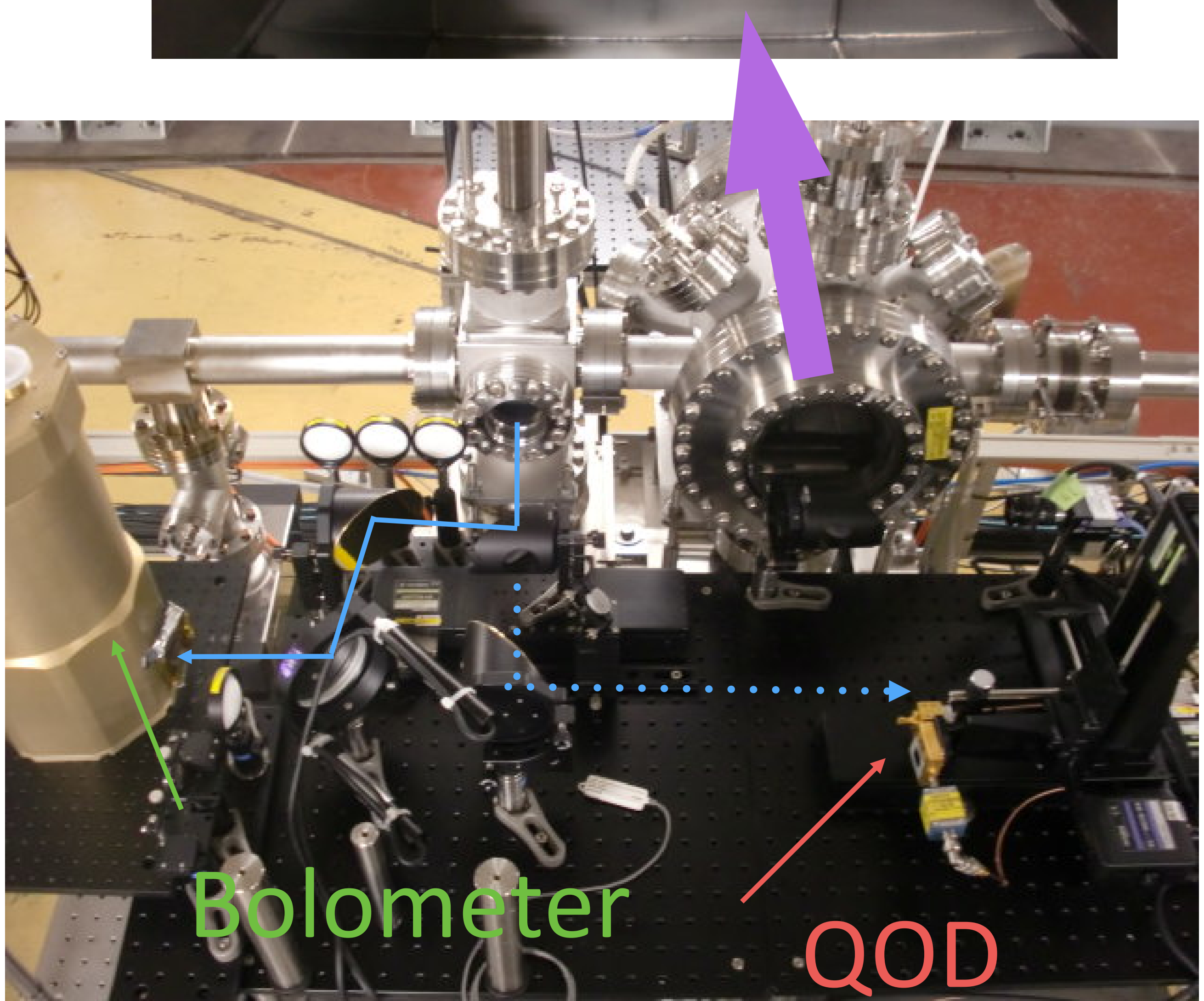


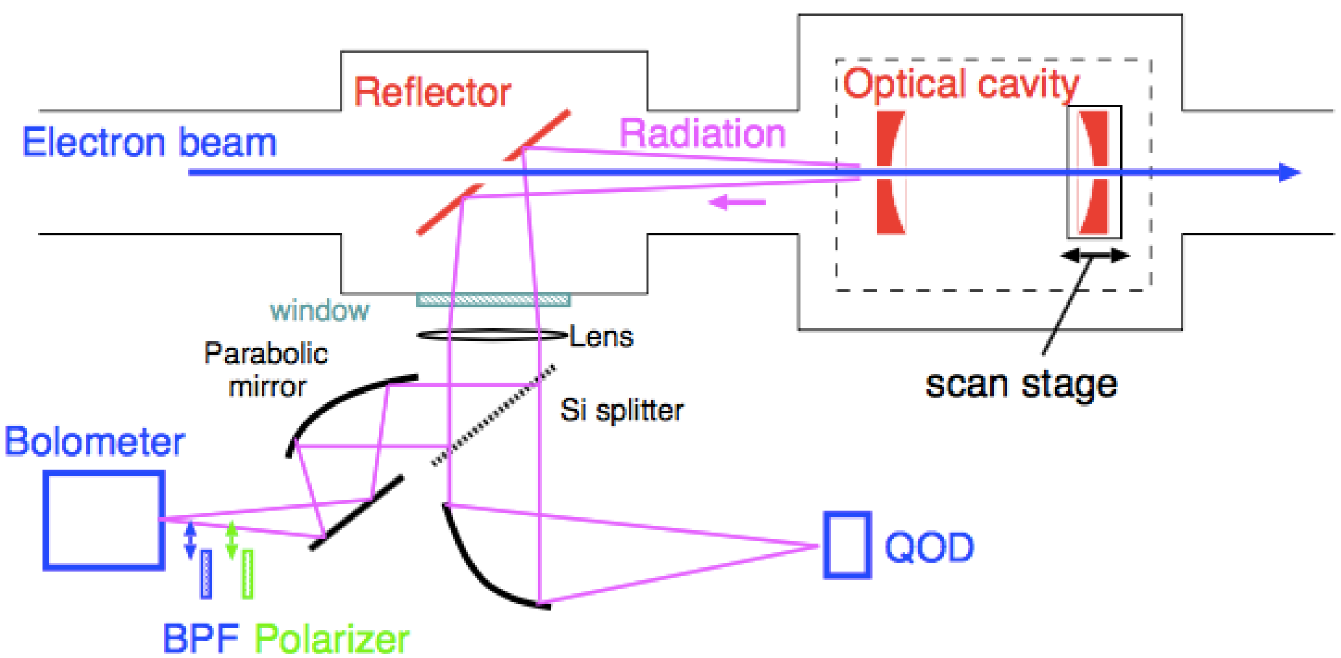
Parameter		value
Bunch repetition	f	1.3 GHz
Beam energy	E	20 MeV
Bunch charge	q	1 pC
Normalized emittance	ϵ_n	1 μm
Bunch length	σ_t	150 fs
Cavity length	L	115 mm
Mirror curvature radius	R	115 mm
Mirror hole diameter	d	3 mm
Mirror diameter	D	50 mm
Cavity loss	η	0.05
Extraction efficiency	T	0.025
Target frequency	ν	0.5 THz

Setup



- Two THz detectors
  - Bolometer
    - sensitive at 0.4~5 THz
    - with/without BPF 0.5THz
  - QOD
    - fast response
    - low freq. mainly <0.4 THz





Experimental Result

- Observation of resonance peaks
- Signal growth waveform
- Beam deceleration

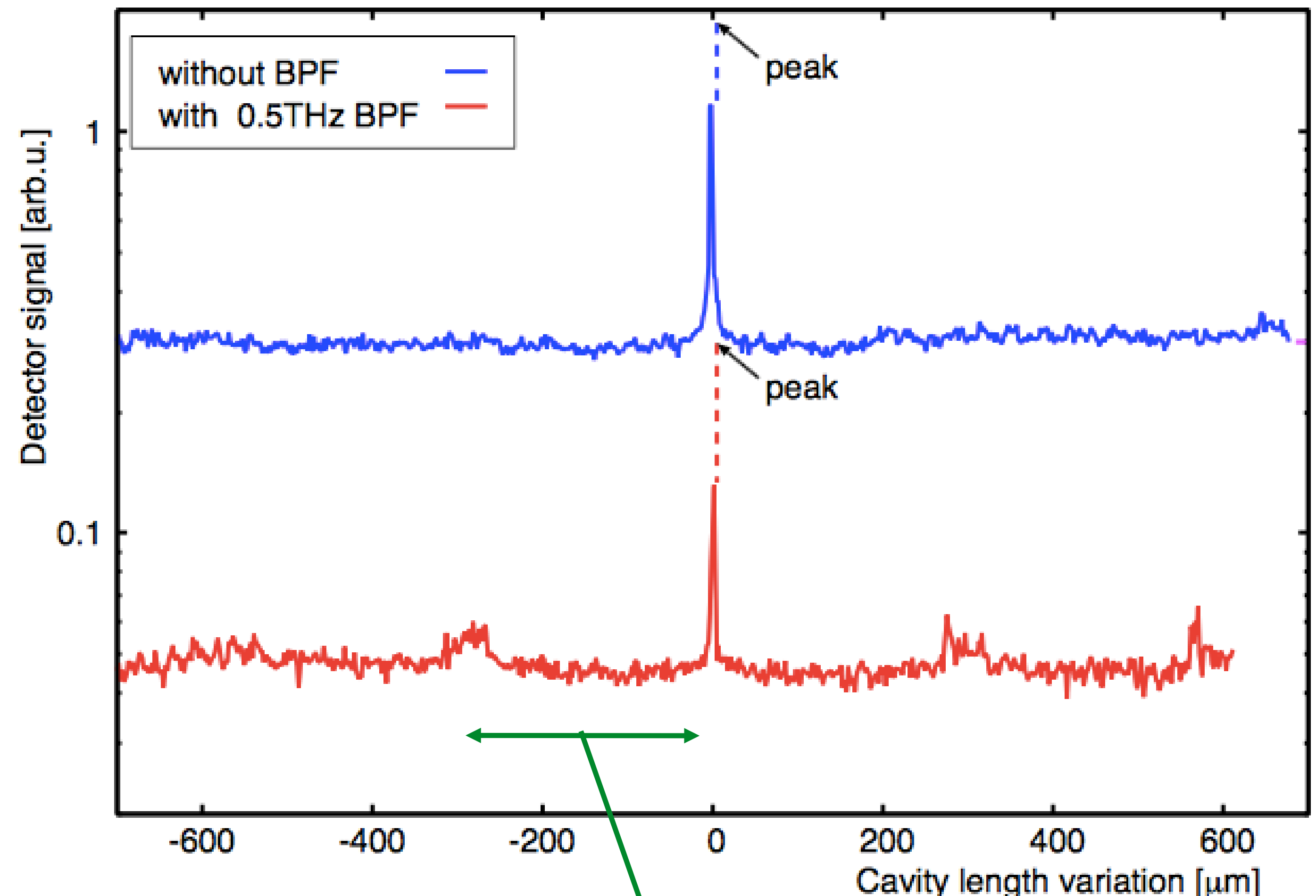
Resonance peak

- Scan cavity length, measuring THz power.
- A sharp peak was observed

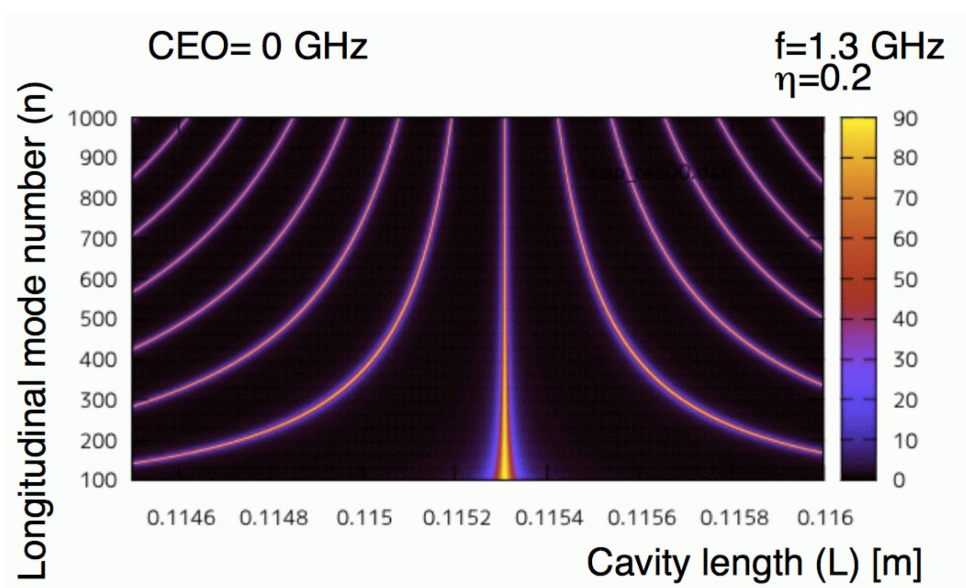
Wide-band

Narrow-band

(with 0.5THz BPF)



λ/2 of 0.5THz (λ=600um)

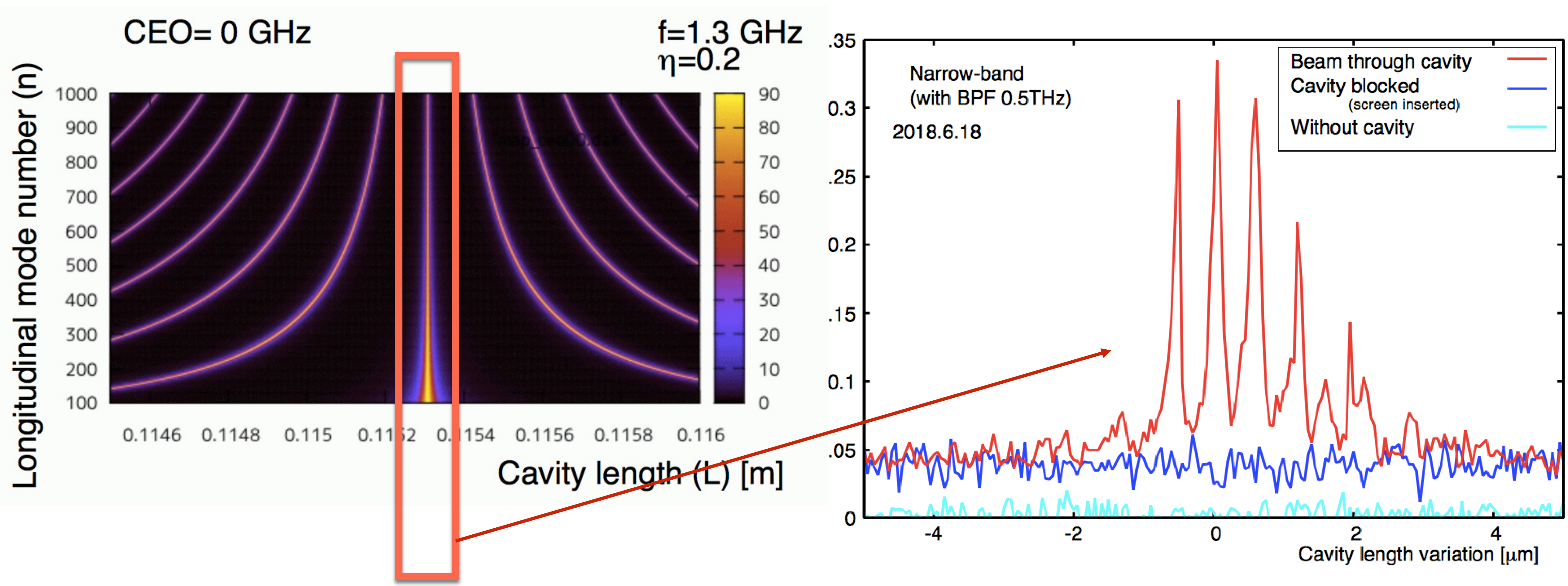


Scan in this range

- Confirms zero-CEP design

Fine scan

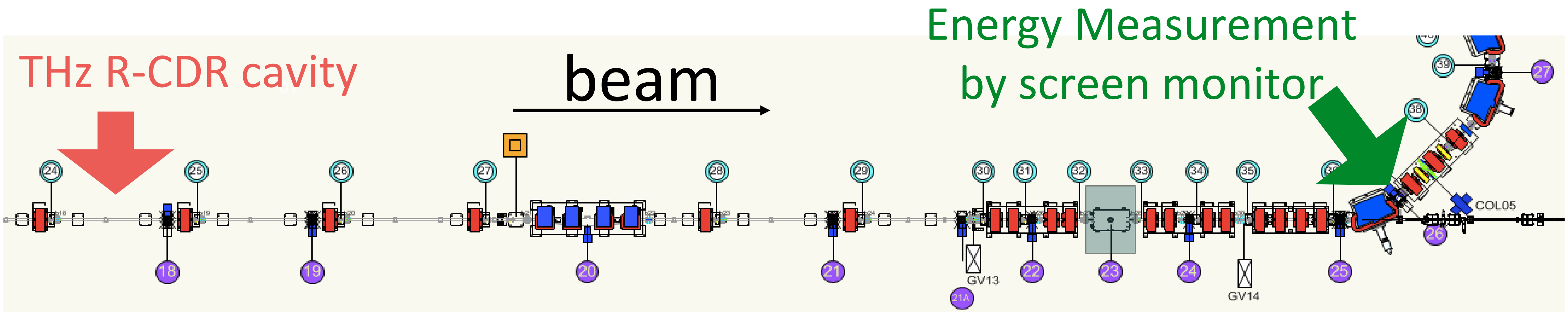
- The resonance peak has a fine structure.
  - (May be caused by higher-order transverse modes.)
- The peaks disappear when the cavity was blocked by inserting a screen monitor. (confirm resonance)

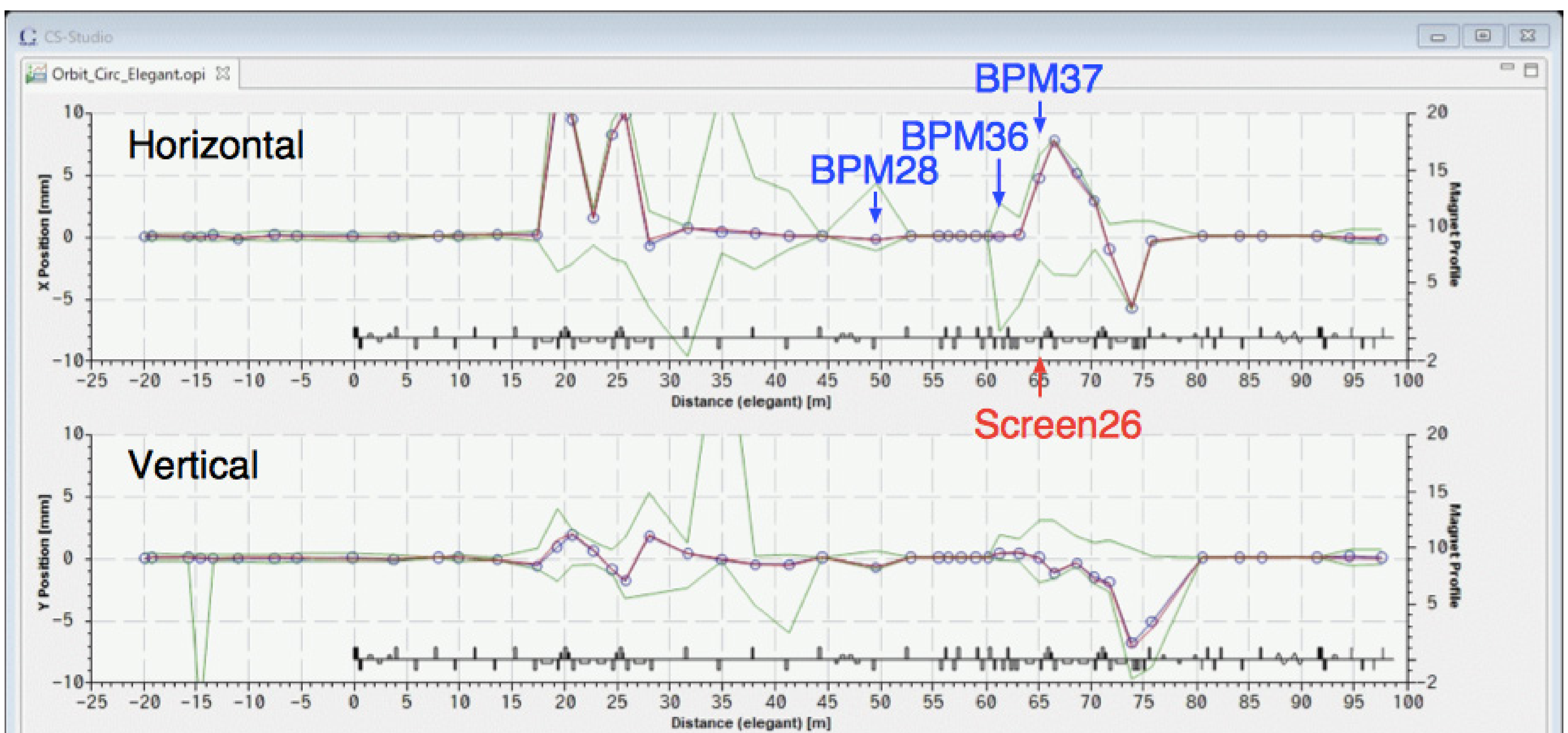


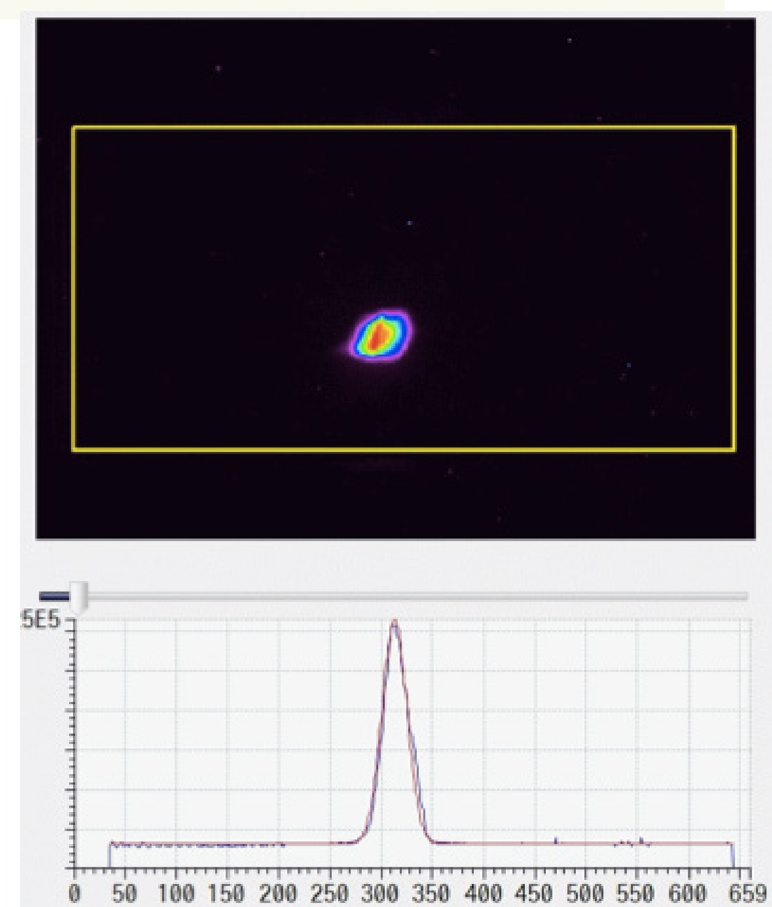
Scan in this range

Deceleration measurement

- H beam size: ~1.3mm(RMS)
- Dispersion: 0.49m.
  - 0.5mm shift for 10^-3 energy variation.







Beam deceleration

- Energy conservation

$$P_{total} = \frac{4Fq^2}{\eta\pi\epsilon_0 L}$$

Number of modes (F=385, <0.5THz)

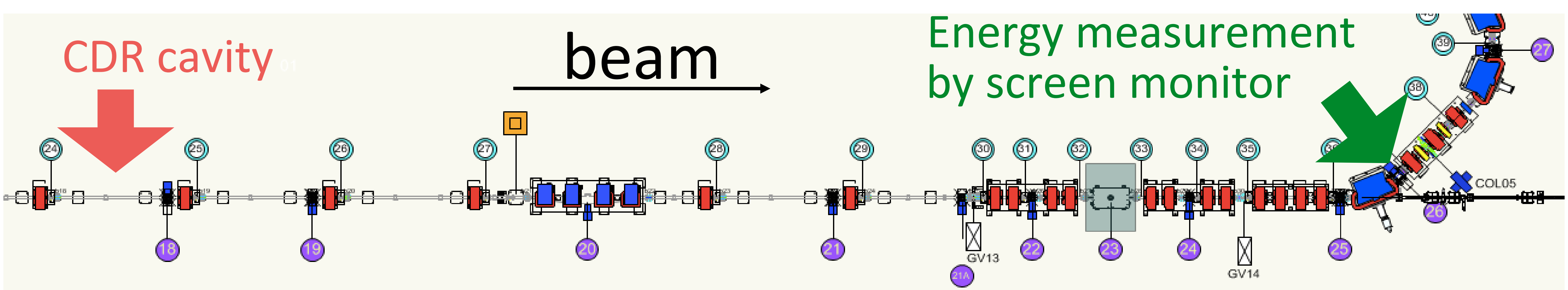
Bunch charge (q=1.2pC)

P: Radiation power (= Beam energy loss)

Cavity loss (η=0.011)

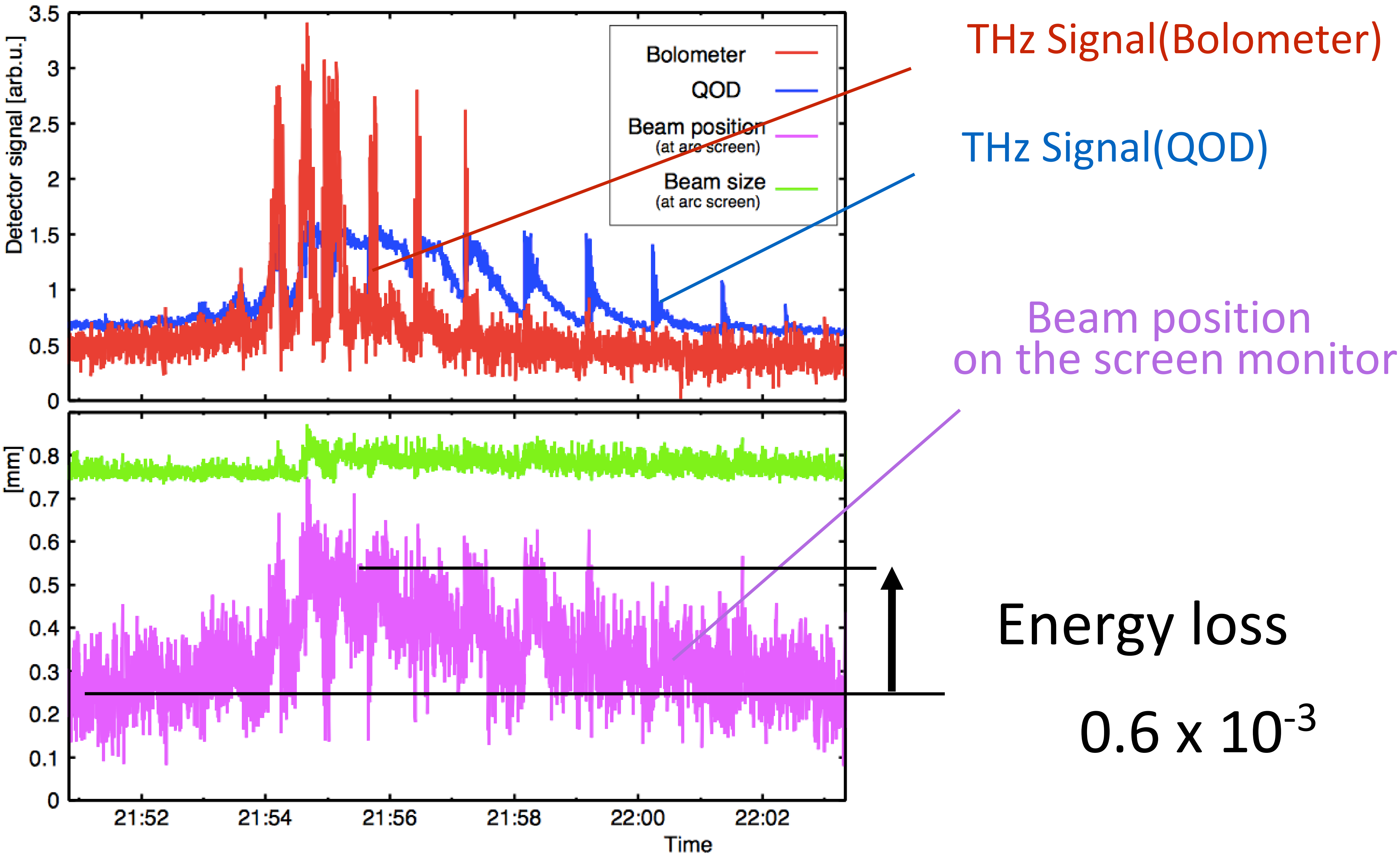
Cavity length (L=115mm)

- Estimation: ~90 W in the above parameter (too ideal).
- More reasonable estimation: ~10 W
  - (considering cut-off effects of hole, finite bunch length etc.)
- Energy loss for 17.8 MeV beam should be 10^{-3}~10^{-4}



Deceleration

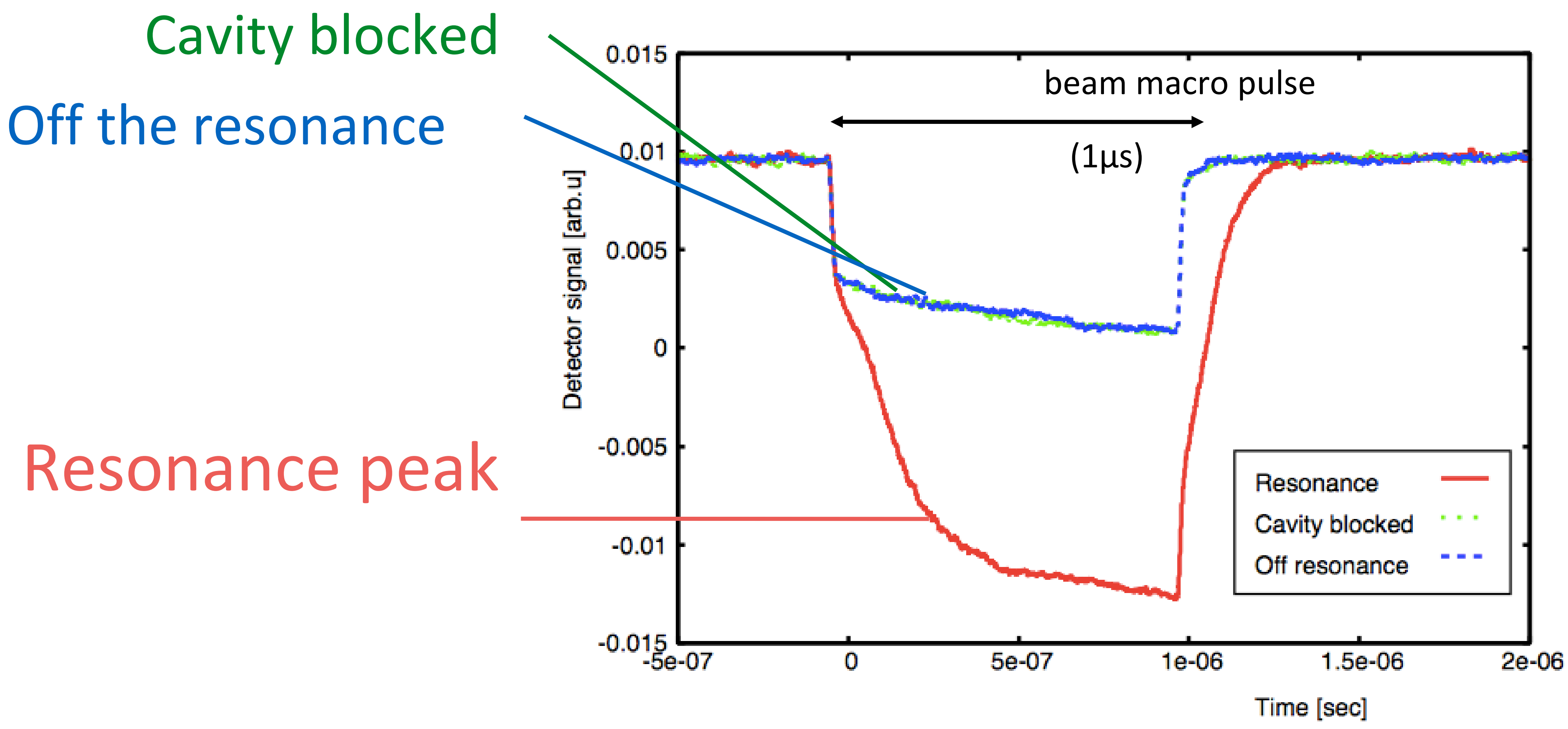
- Scan the cavity length while measuring THz power and beam energy.



Waveform

- Measured by a fast diode detector (QOD)
- Time constant τ= 67ns +- 5ns
  - Loss estimated from τ is η= 0.0114

$$\tau = \frac{2L}{c\eta}$$



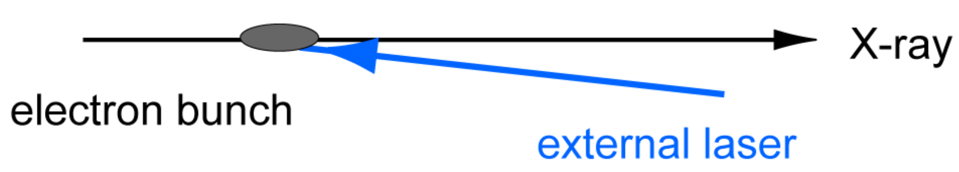
- Growth/decay time constant shows resonance nature

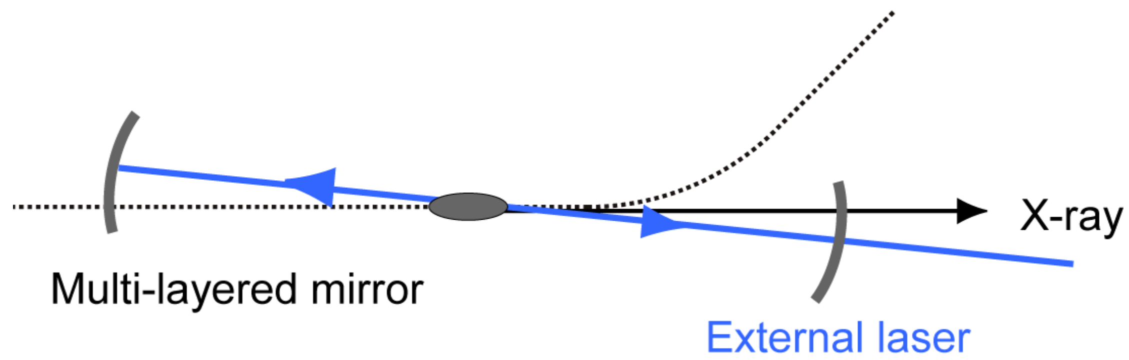
Future plan for CSR inverse Compton scattering

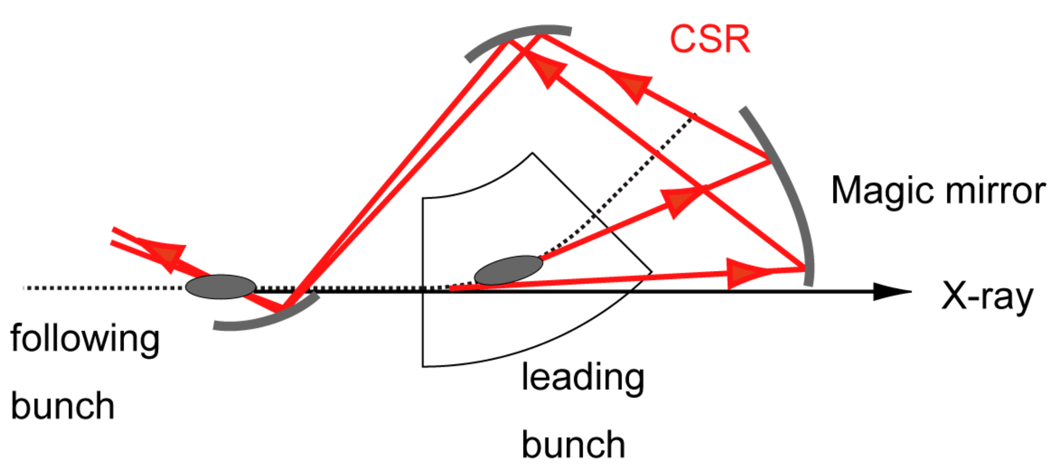
Inverse Compton Scattering by Coherent Synchrotron Radiation

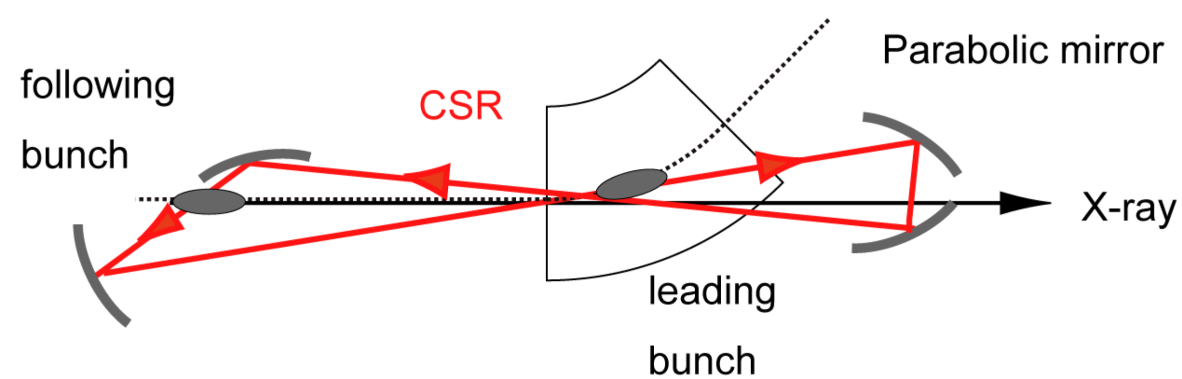
Head-on ICS $$E_X = \frac{4\gamma^2}{1+K^2} E_L$$

Scattered photon energy E_x
Laser energy E_L









M. Shimada and R. Hajima, PRSTAB **13,** 100701,(2010)

CSR-ICS proposal

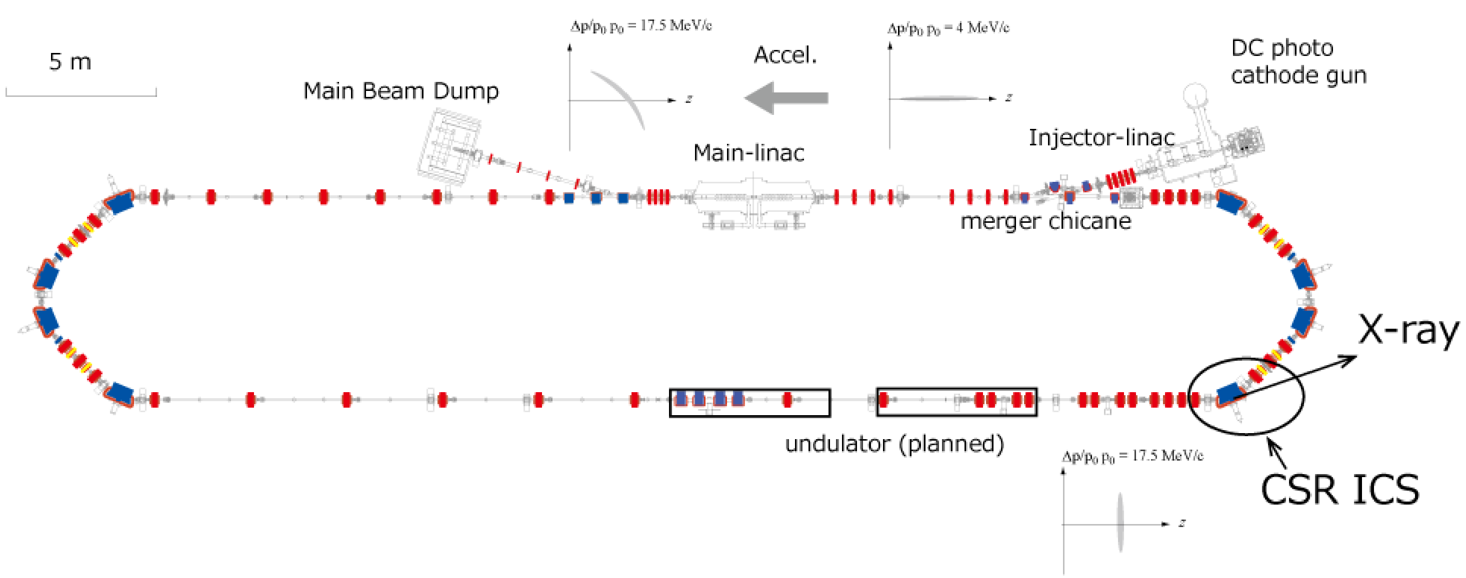
	GeV class ERL	Compact ERL	
	Case 1	Case 2	Case 3
Electron beam			
Beam energy	5 GeV	200 MeV	60 MeV
Electron Charge	1nC	1 nC	0.5 nC
Bunch length	30 fs	1 ps	1 ps
Scattered photon			
Photon energy	8 MeV	0.4 keV	0.04 keV
Flux	3x10e16	3x10e13	0.7x10e13

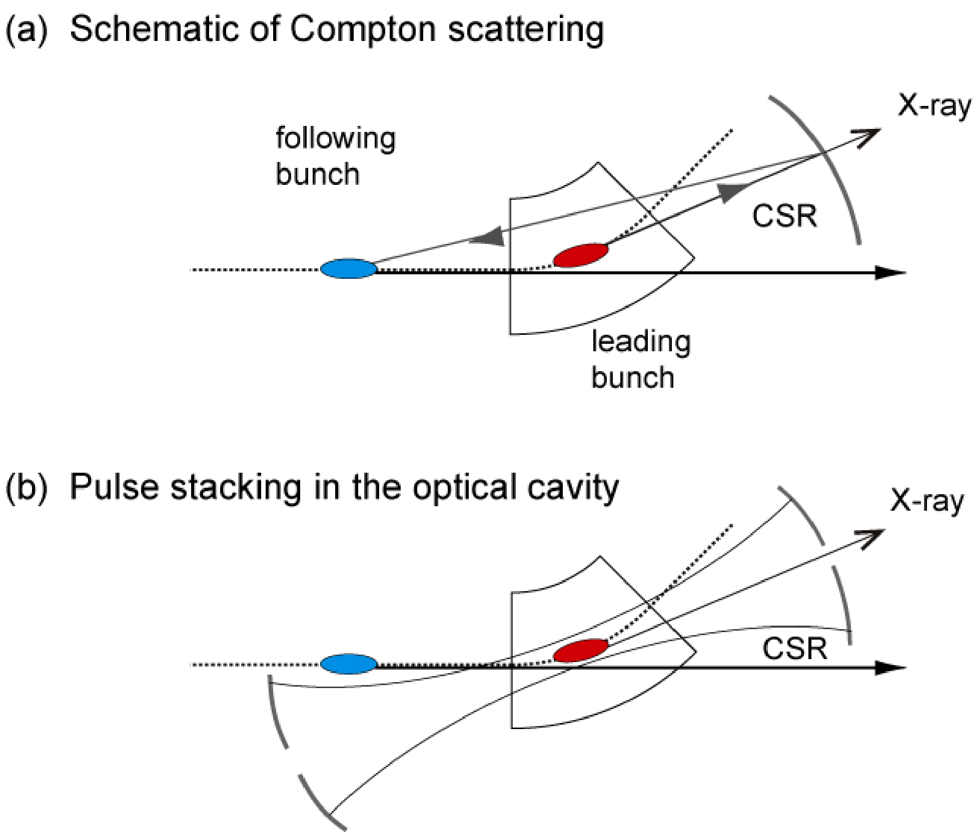
Intense gamma-ray
for ILC positron source

Soft X-ray source at cERL

CSR-ICS plan at cERL

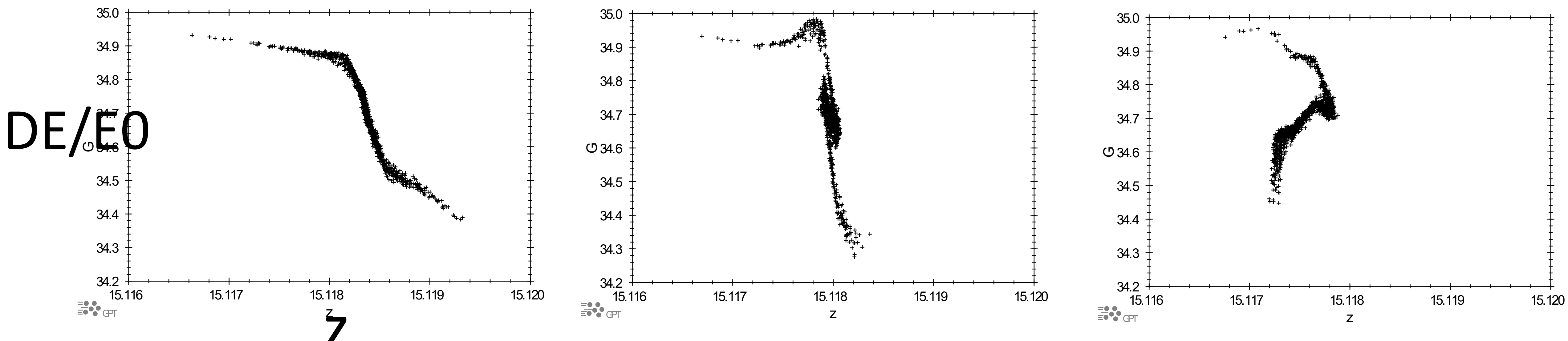
- We have a plan of CSR-ICS at the entrance of the return arc in the future.
- Expected scattered photon is VUV (20-30 eV)
- Start from two mirror scheme



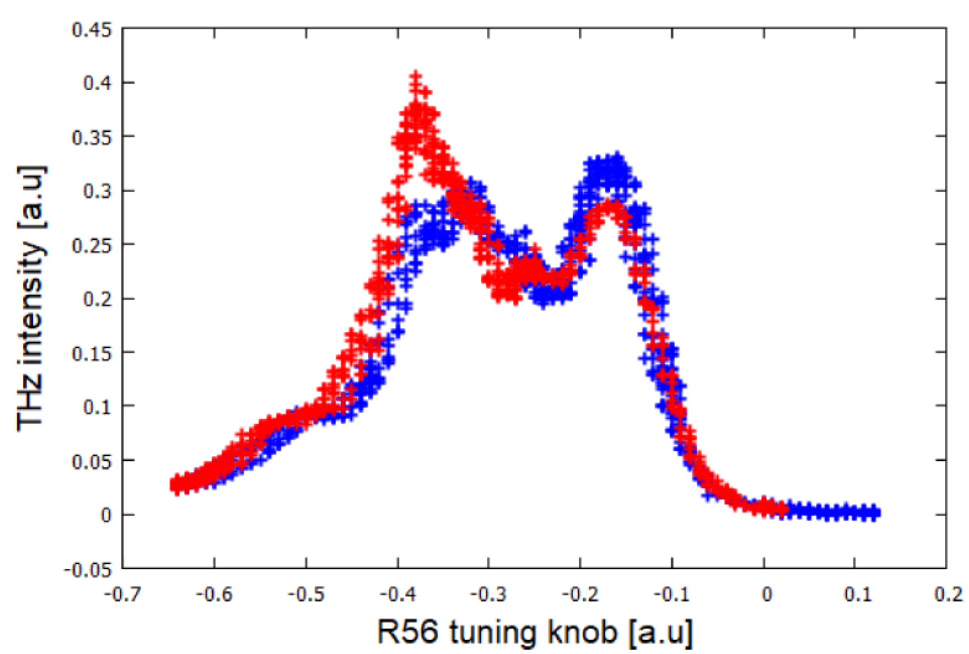


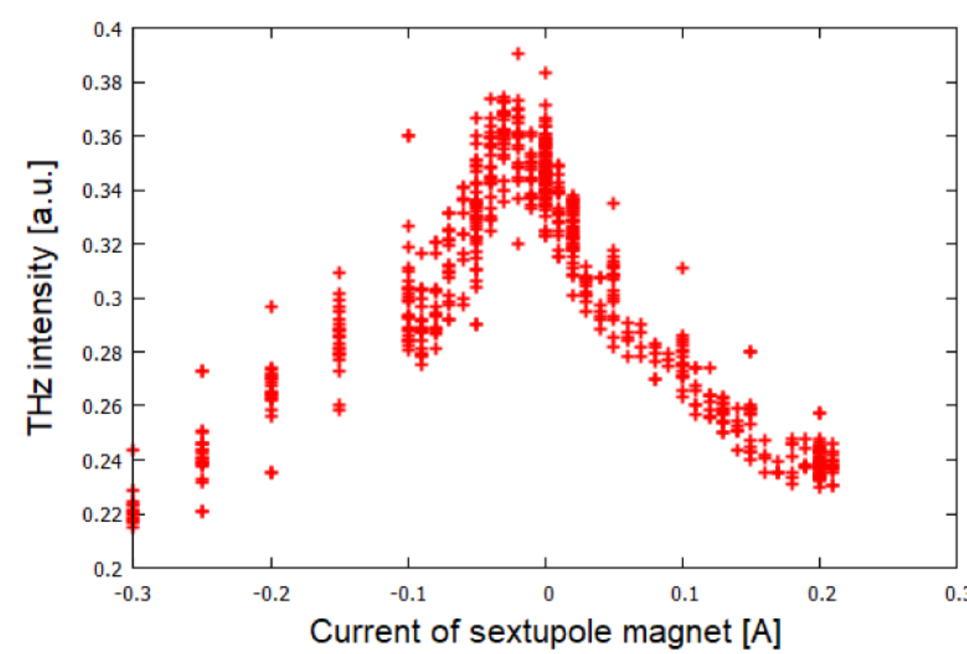
Beam Optics of Bunch Compression at the Compact ERL (poster WEPNEC12)

- Tracking simulation by General Particle Tracer



- Beam tuning





Summary

- We performed an experiment showing Stimulated Coherent Diffraction Radiation in Optical Cavity using a modern ERL test accelerator.
- Extract more power from the beam by coherent stacking mechanism.
- Key in the design is Zero-CEP for broad-band excitation.
- Experimental Results
  - Observed sharp resonance peak, showing broadband excitation.
  - Time domain measurement shows time constant characteristics.
  - Observed beam deceleration simultaneously with THz radiation.
- Next step
  - Understanding the fine structure in the resonance peak.
  - CW beam operation with the small aperture.
- Future plan for CSR inverse Compton scattering
  - High-intensity X-ray and gamma-ray source based on the ERL