Coherent Radiation from High-Current Electron Beams of a Linear Accelerator and Its Applications

S. Okuda

1987-2002 ISIR, Osaka Univ.
2002- Research Institute for Advanced Science and Technology (RIAST), Osaka Prefecture Univ.

Coworkers:

Osaka Pref. Univ.	R. Taniguchi, T. Kojima
Osaka Univ.	M. Nakamura, M. Takanaka, R. Kato
Kyoto Univ.	T. Takahashi
Kangwon Univ.	S. Nam

High-current electron linear accelerator (linac)

- High-current thermionic gun
- 3 SHBs

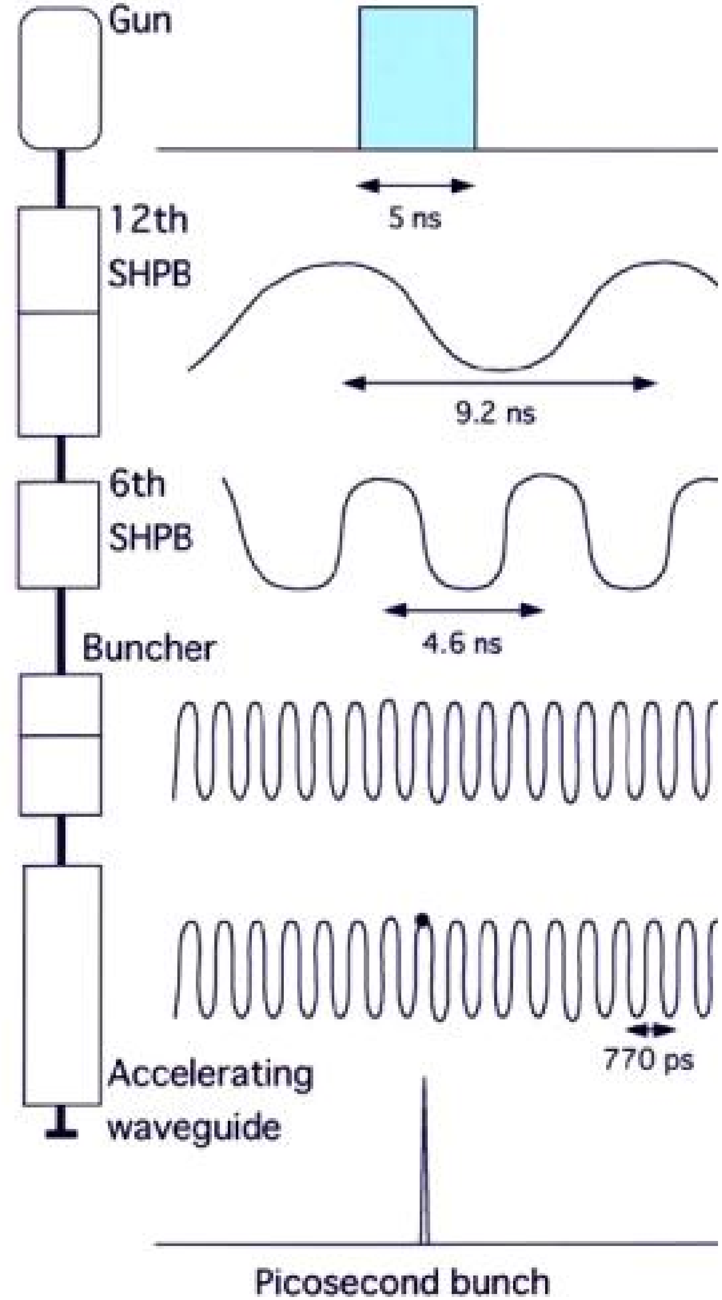
Coherent radiation from electron beams

- Free-electron lasers
- Coherent radiation with a broad spectrum

Applications of the radiation

- Electron bunch shape monitor
- Absorption spectroscopy

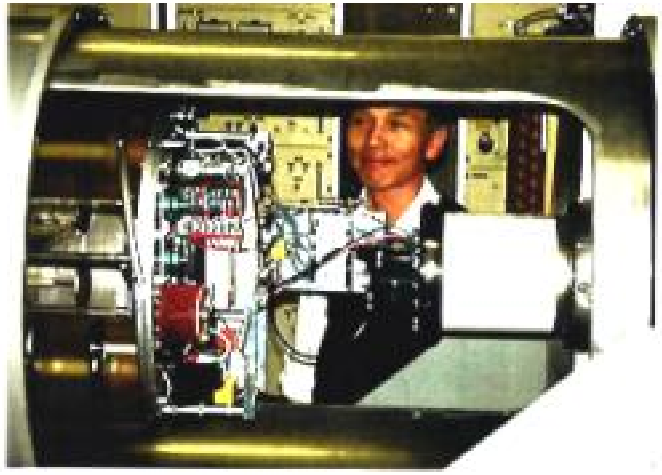
38 MeV L-band linac at Osaka Univ.

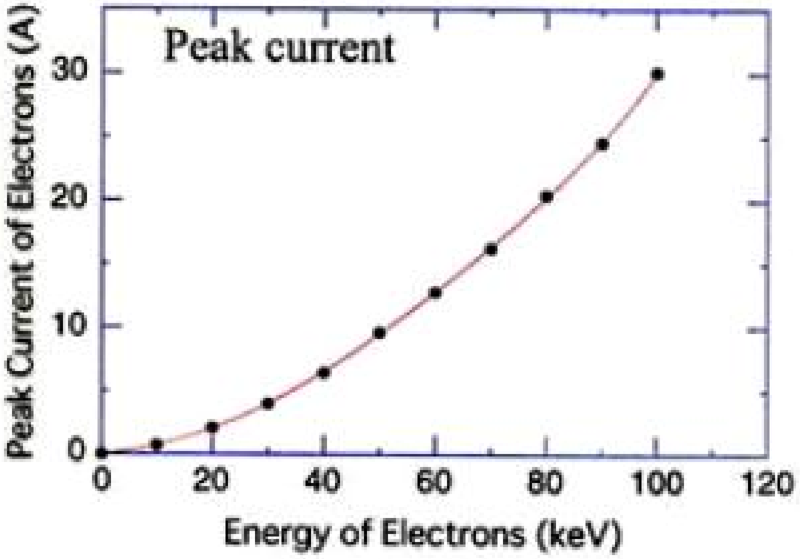


Single-bunch electron beam parameters

Repetition rate	120 pps
Energy	27 (38 max.) MeV
Energy spread	1-2.5% FWHM
Maximum Charge	91 nC/bunch
Micropulse length	20-30 ps
Normal. rms emittance	70-200 π mm mrad

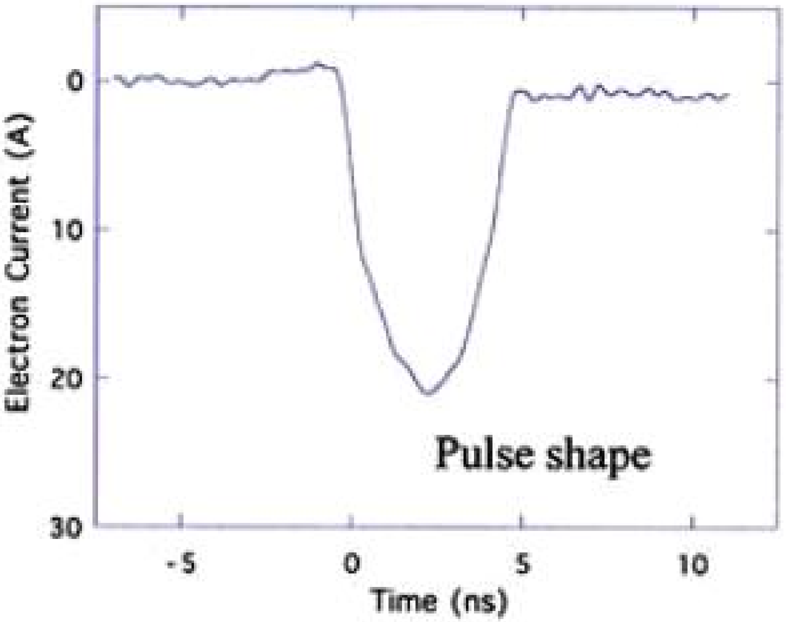
High-current thermionic electron gun





Maximum peak current: 30.1 A

Electron current density: 9.6 A/cm^2



Pulse width: 5 ns (FWHM)

Anode voltage: 90 kV

Pulse rise time (0.1-0.9): 1.6 ns → <0.5 ns

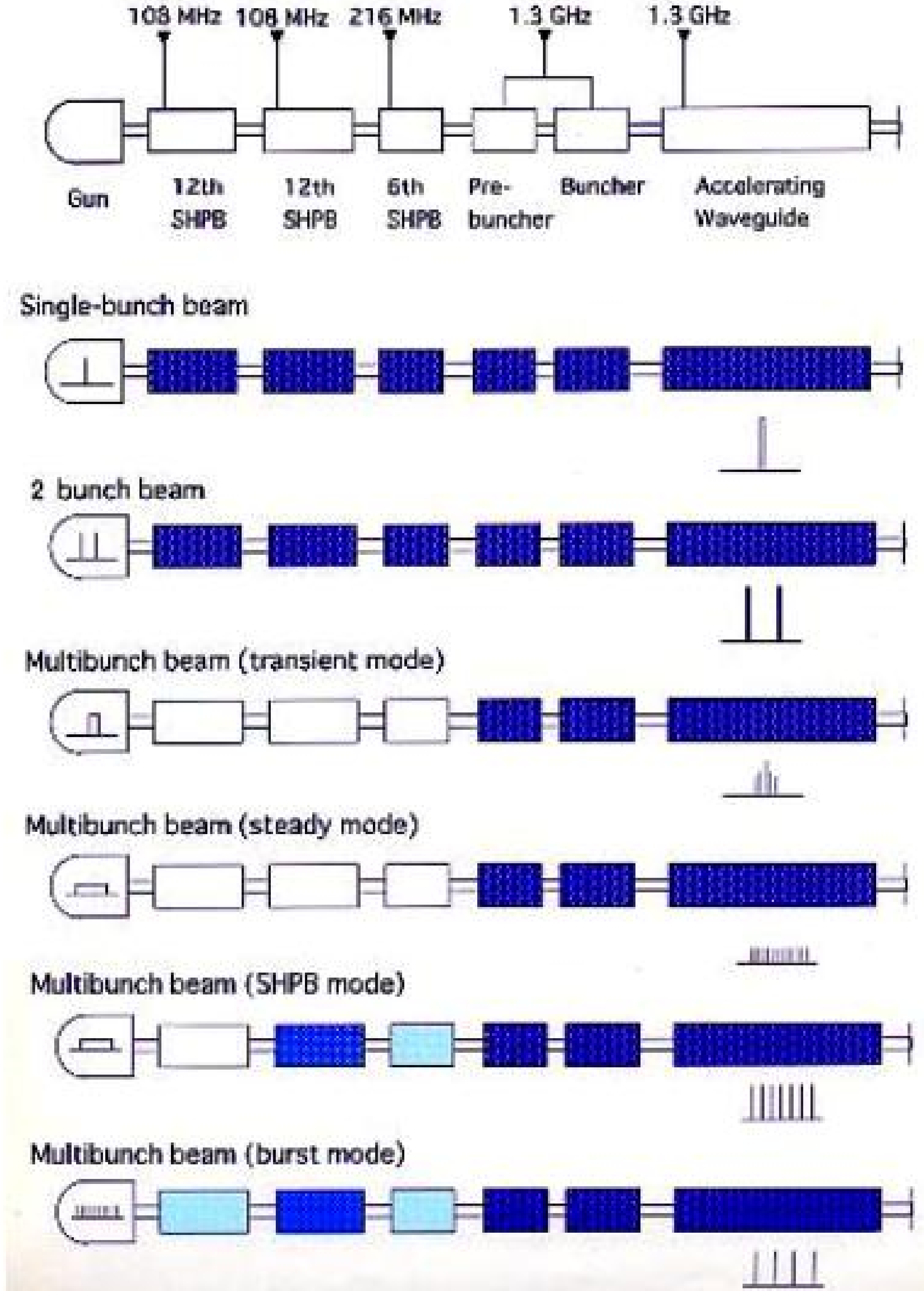
High-current and high-brightness beams

	Osaka (2002)	Argonne (2002)	X-ray SASE
Gun, Injector	thermionic SHPBs	photocathode rf (half cell)	photocathode
rf frequency (MHz)	1300	1300	
Repetition rate (pps)	120		
Energy (MeV)	27 (38 max.)	14	
Energy spread (% FWHM)	1-2.5		
Charge (nC/bunch)	91	100	a few
Micropulse length (ps)	20-30	15-40	10
Normalized rms emittance (πmm mrad)	70-200	1700	2

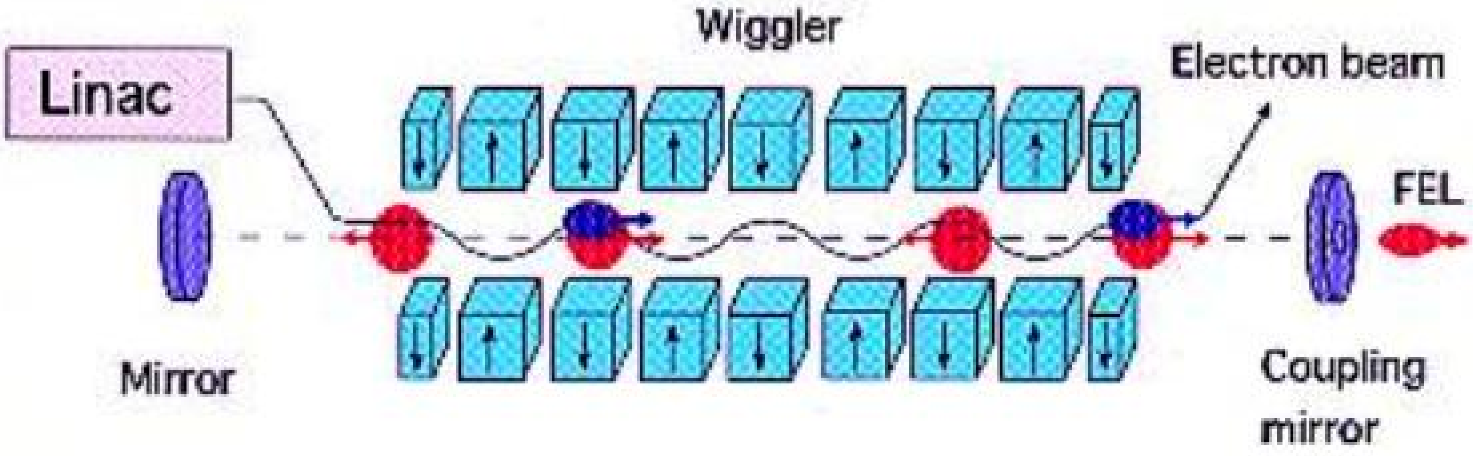
Estimated

Measured

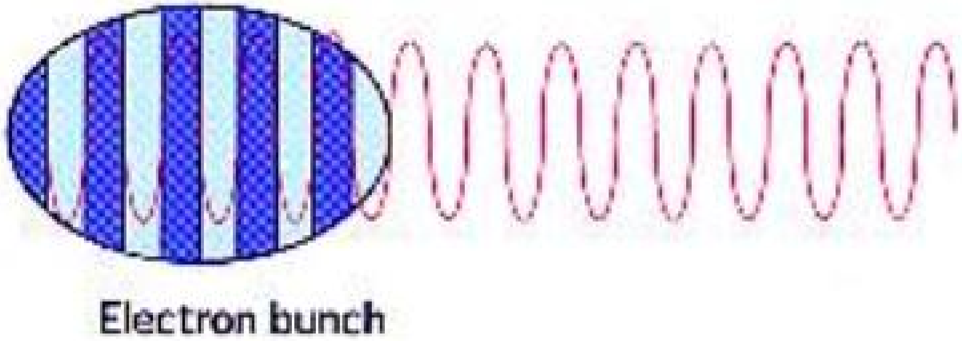
Operational modes of the linac



Free-electron lasers (FELs)



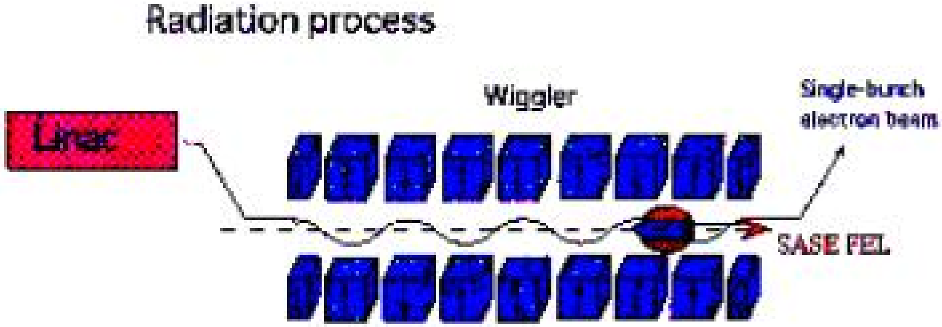
Density modulation and coherent radiation



Features of FELs

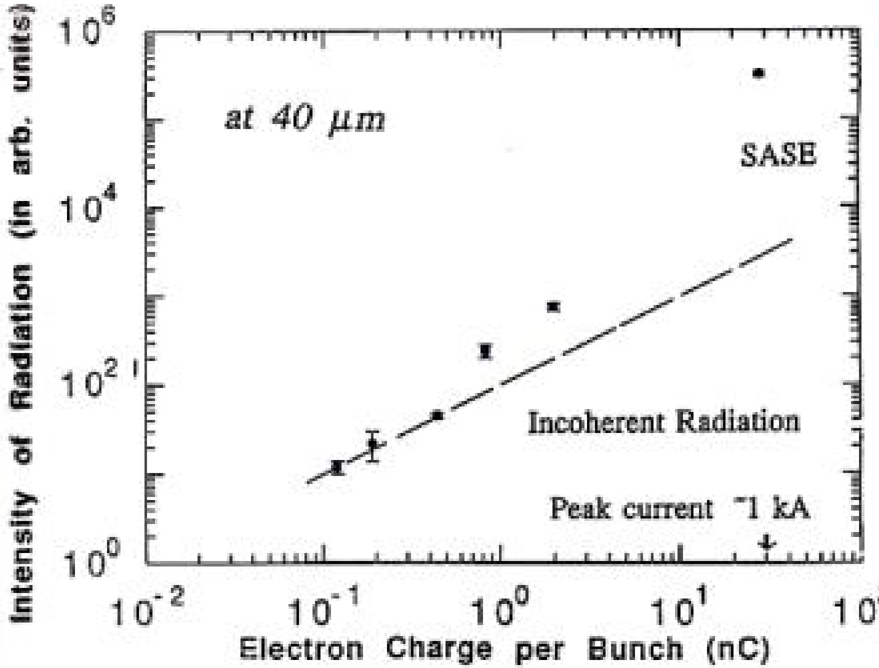
- Tunability
- Subpicosecond short pulse
- High peak power (MW)

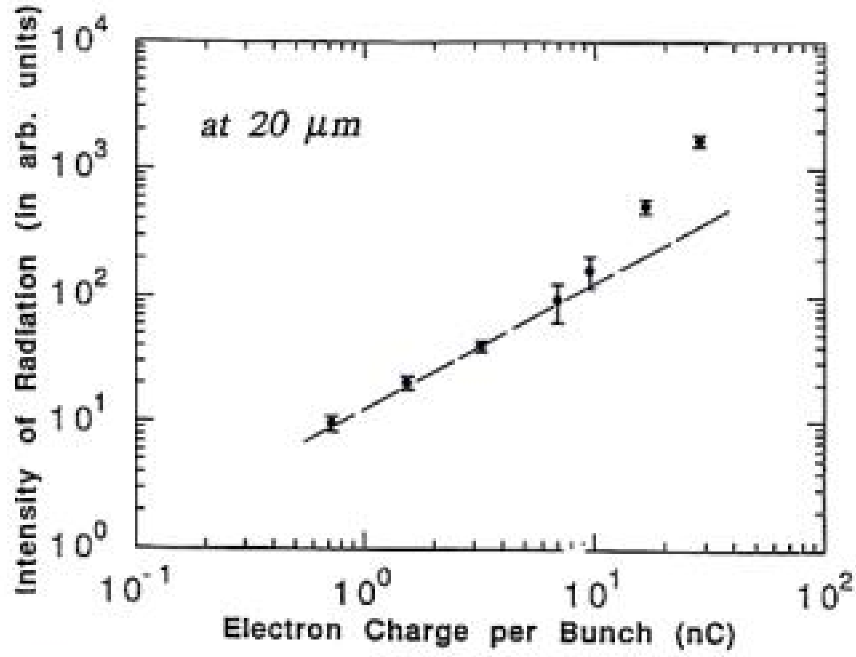
SASE (Self-amplified spontaneous emission) FEL



First lasing: 1991

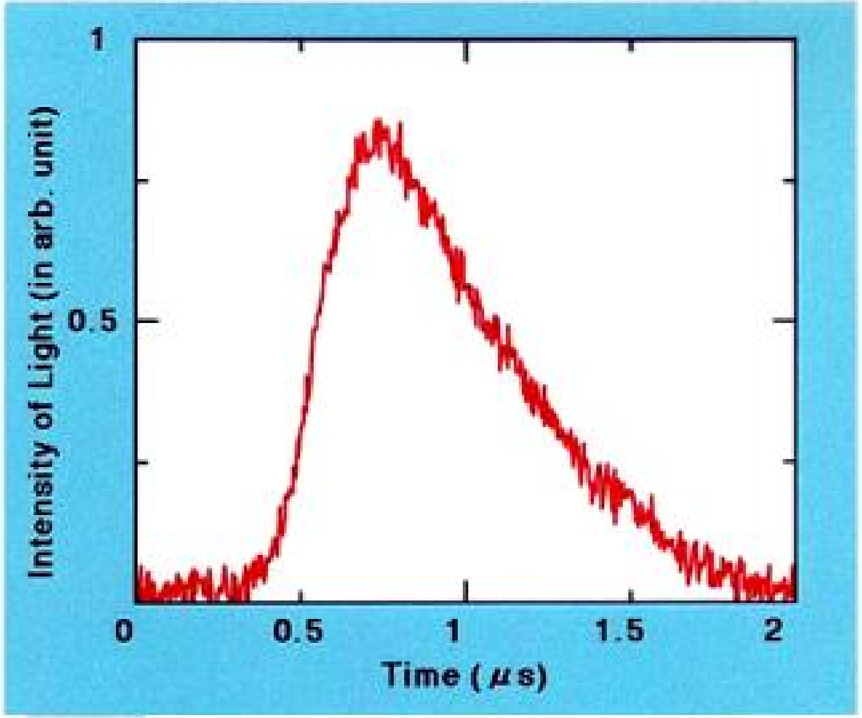
Single passage (no cavity mirror)
High gain
X-ray FEL





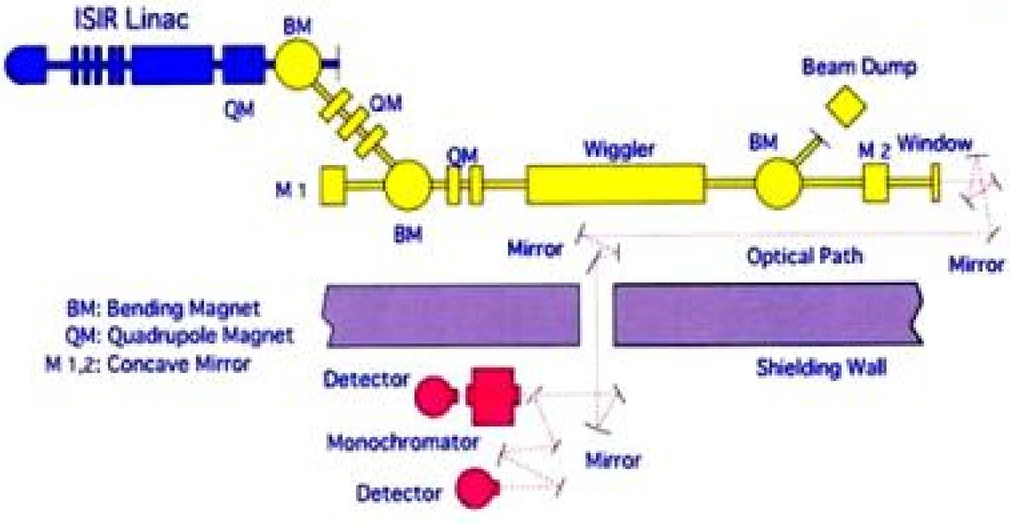
Oscillation FEL

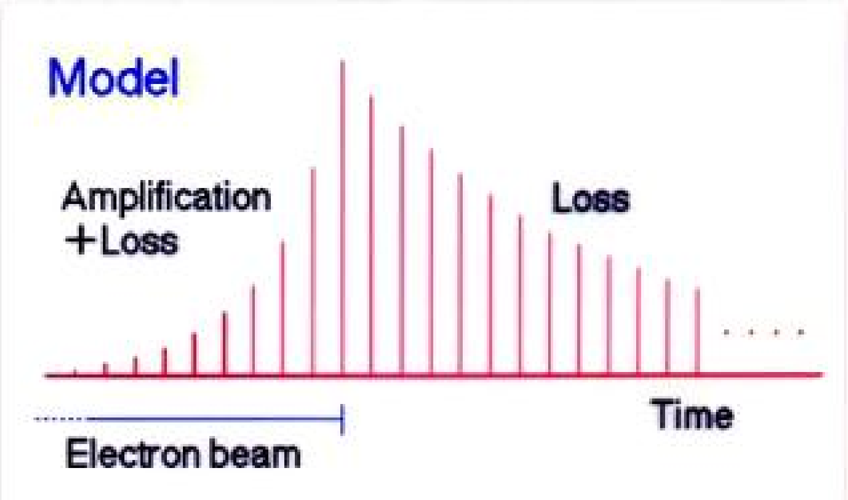
Output power of FEL light



Wavelength: 40 μm
Output power: 800 μJ/macropulse

First lasing: 1994






FEL facility
at Osaka Univ.

FEL研究の現状と動向

短波長化（SASE FEL）
DESY TTF (Germany, SASE, 80 nm)
APS (USA, SASE)
短波長化（蓄積リング）
Duke Univ. (USA)
電総研(Japan)，分子研(Japan)
Super ACO (France)
赤外ー遠赤外User Facility
Stanford Univ. (USA, SC linac), Vanderbilt Univ. (USA)
CLIO (France)
FELIX (Netherlands)
iFEL阪大(Japan, from FELI),東京理科大(Japan)
赤外高出力化
原研超伝導ライナックFEL(Japan, 2.3 kW av.)
Jefferson Lab.超伝導ライナックFEL(USA, 1.7 kW av.)
サブミリーミリ波、長波長域
UCSB (USA, Van de Graaff)
京大炉(Japan, Coherent radiation)，阪大産研(Japan, Coherent radiation)
研究装置
Los Alamos (USA, Oscillation), LBL (USA)
阪大産研(Japan, SASE, Oscillation)
Beijing FEL (China, Oscillation)
KAERI (Korea, Microtron)

日本の計画
日大(Oscillation) 、SPring-8(SASE) 、立命館大（Ring）、東北大(Pre-bunched FEL) 、佐賀(Oscillation)

FEL facilities

IR-FIR user facilities

Visible-UV Storage ring FELs

High power IR FELs

Superconducting linacs

X-ray SASE projects

Coherent radiation from an electron bunch

Power of radiation

$$P(\lambda) = p(\lambda)\, N\, [\, 1 + (N-1) f(\lambda)\,]$$

$p(\lambda)$: Power of radiation from one electron

λ : Wavelength of radiation

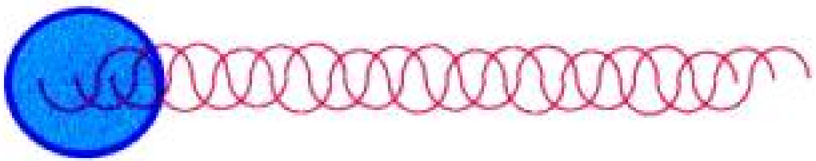
N: Number of electrons in a bunch

$f(\lambda)$: Bunch form factor

$$f(\lambda) = \left| \int S(x) \exp i(2\pi x/\lambda)\, dx \right|^2$$

$S(x)$: Normalized density distribution of electrons in a bunch

Electron bunch



Incoherent radiation

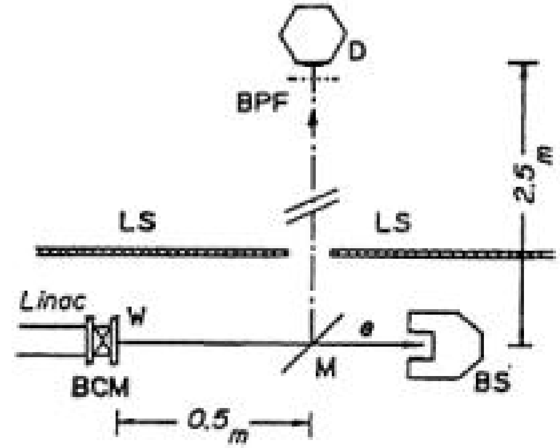
$$P \propto N e^2$$

$\times N\ (\sim 10^{11})$

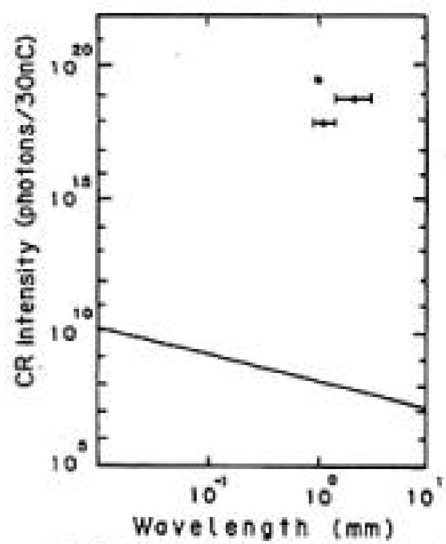
Coherent radiation

$$P \propto N^2 e^2$$

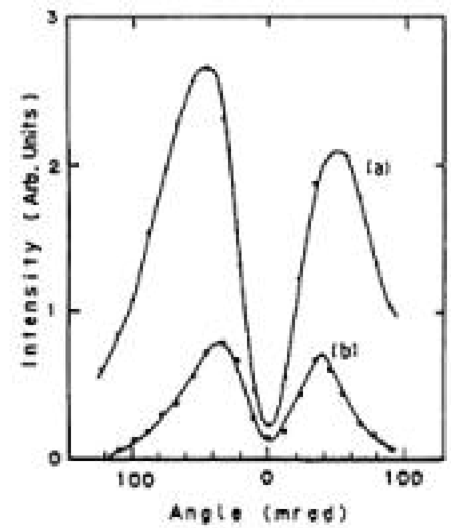
Our observation of coherent radiation



Schematic diagram of the experimental setup (BCM denotes beam current monitor, M denotes Au surface mirror, BS denotes beam stopper and current monitor, LS denotes light shield, BPF denotes bandpass filter, D denotes detector of Si bolometer for far-infrared light, and W denotes Ti-foil window).



The intensity of the CR measured for the bandwidths indicated with horizontal bars, the spectrum calculated according to Eq. (1) for 10% bandwidth (solid line), and the intensity expected for the complete coherence over the bunch for 10% bandwidth (open circle).



Relative angular distributions of the CR measured r bandwidths of (a) 0.4–3 mm and (b) 1–1.4 mm.

Phys. Rev. Lett. 1991

Characteristics of CR

High intensity in a submillimeter to millimeter range
(THz – 100 GHz)
Continuous spectrum
Coherence
Pico-second short pulse
Synchronization with the electron bunch

Applications of CR

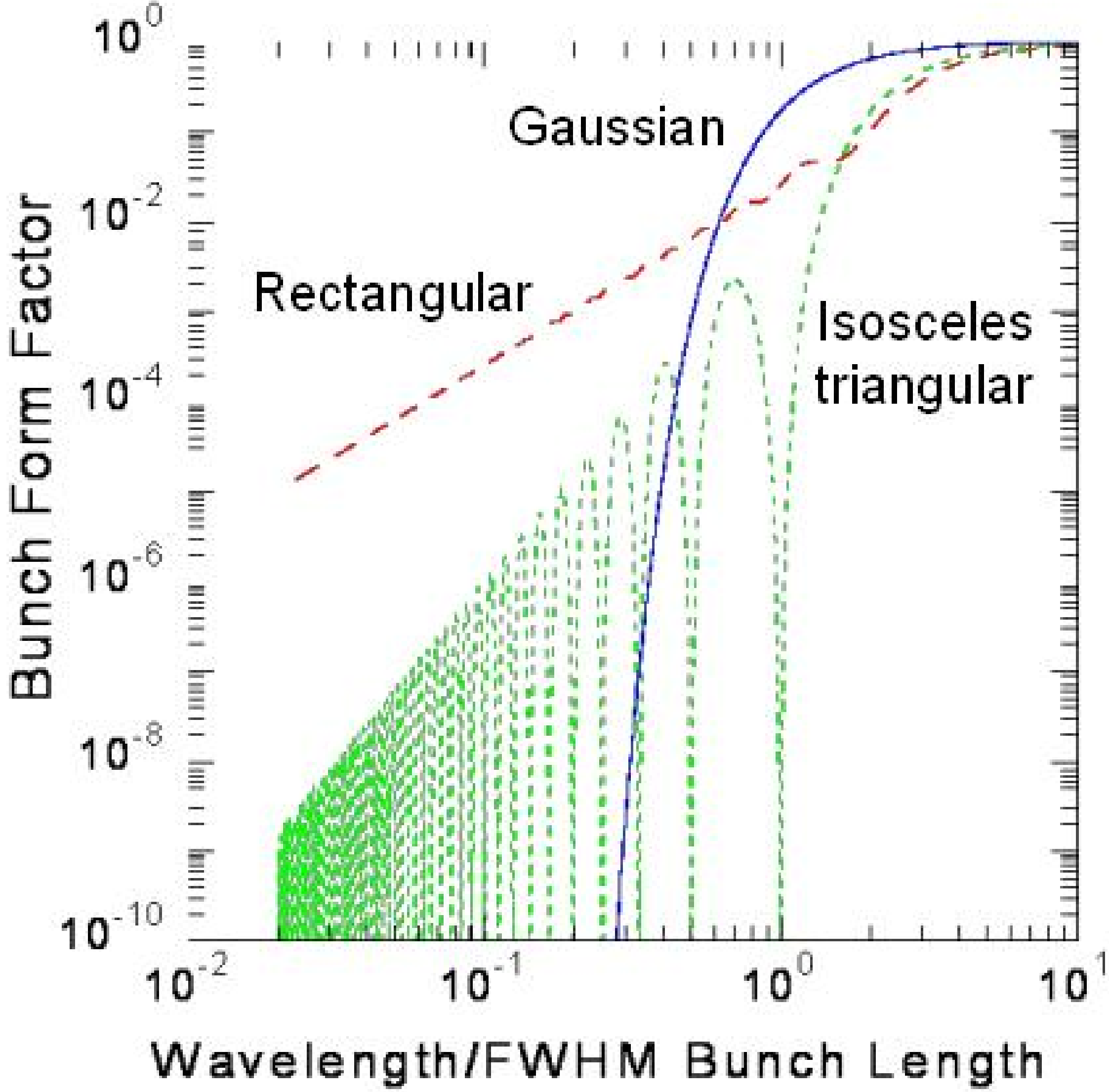
Absorption spectroscopy
Analysis of transient phenomena
Imaging
Coherent excitation
Pump and probe analysis

Applications of the radiation

Electron bunch shape monitor

Far-infrared light source
for absorption spectroscopy

Bunch form factors for various bunch shapes



Wavelength is normalized by the FWHM bunch length.

Bunch sape monitoring system

Streak measurement

Time resolution 0.9 ps

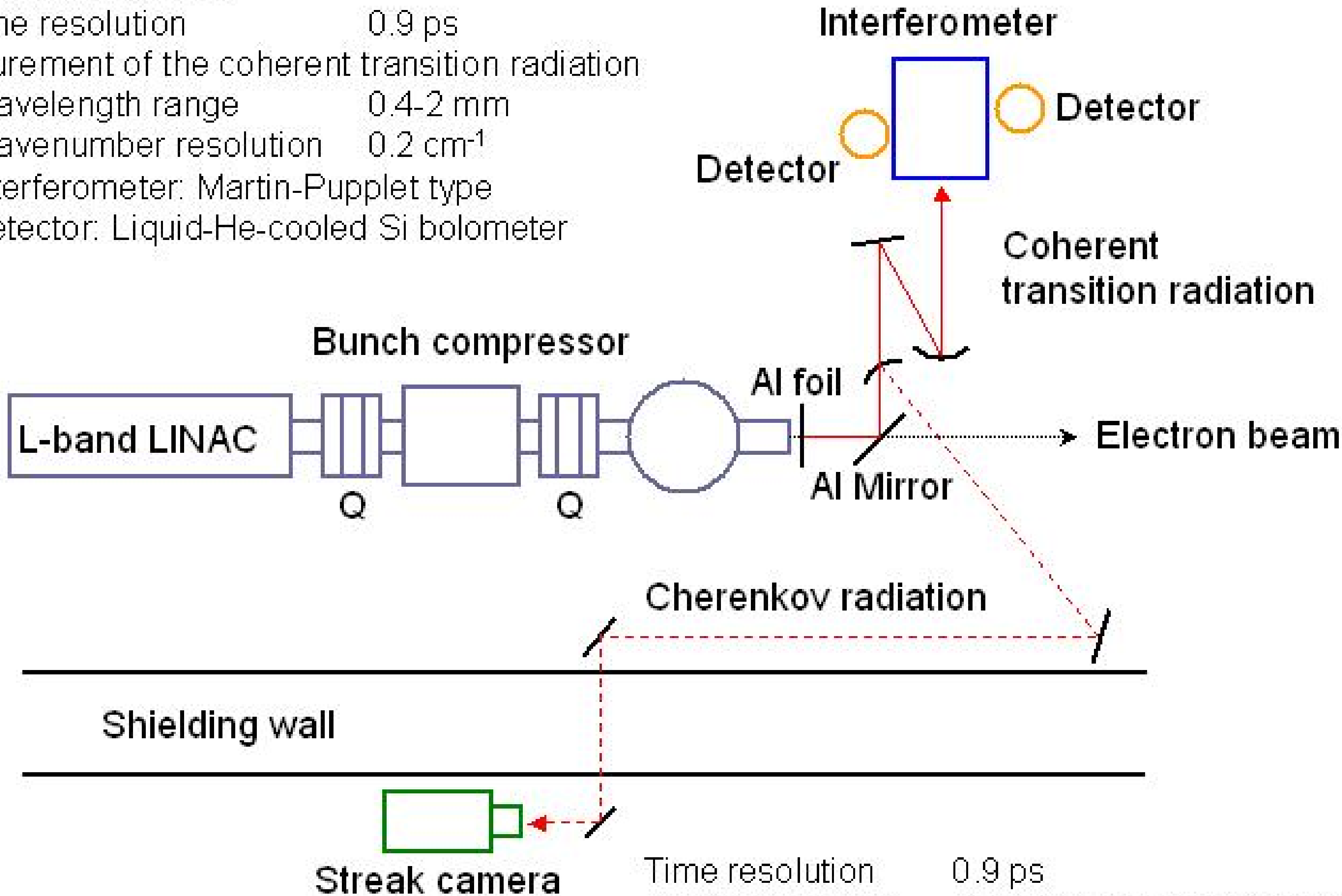
Measurement of the coherent transition radiation

Wavelength range 0.4-2 mm

Wavenumber resolution 0.2 cm^{-1}

Interferometer: Martin-Pupplet type

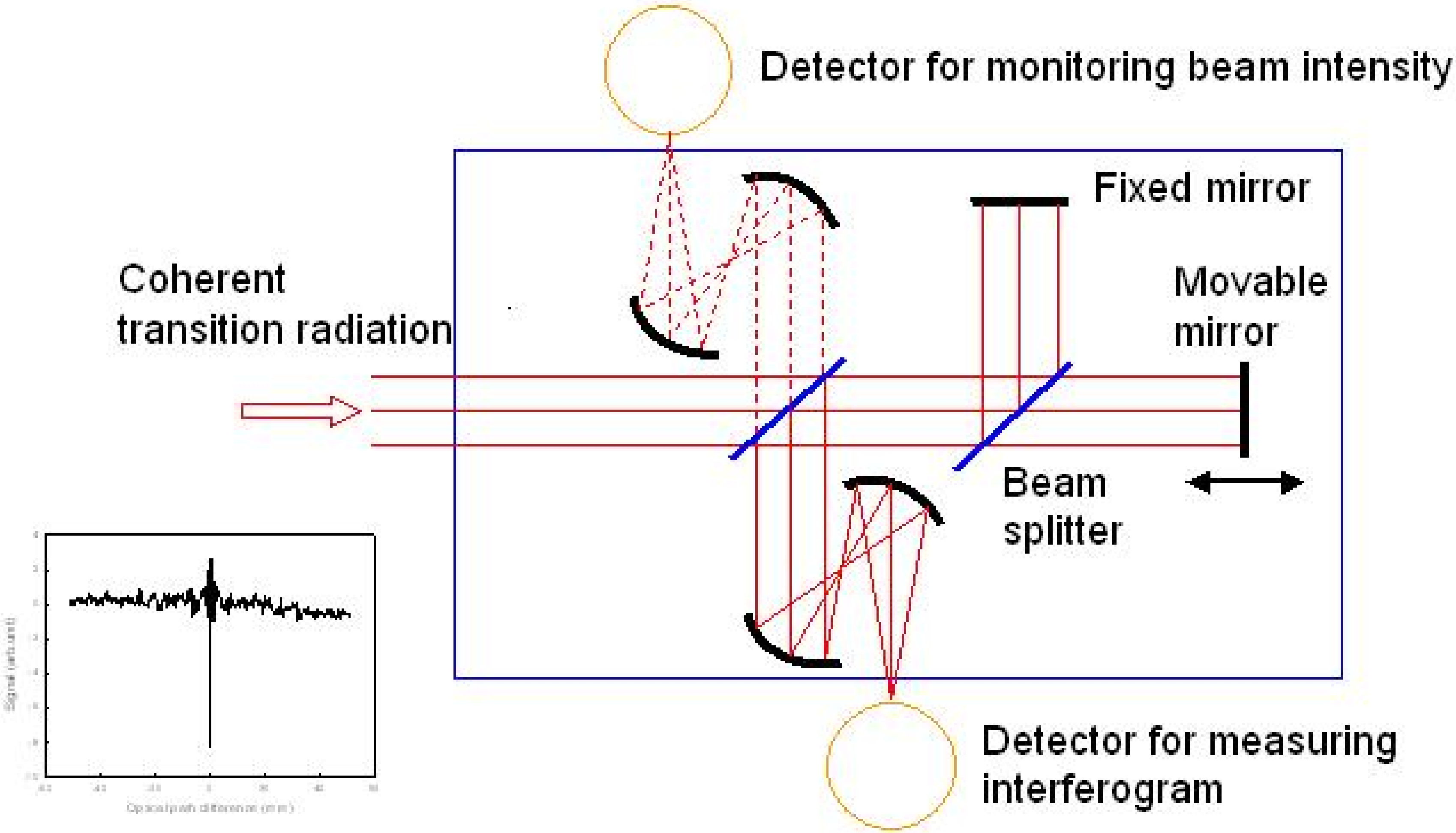
Detector: Liquid-He-cooled Si bolometer



Time resolution 0.9 ps

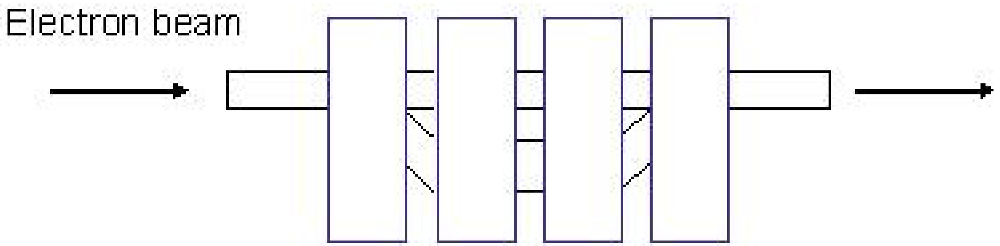
Interference filter 478.5 nm (B. W.: 11.3 nm)

Martin-Pupplet interferometer



Beam splitter : wire grid with a wire spacing of 25 μm

Bunch compression with a bunch compressor

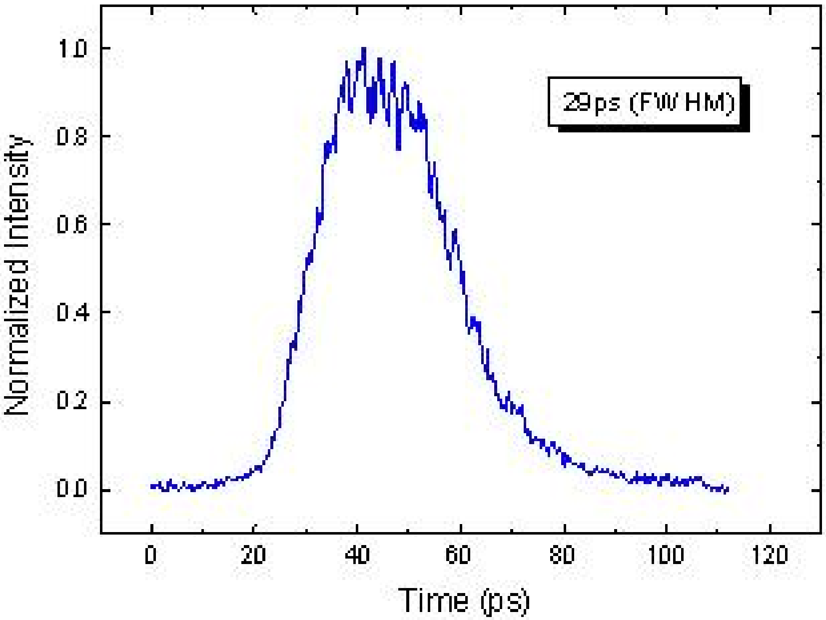


4 pole chicane-type bunch compressor

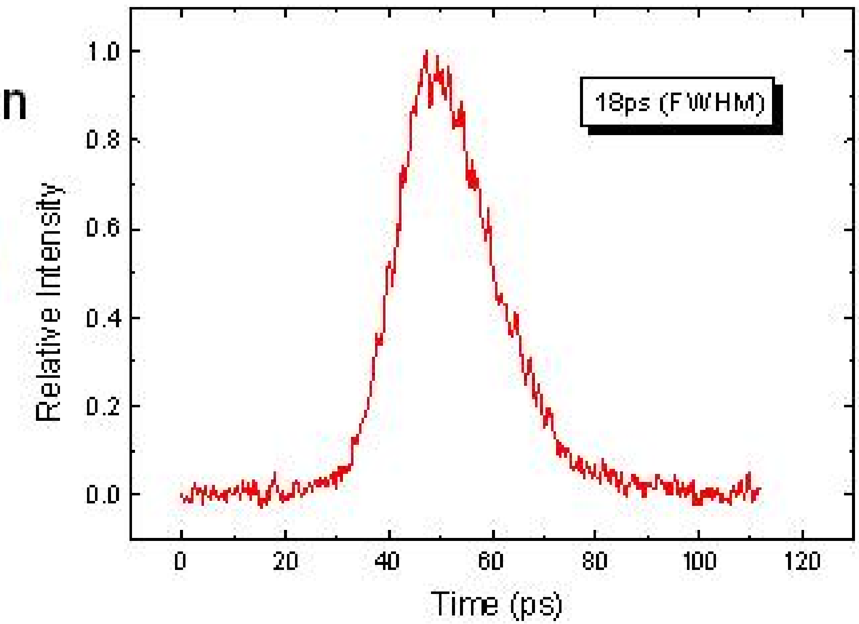
Magnetic field	0.105 T
Deflection angle	0.27 rad

Single-bunch beam parameters

Energy	27 MeV
Energy spread	1.1 % (FWHM)
Charge/bunch	13.5 nC



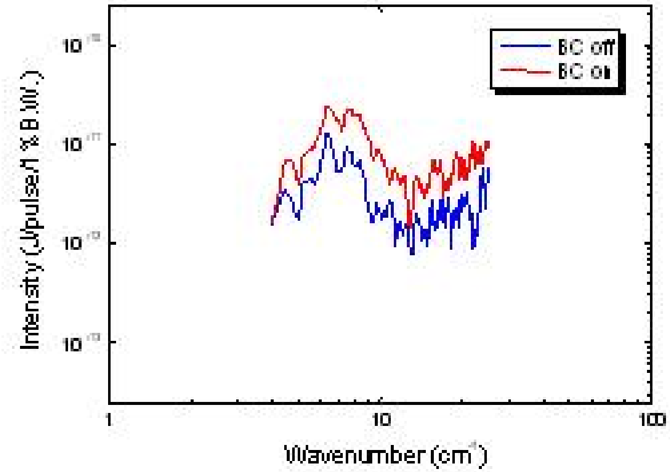
B.C. on



Bunch shapes measured with a streak camera

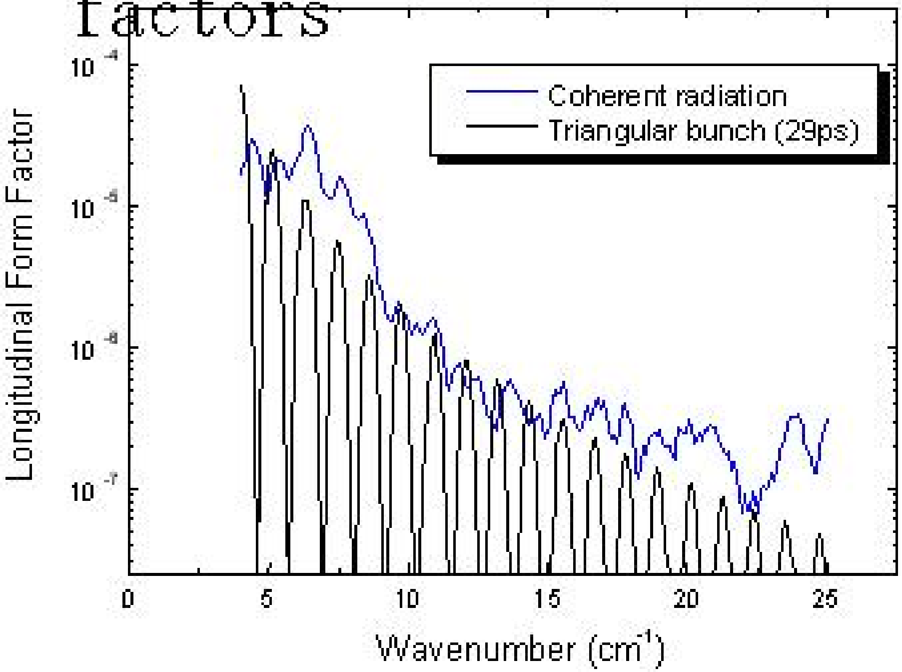
Spectra of CR and bunch form factors

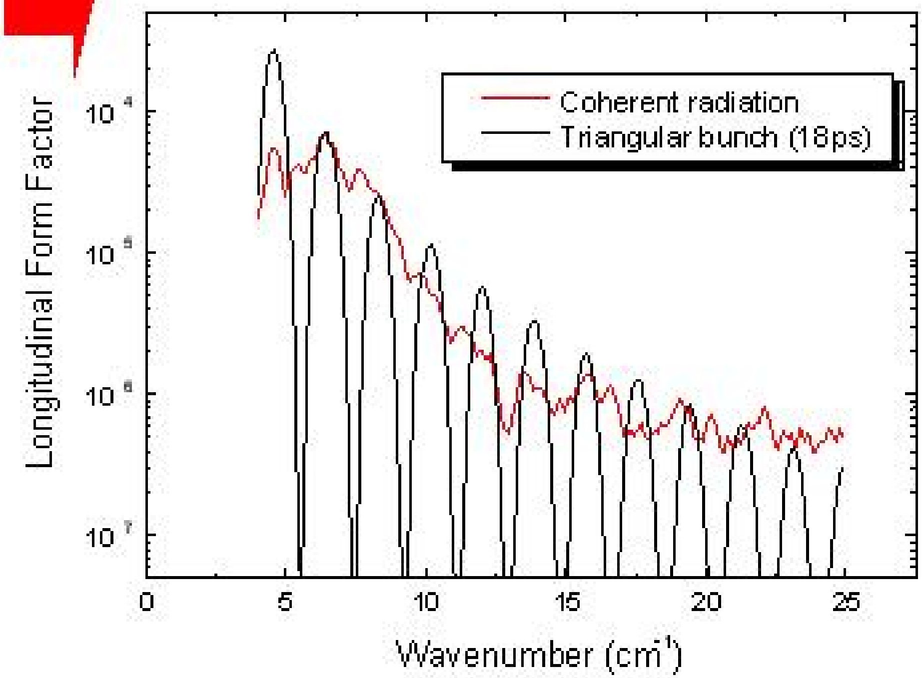
Spectra of CR



B.C. on

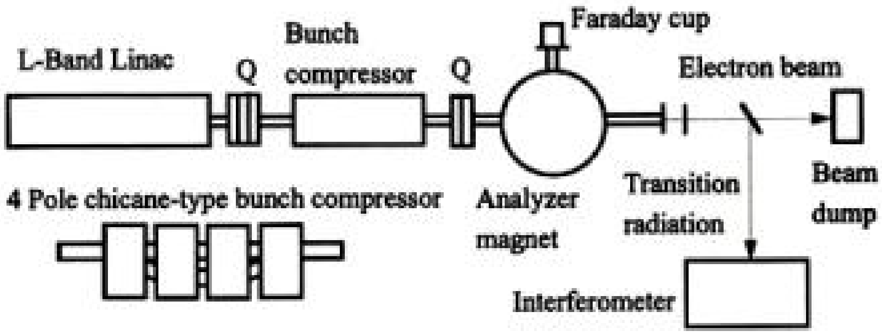
Bunch form factors





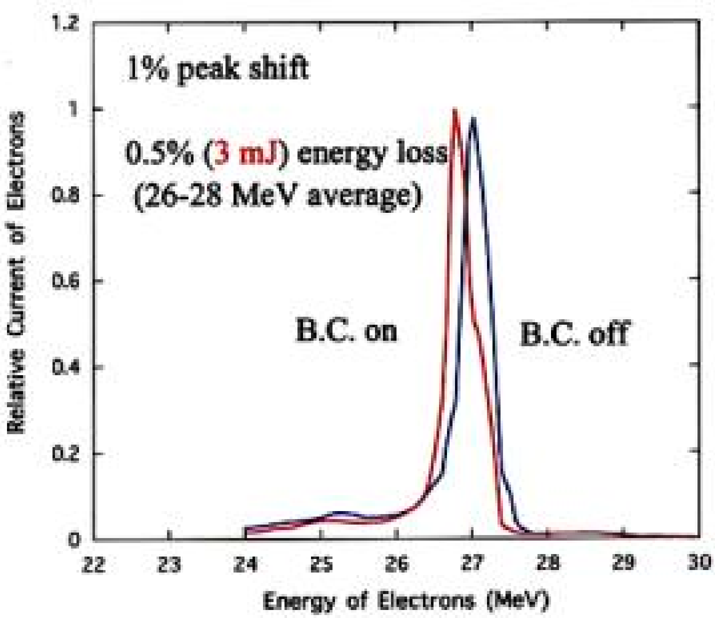
Bunch form factor at λ=1 mm: $10^{-6} \rightarrow 10^{-5}$

Radiation loss of the single-bunch beam energy in the bunch compressor



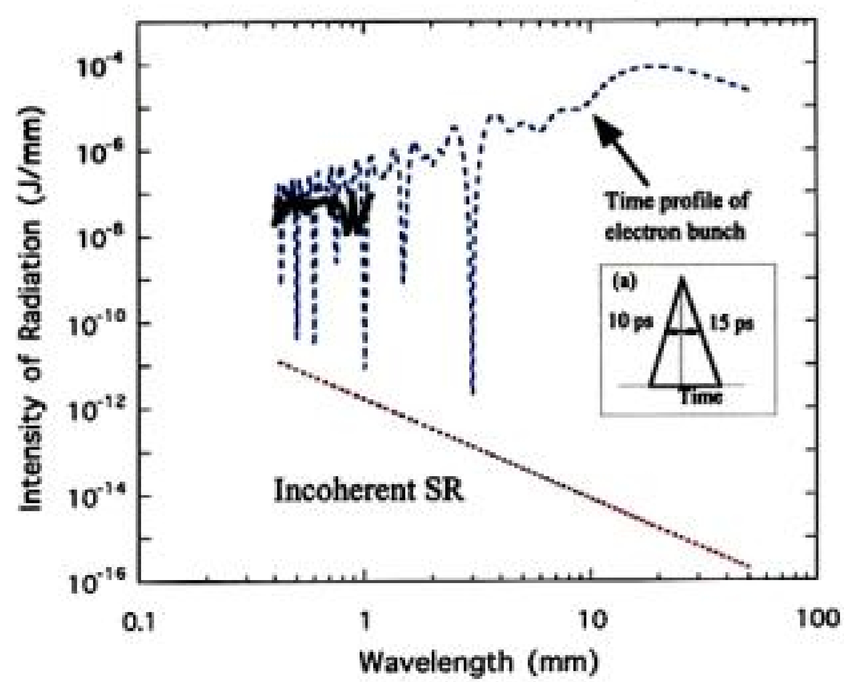
Peak energy: 27 MeV
Energy spread: 1.4% (FWHM)
Bunch length: 25 ps (FWHM)
Charge: 22 nC/bunch

Energy spectra of the electron beams



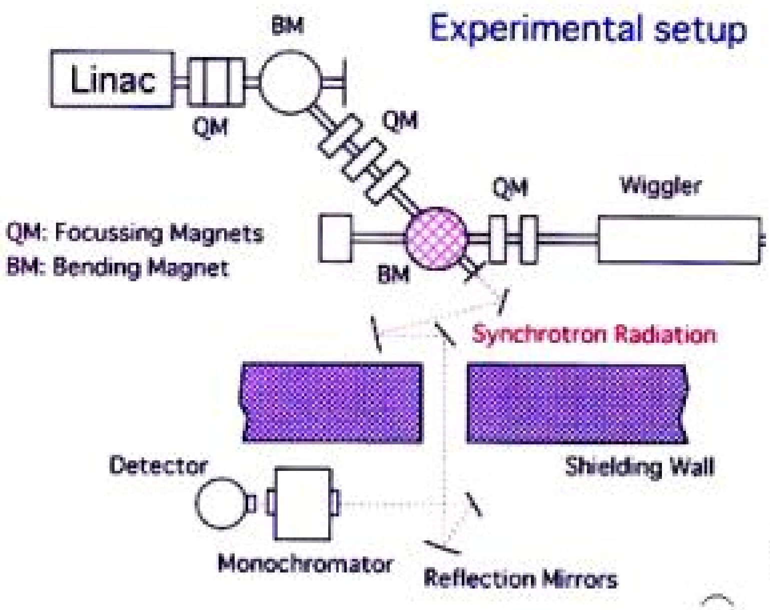
Energy resolution: 0.1%

Radiation spectra from B.C. obtained from the interferogram

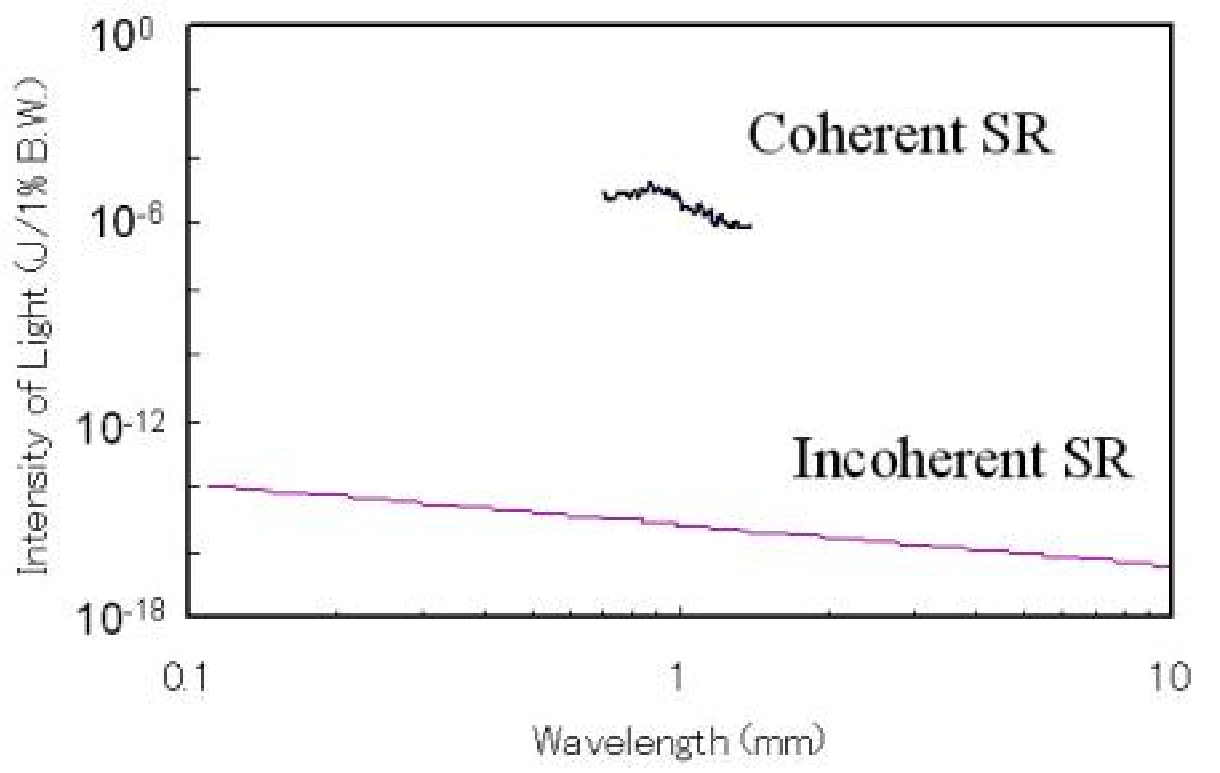


Energy loss evaluation: 2 mJ

Coherent synchrotron radiation light source



Beam conditions
- Energy: 27 MeV
- Electron charge: 30 nC/bunch
- Bunch length: 5-10 ps



CSR power

1 μJ/%B.W. at 1 mm

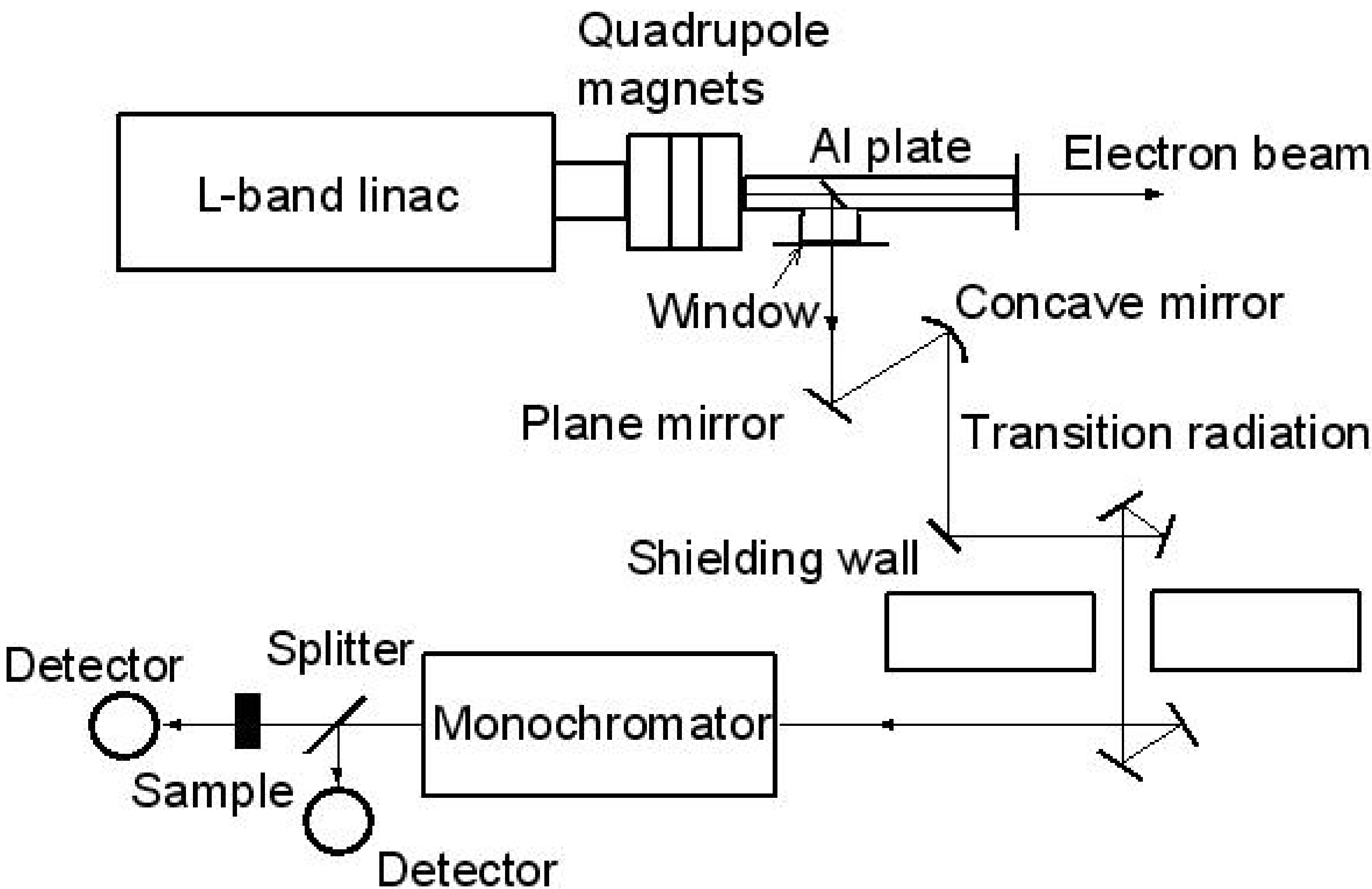
0.3 mJ at 0.7-1.4 mm

(>30 MW peak power)

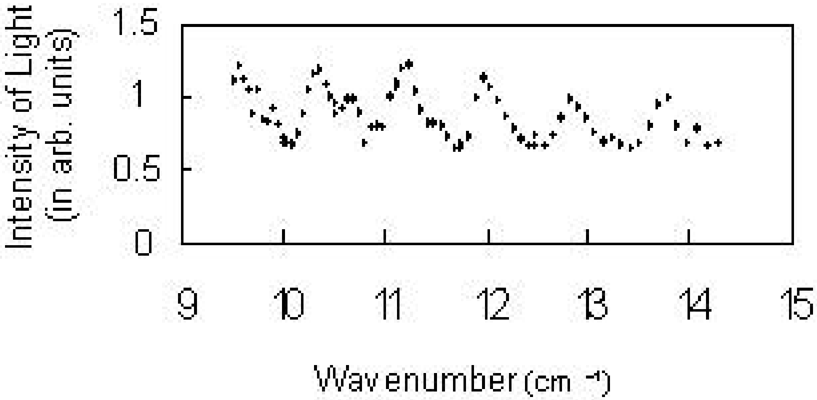
Submillimeter to millimeter wave light sources

Peak power	(at λ=1 mm)	Averaged power
1	Coherent radiation (100 Hz)	1
10^{-5}	Terahertz radiation source (10 MHz)	10^{-1}
10^{-12}	Incoherent SR source (10 MHz)	10^{-4}
10^{-20}	Blackbody source (DC)	10^{-5}

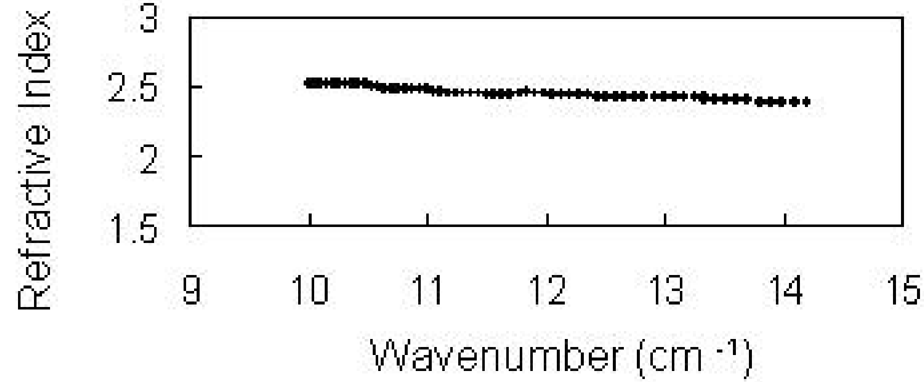
Experimental setup for absorption spectroscopy using CTR



Absorption spectroscopy for water



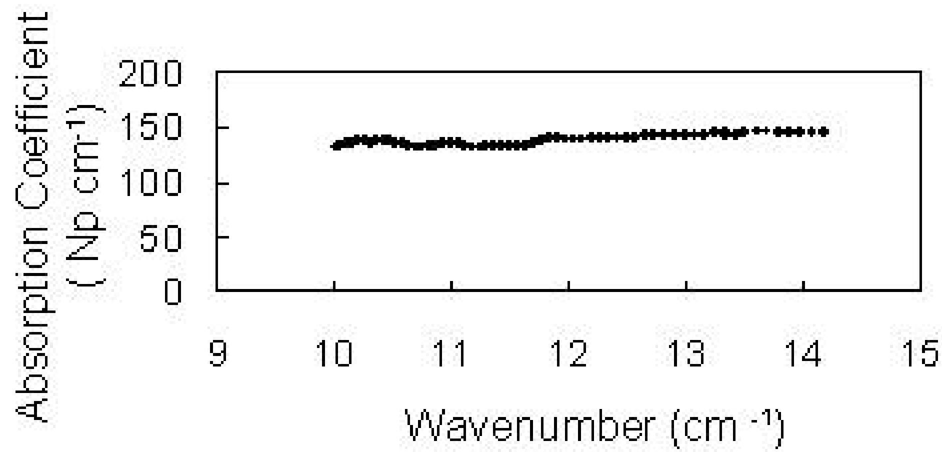
(a)

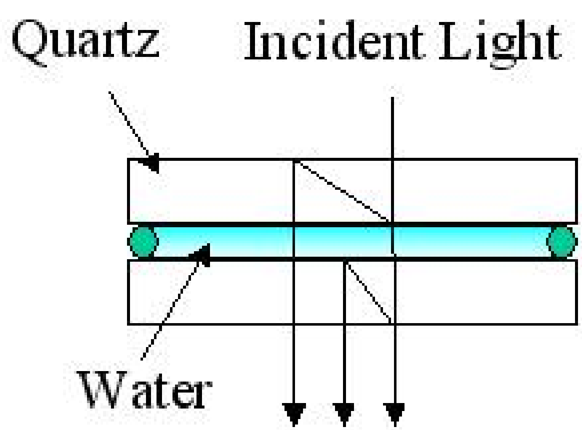


Temperature: 22 ℃

Thickness of the sample: 186 μm

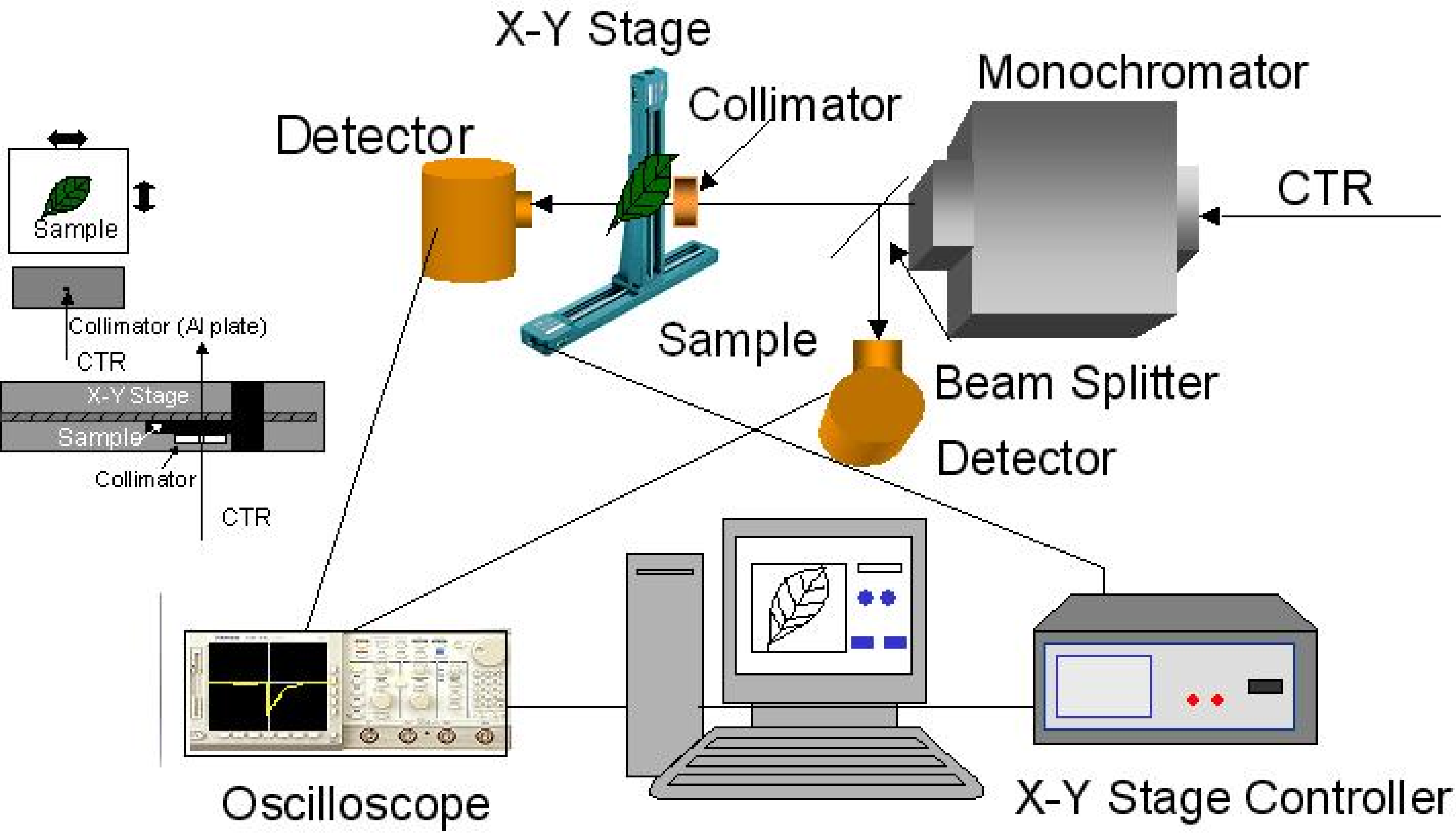
(b)





Resolution: 1%

Setup for imaging



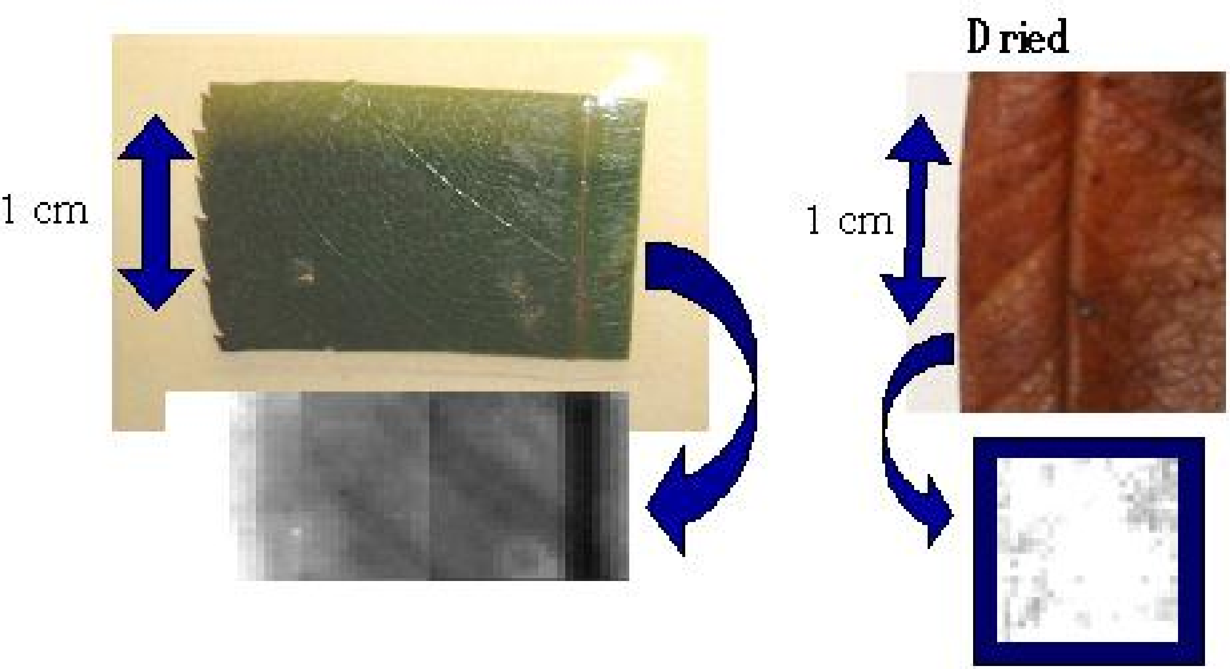
Imaging with CTR

Print

Peak wavenumber : 11.1 cm^{-1}

Wavenumber width: 0.2 cm^{-1}

Resolution: 0.8 mm



Leaf

Peak wavenumber : 10.7 cm^{-1}

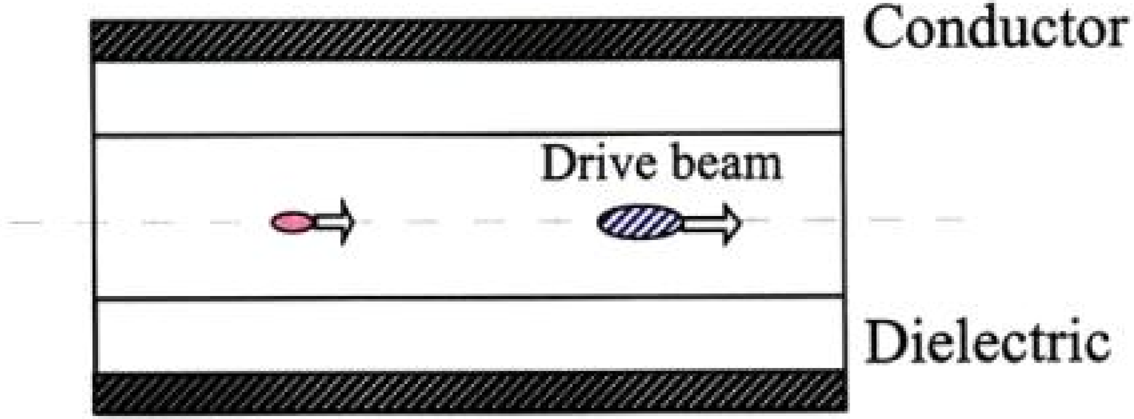
Wavenumber width: 3.5 cm^{-1}

Resolution: 0.8 mm

Transmission (%)

Other application

Wakefield Acceleration



Summary

High-current electron linac

91 nC/bunch (kA peak current)

Coherent radiation from electron beams

FELs

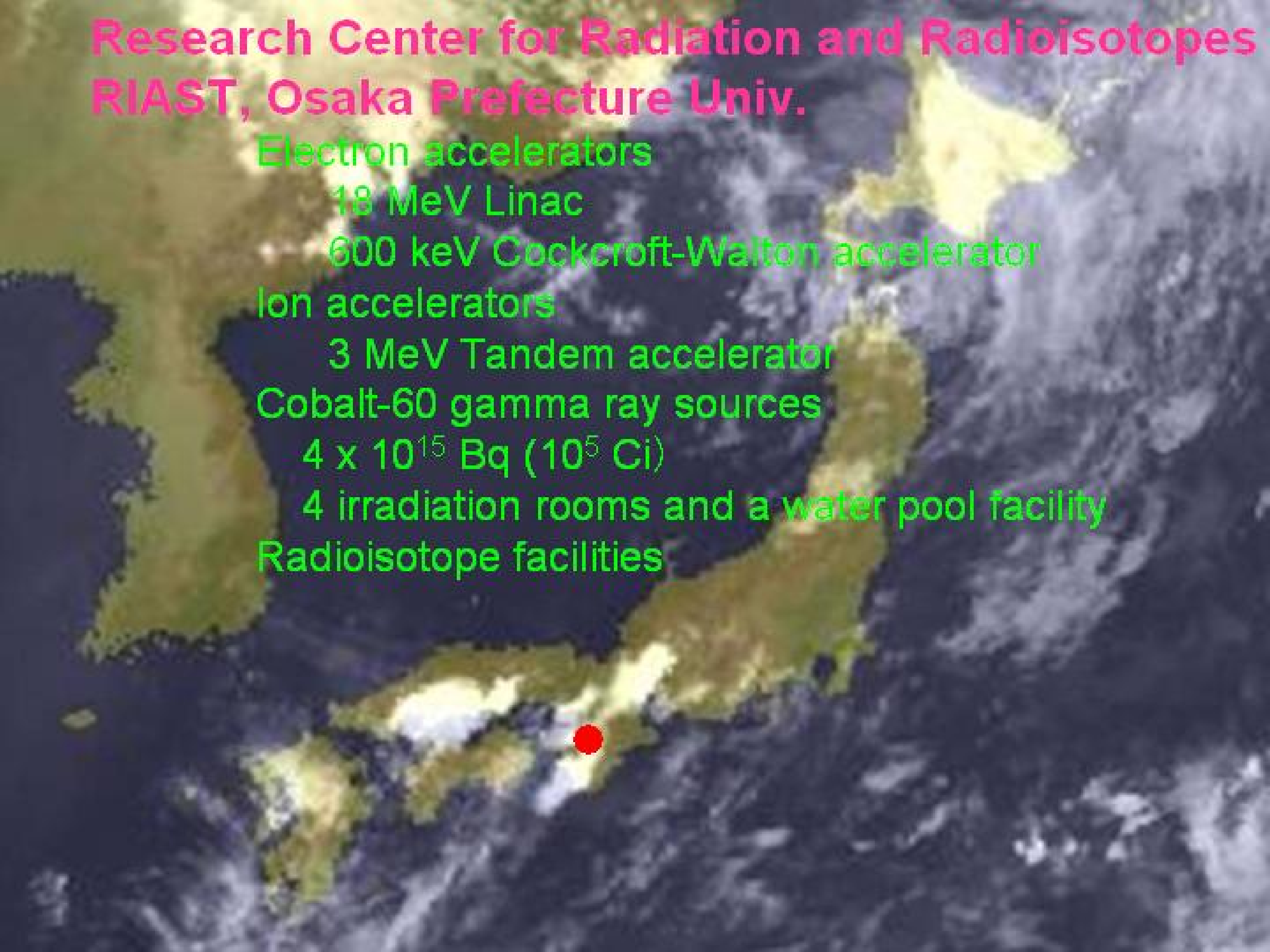
Coherent radiation

Applications of the coherent radiation

Electron bunch shape monitor

Absorption spectroscopy

Other applications


Research Center for Radiation and Radioisotopes
RIAST, Osaka Prefecture Univ.
Electron accelerators
18 MeV Linac
600 keV Cockcroft-Walton accelerator
Ion accelerators
3 MeV Tandem accelerator
Cobalt-60 gamma ray sources
4 x 10^{15} Bq (10^5 Ci)
4 irradiation rooms and a water pool facility
Radioisotope facilities

Water pool for ^{60}Co γ-ray sources


Cherenkov radiation
from ^{60}Co γ-ray sources
installed