FRAAU04

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Re-Commissioning of the Far-Infrared Free Electron Laser for Stable and High Power Operation after the Renewal of the L-Band Linac at ISIR, Osaka University

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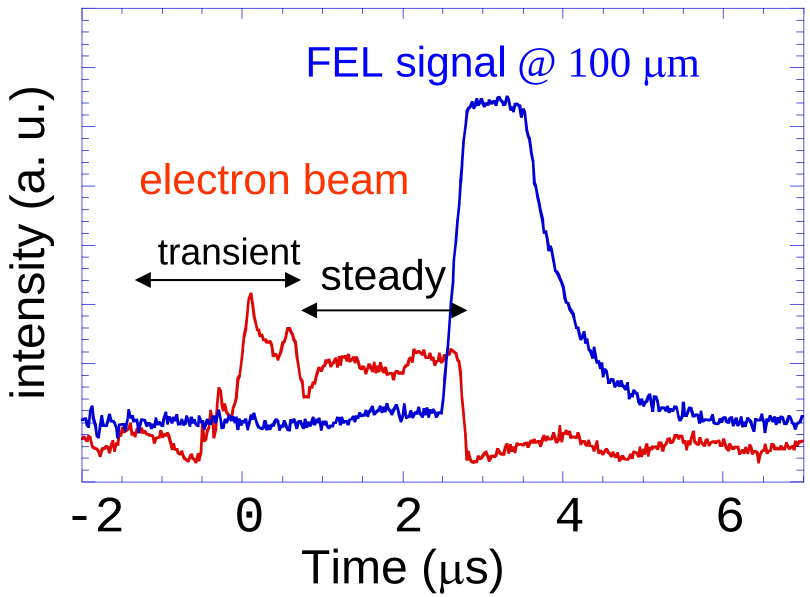
Progress of Far-Infrared FEL at ISIR, Osaka University

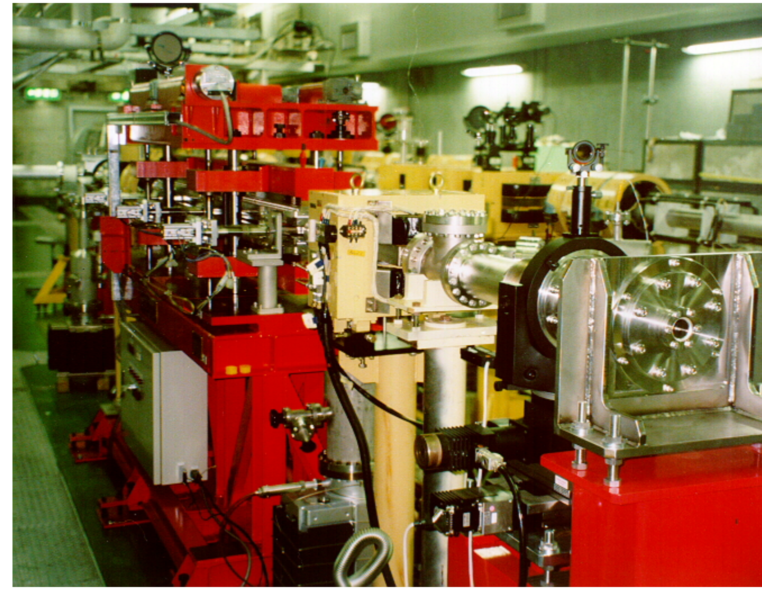
- FAR-IR FEL development started (‘89)
- First lasing at 32-40 μm (‘94)
- Gain, loss measured. (‘95)
  - 58 %, 6 % @40 μm
- Modification started for longer wavelengths (‘96)
  - target wavelength > 150 μm
- Lasing at 21-126 μm (‘97)
- Lasing at 150 μm (‘98)



- FEL power saturation not realized

- Important problems:
  - Stability of the linac not sufficient.
  - Macropulse duration short (~2 μs) .
    - Due to a long filling time of the accelerating tube (~2 μs)
    - Number of amplifications limited to ~50

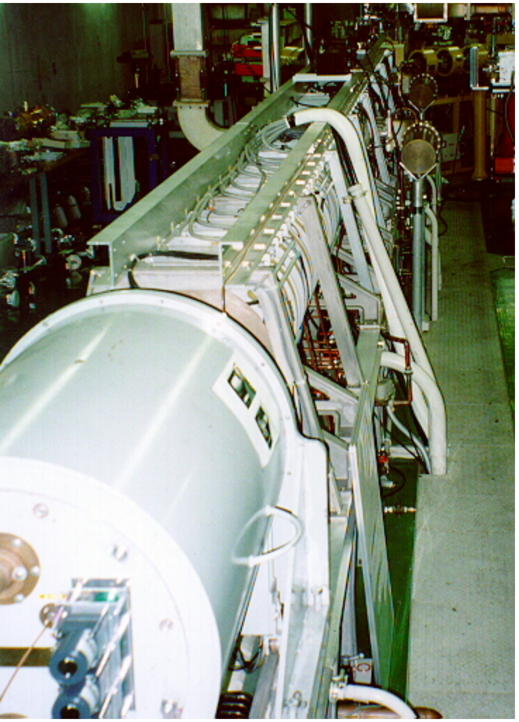
ISIR-FEL System

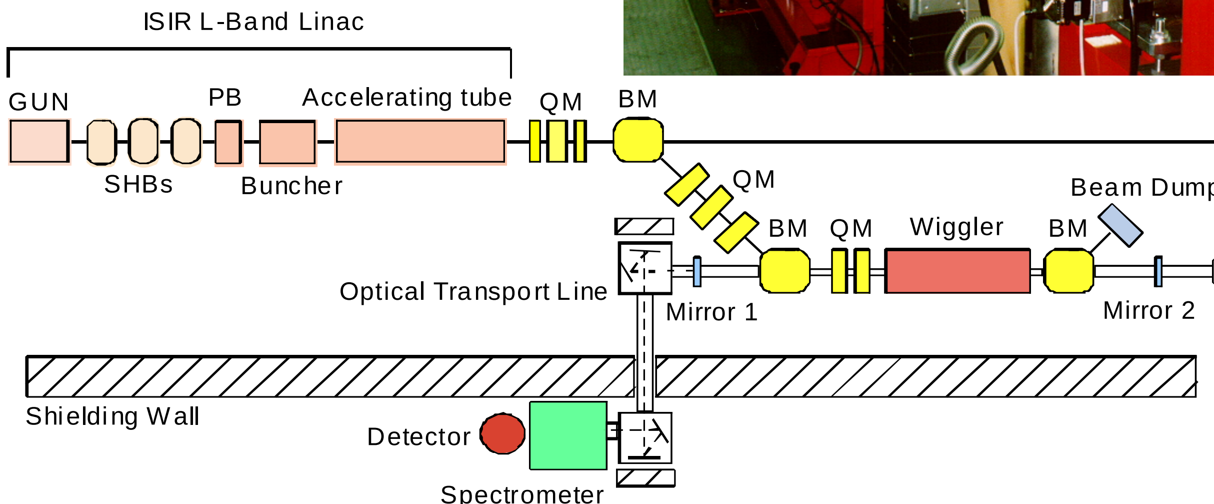


Wiggler : EF planar, Nd-Fe-B

L_w=1.92 m, λ_w=60mm, N_w=32

gap=120-30mm, K=0.013-1.472





Linac : L-band (1.3 GHz)

E_{max}=40 MeV, L_{bunch}=20-30 ps

Single bunch operation using the three stage sub-harmonic buncher system (SHB:2×108MHz+1×216MHz)

→ max. 91nC/bunch

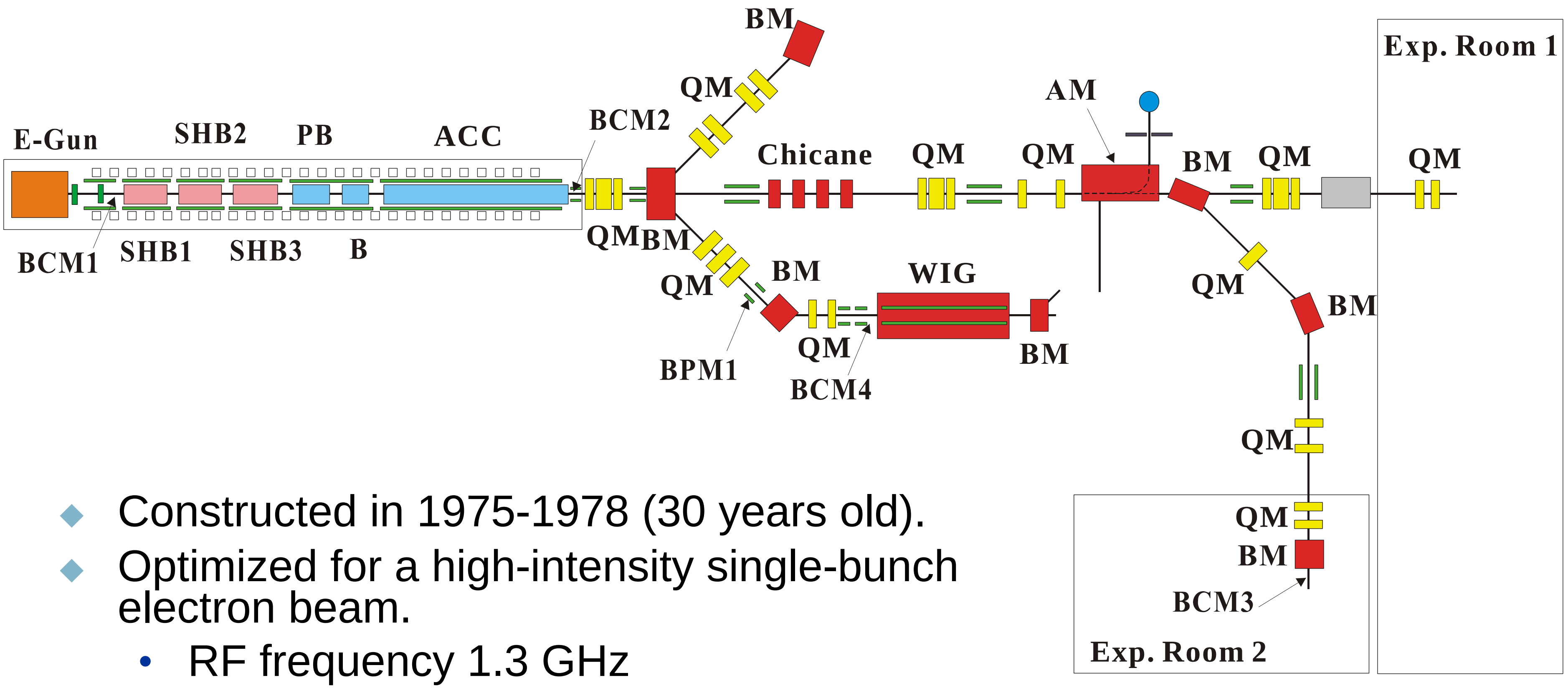
Monochromator :

Cross Czerny-Turner type with a plane grating (7.9 grooves / mm)

Detector :

Ge:Ga photo conductive

L-band Linac



- Constructed in 1975-1978 (30 years old).
- Optimized for a high-intensity single-bunch electron beam.
  - RF frequency 1.3 GHz
  - Three-stage sub-harmonic buncher system
  - Maximum charge per bunch 91 nC
    30 nC (typical)

Renewal of the L-band linac

- Budget approved in 2002 to modify the linac.
- Objective
  - Highly stable and reproducible operation
  - Easy operation for users experiments
- Policy for remodeling
  - Basic components of the linac unchanged, such as accelerating tubes and bending magnets.
  - Introduction of a computer control system
  - Replacement of almost all the power supplies for the linac, including a klystron and its pulse modulator
- Klystron and its pulse modulator
  - Normal mode: 4 μs duration and 30 MW
  - Long pulse mode for FEL: 8 μs and 25 MW

- FEL development suspended for renewal or modification on the linac.

Commissioning of the Linac

- Began in the autumn of 2003 and it took a year.
- Many problems
  - Discharge in components of the RF power transmission line.
  - Fine and random fluctuations of RF power.
  - Not only new components but also old ones.

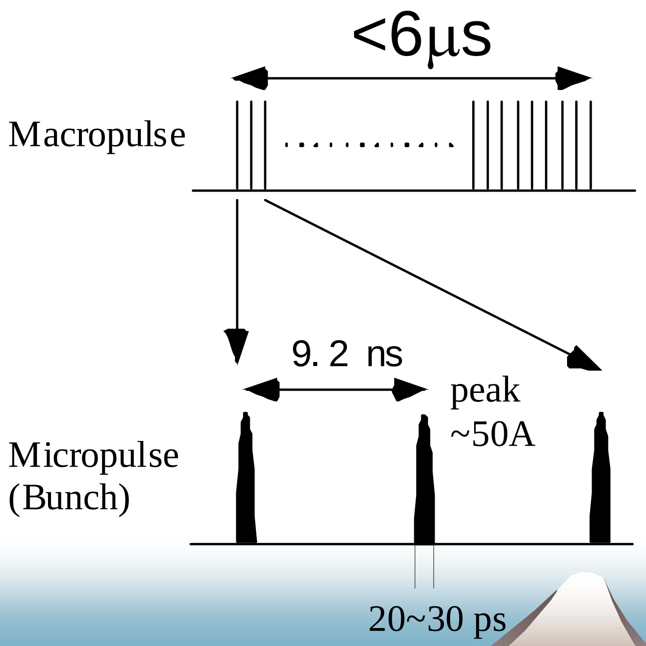
- User experiments using two short pulse modes began in the autumn of 2004.
  - Transient mode for pulse radiolysis in the nanosecond region
  - Single bunch mode for pulse radiolysis in the sub-picosecond region and for SASE in the far-infrared region.

- In parallel with user experiments, commissioning of the long-pulse mode continued.
  - Steady mode (w/o SHB)
  - Multi-bunch mode for FEL (w SHB)

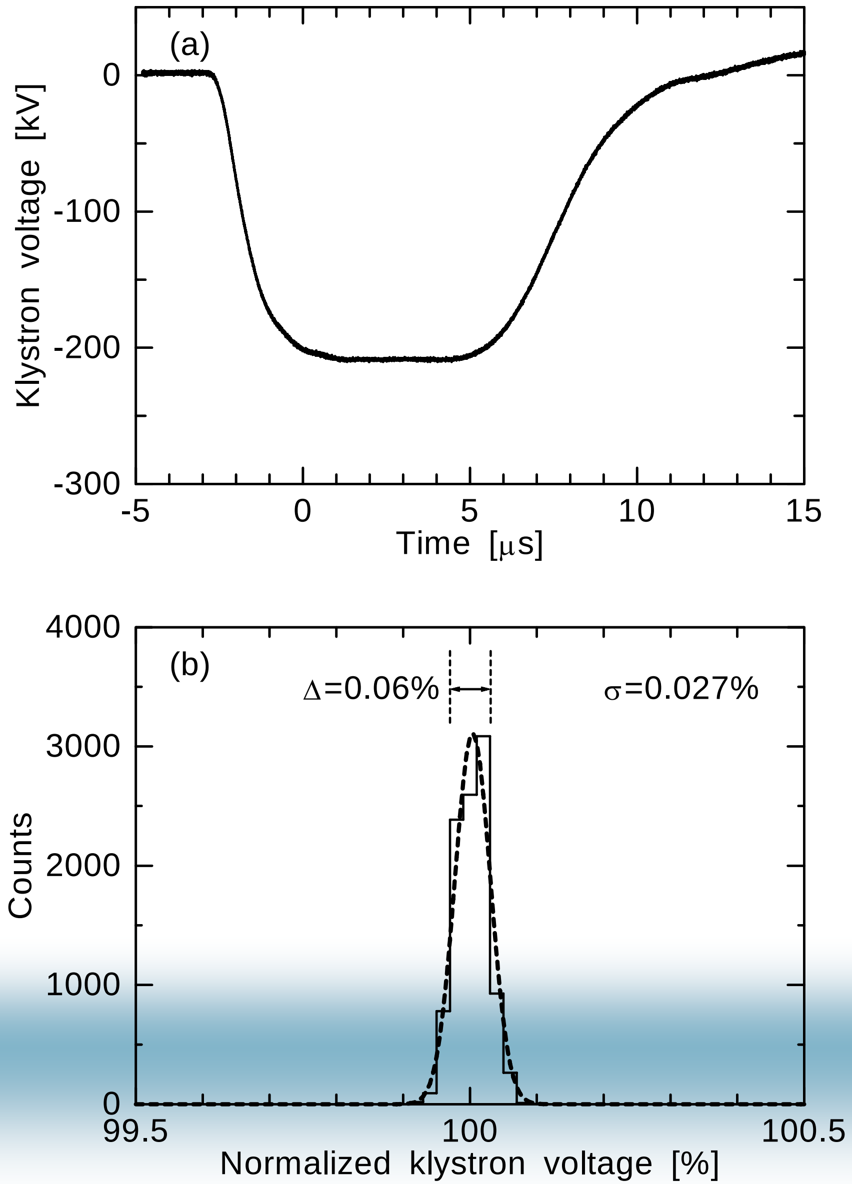
Multi-Bunch Mode for FEL

- Second 108 MHz and the 216 MHz cavities of the SHB system turned on.
- Klystron modulator operated in the long pulse mode.
- Long pulse electron beam with duration up to 8 μs injected from the thermionic electron gun.

Electron beam	
energy	11-19 MeV
accelerating freq.	1.3 GHz
bunch spacing	9.2 ns
repetition	< 30 Hz
macropulse length	< 6 μs
energy spread	1.5-5 %
charge per bunch	< 2 nC
bunch length	20-30 ps
peak current	< 50 A
norm. emittance	100-150 π mm mrad

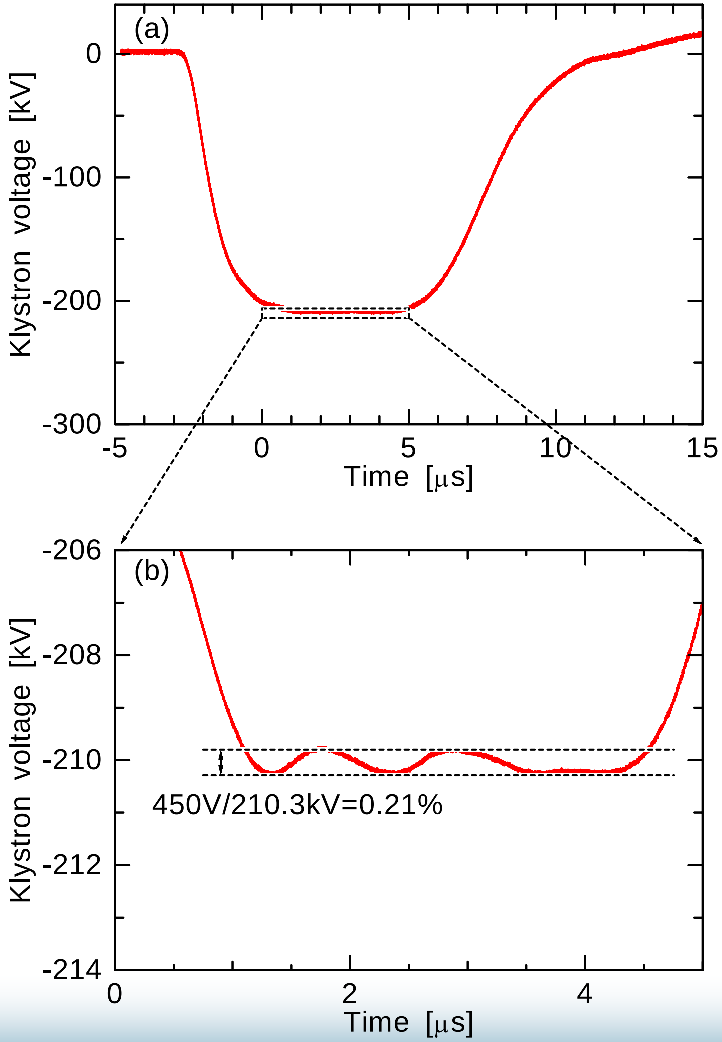


Stability of Klystron Voltage



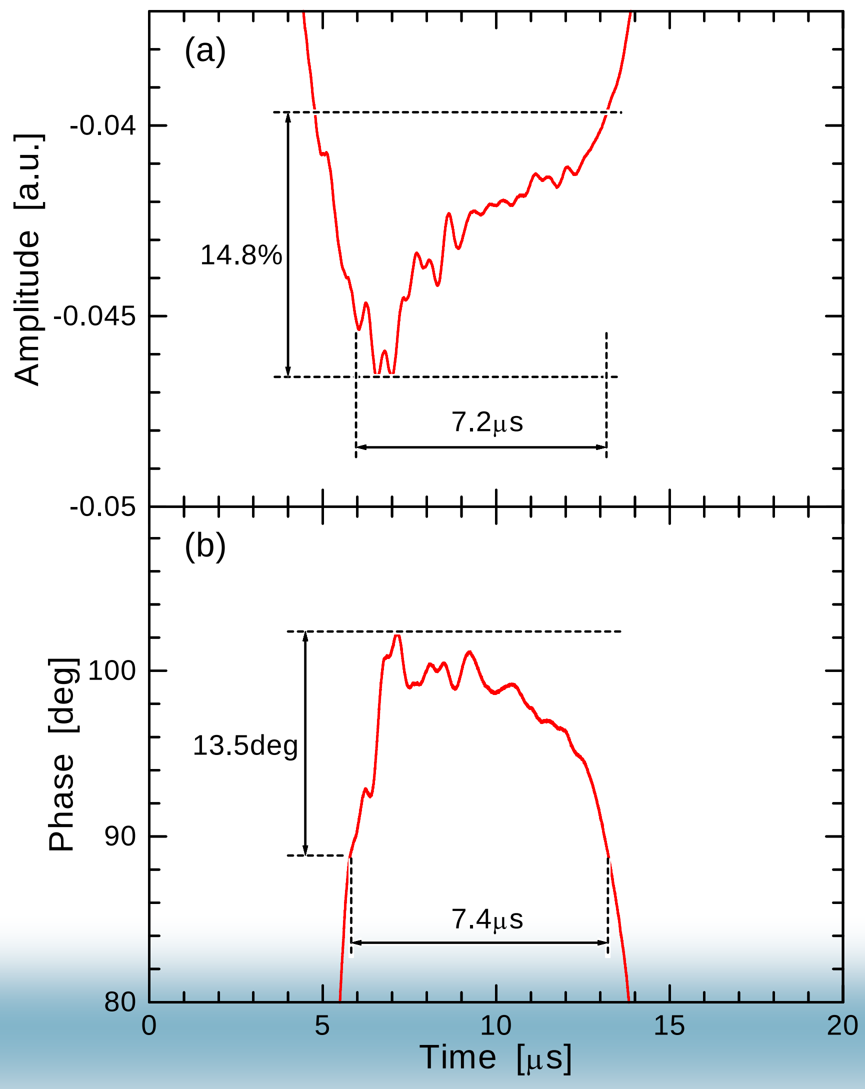
- For FEL experiments, stability of the pulse height and flatness of the Klystron voltage crucial.
- (a) Pulse wave form of the modulator output in the normal mode applied to the klystron.
- (b) Histogram of peak intensities measured for two hours.
- Stability of Klystron voltage
  - $\sigma = 0.027$ %

Flatness of Klystron Voltage Flat Top



- Specifications for the klystron modulator
  - < 0.1 % peak-to-peak
- (a) Pulse wave form of the modulator output and (b) its enlarged flat top in the normal mode applied to the klystron.
- Measured undulation of flat top
  - 0.21 % peak-to-peak
  - Due to ringing artifacts near the leading edge
  - < 0.1 % in the latter third
- RF amplitude and phase should be constant over the macropluse

Measured RF Amplitude and RF Phase

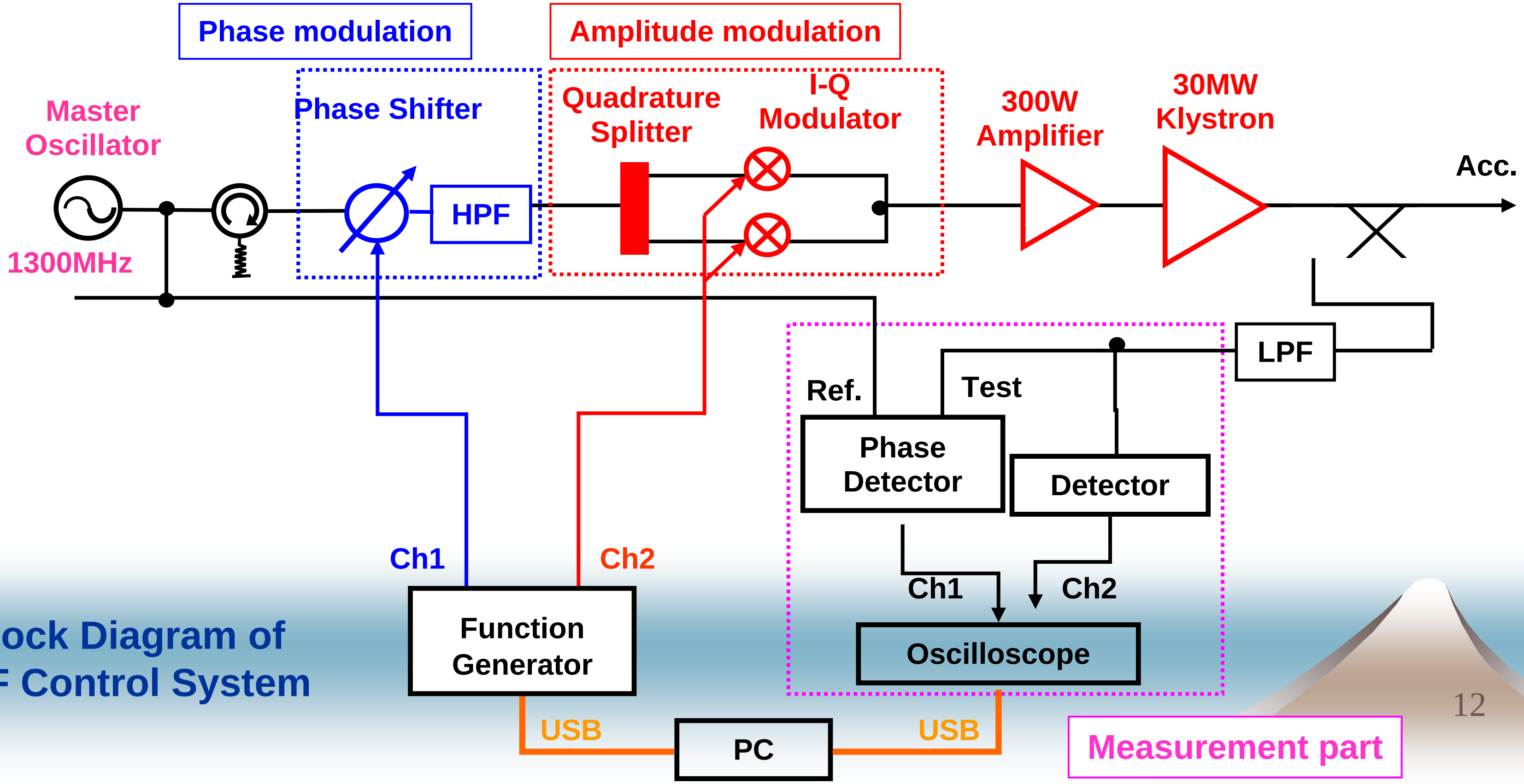


- (a) Amplitude measured with a diode detector and (b) the phase with a phase detector in the long-pulse mode.
- Measured variations in the long-pulse mode
  - ~15 % in amplitude
  - ~14 deg in phase

  in the flat-top.
- Energy of electrons vary considerably in macropulse.

Feed Forward Control of Amplitude and Phase

- To compensate variations of amplitude and phase
- Feed forward control introduced. Because…
  - Stability of Klystron voltage very high.
  - Amplitude and phase variations reproduced precisely



Block Diagram of FF Control System

Overdrive Control

- Response time of

  a variable attenuator (I-Q modulator) +AB class transistor amplifier 50 ns

  a phase shifter (analog phase shifter with PIN diodes) 780 ns

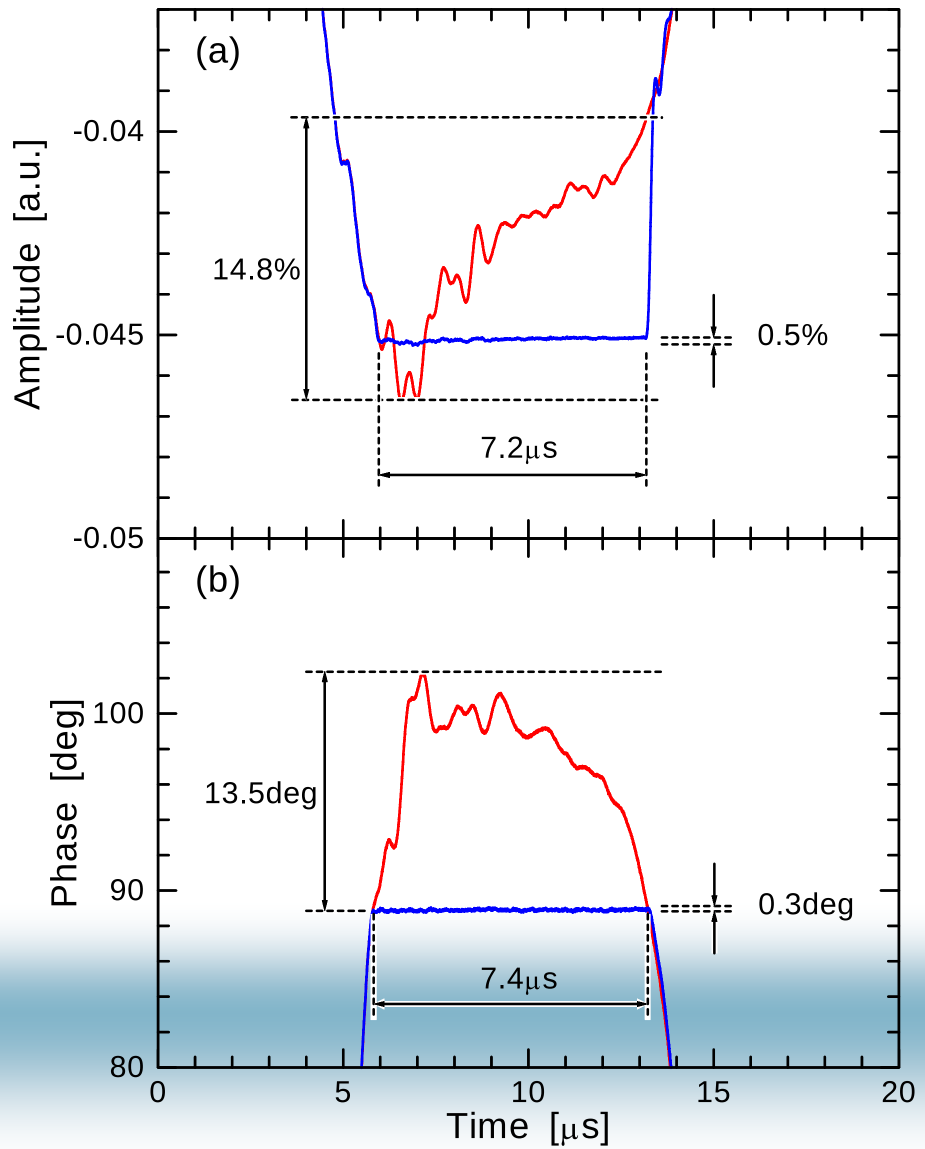
  are comparable to or larger than necessary time resolution.

- To compensate effects of response time and delay time, Control voltage derived by the equation

$$V_{in}(t-\Delta t) = V_c(t) + \tau \frac{dV_c(t)}{dt}$$

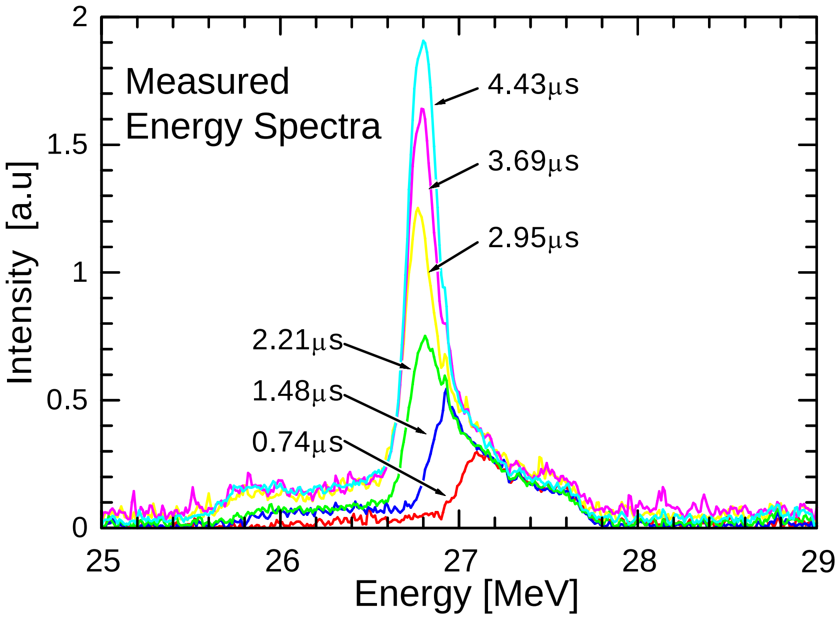
  - $V_{in}(t-\Delta t)$: overdriving control voltage applied to the control device.
  - $V_c(t)$: correction voltage to cancel variations.
  - τ: response time of the control device.
  - Δt: delay time in the control loop.

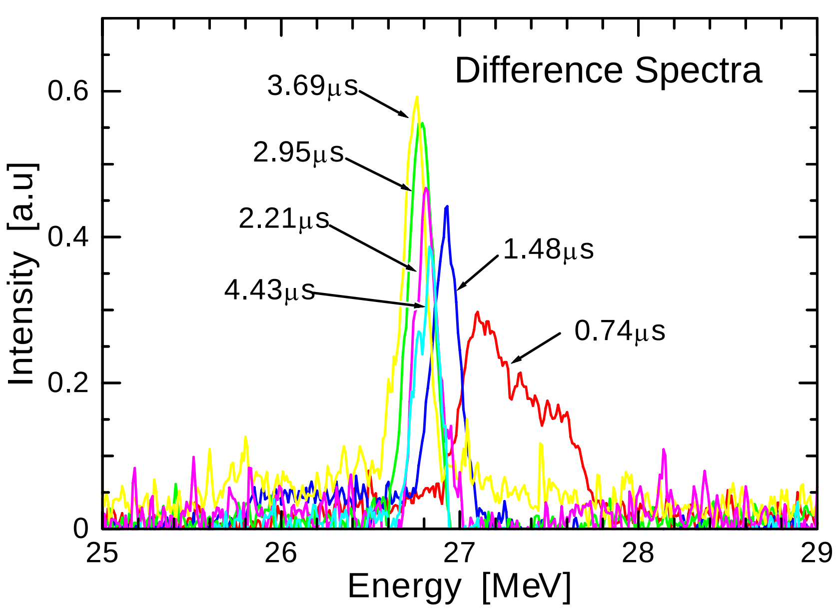
Simultaneous Compensation of Amplitude and Phase Variations



- (a) Amplitude and (b) phase variations of the RF power in the long pulse mode.
- Feed forward control with overdrive
  - Iterating some times
- Variations after iterative compensation
  - Amplitude: 14.8 % => 0.5 %
  - Phase: 13.5 deg => 0.3 deg

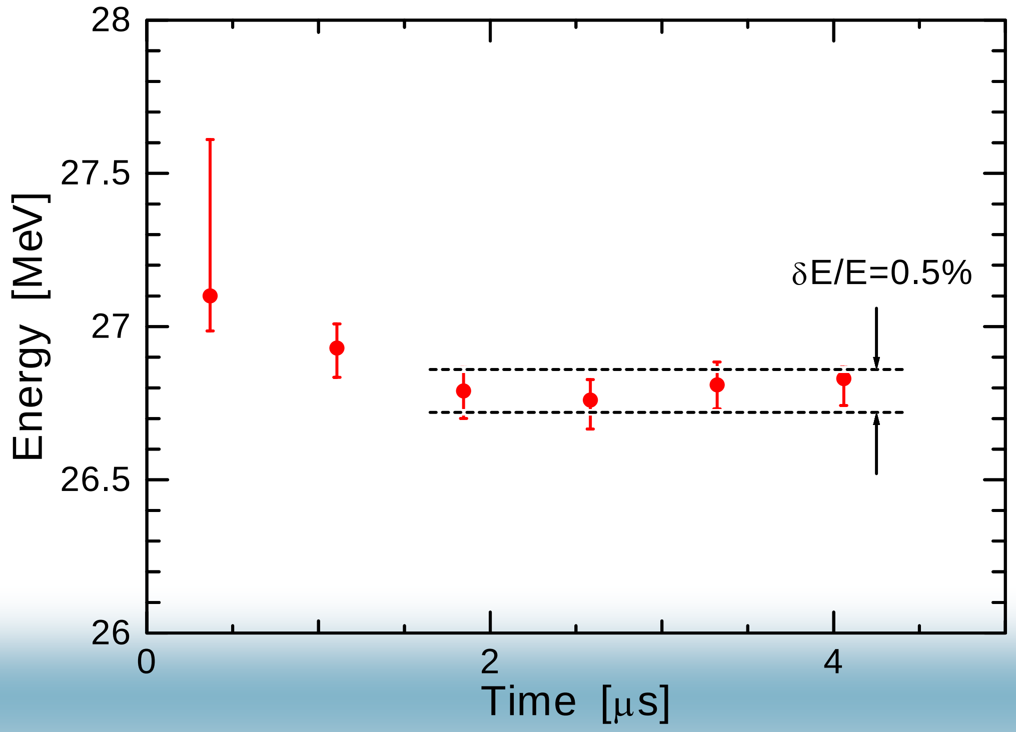
Energy Spectra of the Long Pulse Beam





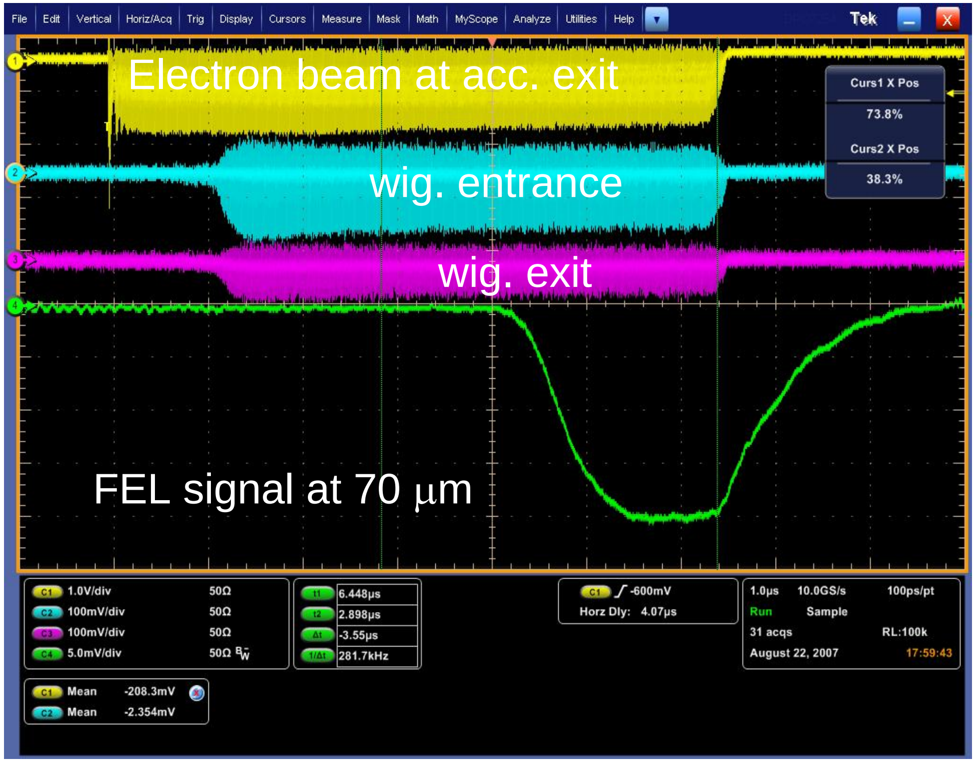
- Linac operated in the steady mode, which is the long pulse mode without the SHB system.
- Energy spectra of the electron beam measured by varying the macropulse duration.
  - Energy spectra for the first two durations (< 2 μs) broad
  - Lower energy peaks grow up for longer durations (> 2 μs)

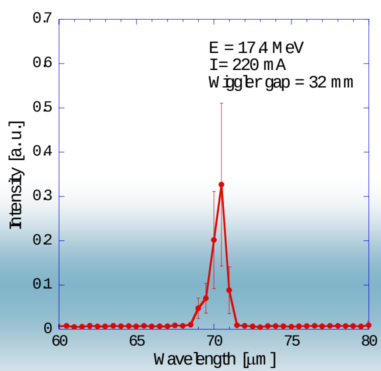
- Transient time, in which the beam energy reaches stable energy, is
  - 2 μs
  - consistent with the filling time of the accelerating tube.
- Multi-bunch mode with the SHB system also commissioned.
- Now ready for FEL experiment.



Peak energy and energy spread in the macropulse

First Lasing after Renewal





Gain: 20-30 %
Loss: 6 %

- Conducted FEL experiments in August 20-22, 2007 (last week).
- Lasing around 70 μm obtained on the second day.
- Laser power considerably increased on the last day.
  - No amplifier
  - Optical attenuator :
    - 3 cm Teflon block

- Beam conditioning not sufficient.
  - I_{inj}=220mA (<600mA typ.)

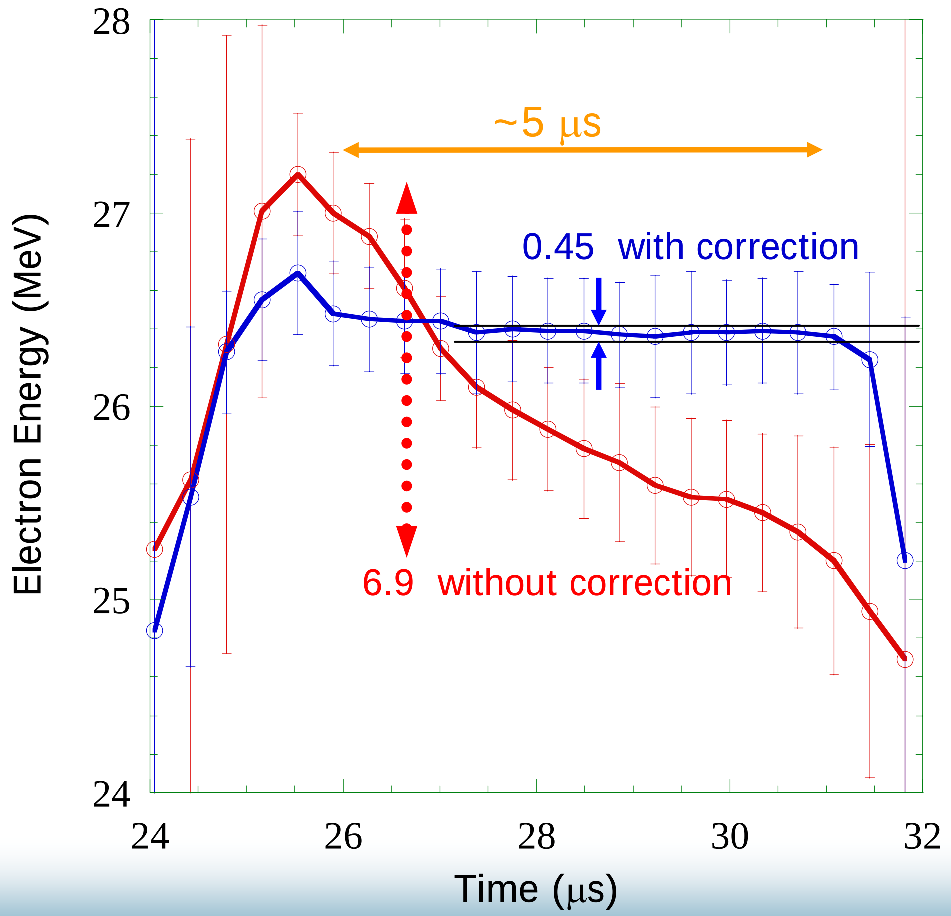
- FEL signal lost after saving Osc. Image…
  - Ge:Ga detector broke.

Summary and Conclusions

- L-band linac at ISIR, Osaka University largely remodeled for higher stability and reproducibility of operation as well as for FEL.
- Multi-bunch mode for FEL successfully commissioned with the feed-forward control of the amplitude and phase of the RF power.
- FEL in the far-infrared region has begun operation at 70~90 μm again after a long break.
- Power saturation realized?

- Linac and the FEL system will be tuned to increase the power and to expand the wavelength region.
- Hope to serve as an FEL users facility.

Energy of Electrons in a Micropulse

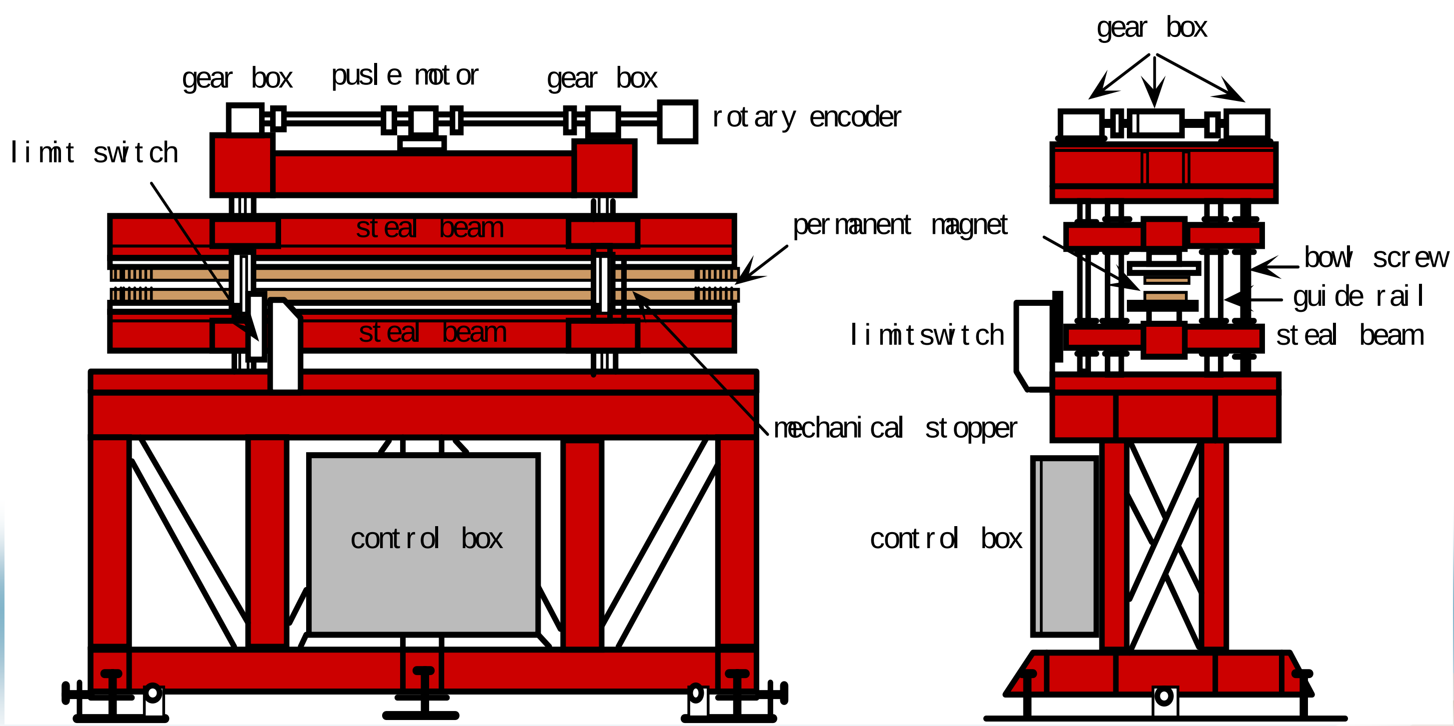


- Electron energy change measured in the transient mode with the duration ~5 ns as a function time in a macropulse.
- Before correction
  - 6.9 % in 5 μs
- After feed forward control
  - 0.45 % in 5 μs
- Amplitude an phase measurements as well as their compensation confirmed with the electron beam.

Wiggler and Optical resonator

Wiggler	
permanent magnet	Ne-Fe-B
total length	1.92 m
magnetic period	60 mm
no. of periods	32
magnet gap	120-30 mm
peak field	0.37 T
K-value	0.013-1.472

Optical Resonator	
resonator length	5.531 m
radii of mirrors	3358 mm (M1) 2877 mm (M2)
diameter of mirrors	80 mm
Rayleigh range	1 m
waist radius	3.5 mm (at 40 μm) 5.6 mm (at 100 μm) 6.8 mm (at 150 μm)
output coupling	φ3 mm hole of M1



Evacuated far-infrared spectrometer

- A cross Czerny-Turner type monochromator
  - effective aperture ratio : f/4.0
  - focal length : 500 mm
  - size : 120×120 mm^2
  - A plane reflective grating (Milton Roy)
    - 7.9 grooves / mm
    - braze wavelength : 112.5 μm
    - size : 64×64 mm^2
  - usable wavelength : from 60 to 190 μm
  - wavelength resolution :
    - better than 0.8 μm (Slit 3mm)
      1.5 μm (Slit 6mm)

FEL gain

<50μm Ge:Be detector

Y-646B (0.5cm^2; 60-100πmm.mrad) ΔE/E<1.5-3%

>50μm Ge:Ga detector

YU-156 (3cm^2; 150-200πmm.mrad) ΔE/E=3-5%

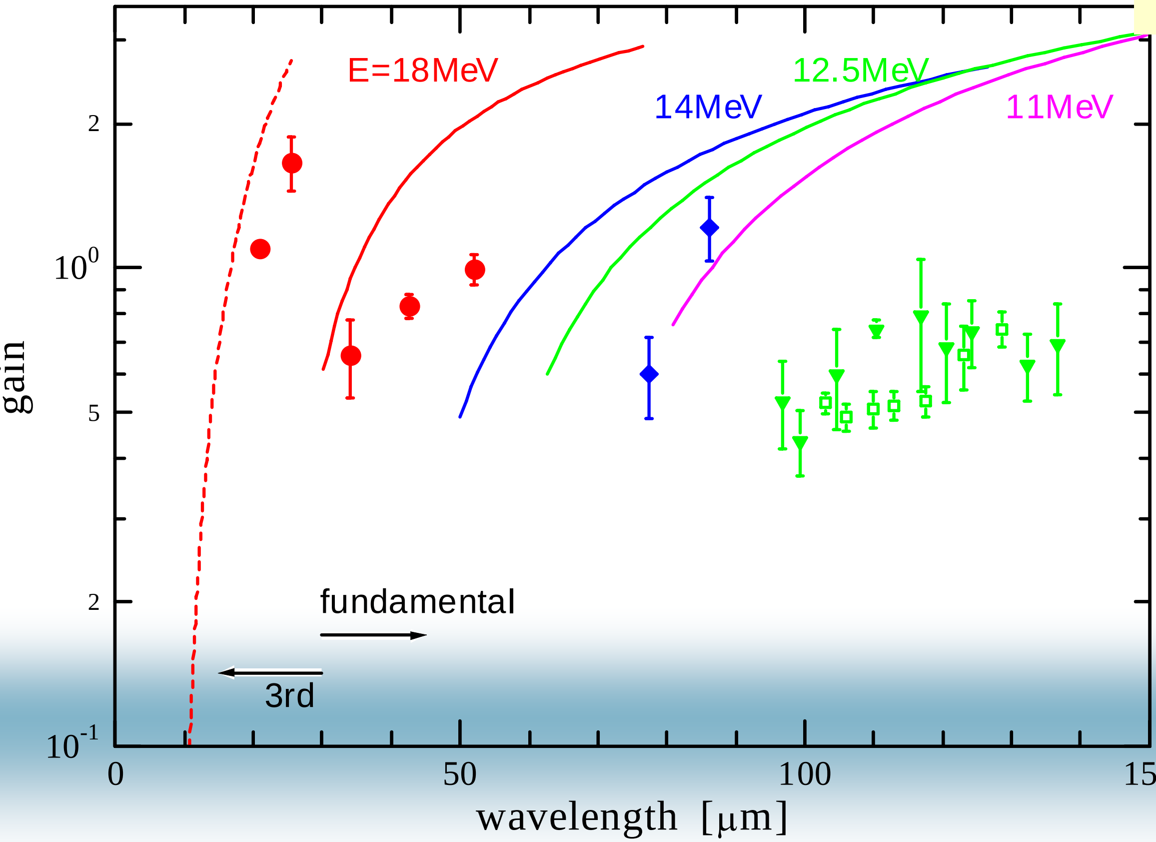
Max. FEL gain

fundamental ~120%, 3rd harmonic > 160%

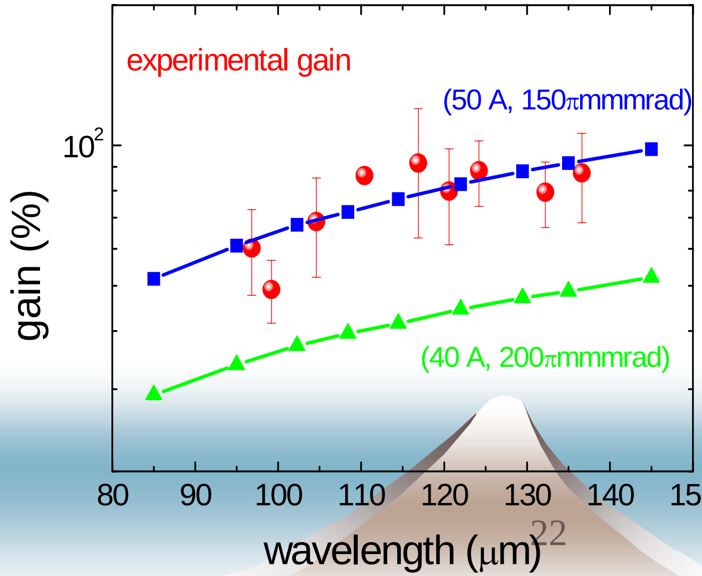
Reason why FEL gain is not so high in the longer wavelength region…

•Emittance(Y-646B→YU156)

•Relative energy spread



Good agreement with Simulation code TDA3D.
(TDA3D with measured emittance and time-sliced energy spread)



Optical Resonator Loss

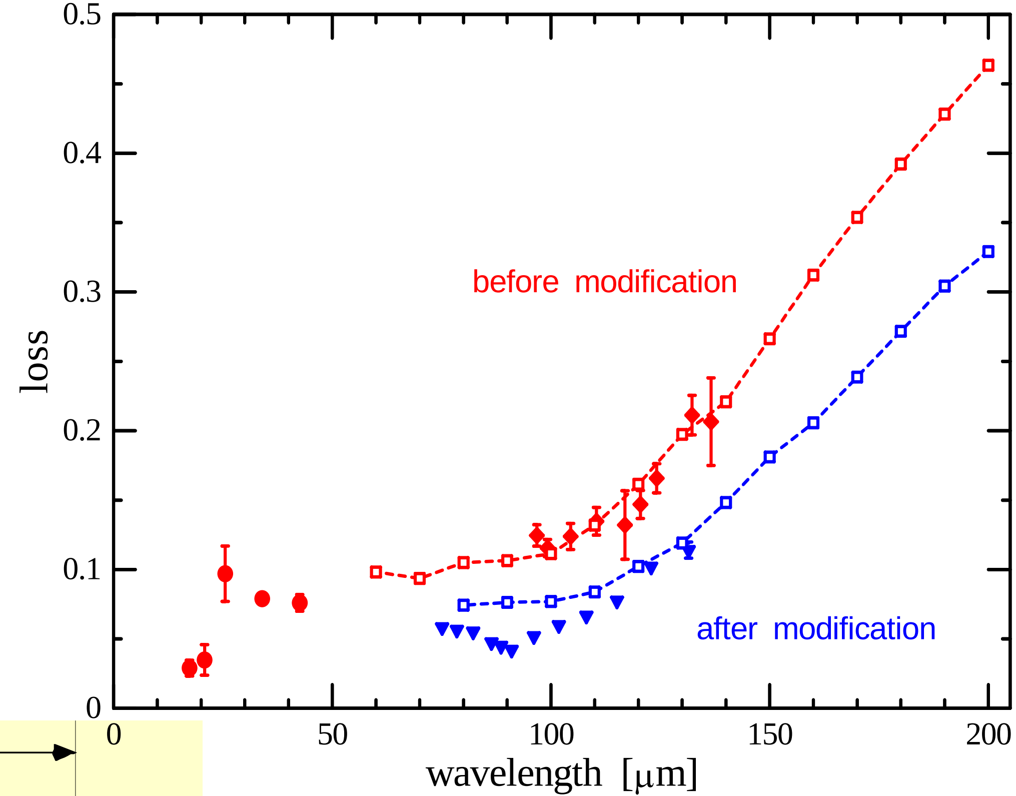
Optical resonator loss

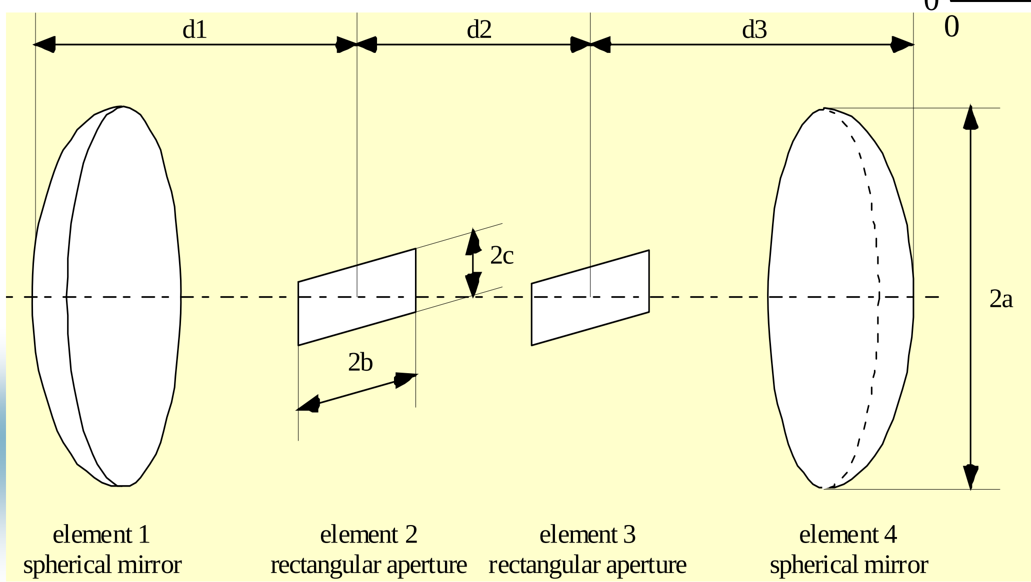
- Diffraction loss

  Mirror apertures: ϕ 60mm → ϕ 80mm
- Optical scattering and absorption on mirrors

  Reflectivity of Au: 0.993
- Coupling hall

  Hall: ϕ 3mm → ϕ 3mm and ϕ 1mm





$$u_2(\mathbf{x}_2) = \frac{i}{2\lambda}\iint_S u_1(\mathbf{x}_1)\frac{e^{-jkR}}{R}\left(1+\frac{d}{R}\right)d\mathbf{x}_1$$

$$\mathbf{x}_i = (x_i, y_i) \qquad k = 2\pi/\lambda$$

$$R^2 = (x_2 - x_1)^2 + (y_2 - y_1)^2 + d^2$$

$$R^2 = (x_2 - r_1\cos\phi_1)^2 + (y_2 - r_1\sin\phi_1)^2 + \left(d - r^2/2\rho_i\right)^2$$