Compton Scattering Monochromatic Tunable X-ray Source based on X-band Multi-bunch Linac at the University of Tokyo

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Contents

- Compton scattering monochromatic X-ray source based on X-band linac at the University of Tokyo.
- Experimental results and present status of the X-ray source.
  - Beam generation by X-band linac.
  - Laser system and its properties.
  - X-ray generation via Compton scattering.
  - Upgrade of X-band thermionic RF-gun.
- Summary and future works.

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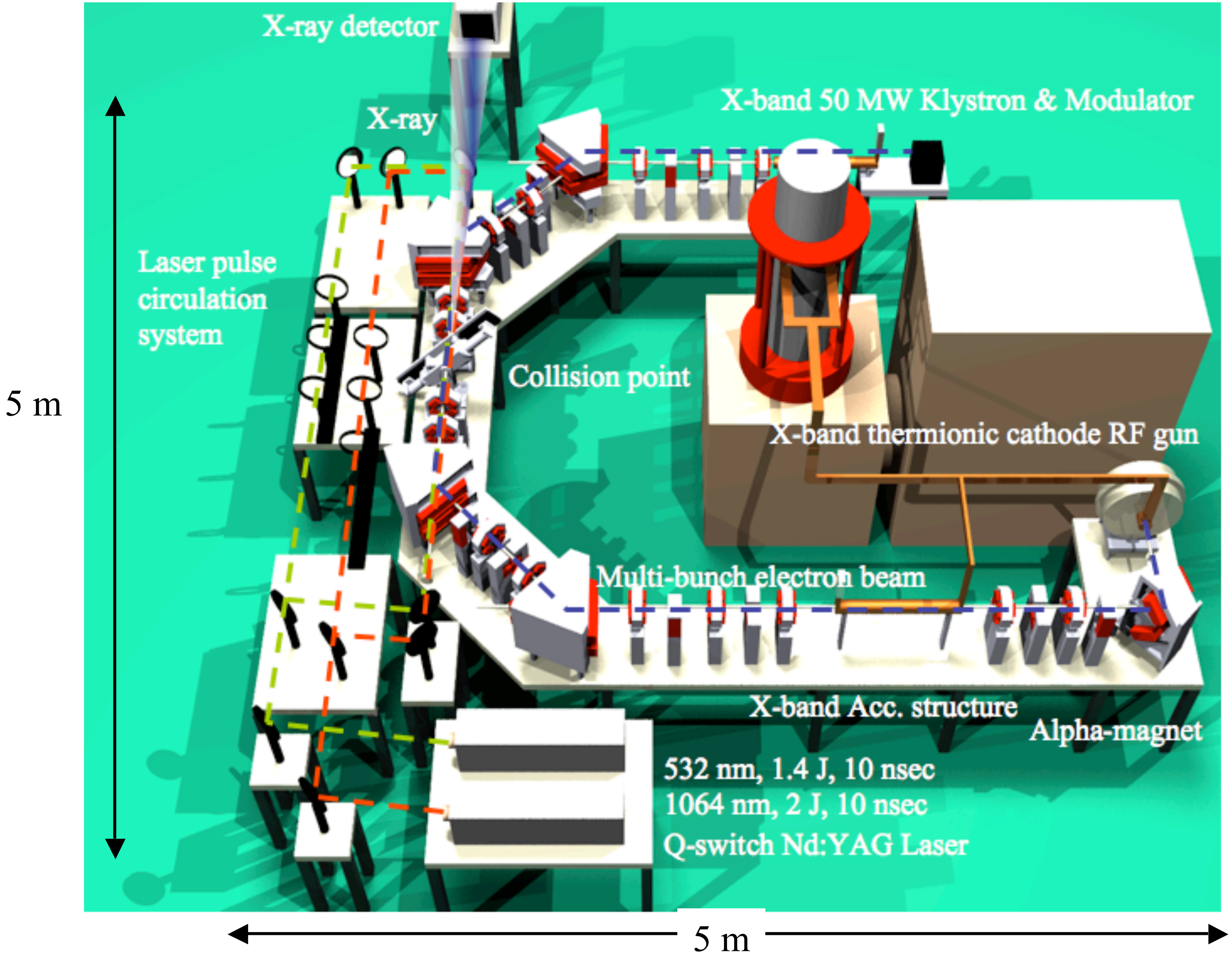
Example on performance of Linac/Laser Compton X-ray source for medical and industrial applications

Laboratory	Electron Energy	Charge	Laser	X-ray energy and intensity	Application
AIST[1] (Operating)	20-42 MeV (S-band)	0.8 nC Single bunch (Multi bunch)	800 nm, 140 mJ, (Ti:Sapphire, 100 fs) (Multi pulse)	10-40 keV 1.0E+7 photons/s (10E+9 photons/s by multi)	Medical
Waseda Univ. [2] (Operating)	4.6 MeV (RF-gun) (S-band)	350 pC Single bunch	1047 nm, 36 mJ (Nd:YLF, 10 ps)	0.25〜0.5 keV 3.28E+4 photons/pulse	Radiation chemistry
LLNL[3] (Operating)	120 MeV (S-band)	250 pC Single bunch	800 nm, 500 mJ (Ti:Sapphire, fs)	40〜80 keV 1.0E+7 photons/s	Heavy atom imaging
KEK[4] (Operating)	43 MeV (S-band)	2 nC ×100 Multi bunch	1064 nm, 2 kW (Nd:YAG, Super Cavity)	33 keV 1.0E+8~9 photons/s	Medical
U-Tokyo[5] (Constructing)	30 MeV (X-band)	20 pC×10000 Multi bunch	532 nm, 1.4 J, (Nd:YAG, 10 ns)	20-40 keV 1.0E+8~9 photons/s (By laser pulse circulation)	Medical

We are proposing “compact and high intensity Compton source” by adopting X-band(11.424 GHz) multi bunch linac.

[1]R. Kuroda et. al., Compton Sources for X/gamma Rays, 2008
[2]A. Masuda et. al., Proc of Particle Accelerator Society Japan, 2007
[3]W. J. Brown et. al., PRL-ST 7,060702(2004)
[4]M. Fukuda et. al., Proc of Particle Accelerator Society Japan, 2007
[5]M. Uesaka et. al., NIM B, 261, (2007) 867-870

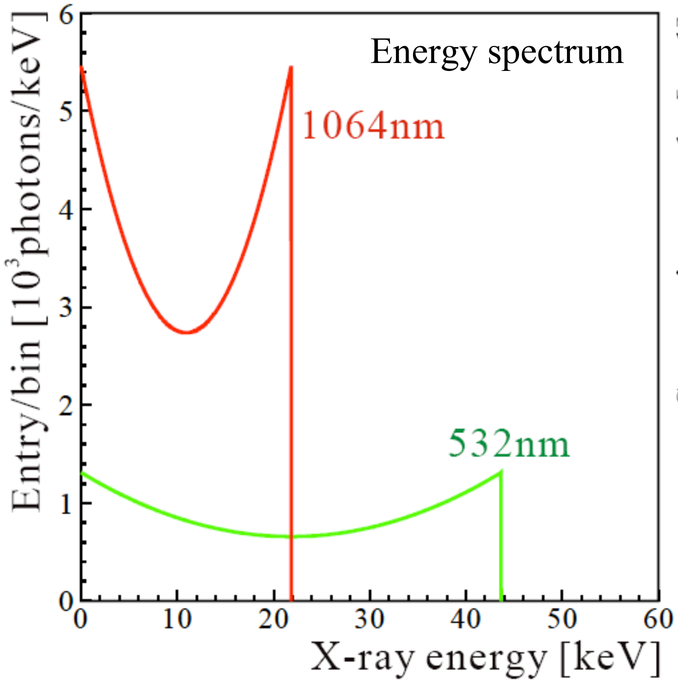
Compton scattering X-ray source at the University of Tokyo

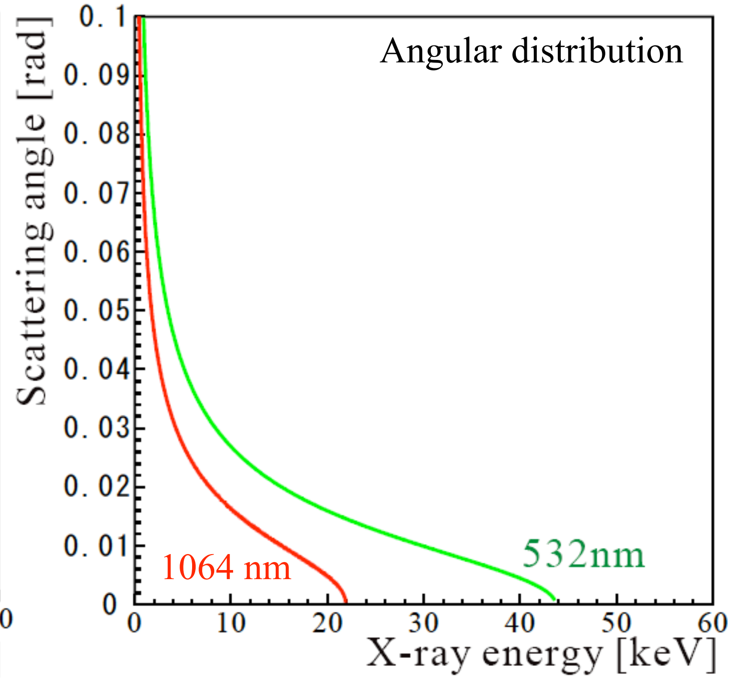


Properties of X-ray

Design beam parameters

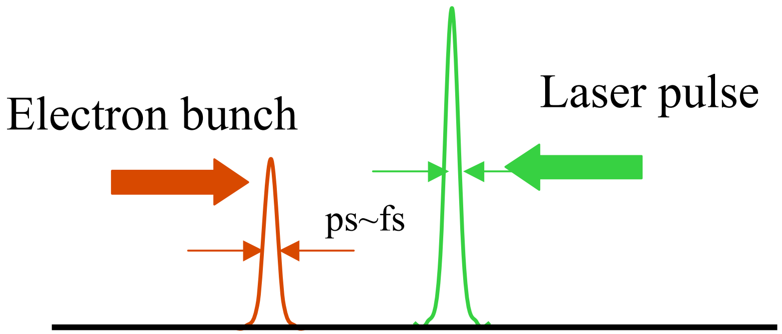
Electron beam:		30 MeV, 20 pC/bunch, 10^4 bunches/RF pulse(1μs), 10 pps
Laser:		1064 nm, 2.0 J, 10 ns, 10 pps
	X-ray :	21.9 keV, $9.9*10^8$ photons/s (Full band width)
		532 nm, 1.4 J, 10 ns, 10 pps
	X-ray :	42.9 keV, $4.7*10^8$ photons/s (Full band width)



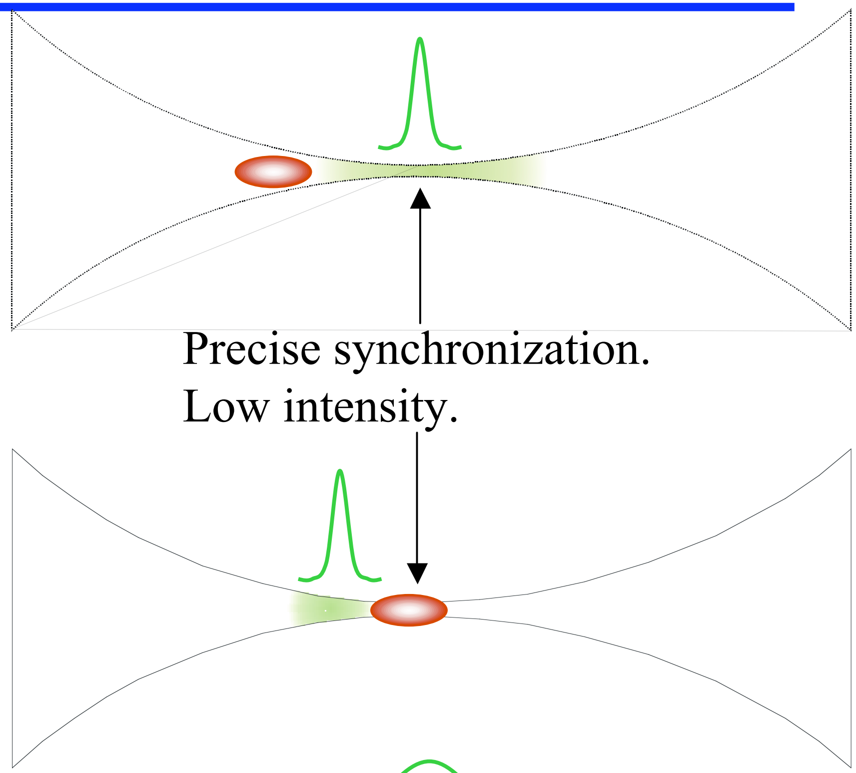


Multi-collision scheme

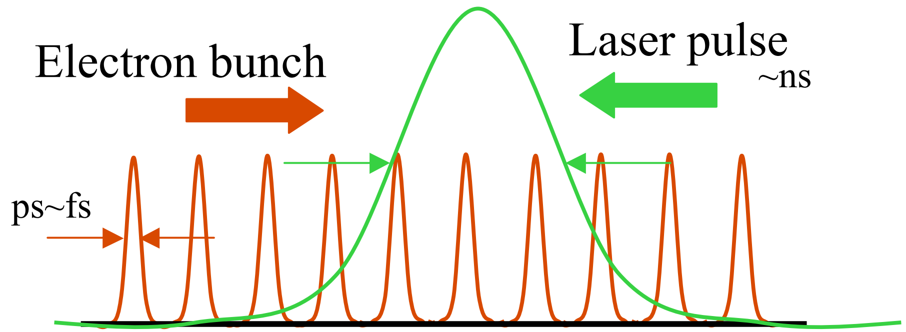
Single-collision scheme (Ultra-short X-ray)



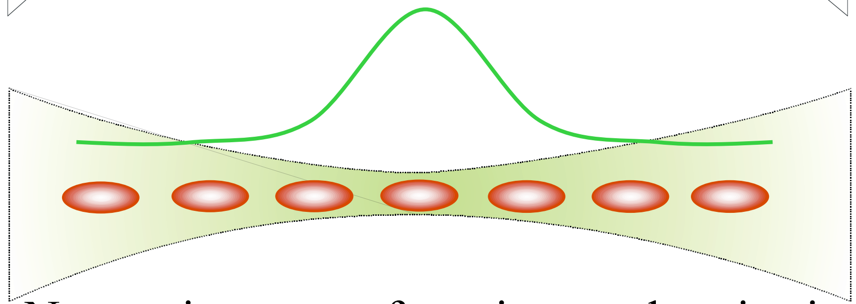
Collision between ultra-short (ps ~ fs) pulses.



Multi-collision scheme (High intensity X-ray)



Collision between ~ns laser pulse and multi-bunch electron beam



No requirements of precise synchronization.

Time structure and beam size dependency of X-ray

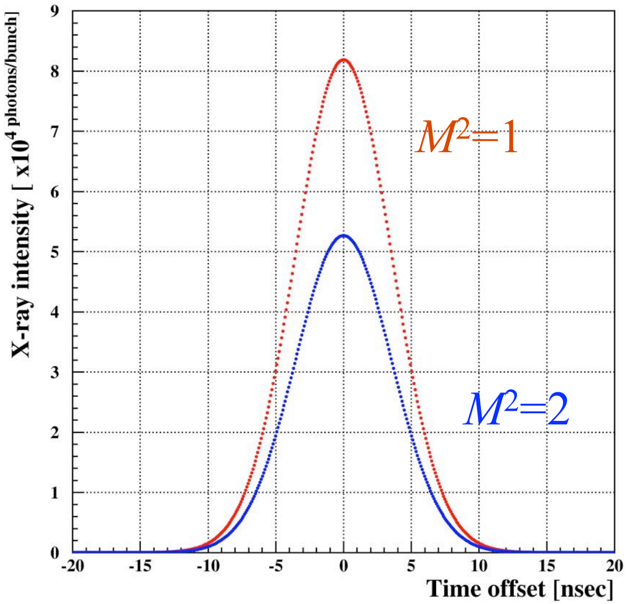
$$N = \sigma_{cross} L = \sigma_{cross} N_e N_l \frac{1}{2\pi} \frac{1}{\sqrt{\sigma_{xe}^2 + \sigma_{xl}^2}} \frac{1}{\sqrt{\sigma_{ye}^2 + \sigma_{yl}^2}}$$

$$\sigma_{me} = \sqrt{\varepsilon_m \beta_m(s) + \left(\frac{\Delta P}{P}\eta_m(s)\right)}$$

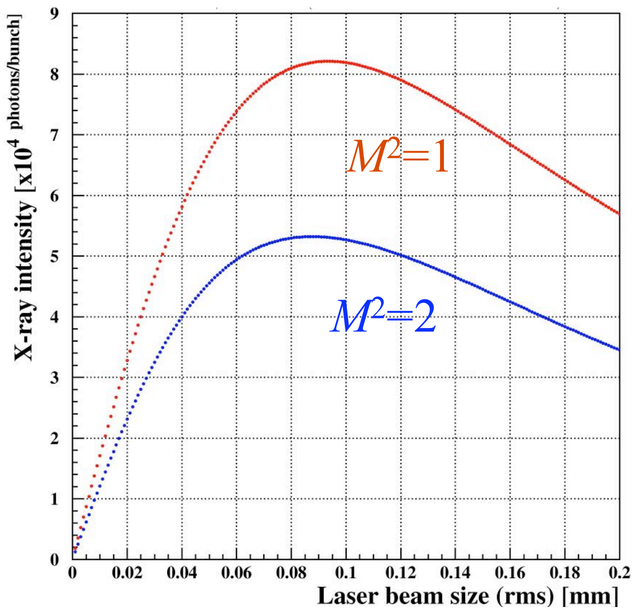
$$\sigma_l(s) = \sigma_{0l}\sqrt{1 + \left(\frac{s^2}{s_{0l}}\right)^2}$$

Energy : 30 MeV
Emittance : 10 πmm-mrad
Charge : 20 pC/bunch,
RF pulse width :1 μs
Laser energy: 1.4 J
Wavelength : 532 nm
Pulse length : 10 ns

σ_{cross}:Total cross section given by Klein-Nishina's formula



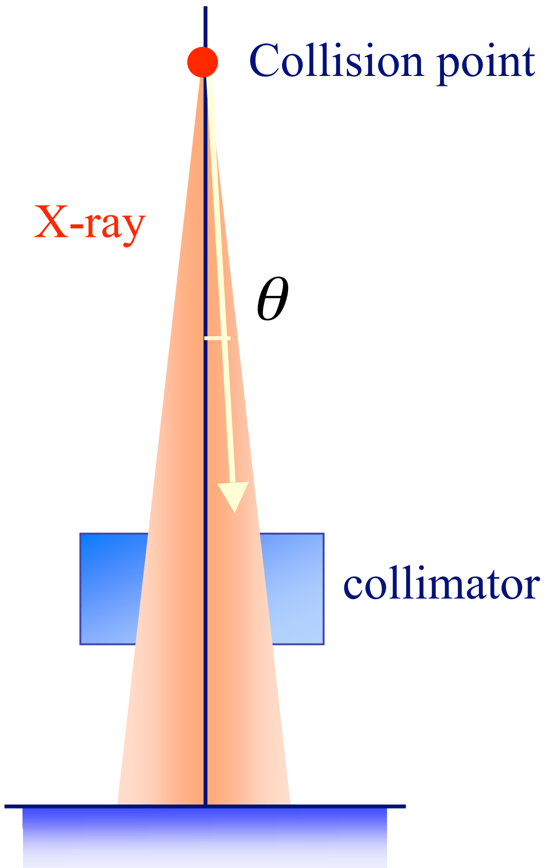
Time structure of X-ray

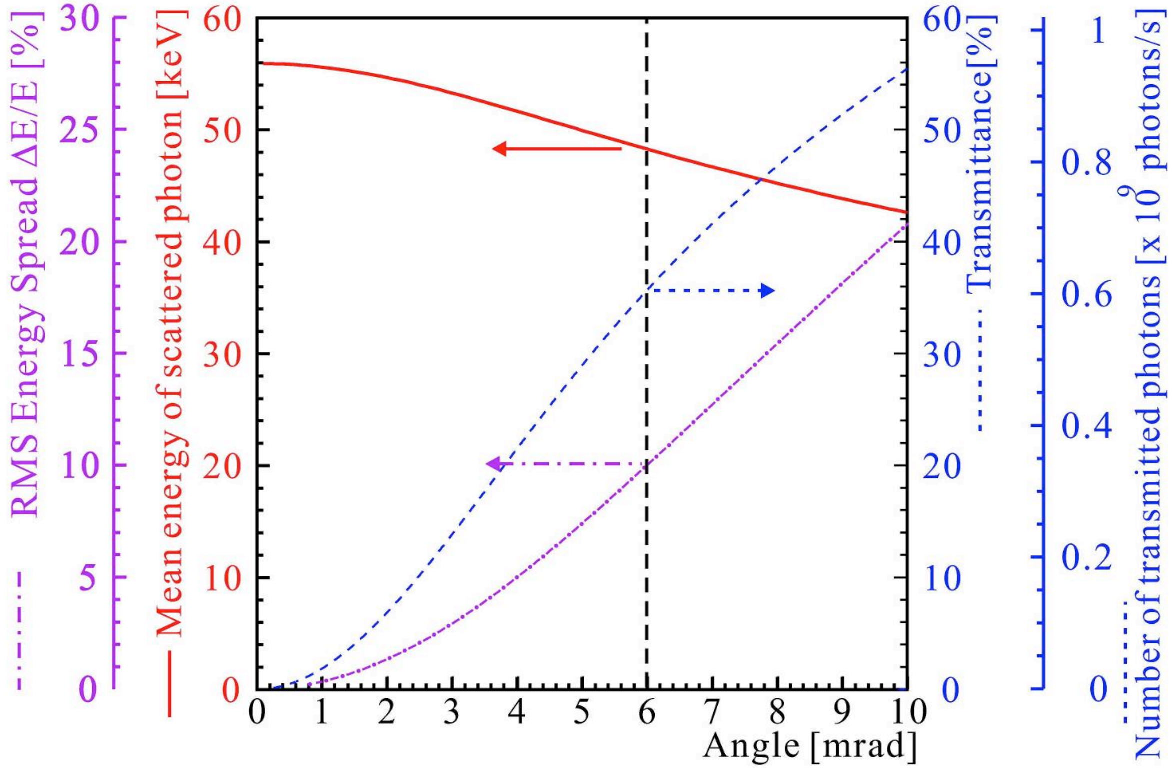


Laser size dependency for electron beam100 μm

Laser pulse collide with ~100 electron bunch.

Monochromatically of X-ray by collimator





(Example for 50 MeV electron beam and 532 nm laser.)

Energy spread of 10 % can be obtained if the collimate angle set to 6 mrad.

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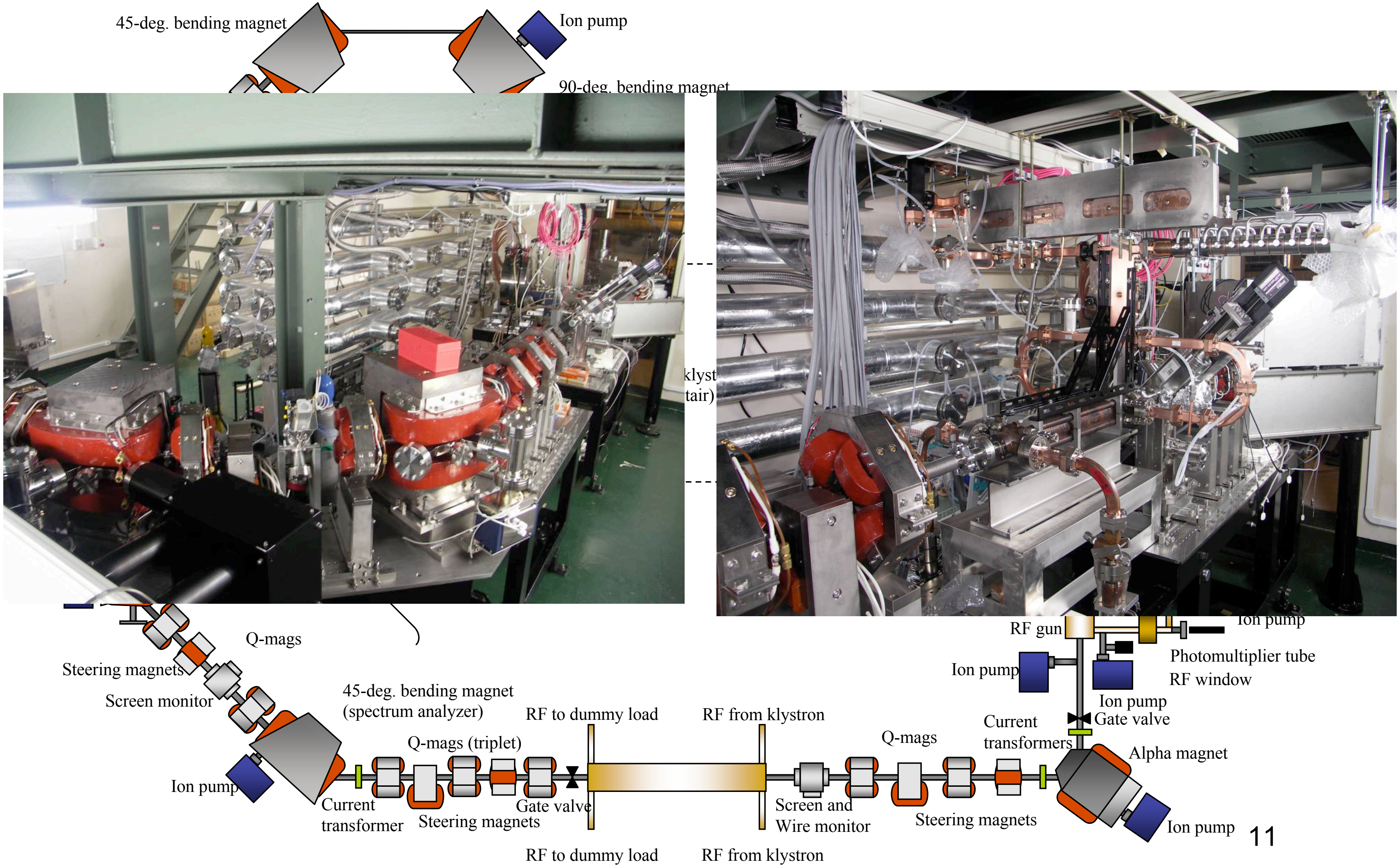
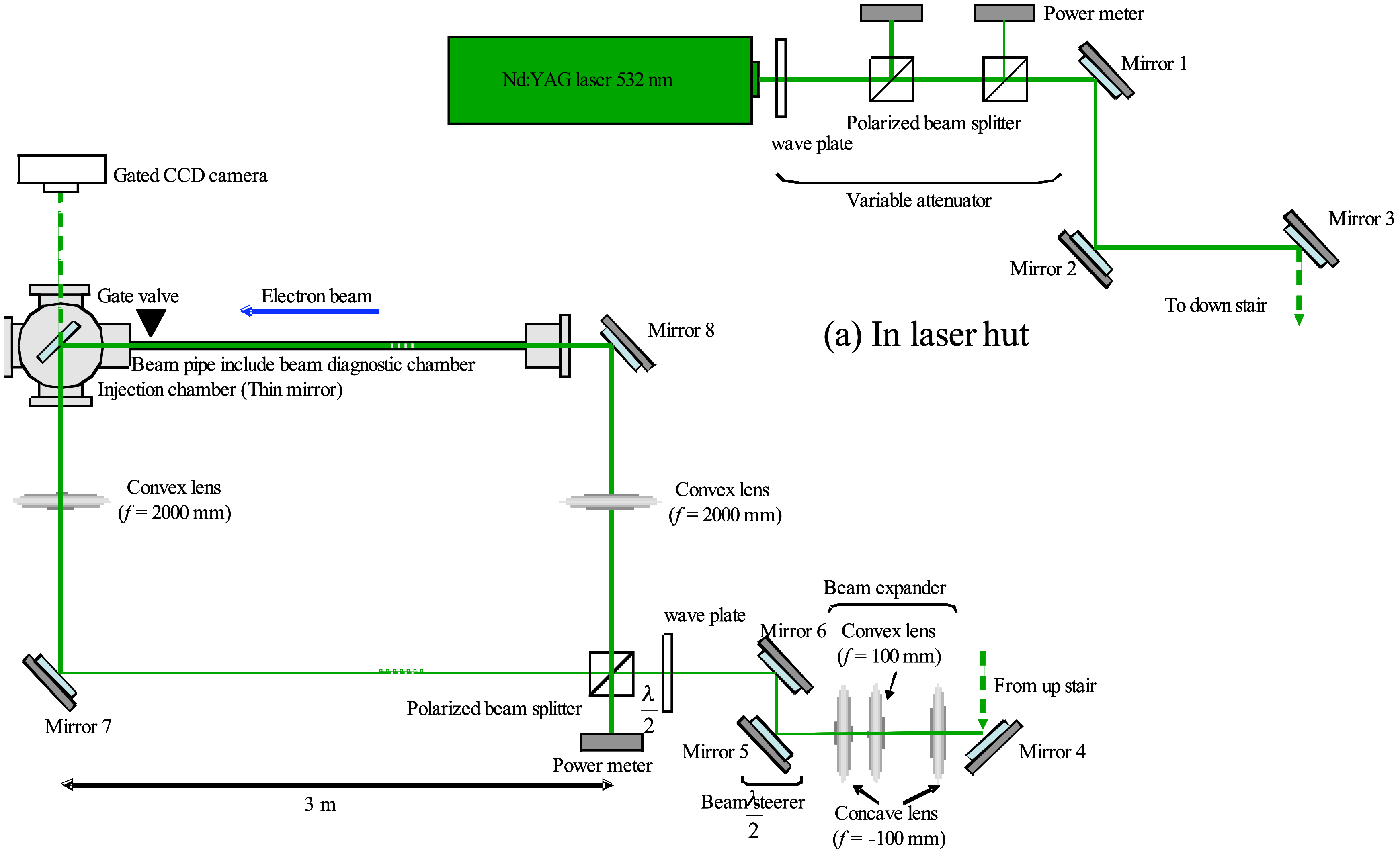
X-band linac system (Electron beam source)



Laser optics for Compton scattering experiment

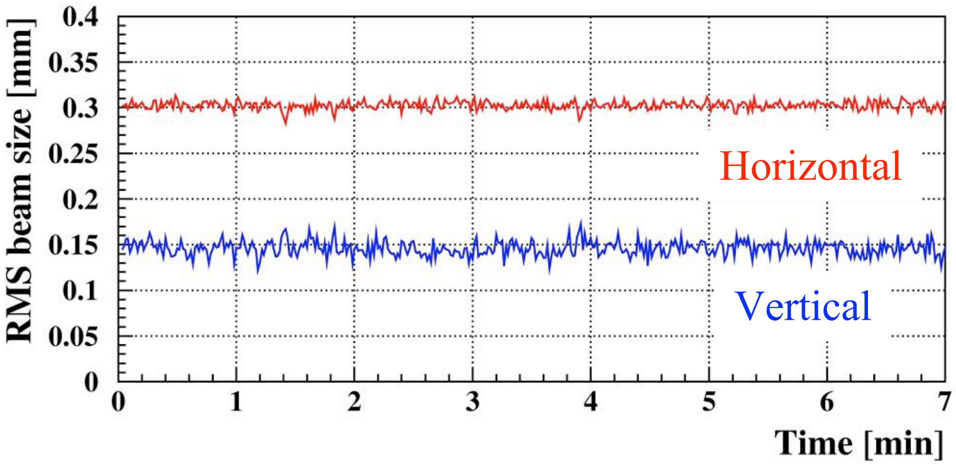


(b) In beam line

Measurement of laser properties

Laser parameter

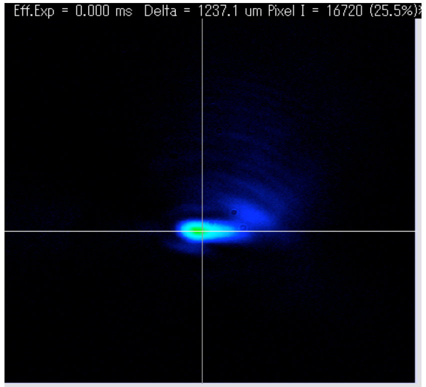
Nd:YAG 532 nm (2nd harmonic)
Pulse energy : 1.4 J
Pulse duration : 10 ns (FWHM)



Stability of laser spot size.

Position, spot size, energy stability : <5%
M-square : 1.6 for horizontal, 1.8 for vertical.

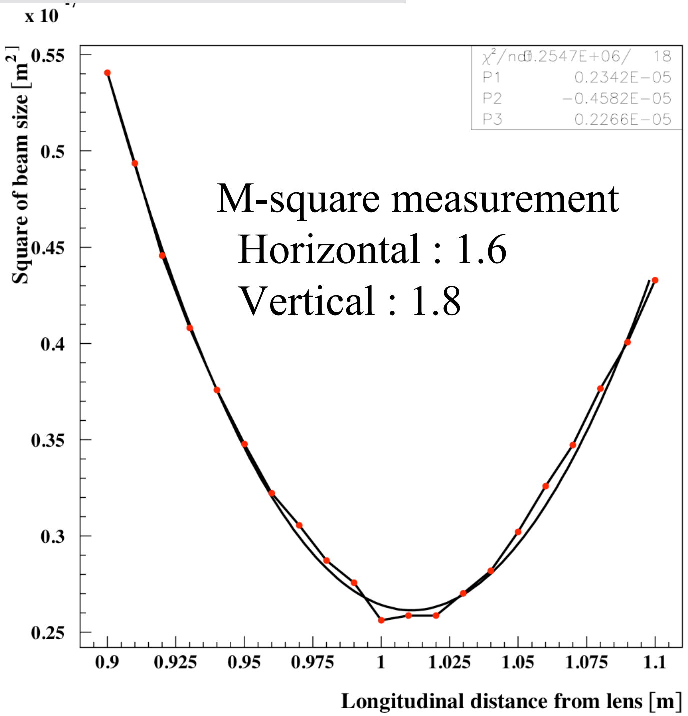
Beam profile at collision point.



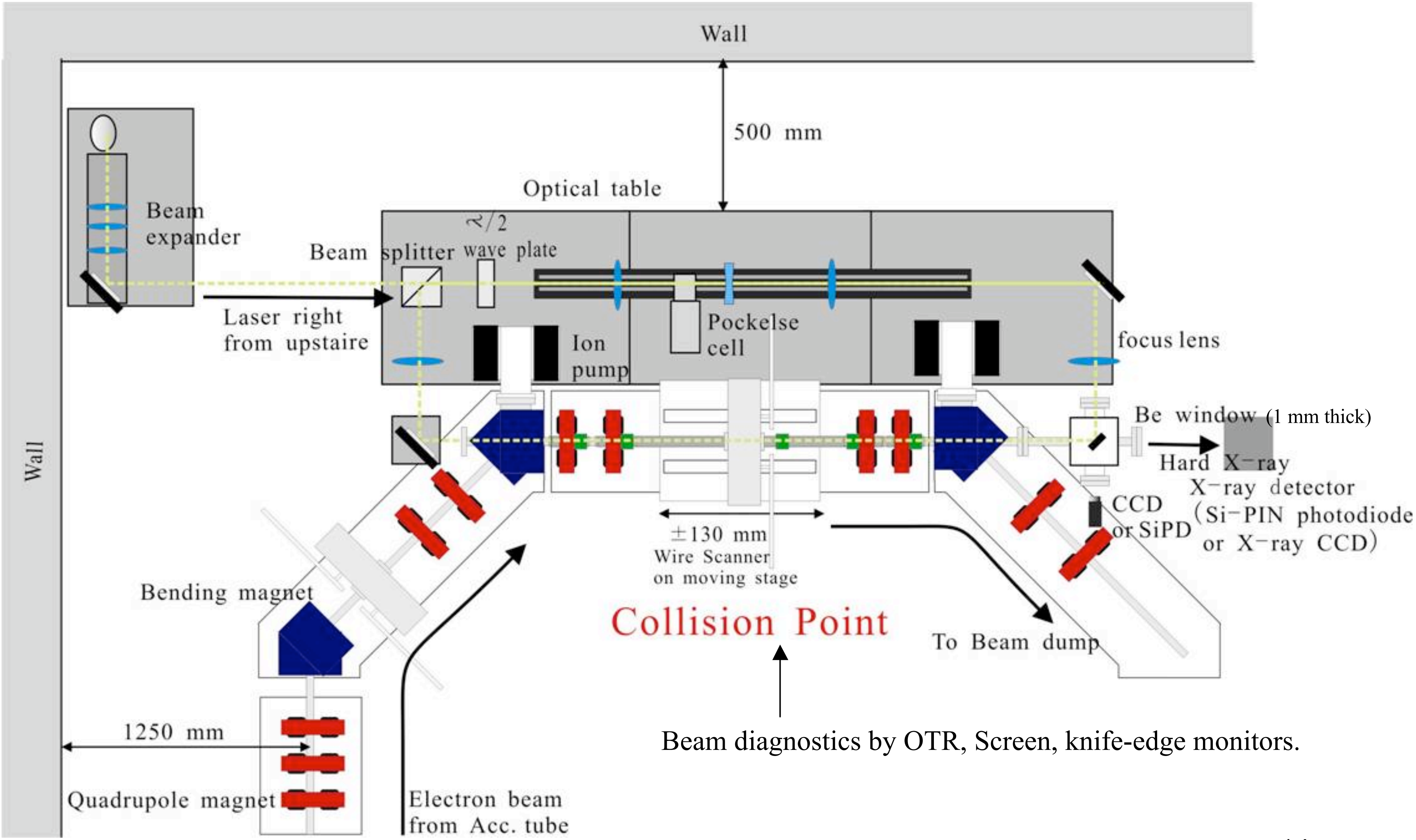
Spot size

Vertical :150 μm (rms)

Horizontal:300 μm (rms)

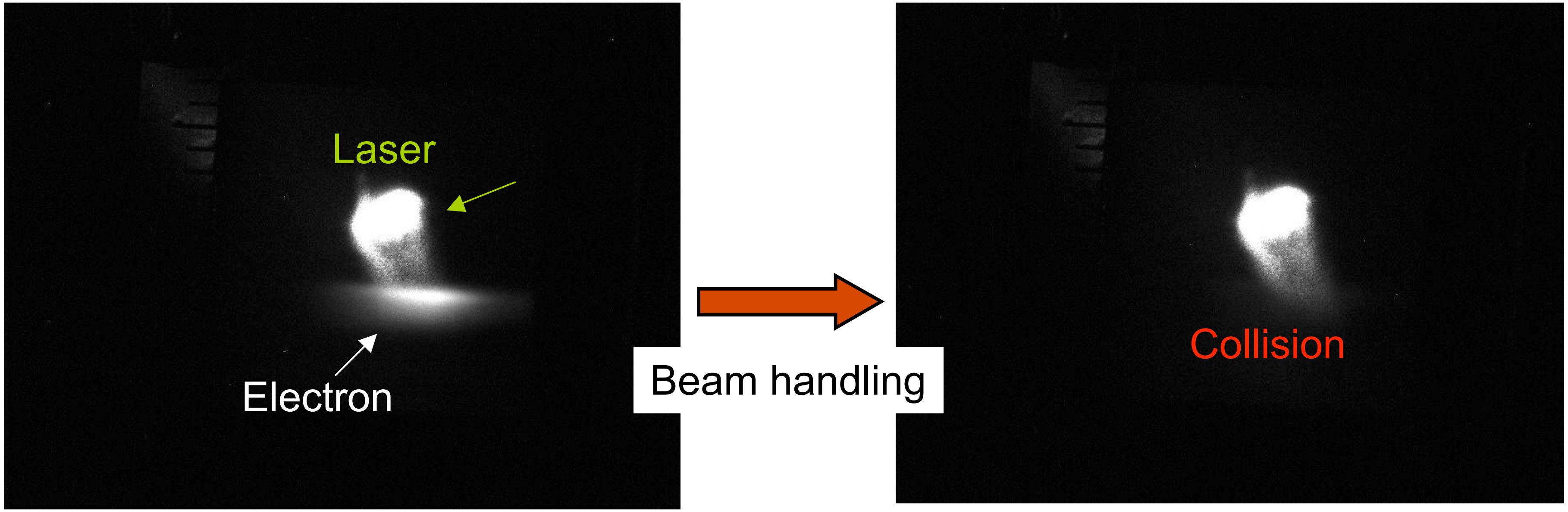


Experimental setup for X-ray generation via Compton scattering



Beam diagnostics by OTR, Screen, knife-edge monitors.

1st experiments on electron acceleration and X-ray generation

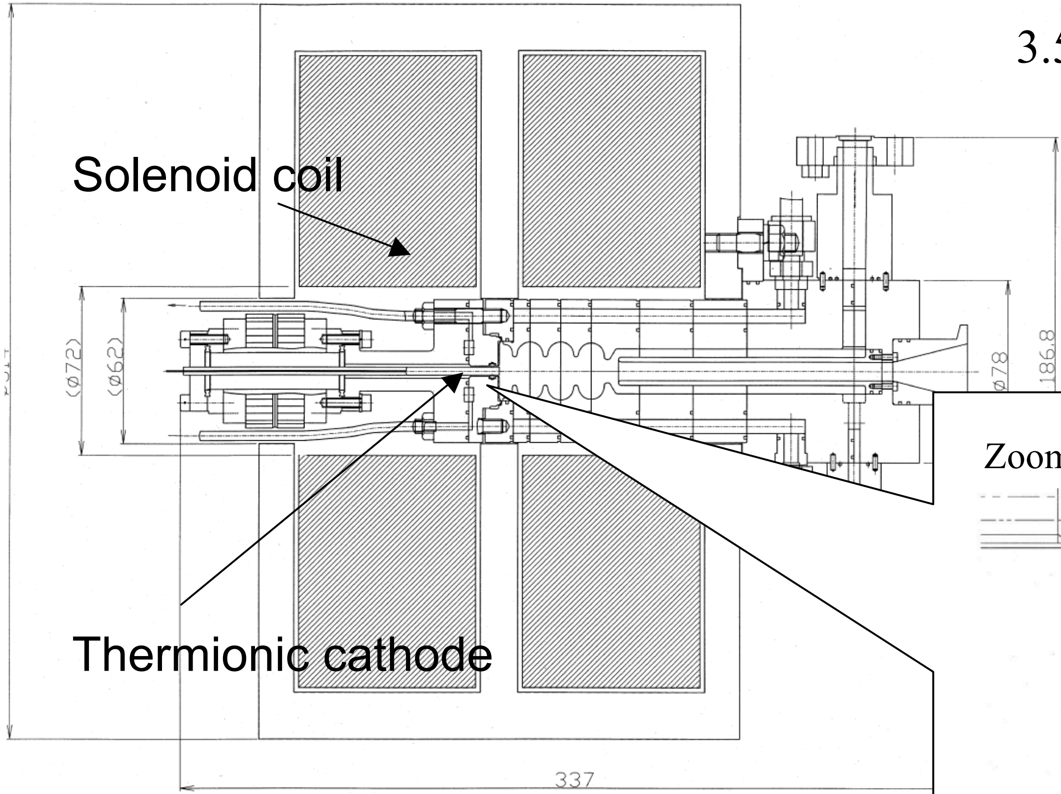


Electron（22 MeV）･Laser（800 mJ） Collision and X-ray generation

However, the electron energy (22 MeV) is lower than the design (30 MeV) and X-ray intensity is quite low.

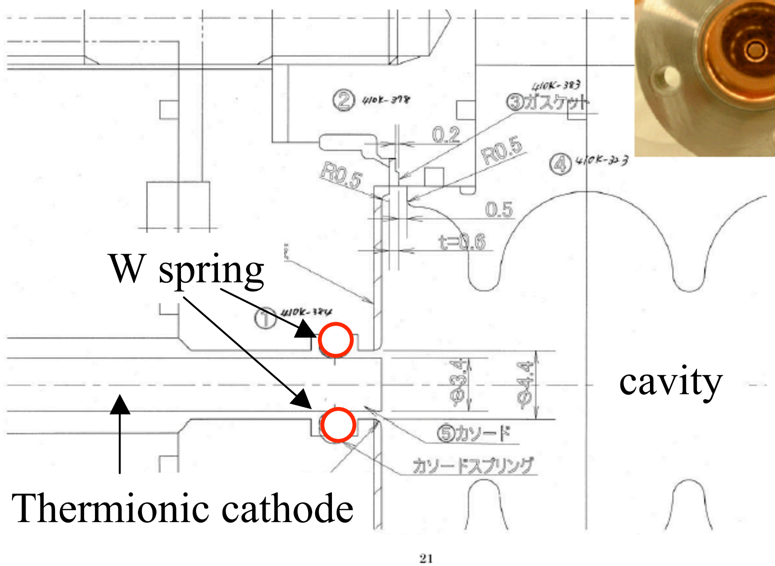
What is the issue ? → Thermionic cathode RF-gun.

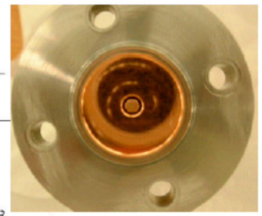
Issue at thermionic X-band RF-gun



3.5-cell X-band thermionic cathode RF gun

Zoom up around thermionic cathode

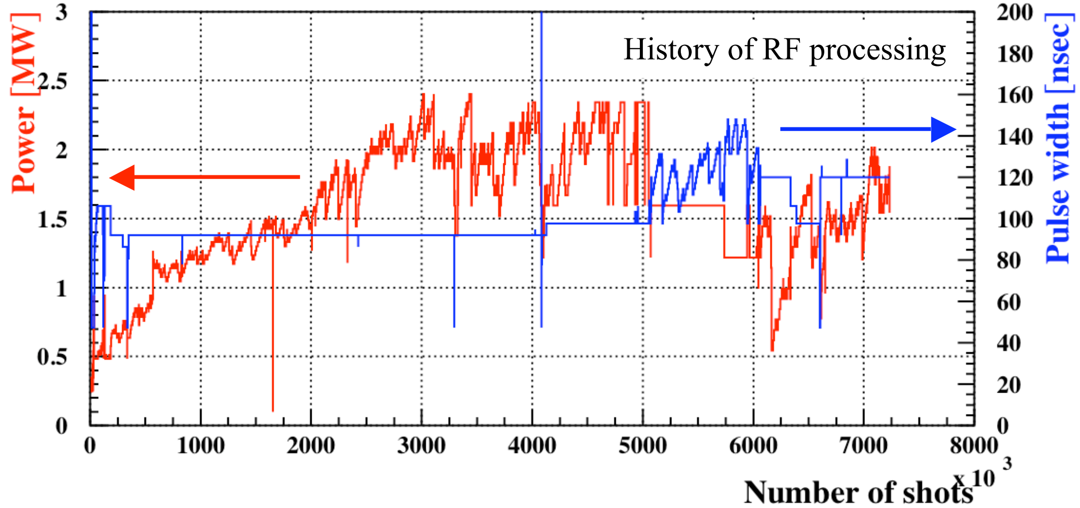


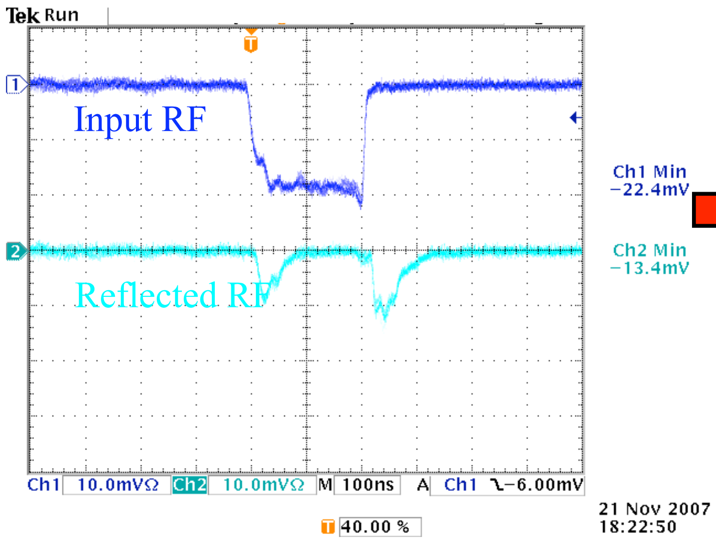


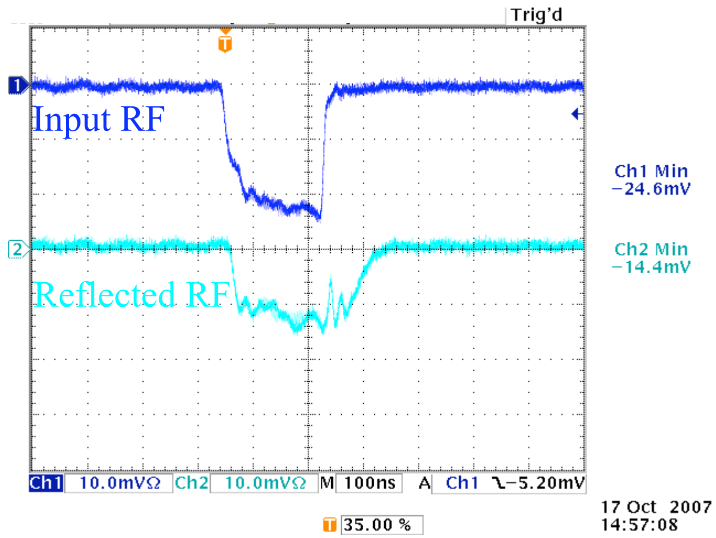
W spring is set for purposes of RF shielding and cathode support.

W spring is broken by high-power RF field and detune the cavity resonance.

Typical waveform before and after high-power feeding







Detune of cavity occurred at 2 MW @100 ns. ⇒ W spring was broken.

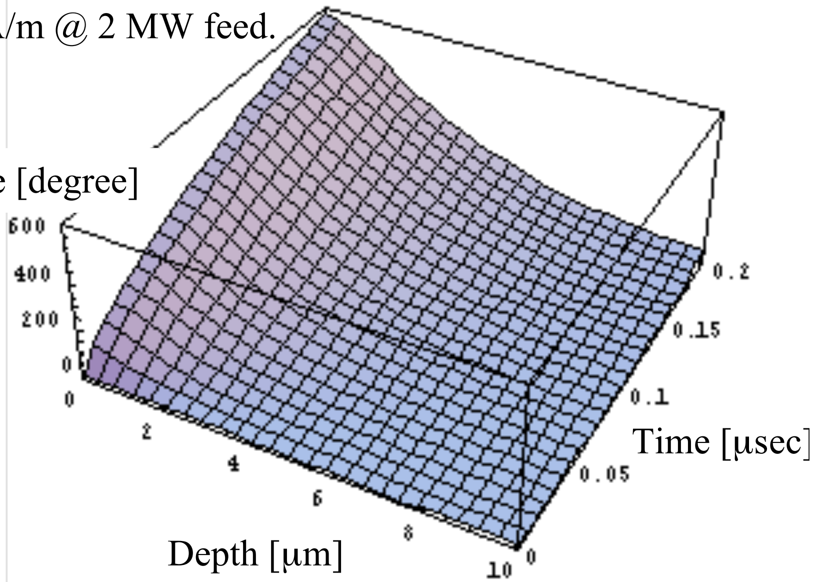
Evaluation of thermal diffusion at tungsten spring surface by RF pulse

<u>One-dimensional thermal diffusion equation.</u>

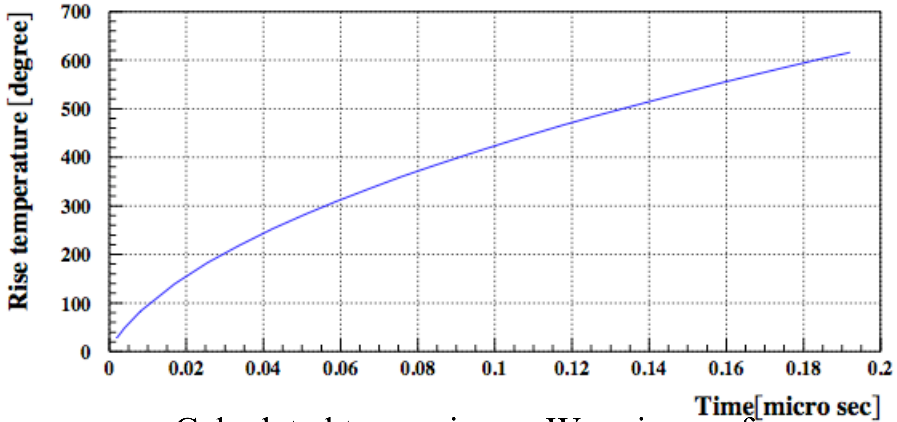
$$\alpha\rho\frac{\partial T}{\partial t} = k\frac{\partial^2 T}{\partial y^2} + \frac{H_{0x}^2}{\sigma\delta^2}\exp\left(\frac{2y}{\delta}\right)$$

α: specific heat, ρ: density, σ: elec. conductance, δ: skin depth, k: thermal conductivity, y: depth, T: temperature, t: time, H: surface magnetic field

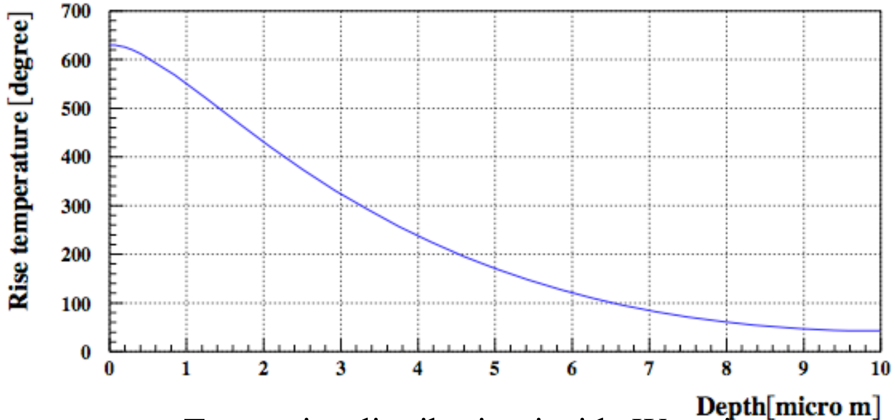
H=0.09 MA/m @ 2 MW feed.



2MW input power produces temperature rise of ~630℃ on tungsten surface. However, melting point of tungsten is higher than 600℃ (about 3000℃ in vacuum.).



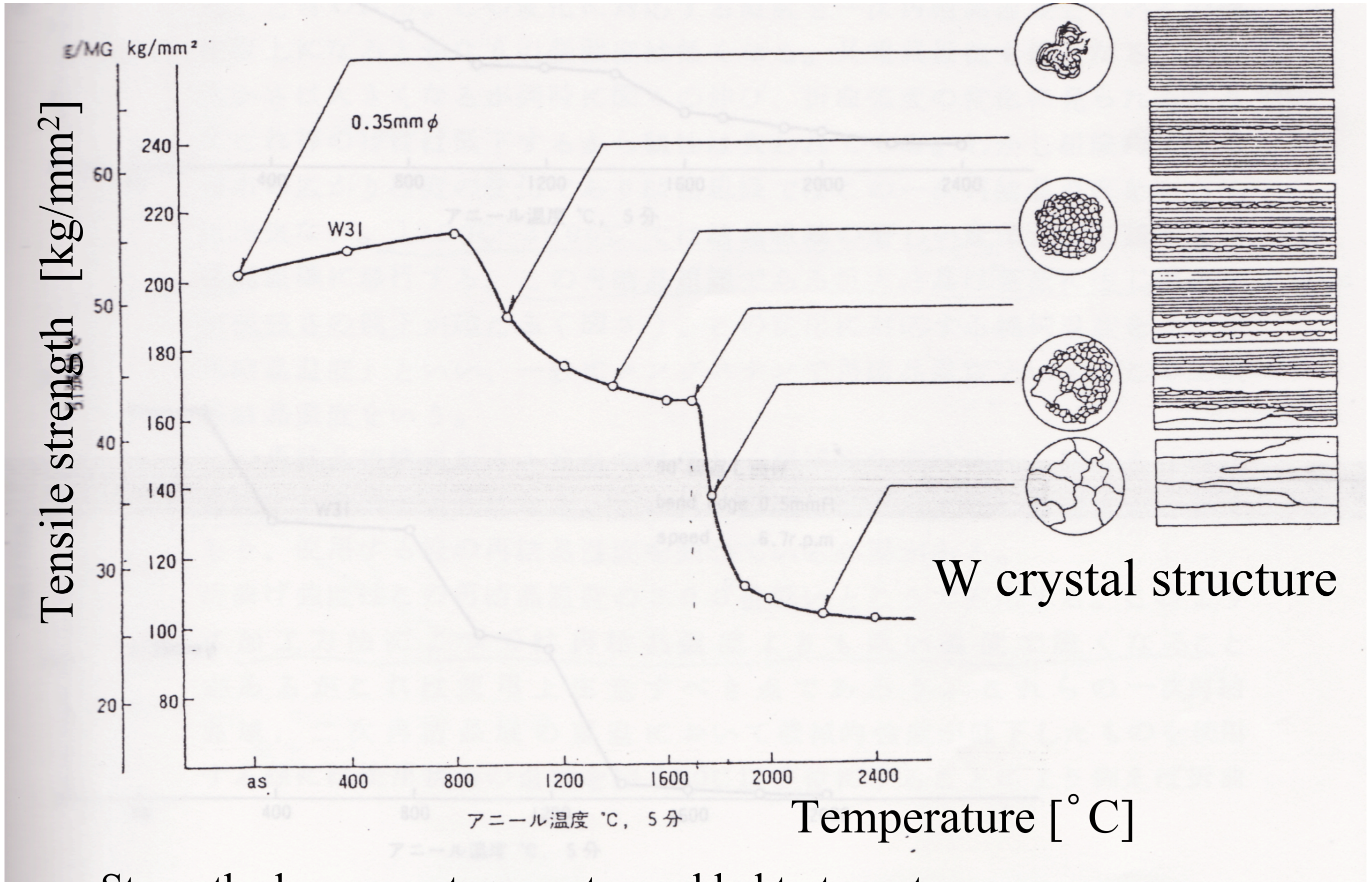
Calculated temp. rise on W spring surface as a function of time



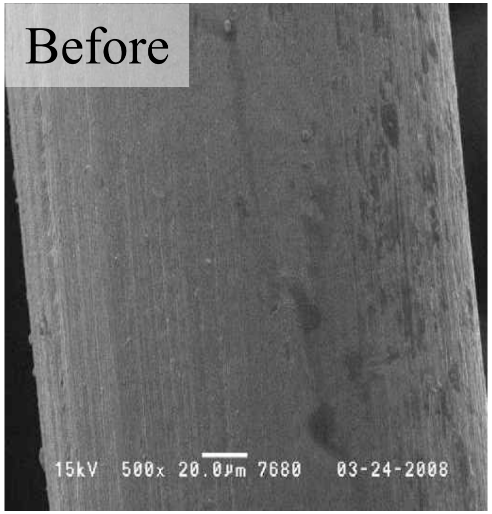
Temp. rise distribution inside W spring @ t=200 ns

What happens ??

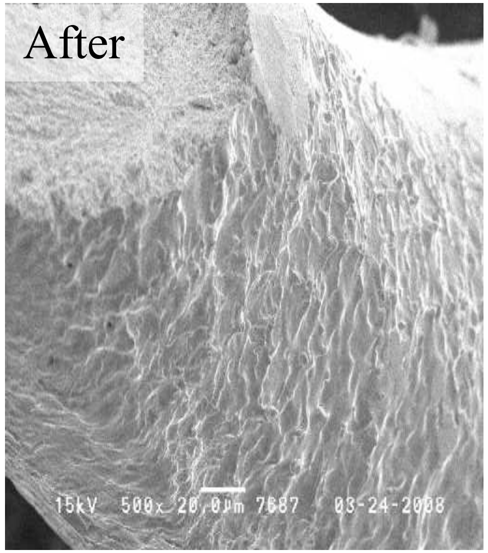
Discussion : Change in W crystal structure induced by temp. rise



Strength change vs. temperature added to tungsten
（Ref. Sanwa electric Co.,Ltd. Technical Report ）



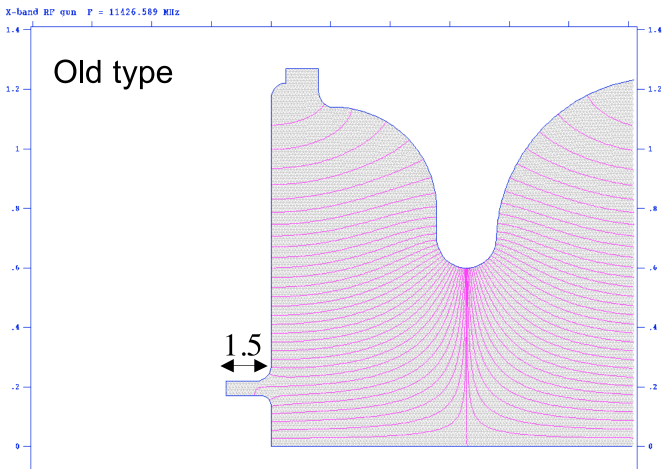
SEM image

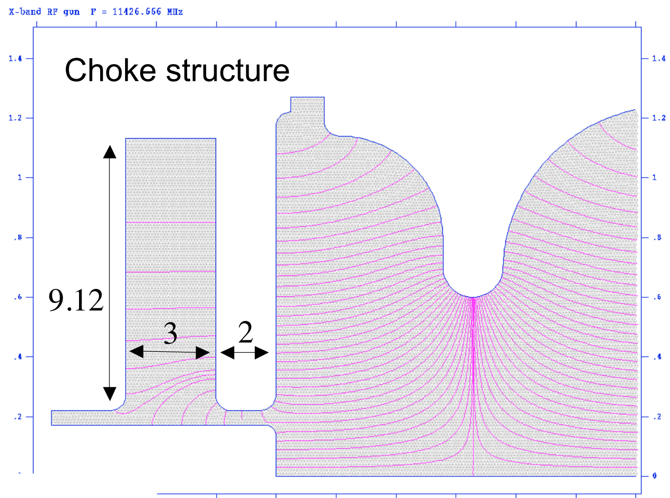


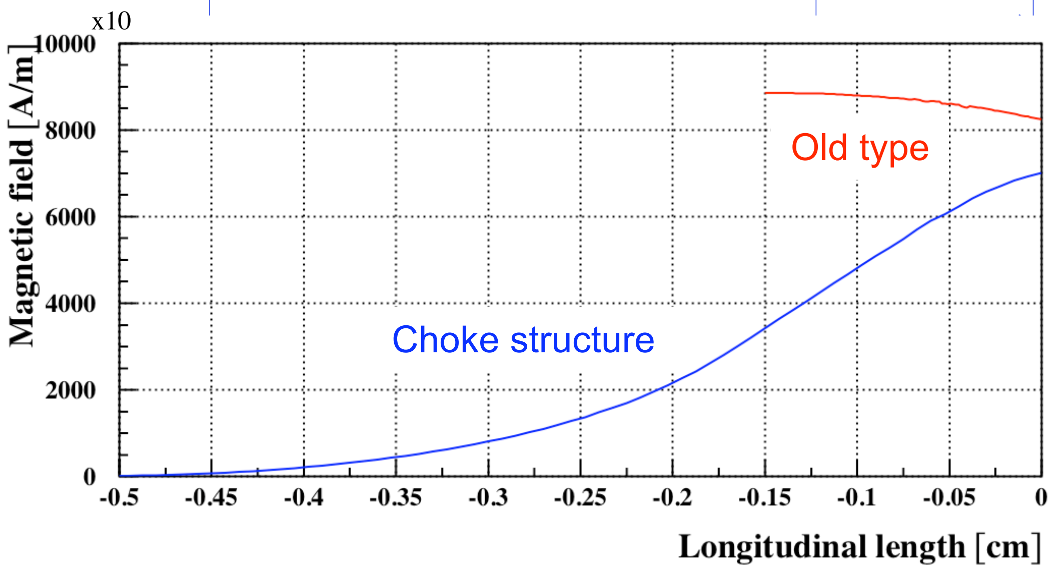
Temperature rise by RF (~600 ℃) plus the thermal diffusion from the thermionic cathode (~800℃) change the crystal structure of tungsten (Ductility → Brittleness).

Upgrade of RF-gun

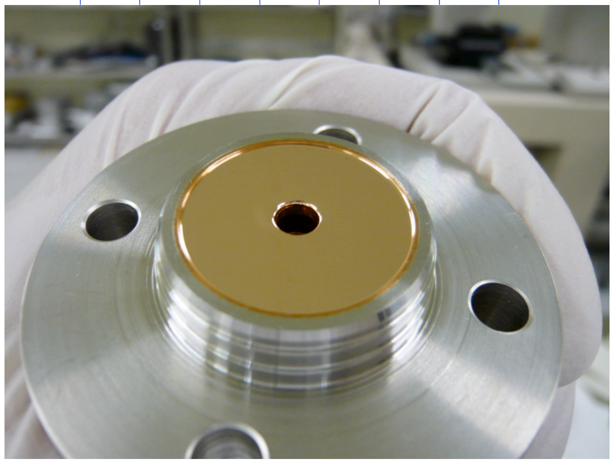
RF shielding at co-axial structure → "choke" structure.
Support of thermionic cathode → W spring.







Magnetic field is reduced below 10^{-6} at the W spring.



New cavity with choke structure

Summary and next works

Summary

We are developing "compact and high-intensity" Compton scattering monochromatic X-ray source for medical application at the University of Tokyo.

- X-band multi-bunch linac and Nd:YAG laser are adopted to realize compact and high stable X-ray generation.
- Whole components include beam line and laser system are installed.
- Upgrade of the X-band thermionic RF-gun with choke structure is underway.

Next works

- High-power experiment of the RF-gun. (Test of the choke structure)

  Now, the experiment is under way.

- Beam generation, acceleration and X-ray generation experiments.

  Next month