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DESY, Hamburg, Germany

The CeB_6 Electron Gun for the Soft-X-ray FEL Project at SPring-8

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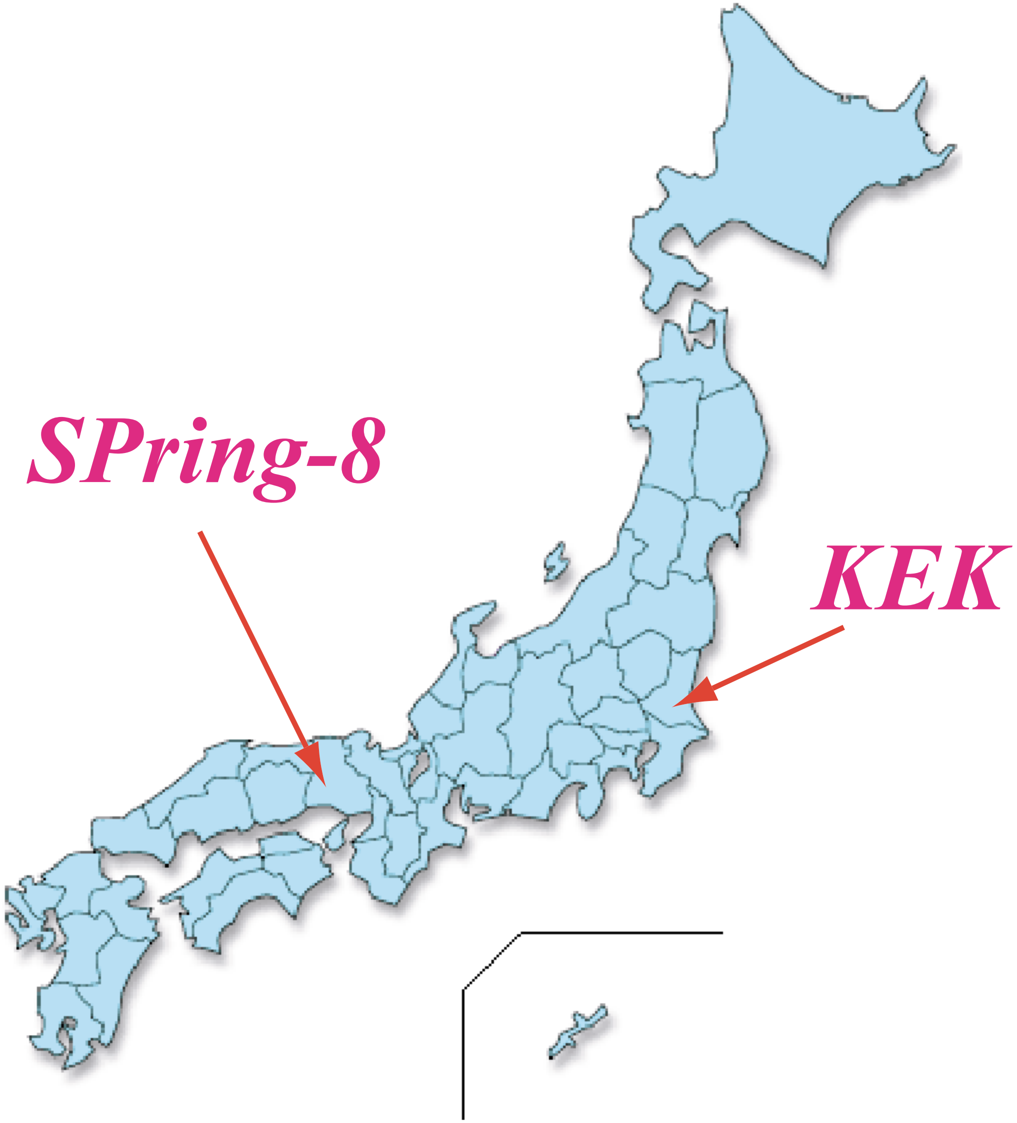
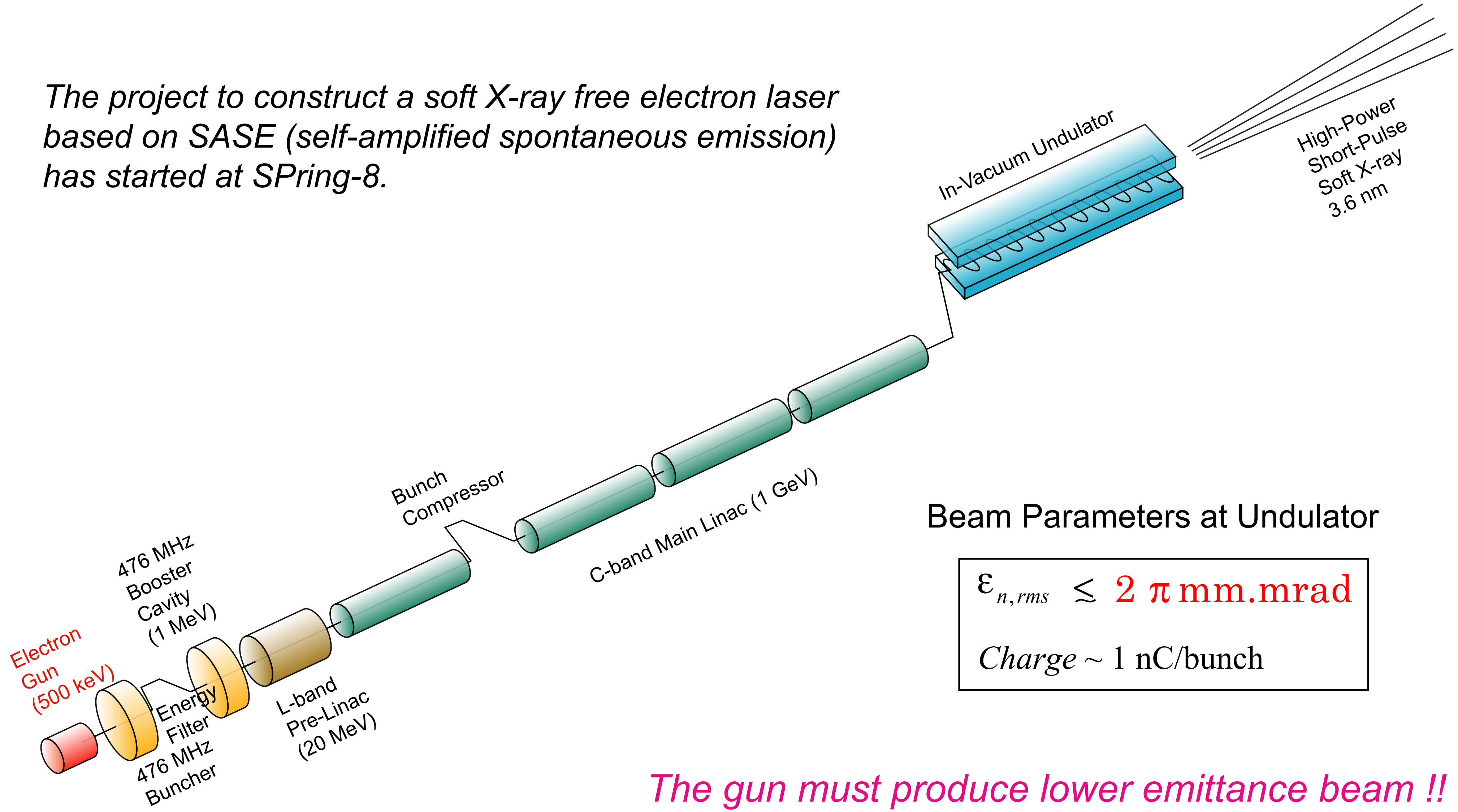
Where is SPring-8 ?

Harima Science Garden City



SPring-8 Compact SASE Source (SCSS Project)

The project to construct a soft X-ray free electron laser based on SASE (self-amplified spontaneous emission) has started at SPring-8.



Beam Parameters at Undulator

$$\varepsilon_{n,rms} \lesssim 2\,\pi\,\mathrm{mm.mrad}$$

Charge ~ 1 nC/bunch

The gun must produce lower emittance beam !!

Requirements of X-FEL Electron Source

1) Low Emittance

<1 π mm.mrad

→ SASE-FEL Saturation

2) High Charge

~1 nC/bunch

3) High Beam Quality

No Beam Halo, No Dark Current

→ Precise Alignment
Protection of Undulator Magnet

4) Stable

Small Jitter, Long Lifetime

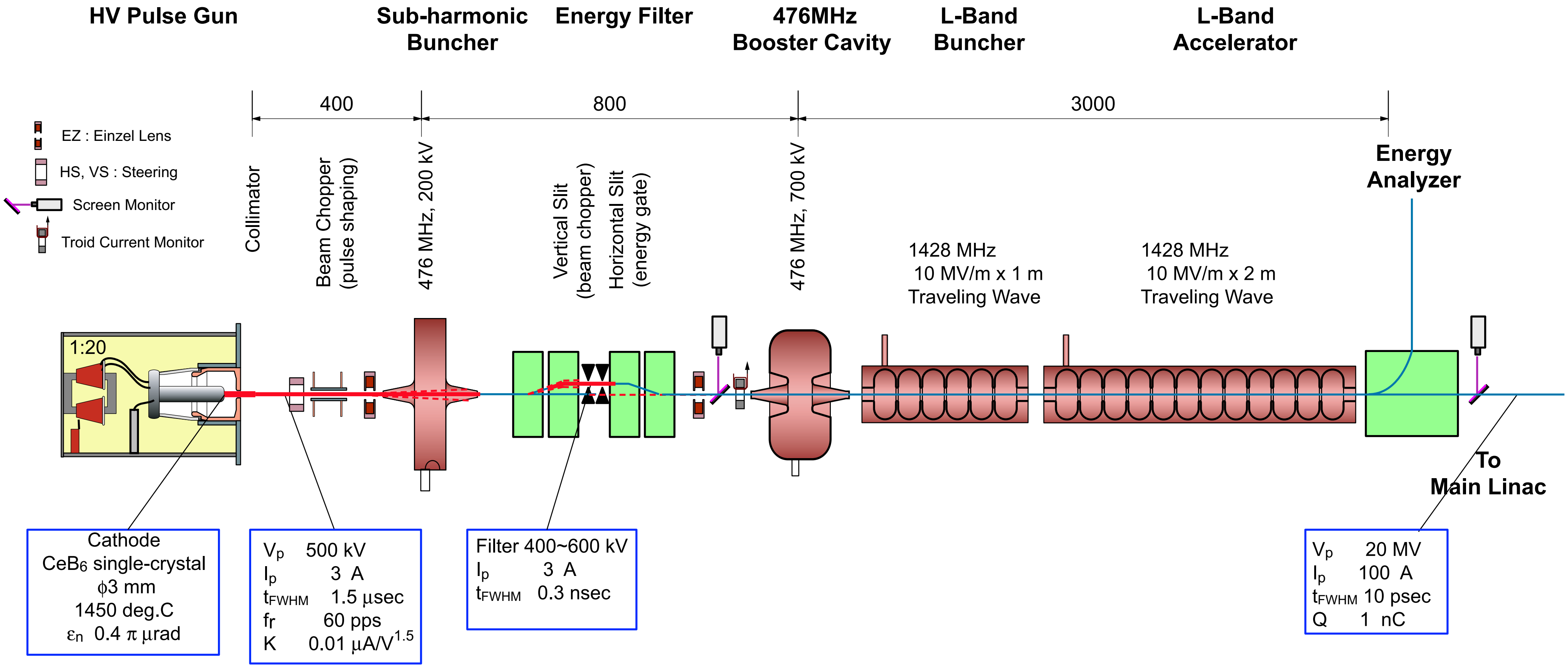
→ User Experiments

Thermionic Gun   RF-Gun

2002 July

Low Emittance Injector for SASE-FEL

X-ray FEL



Why do we use the HV thermionic gun ?

1) Stable and Long Lifetime

- Simple.
- High power pulsed technology and thermionic cathode technology is well established, and used for various electron devices.

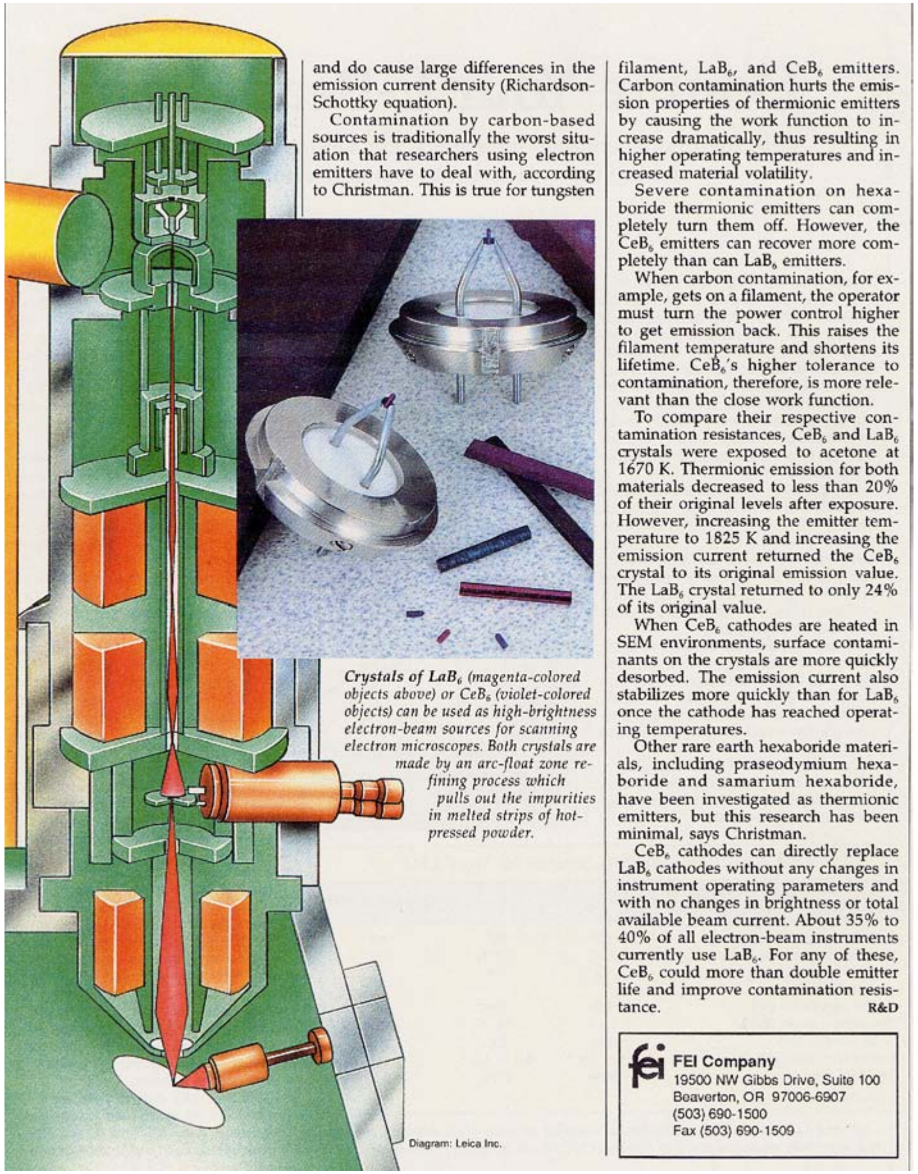
2) Low Emittance and Uniform Emission

- Single crystal cathode has very flat surface.
- Single crystal cathode provides uniform emission.

CeB_6 Cathode Development

CeB_6 (Cerium Hexaboride) Single-Crystal Cathode

CeB_6 cathode is widely used in electron microscope !!



and do cause large differences in the emission current density (Richardson-Schottky equation).

Contamination by carbon-based sources is traditionally the worst situation that researchers using electron emitters have to deal with, according to Christman. This is true for tungsten filament, LaB_6, and CeB_6 emitters. Carbon contamination hurts the emission properties of thermionic emitters by causing the work function to increase dramatically, thus resulting in higher operating temperatures and increased material volatility.

Severe contamination on hexaboride thermionic emitters can completely turn them off. However, the CeB_6 emitters can recover more completely than can LaB_6 emitters.

When carbon contamination, for example, gets on a filament, the operator must turn the power control higher to get emission back. This raises the filament temperature and shortens its lifetime. CeB_6's higher tolerance to contamination, therefore, is more relevant than the close work function.

To compare their respective contamination resistances, CeB_6 and LaB_6 crystals were exposed to acetone at 1670 K. Thermionic emission for both materials decreased to less than 20% of their original levels after exposure. However, increasing the emitter temperature to 1825 K and increasing the emission current returned the CeB_6 crystal to its original emission value. The LaB_6 crystal returned to only 24% of its original value.

When CeB_6 cathodes are heated in SEM environments, surface contaminants on the crystals are more quickly desorbed. The emission current also stabilizes more quickly than for LaB_6 once the cathode has reached operating temperatures.

Other rare earth hexaboride materials, including praseodymium hexaboride and samarium hexaboride, have been investigated as thermionic emitters, but this research has been minimal, says Christman.

CeB_6 cathodes can directly replace LaB_6 cathodes without any changes in instrument operating parameters and with no changes in brightness or total available beam current. About 35% to 40% of all electron-beam instruments currently use LaB_6. For any of these, CeB_6 could more than double emitter life and improve contamination resistance. R&D

Crystals of LaB_6 (magenta-colored objects above) or CeB_6 (violet-colored objects) can be used as high-brightness electron-beam sources for scanning electron microscopes. Both crystals are made by an arc-float zone refining process which pulls out the impurities in melted strips of hot-pressed powder.

Diagram: Leica Inc.

Properties

- Very flat surface
  (surface roughness <1 μm)
- Low workfunction (~2.4 eV)
- Long lifetime (>10,000 hours)
- Rapid recovery from contamination

Design parameter of SCSS cathode

Thermal Emittance

$$\varepsilon_{n,rms} = \frac{r}{2}\sqrt{\frac{k_B T}{m_e c^2}} = 0.4\,\pi \text{ mm mrad}$$

Cathode Radius $r=1.5$ mm

Temperature $T=1450$°C (1723 K)

Emission Current Density

Richardson-Dashman's Formula (Ideal Case)

$$J = 120.4\ T^2 \exp(-\phi' / k_B T) > 42 \text{ A/cm}^2$$

Boltzmann's Constant $k_B = 8.617 \times 10^{-5}\ (eV/K)$

Effective Workfunction $\phi' = \phi - \frac{e}{2}\sqrt{\frac{eE}{\pi\varepsilon_0}}$ ~2.3 (eV)

Property of CeB6 Cathode

Thermal Emittance

Normalized Emittance (RMS)

$$\varepsilon_{n,rms} = \frac{r_c}{2}\sqrt{\frac{k_B T}{m_e c^2}} = 0.4\,\pi\ \mathrm{mm.mrad}$$

Cathode Radius $r=1.5\ mm$

Temperature $T=1450$°C $(1723\ K)$

Emission Current Density

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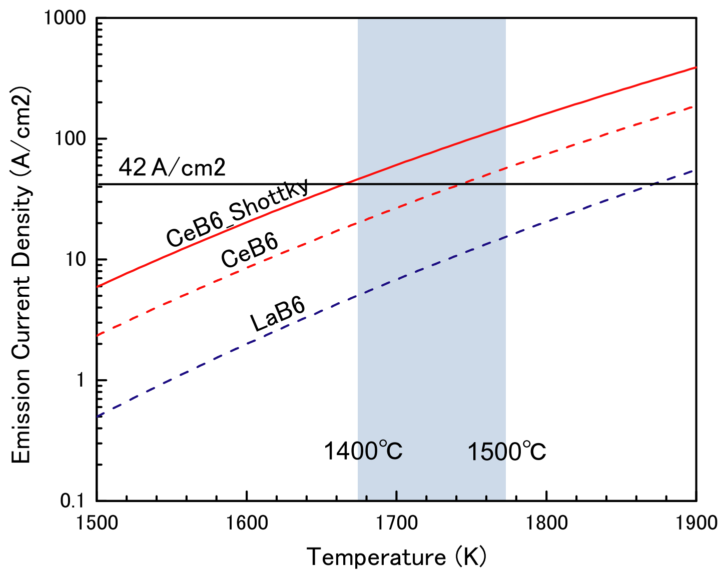
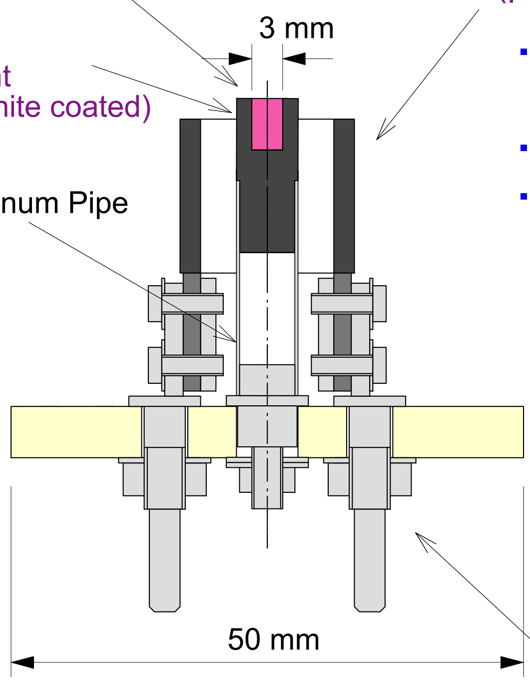
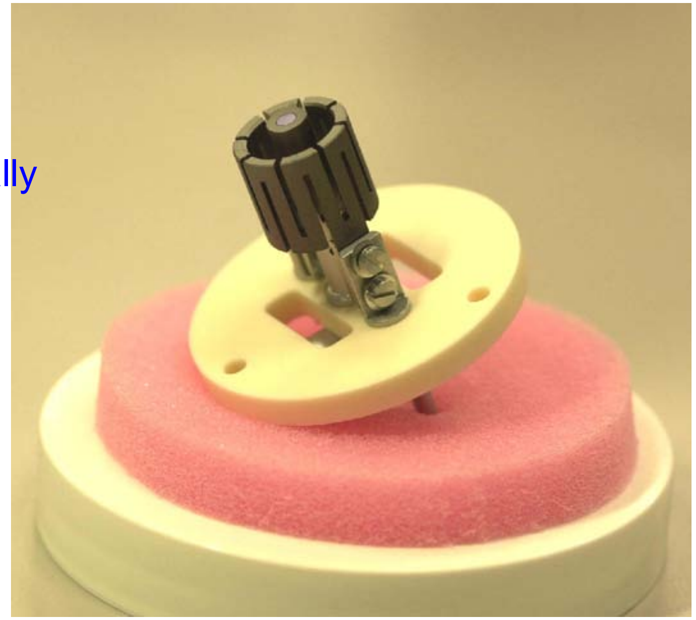
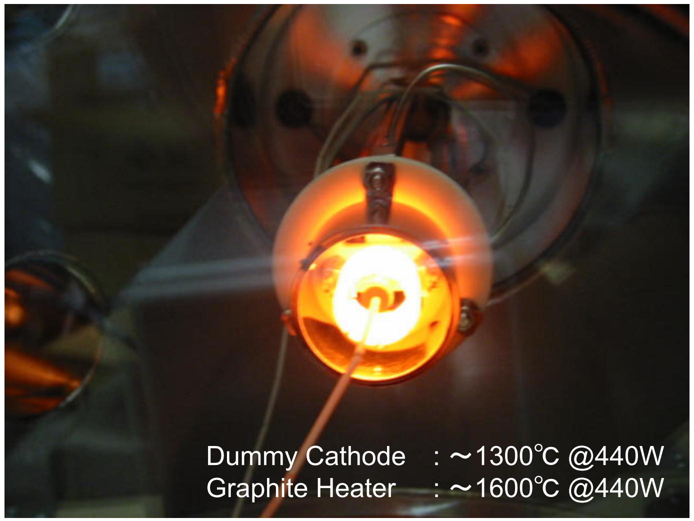


CeB6 Cathode Assembly (First Model)



- Mechanically and Chemically Stable in Vacuum
- Stable Electric Resistance
- High Purity

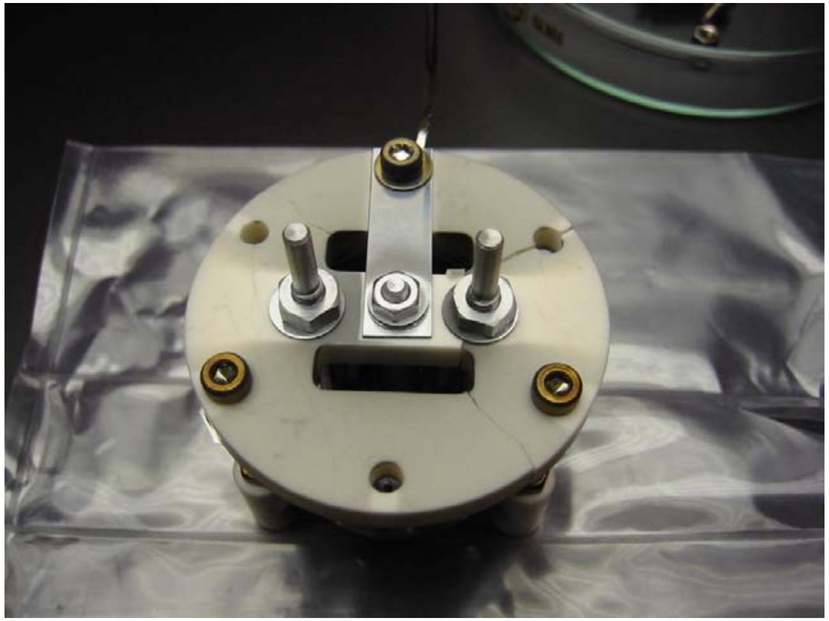




Operational Cathode Temperature ~ 1500℃
(much higher than conventional cathodes)

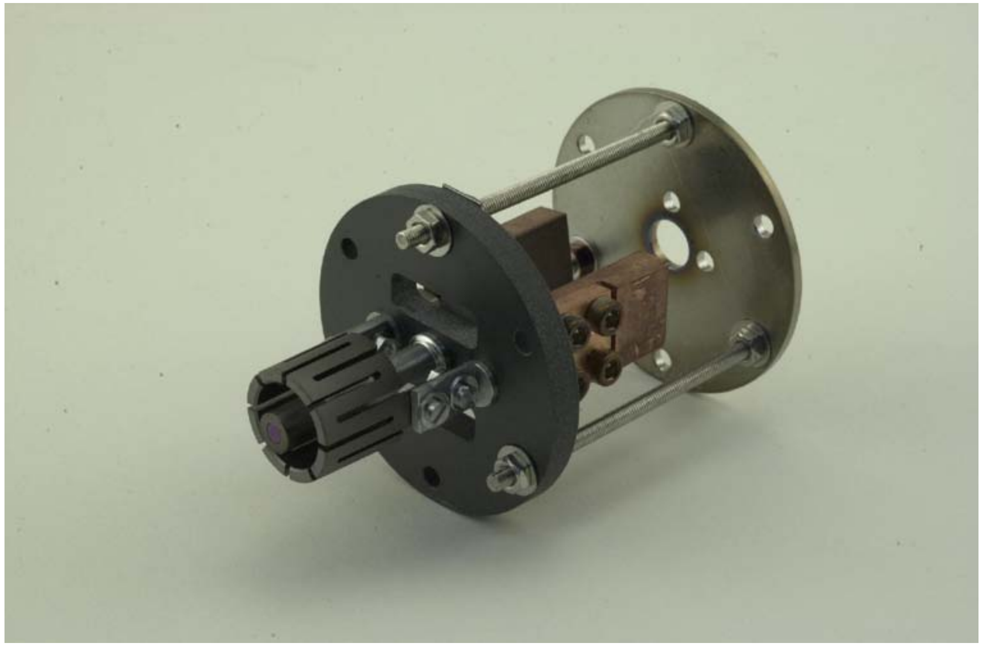
Technical Challenge !!!

Ceramic Base of Cathode Assembly



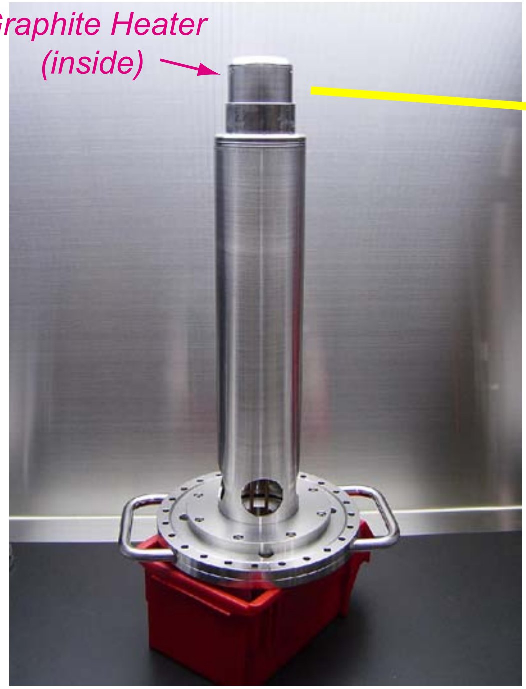
Alumina (Al_2O_3) ceramic base was broken by thermal heating.

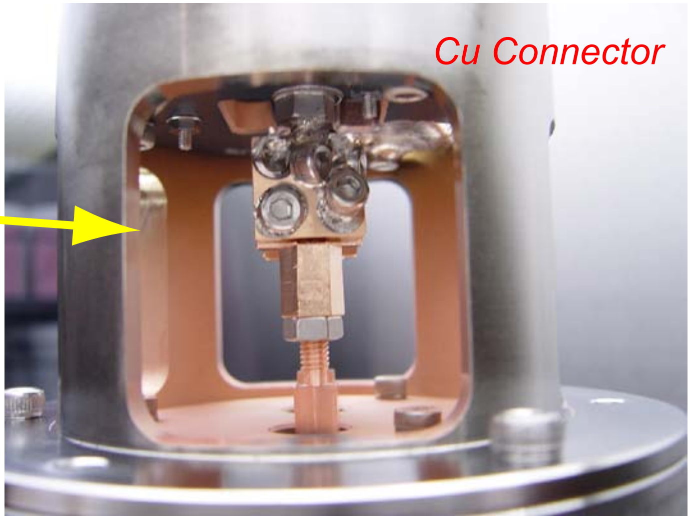
Si_3N_4 ceramic base
Very strong against thermal stress !!

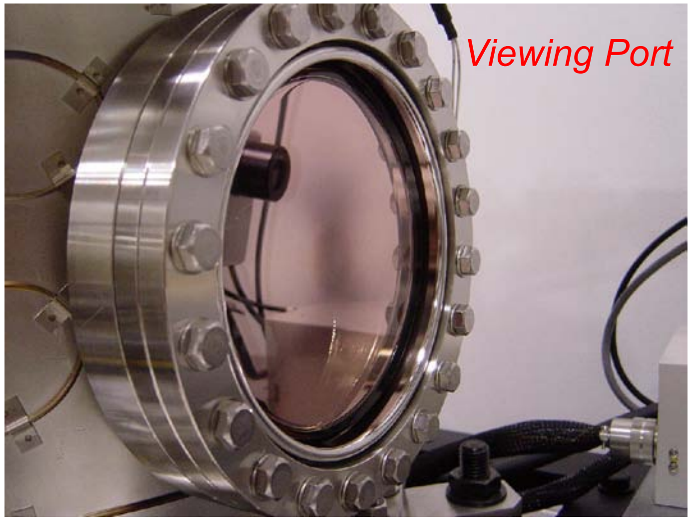


Melting of Copper Connector

Cathode Stem

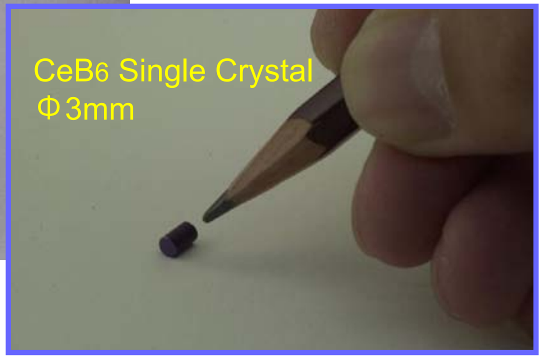


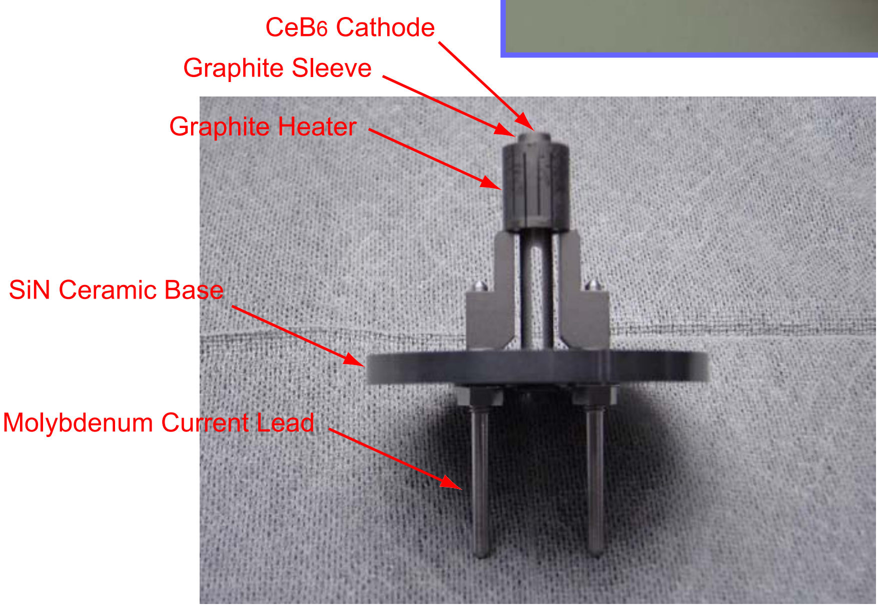




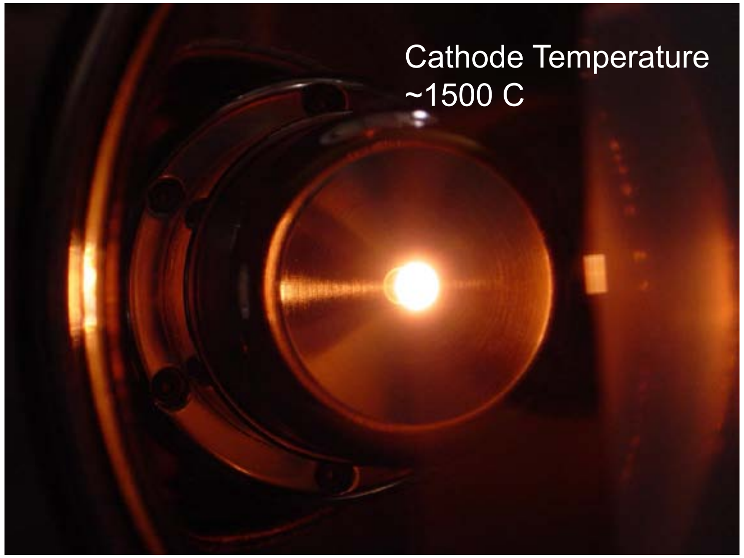
CeB6 Cathode Assembly (New Model)

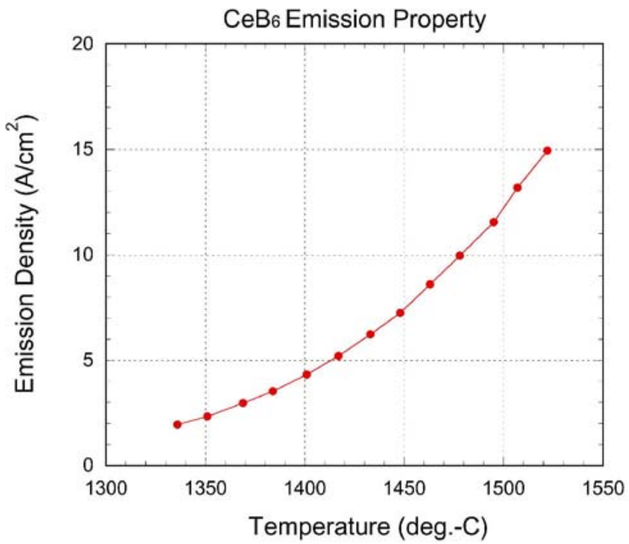
Cathode Assembly





Heated Cathode in Stem



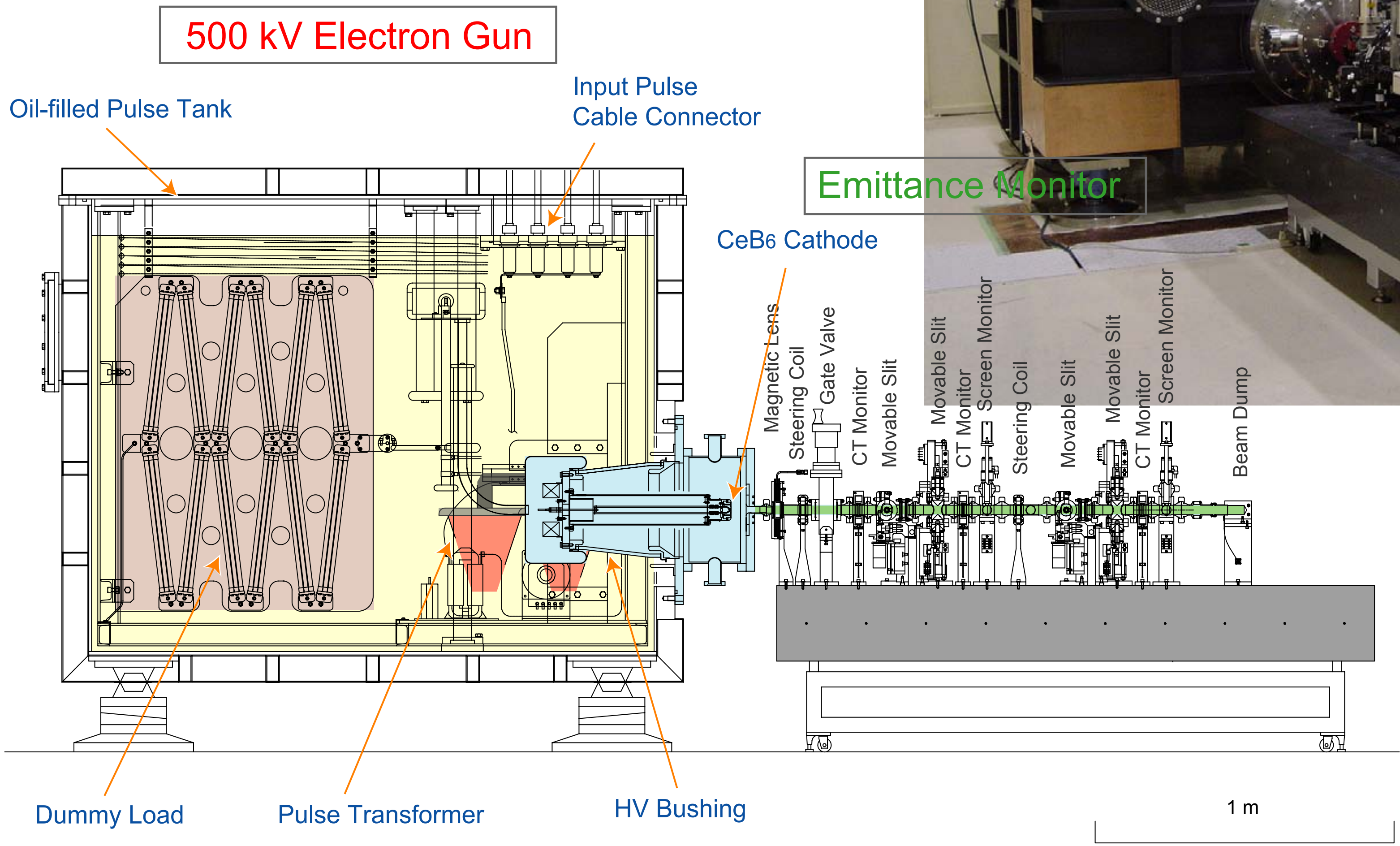


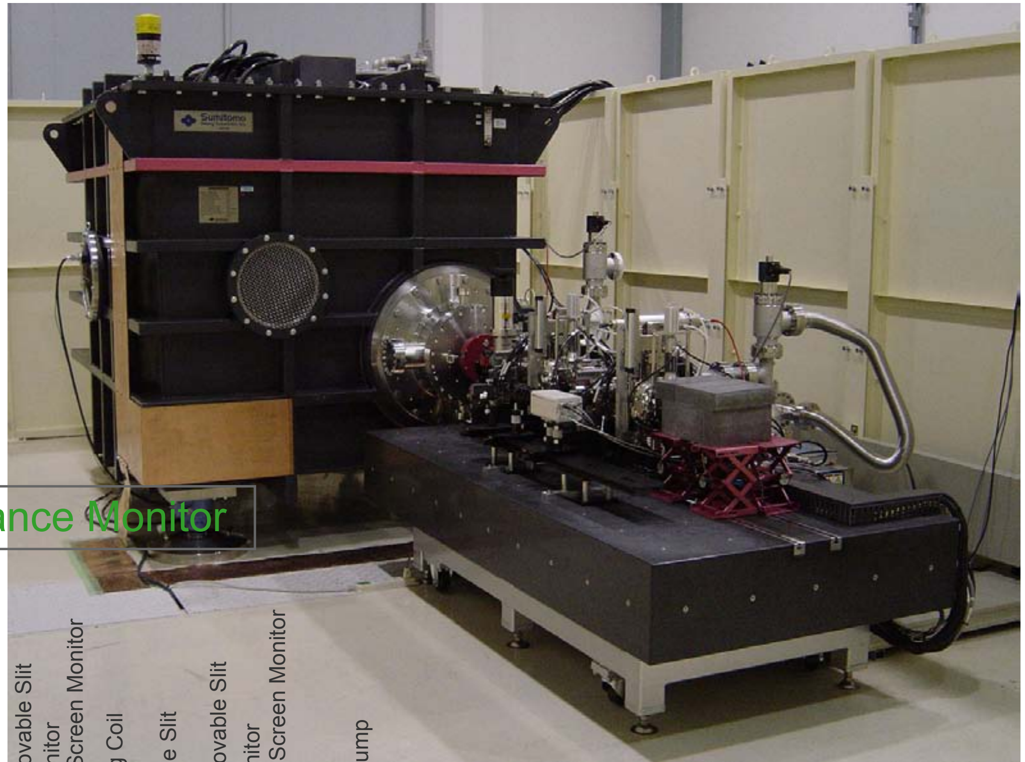
The gun voltage=500 kV
Temperature was measured at the graphite sleeve by a radiation monitor.

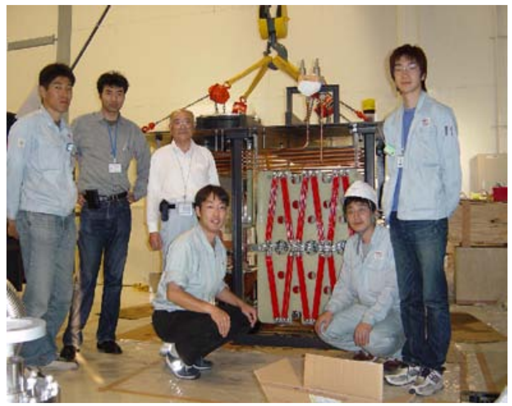
500 kV Electron Gun

500 kV Electron Gun

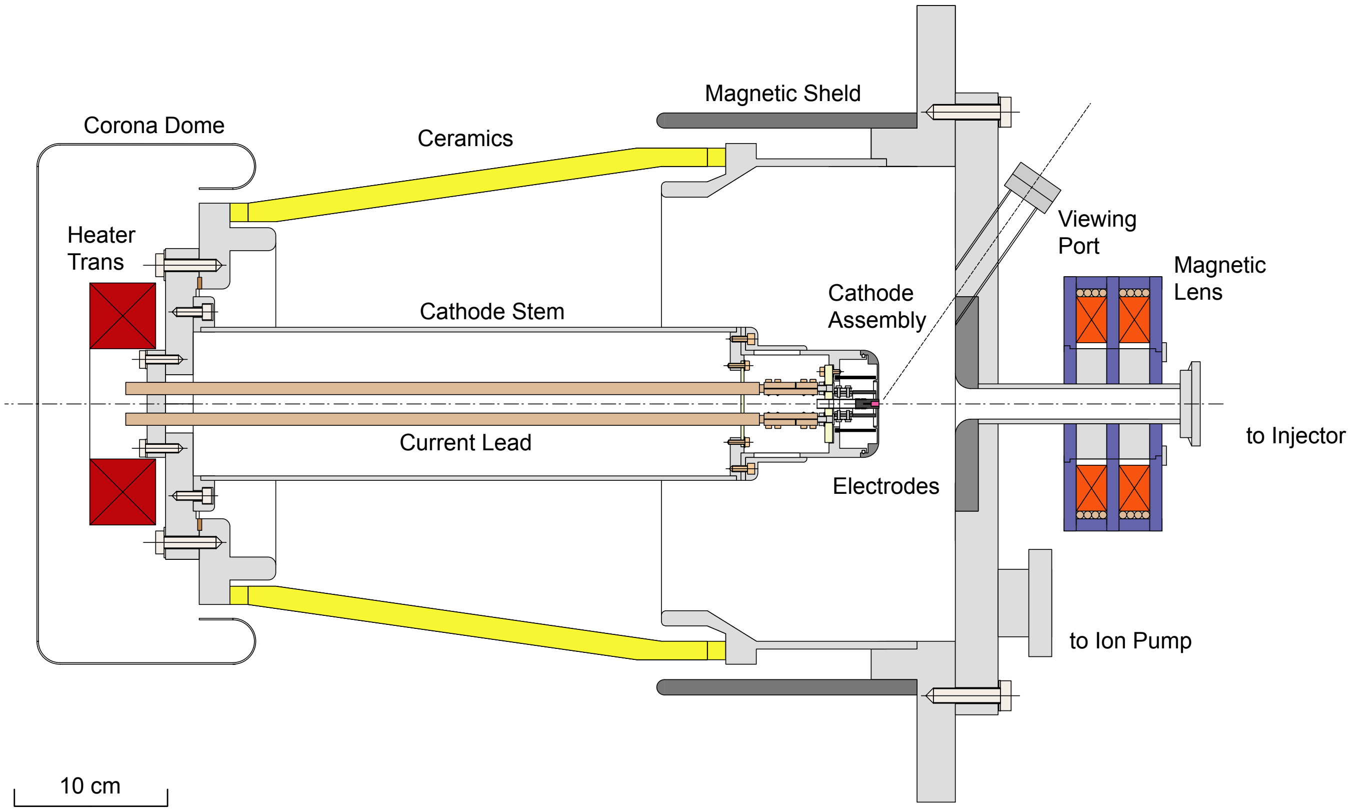
C-band klystron modulator is used as a HV pulsed power supply.





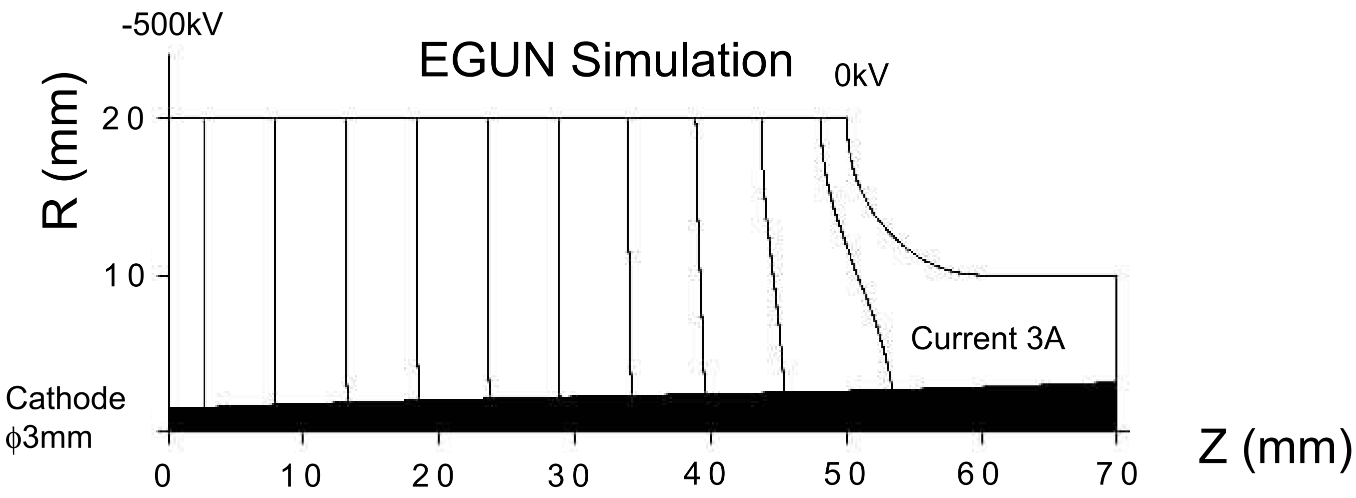


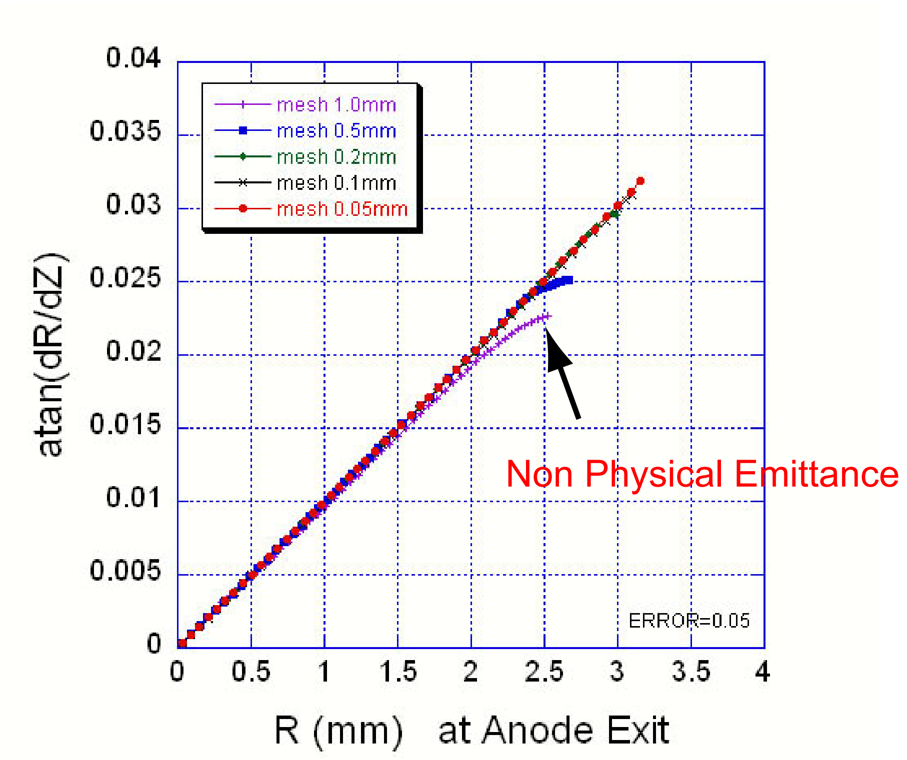
500 kV Electron Gun Chamber

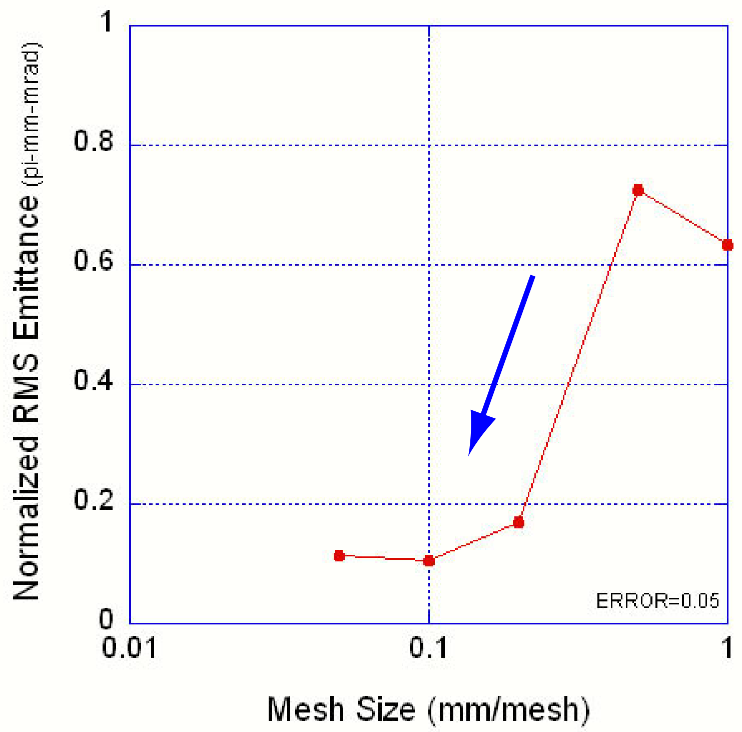


Conceptual Design (2001)

Emittance at Gun Exit (Simulation)

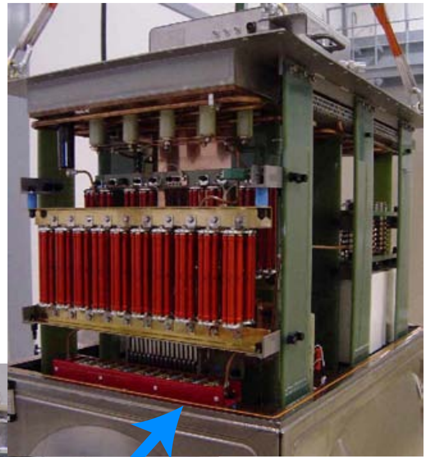




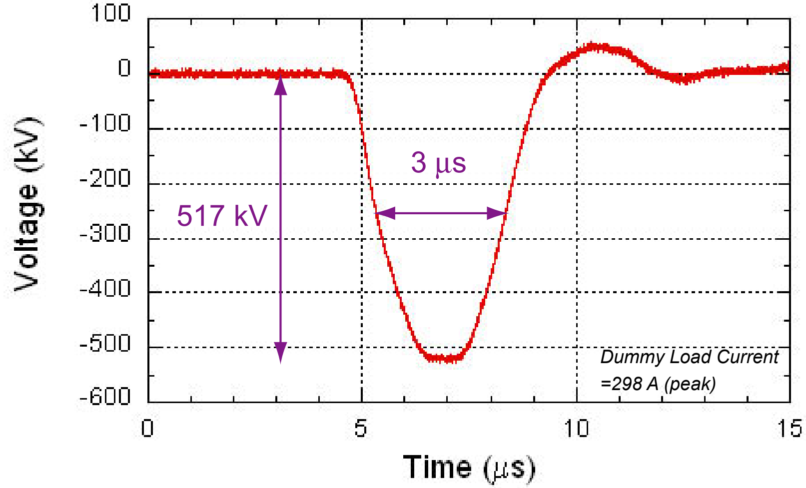


C-band Klystron Modulator

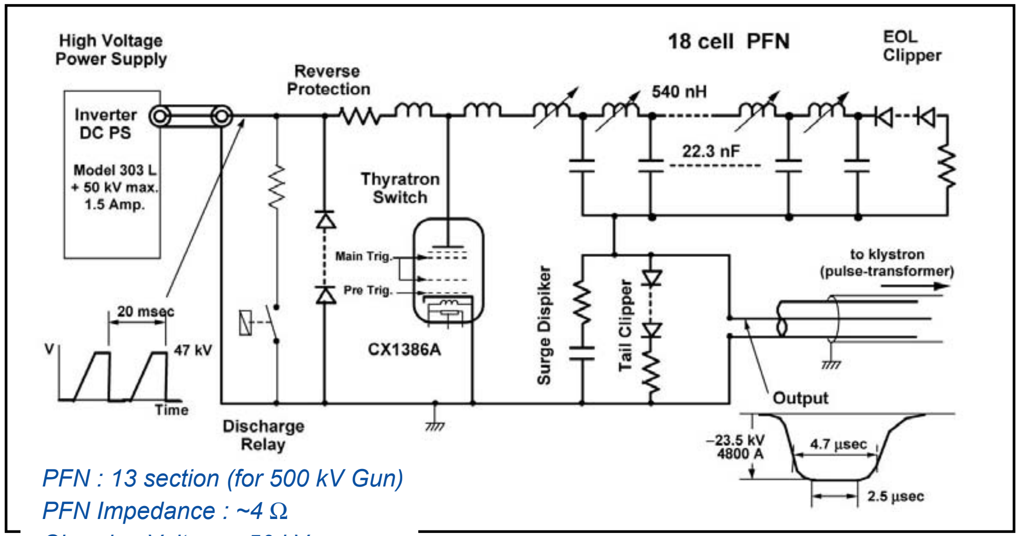
Same model of the C-band klystron modulator is used for the 500 kV electron gun.



Gun Pulse Waveform



Circuit Diagram

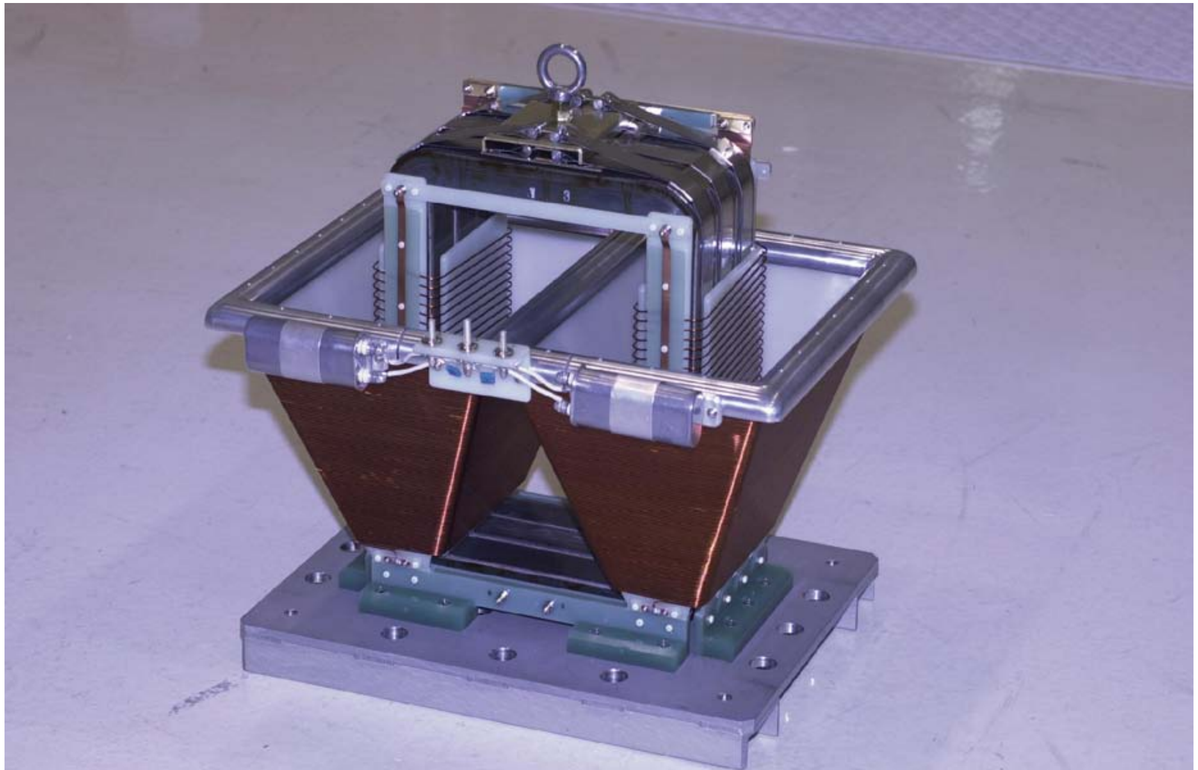


PFN : 13 section (for 500 kV Gun)
PFN Impedance : ~4 Ω
Charging Voltage : 50 kV max
Max. Repetition Rate : 60 pps

500 kV Pulse Transformer

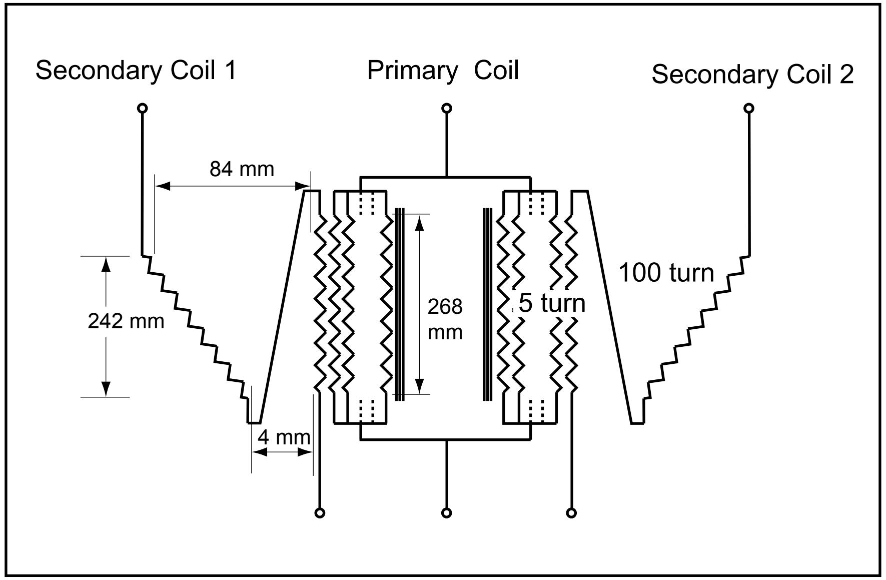
Conducted by Prof. Baba

Pulse Transformer of 500 kV Electron Gun



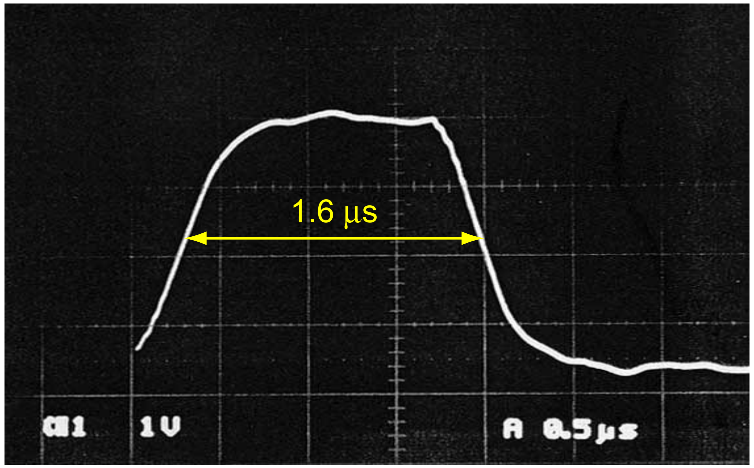
Fabricated by NIHON DENJI KOGYO Co., Ltd.

Winding Circuit

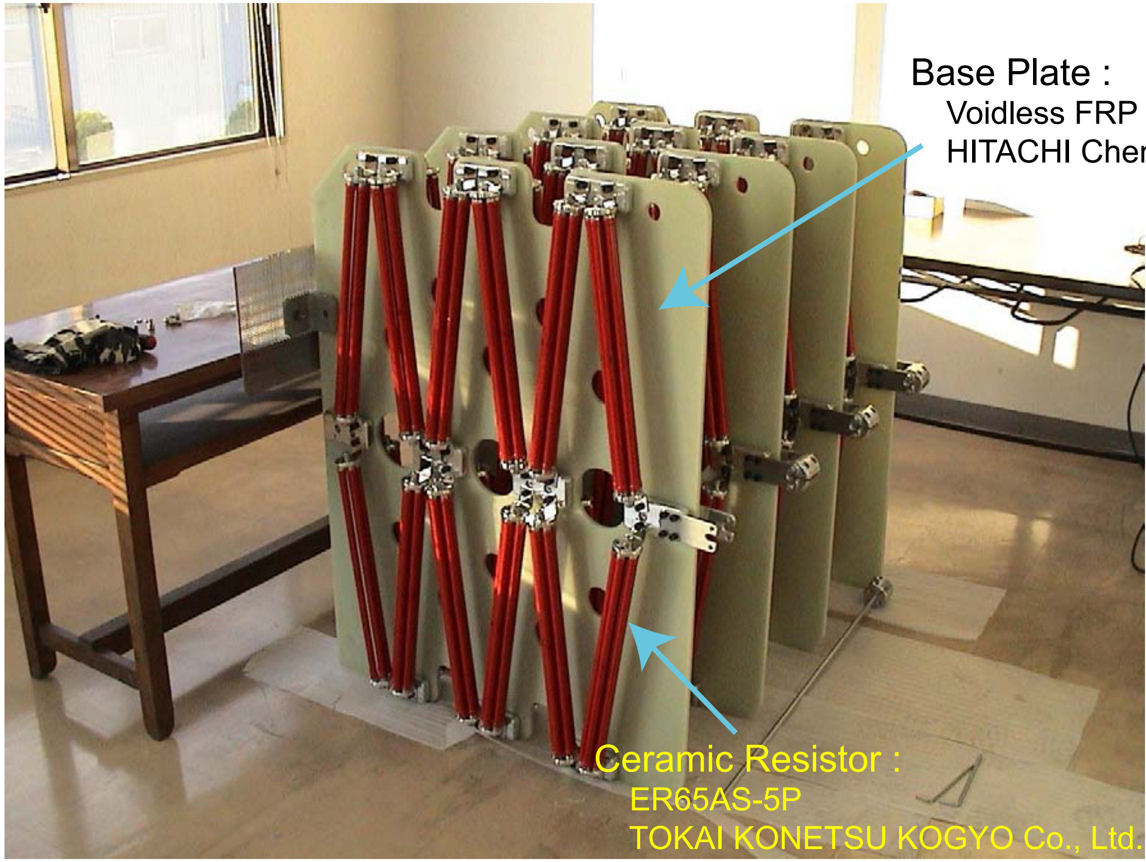


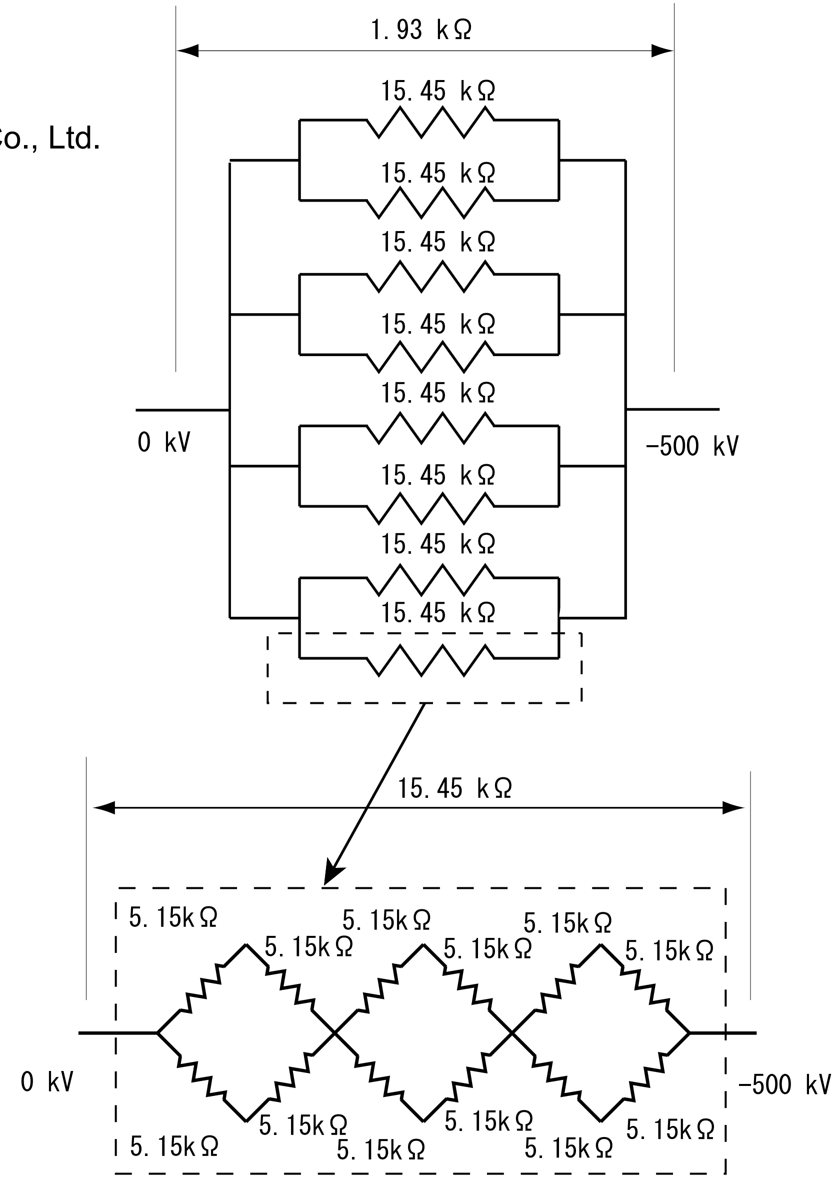
- Turn Ratio — 1:21
- Input Pulse from Modulator — 23.8 kV, 5502 A
- Output Pulse to Cathode & Dummy Load — 500 kV, 262 A
- Pulse Width — 1.6 µs

Pulse Shape (@Low Voltage)



500 kV Dummy Load

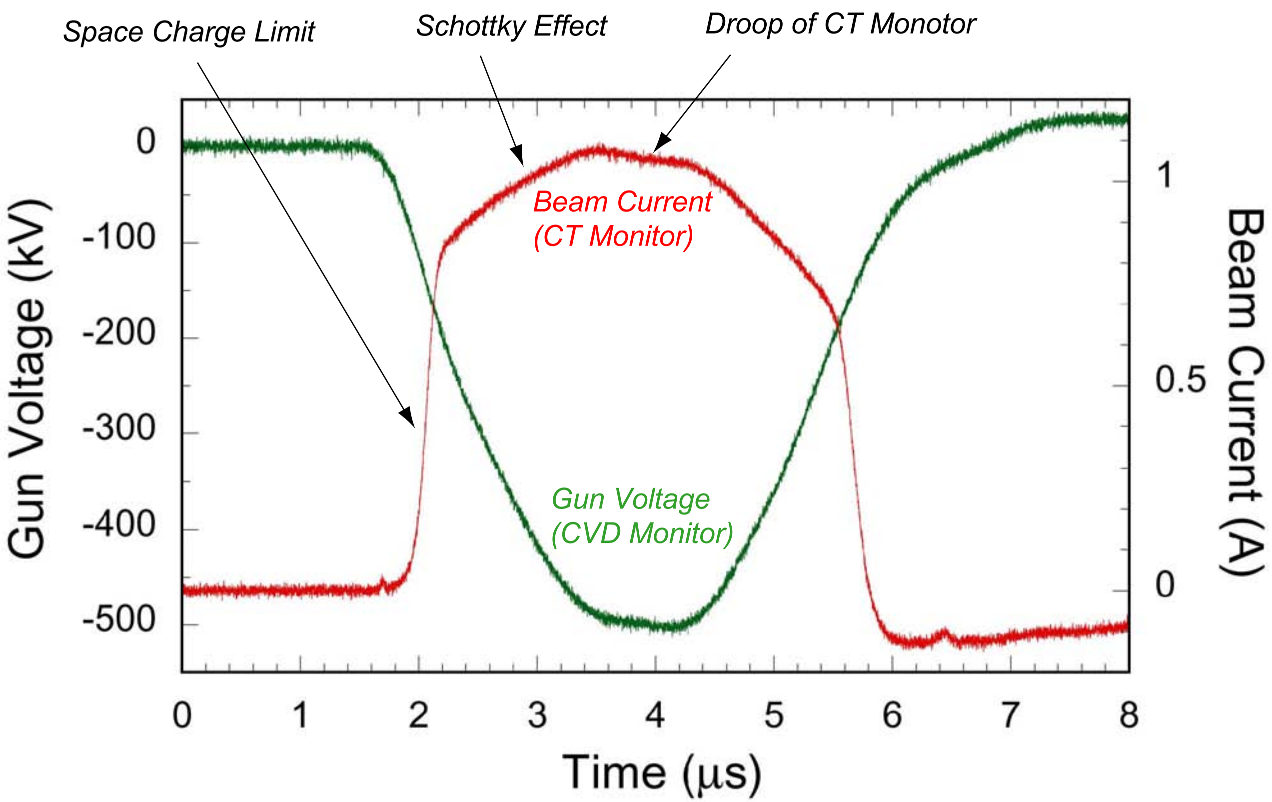




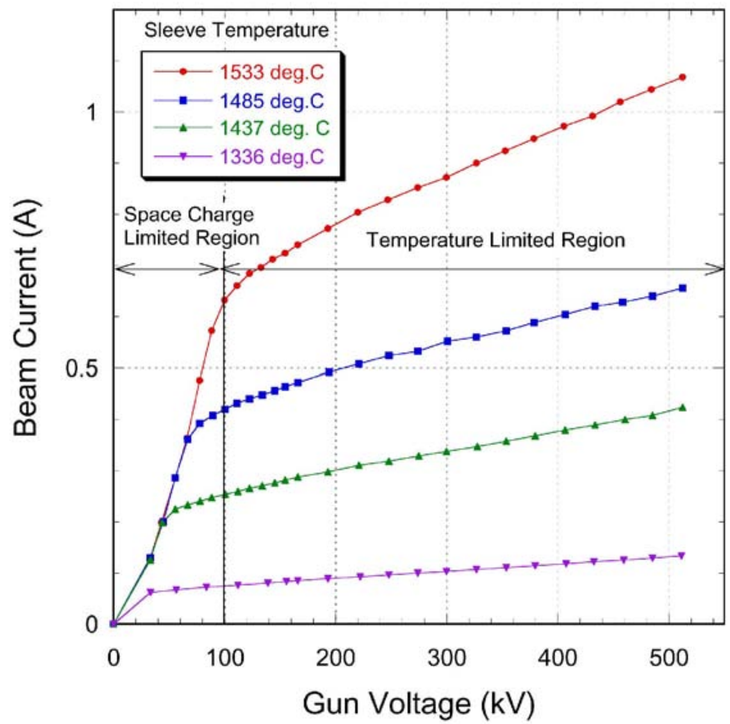
・Pulse High Voltage	500 kV
・Peak Current	259 A
・Pulse Width	1.6 μs
・Dummy Load Impedance	1.93 kΩ
・Average Power	12.4 kW

500 keV Beam Production

Beam Waveform



I-V Curve



~1 ns part will cut out from the flattop by a beam deflector, and be used for the SCSS accelerator.

We operate the gun in temperature limited region to reduce emittance growth due to space charge.

Emittance Measurement

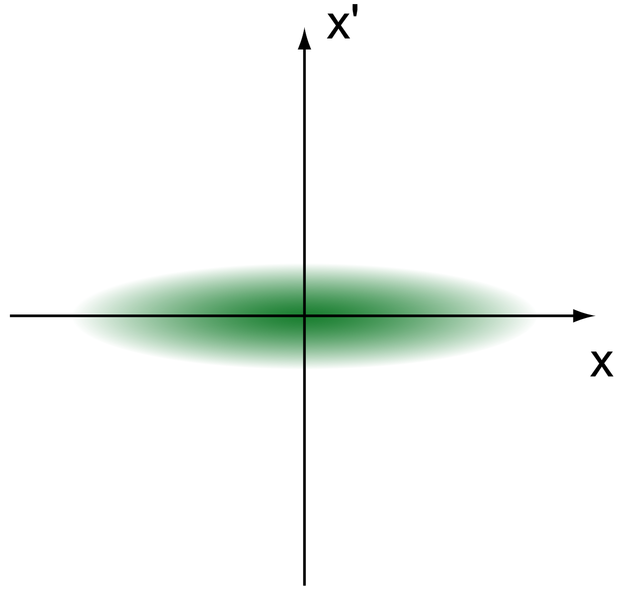
Normalized rms Emittance

Definition

$$\varepsilon_{n,rms} = \frac{1}{m_0 c}\sqrt{\langle x^2\rangle\langle p_x^2\rangle - \langle x\cdot p_x\rangle^2}$$

$$= \beta\gamma\sqrt{\langle x^2\rangle\langle x'^2\rangle - \langle x\cdot x'\rangle^2}$$

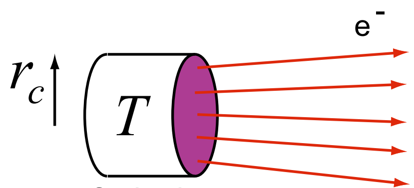
unit : π mm.mrad



$$\langle x^2\rangle = \frac{\iint x^2 i\,(x,x')dxdx'}{\iint i\,(x,x')dxdx'}$$

$$\langle x'^2\rangle = \frac{\iint x'^2 i\,(x,x')dxdx'}{\iint i\,(x,x')dxdx'}$$

$$\langle x\cdot x'\rangle = \frac{\iint x\cdot x' i\,(x,x')dxdx'}{\iint i\,(x,x')dxdx'}$$

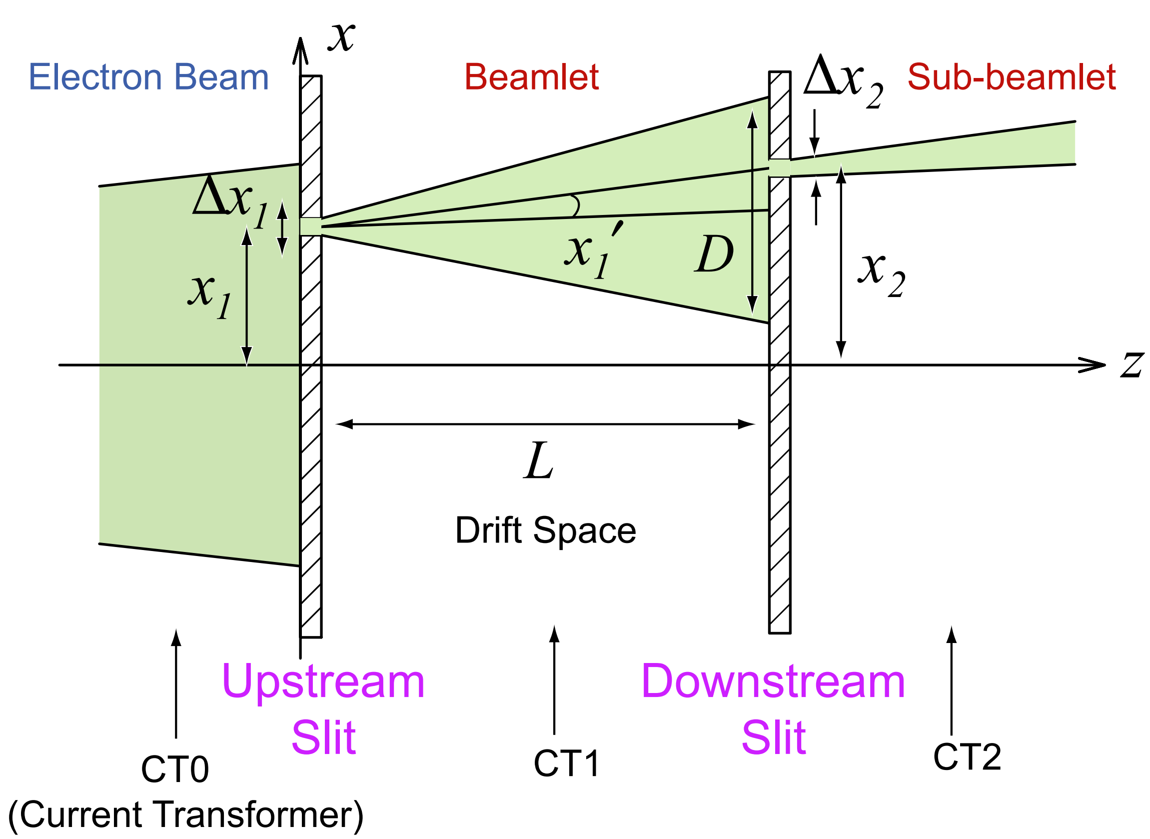


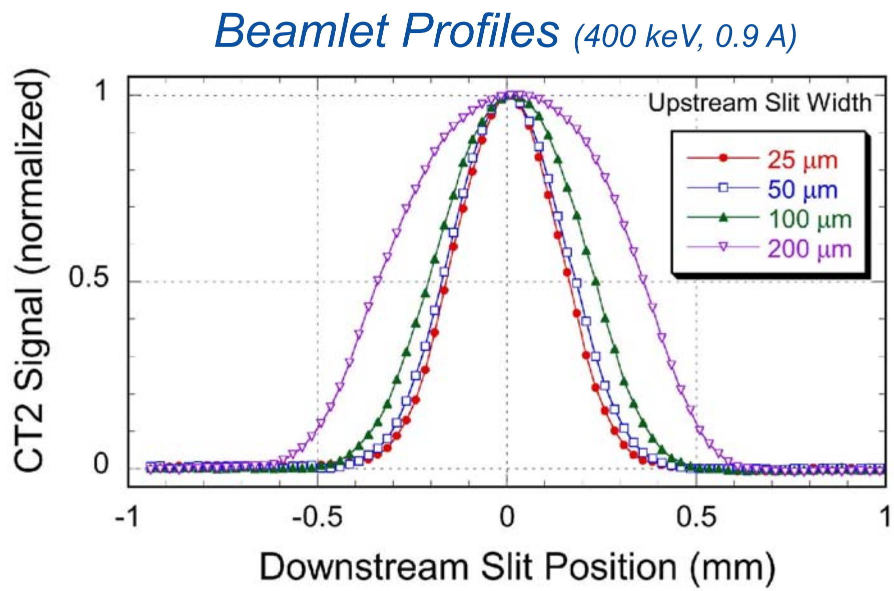
$$\varepsilon_{n,rms} = \frac{r_c}{2}\sqrt{\frac{k_B T}{m_0 c^2}}$$

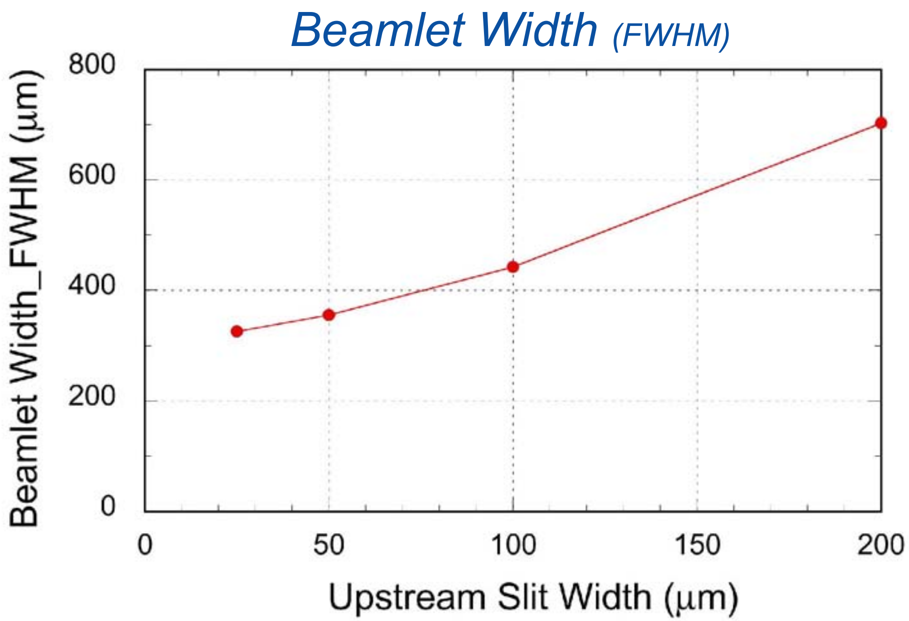
= 0.4 π mm.mrad

(r_c = 1.5 mm, T = 1723 K (1450°C))

Emittance Measurement by Double-slits

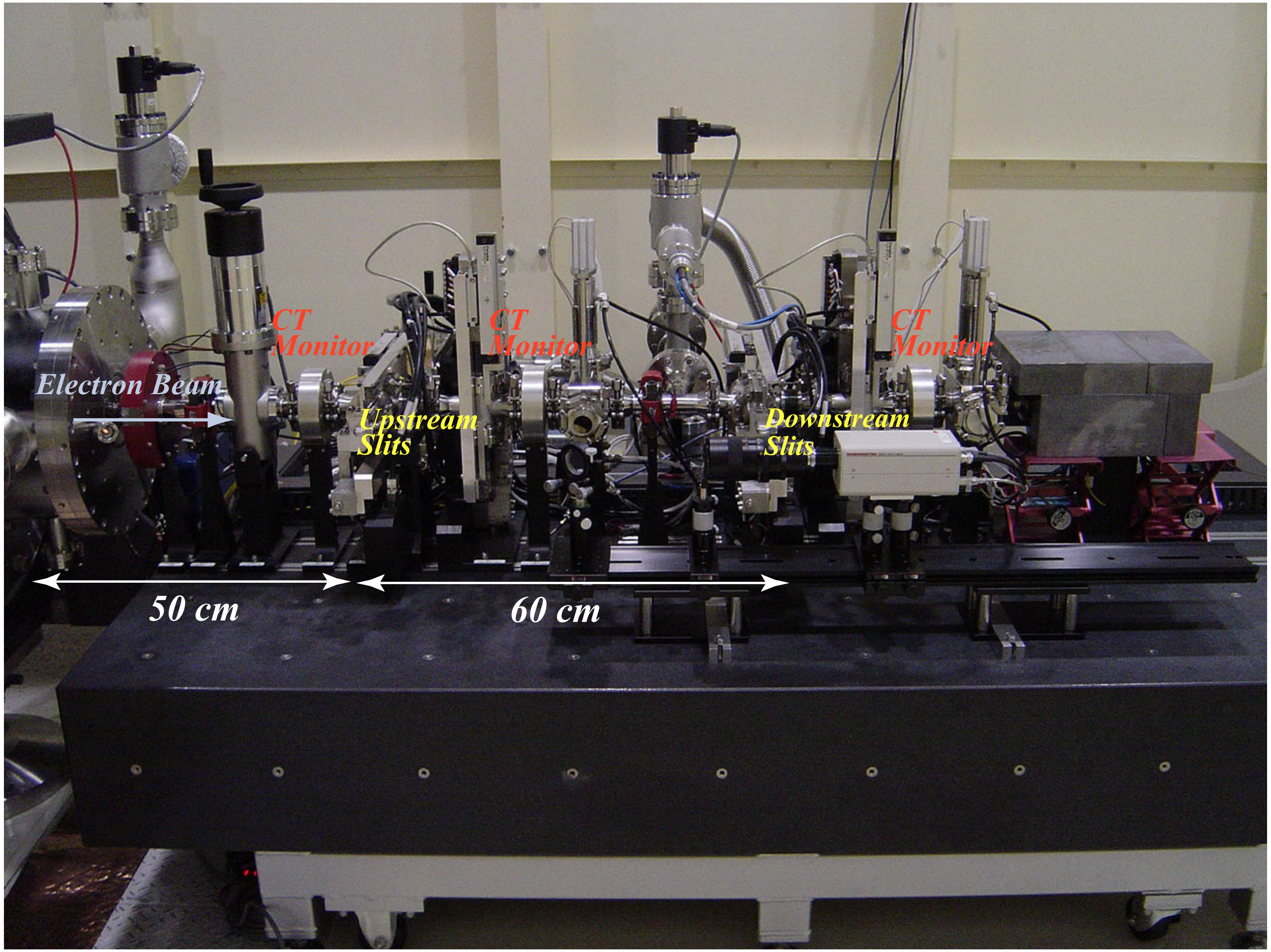






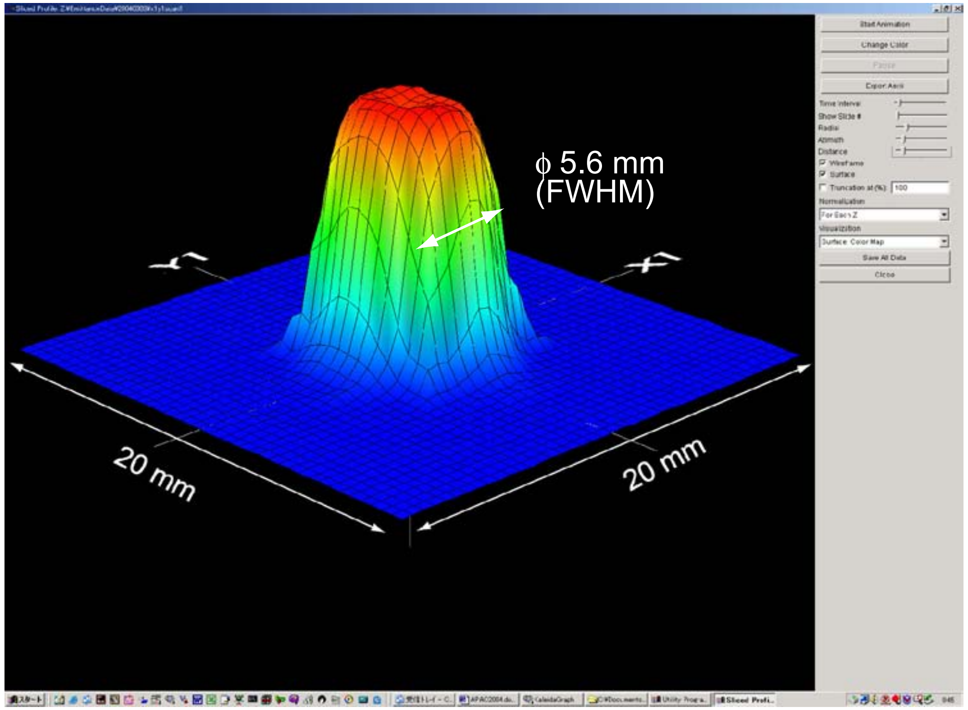
Beamlet spread due to space charge is about 15% at 50 μm width.

Emittance Monitor

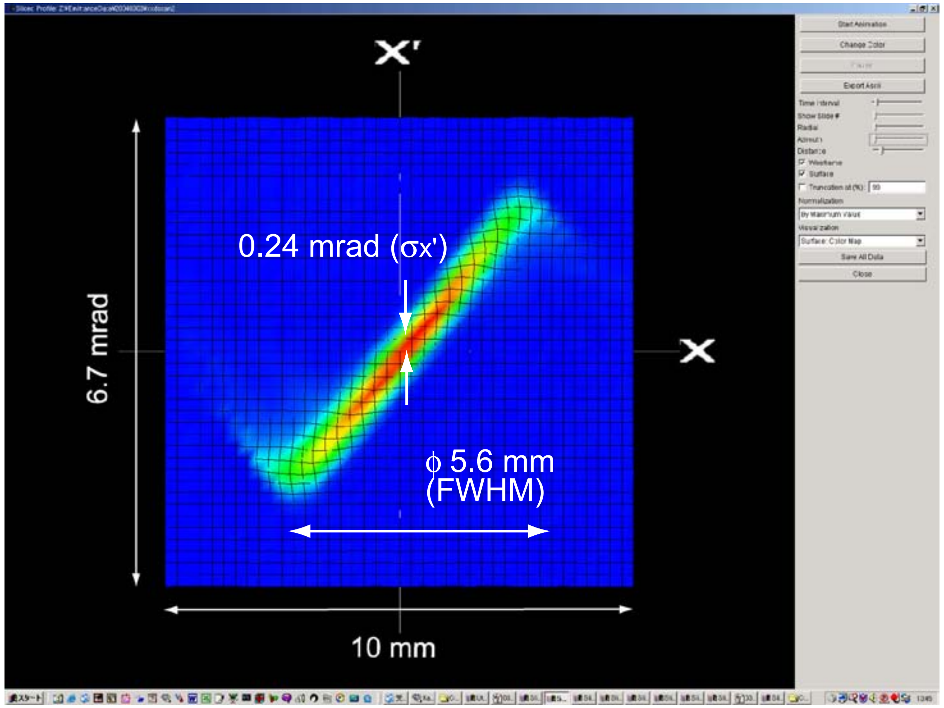


Emittance of 500 keV Beam

Beam Profile



Phase Space Profile



Beam Energy : 500 keV
Peak Current : 1.0 A
Pulse Width : 3 μs

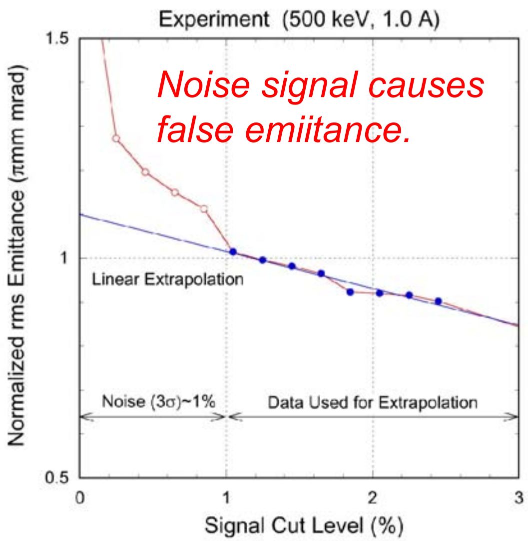
Emittance ($\varepsilon_{n,rms}$)

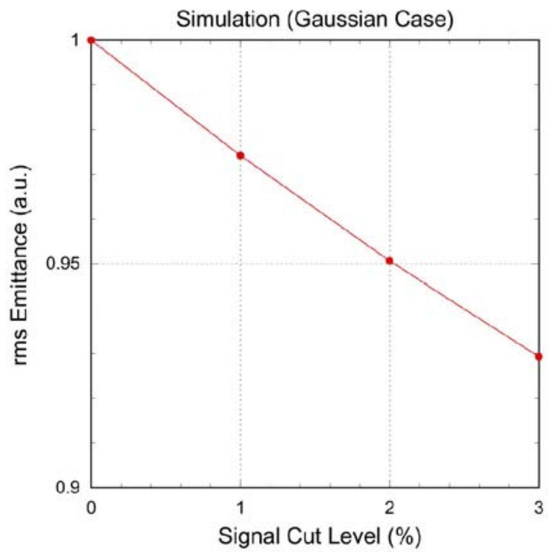
Requirement : 2π mm.mrad @Undulator

Experiment : 1.1π mm.mrad @Gun (preliminary)

Emittance Analysis

Analysing Method

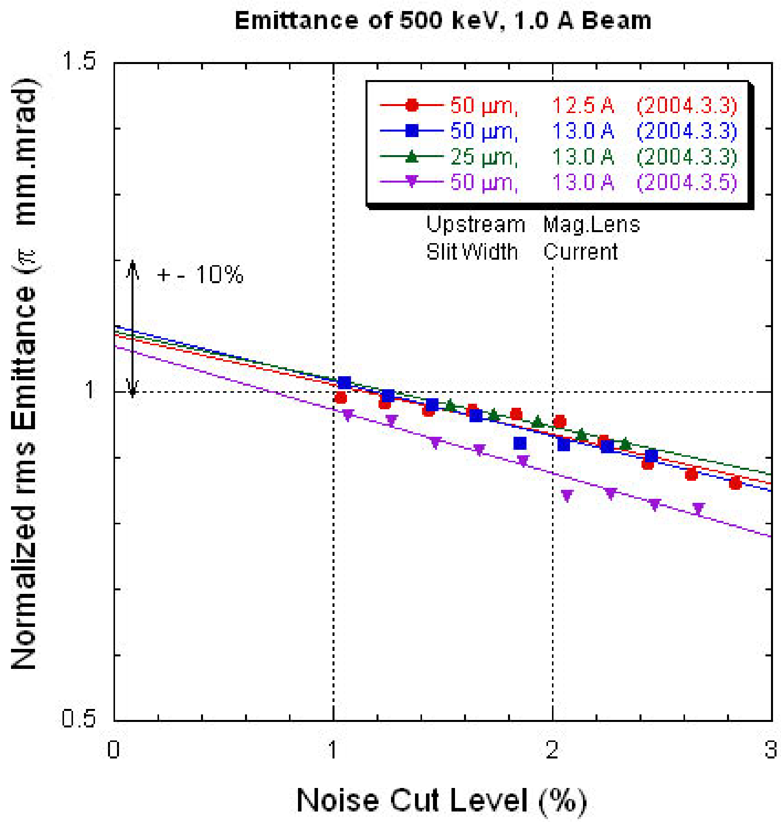




1) Remove signal data whose amplitude is less than noise level (3σ). Typically, the signal cut level is ~1% of the peak signal.

2) Data is corrected to zero cut level by extrapolation using linear function.

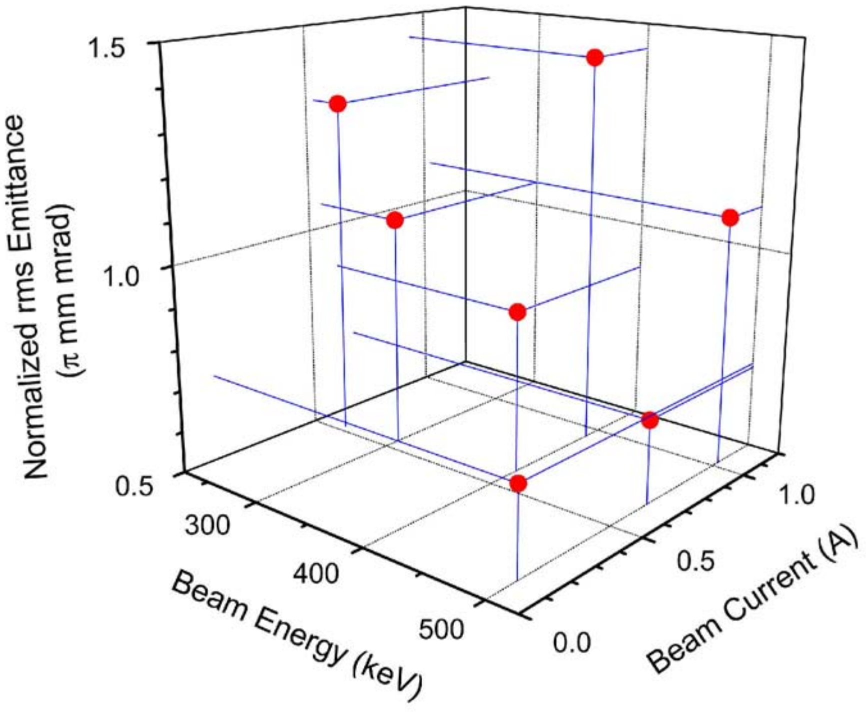
Reproduction



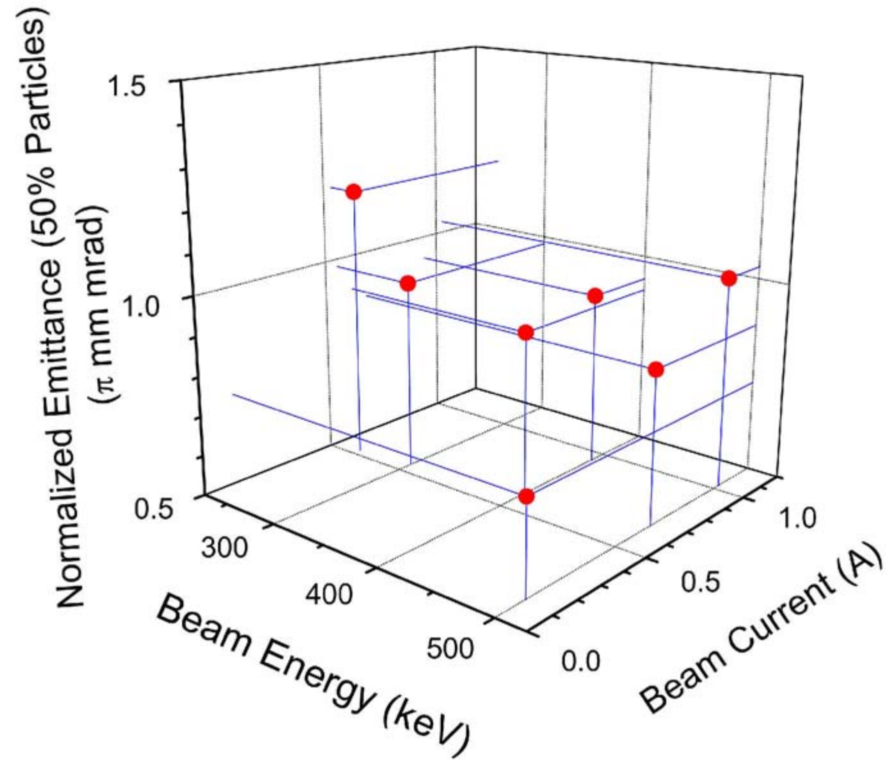
We need more studies about noise reduction and analysing method.

Emittance Map

rms Emittance



Area Emittance including 50% particles



Summary

1) We have succeeded in producing a 500 keV, 1 A beam from the CeB_6 gun.

2) Measured emittance was ~1π mm mrad.

3) In 2004, we will construct a buncher system and measure the bunched beam emittance.