Small Emittance Sources/Guns

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Spring-8/RIKEN Hyogo Japan

Electron source for SASE-FELs, ERLs

Topics

- *This is not a review talk on rf photo-injector. About rf photo-injectors there are ton's of papers.*
  - *LCLS design report Chap. 6 available from http://www-ssrl.slac.stanford.edu/lcls/CDR/*

- *In our X-ray FEL project at RIKEN/SPring-8, we choose HV pulse gun using thermionic cathode (CeB_6 single crystal).*

- *How did I make this decision…..*
  - *Basic physics around the low emittance electron source.*
  - *Practical things..*

before the "emittance" Such Beam Source Should be

- ***Stable***……...charge, energy, pointing,
  - *important for the machine tuning and performance.*
  - *stable X-ray beam delivery to the user.*

    (SASE fluctuation can be reduced by seeding)
- ***Clean*** ……...no halo, no dark current

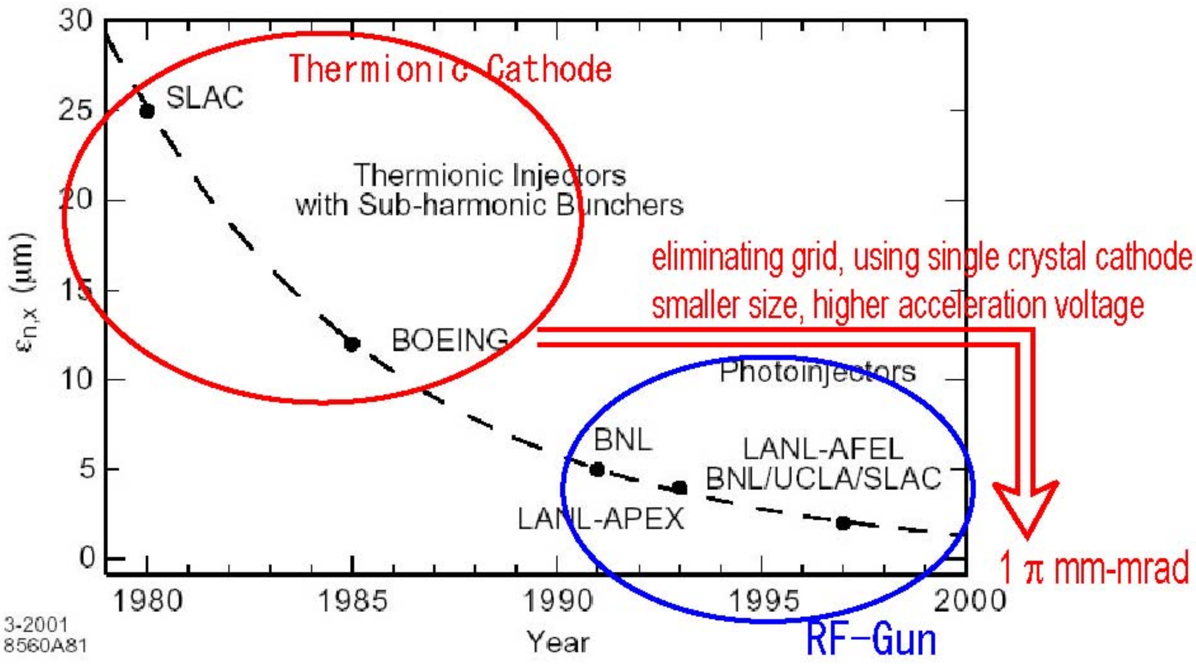
  (high field on cathode such as 100 MV/m will not be good).
  - *important for*
    - *undulator protection*
    - *accurate beam position monitoring*
- ***Uniform*** ……...*current density*
  - *eliminate gain variation due to local lasing.*
  - *deliver an uniform and stable X-ray beam to the user.*
- ***Maintenance Free***

Like a Full Moon
(stable and clean)

「月待図」『江戸年中行事図聚』より

Technical Challenge of Thermionic Injectors to 1 π mm-mrad emittance

this picture is copied from LCLS "Conceptual Design Report", SLAC-R-593 UC-414



Normalized rms transverse emittance measured by the leading thermoionic (SLAC, BOEING) and rf photocathode injectors [16]. All data are for bunched beams with approximately 1 nC of charge.

- *Eliminating control grid from cathode.*
- *Smaller size cathode, from 8 mm to 3 mm diameter.*
- *Higher gun voltage, 150 kV to 500 kV.*
- *Using single crystal CeB6 cathode.*

SCSS & X-ray FEL Beam Parameter

X-ray FEL

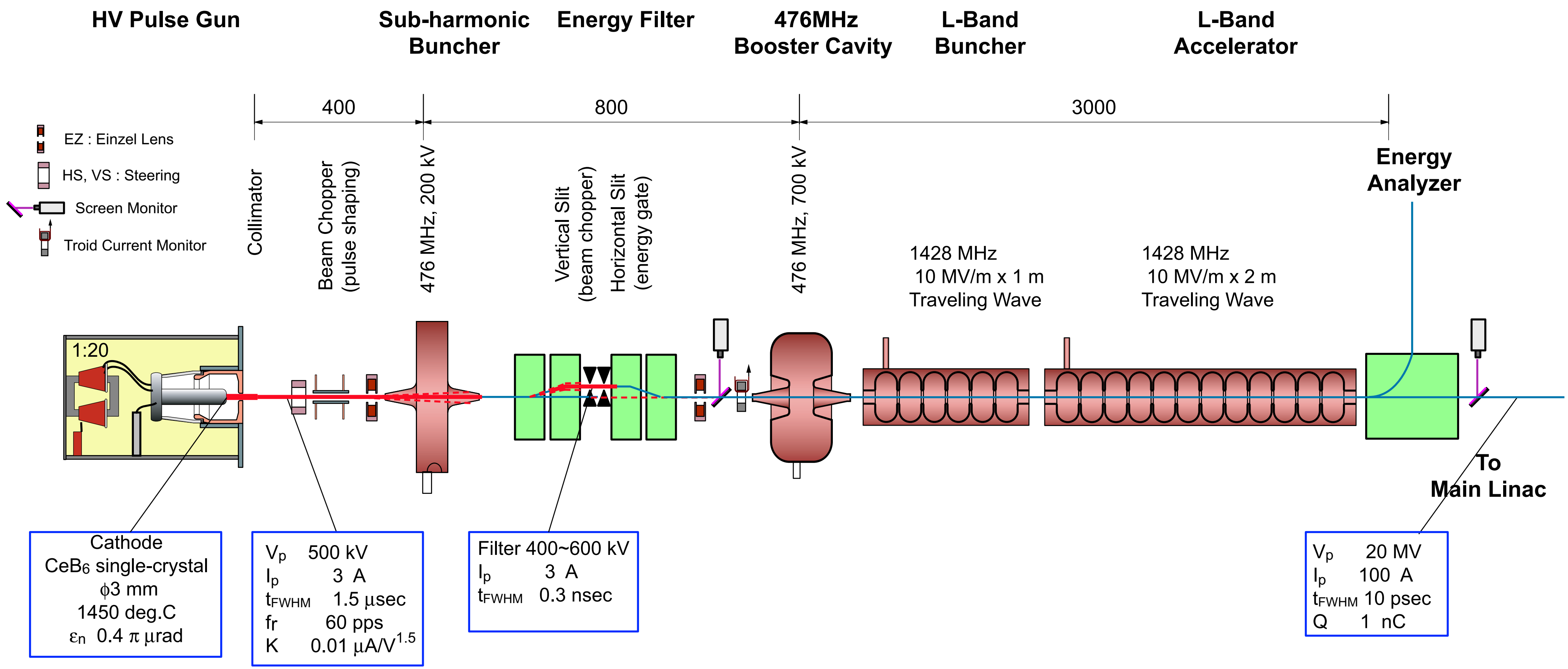
at undulator section

		SCSS	X-ray FEL	
Beam Energy	E	1.0	6.0	GeV
X-ray Wavelength	λ	3.6	0.1	nm
Beam Emittance	ε_n	2	1	πmm.mrad
Bunch Length	Δz	150	75	μm
	FWMH	0.5	0.25	psec
Transverse Beam Size	$\sigma_{x,y}$	100	25	μm
Peak Current	I_p	2	4	kA
Charge per bunch	q	1	1	nC
Undulator Parameter	λ_u	15	15	mm
	K	1.3	1.3	
Length	L	22.5	30	m
FEL Saturation Length	L_{sat}	20	30	m

2002 July

Low Emittance Injector for SASE-FEL

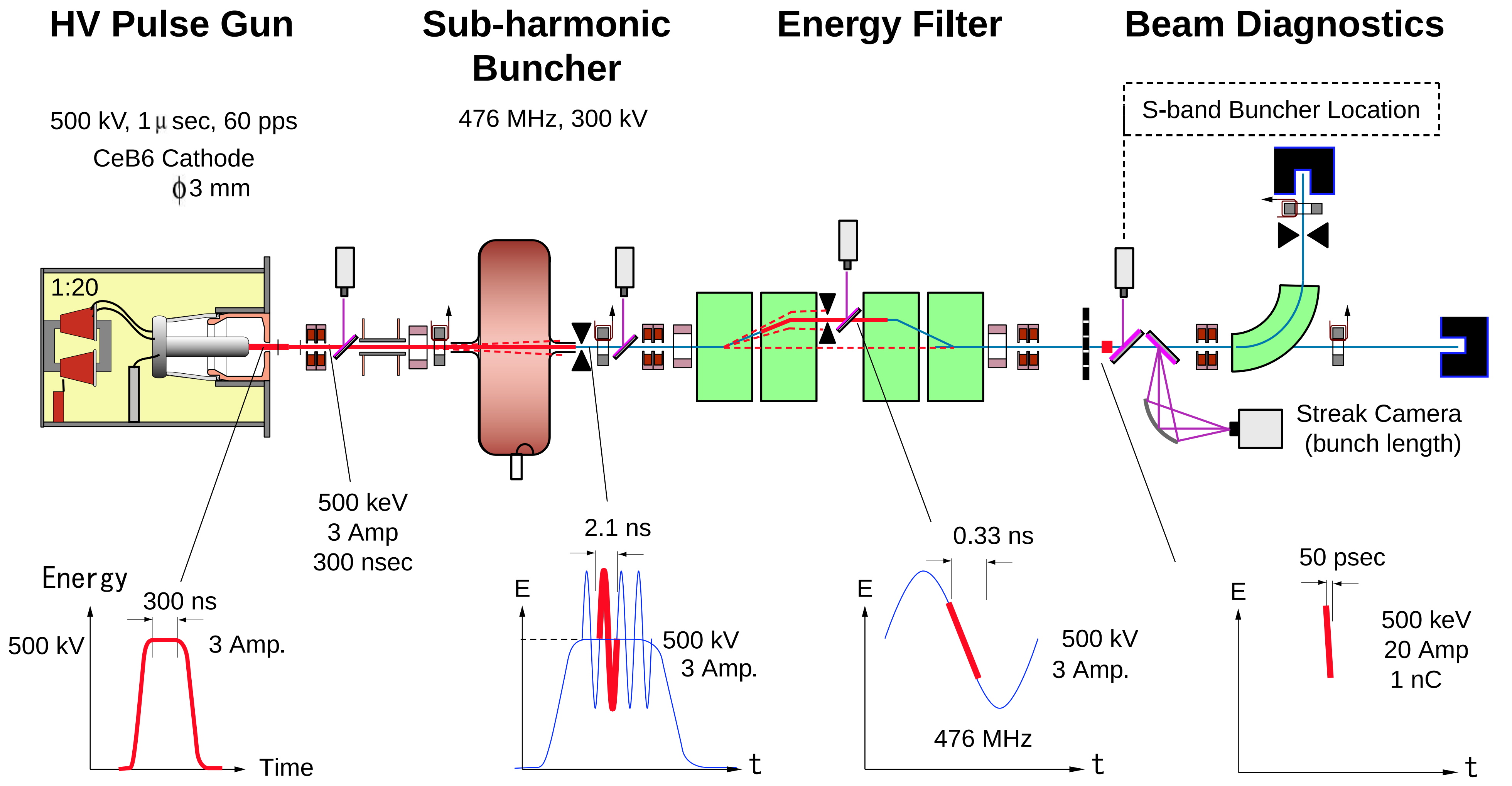
X-ray FEL



Beam Formation in 500 kV Electron Gun

T.Shintake
2001 March

X-ray FEL



CeB_6 Cathode & Heater Assembly

X-ray FEL

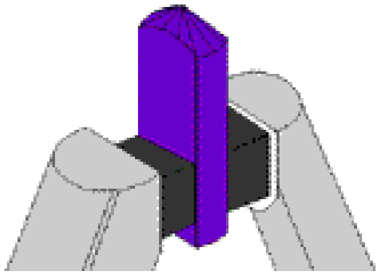
- CeB_6 Cathode 3 mm Diameter
- Emittance 0.4 π.mm.mrad
  (thermal emittance, theoretical)
- Beam Current 3 Amp.
  at 1450 deg.C
  (using graphite heater)
- Current Density > 40 A/cm^2

LaB6/CEBIX sections...

FEI COMPANY™

LaB_6 / Cebix Cathodes

FEI Beam Technology Division is th

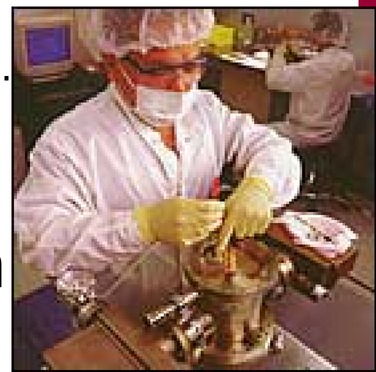


LaB_6 and CeBix cathodes and mate
partnership with each electron bean
to ensure our cathodes meet the re
equipment and application. Included with each cathode is
handling and operating guideline for the specific instrument. FEI maintains a la
inventory of cathodes, and orders are typically shipped the next day.

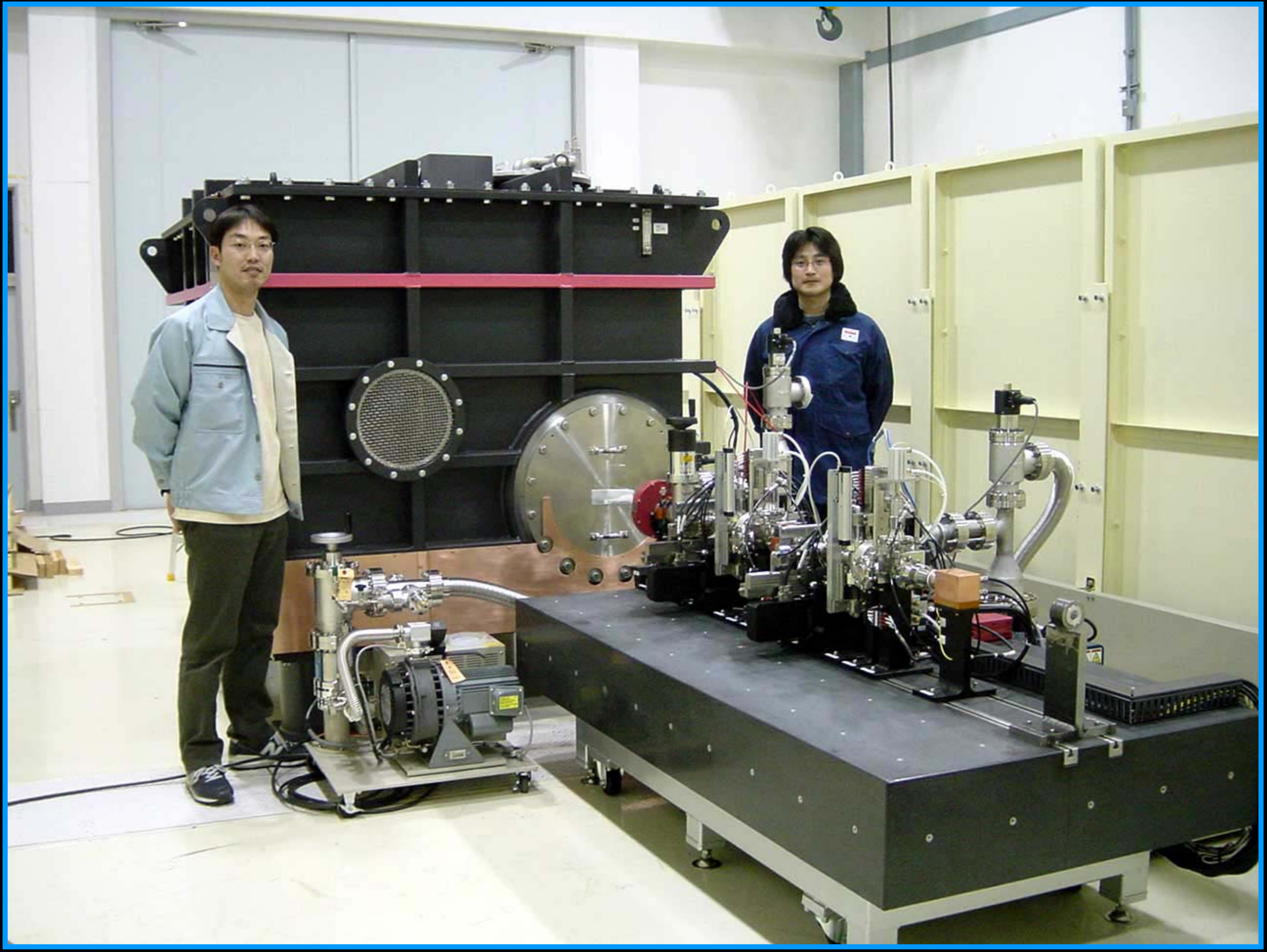
FEI Mini Vogel Mount (MVM) cathodes provide stable, high-brightness, long-lifetime operation for all major electron beam instruments. View FEI's standard parts for all major electron beam instruments in use worldwide on our Applications Chart.

The superiority of the MVM comes from the simplicity of its design.

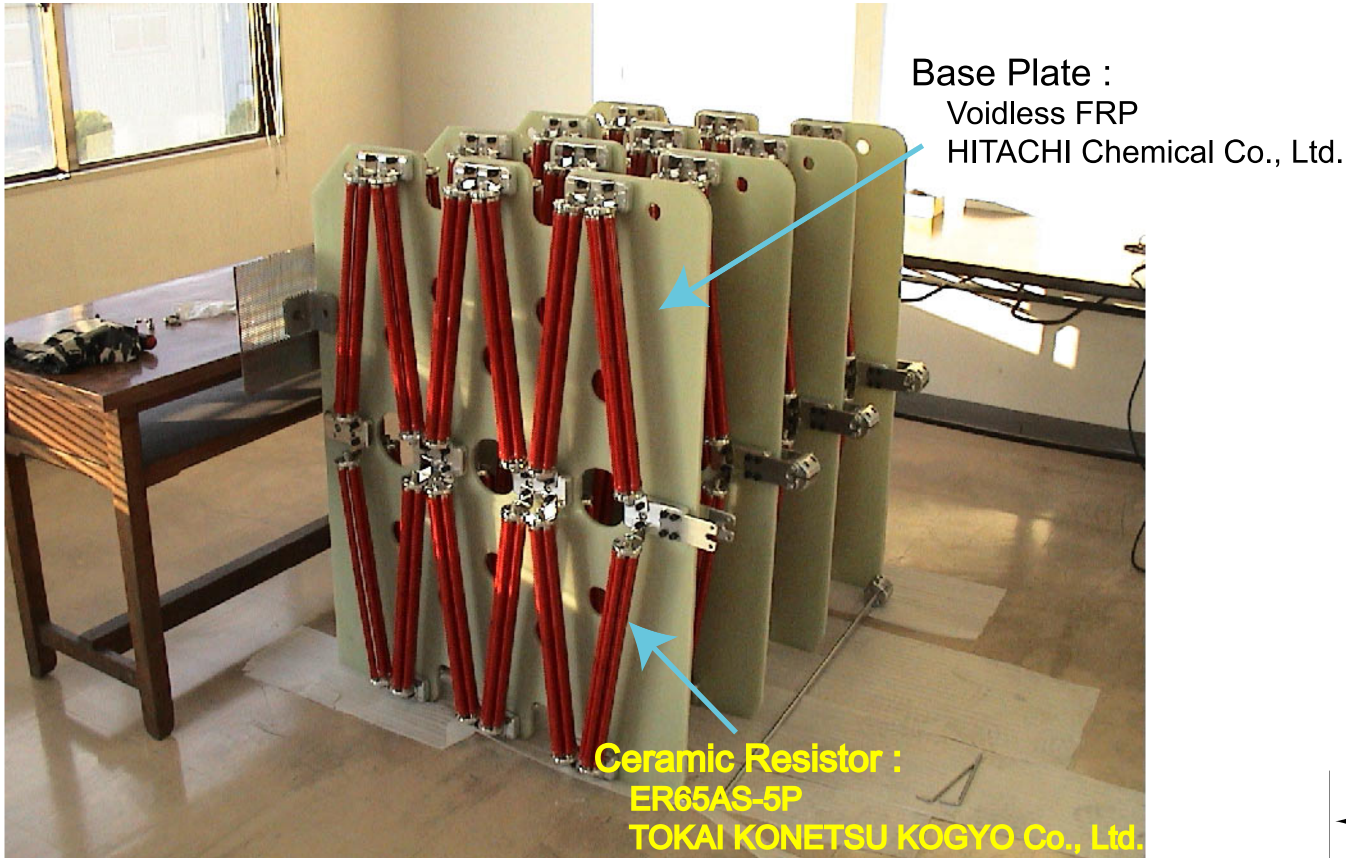
http://www.feibeamtech.com

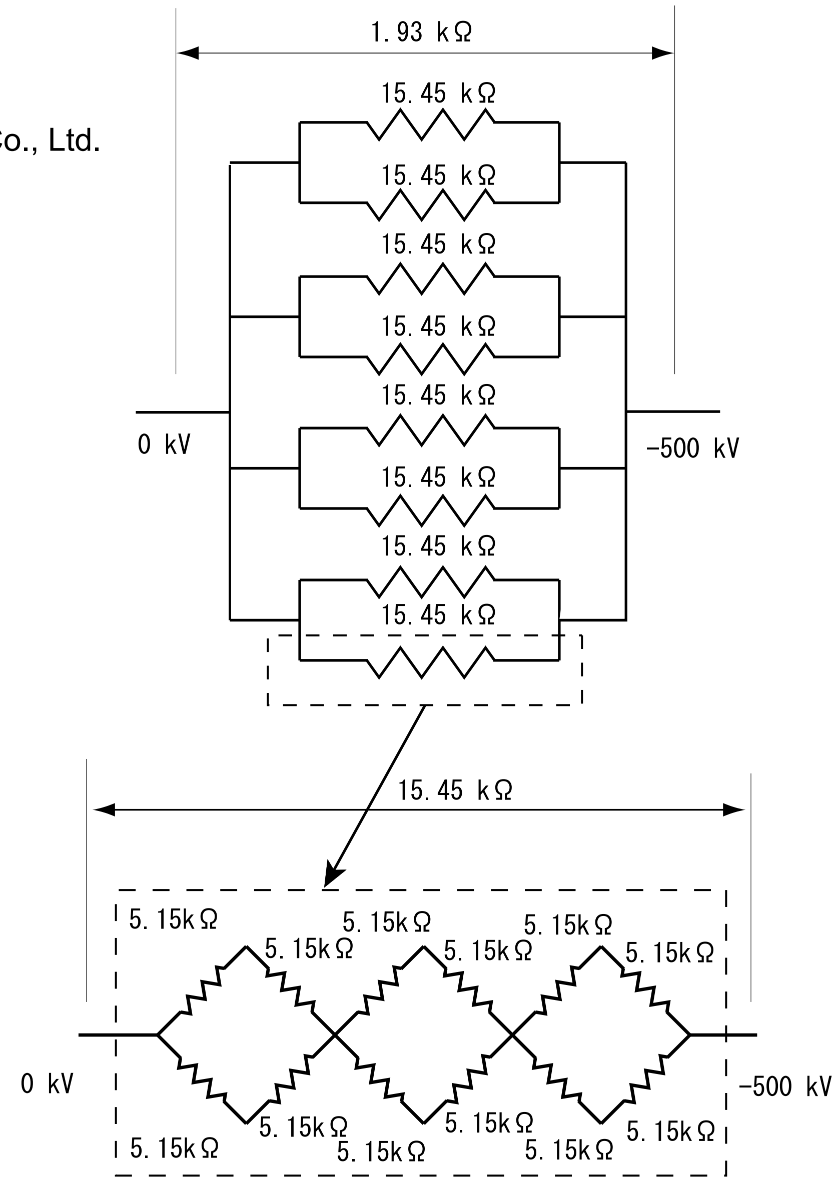


Low-Emittance 500kV Electron Gun R&D



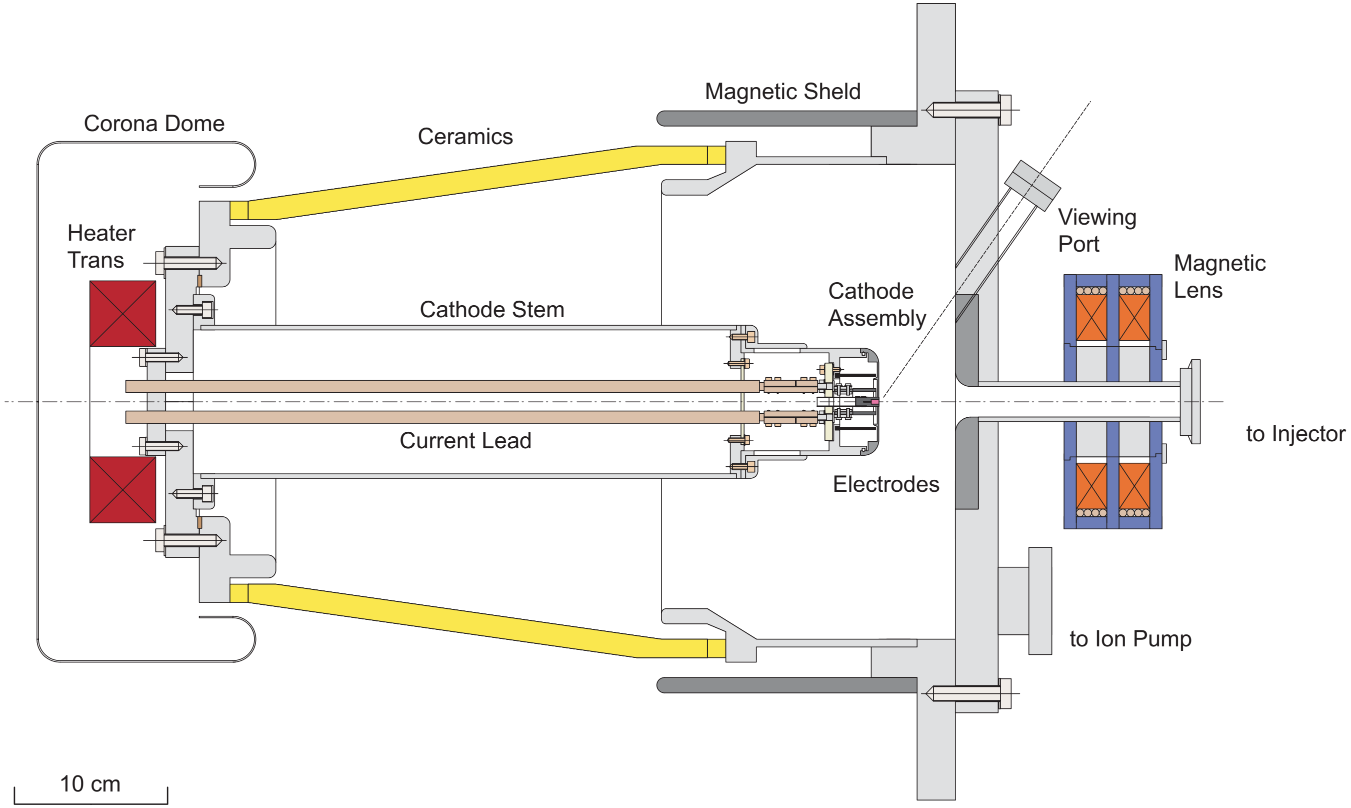
500kV Dummy Load





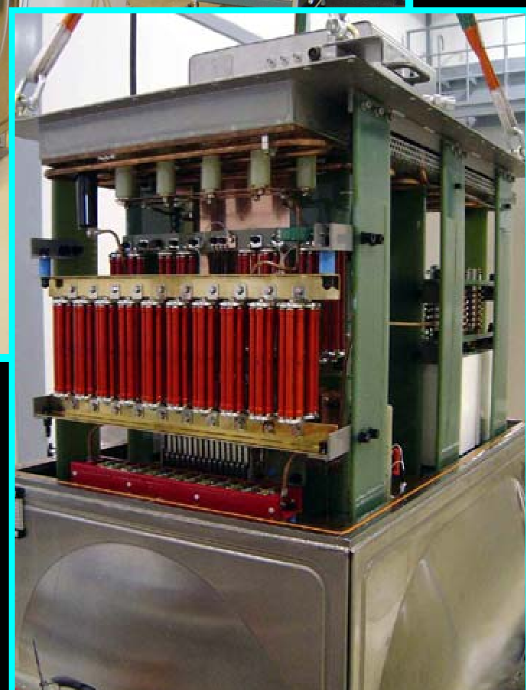
Pulse High Voltage	500 kV
Peak Current	259 A
Pulse Width	1.6 micro-s
Dummy Load Impedance	1.93 kΩ
Average Power	12.2 kW

500kV Electron Gun



Closed Compact Modulator for C-band Accelerator

X-ray FEL



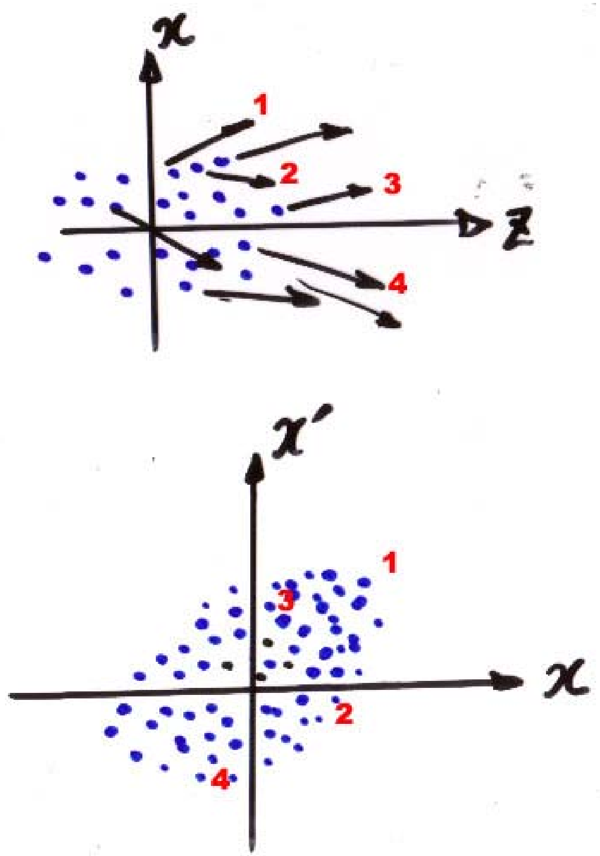
- Compact.
  W 1.7 m x D 1.2 m x H 1m.
- Good EMI shield.

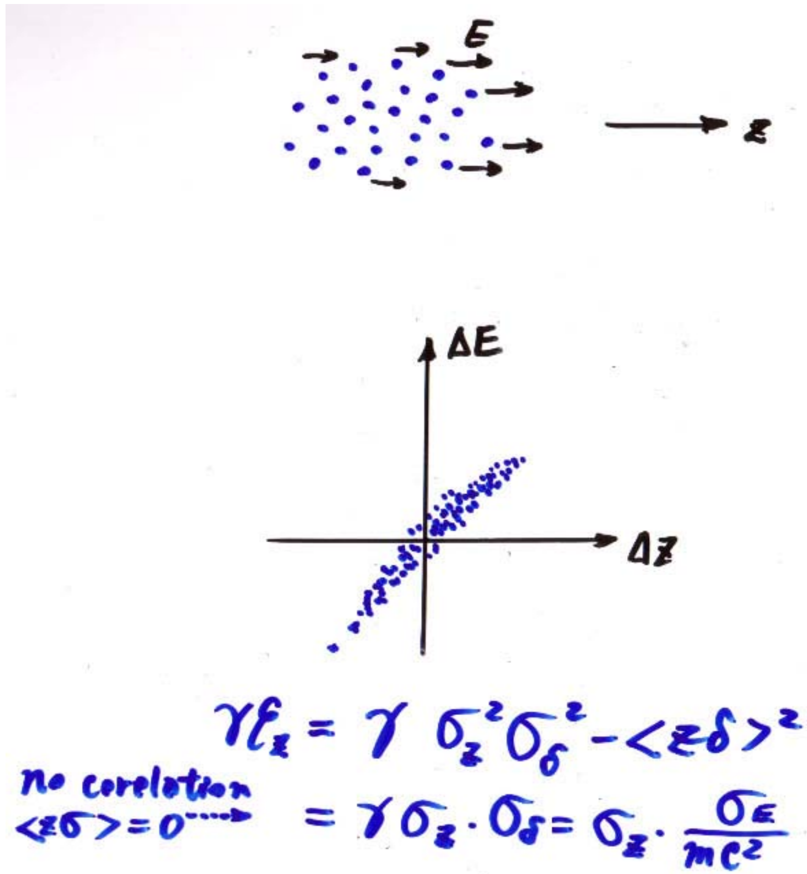
- Better cooling for
  HV component.

- Eliminating cooling air fan.
- No dust accumulation
  due to high voltage in air.

- No environmental effects:
  moisture and temperature
  variation.

Transverse & Longitudinal Emittance





Transverse (x,x'), (y,y')

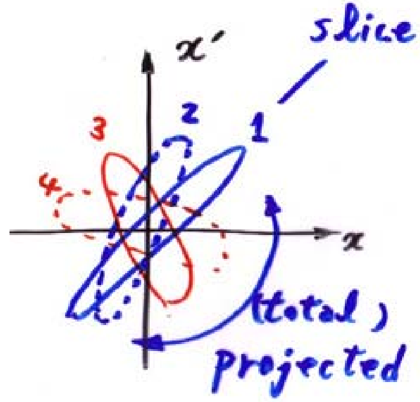
R&D Challenge

Longitudinal (z, E)

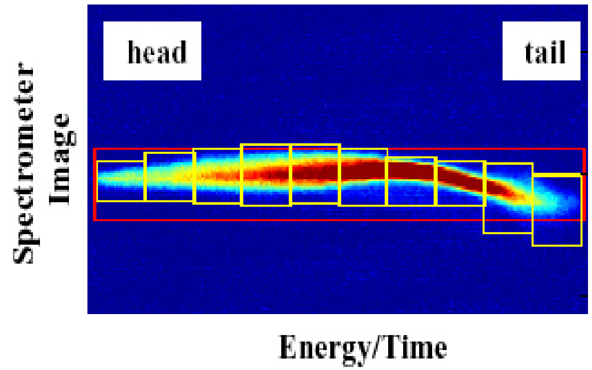
Easily obtainable.

All Three Emittance have to be Small

- ***Slice Emittance***
  ε_{slice} *(un co-related)*
  thermal emittance
  define SASE FEL gain

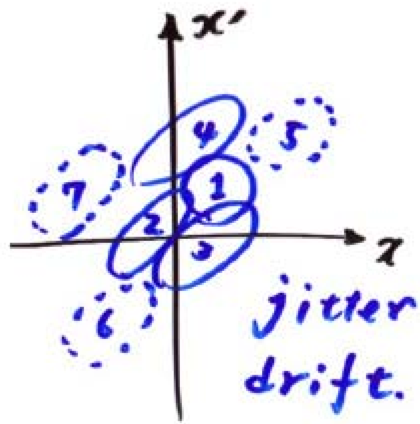


courtesy D. Dowell



- ***Projected Emittance***
  (bunch emittance)
  ε_{proj} *(co-related)*
  measure of wakefield, space-charge, etc.

- ***Multiple Bunch Emittance***
  ε_{multi} *(include jitter & drift)*
  stability measure, affect X-ray beam delivery efficiency

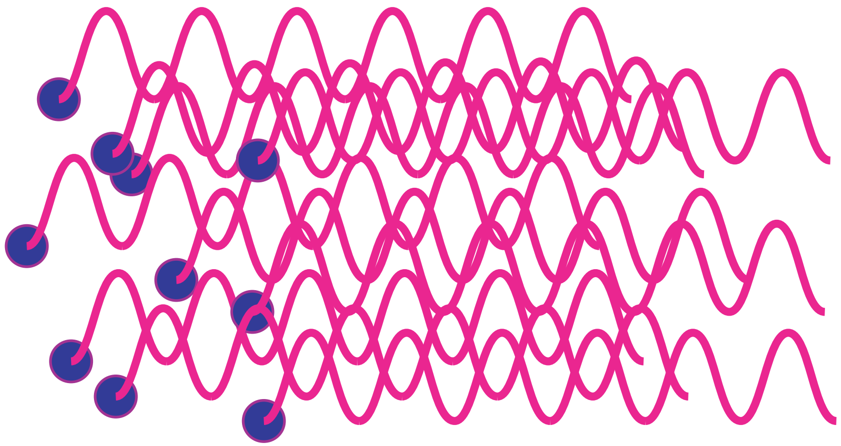


ε_{slice}	<	ε_{proj}	<	ε_{multi}
(fs)		(ps)		(sec, minute,)

From SR to FEL

SR or ERL

Spontaneous Radiation



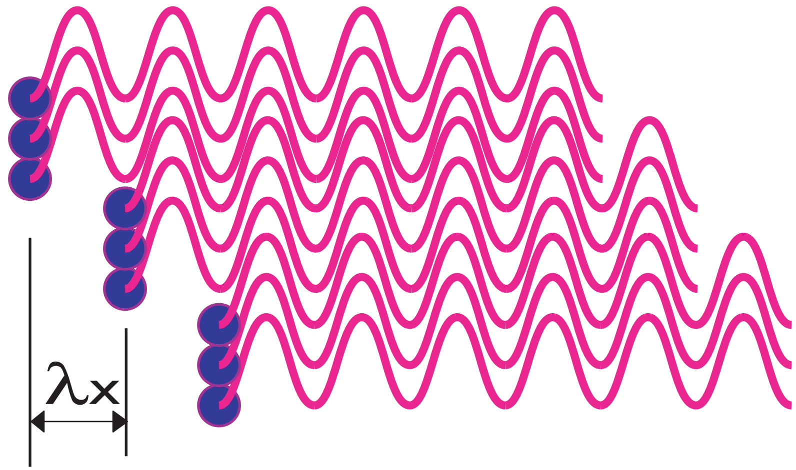
***N*-electrons**
random distribution

$E_{spt} \sim \sqrt{N}\, E_1$

$P_{spt} \sim N\, P_1$

FEL: Free Electron Laser

Coherent Radiation

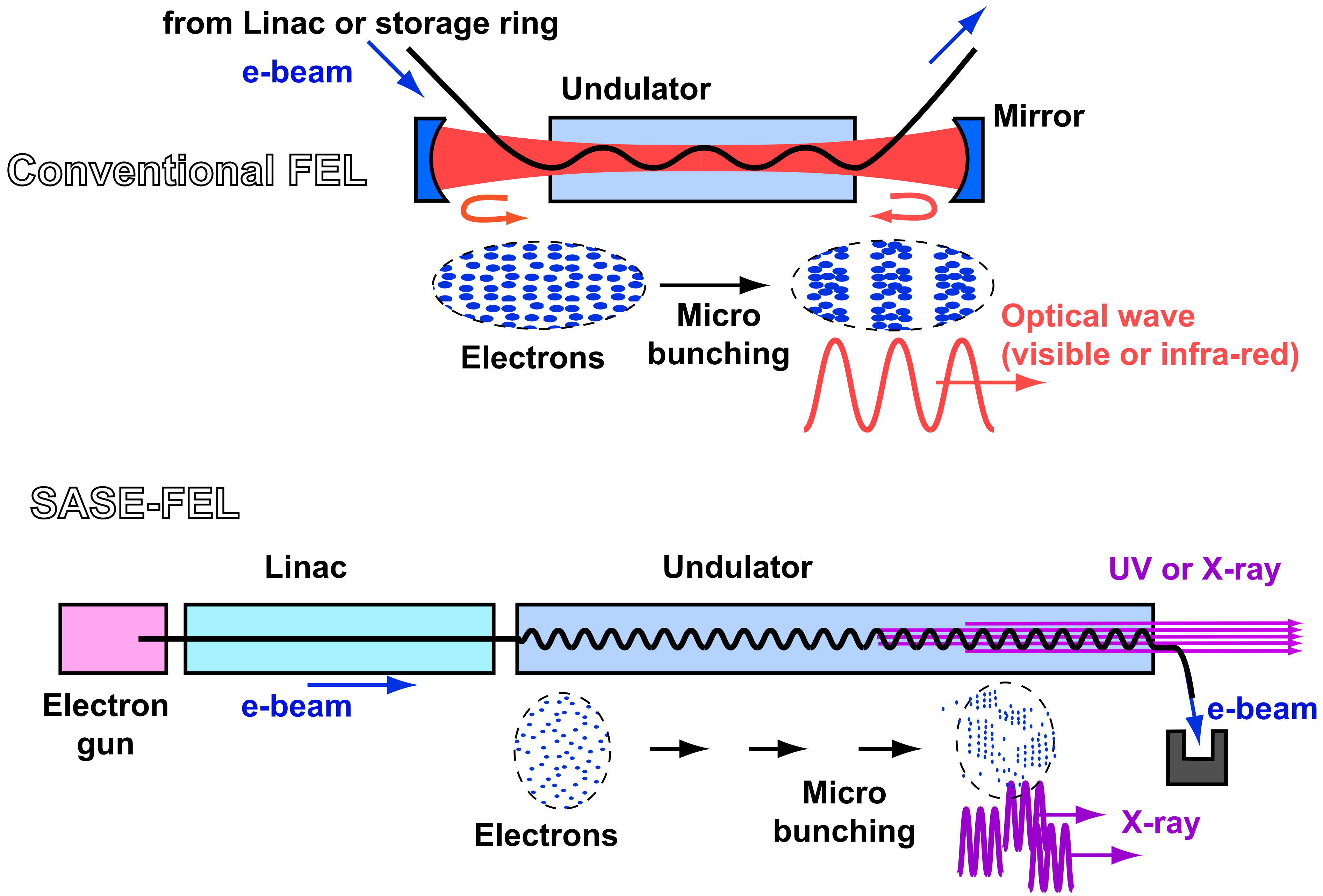


***N*-electrons**
micro-bunched

$E_{coherent} \sim N\, E_1$

$P_{coherent} \sim N^2 P_1$

From Cavity Type FEL to SASE-FEL



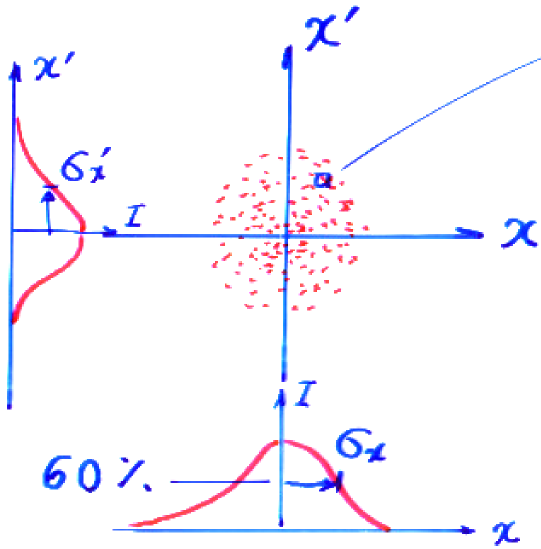
Emittance Definition

We use Normalized r.m.s. emittane

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

$$= \frac{1}{m_0 c}\sqrt{\langle x^2\rangle\langle P_x^2\rangle - \langle x P_x\rangle^2}$$

Gaussian Beam



$$dN = \frac{Ne}{2\pi\sigma_x\sigma_{x'}} e^{-\left(\frac{x^2}{2\sigma_x^2} + \frac{x'^2}{2\sigma_{x'}^2}\right)} \cdot dx\,dx'$$

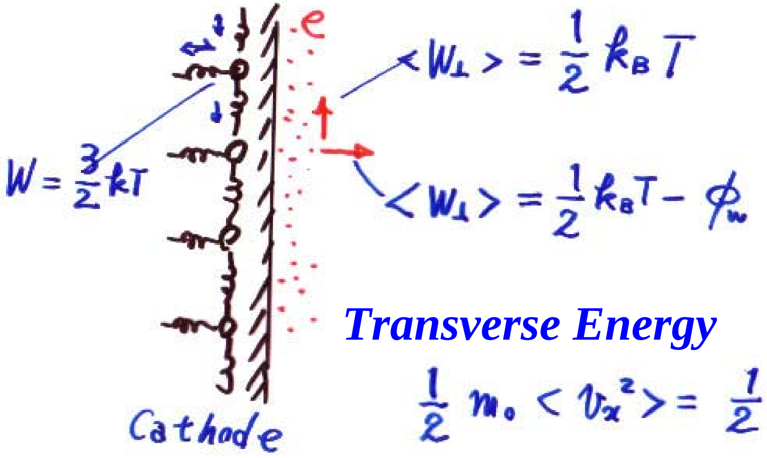
$$\langle xx'\rangle^2 = 0$$

$$\langle x^2\rangle = \frac{\iint x^2\,dN}{\iint dN} = \cdots = \sigma_x$$

$$\langle x'^2\rangle = \frac{\iint x'^2\,dN}{\iint} = \cdots = \sigma_{x'},$$

$$\boxed{\varepsilon_n = \gamma\beta\,\sigma_x\sigma_{x'} \iff \text{Area}: A = \pi\,\sigma_x\sigma_{x'}}$$

Thermal Emittance (lower limit)



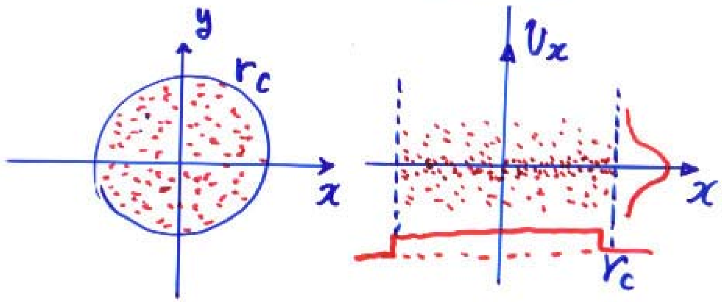
Transverse Energy

$$\frac{1}{2} m_0 \langle v_x^2 \rangle = \frac{1}{2} k_B T$$

Transverse Momentum

$$\sqrt{\langle p_x^2 \rangle} = \gamma m_0 \sqrt{\langle v_x^2 \rangle}$$

$$= \gamma \sqrt{m_0 k_B T}$$



r.m.s Cathode Size

$$\langle x^2 \rangle = \frac{\int x^2 dS}{\int dS}$$

$$= \frac{r_c^2}{4}$$

$$\sqrt{\langle x^2 \rangle} = r_c/2$$

Thermal Emittance

$$\varepsilon_{xN} = \frac{1}{m_0 c}\sqrt{\langle x^2 \rangle \langle p_x^2 \rangle - \langle x p_x \rangle^2}$$

$$= \frac{\gamma r_c}{2}\sqrt{\frac{k_B T}{m_0 c^2}}$$

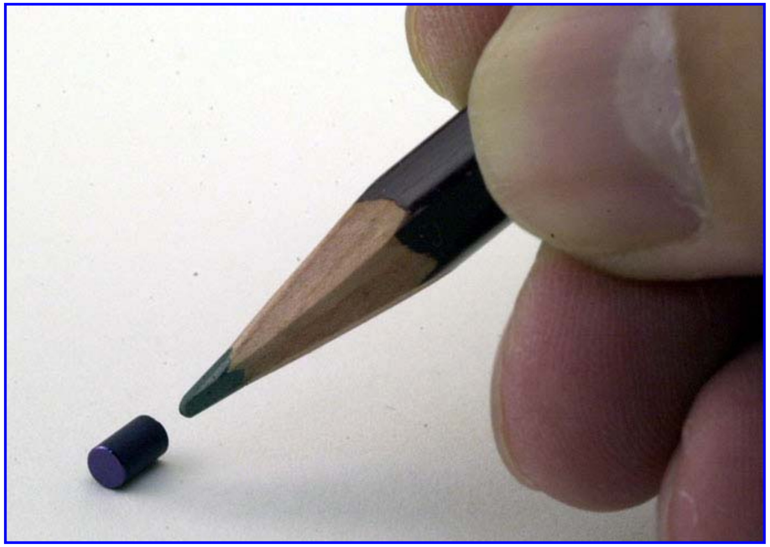
Boltzmann constant

$$k_B = 1.38 \times 10^{-23}\ (J/\deg)$$

Use Small Size Cathode

…First Strategy for smaller thermal emittance

- *Thermionic cathode*



3mm *diameter cathode (CeB6) is used in a low emittance injector. (SCSS SPring-8/RIKEN)*

Operating Temperature 1450°C

$$w_e = \frac{3}{2} k_B T = 223 \text{ meV}$$

Thermal Emittance

$$\varepsilon_{xN} = \frac{\gamma r_c}{2} \sqrt{\frac{k_B T}{m_0 c^2}} = 0.4\ \pi \text{ mm-mrad}$$

0.28 π mm-mrad/mm

- *RF photo-cathode injector.*

Today's RF photo injectors use ~ 1 mm spot radius.

$$\varepsilon_{xN} = \frac{\gamma r_c}{2} \sqrt{\frac{k_B T_e}{m_0 c^2}} = 0.35\ \pi \text{ mm-mrad}$$

Same order!

T_e is "measured" effective electron temperature of copper cathode using 266 nm laser (ref. 2). k T_e = 0.27 eV (2360°C).

How "meV" can be important on "GeV" beam?

- Transverse energy along x-direction.

10^{-12} difference!

$$\frac{1}{2} m_e \langle v_x^2 \rangle = \frac{1}{2} k_B T = 74 \text{ meV}$$ ⟺ **GeV**

wrong feeling

- Transverse momentum

Momentum ratio ~10^{-7}

$$p_x = \gamma m_0 v_x = \beta \frac{\gamma m_0 c^2}{c} = \beta \frac{E}{c} = 274 \text{ eV/c}$$ ⟺ **GeV/c**

$$w_k = 74 \text{ meV}, v = 161 \text{ km/sec}, \quad \varepsilon_{xN} = \gamma \sigma_x \sigma_x' = 1\pi \text{ mm-mrad}$$

$$\beta = 0.00054, \gamma = 1 \quad \gamma = 2\times 10^3, \ \sigma_x = 1 \text{ mm}, \ \sigma_x' = 5\times 10^{-7}$$

Emittance is a measure of the transverse momentum.

Use Small Size Cathode….2

to reduce transverse kick by rf acceleration field.

TM0-mode axial-symmetric field in the accelerating rf cavity.

Using Maxwell's equation,

$$\nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t} \quad \rightarrow \quad \frac{1}{r}\frac{\partial}{\partial r}(rH_\theta) = j\omega\varepsilon_0 E_z$$

Integrating near the axis,

$$H_\theta = \frac{r}{2} \cdot j\omega\varepsilon_0 E_{z0} \propto \frac{r}{\lambda}$$

From the Gauss's law,

$$\nabla \cdot \mathbf{E} = 0 \rightarrow \quad \frac{1}{r}\frac{\partial}{\partial r}(rE_r) + \frac{\partial E_z}{\partial z} = 0 \rightarrow \quad E_r = -\frac{r}{2}\left(\frac{\partial E_z}{\partial z}\right)_{r=0} \propto \frac{r}{\lambda}$$

Transverse Kick

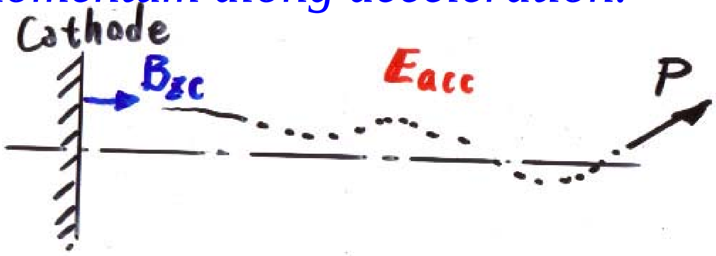
$$P_r = q(E_r + u_z \times B_\theta) \propto \frac{r}{\lambda}$$

For low emittance,	
•smaller cathode size and	*use 1 mm laser spot than 10 mm spot.*
•lower rf frequency is desirable.	*use 476 MHz, 714 MHz or 1.3 GHz, than S-band, C-band or X-band. Note on available field gradient.*

Magnetic Field on the Cathode Must be Zero

- *Conservation of transverse generalized momentum along acceleration.*

$$\mathbf{p}_\perp = \gamma m_0 \mathbf{u}_\perp + q\mathbf{A}_\perp = \text{constant}$$



- *Initial condition on the cathode.*
  If magnetic field is not zero,

$$\mathbf{p}_\perp^0 = q\mathbf{A}_\perp^0 \qquad u_\perp = 0, \quad A_\perp \neq 0$$

- *At high energy after acceleration, the transverse momentum in free space is given by* $\mathbf{p}_\perp = \gamma m_0 \mathbf{u}_\perp = \mathbf{p}_\perp^0 = q\mathbf{A}_\perp^0$ **Bush's Theorem**

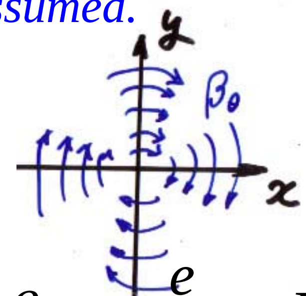
- *Axial symmetric case. Field leakage on the cathode :* B_{zc} $\quad \mathbf{A}_\theta = \frac{1}{2} r_c B_{zc}$

$$\varepsilon_{xN} = \frac{e}{2m_0 c}\sigma_{xc}^2 B_{zc}$$

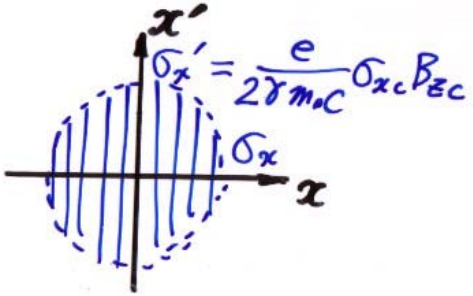
laminar flow is assumed.

$$\sigma_x = \sigma_{xc} = 1\ \text{mm},\ B_{zc} = 100\ \text{Gauss}$$

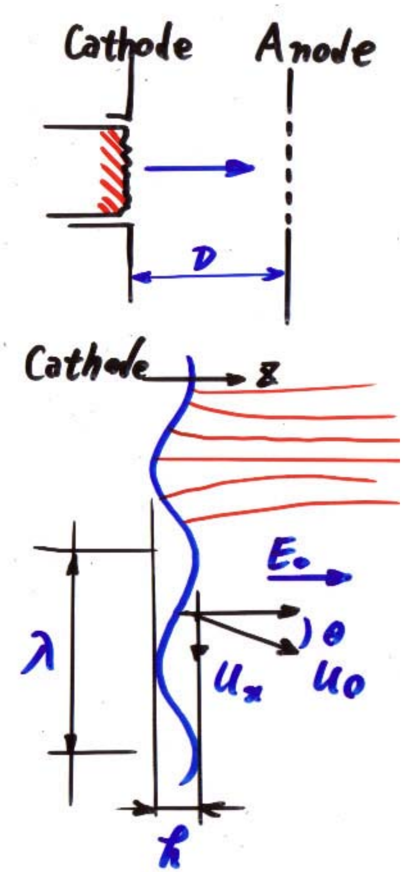
$$\varepsilon_{xN} = 2.9\ \pi\ \text{mm-mrad}$$



$$\gamma\beta_\theta = \frac{e}{2m_0 c} r_c B_{zc}$$



Emittance Dilution due to Surface Roughness of Cathode



Simple roughness model

Simplified surface curve: $z = \frac{h}{2}\cos(\frac{2\pi z}{\lambda})$

Tangential velocity: $u_x = \frac{dz}{dx} \cdot u_0 = \frac{\pi h}{\lambda} \cdot u_0 \sin(\frac{2\pi z}{\lambda})$

Average velocity: $\langle u_x^2 \rangle = \frac{1}{2}\left(\frac{\pi h}{\lambda}\right)^2 \langle u_0^2 \rangle = \frac{ehE_0}{2m_0}\left(\frac{\pi h}{\lambda}\right)^2$

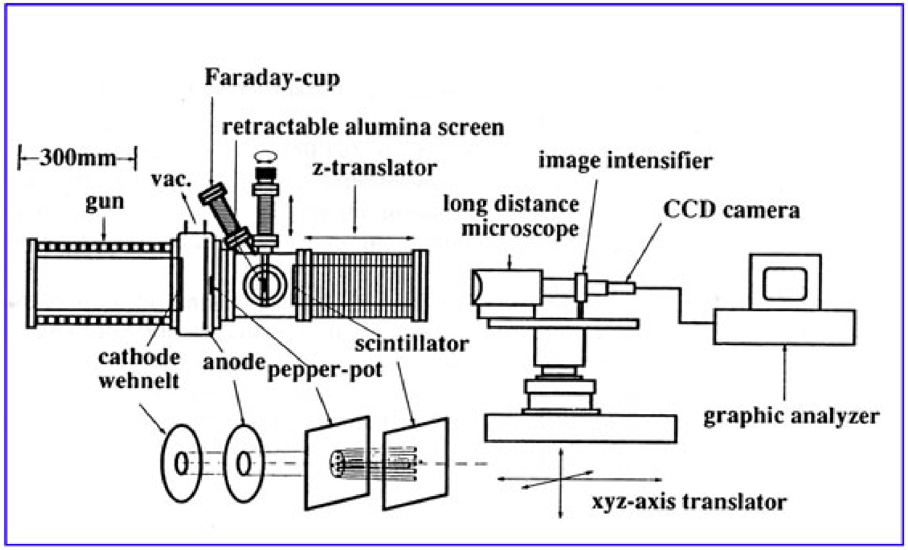
Emittance: $\varepsilon_{nN} = \frac{1}{m_0 c}\sqrt{\langle P_x^2 \rangle} \cdot \sigma_x = \frac{\gamma r_c}{2}\sqrt{\frac{eE_0}{2m_0 c^2}} \cdot \frac{\pi h^{1.5}}{\lambda}$

Required Smoothness

Accelerating Field: E_0(MV/m)	1	10	**100**
Roughness: h(μm)	3	1	**0.3**

$\varepsilon_{nN} < 0.3\ \pi$ mm-mrad, λ= 10 μm, r_c = 1 mm

Emittance Measurement on Thermionic Cathode



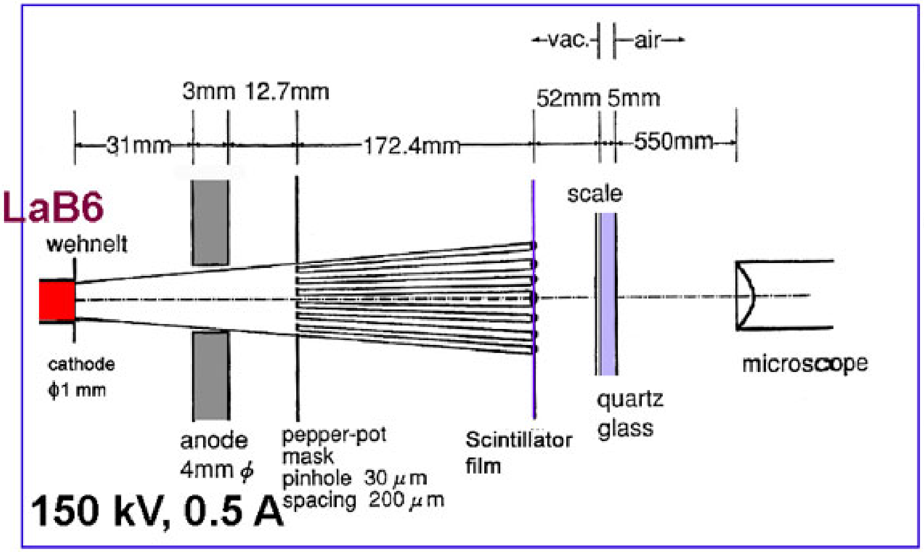
H. Kobayashi, et.al, "Emittance Measurement for High Brightness Electron Guns", Proc. 1992 Linear Accelerator Conference, Ottawa, Aug.23-28, 1992

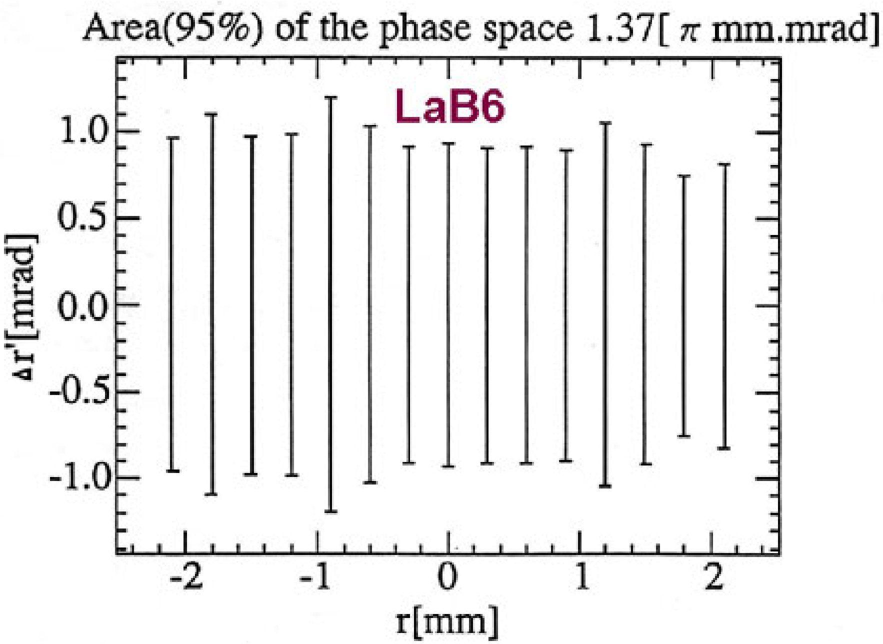
Y. Yamazaki, T. Kurihara, H. Kobayashi, I Sato and A. Asami @ KEK "High-precision pepper-pot technique for a low-emittance electron beam" Nncl. Instrum. and Methods in Phys. Research A322(1992) 139-145

Measured Emittance = 0.34 π mm-mrad

Theoretical Emittance= 0.13 π mm-mrad

resolution limited.





Beam Quality from Three Type Cathode

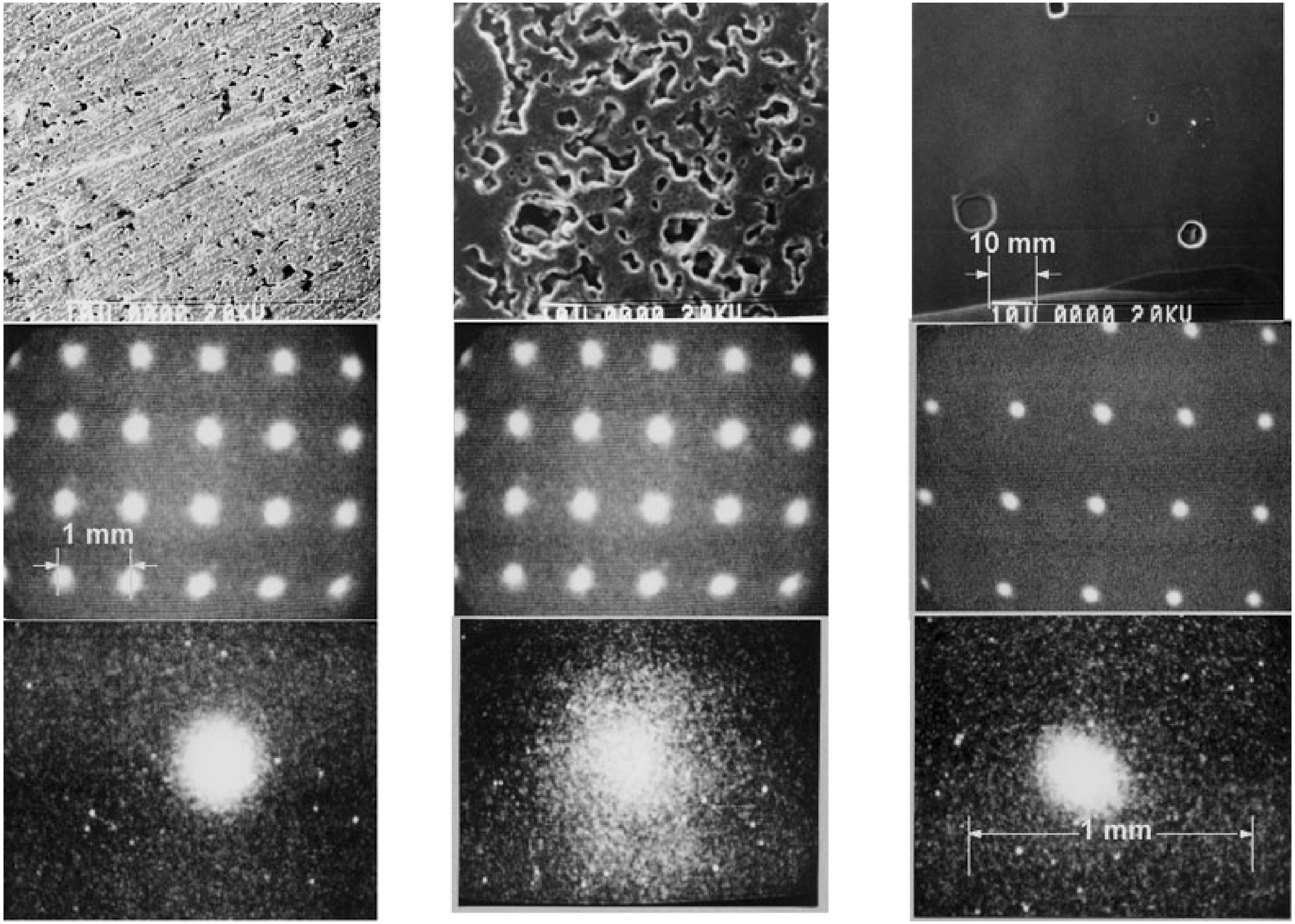
Hitoshi Kobayashi KEK

Dispenser Cathode | **LaB6 Poly-crystal** | **LaB6 Single Crystal**

SEM Image

Pepper-pot Image

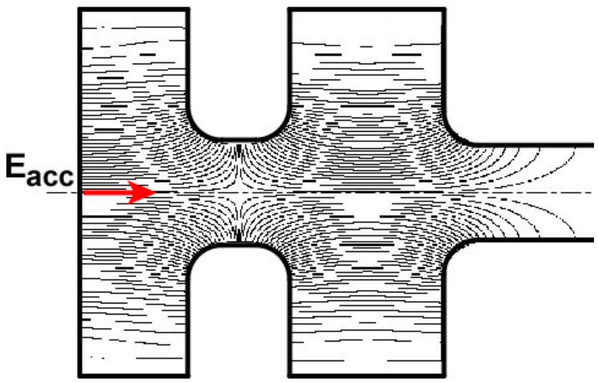
Magnified Spot



Space Charge Effect…in rf gun

- *Maxwell's equation is linear, thus any field can be analyzed by linear superposition. (no E^2, H^2, EH terms)*
- *RF-acceleration field in the cavity + space charge.*

Acceleration rf field



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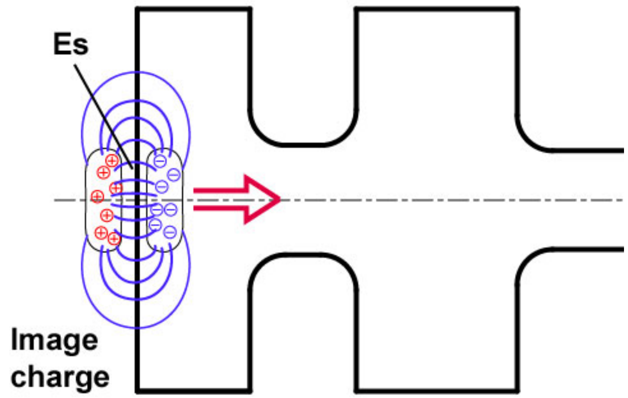
Space charge field



Maximum space charge field at cathode

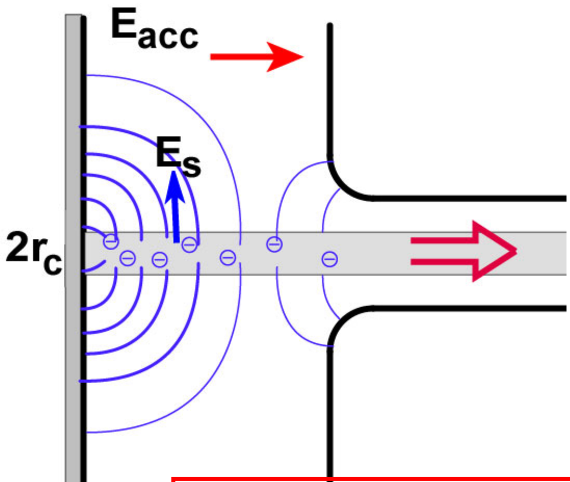
$$E_{spc.\max} = \frac{Q}{\pi \varepsilon_0 r_c^2}$$

The non-linear space charge field runs with bunch.

$$Q = 1 \text{ nC}, r_c = 1 \text{ mm} \rightarrow E_{spc.\max} = 36 \text{ MV/m}$$

The tail electron feels lower acceleration field. To overcome this energy difference, we need very high field gradient: 100 MV/m ~ 140 MV/m.

Space Charge Effect…in HV gun.



- *DC or long pulse beam.*
- *Beam becomes a column shape.*
- *The nonlinear space charge field is localized just near to the cathode (distance ~r_c), thus space-charge field contribution to emittance is small.*

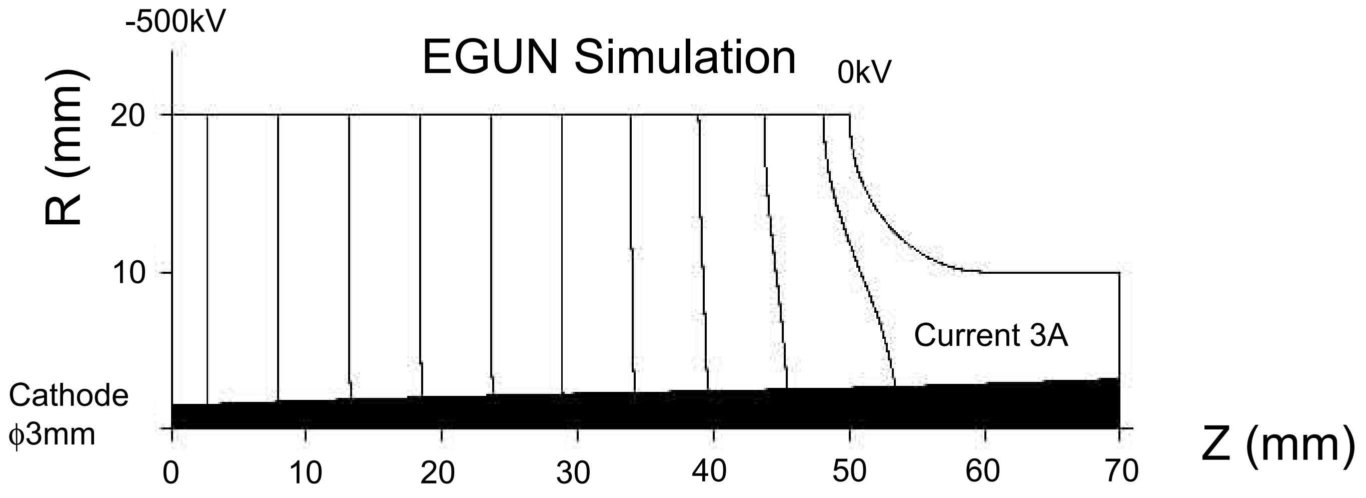
Specially in "temperature limited cathode condition", beam trajectory becomes straight, and space charge field is very linear, thus the emittance becomes negligibly small.

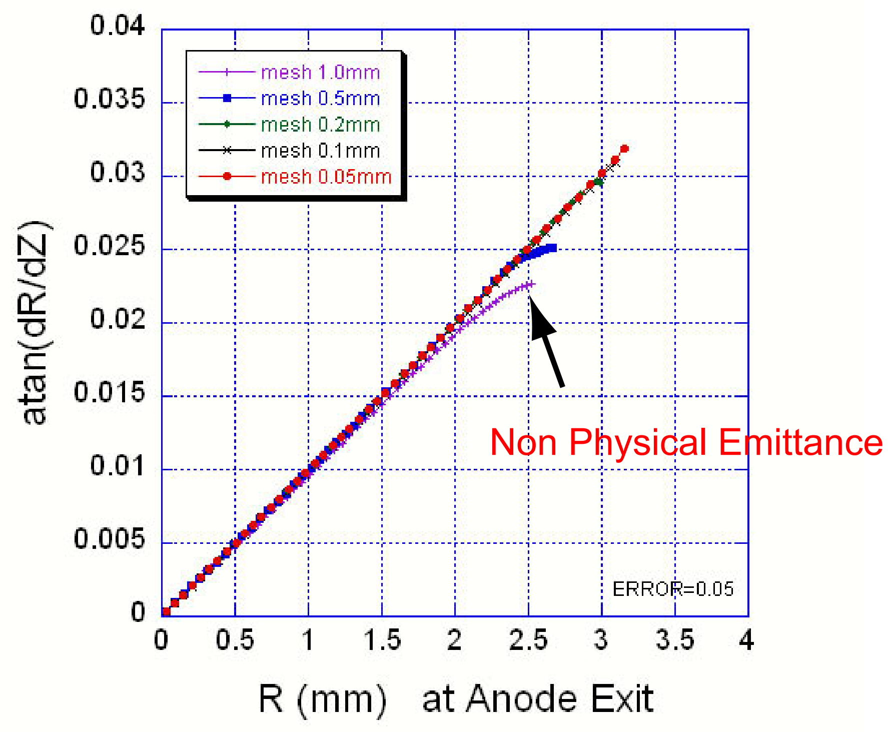
$$E_s \simeq E_r = \frac{I_z}{\pi \varepsilon_0 R^2 u_z} \cdot r$$

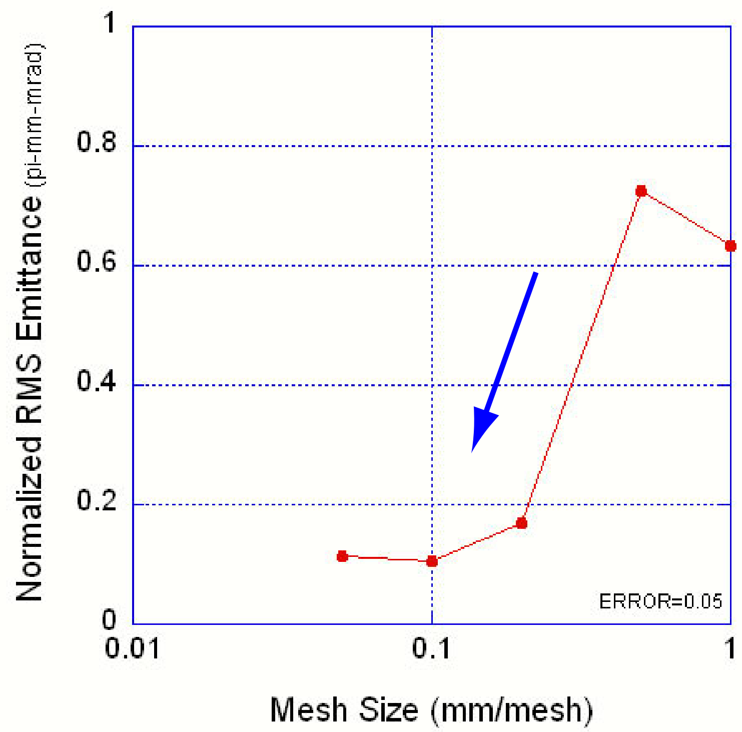
To do this, we apply 500 kV on 5 cm gap for 3 A beam in SCSS gun.

E-Gun simulation says: $\varepsilon_n < 0.1\ \pi$ mm-mrad *thermal emittance is not included.*

Emittance at Parallel Electrodes

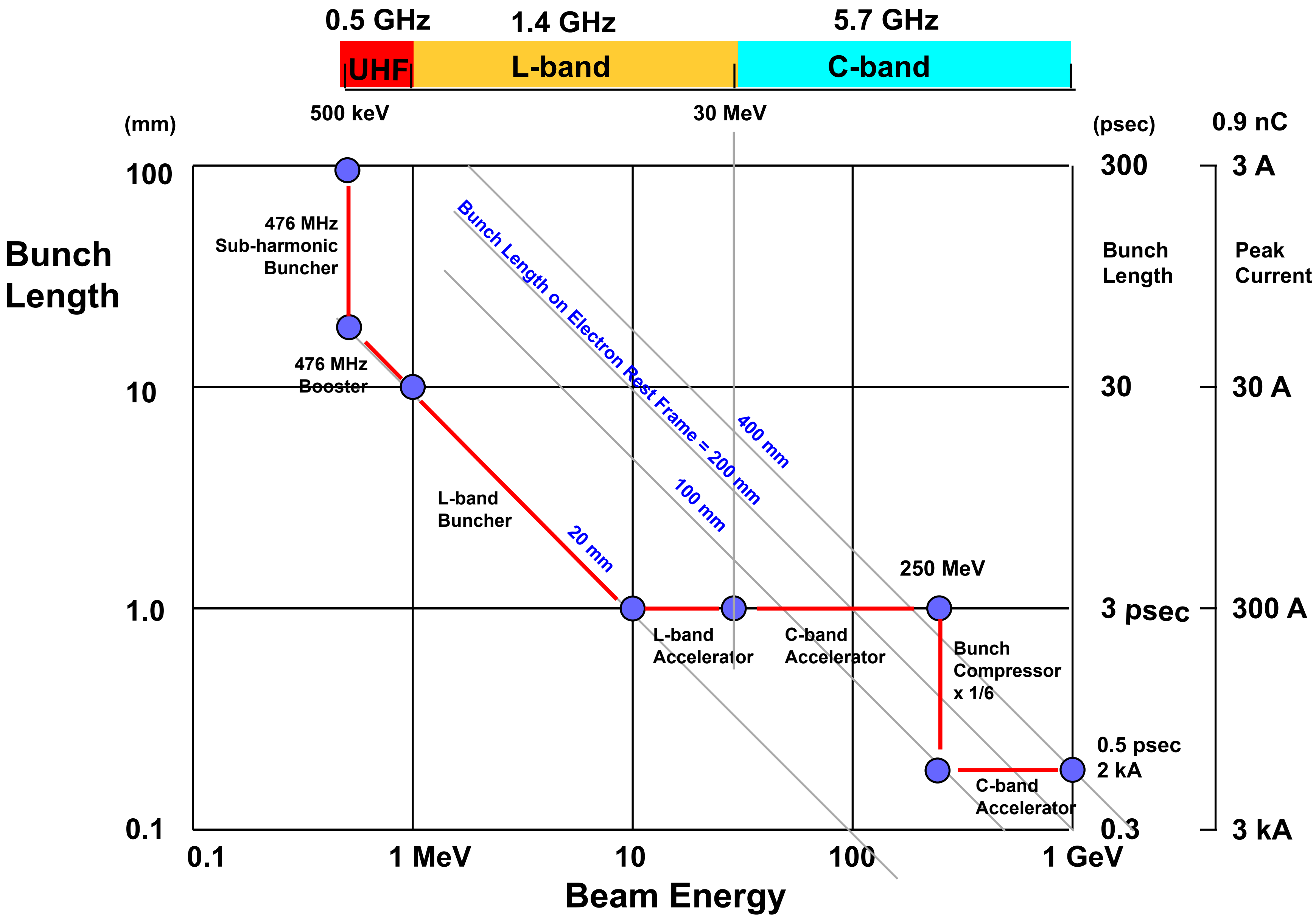






Bunch Compression after the Gun

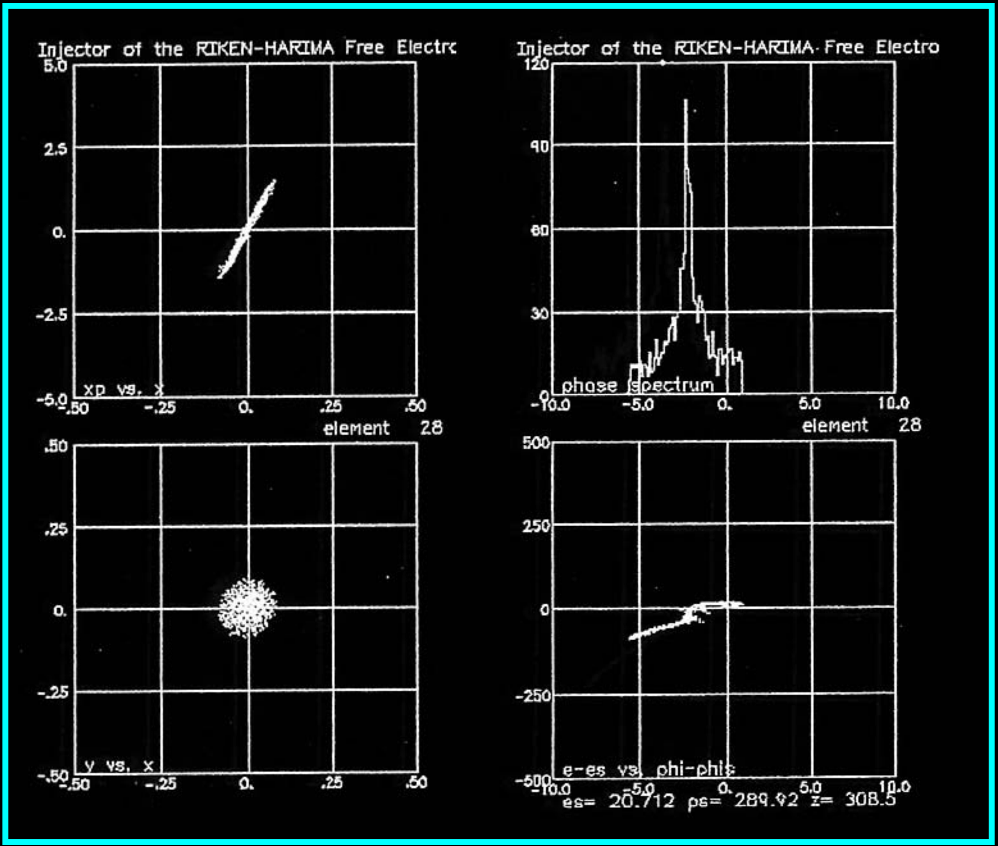
Maintain bunch-length on the electron rest-fram being constant.



Injector Beam Simulation Result

At exit of L-band accelerator.

By K. Sawada, SUMITOMO Heavy Ind.



Parmella Simulation

- Q 0.92 nC
- ε_n 1.9 πmm.mrad
- Δt 12.7 ps
- $\Delta\phi$ 6.5 deg.

Dark Current from the Gun

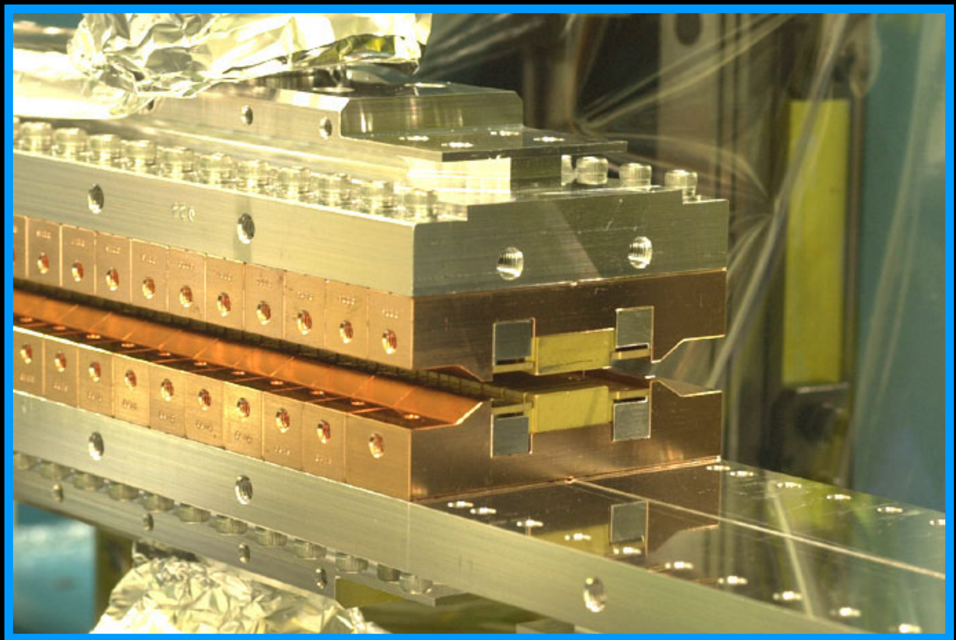
- *The dark current will potentially kill the permanent magnet in the undulator.*
- *The dark current will create an off-set information on the beam-position monitor.*
- *Dark current generated from the accelerating structure can be easily cleaned by Q-magnet focusing because of the energy difference.*
- *But, the dark current from the gun will remain with core beam.*
- *RF-gun is potential source of the dark current because of its high field 100 MV/m.*
- *SCSS high voltage gun runs at 10 MV/m, dark current generation will be small.*

SCSS Undulator In-Vacuum Type

X-ray FEL

- Segment length 4.5 m
- N=300/segment, λ_u=15mm
- Mechanical minimum gap = 2mm
- Nominal gap ~ 3.5mm (K~1.3)
- 45-deg. tilted Halbach type
- More compact than ordinary ones

First prototype model arrived, Sep. 2002



Photocathode rf-injector v.s. Thermionic HV gun injector

	Photocathode rf-injector (Cu, Mg)	Thermionic-cathode injector (LaB6, CeB6)
Thermal Emittance	0.4 π mm-mrad/mm	0.3 π mm-mrad/mm
Emittance at 20~100 MeV	best record 2 π mm-mrad/nC/3psec on the simulation < 1 is possible.	2 π mm-mrad/nC/3psec (simulation only, no experimental data)
Cathode Lifetime	OK for copper cathode, but QE is low (< QE10^{-4}). Mg cathode has high QE (0.2%), but needs cleaning once per week.	OK >3000 hour lifetime is reported in electron microscope application.
Surface Roughness	h < 300 nm/10μm Need to maintain a flat surface under HV processing and discharge at 100 MV/m. It can limit actual lifetime of the cathode.	OK LaB6 and CeB6 keep is flat surface in nm range after usage at high temperature (auto cleaning by evaporation of cathode material)

Photocathode rf-injector v.s. Thermionic HV gun injector

Continued

	Photocathode rf-injector (Cu, Mg)	*Thermionic-cathode injector (LaB6, CeB6)*
Timing	*Laser light defines timing of the electron emission from the cathode, and it also carries timing to the seeding, and also pomp-probe experiment in sub-pico-sec or femto-sec range.*	*Need careful design on phase-stable rf drive line.* *Timing of electron bunching is defined by phase in the rf-power system for the buncher, which is basically same order as the mode-locking in pulsed laser.*
Cost & Manpower	*To maintain the laser system, we need manpower.* *We have to pay for the laser system and accessories (clean room, temperature control system).*	*More costly: The high voltage gun and the buncher system will cost mare than rf-gun cavity. But it will be comparable to total system cost of photo-injector including laser system and its accessories.*
Who is doing?	*BNL, ANL, SLAC GTF, DESY TTF, DESY Zeuthen, CERN CTF, Frascati SPARC, Tokyo University, and many others.*	*SCSS(RIKEN/SPring-8)* *Small emittance gun using BaO cathode: MIT 17GHz injector*