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National Synchrotron Radiation Research Center

High Brightness Electron Beam Technologies

An-ping Lee (李安平)

Linac Group
National Synchrotron Radiation Research Center

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Outline

- High brightness electron injector
- Electron Sources
- Electron guns
- Beam diagnostics

- **High brightness electron injector**
- Electron Sources
- Electron guns
- Beam diagnostics

High Brightness Beam Source

- The brightness of a charged particle beam, defined as the number of electrons within the 6-D phase space volume.
- The wavelength λ of the free-electron laser (FEL) is governed by the emittance ε_n of the electron beam which sets the lower limit on the wavelength deliverable by an FEL.
- As the wavelength of the FEL gets shorter, the required emittance gets lower and thereby brightness increases.
- In the free electron laser , the beam quality is determined by the injector and electron source.

Brightness

$$B = \frac{I}{\varepsilon_{nx}\varepsilon_{ny}\sigma_E}$$

$$\frac{\varepsilon_n}{\gamma} < \frac{\lambda_{FEL}}{4\pi}$$

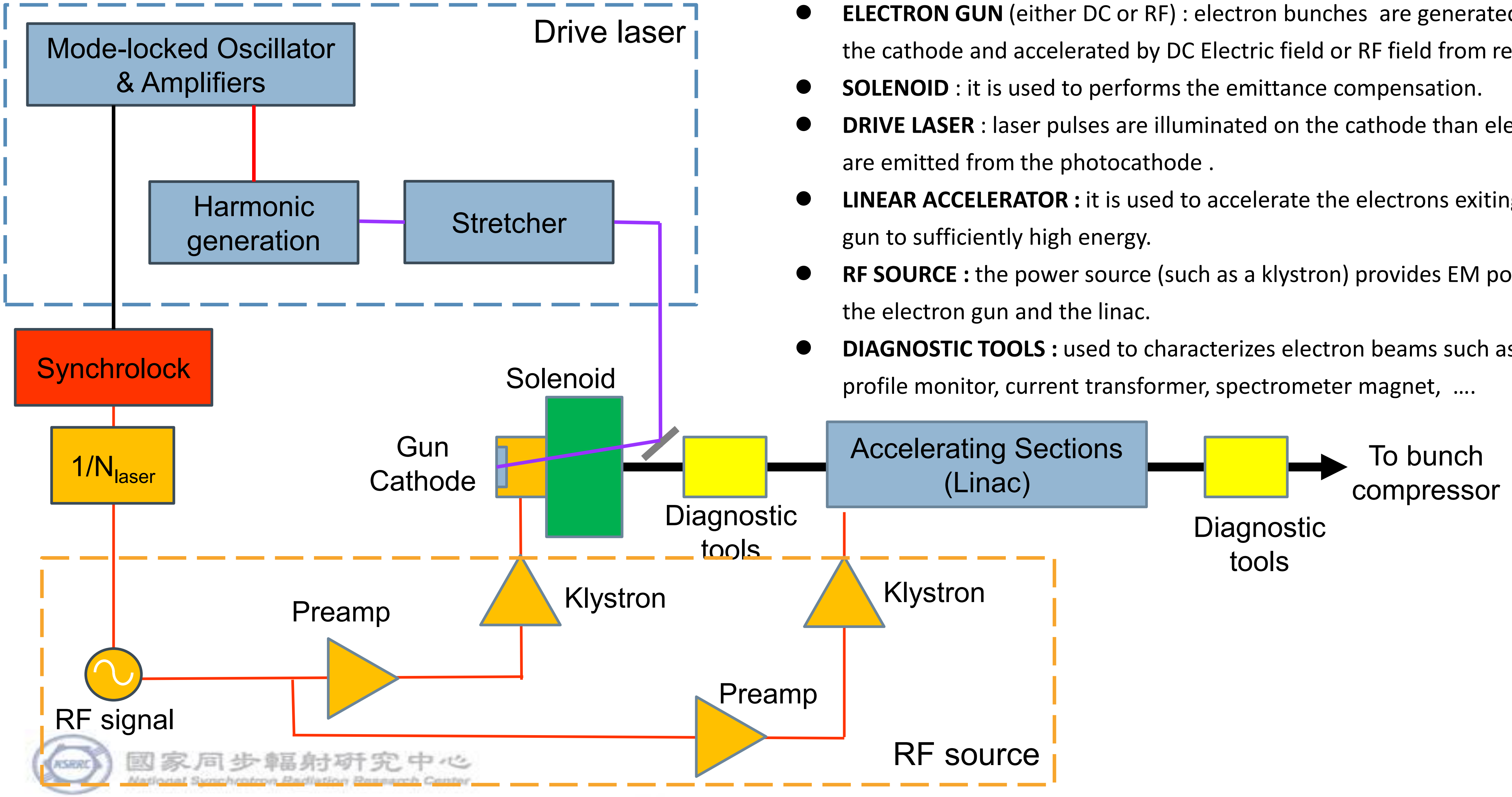
Any linac based, high brightnees light source contains the following main components:

- electron source →space charge force
- accelerating sections → wake field
- bunch compressor → coherent synchrotron radiation

⇒ Increase ε_n !

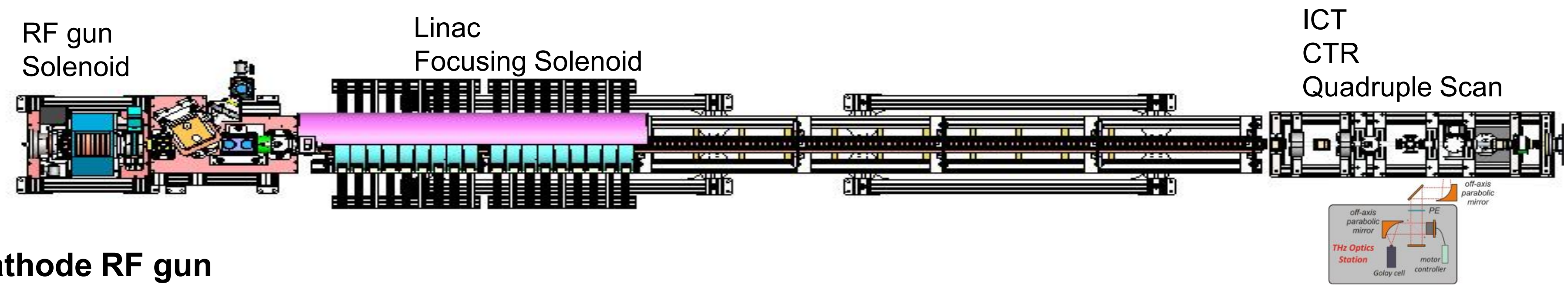
→ The Injector has to produce lowest possible emittance

Typical Photo-injector



- **ELECTRON GUN** (either DC or RF) : electron bunches are generated from the cathode and accelerated by DC Electric field or RF field from rest.
- **SOLENOID** : it is used to performs the emittance compensation.
- **DRIVE LASER** : laser pulses are illuminated on the cathode than electrons are emitted from the photocathode .
- **LINEAR ACCELERATOR :** it is used to accelerate the electrons exiting the gun to sufficiently high energy.
- **RF SOURCE :** the power source (such as a klystron) provides EM power for the electron gun and the linac.
- **DIAGNOSTIC TOOLS :** used to characterizes electron beams such as beam profile monitor, current transformer, spectrometer magnet, ...

NSRRC Photo-injector



Photocathode RF gun
- S-band 1.6-cell copper cavity
- Cu photocathode (QE:10^{-6}~10^{-5})
- Emittance compensation solenoid

Laser system
- IR(800 nm) & UV (266 nm) sources
- Beam shaping elements

RFsource
- Canon 35MW pulsed klystron
- Power devider and Phase shifter

Beam Diagnostic Tools
- ICT, Faraday cup, YAG screen, multislit,
- spectrometer, quadruple scan, CTR…

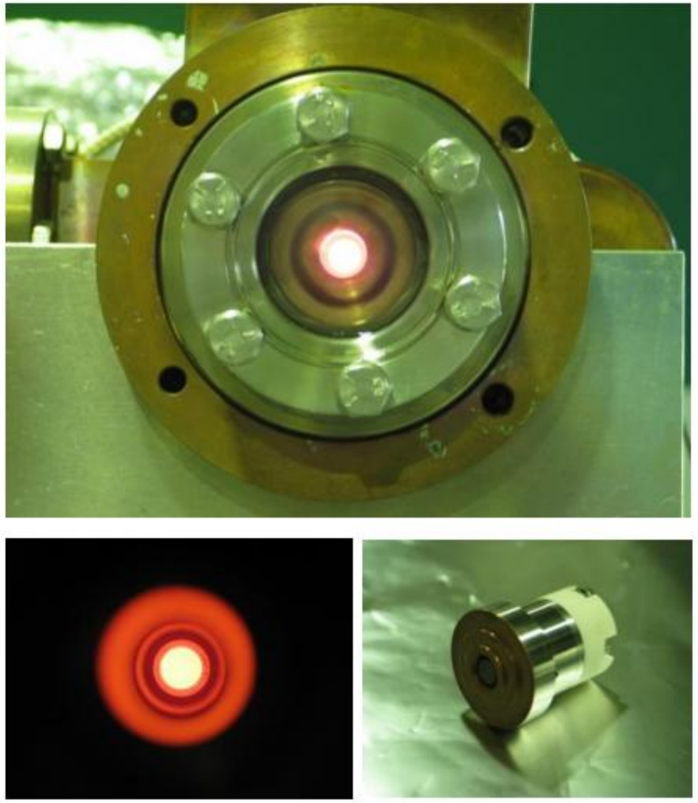
Linac
- S-band, 5.2 m, 156-cell copper, constant gradient
- Focusing Solenoid

- High brightness electron injector
- **Electron Sources**
- Electron guns
- Beam diagnostics

Electron emission from cathode

Types of electron emission:

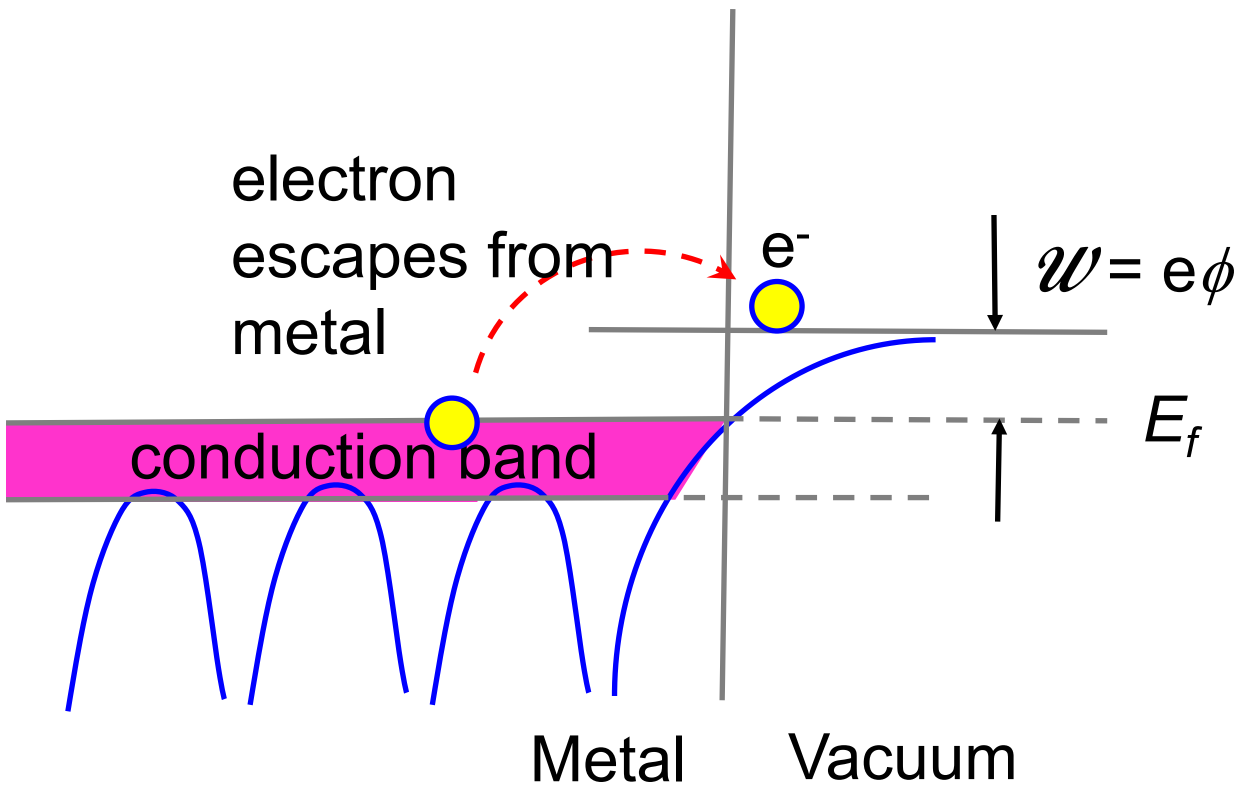
- Thermionic emission
- Photo- emission
- Field emission



The thermionic cathode operating at 1100 °C during activation

Thermionic Emission

Energy Level Diagram for Electrons Near the Surface of Metal



- Work function *W* depends on cathode material and operation temperature
- The cathode can be a metal, a coated metal, or borides.
- Common thermionic cathode materials are W (Tungsten), LaB_6, Ba etc..
- For W (Tungsten), *W* = 4.6 eV; Cu, *W = 4.3 eV* and for Ba, *W*=1.8 eV.
- Richardson-Dushmann equation:

$$J_{th} = AT^2 e^{-\frac{W}{kT}}$$

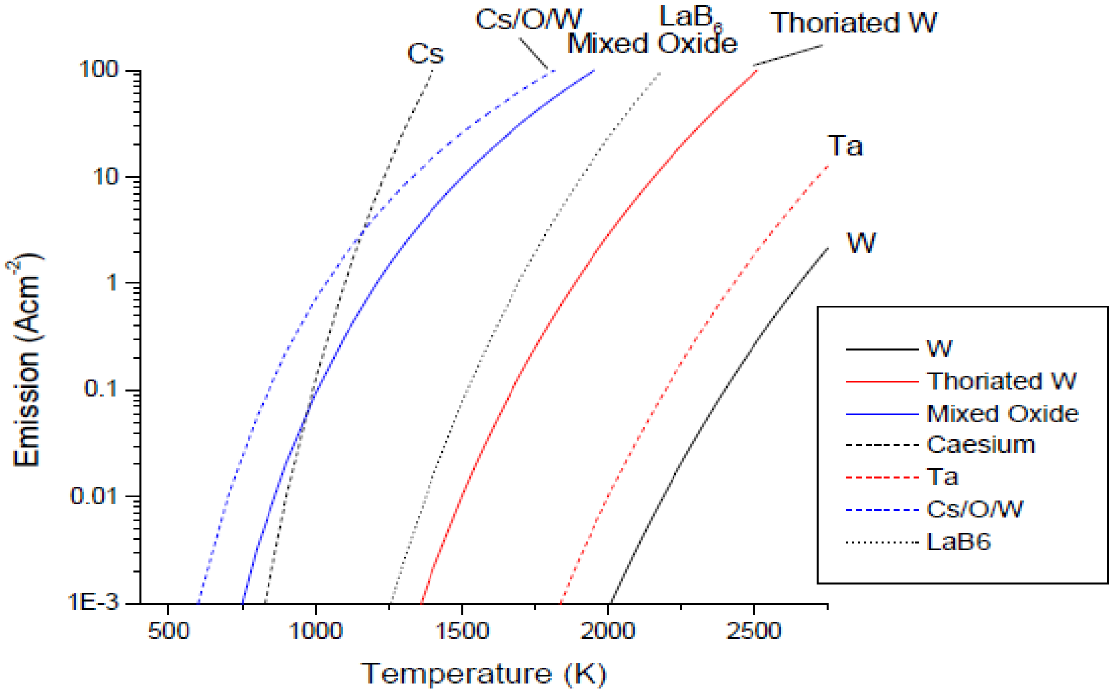
$$A = \lambda_R A_0$$

λ_R : material-specific correction factor

$$A_0 = \frac{4\pi emk^2}{h^3} = 120A/cm^2K^2$$

Thermionic Emission of Various Cathode Materials

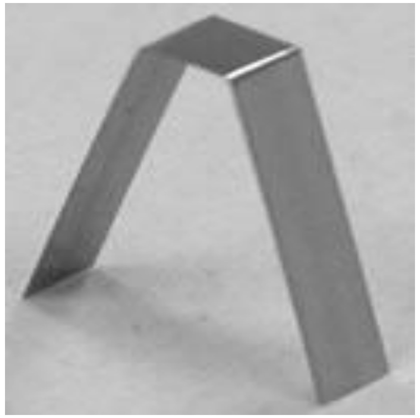
	A ($Acm^{-2}K^{-2}$)	ϕ (eV)	Melting Temp. (°C)
Ba	60	2.11	720
Cesium	160	1.81	28
Ta	60	4.12	2850
W	60	4.54	3370
Thoriated W	3	2.63	--
Mixed oxide	0.01	~1	--
Cs/O/W	0.003	0.72	--
LaB_6	29	2.66	2210



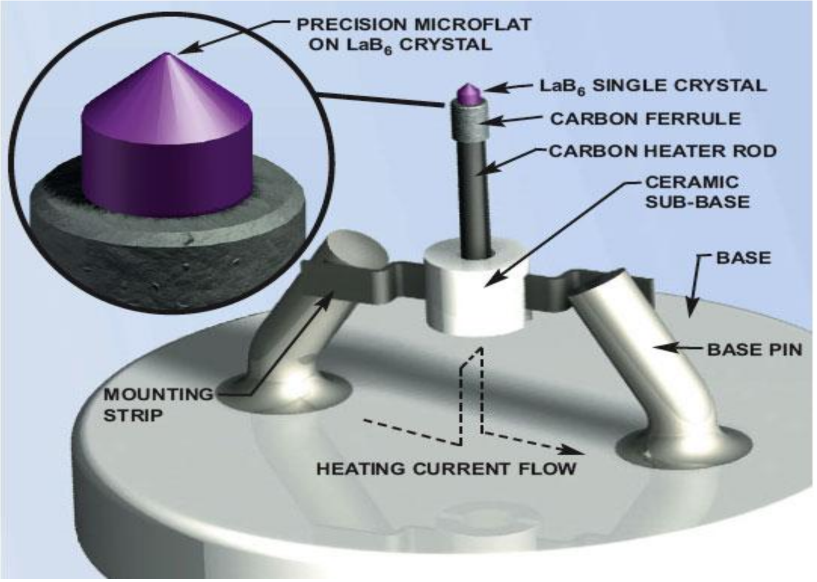
Thermionic Cathode

- Tungsten filament cathodes
- Dispenser cathodes
- Single crystal cathodes

tungsten filament for electron microscope



filament cathode for e-beam welder



LaB_6 cathode for electron microscope

a typical type B dispenser cathode for linac system

Emittance of a Thermionic Cathode

Assume a thermonic cathode of radius r_s is operating at temperature T, RMS velocity spread is

$$\tilde{v}_x = \tilde{v}_y = \left(\frac{k_B T}{m}\right)^{1/2}$$

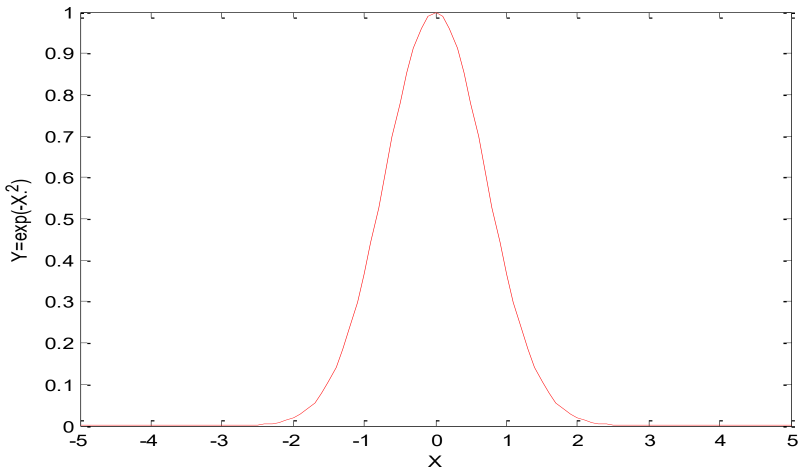
RMS thermal velocity spread is related to rms beam divergence as

$$\tilde{x}' = \tilde{v}_x / v_0$$

On the other hand, *RMS* beam size is $\tilde{x} = \tilde{y} = r_s / 2$, since

$$\tilde{x} = \frac{\tilde{r}}{\sqrt{2}} = \frac{1}{\sqrt{2}}\left[\frac{2\pi n_0 \int_0^a r^3 dr}{2\pi n_0 \int_0^a r dr}\right]^{1/2}$$

Maxwellian velocity distribution

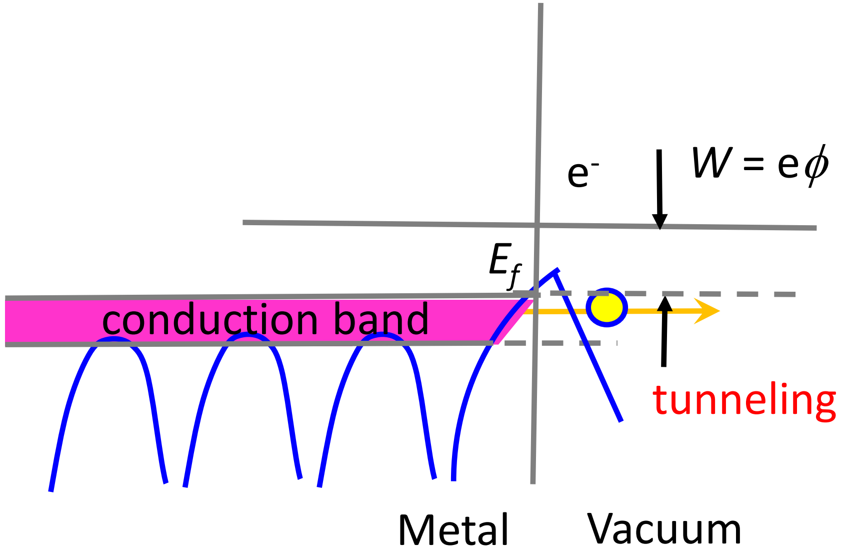


$$f(v_x, v_y, v_z) = f_0 \exp\left[-\frac{m(v_x^2 + v_y^2 + v_z^2)}{2k_B T}\right]$$

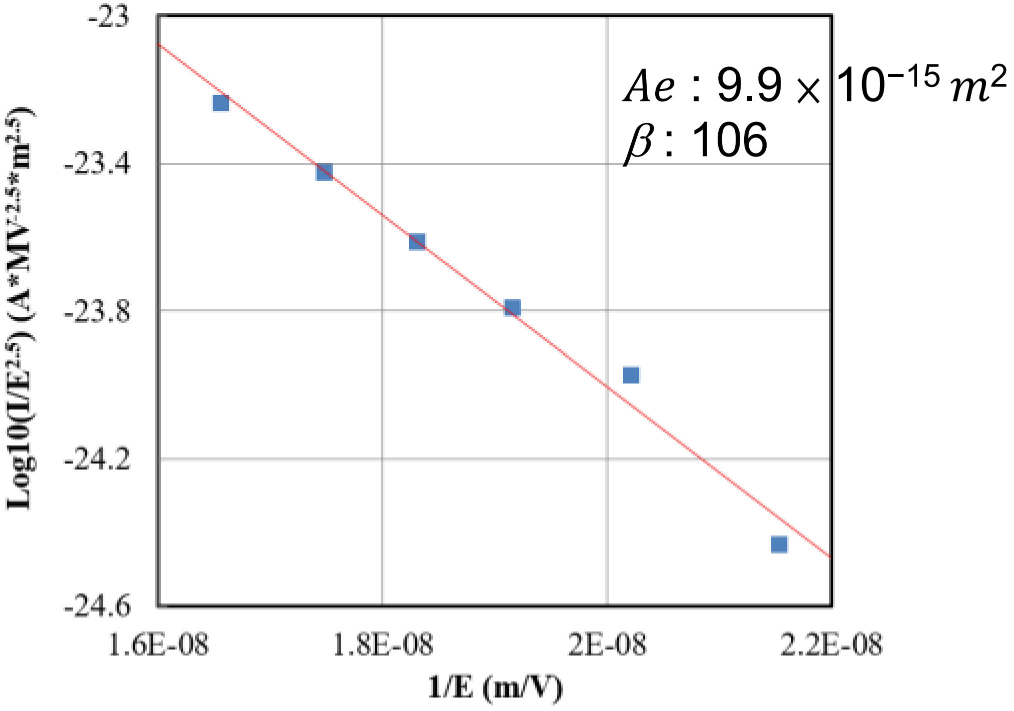
$$\tilde{\varepsilon}_{x,y} = \tilde{x}\tilde{x}' = 2r_s \frac{\left(\frac{k_B T}{m}\right)^{1/2}}{v_0} \Rightarrow \tilde{\varepsilon}_n = 2r_s \left(\frac{k_B T}{m v_0^2}\right)^{1/2}$$

low temperature, small cathode → low emittance

Field Emission and Dark Current



- The electron current depends upon the gradient of the electric field applied to the surface.
- Field emission (FE) current generally follows the Fowler-Nordheim law.



Fowler-Nordheim plot in dark current measurement (PITZ photocathode RF gun)

Fowler-Nordheim equation:

$$I_F = \frac{5.7\times10^{-12}\times10^{4.52}A_e(\beta E^{2.5})}{\phi^{1.75}}\exp\left(-\frac{6.53\times10^{9}\phi^{1.5}}{\beta E}\right)$$

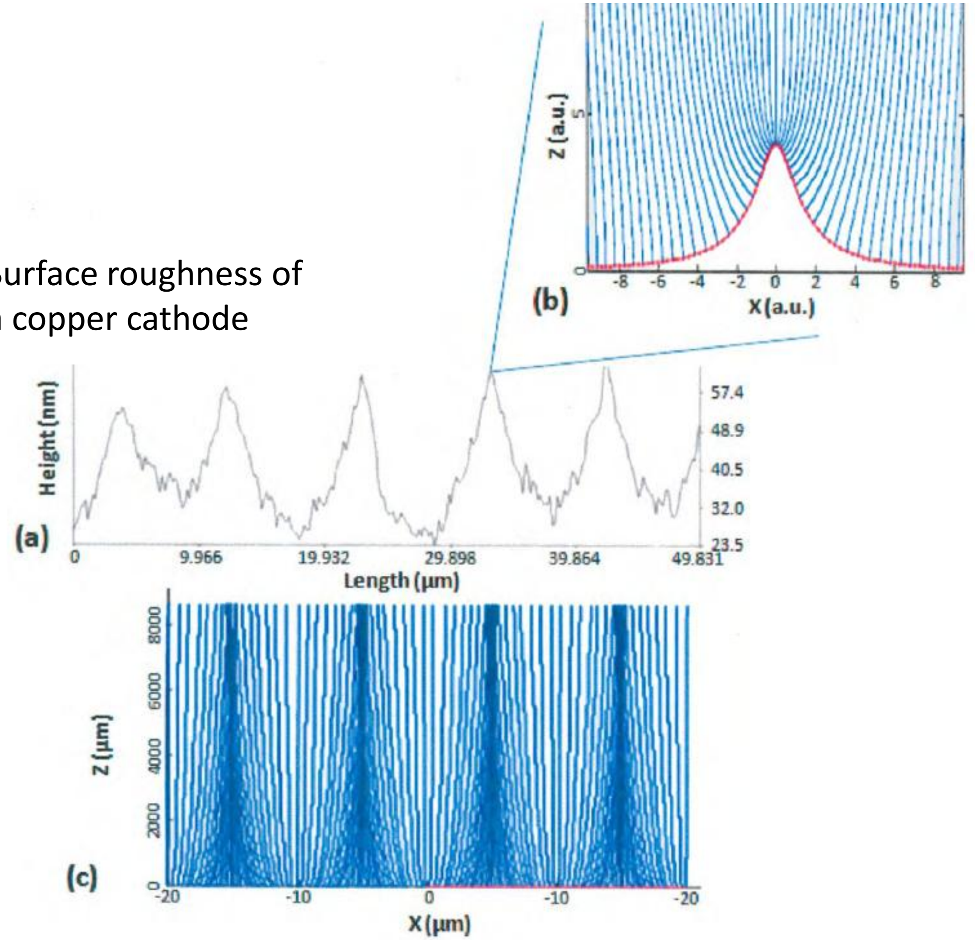
E : the surface electric field in V/m
ϕ : the work function of the emitting material in eV
Ae :the effective emitting area in m^2
β : the field enhancement factor induced by microscopic surface defects such as scratches, protrusions and particulates

Effect of Surface Roughness on Emission

- Micro-protrusions and surface contaminants can effectively enhance the field at the emitting surfaces.
- Field enhancement due to surface roughness, non-metallic inclusions in cracks or grain boundaries etc. has negligible effect on QE for planar geometries.
- Normalized emittance varies as the effective work function and the field distribution change from the peak to the valley of the rough cathode surface.
- Non-uniform charge density at/near the cathode surface.

distribution of field lines in the vicinity of one of the protrusions

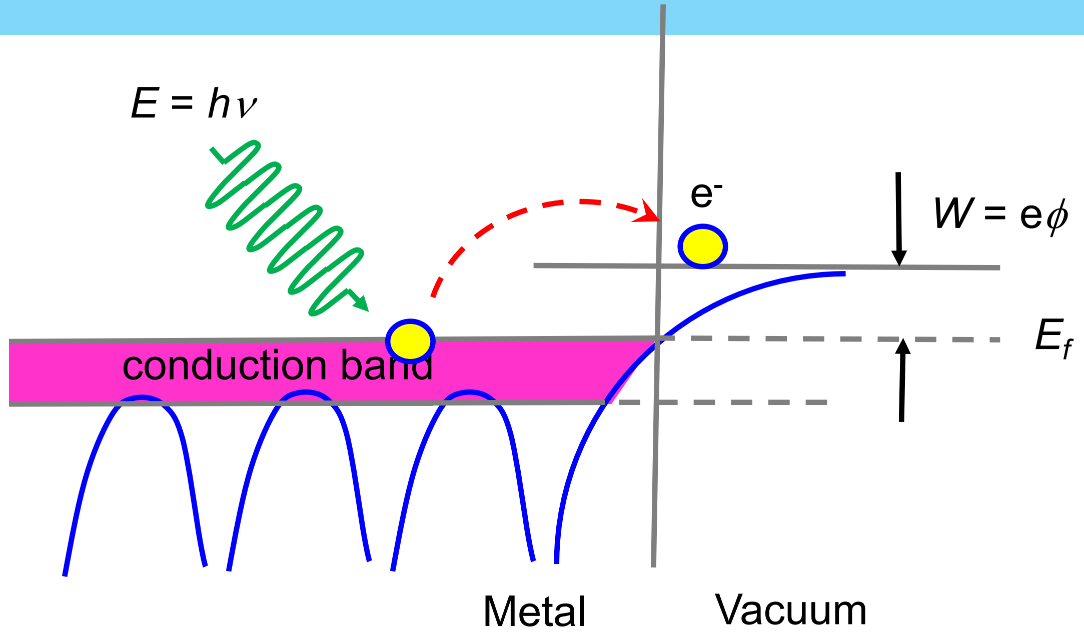
Surface roughness of a copper cathode



distribution of the emitted charge in the vicinity and a few mm away from the cathode

T. Rao and D.H. Dowell, "An Engineering Guide to Photoinjectors" (2013)

Photo Emission



Quantum efficiency:

$$QE = \frac{n_e}{n_p}$$

n_p is the number of incident photons

QE can be expressed as :

$$QE = \frac{h\nu[eV]}{E_{laser}[J]} \cdot q[C]$$

QE is a function of photon energy and work function.

$$QE(\nu) \propto (h\nu - \phi)^2$$

Spicer's three step model:

1.Photon energy absorption by electron

2.Electron move toward the crystal surface

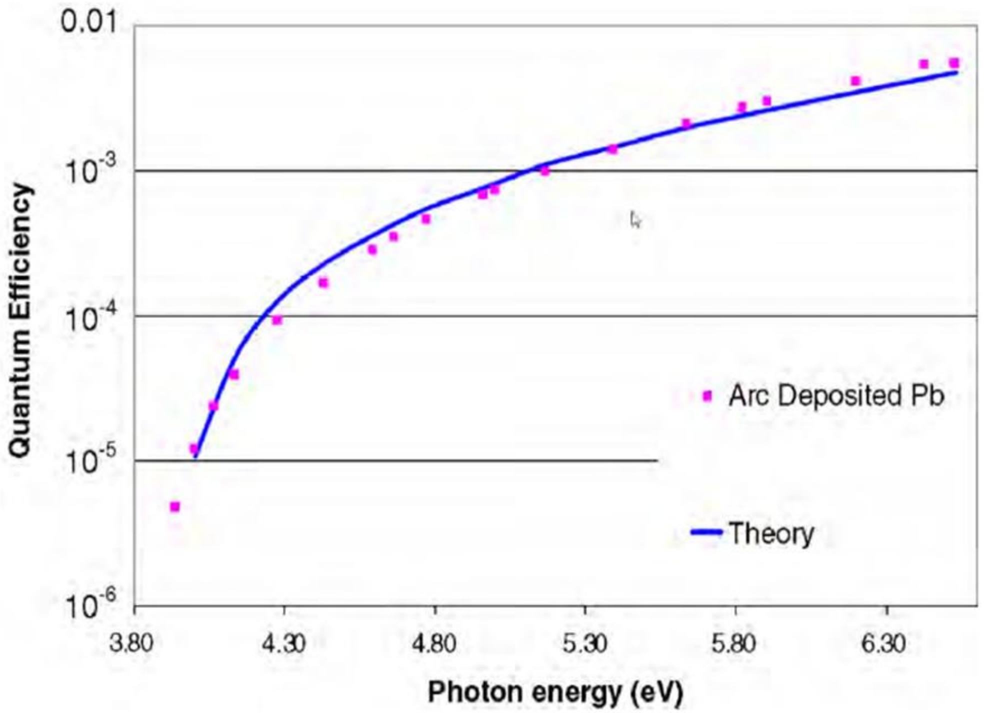
3.Electron escape to the surface through the potential barrier

Intrinsic emittance of metallic photo-cathode:

$$\varepsilon_n = \sigma_x \sqrt{\frac{h\nu - \phi}{3mc^2}}$$

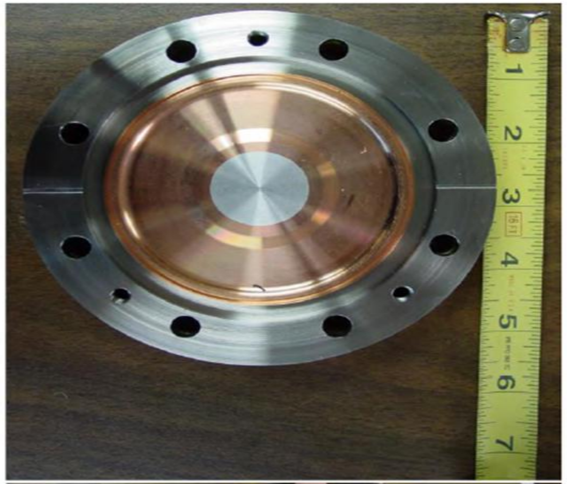
e.g. a Cu cathode with a 266nm driven laser and beam radius 1mm, ε_n ~ 0.45 um

QE of common metal photo-cathodes

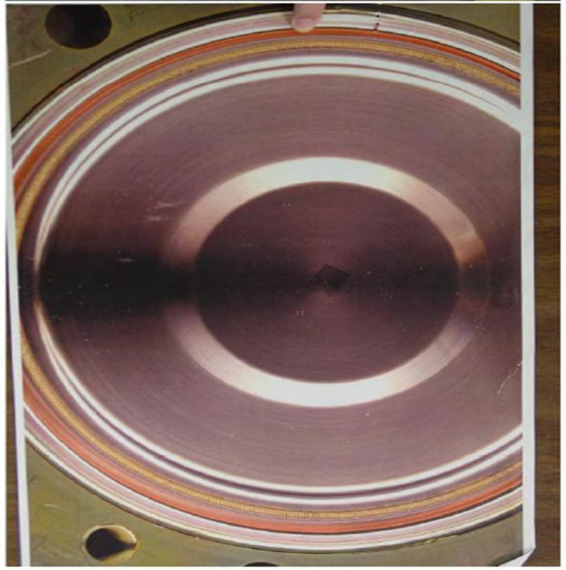


J. Smedley, T. Rao and J. Sekutowicz, "Lead photocathodes" (2008)

Metal @ Electric Field	Wavelength [nm]	QE [%]
Copper @ 100 MV m^{-1}	266	0.014
Magnesium @ 100 MV m^{-1}	266	0.62
Niobium @ 2 MV m^{-1}	266	~0.001
Lead @ 2 MV m^{-1}	248	0.016



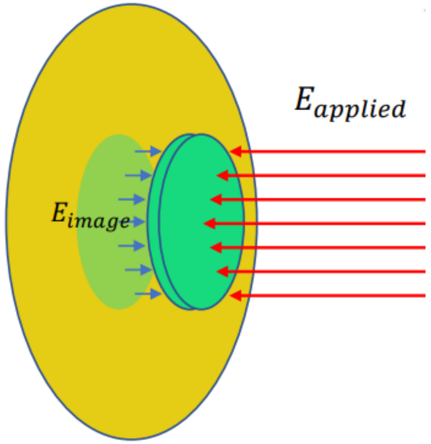
Mg cathode



Cu cathode

Image Charge Field

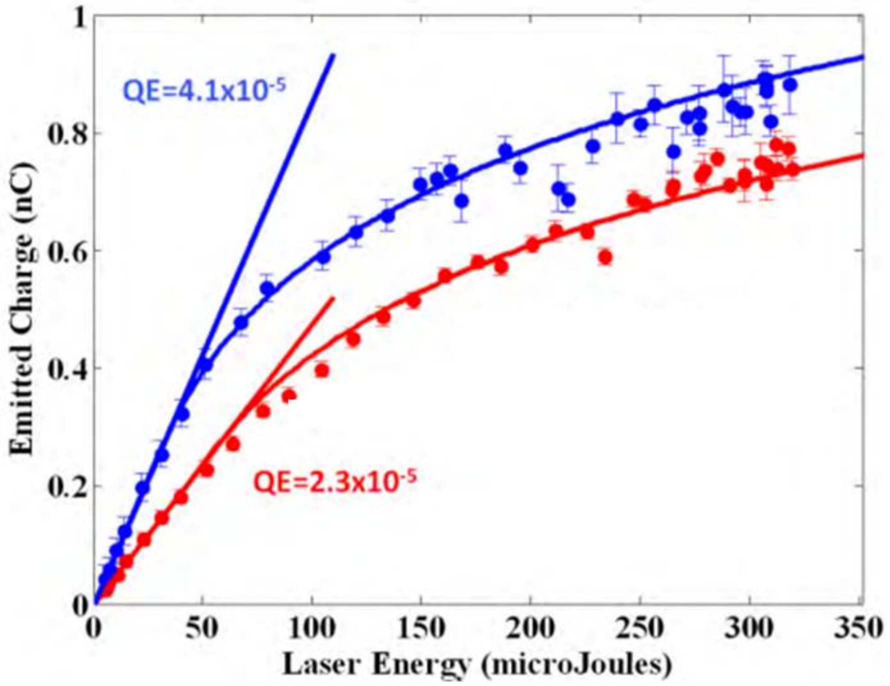
Gauss law : a pancake of electrons with charge q over an area A produces an image electric field opposing the applied electric field at the cathode.



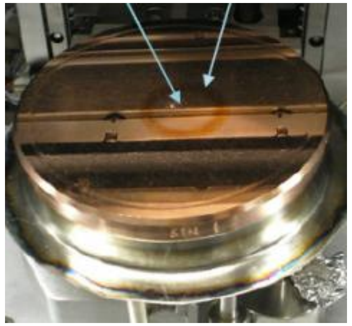
Cathode field $E_{cathode} = E_{applide} - E_{image}$

Image charge field $E_{image} = \frac{q}{\epsilon_0 A}$

Due to the image charge field, the slope of photocurrent vs. laser power curve decreases at high laser power (the apparent QE is reduced at high bunch charge). The maximum bunch charge can be limited by the laser energy and the image charge force.



Common Photo-cathodes



- **Metal: Cu**

  - <~sub-picosecond pulse capability
  - minimally reactive; requires ~ 10^{-8} Torr pressure
  - low QE ~ 10^{-5}~10^{-4}
  - requires UV light
  - for nC, 120 Hz reptition rate, ~ 2 W of IR required

- **PEA Semiconductor: Cesium Telluride Cs_2Te**

  - <~ps pulse capability
  - relatively robust and un-reactive (operates at ~ 10^{-9} Torr)
  - Successfully use in NC RF and SRF guns
  - high QE > 5%
  - photo-emits in the UV ~250 nm

- **NEA Semiconductor: Gallium Arsenide GaAs**

  - tens of ps pulse capability with phonon damping
  - reactive; requires UHV <~ 10^{-10} Torr pressure
  - high QE (typ. 10%)
  - Photo-emits already in the NIR,
  - for nC, 1 MHz, ~50 mW of IR required
  - operated only in DC guns at the moment

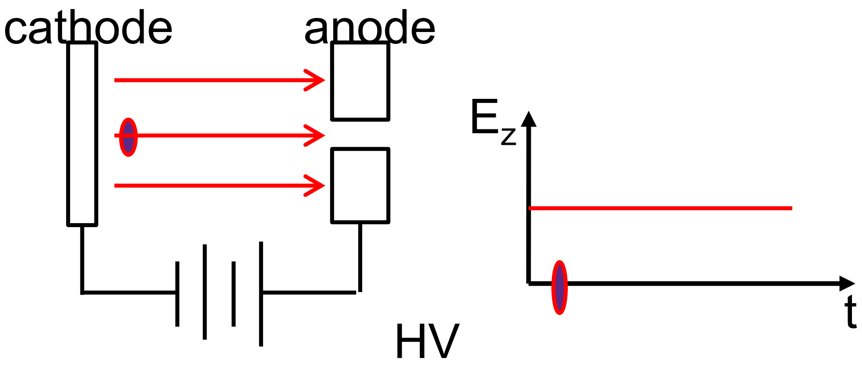
In general :

- Metal cathodes are more robust but show much lower QE.
- Semiconductor cathodes have high QE. but short life time.

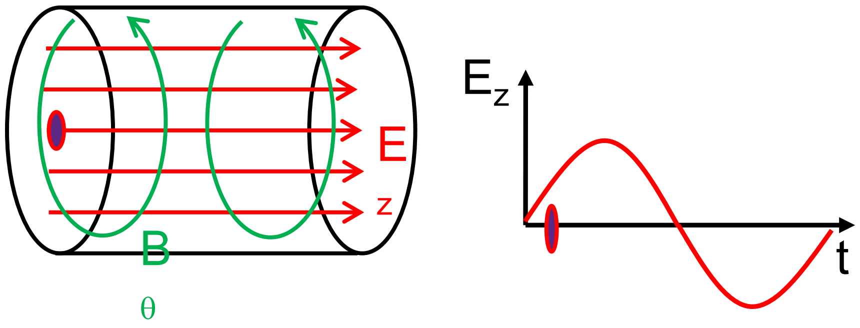
- High brightness electron injector
- Electron Sources
- **Electron guns**
- Beam diagnostics

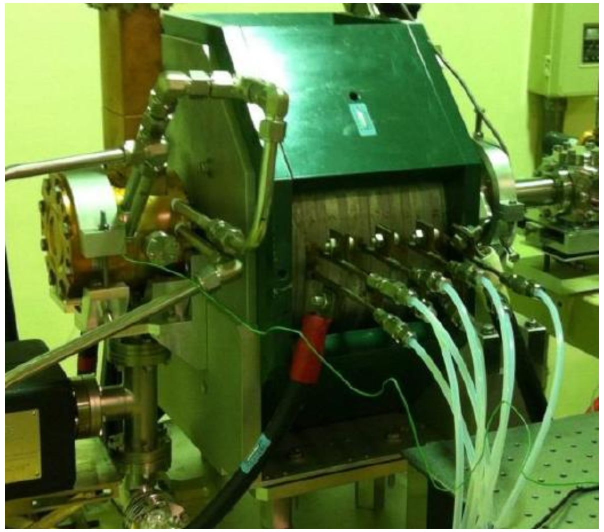
DC and RF Acceleration

DC acceleration



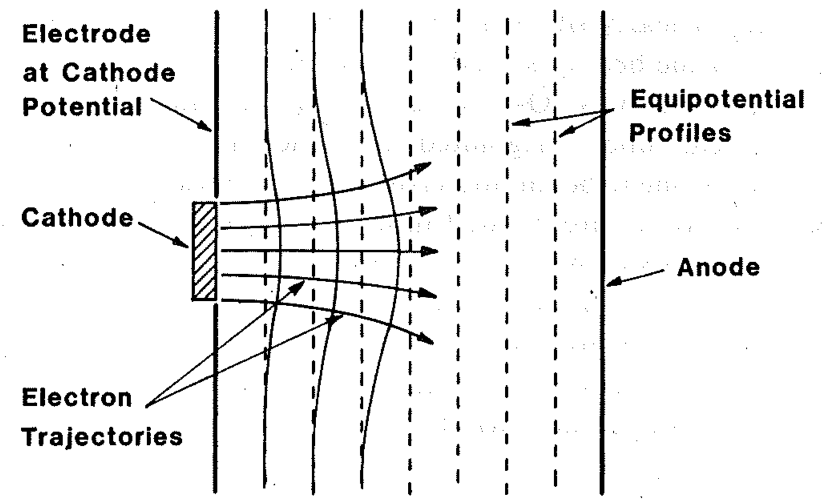
RF acceleration



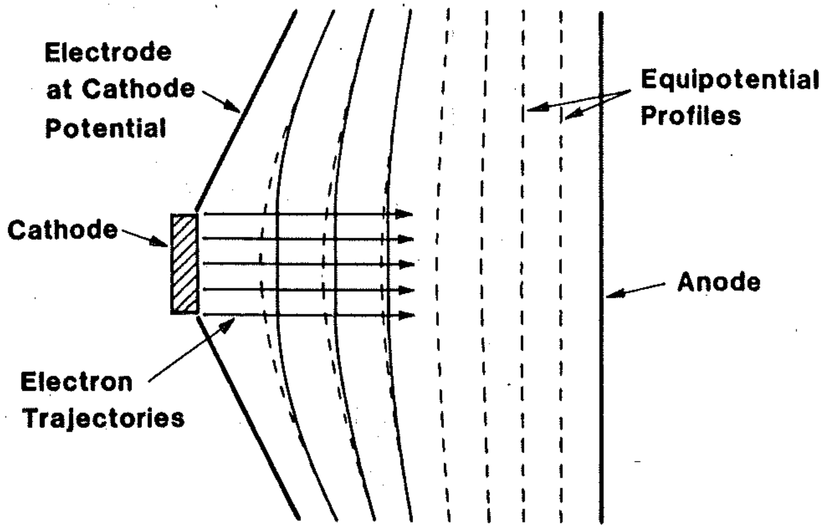


Electron Gun with Pierce Electrode

- Electrostatic repulsion forces between electrons tend to diverge the beam.
- The required current density of electron beam is usually far greater than the available emission density of cathode.
- Optimum angle of focusing electrode for a parallel beam is referred to as 'Pierce electrodes'.
- Defocusing effect of *anode aperture* has to be considered.



a simple parallel-plate diode



a diode gun with Pierce electrodes (Pierce gun)

TM Modes in a Pillbox

For TM_{nml} mode:

$$E_z = E_0 J_m(k_{mn} r)\cos(m\theta)\cos(k_l z)e^{j\omega t}$$

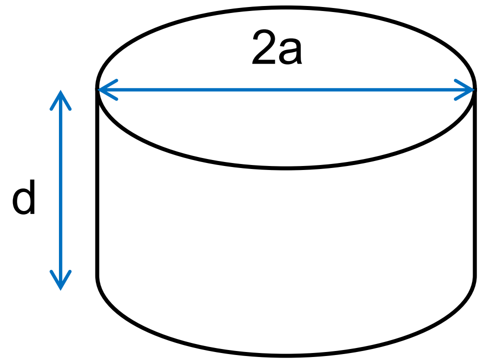
$$E_r = -\frac{jk_l}{k_{mn}} E_0 J_m{}'(k_{mn} r)\cos(m\theta)\sin(k_l z)e^{j\omega t}$$

$$E_\theta = -\frac{k_l m}{k_{mn}^2 r} E_0 J_m(k_{mn} r)\sin(m\theta)\sin(k_l z)\, e^{j\omega t}$$

$$B_r = \frac{\omega m}{k_{mn}^2 c r} E_0 J_m(k_{mn} r)\sin(m\theta)\cos(k_l z)\, e^{j\omega t}$$

$$B_\theta = \frac{j\omega}{k_{mn}^2 c} E_0 J_m{}'(k_{mn} r)\cos(m\theta)\cos(k_l z)\, e^{j\omega t}$$

$$B_z = 0$$



Where $k_l = l\pi/d\,, l = 0,1,2,\dots$

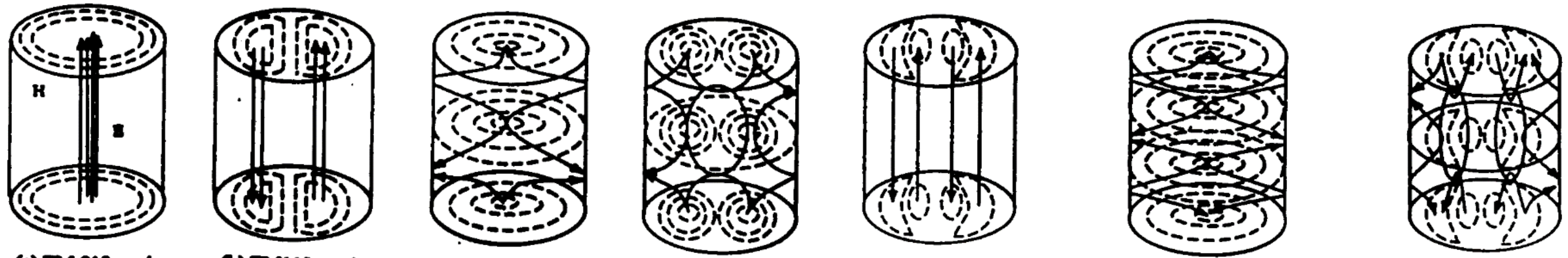
$k_{mn} = x_{mn}/a$

The n[th] zero of $J_{mn}(x)$

E_0 : the field normalization
J_m : the mth -order Bessel function,
k_{mn} : the nth zero of the mth -order Bessel function
ω : the RF angular frequency.
k_z : the longitudinal wave number

a : the internal radius of the cavity
d : the cavity length

Resonant frequency : $f_{mnl} = \frac{c}{2\pi}\sqrt{\left(\frac{l\pi}{d}\right)^2 + \left(\frac{x_{mn}}{a}\right)^2}$



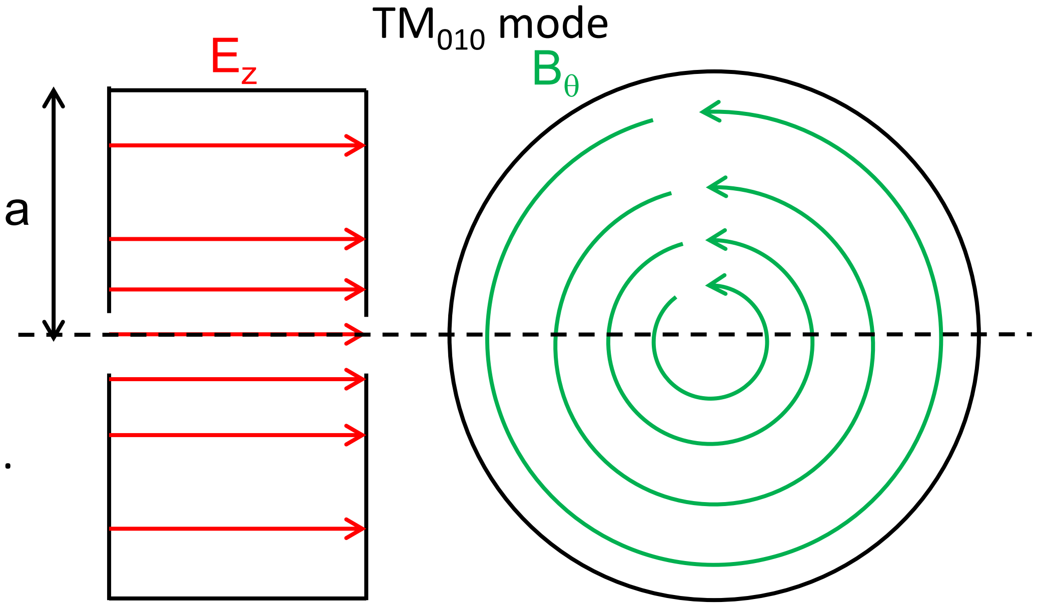
(a) TM 010 mode (b) TM110 mode (c) TM012 mode (d) TM112 mode (e) TM120 mode (f) TM013 mode (g) TM122 mode

Cavity Mode for Particles Acceleration

To accelerate electrons, the accelerating mode is with large longitudinal electric fields

We desire to produce a beam with rotational symmetry, m = 0 for all RF guns.

The lowest-frequency TM mode is TM_{010} with cell length = $\lambda/2$.



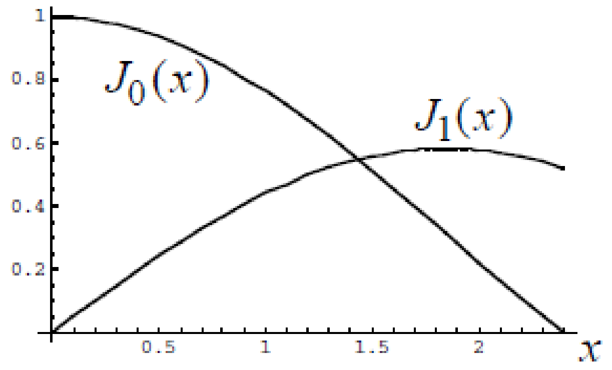
$$E_z = E_0 J_0(k_{01} r) e^{j\omega t} \qquad B_\theta = \frac{j\omega}{k_{01} c} E_0 J_0{}'(k_{01} r) e^{j\omega t}$$

$$E_r = 0 \qquad B_r = 0$$

$$E_\theta = 0 \qquad B_z = 0$$

TM_{010} resonance frequency : $f_{01} = \frac{2.405}{2\pi} \frac{c}{a}$

Example : *a = 3.825 cm,* $f_{01} = 3\ GHz$



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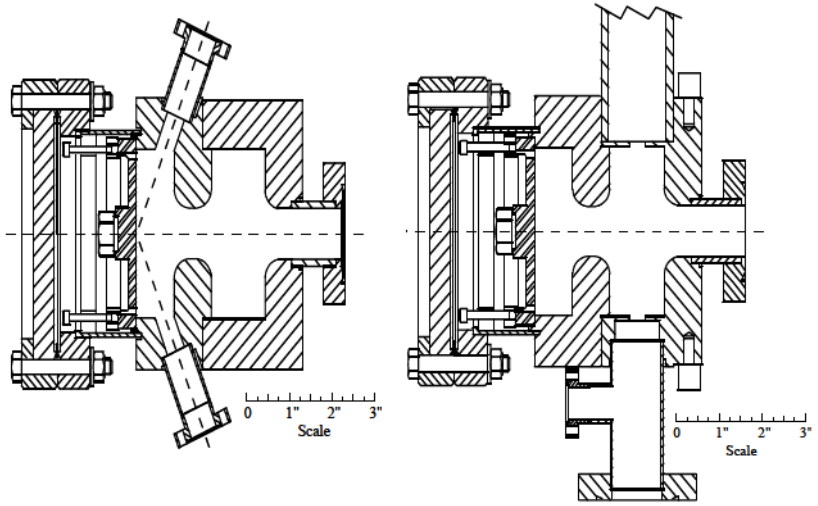
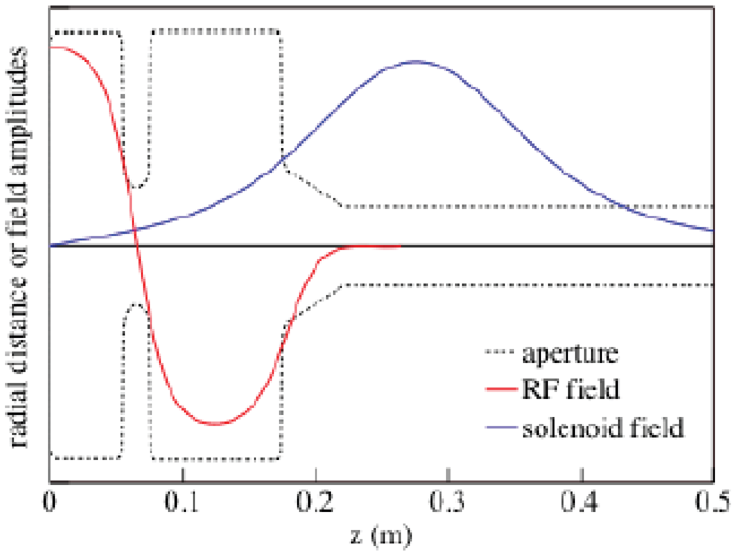
RF Gun

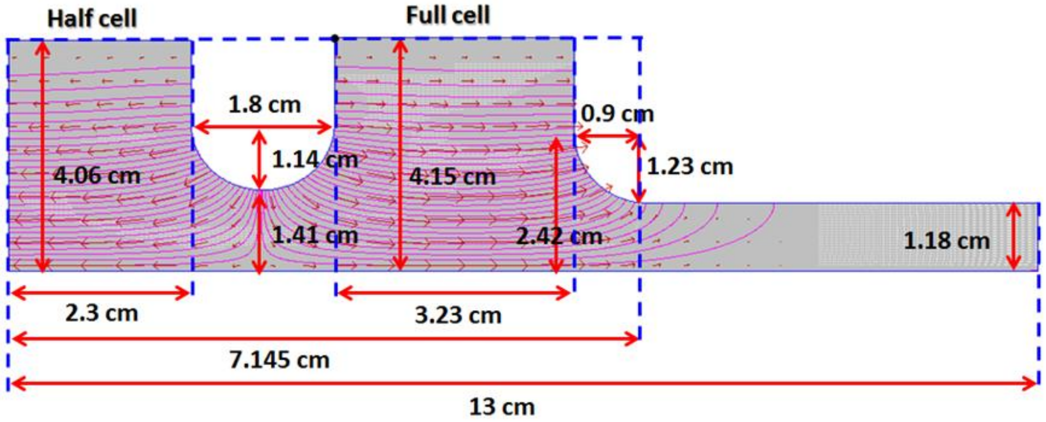
- RF guns are used to produce high peak current electron beams
- Usually operate at low repetition and GHz frequencies range (typically 3GHz).
- The cavity structure is usually n+1/2cell(n=1,3…)
- Standing wave structure, TM mode to accelerate the beam
- The cathode is placed in the half cell (max field)
- The RF gun accelerates the photoelectrons emitted at the photocathode surface, up to a relativistic speed ***in a time shorter than the RF period.***

The BNL/SLAC/UCLA photocathode RF Gun

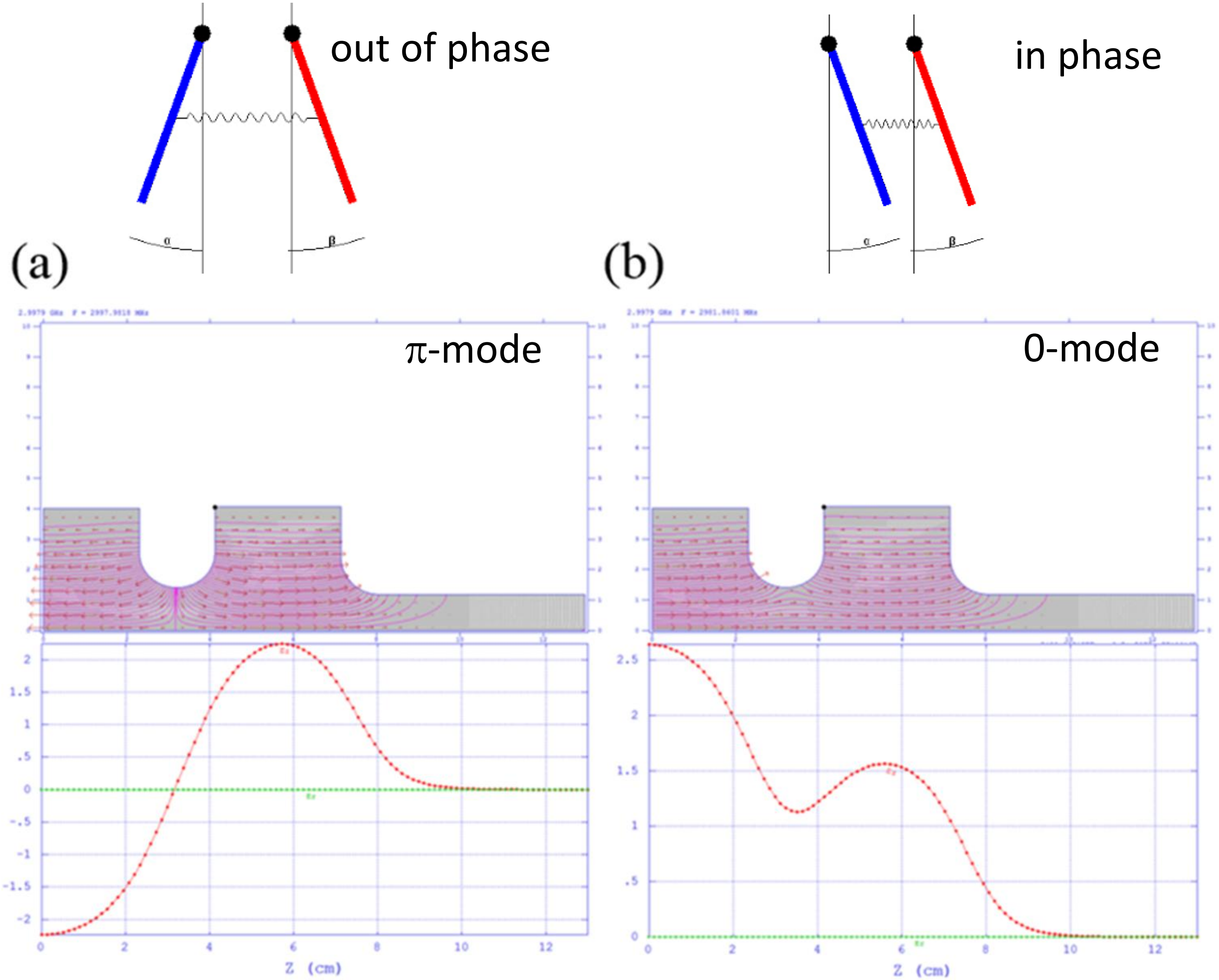




Gun Cavity

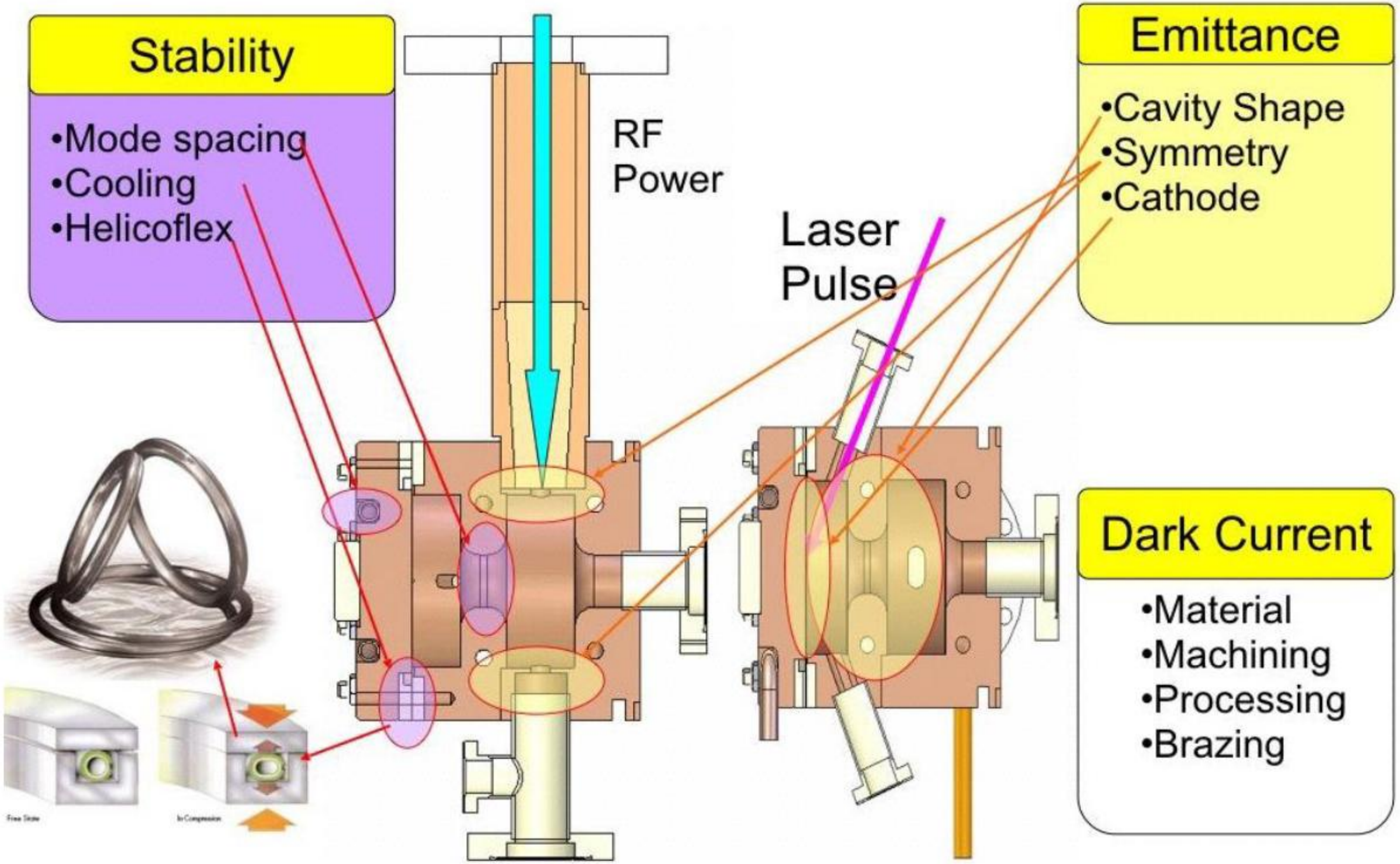


- Coupled cavity mode is π-mode.
- The cavity cells are on-axis coupled through apertures, coupling strength depends on diameter of apertures.



* balance of field amplitude for efficient acceleration

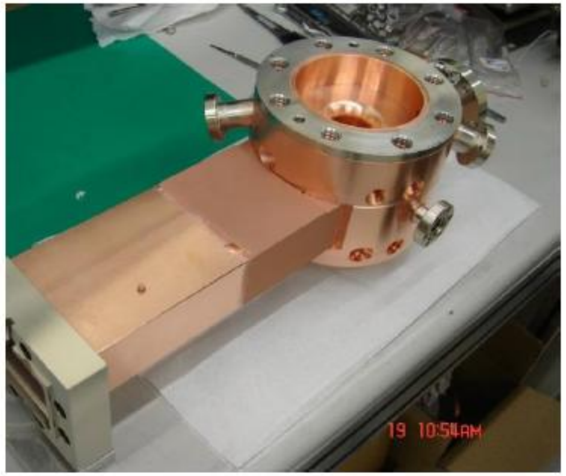
Gun Fabrication



Gun Fabrication

Fabrication

Vacuum Brazing



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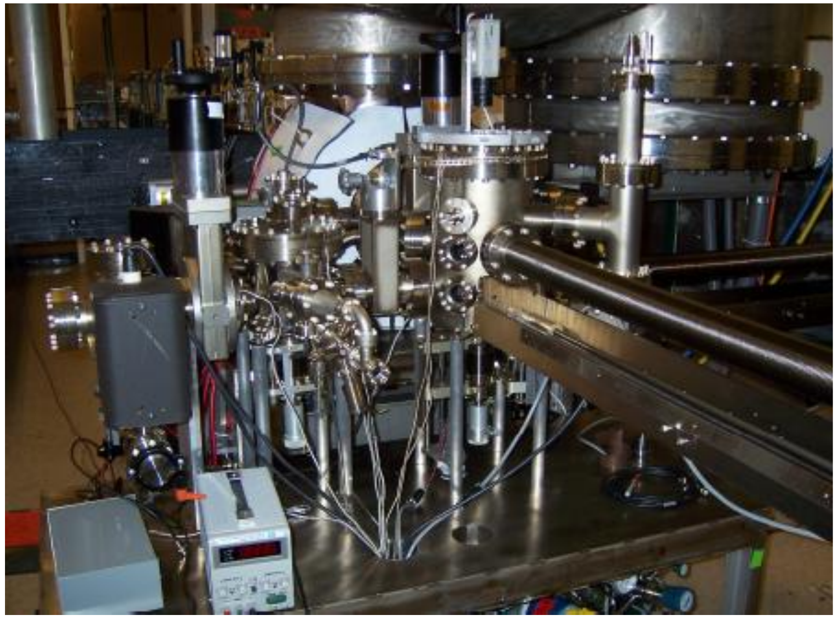
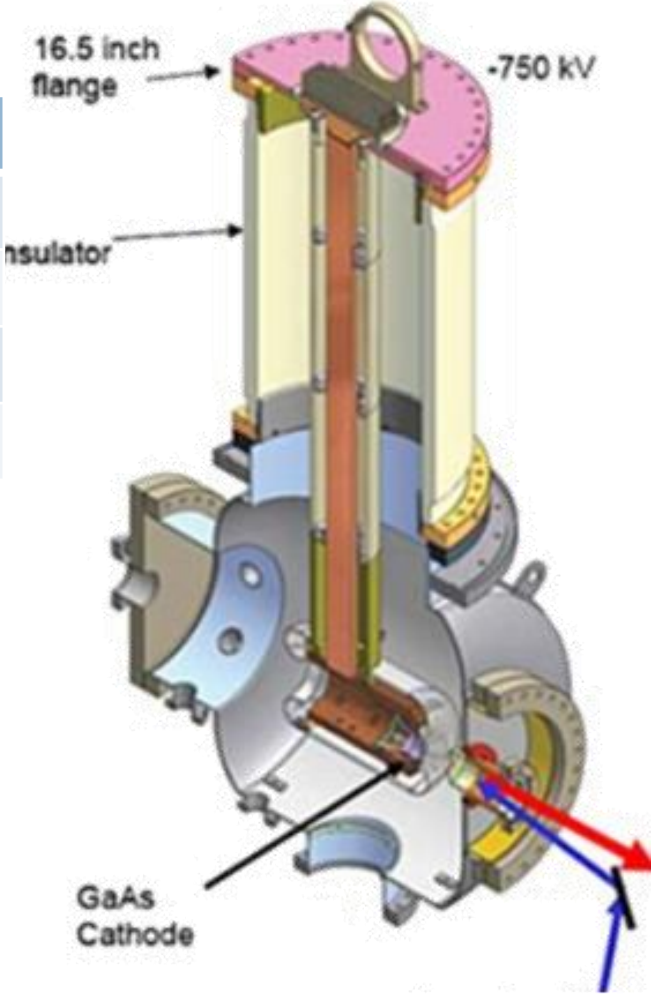
Cornell Photocathode DC Gun



Cornell DC gun	
Gun exit energy	0.35 MeV
repetition rate	1300 MHz
rms emittance	0.5 mm at 80 pC
Average current	65 mA (at 50 pC)

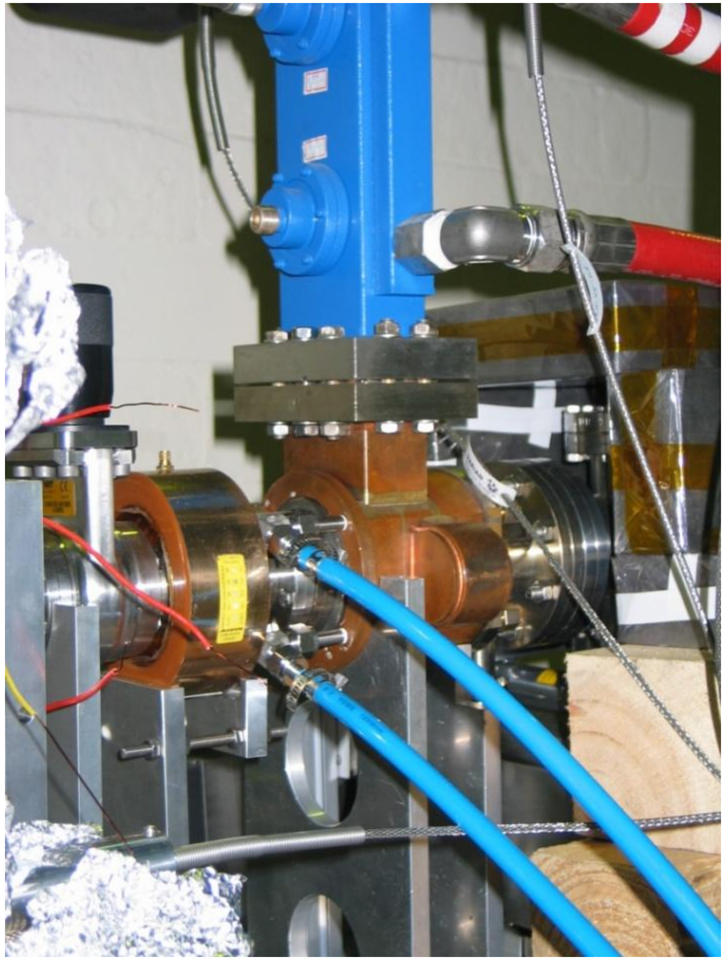


Cornell DC gun

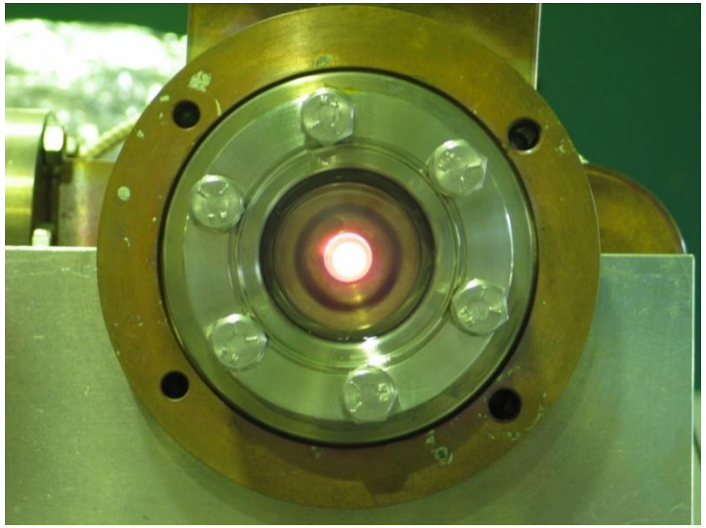
- High QE cathode
- GaAs cathode, require ultra high vacuum at 10^{-12} mbar
- Smooth electrode surfaces to minimize field emission
- Need reliable HVDC power supply and insulator design
- Low beam energy, need more complicated injector design.
- Capability to provide sub-µm, few hundred pC beam.
- Stable operation at ~ 400 kV

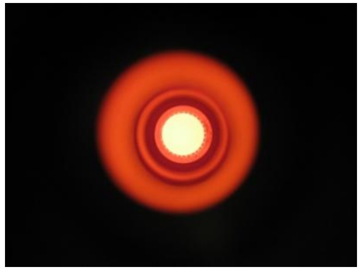
K. Smolenski et al., "Design and Performance of the Cornell ERL DC Photoemission Gun" (2009)

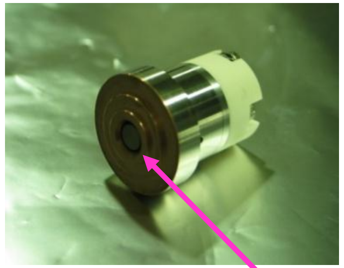
Thermionic Cathode Radio Frequency Electron Gun



Thermionic Cathode RF Gun

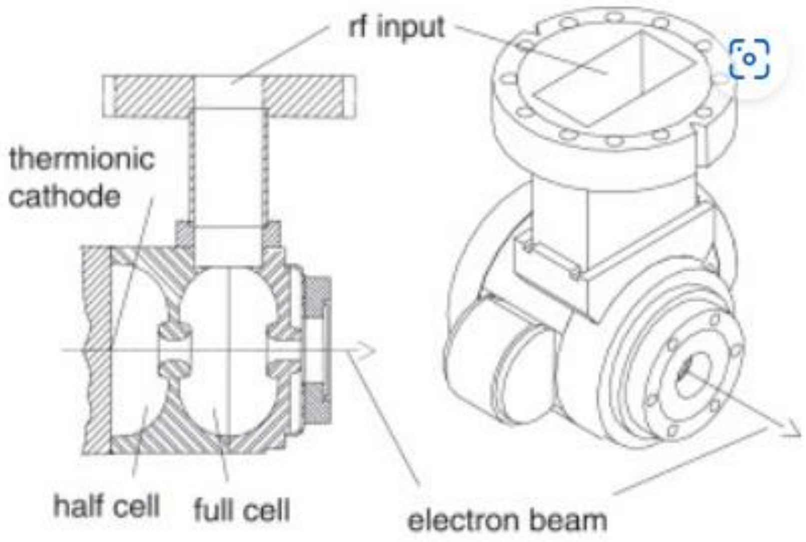






cathode operating
at 1100 °C during activation

1.5 cell side-coupled cavity



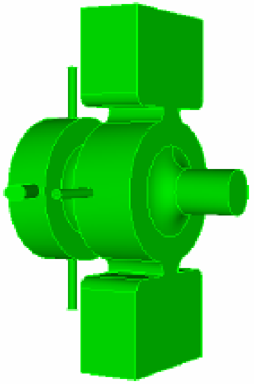
cathode assembly with heat barrier

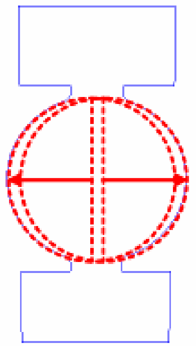
LCLS S-BAND NC RF Gun

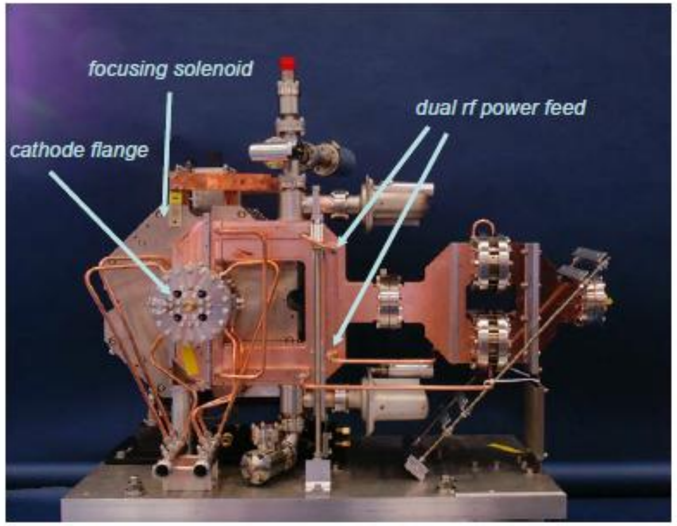
The LCLS S-Band Gun :

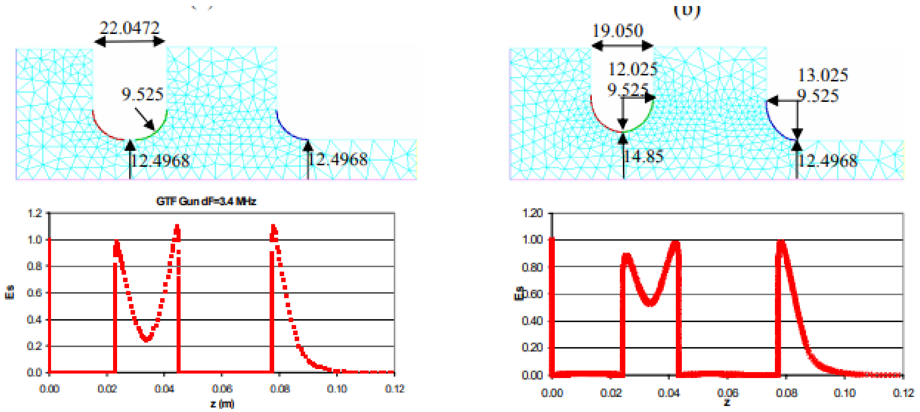
- Dual RF Feeds – to eliminate the dipole modes
- Racetrack shape of the full cell – to minimize the quadruple mode
- Elliptical disk iris shape : to reduce the surface field.
- Z-coupling of RF feeds : to reduce the pulsed heating
- Increase the mode separation : to reduce the 0 mode amplitude

	BNL/SLAC/UCLA Gun III	LCLS Gun
cathode field	120MV/m	140MV/m
rf feed	single w/compensation port	dual feed
cavity shape	circular	racetrack
0-π mode separation	3.4MHz	15MHz
repetition rate	10Hz	120Hz
peak quadrupole field	4 mrad/mm	0.1 mrad/mm
RF tuners	plunger/stub	deformation
cathode	copper or Mg	copper
rf coupling	theta (azimuth)	z (longitudinal)
β-coupling	1.3	2.0
laser incidence	grazing or normal	grazing or normal



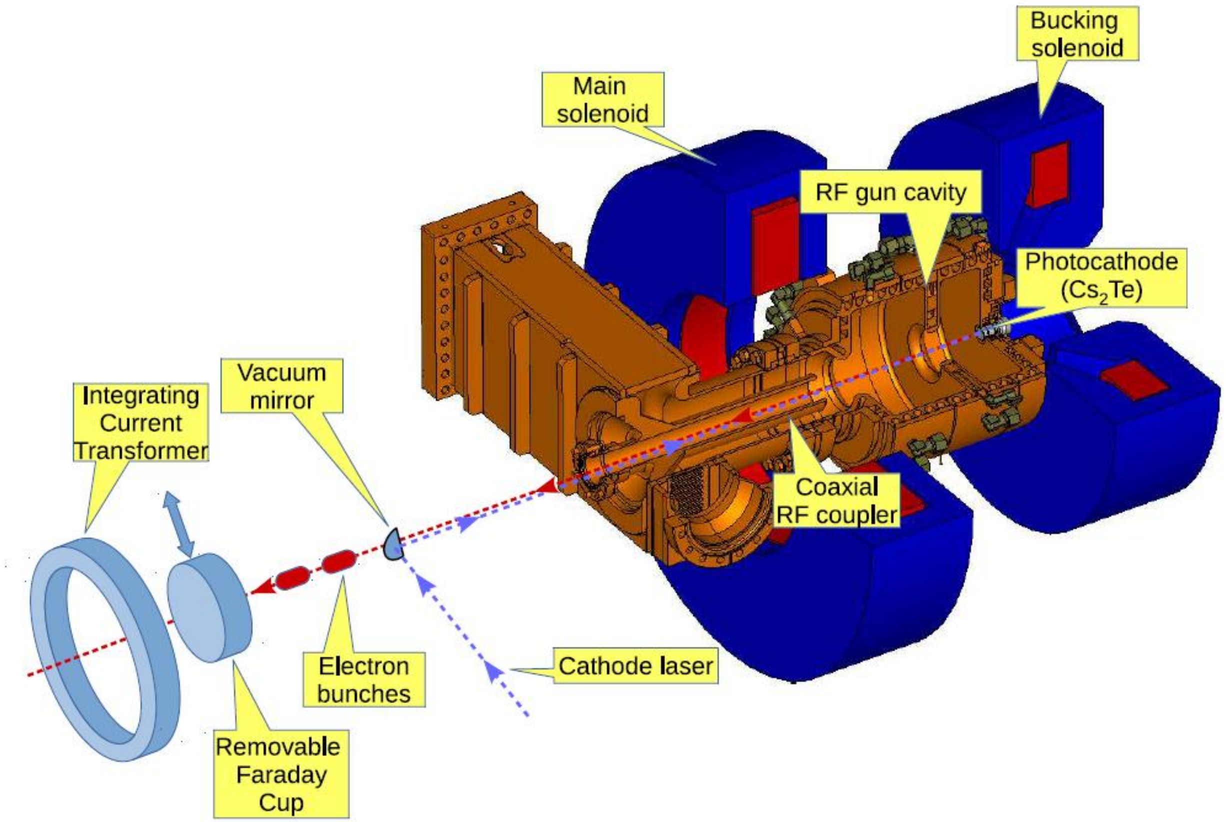






C.Limborg et al.,"RF Design of the LCLS Gun", SLAC-TN-10-094, 2005

The PITZ Gun

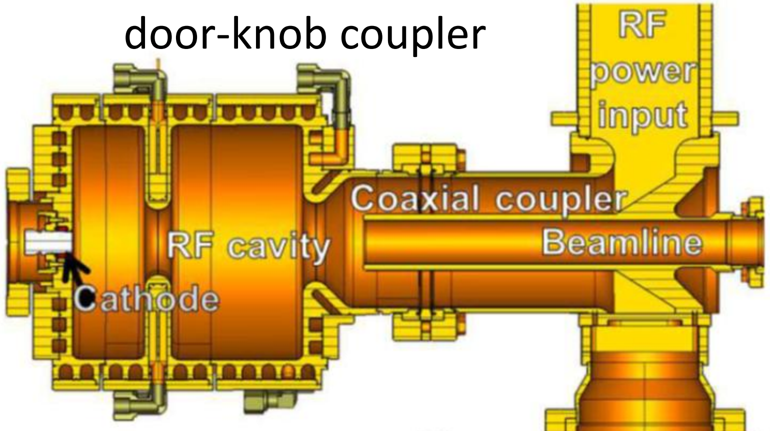


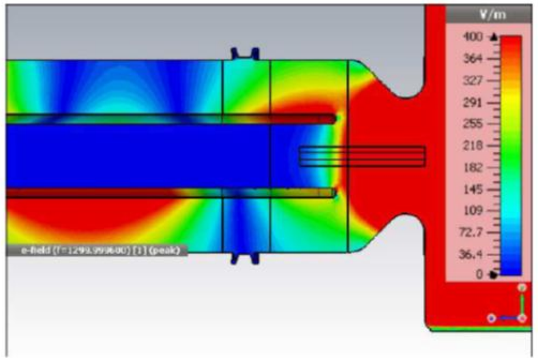
- operating frequency @ 1300 MHz
- Cs_2Te cathode delivers 0.001 – 4 nC bunch charge
- Beam mean energy 6.5 MeV
- Number of electron pulses in bunch train < 800
- Macropulse repetition rate 10 Hz
- Bunch rep.-rate 1kHz
- Average beam current 32 μA max.
- Optimized emittance < 0.9 μm

Igor Isaev, “Stability and Performance Studies of the PITZ Photoelectron Gun”, University of Hamburg dissertation (2017)

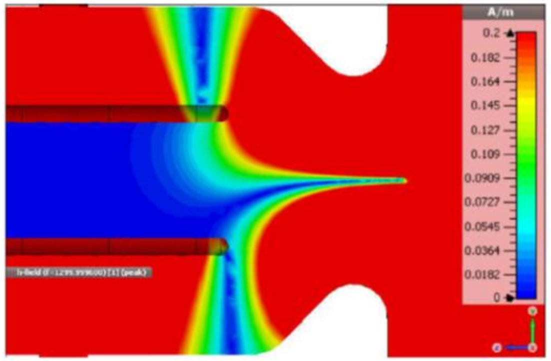
The PITZ Gun

door-knob coupler



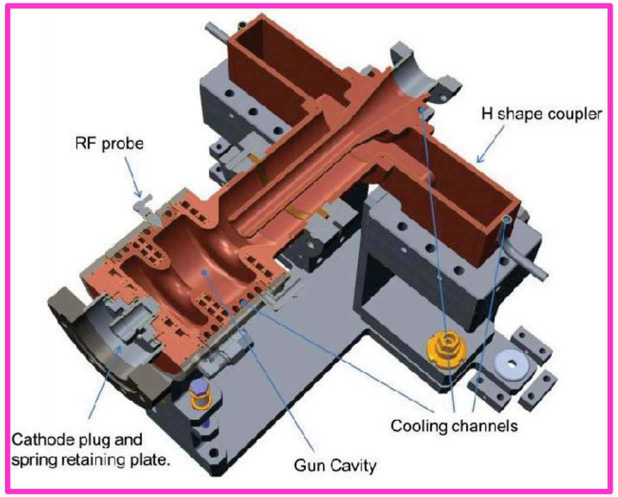


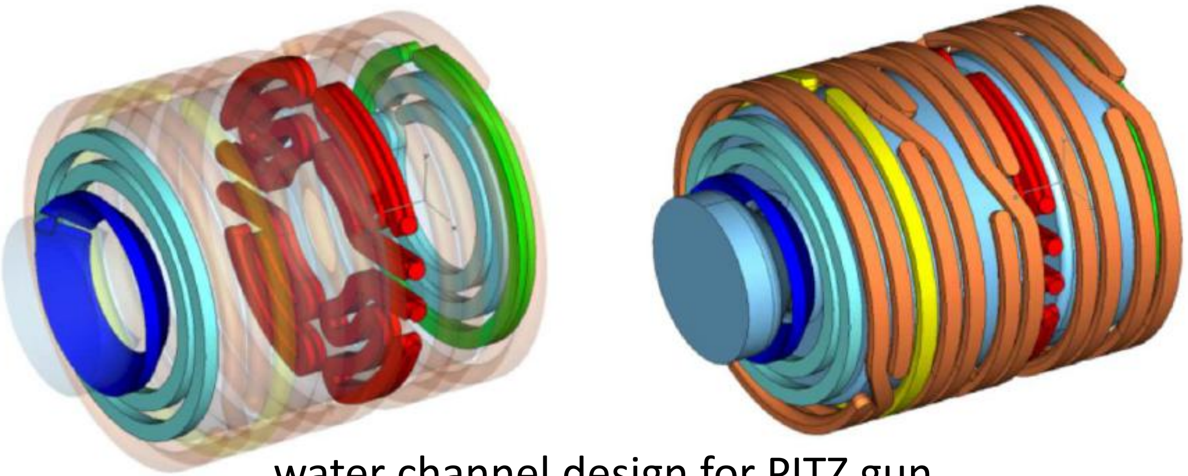
(a) E RF field distribution



(b) H RF field distribution

CLARA S-band photocathode rf gun





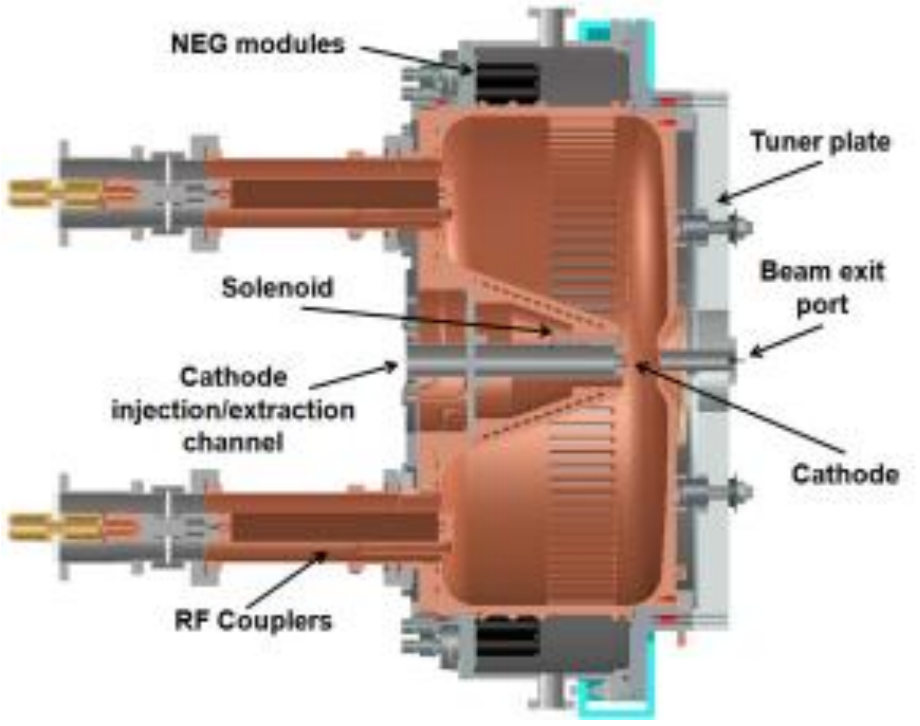
water channel design for PITZ gun

Igor Isaev, “Stability and Performance Studies of the PITZ Photoelectron Gun”, University of Hamburg dissertation (2017)

LBNL CW Photocathode RF Gun

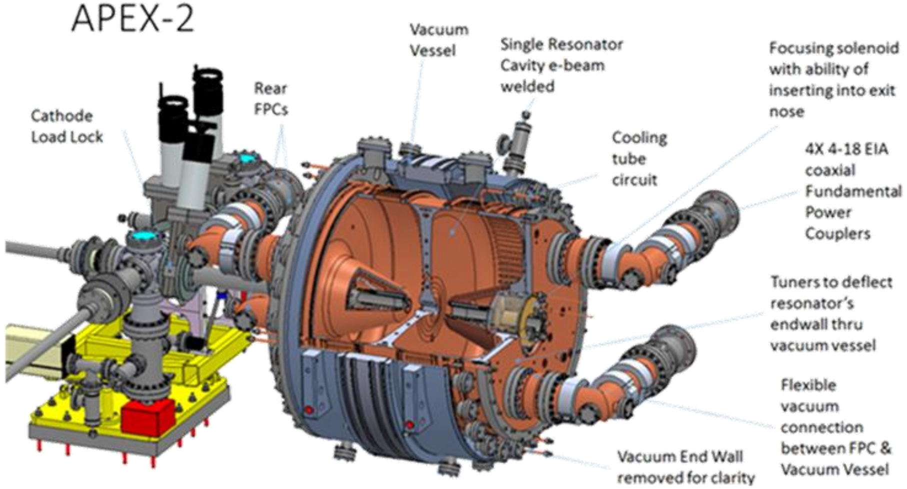
- At the VHF frequency, the cavity structure is large enough to withstand the heat load at a level that conventional cooling techniques can be used to run in CW mode.
- The long wavelength allows for large apertures and thus for high vacuum conductivity.

Total length [m]	0.35
Cavity internal diameter [m]	0.694
Accelerating gap [mm]	40
Frequency [MHz]	187
Q_0 (ideal copper)	30877
Gap voltage [MV]	0.75
Electric field at the cathode [MV/m]	19.5
Peak surface electric field [MV/m]	24.1
Stored energy [J]	2.3
Shunt impedance [MΩ]	6.5
RF power for 0.75 MV at Q_0 [kW]	87.5
Peak wall power density at 0.75 MV [W/cm^2]	25.0



186 MHz LBNL CW photo-cathode rf gun

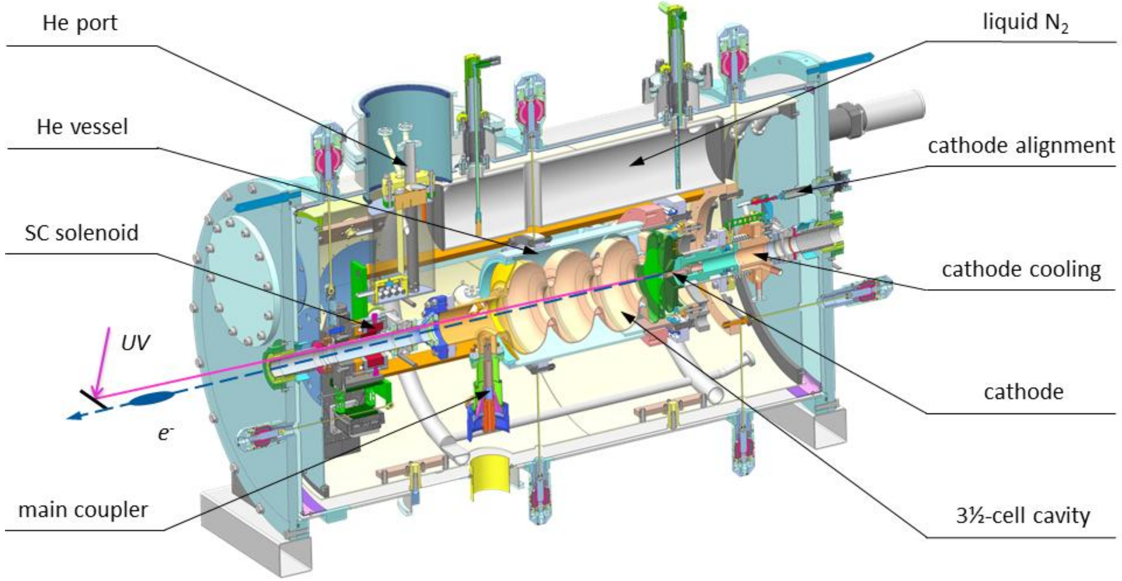
APEX-2

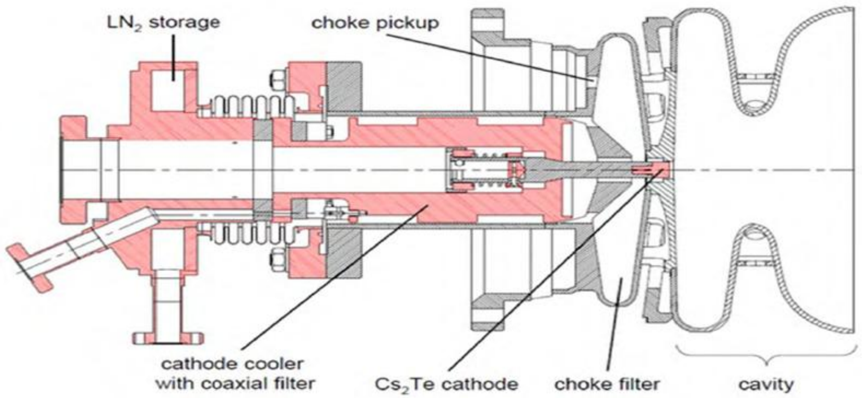


2-cell cavity operating at 162.5 MHz

F. Sannibale et al., STATUS OF THE LBNL NORMAL-CONDUCTING CW VHF ELECTRON PHOTO-GUN, WEBP36, Proceedings of FEL2021

ELBE 1.3 GHz, 3-1/2-cell SRF Gun





Parameter	SRF Gun II	SRF Gun III
Gradient	8 MV/m	12 MV/m
Peak field on axis	20.5 MV/m	30.7 MV/m
Kinetic energy	4 MeV	6 MeV
Bunch charge	300 pC	500 pC
Beam current	30 μA	50 μA,[1)]500 μA[2)]
Pulse rep. rate	0.1-0.5 MHz,[1)] 13MHz[2)]	0.025-1 MHz,[1)] 13 MHz[2)]
Photocathode	Mg, Cs_2Te	Mg, Cs_2Te
Quantum efficiency	0.2-0.3%,[1)] >1 %[2)]	0.2%,[1)] >1%[2)]
Dark current	35 nA	<50 nA

[1)] Mg cathode, [2)] Cs2Te cathode

J. Teichert et al., “DESIGN UPGRADES OF THE NEXT SUPERCONDUCTING RF GUN FOR ELBE”,MOP100,SRF 2019.

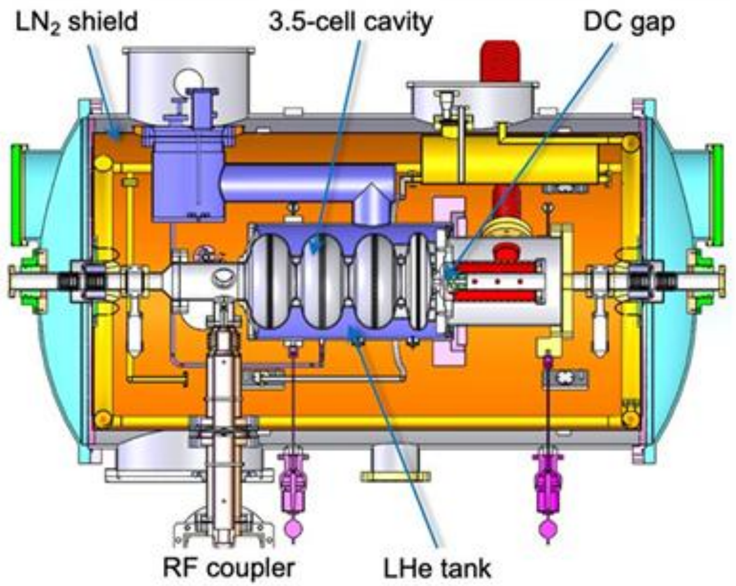
The Peking University Hybrid Gun

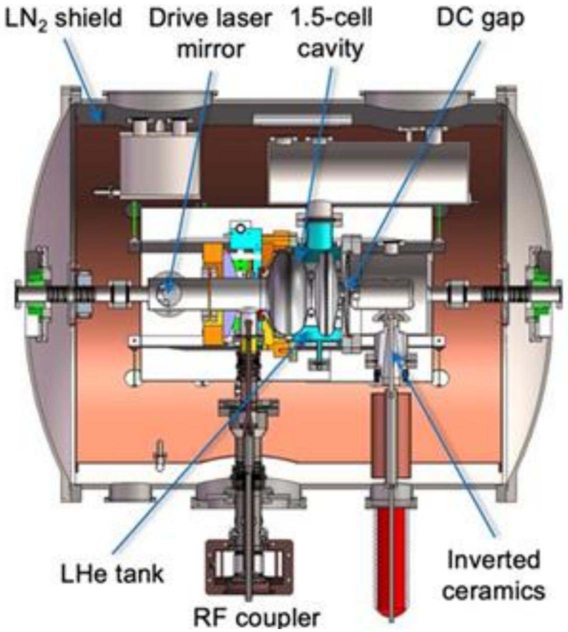
1st-generation DC-SRF gun,DC-SRF-I (2007~2016)

- Stable operation achieved (2014)
- MHz-rate super-radiant THz radiation
- MHz-rate UED (3 MeV)
- Transported to Shanghai for beam test of SHINE cryomodule (2021~2023)

2nd-generation DC-SRF gun,DC-SRF-II (2017~)

- with widely tunable bunch rate (1 Hz ~ 81.25 MHz), bunch charge (10s fC ~ 500 pC), and current (nA ~ mA)



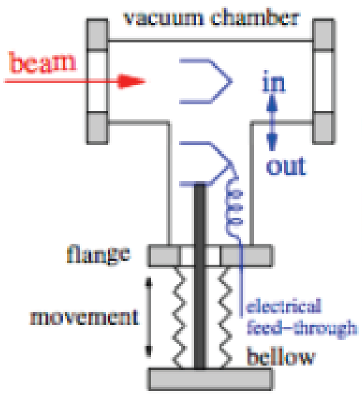


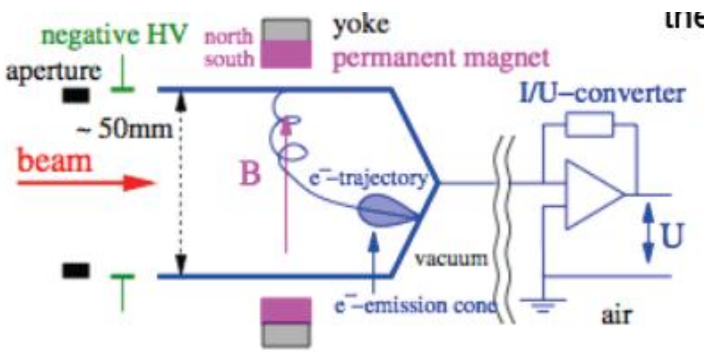
	DC-SRF-I	DC-SRF-II
DC voltage	90 kV (45-50 kV in operation)	100 kV
Photocathode surface field	5 MV/m @ 90 kV	6 MV/m @ 100 kV
Peak field on DC electrode surfaces	13 MV/m @ 90 kV	10 MV/m @ 100 kV
SRF cavity and gradient (E_{acc})	3.5-cell, 7-9 MV/m	1.5-cell, 13~14 MV/m (**$E_{z,max}$: 20~22 MV/m**)
Photocathode	Cs_2Te	K_2CsSb
Drive laser	266 nm; w/o shaping, ~5 ps	515 nm; transversely truncated Gaussian (1σ); longitudinally flattop (20~30 ps)

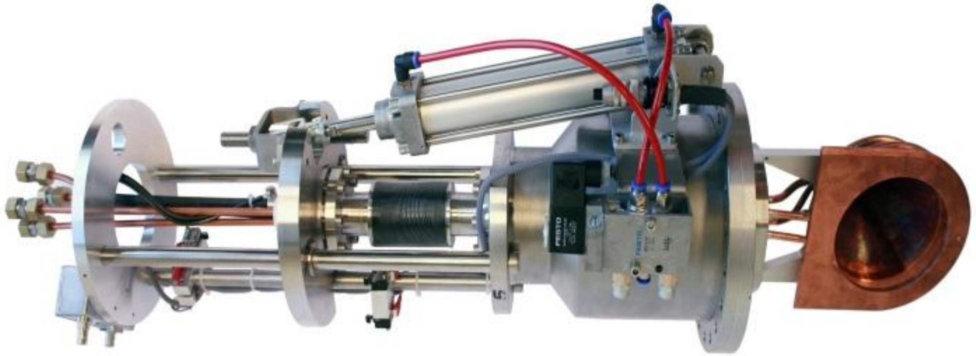
Bunch Charge Measurement

Intercepting diagnostic: ***the Faraday cup***

- The FC is a beam stopper that can be inserted when needed in the beamline.
- An isolated metal cup stops the beam. The electron current is *directly* read by a readout electronics connected to the cup.
- Secondary electron production can add systematic errors to the measurements. When electrons hit the cup surface low energy SE can be created. If they exit from the cup they lower the readout (less charge in the cup) .
- To avoid this:
- longer FC
- HV (~100V) at the exit pushing back the SE.
- Solenoid field to create spirals and have the SE hit the wall



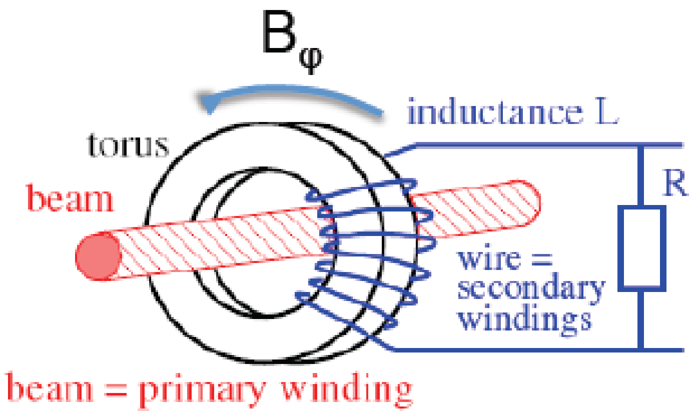


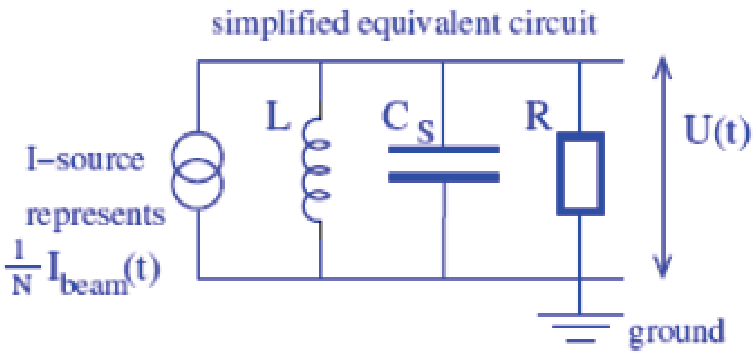


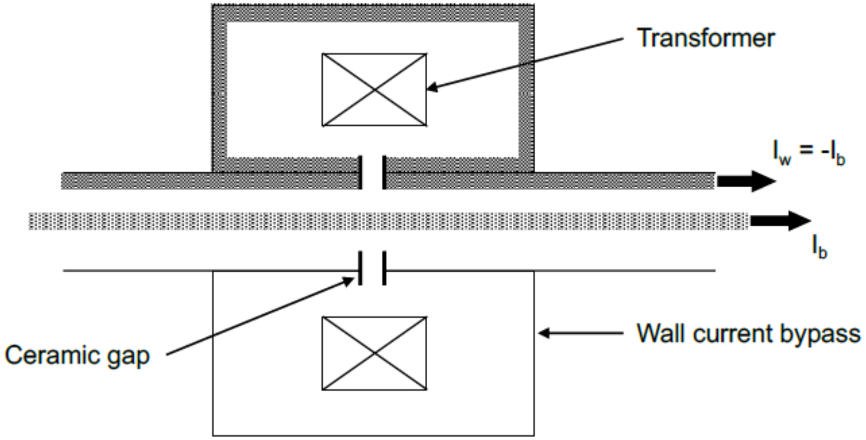
Bunch Charge Measurement

Non-Intercepting diagnostic: the **beam current trnaformer**

- Beam used as primary winding of a transformer:

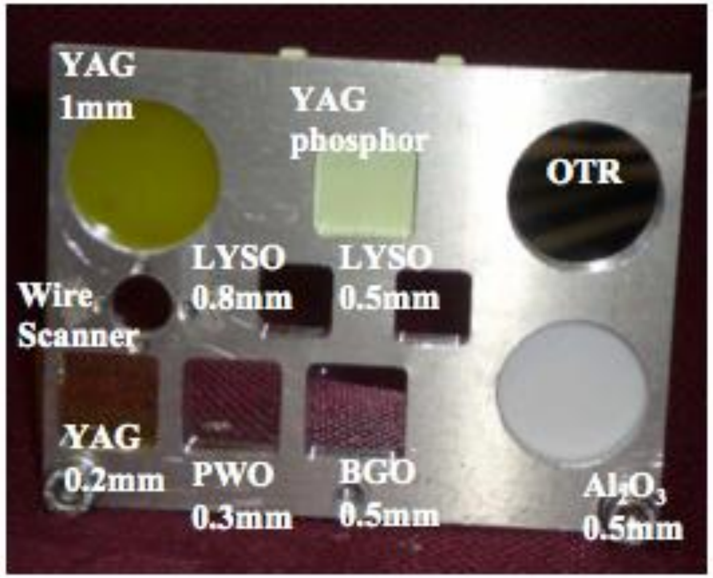






Beam Profile Measurement

- Destructive Measurement
- Measure current density as function of transverse coordinates
- Must verify screen and detector not saturated
- Common Screen Materials
  - Phosphor
  - YAG
  - OTR
  - Wire scaner



Screen	Resolution	Dynamic Range	Time Response
Phosphor	≈ 50 μm	small	ms
YAG	≈ 20 μm	medium	< ms
OTR	≈ 10 μm	large	fs
Wire	≈ 10 μm	large	ns

國家同步輻射研究中心
National Synchrotron Radiation Research Center

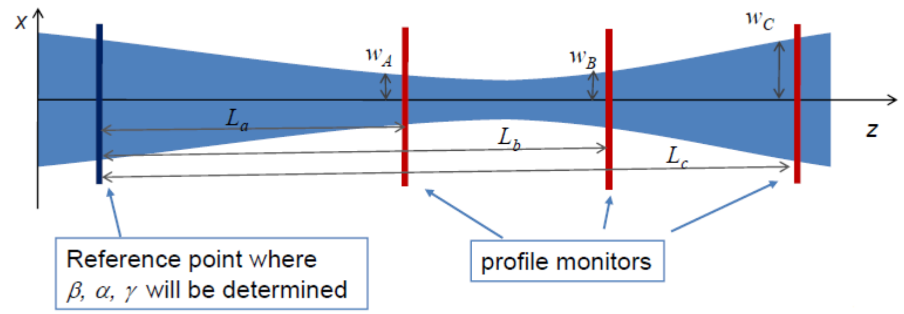
Emittance Measurement

- Quadruple scan for high energy beam when linear beam optics is valid, i.e. when space charge forces are small and energy spread is not too large

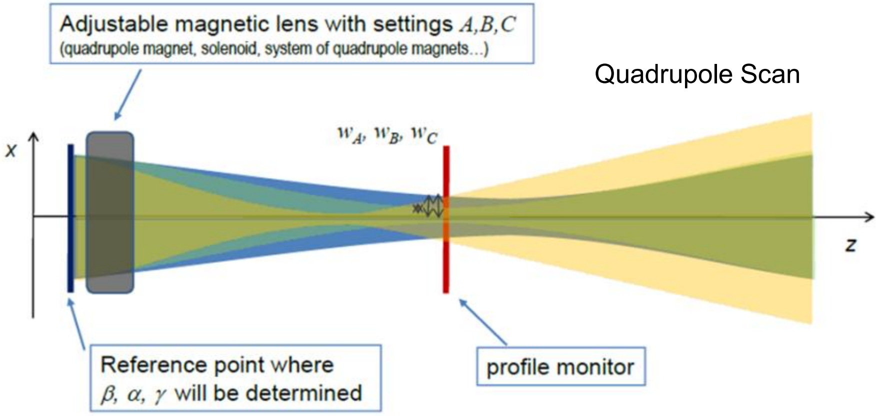
- Slit method for low energy beam when space charge forces are small, and beam can be stopped by the slit mask

	High Energy	High Space Charge Force	Large Energy Spread
3 Screen	+	-	+
Quadruple Scan	+	-	-
Slit	-	+	+

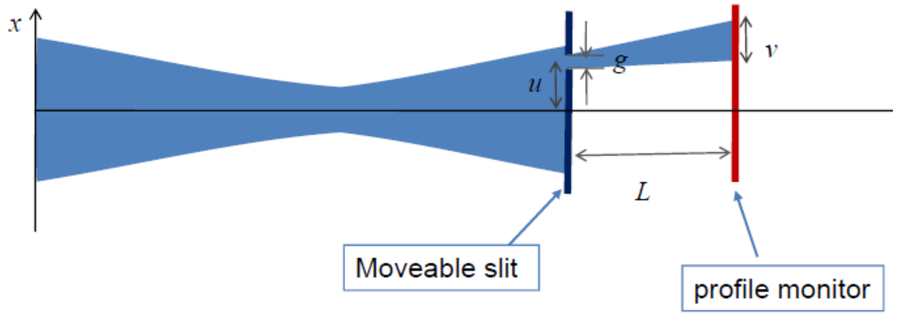
3-screen



Quadrupole Scan

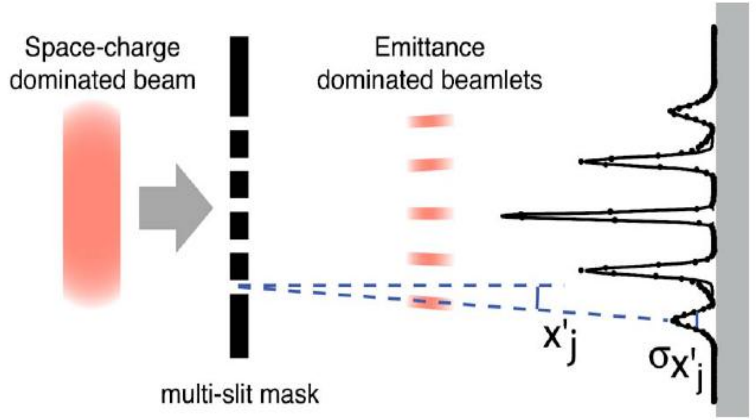


Slit Method



Emittance Measurement : Multi-slit or Pepper Pot

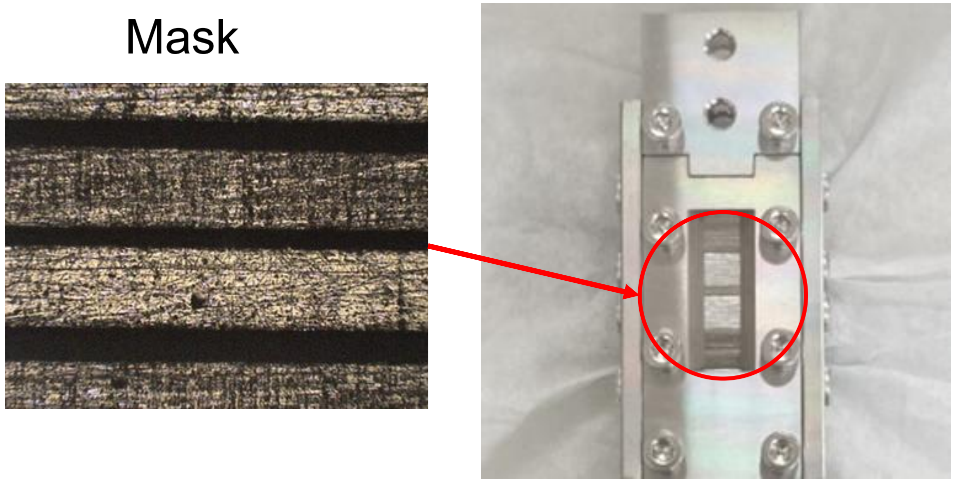
- To measure emittance requires emittance dominated beam
- Space charge dominated beam must be converted to emittance dominated
- N measurements made simultaneously
- Measure angle and spread downstream of slit on a screen as a function of slit position

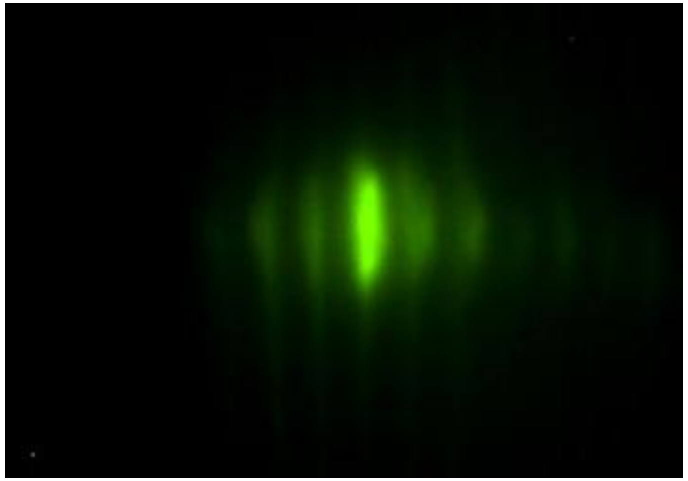


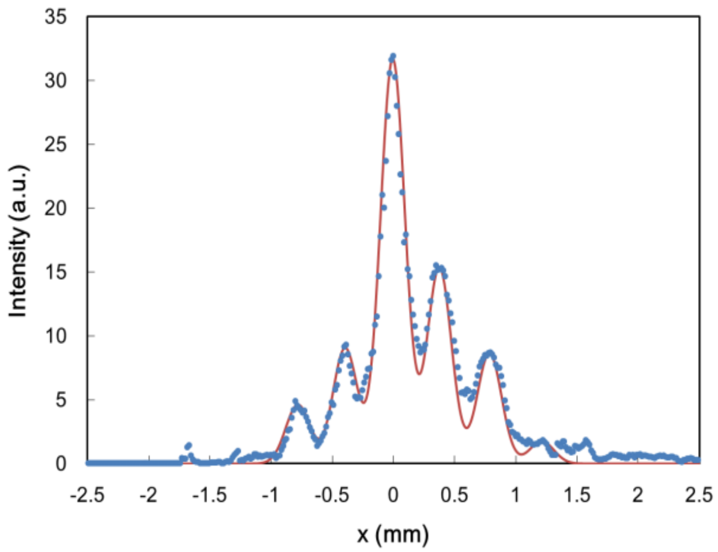
$$\epsilon_x{}^2 = <x^2><x'^2> - <xx'>^2$$

$$\approx \frac{1}{N^2}\left\{\left[\sum_{j=1}^{p} n_j(x_{sj}-\bar{x})^2\right]\left[\sum_{j=1}^{p}\left[n_j\sigma_{x_j'}{}^2 + n_j(\bar{x}_j'-\bar{x})^2\right]\right] - \left[\sum_{j=1}^{p} n_j x_{sj}\bar{x}_j' - N\bar{x}\bar{x}'\right]^2\right\}$$

Mask

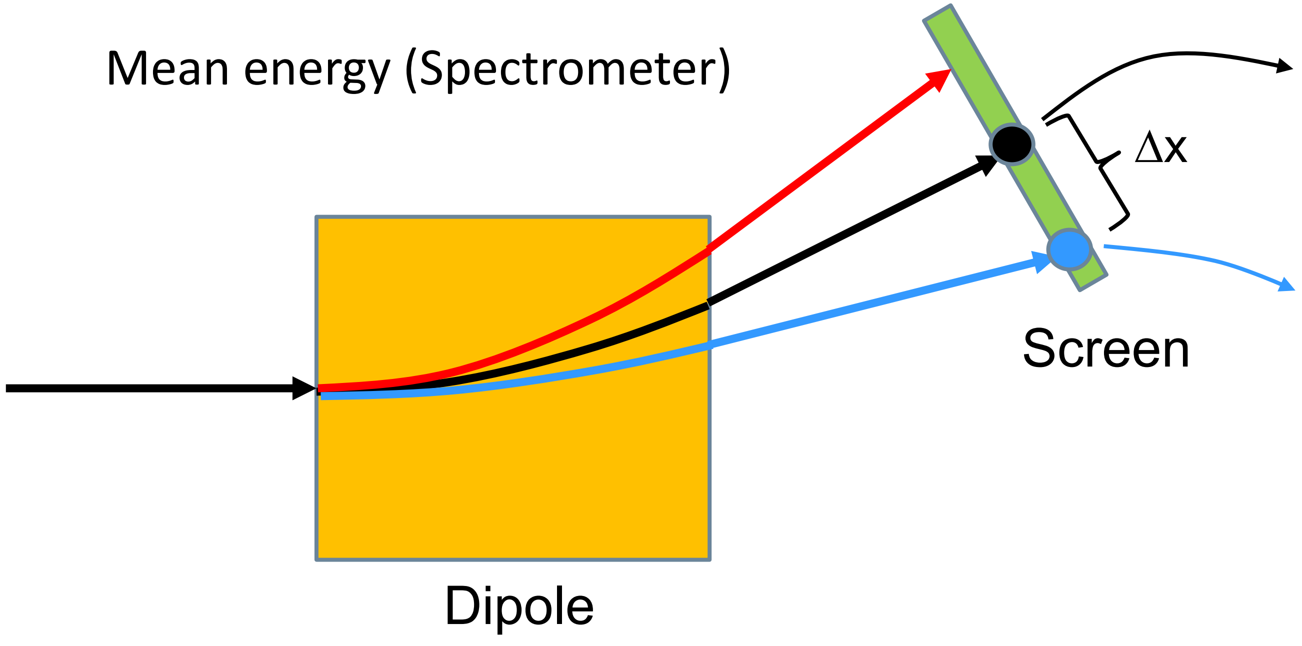






Energy Measurement

Mean energy (Spectrometer)



"on-energy" particle centers the screen

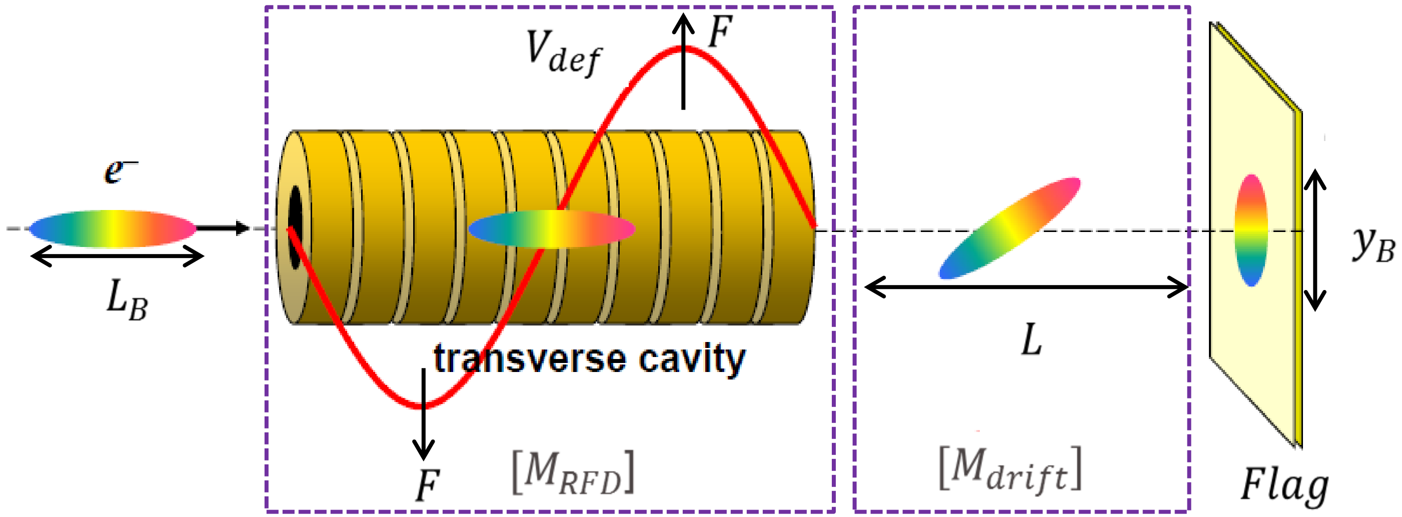
$$\langle p_z \rangle \left[\frac{GeV}{c}\right] = 0.3 B_{y0}[T] R[m]$$

"off-energy" particle centers the screen

$$p_z = \langle p_z \rangle \left(1 + \frac{\Delta x}{\eta_x}\right)$$

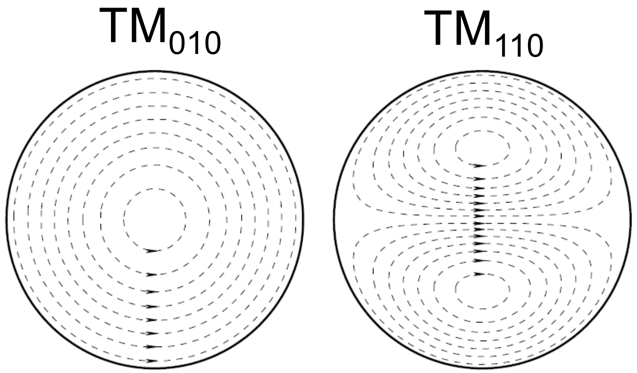
1. geometry of the ref. trajectory (q, R) is fixed by the mechanical assembly,
2. B_y is chosen to center the beam onto the detector (screen or BPM),
3. calculate $\langle p_z \rangle$.

RF Deflector

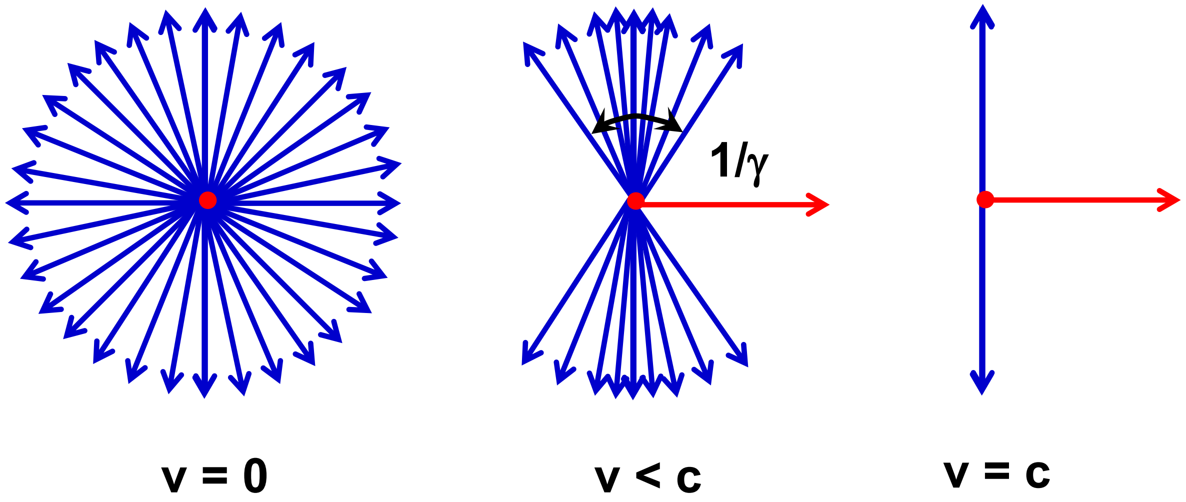


- Measure bunch length
- Slice Emittance or Energy Spread
- Single Shot Longitudinal Phase Space
- Resolution limited by beam size
- RFD + Dipole
  - Bunch length
  - Energy distribution
  - Longitudinal phase space
- RFD + Quadrupole
  - Slice emittance
  - Transverse phase space

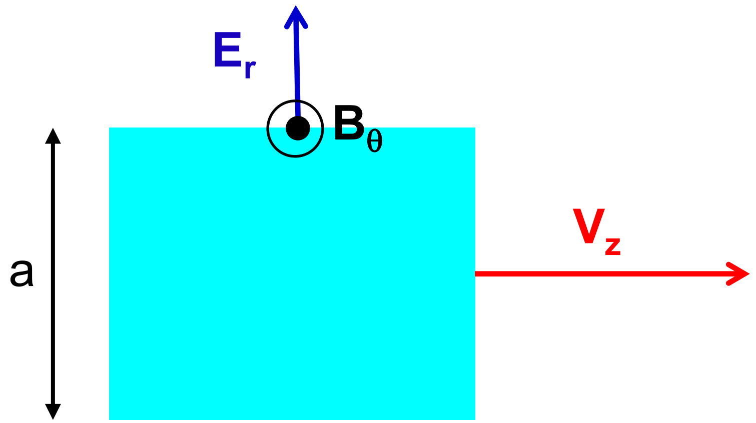
Use TM 110 like mode to deflected the electron beams



Transverse Space Charge Force



electric fields of a uniformly moving charged particle



cylindrical electron bunch

Consider a cylindrical electron bunch with current I, uniform charge and current density ρ and J:

$$\rho = \frac{I}{\pi a^2 v_z} \qquad J = \frac{Ir}{\pi a^2}$$

Transverse space charge fields for *r < a:*

$$E_r = \frac{\rho r}{2\varepsilon_0} \qquad B_\theta = \frac{\mu_0 J r}{2} = \frac{v_z}{c^2} E_r$$

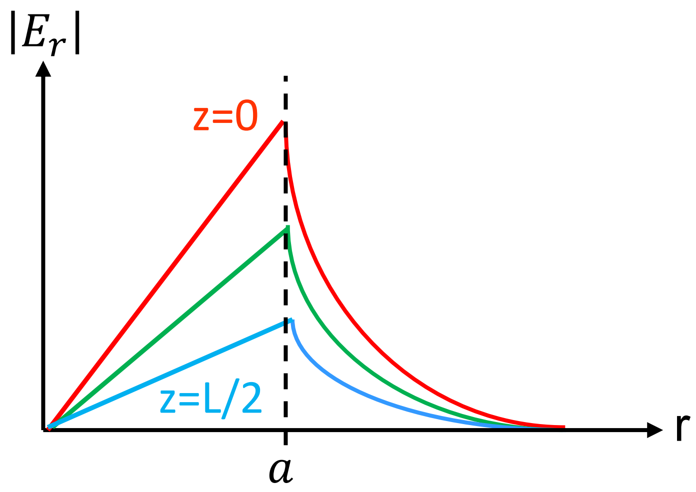
Lorentz force:

$$F_r = e(E_r - v_z B_\theta) = eE_r(1-\beta^2)$$

$$F_r = \frac{eE_r}{\gamma^2} \qquad \text{v} \rightarrow \text{c}, F_r \rightarrow 0$$

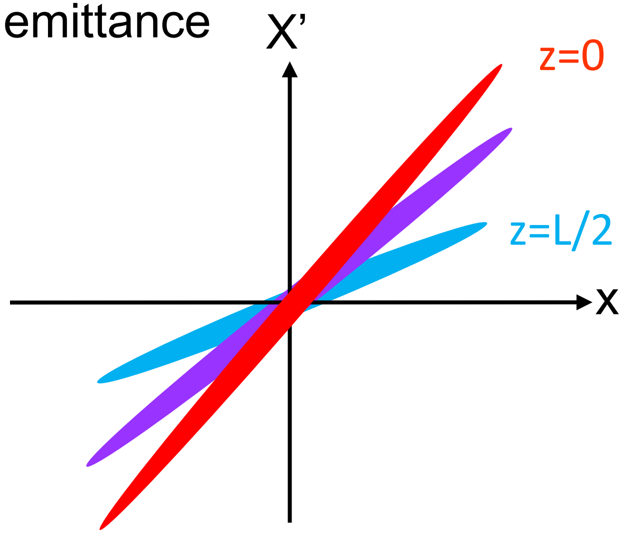
Space Charge Force

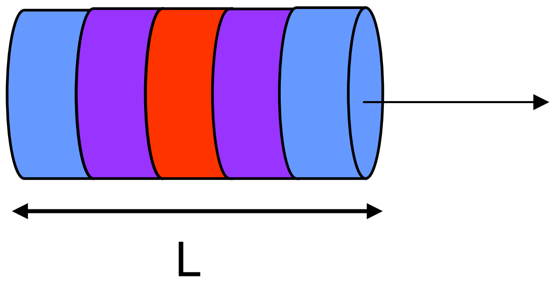
a bunch of relativistic electrons can be viewed as a collection of independent slices

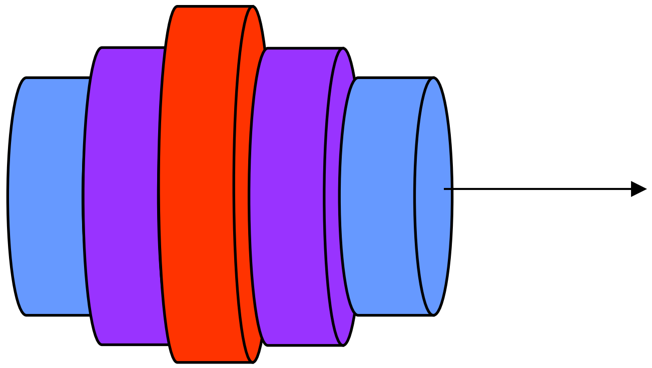


Transverse space charge force is highest at z=0

Projected emittance

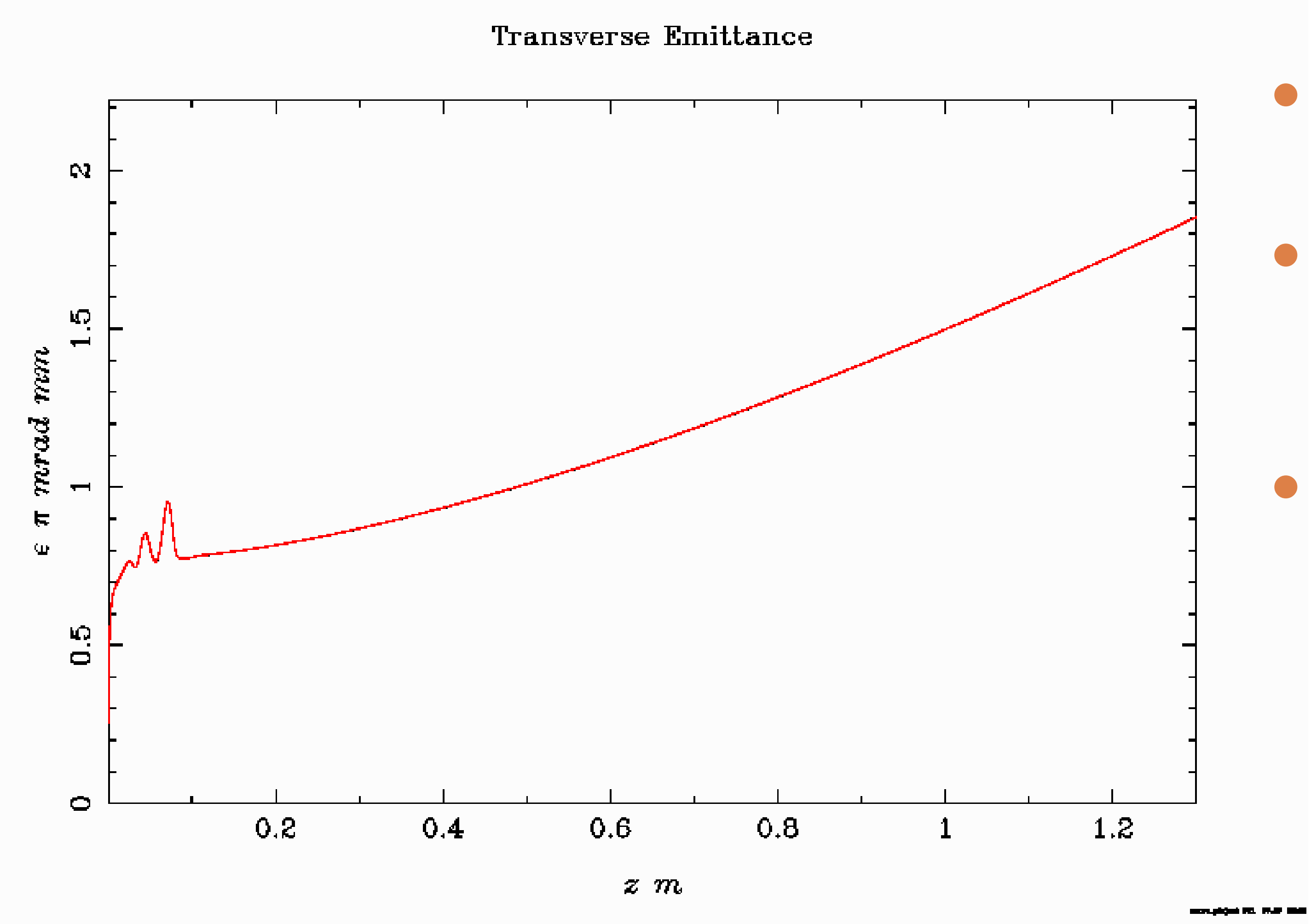






Different slices expand radially at different rate

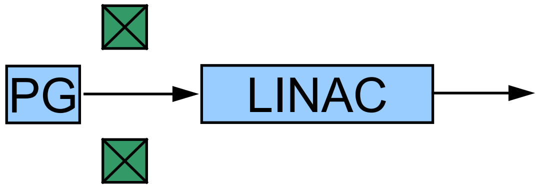
Emittance Reduction Techniques

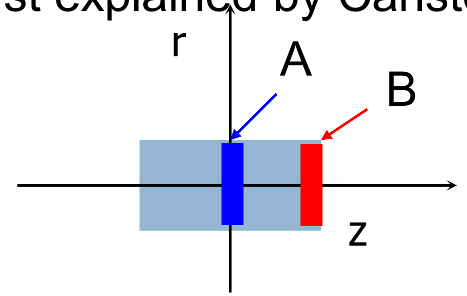


- Emittance grows continuously after leaving the gun cavity.
- Control of emittance is essential in high brightness electron beam design
- Reduction techniques of space charge:
  - emittance compensation solenoid
  - Shaping of electron distribution with laser

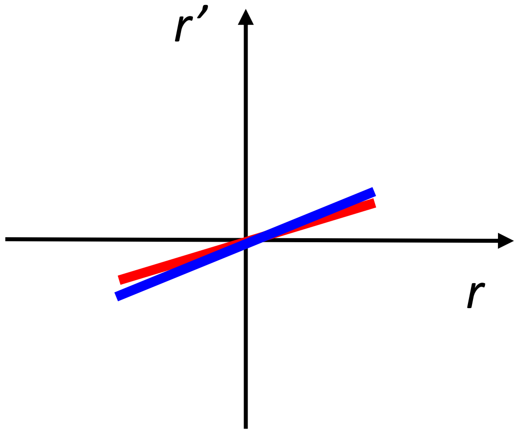
Emittance Compensation

Emittance compensation with a solenoid was first explained by Carlsten (1989)

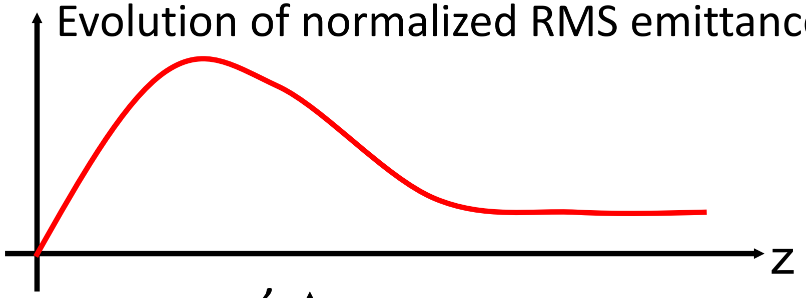


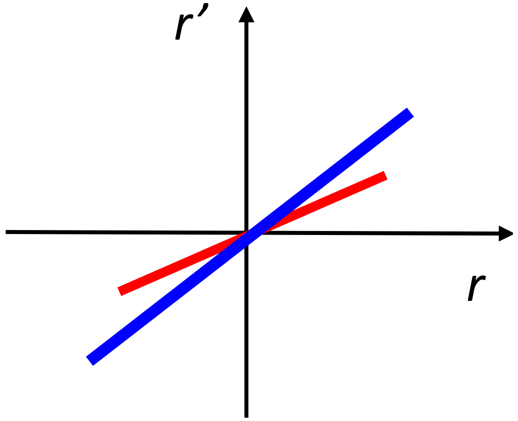


an electron bunch from the photo-cathode rf gun, particles near A experience different space charge force from particles near B

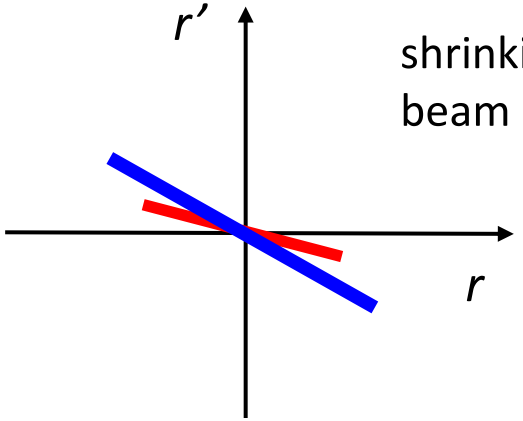


beam at gun exit



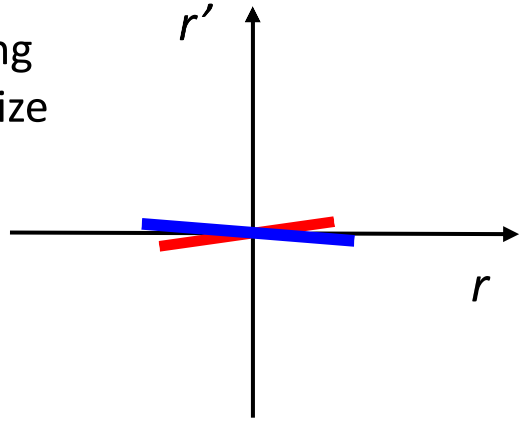


after a drift section

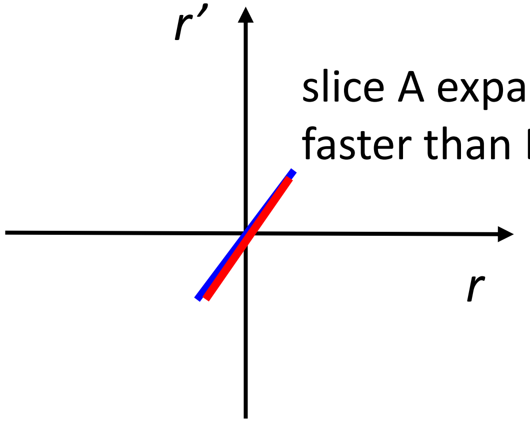


shrinking beam size

after focusing solenoid



close to focal point of slice A



slice A expands faster than B

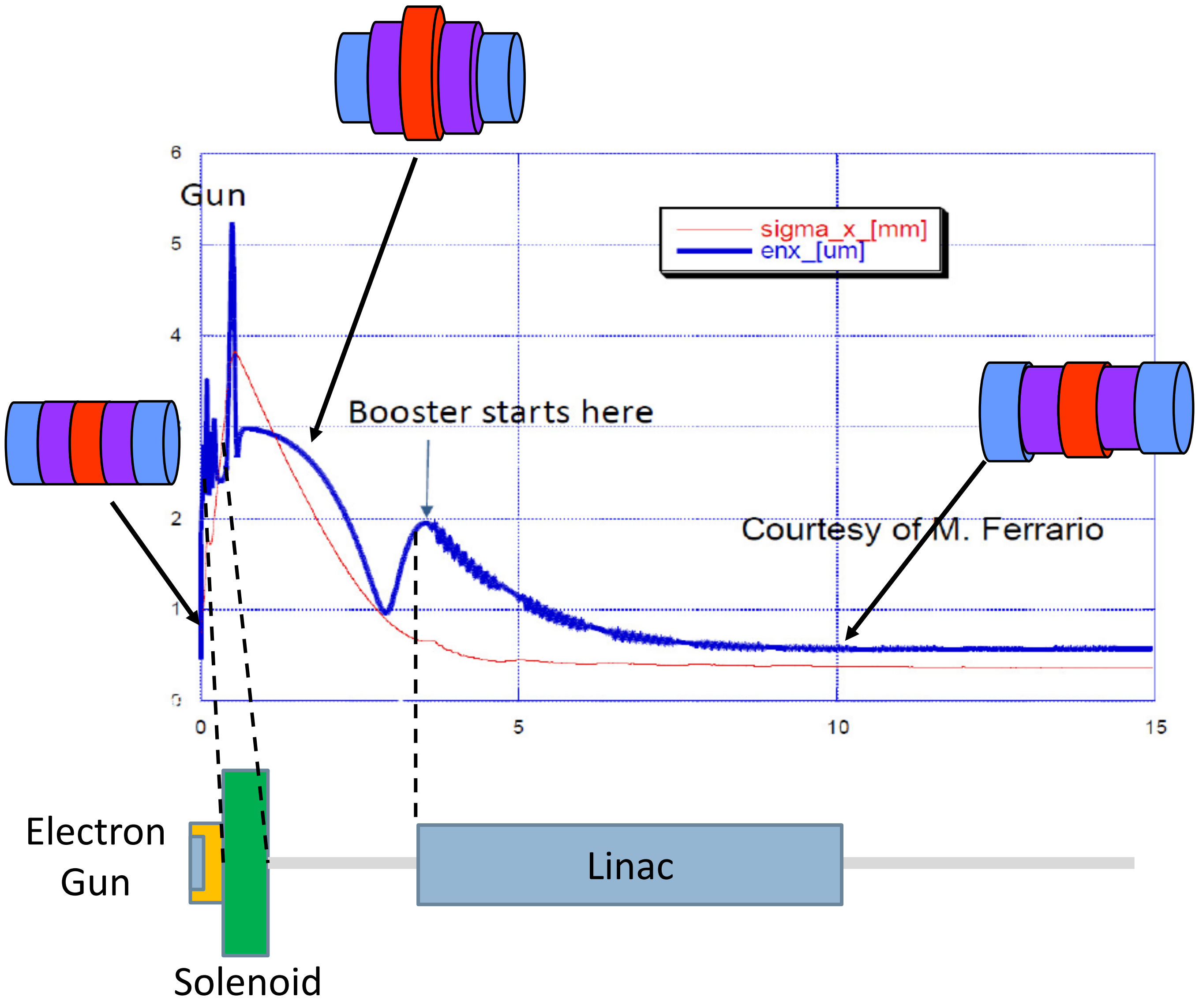
after focal point of slice A

Focusing realign slice emittance reducing projective emittance

Matching to Linac

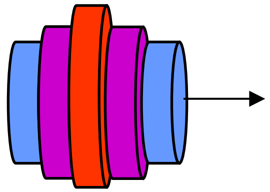
- To keep the low emittance obtained, the smallest emittance can be freeze by acceleration.
- An optimum injection condition, the invariant envelope matching condition into the Linac.
- The beam waist is located at the entrance to the high-energy linac which rapidly accelerates the beam to relativistic energy from the space charge dominated to emittance dominated regimes. Acceleration in the booster linac reduce the emittance growth at higher energy.

$$\sigma_{in} = \frac{2}{\gamma'}\sqrt{\frac{I_p}{2I_0\gamma}} \qquad \sigma' = 0 \qquad \gamma' = \frac{2}{\sigma}\sqrt{\frac{I_p}{2I_0\gamma}}$$



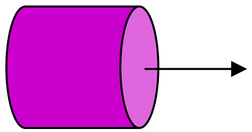
M. Ferrario, et al., "HOMDYN study for the LCLS RF photoinjector" (2000)

Emittance Control by Laser Pulse Shaping

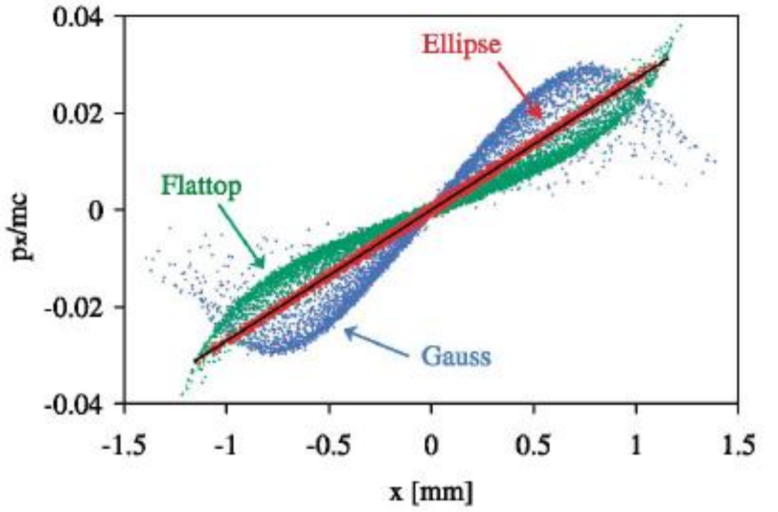


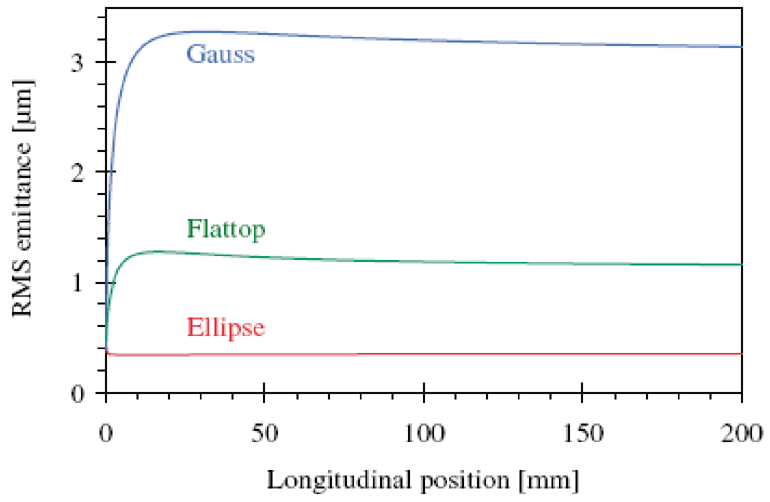
Different slices in a non-uniform bunch (e.g. Gaussian) experience different space charge force, emittance compensation by solenoid will be difficult.

- Uniform transverse profile
- Flattop temporal profile



A uniform cylindrical electron beam can reduce emittance (an ellipsoid will be ideal)





(O.J. Luiten et al., PRL 094802, 2004)

Thanks for your attention!