The 12th OCPA Accelerator School
2025.07.28-2025.08.08, Thailand

Electron Gun (source)

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Outline

- Introduction
- Some topics in electron gun
- Typical guns for accelerator facilities

Acknowledgements

- Some materials for this lecture is literally taken from talks / reports / papers / notes from a large number of people
- Stimulating discussions with many colleagues and friends in the electron source / accelerator / ultrafast science communities over the past many years

- References:
  - An Engineering Guide to Photoinjectors
    - https://arxiv.org/abs/1403.7539
  - Several USPAS courses / lecture notes
    - http://uspas.fnal.gov/
  - Photocathode Physics for Photoinjectors Workshop series
    - Both in U.S. and Europe
  - Tons of journal and conference papers

半亩方塘一鉴开，
天光云影共徘徊。
问渠那得清如许？
为有源头活水来。

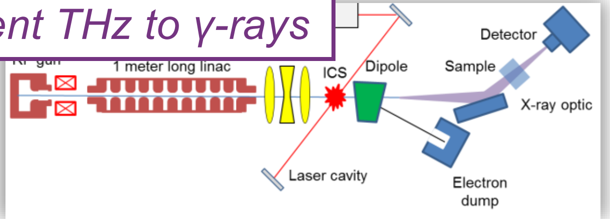
—— 朱熹《观书有感》

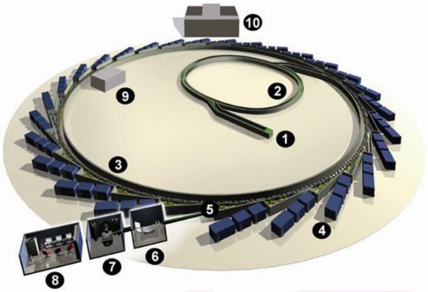
“源对装置的性能有决定性的影响”

E-beam-driven facilities and instruments

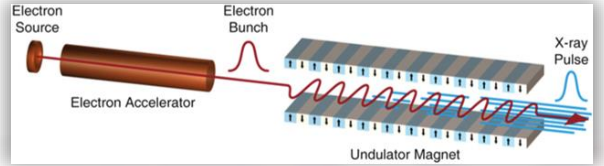
Photon sciences:
coherent THz to γ-rays

PRSTAB 17 (2014) 1

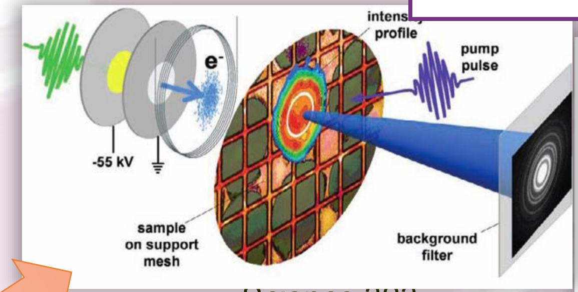




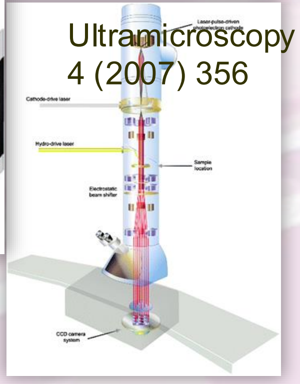
Rev. Mod. Phys. 88 (2015) 015006



Electron scattering:
Diffraction, imaging, EELS



Science 323, 1033 (2009)

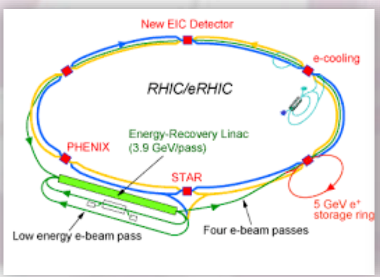


Ultramicroscopy 4 (2007) 356

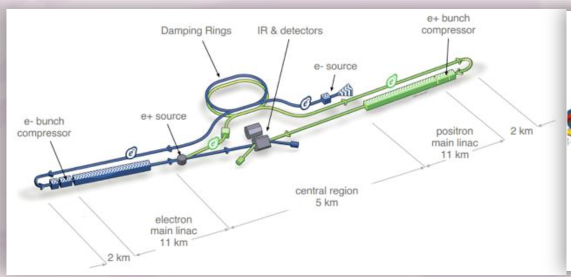
Electrons sources

Industrial applications:
Nondestructive testing, therapy, irradiation

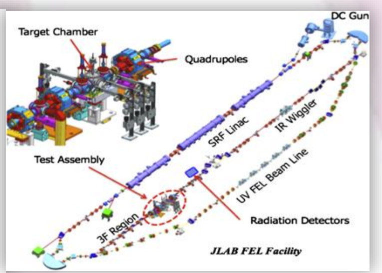
High energy physics:
Colliders, dark matter search



https://www.bnl.gov/rhic/news/081407/story1.asp

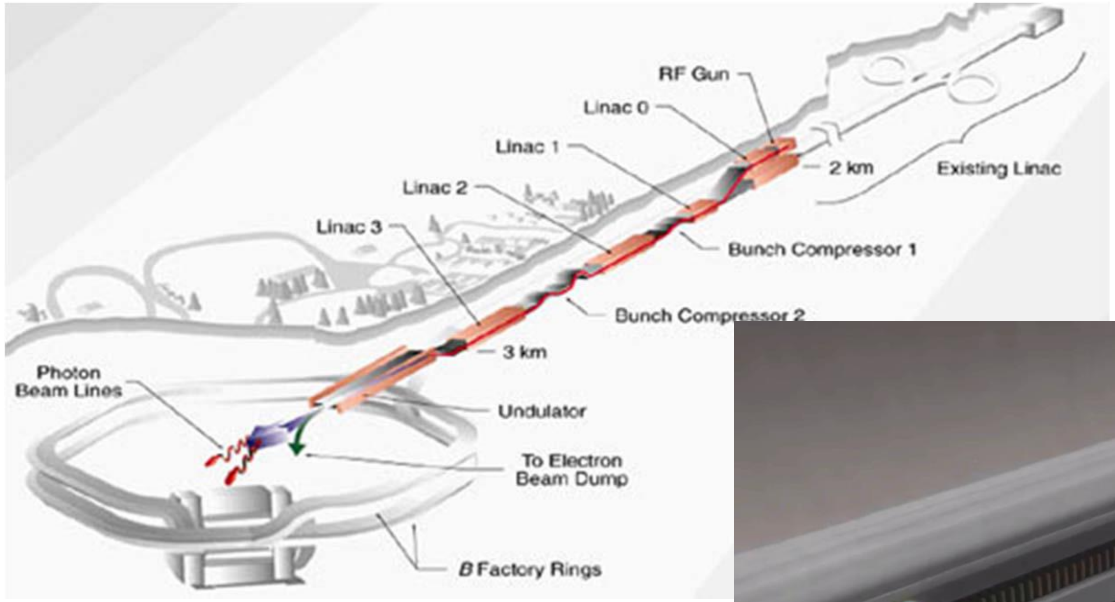


ILC CDR

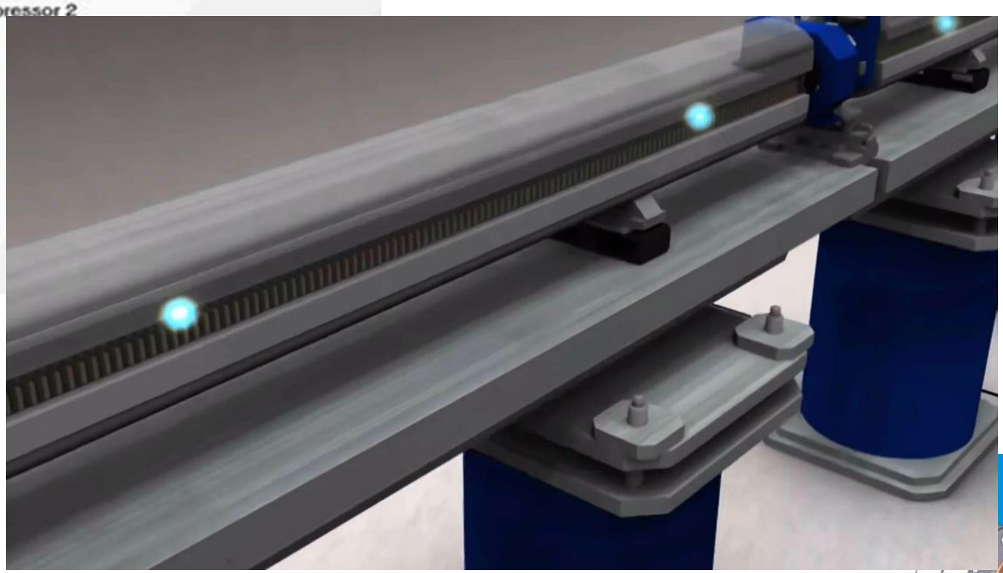


NIMA 729 (2013) 69

Short wavelength free-electron lasers



- Advanced electron sources is one of the enabling technologies for the XFEL
- Photoinjectors delivered the required high brightness beams



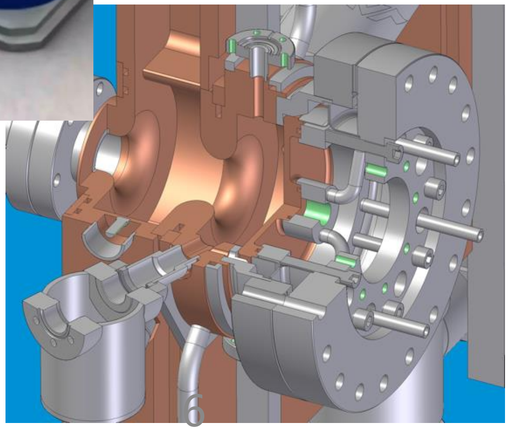
Demands:

– Ultralow normalized emittance

– High current (kAmp)

– Beam charge ranging from 10 pC - 1 nC

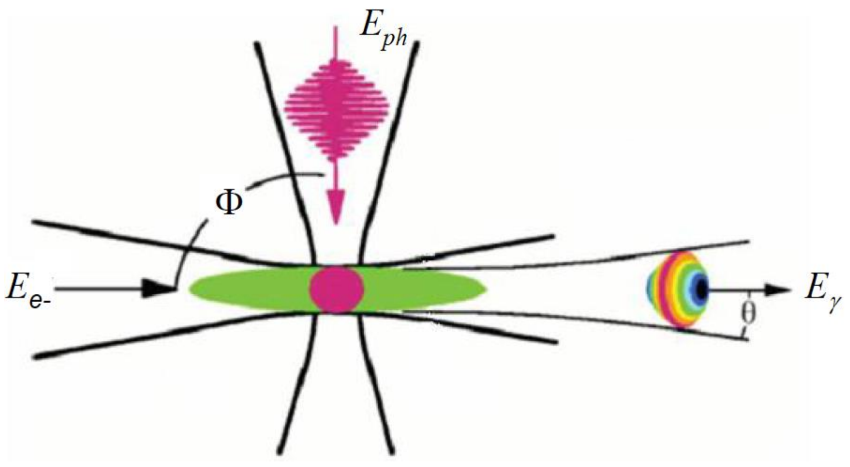
$$\rho = \left[\frac{1}{16} \frac{I_e}{I_A} \frac{K_0^2 [JJ]^2}{\gamma_0^3 \sigma_x^2 k_u^2} \right]^{1/3} \qquad \frac{\epsilon_n}{\gamma_0} \leqslant \frac{\lambda}{4\pi}$$



Photoinjectors deliver required e-beams for FEL

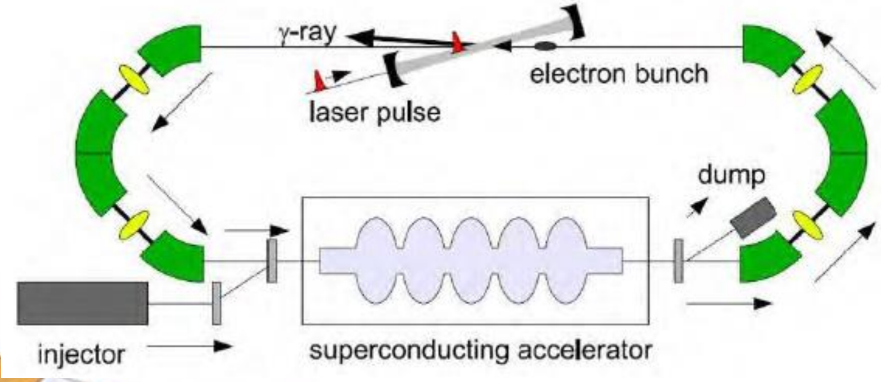
Cut-away view of the LCLS gun. Courtesy of E. Jongewaard

Inverse Compton scattering sources



R. Schoenlein et al., Science 274, 236 (1996)
Y. Du et al., RSI 84, 053301 (2013)

- Most promising approach for generating ultrafast gamma-ray pulses, for the emerging field of nuclear photonics
- Requires high intensity, small spot, low divergence, ultrashort, well synchronized electron and laser beams

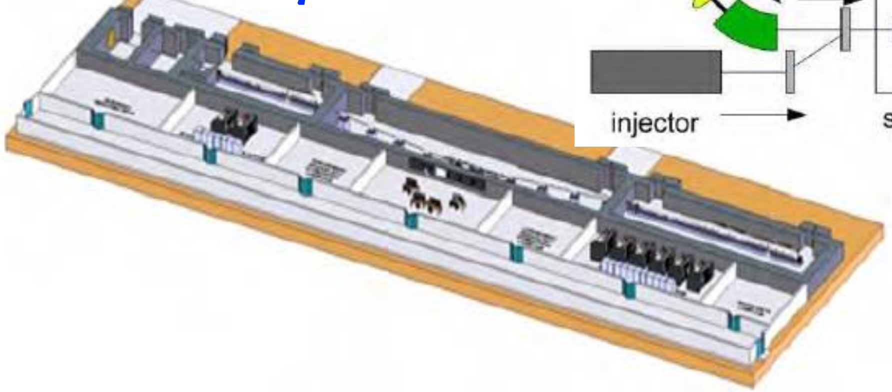


Demands:

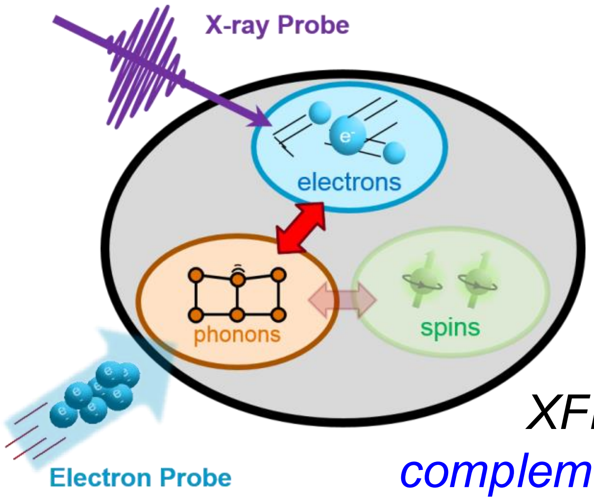
– Ultralow normalized emittance (~ 1 um)

– Beam charge from 100 pC - 1 nC

ELI-NP γ source



Visualizing the ‘ultrasmall’ and ‘ultrafast’



XFEL and UES are complementary tools towards a complete picture of dynamics

Demands:

– Ultralow normalized emittance (nm rad)

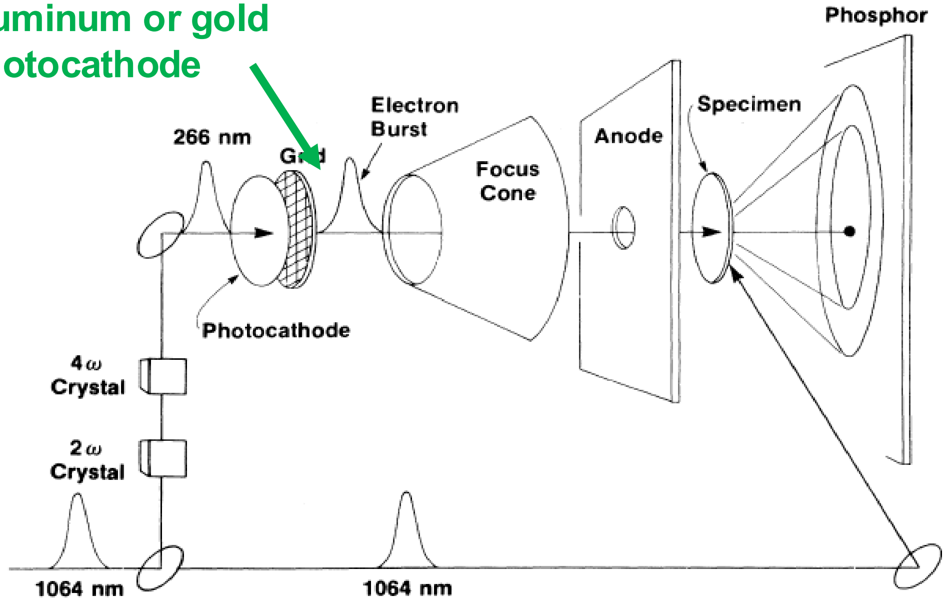
– Ultrashort bunch length,~10’s fs

– well synchronized to laser with in 10-100fs

– Beam charge from fC - pC

G. Mourou and S. Williamson, APL 41, 44 (1982)

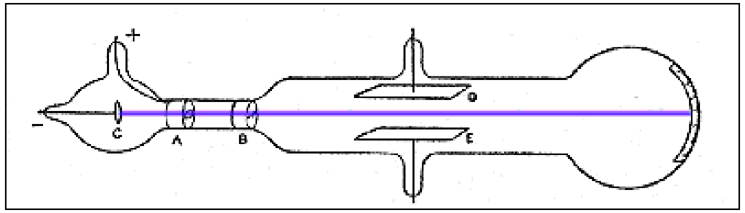
S. Williamson, G. Mourou and J. C. M. Li, PRL 52, 2364 (1984)



Science outcome:

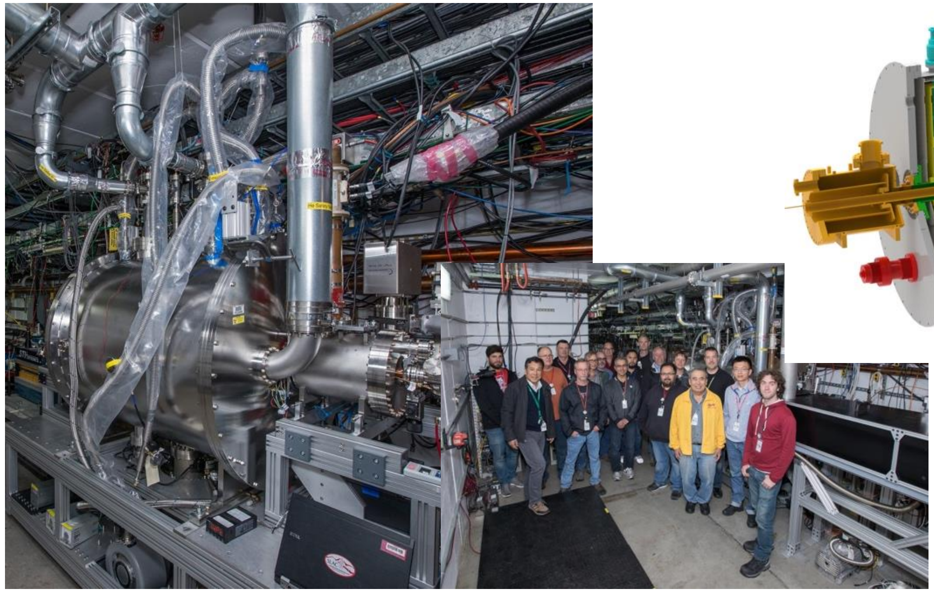
See e.g. M. Chergui and A. H. Zewail, *ChemPhysChem* **10**, 28 (2009); R. J D. Miller, *Science.* **343**, 1108 (2014) and etc.

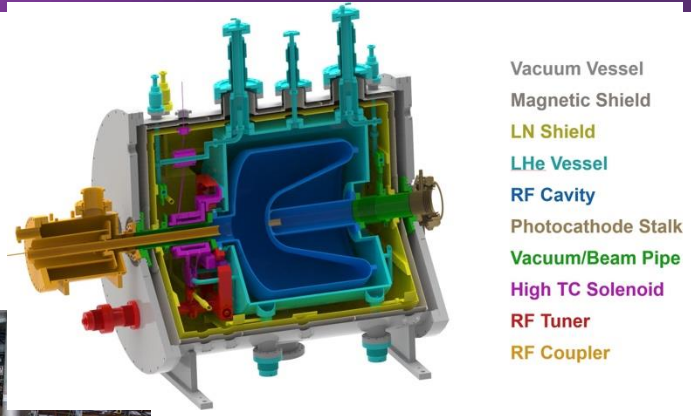
100+ years development of electron sources



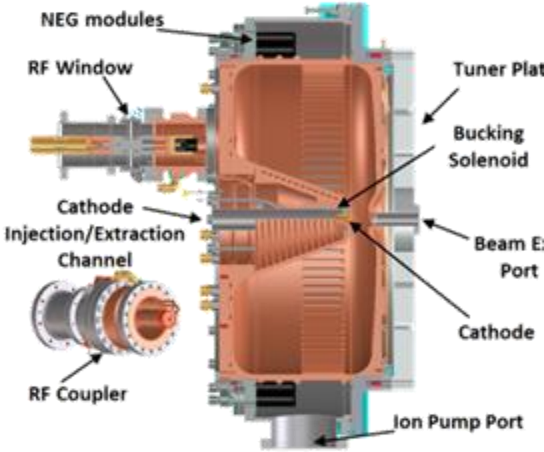
Crookes–Hittorf tube

J. J. Thomson, discovered electron using a cathode ray tube (1897)



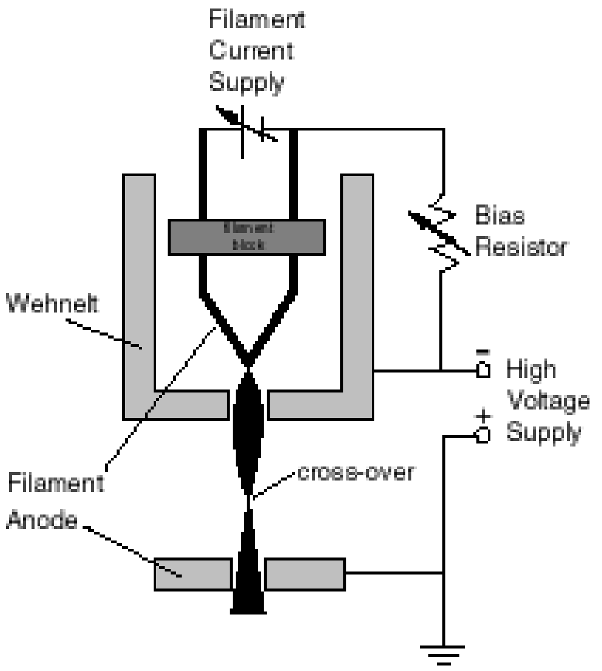


https://www6.slac.stanford.edu/news/2018-04-09-slac-produces-first-electron-beam-superconducting-electron-gun.aspx



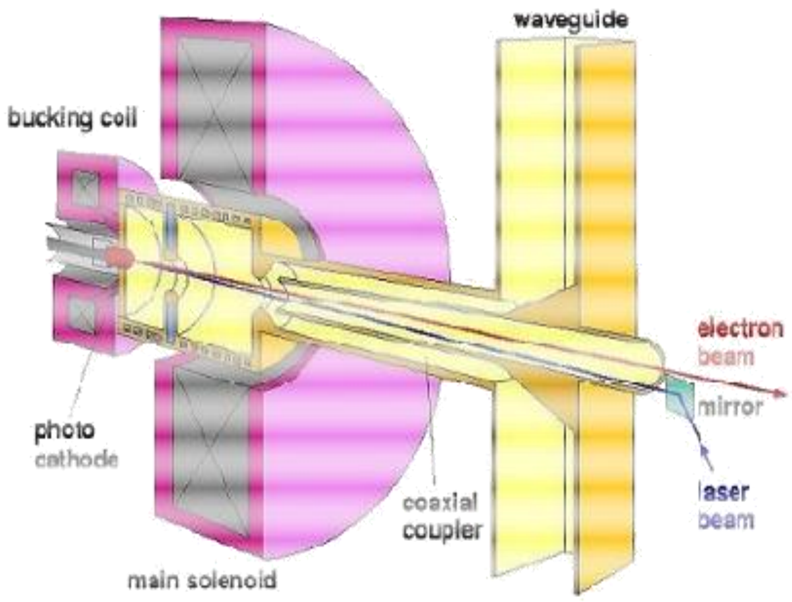
Part of the LBNL team and the LCLS-II gun (2017)

Components of an electron gun



DC gun for TEM

- Gun type: DC or RF gun
- Main components:
  - A Cathode of some type for generating electrons
  - Accelerating Voltage between the cathode and anode
  - Anode(or not?)
  - Focusing structures
  - Auxiliary system, Vacuum, power, cooling ……



PITZ RF gun for XFEL

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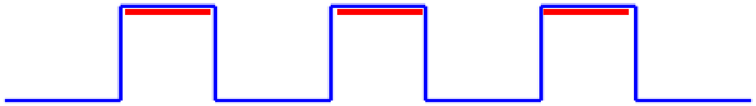
Typical beam time structures of gun

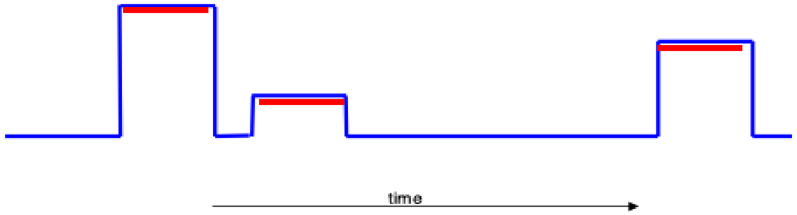
DC gun

DC always ON

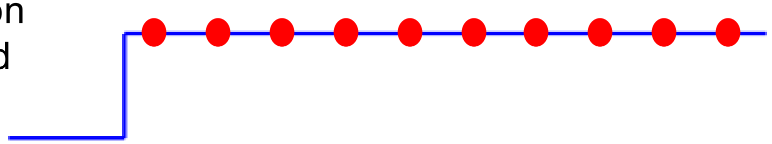
DC Pulsed



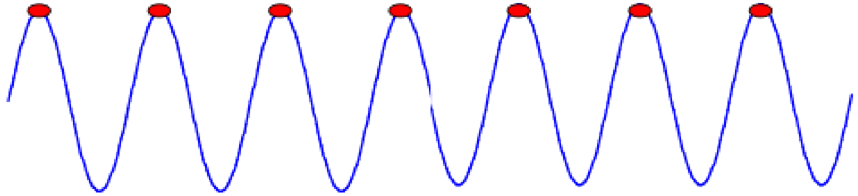
DC Pulsed, Amp &Freq modulated



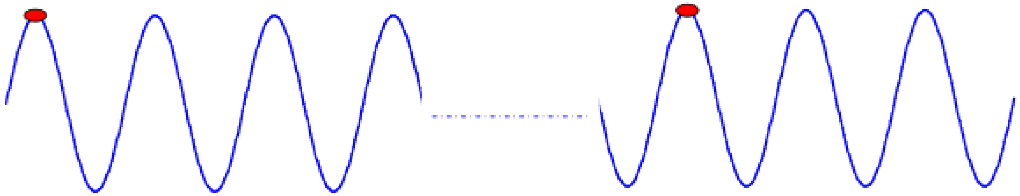
DC always on Beam pulsed



RF gun



CW – bunch of e- in every RF bucket, typically from 100’s of MHz to GHz, up to 100’s of pC per bunch



pulsed – not every RF bucket is filled, RF frequencies of 100’s of MHz to GHz, up to ~nC per bunch, with bunch rep rates of Hz to 1 MHz

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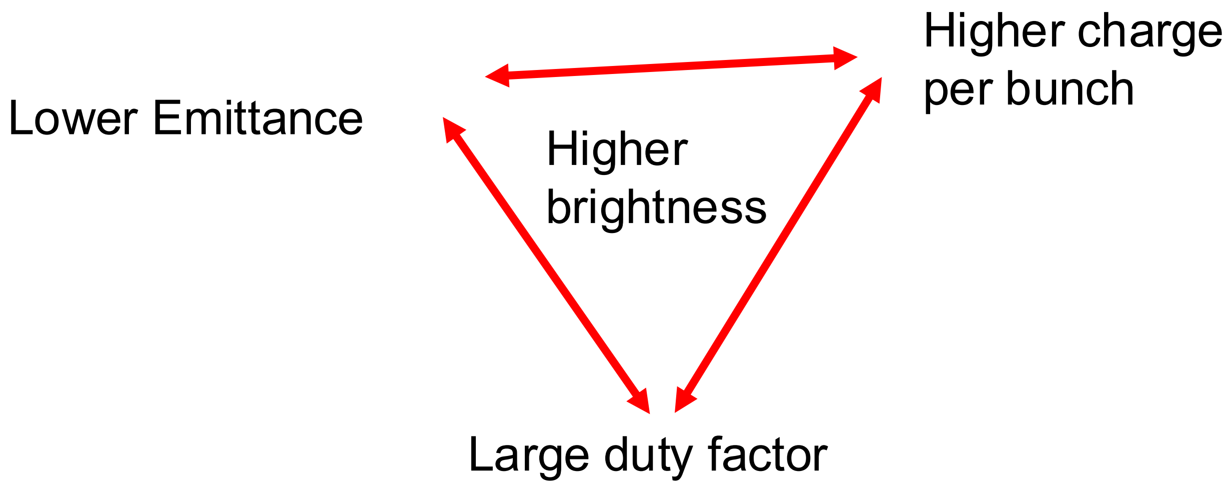
What properties we care about?

- Current (average, peak)
- Bunch charge
- Pulse length
- Beam size
- Emittance
- Beam brightness
- Reliability
- Physical size
- Cost
- ……

“I Want……”



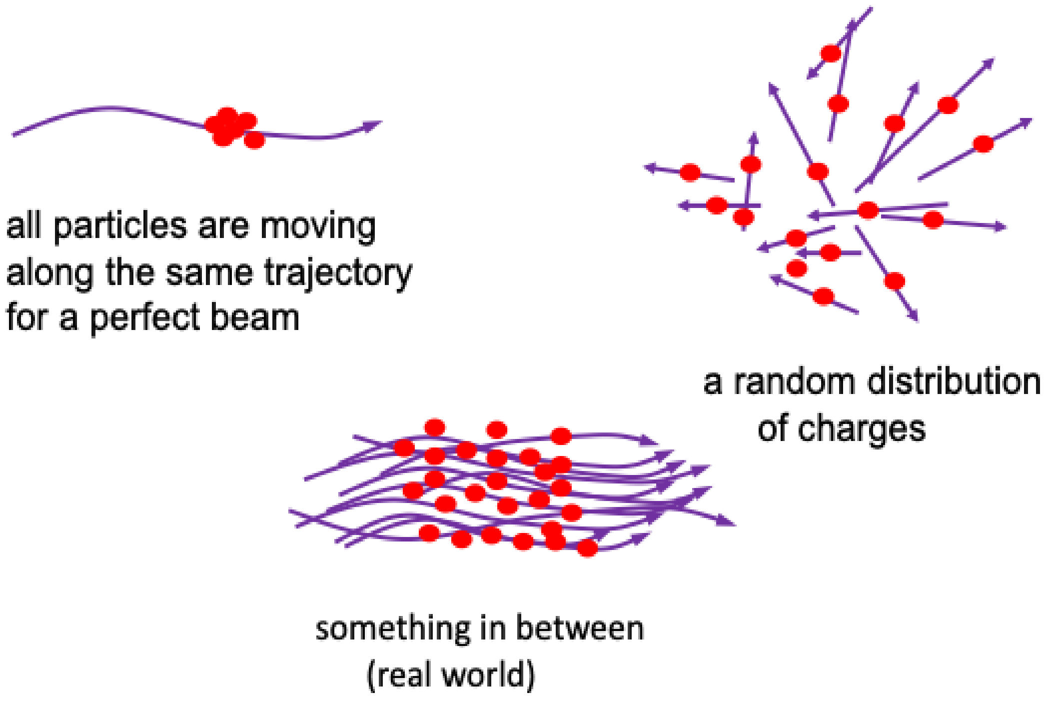
No matter what – people always want more than they have!

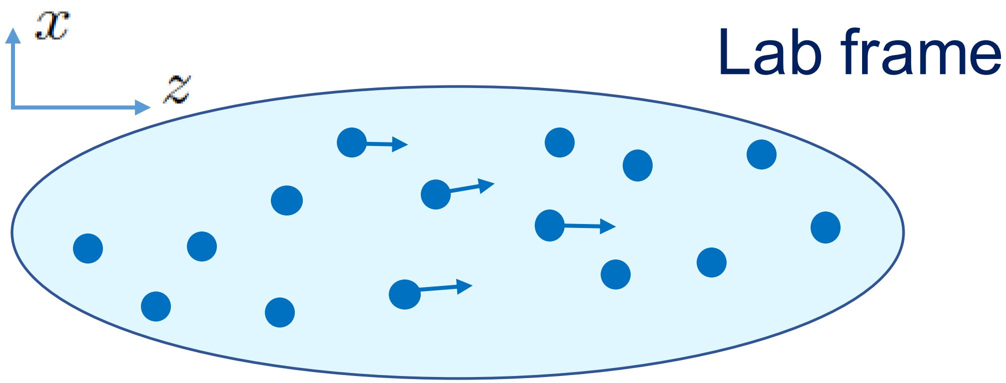
“Gun determines all”

- Some topics in an electron gun
  - Emittance and phase space
  - Cathode and electron emission
  - Beam emittance in photo-cathode RF gun

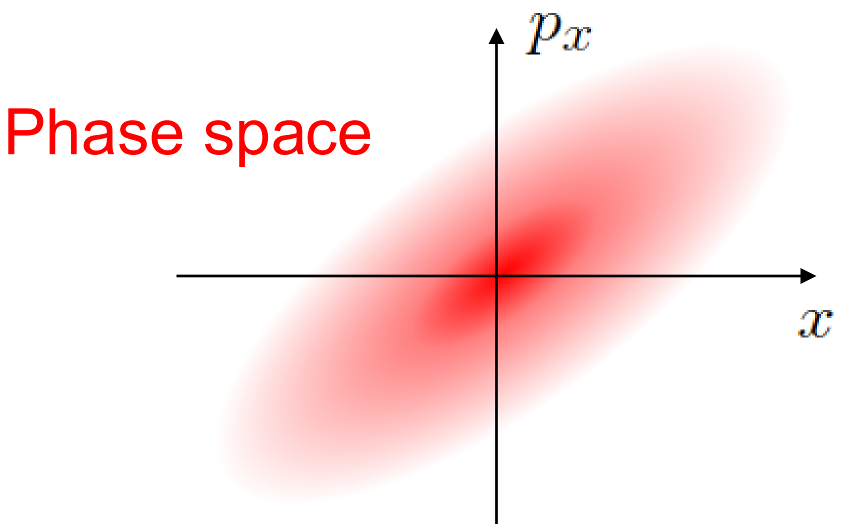
How good is a Charged Particle Beam?

an "ordered flow" of charged particles





Phase space (x, y, z, p_x, p_y, p_z) or (x, y, t, p_x, p_y, E)



Emittance (***volume***) $\epsilon_{nx} = \sigma_x \sigma_{p_x}$

Phase space and beam emittance

Emittance is less strictly defined as the area occupied by the a bunch of charged particles in trace space. i.e.

$$\varepsilon_x = A_x = \iint \mathrm{dxdx}'. \qquad [\pi \text{ m-rad}]$$

The trace-space area A_x is related to the phase-space area in x-p_x plane by

$$A_x = \iint dx\, d\frac{p_x}{p} = \frac{1}{< p_z >}\iint dxdp_x = \frac{1}{\gamma\beta}\cdot\frac{1}{mc}\iint dxdp_x \qquad p_Z \gg p_x$$

It's useful to define 'normalized emittance' that is independent of particle energy such that

$$\varepsilon_n = \gamma\beta\varepsilon$$

But beams with quite different distributions in trace space may occupy the same area!!

Define RMS emittance as

$$\varepsilon_x = \sqrt{< x^2 >< x'^2 > - < xx' >^2} = \sqrt{\sigma_x^2\sigma_{x'}^2 - \sigma_{xx'}^2} = \sqrt{\det\sigma} \qquad \sigma = \begin{bmatrix} \sigma_x^2 & \sigma_{xx'} \\ \sigma_{xx'} & \sigma_{x'}^2 \end{bmatrix}$$

If x and x' are not correlated (e.g. at beam waist)

$$\varepsilon_x = \sqrt{< x^2 >< x'^2 >} = \sigma_x\sigma_{x'}$$

RMS emittance provides a quantitative description of beam quality

Beam size and beam divergence

root-mean square (RMS) of a set of n values is defined as:

$$x_{rms} = \sqrt{\frac{1}{n}\left(x_1^2 + x_2^2 + \cdots + x_n^2\right)}$$

Let $f(x,x')$ be the distribution function such that $\int f(x, x')dxdx' = N$. N is the total number of particles. Beam parameters can be defined accordingly as:

$$\langle x\rangle = \int x f(x,x')dxdx' / \int f(x,x')dxdx'$$ averaged beam size

$$\langle x'\rangle = \int x' f(x,x')dxdx' / \int f(x,x')dxdx'$$ averaged beam divergence

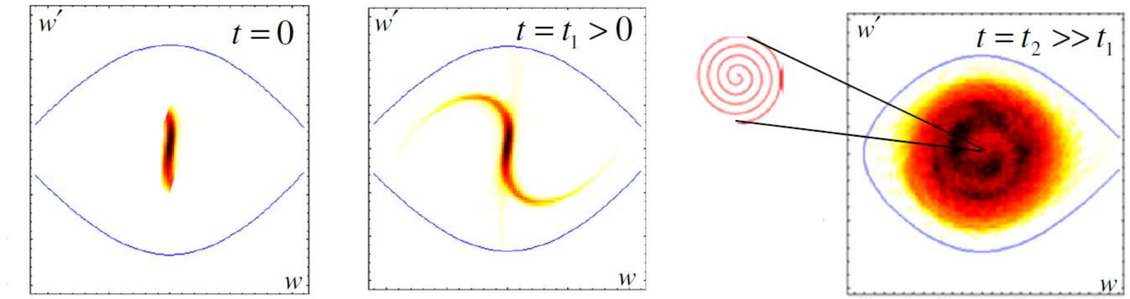
$$\sigma_x = \sqrt{\int (x-\langle x\rangle)^2 f(x,x')dxdx' / \int f(x,x')dxdx'}$$ rms beam size

$$\sigma_{x'} = \sqrt{\int (x'-\langle x'\rangle)^2 f(x,x')dxdx' / \int f(x,x')dxdx'}$$ rms beam divergence

$$\sigma_{xx'} = \sqrt{\int (x-\langle x\rangle)(x'-\langle x'\rangle) f(x,x')dxdx' / \int f(x,x')dxdx'}$$ beam correlation

Phase space and beam emittance

- RMS emittance gives more weight to the particles in the outer region of the trace- space area. Therefore, removing some outer particles will significantly reduce RMS emittance without too much degradation of beam intensity.
- Liouville theorem states that for Hamiltonian systems the phase space density stays constant.
- As long as the particle dynamics in the beamline elements (transport optics, accelerating sections) can be described by Hamiltonian functions (no binary collisions, stochastic processes, etc.), the phase space density will stay constant throughout the accelerator.
- The phase space density obtained at the electron source is a critical parameter.
- In real machines, rms emittances are conserved only when linear forces act on the distribution



M. Reiser, Theory and Design of Charged Particle Beams (2008)

- Beam brightness(density) is simply defined as

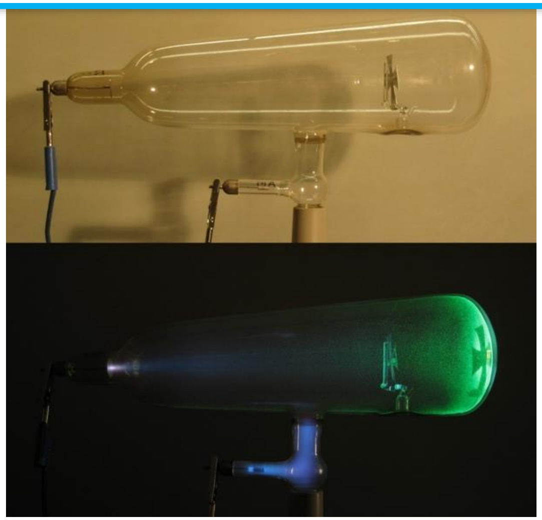
$$\mathcal{B} = \frac{N}{\epsilon_{nx} \cdot \epsilon_{ny} \cdot \epsilon_{nz}}$$

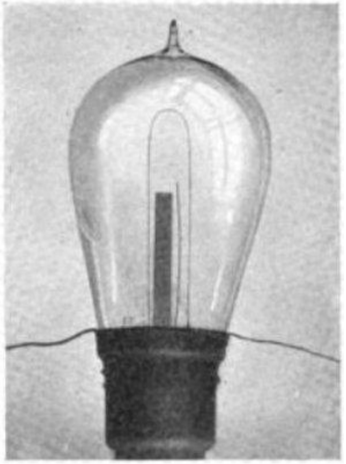
- Some topics in an electron gun
  - Emittance and phase space
  - Cathode and electron emission
  - Beam emittance in photo-cathode RF gun

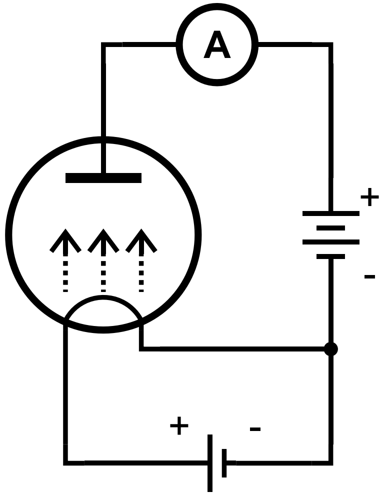
How to generate free electrons?

- Charging by friction, voltaic battery
- Cathode Ray, Crookes tube
- Guthrie measured the discharge of a positively charged, red-hot sphere into air, helping establish understanding of the thermionic emission phenomenon(1873)
- Edison's work with the light bulb

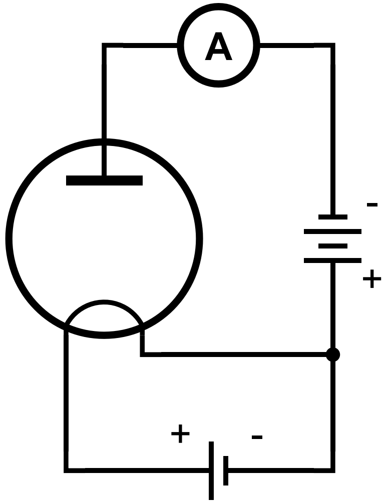
Crookes–Hittorf tube







Electron flow



No current

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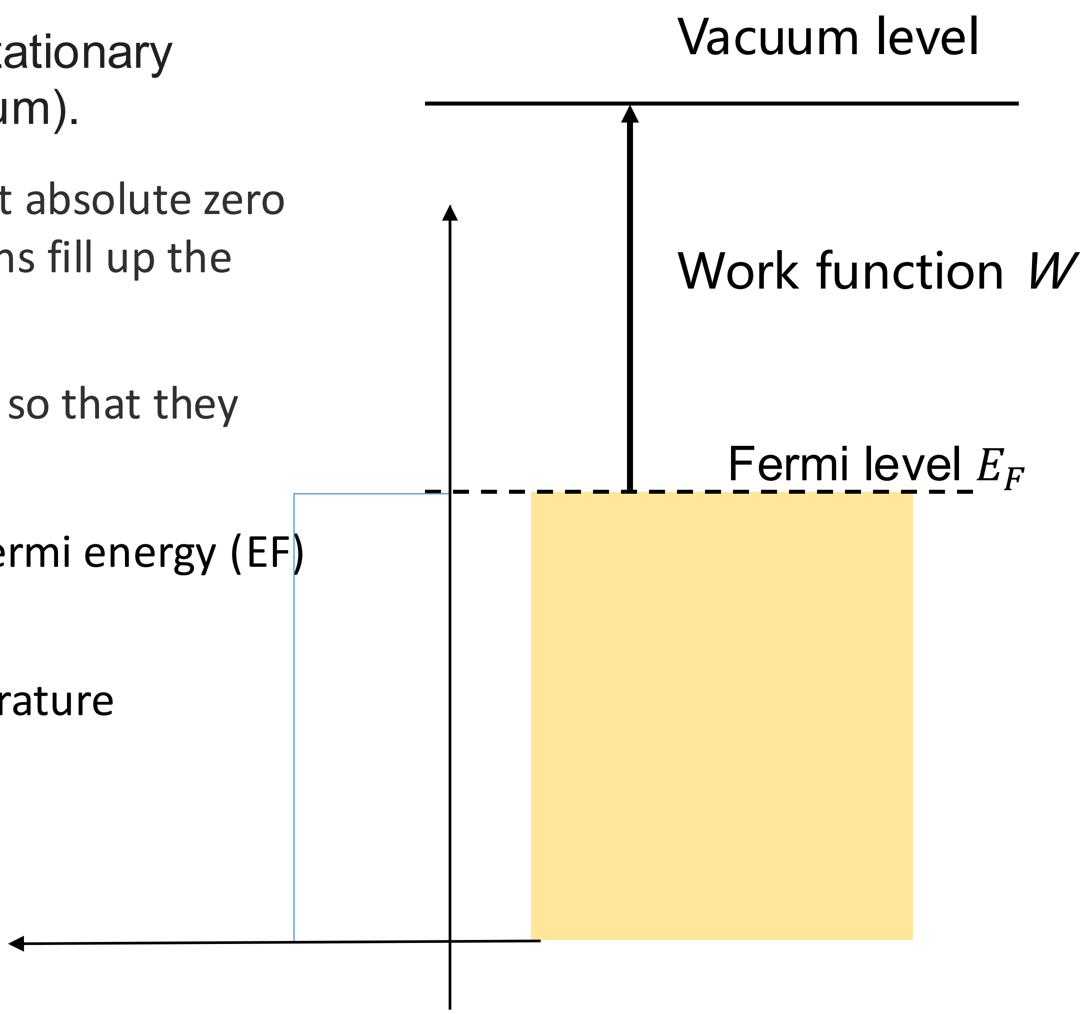
How to generate free electrons?

- In physics, the **vacuum level** refers to the energy of a free stationary electron that is outside of any material (it is in a perfect vacuum).
- Fermi level: the highest energy level that an electron can occupy at absolute zero temperature. At absolute zero temperature (0 Kelvin), the electrons fill up the energy levels starting from the lowest.
- Give electrons enough energies to overcome the potential barrier, so that they escape from material into vacuum
- Work function, the energy that an electron must gain above the Fermi energy (EF) in order to emit into vacuum, W = vacuum level-Fermi level
- Work function depends on cathode material and operation temperature



Ag	4.26 – 4.74	Al	4.06 – 4.26	As	3.75
Au	5.10 – 5.47	B	~4.45	Ba	2.52 – 2.70
Be	4.98	Bi	4.31	C	~5
Ca	2.87	Cd	4.08	Ce	2.9
Co	5	Cr	4.5	Cs	1.95
Cu	4.53 – 5.10	Eu	2.5	Fe:	4.67 – 4.81

Type of electron emission

- Give the conduction band electrons extra energy:
  - thermionic emission,
  - photoemission,
  - secondary emission
- Change the potential barrier:
  - field emission,
  - plasma emission

Give electrons enough energies to overcome the potential barrier, so that they escape from material into vacuum

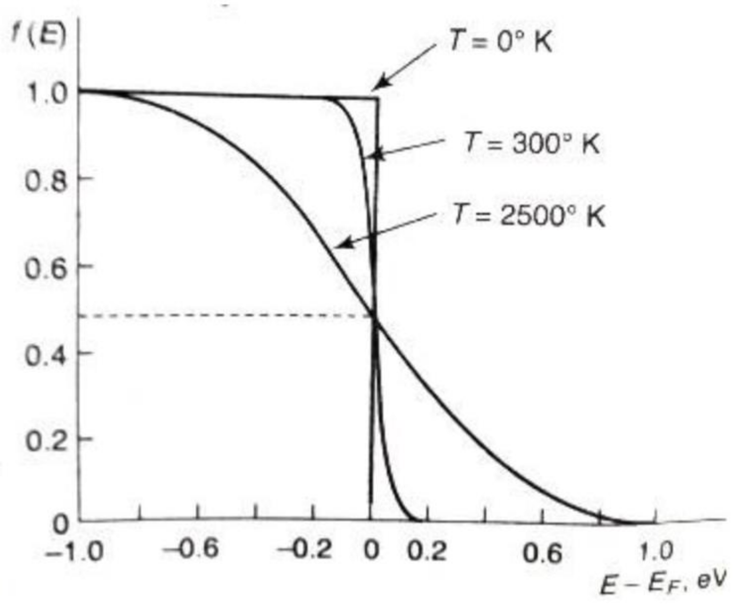
- The Fermi level (E_F) can be defined from the Fermi-Dirac distribution, which is:

$$f_{FD}(E) = \frac{1}{e^{(E-E_F)/kT}+1}$$

- Where:
  - f(E) is the Fermi-Dirac distribution function, representing the probability of finding an electron with energy state E.
  - E is the energy of the electron
  - E_F is the Fermi level
  - k_B is Boltzmann's constant, k=1.380649 × 10^{-23} J/K,
  - T is the temperature in Kelvin

Heaviside-step function, H(x) when T -> 0

$$E_f = \frac{h^2}{8m}\left(\frac{3n}{2}\right)^{2/3}$$ n = N/V is the electron density



Element	Fermi Energy [eV]
Cu	7.00
Mg	7.08
Ba	3.64
Pb	9.47

Density of available states in metal

- Electron motion in the conduction band can be approx. modeled by free particles bound by infinite potential barriers located at the physical boundaries of the metal
- Solving the time independent Schrodinger equation under these boundary conditions, **Born-Karman boundary conditions**
- The corresponding wave functions are:

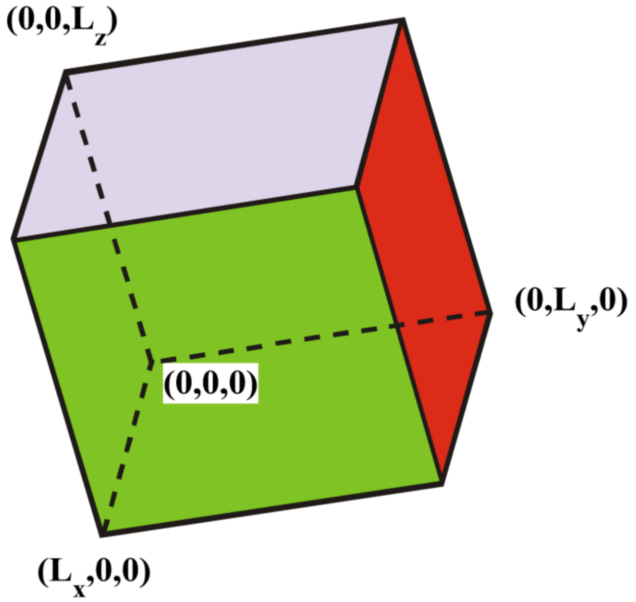
$$\Psi(x,y,z) = \sin(k_x x)\sin(k_y y)\sin(k_z z)$$

- Where:

$$k_x L_x = 2\pi n_x, k_y L_y = 2\pi n_y, k_z L_z = 2\pi n_z$$

$$n_i = 1,2,3,4 \ldots \ldots \infty,$$

$$E(k) = \frac{\hbar^2 k^2}{2m} = \frac{\hbar^2}{2m}\left(k_x^2 + k_y^2 + k_z^2\right) \qquad E = \frac{p^2}{2m} = \frac{1}{2}mv^2$$



Density of available states in metal

- Density of state in k-space:

$$\frac{k_x k_y k_z}{n_x n_y n_z} = \Delta\tilde{k} = \left(\frac{2\pi}{L_x}\right)\cdot\left(\frac{2\pi}{L_y}\right)\cdot\left(\frac{2\pi}{L_z}\right) = \frac{(2\pi)^3}{V}$$

$$\rho(k) = \frac{1}{\Delta\tilde{k}} = \frac{V}{8\pi^3}$$

- Total number of k value in k-space: $\rho(\boldsymbol{k})\cdot\frac{4}{3}\pi k^3$

- Total number of energy state:

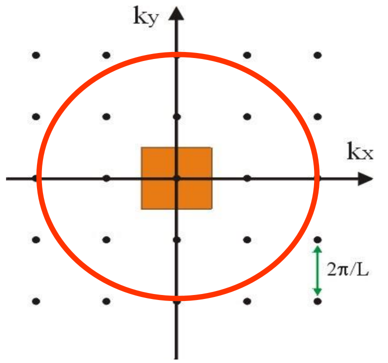
Electron is fermion, Pauli exclusion principle, different spin

$$Z(E) = 2\cdot\rho(k)\cdot\frac{4}{3}\pi k^3 = 2\cdot\frac{V}{8\pi^3}\cdot\frac{4}{3}\pi\frac{(2m)^{\frac{3}{2}}}{\hbar^3}E^{\frac{3}{2}} = \frac{V(2m)^{\frac{3}{2}}}{3\pi^2\hbar^3}\cdot E^{\frac{3}{2}} = N$$

- Density of state per unit volume per unit energy interval

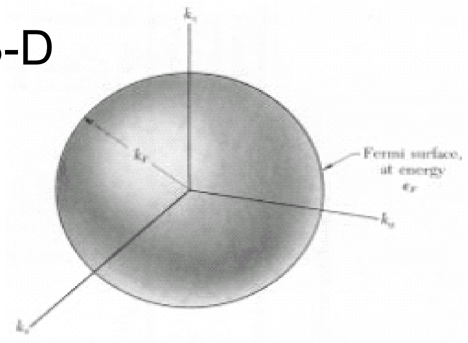
$$n(E) = \frac{d\frac{Z(E)}{V}}{dE} = \frac{(2m)^{\frac{3}{2}}}{2\pi^2\hbar^3}\cdot E^{\frac{1}{2}} = \frac{8\sqrt{2}\pi m^{\frac{3}{2}}}{h^3}E^{\frac{1}{2}}$$

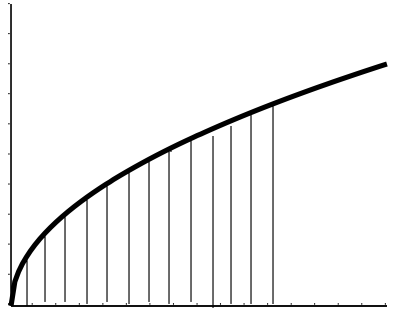
2-D



$S=(2\pi/L)^2$

3-D





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- Fermi-Dirac distribution function

$$f_{FD}(E) = \frac{1}{e^{(E-E_F)/kT}+1}$$

- Density of electrons per unit energy interval

$$n(E)dE = \frac{8\sqrt{2}\pi m^{\frac{3}{2}}}{h^3} E^{\frac{1}{2}} \frac{1}{e^{(E-E_F)/kT}+1}$$

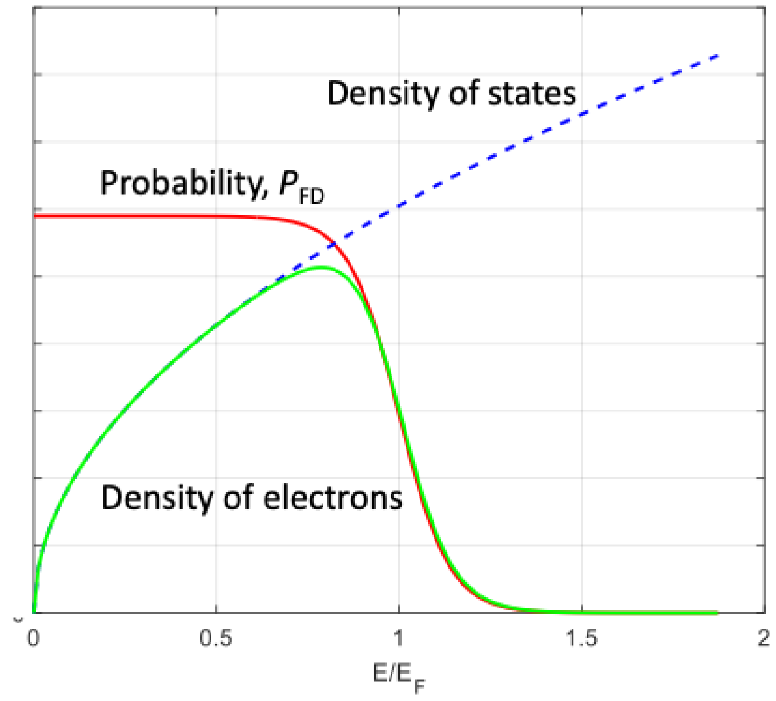
- Number of state in p or k or v space

$$dS = 2V dk_x dk_y dk_z/(2\pi)^3 \qquad \Delta\tilde{k} = \left(\frac{2\pi}{L_x}\right)\cdot\left(\frac{2\pi}{L_y}\right)\cdot\left(\frac{2\pi}{L_z}\right) = \frac{(2\pi)^3}{V}$$

$$k = \frac{2\pi}{\lambda} = \frac{2\pi p}{h}$$

$$dS = \frac{2V}{h^3} dp_x dp_y dp_z \qquad E = \frac{p^2}{2m} = \frac{1}{2} m v^2$$

- Where $p_x = m v_x \Longrightarrow dp_x = m dv_x$, so $dS = \frac{2V}{h^3} \cdot m^3\, dv_x dv_y dv_z$



Thermionic emission

- Some electrons can reach energy greater than fermi level and vacuum level and escape to vacuum when the temperature T is high enough.

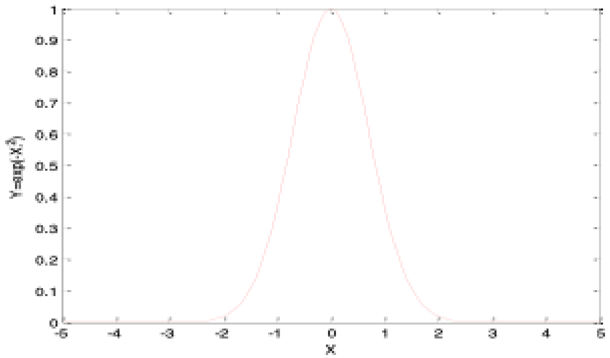
- The number of electrons in velocity space $v_x \to (v_x + dv_x)$, $v_y \to (v_y + dv_y)$, $v_z \to (v_z + dv_z)$ is

$$dN = f(E) \cdot dS = \frac{1}{e^{(E-E_F)/kT}+1} \frac{2V}{h^3} \cdot m^3\, dv_x dv_y dv_z$$

and the density: $dn = \frac{dN}{V}$

- For thermionic emission, $E - E_F \gg kT$, then

Maxwellian velocity distribution



$$f_{FD}(E) \approx e^{-(E-E_F)/kT} = e^{\frac{E_F}{kT}} \cdot e^{-\frac{1}{kT}\cdot\frac{1}{2}m(v_x^2+v_y^2+v_z^2)}$$

$$dn = \frac{dN}{V} = \frac{2m^3}{h^3} e^{\frac{E_F}{kT}} \cdot e^{-\frac{m}{2kT}v_x^2} dv_x \cdot e^{-\frac{m}{2kT}v_y^2} dv_y \cdot e^{-\frac{m}{2kT}v_z^2} dv_z$$

- The density of current:

$$dJ = ev_z dn = ev_z \frac{2m^3}{h^3} e^{\frac{E_F}{kT}} \cdot e^{-\frac{m}{2kT}v_x^2} dv_x \cdot e^{-\frac{m}{2kT}v_y^2} dv_y \cdot e^{-\frac{m}{2kT}v_z^2} dv_z$$

Z is direction of emission, normal to cathode surface.

Richardson-Dushmann equation

- Only electrons with energy greater than $E_F + W$ and with velocity v_z in z-direction larger than the critical velocity v_{z0} contribute to thermionic emission, so the current is

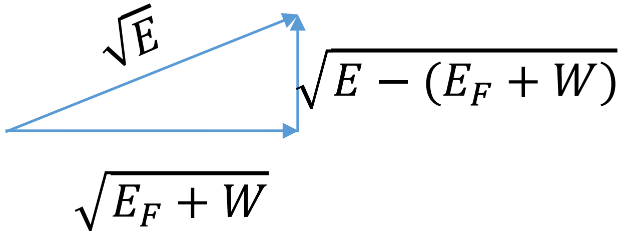
$$\frac{1}{2}mv_z^2 \geq E_F + W,$$

$$v_{z0} = \sqrt{\frac{2(E_F + W)}{m}}$$

$$J = \int dJ = \frac{2em^3}{h^3} e^{\frac{E_F}{kT}} \int_{-\infty}^{+\infty} e^{-\frac{m}{2kT}v_x^2} dv_x \int_{-\infty}^{+\infty} e^{-\frac{m}{2kT}v_y^2} dv_y \int_{v_{z0}}^{+\infty} v_z e^{-\frac{m}{2kT}v_z^2} dv_z$$

$$\int_{-\infty}^{+\infty} e^{-ax^2} dx = \sqrt{\pi/a}, \quad \text{so} \int_{-\infty}^{+\infty} e^{-\frac{m}{2kT}v_x^2} dv_x = \sqrt{\frac{2\pi kT}{m}}$$

$$\int xe^{-ax^2} dx = -\frac{e^{-ax^2}}{2a}, \quad \text{so} \int_{v_{z0}}^{+\infty} v_z e^{-\frac{m}{2kT}v_z^2} dv_z = \frac{kT}{m} e^{-\frac{E_F+W}{kT}}$$



$$J = \frac{2em^3}{h^3} e^{\frac{E_F}{kT}} \cdot \frac{2\pi kT}{m} \cdot \frac{kT}{m} e^{-\frac{E_F+W}{kT}} = \frac{4\pi emk^2}{h^3} T^2 e^{-\frac{W}{kT}} = A\,T^2 e^{-\frac{W}{kT}}$$

$$A = \frac{4\pi emk^2}{h^3} = 1.202 \times 10^6 \text{ A m}^{-2}\text{K}^{-2}$$

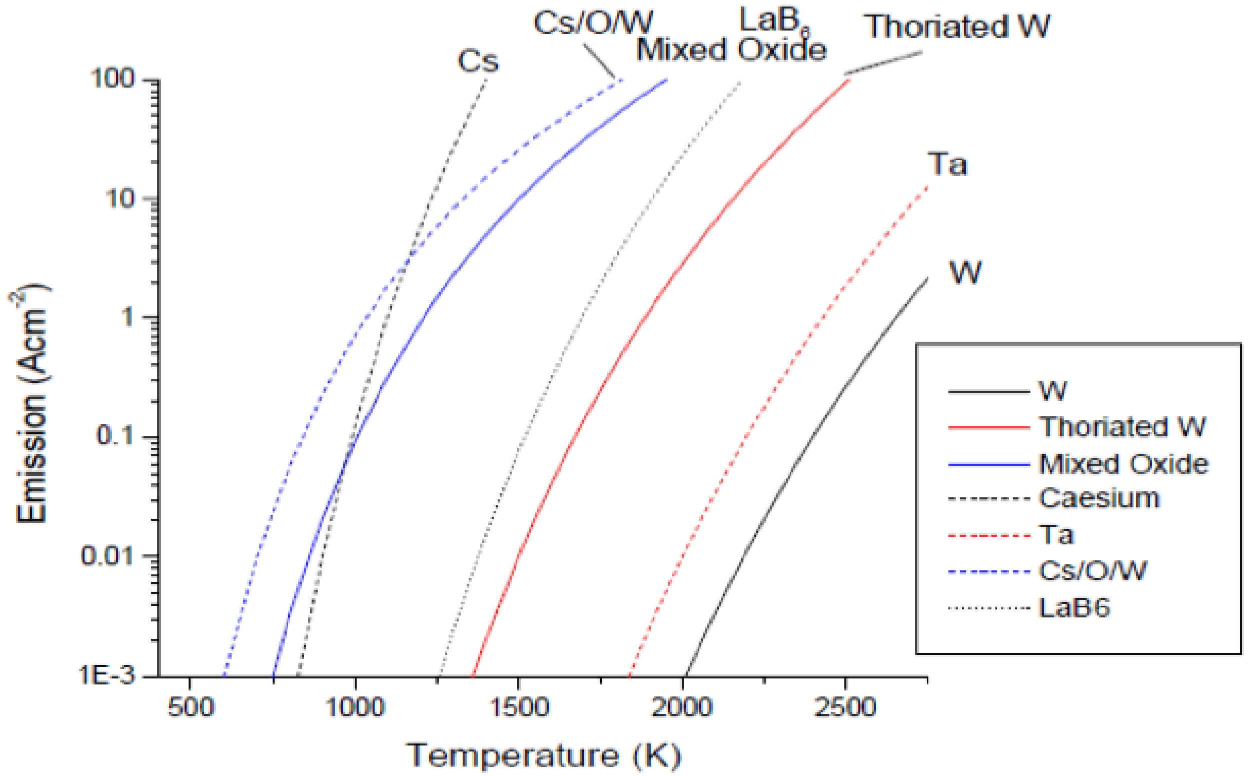
Richardson-Dushmann equation : $J_{th} = A\,T^2 e^{-\frac{W}{kT}}$

Richardson-Dushmann equation

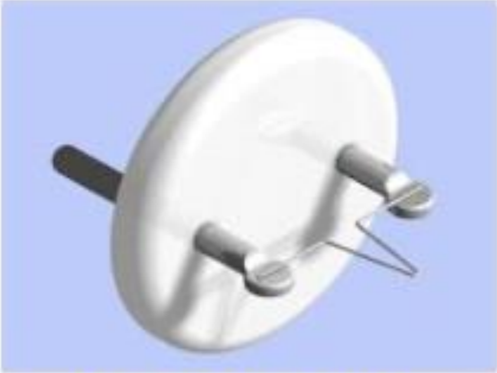
- Work function and Richardson constant of various materials

Material	W (eV)	A*b (A cm^{-2} K^{-2}) (b is material correction factor)
Molybdenum	4.15	55
Nickel	4.61	30
Tantalum	4.12	60
Tungsten	4.54	60
Barium	2.11	60
Cesium	1.81	160
Iriduim	5.40	170
Platinum	5.32	32
Rhenium	4.85	100
Thorium	3.38	70
Ba on W	1.56	1.5
Cs on W	1.36	3.2
Th on W	2.63	3.0
Thoria	2.54	3.0
BaO + SrO	0.95	$\sim 10^{-2}$
Cs-oxide	0.75	$\sim 10^{-2}$
TaC	3.14	0.3
LaB_6	2.70	29
theoretical:		120.2 (b=1)

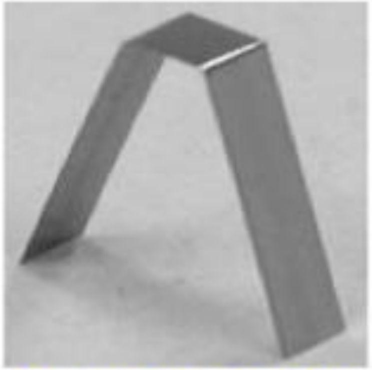
- Thermionic emission of various cathode materials



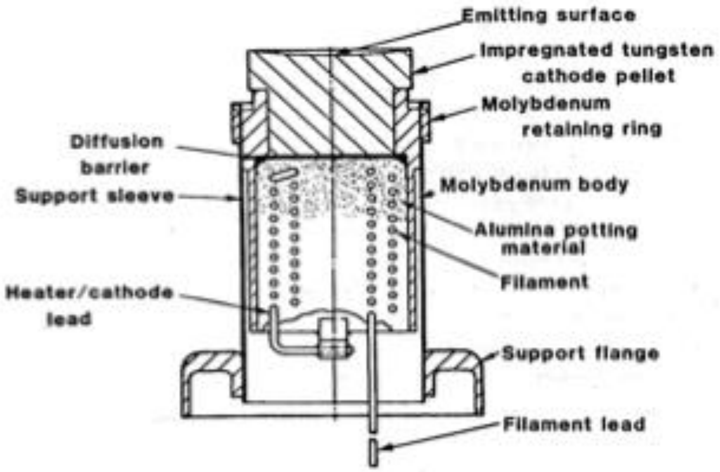
Common thermionic cathodes

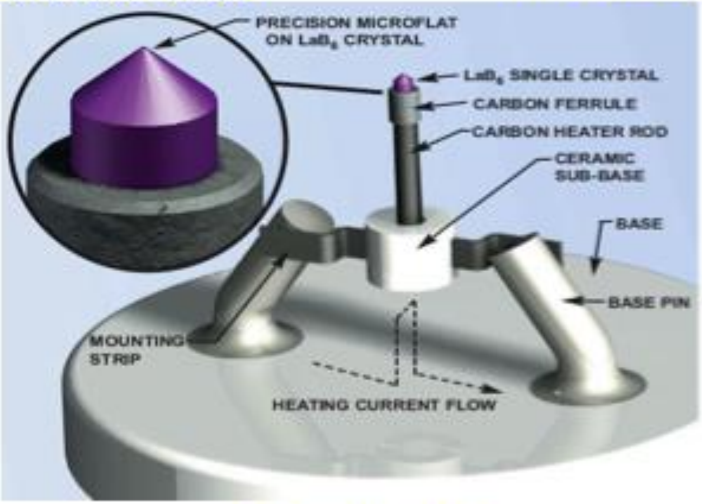


tungsten filament for electron microscope



filament cathode for e-beam welder



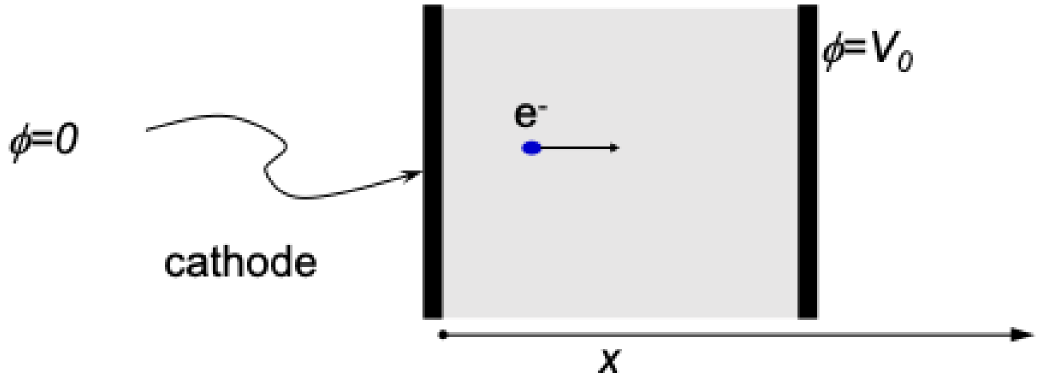


LaB_6 cathode for electron microscope

a typical type B dispenser cathode for linac system

Planar diode with space charge – Child-Langmuir Law

$$\begin{cases} \nabla^2\phi = \dfrac{d^2\phi}{dx^2} = -\dfrac{\rho}{\varepsilon_0} \\ J_x = \rho\dot{x} = const \\ \dfrac{m}{2}\dot{x}^2 - e\phi(x) = 0 \end{cases}$$



$$\Rightarrow \frac{d^2\phi}{dx^2} = \frac{J}{\varepsilon_0(2e/m)^{1/2}}\frac{1}{(\phi)^{1/2}}$$

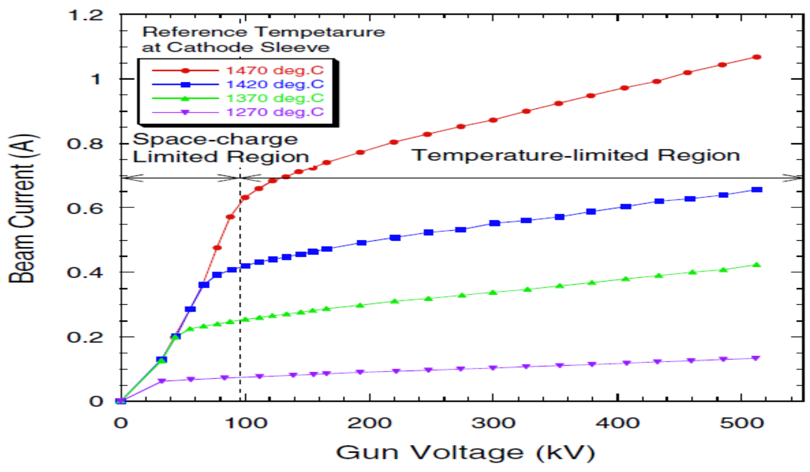
$$\Rightarrow \left(\frac{d\phi}{dx}\right)^2 = \frac{4J}{\varepsilon_0(2e/m)^{1/2}}\phi^{1/2} + C$$

C=0 under the boundary conditions: ϕ=0 and $d\phi/dx$=0 at x=0; the condition $d\phi/dx$=0 at x=0 implies that the special case **electric field at cathode surface is null** (a steady state solution).

$$\Rightarrow \frac{4}{3}\phi^{3/4} = 2\left(\frac{J}{\varepsilon_0}\right)^{1/2}\left(\frac{2e}{m}\right)^{-1/4}x$$

$$\Rightarrow \phi(x) = V_0\left(\frac{x}{d}\right)^{4/3} \quad \text{with} \quad J = \frac{4}{9}\varepsilon_0\left(\frac{2e}{m}\right)^{1/2}\frac{V_0^{3/2}}{d^2}$$

Child-Langmuir law



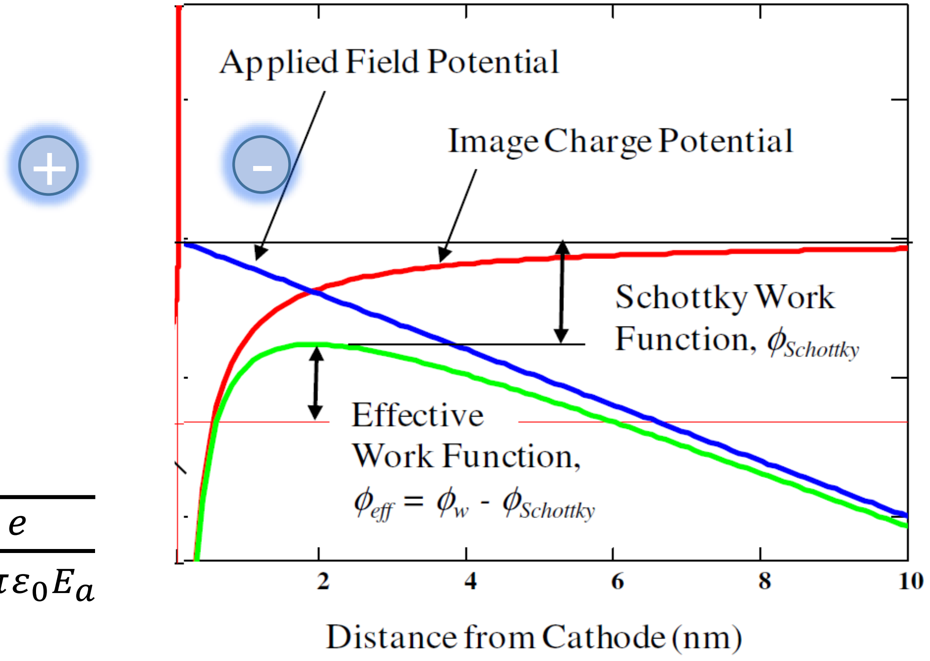
Schottky effect

Image charge force: $eE_I(x) = \frac{-e^2}{4\pi\varepsilon_0(2x)^2}$

Image charge potential: $\phi_I(x) = -\int_x^{\infty} E_I(x)dx = \frac{e}{16\pi\varepsilon_0 x}$

With applied field potential: $\phi(x) = -eE_a x - \frac{e^2}{16\pi\varepsilon_0 x}$

$$\frac{d\phi}{dx} = -eE_a + \frac{e^2}{16\pi\varepsilon_0 x^2} = 0 \Rightarrow x_m = \sqrt{\frac{e}{16\pi\varepsilon_0 E_a}}$$



Maximum of potential: $\phi_m = -W = -e\sqrt{\frac{eE_a}{4\pi\varepsilon_0}}$

$$\Delta W = e\sqrt{\frac{eE_a}{4\pi\varepsilon_0}}$$

Schottky barrier lowering

Effective work function: $\phi_{eff} = \phi_w - \phi_{schottky}$

$$J_e = A\,T^2 e^{-\frac{W-\Delta W}{kT}} = J_{th}\mathrm{Exp}\left(\frac{e(eE/4\pi\varepsilon_0)^{\frac{1}{2}}}{kT}\right)$$

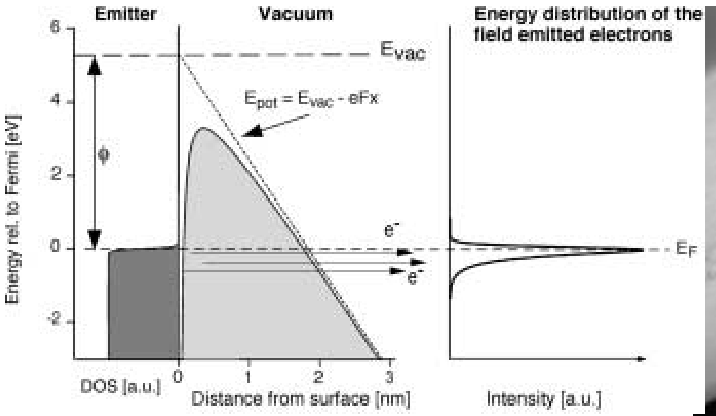
Field emission

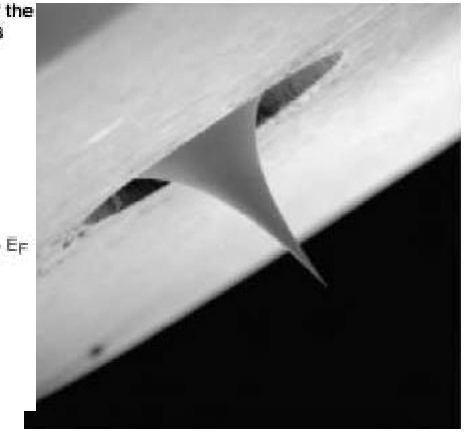
- When the electric field at the surface of a cathode reaches a critical level, the diode current is observed to rise sharpy.
- The potential barrier is suppressed and distorted by applied field, and electron can "tunnel" through the barrier. The barrier penetration depends on the work function, the Fermi level, and the field strength.
- The emission current density is given by the Fowler-Nordheim equation, the current density is extremely sensitive function of the field.
- The required field are quite high(10^7-10^8 V/m), significant field enhancement occurs on the tip.
- The source of dark current in a gun

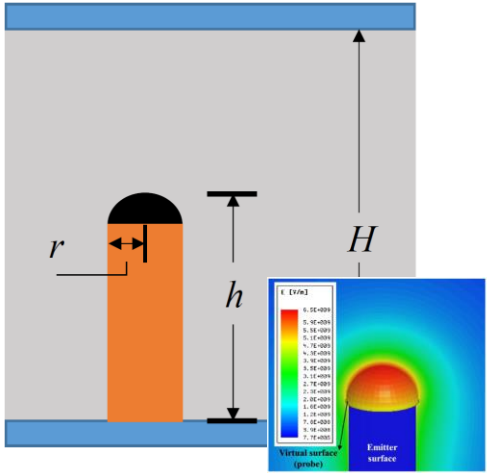
$$J_{FN}(F) = A_{FN}E^2\exp(-\frac{B_{FN}W^{3/2}}{E})$$

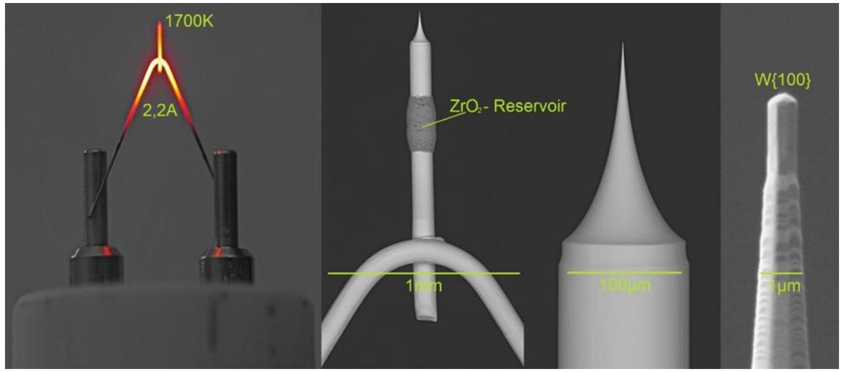
$$E_{\text{apex}} = \beta E_M = \beta\frac{V}{H}$$

β: field enhancement factor





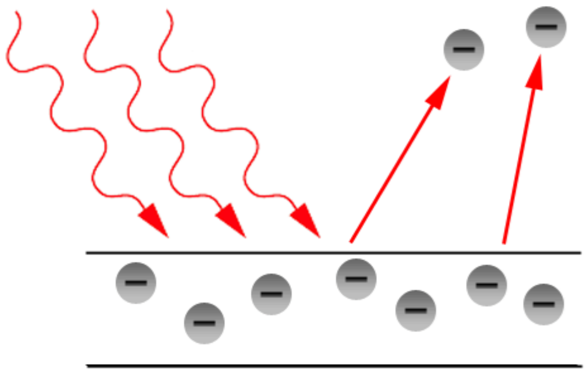


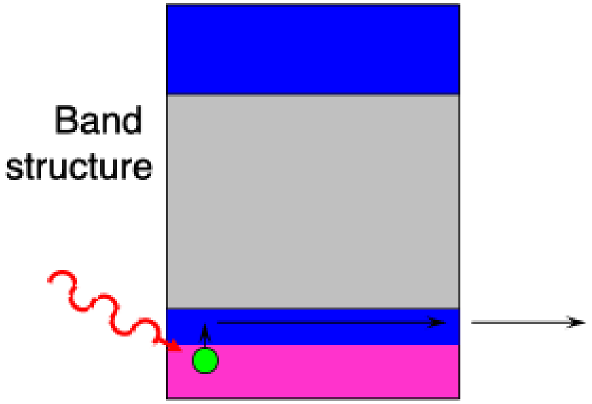


Thermionic and cold field emission

Photoelectric emission

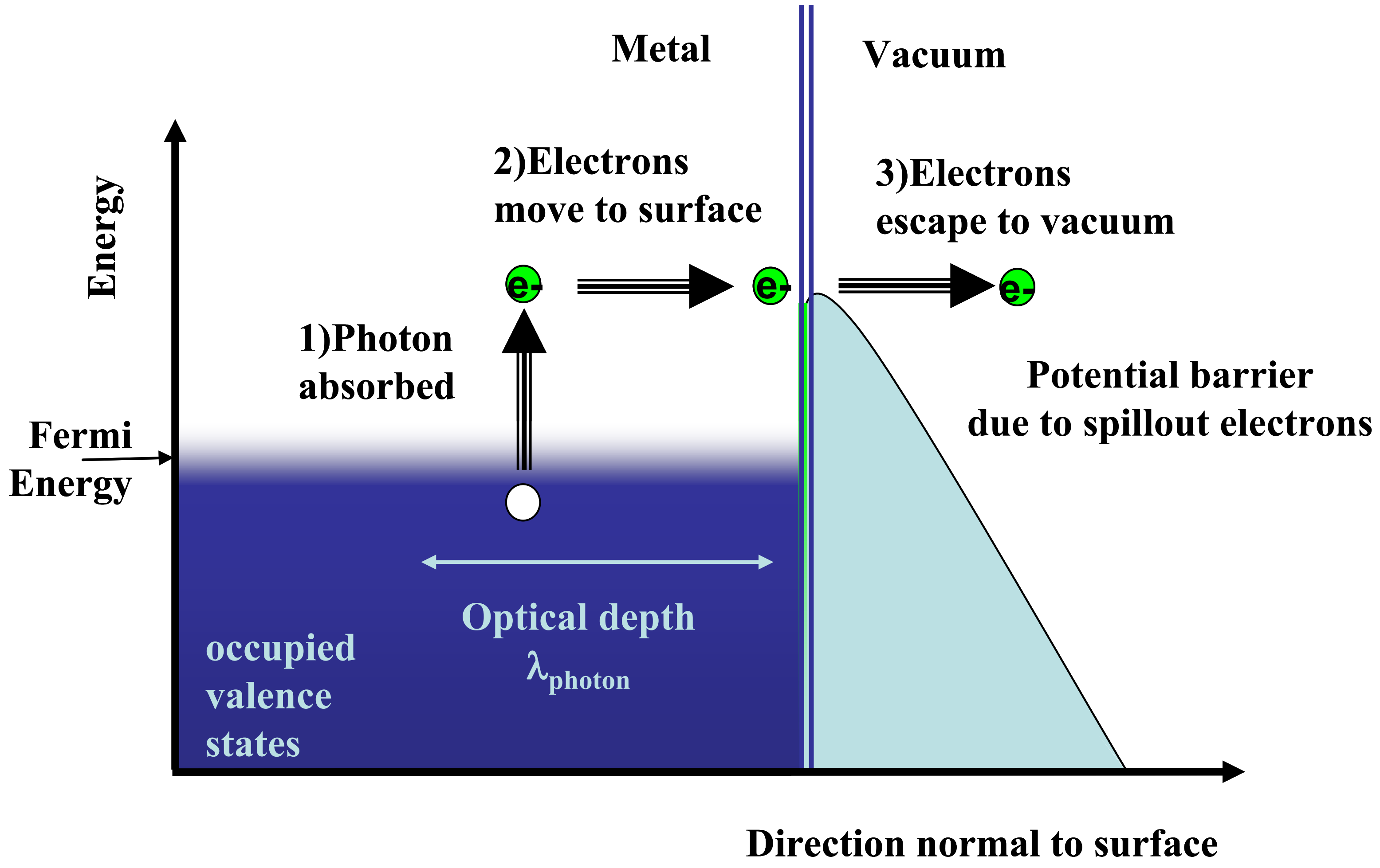
- Electron produced by shining light on surface of metal
  - Below the threshold energy(wavelength) no electrons are emitted
  - Above the threshold, electron energy is the same at any wavelength of light independent of intensity
- Einstein proposed that this is due to the particle nature of light, predicted energy dependence of electrons on incident light wavelength (Nobel prize for work on the photoelectric effect)
- Type of photocathodes:
  - Metals: copper, Mg; low efficiency, good time response, resistant to contamination, UV laser
  - Semi-conductors: GaAs, Cs2Te, K2CsSb, GaN; high efficiency, slower time response, sensitive to contamination, visible/IR/UV laser





Photoelectric emission

- 3-step model (excite, transport, escape) used to explain the emission process

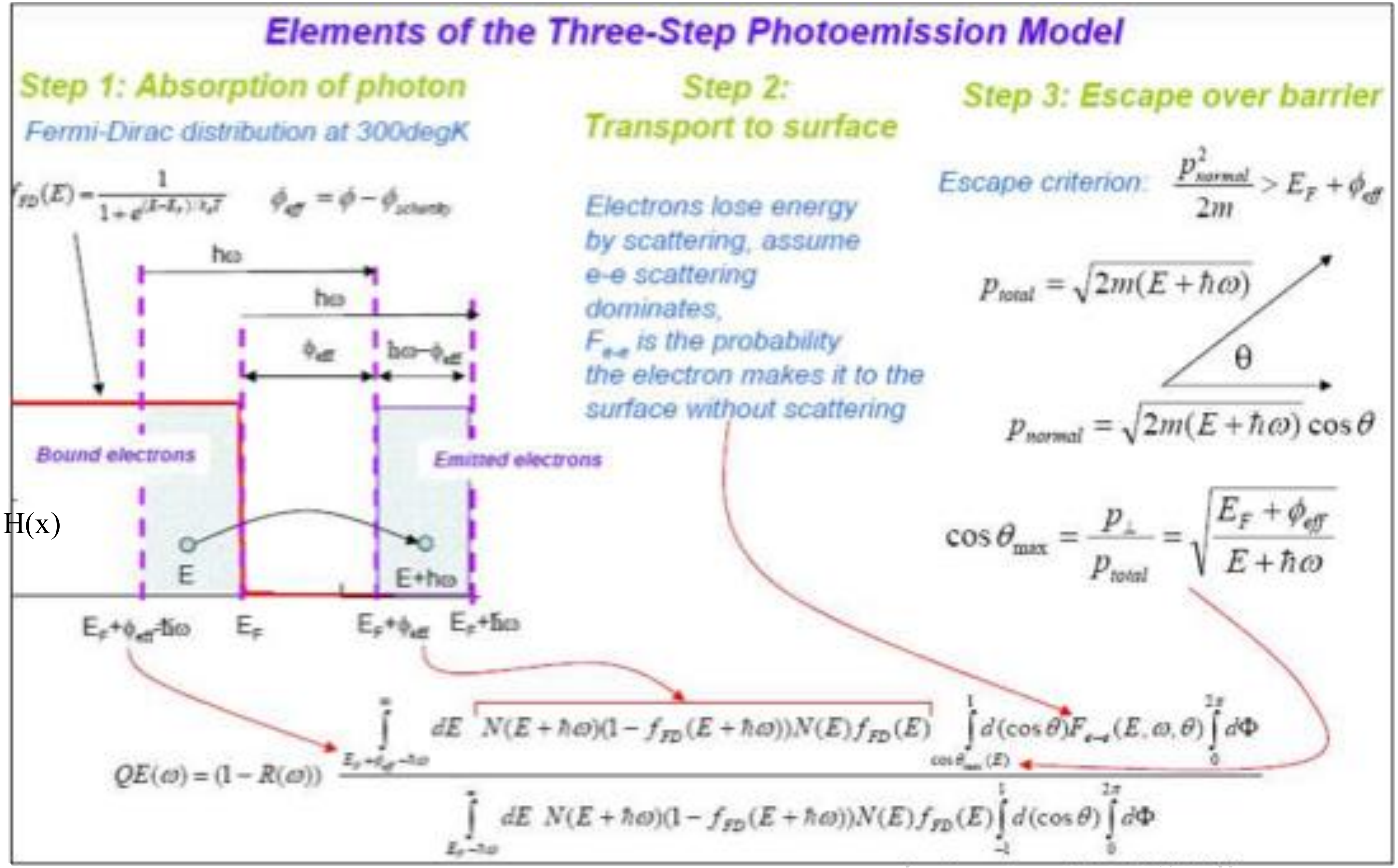


Quantum efficiency

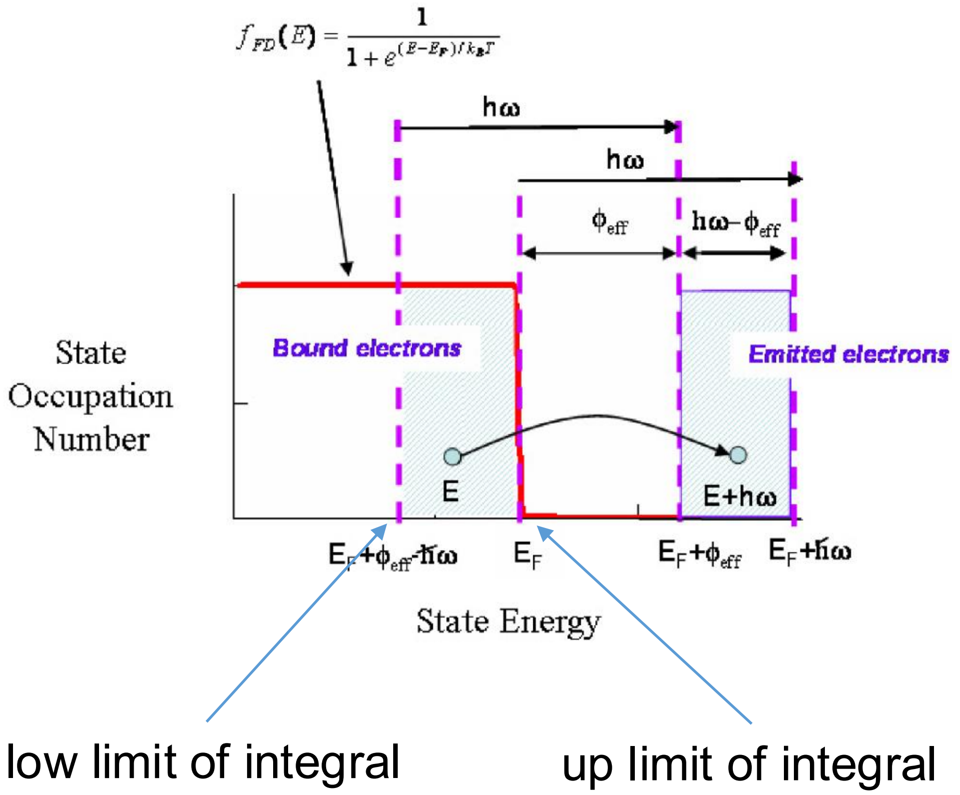
$$\mathrm{QE} = \frac{N_e}{N_{ph}}$$

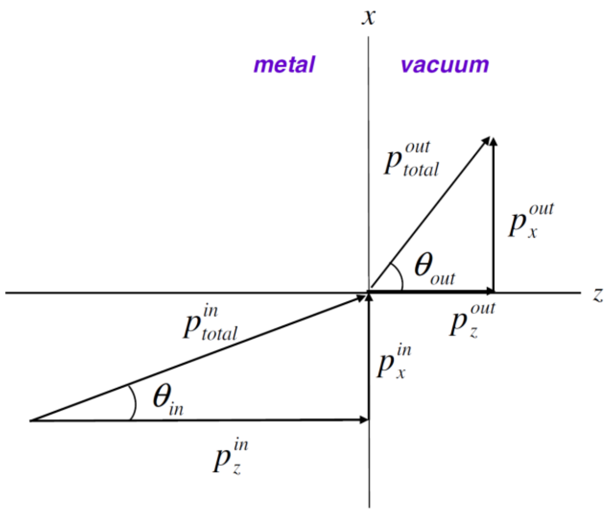
Heaviside-step function, H(x)

$kT \ll h\omega$

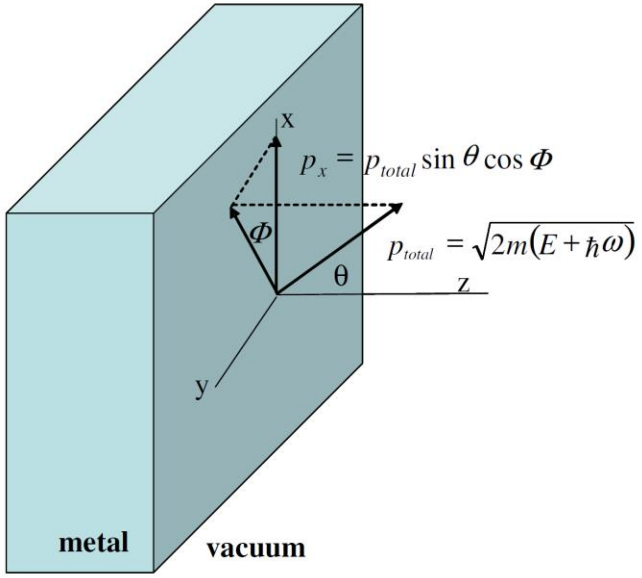


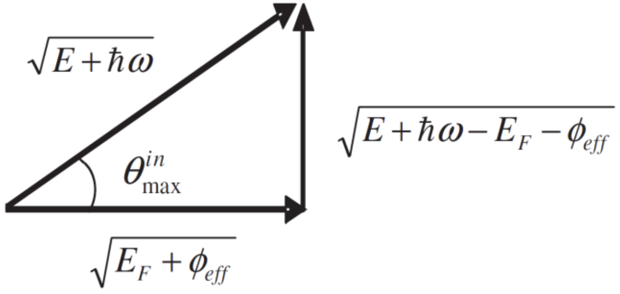
Courtesy Dave Dowell (SLAC)





$$\cos\theta_{\max}^{\text{in}} = \sqrt{\frac{E_F + \phi_{\text{eff}}}{E + \hbar\omega}}.$$





Quantum efficiency

$$\mathrm{QE}(\omega) = [1 - R(\omega)] \frac{\int_{E_F+\phi_{\mathrm{eff}}-\hbar\omega}^{\infty} dE [1 - f_{\mathrm{FD}}(E+\hbar\omega)] f_{\mathrm{FD}}(E) \int_{\cos\theta_{\max}(E)}^{1} d(\cos\theta) F_{e\text{-}e}(E,\omega,\theta) \int_0^{2\pi} d\Phi}{\int_{E_F-\hbar\omega}^{\infty} dE [1 - f_{\mathrm{FD}}(E+\hbar\omega)] f_{\mathrm{FD}}(E) \int_{-1}^{1} d(\cos\theta) \int_0^{2\pi} d\Phi}$$

$$QE(\omega) = \frac{1 - R(\omega)}{1 + \frac{\lambda_{opt}(\omega)}{\bar{\lambda}_{e-e}(\omega)}} \frac{(E_F + \phi_{eff})}{2\hbar\omega} \left[1 - \sqrt{\frac{E_F + \phi_{eff}}{E_F + \hbar\omega}}\right]^2$$

$$QE(\omega) = QE\Big|_{\hbar\omega=\phi_{eff}} + \frac{dQE}{d\hbar\omega}\Big|_{\hbar\omega=\phi_{eff}} (\hbar\omega - \phi_{eff}) + \frac{1}{2}\frac{d^2QE}{d\hbar\omega^2}\Big|_{\hbar\omega=\phi_{eff}} (\hbar\omega - \phi_{eff})^2 + \cdots$$

$$QE(\omega) \approx \frac{1 - R(\omega)}{1 + \frac{\lambda_{opt}(\omega)}{\bar{\lambda}_{e-e}(\omega)}} \frac{(\hbar\omega - \phi_{eff})^2}{8\phi_{eff}(E_F + \phi_{eff})}$$

$$\begin{aligned} F_{e\text{-}e}(\omega) &= \int_0^{\infty} f(s, \theta = 0, \omega) ds \\ &= \int_0^{\infty} \frac{1}{\lambda_{\mathrm{opt}}(\omega)} e^{-s\{[1/\lambda_{\mathrm{opt}}(\omega)] + (1/\bar{\lambda}_{e\text{-}e})\}} ds \\ &= \frac{1}{1 + \frac{\lambda_{\mathrm{opt}}(\omega)}{\bar{\lambda}_{e\text{-}e}}}. \end{aligned}$$

$$\bar{\lambda}_{e\text{-}e}(\omega) = \frac{\int_{\phi_{\mathrm{eff}}}^{\hbar\omega} \lambda_{e\text{-}e}(E) dE}{\int_{\phi_{\mathrm{eff}}}^{\hbar\omega} dE} = \frac{2\lambda_m E_m^{3/2}}{\hbar\omega\sqrt{\phi_{\mathrm{eff}}}} \frac{1}{\left(1 + \sqrt{\frac{\phi_{\mathrm{eff}}}{\hbar\omega}}\right)}.$$

More details: An Engineering Guide to Photoinjectors

transverse emittance in the three-step mode

$$\varepsilon_x = \sqrt{< x^2 >< x'^2 > - < xx' >^2} = \sqrt{\sigma_x^2 \sigma_{x'}^2 - \sigma_{xx'}^2} = \sigma_x \sigma_{x'}$$

$$\varepsilon_{xn} = \beta\gamma\varepsilon_x = \frac{1}{mc}\sqrt{\langle x^2\rangle}\sqrt{\langle p_x^2\rangle} = \sigma_x \sigma_{px}$$

$$\sigma_{p_x} \equiv \frac{\sqrt{\langle p_x^2\rangle}}{mc}$$

the dimensionless rms transverse momentum

$$\sigma_{p_x}^2 = \frac{\int_{E_F+\phi_{\mathrm{eff}}-\hbar\omega}^{\infty} dE[1 - f_{\mathrm{FD}}(E+\hbar\omega)]f_{\mathrm{FD}}(E)\int_{\cos\theta_{\max}(E)}^{1} d(\cos\theta)\int_0^{2\pi} d\Phi\, p_x^2 \int_0^{\infty} ds f(s, E, \theta, \omega)}{(mc)^2 \int_{E_F+\phi_{\mathrm{eff}}-\hbar\omega}^{\infty} dE[1 - f_{\mathrm{FD}}(E+\hbar\omega)]f_{\mathrm{FD}}(E)\int_{\cos\theta_{\max}(E)}^{1} d(\cos\theta)\int_0^{2\pi} d\Phi \int_0^{\infty} ds f(s, E, \theta, \omega)}$$

⇓

$$\sigma_{p_x} = \sqrt{\frac{\hbar\omega - \phi_{\mathrm{eff}}}{3mc^2}}$$

The normalized emittance

$$\varepsilon_n = \sigma_x \sigma_{p_x} = \sigma_x \sqrt{\frac{\hbar\omega - \phi_{eff}}{3mc^2}}$$

Mean Transverse Energy: $\mathrm{MTE} = \frac{1}{2}mv^2$

$$\mathrm{MTE} = \frac{1}{N}\sum_1^N \frac{p_{x,y}^2}{2m}$$

$$\varepsilon_n = \sigma_x \sigma_{p_x} = \sigma_x \sqrt{\frac{\mathrm{MTE}}{mc^2}}$$

Tsinghua University

Widely used (still not fully understood) photocathodes

	Metallic	Semi-conductor
QE	10^{-5}-10^{-3}	>10^{-2}
λ_{ph}	UV	UV-IR
$t_{response}$	~10 fs	>sub-ps
Vacuum	10^{-9} torr	<10^{-10} torr
Life time	years	up to months

Metal Cathodes	Wavelength & Energy: λ_{opt} (nm), $\hbar\omega$(eV)	Quantum Efficiency (electrons per photon)	Vacuum for 1000 Hr Operation (Torr)	Work Function, ϕ_W(eV)	Thermal Emittance (microns/mm(rms))	
					Theory	Expt.
Bare Metal						
Cu	250, 4.96	1.4×10^{-4}	10^{-9}	4.6 [34]	0.5	1.0±0.1 [39] 1.2±0.2 [40] 0.9±0.05 [3]
Mg	266, 4.66	6.4×10^{-4}	10^{-10}	3.6 [41]	0.8	0.4±0.1 [41]
Pb	250, 4.96	6.9×10^{-4}	10^{-9}	4.0 [34]	0.8	?
Nb	250, 4.96	~2 10^{-5}	10^{-10}	4.38 [34]	0.6	?
Coated Metal						
CsBr:Cu	250, 4.96	7×10^{-3}	10^{-9}	~2.5	?	?
CsBr:Nb	250, 4.96	7×10^{-3}	10^{-9}	~2.5	?	?

Typical MTE 0.5 eV → ~1 mrad

Common cathode materials:

- Metals: Cu, Mg, Au, Pb, …
- Semiconductors: Cs2Te, K2CsSb, GaAs

Cathode Type	Cathode	Typical Wavelength, λ_{opt}(nm), (eV)	Quantum Efficiency (electrons per photon)	Vacuum for 1000 Hrs (Torr)	Gap Energy + Electron Affinity, $E_A + E_G$ (eV)	Thermal Emittance (microns/mm(rms))	
						Theory	Expt.
PEA: Mono-alkali	Cs_2Te	211, 5.88 264, 4.70 262, 4.73	~0.1 - -	10^{-9} - -	3.5 [42] “ ”	1.2 0.9 0.9	0.5±0.1 [35] 0.7±0.1 [35] 1.2 ±0.1 [43]
	Cs_3Sb	432, 2.87	0.15	?	1.6 + 0.45 [42]	0.7	?
	K_3Sb	400, 3.10	0.07	?	1.1 + 1.6 [42]	0.5	?
	Na_3Sb	330, 3.76	0.02	?	1.1 + 2.44 [42]	0.4	?
	Li_3Sb	295, 4.20	0.0001	?	?	?	?
PEA: Multi-alkali	Na_2KSb	330, 3.76	0.1	10^{-10}	1+1 [42]	1.1	?
	$(Cs)Na_3KSb$	390, 3.18	0.2	10^{-10}	1+0.55 [42]	1.5	?
	K_2CsSb	543, 2.28	0.1	10^{-10}	1+1.1 [42]	0.4	?
	$K_2CsSb(O)$	543, 2.28	0.1	10^{-10}	1+<1.1 [42]	~0.4	?
NEA	GaAs(Cs,F)	532, 2.33 860, 1.44	~0.1 -	? ?	1.4±0.1 [42] ”	0.8 0.2	0.44±0.01 [44] 0.22±0.01 [44]
	GaN(Cs)	260, 4.77	-	?	1.96 + ? [44]	1.35	1.35±0.1 [45]
	GaAs(1-x)Px x~0.45 (Cs,F)	532, 2.33	-	?	1.96+? [44]	0.49	0.44±0.1 [44]
S-1	Ag-O-Cs	900, 1.38	0.01	?	0.7 [42]	0.7	?

Important References:

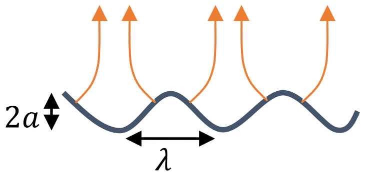
– *D. Dowell* et al. *Cathode R&D* for future light sources. NIMA 622:13 (2010)

– Photocathode Physics for Photoinjectors workshop series.

Simple metallic cathodes are not so simple

- Cu, most widely used, happen to be the cavity wall material
- 3-step model (excite, transport, escape) used to explain Cu
- Surface composition and morphology play significant roles

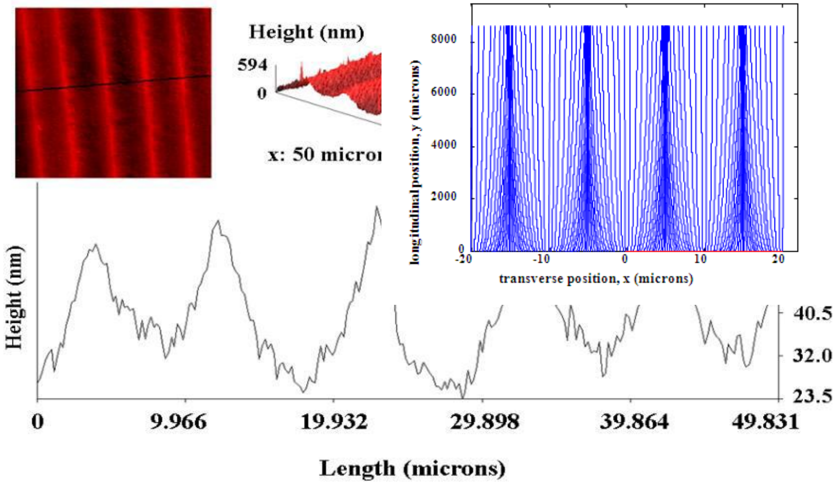
Physical Roughness



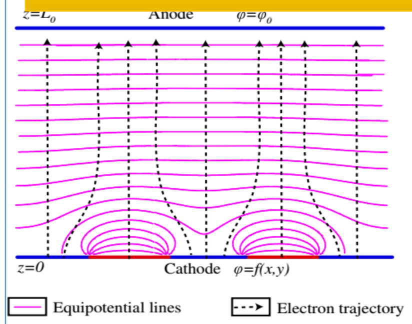
$$\text{MTE}_{field} = \frac{\pi^2 a^2 E_0 e}{2\lambda}$$

J. Feng, S. Karkare *et al*, J. Appl. Phys. 121, 044904 (2017)

Modulation amplitude = 20 nm
Spatial wavelength = 10 microns
Emittance = 0.15 microns /mm-rms



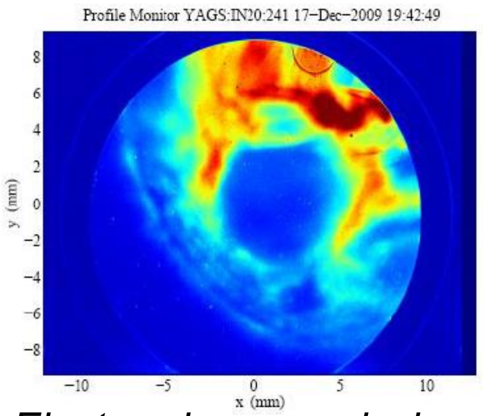
Chemical Roughness



$$\text{MTE}_{wf} = \frac{\pi^2 h^2 e}{4\sqrt{2} a E_0}$$

S. Karkare and I. Bazarov, Phys. Rev Applied, 4, 024015 (2015)

G. Gevorkyan et al. PRAB, 21, 093401(2018)



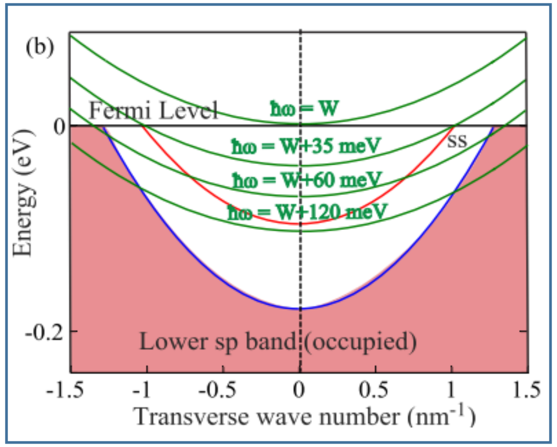
- Surface chemistry
- Morphology
- Optical absorption
- Electron scattering

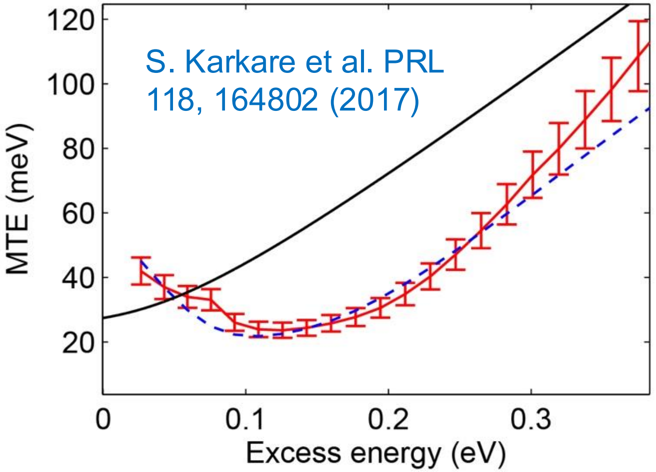
Electron beam emission image of the cathode after >1 yr of operation

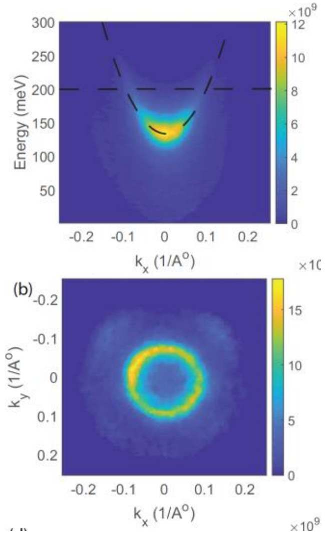
Ordered, Clean surface

- Laser skin depth typically ~10 nm for metallic photocathodes
- Clean, order surface has distinct band structure and can emit in one step

Effect surface state of Ag(111)



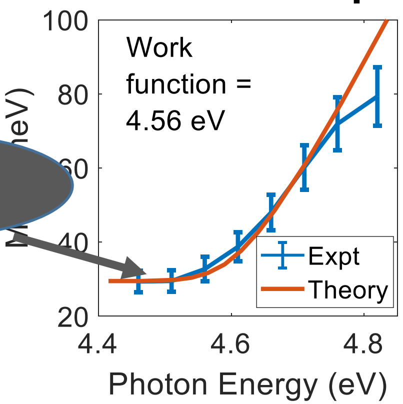




Room temp.
25 meV

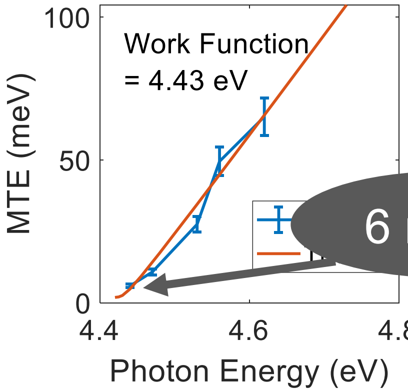
Cooled, clean Cu(100) surface

Room Temp.



30 meV

30 K

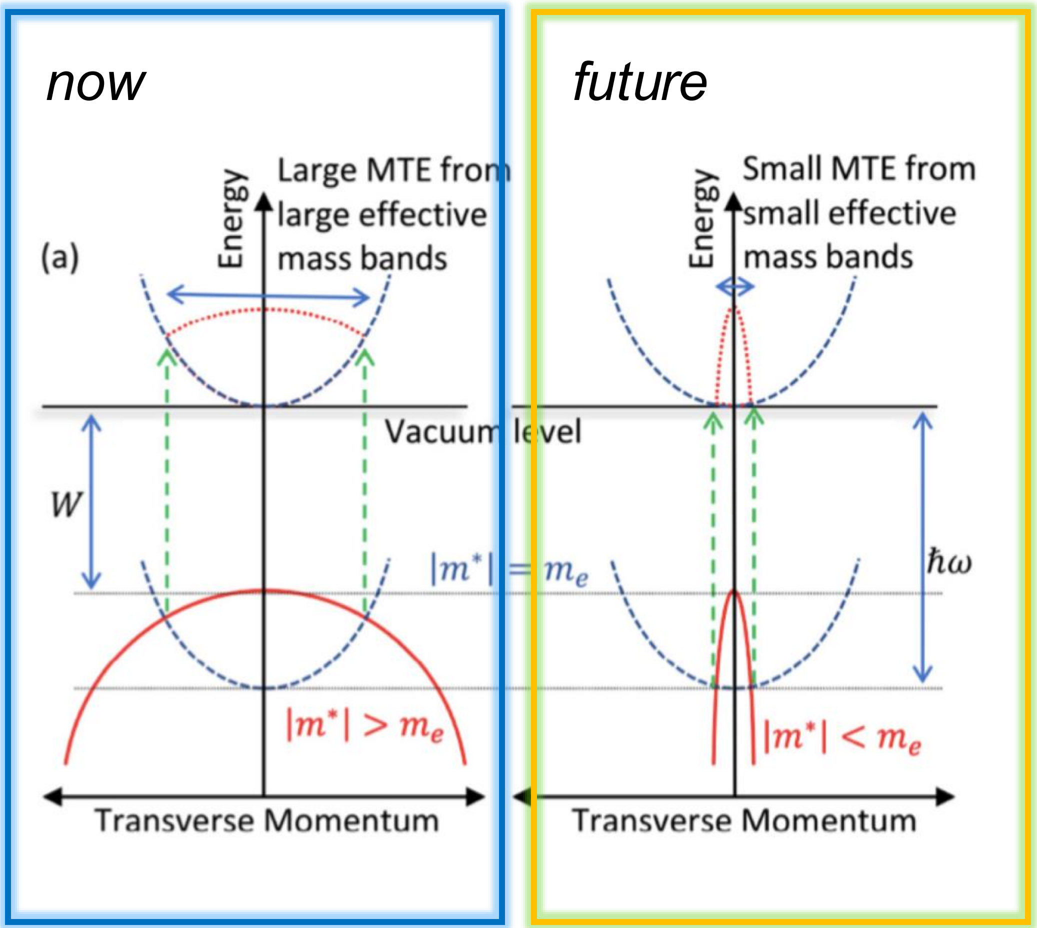


6 meV!!

S. Karkare et al. talk at
2018 P3 Meeting

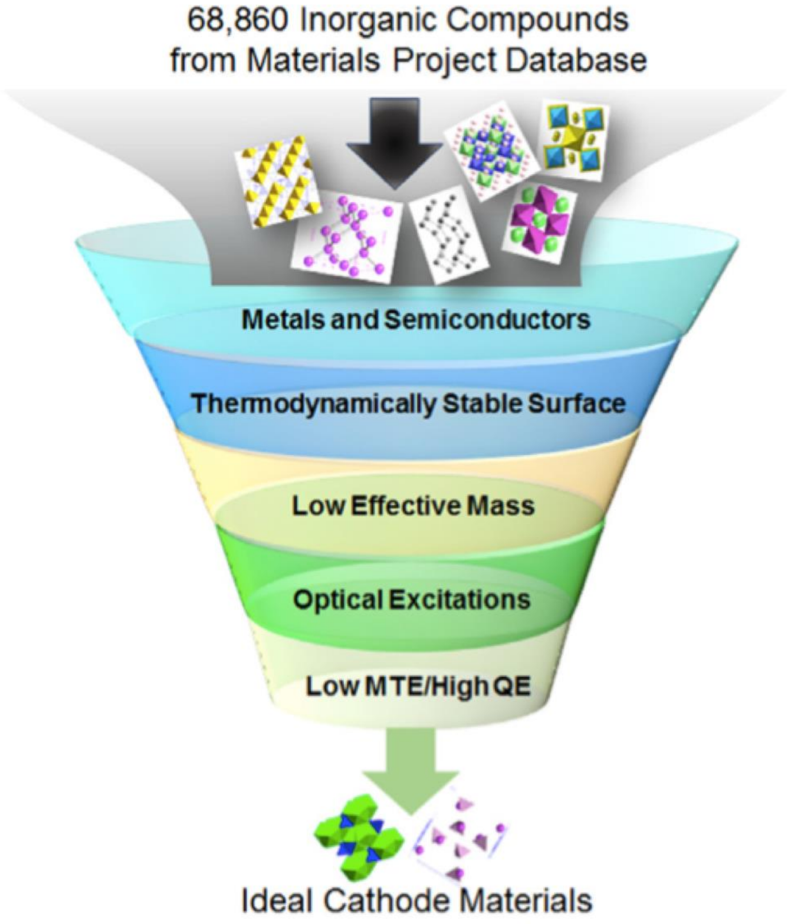
New photocathode materials by design

- Engineer materials with small effective mass & crystal-*k* conservation



Center for bright beam (CBB) website

- Computational screening of candidate materials



- Some topics in an electron gun
  - Emittance and phase space
  - Cathode and electron emission
  - Beam emittance in photo-cathode gun

Beam dynamics in photocathode RF gun

- Motion equation of an electron in electromagnetic field

$$\frac{d\boldsymbol{p}}{dt} = \boldsymbol{F} = e(\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B})$$

- Acceleration by longitudinal E-field

$$\frac{d\boldsymbol{p_z}}{dt} = \boldsymbol{F_z} = e\boldsymbol{E_z}$$

- Transverse bending/focusing/defocusing

$$\frac{d\boldsymbol{p_x}}{dt} = \boldsymbol{F_x} = e(\boldsymbol{Ex} - v_z\boldsymbol{B_y}) \qquad \frac{d\boldsymbol{p_y}}{dt} = \boldsymbol{F_y} = e(\boldsymbol{Ey} + vz\boldsymbol{B_x})$$

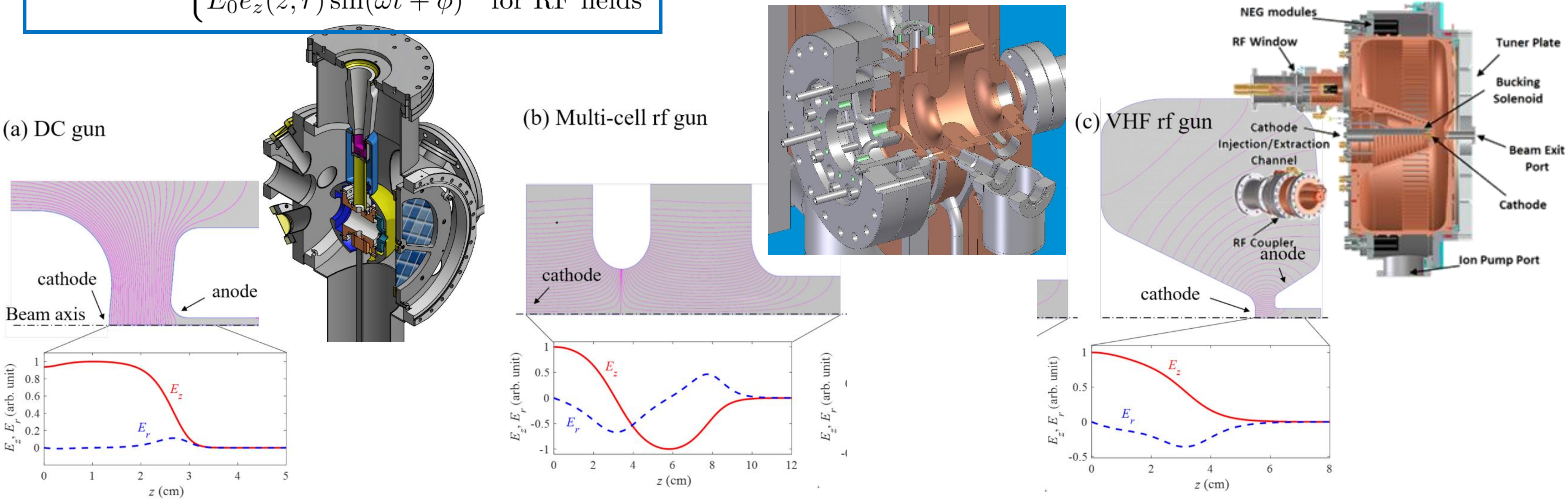
$$\frac{d\boldsymbol{p_r}}{dt} = \boldsymbol{F_r} = e(\boldsymbol{Er} - v_z\boldsymbol{B_\theta})$$

$(\boldsymbol{r}, \boldsymbol{\theta}, \boldsymbol{z})$ coordinate

Field in a gun

- Guns designed with quite different field distribution and strength
- DC gun, RF gun

$$E_z(z,r,t) = \begin{cases} E_0 e_z(z,r) & \text{for DC fields} \\ E_0 e_z(z,r)\sin(\omega t+\phi) & \text{for RF fields} \end{cases}$$



5-10MV/m

～100MV/m

20-30MV/m

Longitudinal acceleration

- DC gun

$$E(z,r,t) = E_0 e(z)$$

$$\frac{d\gamma}{dz} = \frac{eE_0 e(z)}{2mc^2} \qquad \gamma = \int_0^z \frac{d\gamma}{dz} dz = \frac{eE_0 \int_0^z e(z)dz}{2mc^2}$$

- RF gun (standing wave structure)

$$E(z,r,t) = E_0 e(z)\sin(\omega t + \phi_0)$$

define electron phase with respect to rf field as

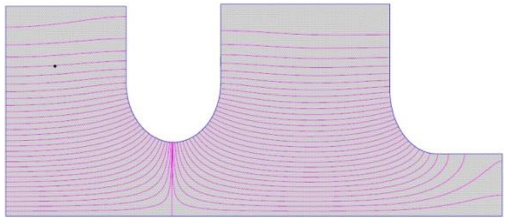
$$\phi = \omega t - kz + \phi_0 \quad \text{or} \quad \phi = k\int_0^z \left(\frac{\gamma}{\sqrt{\gamma^2 - 1}}\right) dz + \phi_0$$

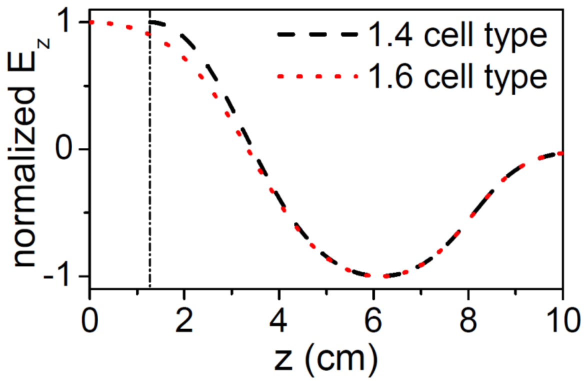
$$\frac{d\gamma}{dz} = \frac{eE_0 e(z)\sin(\omega t + \phi_0)}{2mc^2}$$ can be calculated with Runge-Kutta method

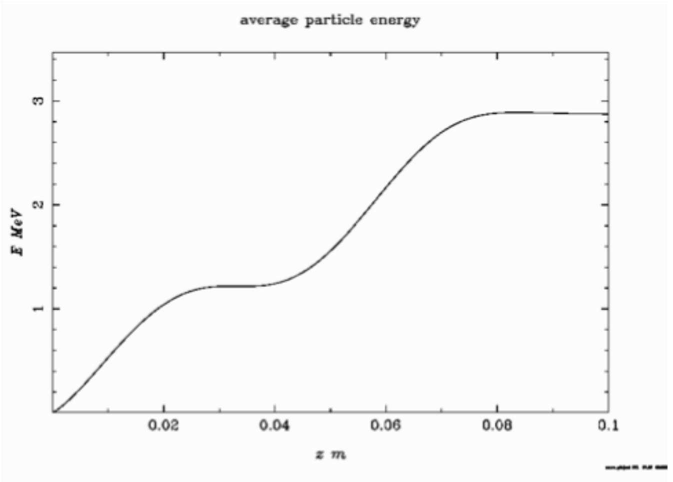
For 1.5cell pi-mode RF gun, $E(z,r,t) \approx E_0 \cos kz \sin(\omega t + \phi_0)$

$$\frac{d\gamma}{dz} = \frac{eE_0[\sin(\phi) + \sin(\phi + 2kz)]}{2mc^2}$$

1.6 cell type

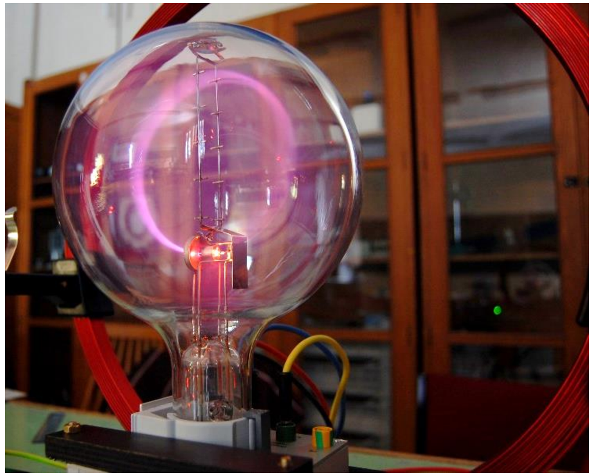


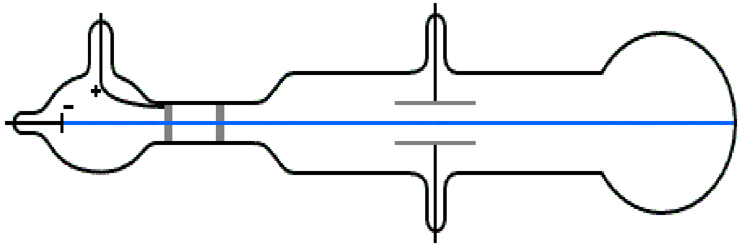




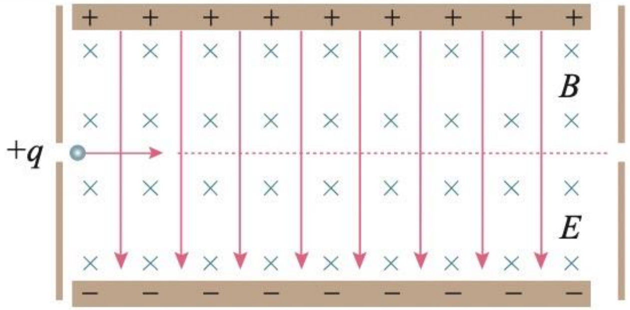
Transverse motion

$$\frac{d\boldsymbol{p}_x}{dt} = \boldsymbol{F}_x = e(\boldsymbol{E}\boldsymbol{x} - v_z \boldsymbol{B}_y)$$

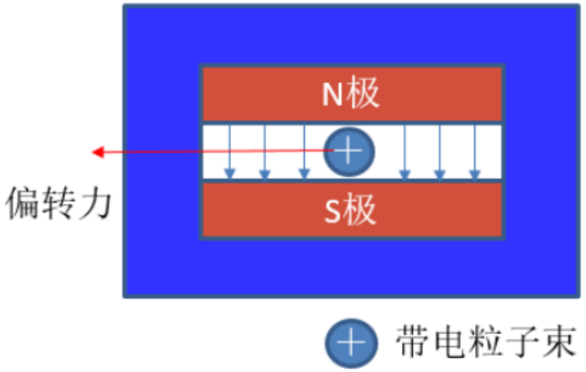




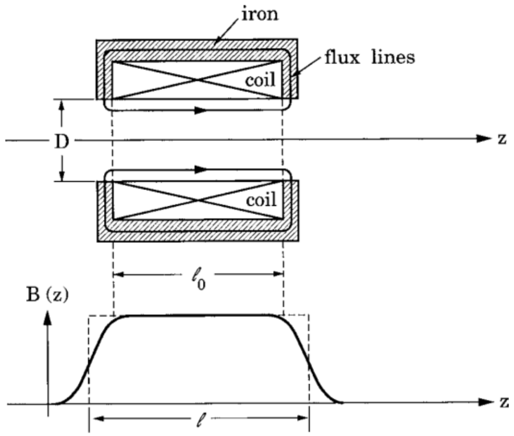
带电粒子速度选择器



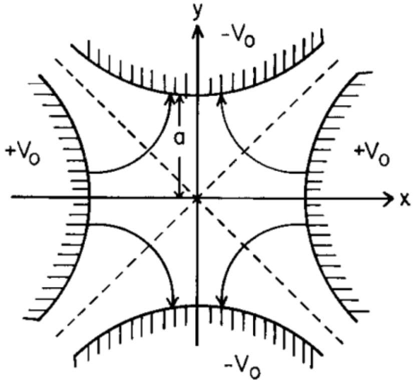
$$v = E/B$$

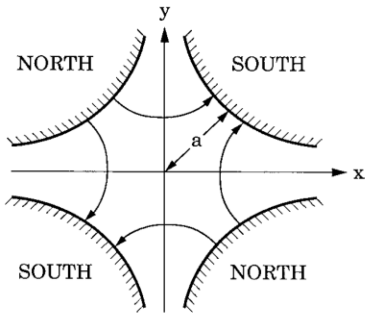


$$p = erB$$



$$\frac{1}{f} = -\frac{\Delta r'}{r} = \left(\frac{e}{2mc\beta\gamma}\right)^2 \int_{z_1}^{z_2} B^2 dz$$





$$\kappa = \frac{eV_0/a}{\gamma\beta^2 m_0 c^2}$$

$$\kappa = \frac{eB_0/a}{\gamma\beta m_0 c}$$

Emittance growth due to rf field

- With longitudinal E-field E_z, transverse fields can be found from Maxwell equations(paraxial approximation):

$$E_r = -\frac{r}{2}\frac{\partial E_z}{\partial z} \qquad eB_\theta = \frac{r}{2}\frac{\partial E_z}{\partial t}$$

$$F_r = e(E_r - \beta c B_\theta) - \frac{r}{2}\frac{\partial E_z}{\partial z} \qquad E(z,r,t) = E_0 e(z)\sin(\omega t + \phi_0) \approx E_0 \cos(kz)\sin(\omega t + \phi_0)$$

$$F_r = er\left\{-\frac{1}{2c}\frac{d}{dt}\left[E(z)\sin kz\cos(\omega t+\phi_0)\right] - \frac{1}{2}\left[\frac{dE(z)}{dz}\right]\cos kz\sin(\omega t+\phi_0) + \frac{\beta}{2}\left[\frac{dE(z)}{dz}\right]\sin kz\cos(\omega t+\phi_0)\right\}$$

Assume transverse deflection is small, r can be regards as constant and integrate the equation of radial motion give the radial impulse

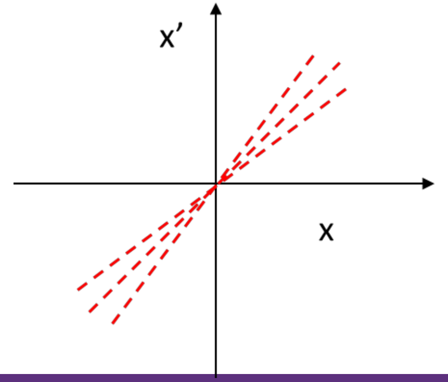
0 for axial symmetric field

Phase dependence

$$p_r = \frac{1}{mc}\int_0^f F_r dt \qquad p_r = p_{r0} + \alpha k r\left[\beta\cos z_f \sin(\omega t + \phi_0) - \sin k z_f \cos(\omega t + \phi_0)\right] \approx \alpha k r \sin\phi$$

Emittance increase due to transverse rf field:

$$\varepsilon_x^{rf} = \sqrt{\langle x^2\rangle\langle p_x^2\rangle - \langle x p_x\rangle^2} \approx \alpha k r \langle x^2\rangle\sqrt{\langle\sin^2\phi\rangle - \langle\sin\phi\rangle^2} \approx \frac{eE_0}{2mc^2}\frac{\langle x^2\rangle\sigma_\phi^2}{\sqrt{2}}$$



Emittance growth due to multipole field in gun

- Previous page gives the emittance growth due to monopole field in the gun
- Non-axisymmetric structure excites multipole field components, such as the dipole, quadrupole, and octopole, which kick the beam time dependently, leading to the emittance growth

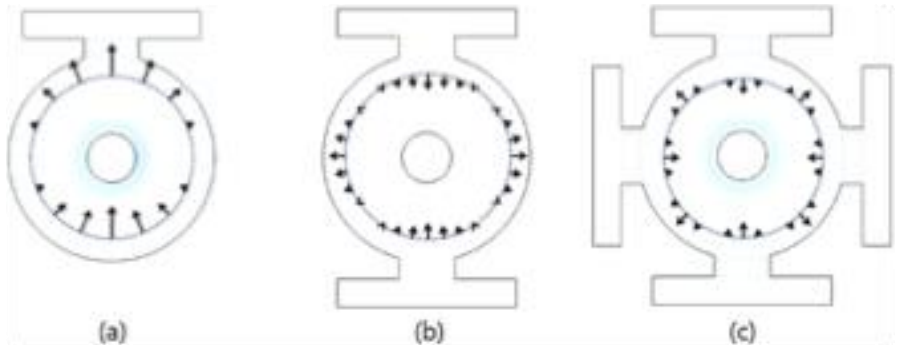
$$E_z^{110} \approx E_1 \sin(\omega t + \phi_0)\cos(kz)\, J_1(k_c r)\cos\left(\theta - \frac{\pi}{2}\right) = \alpha_{110}\, E_0 \sin(\omega t + \phi_0)\cos(kz)\, y$$

$$p_y^{110} \approx -\alpha_{110}\alpha L \sin\phi_0\, \hat{y}$$

$$\varepsilon_{n,y}^{110} \approx \alpha_{110}\alpha L \cos\phi_0\, \sigma_y \sigma_\phi$$

$$E_z^{210} \approx \alpha_{210}\, E_0 \sin(\omega t + \phi_0)\cos(kz)\,(x^2 + y^2)$$

$$\varepsilon_{n,y}^{210} \approx 2\alpha_{210}\alpha L \cos\phi_0\, \sigma_y^2 \sigma_\phi$$



Schematic drawing of each multipole mode in the rf gun. (a) Dipole mode. (b) Quadrupole mode. (c) Octopole mode.

$\alpha_{110}, \alpha_{210}$: ~10^{-4} to 10^{-6} for fine designed RF structure, emittance growth : ~0.01-0.1 mm mrad

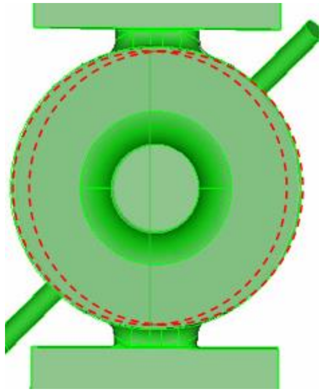
CHAE et al, Phys. Rev. ST Accel. Beams 14, 104203 (2011)

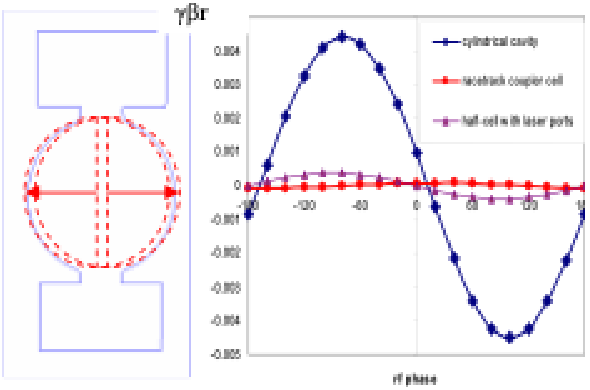
Emittance growth due to multipole field in gun

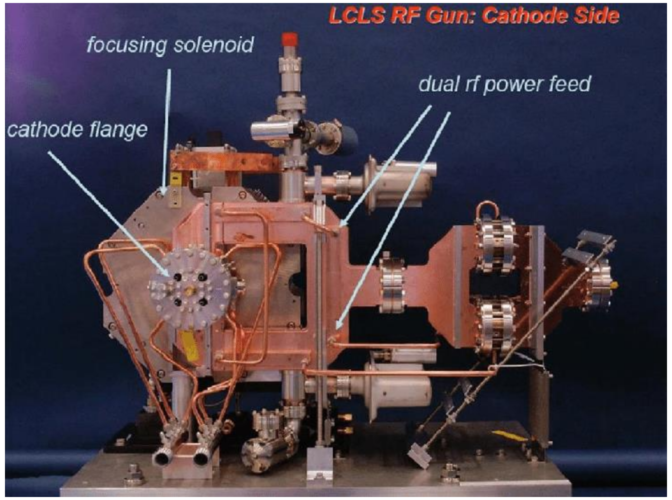
Structure design to eliminate the multipole

SLAC LCLS gun design

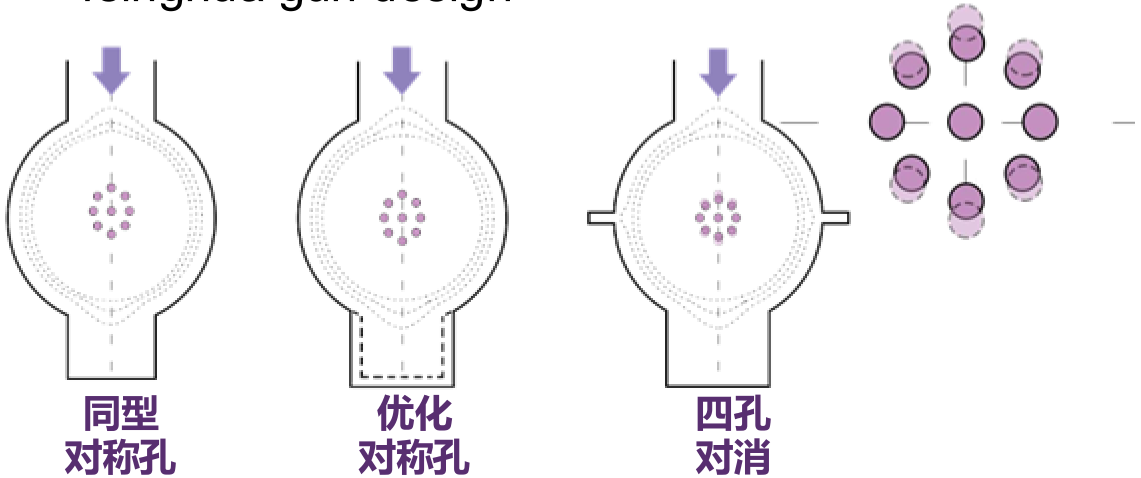
Dual feed + racetrack

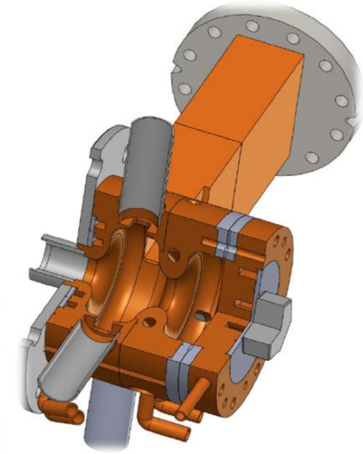






Tsinghua gun design





Houjun Qian et. al, NIMA 597, 121 (2008)

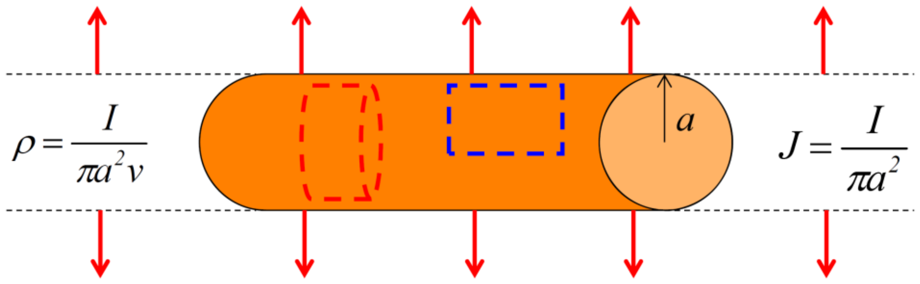
Xin Guan et. al, NIMA 574, 17 (2007)

Emittance growth due to space charge (SC) forces

- For infinite length, uniform beam, the E-M field generated by beam:

$$\int \varepsilon_0 E \cdot dS = \int \rho dV \qquad \int B \cdot dl = \int \mu_0 J \cdot dS$$

$$2\pi r l \cdot \varepsilon_0 E_r = \rho \cdot \pi r^2 l \qquad B_\theta \cdot 2\pi r = \mu_0 J \cdot \pi r^2$$



$$E_r = \frac{\rho r}{2\varepsilon_0} = \frac{Ir}{2\pi\varepsilon_0 a^2 v} \text{ for } r \le a \qquad B_\theta = \frac{\mu_0 J r}{2} = \frac{\mu_0 I r}{2\pi a^2} \text{ for } r \le a$$

- The force to the electron

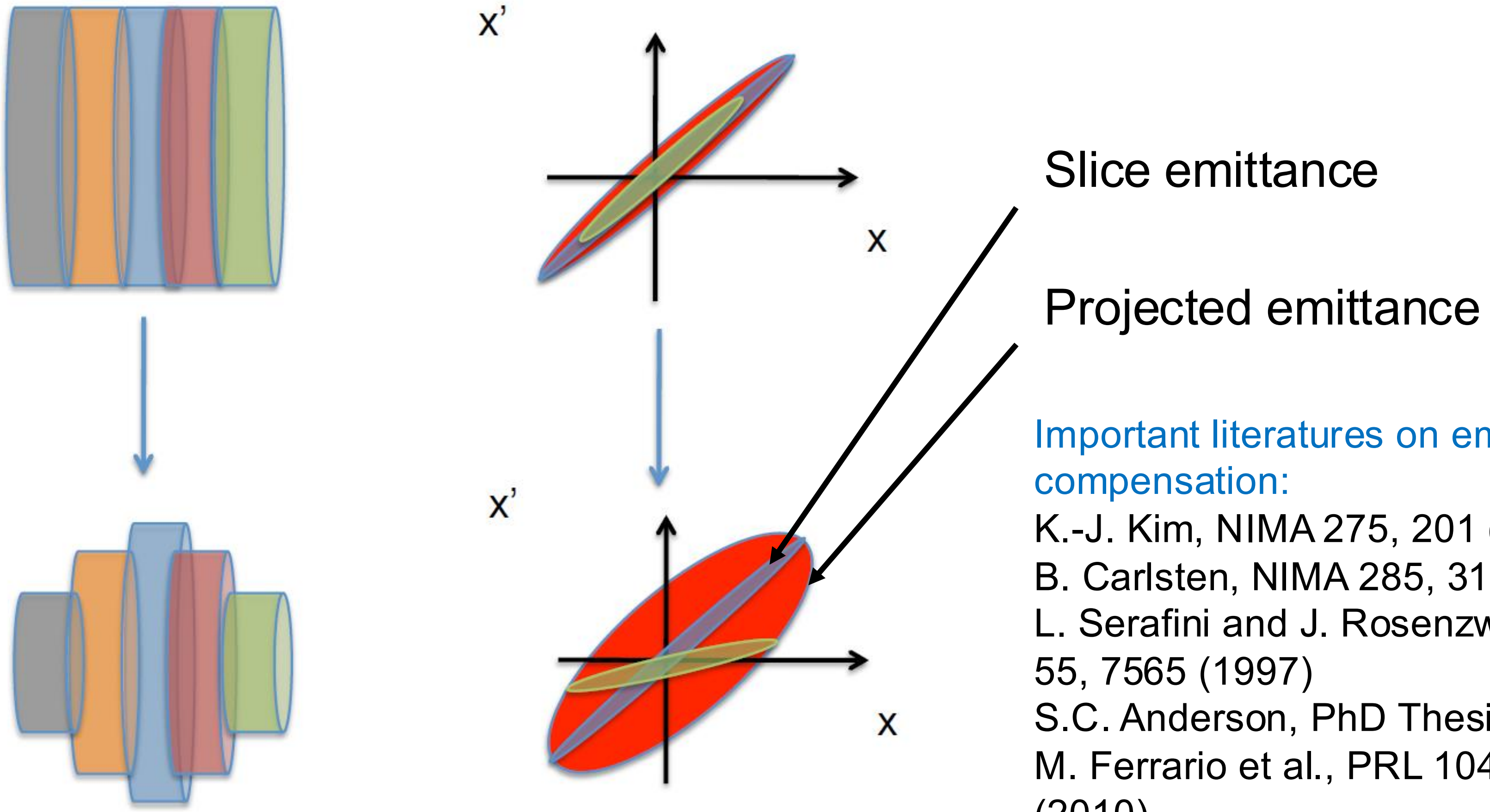
$$F_r = e(E_r - \beta c B_\theta) = e(1-\beta^2)E_r = \frac{eE_r}{\gamma^2}$$

- Equation of motion:

$$\frac{d^2 r}{dz^2} = \frac{eI}{2\pi m \gamma^3 \varepsilon_0 a^2 v^3} r = \frac{K}{a^2} r, \text{ 其中 } K = \frac{2I}{I_A(\beta\gamma)^3}, \; I_A = \frac{4\pi\varepsilon_0 m c^3}{e}$$

Emittance growth due to space charge (SC) forces

- Beam dynamics are almost decoupled in longitudinal and transverse directions
- Thus we usually treat the entire beam as many slices
- SC acts as defocusing lens, and the strength ∝ charge density of each slice
- There is slight different for each slice with finite length bunch

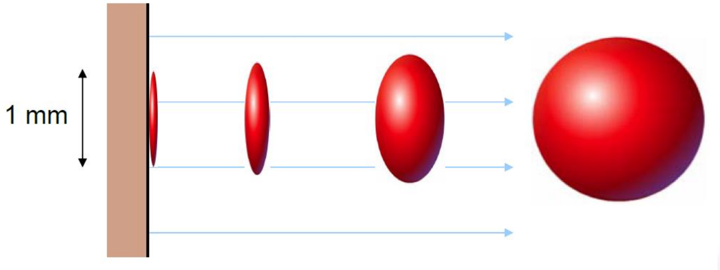


Important literatures on emittance compensation:

K.-J. Kim, NIMA 275, 201 (1988)
B. Carlsten, NIMA 285, 313 (1989)
L. Serafini and J. Rosenzweig, PRE 55, 7565 (1997)
S.C. Anderson, PhD Thesis (2002)
M. Ferrario et al., PRL 104, 054801 (2010)

Beam shaping via laser shaping

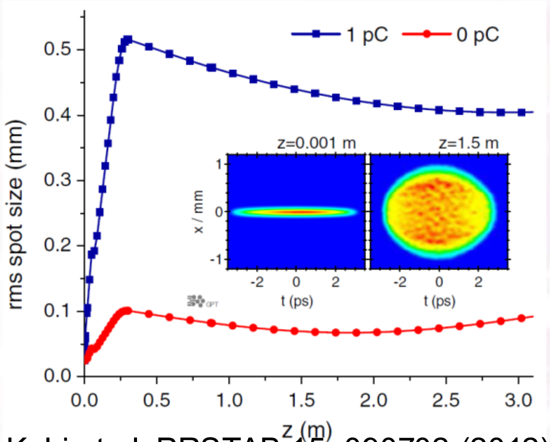
Pancake: a transversely spherical, ultrashort electron beam



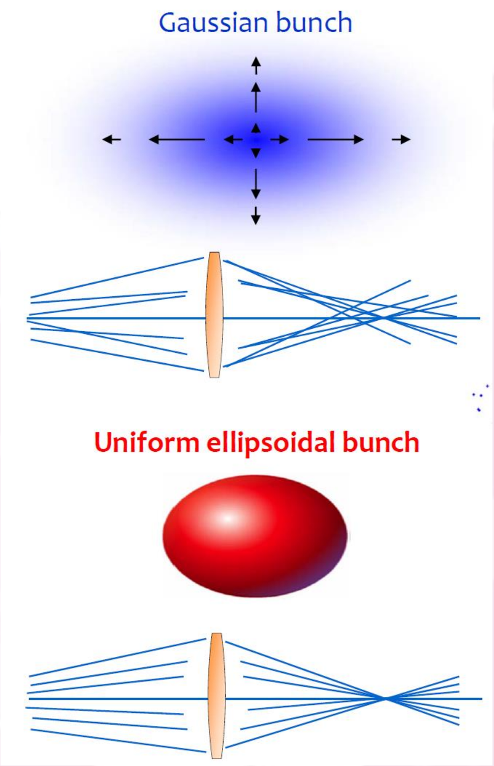
Luiten et al., PRL 93, 094802 (2004)

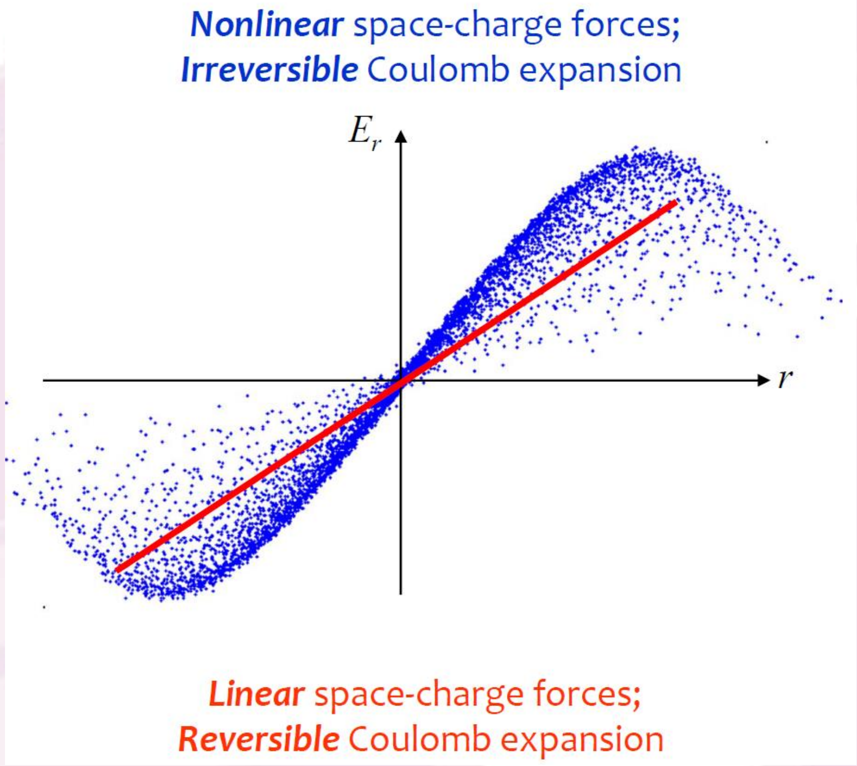
Cigar: a longitudinally parabolic, relatively long electron beam

- Transverse expansion
- Much lower emittance (10s of nm)



R. K. Li et al, PRSTAB 15, 090702 (2012)





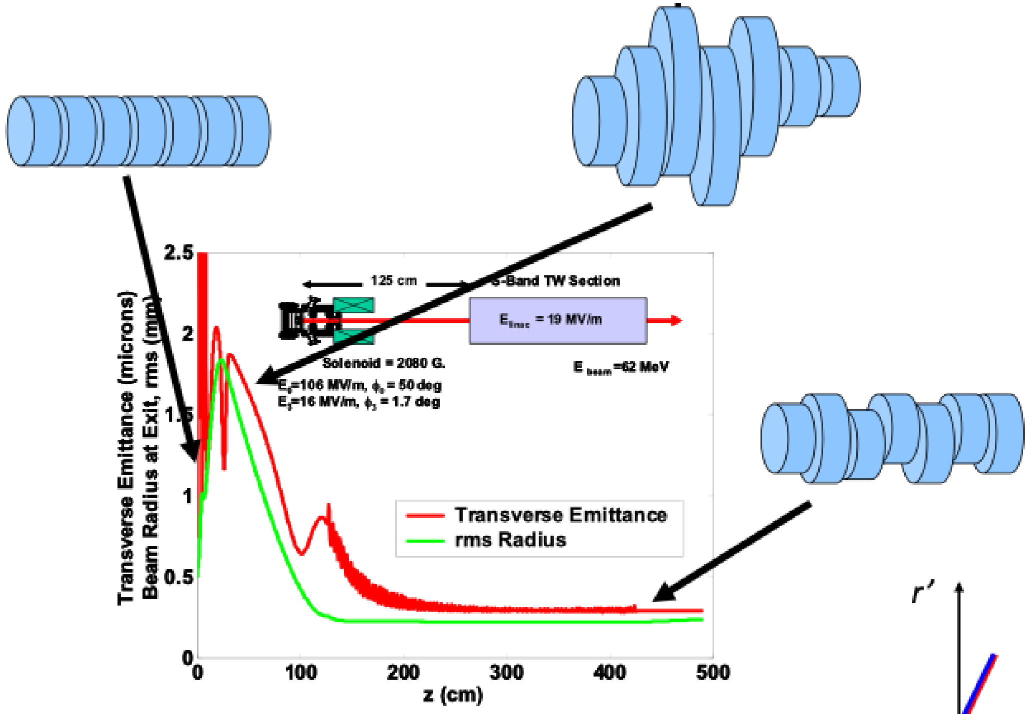
$$\left(\frac{x}{A}\right)^2 + \left(\frac{y}{B}\right)^2 + \left(\frac{z}{C}\right)^2 = 1$$

$$\vec{E} = (E_x, E_y, E_z) = \frac{\rho_0}{\varepsilon_0}(M_x x, M_y y, M_z z)$$

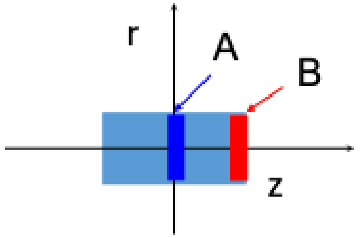
Kapchinskii and Vladimirskii, 1959
Luiten et al., PRL 93, 094802 (2004)

Emittance oscillation and compensation in a photo-injector

- slice phase space is rotated and oscillation with rf field, space charge force, solenoid focusing field
- Emittance due to the linear space charge force, rf field, solenoid can be compensated, but it's not all
- minimum projected emittance achieves when phase space of most of slices are aligned



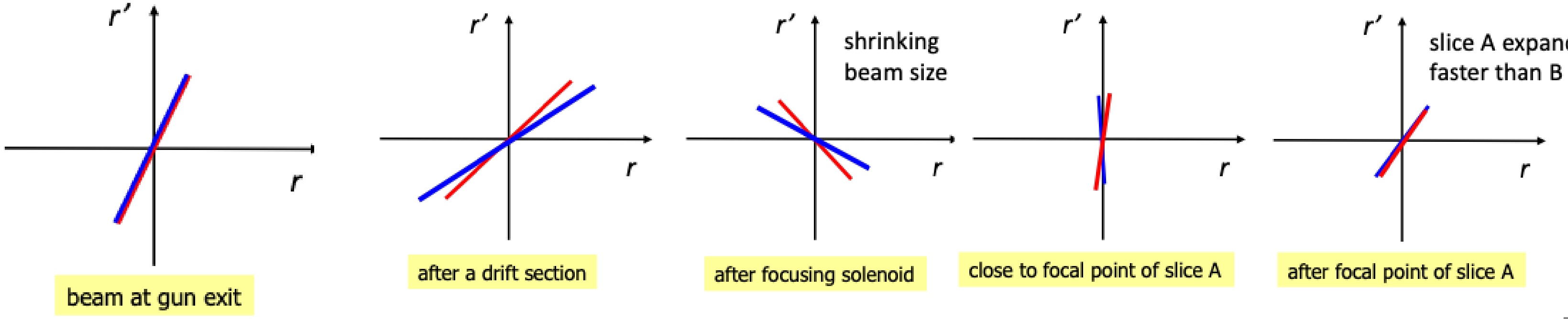
Evolution of normalized RMS emittance and RMS beam size



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

Important literatures on emittance compensation:

K.-J. Kim, NIMA 275, 201 (1988)
B. Carlsten, NIMA 285, 313 (1989)
L. Serafini and J. Rosenzweig, PRE 55, 7565 (1997)
S.C. Anderson, PhD Thesis (2002)
M. Ferrario et al., PRL 104, 054801 (2010)



Total emittance

- Total emittance of a beam from photo-injector

$$\varepsilon_{total} = \sqrt{\varepsilon_{thermal}^2 + \varepsilon_{rf}^2 + \varepsilon_{sc}^2 + \varepsilon_{optics}^2 + \cdots}$$

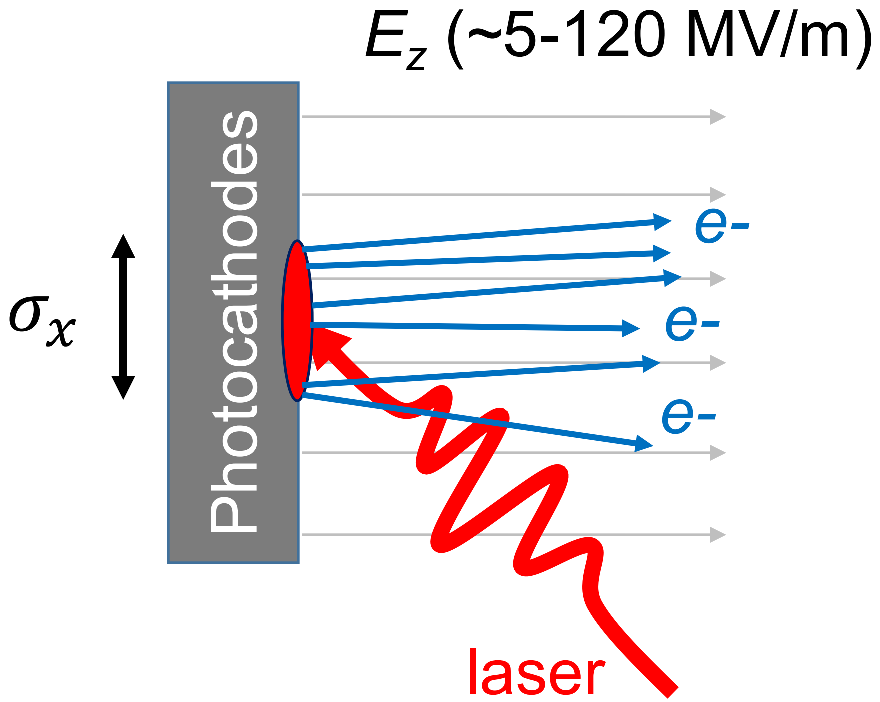
$\varepsilon_{thermal}$: initial emittance from cathode, depended on the emission process, minimum emittance which can be achieved

ε_{rf}: rf field is time varying and kick the beam time dependently, leading to the emittance growth

ε_{sc}: linear space charge forces effects can be compensated by solenoid; non-linear space charge forces leading to emittance growth; pulse shaping, high gun gradient are very helpful.

ε_{optics}: Aberrations of magnetic lenses

Performance limit of electron sources



4D beam brightness

$$\mathcal{B}_{4D} \propto f_e \frac{N}{\left(\sigma_x \cdot \sqrt{\mathrm{MTE}}\right)^2}$$

Mean Transverse Energy $\mathrm{MTE} = \frac{1}{2} m v^2$

Preservation of the brightness f_e

$$\mathcal{B}_{4\mathrm{D}} \propto f_e \frac{E_z}{\mathrm{MTE}}$$ for pancake (A>>1) beam, where aspect ratio

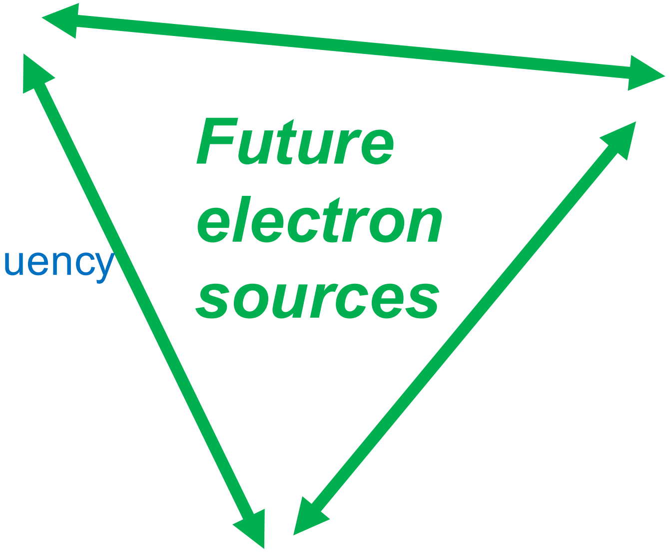
PRL 102, 104801

$$A = \frac{\sigma_x m_e}{\sigma_t^2 E_z e}$$

$$\mathcal{B}_{4\mathrm{D}} \propto f_e \frac{E_z^{3/2}}{\mathrm{MTE}} \frac{\sigma_t}{\sigma_x^{1/2}}$$ for cigar shape (A<1) beam

PRAB 17, 024201

Strategy to generate brighter beams



E_z, *Higher gradient*

New materials
Surface processing
DC vs rf, higher frequency
Local enhancement

f_e, *Brightness preservation*

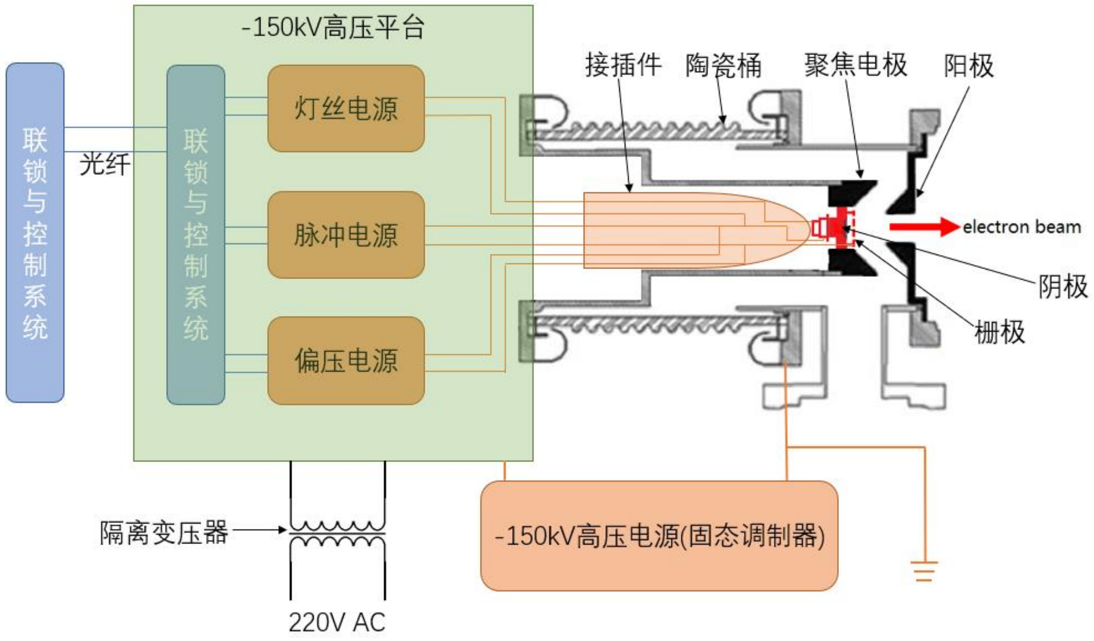
Emittance compensation
Beam shaping
Aberration control
Precise characterization

Lower MTE

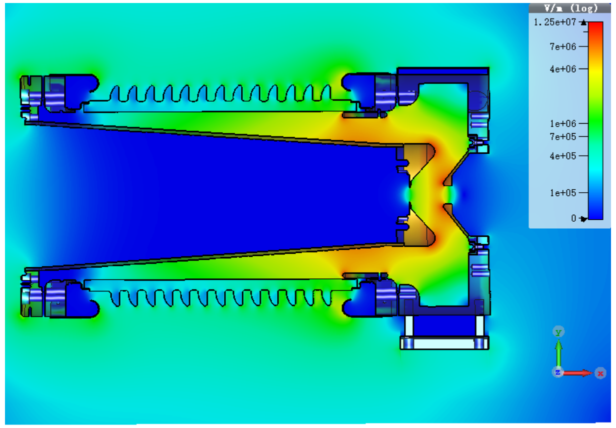
New cathode material
Cooling
Tuning laser wavelength
Cathode by design

Typical guns for accelerators

High voltage gridded thermionic cathode electron gun



参数名称	数值	单位
宏脉冲电荷量	0.5~10	nC
束流脉冲半高全宽	≤1.0	ns
束流脉冲底宽	≤1.6	ns
非归一化4*RMS发射度	≤30	μm·rad
阴极高压	≥150	kV
高压稳定度	≤0.5	%
重复频率	50	Hz
工作模式	单脉冲	-



Maximum gradient at surface:~12.5MV/m

(a)

The 140 kV Electron Gun System for Taiwan Light Source

Ion pump

electron gun in ceramic HV insulator

corona shields

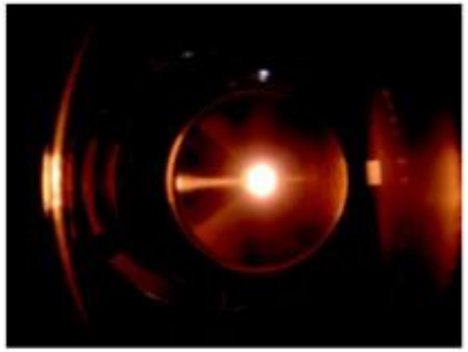
HV insulator

HVDC power supply

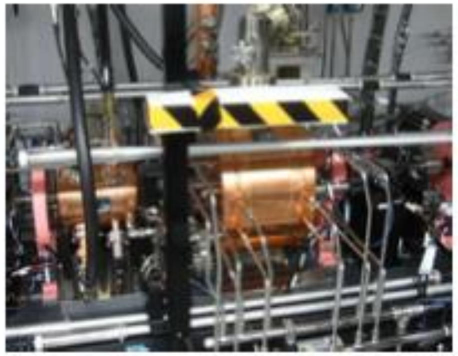
Thermionic gun for low emittance beam(SACLA injector)

30 MeV Low Emittance Thermionic Gun Injector

500 kV, 60 Hz pulser

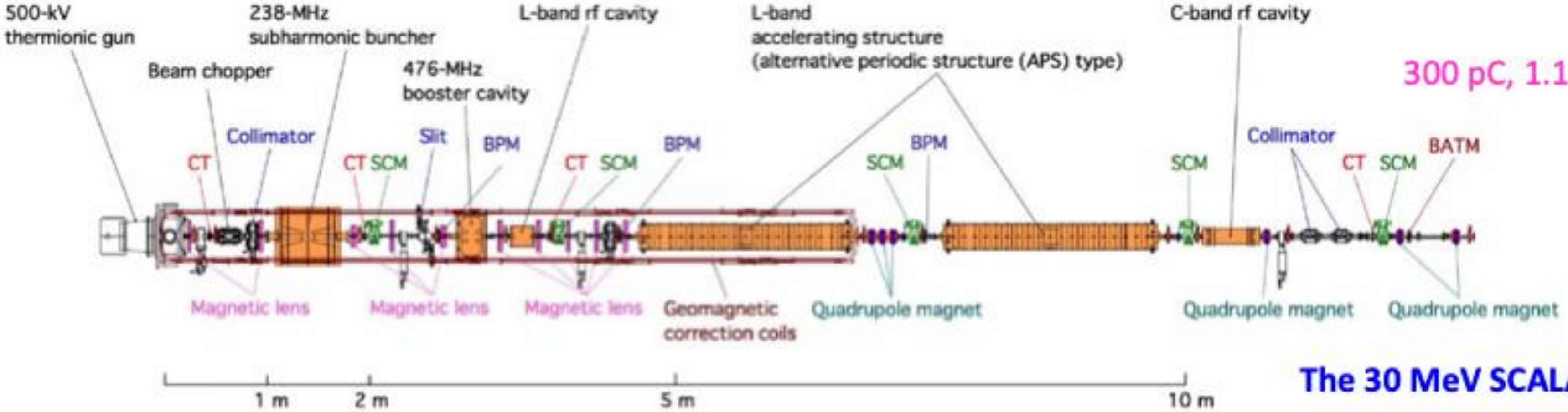


Thermionic gun with ϕ 3mm CeB_6 cathode



476 MHz booster cavity + L-band correction cavity

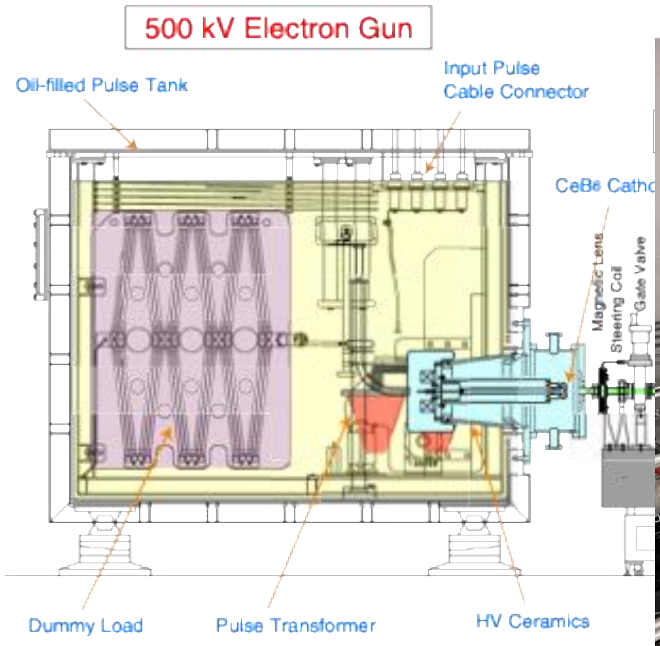
L-band linac

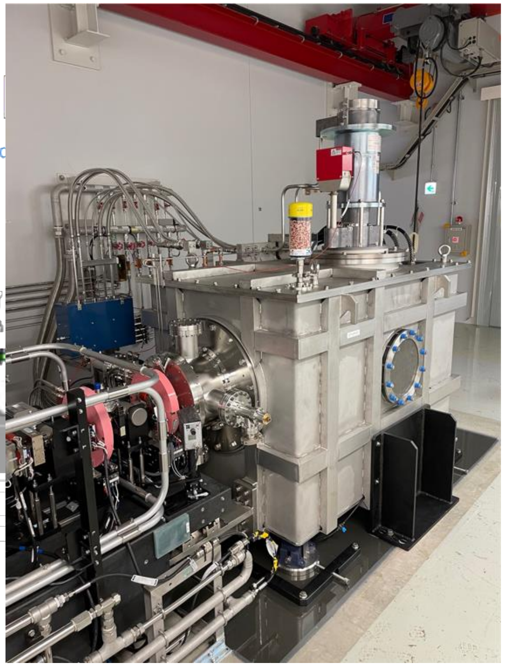


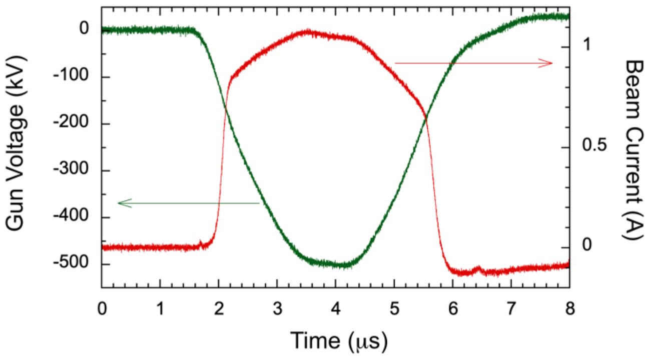
300 pC, 1.1 mm-mrad

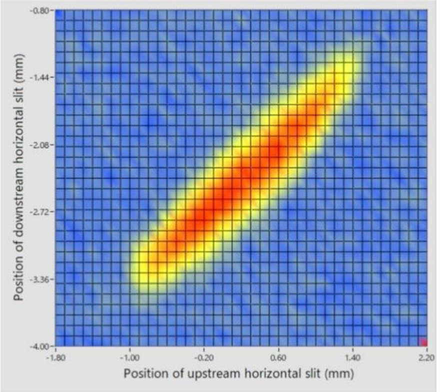
The 30 MeV SCALA XFEL injector

Thermionic gun for low emittance beam(SACLA injector)

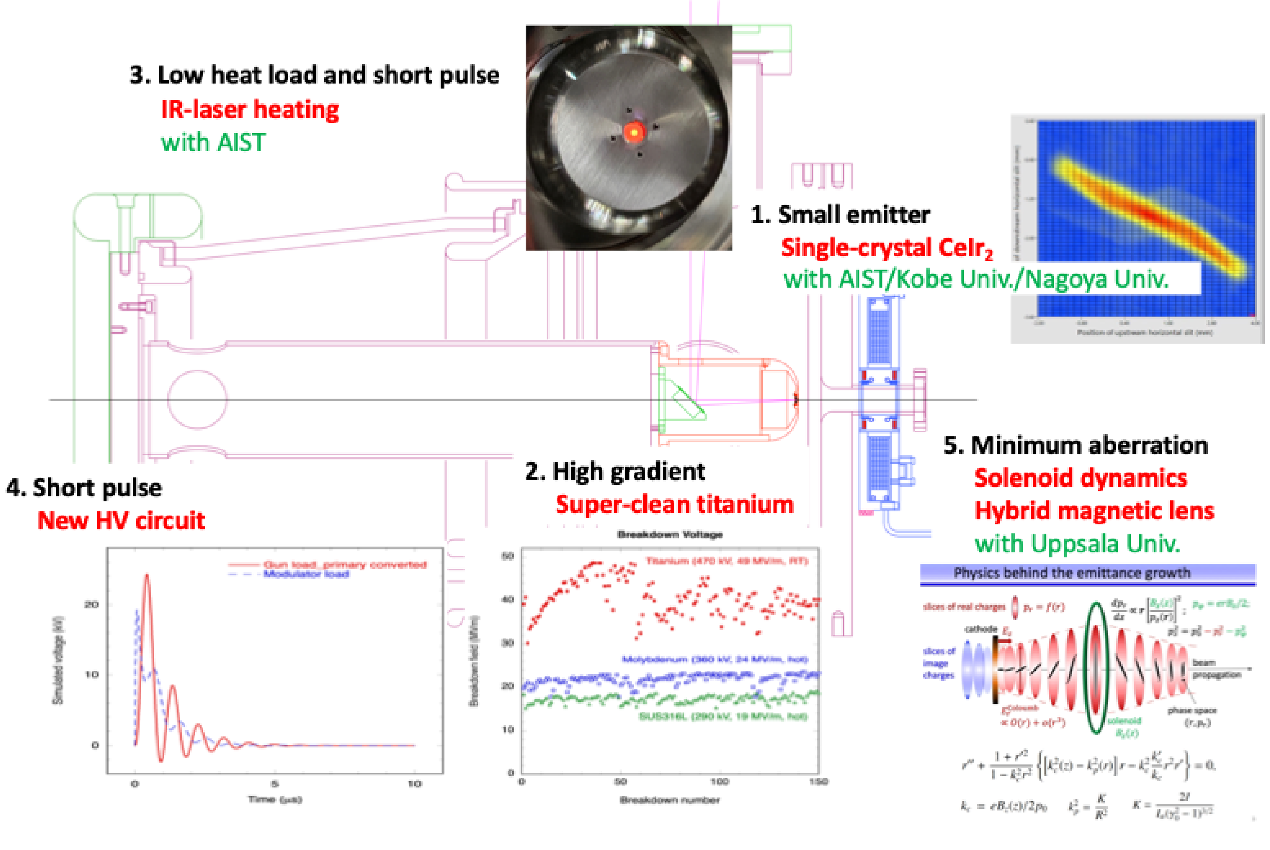






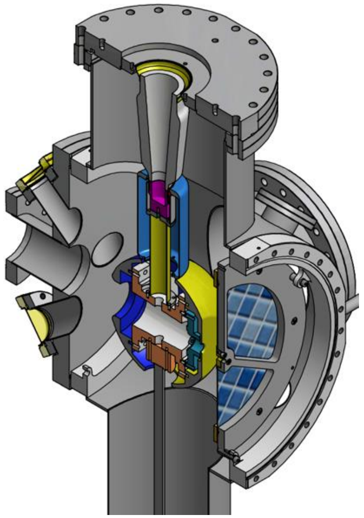


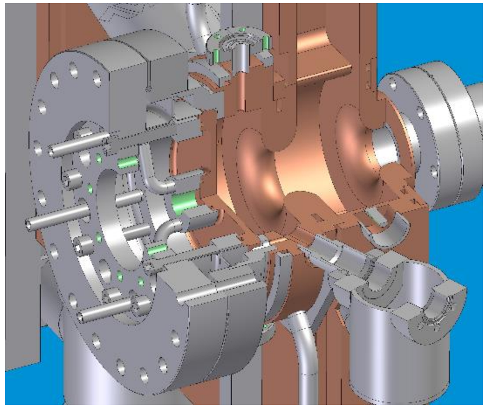
Toward ultimate-brightness thermionic electron gun

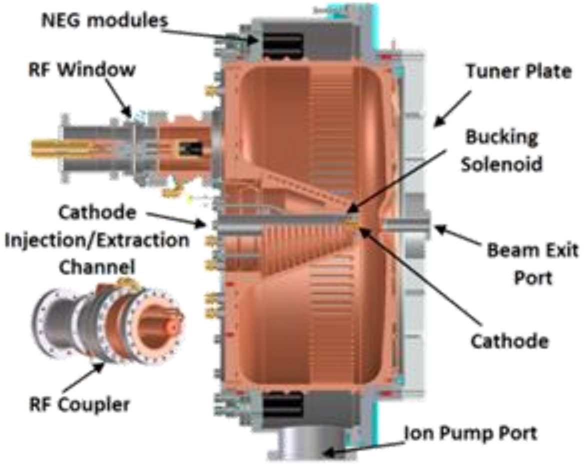


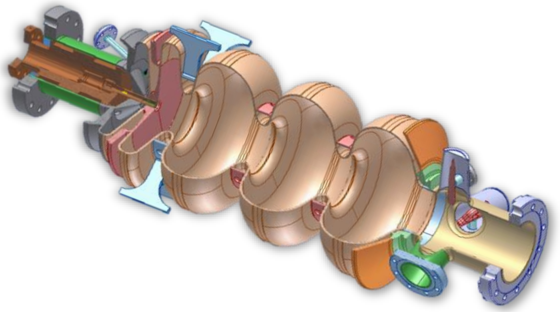
Only 1-ns cut by chopper Normalized emittance 0.4 μm

high brightness photocathode guns





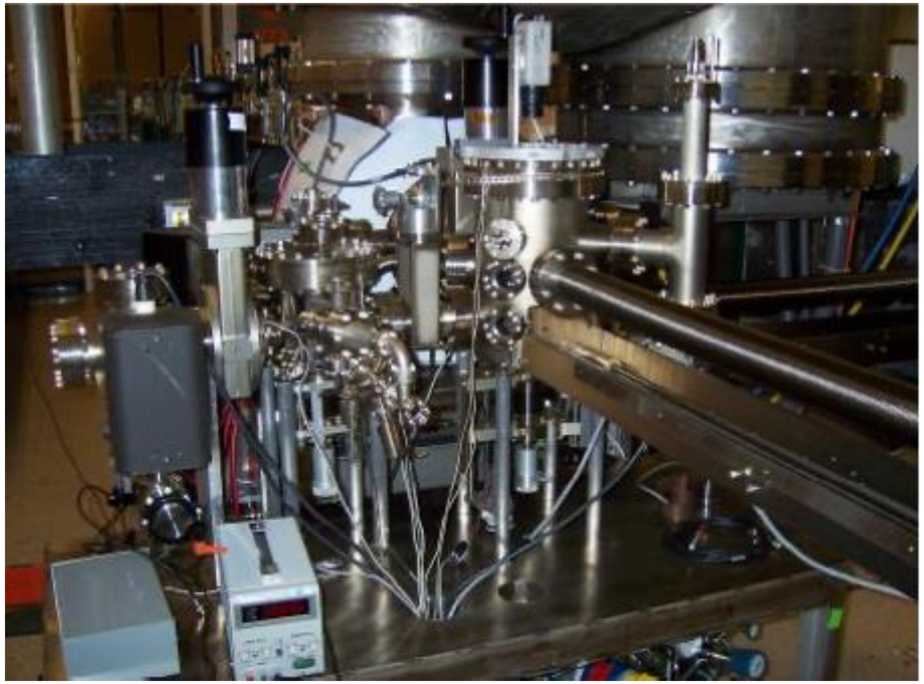




	DC	Pulsed NC RF	CW NC RF	SRF
Cathode environment	Good vacuum, cold	Worse vacuum, hot	Worse vacuum, hot	Good vacuum, cold
Gradient	<10 MV/m	~100-120MV/m	20(35) MV/m	~20(40) MV/m
Energy	<0.5 MeV	5MeV	0.75(1.5-2) MeV	>2 MeV
Main challenge	Limited gradient and energy	Limited repetition	Heat load, operation reliability	cavity-cathode joint, cavity contamination

Tsinghua University

Cornell photocathode DC gun



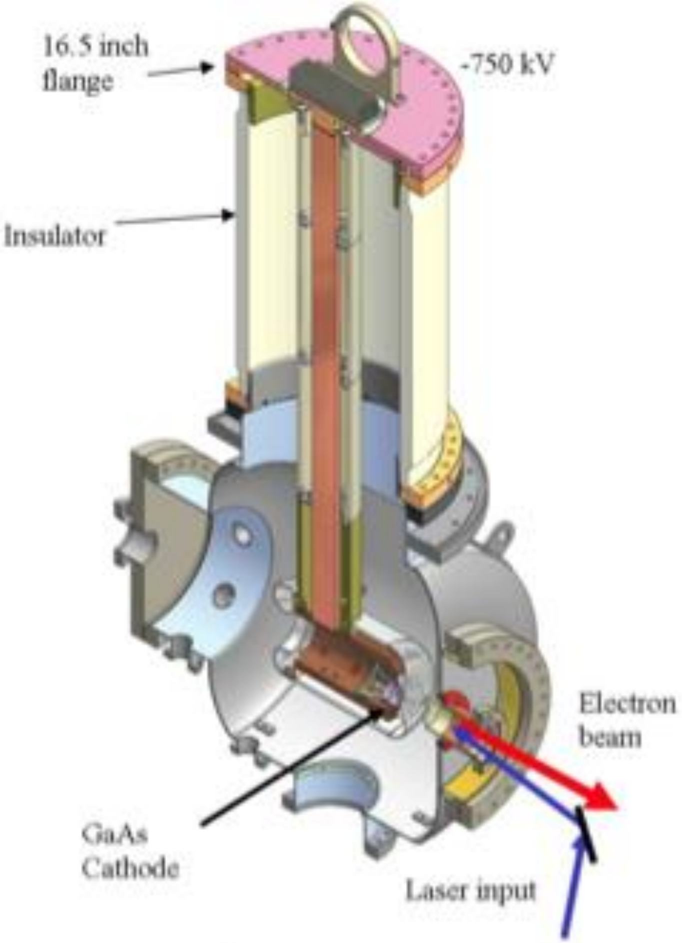
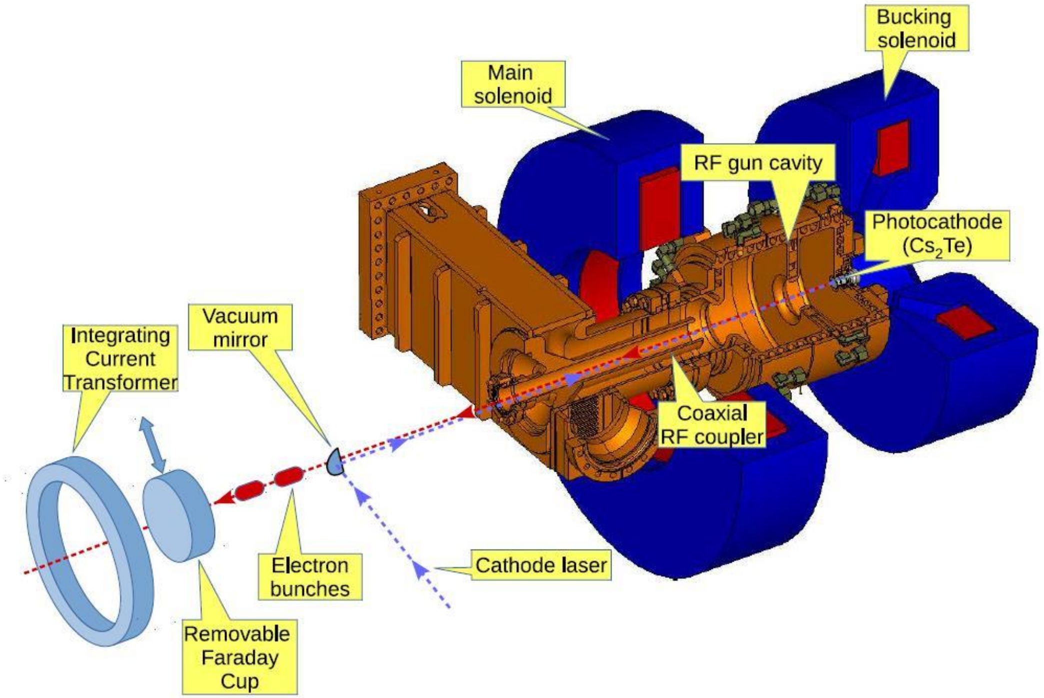


FIGURE 2. The Cornell Photoemission Gun.

- High QE cathode to minimize laser heating
- 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 has been demonstrated.
- Stable operation at ~ 400 kV

The PITZ gun

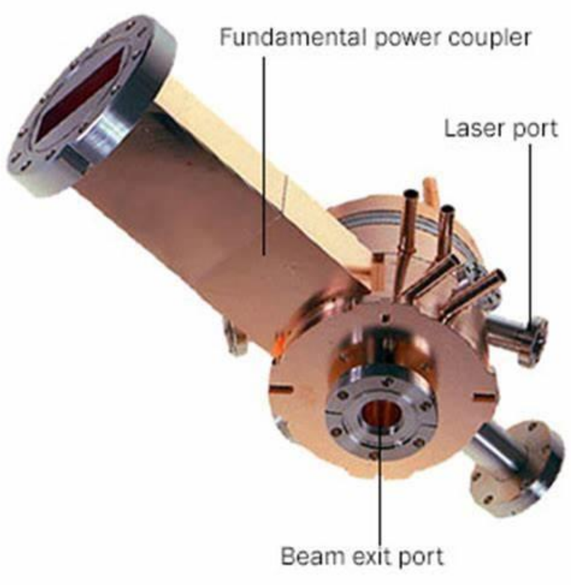


- operating frequency @ 1300 MHz
- Cs_2Te cathode delivers 0.001 – 4 nC bunch charge
- Beam mean energy 6.5 MeV
- Number of electron pulses in bunch train < 800
- Macro pulse repetition rate 10Hz
- Bunch rep.-rate 10kHz
- Average beam current 32 μA max.
- Optimized emittance < 0.9 μm

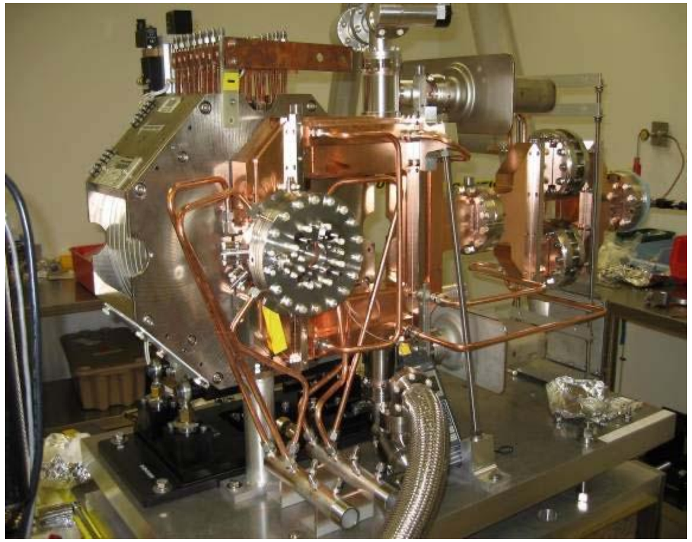
1.Igor Isaev, “Stability and Performance Studies of the PITZ Photoelectron Gun”, University of Hamburg dissertation (2017) http://bib-pubdb1.desy.de/record/400083/files/Igor%20Isaev%20Thesis%202017%20final%20for%20publishing.pdf

1.6 Cell S-band high gradient photocathode gun

BNL-type gun

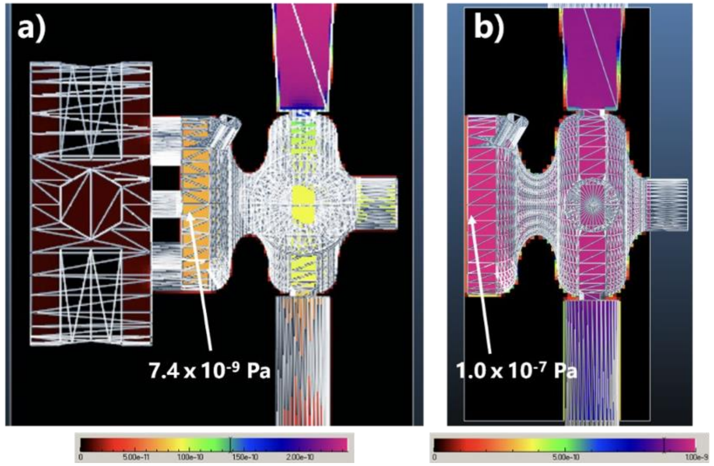


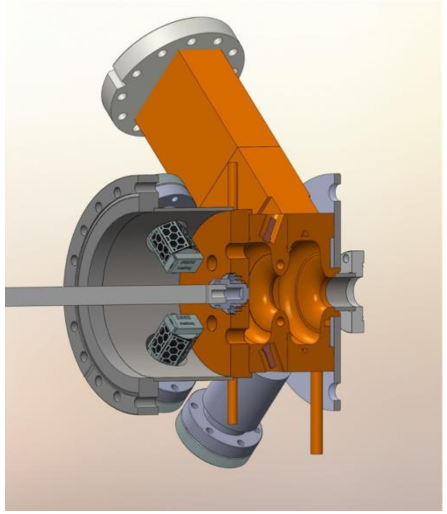
SLAC LCLS gun



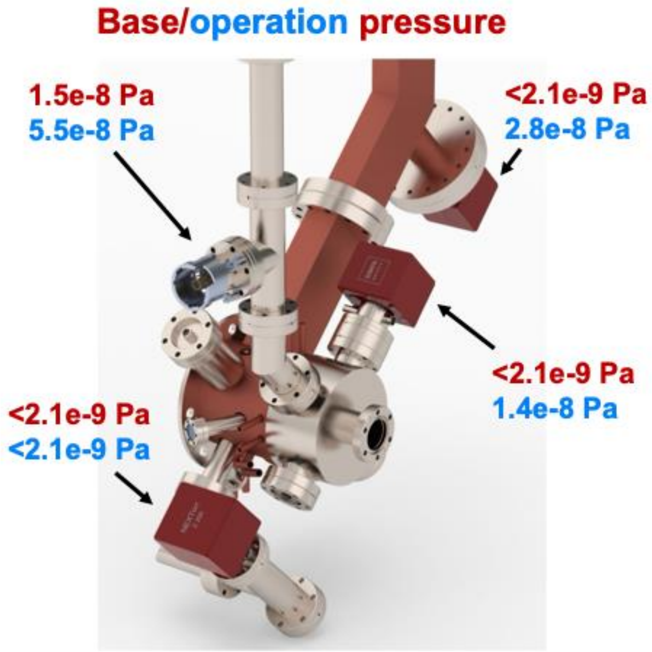
- operating frequency @ 2856 MHz
- High gradient, 100-120MV/m with beam energy >5MeV
- Widely used for high brightness electron beam accelerator, XFEL, ICS, UED, et al.
- copper cathode delivers sub-nC bunch charge
- Cs_2Te cathode also widely used for long term operation
- Macro pulse repetition rate ~10-100Hz
- Optimized emittance < 0.9 μm @1nC

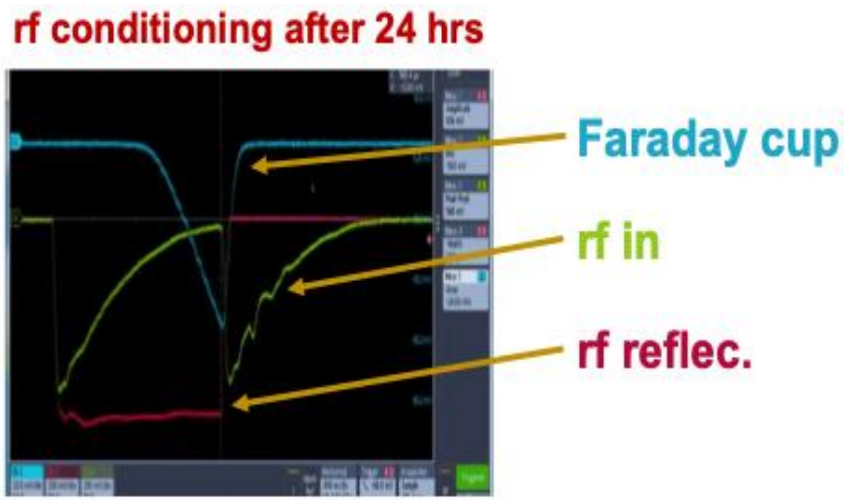
High vacuum S-band gun at Tsinghua

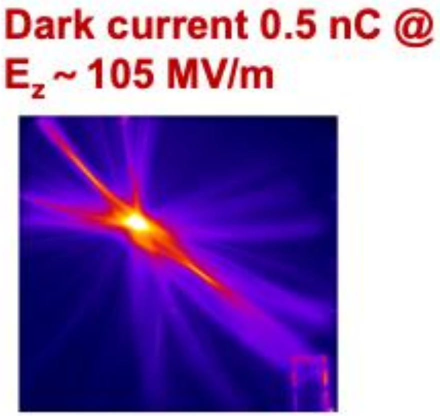


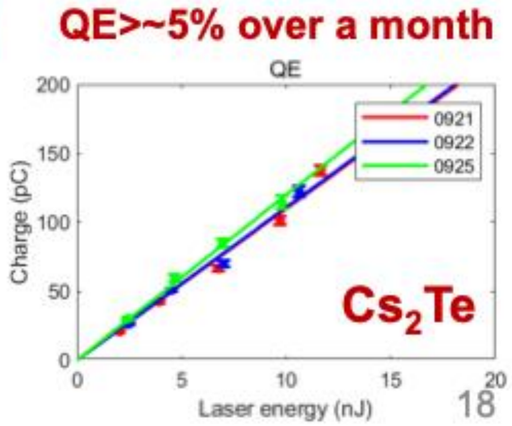


- Special vacuum design based on the normal S-band RF gun
- High gradient, ~100MV/m
- good vacuum, <5x10-8pa operation pressure
- Operate successfully with semi-conducting photocathode such as Cs2Te, K2CsSb



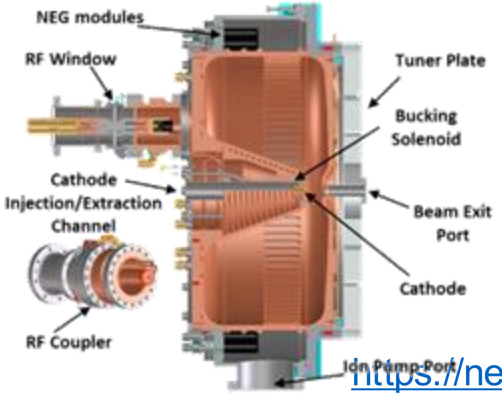






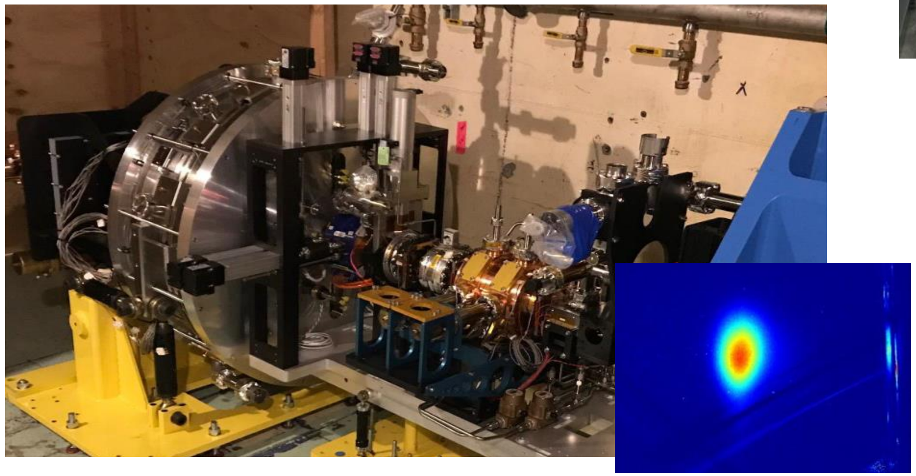
NC CW VHF RF gun

APEX now dedicated for high rep-rate UED



https://newscenter.lbl.gov/2016/04/26/electron-eye/

LCLS-II produced first beams in May 2019



https://www6.slac.stanford.edu/news/2019-05-30-slac-fires-electron-gun-lcls-ii-x-ray-laser-upgrade.aspx

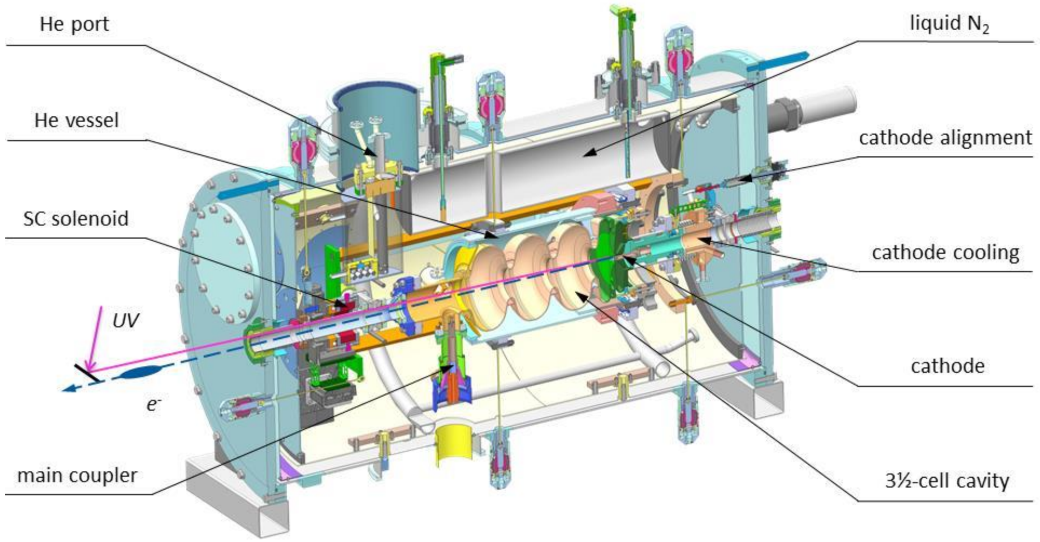
SHINE gun

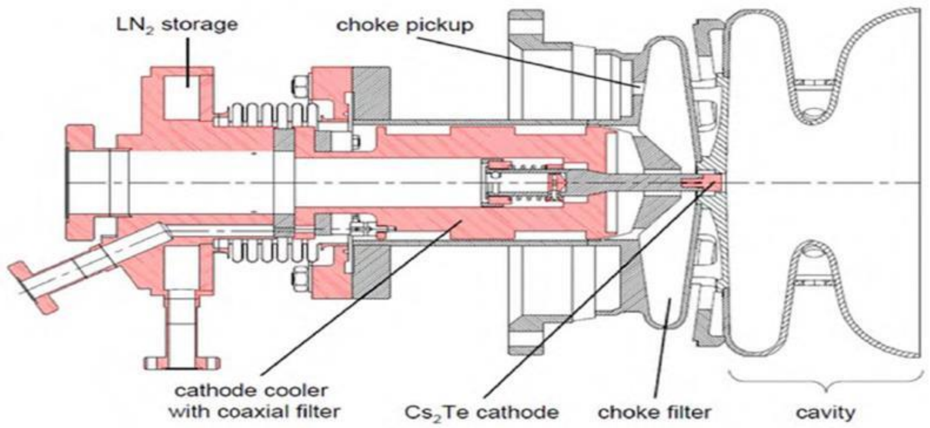
DALS gun

ZjLab gun

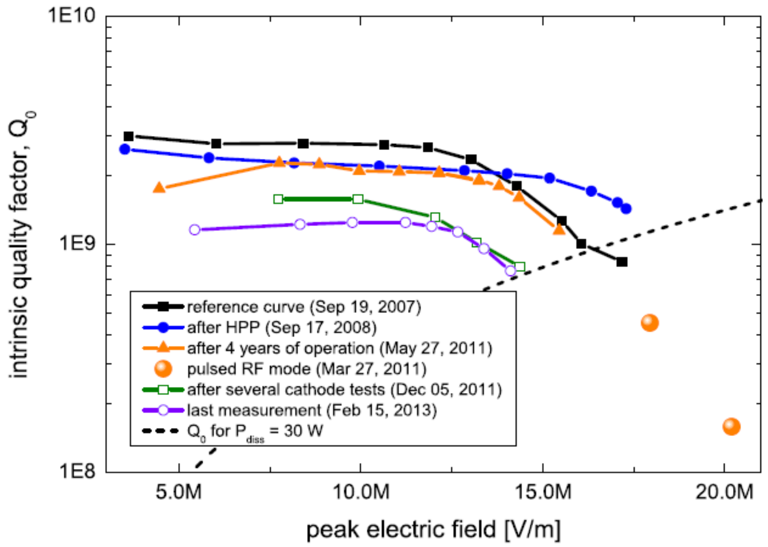
- CW operation with 100uA (100pC/1MHz) in SHINA,DALS, and 3mA successfully are generated in Zjlab.
- Cathode gradient: ~20-30MV/m, ~750kV
- Main Challenge: huge heat load (80-100 kW) and related - material, mechanical, vacuum, lifetime of components etc.

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

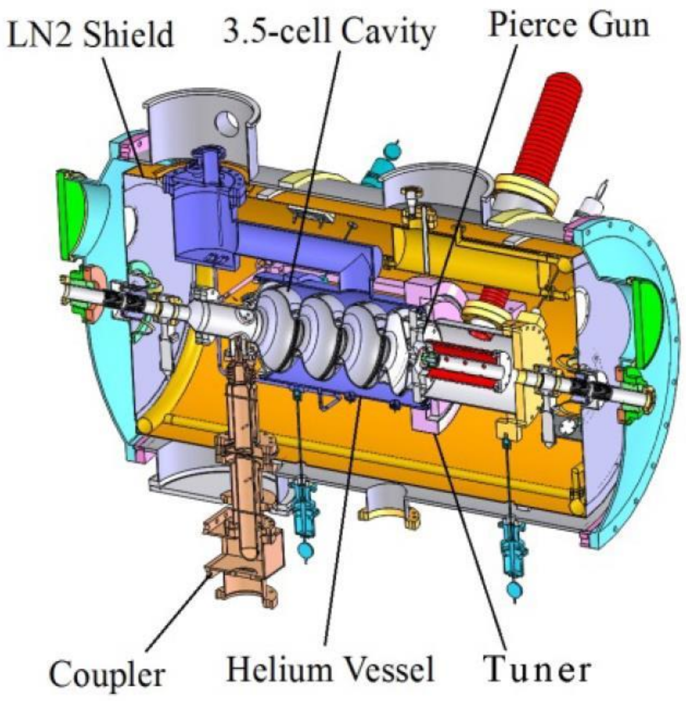




- 1.3 GHz, 3-1/2-cell SRF cavity; 16 MV/m in CW mode; 21.5 MV/m for pulsed rf.
- LN2-cooled Cs_2Te cathode with rf choke to prevent RF leakage.
- Repetition rate of laser system up to 13 MHz. 20 pC bunch charge.
- Beam energy at 3 MeV in CW mode; 4 MeV in pulsed rf mode.
- 1 μm/mm beam transverse emittance; energy spread 24 keV.



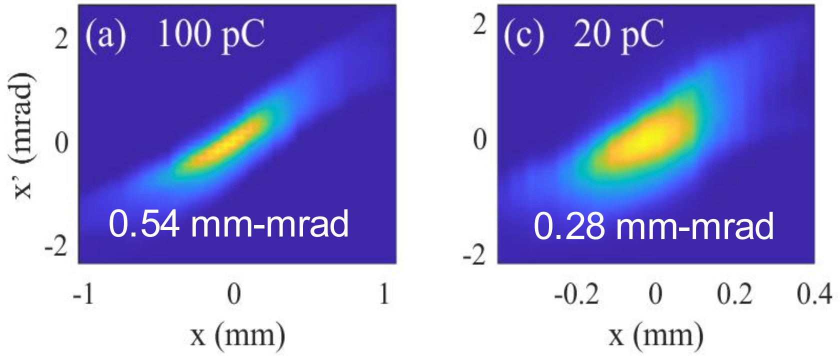
The Peking University Hybrid Gun

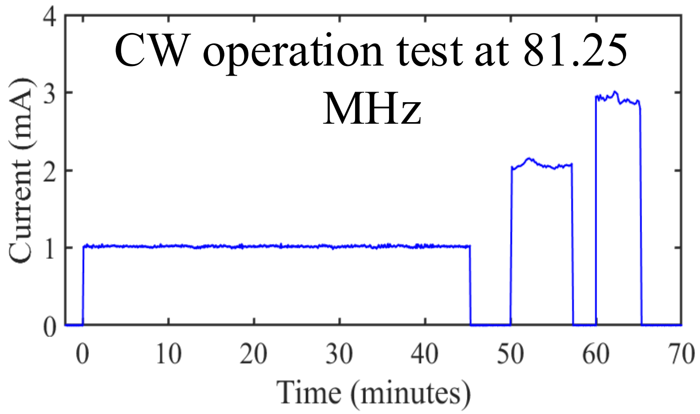


DC + SRF

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

- **Stable CW operation achieved (2023)**
  High-brightness beam test @ 1 MHz
  High average current test @ 81.25 MHz
  Widely tunable current (nA ~ mA)
- **Joint operation with SRF linac** at 10 MeV, 1 mA, 10% duty factor (2024)
- **DC @ 100 kV; 1.5-cell SRF cavity with $E_{z,max}$ ~22 MV/m**
- **K_2CsSb cathode, 515 nm laser + shaping**





Maximum average beam current ~3 mA; maximum beam power ~5.1 kW

homework

1、Calculate the normalized thermal emittance of a thermionic cathode with cathode temperature T

2、the work function of a photocathode is 4.2eV, is it possible to get photonic emission when a 400nm laser shining on this cathode? If 100MV/m electric field is applied in the gun, the Schottky effect will suppress the barrier, is it possible to get photonic emission with the same laser?