Electron Guns

Spring, 2021

Kyoung-Jae Chung

Department of Nuclear Engineering

Seoul National University

Pierce method for gun design

- The first step in the charged-particle acceleration process is to extract low-energy particles from a source and to form them into a beam. The particle source and initial acceleration gaps constitute the injector. The particles move slowly in the first acceleration gap, and the space-charge forces are correspondingly strong.
- The analytic derivation of Pierce gives a self-consistent solution for a space-charge dominated injector. The procedure predicts the shapes of accelerating electrodes to produce a laminar beam with uniform current density.
- Although the treatment holds only for the special geometry of a sheet beam accelerated through an extraction grid, it gives valuable insights into the design of more complex guns.
- Assumptions:
    - A space-charge-limited injector creates a sheet beam of width $\pm x_0$.
    - Particle motion in the extraction gap is non-relativistic.
    - The force from beam-generated magnetic fields is small.
    - Potentials at the surface and extractor electrodes are determined by conducting surfaces—the beam exits the gap through a grid or foil.

[Remind] Potential distribution across a gap for space-charge-limited ion flow

- Space-charge-limited current in a plane diode

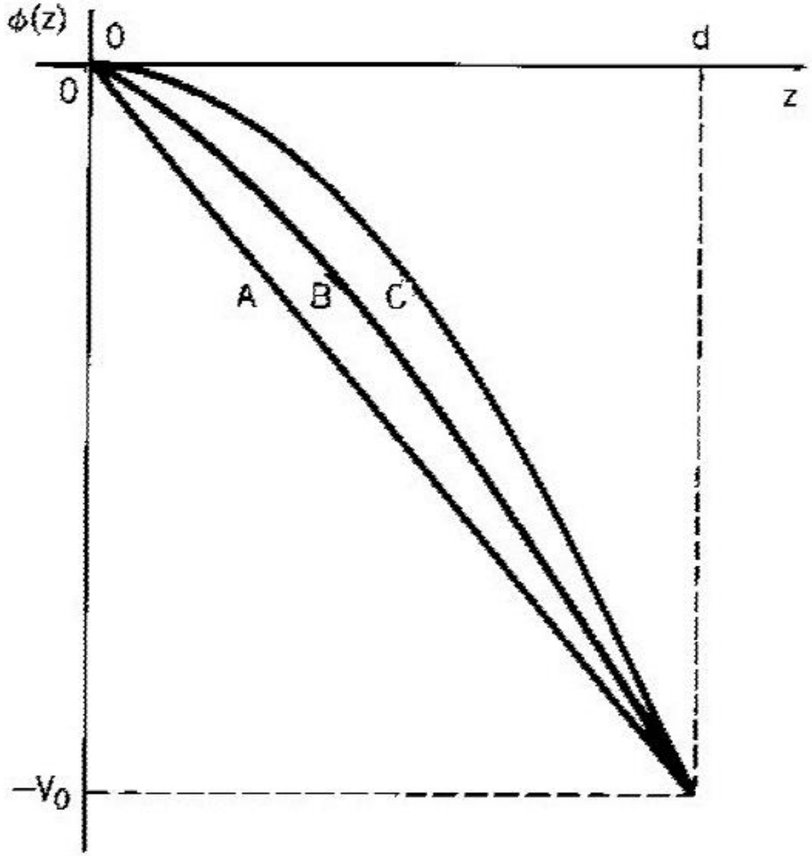
$$J_0 = \frac{4}{9}\epsilon_0 \left(\frac{2e}{M}\right)^{1/2} \frac{V_0^{3/2}}{d^2}$$

- Potential distribution within the gap

$$\phi(z) = -V_0 \left(\frac{z}{d}\right)^{4/3}$$

- Electric field distribution within the gap

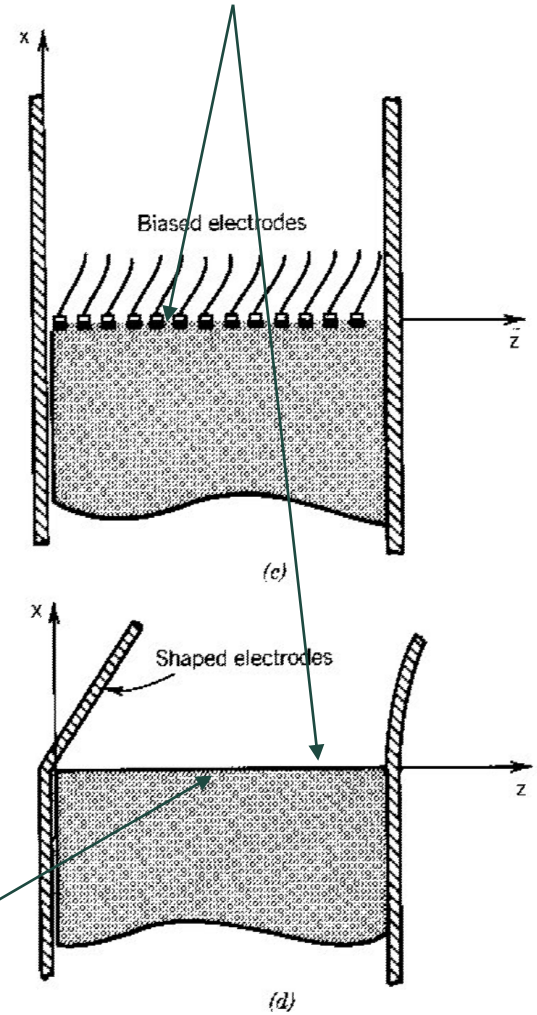
$$E = \frac{4}{3}\frac{V_0}{d}\left(\frac{z}{d}\right)^{1/3}$$



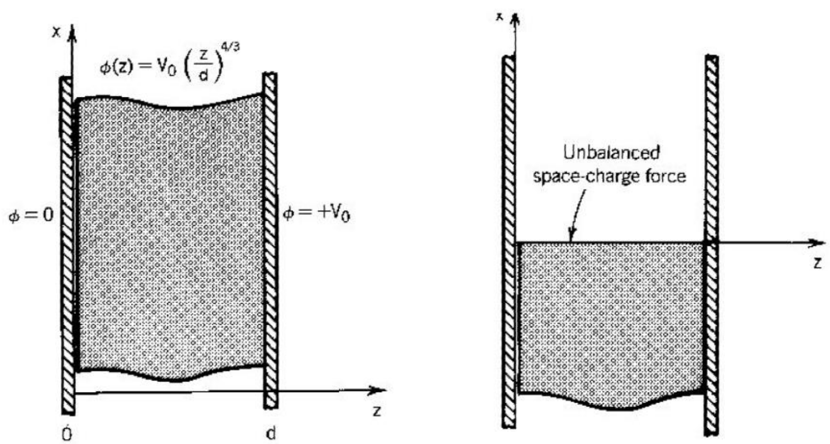
Pierce extraction system

- The essential principle of a Pierce extraction system is that the effect of the particles external to the chosen region can be represented by means of a single unipotential electrode, called the beam-forming or focusing electrode.
- This electrode should cause the field in the region external to the beam satisfy the proper boundary conditions at the beam edge, i.e. the transverse electric field is zero everywhere at the beam edge and the electric potential along the beam boundary is the same as in the corresponding idealized SCL diode.

$$\phi(0,y,z) = V_0\left(\frac{z}{d}\right)^{4/3}$$



$$\frac{\partial\phi}{\partial x} = 0$$



SEOUL NATIONAL UNIVERSITY

Pierce extraction system

- The desired potential distribution external to the beam is given by

$$\phi(x,z) = \frac{V_0}{d^{4/3}}(x^2+z^2)^{2/3}\cos\left(\frac{4}{3}\tan^{-1}\left(\frac{x}{z}\right)\right)$$

- In principle, the desired potential distribution in the region external to the beam will be completely determined by two properly formed electrodes: the focusing electrode and the extraction electrode.

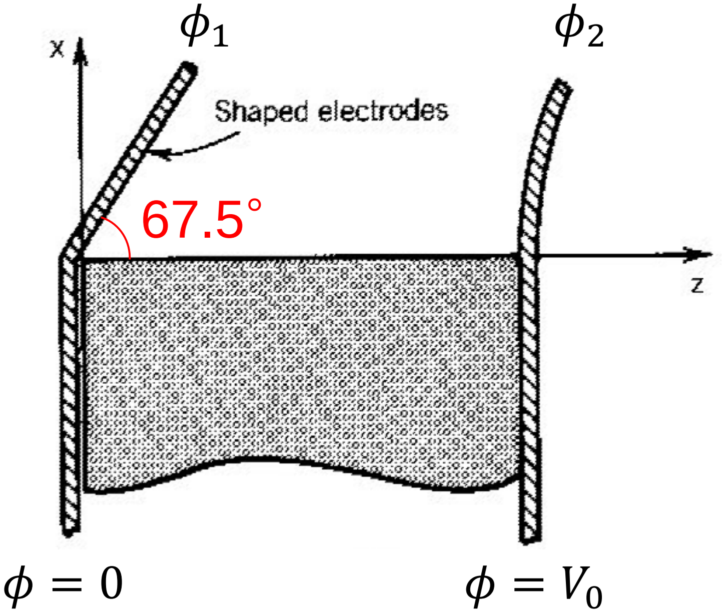
$$\phi_1(x,z) = 0$$

$$\frac{4}{3}\tan^{-1}\left(\frac{x}{z}\right) = \frac{\pi}{2} \Rightarrow \frac{x}{z} = \tan\left(\frac{3\pi}{8}\right)$$

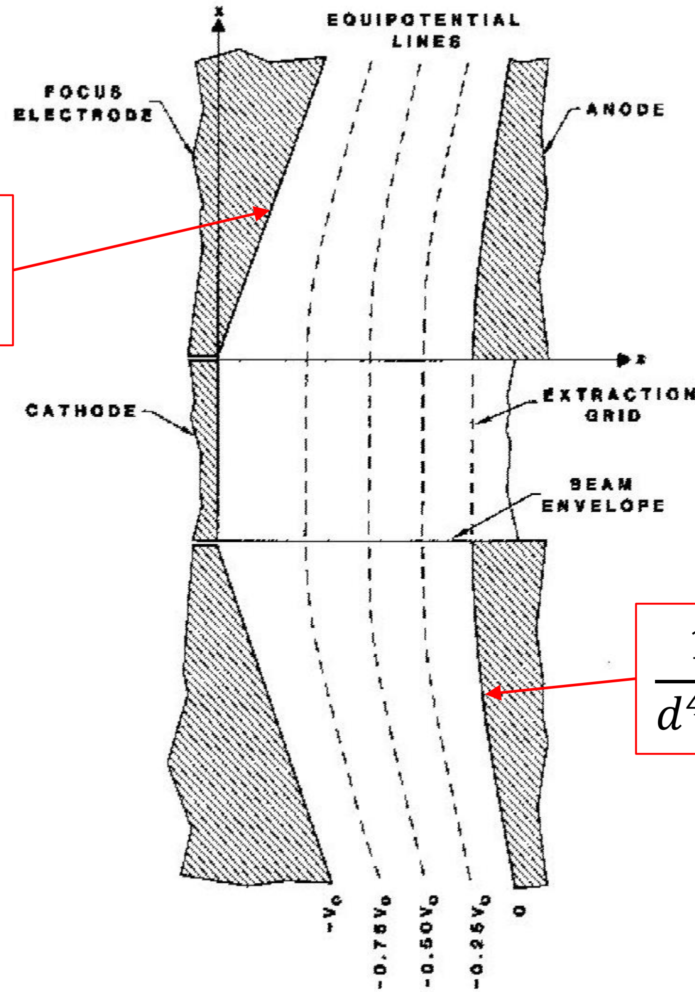
$$\phi_2(x,z) = V_0$$

$$\frac{1}{d^{4/3}}(x^2+z^2)^{2/3}\cos\left(\frac{4}{3}\tan^{-1}\left(\frac{x}{z}\right)\right) = 1$$

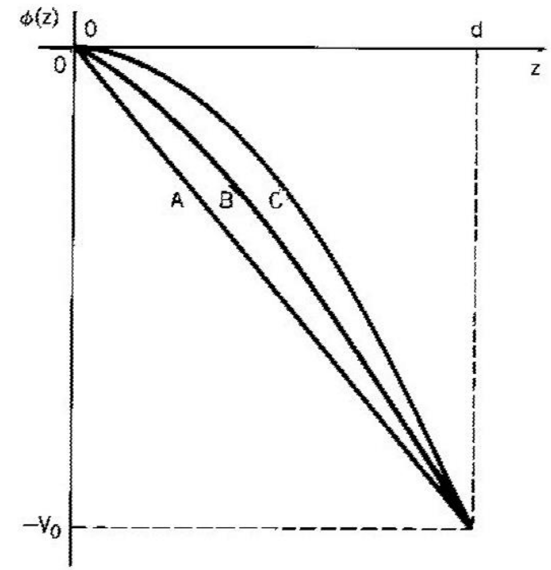
⇨ Very complex



Geometry of planar Pierce extraction system



$$x = z\tan\left(\frac{3\pi}{8}\right)$$



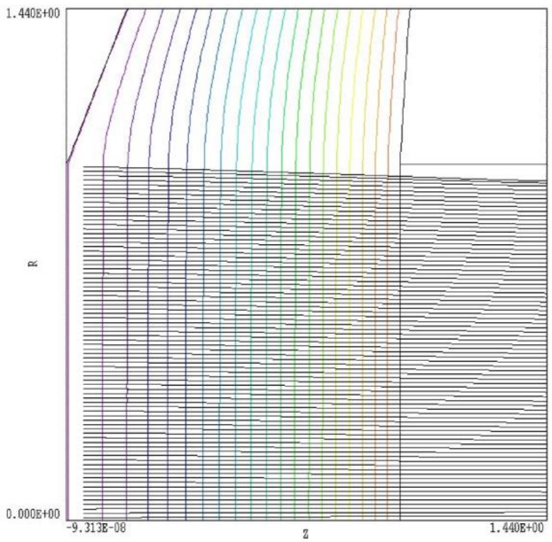
$$\frac{1}{d^{4/3}}(x^2+z^2)^{2/3}\cos\left(\frac{4}{3}\tan^{-1}\left(\frac{x}{z}\right)\right) = 1$$

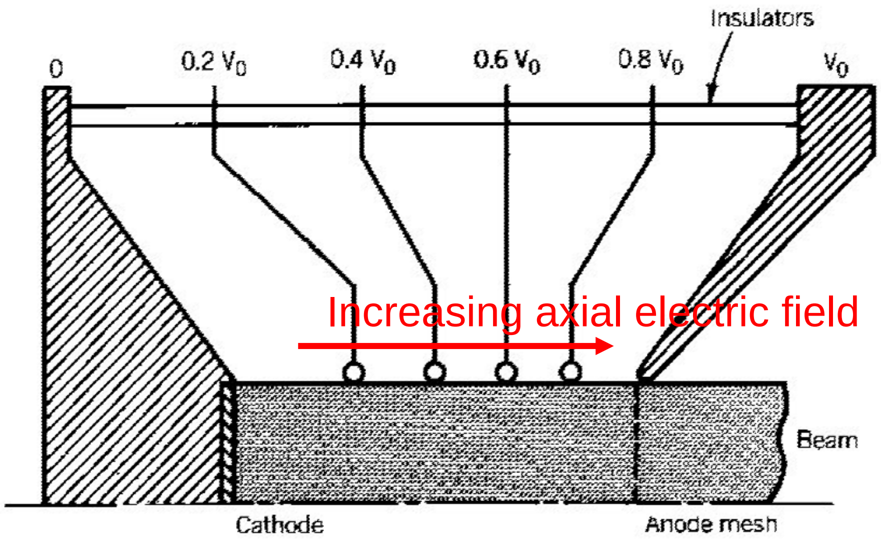
Axisymmetric Pierce extraction system

- Many applications require cylindrical electron beams. The design of a cylindrical gun follows the same procedure as a sheet beam gun. We can apply numerical methods to search for cylindrical electrode shapes that give the variation of potential along a beam boundary at r_o:

$$\phi(r_o, z) = V_0 (z/d)^{4/3}$$

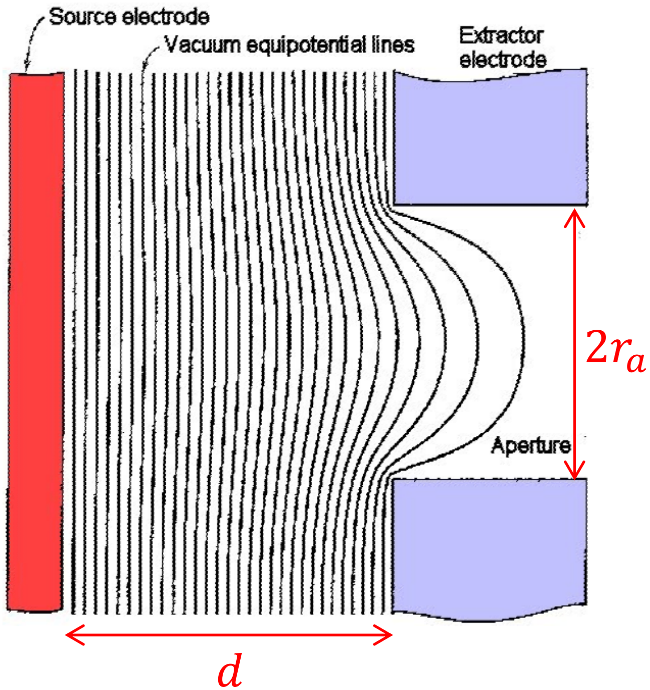
- In this case, the zero potential surface (focusing electrode) is a conical curved surface having a gradually increasing angle with the emission electrode from 67.5° to 74.16°.





Distortion of electric field due to anode aperture

- In the previous analyses, we ignored the effects of an anode aperture. In most cases, however, an anode aperture modifies the electric fields in an electron gun.
- The radial electric fields defocus exiting electrons. The fields act like an electrostatic lens with negative focal length—the defocusing action is called the negative lens effect. Also, the anode aperture reduces the axial electric field at the center of the cathode, leading to depressed beam current density.



- The change in cathode electric field is small if the diameter of the anode aperture is small compared with the gap width:

$$2r_a \ll d$$

- The field perturbation is strong if

$$2r_a \geq d$$

- Then, we must modify the geometry of the gun to achieve an output beam with uniform current density.

Perveance

- Space-charge-limited current in a cylindrical gun:

$$I = \frac{4}{9}\epsilon_0 \left(\frac{2Ze}{m_0}\right)^{1/2} \frac{\pi r_a^2}{d^2} V_0^{3/2}$$

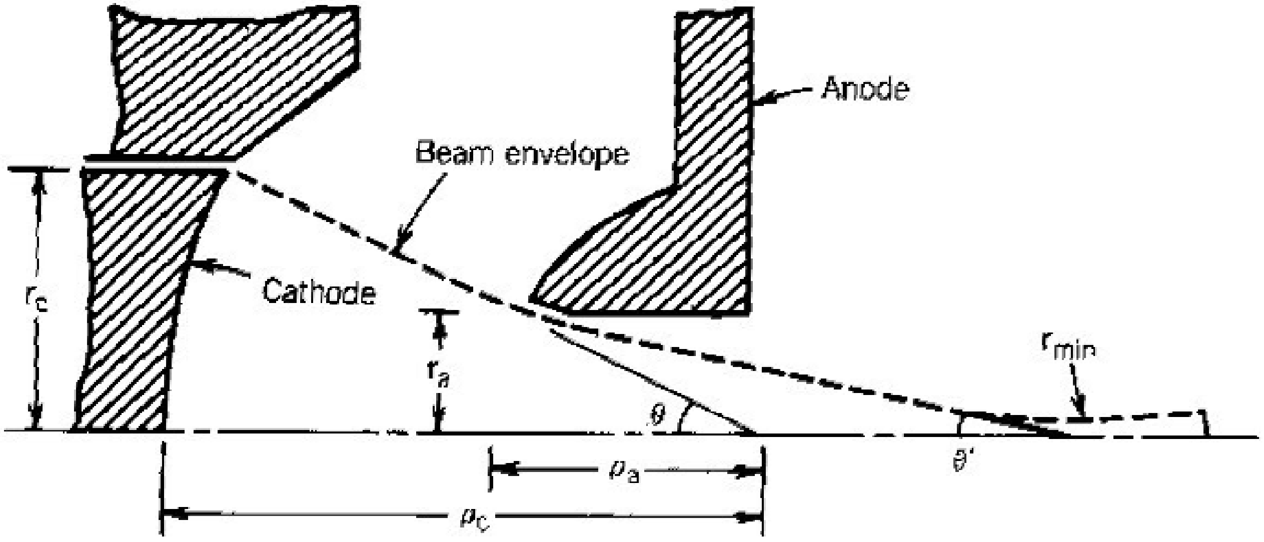
- Perveance: the quantity depends only on the geometry of the extractor and the type of particle.

$$P = I/V_0^{3/2} = \frac{4}{9}\epsilon_0 \left(\frac{2Ze}{m_0}\right)^{1/2} \frac{\pi r_a^2}{d^2} \approx 1.8 \times 10^{-6} \left(\frac{2r_a}{d}\right)^2$$

- Classification
  - Low-perveance guns: $P \leq 0.1 \times 10^{-6} AV^{-3/2}$ or $d/2r_a \geq 4$
  - Medium-perveance guns: $0.1 \times 10^{-6} \leq P \leq 1 \times 10^{-6} AV^{-3/2}$ or $1.35 \leq d/2r_a \leq 4$
  - High-perveance guns: $P \geq 1 \times 10^{-6} AV^{-3/2}$ or $d/2r_a \leq 1.35$

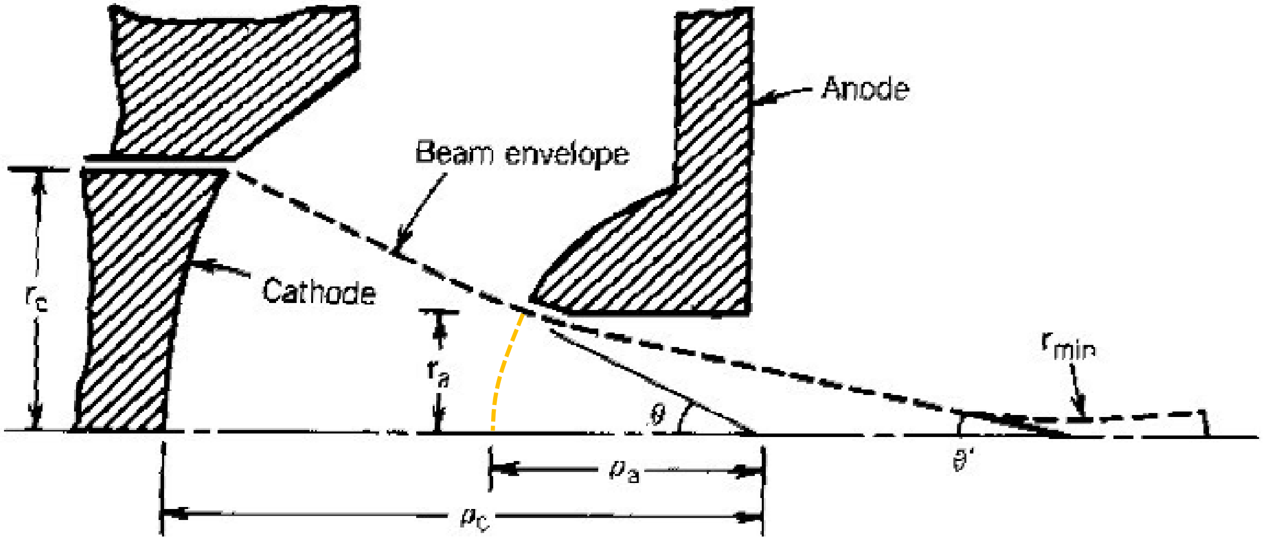
Medium-perveance guns

- Moderate perveance guns usually have the converging geometry whose advantages are:
  - The aperture diameter can be small because the beam has the minimum radius at the anode.
  - A source with limited current density can generate a high current beam because the beam width is large at the cathode.
  - The space-charge-limited current for a given aperture area is higher than that of a planar gun because the beam density is smaller near the cathode.
  - With converging electrons, it is possible to counter the negative lens effect to generate a parallel output beam.



Medium-perveance guns

- For small aperture perturbations, we can design a non-relativistic electron gun by dividing beam motion through the extractor into three roughly independent phases:
  - (1) We treat electron motion from the cathode to the anode using the theory of space-charge-limited flow between spherical electrodes.
  - (2) We assume that aperture field perturbations are localized near the anode and we represent their effect as a thin linear lens with negative focal length.
  - (3) In the propagation region beyond the anode, we treat space-charge expansion of the beam using the paraxial theory.



Medium-perveance guns: (1) converging electron flow between spherical electrodes

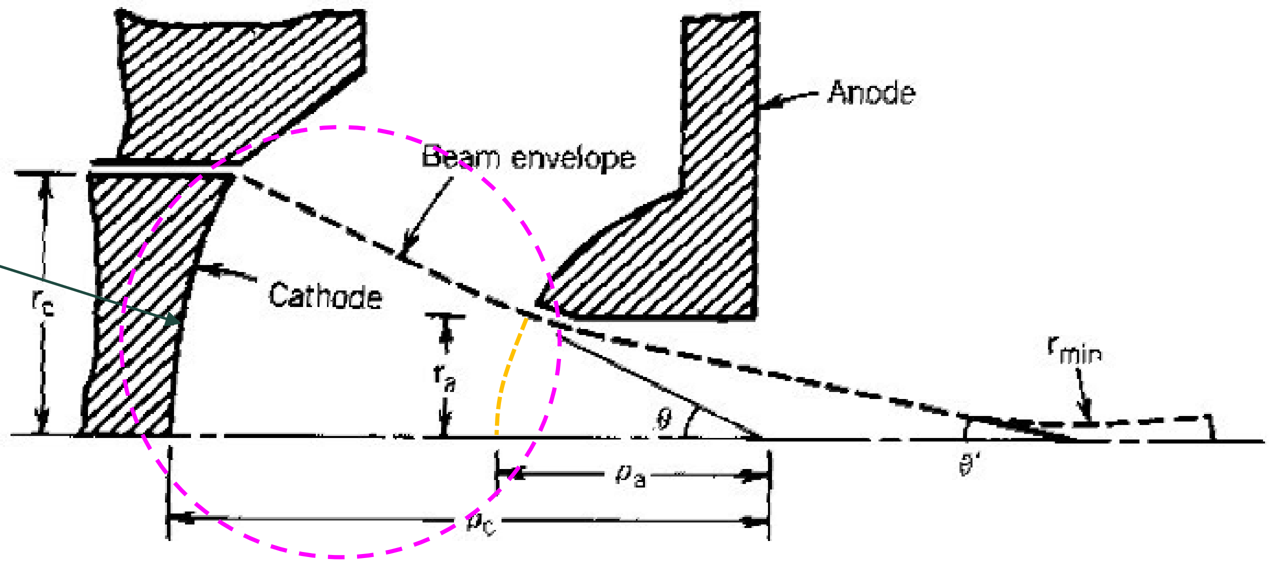
- The perveance of a full spherical electron beam:

$$\frac{I_{sphere}}{V_a^{3/2}} = \frac{4}{9}\epsilon_0\left(\frac{2e}{m_0}\right)^{1/2}\frac{4\pi}{[\alpha(\rho_a/\rho_c)]^2} \quad \text{x} \quad \frac{4\pi\rho_c^2\sin^2(\theta/2)}{4\pi\rho_c^2}$$

- For the focusing electrode below, the perveance is

$$\frac{I_{sphere}}{V_a^{3/2}} = \frac{16\pi\epsilon_0}{9}\left(\frac{2e}{m_0}\right)^{1/2}\frac{\sin^2(\theta/2)}{[\alpha(\rho_a/\rho_c)]^2} \approx 29.4\frac{\sin^2(\theta/2)}{[\alpha(\rho_a/\rho_c)]^2} \quad \text{μperv}$$

$$A_c = \int_0^\theta 2\pi\rho_c \sin\theta\, \rho_c d\theta$$



Medium-perveance guns: (2) defocus of electrons by radial fields near the anode aperture

- The focal length for the negative lens action of the aperture is roughly:

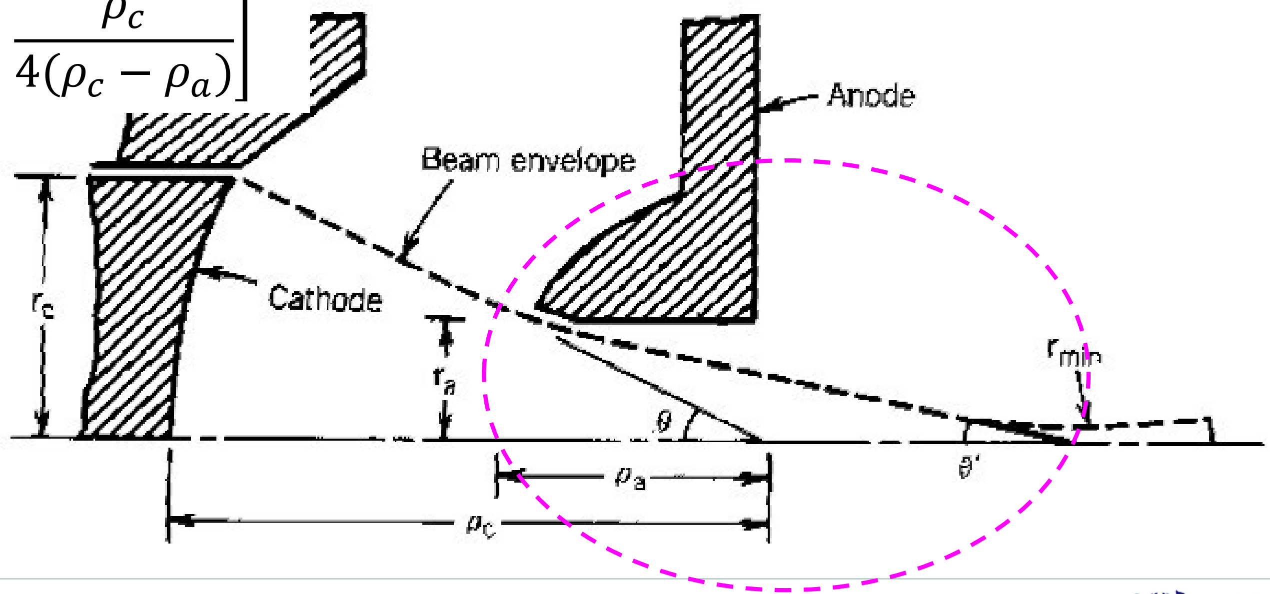
$$f = -4V_0/E_a$$

- To estimate the effect, we set E_a equal to the value of electric field without the beam and aperture

$$E_a \approx V_0(\rho_c/\rho_a)/(\rho_c - \rho_a) \quad \Longrightarrow \quad f \approx -4\,(\rho_a/\rho_c)(\rho_c - \rho_a)$$

- Passing through the aperture, the beam envelope convergence angle changes from θ to θ'

$$\theta' = \theta - \frac{r_a}{f} \approx \theta\left[1 - \frac{\rho_c}{4(\rho_c - \rho_a)}\right]$$



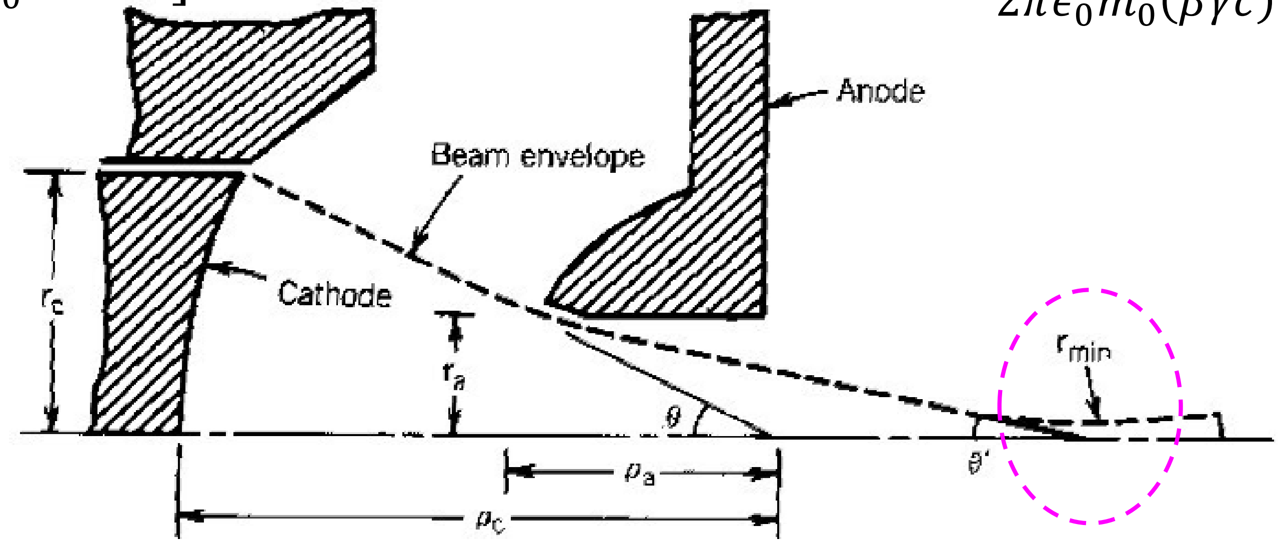
Medium-perveance guns: (3) The minimum radius of the beam emerging from the aperture of a converging gun

- The beam emerging from the aperture of a converging gun usually has strong space-charge forces and low emittance.
- We can find the axial location where the beam reaches a neck using the beam current (I), kinetic energy (eV_0), initial radius (r_a) and envelope angle ($-\theta'$).
- The minimum beam radius in terms of the envelope angle and beam perveance at the anode is given by:

$$\frac{dR}{dz} = \sqrt{2K}\sqrt{\ln(R(z)/R_m)}$$

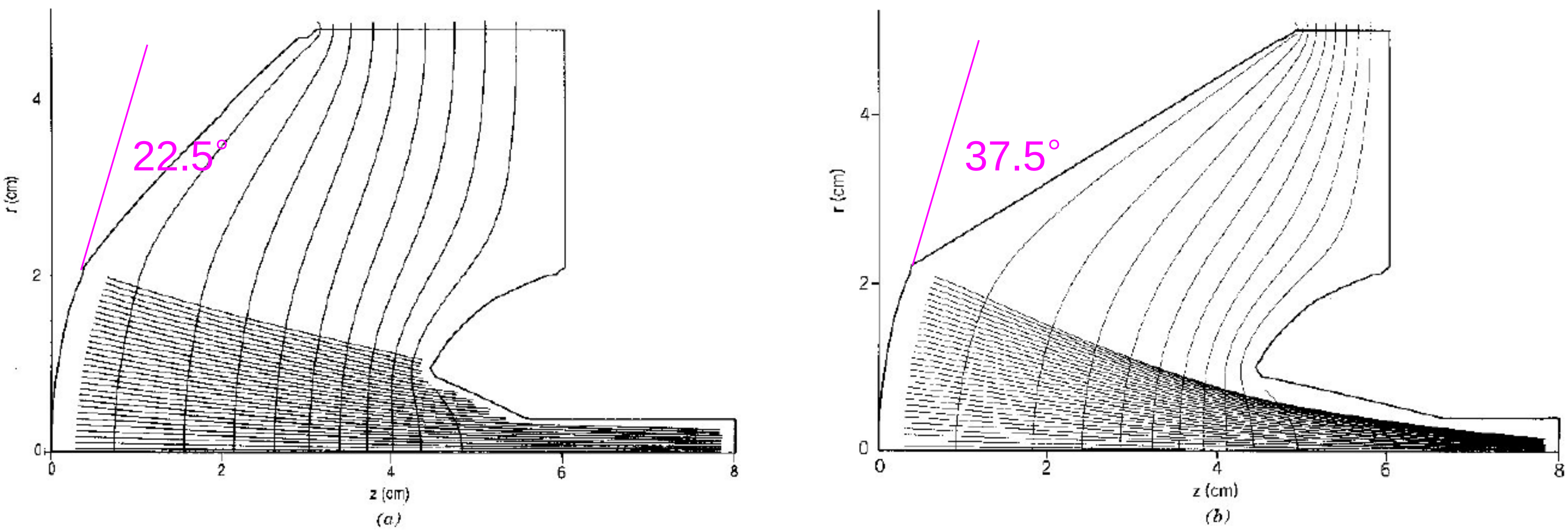
$$\frac{r_{min}}{r_a} = \exp\left[\frac{-3.3\times 10^{-5}\,\theta'^2}{I/V_0^{3/2}}\right]$$

$$K \equiv \frac{eI_0}{2\pi\epsilon_0 m_0(\beta\gamma c)^3}$$



Medium-perveance guns: Example

- Numerical calculations of converging gun properties using the EGUN code.
- Figures show electrodes, computational rays, and electrostatic equipotential lines. Left-hand-side: spherical-section cathode and focusing electrode. Right-hand-side: shaped anode and output tube. V_0 = 20 kV, I_0 = 1 A. Calculation extends 5 cm in radius and 8 cm along the z axis. (a) Initial run — most of the available current strikes the anode. (b) With a corrected focusing electrode, the full current enters the output tube.



SEOUL NATIONAL UNIVERSITY

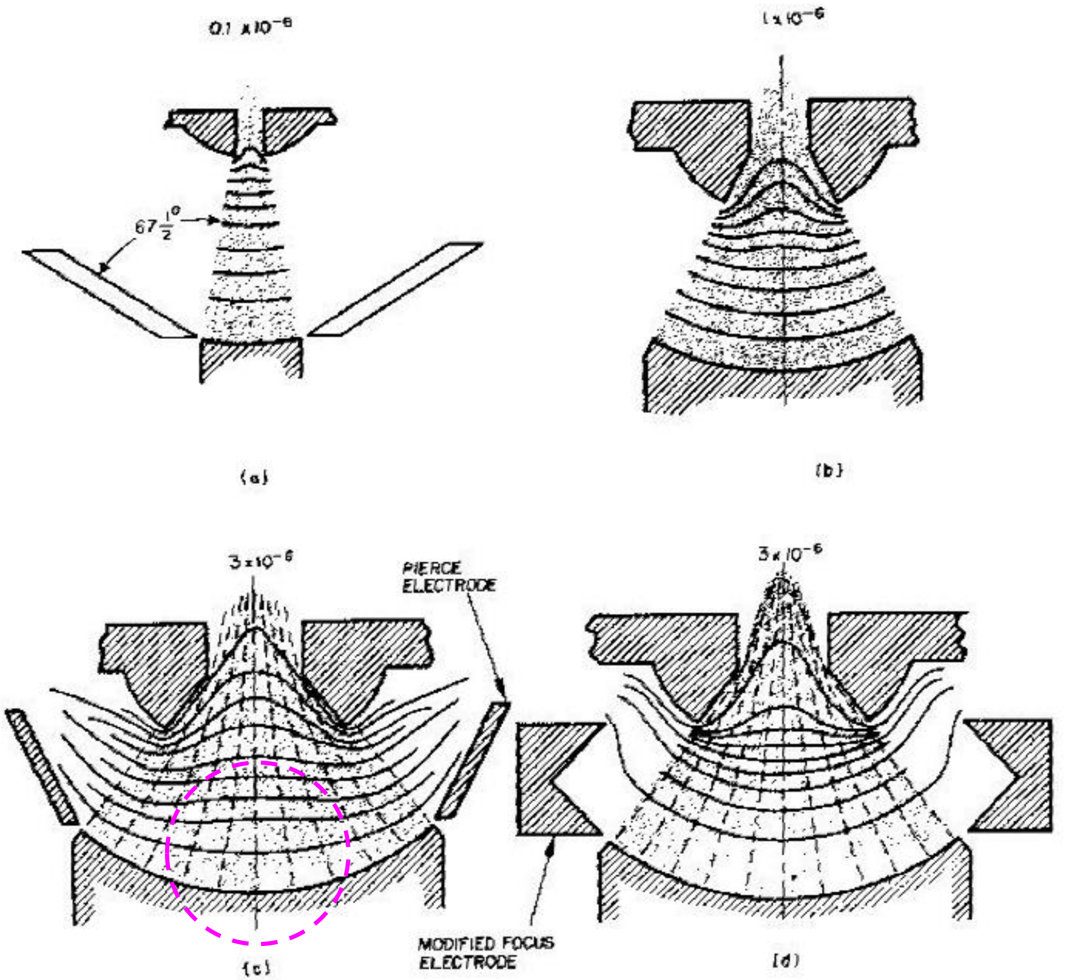
Problems in high-perveance gun design

a. Low-perveance gun follows the Pierce design procedure — anode aperture has a negligible effect on particle extraction.

b. Moderate-perveance converging gun — anode aperture has a small effect on electric fields at the cathode.

c. High-perveance gun — anode aperture reduces the electric field at the cathode center.

d. High-perveance gun — modified focus electrode to produce an almost uniform electric field on the cathode surface.



- Low axial field at the center of the cathode → nonuniform current density → emittance growth
- Existence of transverse electric field → particle deflection

Gun design using ray-tracing codes

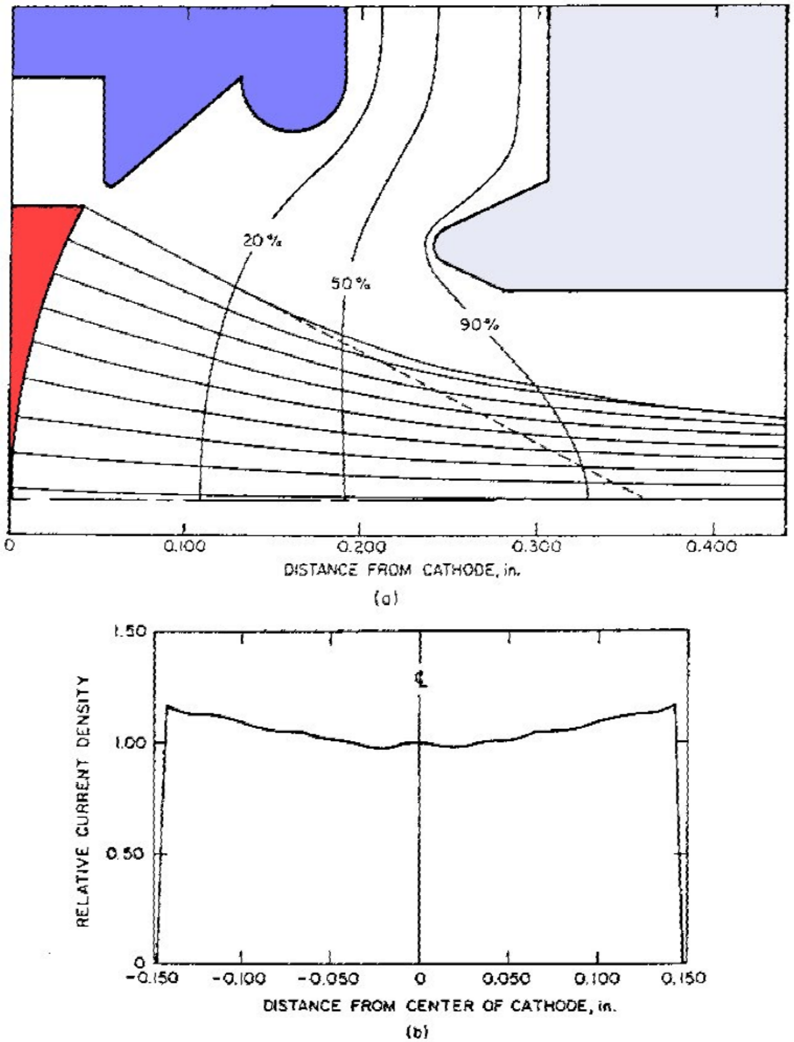
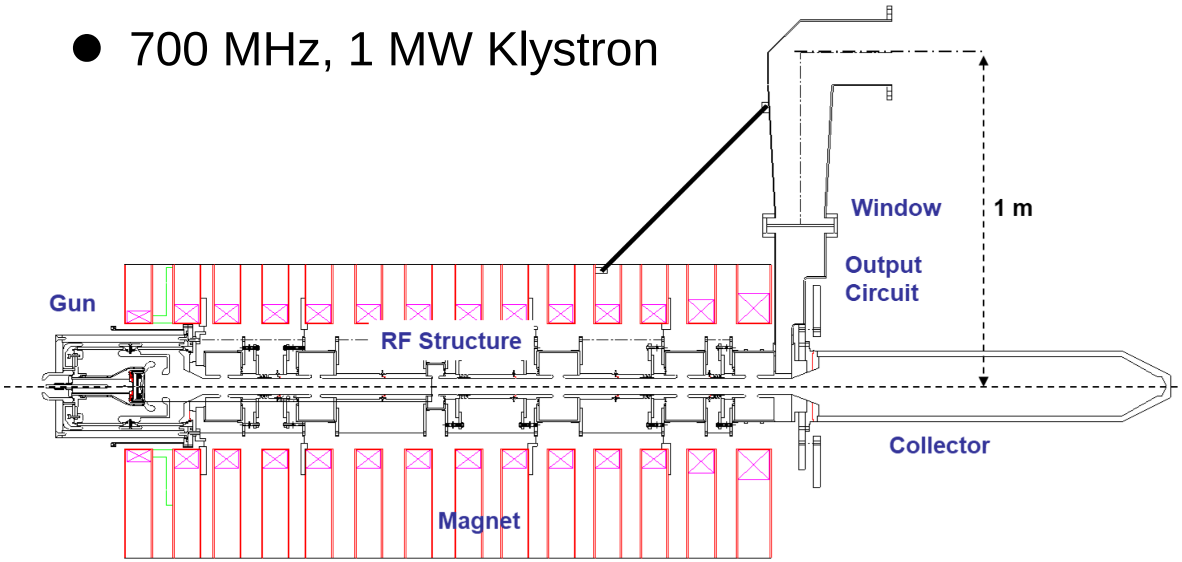


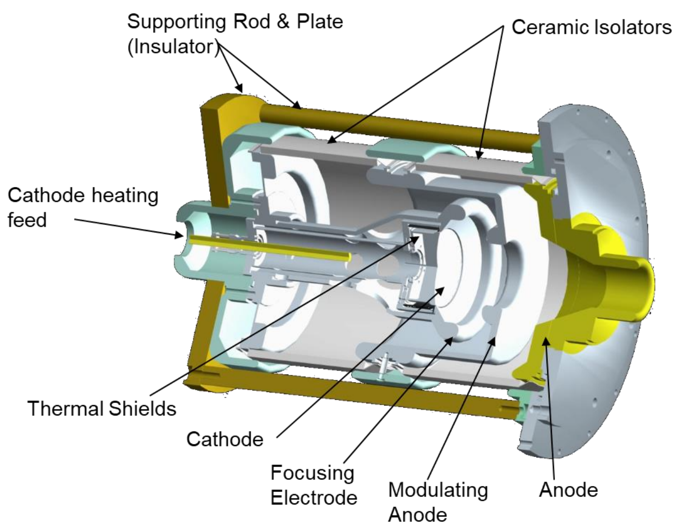
Figure 7.9. High-perveance electrion gun design, P = 1.4 μperv. Top: Rays, electrode outlines and equipotential lines. Bottom: Current density distribution at cathode.

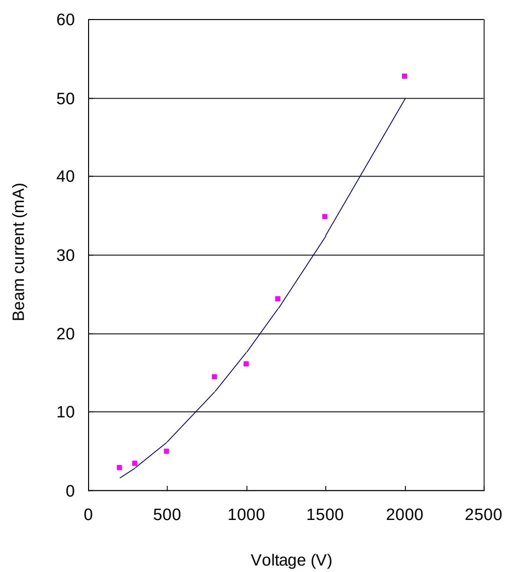
Gun design using ray-tracing codes

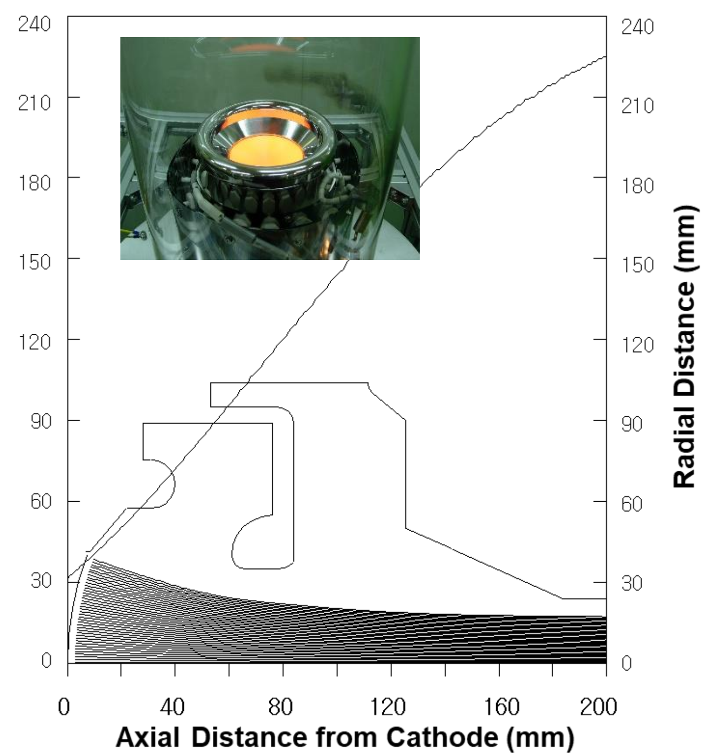
- 700 MHz, 1 MW Klystron



- Anode voltage: 95 kV
- Modulating anode voltage: 51 kV
- Beam current : 16.5 A
- Perveance: 0.56 μperv.







High-current electron sources: thermionic sources

- High-current cathodes are important for microwave tubes, pulsed RF linacs, and induction linac injectors. Recently, there has been considerable interest in sources for high brightness beams that can drive free electron lasers.
- High-current electron sources either have a large area or produce a high electron flux. Here, we concentrate on sources that can supply high-current density (> 10^5 A/m^2).
- Thermionic sources emit electrons according to Richardson-Dushman law:

$$j_e = AT^2 \exp\left(-\frac{11600\phi_w}{T}\right)$$

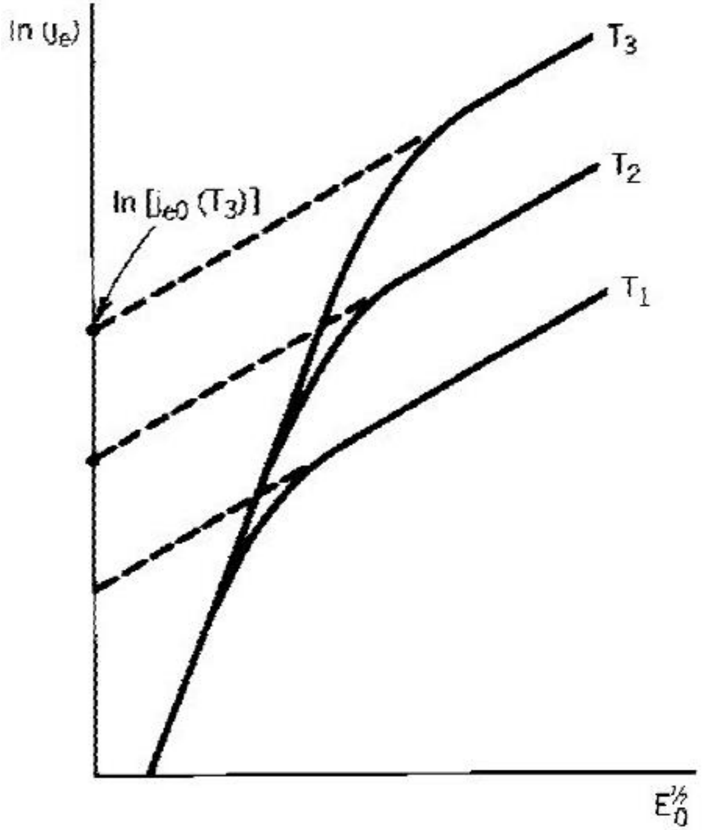
- Schottky effect (field enhanced thermionic emission): For a constant temperature, the current still slowly increases with the applied extraction potential by lowering the surface barrier:

$$j_e = AT^2 \exp\left(\frac{139E_s^{1/2}}{T} - \frac{11600\phi_w}{T}\right)$$

E_s : Electric field normal to the surface [kV/cm]

Schottky plot

- The properties of different thermionic cathode materials are usually compared in terms of the zero field current density, j_{e0}. The zero field current density is the value given by Schottky equation when $E_s = 0$.
- Schottky plot: current density from a thermionic electron source as a function of temperature and applied electric field.
- At low values of E_0, there is significant negative space-charge near the cathode — the negative electric field suppresses the current.
- At values of E_0 where all electrons leave the cathode, the electric field on the surface is roughly equal to the vacuum field.
- We can find the zero field current by extrapolating the measurement to the $E_0 = 0$ axis.



Cathode materials

- Commercial thermionic cathodes consist of a high temperature metal substrate (W) coated with a material with low work function (Ba). Unfortunately, barium evaporates rapidly at high temperature.
- Dispenser cathodes are fabricated by impregnating porous tungsten with chemical compounds that generate barium when heated. Available dispenser cathodes generate current density in the range 20×10^4 A/m^2 at a maximum operating temperature of 1100°C. To avoid cathode poisoning, dispenser cathodes require a clean vacuum less than 5×10^{-7} torr.
- Lanthanum hexaboride, LaB_6, is an alternative to dispenser cathodes — it has some advantages for pulsed-beam accelerators. The homogeneous material has adequate mechanical strength and an inherently low work function. The material is resistant to poisoning, maintaining its emission properties at pressures in the 10^{-5} torr range. Also, there is less problem with evaporation of the active material.

Type	ϕ_w (eV)	α (V/°K)	A (A/m^2-°K^2)
411	1.67	2.82×10^{-4}	3.68×10^{6}
411M	1.43	3.99×10^{-4}	3.50×10^{6}
411 scandate	1.43	4.01×10^{-4}	3.52×10^{6}
LaB_6	2.66		2.90×10^{5}

Cathode materials

Metal	*Work function* *eV*	*Melting temperature* °C
Aluminum	3.0	660
Barium	1.8	720
Carbon	4.8	>3500
Cesium	1.7	28
Copper	4.3	1083
Gold	4.8	1063
Lithium	2.2	186
Molybdenum	4.2	2620
Nickel	5.0	1455
Platinum	6.3	1773
Potassium	1.9	62
Rubidium	1.8	38
Silver	4.6	960
Sodium	2.0	97
Strontium	2.0	800
Tantalum	4.1	2850
Thorium	3.5	1845
Tungsten	4.6	3370