Introduction to Electron Guns for Accelerators

Bruce Dunham

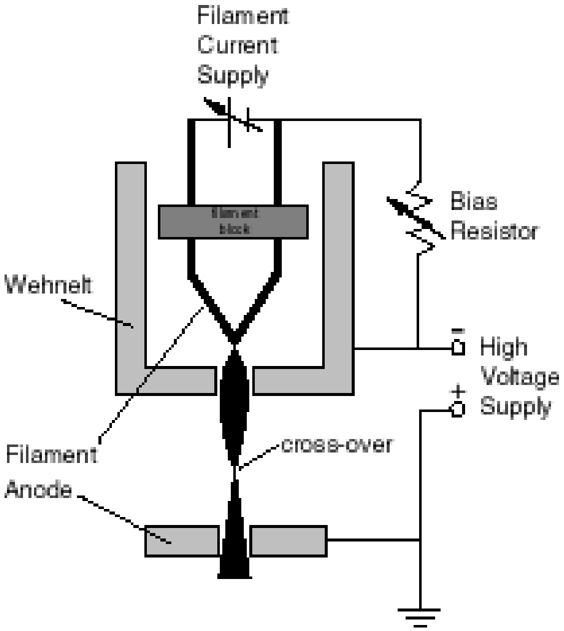
February 25, 2008

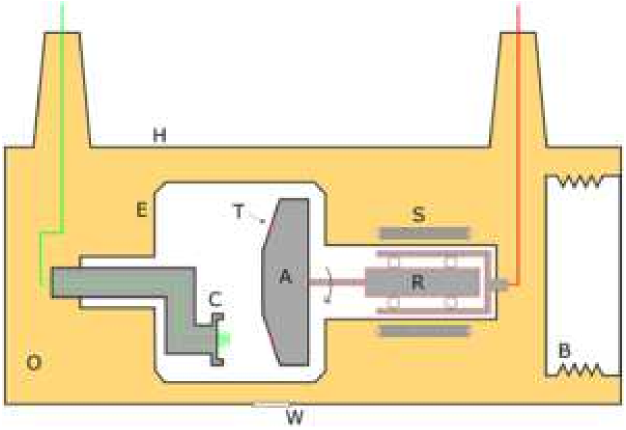
Outline

- The Basics
- Cathodes
- Details of Different Accelerator Guns
    - RF Guns
    - SRF Guns
    - DC Guns
    - Polarized Electron Guns
- Photoemission Guns for an ERL
    - High Voltage
    - Vacuum
    - Laser System

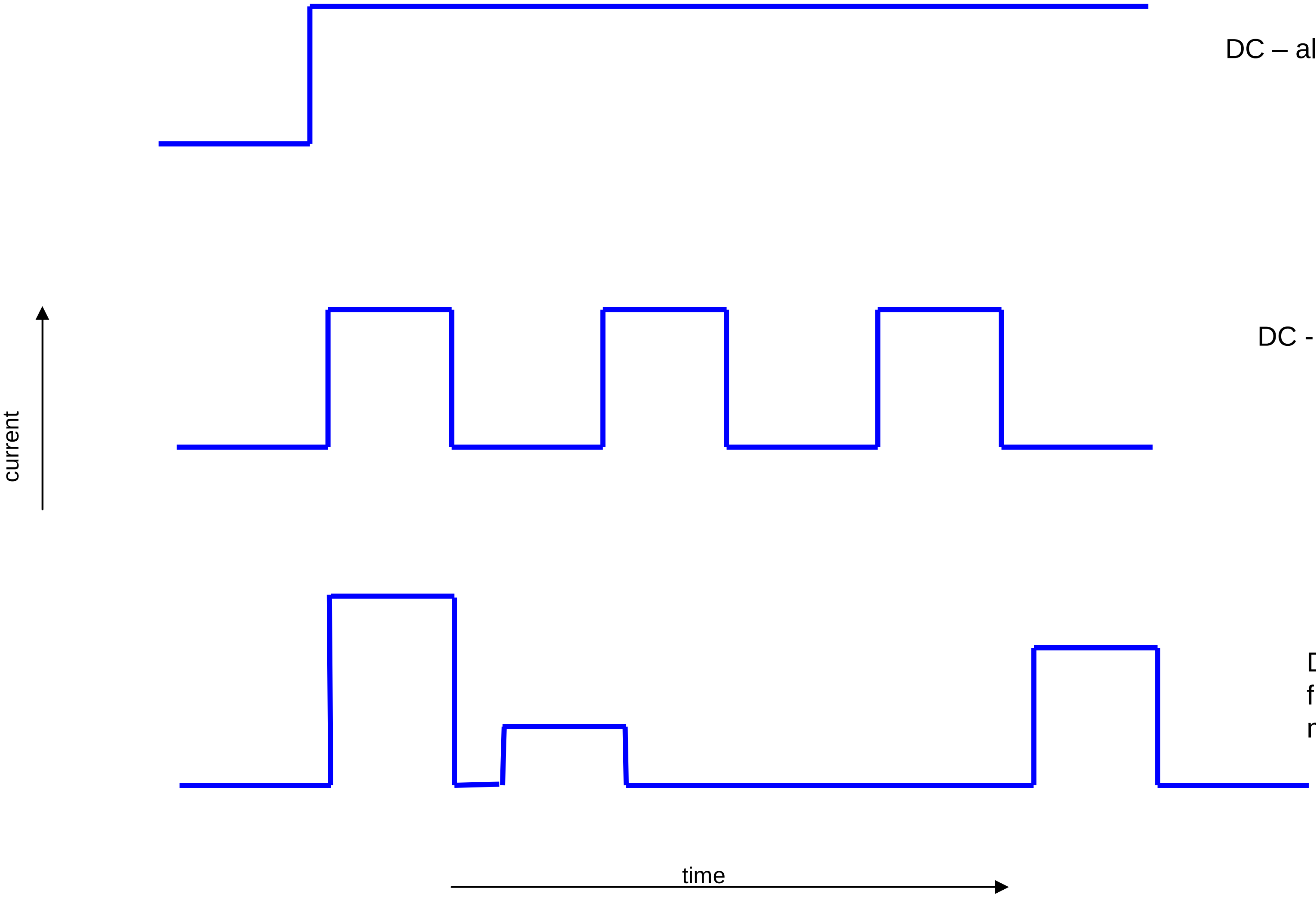
Components of an electron gun

- A cathode of some type for generating electrons
- A focusing structure
- An anode (with or without a hole)
- Vacuum
- Accelerating voltage





DC Type Guns

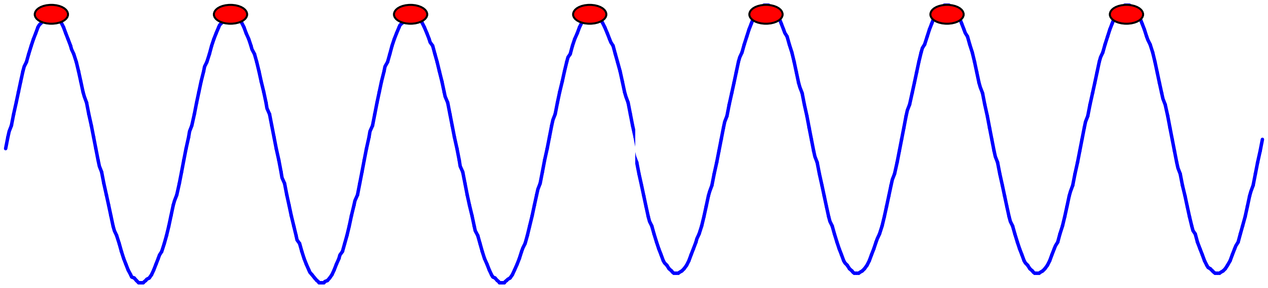


DC – always on

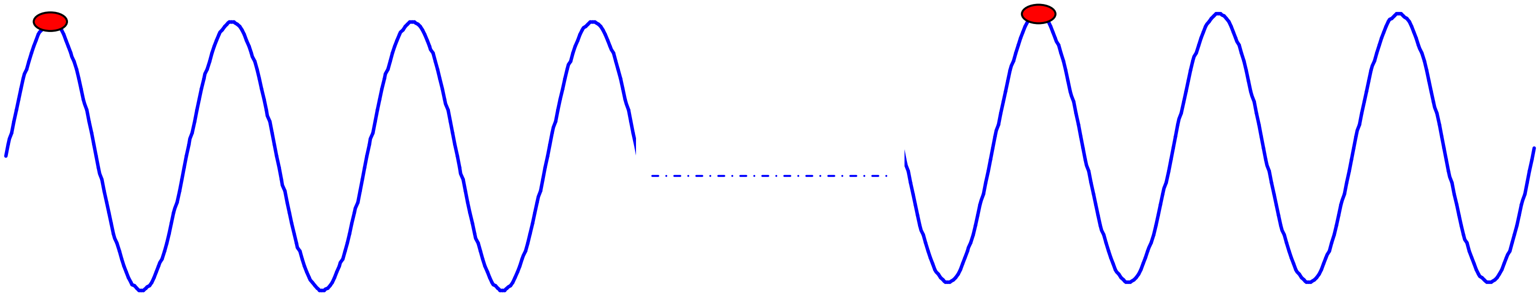
DC - pulsed

DC – amplitude,
frequency
modulated

RF Type Guns



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

Other properties we care about

- average current
- Peak current
- Pulse length
- Emittance (beam quality)
- Reliability (lifetime)
- Physical size
- Cost

“I Want...”

- Lower emittance
  - higher gradient
  - lower QE
  - faster cathode
  - lower bunch charge
  - smaller emission radius

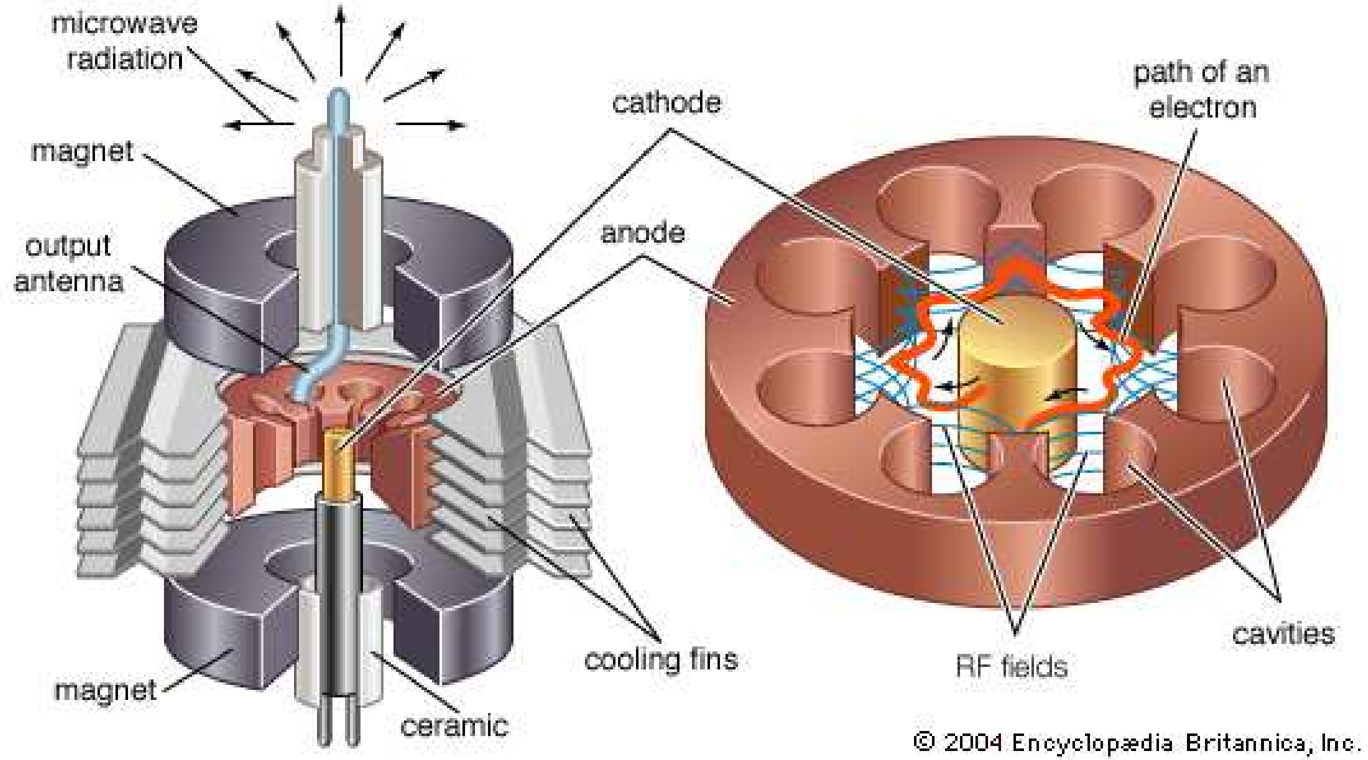
- Larger duty factor
  - lower gradient
  - higher QE
  - lower bunch charge

- Higher charge per bunch
  - higher gradient
  - higher QE
  - larger emission radius

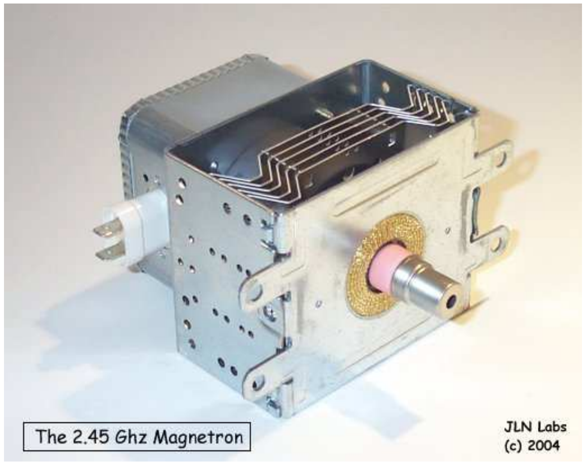
No matter what – people always want more!

Electron Gun Examples

Microwave Oven Power Source



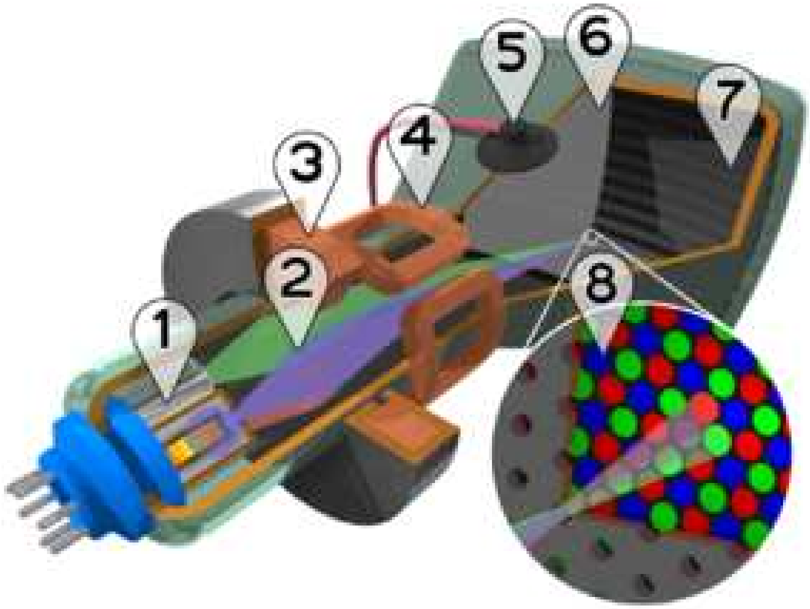
© 2004 Encyclopædia Britannica, Inc.



The 2.45 Ghz Magnetron

JLN Labs
(c) 2004

Cathode Ray Tube Electron Gun



Cutaway rendering of a color CRT: **1.** Electron guns **2.** Electron beams **3.** Focusing coils **4.** Deflection coils **5.** Anode connection **6.** Mask for separating beams for red, green, and blue part of displayed image **7.** Phosphor layer with red, green, and blue zones **8.** Close-up of the phosphor-coated inner side of the screen

NDI-225-21

Stationary Anode X-Ray Tube

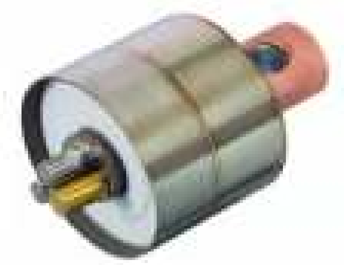
Product Description

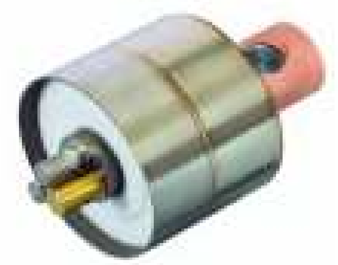
The NDI-225-21 is a 225 kV, water cooled stationary anode metal ceramic X-ray source. This source is specifically designed for Non-Destructive Imaging Applications.

X-Ray Tube Specifications

Maximum Peak Voltage	225 kV
Focal Spot EN12543	
Small	D = 1.0 mm
Large	D = 3.0 mm
Focal Spot IEC	
Small	0.4 mm
Large	1.5 mm
Maximum Continuous Rating	
Small	640 W with 4 Litre/min cooling flow
Large	1600 W with 4 Litre/min cooling flow
Target Angle	20°
Cooling Medium	Water
Reference Axis	Perpendicular to port face.
Radiation Coverage	40°
Loading Factors for Leakage Radiation	225 kV, 7 mA
X-Ray Tube Assembly Permanent Filtration	0.8 mm Be
High Voltage Cable	R24
Weight (approx.)	11 kg (24.5 lbs)

Comet Corp. industrial x-ray tubes





MIR-160E	MIR-200E	MIR-201E	MIR-301E
915328.11	915328.01	915352.01	915338.01
160 kV	200 kV	200 kV	300 kV
900 W	900W	600W	900 W
d = 3.0 mm	d = 3.0 mm	d = 1.0 mm	d = 3.0 mm
1.5	1.5	0.4	1.5
3.8 A	3.8 A	4.1 A	3.8 A
4.6 V	4.6 V	3.0 V	4.6 V
0.8 mm Be	0.8 mm Be	0.8 mm Be	0.8 mm Be
W	W	W	W
20°	20°	20°	20°
60° x 40°	60° x 40°	60° x 40°	60° x 40°
Air	Air	Air	Air
100° C	100° C	100° C	100° C
1.9 kg	1.9 kg	1.9 kg	3.7 kg

SLAC Klystron Electron Gun

Cathodes

Types of Electron Emission

- Give the conduction band electrons extra energy
    - Thermionic emission
    - Photoemission
    - Secondary emission

- Change the potential barrier
    - Field emission
    - Plasma emission

Work Functions for Various Metals

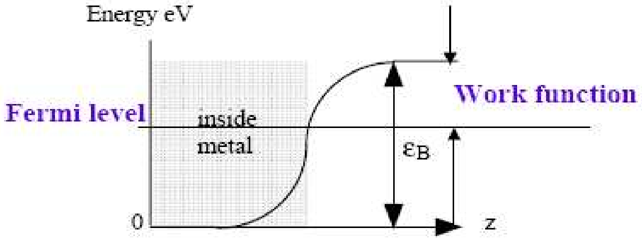
- Assume that the zero energy level represents the bottom of the conduction band.
- Electrons in the conduction band obey Fermi-Dirac statistics
  - $f(\varepsilon) = \{1 + \exp[(\varepsilon - \varepsilon_F)/kT]\}^{-1}$

    $\varepsilon_F = 3.64\text{x}10^{-19}\, n_F^{2/3}$, $n_F = N_V / d^{\,3}$
- N_V is the number of valence electrons per atom, and d is the lattice spacing.
- A crude estimate for the barrier height is

  $\varepsilon_B = 0.33\, [e^2 N_V / (\pi\varepsilon_o d)]$
- The work function is the difference between the barrier height and the Fermi level:

  $\varepsilon_W = \varepsilon_B - \varepsilon_F = 8.3 - 6.9 = 1.4$ eV, for Cs

  ($N_V = 1$, and d = 2.3 Angstroms)

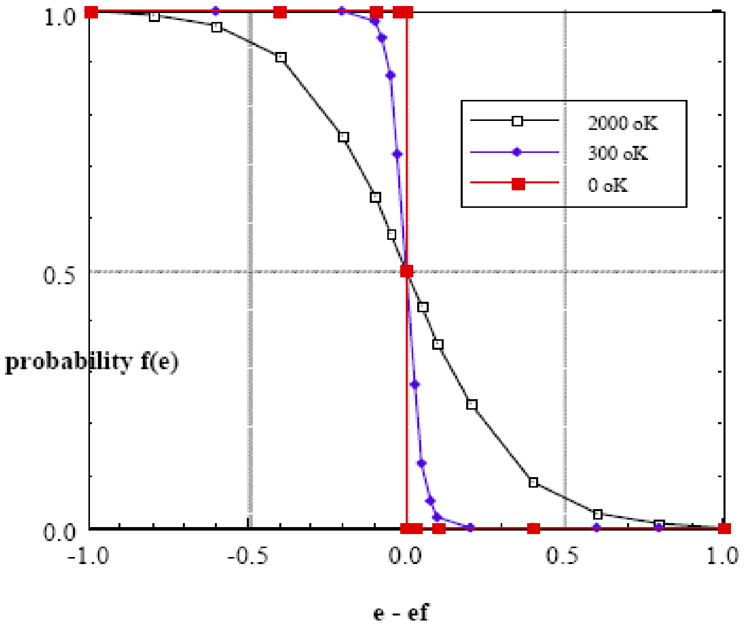


Metal	ε_w (eV)*	Melting Point (oC)
Aluminum	3.7	660
Barium	2.3	725
Carbon	4.4	~3550
Cesium	1.9	28
Copper	4.5	1083
Gold	4.6	1064
Iridium	5.2	2410
Iron	4.4	1535
Molybdenum	4.3	2620
Osmium	5.4	3045
Rhenium	5.1	3180
Thorium	3.4	1750
Tungsten	4.5	3410

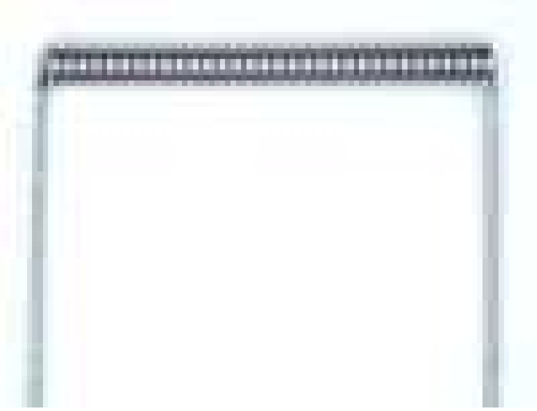
Pure metals with low work functions have low melting points.

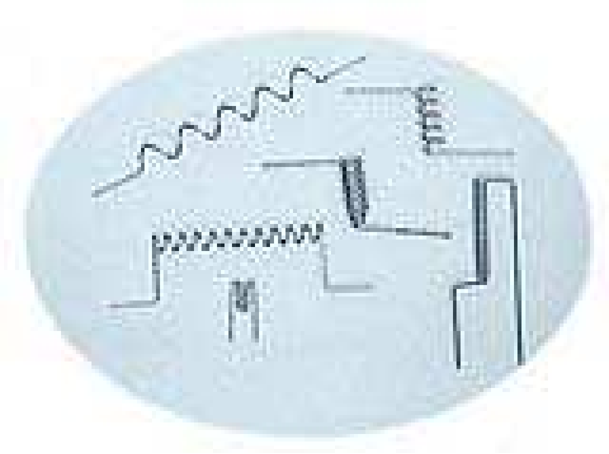
Thermionic Emission

- The kinetic energy of electrons in the conduction band depends on the temperature.
  - $f(\varepsilon) = \{1 + \exp[(\varepsilon - \varepsilon_F)/kT]\}^{-1}$
- The critical z-directed momentum for escape from the surface is
  - $[p_{zc}^2/(2m)] > \varepsilon_B = \varepsilon_F + \varepsilon_W$
- The emission current density is found by integrating the +z directed current of electrons in the conduction band over all momentum states.
- The result is the Richardson-Dushman equation:
  - $j\ (\text{amps/m}^2) = 1.2 \times 10^{-6}\, T^2 \exp(-\varepsilon_W/kT)$



The thermionic emission current density is a function of the temperature and the work function.





Tungsten is one of the most common thermionic emitters. A good figure of merit is how many electrons can be produced per mass of evaporated cathode surface that evaporates – before it break!

Tungsten can operate at high temperatures, but still has a high work function – what else can be used?

-oxide coated tungsten (W=1.6eV), but they are sensitive to vacuum and brittle

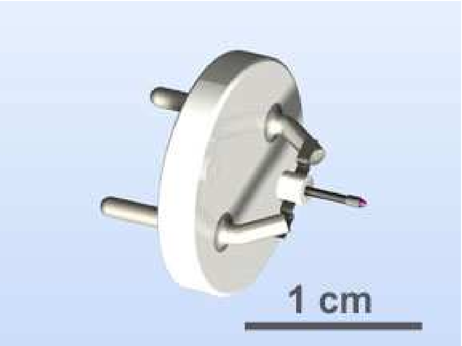
-dispenser cathodes

porous tungsten impregnated with

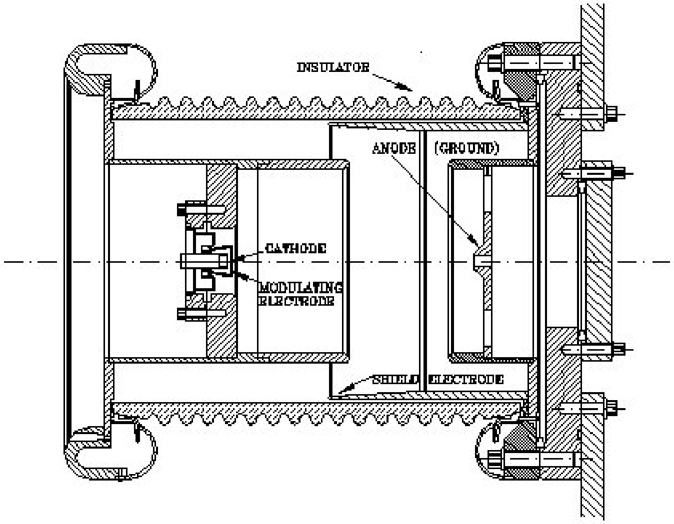
BaO, CaO

maybe coated with Ir, Os, Rh

scandate - 5% by wt of Sc_2O_3, can generate 10s of A/cm^2 for 1000's of hours

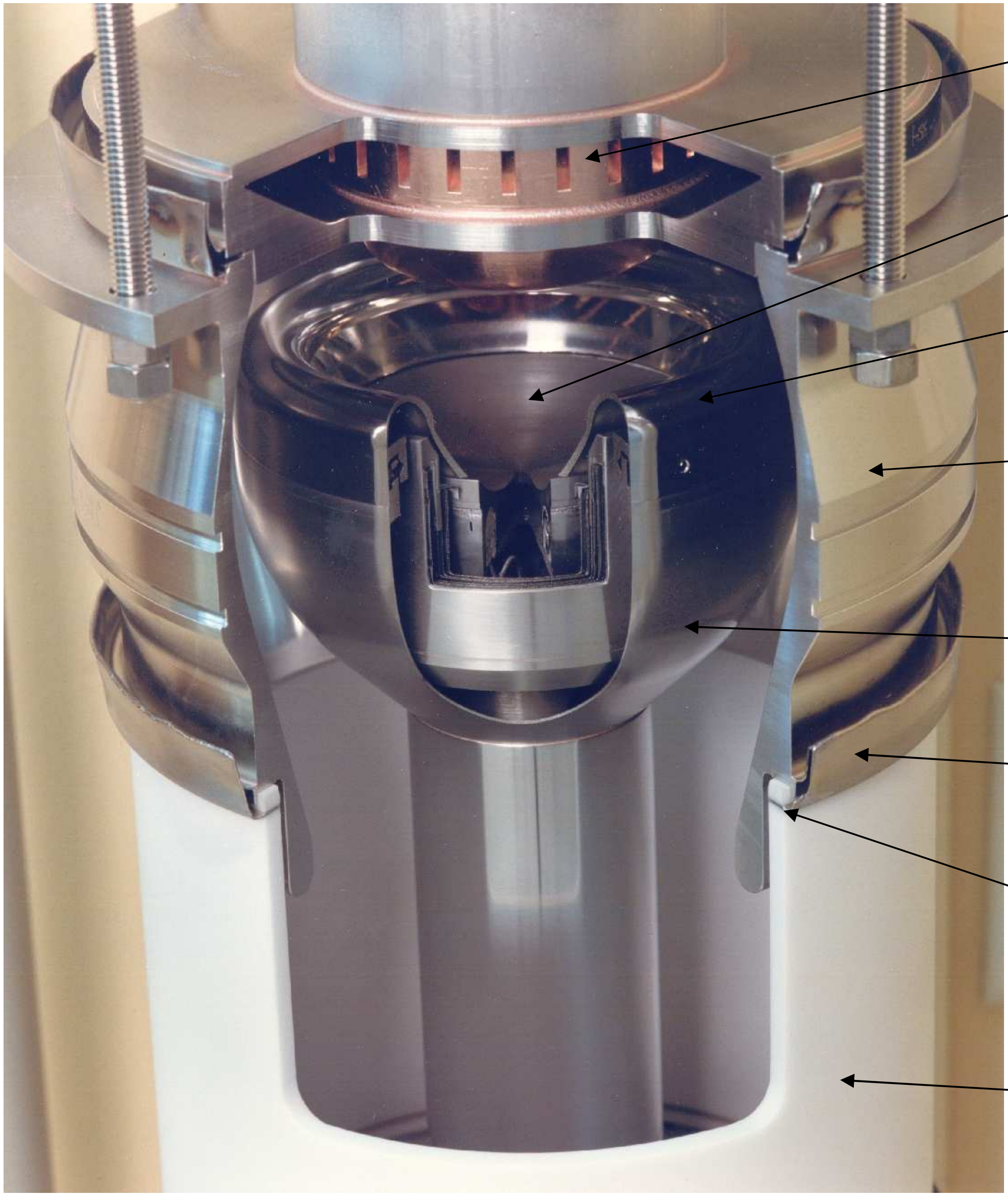


Dispenser Cathodes



EIMAC (CPI)

SLAC Klystron Electron Gun



OFE Copper

Porous Tungsten

317L Stainless Steel

304L VAR Stainless Steel

304L Stainless Steel

Cupronickel

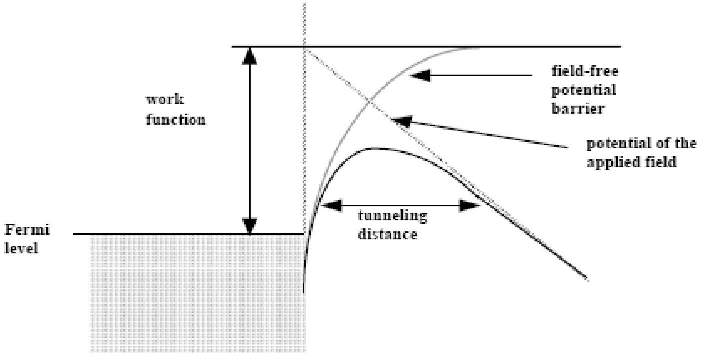
Moly-Manganese Ceramic Metalization

Aluminum Oxide

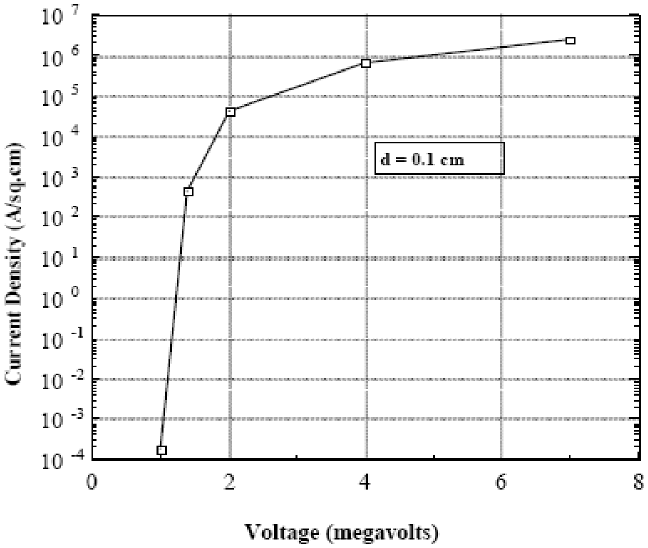
Electron Field Emission

- When the electric field at the surface of a thermionic cathode reaches a critical level, the diode current is observed to rise sharply - the potential barrier is distorted by the applied field.
- Electrons are able to “tunnel” through the barrier. The barrier penetration probability depends on the work function, the Fermi level and the field strength:

$$\psi^*\psi \sim \exp\{[(-2\pi\varepsilon_B)/(heE_a))](2m\varepsilon_W)^{1/2}\}$$



- The required electric fields are quite high (10^7-10^8 V/cm)
- The emission current density is given by the Fowler-Nordheim equation, corrected for space-charge effects. The current density is an extremely sensitive function of the field.
- To date, field emission cathodes have been fabricated in arrays (FEAs), with the tip design providing significant field enhancement.
  - Ion back bombardment can cause a serious deterioration of performance
  - Transition to explosive emission must be avoided



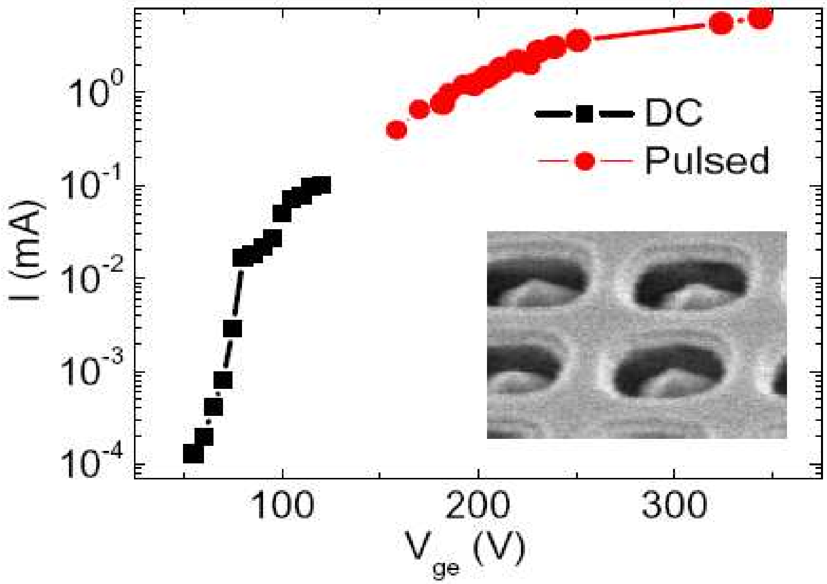


Figure 1: Current-voltage characteristic in DC and pulsed regime for a XDI Inc. FEA (170 µm diameter, 3,000 diamond tips). Insert: SEM picture of some pyramidal diamond tips.

ULTRA-LOW EMITTANCE ELECTRON GUN PROJECT FOR FEL APPLICATION

R. Ganter, M. Dehler, J. Gobrecht, C. Gough, G. Ingold, S.C. Leemann, M. Paraliev,
M. Pedrozzi, J.-Y. Raguin, L. Rivkin, V. Schlott, A. Streun, A. Wrulich,
Paul Scherrer Institut, Villigen, Switzerland
A. Candel, K. Li, Swiss, Federal Institute of Technology, Zürich, Switzerland

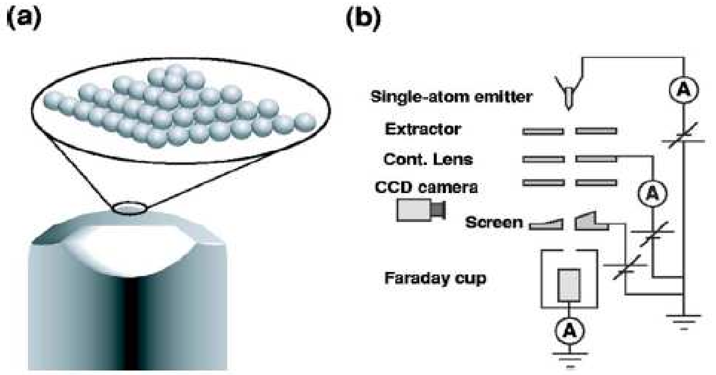


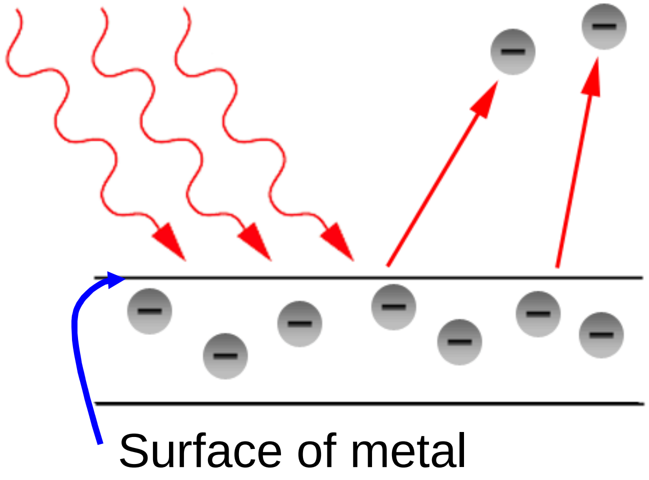
FIG. 1. (Color online) (a) Schematic drawing of the apex of the single-atom source: The ball model of the pyramidal structure at the tip apex is shown. Three sides of the pyramid correspond to three {211} facets. (b) The schematic diagram of the electron gun system.

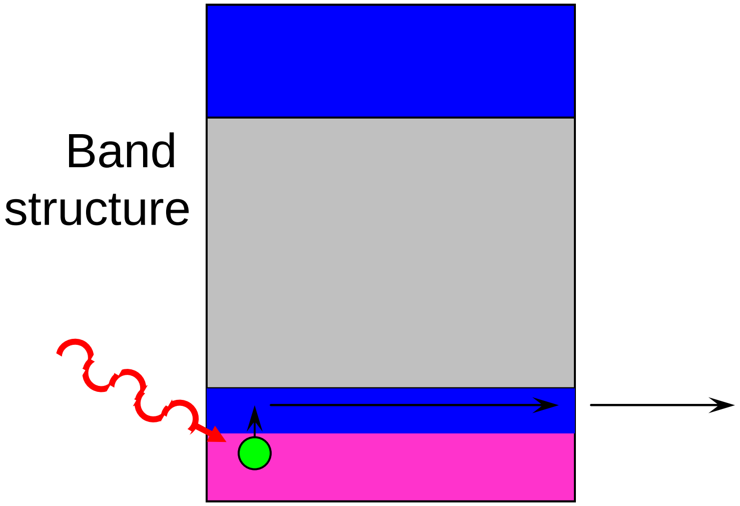
Appl. Phys. Lett. **90**, 143120 (2007)

Photoelectric Effect

Einstein won his Noble prize for work on the photoelectric effect

- Electrons produced by shining light on surface of metal
  - Below threshold energy (wavelength) no electrons are emitted
  - Above threshold, electron energy is the same at any color (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
- Electrons emitted from metals are not polarized



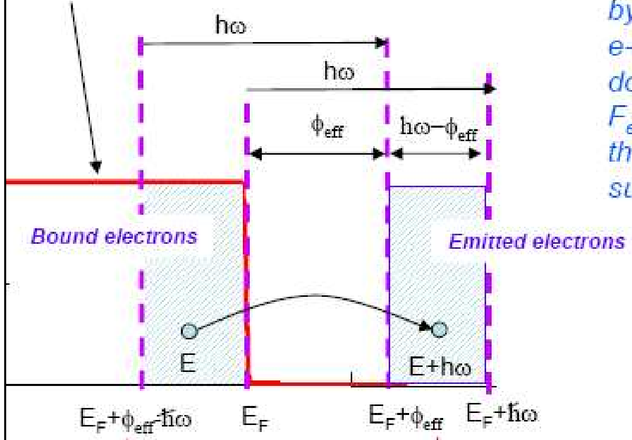


Elements of the Three-Step Photoemission Model

Step 1: Absorption of photon

Fermi-Dirac distribution at 300degK

$f_{FD}(E) = \frac{1}{1+e^{(E-E_F)/k_BT}}$ $\phi_{eff} = \phi - \phi_{schottky}$



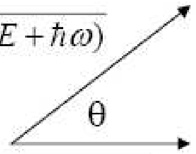
Step 2: Transport to surface

Electrons lose energy by scattering, assume e-e scattering dominates,
$F_{e\text{-}e}$ is the probability the electron makes it to the surface without scattering

Step 3: Escape over barrier

Escape criterion: $\frac{p_{normal}^2}{2m} > E_F + \phi_{eff}$

$$p_{total} = \sqrt{2m(E+\hbar\omega)}$$



$$p_{normal} = \sqrt{2m(E+\hbar\omega)}\cos\theta$$

$$\cos\theta_{max} = \frac{p_\perp}{p_{total}} = \sqrt{\frac{E_F+\phi_{eff}}{E+\hbar\omega}}$$

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

Courtesy Dave Dowell (SLAC)

Types of Photocathodes

Metals – low efficiency, good time response (prompt), resistant to contamination, need UV laser (copper, Mg)

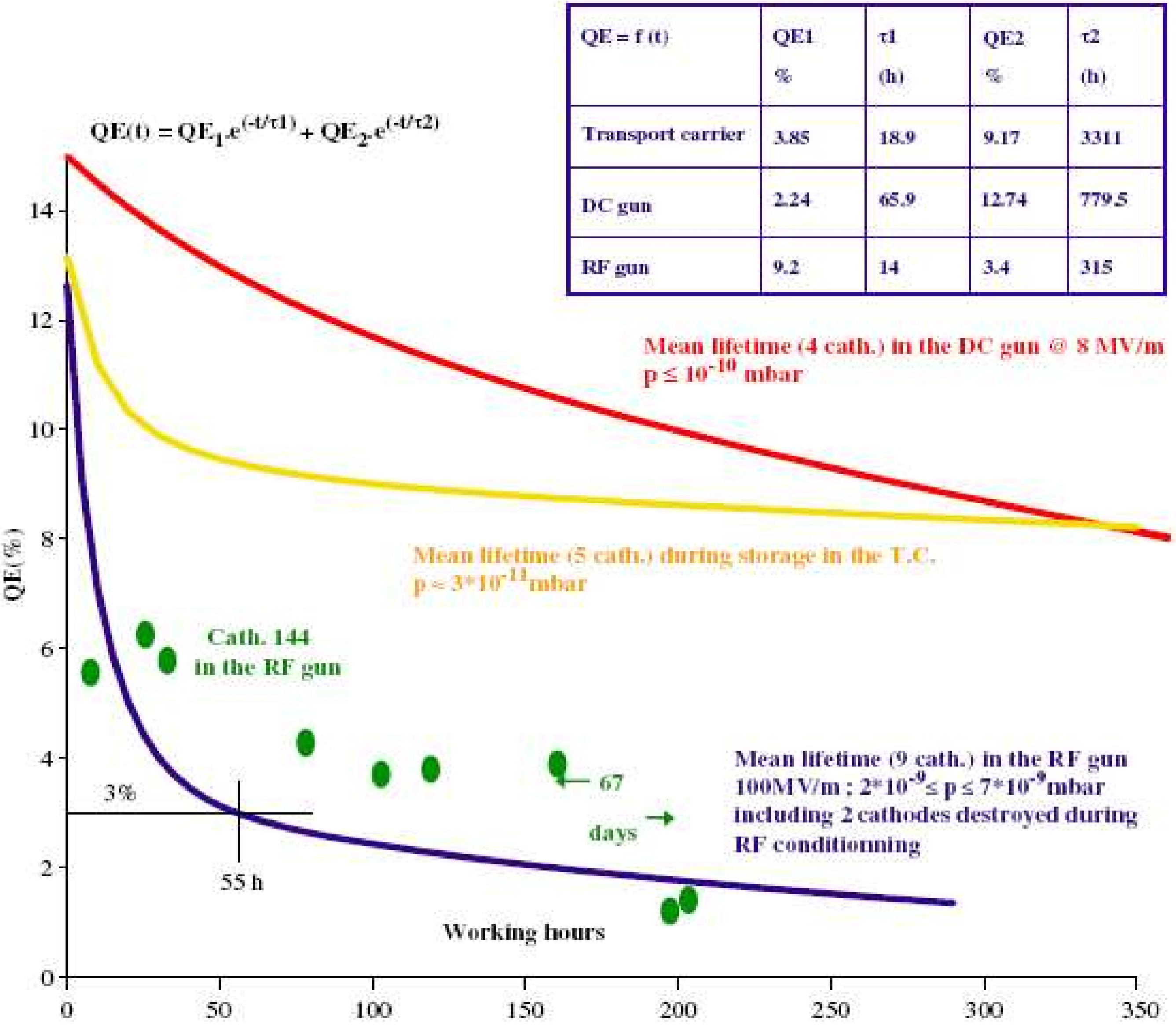
Semi-conductors – high efficiency, slower time response, sensitive to contamination, visible/IR lasers (GaAs, Cs_2Te, K_2CsSb, GaN)

Quantum Efficiency is the figure of merit for photocathodes

QE = # electrons emitted/#incident photons

= S(mA/W) $h\nu/e$ = 1.24 S(mA/W)/λ(nm)

T. Rao et al. / Nuclear Instruments and Methods in Physics Research A 557 (2006) 124–130



QE = f (t)	QE1 %	τ1 (h)	QE2 %	τ2 (h)
Transport carrier	3.85	18.9	9.17	3311
DC gun	2.24	65.9	12.74	779.5
RF gun	9.2	14	3.4	315

$$QE(t) = QE_1 e^{(-t/\tau 1)} + QE_2 e^{(-t/\tau 2)}$$

Fig. 2. Performance of Cs_2Te under different operating conditions.

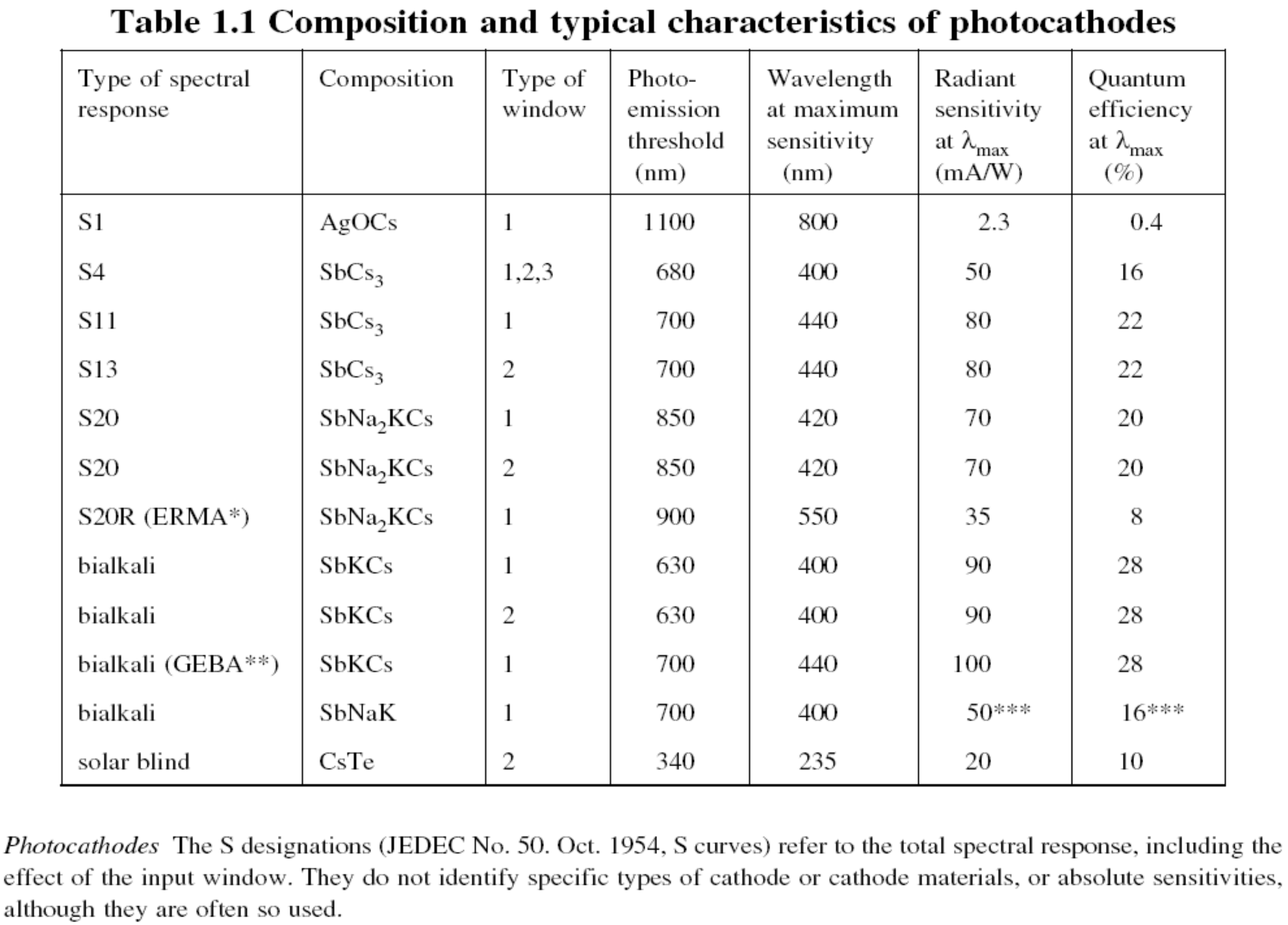


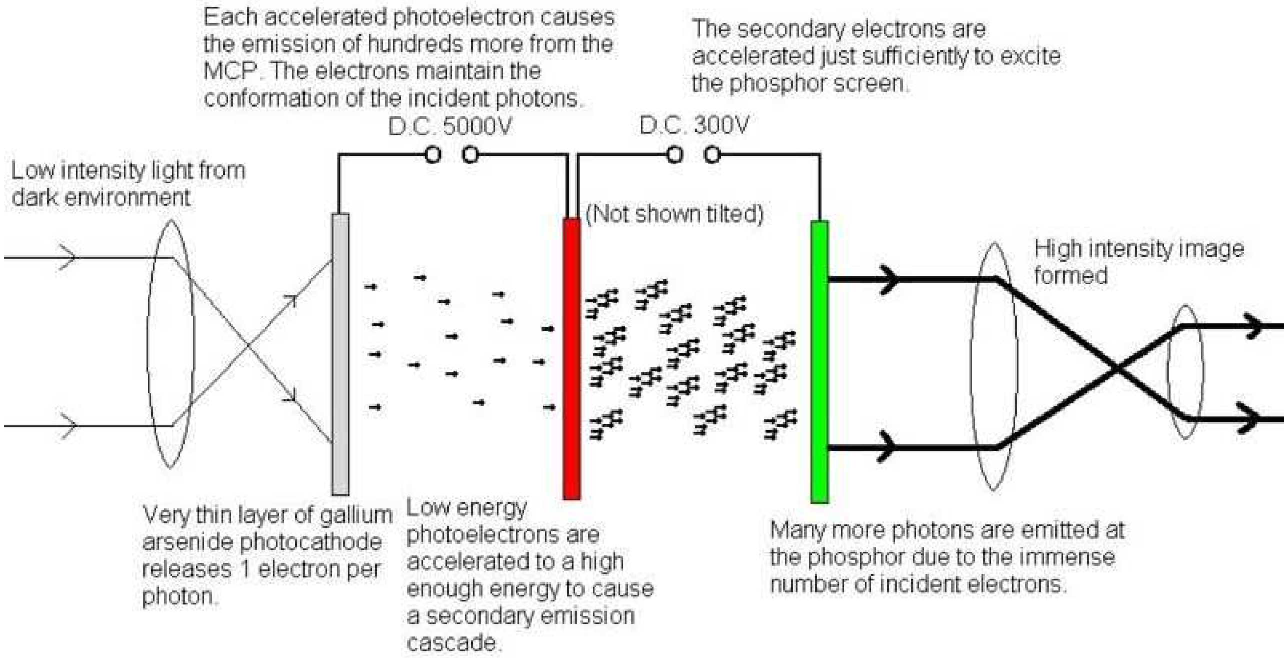
Table 1.1 Composition and typical characteristics of photocathodes

Type of spectral response	Composition	Type of window	Photo-emission threshold (nm)	Wavelength at maximum sensitivity (nm)	Radiant sensitivity at λ_{max} (mA/W)	Quantum efficiency at λ_{max} (%)
S1	AgOCs	1	1100	800	2.3	0.4
S4	$SbCs_3$	1,2,3	680	400	50	16
S11	$SbCs_3$	1	700	440	80	22
S13	$SbCs_3$	2	700	440	80	22
S20	$SbNa_2KCs$	1	850	420	70	20
S20	$SbNa_2KCs$	2	850	420	70	20
S20R (ERMA*)	$SbNa_2KCs$	1	900	550	35	8
bialkali	SbKCs	1	630	400	90	28
bialkali	SbKCs	2	630	400	90	28
bialkali (GEBA**)	SbKCs	1	700	440	100	28
bialkali	SbNaK	1	700	400	50***	16***
solar blind	CsTe	2	340	235	20	10

Photocathodes The S designations (JEDEC No. 50. Oct. 1954, S curves) refer to the total spectral response, including the effect of the input window. They do not identify specific types of cathode or cathode materials, or absolute sensitivities, although they are often so used.

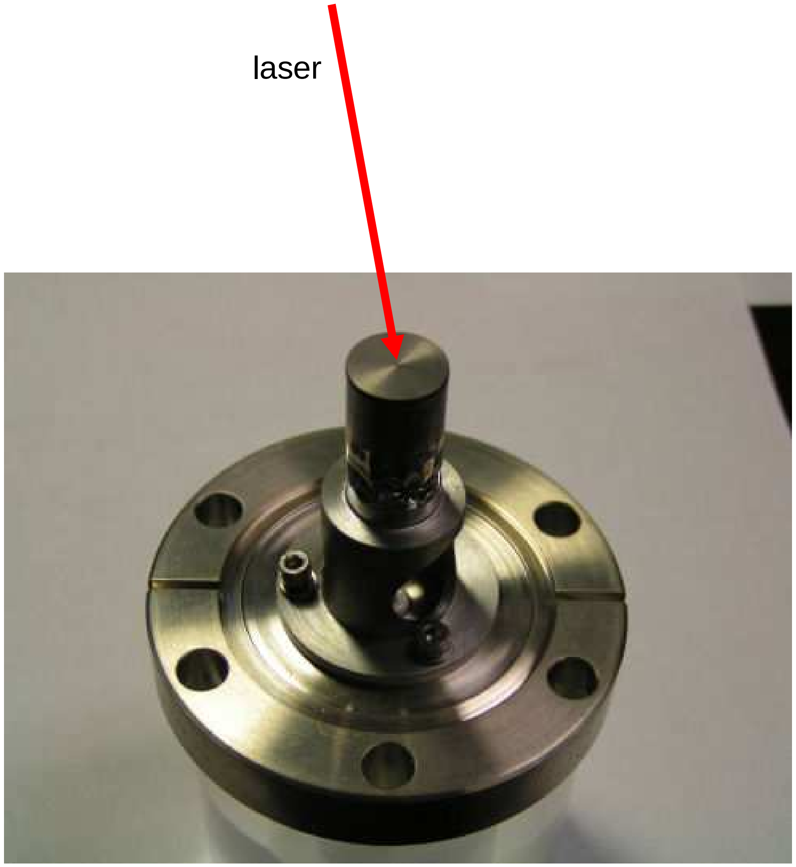
Photonis.com – cathodes used in photomultiplier tubes

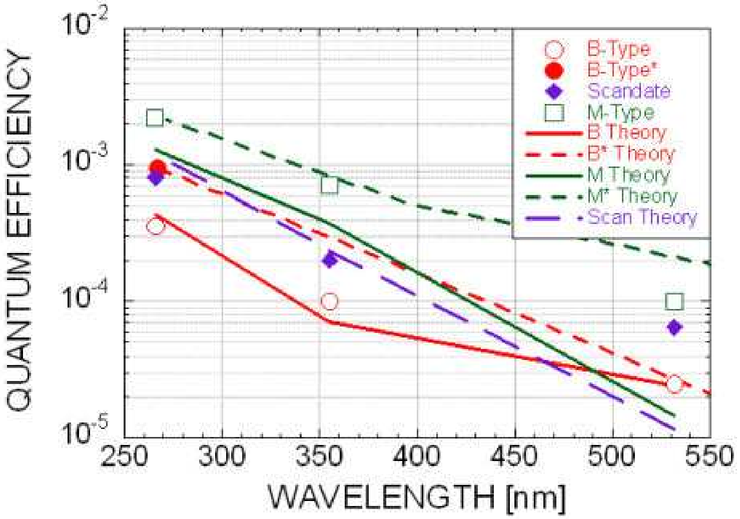
Night Vision Goggles



http://en.wikipedia.org/wiki/Photocathode

Combined Dispenser cathode with photoemission

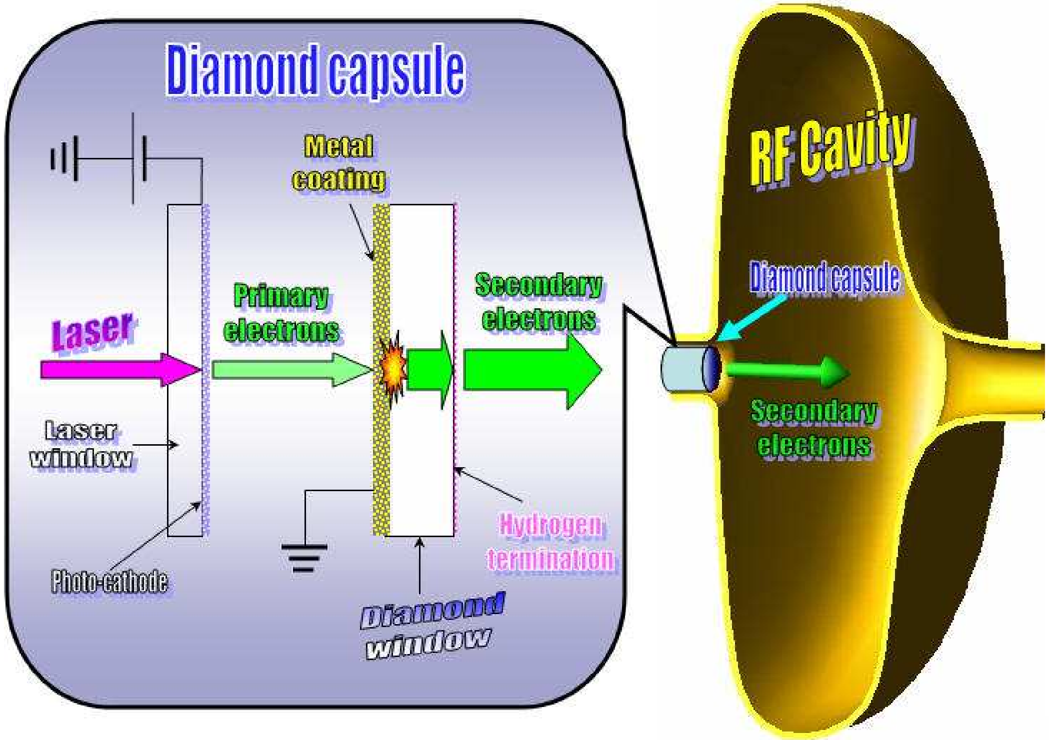




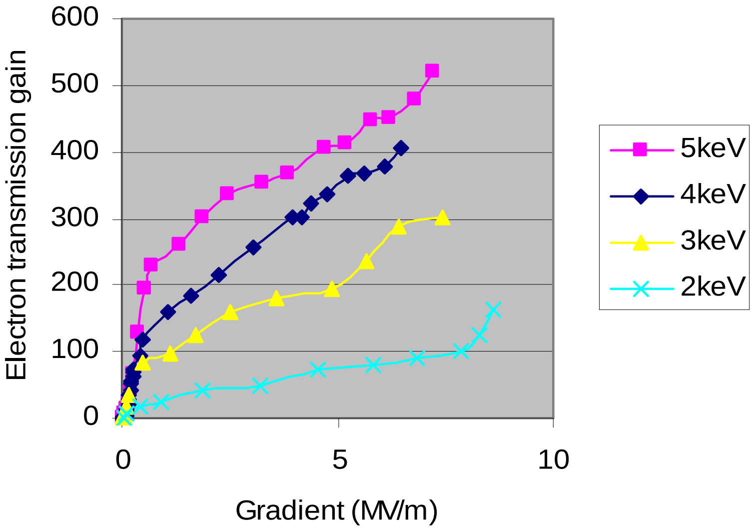
Heat the cathode up to just below the threshold for emission, then use the laser energy to emit a pulse of electrons

http://www.ireap.umd.edu/FEL/Research/Photocathode.htm#thermionic

Diamond Amplifier



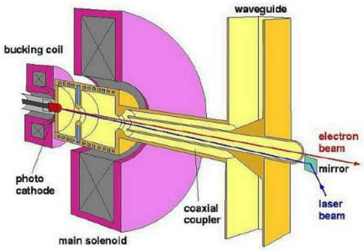
http://www.bnl.gov/cad/ecooling/DAP_principles.asp



www.agsrhichome.bnl.gov/AP/BNLapSeminar/
2005_sept16.ppt

Electron Guns for Accelerators

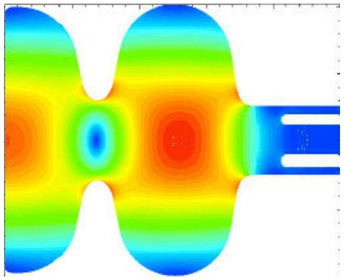
NCRF



pulsed!

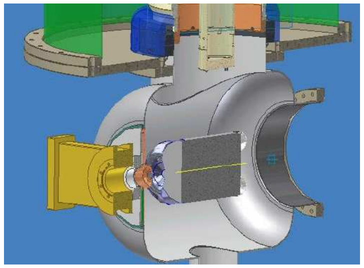
E_{cath} = 120 MV/m
τ_{laser} = 2.7 ps rms
σ_{laser} = 0.5 mm rms

SRF



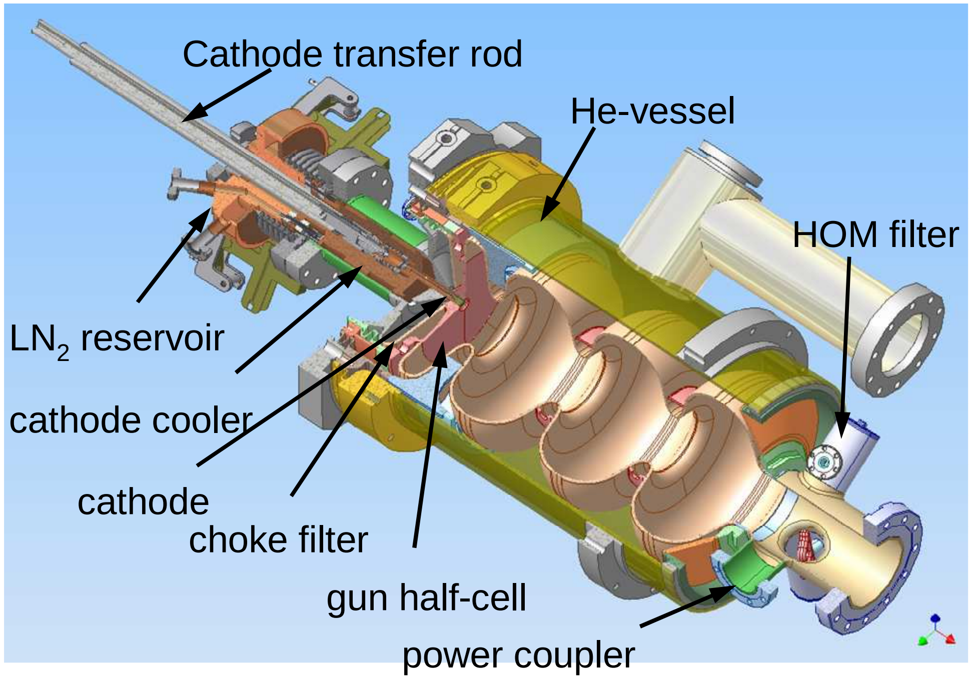
E_{cath} = 43 MV/m
τ_{laser} = 5.8 ps rms
σ_{laser} = 0.85 mm rms

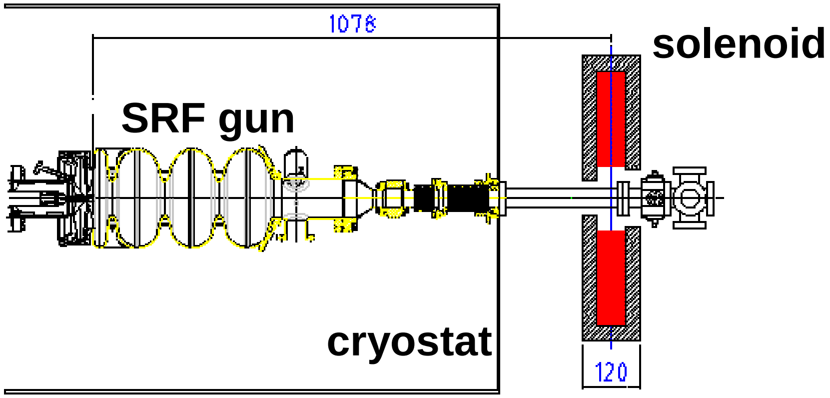
DC

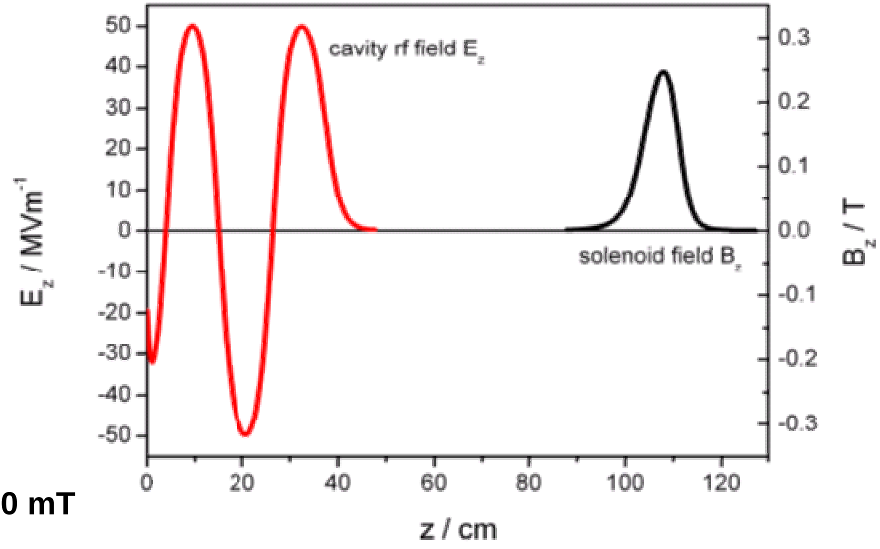


E_{cath} = 8 MV/m
τ_{laser} = 13 ps rms
σ_{laser} = 2 mm rms

$3^1/_2$ cell SRF gun Rossendorf







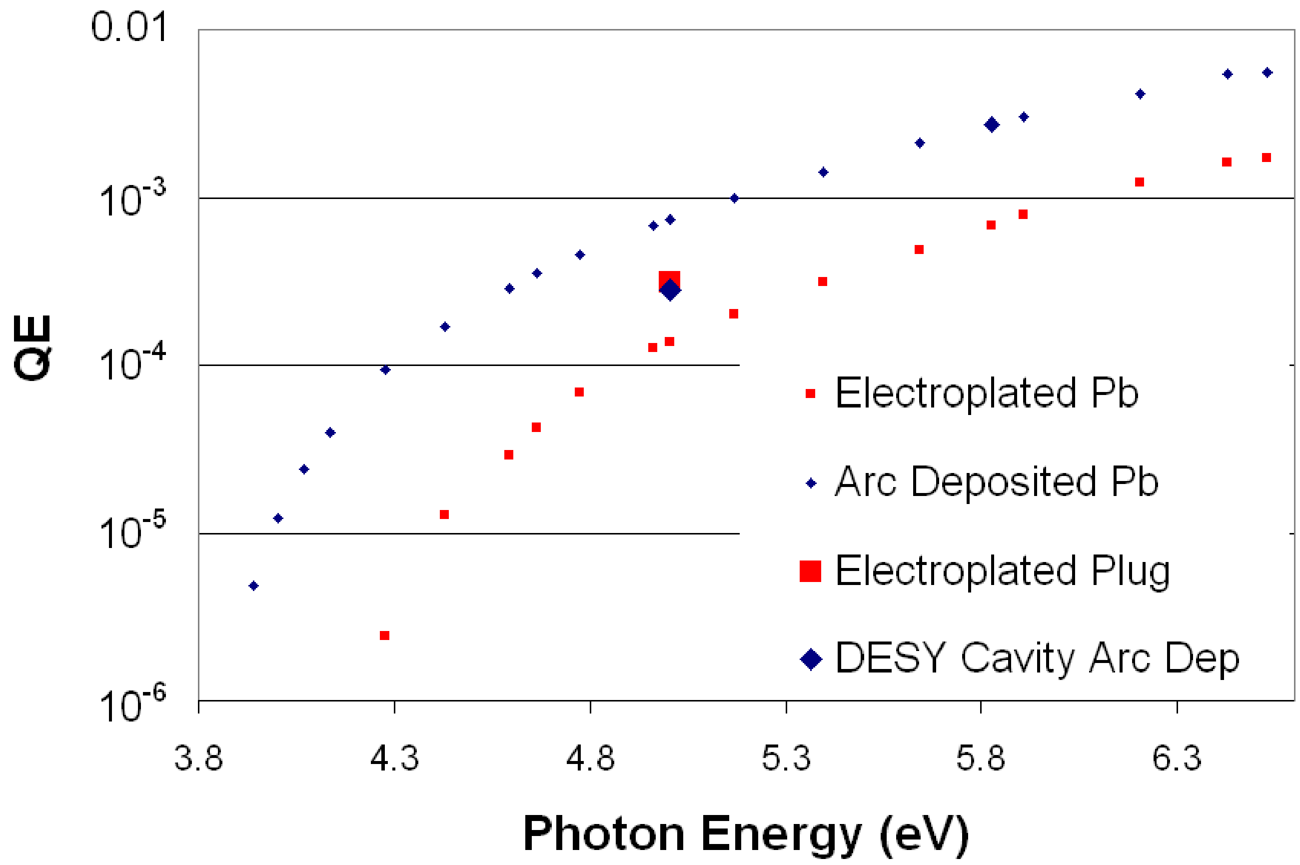
B_{max} = 110 mT

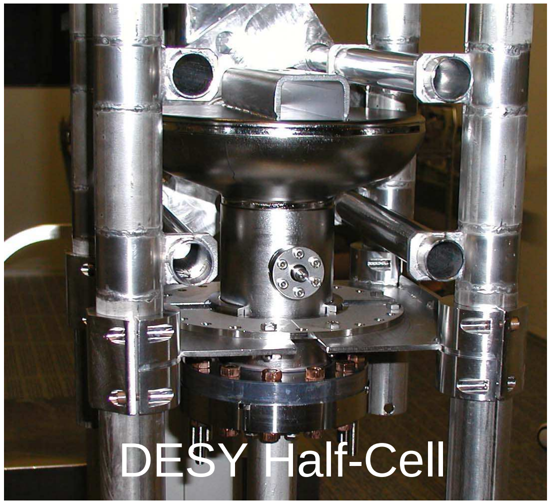
Friedrich Staufenbiel

Forschungszentrum Dresden-Rossendorf
Zentralabteilung Strahlungsquelle ELBE
PF 510119, 01314 Dresden
F.Staufenbiel@fzd.de

ERL 2007, May 21 – 25

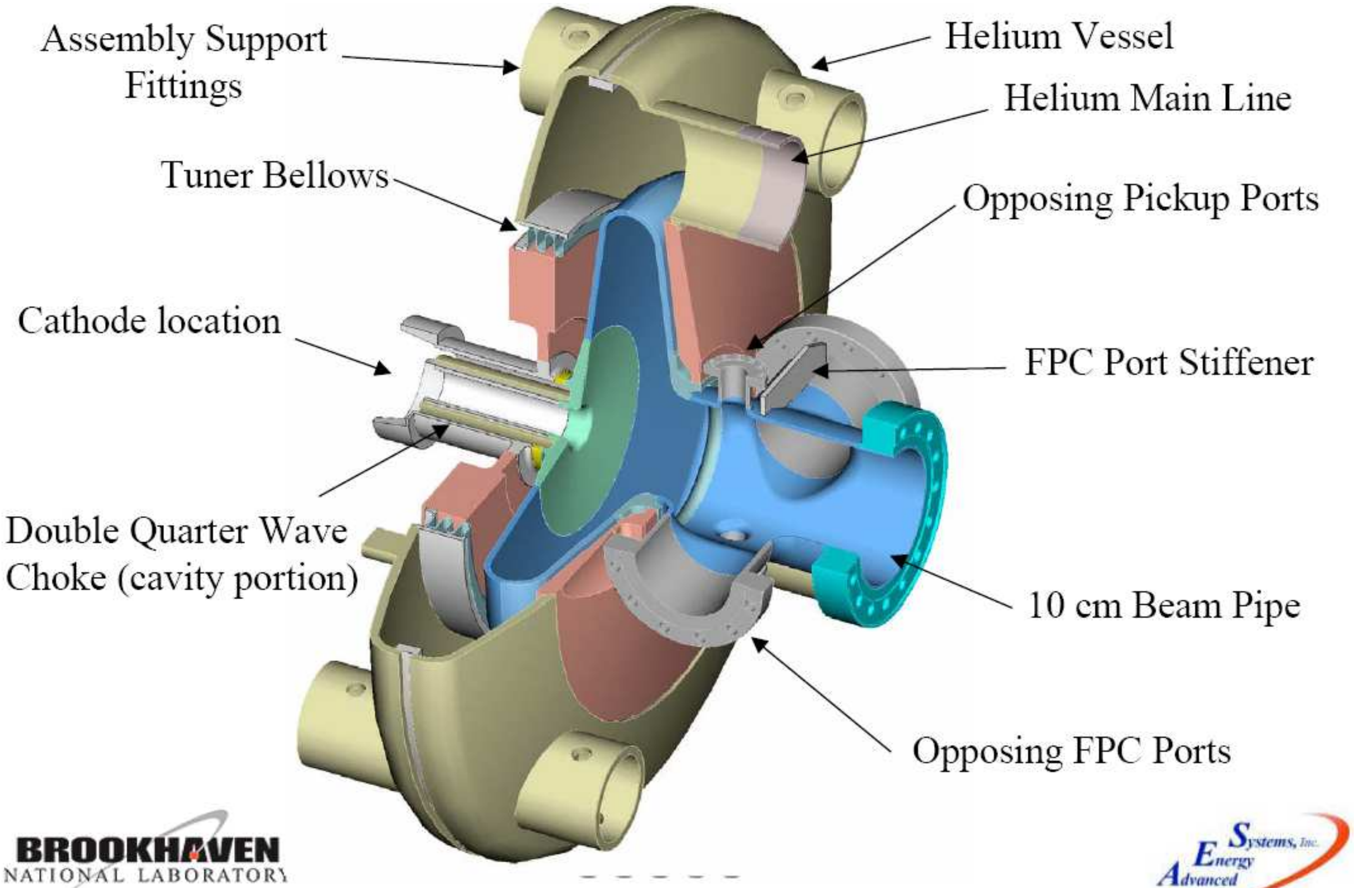
Cathodes for Superconducting RF cavities





Courtesy John Smedley (BNL)

BNL SRF Gun Design

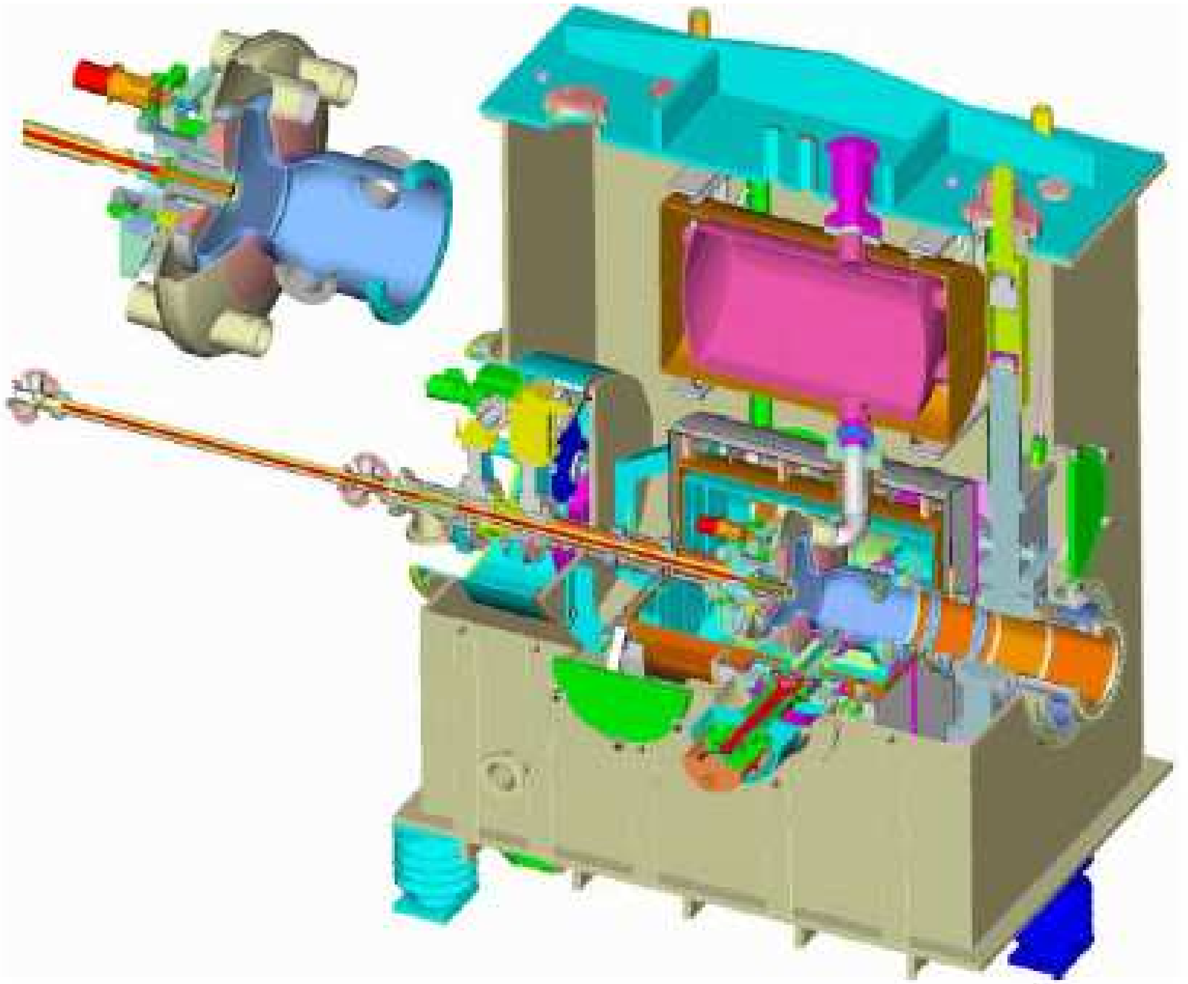


BROOKHAVEN NATIONAL LABORATORY

Advanced Energy Systems, Inc.

Photoinjector designed to deliver 2 MeV beam, 5 nC/bunch at 9.38 MHz

BNL Gun Cryomodule

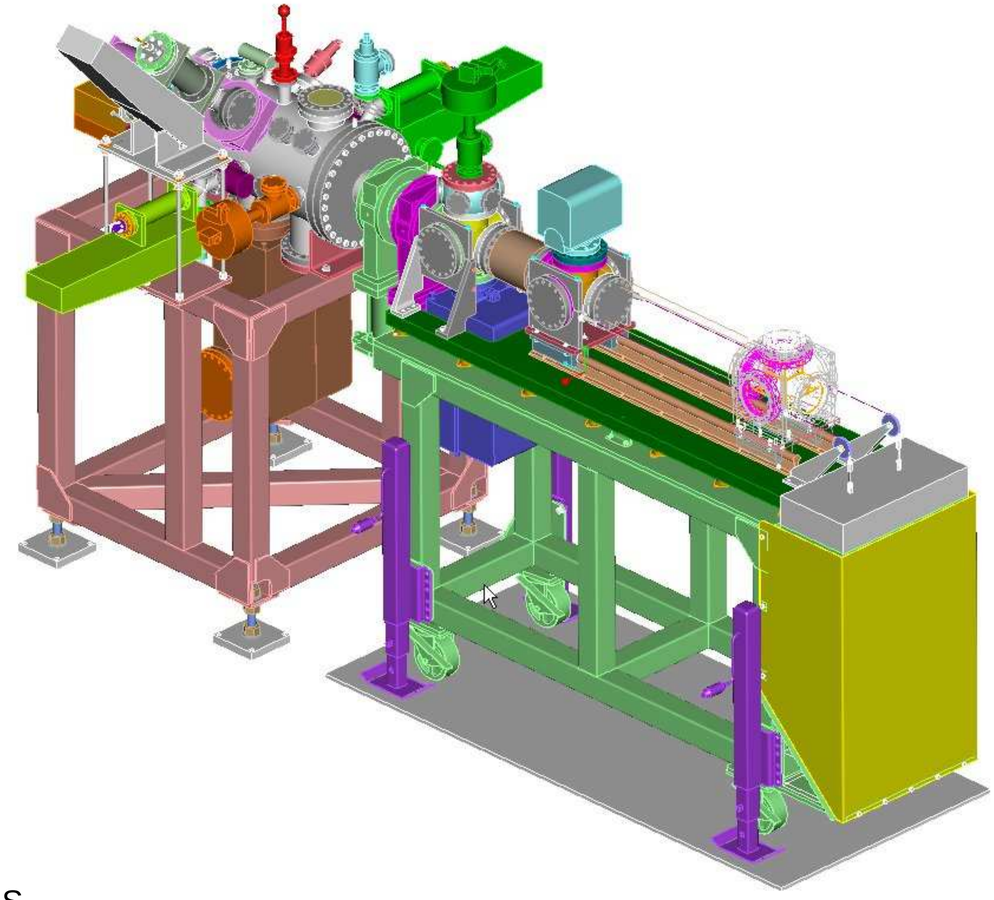


Photocathode choice and challenges

- CsK_2Sb is cathode of choice, with a diamond amplified photocathode as the next generation cathode
- Lots of experience with CsK_2Sb photocathode deposition, extensive R&D on diamond amplified photocathode

Challenges	Solutions
Cathode lifetime	No vacuum degradation
Thermal isolation	Actively cooled cathode stalk
Particulate and interface to gun	Proper engineering and design

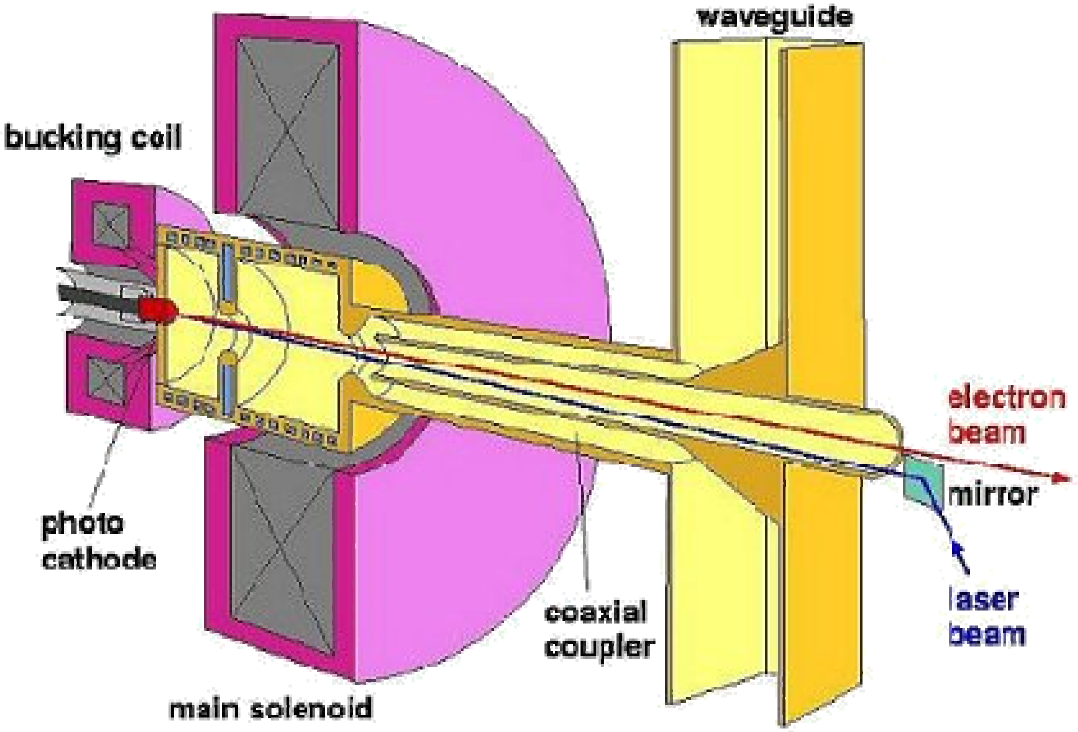
BNL Photocathode deposition system



Designed by AES

Normal Conducting RF Gun

Much simpler than an SC RF Gun!



PITZ NC RF gun, 1 nC, 10 kHz

Boeing RF Gun

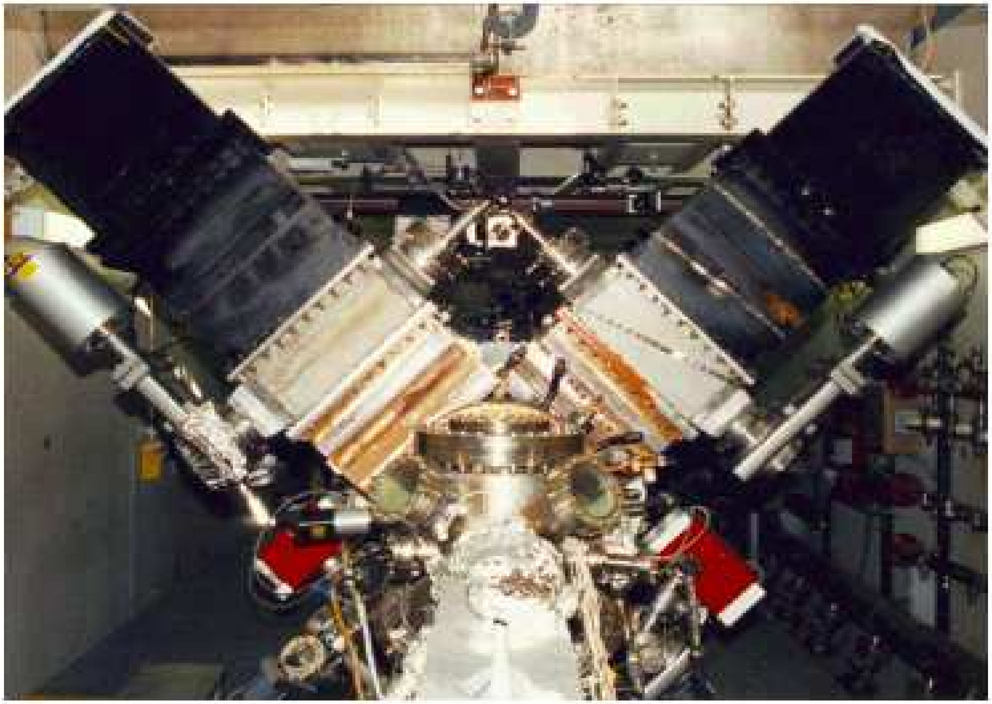


Fig. 1. Photograph of the Boeing/LANL 433 MHz NCRF gun in the test vault.

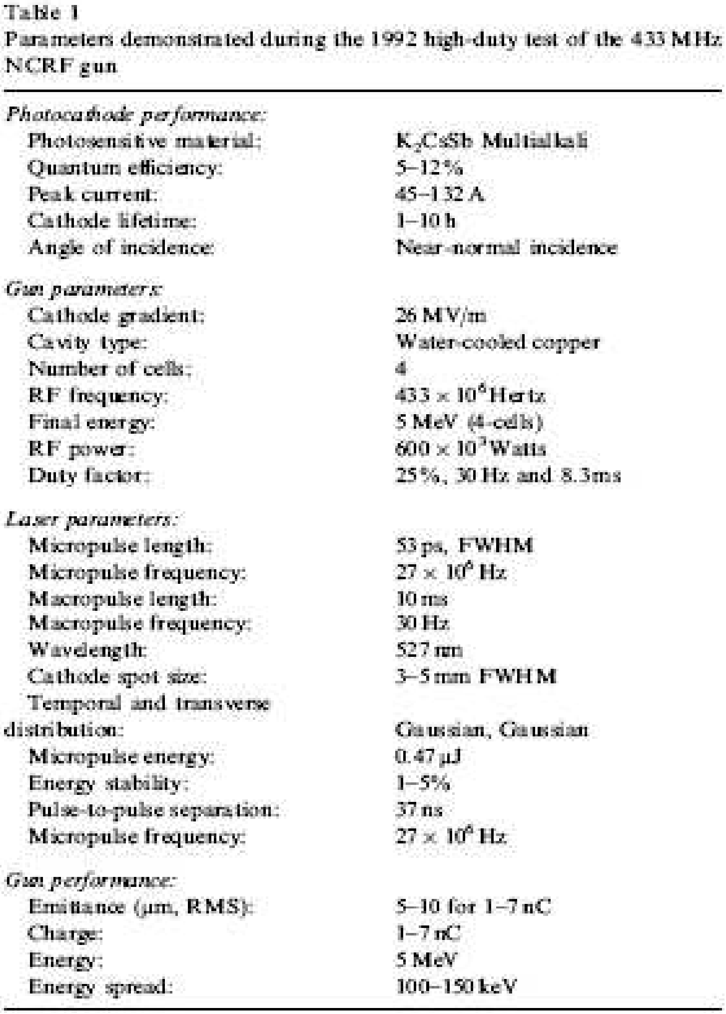


Table 1
Parameters demonstrated during the 1992 high-duty test of the 433 MHz NCRF gun

Photocathode performance:	
Photosensitive material:	K_2CsSb Multialkali
Quantum efficiency:	5–12%
Peak current:	45–132 A
Cathode lifetime:	1–10 h
Angle of incidence:	Near-normal incidence
Gun parameters:	
Cathode gradient:	26 MV/m
Cavity type:	Water-cooled copper
Number of cells:	4
RF frequency:	433×10^6 Hertz
Final energy:	5 MeV (4-cells)
RF power:	600×10^3 Watts
Duty factor:	25%, 30 Hz and 8.3 ms
Laser parameters:	
Micropulse length:	53 ps, FWHM
Micropulse frequency:	27×10^6 Hz
Macropulse length:	10 ms
Macropulse frequency:	30 Hz
Wavelength:	527 nm
Cathode spot size:	3–5 mm FWHM
Temporal and transverse distribution:	Gaussian, Gaussian
Micropulse energy:	0.47 μJ
Energy stability:	1–5%
Pulse-to-pulse separation:	37 ns
Micropulse frequency:	27×10^6 Hz
Gun performance:	
Emittance (μm, RMS):	5–10 for 1–7 nC
Charge:	1–7 nC
Energy:	5 MeV
Energy spread:	100–150 keV

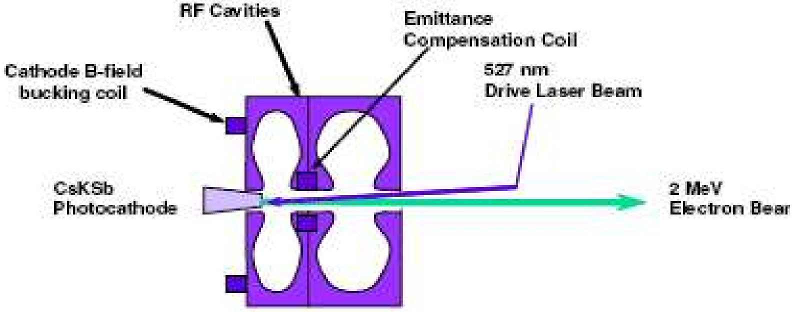
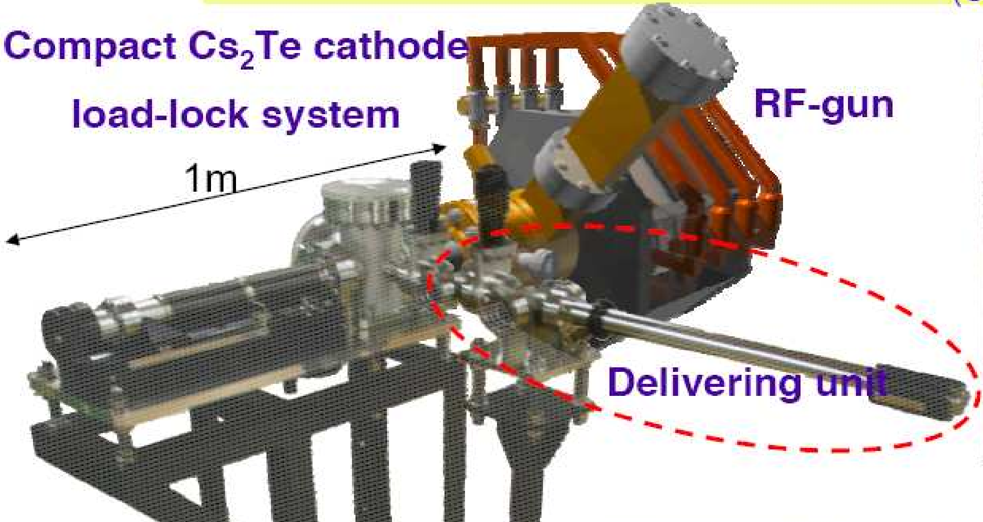


Fig. 2. Drawing of the 433 MHz gun showing the re-entrant design and the locations of the emittance compensation coil and cathode field-bucking coil. Cells 3 and 4 indicated in Table 1 are not shown. The cathode was fabricated in an attached deposition chamber and inserted into the gun under vacuum via a long cathode stick. See Fig. 1 and Refs. [2,3].

Development of Cs_2Te compact load-lock system for multi-bunch electron beam generation

(Collaborating with KEK, Waseda Univ.)

Compact Cs_2Te cathode load-lock system



Te 50nm

Cs >10nm

Los Alamos High Avg Current RF Gun

Funded by NAVSEA and the JTO, Los Alamos and Advanced Energy Systems (AES) have designed a water-cooled 700 MHz copper photocathode gun with a dense array of cooling channels for thermal management and sufficient vacuum pumping to provide a good vacuum in the photocathode cell [5]. The design of a normal-conducting, 700 MHz gun operating at 7, 7 and 5 MV/m is shown in Fig. 3. The photocathode gun is designed to produce 2.5 MeV electron beams. It consists of a π-mode, $2\frac{1}{2}$-cell, RF cavity with on-axis electric coupling and emittance compensation, and a non-resonant vacuum plenum. The non-resonant vacuum plenum can accommodate up to eight ion pumps to ensure adequate vacuum pumping of the RF injector. Large-diameter apertures between the resonant cells and the non-resonant vacuum plenum are used to maintain high-conductance passages for pumping the photocathode cell. Heat removal in the resonant cells is achieved via dense arrays of internal cooling passages capable of handling high-velocity water flows. The septum walls are almost flat to keep the cooling channels as close to the RF surface as possible. Megawatt RF power is coupled into the gun through two tapered ridge-loaded waveguides [6]. PARMELA simulations show that the room-temperature RF photocathode gun can produce a 6 mm-mrad emittance at 3 nC bunch charge.

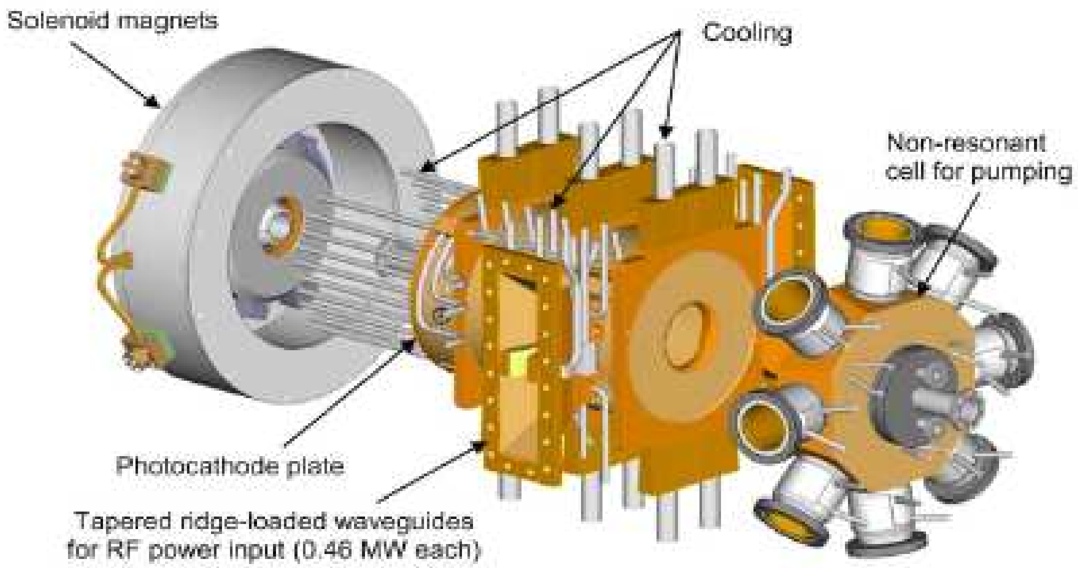
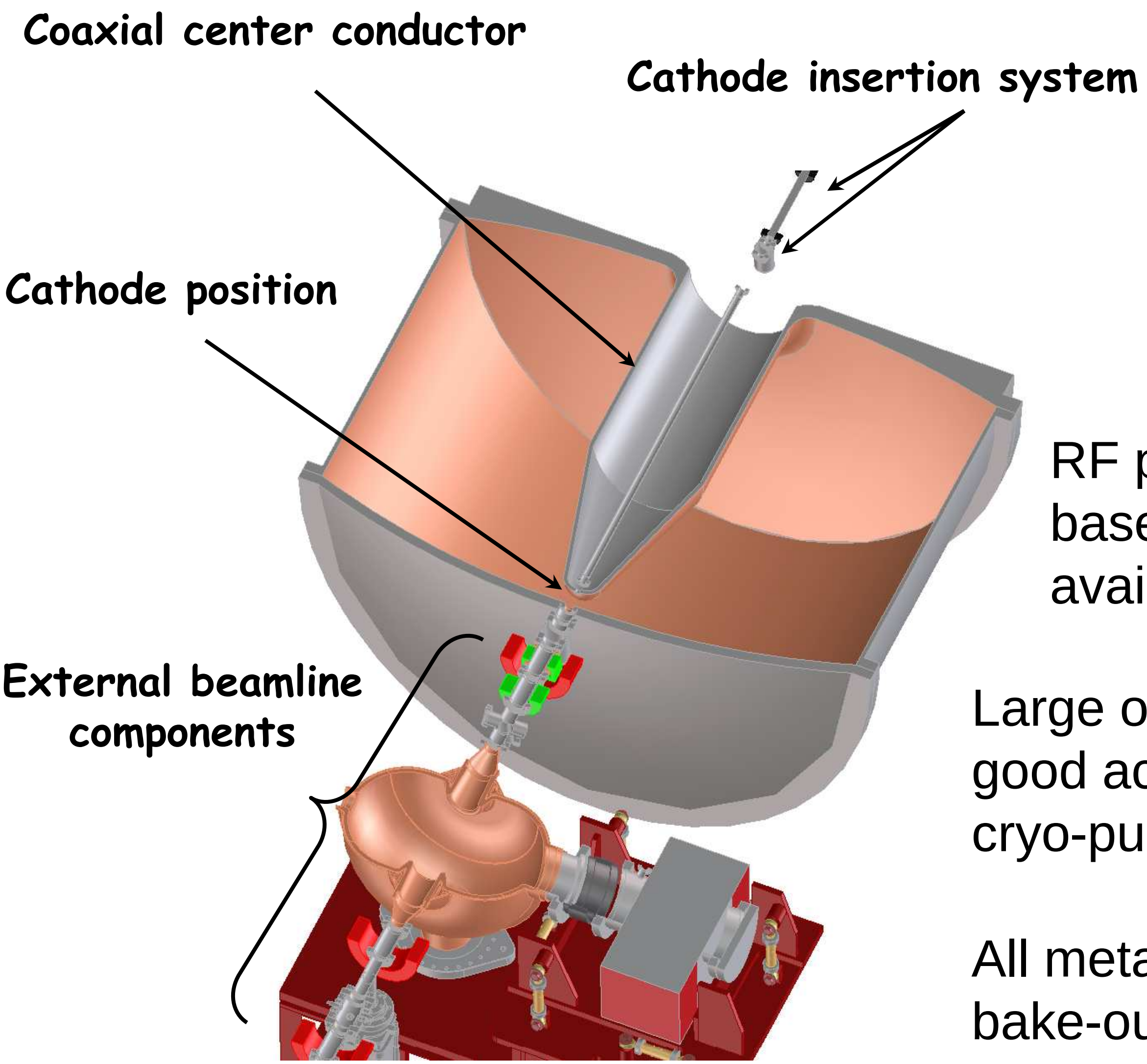


Fig. 3. Exploded view of the $2\frac{1}{2}$—cell NCRF gun being fabricated by AES for LANL. The non-resonant cell provides additional vacuum pumping for th 1.5-cell gun.

LBNL VHF quarter-wave coaxial cavity gun



65 MHz CW
Normal conducting
Cu-plated Al

RF power sources can be based on commercially available broadcast tubes.

Large outer diameter provides good accessibility for ion- and cryo-pumps.

All metal structure suitable for bake-out.

Steve Lidia, LBNL, ERL 2007 Workshop

Example VHF gun performance

Frequency	65	MHz
Pulse rate	CW	
Gap Voltage	0.6-1.0	MV
Unloaded *Q*	$3.5\mathrm{x}10^{4}$	
Effective Gap Length	4	cm
Range of field in planar gap	15-25	MV/m
Cavity length	1	meter
Cavity diameter	1.4	m
Inner conductor diameter	0.3	m
RF power for 0.75 MV on gap	65	kW
Peak wall power density	7	W/cm^2
Vacuum	10^{-11}	Torr
Required pumping speed	25000	liter/sec
Stored energy	5-8	J