Particle sources: Electron sources

Nicolas Delerue

LAL (CNRS and Université de Paris-Sud)

About me

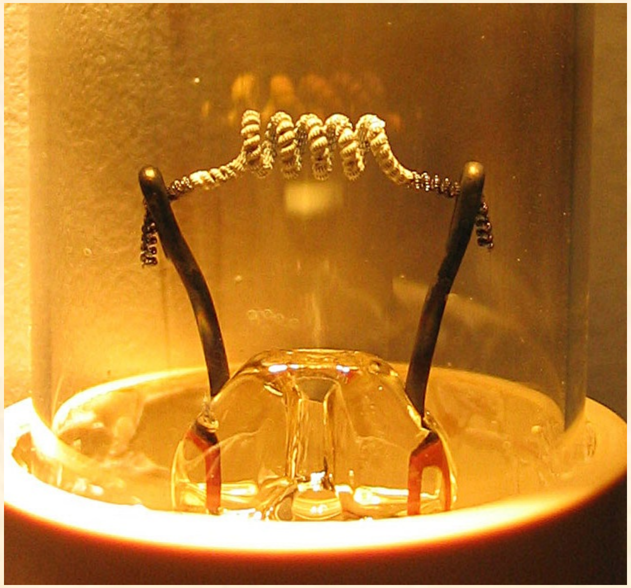
- Researcher in the Accelerator department of IJCLab.
- Deputy head of the national research group (GdR) dedicated to laser-plasma acceleration.
- Main research area:
  - Beam diagnostics
  - Laser-plasma acceleration
  - Compton sources

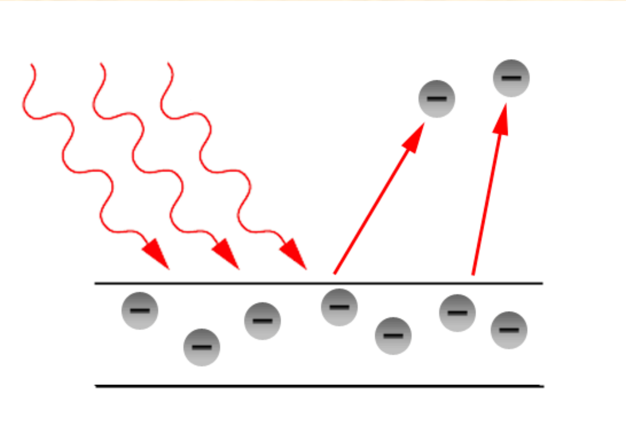
Electron sources: Content

- Physical processes leading to the emission of electrons
- Gun design
- Beam dynamics in the gun
- Diagnostics
- Types of electron guns

Physical process: extracting electrons

In this first part of the lecture we will see what are the conditions to be met to extract electrons from a metal.



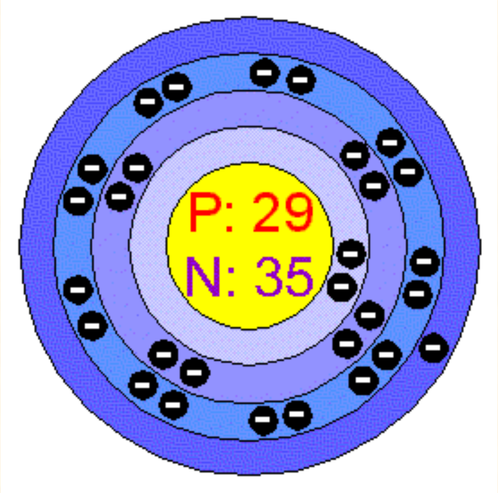


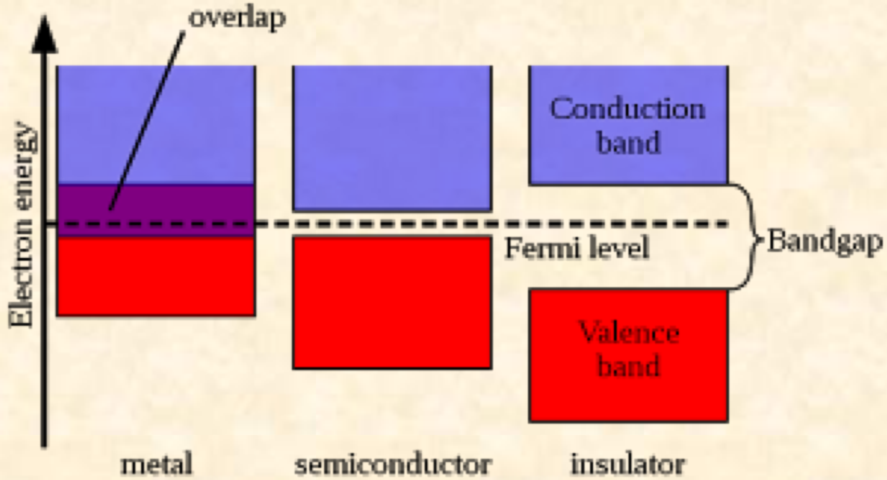
Physical process: Electrons in metal

- Electrons are readily available in metals.
- Eg: Copper:
  - 29 electrons/atom,
  - $9 g/cm^3 \Rightarrow 0,14 mol/cm^3$
  $\Rightarrow 2.\ x10^{24}$ electrons/cm^3
- However theses electrons are 'trapped' in the metals.

Electrons in metal: energy levels

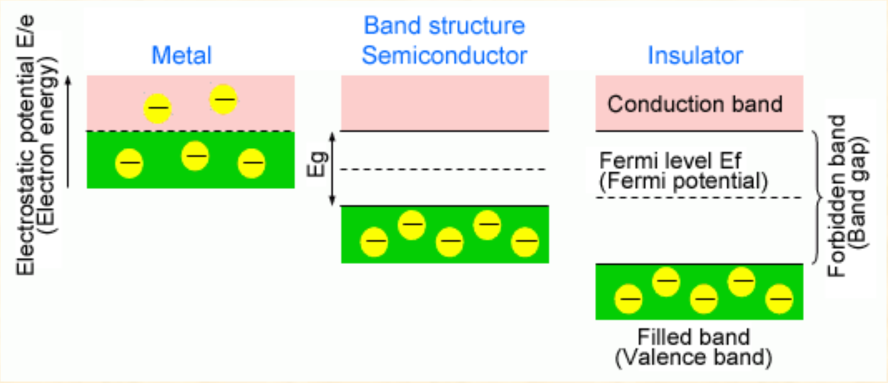
- In a free atom the electrons are located on orbits of increasing energy around the nucleus.
- In a solids these orbits are replaced by the conduction band and the valence band.

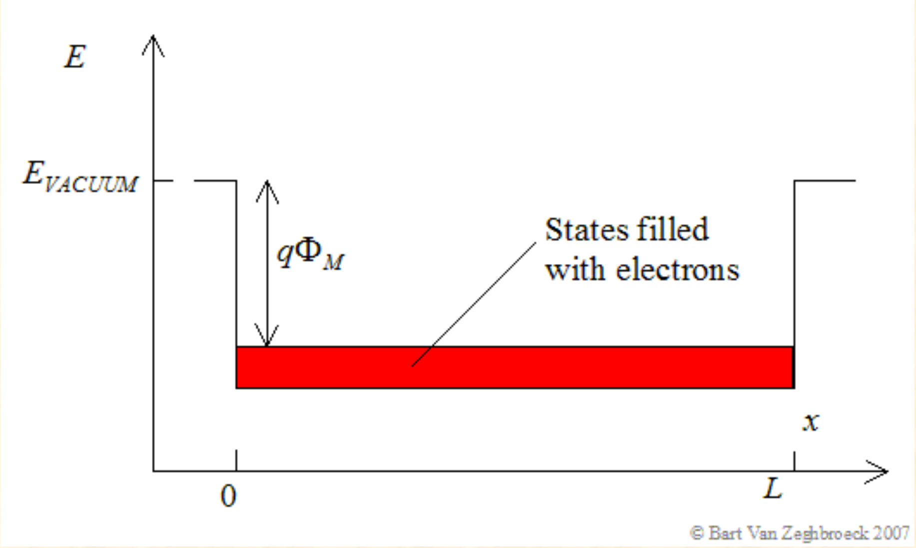




Extracting electrons from metal

- The energy needed to free the electron from a solid is called "Work function".
- This work function is different for each material.

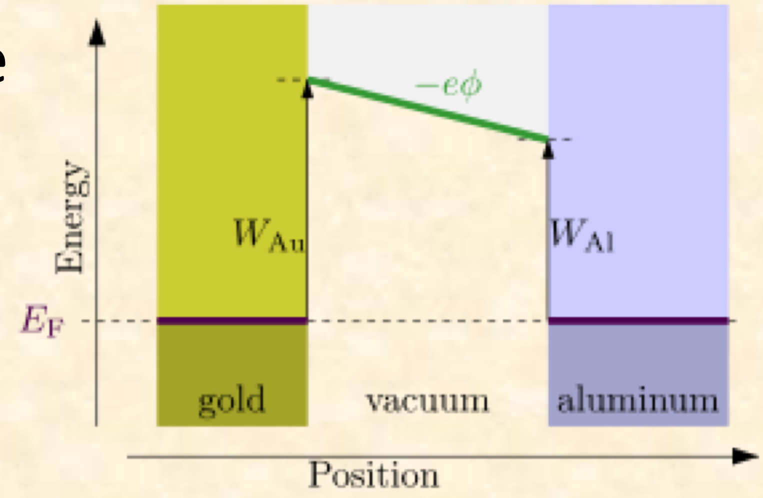




Work function

- The work function (W) is the minimum thermodynamic work needed to remove an electron from a solid to a point in the vacuum immediately.
- E_F: Fermi energy (energy of the electrons at equilibrium).
- ϕ electrostatic potential.
- This depends on the configuration of the atoms on the surface so the same chemical element with different crystalline configuration will have different work function.

$$W = -e\phi - E_F$$



Work function for different materials

- Values of work functions are tabulated.

Source: wikipedia

Work function of elements, in units of electron volt (eV).

Ag	4.26 – 4.74	Al	4.06 – 4.26	As	3.75
Au	5.1 – 5.47	B	~4.45	Ba	2.52 – 2.7
Be	4.98	Bi	4.31	C	~5
Ca	2.87	Cd	4.08	Ce	2.9
Co	5	Cr	4.5	Cs	2.14
Cu	4.53 – 5.10	Eu	2.5	Fe:	4.67 – 4.81
Ga	4.32	Gd	2.90	Hf	3.9
Hg	4.475	In	4.09	Ir	5.00 – 5.67
K	2.29	La	3.5	Li	2.9
Lu	~3.3	Mg	3.66	Mn	4.1
Mo	4.36 – 4.95	Na	2.36	Nb	3.95 – 4.87
Nd	3.2	Ni	5.04 – 5.35	Os	5.93
Pb	4.25	Pd	5.22 – 5.6	Pt	5.12 – 5.93
Rb	2.261	Re	4.72	Rh	4.98
Ru	4.71	Sb	4.55 – 4.7	Sc	3.5
Se	5.9	Si	4.60 – 4.85	Sm	2.7
Sn	4.42	Sr	~2.59	Ta	4.00 – 4.80
Tb	3.00	Te	4.95	Th	3.4
Ti	4.33	Tl	~3.84	U	3.63 – 3.90
V	4.3	W	4.32 – 5.22	Y	3.1
Yb	2.60 [13]	Zn	3.63 – 4.9	Zr	4.05

Quizz

- Copper has a work function between 4.53 eV and 5.10 eV.
- What is the wavelength of a photon with an energy of 5 eV?
  (a) 250 mm
  (b) 250 um (micrometers)
  (c) 250 nm
  (d) 250 A (Angstrom)

$$e = \frac{hc}{\lambda}$$

- Reminder: $c=3.10^{8}$ m/s
  $h=6x10^{-34}$J.s
  $1eV=1.6\ 10^{-19}$J

Answer (c)

- Copper has a work function between 4.53 eV and 5.10 eV.
- What is the wavelength of a photon with an energy of 5 eV?
  (a) 250 mm
  (b) 250 um (micrometers)
  (c) 250 nm
  (d) 250 A (Angstrom)

$$e = \frac{hc}{\lambda}$$

- Reminder: $c=3.10^{8}$ m/s
  $h=6\text{x}10^{-34}$J.s
  $1\text{eV}=1.6\ 10^{-19}$J
- As a physicist, you need at least to remember the order of magnitude a visible photon's wavelength (2eV~620nm).

Fermi-Dirac statistics

- Electrons have a spin ½ so they are fermions and follow the Fermi-Dirac statistics.
- Distribution (ni) of occupied states of energy (Ei) [Sommerfeld 1927]:

$$n_i = \frac{1}{e^{\frac{E_i - E_F}{k_B T}} + 1}$$

- E_F: Fermi energy, k_B Boltzmann constant

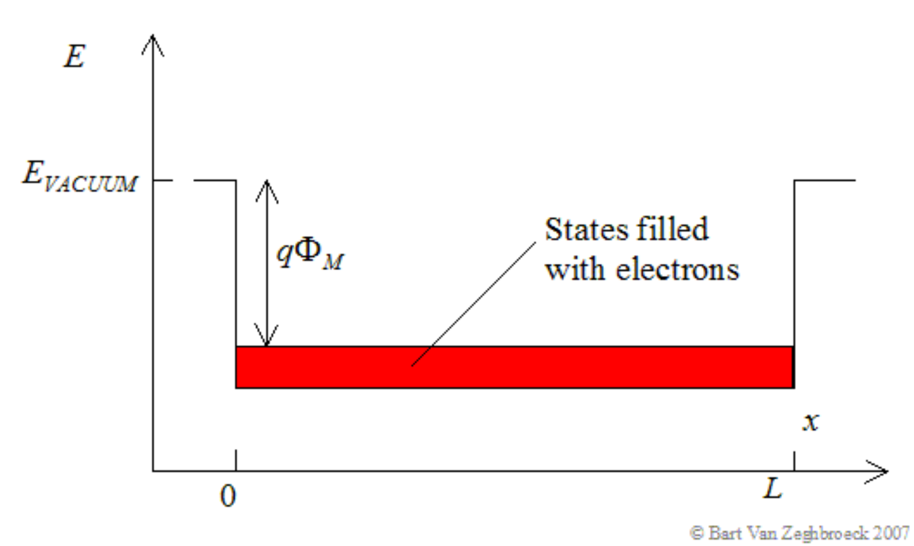
Fermi-Dirac statistics at high energy

$$n_i = \left(\frac{1}{e^{\frac{E_i - E_F}{k_B T}} + 1} \right)_{E_i >> E_F} \sim \frac{1}{e^{\frac{E_i}{k_B T}}} \sim e^{-\frac{E_i}{k_B T}}$$

- At high energy the Fermi-Dirac statistics and the Maxwell-Boltzmann statistics tend toward the same value.
- To increase the number of electron in the high energy levels you need to heat them!

Extracting electrons from matter

- To free the electrons you can give them more energy.
  - This can be done by heating
    => Thermionic effect
  - This can also be done with a laser
    => Photoelectric effects
- Or one can reduce the work function, for example with a strong magnetic field => Schottky effect



Numerical application

- Copper work function: W~5eV
- K_B=8.6 10^{-5} eV.K^{-1}
  => T~60000K
- In fact this would mean that all atoms emit an electron at the same time.
- To get only some atoms to emit electrons a lower temperature is acceptable.
- A significant thermionic emission starts at about 2500K.

$$n_i \sim e^{-\frac{E_i}{k_B T}}$$

$$E_i \sim k_B T$$

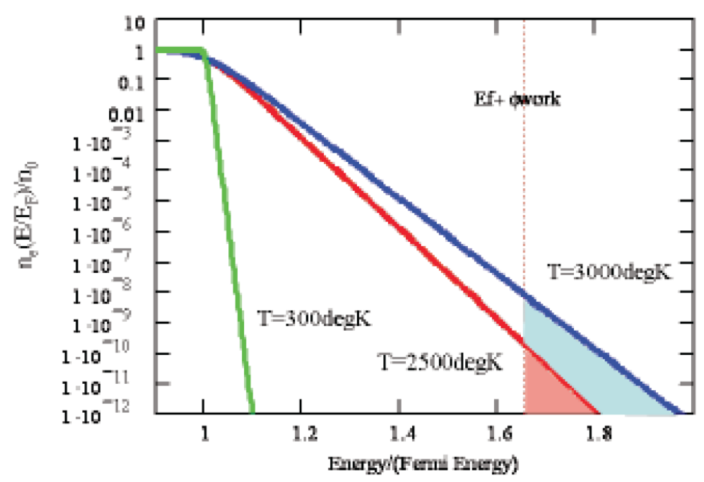


FIGURE 3. Fermi-Dirac energy distributions for thermionic emission. Electrons in the high energy tail of the distribution (energies greater than the work function) are thermally emitted for cathode temperatures of 2500 (red-pink) and 3000 (blue-aqua) degK.

Density of states for different temperatures

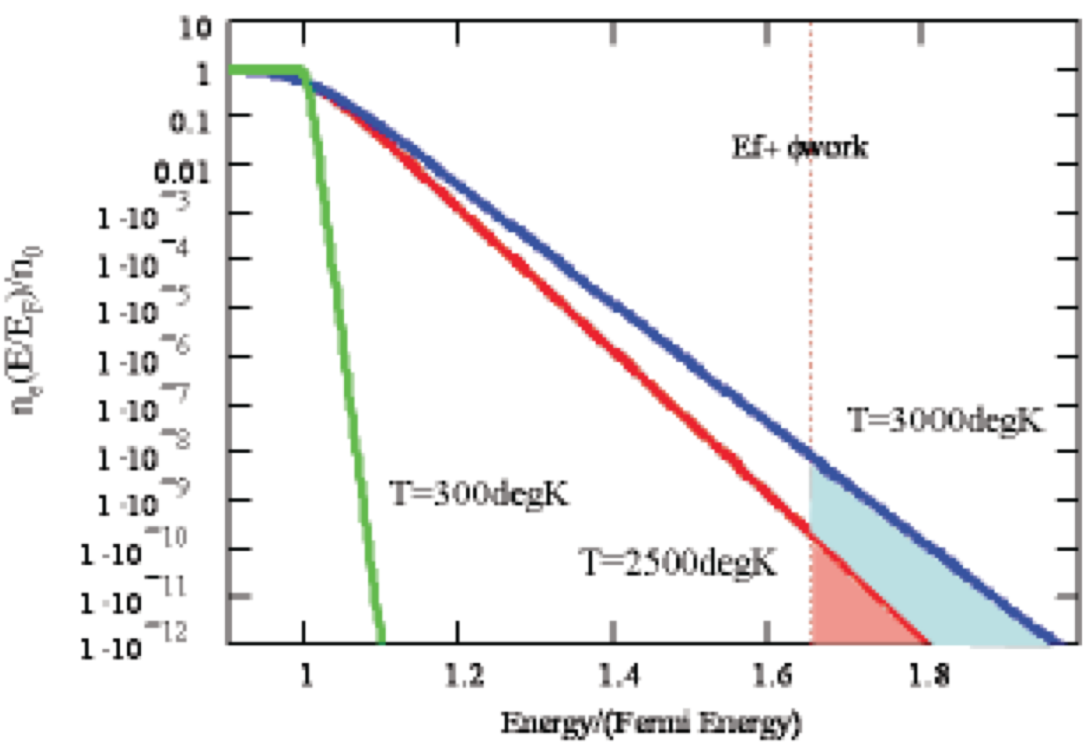
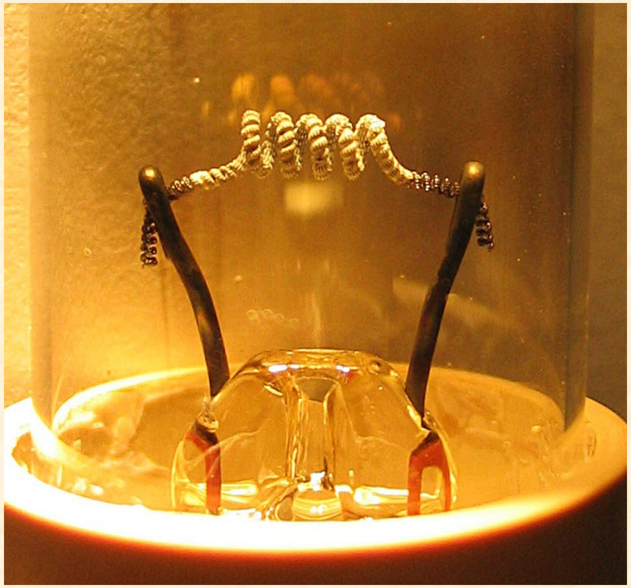


FIGURE 3. Fermi-Dirac energy distributions for thermionic emission. Electrons in the high energy tail of the distribution (energies greater than the work function) are thermally emitted for cathode temperatures of 2500 (red-pink) and 3000 (blue-aqua) degK.

Source:
D.H.Dowell, USPAS

Extracting electrons… Richardson's law

- We do not need all the atoms to emit electrons.
- We only want a certain current.
- The current density emitted (J) was studied in 1901 by Richardson.
- *Lambda_R: correction factor specific to a given material.*



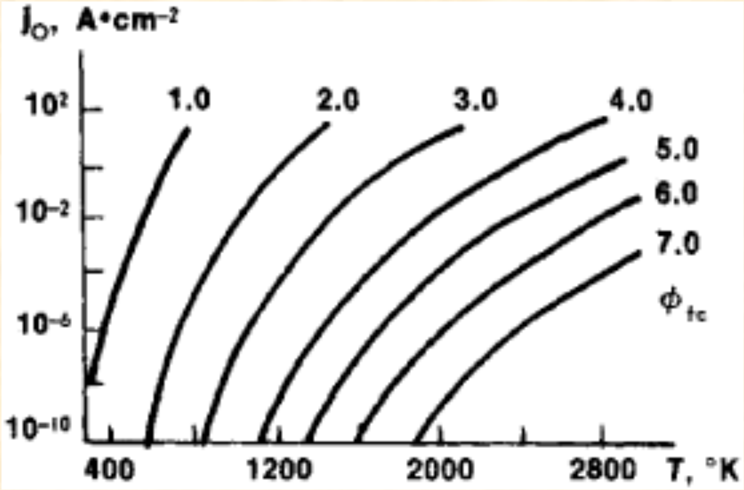
$$J = A_G T^2 e^{-\frac{W}{k_B T}}$$

$$A_G = \lambda_R A_0$$

$$A_0 = \frac{4\pi m k^2 e}{h^3} \sim 1.2 \times 10^6 A m^{-2} K^{-2}$$

Richardson's constant

- Richardson's constant is still not completely understood.
- Theoretical value : $1200 mA.mm^{-2} K^{-2}$ but it has to be corrected for each material.



Source: http://encyclopedia2.thefreedictionary.com/Richardson's+constant

$$A_0 = \frac{4\pi m k^2 e}{h^3}$$

Numerical application

- W=5eV
- A=1200A m^{-2} K^{-2}
- K_B=8.6 10^{-5} eV.K^{-1}
- Cathode area: 1 cm^2 = 100 mm^2

$$J = A_G T^2 e^{-\frac{W}{k_B T}}$$

$$J = 1200 T^2 e^{-\frac{5}{8.6\times 10^{-5} T}} \times \text{area}$$

$$J = 1200 T^2 e^{-\frac{60000}{T}} \times 10^2$$

$$T = 2500K => J = 28mA$$

$$T = 3000K => J = 2200mA$$

Transverse energy

- A hotter cathode gives a larger current.
- However electrons above the emission threshold will be emitted with some kinetic energy.
- Some of this kinetic energy will be converted in transverse energy.
- The product of the transverse beam size by its transverse energy at a waist is called "transverse emittance".
- This will be discussed further later.

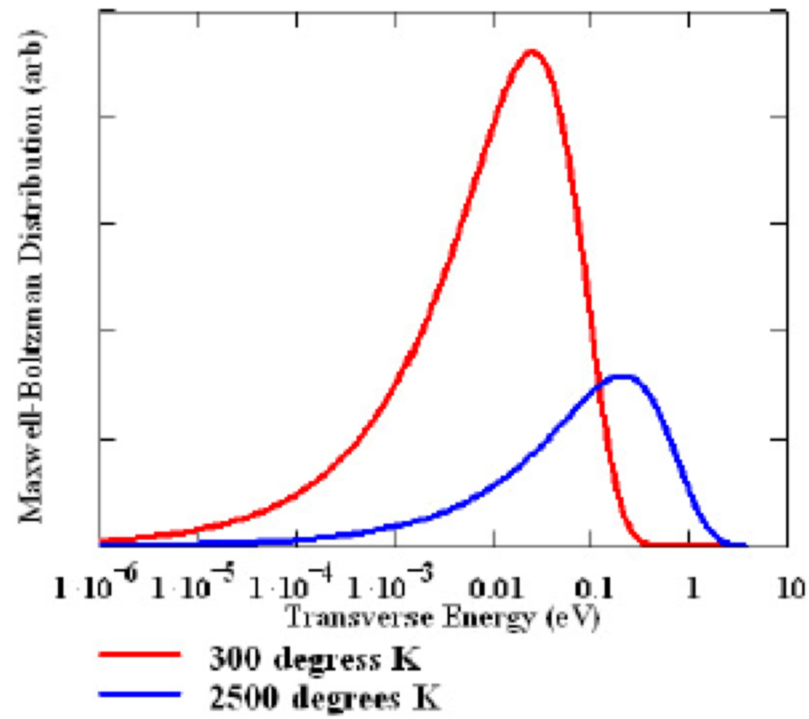
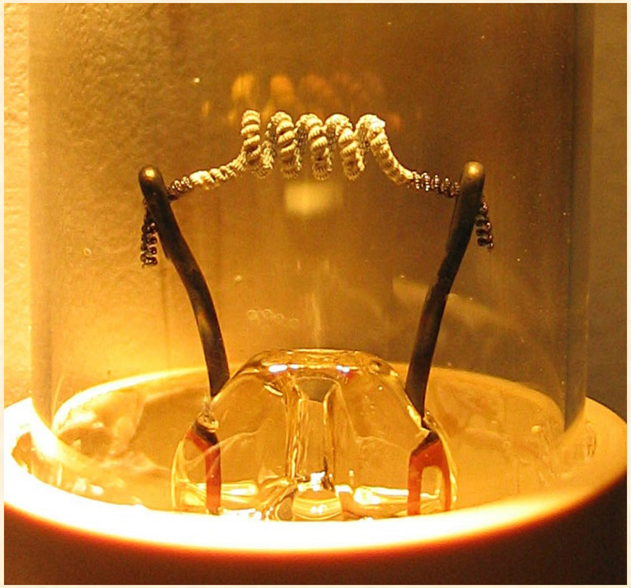


FIGURE 4. Maxwell-Boltzmann electron energy distributions at 300 degK where the rms electron energy spread is 0.049 eV, and at 2500 degK corresponding to an rms energy spread of 0.41 eV.

Source: D.H.Dowell, USPAS

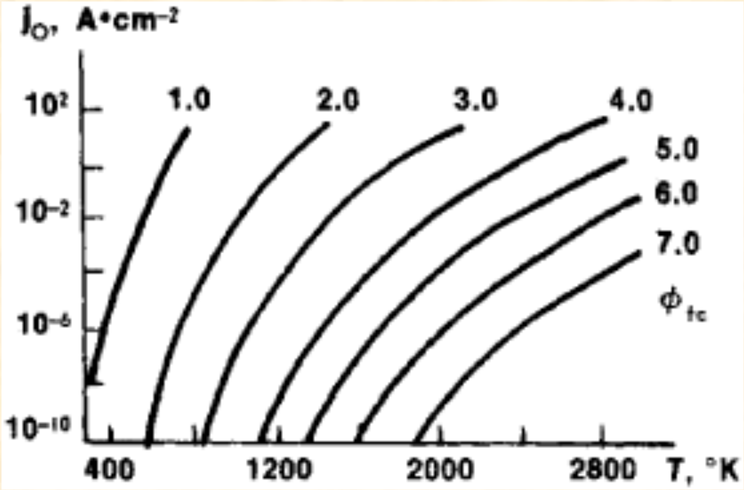
Quizz

- Let's consider two metals with different work function.
- Both metals are heated to the same temperature so that they emit electrons.
- Which metal will emit the highest current?
  (a) Electron emission is independent from the work function.
  (b) The metal with the highest work function emits more electrons.
  (c) The metal with the lowest work function emits more electrons.



Answer (c)

- The metal with the lowest work function emits more electrons.
- The work function express the work an electron has to do to be emitted.
- The lower the work function the more electrons will be emitted (at the same temperature).

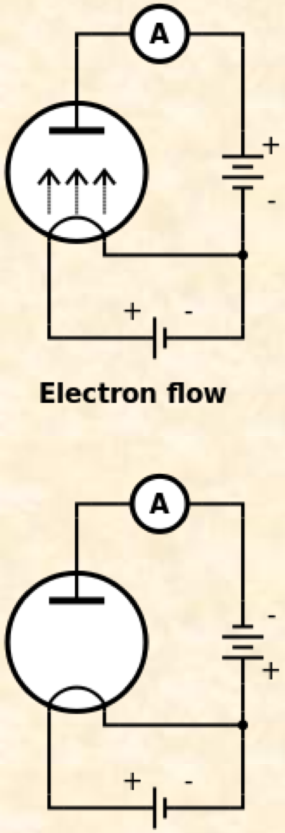


$$J = A_G T^2 e^{-\frac{W}{k_B T}}$$

Schottky emission

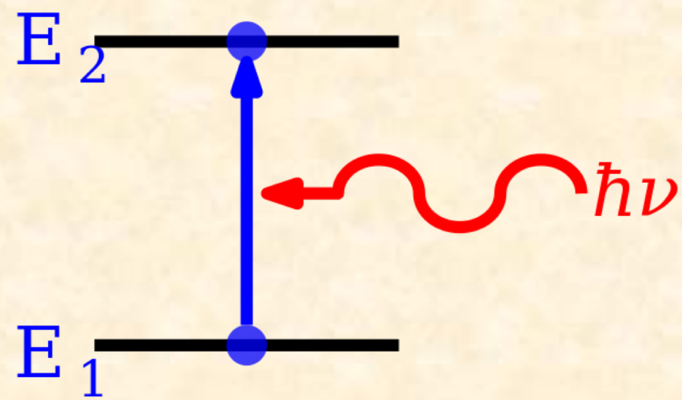
$$\Delta W = \sqrt{\frac{e^3 F}{4\pi\epsilon_0}}$$

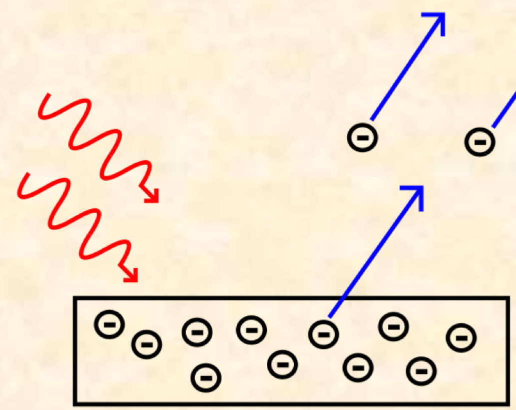
- When a strong electric field (F) is applied the barrier for electrons to escape from the solid is lowered.
  => The work function is reduced.
- If the field exceeds 10^8V/m then the electrons can also tunnel out of the solid.
  => Fowler-Nordheim tunneling (enhanced emission).
- This effect (under the name "Edisson effect") was used in old diode tubes.



Photoelectric emission

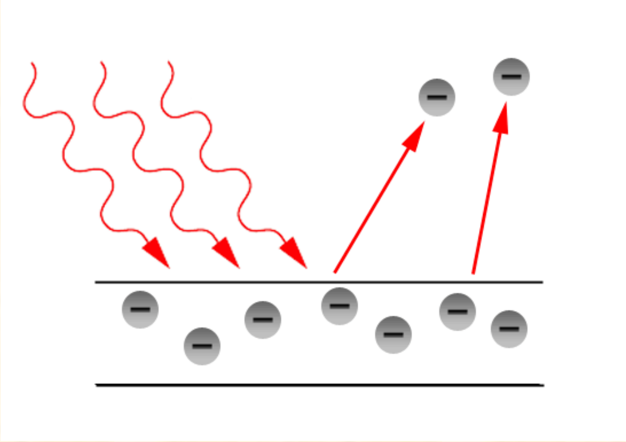
- Electrons can also receive energy by absorbing a photon.
- If the energy of the photon is sufficient they will be emitted.
- This is called photoelectric emission.





Wavelength for photoemission

- Remember:
  - Copper work function: 5eV
  - 2eV ~620nm
  or 5eV ~ 250nm.
- The typical wavelength for photoemission is in the Ultraviolet, not in the visible.
- The photoelectric effect was historically observed when a cathode was illuminated under UV light and it started to spark.



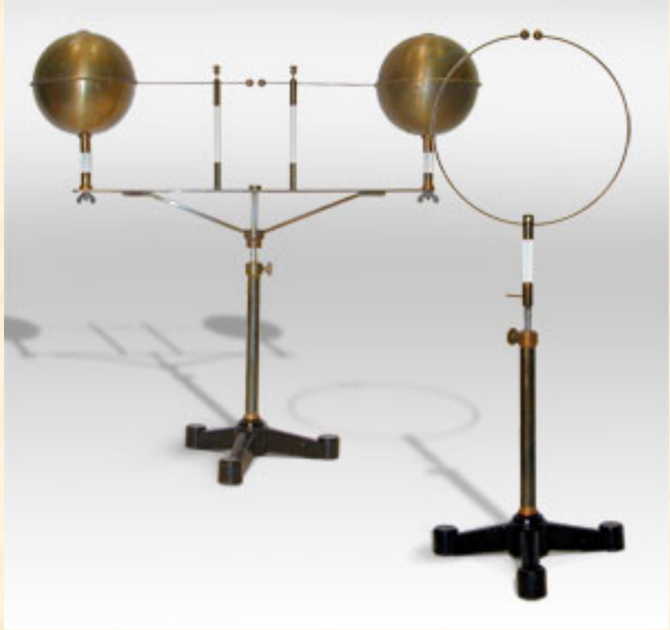
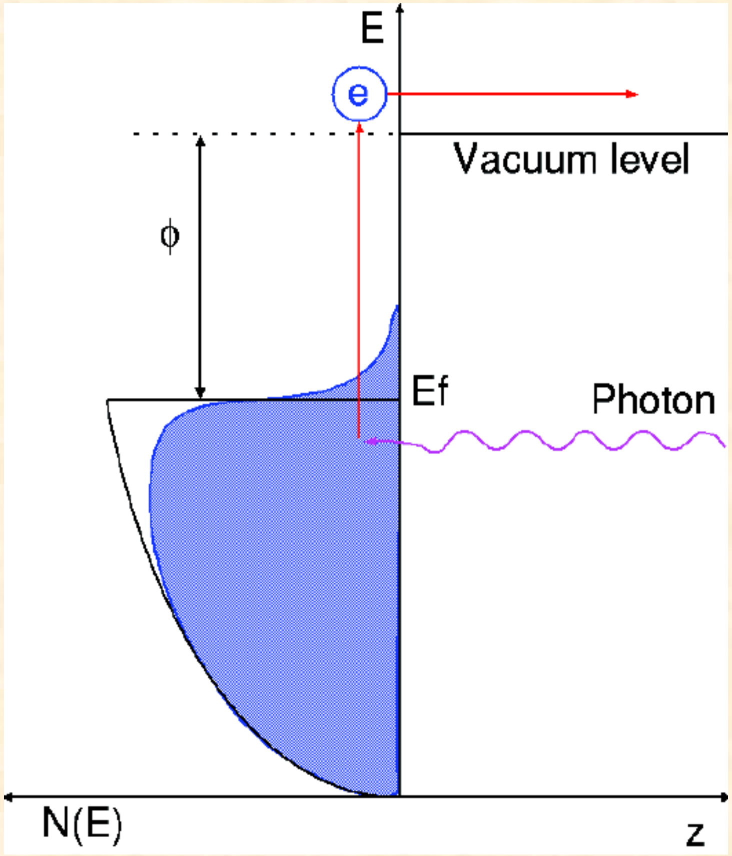


Photo-electric emission

- A photon incident on a material will transfer its energy to an electron present in the metal.
- If the energy of this electron becomes bigger than the work function of the material, the electron can be emitted.
- This is called photo-electric emission.

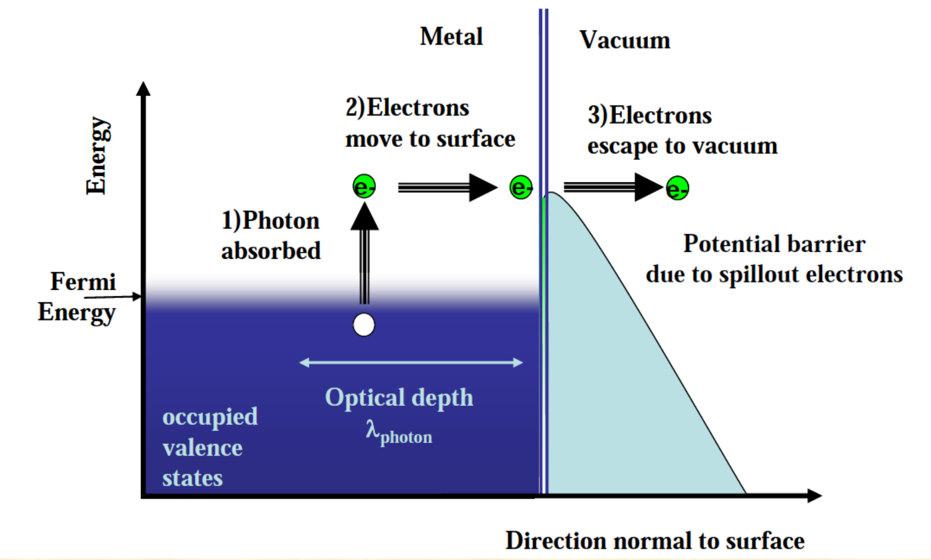


(image source: Masao Kuriki, ILC school)

The 3 steps of photo-electric emission

Photo-electric emission takes place in 3 steps:

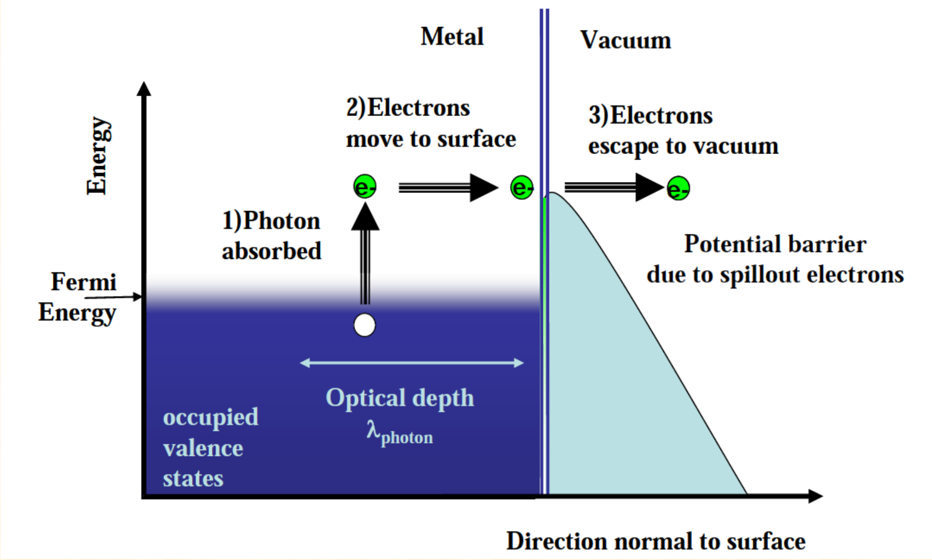
1) Absorption of a photon by an electron inside the metal. The energy transferred is proportional to the photon energy.
2) Transport of the electronto the physical surface of the metal. The electron may loose energy by scattering during this process.
3) Electron emission (if the remaining energy is above the work function; including Schottky effect)



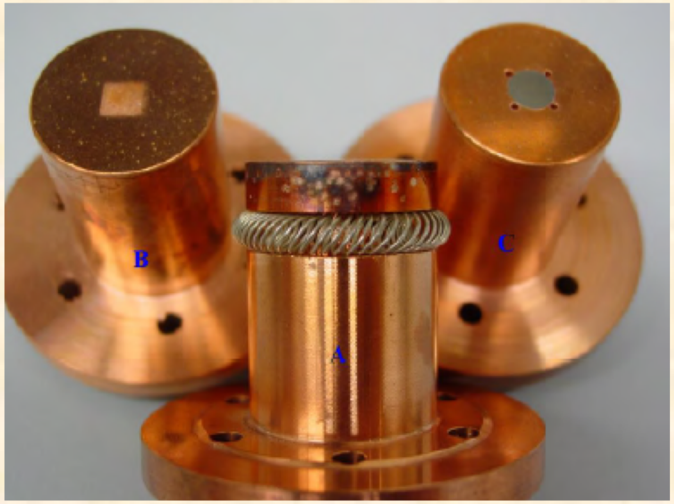
The efficiency of this process is called "quantum efficiency".

Quantum efficiency

- Not all incident photons lead to the emission of an electron.
- Typical quantum efficiency is below a few percent, sometimes as low as 10^{-5}.
- As the cathode is used its surface will change and the QE will decrease.



Typical cathode materials



- The choice of material is a trade-off between several parameters:
  - quantum efficiency
  - environmental sensitivity
  - damage threshold
  - availability in the industry
  - easy handling and preparation (safety requirements)
- Copper is an easy choice but with a low QE.
- Cs2Te has a much higher QE but is more difficult to prepare.
- Other materials: Magnesium, Niobium, GaAs:Cs
- Note: GaAs:Cs can also produce polarized beams.

Multiphotonic effect

- Laser light conversion efficiency from IR to UV is very low and UV light transport is difficult.
- Some groups have suggested that it is more efficient to illuminate a cathode with IR photons rather than converting these photons to UV:
  3 IR photons can lead to the emission of an electron like an UV, however these 3 IR photons must interact with the same atom.

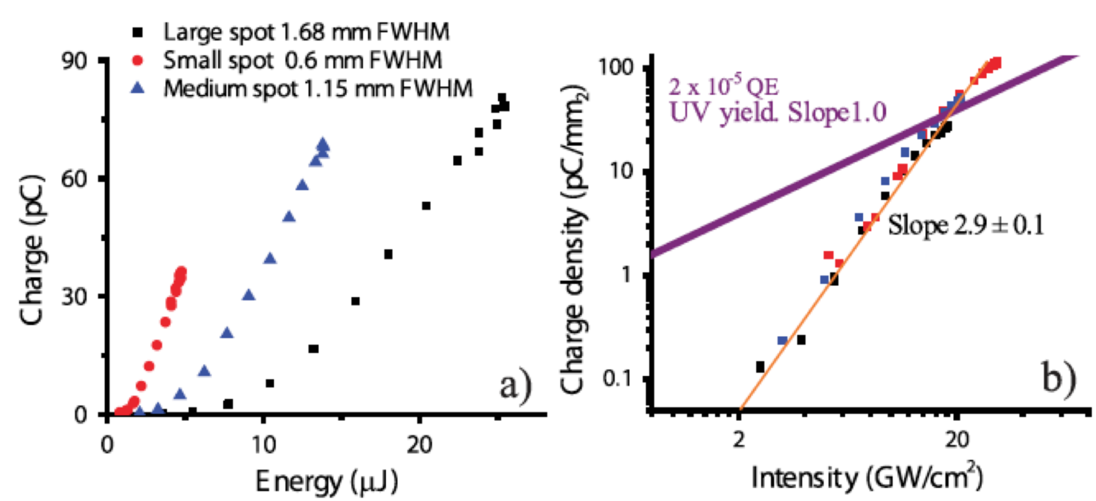
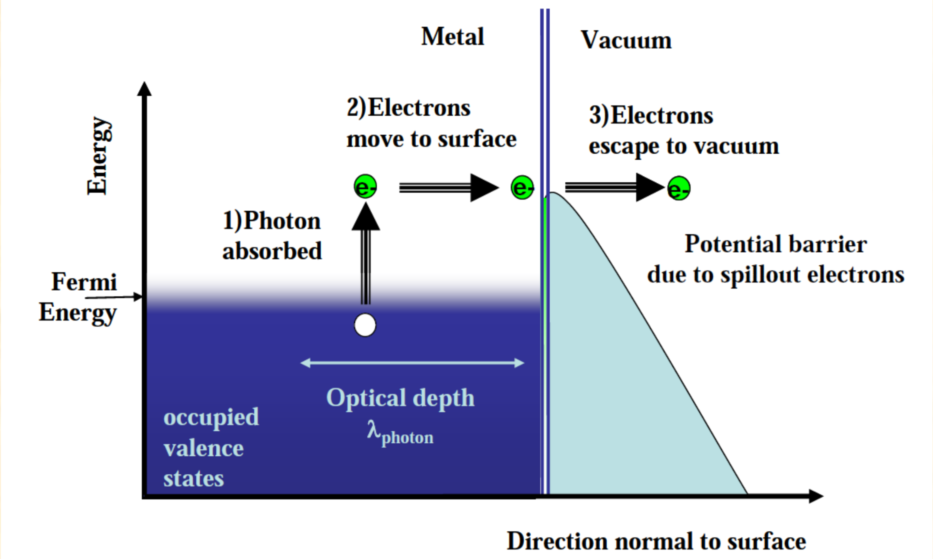


FIG. 1 (color online). (a) Charge yield for different spot sizes at the cathode as a function of laser energy. (b) Emitted charge density vs laser intensity. The curve for uv photoemission with the measured QE of 2×10^{-5} is also reported.

PRL 104, 084801 (2010)

Transverse energy

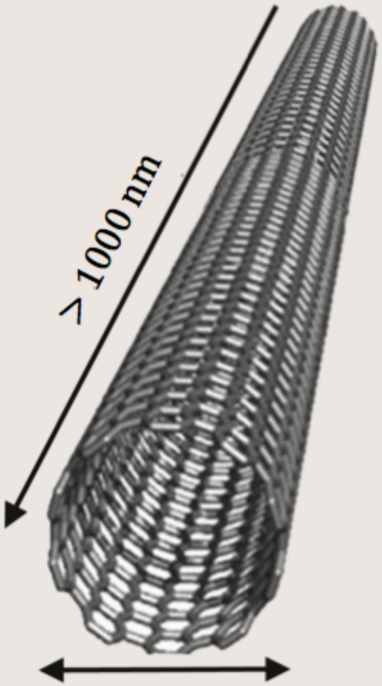
- Depending on the incident photon's energy and the travel to the surface the emitted electron will have more or less remaining kinetic energy after emission.
- Once again part of this energy will be converted in transverse energy.
- A higher photon energy will lead to a higher beam emittance.



More exotic cathode materials

CNT's as Field Emitters I

radiabeam TECHNOLOGIES



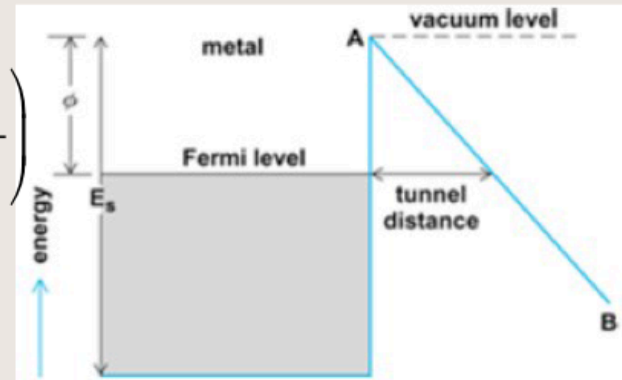
1-50 nm

CNTs were invented in 1991 [S. Iijima, Nature, 354 56 (1991)]

<u>Field Emission</u>: electron escape from a bound state to vacuum level through *quantum tunneling* in the presence of an external electric field.

$$j = aE^2 \exp\left(-\frac{b}{E}\right)$$

Fowler-Nordheim Relationship (1928):



j: Current density
E: Electric field strength: $\beta E_{applied}$
β: Enhancement factor
Φ: Work function, 4.9 eV
a: $1.42\times10^{-6}/\Phi \exp(10.4/\Phi^{1/2})$*
b: $-6.56\times10^{9}\ \Phi^{3/2}$

*E. Minoux et al., Nano Lett., 5 (11), 2135 (2005). doi: 10.1021/nl051397d

- Extreme aspect ratio gives large enhancement factor ($\beta \sim$ 100-1000)
- $E_{applied} \approx 1 \div 100$ MV/m (Macroscopic Field)

2nd European Advanced Accelerator Workshop (EAAC), 13-19 September 2015, Elba, Italy

Quizz

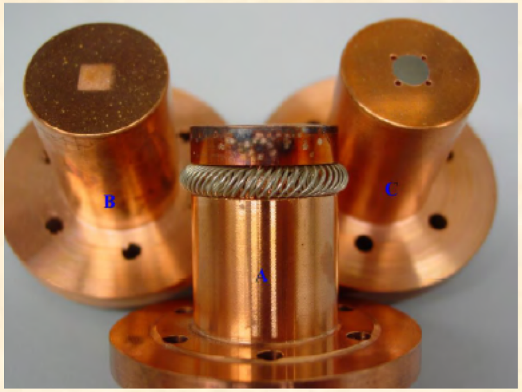
- Which phenomena leads to the sparking (electron emission) when a metallic object is placed in a microwave oven?
  (a) Thermionic emission (because the object is heated)
  (b) Schottky emission (because of the electric field in the oven)
  (c) Photoemission (because of the photons emitted by the RF generator of the oven)

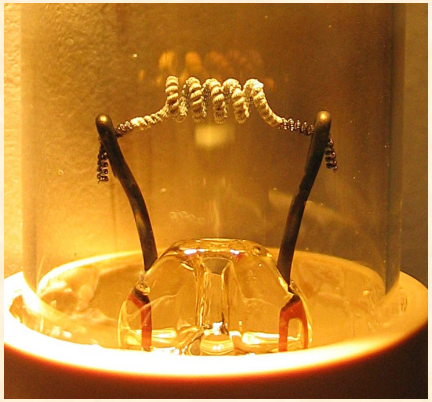
Answer (b)

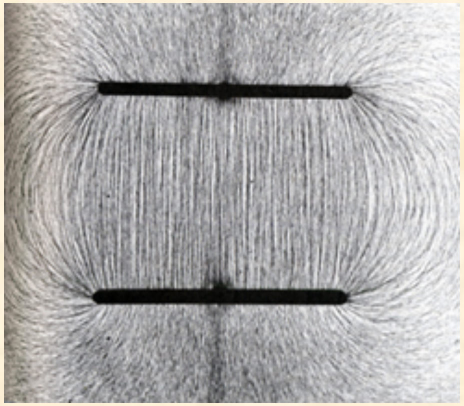
- In a microwave oven a very intense electric field can be induced in metallic objects.
- This will lead to Schottky emission (sparks).
- Note: these sparks also create X-rays…

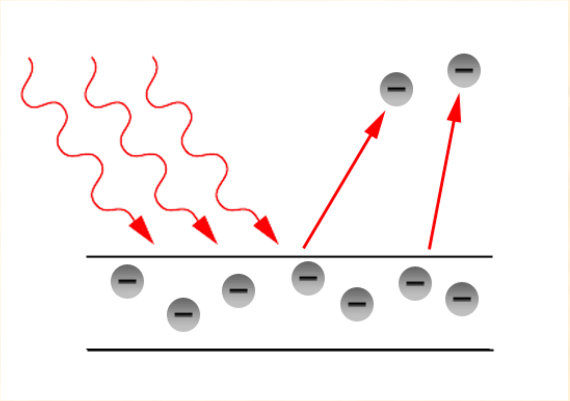
Physical effects summary

- Electrons are emitted when their energy exceeds the work function of the material.
- 3 effects can leads to this:
  - Thermionic emission (when the material is heated)
  - Schottky emission (lower emission threshold under an intense electric field)
  - Photoelectric emission (under illumination by energetic photons)
- Material and material properties play an important role in determining the threshold and yield of these emissions.







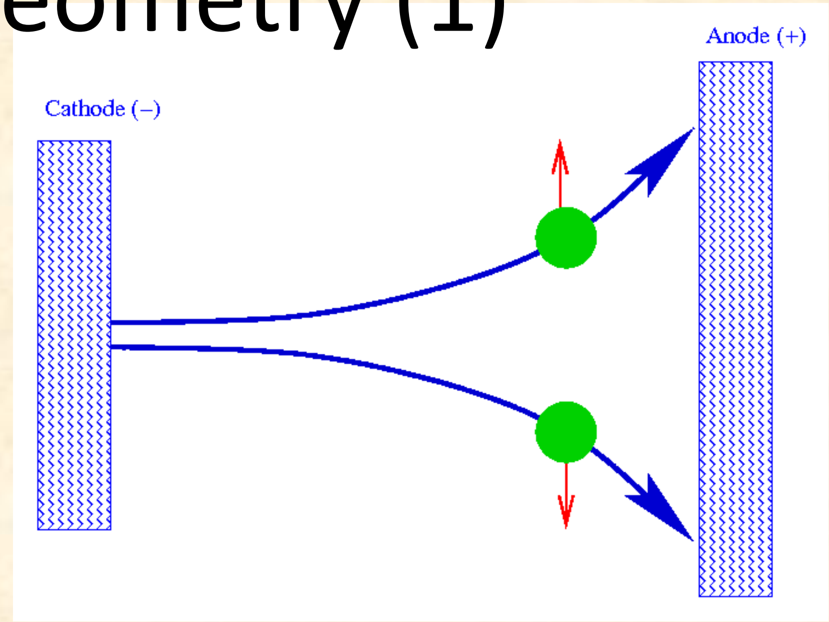


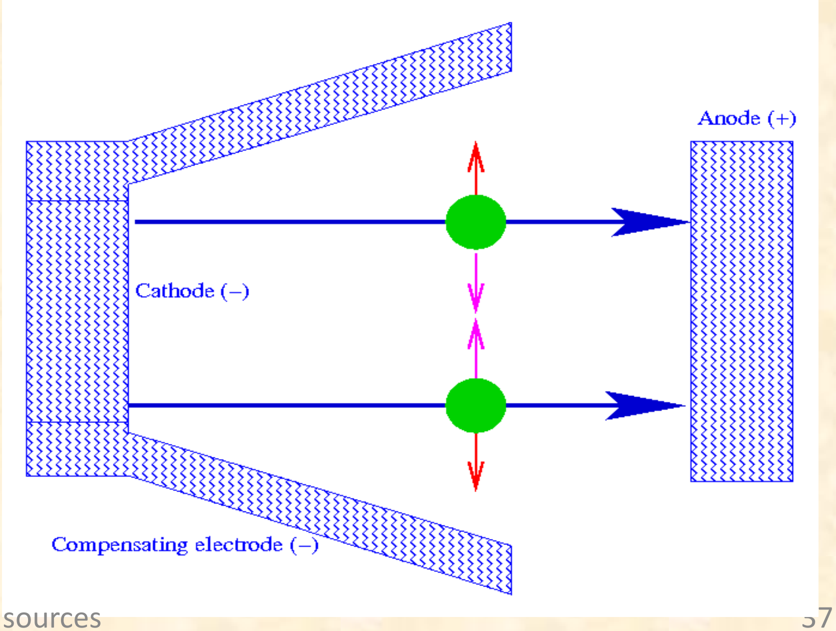
Designs of electron guns: Thermionic guns

- A thermionic cathode is not sufficient to produce electrons. It must be inserted into a gun.
- A thermionic gun must answer several constraints:
  - the cathode must be brought to a high temperature.
  - there must be a high electric field between the cathode and the exit of the gun (anode).

Electrodes geometry (1)

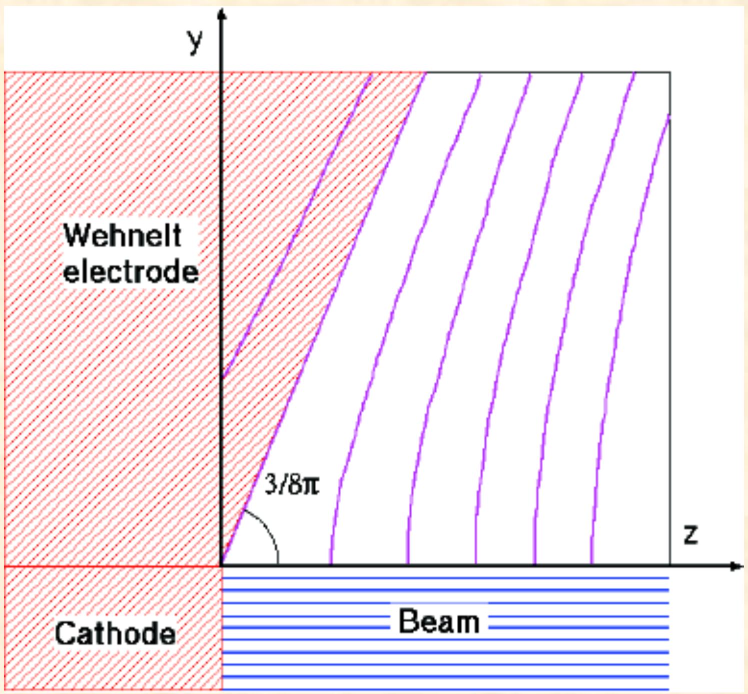
- Two emitted electrons repel each other.
- If the anode and the cathode are flat the beam will diverge due to the charges emitted.
- At low charge this effect will be small but with high current sources this will increase significantly the beam emittance.
- To avoid this the shape of the electrode must compensate the space charge forces.



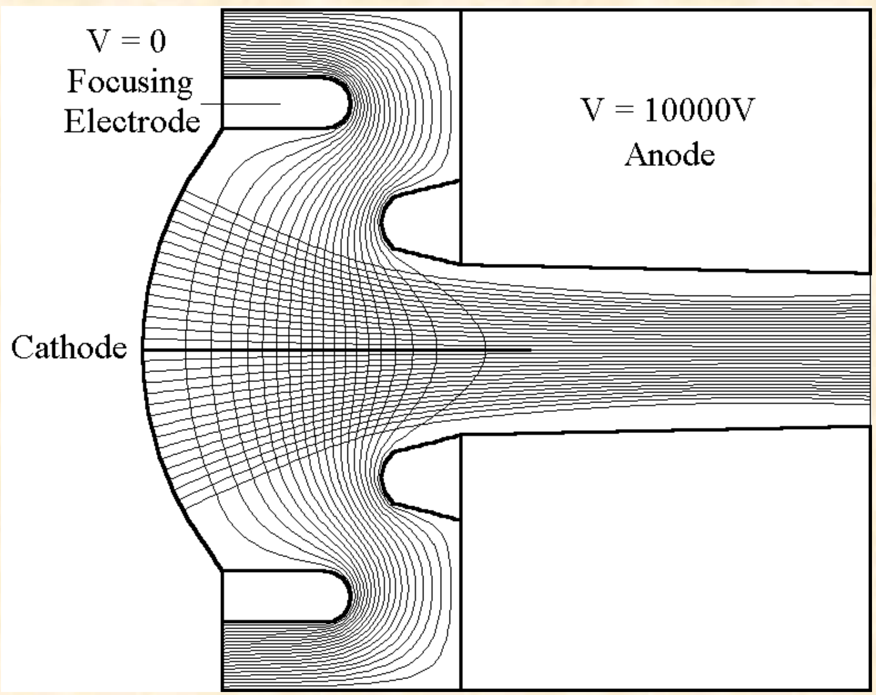


Electrodes geometry (2)

- The correct electrode shape will depend on the forces that must be compensated (ie beam current).
- By solving Laplace equation it is possible to find the best shape.



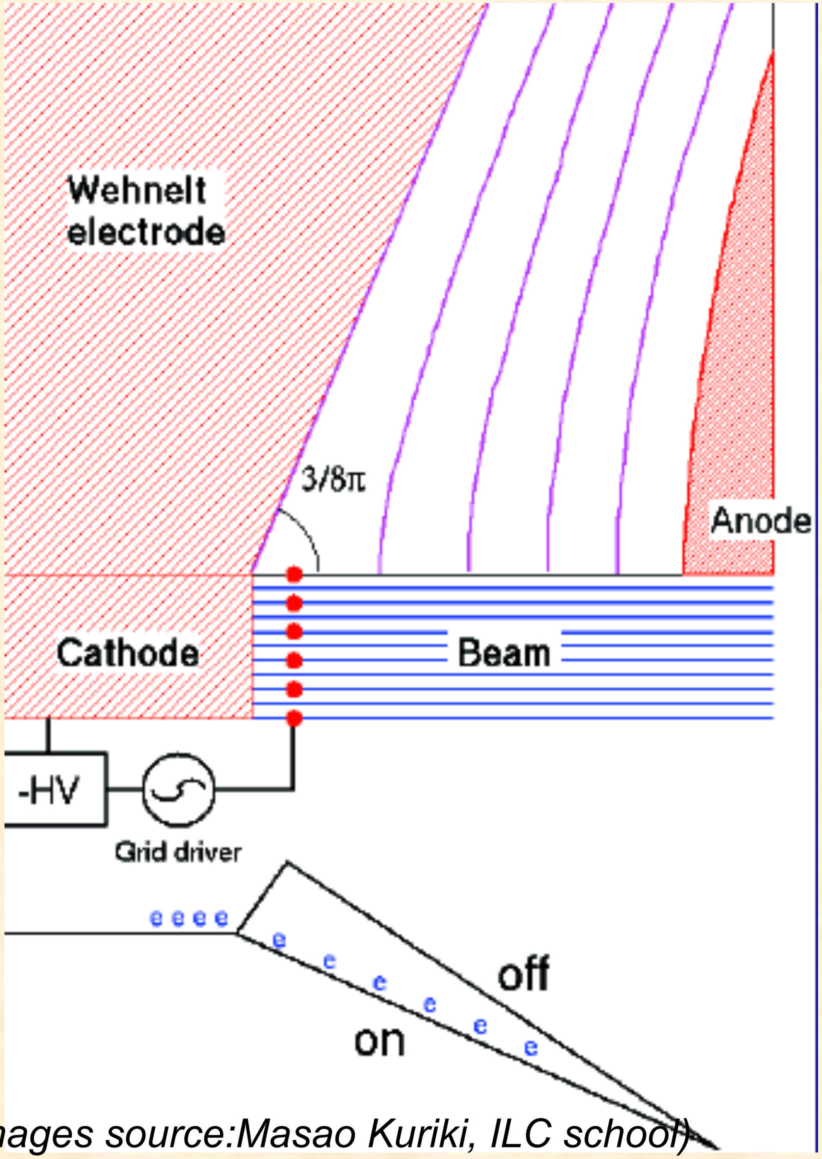
(images source:Masao Kuriki, ILC school)



(images source: MEBS)

Pierce gun
Thermionic DC Gun

- Simplest gun design.
- Main features:
  - Thermionic cathode
  - Emission of the beam is controlled by a HV grid.
  - Compensating electrode
- Grid control limits pulse length. Typically >1ns.
- Operated in space charge limit.
- Such design is widely used.

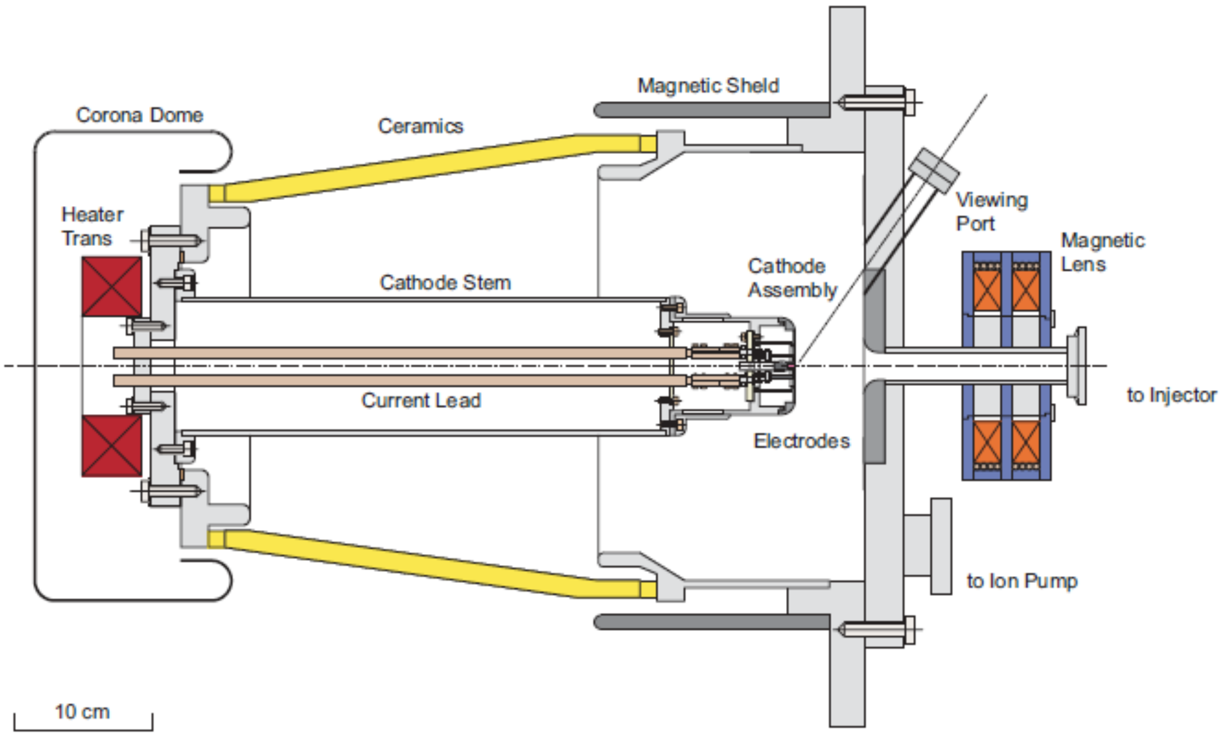


(images source:Masao Kuriki, ILC school)

Example of thermionic gun

SCSS

500kV Electron Gun

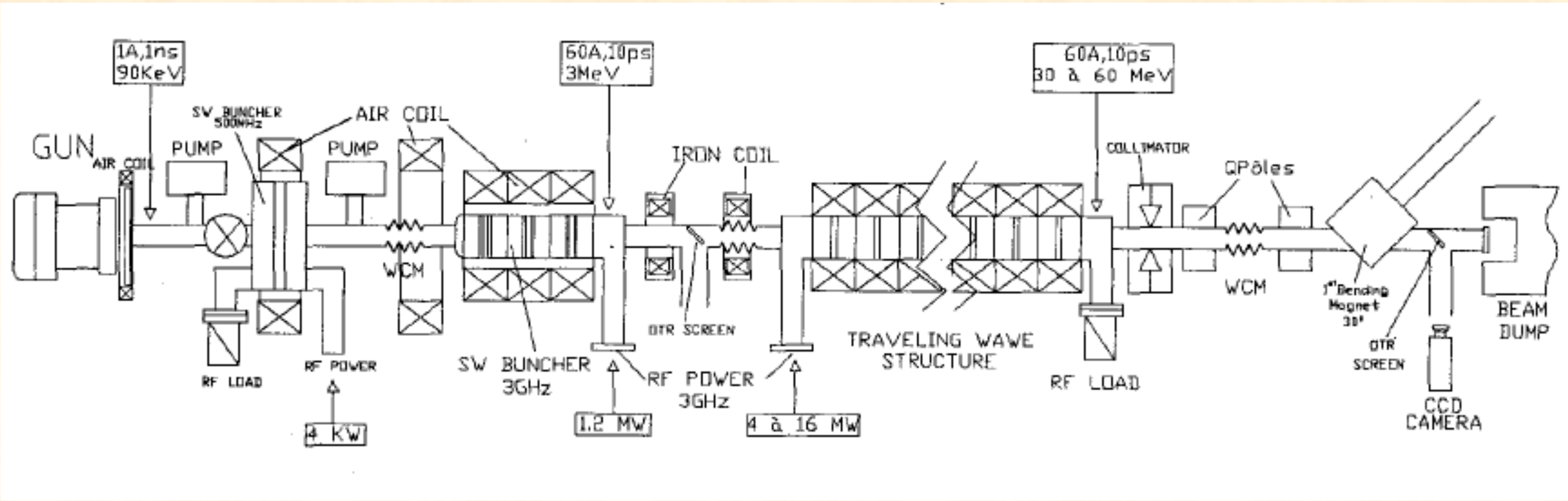


Spring 8 SCSS thermionic gun.
(images source: T. Shintake, Spring-8)

The CLIO Thermoionic gun

- 3 stages to shape the electrons:
  - cathode => 1.5ns bunches
  - pre-buncher => 200ps
  - buncher => few ps

(and then the main linac structure)



Thermionic Injectors(2)

1300 MHz buncher

Cavity	β	E, MV/m
1	0.55	5.9
2	0.66	6.9
3	0.78	7.9
4	1.00	16.3
5	1.00	15.8
6	1.00	15.3

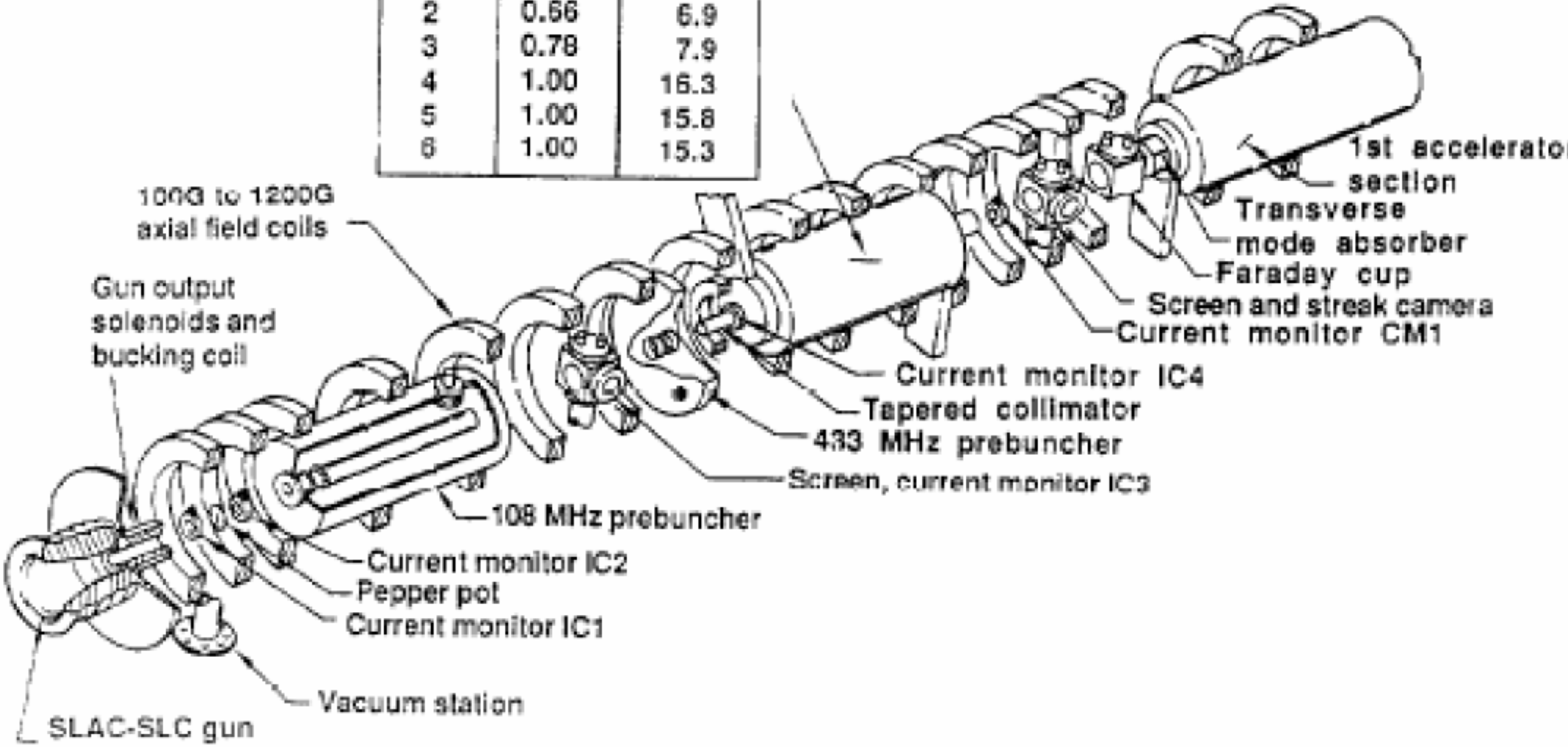
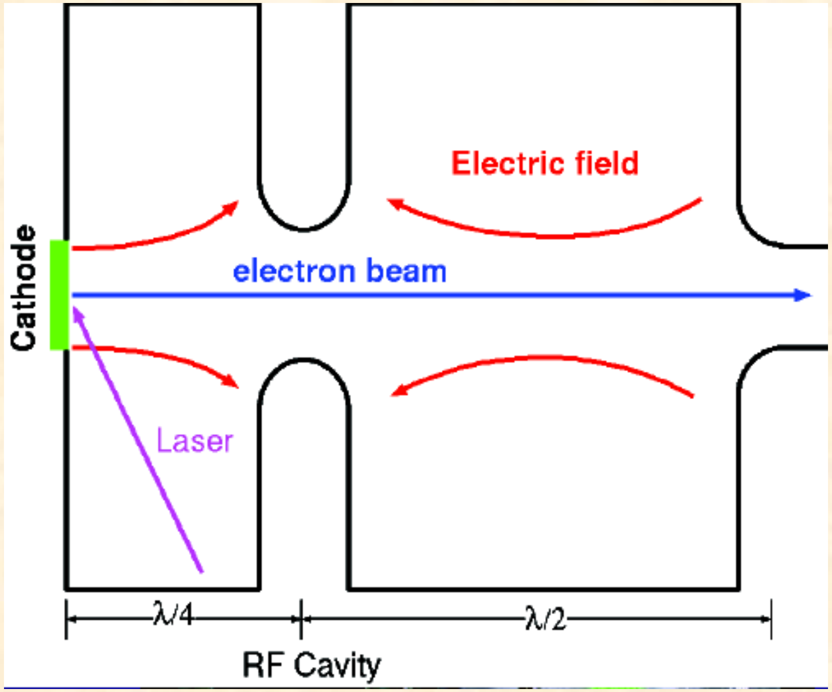


Figure 1. Double subharmonic injector

RF Gun

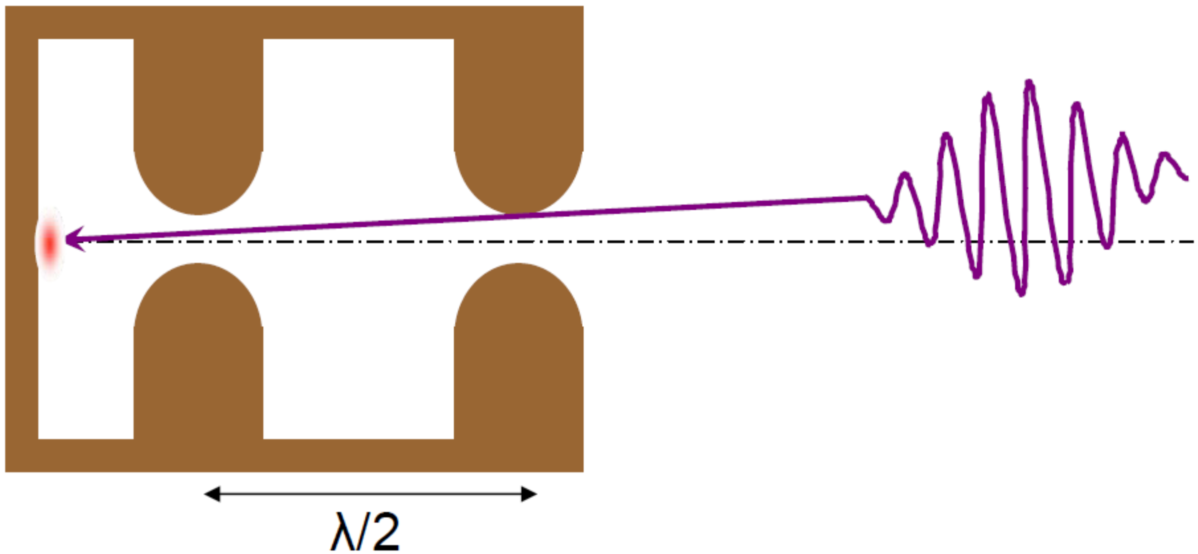
- The high voltage of a DC gun can be replaced by a RF cavity.
- This can provide much higher accelerating gradients and hence limit the space charge.
- RF guns are often coupled with a photo-cathode.
- RF gun can generate shorter bunches (and even shorter using short laser pulses).
- As the RF wave is reflected on the cathode plane, a RF-gun usually has an half-integer number of cells.



(images source:Masao Kuriki, ILC school)

Principle of a RF Photo-gun

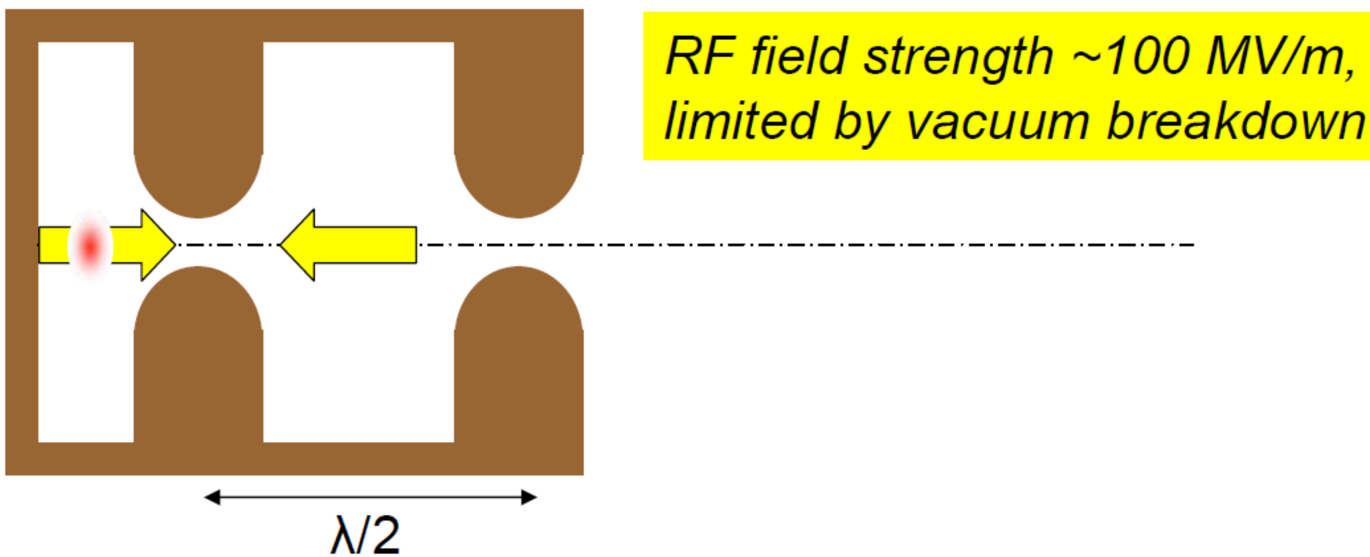
Pulsed laser photoemission...



Courtesy Jom Luiten, TUV Eindhoven

Principle of a RF Photo-gun

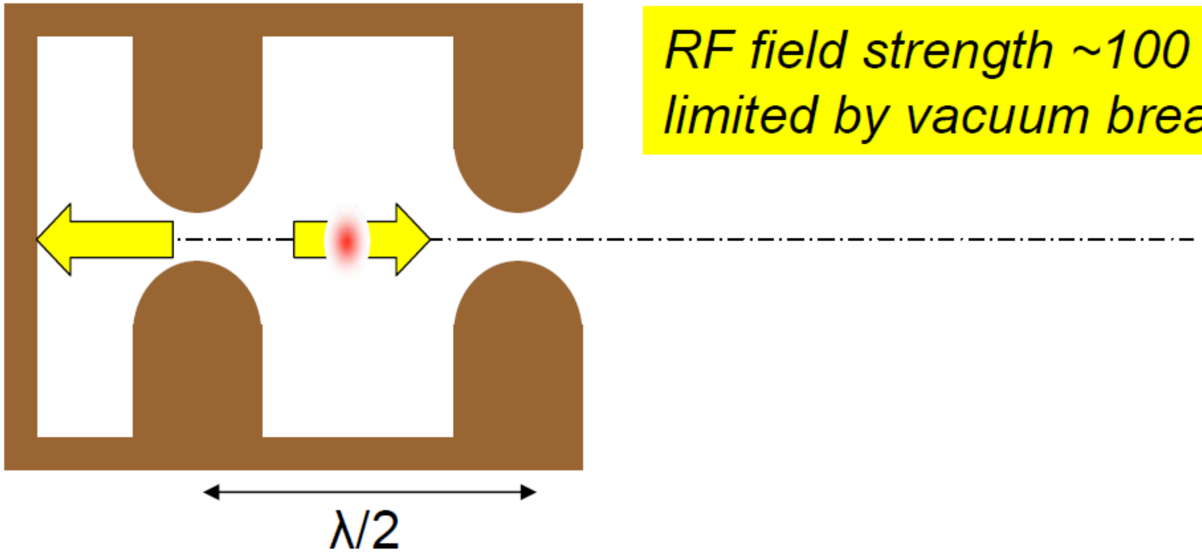
...and RF acceleration.



Courtesy Jom Luiten, TUV Eindhoven

Principle of a RF Photo-gun

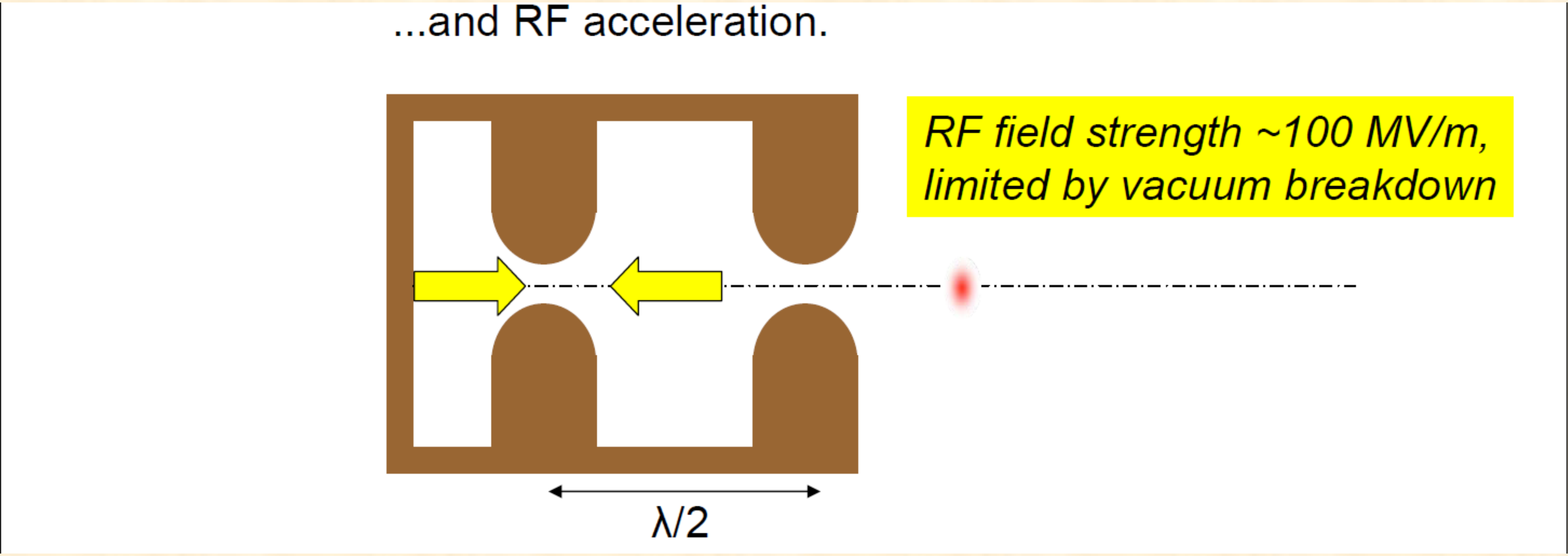
...and RF acceleration.



RF field strength ~100 MV/m, limited by vacuum breakdown

Courtesy Jom Luiten, TUV Eindhoven

Principle of a RF Photo-gun



Courtesy Jom Luiten, TUV Eindhoven

Quizz

Which laser would give the best quantum efficiency on a Copper-based photo-cathode (W=5 eV)

(a) A 5GW CO2 laser (wavelength=10 micrometers)

(b) A 10 kW frequency doubled Nd:YAG laser (wavelength=532nm)

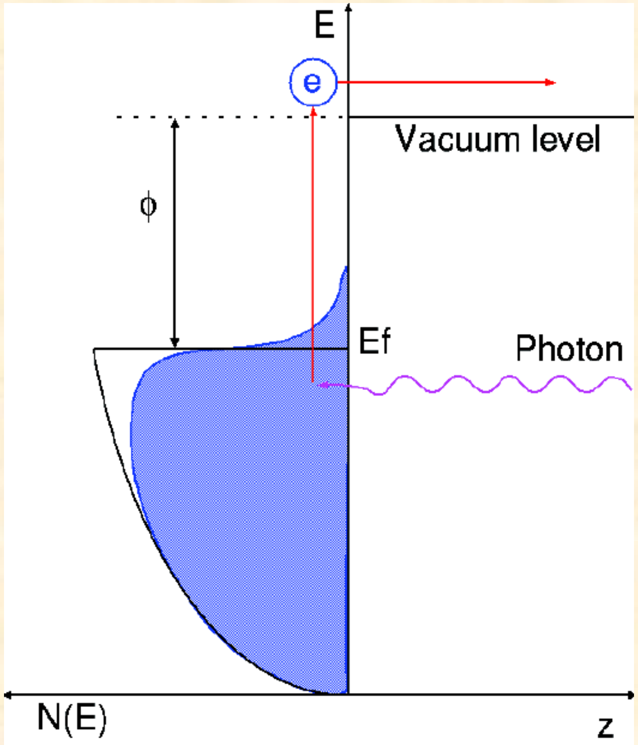
(c)A 3MW frequency quadrupled Ti-Sapphire laser (wavelength=200nm)

Answer : (c)

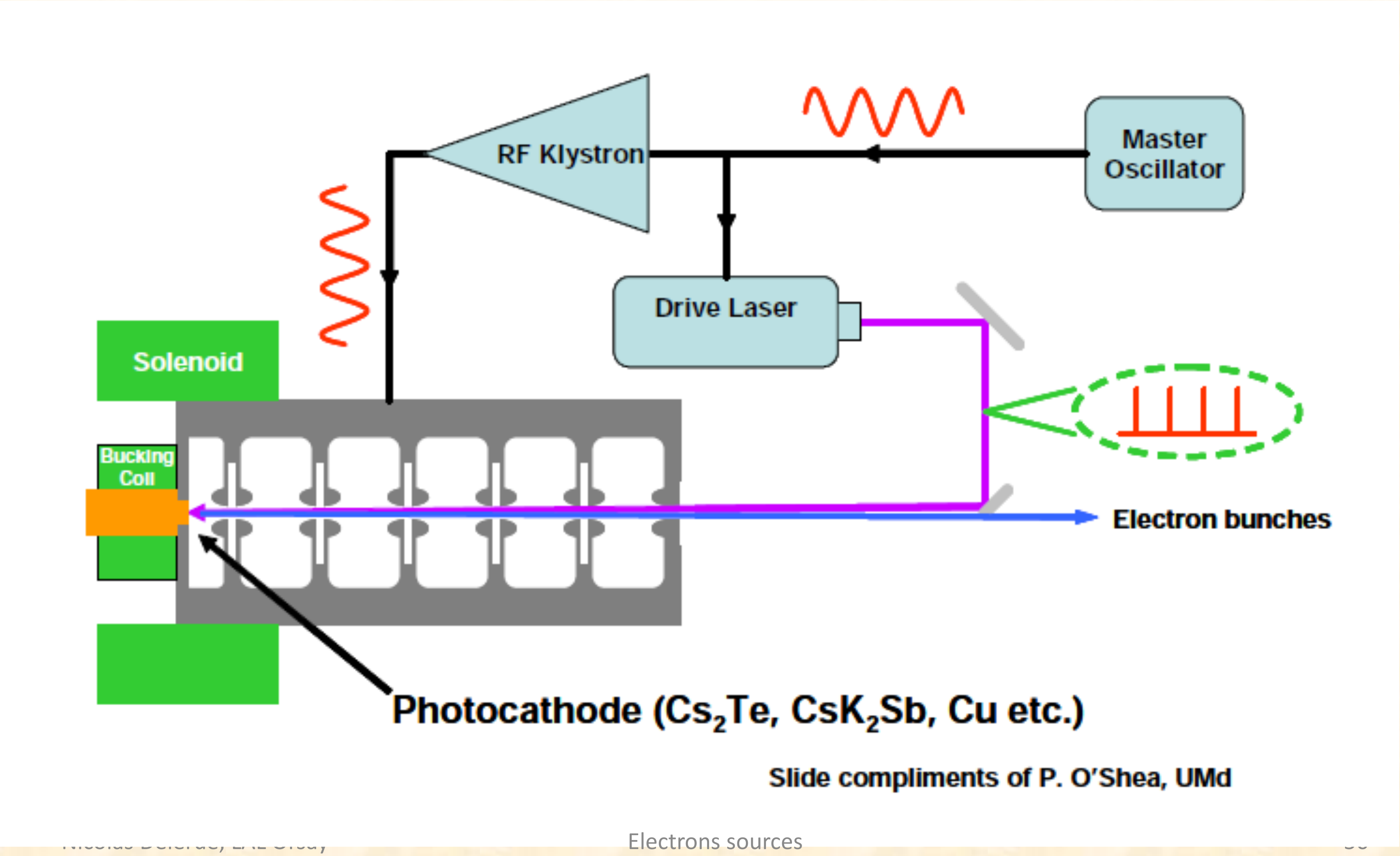
- QE is independent of the laser power: it is the photon energy that matters.
- Remember that

$$E = h\nu = \frac{hc}{\lambda}$$

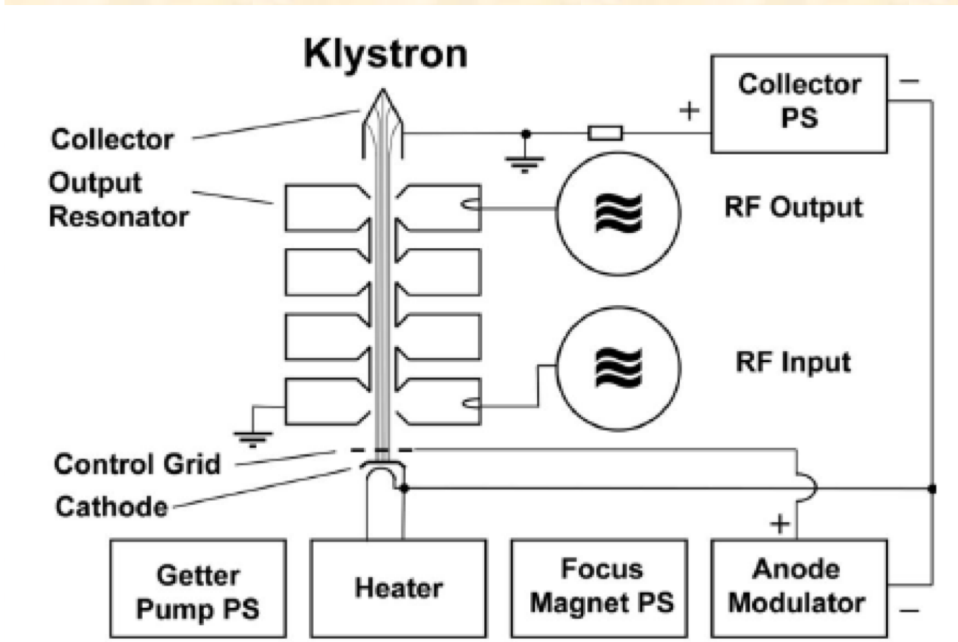
- The shortest the wavelength, the highest the energy. At 200nm a photon carries ~6 eV, so a 400nm photon carries ~3eV.
- Note: photons with a wavelength of 532nm (2.33eV) or 10 micrometer (~0.1eV) will have less energy than the work function of the photo-cathode (but escape by tunnel effect is theoretically possible).



RF photocathode gun



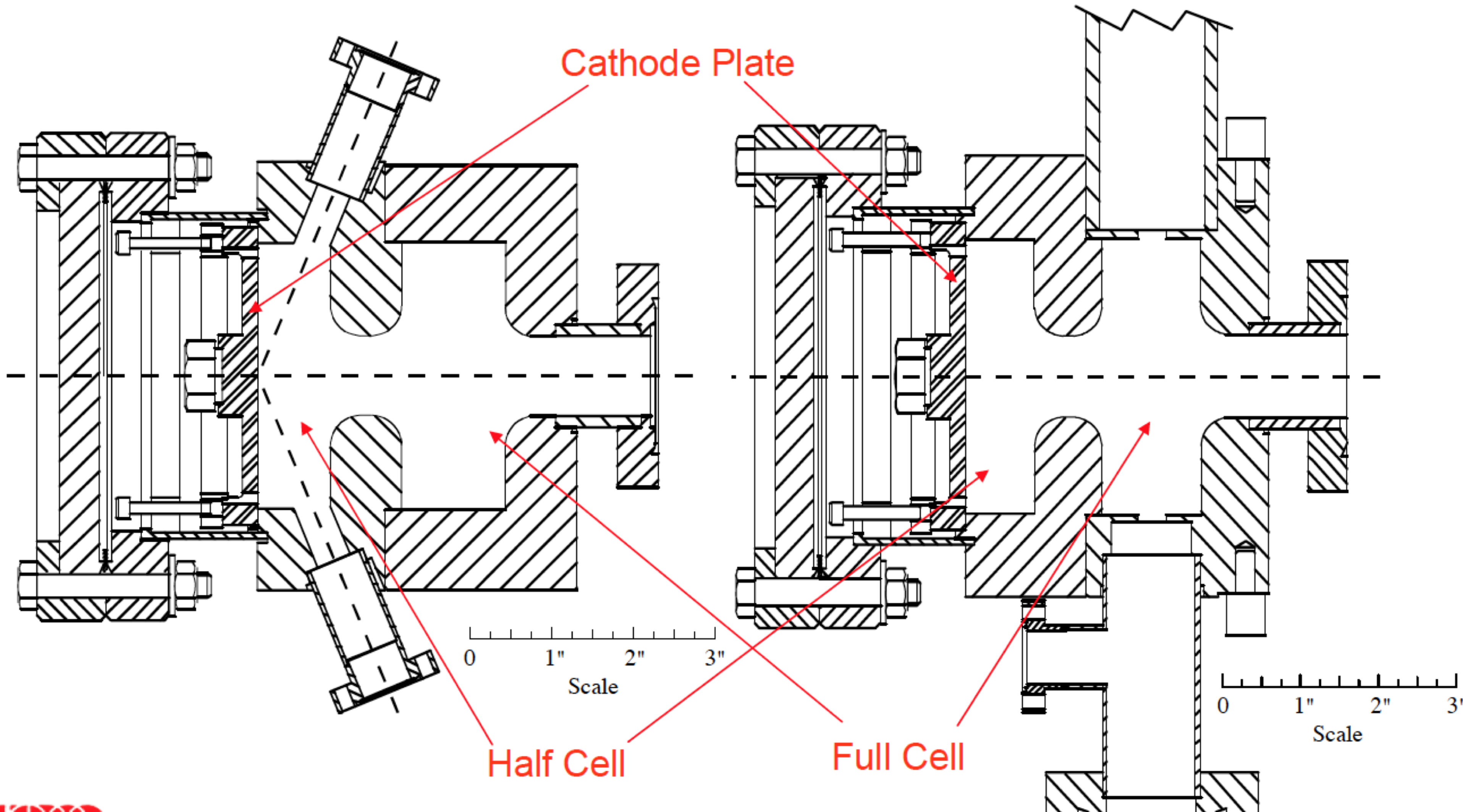
Power amplification: Klystron



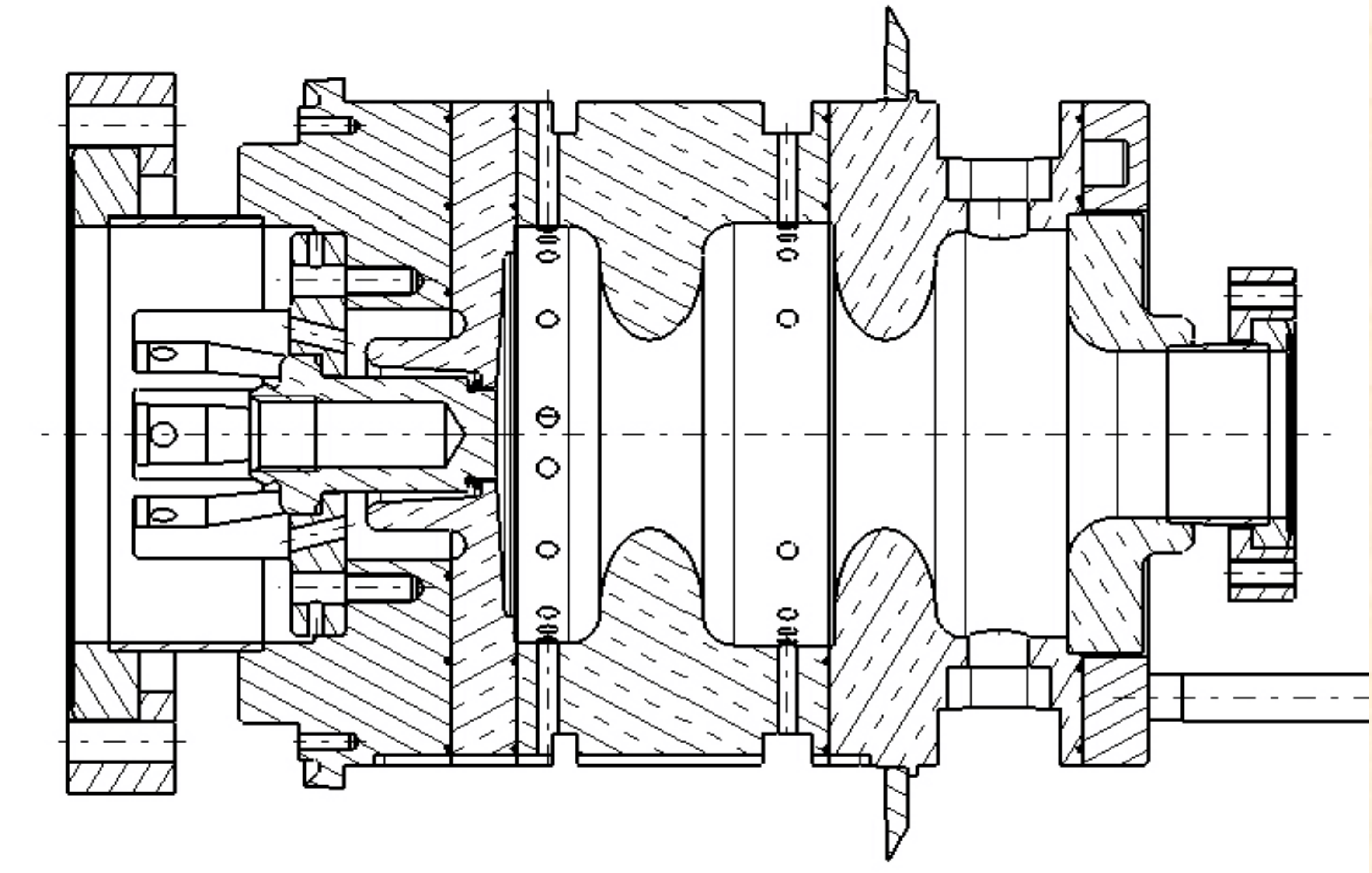
An Engineering Guide to Photoinjectors, T. Rao and D. H. Dowell, Eds.

- A klystron amplifies a milliwatt RF signal to kilowatts or megawatts so that it can be used in RF accelerating cavities.

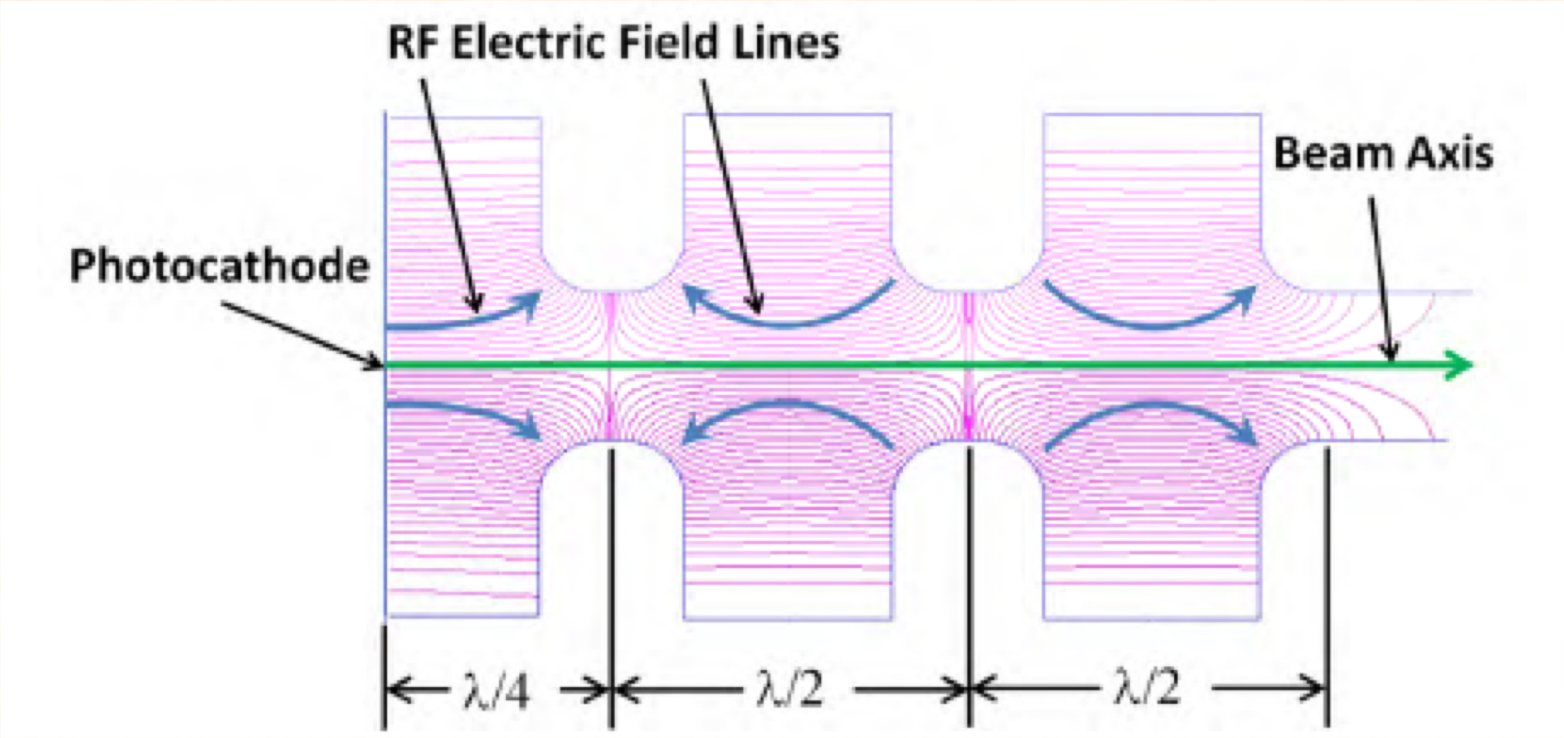
S-Band, 1.6 cell, RF Gun



PHIN RF Gun

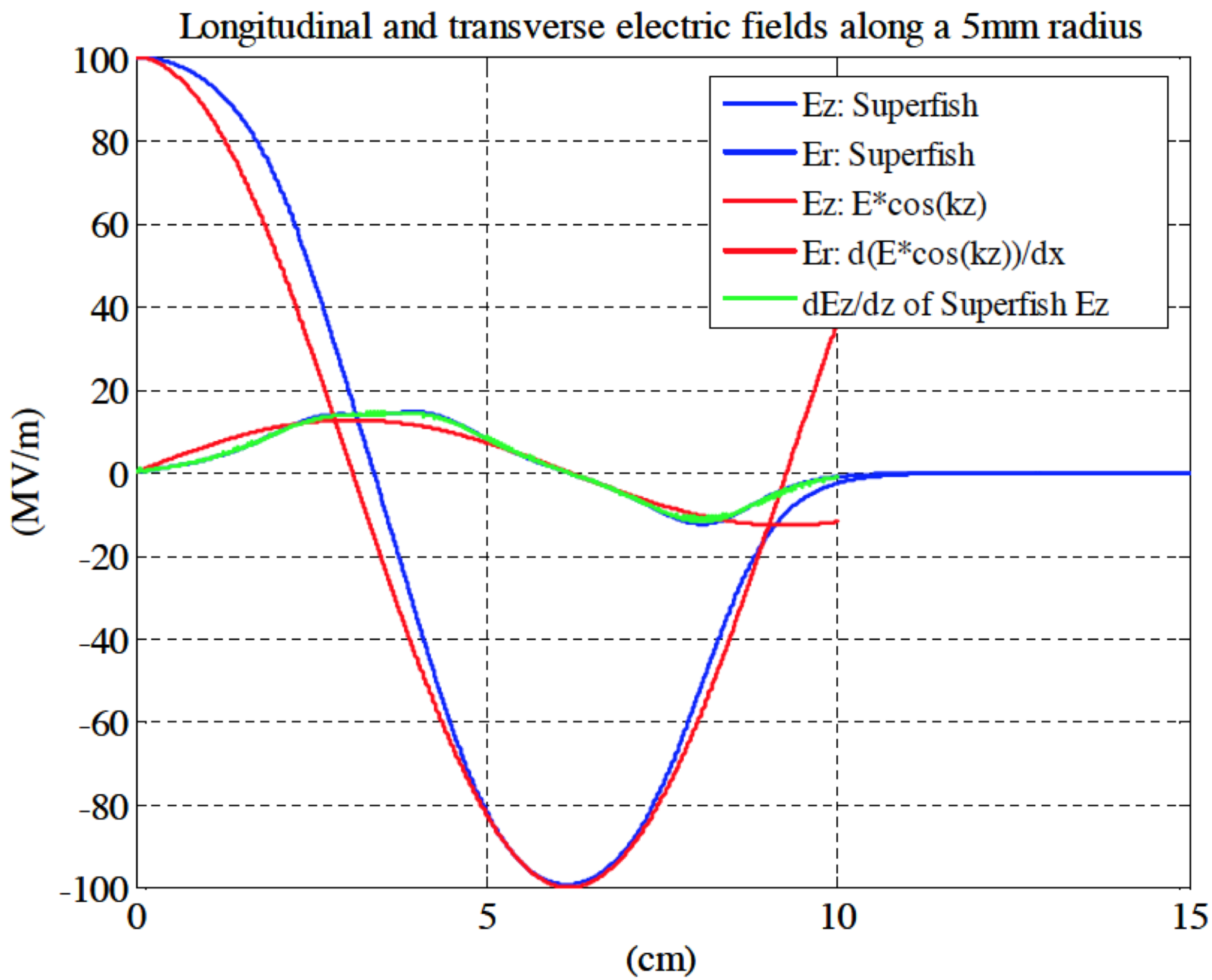


Field line simulations (SUPERFISH)



An Engineering Guide to Photoinjectors, T. Rao and D. H. Dowell, Eds.

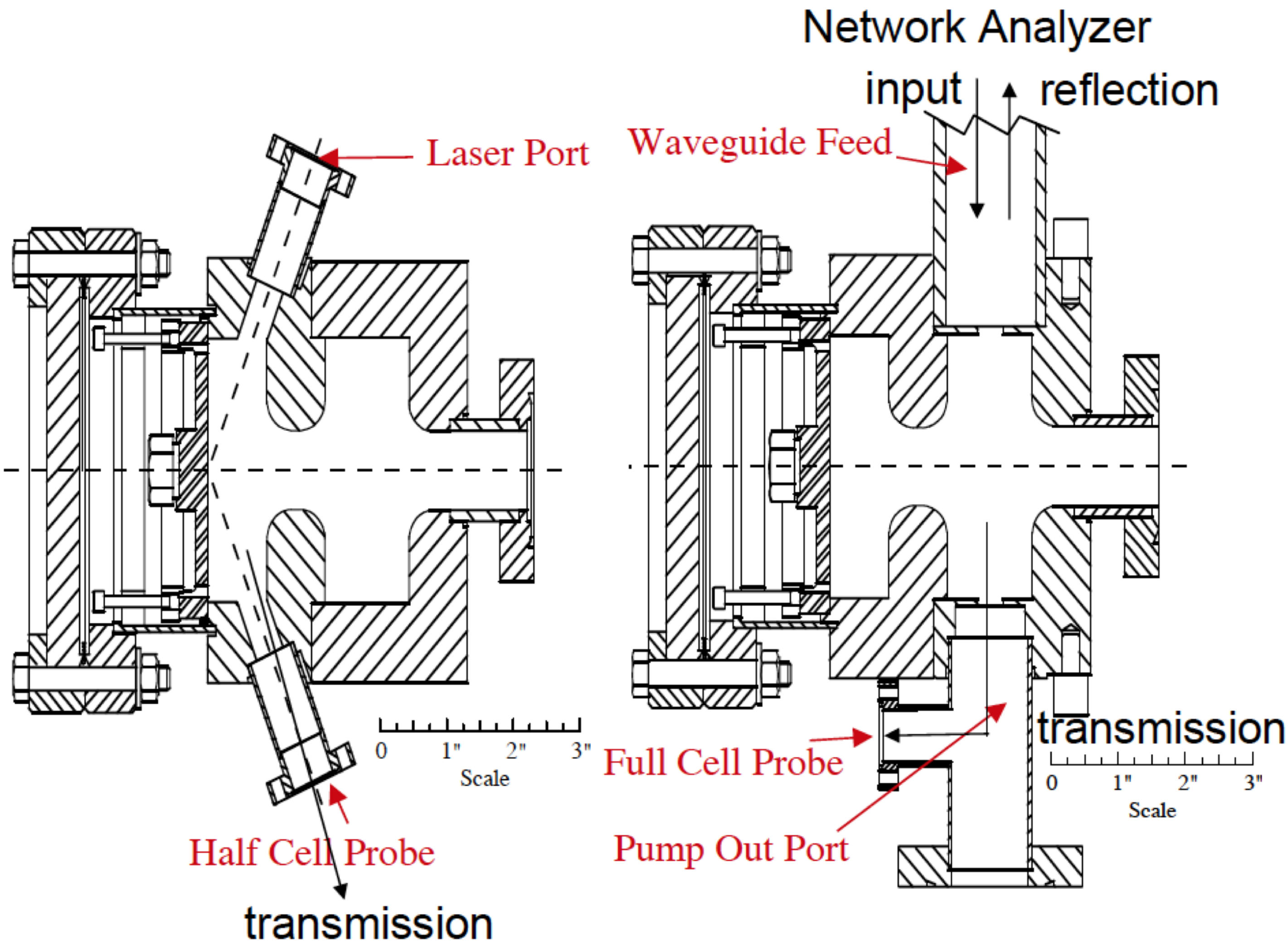
SUPERFISH Simulation 2



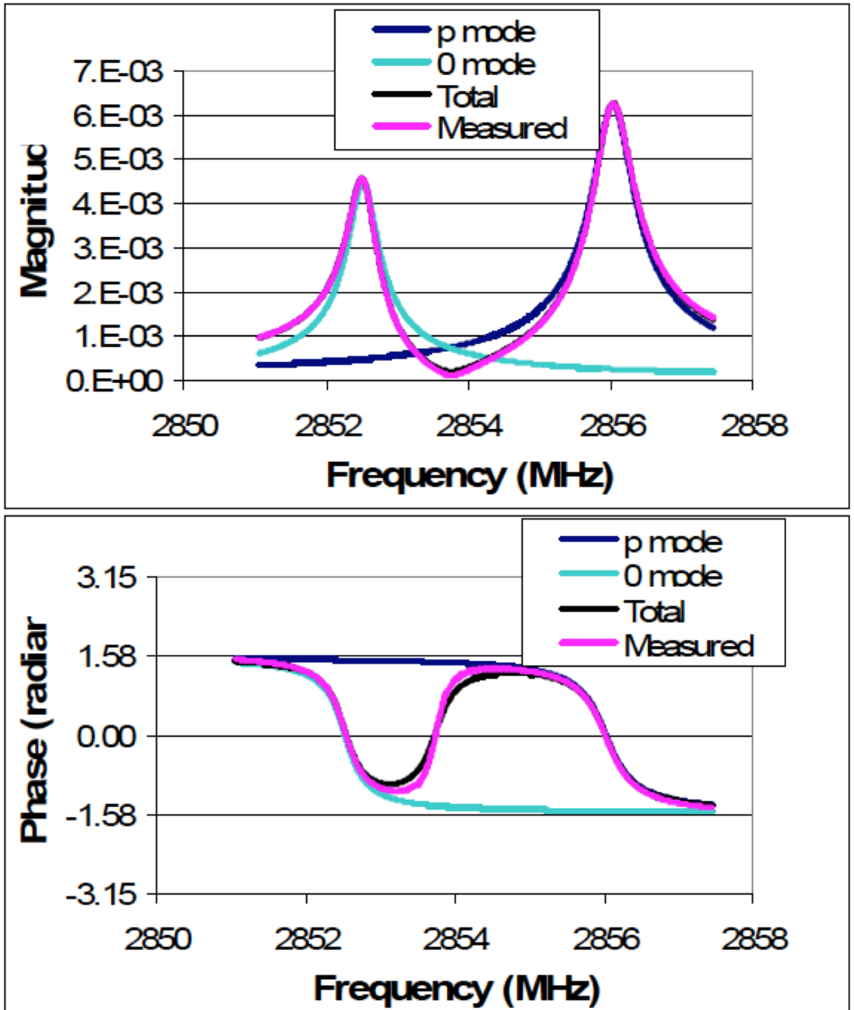
Modes

- Gun has two cells and thus at least two resonances or modes
- The field for the accelerating mode has a 180° phase difference between the two cells. This mode is called the π mode.
- This structure also supports a mode with 0° phase difference between cells. However, the 0 mode does not accelerate electrons since the field has the wrong polarity in the full cell at the time the electron arrives at the full cell.
- In addition there are undoubtedly additional modes at much higher resonant frequencies.

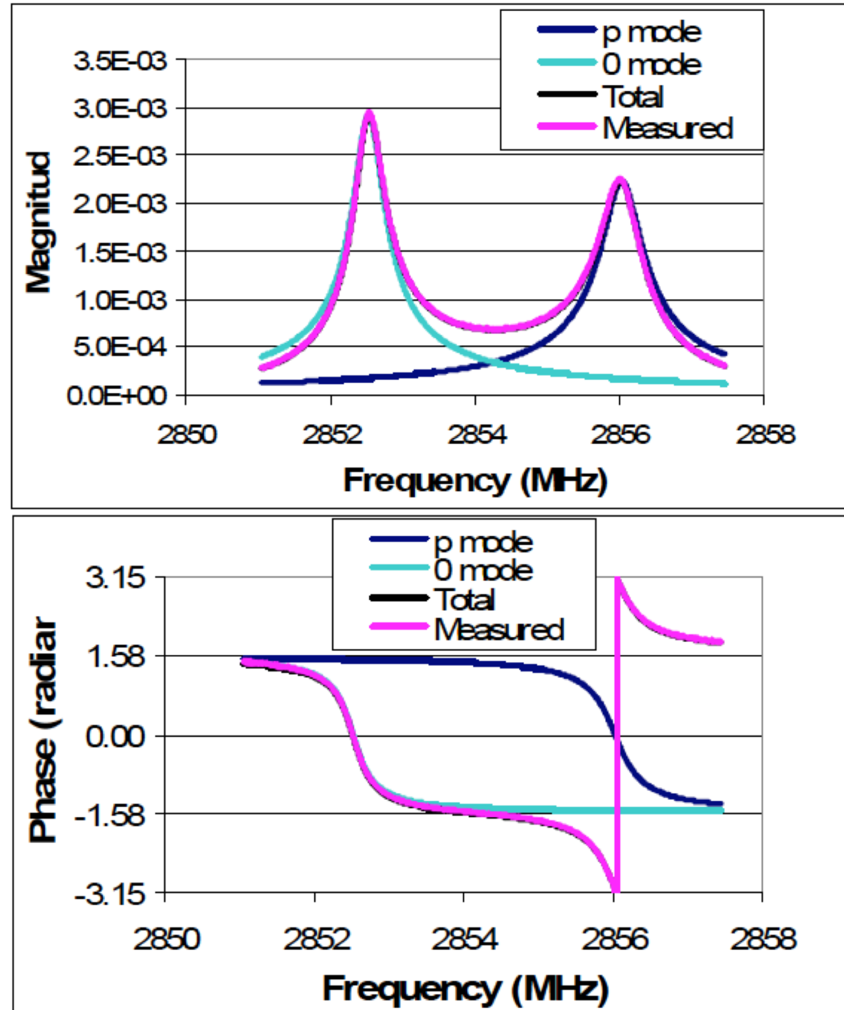
Measurement of Modes



Results

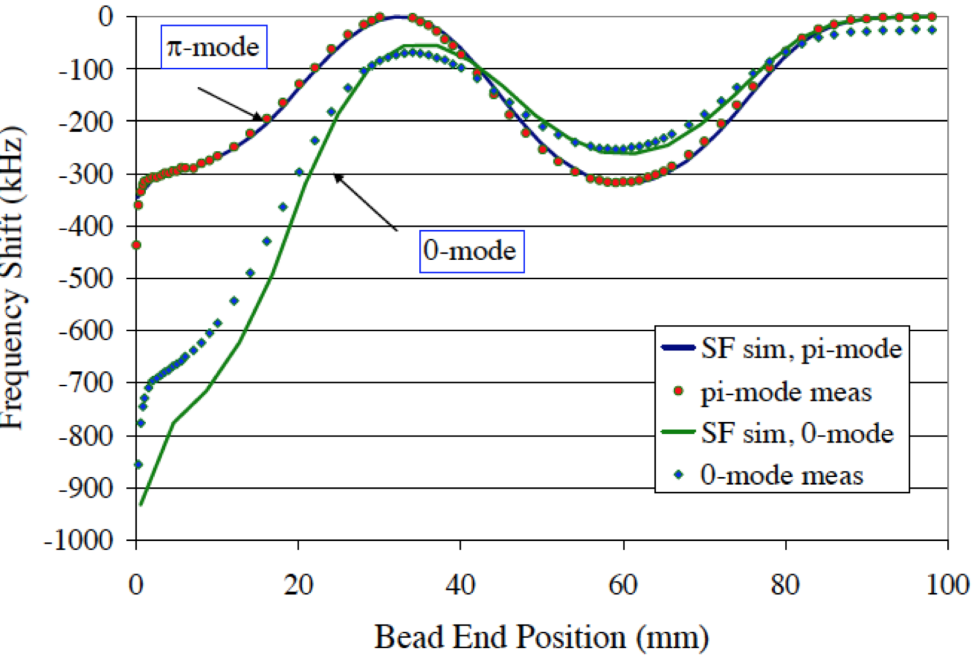


Full Cell Transmission

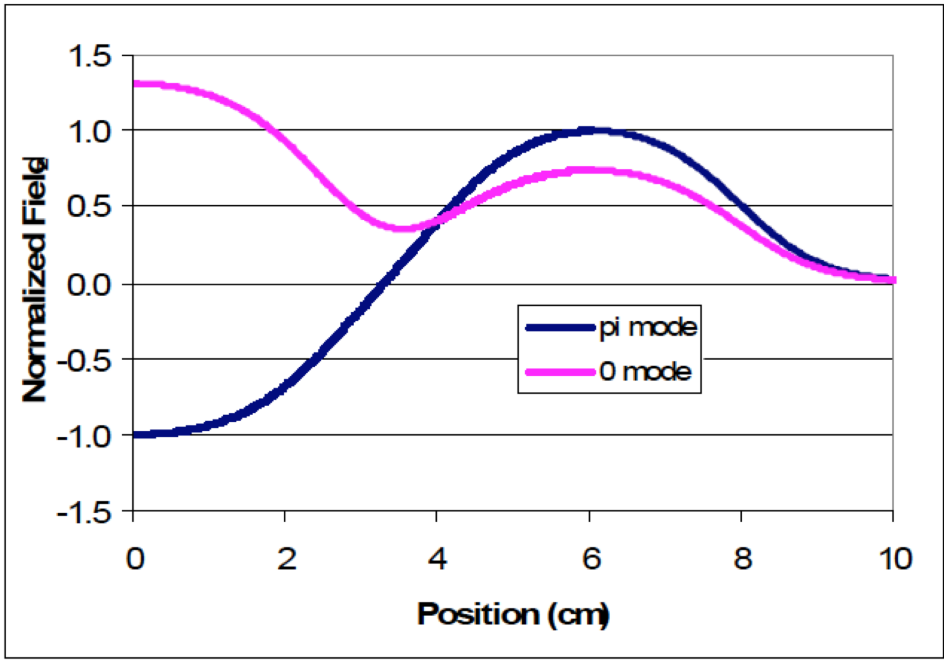


Half Cell Transmission

Field vs Position



Bead Drop Measurement



SUPERFISH simulation

Mathematical Model

- Equivalent to band pass filter (parallel RLC circuit)

$$T(\omega,z)=\frac{jA_\pi(z)\dfrac{\omega_\pi}{Q_\pi}\omega}{\omega_\pi^2-\omega^2+j\dfrac{\omega_\pi}{Q_\pi}\omega}+\frac{jA_0(z)\dfrac{\omega_0}{Q_0}\omega}{\omega_0^2-\omega^2+j\dfrac{\omega_0}{Q_0}\omega}$$

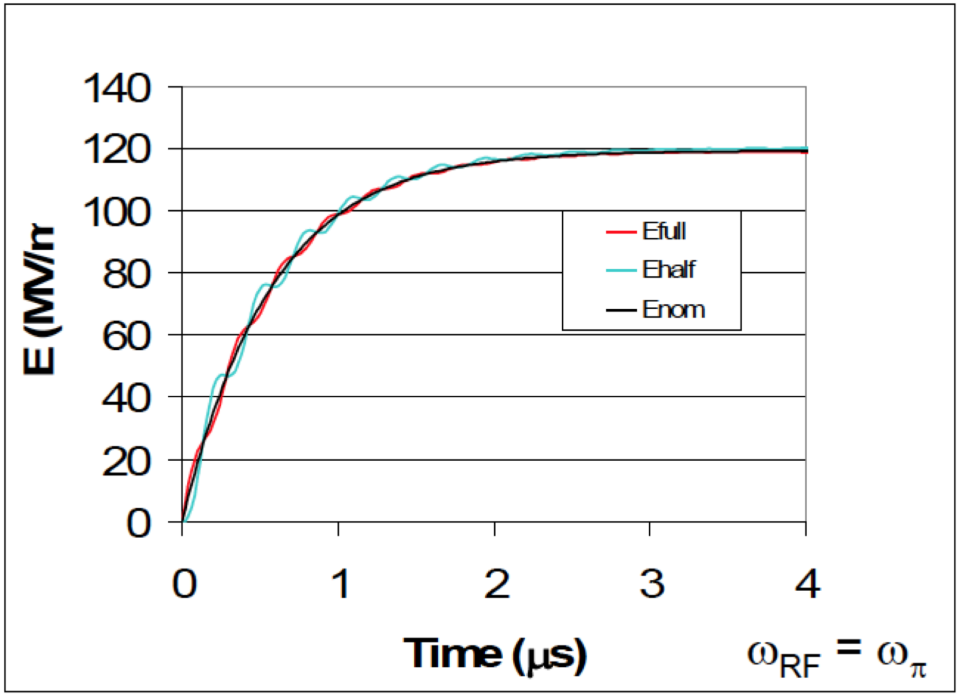
$$\frac{d^4E_{out}}{dt^4}+\left(\frac{\omega_\pi}{Q_\pi}+\frac{\omega_0}{Q_0}\right)\frac{d^3E_{out}}{dt^3}+\left(\omega_\pi^2+\omega_0^2+\frac{\omega_\pi\omega_0}{Q_\pi Q_0}\right)\frac{d^2E_{out}}{dt^2}+\left(\frac{\omega_0^2\omega_\pi}{Q_\pi}+\frac{\omega_\pi^2\omega_0}{Q_0}\right)\frac{dE_{out}}{dt}+\omega_\pi^2\omega_0^2E_{out}$$

$$=\left(\frac{A_\pi\omega_\pi}{Q_\pi}+\frac{A_0\omega_0}{Q_0}\right)\frac{d^3E_{in}}{dt^3}+\frac{\omega_\pi\omega_0}{Q_\pi Q_0}\frac{d^2E_{in}}{dt^2}+\left(\frac{A_\pi\omega_\pi\omega_0^2}{Q_\pi}+\frac{A_0\omega_0\omega_\pi^2}{Q_0}\right)\frac{dE_{in}}{dt}$$

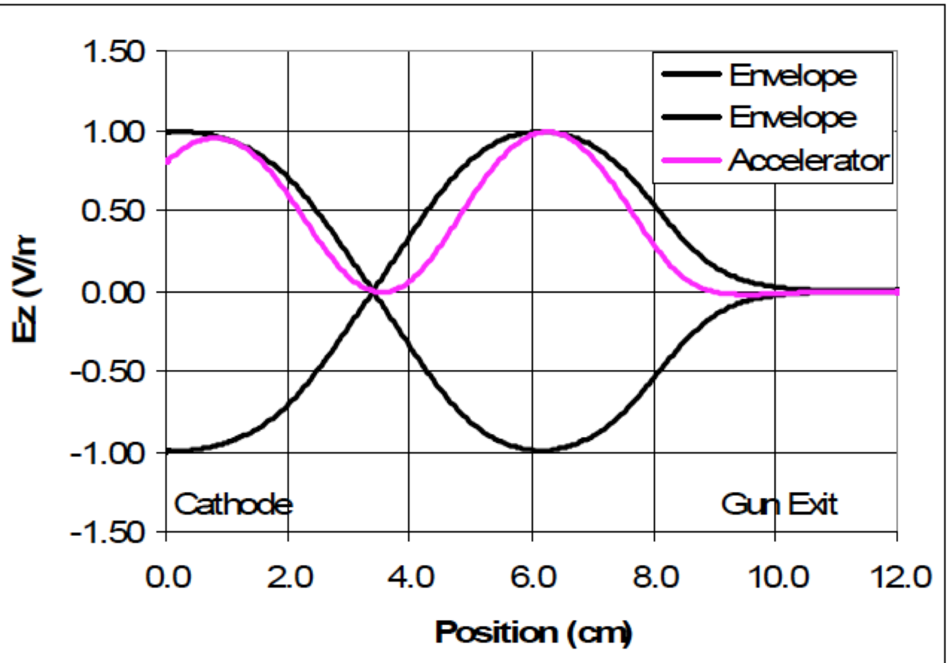
Step Function Excitation

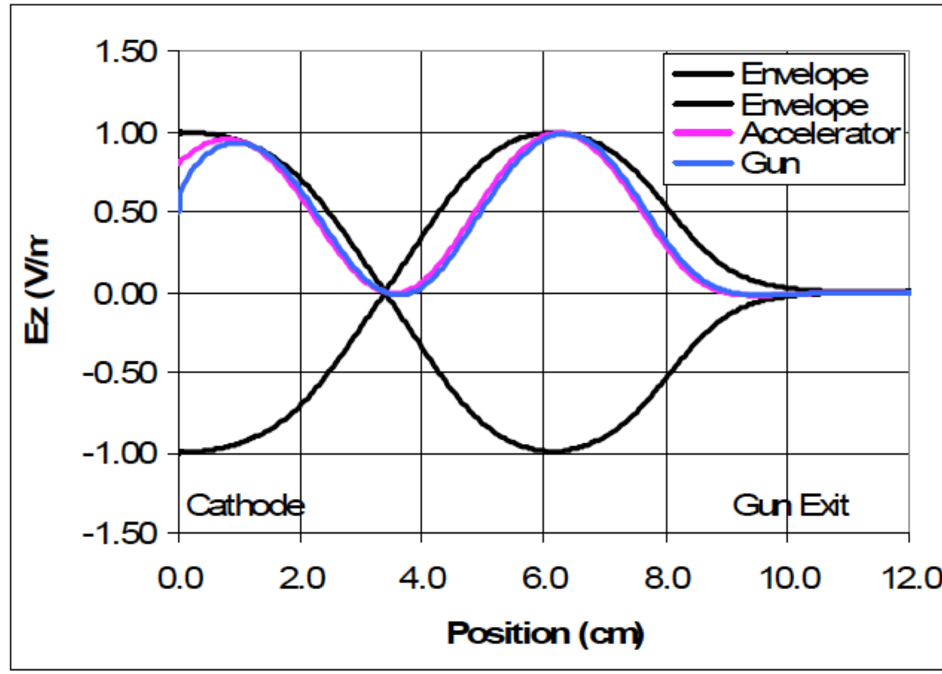
$$\frac{E_{out}(t)}{E_{in}} = E_\pi \cos\left(\omega_{RF} t + \theta_\pi\right) + E_0 \cos\left(\omega_{RF} t + \theta_0\right) + T_\pi e^{-\frac{t}{\tau_\pi}} \cos\left(\omega_\pi t + \phi_\pi\right) + T_0 e^{-\frac{t}{\tau_0}} \cos\left(\omega_0 t + \phi_0\right)$$

$$\frac{E_{steady\ state}(t)}{E_{in}} = E_\pi \cos\left(\omega_{RF} t + \theta_\pi\right) + E_0 \cos\left(\omega_{RF} t + \theta_0\right) = E_{ss} \cos\left(\omega_{RF} t + \theta_{ss}\right)$$



Energy Gain

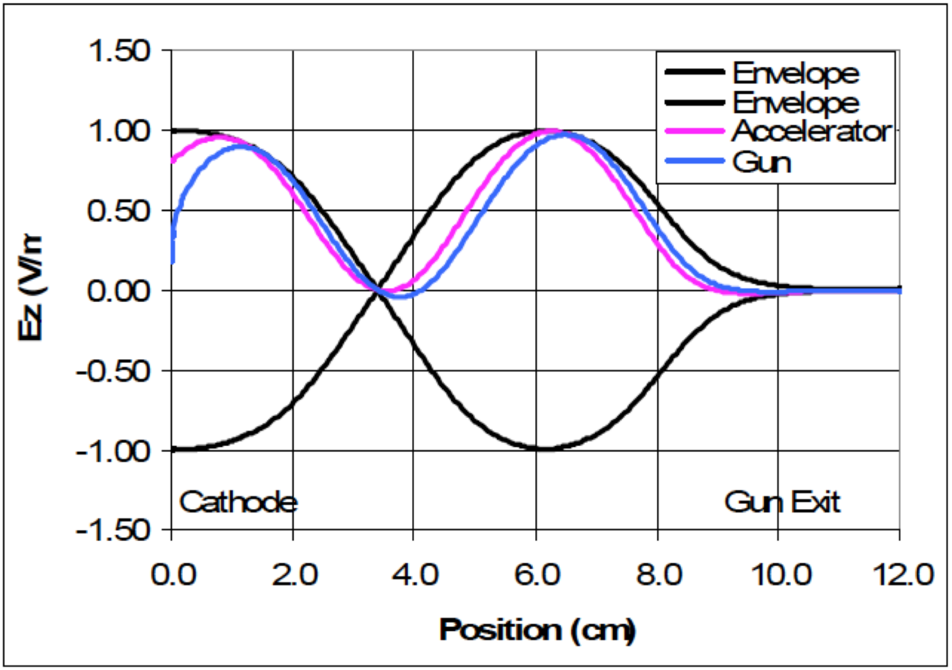


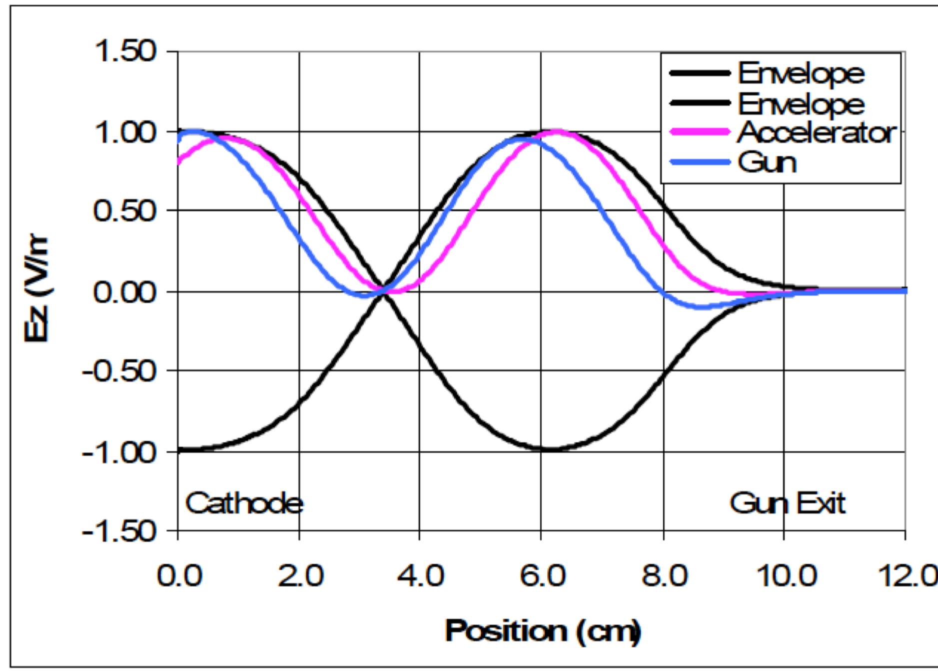


E_{peak} = 120 MV/m
$\theta_{accelerator}$ = 53°
E_{exit} = 6.26 MeV

E_{peak} = 120 MV/m
θ_{gun} = 30°
E_{exit} = 6.17 MeV

Energy Gain

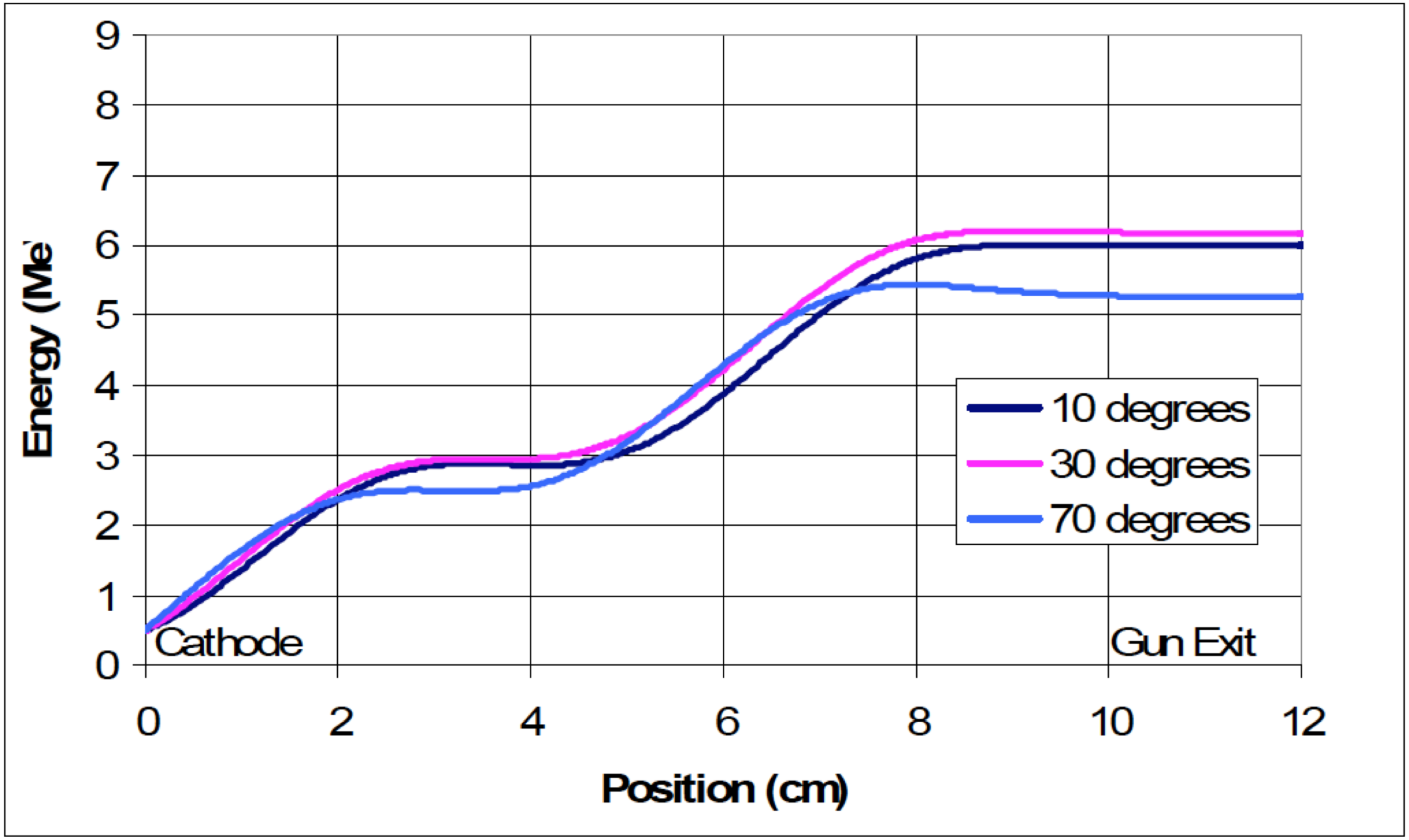




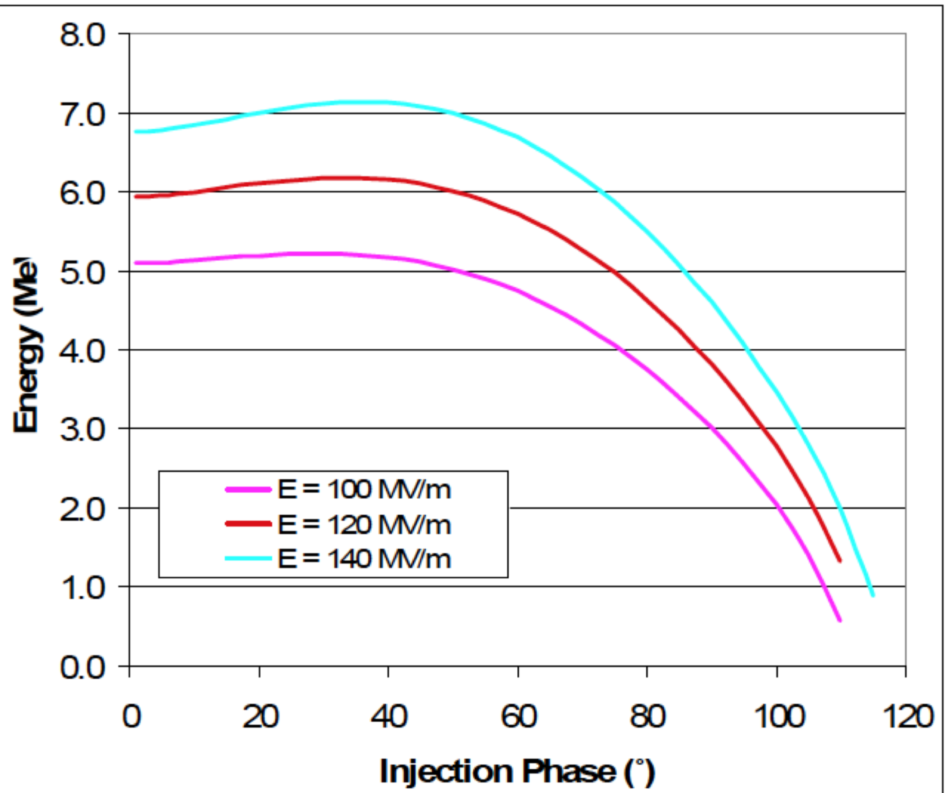
E_{peak} = 120 MV/m
θ_{gun} = 10°
E_{exit} = 6.00 MeV

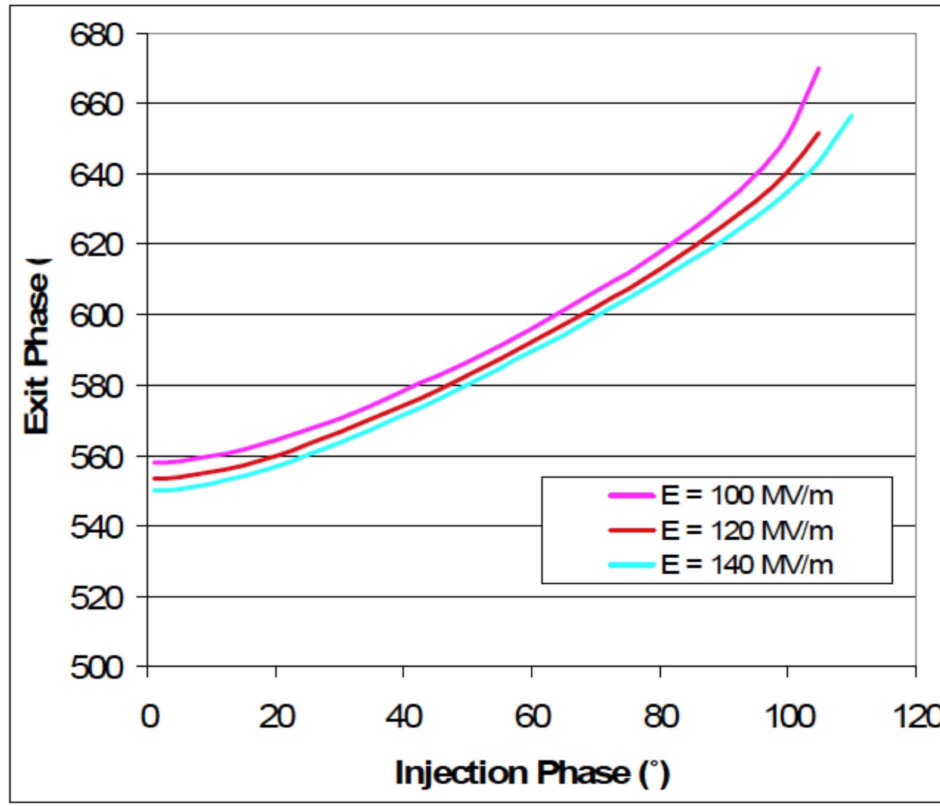
E_{peak} = 120 MV/m
θ_{gun} = 70°
E_{exit} = 5.26 MeV

Energy Gain


9
8
7
6
5
4
3
2
1
0
Energy (Me
0
2
4
6
8
10
12
Position (cm)
Cathode
Gun Exit
10 degrees
30 degrees
70 degrees

Energy and Exit Phase vs Injection Phase





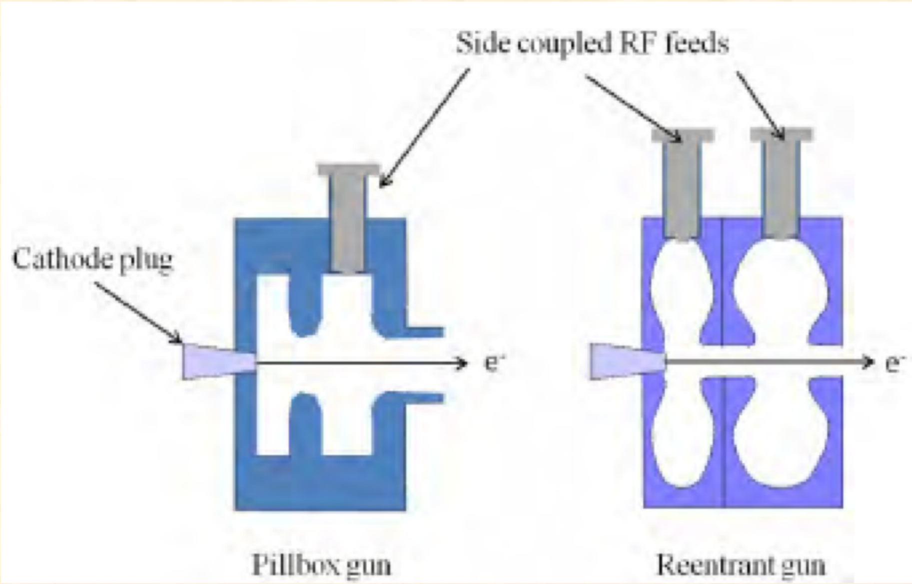
RF Pulse Compression

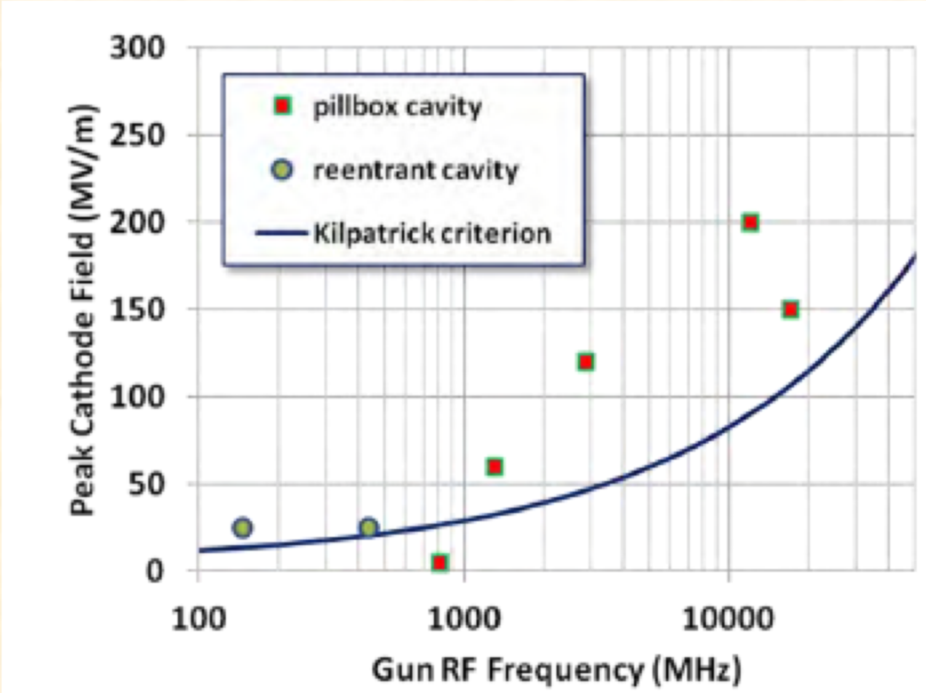
- Exit pulse length depends on injection phase because the transit time is a function of injection phase
- Final pulse length = $d\phi_{exit}/d\phi_{entrance}\Delta\phi_{laser}$
- Compression if $d\phi_{exit}/d\phi_{entrance}<1$
- Expansion if $d\phi_{exit}/d\phi_{entrance}>1$

Energy Spread

- Dominated by correlated energy vs time
- Energy vs time due to field temporal variation
- Energy spread estimated by $dE_{exit}/d\phi_{entrance}\Delta\phi_{laser}$

Cavity shape

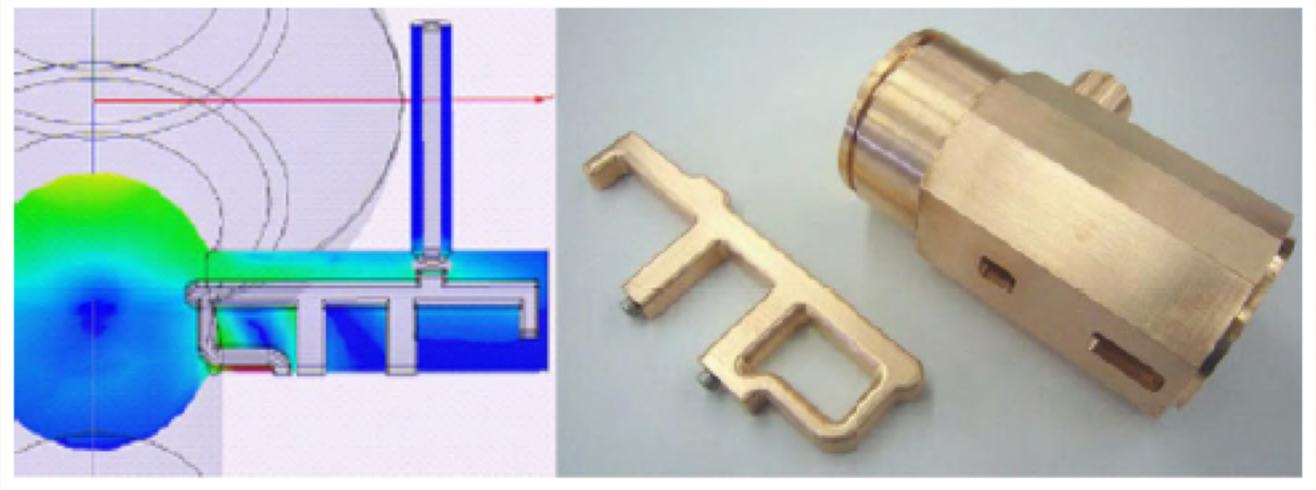




- The cavity shape has an impact on the peak field.
- A higher peak field may lead to more breakdowns and limit the maximum acceleration gradient.

Higher order modes

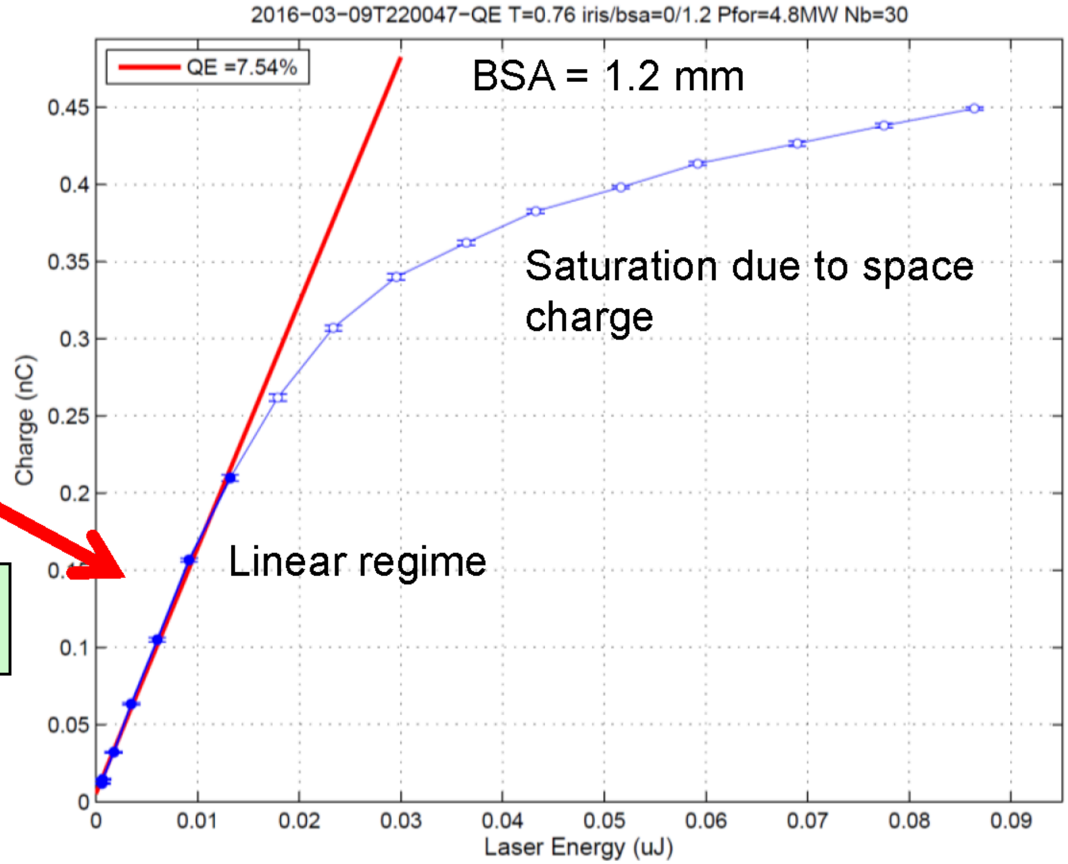
- In addition to the TM010 mode of the cavity, higher order mode may be excited.
- These higher order mode can cause longitudinal and transverse instabilities.
- Special filters are used to remove them.



Quantum Efficiency (QE) measurement

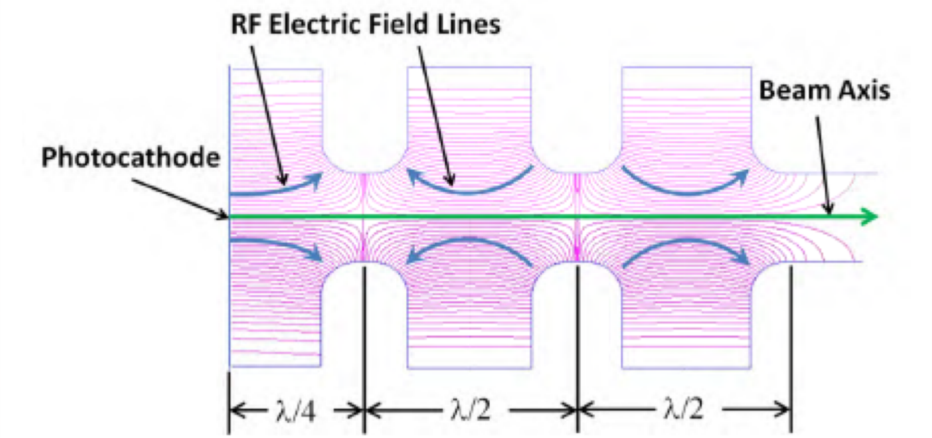
- RF Gun at nominal parameters (4.8 MW), phase 38º off zero crossing
- Laser pulse energy measured with an absolutely calibrated joulemeter (Molectron J-5/9, reflective coating, 17.82 mV/µJ)
- Beamline transmission (68%) measured and corrected for
- Laser wavelength 262 nm
- Charge is measured with the 3GUN toroid T1
- QE is defined as the slope of laser energy vs charge, obtained by a linear fit

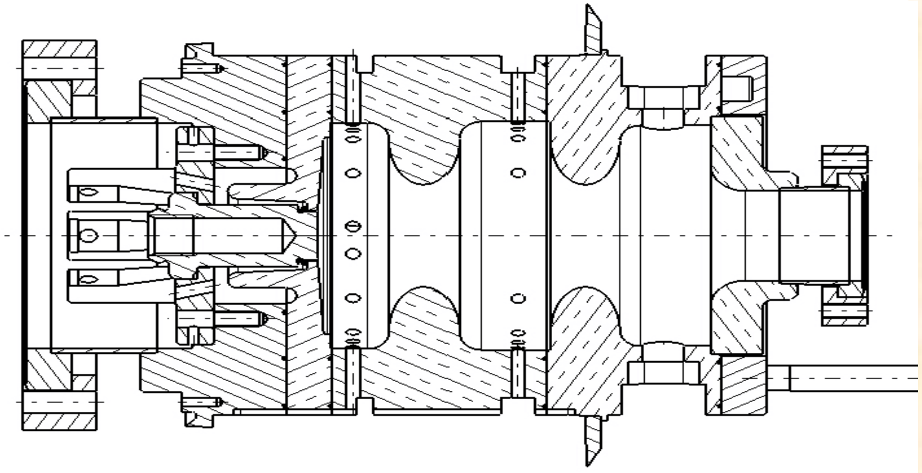
QE = 5% →
Laser pulse energy = 0.1 µJ for 1 nC



Quizz

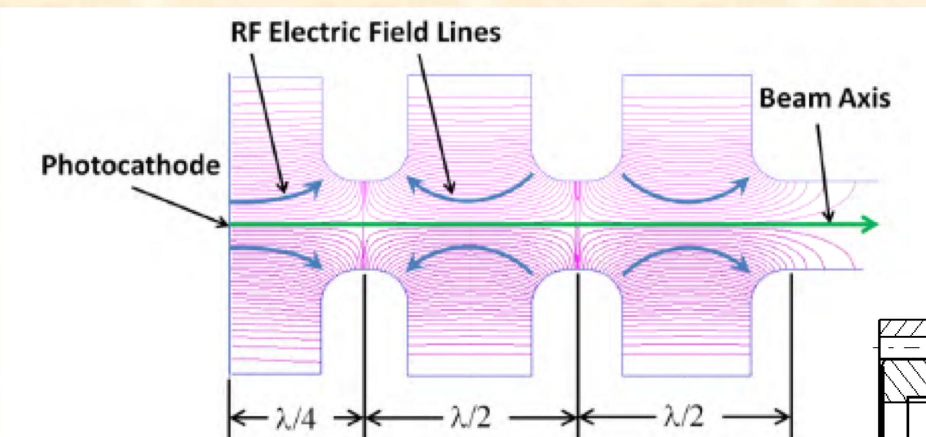
- The RF gun built at LAL have a frequency of 2998MHz.
- What is the length of a full cell?
  (a) 5cm
  (b) 50cm
  (c) 5m

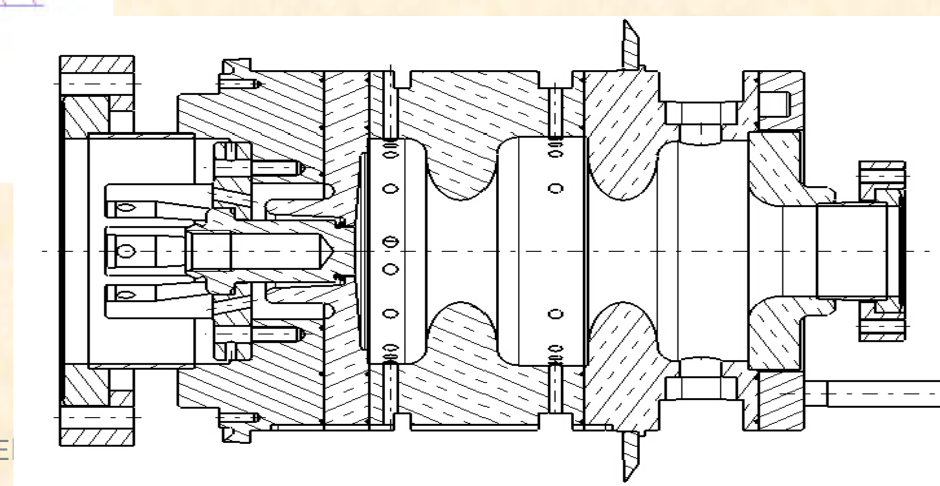




Answer (a)

- One cell is half a wavelength.
- At 3GHz one wavelength is about 10 cm.
- (c/2998MHz)/2 ~5cm





Examples of quantum efficiencies: SLAC-TN-05-080

Source: D.T. Palmer, SLAC-tn-05-080

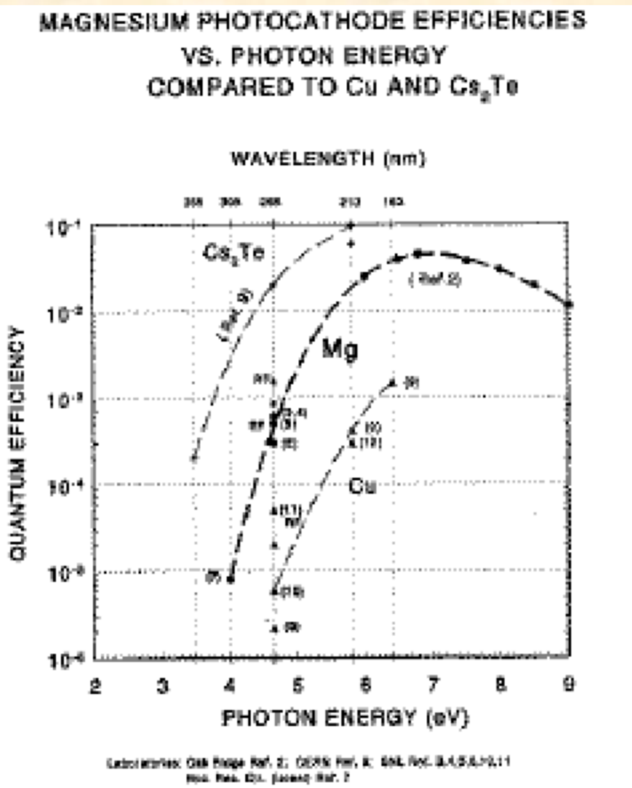


Figure 2: QE data for Cs_2Te, Mg, and Cu photocathodes versus wavelength [0].
http://www.bnl.gov/atf/capfiles/photocat/quantum_eff.html.

Table 2: Copper Quantum Efficiency Data from CERN Reference [1].

Wavelength λ (nm)	Copper QE	Reference
193	2.0×10^{-4}	1
	1.5×10^{-3}	1, 2
213	1.5×10^{-4}	1
	4.2×10^{-4}	1, 2
266	2.2×10^{-6}	1
308	1.6×10^{-7}	1
355	8.0×10^{-8}	1

Table 3: Magnesium Quantum Efficiency Data from an RF Gun Reference [4].

Wavelength λ (nm)	Magnesium QE	RF Field Gradient
266	2.5×10^{-4}	50 MV/m
266	5.0×10^{-4}	~70 MV/m

Quantum efficiency: DESY XFEL (EPAC'04 MOPKF021)

- Material Cs2Te (very high QE)

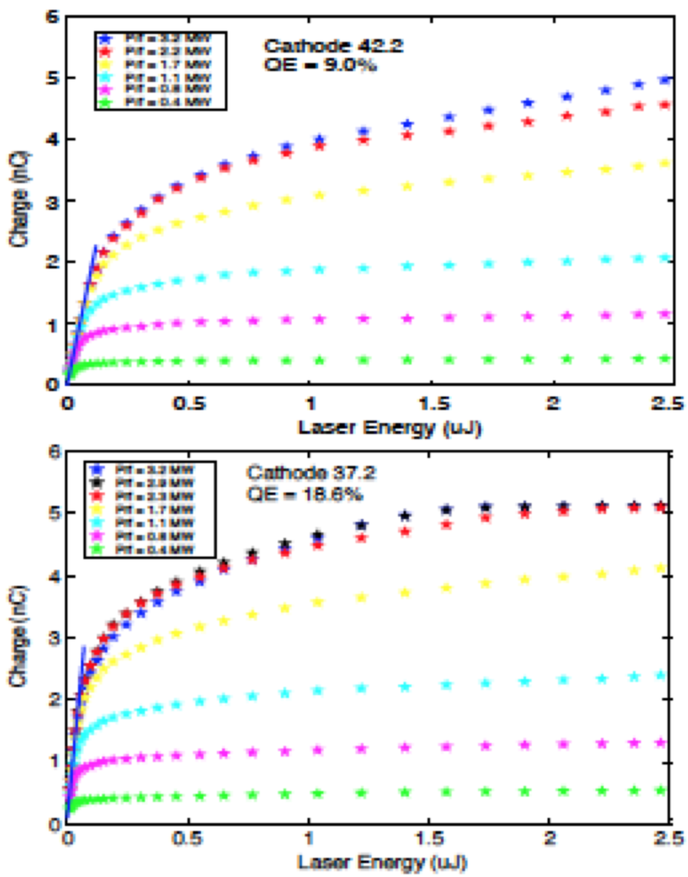


Figure 2: Measured charge output of the RF gun as a function of laser energy on cathode 42.2 after 80 days of running and 37.2 directly after first insertion. The data are plotted for various RF powers in the gun.

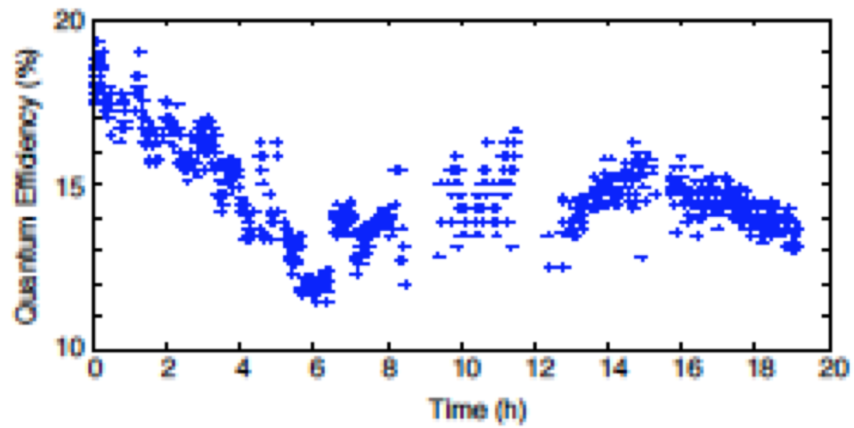


Figure 3: On-line quantum efficiency for the first 20 h after insertion of cathode 37.2 into the gun.

Cathode preparation

- Procure High purity metal from commercial vendor
- Polish using commercial diamond slurry
- Avoid exposure to oxygen containing cleaners
- Rinse in hexane
- Clean in ultrasonicator in hexane bath
- Transport to vacuum chamber in hexane bath
- Bake and pump
- Laser/ion clean in 10^{-9} Torr vacuum

Source: USPAS 2008

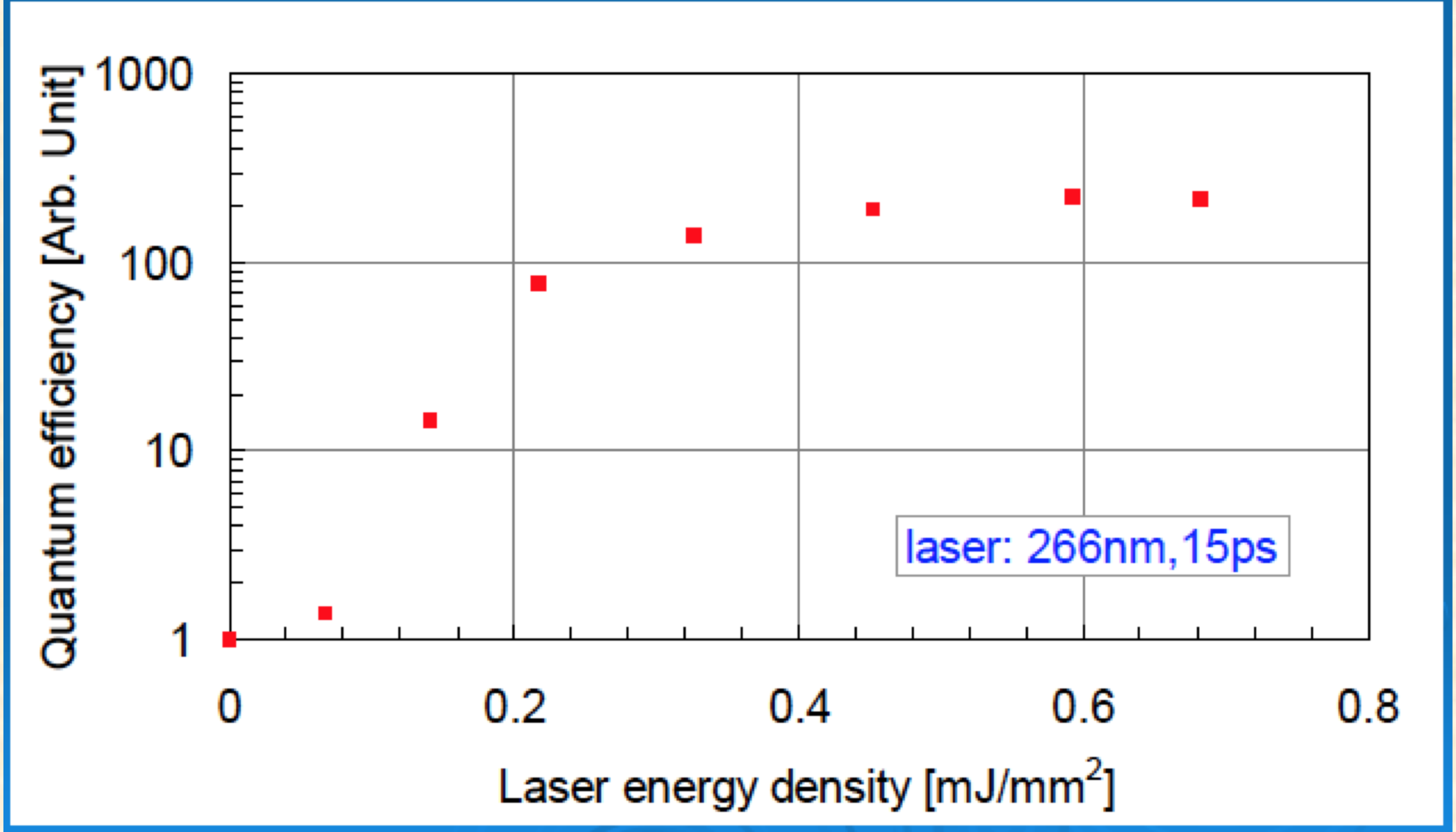
Photocathode preparation and lifetime

Facility	Cathode Material	Preparation	Laser Wavele-ngth	Charge	Pulse Duration	Repetitio n Rate	Lifetime
LCLS	Copper	H_2 Ion Bombardment\ Laser Ablation	253, 255 nm	Up to 1 nC	0.7-3.7 ps	120 Hz	2 yr
BNL-ATF	Copper	Laser Ablation	256 nm	Up to 1 nC	7 ps	Up to 6 Hz	> 5 yrs
BNL-LEAF	Magnesium	Laser Ablation	266 nm	8 nC	5 ps	10 Hz	18 months
UCLA	Copper with MgF_2 Coating	Laser Ablation	266, 800 nm	10 pc	< 1 ps	5 Hz	> 1 yr
INFN: FERMI	Copper	Ozone Cleaning	262 nm	250 pC	6 pc	10 Hz	3 months

Table 6.1. Facilities using metal photocathodes and their performance [6.5].

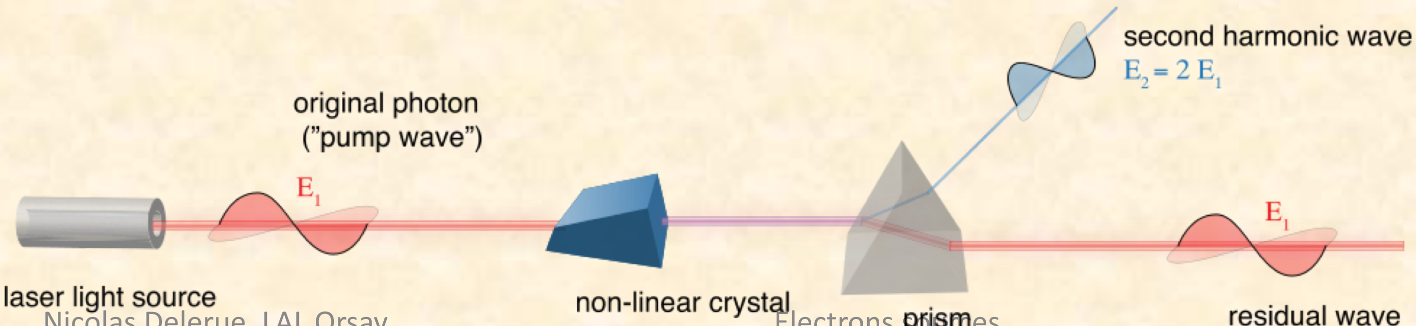
An Engineering Guide to Photoinjectors, T. Rao and D. H. Dowell, Eds.

Niobium cathode – QE vs. laser cleaning

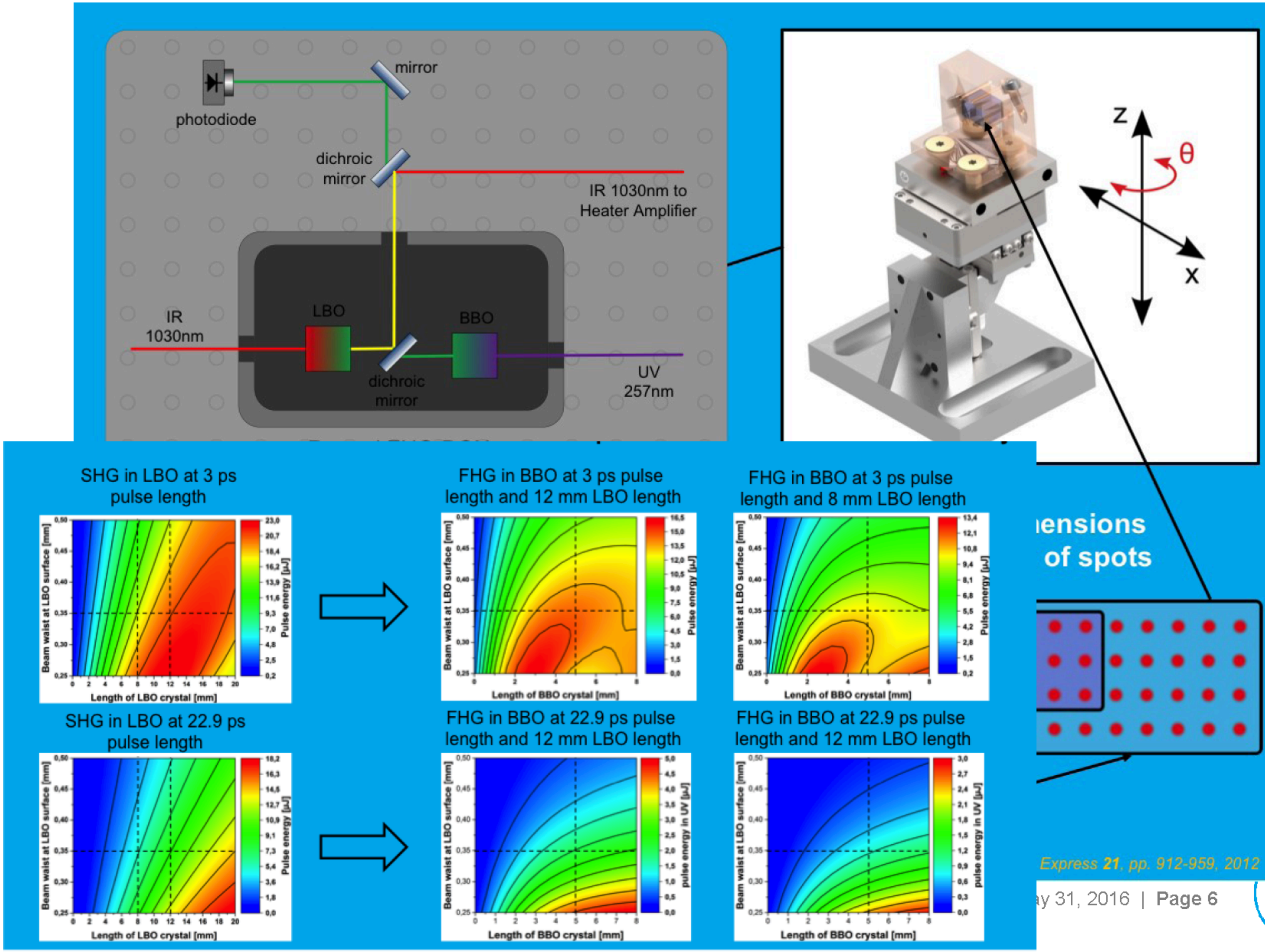


Laser technology

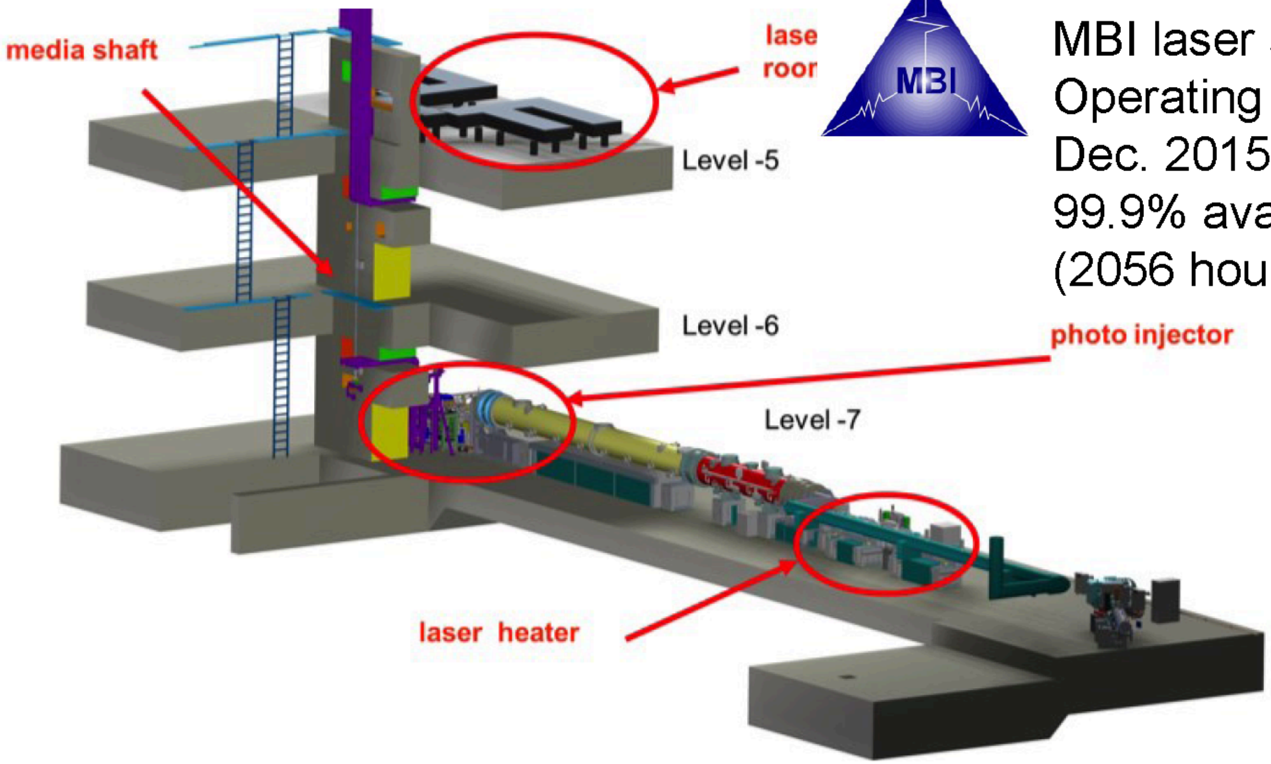
- Lasers can't produce UV light (˜ 260nm; ˜5 eV) directly.
- The most efficient lasers emit in the near infra-red. For example Ti:Saphire [Ti:Al_2O_3] (800nm;1.5eV) or Nd:YAG (1064nm;1.2eV).
- Non linear crystals are then used to triple or quadruple the energy of the photons.
- Such laser systems (and frequency conversion) are rather complex and need special skills to operate.
- See your laser courses for more about this…



UV generation (1030nm → 257nm)



European XFEL photocathode laser and beamline



MBI laser system
Operating 24/7 since Dec. 2015. Status Apr: 99.9% availibility (2056 hours in use)

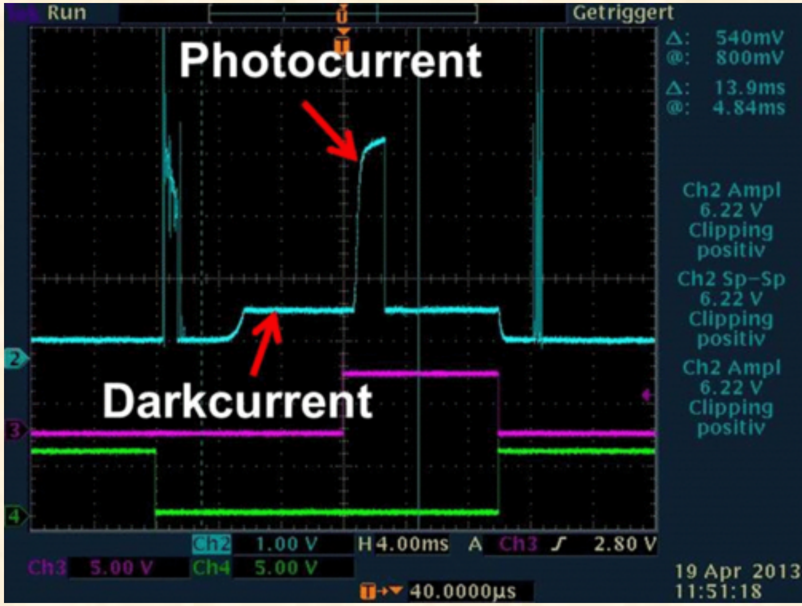
Main Laser Parameters

FLASH.
Free-Electron Laser in Hamburg

	Laser 1	*Laser 2*	*Laser 3*
Laser material	Nd:YLF		Yb:YAG
Wavelength	1047 nm		1030 nm
4^{th} harmonic (UV)	261.7 nm		257.5 nm
Repetition rate	10 Hz		
Burst/train length	800 µs		
Intra-train rate	1 MHz (*)		
Pulses per train	1 … 800		
Pulse energy UV	50 µJ	50 µJ	1 µJ
Average power (IR)	2 W		10 W
Arrival time jitter	60 fs rms		--
Long. shape	Gaussian		
Pulse duration (sigma)	4.5 ps	6.5 ps	0.8 - 1.6 ps
Transverse profile	Flat, truncated Gaussian		
Spot size on cathode	1.2 mm diam.(**)		0.8 mm
Charge stability	<0.5 % rms		1 % rms

Dark current

- Electrons can also be emitted at time when they are not wanted:
  - when the grid is "closed" in a thermionic gun
  - when there is no laser light in a photogun.
- This is called "dark current".
- Dark current particles are often at the wrong phase and therefore at the wrong energy.
- The dark current is a source noise and must be removed.



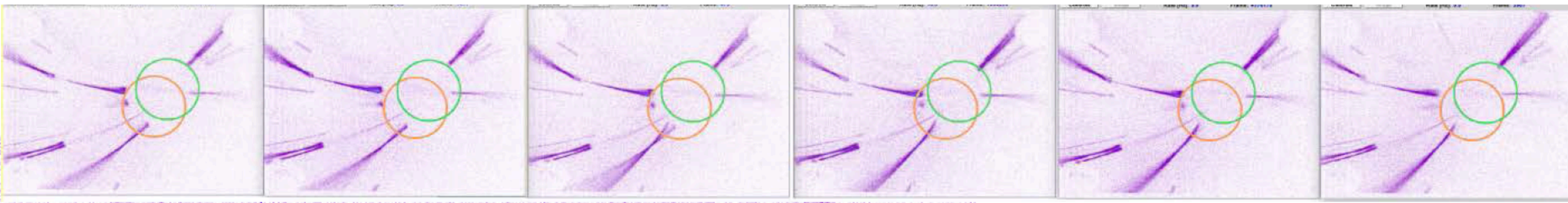
Source: http://journals.aps.org/prstab/abstract/10.1103/PhysRevSTAB.17.043401

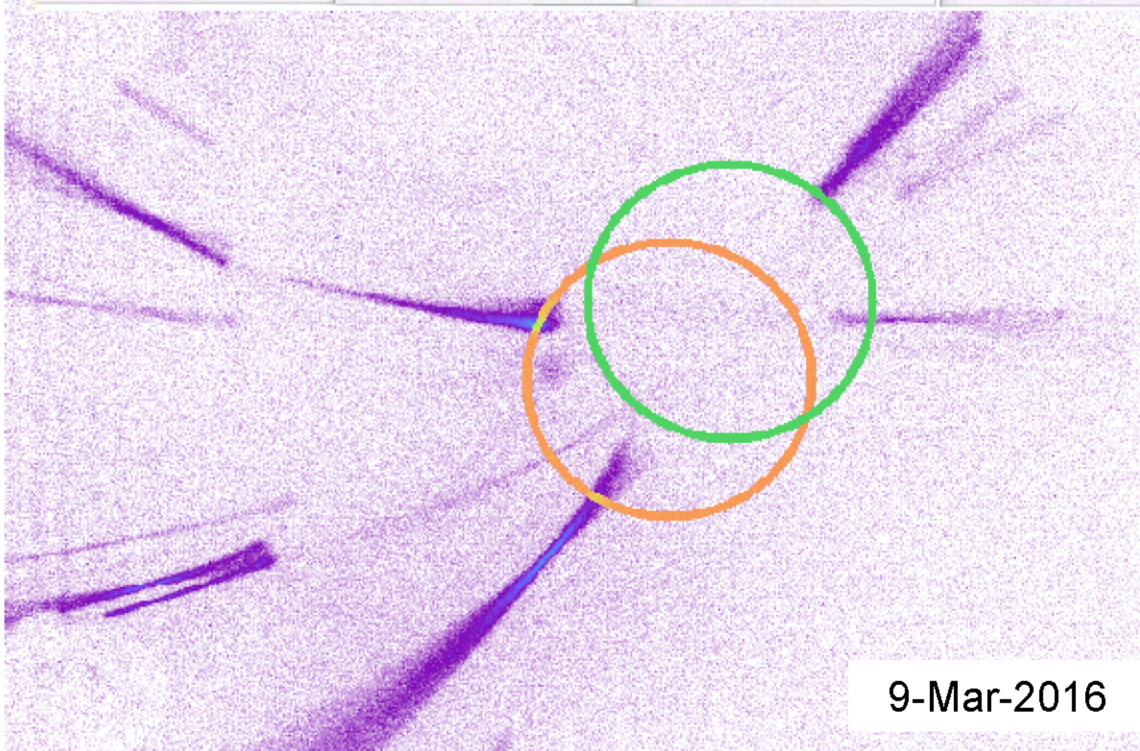
Darkcurrent with Cathode 73.3

FLASH. Free-Electron Laser in Hamburg

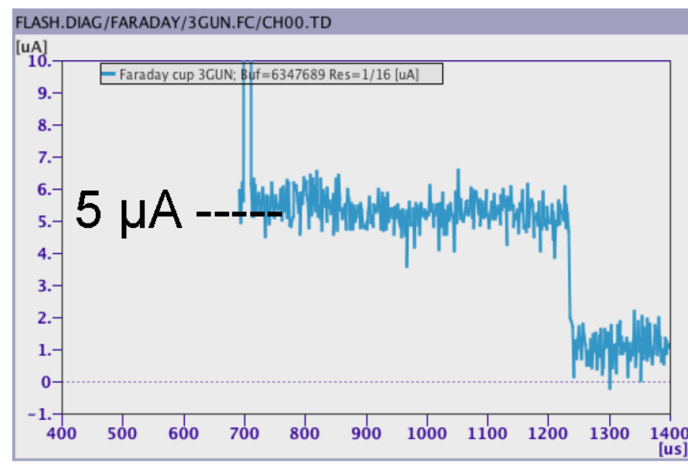
- Stable at 5 µA, stable pattern
- measured at 3GUN; 4.8 MW, 547 µs, Sol. 307.0 A; phase +4 dg

15-Jul-2015 | 18-Aug-2015 | 29-Sep-2015 | 11-Nov-2015 | 22-Dec-2015 | 7-Jan-2015





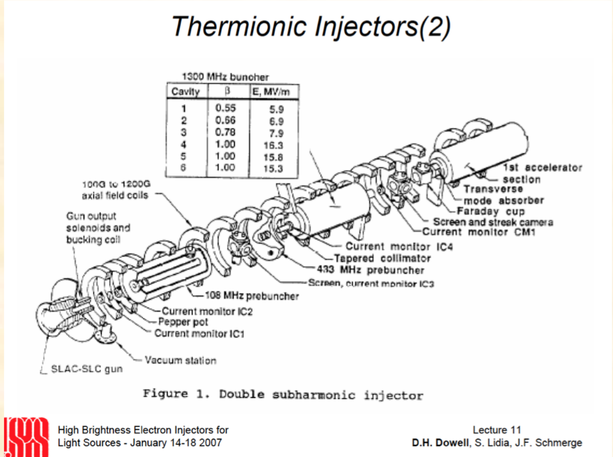
9-Mar-2016

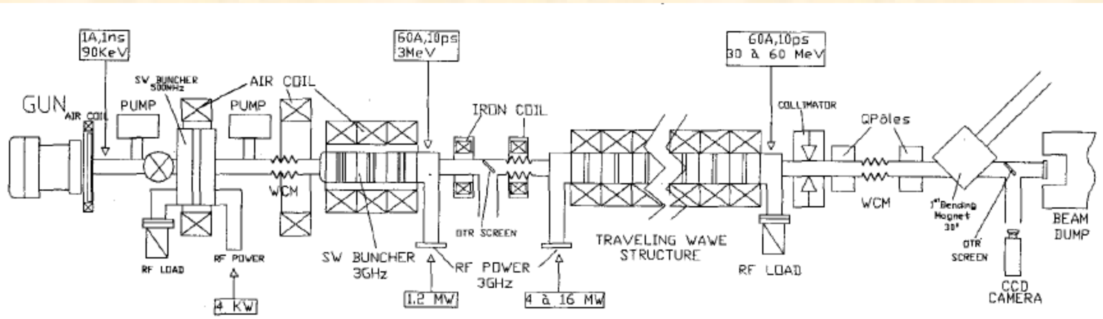


RF gun vs Thermoionic injector

- In a Thermoionic injector the electrons are bunched in several stages.
- In the RF gun the electrons immediately reach the desired pulse length (down to ps).
  => Better compactness
  => Lower emittance

BUT: more complexity (laser, RF,…)





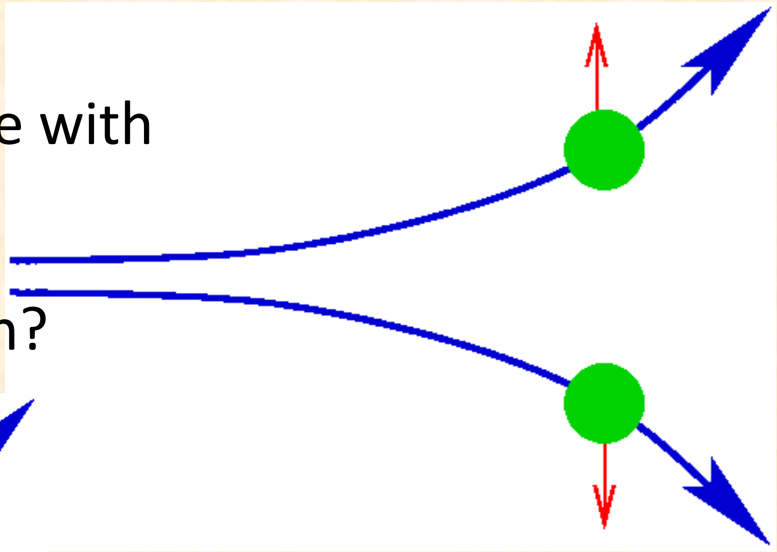
Summary: Gun design

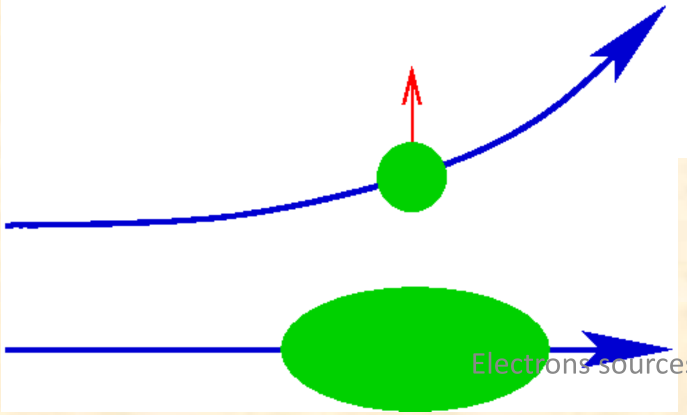
- The shape of the electrodes is important in all electron guns:
  - it will minimize space-charge
  - it will allow to increase the field without breakdowns
- Cavity shape are important in RF guns to increase even further the accelerating field.

BEAM DYNAMICS IN THE GUN

Beam dynamics: Space-charge effect

- Let's consider two particles with similar charges travelling in the same direction.
- Due to their charge these particles will push each other away (Coulomb's law).
- What is the intensity of the force with which they repel each other?
- What is the effect of a full bunch?

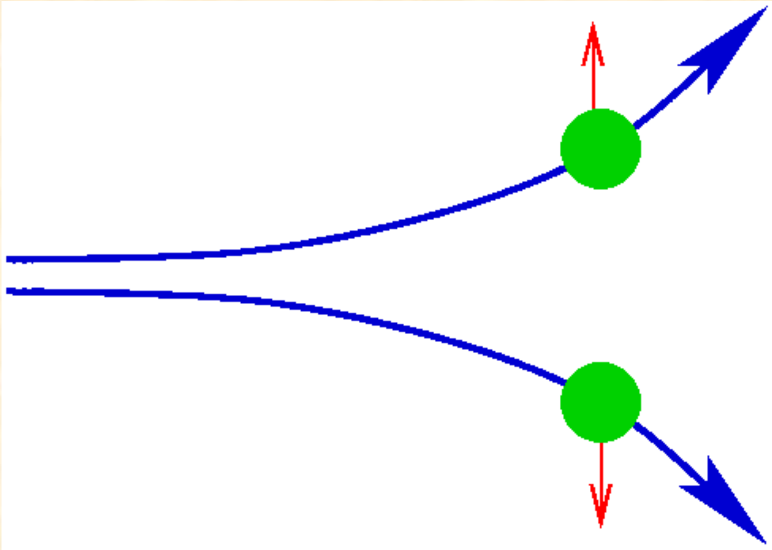


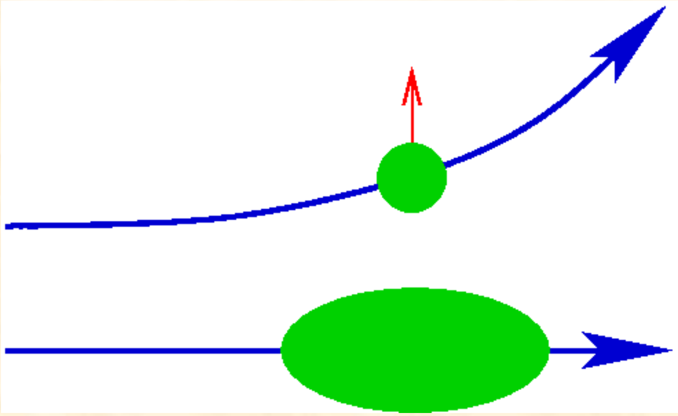


Coulomb force between two electrons

$$f = \frac{1}{4\pi \in_0} \frac{q_1 q_2}{d^2}$$

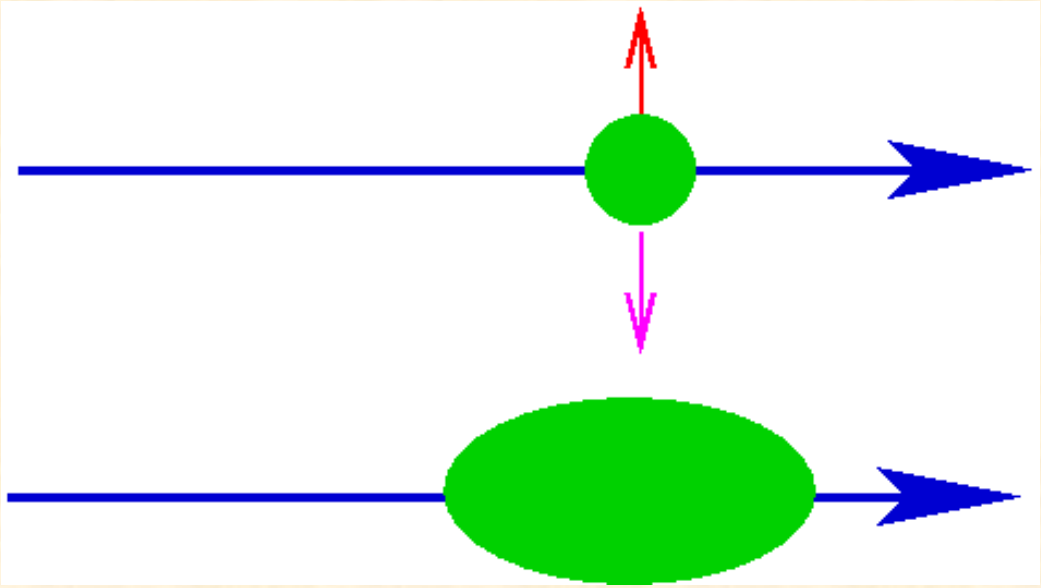
- Assume d=1micrometre.
- $f=2\ 10^{-16}N$
- This may look small but an electron is not very heavy
- $f/m=2.5\ 10^{14}N/kg$
- This force is very intense on the scale of the electrons.
- Typical charge in a bunch: ~100pC = $6\ 10^8$ electrons





Avoiding space-charge effects

- If there is a second force that cancels the effect of the space-charge the particle will not be deviated.
- Let's see how the shape of this electrode is defined...



Electrostatic potential in the beam

- Assume steady state

$$\frac{\partial \rho}{\partial t} = 0$$

- Particle conservation as they propagate
=> Current constant across gap

$$\frac{\partial [Zen(z)v_z(z)]}{\partial z} = 0$$

$$n(z) = \frac{j_0}{Zev_z(z)}$$

- Electrostatic potential is 0 at source hence, particles are accelerated in the gap.

$$\frac{m_0 v^2{}_z}{2} = -Ze\phi$$

- Hence, by substitution

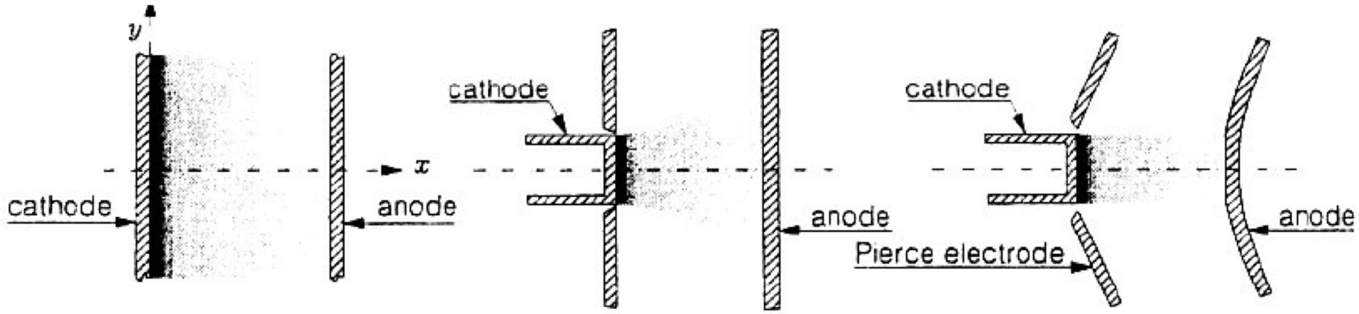
$$\frac{d^2\phi}{dz^2} = \frac{-j_0}{\in_0 \sqrt{-2Ze\phi / m_0}}$$

- And thus

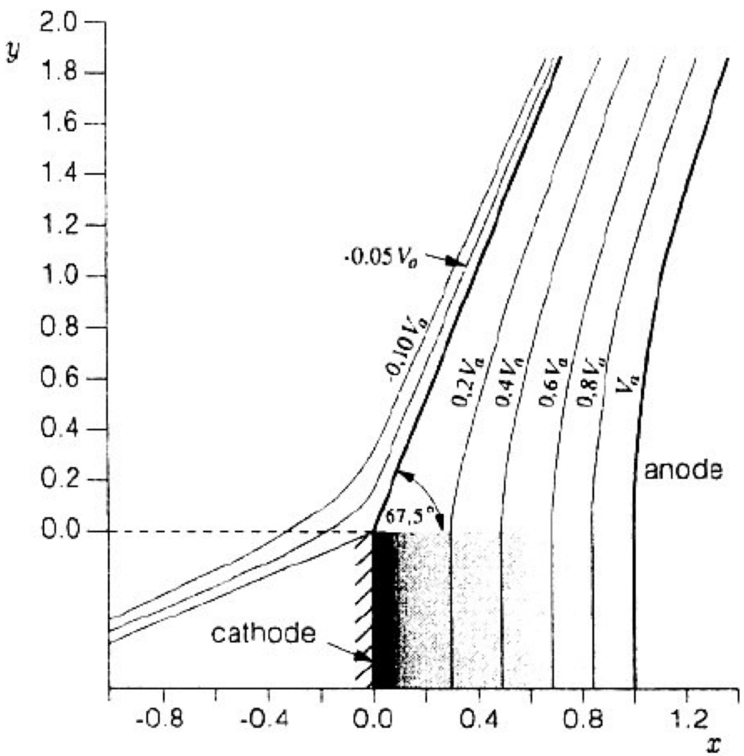
(see also Humphries, CPB, sec 5.2)

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

Pierce Electrode Geometry*



"Infinite" Diode — "finite" Diode — Pierce Diode



Assume $V(x) \propto x^{4/3}$, outside beam for finite (in y-direction) diode.

Use complex formalism $x \rightarrow re^{i\varphi} = \varsigma + i\xi$, $V \rightarrow W = V_R + iV_R$.

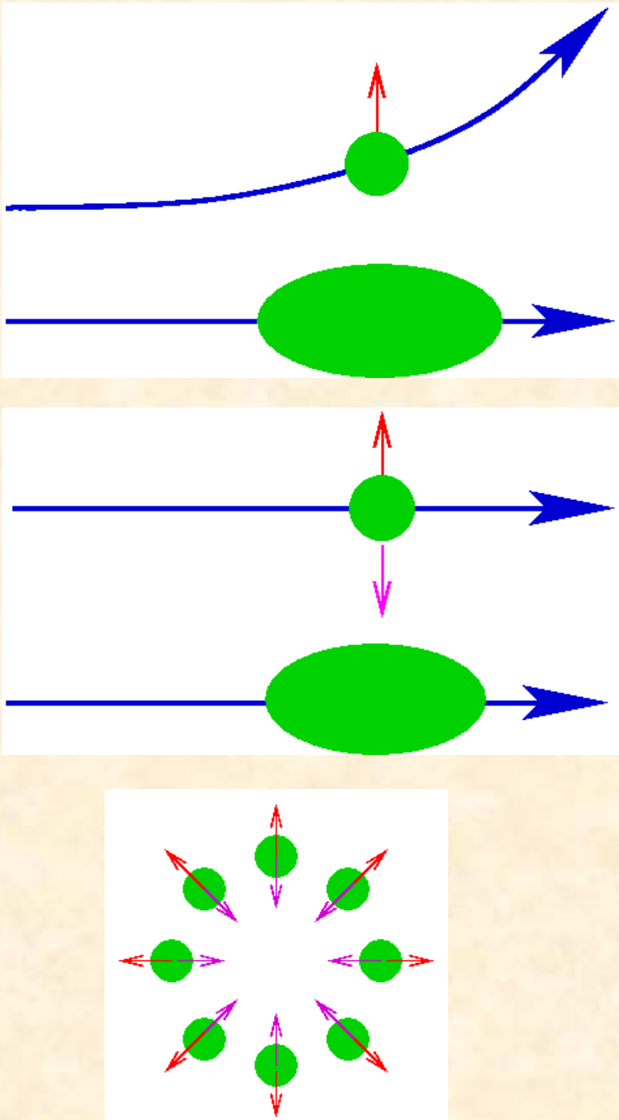
Then $V_R \propto r^{2/3} \cos[(4/3)\arctan(\varsigma/\xi)]$.

Since cathode is grounded, $V_R = 0$, so we need
$(4/3)\arctan(\varsigma/\xi)] = \pi/2$, or slope at x=0 is

$(3/4)\ \pi/2 = 67.5^0$

*Miroslav Sedlacek, Electron Physics of Vacuum and Gaseous Devices, Sec. 6.2 (1996).

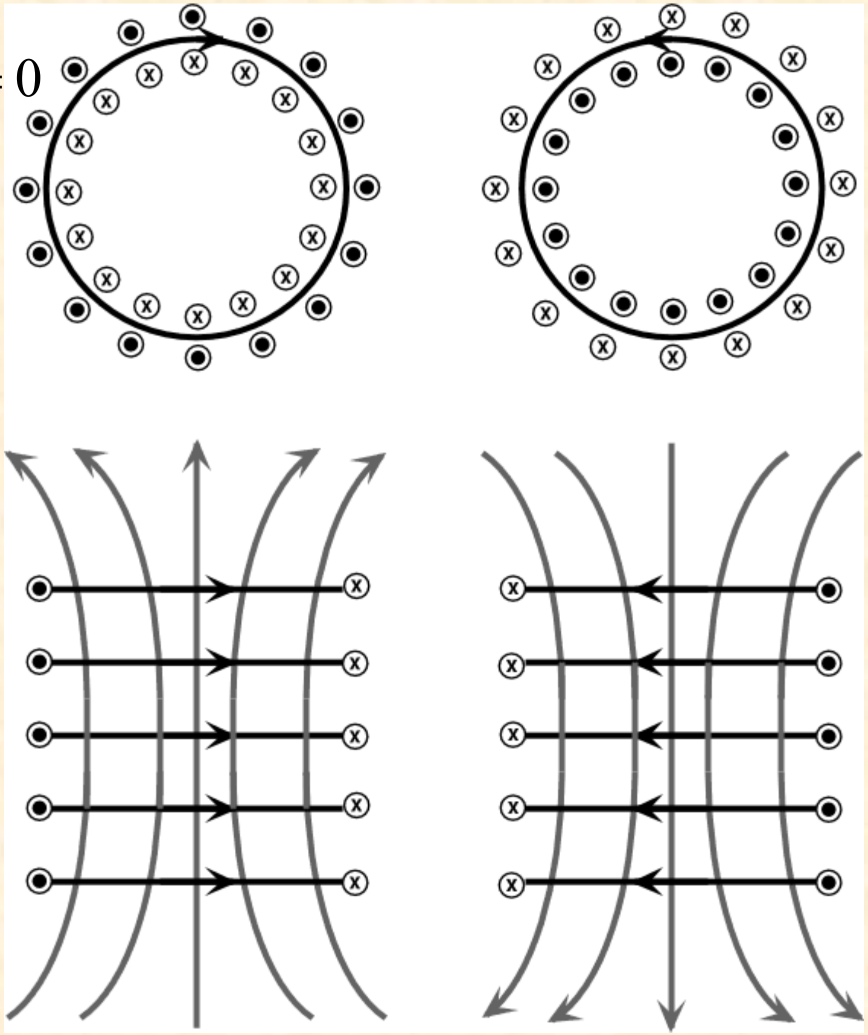
... and then?



- After the anode space charge effects are still present.
- It is not possible to use an electrostatic solution anymore.
- The compensating field must have a circular symmetry...
- This is not easy to achieve!

Compensating solenoid (1)

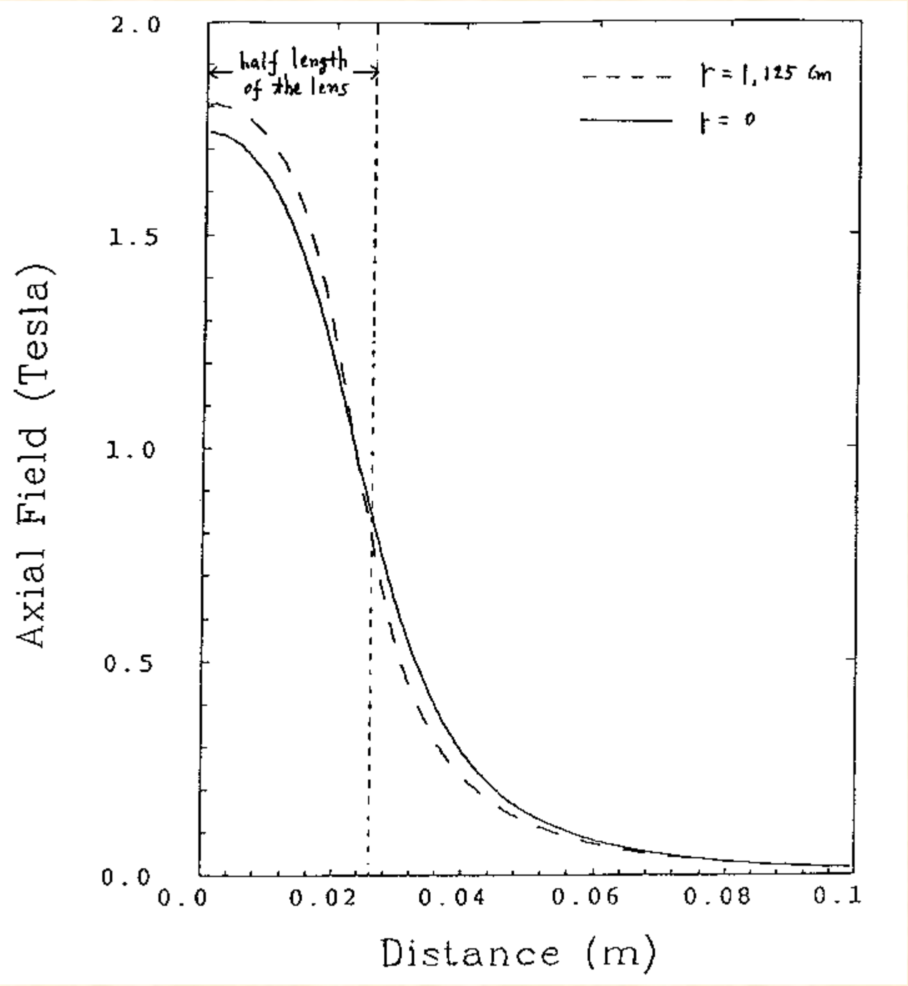
- The solution is to use a compensating solenoid. $\vec{F} = qv\vec{z} \wedge B\vec{z} = 0$
- Inside the solenoid the field is so that the angular momentum of the particles couples with the field.
- BUT at the edge of the solenoid the particles decouple from the field and receive a transverse kick (Busch theorem).



Busch theorem

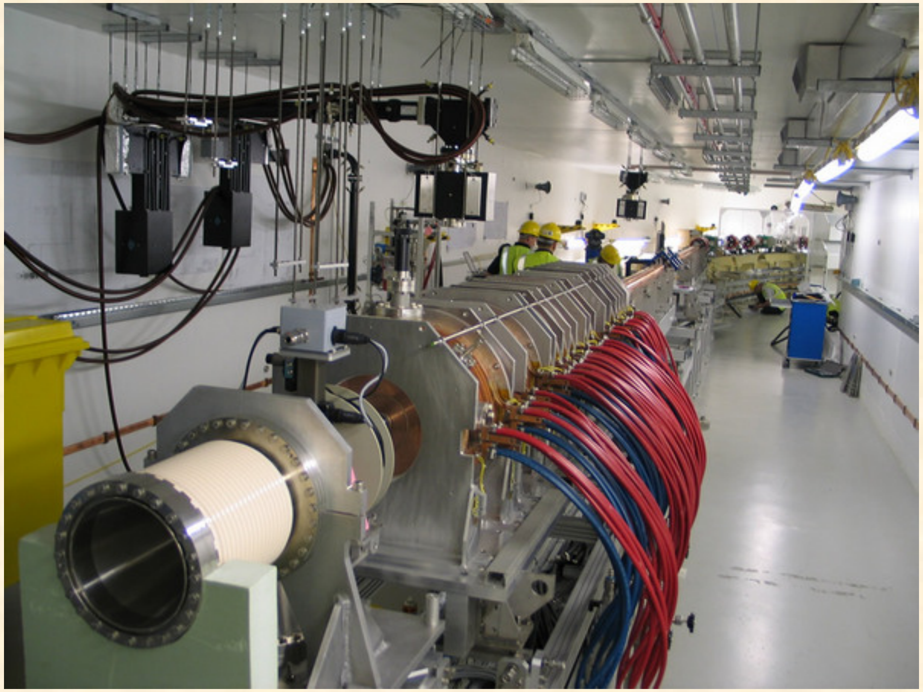
- Canonical angular momentum must be conserved.
- In a solenoid charged particles couple their transverse momentum to the field.
- At the edge of the solenoid the field suddenly decreases.
- To conserve the correct coupling the particles will be deflected toward more intense field (ie the middle of the solenoid)
- This will induce a focussing effect.

$$\Delta p_\phi = -\frac{q}{2} \int B$$



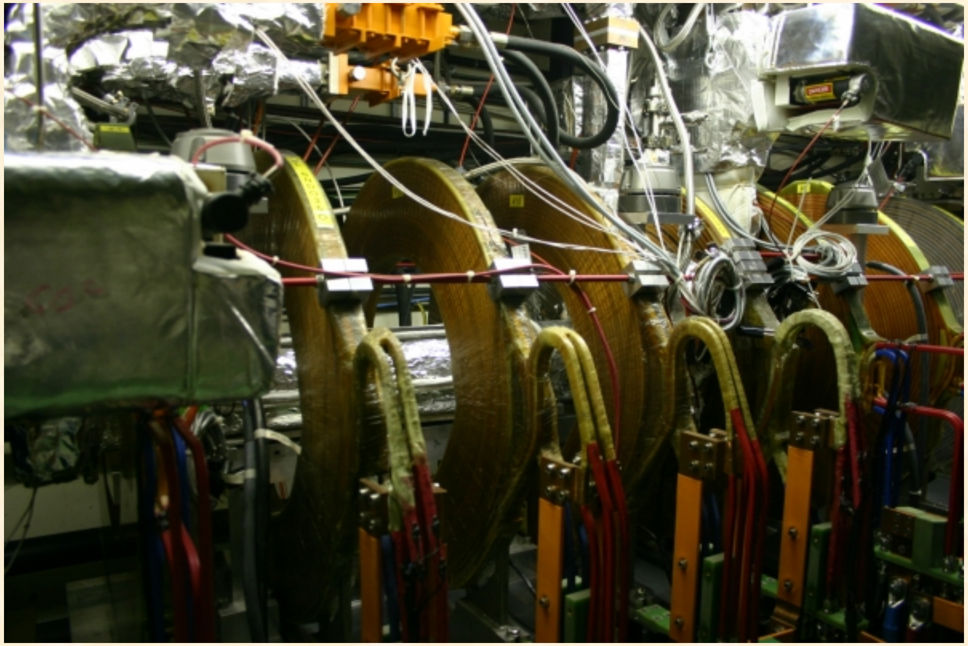
Compensating solenoid (2)

- To achieve the best compensation effect, several small solenoids are much better than a big one (as this maximizes the edge effect).
- This can be seen on this picture of the Diamond gun.
- Once high energies are reached the particles travel fast enough so that the space charge do not need to be compensated any more.



Quiz

- On this image of the CLIC injector the electrons travel from the left to the right.
- In which direction does the current flow in the solenoid to compensate the space-charge effect?



a) Clockwise

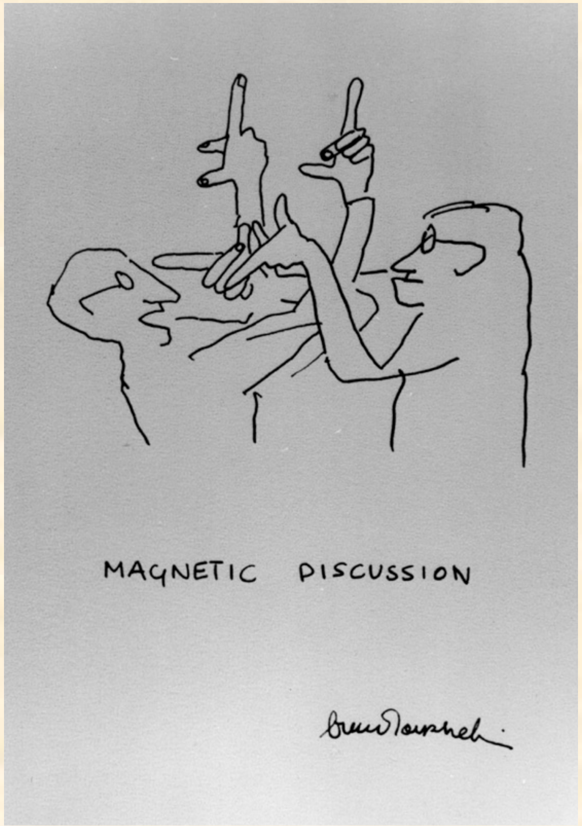
b) Counter clockwise

c) It does not matter

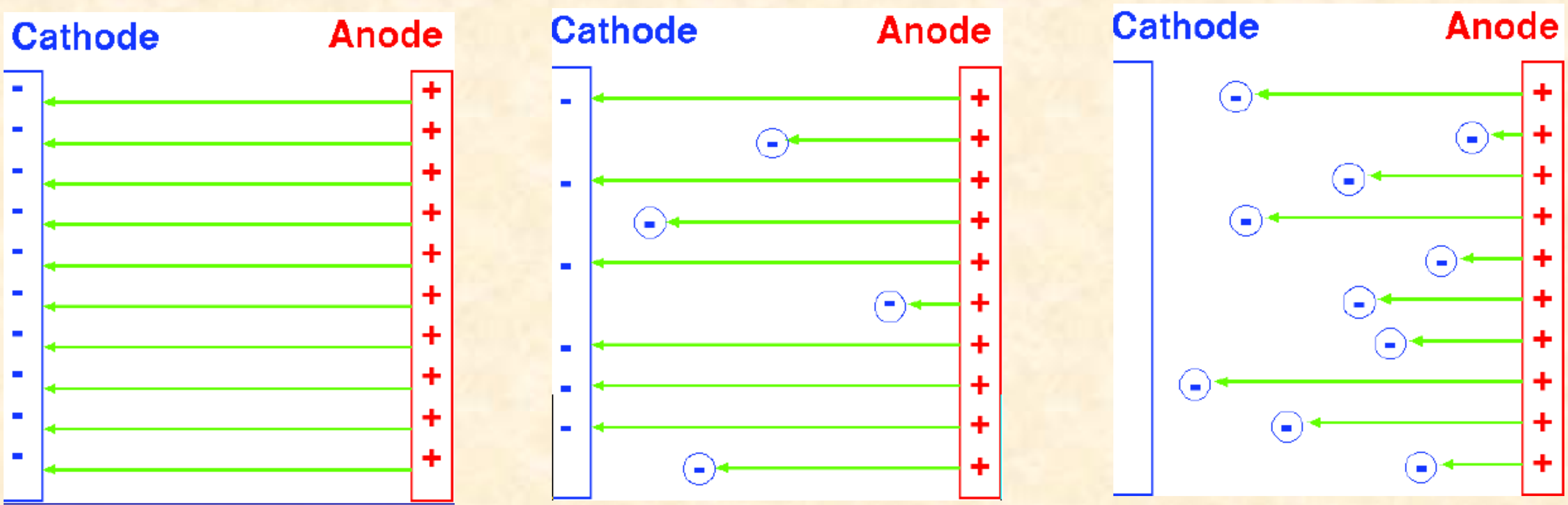
$$\Delta p_\phi = -\frac{q}{2}\int B$$

Answer: a

- Busch theorem: $$\Delta p_\phi = -\frac{q}{2}\int B$$
- To get a negative transverse kick the second term must be positive. $$\Delta p_\phi = -\frac{q}{2}\int B$$
- q is negative.
- So the flux must be positive.
- The electrons must travel in the direction of the flux.
- The current must circulate in a clockwise direction.



Space-charge limitation



(images source:Masao Kuriki, ILC school)

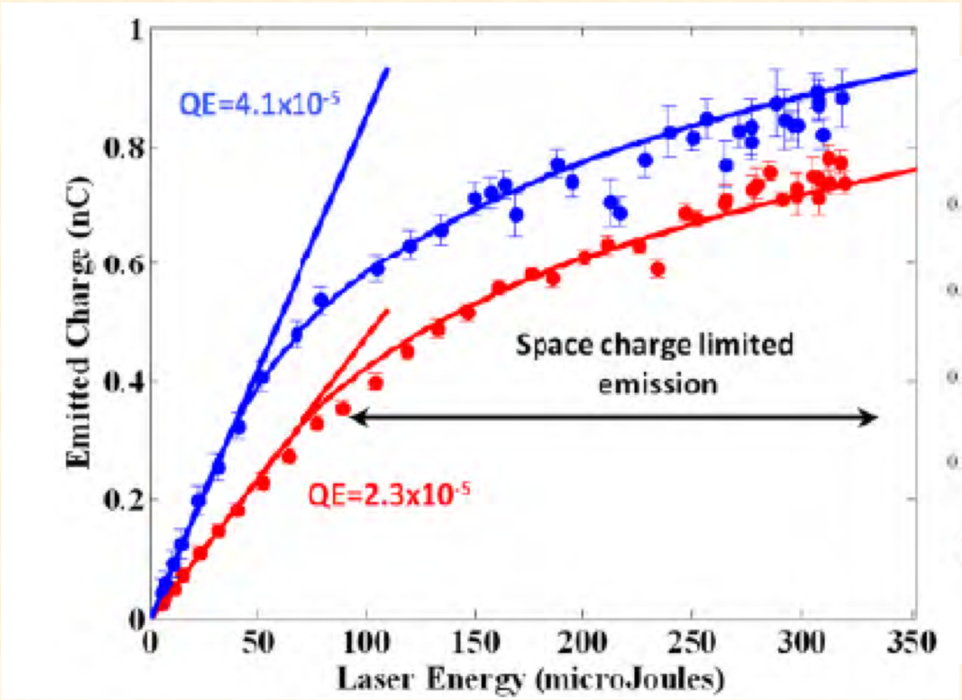
- Emitted electrons shield the cathode from the anode
  => reduced field
- This limits the intensity of the emission.
  Child-Landmuir law (potential Vd, area S, distance d)
  [This is more complex when the field is not constant]

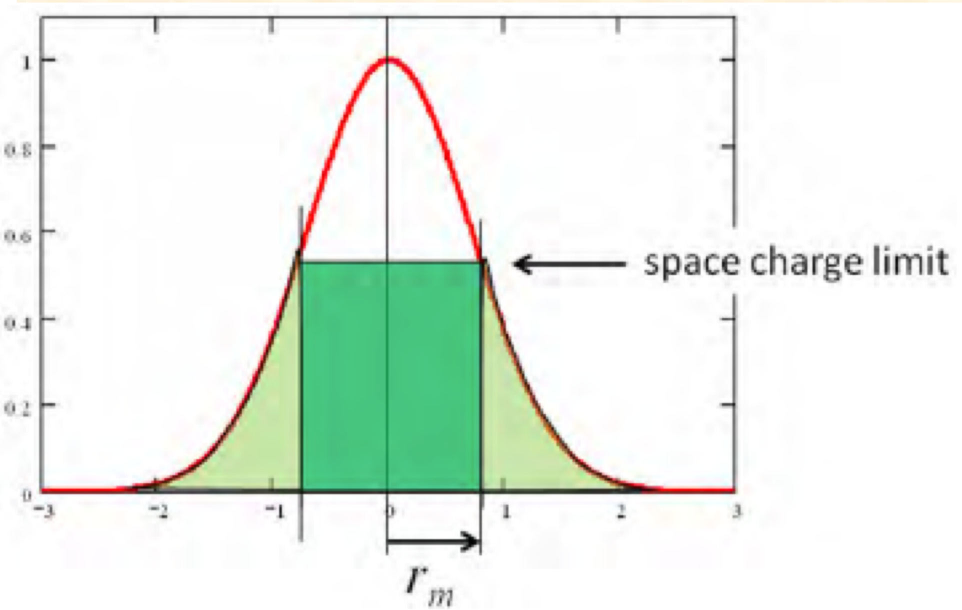
$$J = KS\frac{V_d^{3/2}}{d^2}$$

$$K = 2.33 \times 10^{-6} A.V^{3/2}$$

Space charge limited emission

An Engineering Guide to Photoinjectors, T. Rao and D. H. Dowell, Eds.

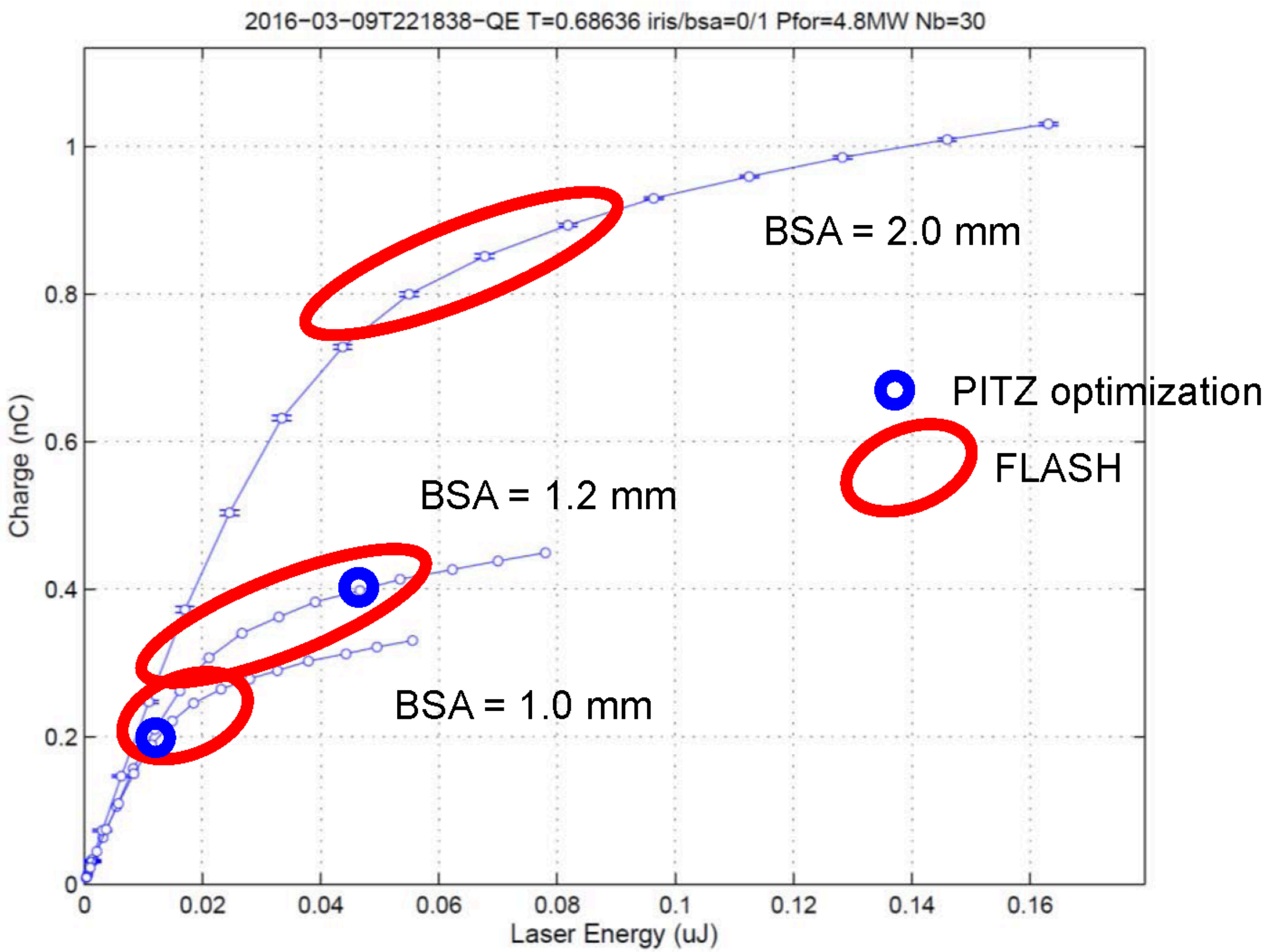




- In the case of a photo-injector the space charge with limit the intensity that can be extracted from the cathode.
- The charge extracted from the cathode will also depend on the shape of the laser pulse.

Typical Working Points

FLASH.
Free-Electron Laser in Hamburg

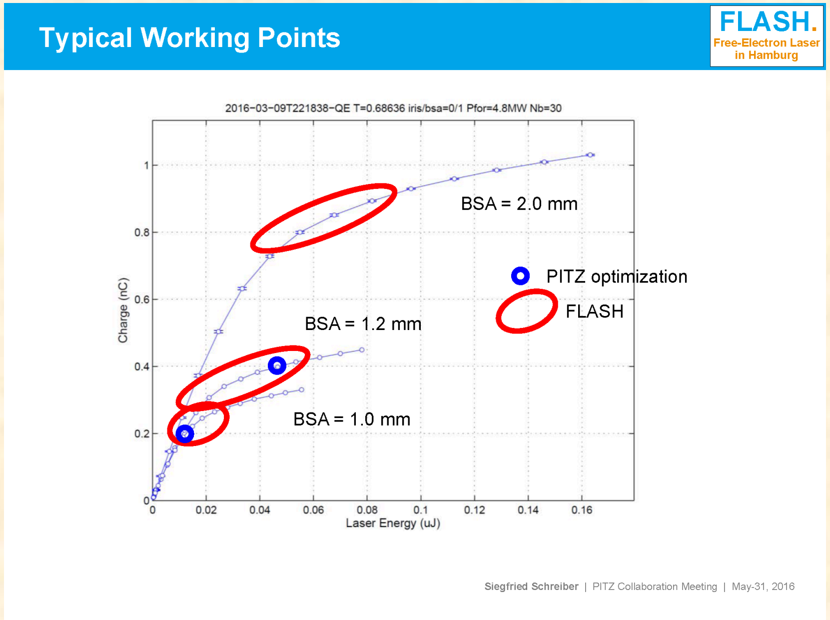


BSA= Laser beam diameter

Quizz:

Why the relation between laser energy and charge is not linear?

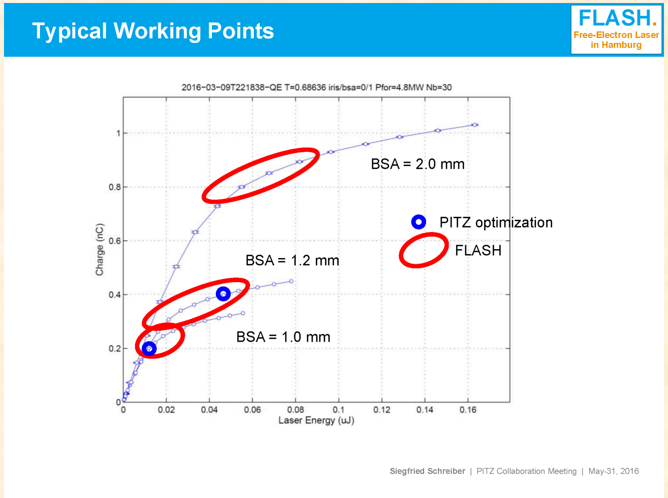
- (a) Because of space-charge.
- (b) Higher laser energy will induce more heating in the cathode and reduce the QE.
- (c) There is a trade off between laser energy and RF power.

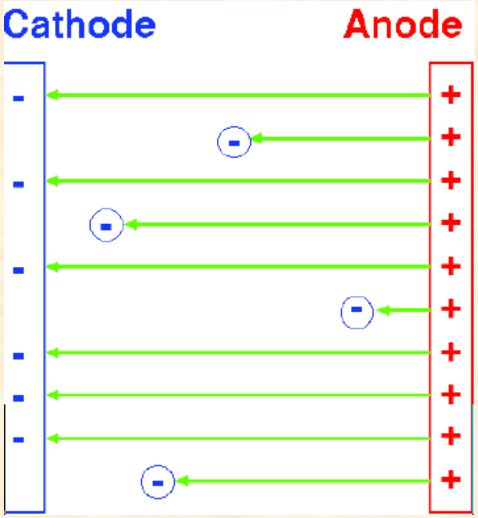


Answer (a)

Why the relation between laser energy and charge is not linear?

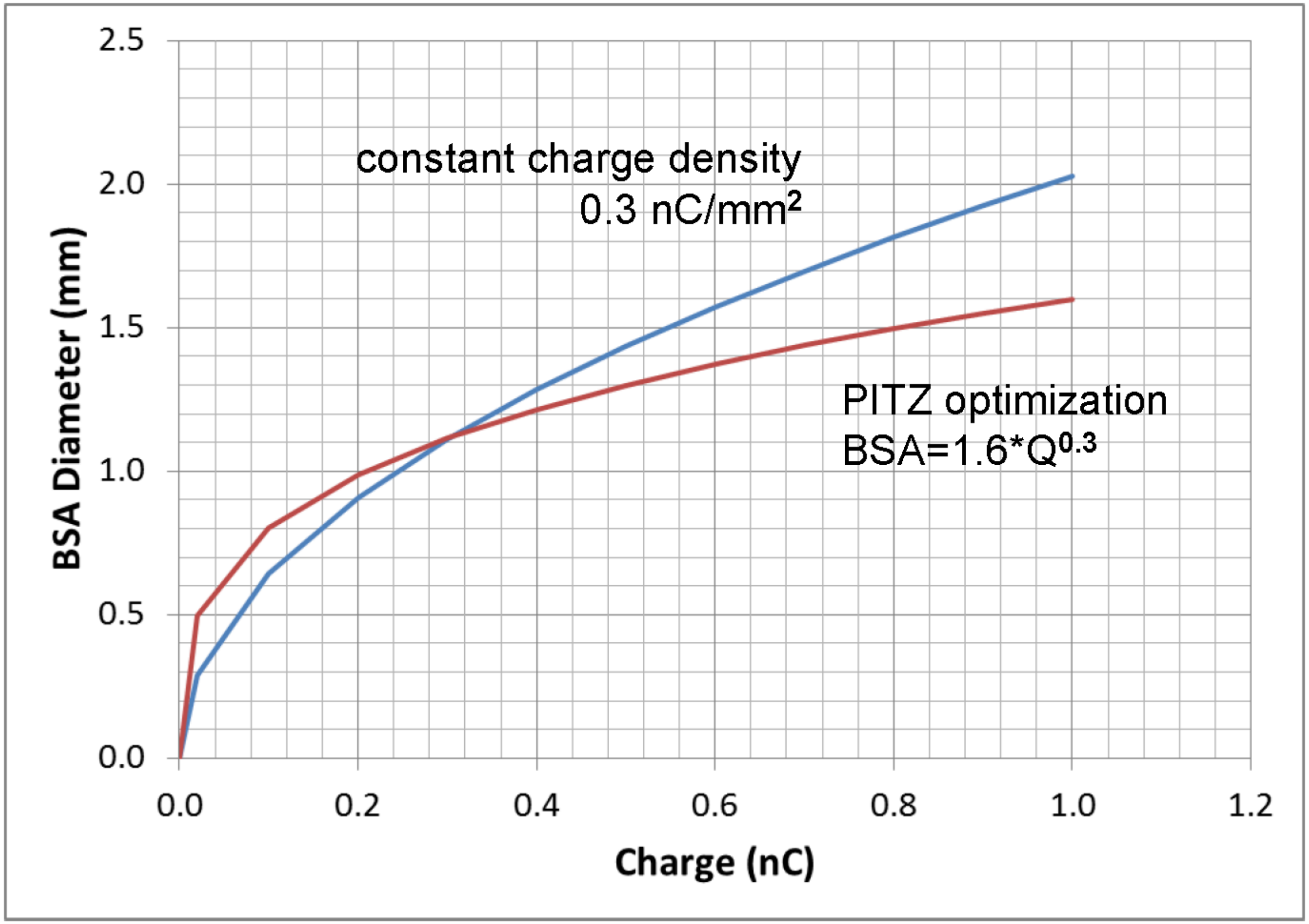
- (a) Because of space-charge.
- (b) Higher laser energy will induce more heating in the cathode and reduce the QE.
- (c) There is a trade off between laser energy and RF power.





Optimized Laser Spot Size vs Charge

- 1st approximation: keep charge density on cathode constant
- Change laser spot size (BSA) rather then laser energy



Quick introduction to emittance

- Remember the perfect gas law: PV=nRT
- This is a statistical law that is also valid for particle bunch.
- V is the volume term (x*y*z)
- P is the pressure term, it corresponds to the kinetic energy of the particles in each plane (x'*y'*z').
- n and R are proportionality terms (R is unit dependent and could be 1 with the correct choice of units).
- T is called the temperature for gas…
  For a particle beam it is called "emittance".
- You can split the emittance into longitudinal emittance (along z or s) and transverse emittance (along x and y).

$$\epsilon = xyzx'y'z' \qquad \epsilon_\perp = xyx'y' \qquad \epsilon_\parallel = zz'$$

Space charge and emittance

An Engineering Guide to Photoinjectors, T. Rao and D. H. Dowell, Eds.

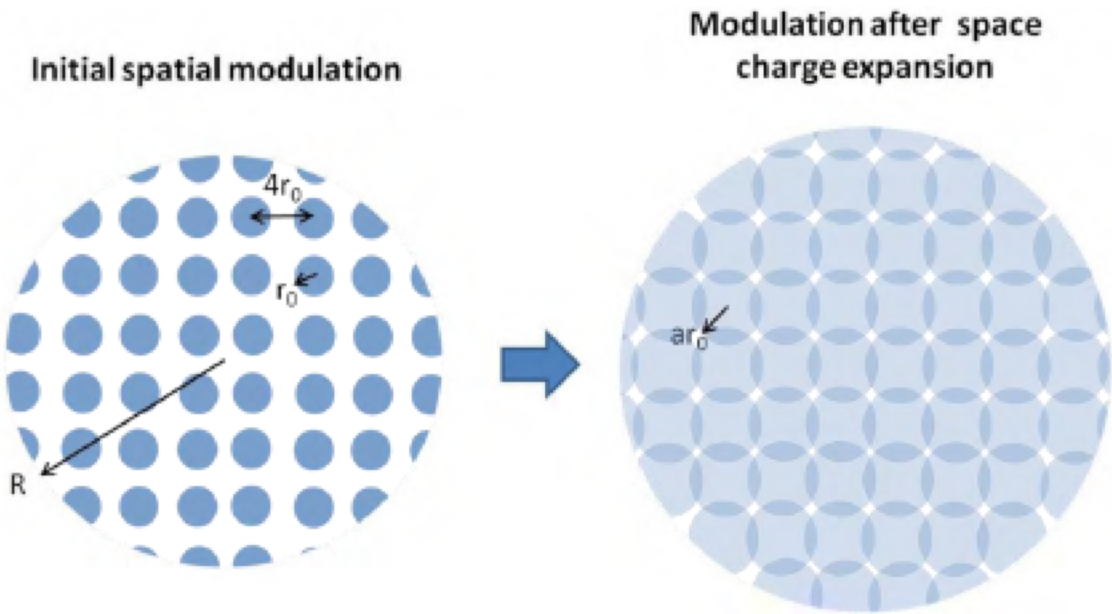


Figure 1.15. Modulation patterns used to compute the space charge emittance. Left: The initial pattern on the cathode consisting of a rectangular array of circles with radius r_0 and a spacing of $4r_0$ within a full beam radius R. Right: Schematic view of the beamlet pattern after expansion due to transverse space charge forces. The integration of the transverse force ends when the beamlets with radius ar_0 begin to overlap and form a quasi-uniform distribution.

- Space charge will lead to an increased emittance => lower beam quality.

Emittance compensation

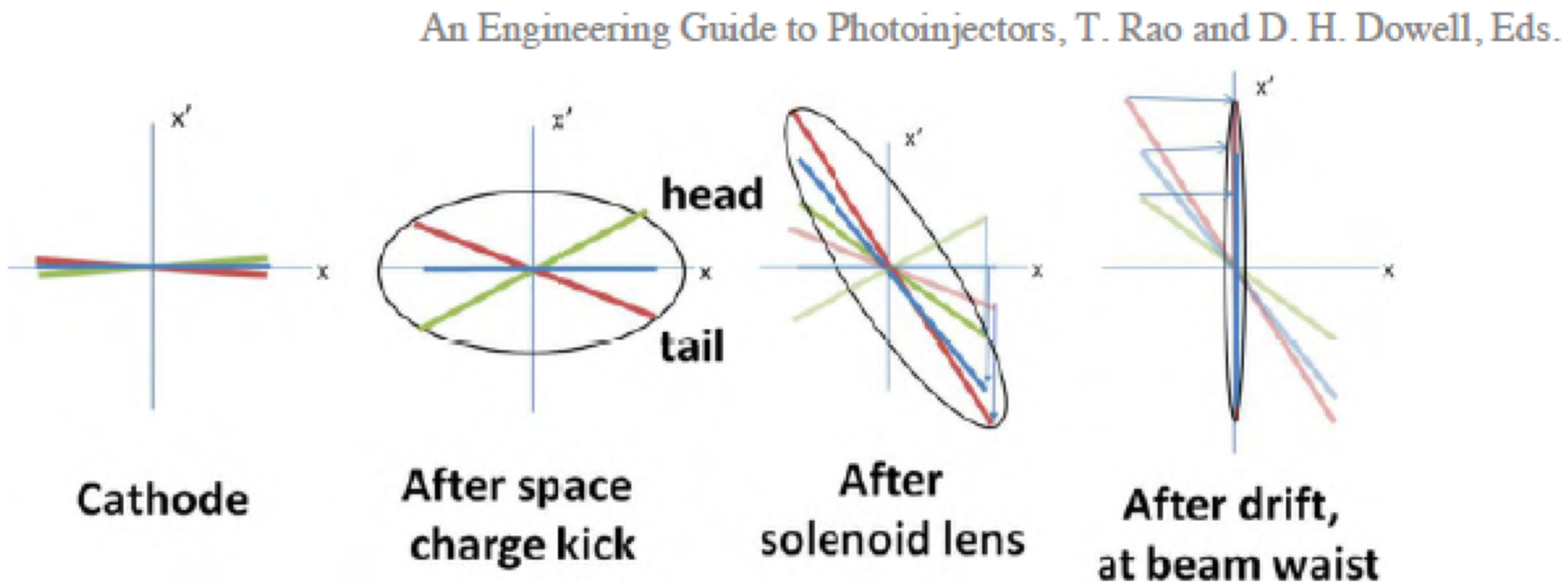
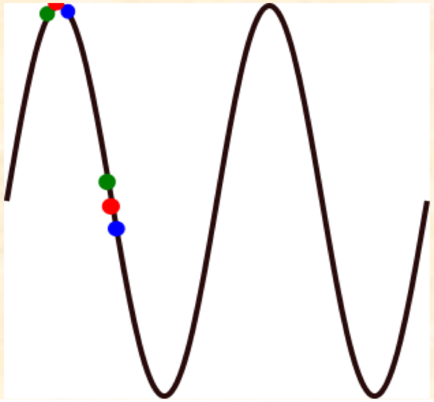


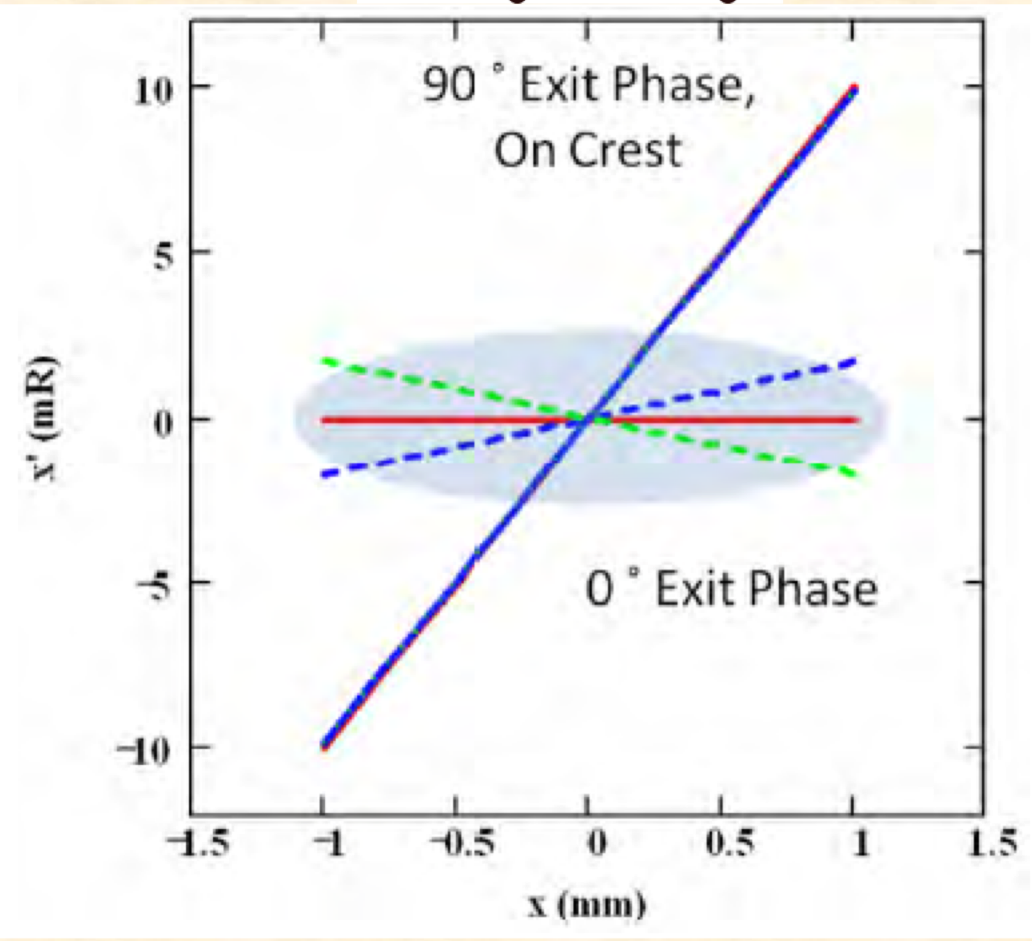
Figure 1.18. Transverse phase space dynamics during emittance compensation. The transverse phase space is shown for different slices along the bunch. The bunch head slice is shown as a green line, the tail slice is red and the center slice is blue. An ellipse has been drawn around the three slices to indicate the projected phase space of the three slices.

- By calculating how the different slices of the beam will propagate in the gun on can minimise the emittance at the exit of the gun.

Transverse dynamics in the gun

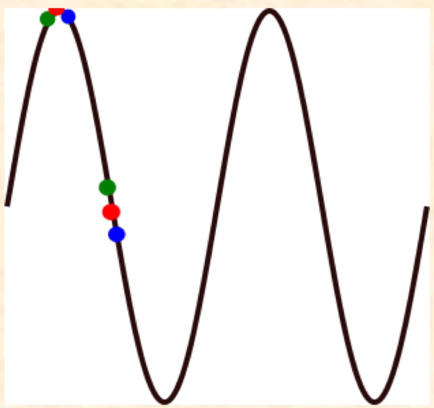


- The emission from the cathode lasts a finite time.
- During that time the RF phase varies.
- Hence the head and the tail of the bunch will experience slightly different acceleration.



Longitudinal dynamics in the gun: velocity bunching

- After the cathode the electrons are not yet relativistic.
- Electrons with more energy will go faster.
- Depending on the phase at which the particles will be produced, the bunch at the exit of the gun can be longer, shorter or have the same length than the initial laser pulse.



Summary for beam dynamics

- The electrons emitted by the gun interact with each other.
- This must be taken into account when trying to optimise the gun.
- Space-charge is one of the dominating effect, but the different phases at which the particles are generated must also be taken into account.
- All these effects, once understood, can be simulated and, sometimes, mitigated.

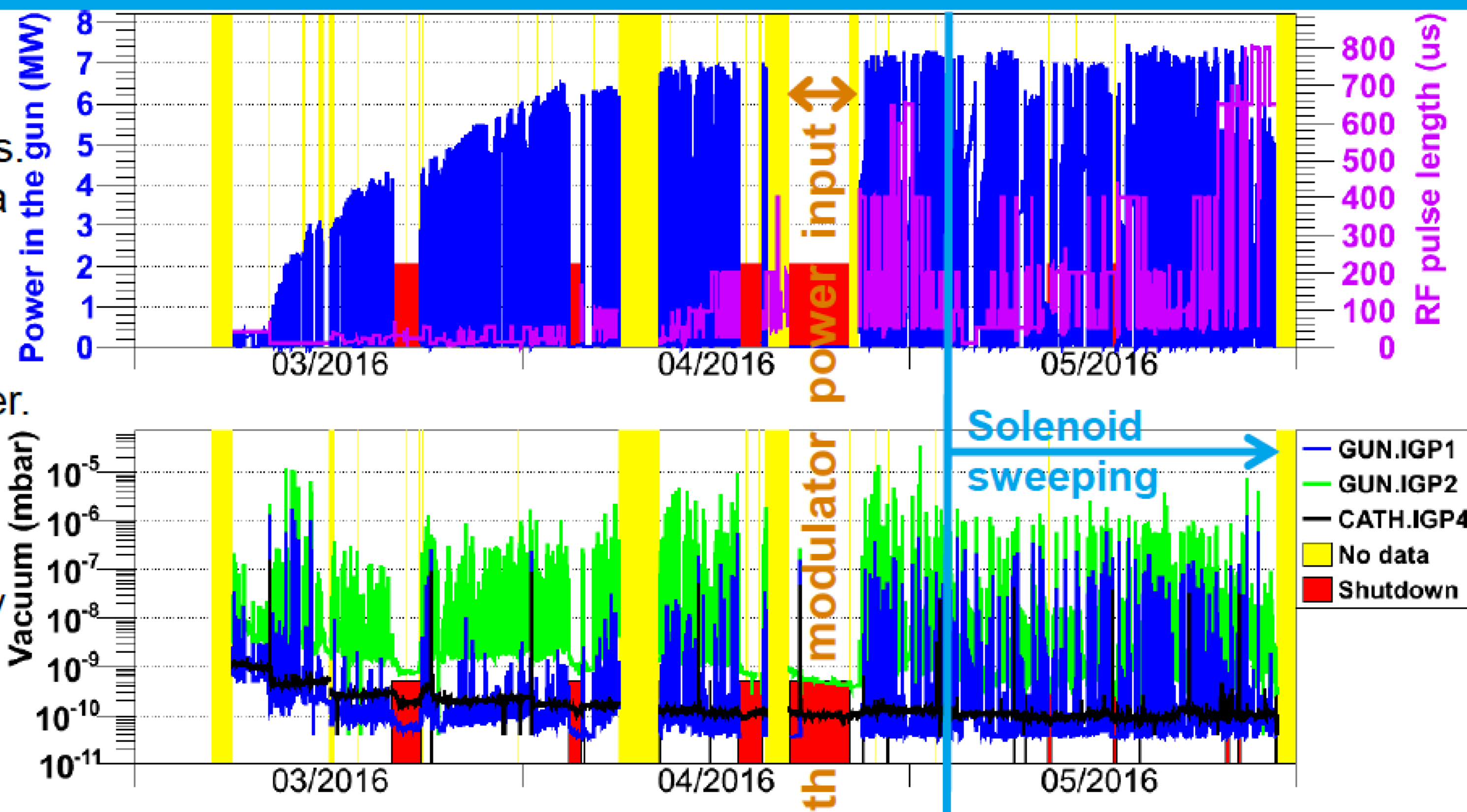
Gun conditionning

- The gun must be conditionned to accept the full RF power.
- During conditionning small impurities and surface defect are burnt out.

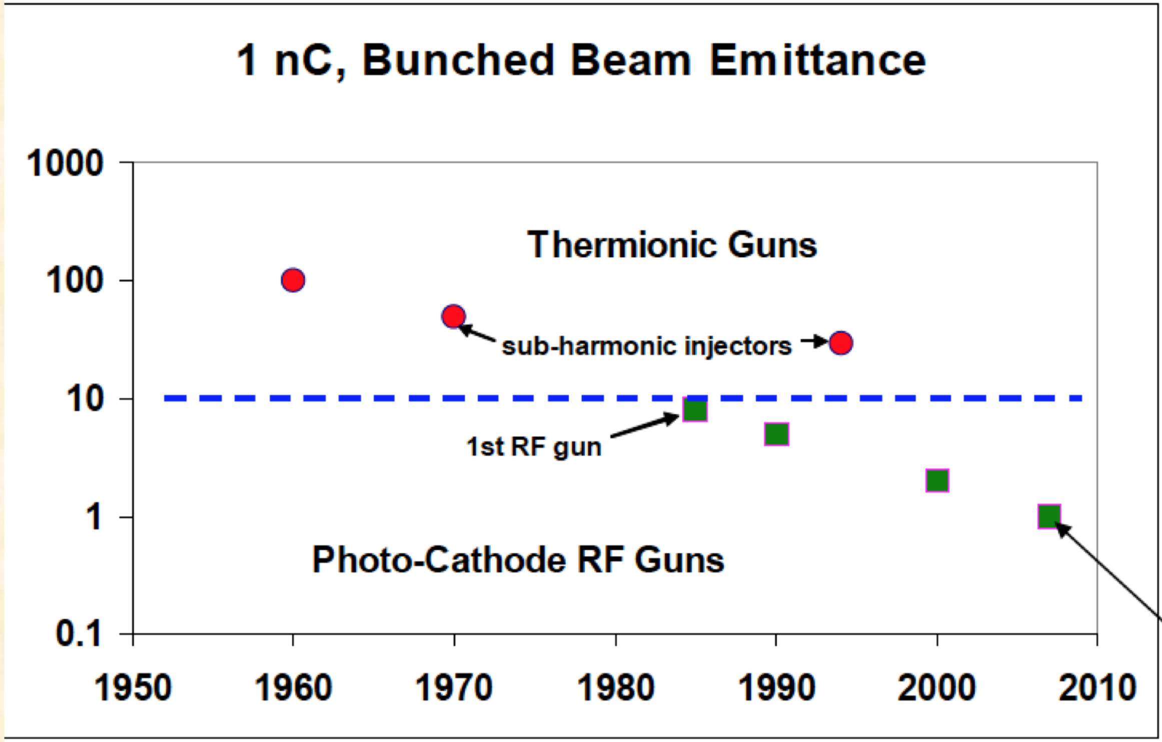
Conditioning history of gun 4.6 (from 07.03 to 23.05.2015)

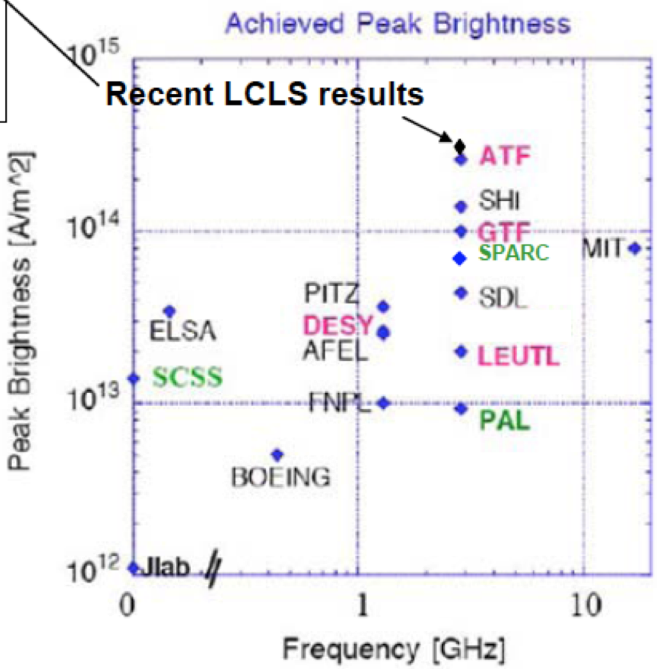
- ~1 month to reach full power @100 us.
- Conditioning was a little slow, but everything is new: gun, directional coupler, T-combiner.

- Vacuum improves continuously.
- No vacuum activity at the cathode.



Evolution of Beam Quality





Rossendorf SRF Gun

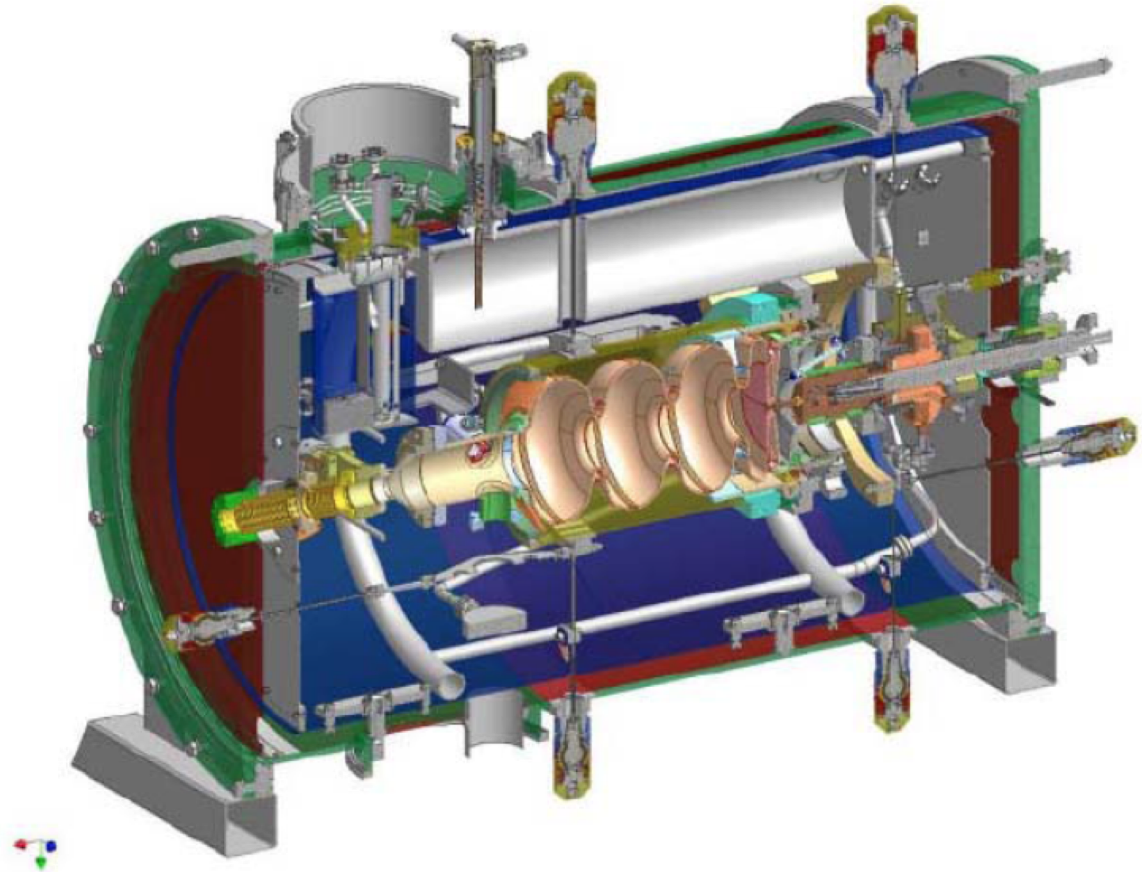


Figure 1: 3-D view of the SRF gun cryomodule.

Examples and classification of injectors

Emission & Initial Acceleration

- Thermionic cathode
  - Gridded-DC gun
  - DC gun
  - NCRF gun
- Photo-electric cathode
  - DC gun
  - NCRF gun
  - SRF gun
- Field-emission cathode
  - Pulsed-DC
  - RF
  - Pulsed-DC+ NCRF

Beam Conditioning

- Emittance compensation
  - Solenoid focusing
  - RF focusing
  - Slice phase space matching
- Ballistic compression
  - Fundamental & sub-harmonic RF
  - Inductive linac
- Magnetic compression
  - RF harmonic linearizing
- RF compression
  - Solenoid focusing
  - Tapered RF phase bunching

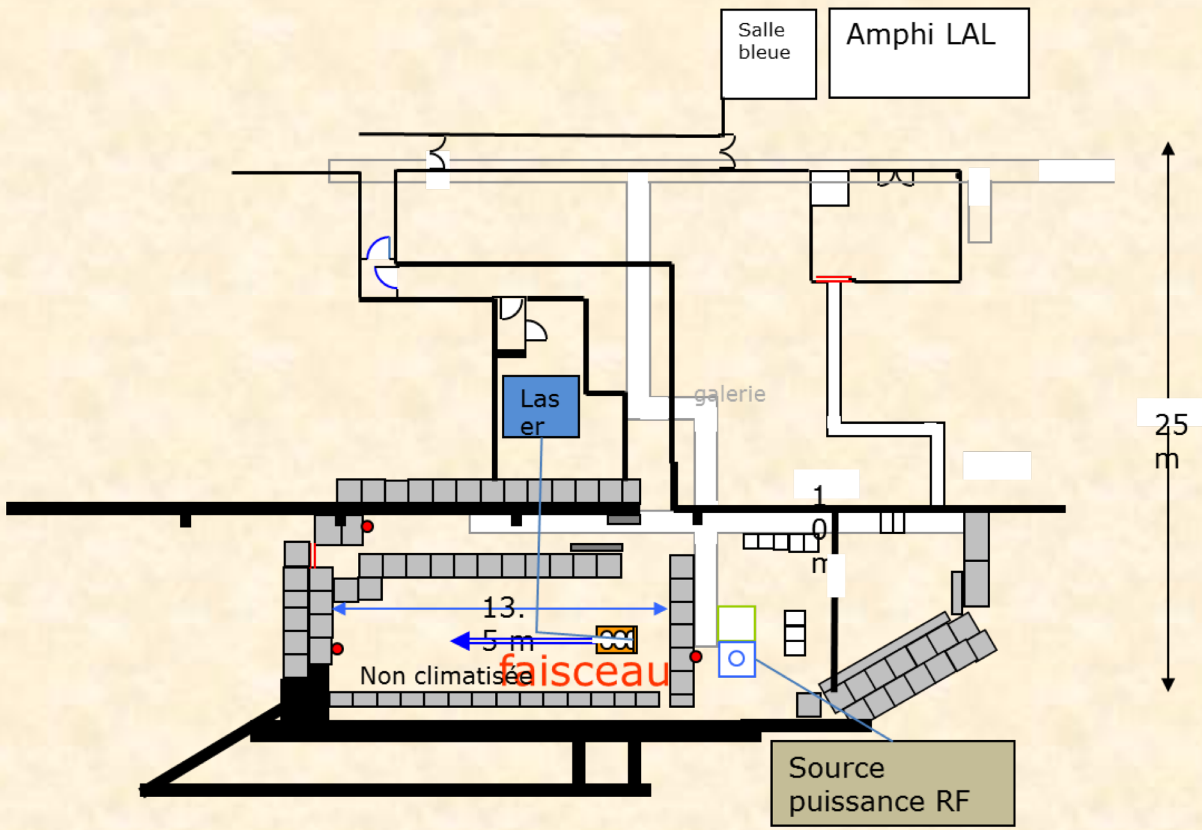
Acceleration

- Capture into booster
- Emittance preservation
- Longitudinal phase space compensation
- Chirping for bunch compressors

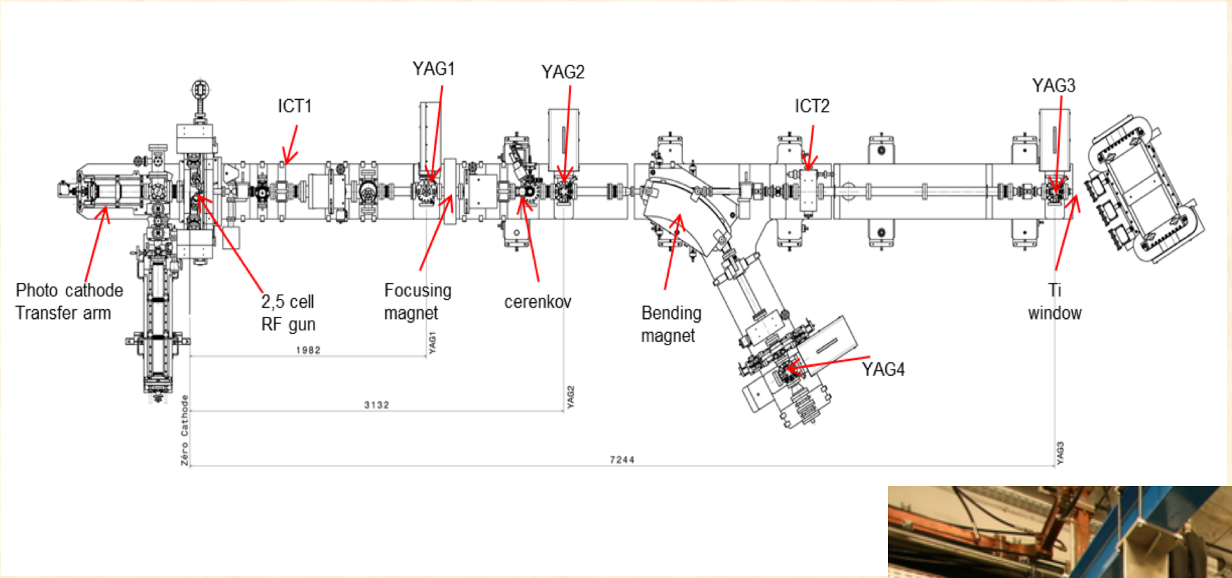
High Brightness Electron Injectors for Light Sources - January 14-18 2007

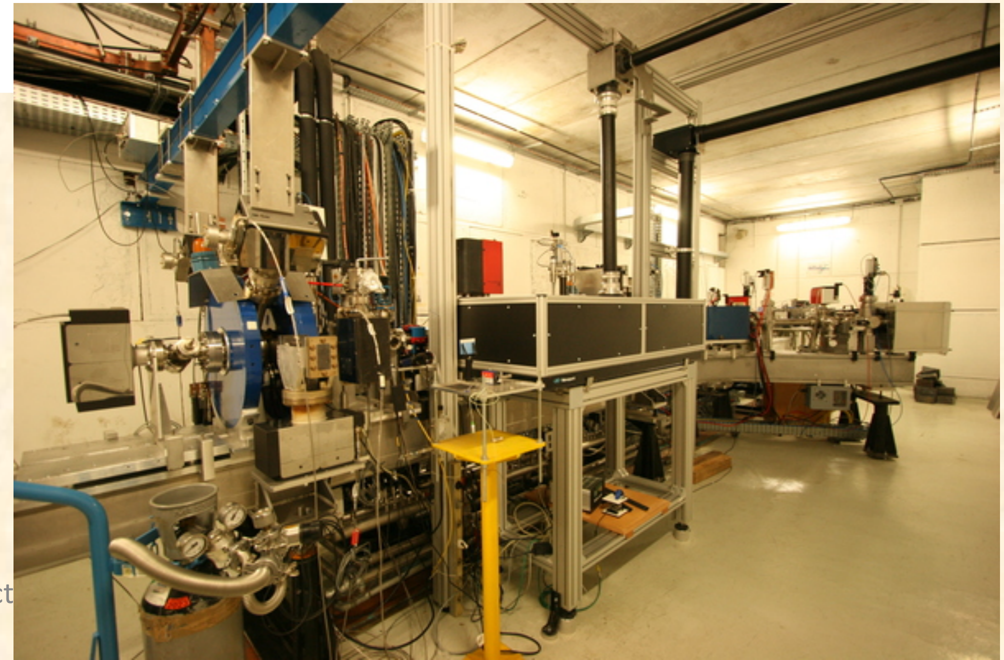
Lecture 11
D.H. Dowell, S. Lidia, J.F. Schmerge

PHIL: Photo injector at LAL: Overall layout

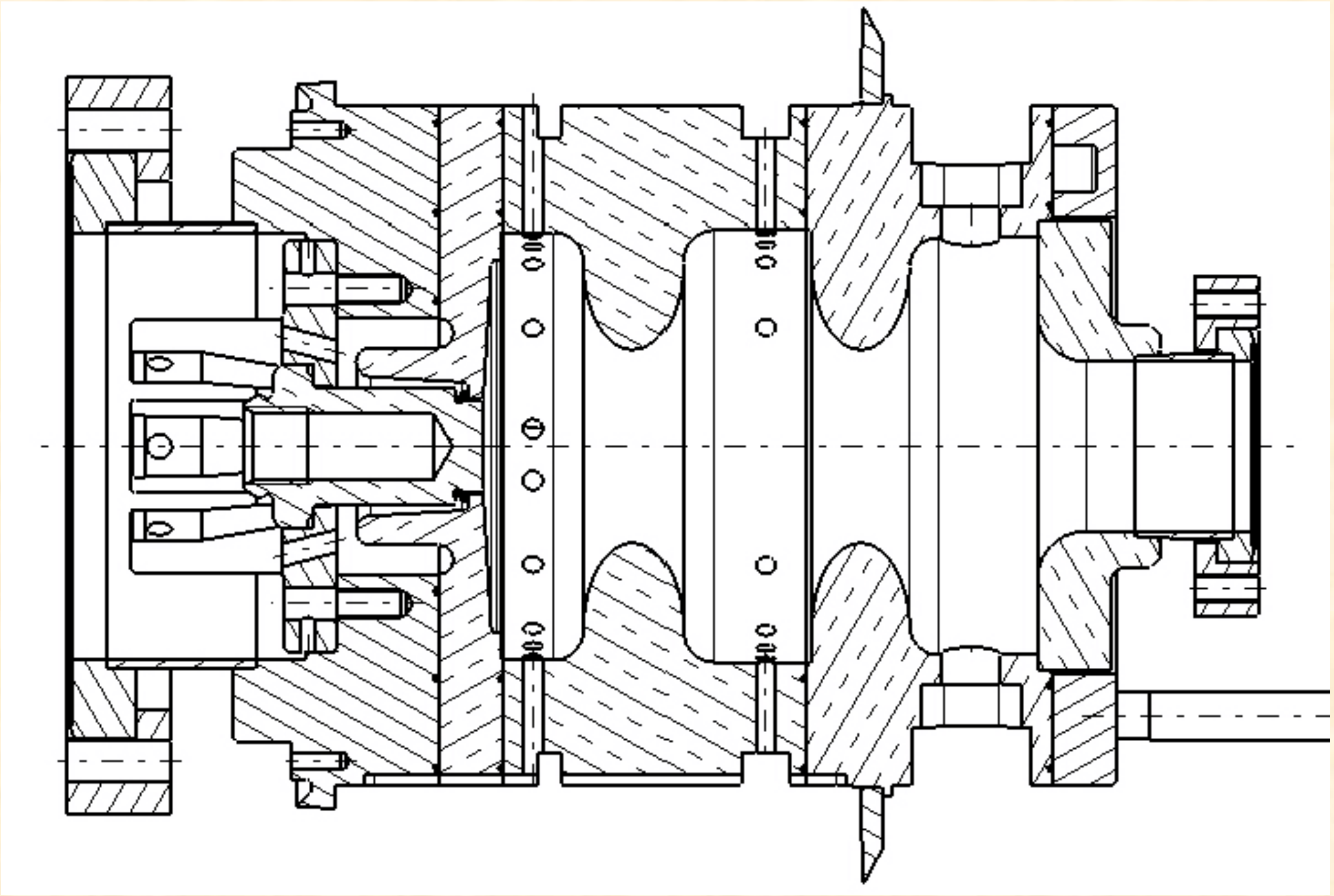


PHIL: Photo injector at LAL: The accelerator



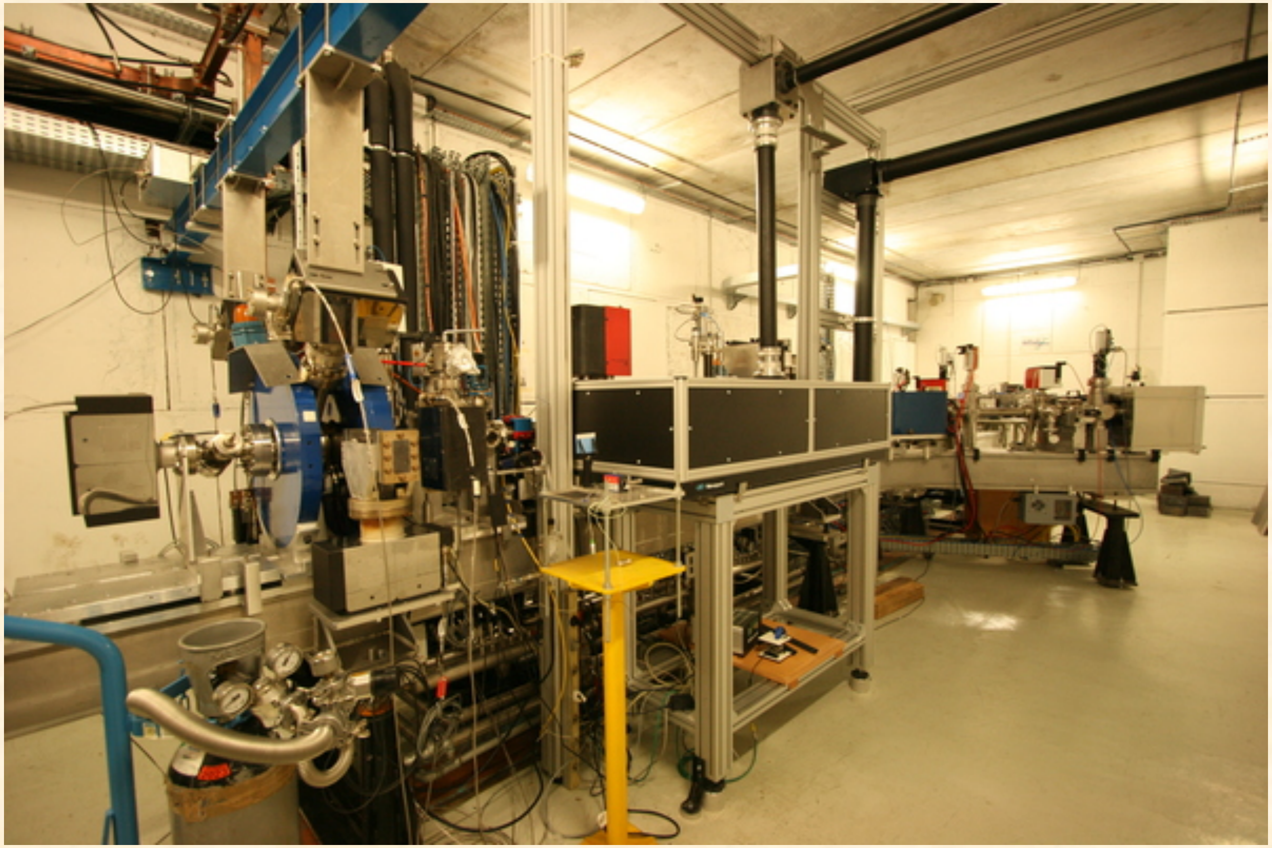


PHIL: Photo injector at LAL: The Gun

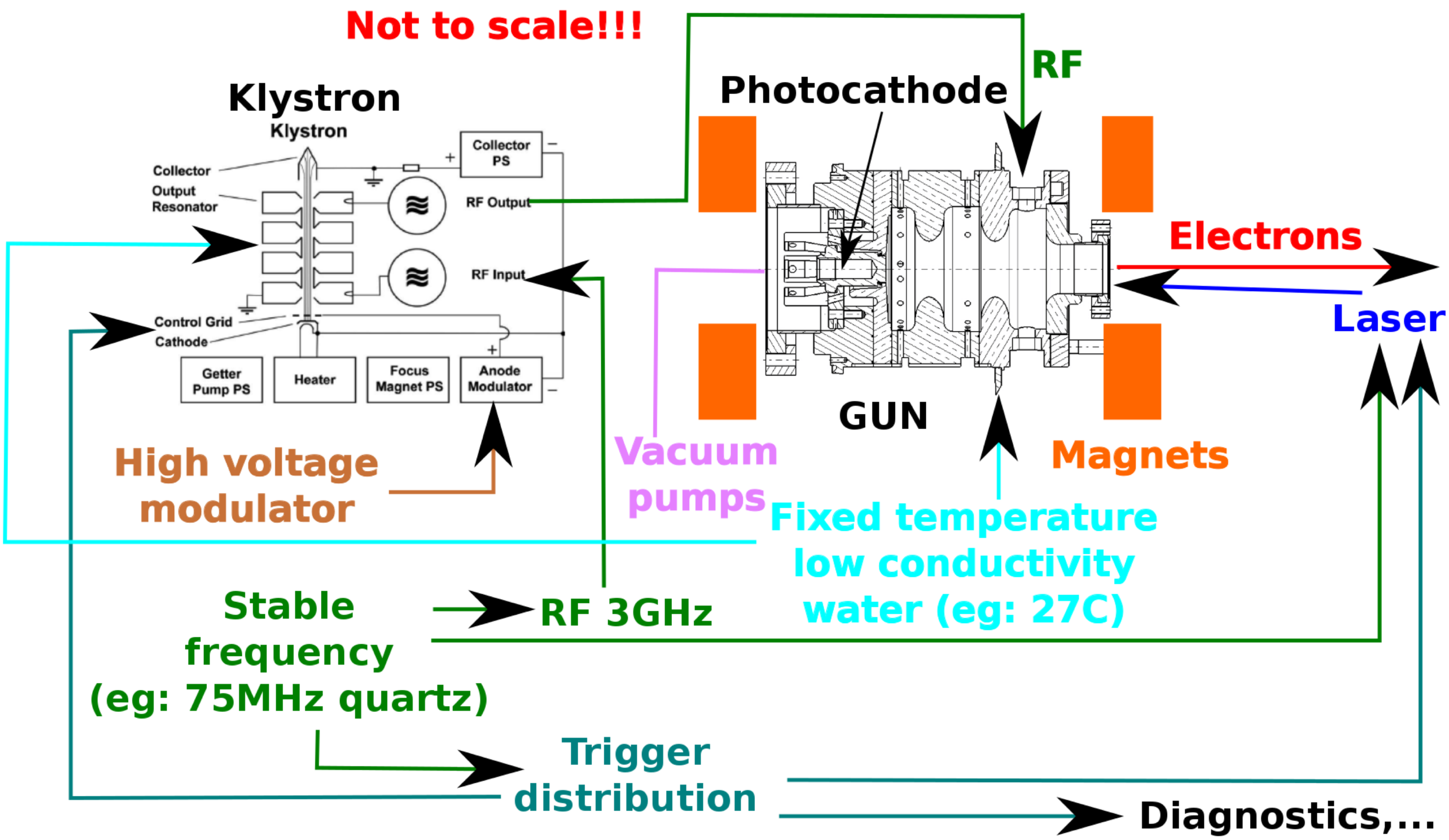


Quizz

- What do you need to build a photoinjector? List the main components…



To build a photo injector you need:



Summary

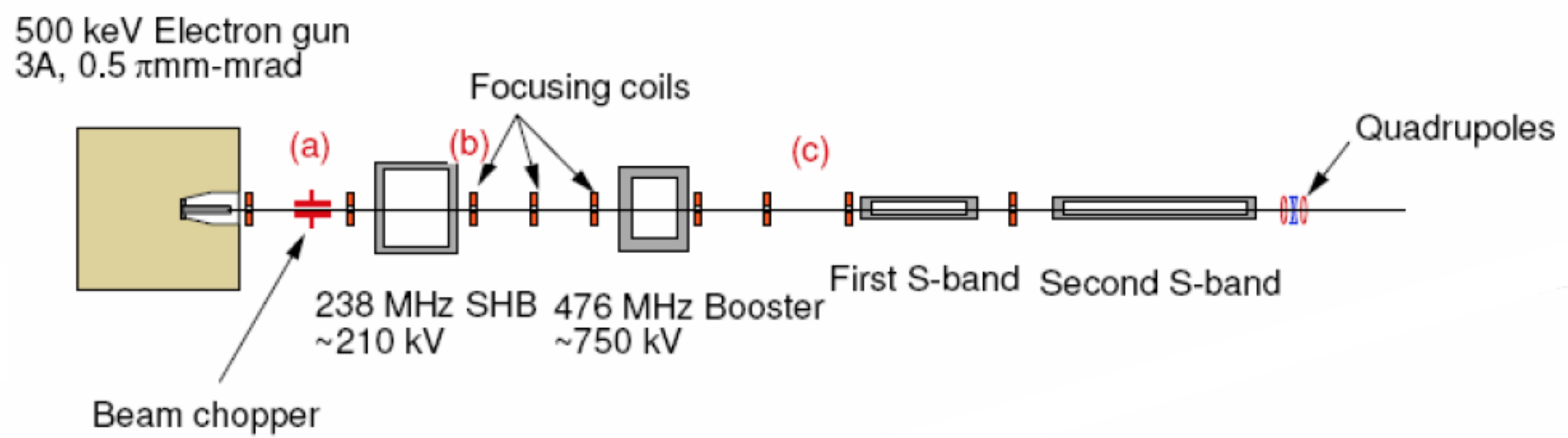
- 3 effects can be used (or combined) to produce electrons: thermionic, schottky and photoelectric.
- Careful design is necessary to reach high electric field.
- To reach the best beam for the application one also need to take into account the dynamic of the particles in the gun (and after).
- There is a large variety of electron gun (current, emittance, rep. rate,…) suited to different applications.

Recommended readings
(and credits for some of the material used in this lecture)

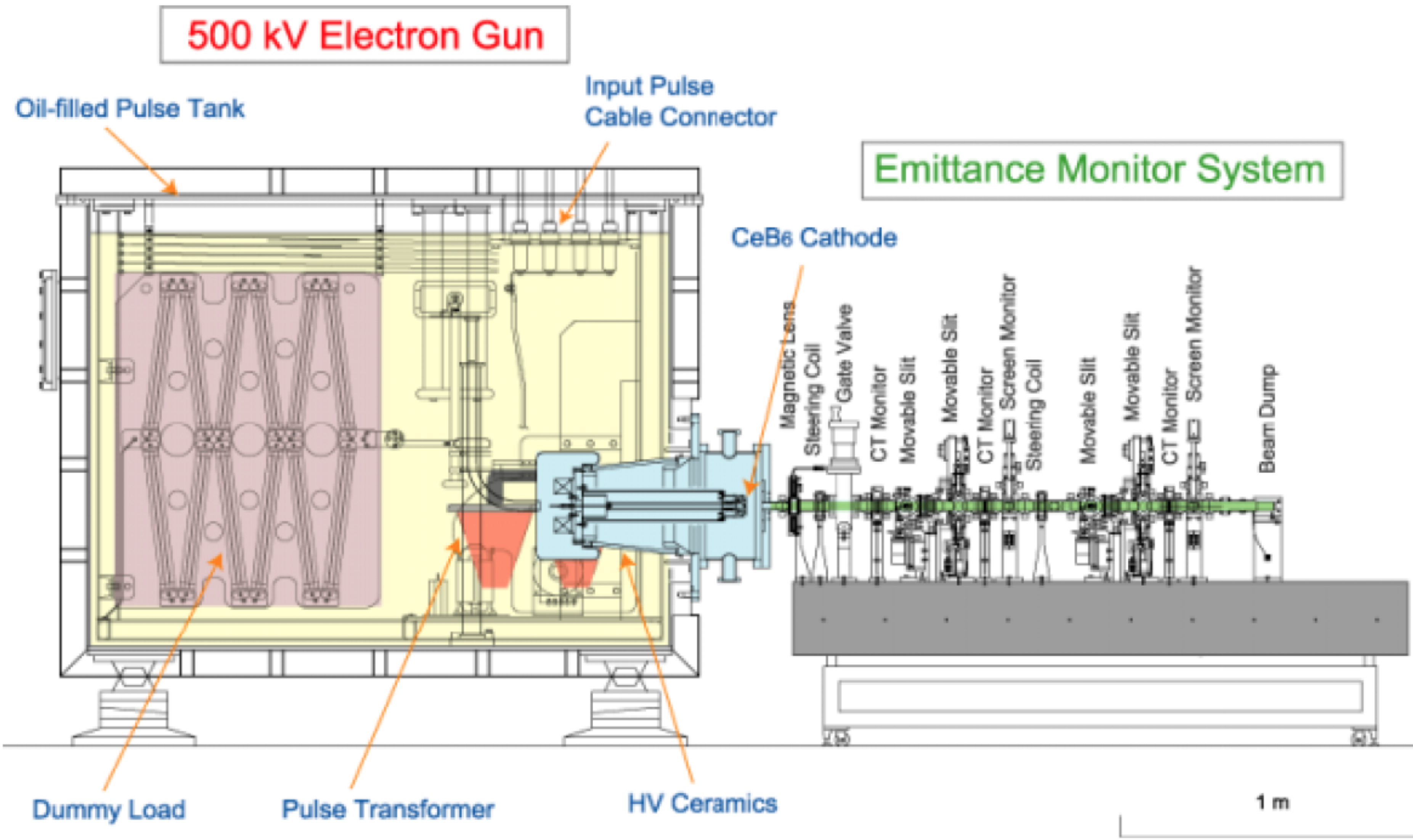
- USPAS course on particle sources D.H.Dowell et al.
- USPAS Course on High Brightness electron injectors, 2007
- An Engineering guide to Photoinjectors, T. Rao and D.H.Dowell

SPring8 SCSS Injector (1)

- *The contemporary version of the thermionic injector is represented by the system for the SPring8 Compact SASE Source (SCSS) XFEL. Due to the increased emittance from a grid, this cathode emits continuously during the 500kV HV pulse with the pulse structure determined by a chopper cavity. The test stand for the gun is shown, consisting of the HV tank and the diagnostics beam line. The injector system architecture is reminiscent of the previous generation of thermionic injector described earlier. Replacing the grid with a chopper eliminates a large source of emittance from the grid itself. (see Pierce and CLIC paper) This design also uses two stages of sub-harmonic bunchers but does not have a rf/velocity compressor cavity.*



SCSS Thermionic Gun



SPring8 SCSS Gun Parameters

Table 1: Gun Parameters

Beam Energy	500 keV
Peak Current	1~3A
Pulse Width (FWHM)	2 μsec
Repetition Rate	60 Hz
Cathode Temperature	1400~1600 deg.C
Cathode Diameter	3mm
Theoretical Thermal Emittance (rms)	0.4 πmm.mrad
Measured Normalized Emittance (rms, 90% particles)	0.6 πmm.mrad [7]

- ***"Graphite Heat Optimized for a Low-Emittance CeB6 Cathode," K. Togawa et al., Proc. of PAC07***

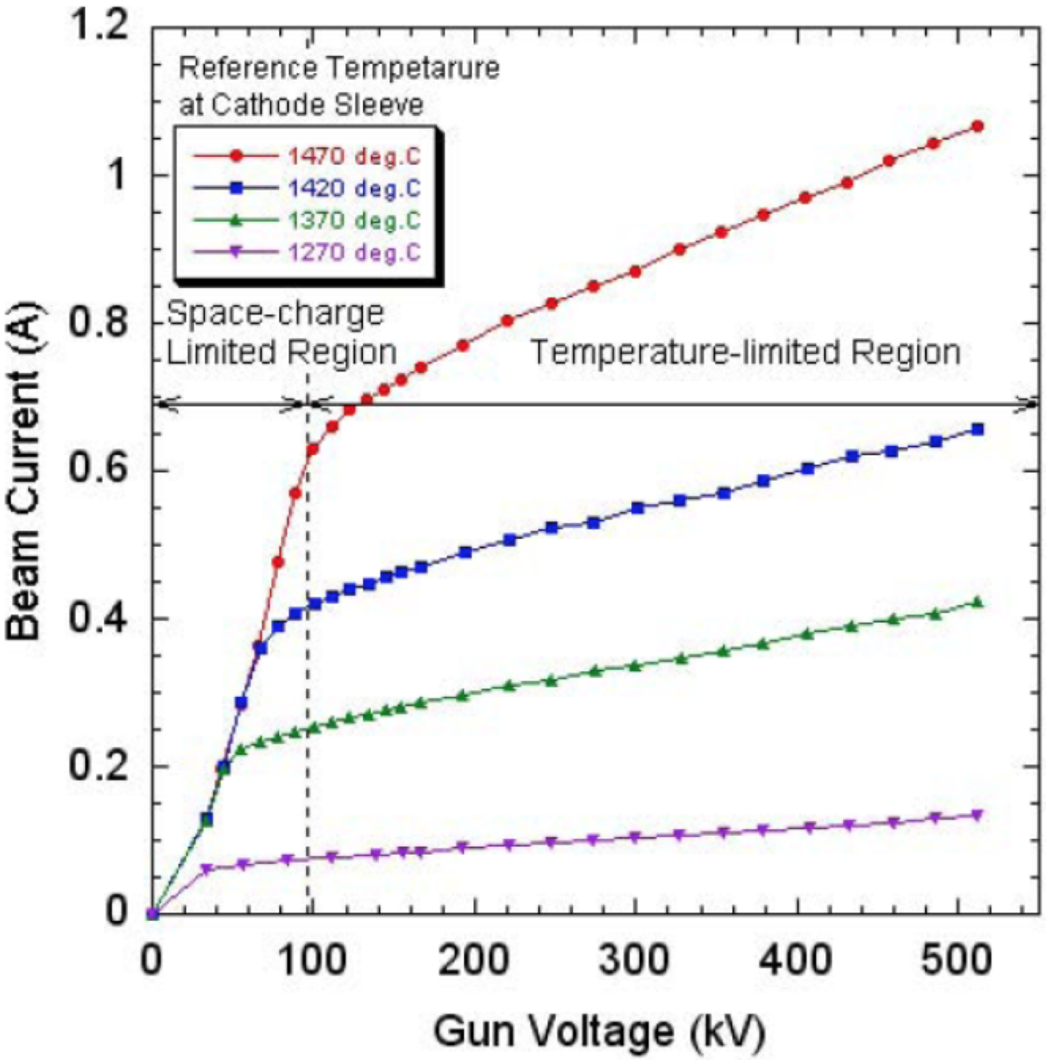
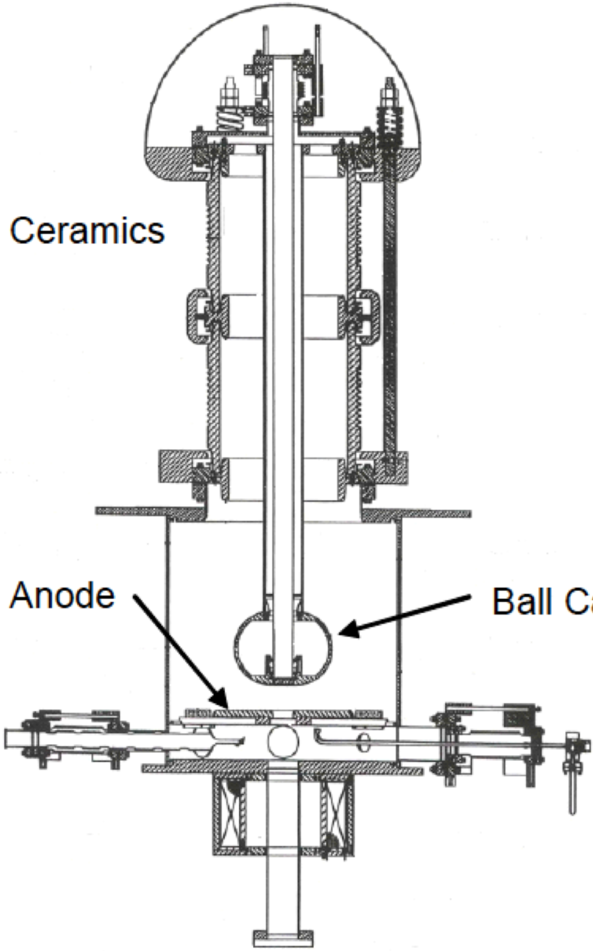


Figure 5: Beam current –voltage characteristics of the CeB_6 electron gun.

DC Photocathode Guns and GaAs(Cs) Cathodes

- *The DC photocathode gun was first developed as a source of polarized electrons for high-energy physics experiments. The cathode material was and remains cesciated gallium arsenide, GaAs(Cs), which produces polarized electrons with the same helicity as that of the incident laser photons. Polarizations greater than 90 percent have been achieved from sophisticated wafers consisting of alternating layers of epitaxially grown structures gallium and arsenic. These negative electron affinity (NEA) cathodes have high quantum yields of a few percent at near IR and visible wavelengths, and the lowest measured thermal emittances.*
- *The disadvantages of GaAs(Cs) are their sensitivity to vacuum contamination, requiring better than 10-11torr, and slow emission time. The electron temporal response exhibits a long tail of 10's of ps on the falling side of the pulse, which is dependent upon how far from within the material the electrons are extracted. The slower temporal response also related to the cathode's charge limit. The low electron mobility limits the flow of electrons needed to replenish the emitted electrons. The DC gun is well suited to this type of cathode because, firstly it has a very open and easily vacuum pumped volume, and secondly the accelerating fields are truly constant.*

Jefferson Lab DC Photocathode Gun



- *A DC photocathode injector for free electron lasers is used in the Jefferson Laboratory IR-kilowatt FEL. The HV gun assembly is a direct descendent of the polarized gun first built at SLAC for polarized electrons and a copy of the polarized e-gun used for the Jefferson Laboratory nuclear physics programs. However it has been modified to adapt it for the CW operation in two ways. The cathode stalk has been tailored to a specific surface resistance by using ion implantation. And the ball electrode has been modified to allow withdrawing the cathode inside for re-cessiation, to keep cesium from reaching the HV surfaces, which greatly shortens the HV processing time after a re-cesiation of the cathode. The HV limit of 350 kV for reliable operation and to 500kV (unreliable) in this design appears to be the dielectric strength of the ceramic insulator standoff.*

Cornell DC Gun Thermal Emittance

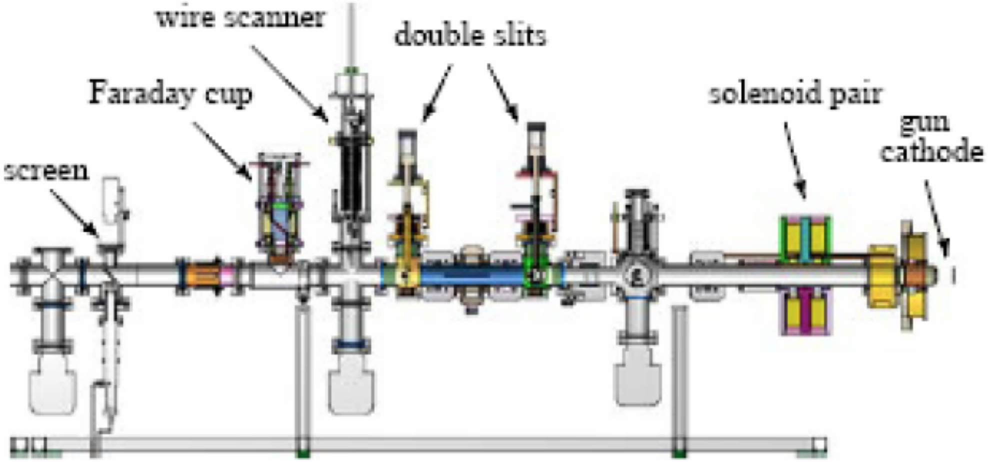


Figure 1: Beamline for thermal emittance studies. Beam direction is to the left.

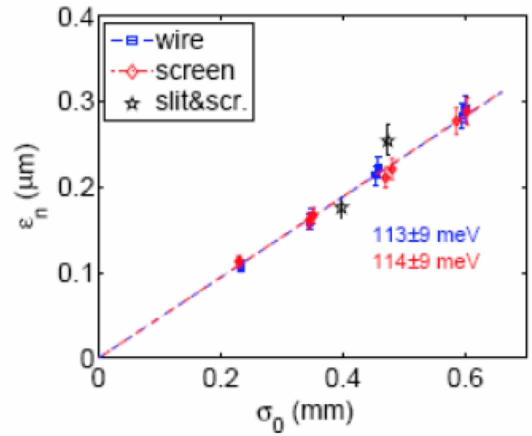
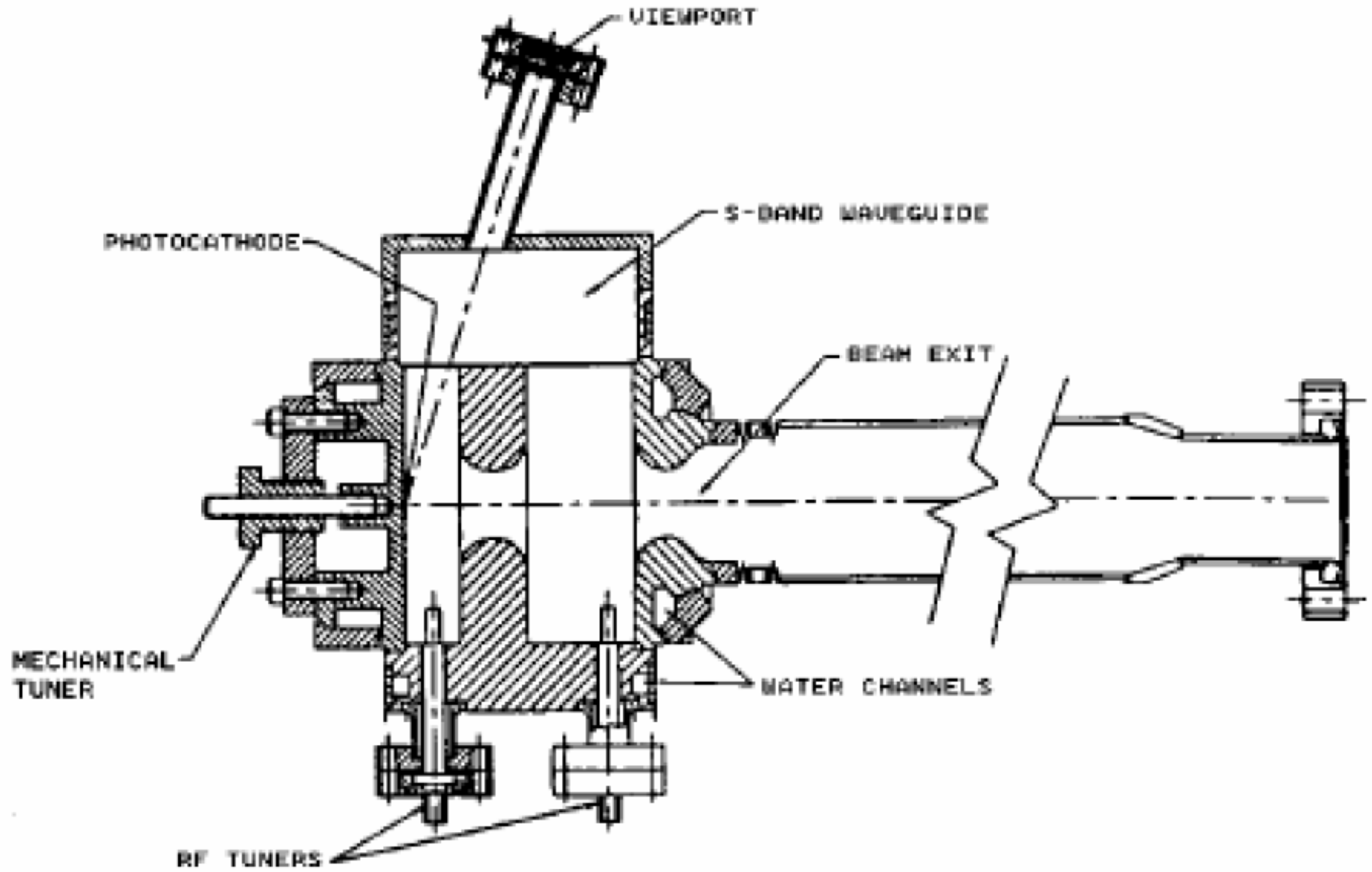


Figure 4: Comparison of various thermal emittance measurement techniques for GaAs at 532 nm.

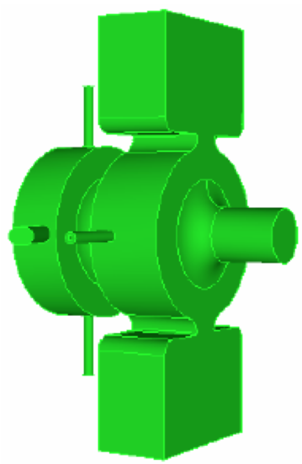
- *Thermal Emittance Measurements from Negative Electron Affinity Photocathodes," I.V. Bazarov et al., PAC07.*

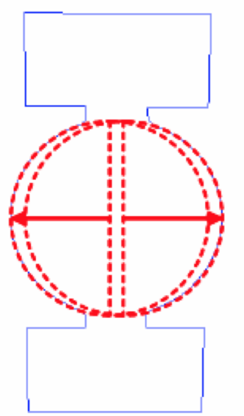
The First BNL S-Band (2856 MHz) Photocathode Gun

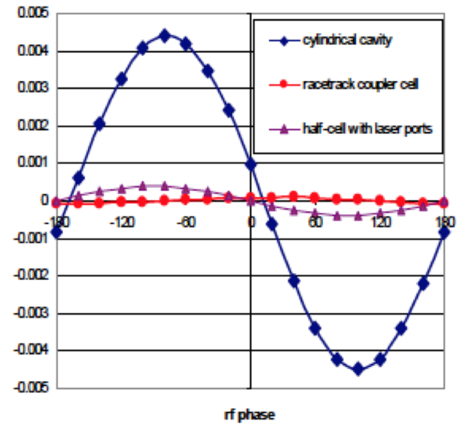


- *The design for the first BNL gun used a single waveguide to side-couple rf power into both cells.*

The LCLS S-Band Gun Design Features



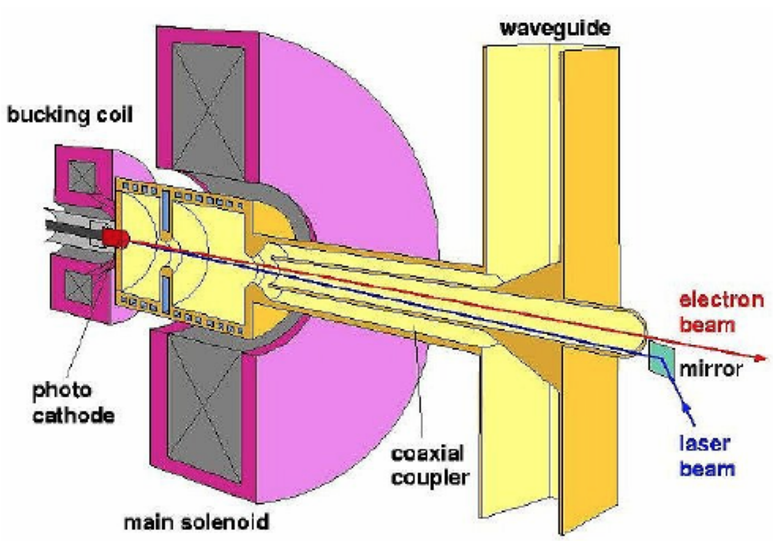


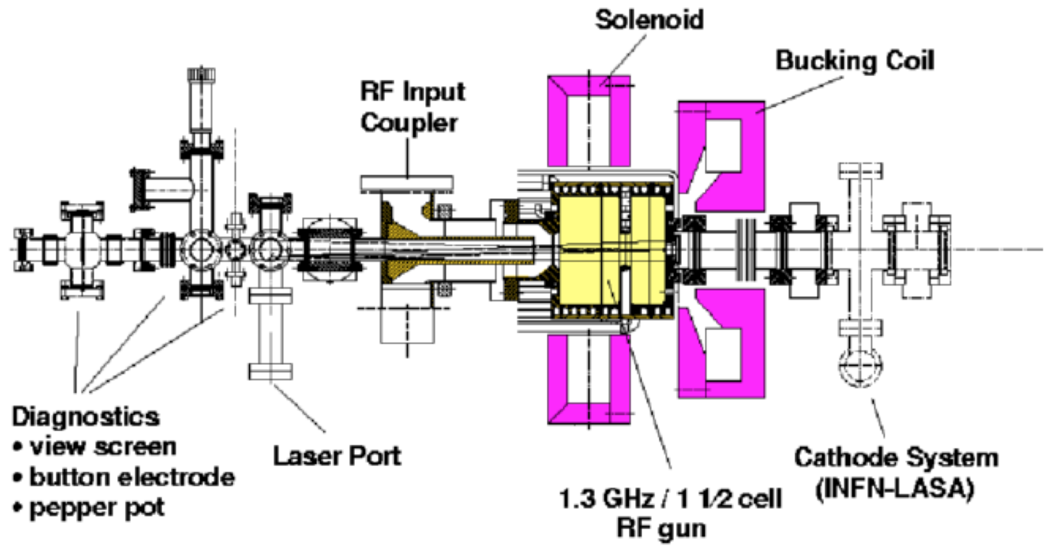


- *The interior volume of the LCLS Gun 1 (top-left drawing) illustrates the dual feed and the z-coupled rf into the full cell.*
- *The top-center drawing shows the offset of circle centers defining the "racetrack" shape of the full cell. The cathode cell (0.6cell) has a circular shape.*
- *Top-right plot: The quadrupole field integrated along the length of the full cell as a function of phase for cylindrical and racetrack shapes and the field for the half-cell due to the laser ports.*

	BNL/SLAC/UCLA; GTF	LCLS Gun 1
cathode field	100MV/m	120MV/m
rf feed	single w/compensation port	dual feed
cavity shape	circular	racetrack
0-π mode separation	3.2MHz	15MHz
repetition rate	10Hz	120Hz
peak quadrupole field	4 mrad/mm	0.1 mrad/mm
rf tuners	plunger/stub	deformation
shunt impedance		
cathode	copper	copper
rf coupling	theta (azimuth)	z (longitudinal)

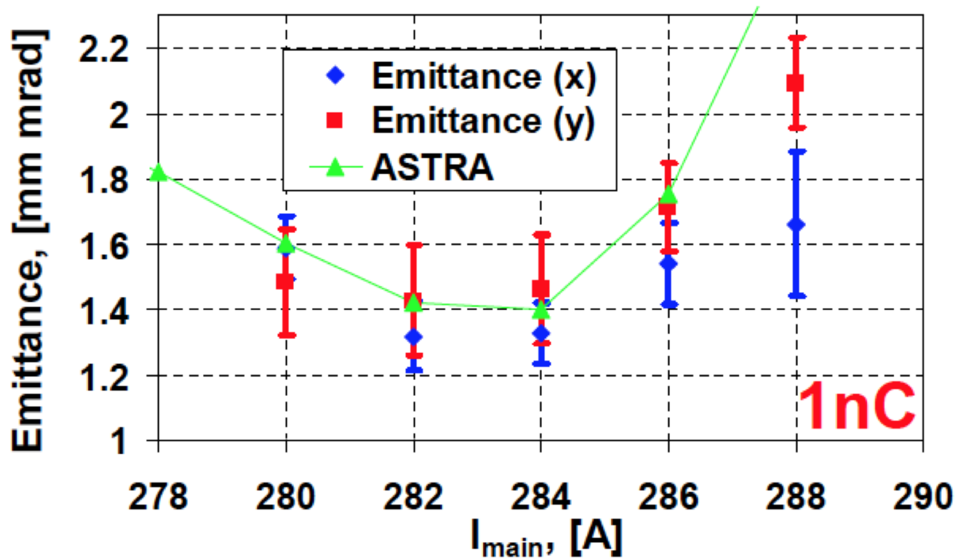
Coaxial RF Photocathode Guns
The TTF/FLASH 1300 MHz Gun





- *This gun has achieved 1.2 micron emittance for 1 nC bunches 17 ps long or 58 amperes of peak current. Unlike the s-band gun, this gun will operate at higher average power producing 10 ms long bunch trains at 10 Hz. Its beam injects into a single-pass SRF accelerator to drive a SASE FEL .*

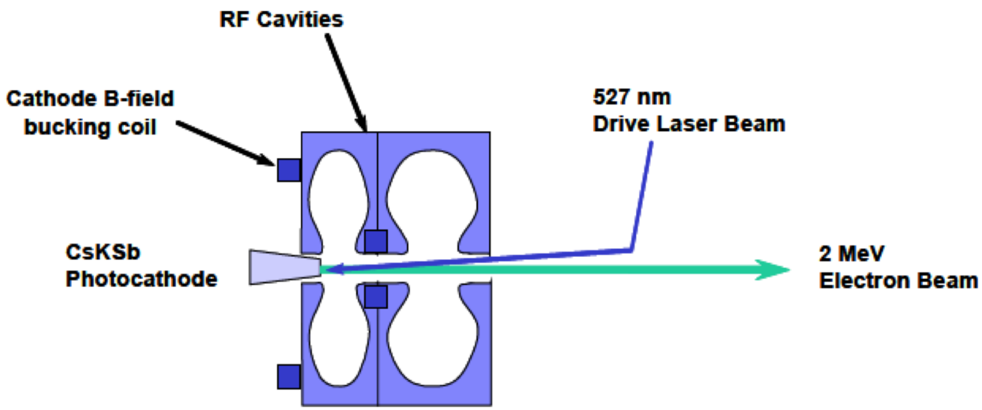
Performance of the Coaxial RF Gun

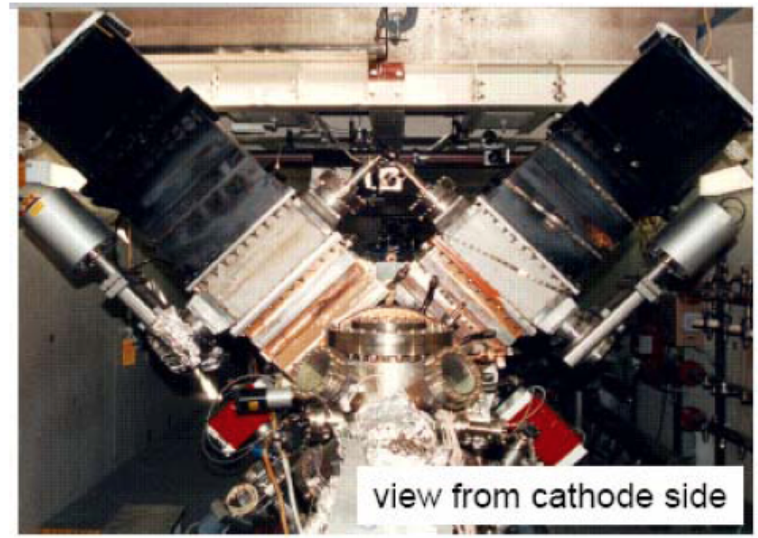


F. Stephan, Proc. FEL2007

- *The optimized emittance plotted as a function of the gun solenoid current. The data shows an x-y plane asymmetry attributed to the wake of the laser injection mirror.*

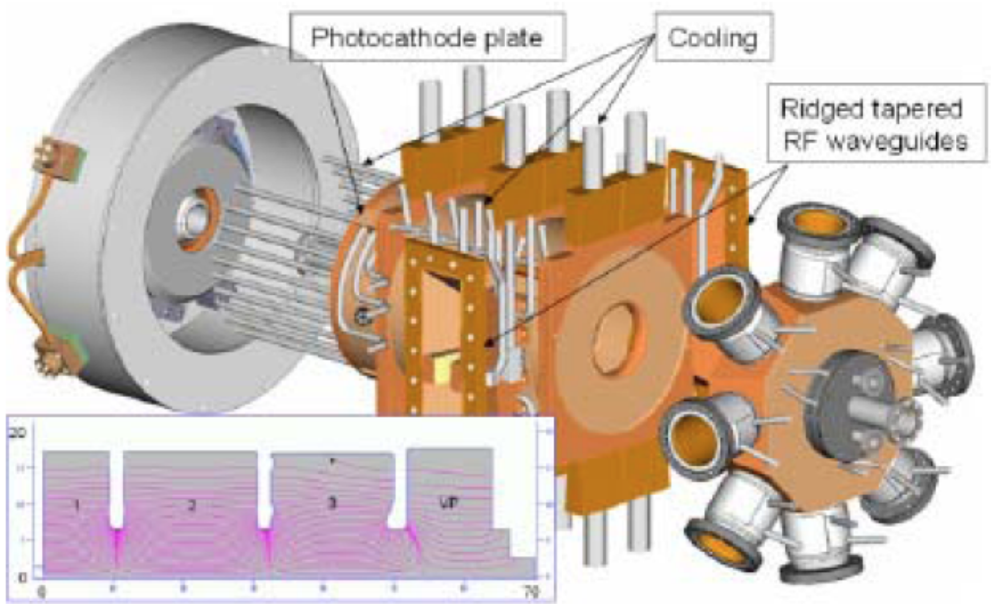
High Average Power Normal Conducting RF (NCRF) Guns





- *The first NCRF gun to operate at high duty factor was the Boeing/LANL gun which operated at 25 percent duty factor in 1992. This gun was built in an industry-laboratory partnership between Boeing and Los Alamos as part of the US Strategic Defense Initiative for the US Department of Defense. Its purpose was to demonstrate the best gun technology for a high power ground based free electron laser system for defense.*

The LANL/AES 700 MHz NCRF Gun



- *A recent version of the CW room temperature rf gun has been built by Advanced Energy Systems for Los Alamos National Laboratory. This 2.5 cell gun shown in Figure 46 operates at 700 MHz to produce a 2.5 MeV beam of a pulse train with 3 nC bunches, and has been designed to produce a 100 mA average current beam, and there are plans to upgrade to one ampere. The normalized transverse emittance is computed to be less than 7 microns by temporally overlapping two Gaussian laser pulses in order to approximate a square pulse. Thermal management is the principle technical challenge for the room temperature gun. The power density dissipated in the cavity walls needs to be less than 200 W/cm2 in order to avoid excessive thermal stress in the structure and this is especially problematic in the areas around the RF coupler irises. This limits the gun's accelerating field to 7MV/m.*