IMPRS: Ultrafast Source Technologies

Lecture VI: March 11, 2014: Ultrafast Electron Sources and Accelerators

Franz X. Kärtner

Electron Gun Key Parameters:

- operation mode: pulsed or CW
- single bunch charge
- time structure of the beam
- normalized transverse emittance
- longitudinal phase space for compression

Different Guns/Photo Injectors for Diff. Applications:

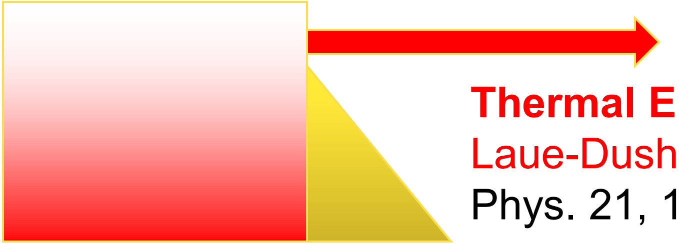
- Direct current (DC) gun
- Normal conducting (NC) RF gun
- Superconducting (SC) RF gun

Electron Emission and Cathode Emittance

There typically is a high electron density in a metal or semi- conductor: 1 electron per unit cell with length scale of about 3 Å.

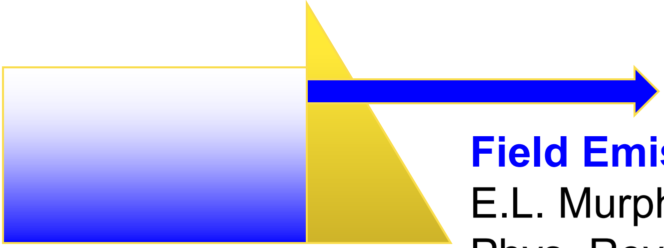
$$N = \frac{1}{(3 * 10^{-8}\,cm)^3} = 10^{22} - 10^{23}\,cm^{-3}$$

We need to apply work to remove electrons from bulk reservoir:



Thermal Emission: Richardson-Laue-Dushman et al., Rev. of Mod. Phys. 21, 185 (1949)

$$J_{RLD}(T) = A_{RLD} T^2 \exp\left(-\frac{\Phi}{k_B T}\right)$$



Field Emission: Fowler Nordheim E.L. Murphy, and R.H. Good, Phys. Rev 102, 1464 (1956).

$$J_{FN}(F) = A_{FN} F^2 \exp\left(-\frac{B\Phi^{3/2}}{F}\right)$$

F: DC, RF, (THZ, MID-IR or VIS)

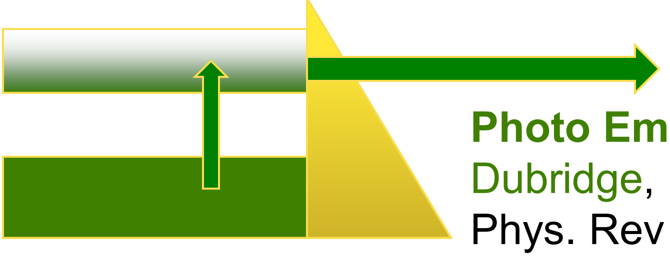


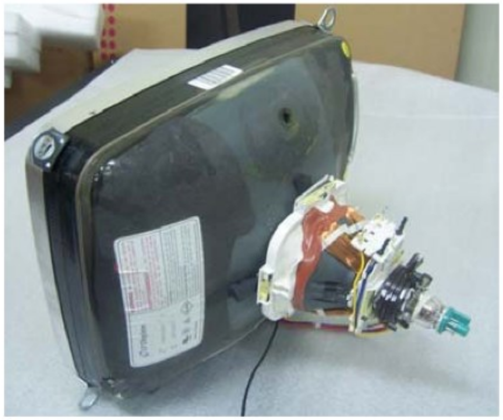
Photo Emission: Fowler-Dubridge, L.A. DuBridge Phys. Rev 43, 0727 (1933).

$$J_{MFD}(\lambda) = \frac{q}{\hbar\omega}(1-R)F_\lambda(\omega)\left(\hbar\omega-\Phi\right)^2 I_\lambda$$

Dr. K. Jensen, Naval Research Laboratory

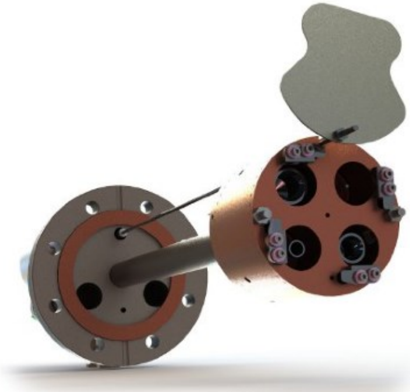
Cathode Applications– Small Electron Guns

- Thermionic guns with relatively low energy are common in a number commercial applications
  - Electron beam welding
  - Electron beam heating
  - Electron beam evaporation
    - These require 0.1 to 1 A, and generally operate at tens of kW
  - Electron beam lithography
  - Cathode ray tubes
- Several research techniques:
  - Electron Diffraction (LEED and RHEED)
  - Flood guns for charge neutralization
  - Ionization of material for mass spectrometry

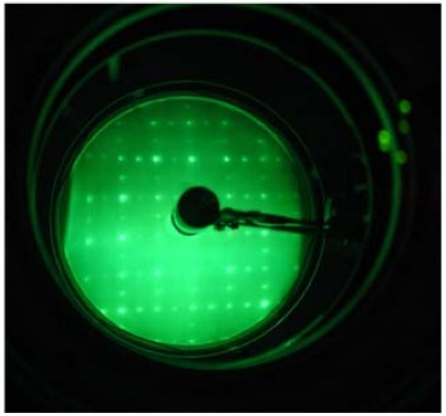


Cathode Ray Tube

Electron Gun



Electron Beam Evaporator

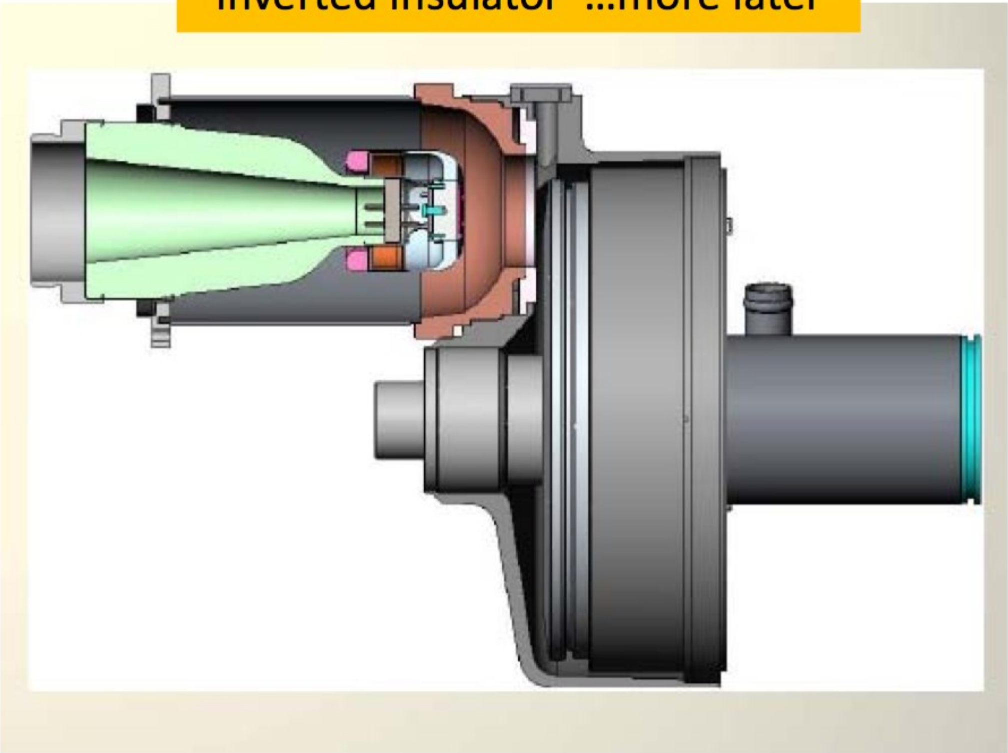


Low Energy Electron Diffraction on Si

Modern X-Ray Sources

Higher e-beam current…..
Higher x-ray flux

“inverted insulator”…more later

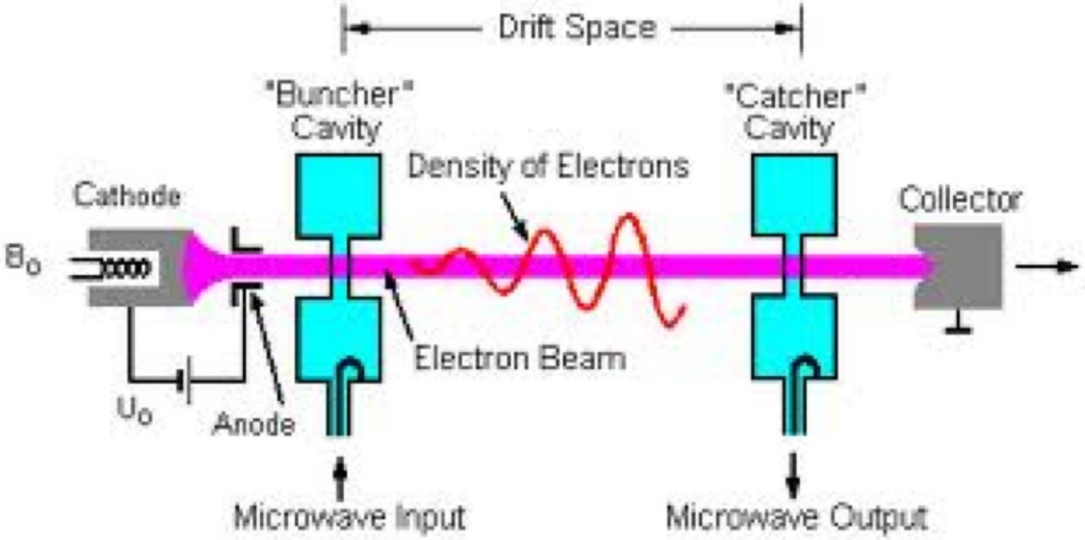


Higher Voltage….
More penetrating
x-ray beam

Courtesy Varian

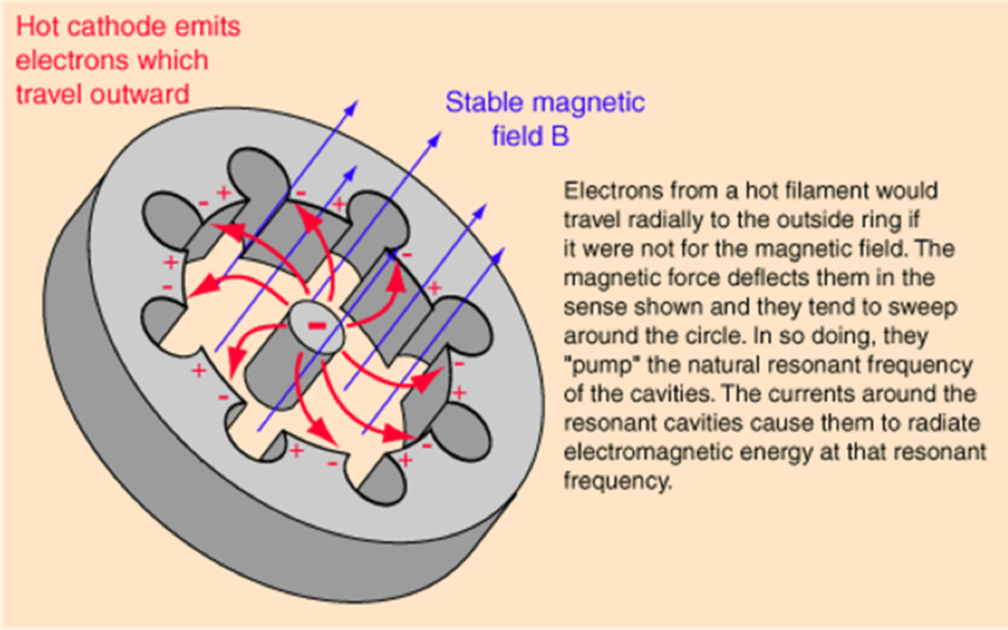
Klystrons — RF generators

- Klystrons use a DC electron beam at a few mA to generate/amplify microwaves by velocity modulation.
- Klystrons use thermionic cathodes to generate the required electron beam.



Magnetrons – RF generators

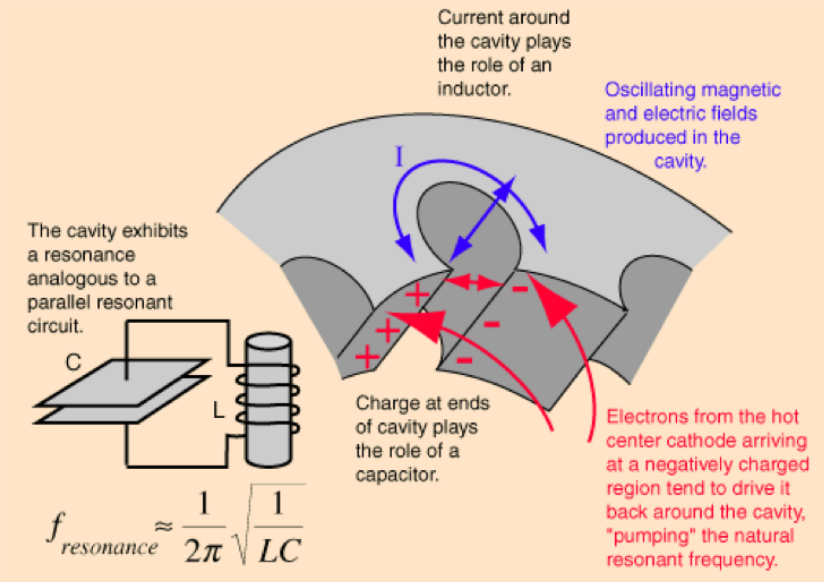
- Invented in 1921 and developed for radar during WWII
- Electrons from a thermionic cathode travel in a circle in presence of strong magnetic field
- Resonances excited in tubes that line the anode



Hot cathode emits electrons which travel outward

Stable magnetic field B

Electrons from a hot filament would travel radially to the outside ring if it were not for the magnetic field. The magnetic force deflects them in the sense shown and they tend to sweep around the circle. In so doing, they "pump" the natural resonant frequency of the cavities. The currents around the resonant cavities cause them to radiate electromagnetic energy at that resonant frequency.



Current around the cavity plays the role of an inductor.

Oscillating magnetic and electric fields produced in the cavity.

The cavity exhibits a resonance analogous to a parallel resonant circuit.

Charge at ends of cavity plays the role of a capacitor.

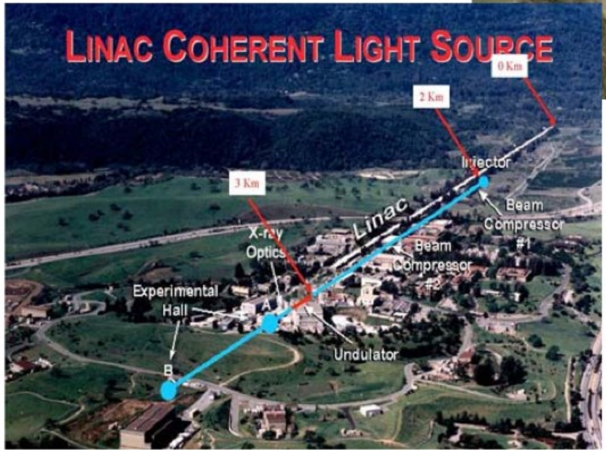
Electrons from the hot center cathode arriving at a negatively charged region tend to drive it back around the cavity, "pumping" the natural resonant frequency.

$$f_{resonance} \approx \frac{1}{2\pi}\sqrt{\frac{1}{LC}}$$

Cathode Applications– Accelerators

- Light sources typically use thermionic sources
  - Beam properties dominated by lattice, not cathode
  - This can be good and bad
- Electron machines for nuclear/particle physics (CEBAF, ILC, SLAC) typically require spin polarization and use special photocathodes
- Linacs (Flash, LCLS, ATF, Jlab FEL) typically use photocathodes – why?
- SCSS at Spring8 in Japan is a notable exception (*student topic?*)

National Synchrotron Light Source II



Key-Quantitiy: Beam Brilliance

$$B = \frac{N_e}{\varepsilon_{nx}\varepsilon_{ny}\varepsilon_{nz}}$$

with N_e the number of electrons per bunch and $\varepsilon_{nx,\,ny,\,nz}$ the normalized emittances for the planes x, y, and z

$$\varepsilon_{nx} = \sigma_x \frac{\sigma_p}{mc} = \gamma\beta\sigma_x\sigma_{x'}$$

X-Ray 4th Generation Light Sources, the Most Challenging Electron Injector Case

- In **FELs, the matching condition for transverse emittance** drives towards **small normalized emittances.**

$$\varepsilon \approx \frac{\lambda}{4\pi} \Rightarrow \frac{\varepsilon_n}{\beta\gamma} \approx \frac{\lambda}{4\pi}$$

- The **minimum obtainable value for ε_n** defines the energy of the beam ($\gamma = E/mc^2$).

(with β the electron velocity in speed of light units, and assuming that an undulator with the proper period λ_u and undulator parameter K exist: $\lambda = \lambda_u / 2\gamma^2(1 + K^2/2)$)

- We will see later, that for the present electron gun technologies: $\varepsilon_n < \sim 1\ \mu\mathrm{m}$ for the typical $< \sim 1\ \mathrm{nC}$ charge/bunch.

For X-Ray machines ($\lambda < \sim 1$ nm) that implies GeV-class electron beam energy, presently obtainable by long and expensive linacs.

- Similar transverse emittance requirements apply also to ERLs.

- In X-Ray FELs the matching condition for the energy spread requires a fairly **low energy spread** as well

$$\frac{\sigma_E}{E} < \sim \rho_{Pierce} < \sim 10^{-3}$$

- Achieving the necessary FEL gain requires high peak current (~ 1 kA), and **hence high charge/bunch and short bunches.**

- In both ERLs and FELs, high-time resolution user-experiments require extremely short X-Ray pulses (down to sub-fs) imposing the need for **small and linear longitudinal emittances** to allow for the proper compression along the linac.

In summary, 4th generation X-Ray facilities challenge the performance of electron injectors.

Courtesy F. Sannibale

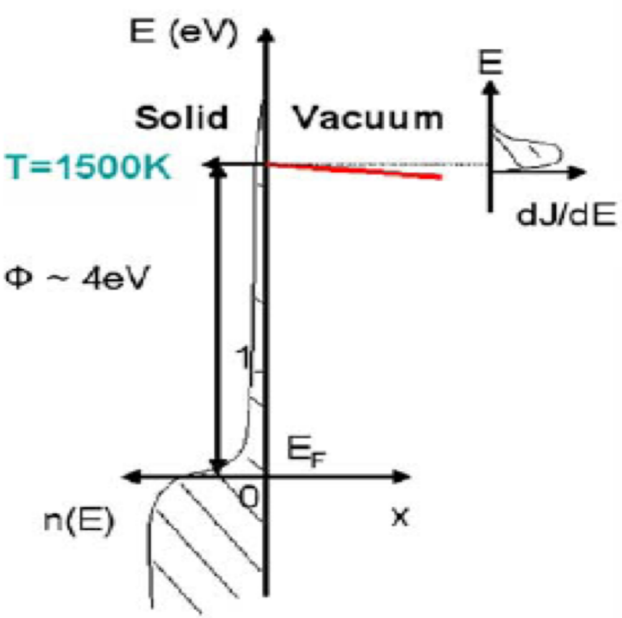
The (obviously) most important Photocathode properties

- **Quantum efficiency**
  - High QE at the longest possible wavelength
  - Fast response time: <100 ps
  - Uniform emission
    - Non-uniform emission seeds emittance growth due to transverse, space charge expansion
  - Easy to fabricate, reliable, reproducible
  - Low dark current, field emission.

- **Intrinsic emittance**
  - Low as possible
    - Atomically flat: ~few nm p-p, to minimize emittance growth due to surface roughness and space charge
  - Tunable, controllable with photon wavelength
    - May need to "chase" the work function: $\varepsilon_{\text{intrinsic}} \propto \sqrt{\hbar\omega - \phi_{eff}}$
  - Better at cryogenic temperatures?

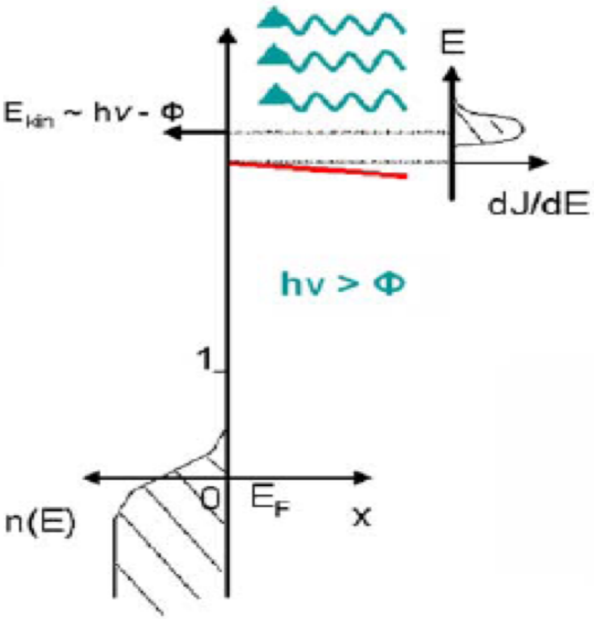
- **Lifetime, survivability, robustness, operational properties**
  - Require >1 year of operating lifetime
    - reasonable vacuum level: 10^{-10} Torr range
  - Easy, reliable cathode cleaning or rejuvenation or re-activation
  - Low field emission at high electric fields
    - needs to be atomically flat: ~few nm p-p
  - Reliable installation and replacement system (load lock)

Emission Options


Themionic Emission

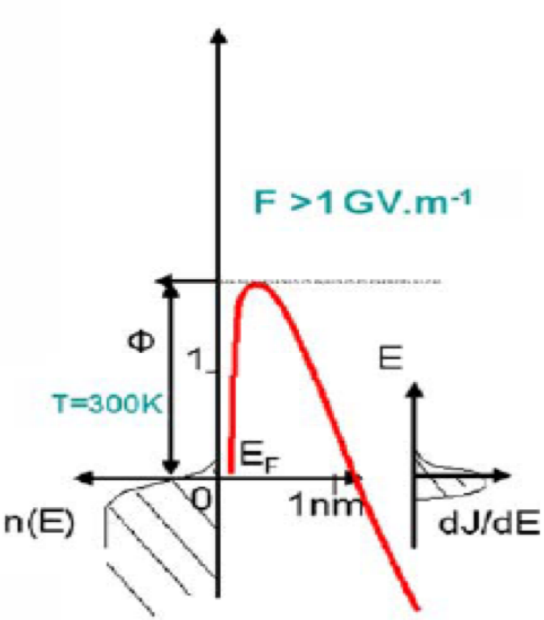
$$E_{kin} \sim \frac{3}{2} kT_{Solid}$$

$$J < 10^6\, A.m^{-2}$$


Photoemission

$$E_{kin} \sim h\nu - \Phi + e\sqrt{\frac{eF}{4\pi\varepsilon_0}}$$

$$J < 10^9\, A.m^{-2}$$


Field Emission

$$E_{kin} \sim 4kT_{Solid}$$

$$J < 10^{12}\, A.m^{-2}$$

$$\varepsilon_{nx} = \sigma_X \frac{\sqrt{\langle p^2 \rangle}}{mc} = \sigma_X \sqrt{\frac{k_B T}{mc^2}}$$

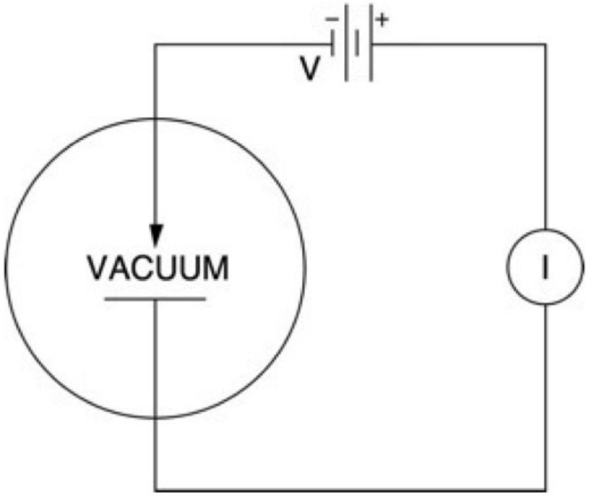
$$\varepsilon_{nx} = \gamma\beta\sigma_X\sigma_{X'} = \sigma_X \sqrt{\frac{\hbar\omega - \Phi_{eff}}{3mc^2}}$$

R. Ganter et al. NIM A **565** (2006) 423–429

$$\varepsilon_{nx} = \gamma\beta\sigma_X\sigma_{X'} = \gamma\beta\sigma_X 1rad$$

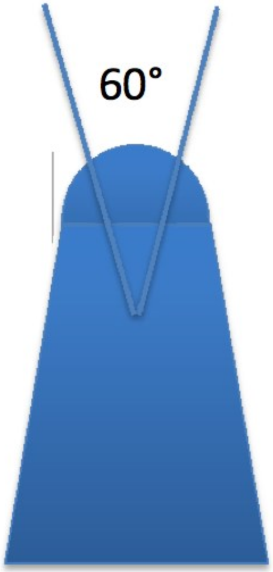
Field Emitter Sources

- Explained by Fowler-Nordheim, 1928: a quantum mechanical tunneling effect
- “bright” e-beam, good for surface science



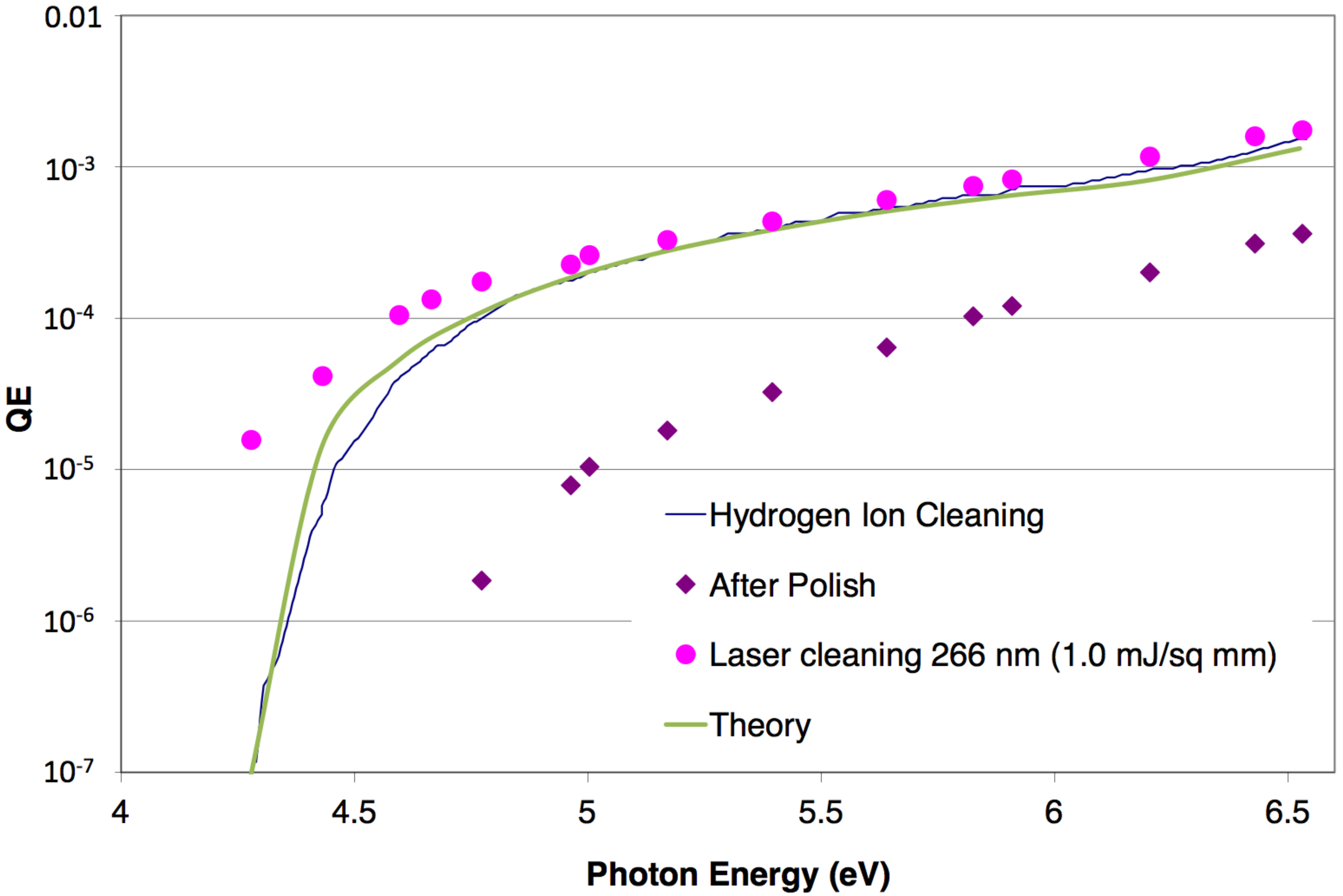
$I = BV^2 \exp(-C/V)$

Vacuum diode



$$I \approx A \times 1.54 \times 10^{-6} \frac{F^2}{\phi} \exp\left[-6.83 \times 10^{9} \frac{\phi^{3/2}}{F}\right]$$

LCLS Copper Cathodes



D. H. Dowell *et al.*, Phys. Rev. ST Accel. Beams 9, 063502 (2006)

Cs_2Te

- Most common cathode for ~1mA injectors
- Work function 3.6eV, E_g= 3.2 eV
- Good QE for UV light (Max >20%, Average ~7% @ 262 nm)
- Deposited in 10^{-11} Torr vacuum
  - Typically sequential (Te->Cs); Cs used to optimize QE
  - Co-deposition increases performance

- Typical lifetime in an RF injector is measured in weeks-months
  - Chemical poisoning (and Cs loss?) is major cause of QE loss
  - Improve vacuum should help (DC/Superconducting injectors)
- Can be shipped in vacuum suitcase

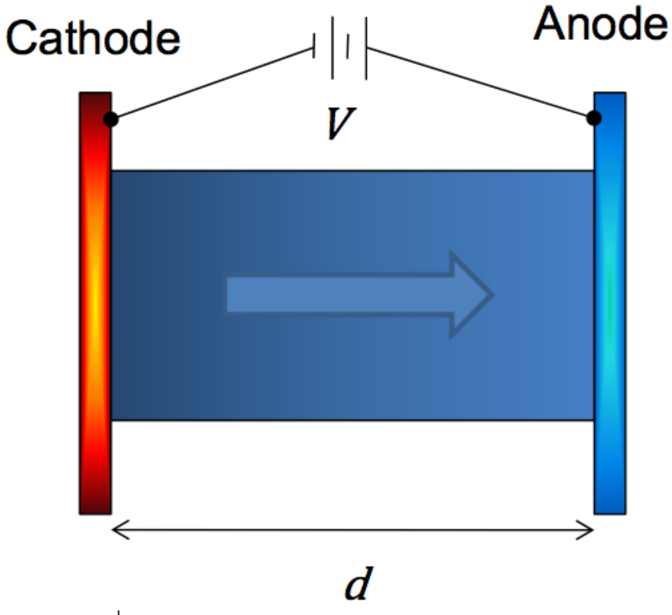
D. Sertore *et al.*, PAC07, 2760
G. Suberlucq, EPAC04, 64
F. Banfi *et al.*, FEL07, 572

Emittance Summary

- The intrinsic emittance of the source is the ultimate limit for the volume of phase space
- The intrinsic emittance for thermionic emission is approximately 0.3 microns/mm for a cathode temperature of 2500 degK.
- The photo-electric emittance for a copper cathode ranges between 0.5 to 1 micron/mm depending upon the photon wavelength
  - Going to higher photon energy improves QE, but also increases emittance
- The field-emission emittance is found to vary between 0.5 to 2 microns/mm for fields from 10^9 to 10^{10} V/m, and hence has larger emittance for the same source size than the other two processes.

- Now we'll address space charge and calculate the ultimate emittance we can achieve

Space Charge Limit (SCL) is different for DC diode and short pulse photo-emission



Space Charge Field Across a Diode, Child-Langmuir law:

$$J_{CL} = \frac{4}{9}\varepsilon_0\sqrt{\frac{2e}{m}}\frac{V^{3/2}}{d^2}$$

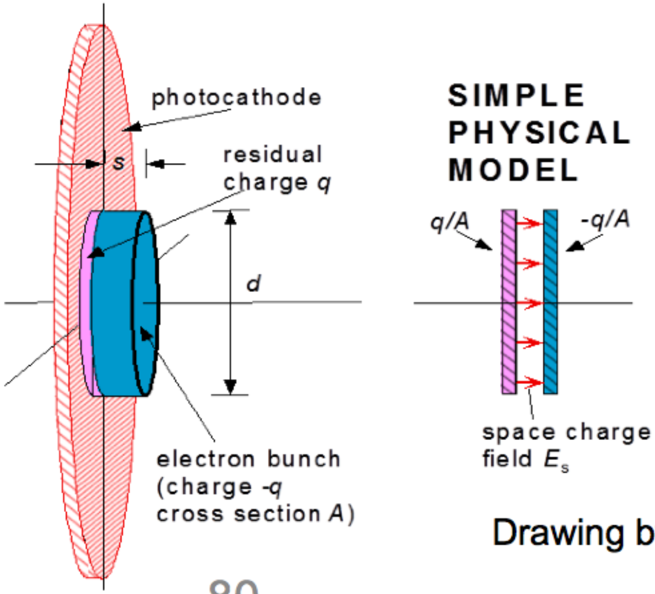
For more complicated geometries:

$$I = P \cdot V^{3/2}$$

Where P

Space Charge Field Across a Short Electron Bunch from a Laser-driven Photocathode, parallel plate (capacitor) model:

$$\sigma_{SCL} = \varepsilon_0 E_{applied}$$

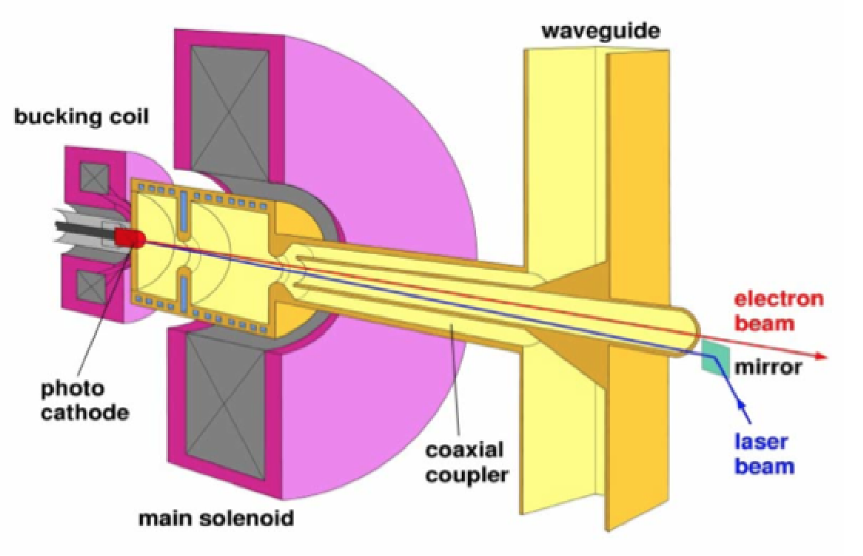


Drawing by A. Vetter

80

NC RF Guns

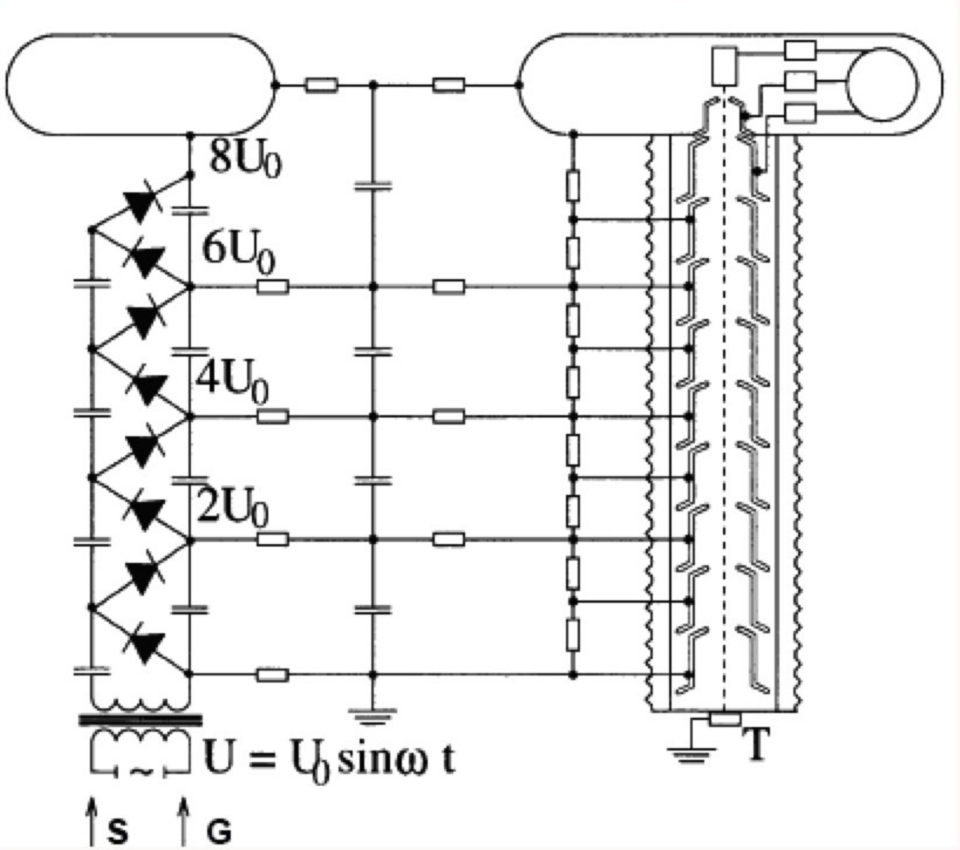
- Advantages
  - high accel. gradient at cathode + good space charge compensation → high bunch charge
  - medium beam energy
  - lots of operating experience, emittance record



- Disadvantages
  - medium vacuum conditions
  - water cooling limits average RF power → broad range of average currents (RF frequency)

DC - Accelerator Technology

Cockcroft-Walton Accelerator



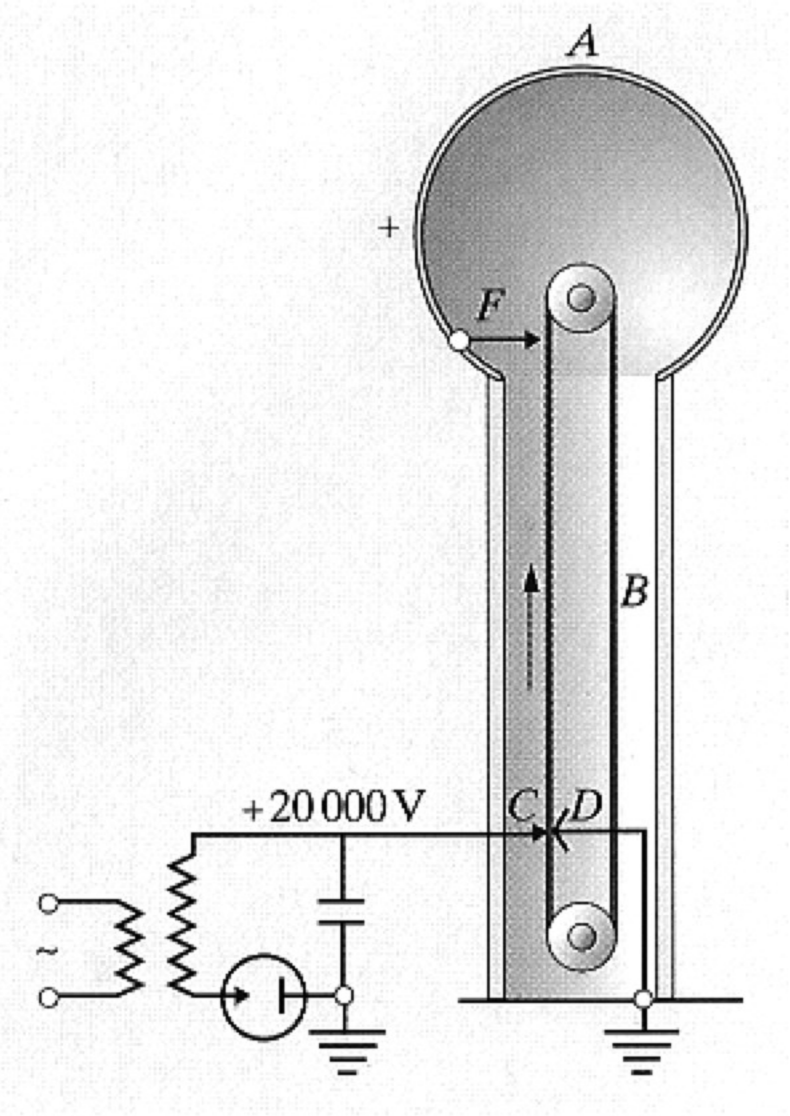
S Schubsäule
G Glättungssäule
T Target

Strahlrohr mit Widerstandskette
und Beschleunigungselektroden

4 MeV, 100 mA

from K. Wille

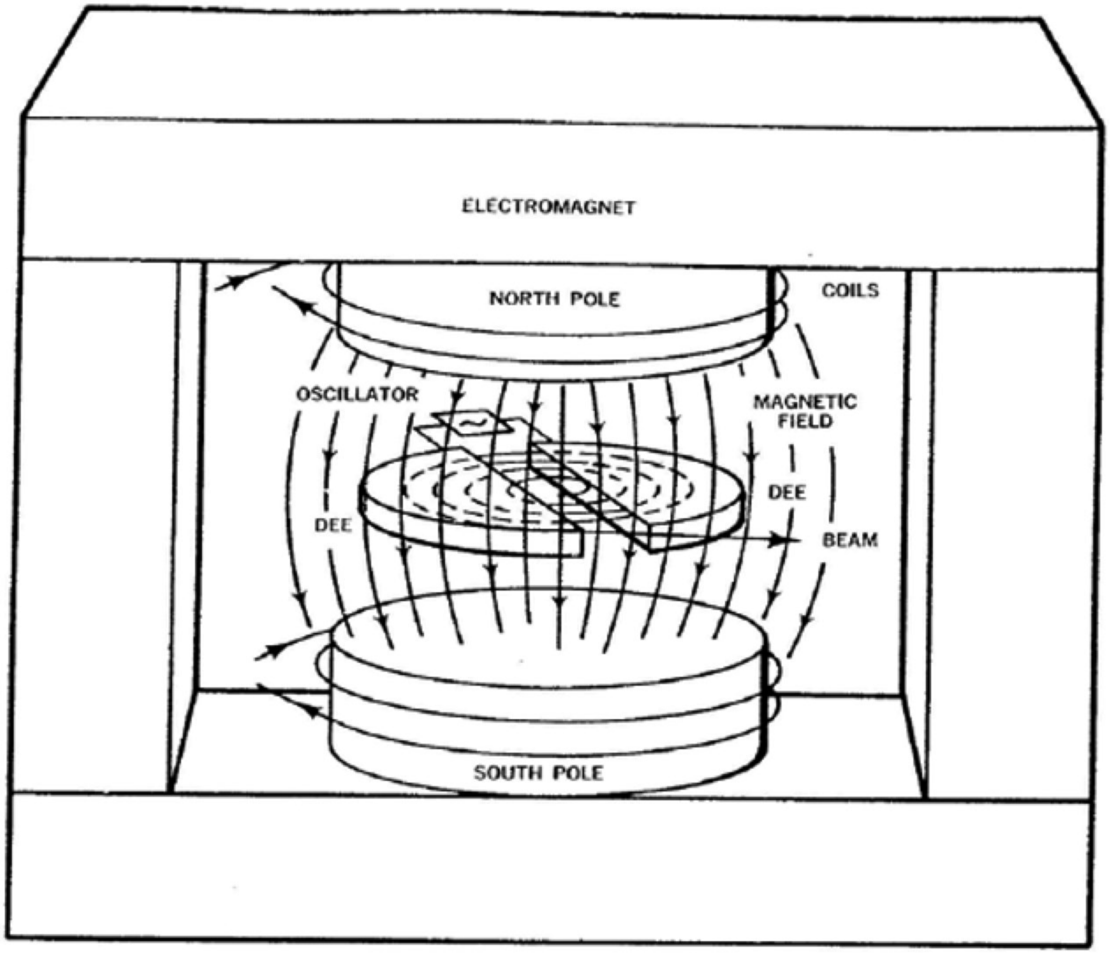
Van de Graaf Generator / Accelerator



10 MeV

from K. Wille

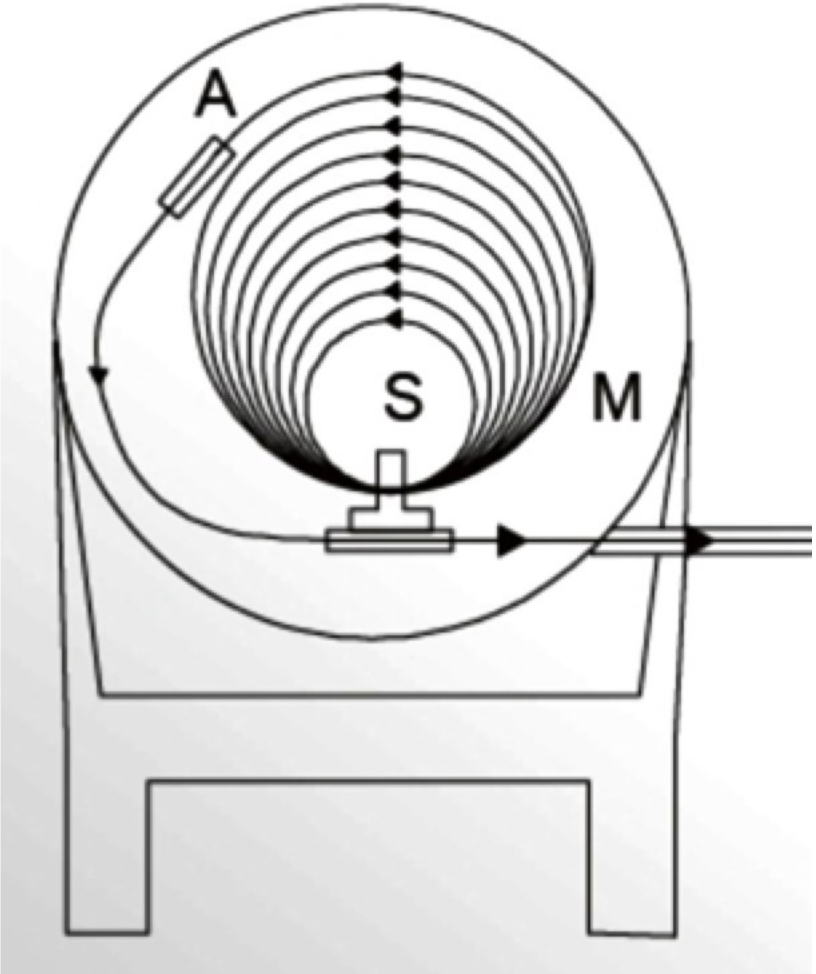
RF - Zyklotron



> 600 MeV

from K. Wille

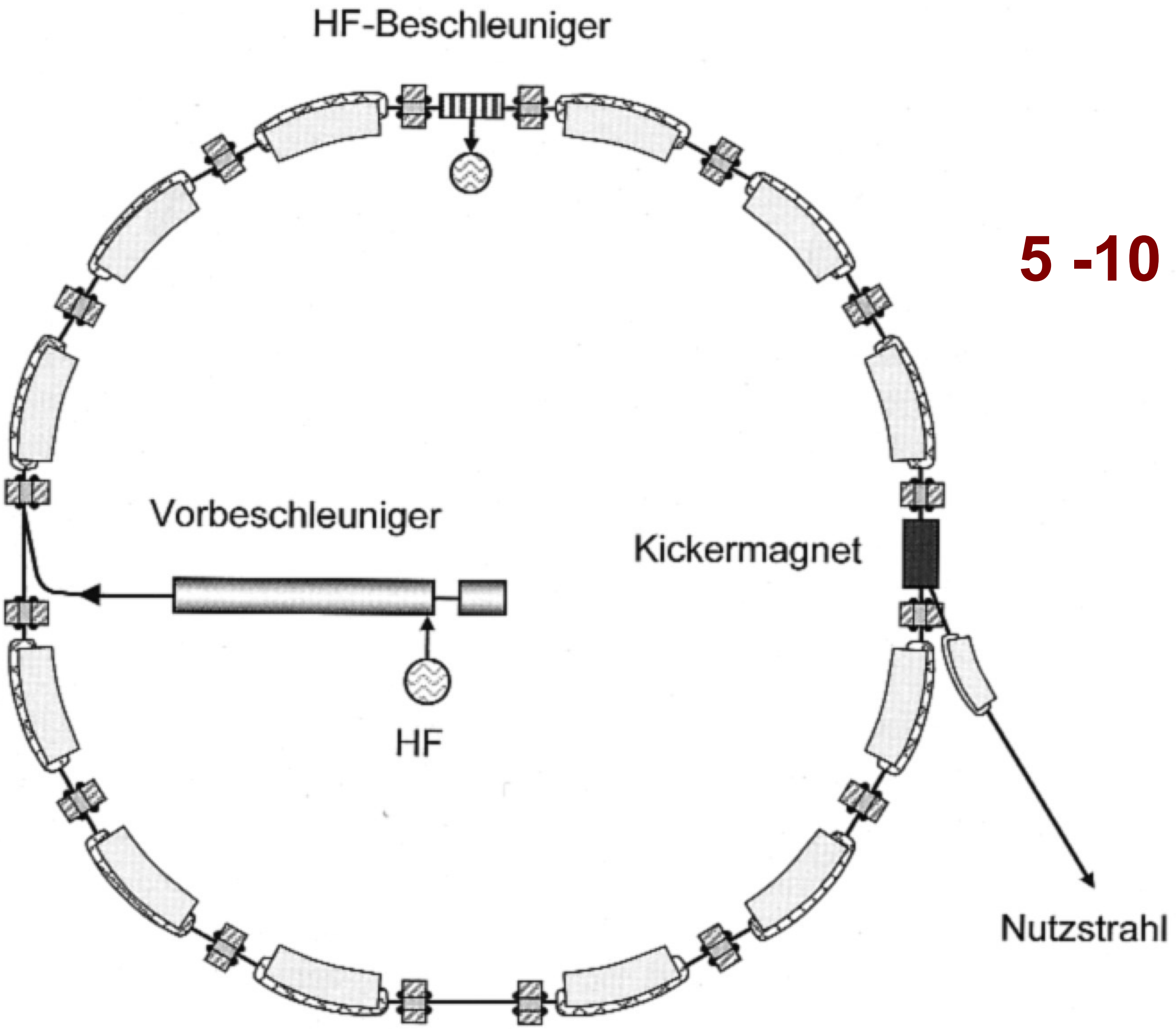
Microtron



850 MeV

from K. Wille

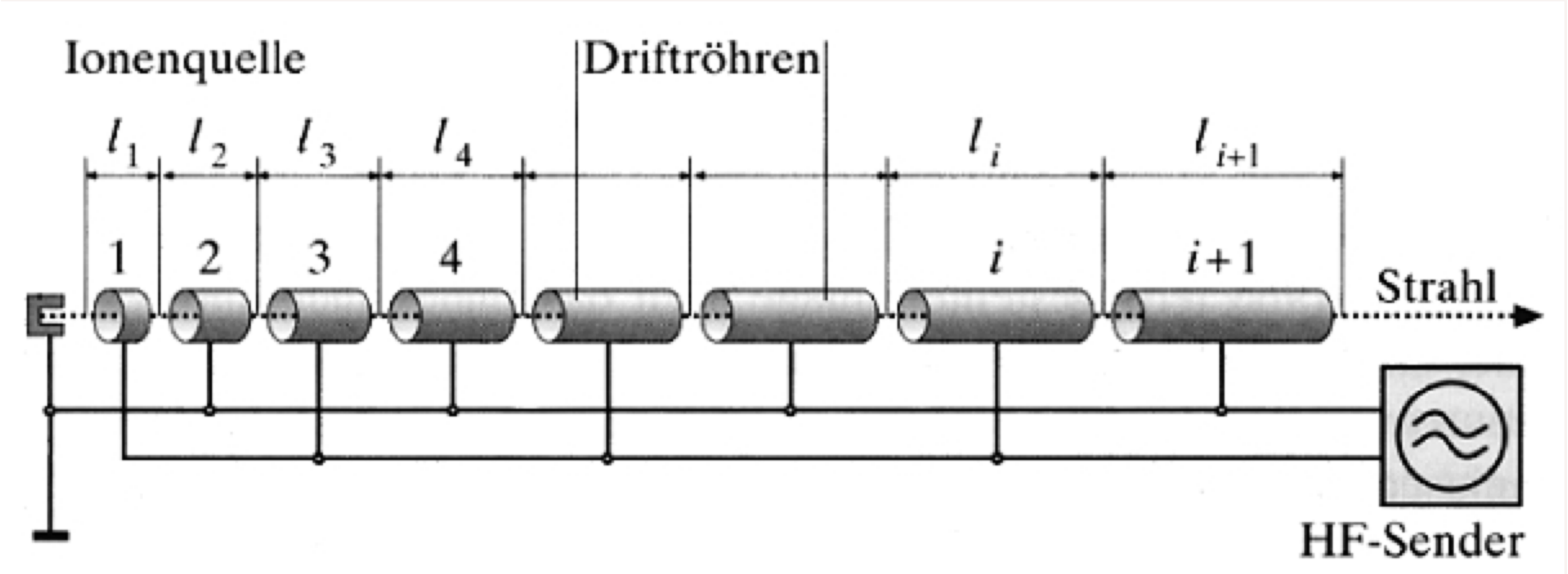
Synchrotron



5 -10 GeV

from K. Wille

RF – Linear Accelerator



SLAC, 50 GeV

References:

K.L. Jensen et al., „Theoretical model of the intrinsic emittance of a photocathode,"Appl. Phys. Lett. 89, 224103 (2006).

W. E. Spicer, Phys. Rev. Lett. 11, 243 (1963).

David H. Dowell and John F. Schmerge, „Quantum efficiency and thermal emittance of metal photocathodes,“ PRSTAB 12, 074201 (2009).

K. Wille, „Physik der Teilchenbeschleuniger und Synchrotronstrahlungsquellen,“ Teubner Studienbücher (1992).

US PARTICLE ACCELERATOR SCHOOL, uspas.fnal.gov