

UFS Lecture 25: Ultrafast Electron Sources and UED

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

Ultrafast Electron Diffraction (UED)

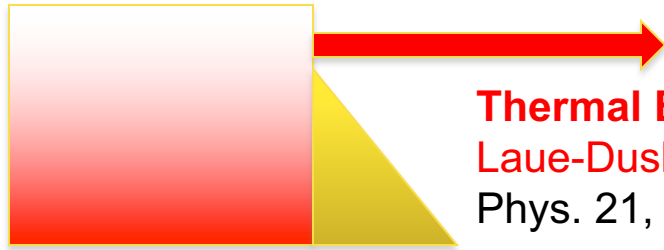
THz enhanced UED

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.

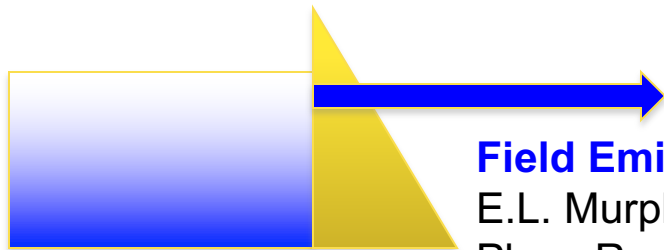
$$N = \frac{1}{(3 * 10^{-8} \text{ cm})^3} = 10^{22} - 10^{23} \text{ cm}^{-3}$$

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)

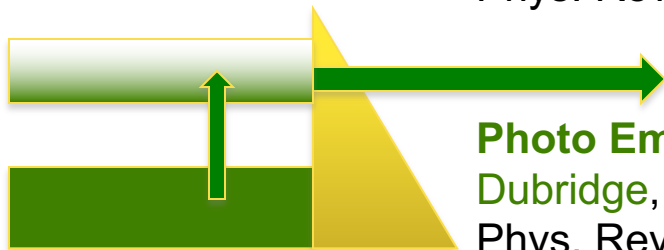


Photo Emission: Fowler-Dubridge, L.A. DuBridge
Phys. Rev 43, 0727 (1933).

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

Cathode Applications– Small Electron Guns

Thermionic guns with relatively low energy are common in a number commercial applications

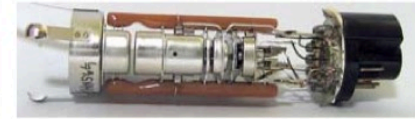
- Electron beam welding
- Electron beam heating
- Electron beam evaporation
 - These require 0.1 to 1 A, and generally operate at tens of kW
- Electron beam lithography
- Cathode ray tubes

Several research techniques:

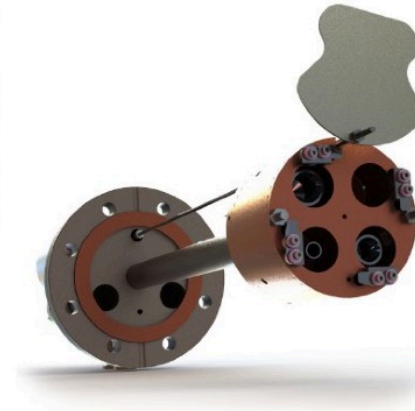
- Electron Diffraction (LEED and RHEED)
- Flood guns for charge neutralization
- Ionization of material for mass spectrometry



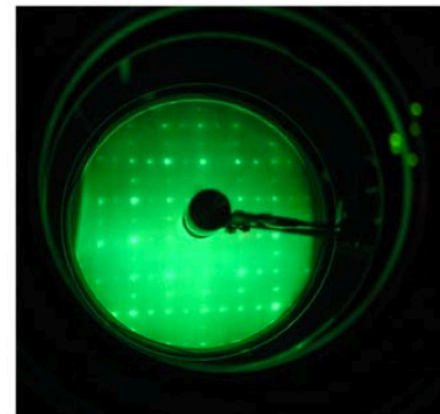
Cathode Ray Tube



Electron Gun



Electron Beam Evaporator



Low Energy Electron Diffraction on Si

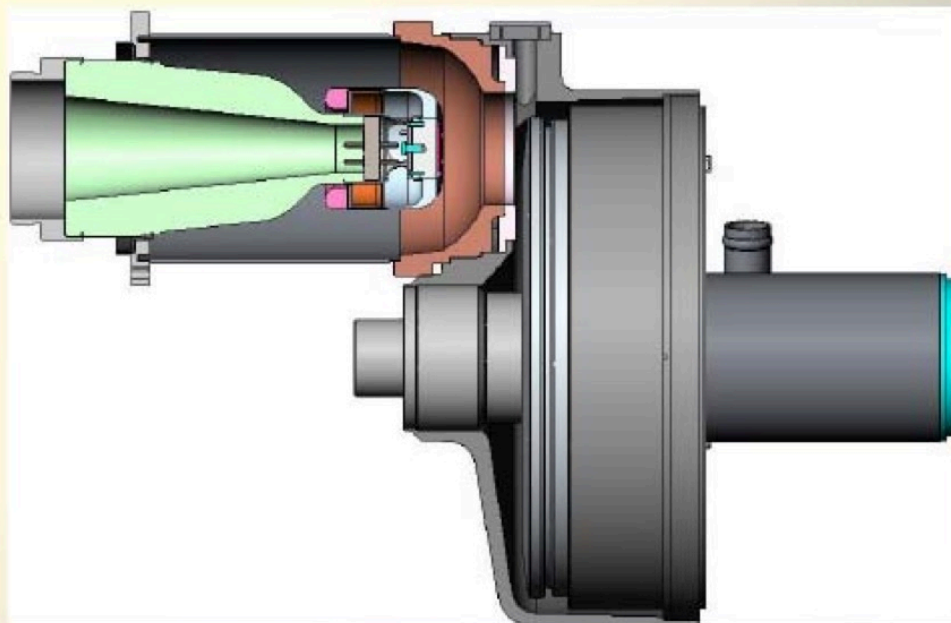
Modern X-Ray Sources

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



Higher Voltage....
More penetrating
x-ray beam

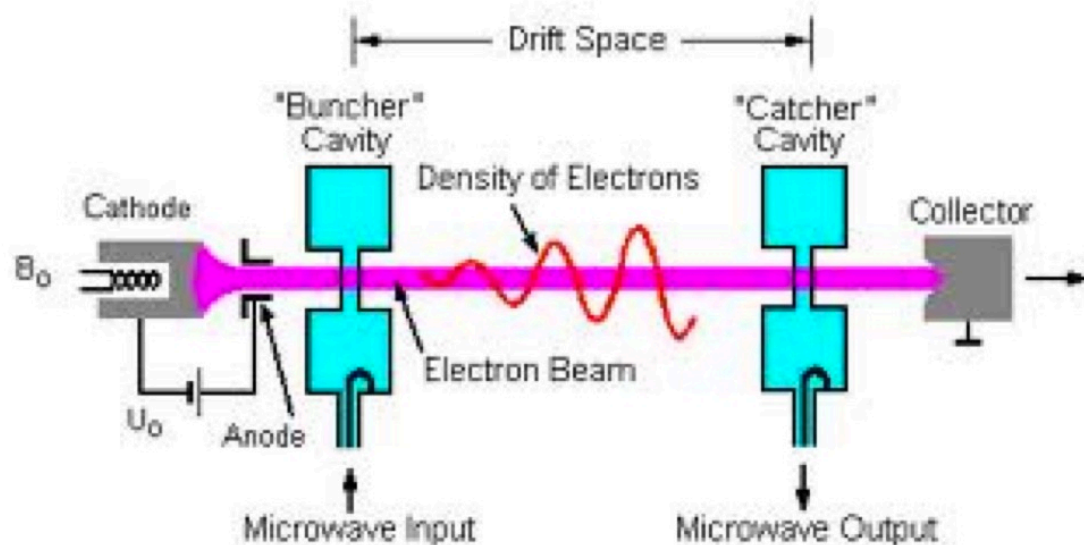
“inverted insulator” ...more later



Courtesy Varian

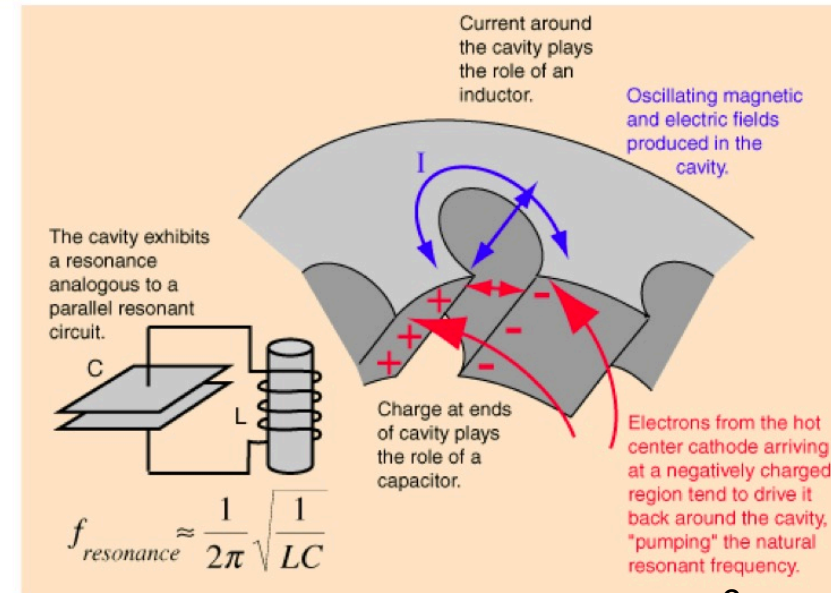
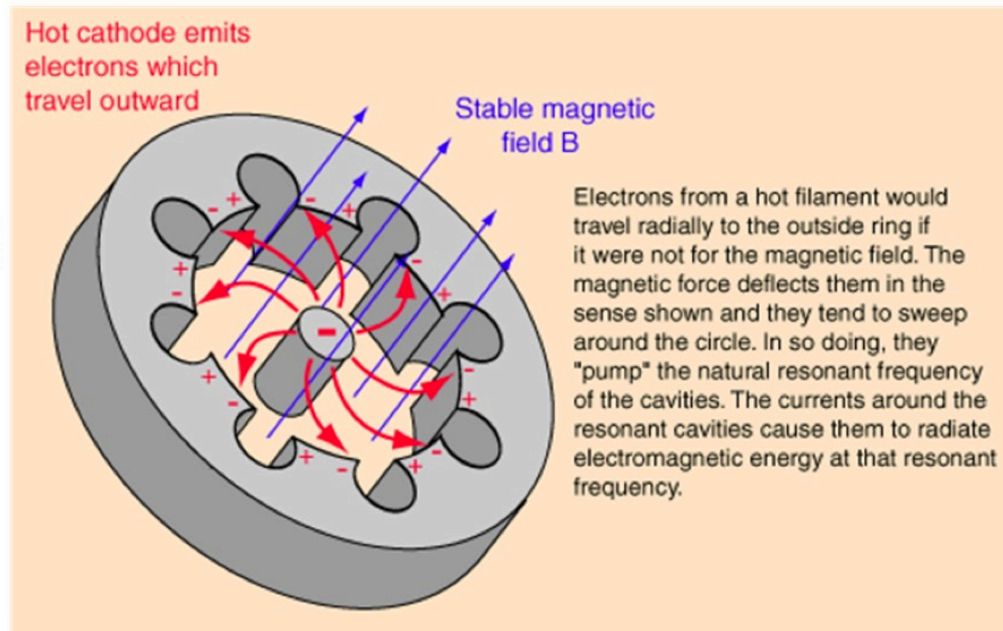
Klystrons — RF generators

- 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

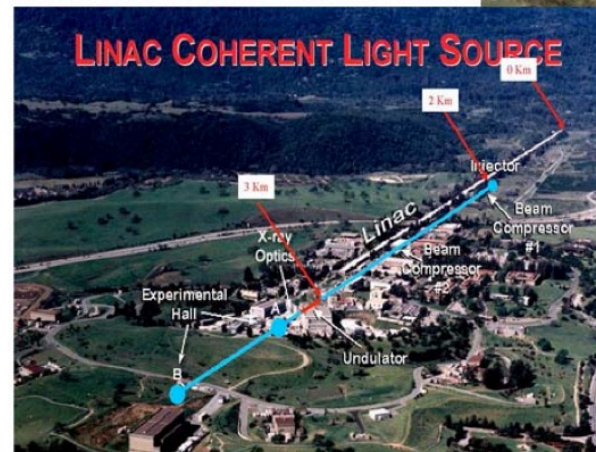
- Invented in 1921 and developed for radar during WWII
- Electrons from a thermionic cathode travel in a circle in presence of strong magnetic field
- Resonances excited in tubes that line the anode



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-Quantity: Beam Brilliance


$$B = \frac{N_e}{\mathcal{E}_{nx} \mathcal{E}_{ny} \mathcal{E}_{nz}}$$

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

$$\mathcal{E}_{nx} = \sigma_x \frac{\sigma_p}{mc} = \gamma \beta \sigma_x \sigma_{x'}$$

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:
 $\varepsilon_n < \sim 1 \mu\text{m}$ for the typical $< \sim 1 \text{ nC}$ charge/bunch.

For X-Ray machines ($\lambda < \sim 1 \text{ nm}$) 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


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

- Achieving the necessary FEL gain requires high peak current ($\sim 1 \text{ kA}$), 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.

Other important cathode properties

Quantum Efficiency: Metals: 10^{-5} Semiconductors: 10^{-2}

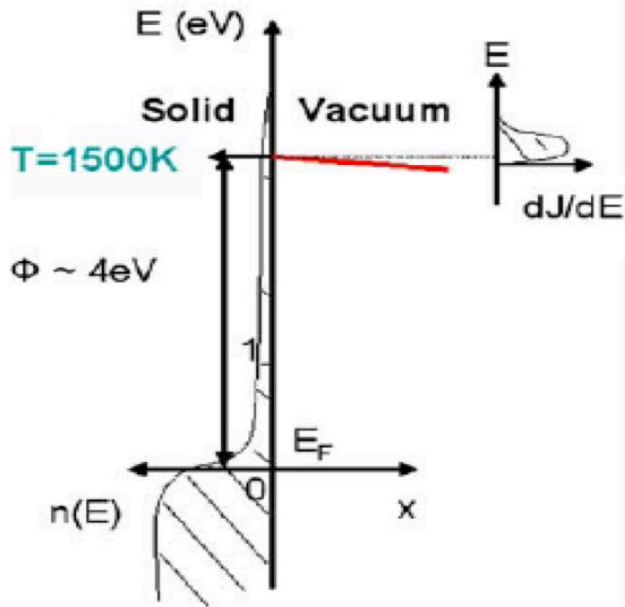
**Fast response time: < 100 ps ; uniform emission, flat surface,
less than nm level surface roughness**

low dark current and low field emission at high fields

life time > 1 year at reasonable pressure $< 10^{-10}$ Torr

Emission Options

Thermionic Emission

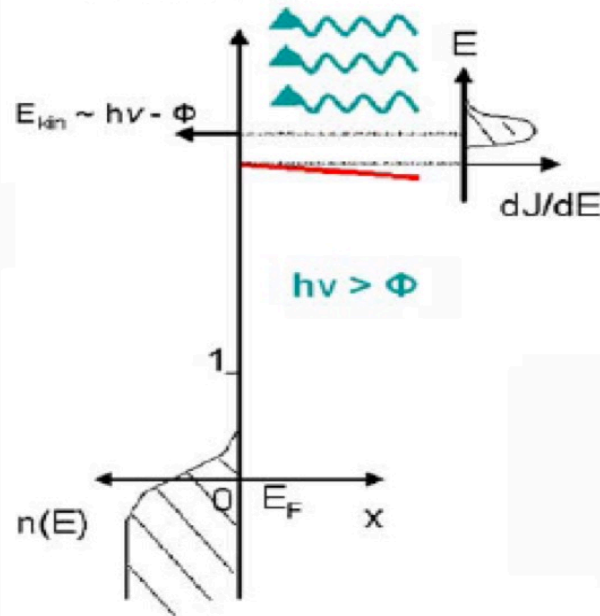


$$E_{kin} \sim \frac{3}{2} kT_{Solid}$$

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

$$\begin{aligned} \varepsilon_{nx} &= \sigma_x \frac{\sqrt{\langle p^2 \rangle}}{mc} \\ &= \sigma_x \sqrt{\frac{k_B T}{mc^2}} \end{aligned}$$

Photoemission



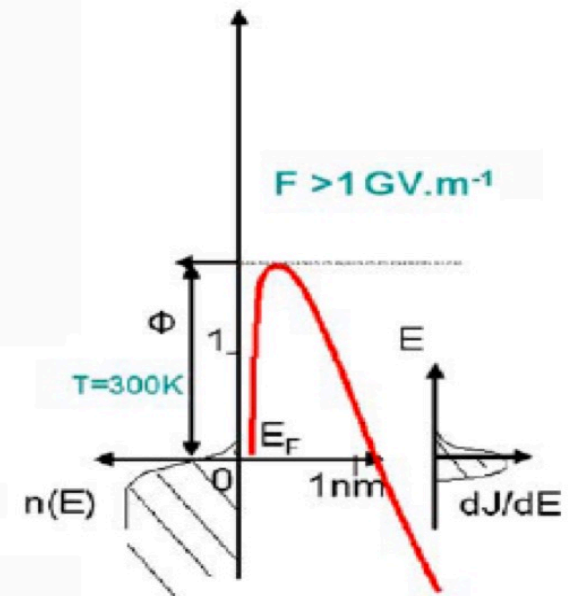
$$E_{kin} \sim h\nu - \Phi + e \sqrt{\frac{eF}{4\pi\epsilon_0}}$$

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

$$\varepsilon_{nx} = \gamma\beta\sigma_x\sigma_{x'} \quad \text{R. Ganter et al. NIM A 565 (2006) 423–429}$$

$$= \sigma_x \sqrt{\frac{\hbar\omega - \Phi_{eff}}{3mc^2}}$$

Field Emission

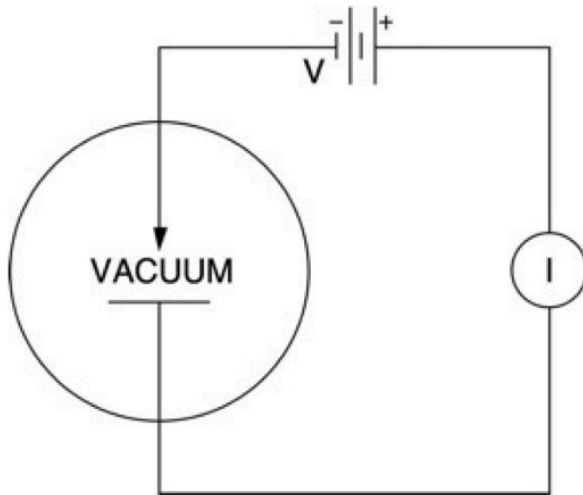


$$E_{kin} \sim 4kT_{Solid}$$

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

$$\begin{aligned} \varepsilon_{nx} &= \gamma\beta\sigma_x\sigma_{x'} \\ &= \gamma\beta\sigma_x 1\text{rad} \end{aligned}$$

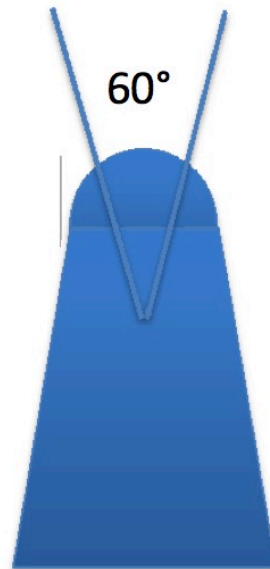
Field Emitter Sources



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

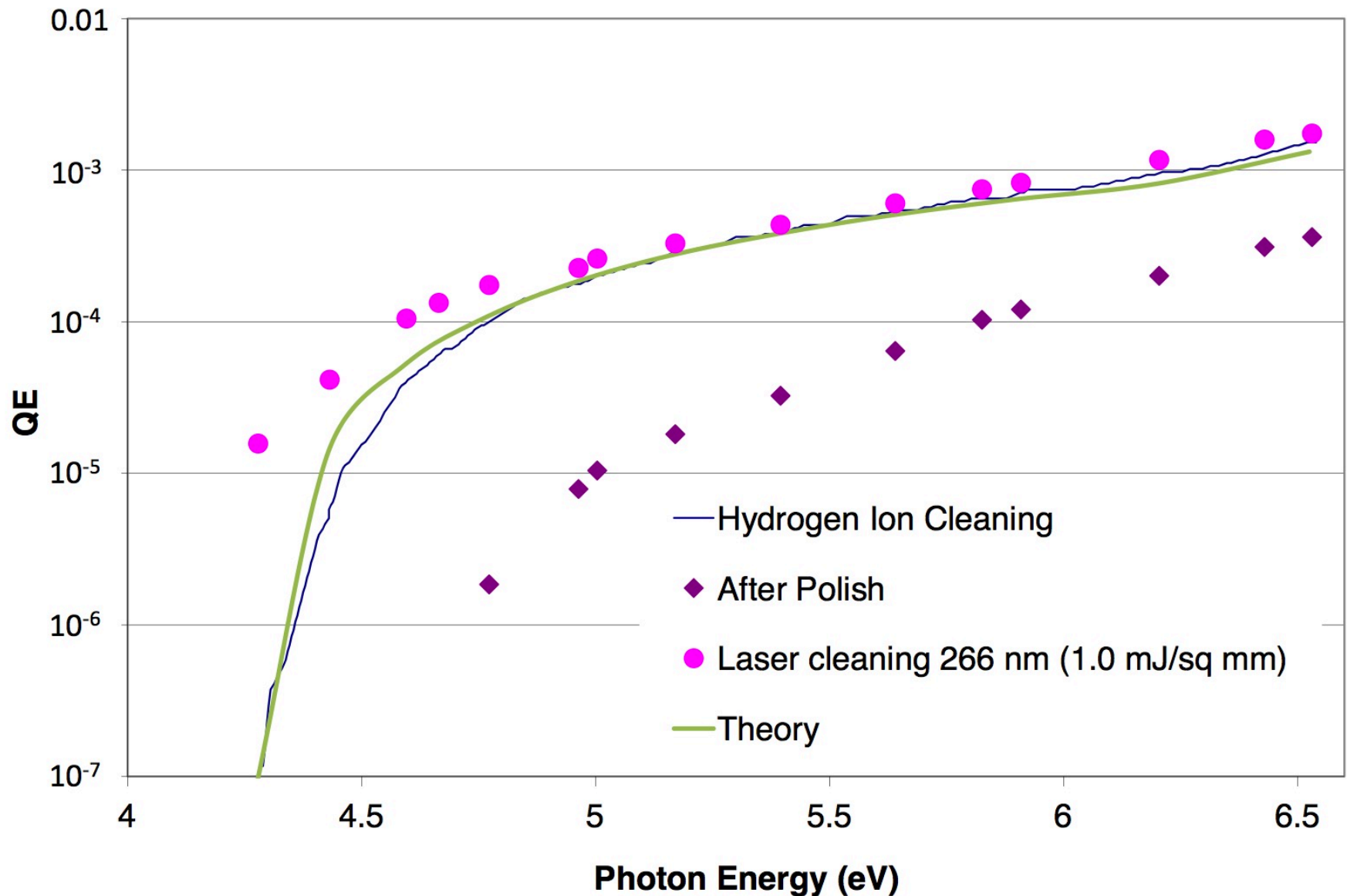
Vacuum diode

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



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

LCLS Copper Cathodes



Cs₂Te

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:**

$$J_{CL} = \frac{4}{9} \epsilon_0 \sqrt{\frac{2e}{m}} \frac{V^{3/2}}{d^2}$$

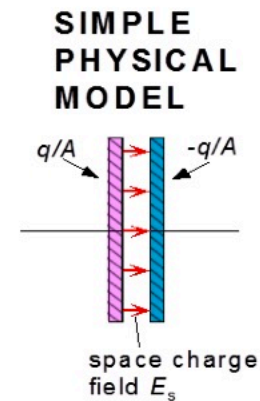
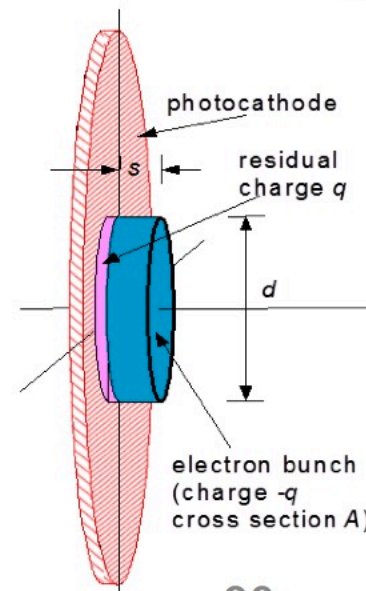
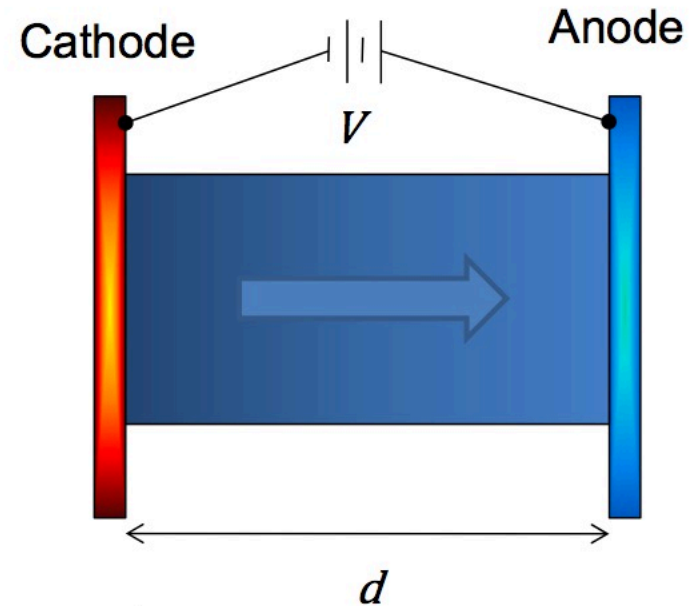
For more complicated geometries:

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

Where P

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

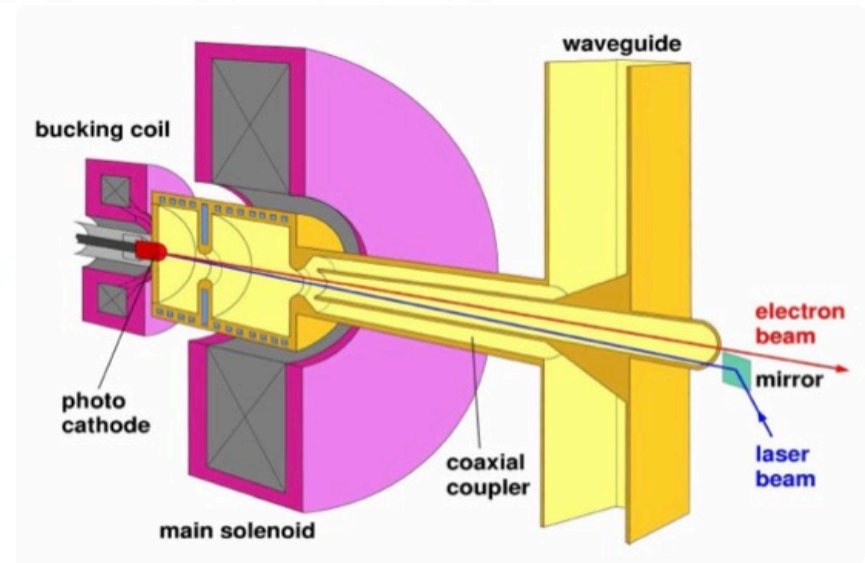
$$\sigma_{SCL} = \epsilon_0 E_{applied}$$



Drawing by A. Vetter

- Advantages

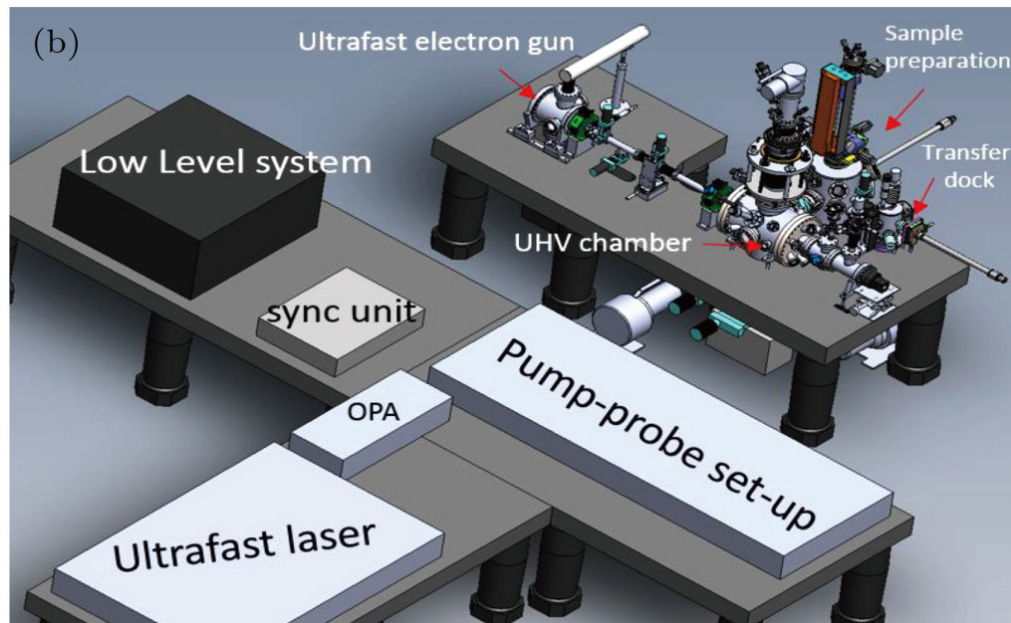
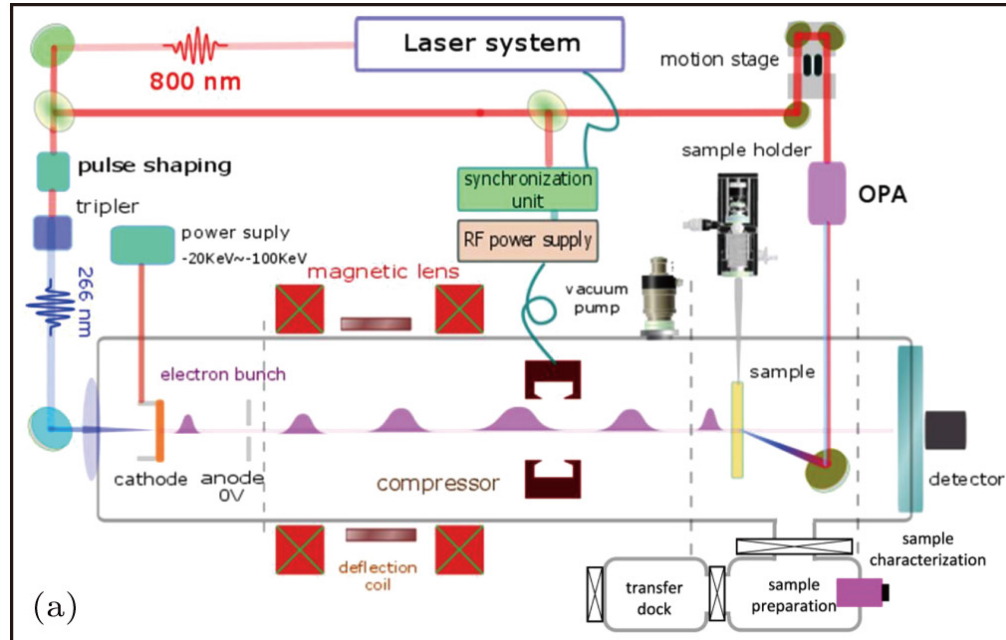
- high accel. gradient at cathode + good space charge compensation
→ high bunch charge
- medium beam energy
- lots of operating experience, emittance record



- Disadvantages

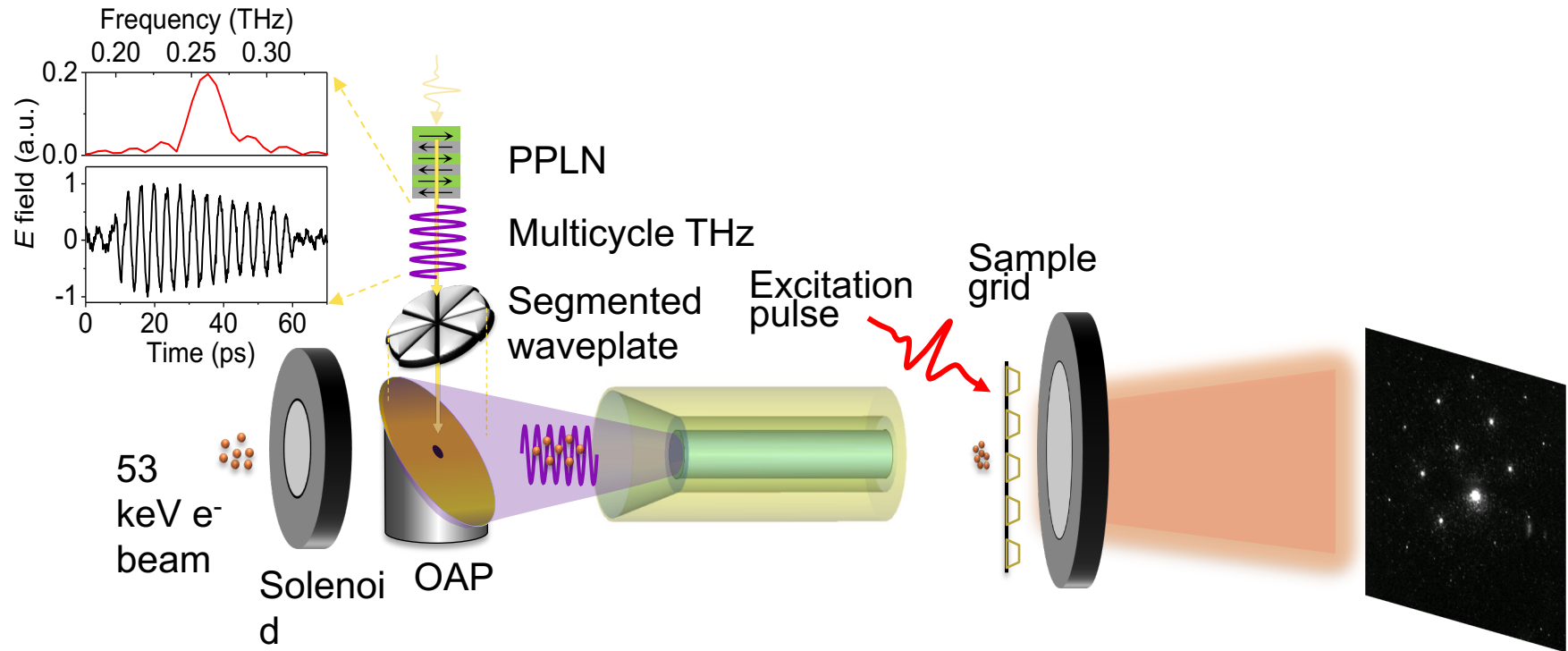
- medium vacuum conditions
- water cooling limits average RF power → broad range of average currents (RF frequency)

Ultrafast Electron Diffractometer



Xuan Wang and
Yutong Li 2018
Chinese Phys. B **27** 076102

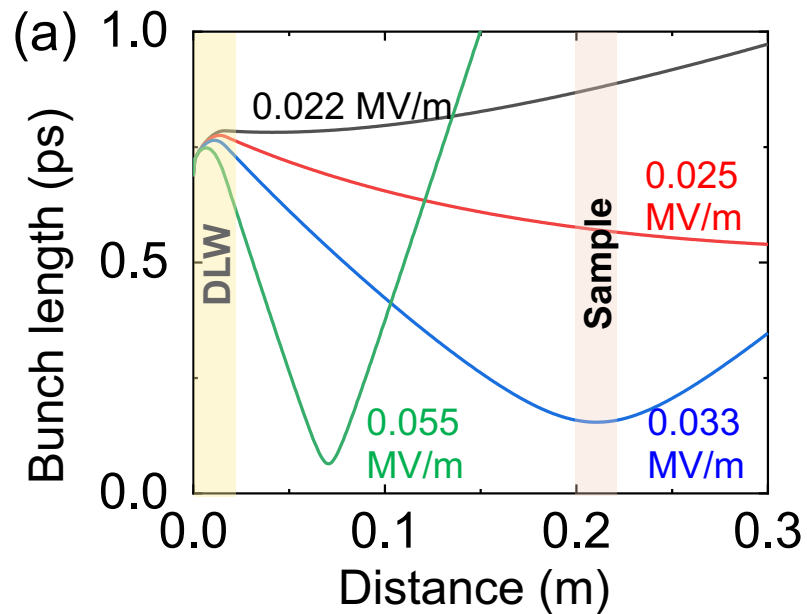
THz enhanced Ultrafast Electron Diffractometer



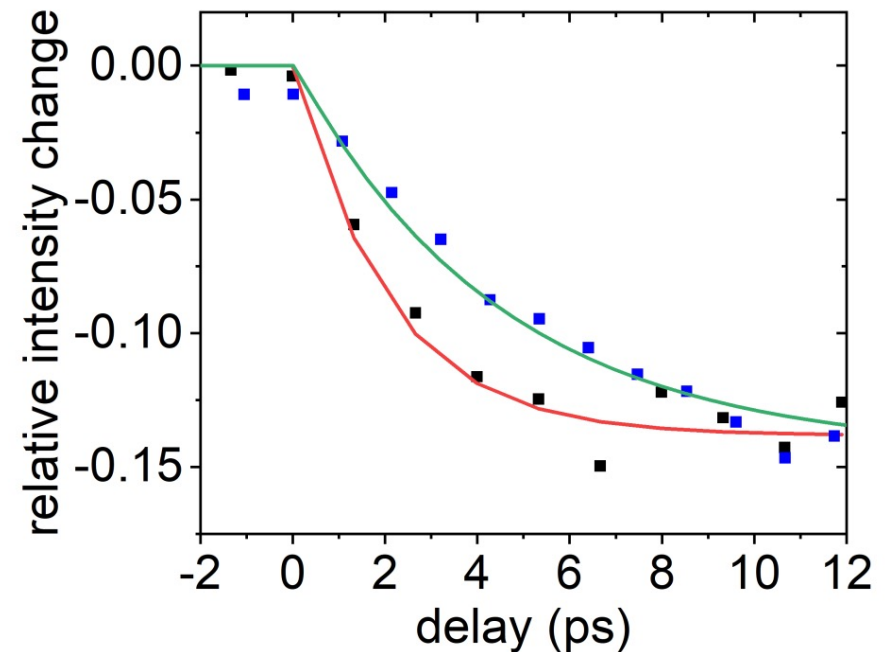
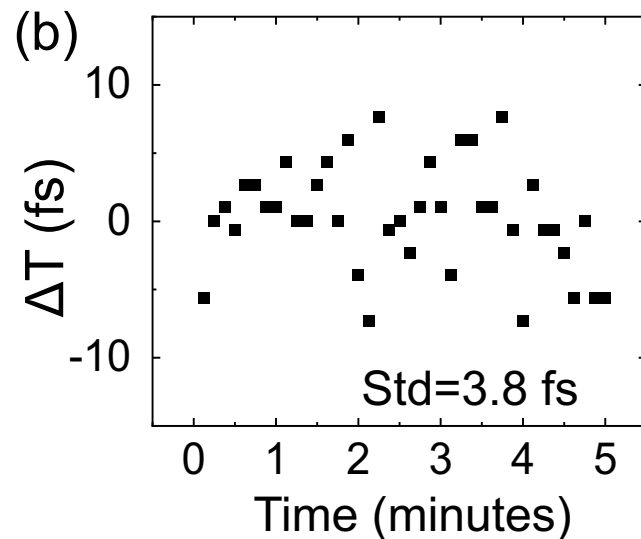
D. Zhang et al., to be published

D. Zhang et al., Phys. Rev. X 10, 011067 (2020).

Electron bunch compression



Melting of
Si-Crystal



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