High Brightness injectors

Houjun Qian, Zhangjiang Lab

qianhj@zjlab.ac.cn

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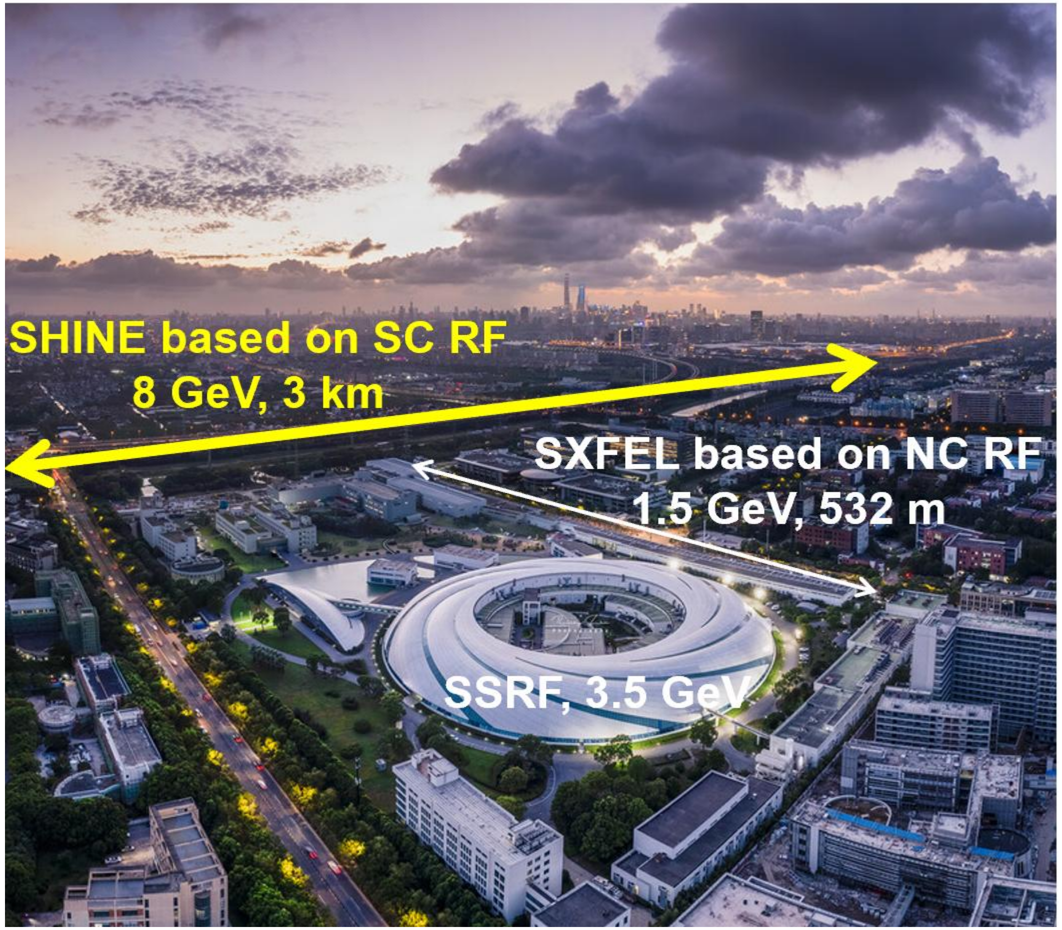


Outline

- Introduction
- Photoinjector basic theory
  - Layout
  - Cathode types
  - Gun types
  - Emittance compensation
- Review of pulsed photoinjectors
- Review of CW photoinjectors
- Photocathode and laser shaping
- Summary

Introduction

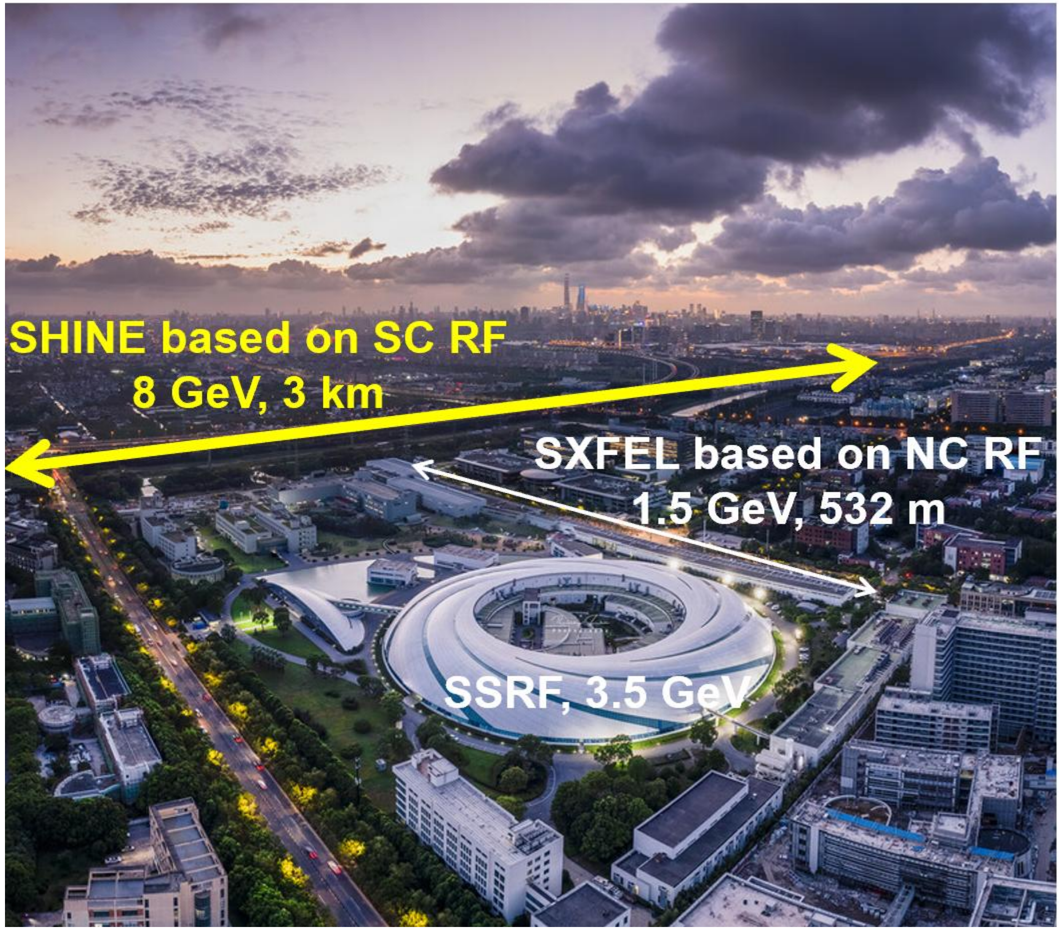
Three light sources @Shanghai Zhangjiang High-Tech Park

Three different injectors

- **Shanghai Synchrotron Radiation Facility**
  - 3.5 GeV, 3rd generation synchrotron
  - Open to user since 2009

- **Shanghai Soft X-ray Free Electron Laser**
  - 1.5 GeV, low rep rate FEL @ pulsed RF linac
  - Open to user since 2023

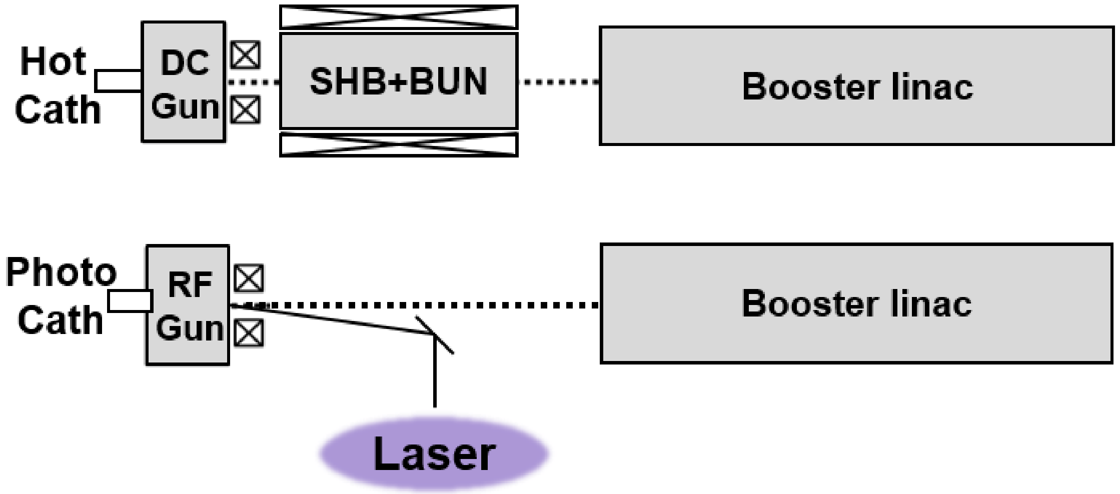
- **Shanghai HIgh repetitioN rate XFEL and Extreme light facility**
  - 8 GeV, MHz rep rate FEL @ CW SRF linac
  - In construction

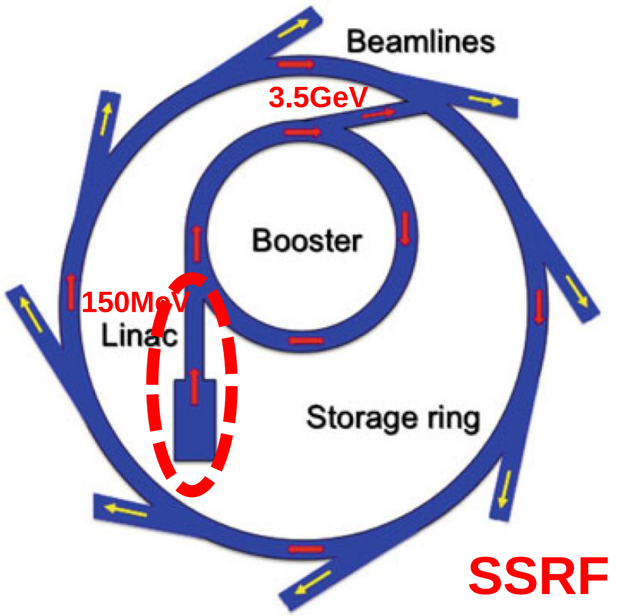


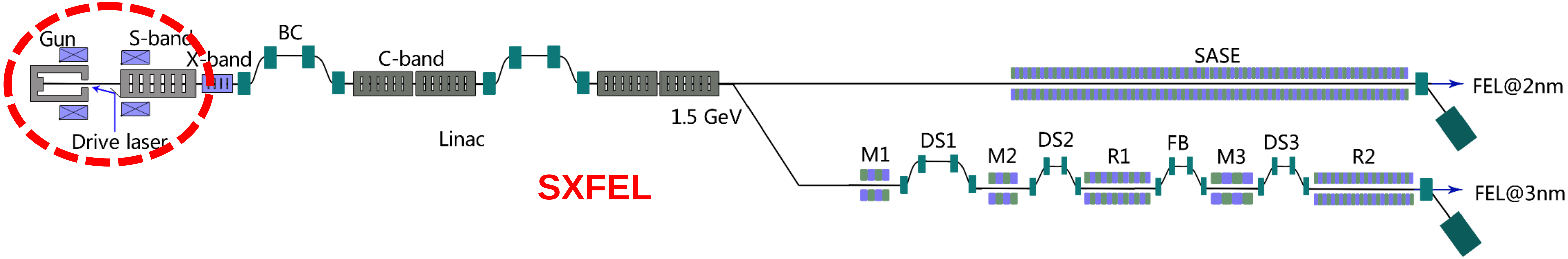
Electron injector for light sources

Two classical injectors

- **Synchrotron injector vs FEL injector**







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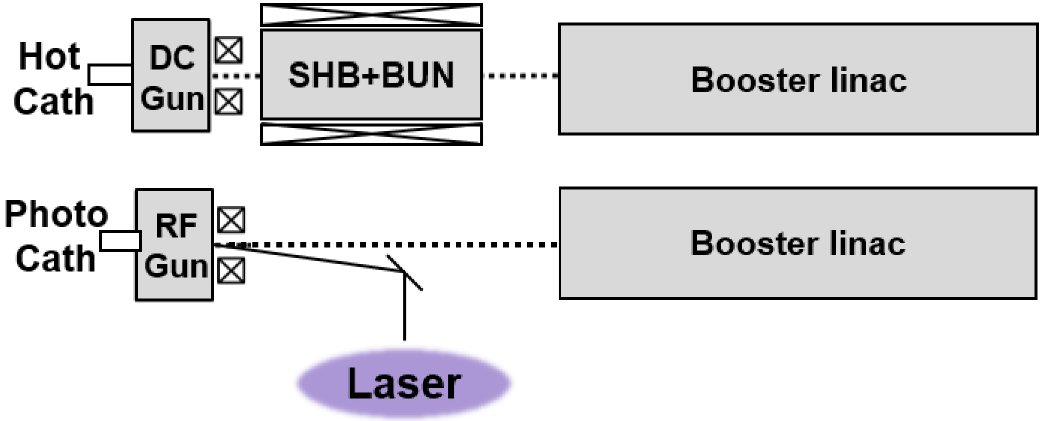


	SSRF injector	SXFEL injector	Units
Bunch charge Q	~0.6	~0.5	nC
Energy E_k	~150	~110	MeV
Energy spread σ_p/p	<0.5%	~0.1%	
Normalized rms $\varepsilon_{x,y}$	<50	~1	mm.mrad
Gun	DC gun	RF gun	
Cathode	Thermionic cathode	Photocathode	

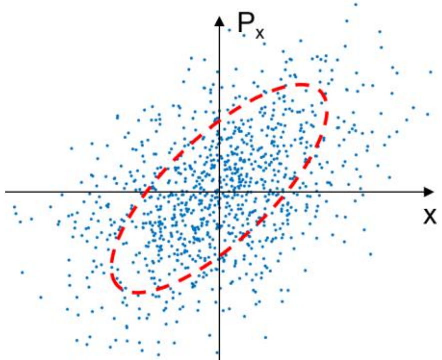
High brightness photoinjector

Emittance and brightness

- **2D RMS Emittance**

$$\varepsilon_x = \sqrt{\langle x^2\rangle\langle x'^2\rangle - \langle xx'\rangle^2}$$

$$\varepsilon_{n,x} = \sqrt{\langle x^2\rangle\langle p_{n,x}^2\rangle - \langle xp_{n,x}\rangle^2}$$



2D illustration

  - During linac acceleration, normalized emittance is conserved, geometry emittance gets smaller.
    - $x' = p_x/p_z = p_x/(\gamma\beta m_0 c)$
    - $p_{n,x} = p_x/(m_0 c)$
    - $\varepsilon_x = \varepsilon_{n,x}/\gamma\beta$
  - When <xx’>=0, $\varepsilon_x = \sigma_x\sigma_{x'}$ $\varepsilon_{n,x} = \sigma_x\sigma_{p_{n,x}}$

- **2D phase space density distribution**

$$f(x,x') = \frac{Q}{2\pi\varepsilon_x} e^{-\frac{\gamma x^2 + 2\alpha x x' + \beta x'^2}{2\varepsilon_x}}$$

  - Twiss parameters
    - $\beta = \frac{\langle x^2\rangle}{\varepsilon_x}$ $\gamma = \frac{\langle x'^2\rangle}{\varepsilon_x}$ $\alpha = -\frac{\langle xx'^2\rangle}{\varepsilon_x}$
  - RMS emittance ellipse
    - $\gamma x^2 + 2\alpha x x' + \beta x'^2 = \varepsilon_x$
    - $1 * \varepsilon_x$ → 39% electrons
    - $4 * \varepsilon_x$ → 87% electrons
    - $9 * \varepsilon_x$ → 99% electrons

High brightness photoinjector

Emittance and brightness

- **2D RMS Emittance**

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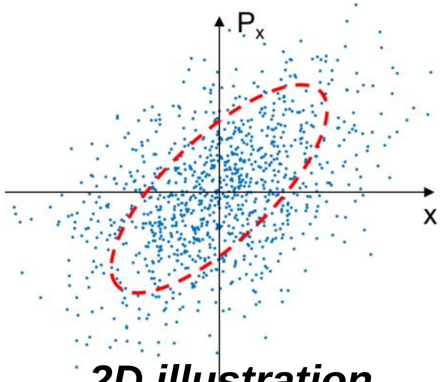

2D illustration

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- When <xx'>=0, $\varepsilon_x = \sigma_x\sigma_{x'}$, $\varepsilon_{n,x} = \sigma_x\sigma_{p_{n,x}}$

- **2D phase space density distribution**

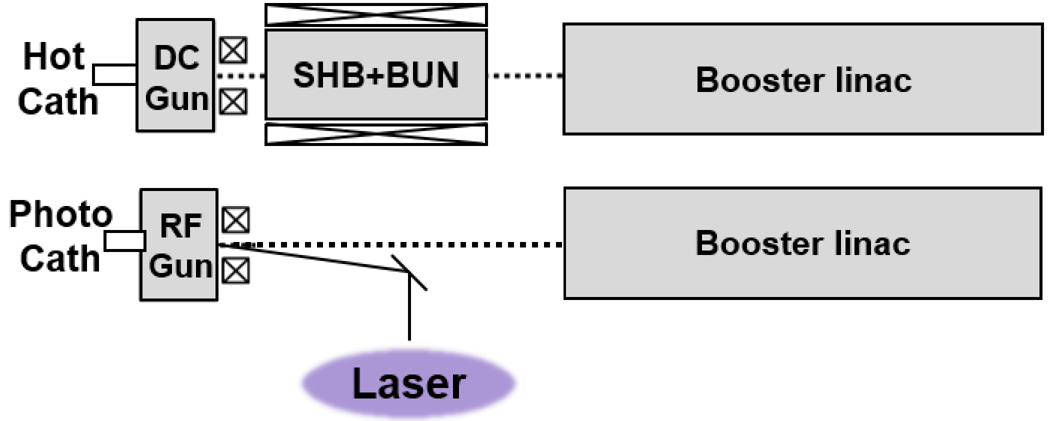
$$f(x,x') = \frac{Q}{2\pi\varepsilon_{g,x}} e^{-\frac{\gamma x^2 + 2\alpha x x' + \beta x'^2}{2\varepsilon_0}}$$

- Brightness in normalized phase space
  - Peak $B_{n,2D} \sim \frac{Q}{\varepsilon_{nx}}$
  - Peak $B_{n,4D} \sim \frac{Q}{\varepsilon_{nx}\varepsilon_{ny}}$
  - Peak $B_{n,6D} \sim \frac{Q}{\varepsilon_{nx}\varepsilon_{ny}\varepsilon_{nz}} \sim \frac{I_{peak}/\sigma_p}{\varepsilon_{nx}\varepsilon_{ny}}$
  - Peak $B_{n,5D} = \frac{I_{peak}}{\varepsilon_{nx}\varepsilon_{ny}}$
    - Photoinjector slice σ_p too low for XFEL applications, drives μBI, needs heating.

Electron injector for light sources

Two classical injectors

- **Synchrotron injector vs FEL injector**



$$\frac{B_{n,4D}(SXFEL\ INJ)}{B_{n,4D}(SSRF\ INJ)} \sim 2000$$

	SSRF injector	SXFEL injector	Units
Bunch charge Q	~0.6	~0.5	nC
Energy E_k	~150	~110	MeV
Energy spread σ_p/p	<0.5%	~0.1%	
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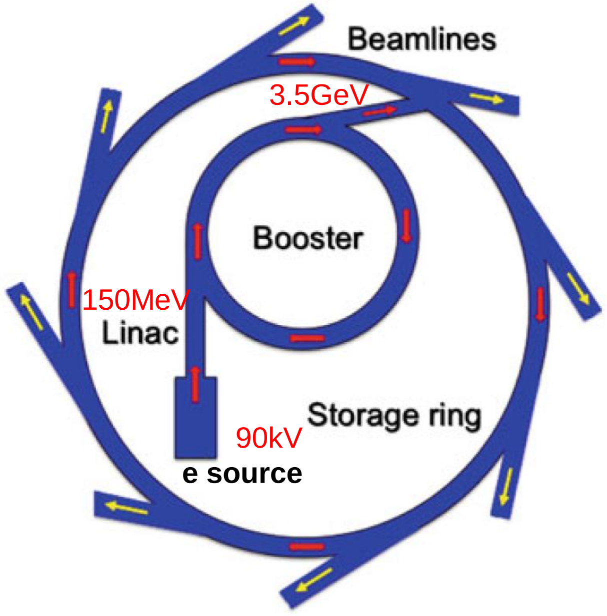
Gun	DC gun	RF gun	
Cathode	Thermionic cathode	Photocathode	

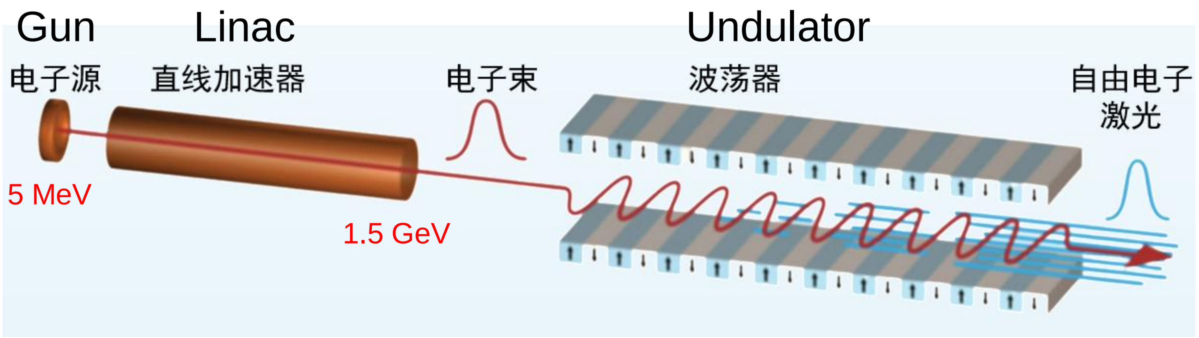
FEL needs high brightness injectors

Ideal injector emittance for FEL

- **Synchrotron vs linac emittance**
  - **SSRF** is based on storage ring, equilibrium beam emittance is decided by ring lattice, not by injector emittance.
  - **SXFEL** is based on single pass linac, beam emittance upper limit is injector emittance.



SSRF



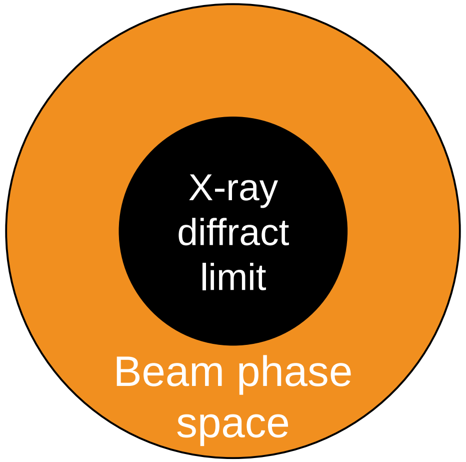
SXFEL

FEL needs high brightness injectors

Transverse beam brightness and emittance

- **X-ray FEL injector requirements**
  - **Low emittance**: <1 mm.mrad

$$\varepsilon_x = \frac{\varepsilon_{n,x}}{\gamma} \sim \frac{\lambda}{4\pi} * 2$$



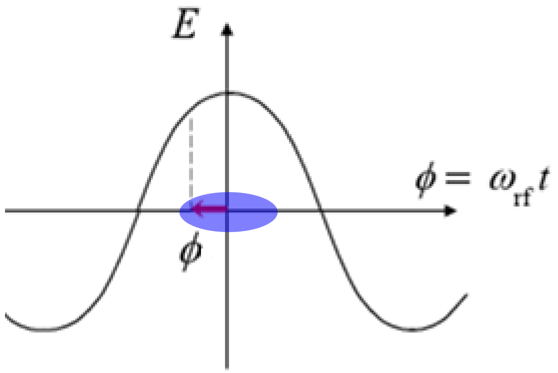
	Charge pC	Ek GeV	Wavlength nm	Emittance mm.mrad
SXFEL	250~500	1.5	2	0.93
SHINE	50~100	8	0.1	0.25

SSRF injector, or typical thermionic injector emittance is far from X-ray FEL injector requirements.

FEL needs high brightness injectors

Longitudinal beam brightness

- **X-ray FEL injector requirements**
  - **High peak current**: 10~50 A
    - FEL bunch charge typically 100-500 pC
    - Bunch length typically <10 ps FWHM, corresponding to 5~10 degrees main linac RF phase, reduces 2nd order energy spread
    - Higher injector current reduces linac bunch length compression factor
  - **Low slice energy spread**: 5~10 keV (~0.01%@100 MeV)
    - Reduces final energy spread, $\frac{I_{linac}}{I_{inj}}\sigma_{p,inj}$
    - Take SXFEL as an example, $\frac{700A}{50A}\sigma_{p,inj} < 0.01\%$
      - Good for seeded FEL, reduces seed laser power, leads to high harmonic FEL conversion efficiency
  - **High longitudinal brightness** $\mathrm{I}_{inj}/\sigma_{p,inj}$ **2~10 A/keV**



$$E = E_{inj} + E_{linac}\cos(\phi)$$
$$= E_{inj} + E_{linac}(1 - \tfrac{1}{2}\phi^2)$$
$$\frac{\sigma_E}{E} \approx \frac{\sigma_\phi^2}{\sqrt{2}}$$

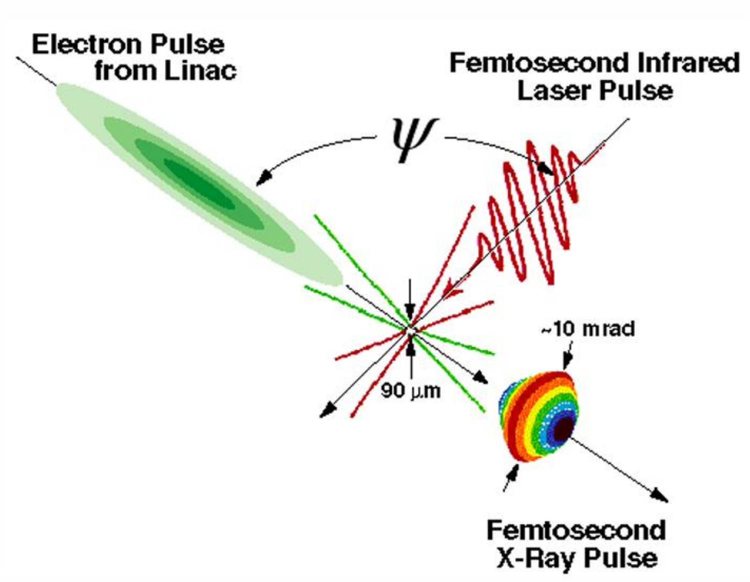
For 1.3 GHz, 10 ps → 5° → 0.08%

For 2.856 GHz, 10 ps →10°→ 0.36%

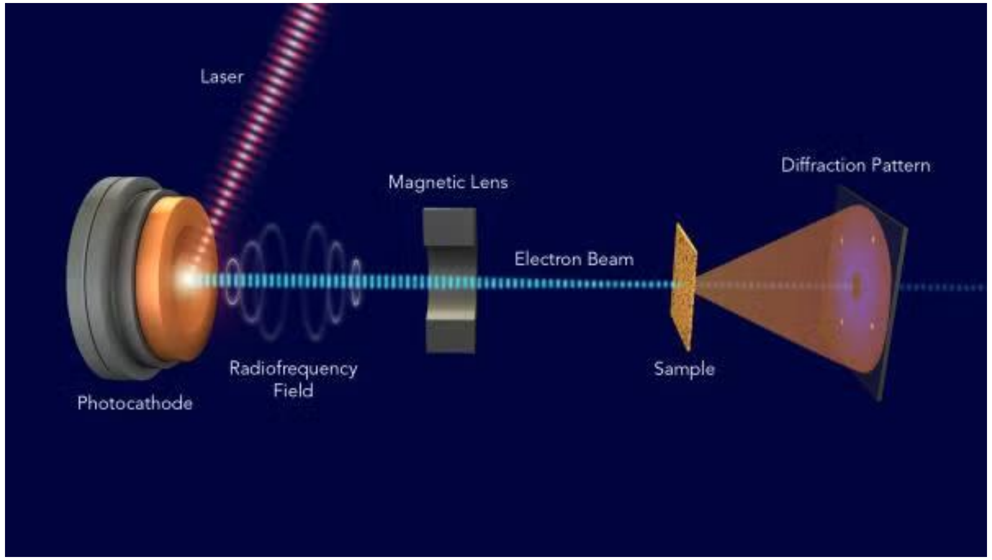
Photoinjector also benefits other applications

Thomson scattering, femtosecond electron diffraction

- **Thomson scattering**
  - Picosecond electron bunch @ <1nC
  - Emittance ~1 mm.mrad
  - Beam energy ~100 MeV
  - Low energy spread



- **Femtosecond electron diffraction**
  - Short electron duration <100 fs rms @ 10-100 fC
  - Low emittance <100 nm.rad
  - Beam energy ~3 MeV
  - Low energy spread



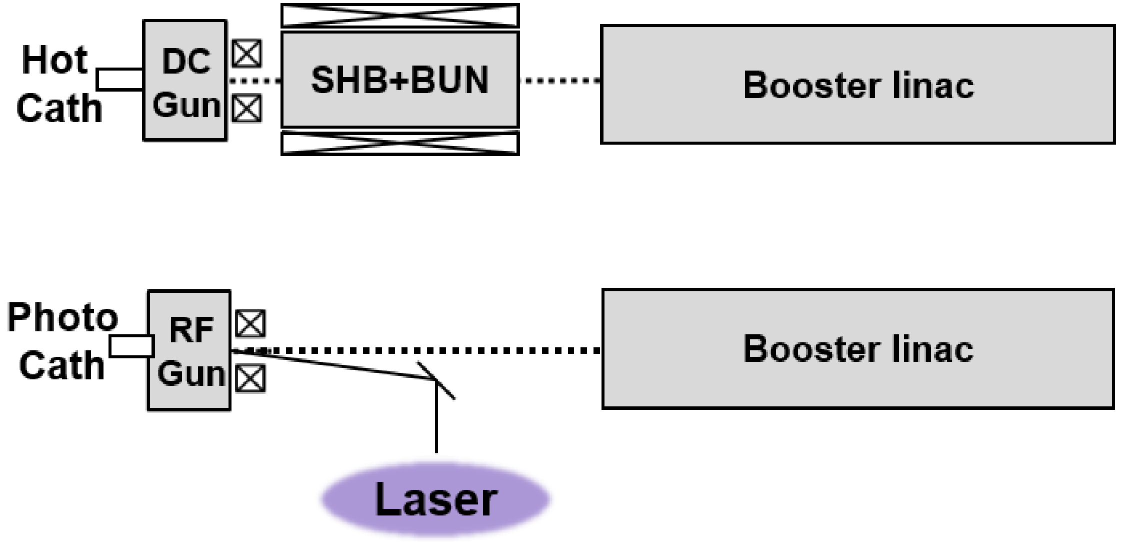
Photoinjector basic theory

Advantage of photoemission

Much Larger emission current density

- **Thermionic emission vs photoemission**

	Hot cathode (SSRF)	Photocathode (SXFEL)	Unit
Excitation	Heat (~10^3 K)	UV laser	
$I_{emission}$	~1	~50	A
t_{FWHM}	1~10	~0.010	ns
Emission D	8	2	mm
$J=I_{em}/A$	~1	~1600	A/cm^2
$\varepsilon_{n,th}/\sigma_{em}$	~0.5	0.5~1	mrad

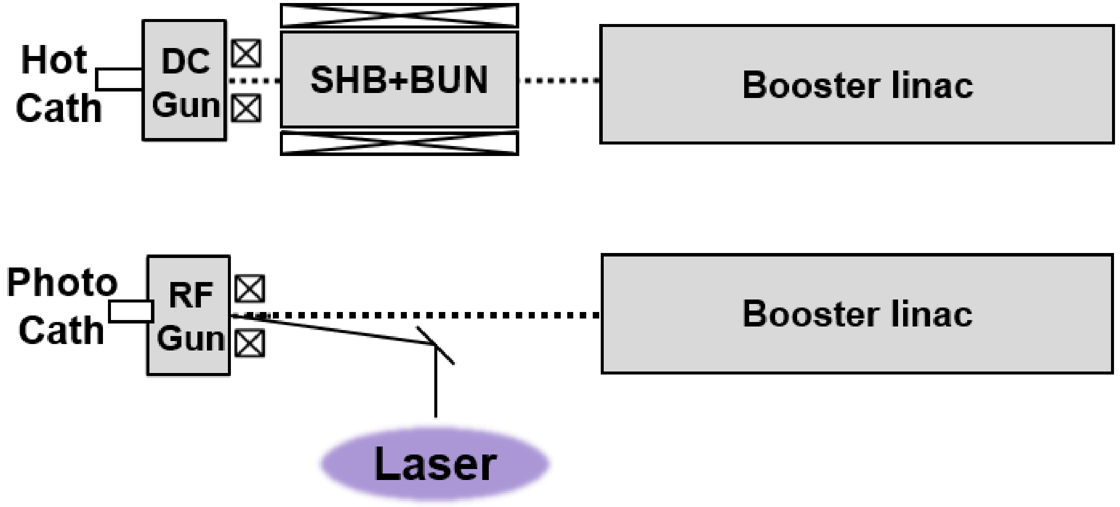


- $Q_{bunch} = \boldsymbol{J} * A * t$
  - Large emission density J (~10^3)
  - Shorter emission time t (~10^{-2}) → direct bunching @cathode
  - Smaller emission area A (~10^{-1}) → lower emission emittance (~$\sqrt{A}$)
  - Laser excitation: flexible e beam 6D manipulation, spatial, temporal, momentum, bunch pattern, charge

Advantage of photoemission

Direct cathode bunching leads to emittance reduction

- $Q_{bunch} = \boldsymbol{J} * A * t$
  - Shorter emission time t (~10^{-2})
    - Direct bunching @cathode, NO buncher section
    - Immediate high gradient RF acceleration from gun, reduce emittance growth by acceleration
      - Space charge force ($F_{spch} \sim \frac{1}{\gamma^2}$)
      - Energy spread ($\frac{\sigma_p}{p_z} \sim \frac{1}{\gamma}$)
      - RF focusing ($\sim k_{rf}\sigma_z$)
      - Beam divergence ($\frac{p_x}{p_z} \sim \frac{1}{\gamma}$) and beam size ($\sqrt{\beta \frac{\varepsilon_n}{\gamma}}$)

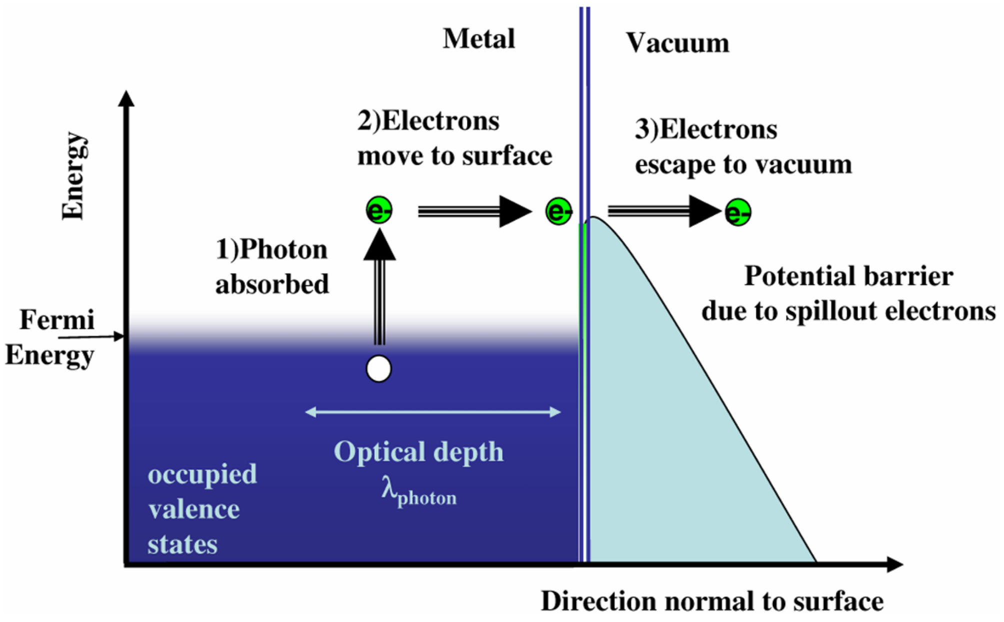


$$\Delta\varepsilon_{n,x} = \Delta\sigma_x * \sigma_{p_x} + \sigma_x * \Delta\sigma_{p_x}$$

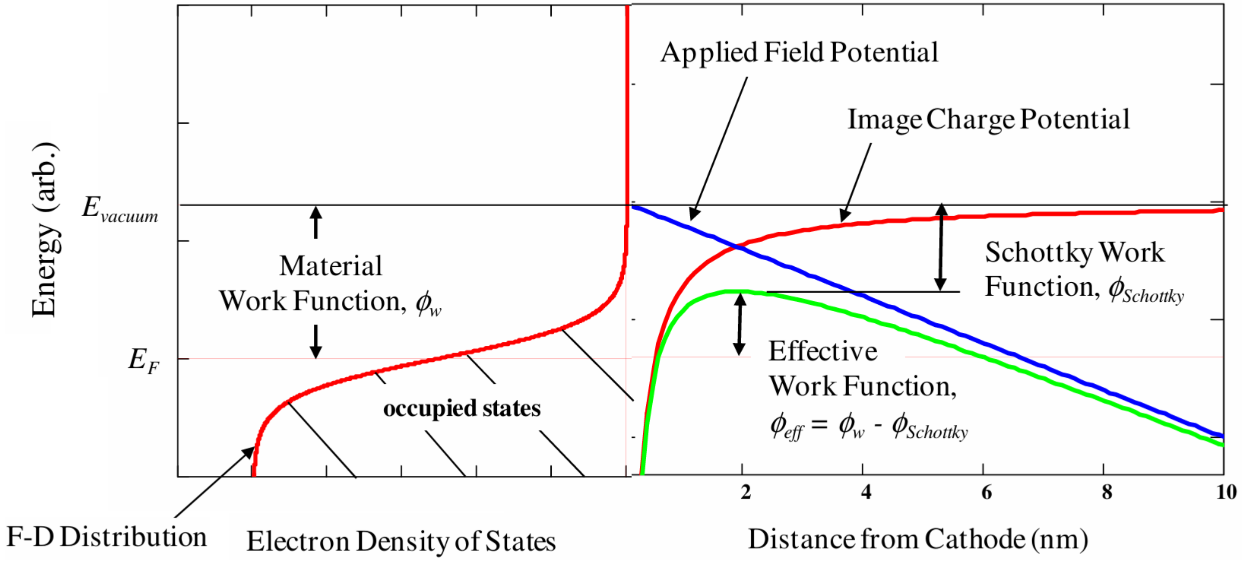
Photoemission physics

Three step model

- **Three step model of photoemission**
  - Photon absorption by electron
  - Electron transport to the surface
  - Electron escape through vacuum barrier



- **QE and thermal emittance derivations**
  - F-D distribution $f_{\mathrm{FD}}(E) = \frac{1}{1 + e^{(E-E_F)/k_B T}}$
    - Room temperature $k_B T$ ~ 26 meV @ 300K
    - Hot cathode $k_B T$ ~ 130 meV @ 1500K
    - Far from fermi surface level E_F, electron density states drop exponentially



D. Dowell et al., *PRAB* **12**, 074201 (2019)

Photoemission physics

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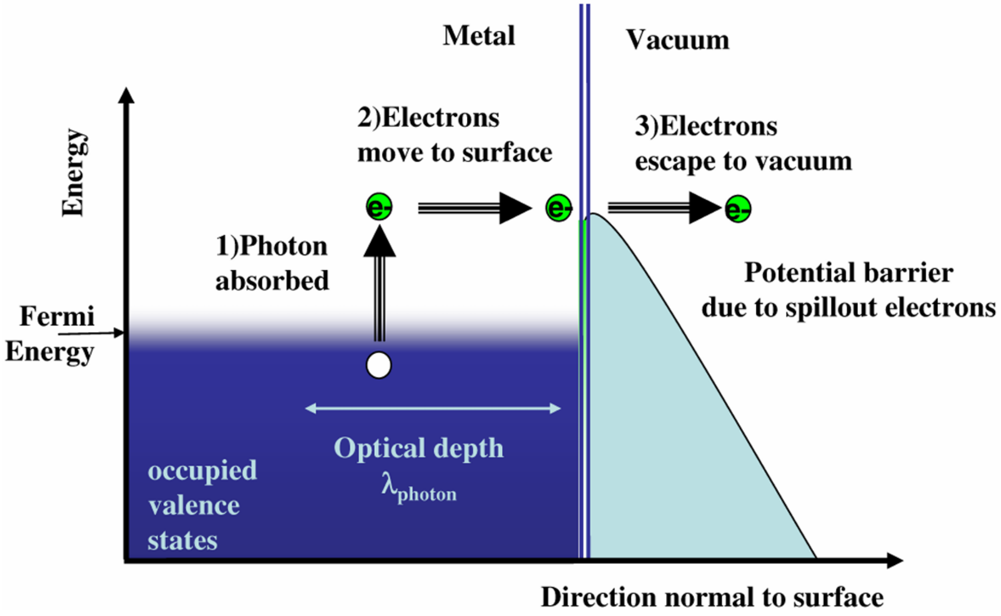
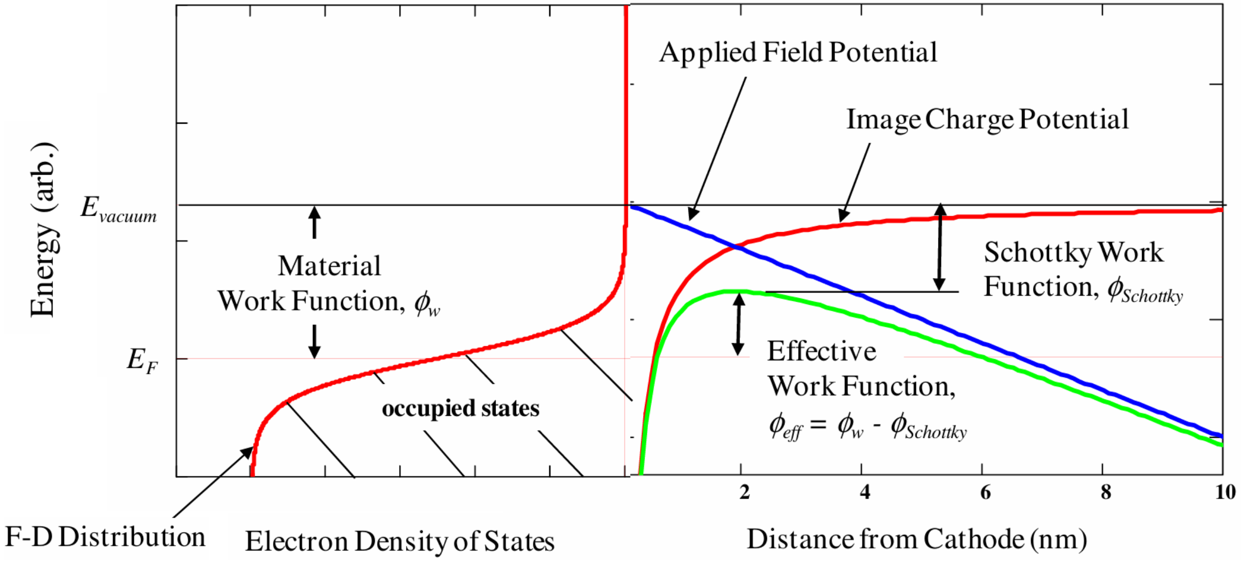


- **QE and thermal emittance derivations**
  - Effective work function
    - e.g. 50 MV/m, $\phi_{schottky}$ ~268 meV, significant effect for threshold photoemission

$$\phi_{\mathrm{eff}} \equiv \phi_w - \phi_{\mathrm{Schottky}} = \phi_w - e\sqrt{\frac{eF_a}{4\pi\varepsilon_0}}$$

$$= \phi_w - 0.037\,947\sqrt{F_a\ (\mathrm{MV/m})}\ \mathrm{eV}$$

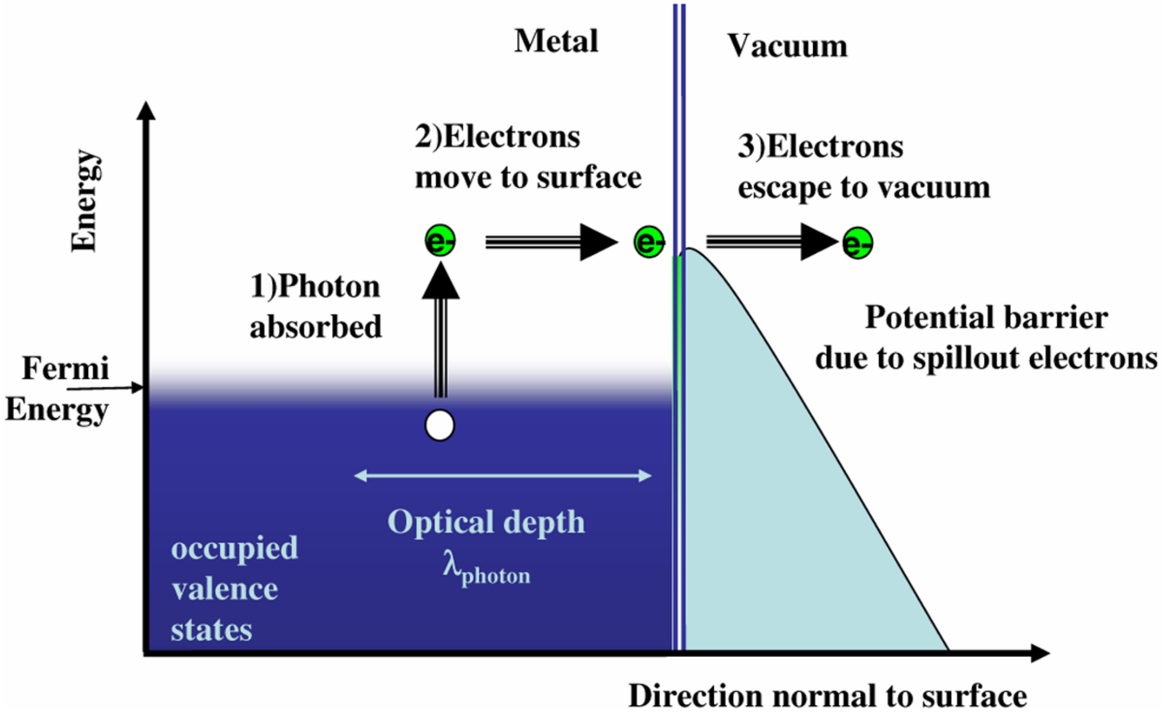


D. Dowell et al., *PRAB* **12**, 074201 (2019)

Photoemission physics

Three step model

- **Three step model of photoemission**
  - Photon absorption
  - Electron drifts to surface
  - Electron escape to vacuum



- **Main conclusions**
  - $\hbar\omega - \phi_{eff} > \mathrm{k_B T}$

$$QE = \frac{1-R(\omega)}{1+\frac{\lambda_{opt}(\omega)}{\lambda_{e-e}(\omega)}} \frac{(\hbar\omega - \phi_{eff})^2}{8\phi_{eff}(E_F+\phi_{eff})}$$

Square dependent

$$\varepsilon_{th} = \sigma_{laser}\sqrt{\frac{\hbar\omega - \phi_{eff}}{3mc^2}}$$

Square root dependent

  - $\hbar\omega - \phi_{eff} \sim 0$ $\quad \epsilon_{thermionic} = \sigma_x \sqrt{\frac{k_B T}{mc^2}}$
  - **M**ean **T**ransverse **E**nergy (MTE)

$$\varepsilon_{th} = \sigma_{laser}\sqrt{\frac{MTE}{mc^2}}$$

D. Dowell et al., *PRAB* **12**, 074201 (2019)

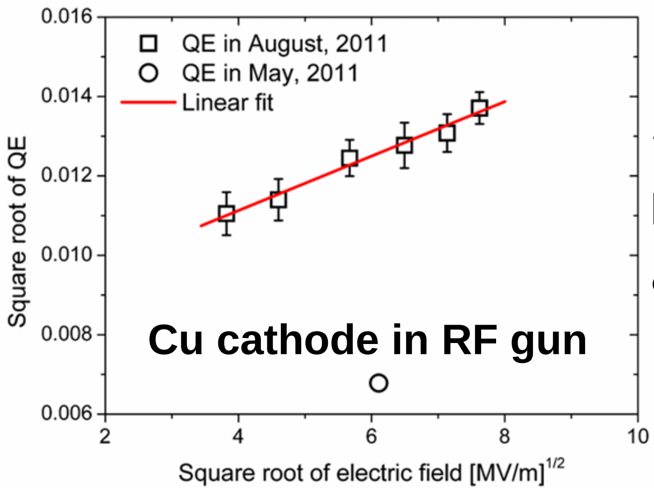
Photoemission physics

Online cathode measurements

- **Work function**

$$QE = A\left(\frac{\hbar\omega - \phi_w}{e\sqrt{e\beta/(4\pi\varepsilon_0)}} + \sqrt{E}\right)^2 = A(p + \sqrt{E})^2$$

$$\hbar\,\omega - \phi_w = e\sqrt{\frac{e}{4\pi\varepsilon_0}}\,p$$



$\hbar\omega$ = 4.66 eV

p = 12.2 (MV/m)$^{0.5}$

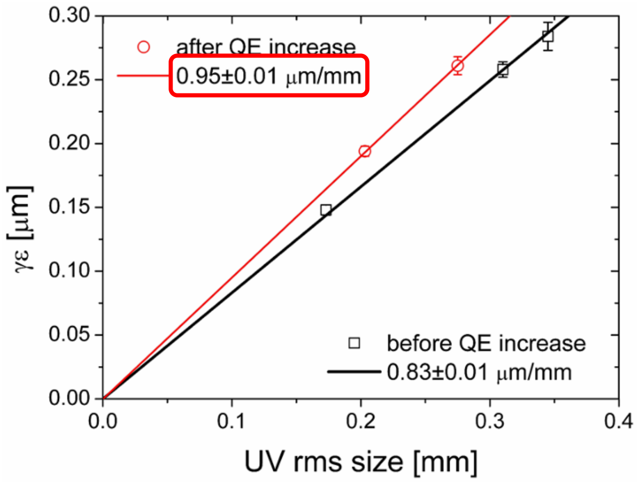
ϕ_w = 4.16 eV

Literature ϕ_w=4.65 eV

- **Thermal emittance**

$$\varepsilon_{th} = \sigma_{laser}\sqrt{\frac{\hbar\omega - \phi_{eff}}{3mc^2}}$$

Theory $\frac{\varepsilon_{th}}{\sigma_{laser}}$=0.67 µm.rad/mm



$\hbar\omega$ = 4.66 eV

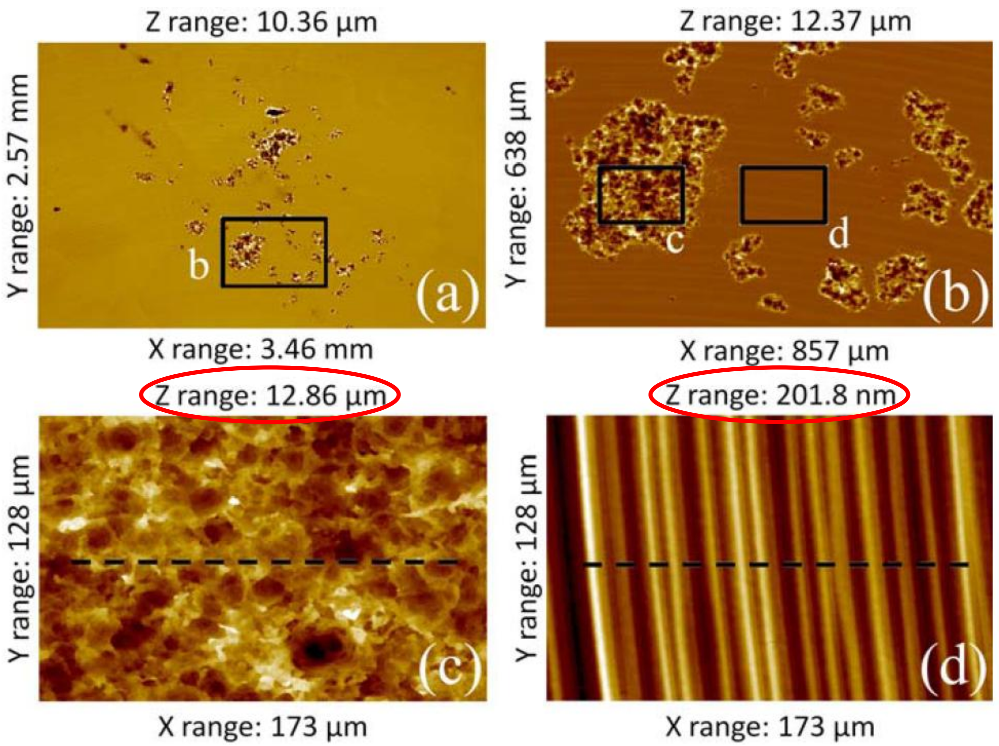
ϕ_w = 4.16 eV

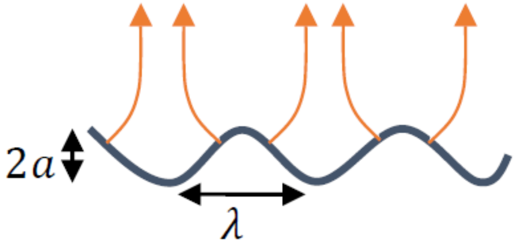
E = 26 MV/m

H. J. Qian et al., *PRAB* **15**, 040102 (2012)

Photoemission physics

Cathode surface roughness effects



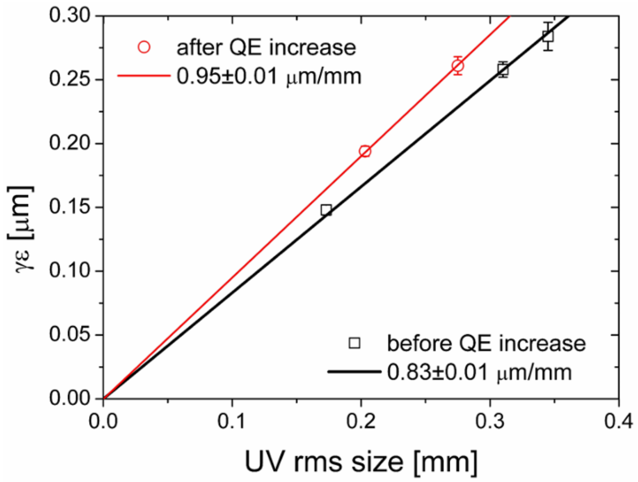


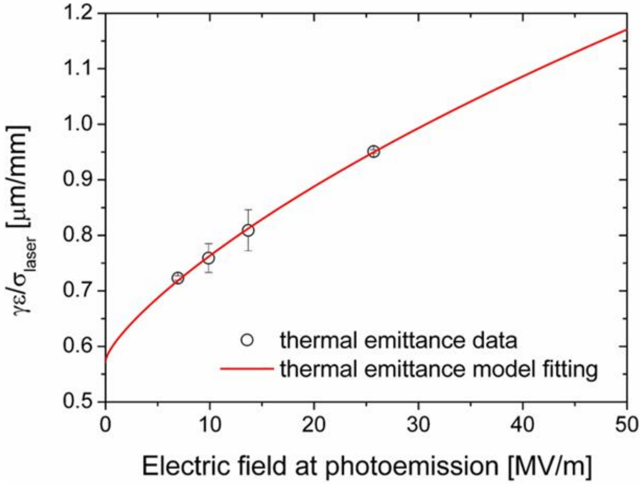
$$\varepsilon_{rough} = \sigma_{laser}\sqrt{\frac{e\pi^2}{2mc^2}\frac{a^2}{\lambda}E}$$

- **Surface roughness leads to thermal emittance growth**

$$\frac{\varepsilon_{\text{thermal}}^{\text{total}}}{\sigma_{\text{laser}}} = \sqrt{\varepsilon_{\text{smooth}}^2 + (\Delta\varepsilon_{\text{roughness}}^{E\text{-field}})^2}/\sigma_{\text{laser}}$$

$$= \sqrt{\frac{1}{3mc^2}\left(\hbar\omega - \phi_w + e\sqrt{\frac{e\beta}{4\pi\varepsilon_0}}\sqrt{E} + X_g E\right)}.$$





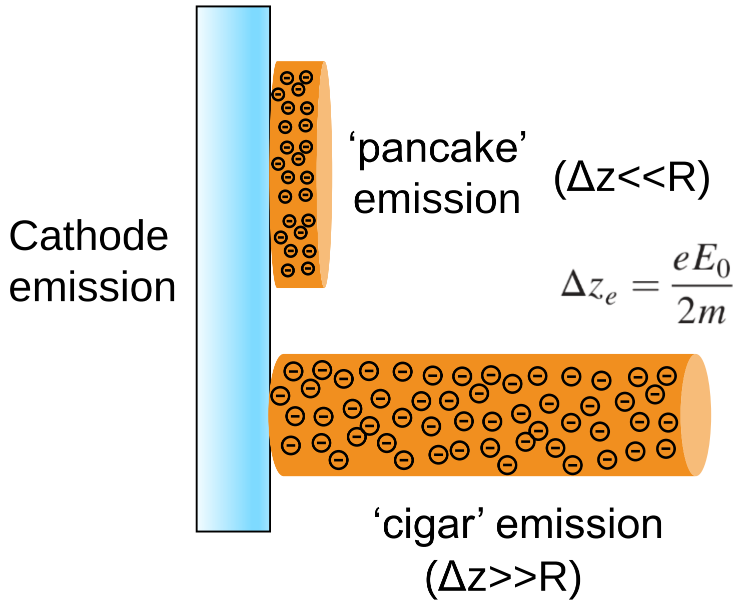
H. J. Qian et al., *PRAB* **15**, 040102 (2012)

Photoemission physics

I. V. Bazarovet al., *PRL* **102**, 104801 (2009)
D. Filippetto et al., *PRAB* **17**, 024201 (2014)

Two types guns, two types of emission regimes and injector layouts

- Two types of guns
  - High freq. high field gun (pulsed RF gun)
    - 100~60 MV/m
    - RF bunching
  - DC or low frequency gun (CW gun)
    - 25~5 MV/m
    - No RF bunching



$$\Delta z_e = \frac{eE_0}{2m}\Delta t^2$$

- Two types of photoemission regimes
  - 'Pancake' emission

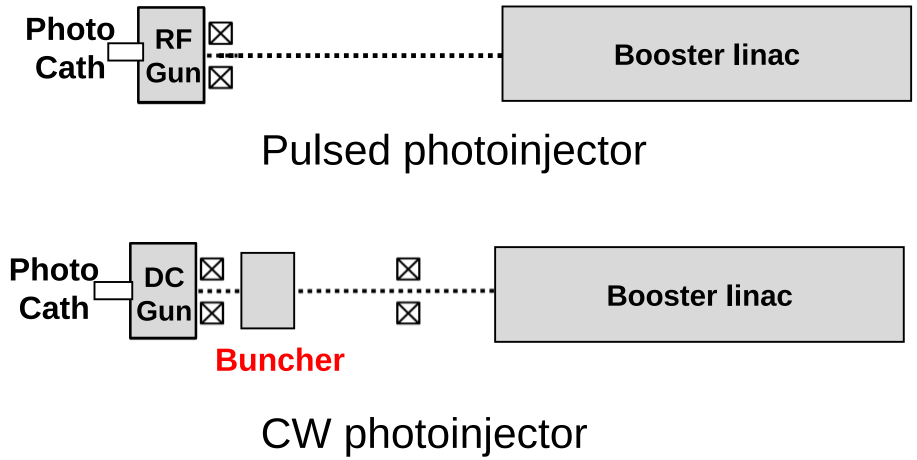
$$\frac{Q}{\varepsilon_n^2} \propto \frac{E_{emission}}{MTE}$$

→ High emission field, Low MTE cathode

  - 'Cigar' emission

$$\frac{Q}{\varepsilon_n^2} \propto \frac{E_{emission}^{1.5}}{MTE}\frac{t_{laser}}{\sqrt{R_{laser}}}$$

→ High emission field, Low MTE cathode, Lower emission current



Photoinjector emittance theory

Kim's RF gun theory

- Phase slippage and max acceleration
  - Electron has a phase slippage near the cathode due to low velocity $\phi = \omega t - kz + \phi_0 = \omega\left(t - \frac{z}{c}\right) + \phi_0$
  - Max acceleration in full cells $\phi(z)\sim 90°$
  - Emission phase ϕ_0 is ahead of 90°

$$\left(\frac{\pi}{2} - \phi_0\right) \sin \phi_0 = \frac{1}{2\alpha} \qquad \alpha = \frac{eE_0}{2mc^2k}$$

  - For S-band gun, 100 MV/m, max Ek emission phase ϕ_0 is about 30°, phase slippage $\Delta\phi$ is about 60°
  - By adjusting the cathode cell length, max Ek emission phase ϕ_0 can be adjusted.

$$E_z = E_0 \cos kz \sin(\omega t + \phi_0)$$

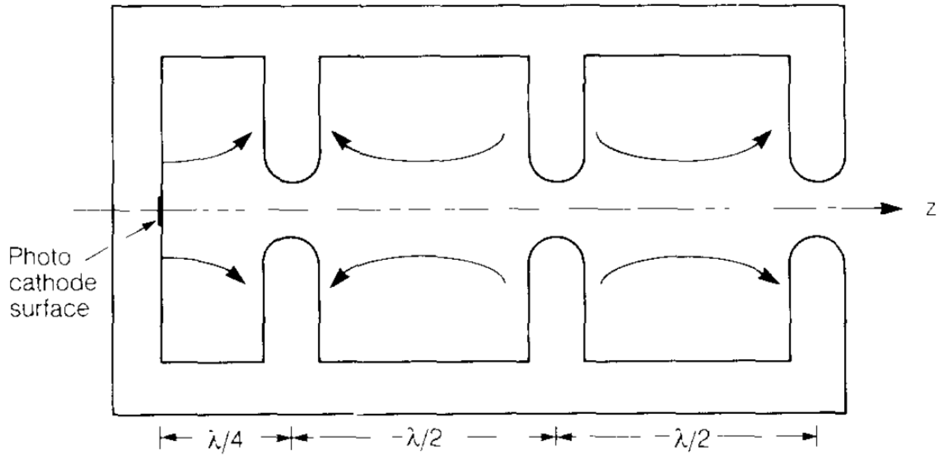


Fig. 1. Schematics of the rf laser gun.

B. Carlsten, NIMA 275, 201 (1989)

Photoinjector emittance theory

Kim's RF gun theory

- Phase slippage and cathode cell bunching
  - Beam is at off-crest phase, e.g. 30°, i.e. the beam is heavily chirped near the cathode
  - The R56 near cathode is quite high, R56=$\frac{L}{(\gamma^2-1)}$
  - Therefore a bunch compression is formed.

$$\frac{\Delta\phi_\infty}{\Delta\phi_0} = 1 - \frac{\cos\,\phi_0}{2\alpha\,\sin^2\phi_0}$$

$$E_z = E_0 \cos kz\, \sin(\omega t + \phi_0)$$

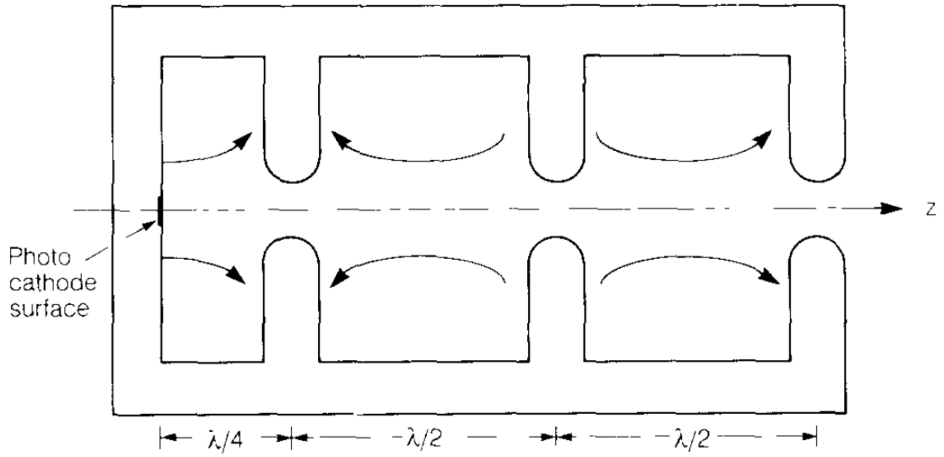


Fig. 1. Schematics of the rf laser gun.

B. Carlsten, NIMA 275, 201 (1989)

Photoinjector emittance theory

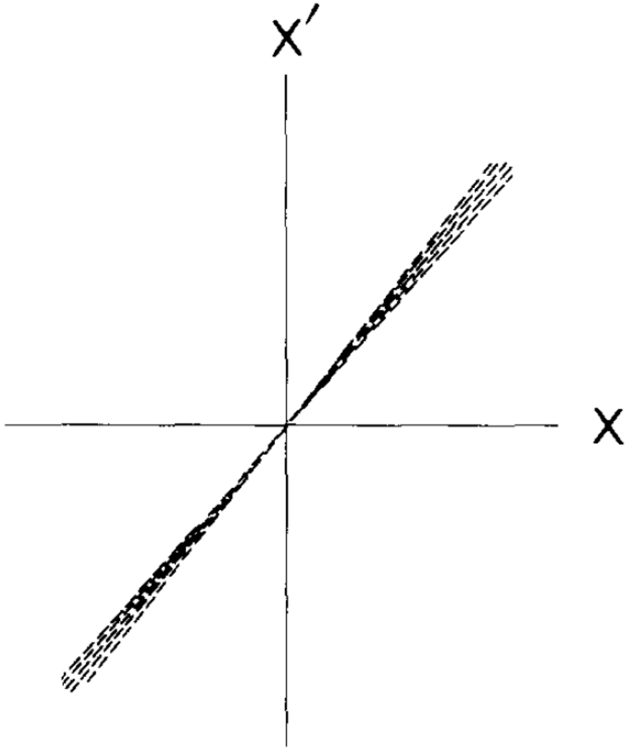
Kim's RF gun theory

- RF focusing emittance
  - Integrated RF focusing is

$$p_x \equiv \beta\gamma x' = (\alpha k \sin\phi)x$$

  - Assuming Gaussian distribution, minimum emittance growth is

$$\epsilon_x^{rf} = \frac{\alpha k \langle x^2 \rangle \sigma_\phi^2}{\sqrt{2}}, \quad \langle\phi\rangle = 90^\circ$$

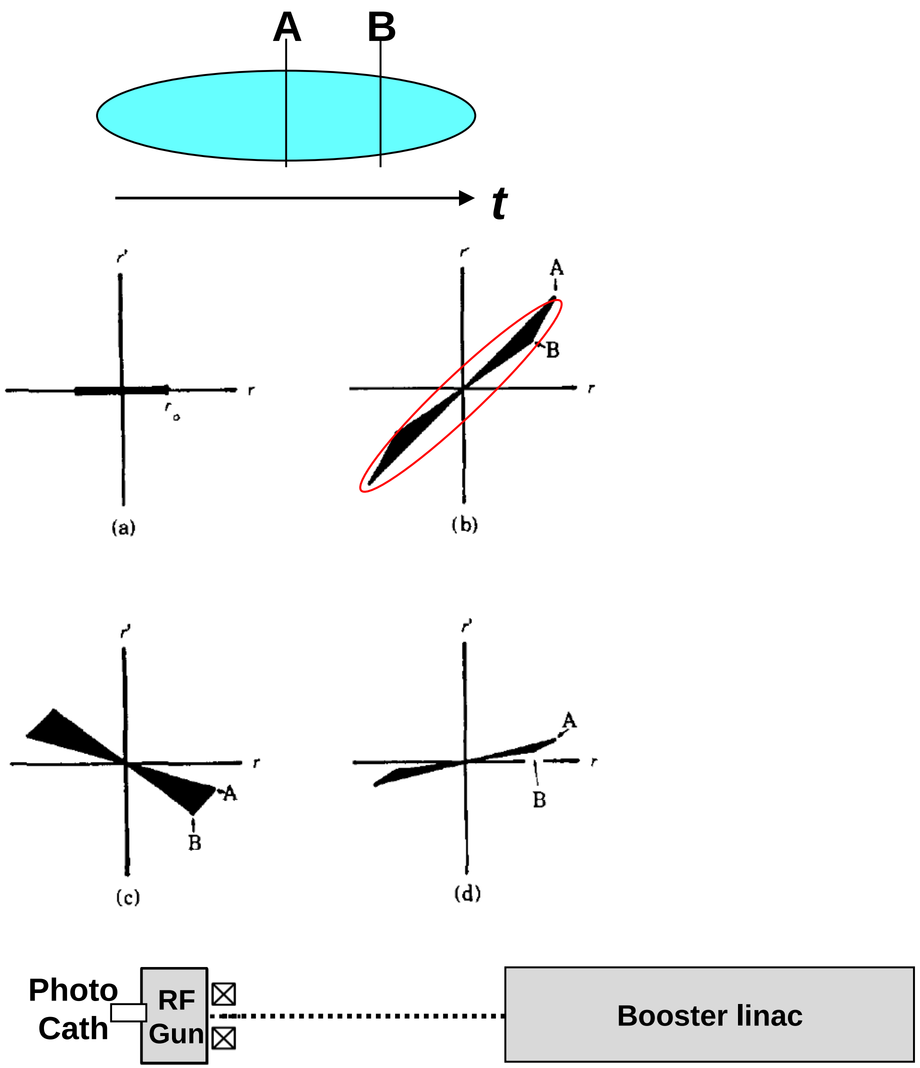


B. Carlsten, NIMA 275, 201 (1989)

Photoinjector emittance theory

Emittance compensation with a solenoid by B. E. Carlsten

- Projected emittance growth
  - Slice A and slice B has different charge density
  - Slice A diverges faster under higher charge defocusing
  - An correlated emittance growth occurs at (b)
- Solenoid focusing
  - Slice A and B become focusing slices
- After solenoid
  - Slice B with lower charge density experiences a beam waist in advance, and starts defocusing again
  - Slice B catches up, realigns with slice A (d), reaches an emittance minimum



B. Carlsten, NIMA 285, 313 (1989)

Photoinjector emittance theory

Emittance compensation with envelope equation analysis

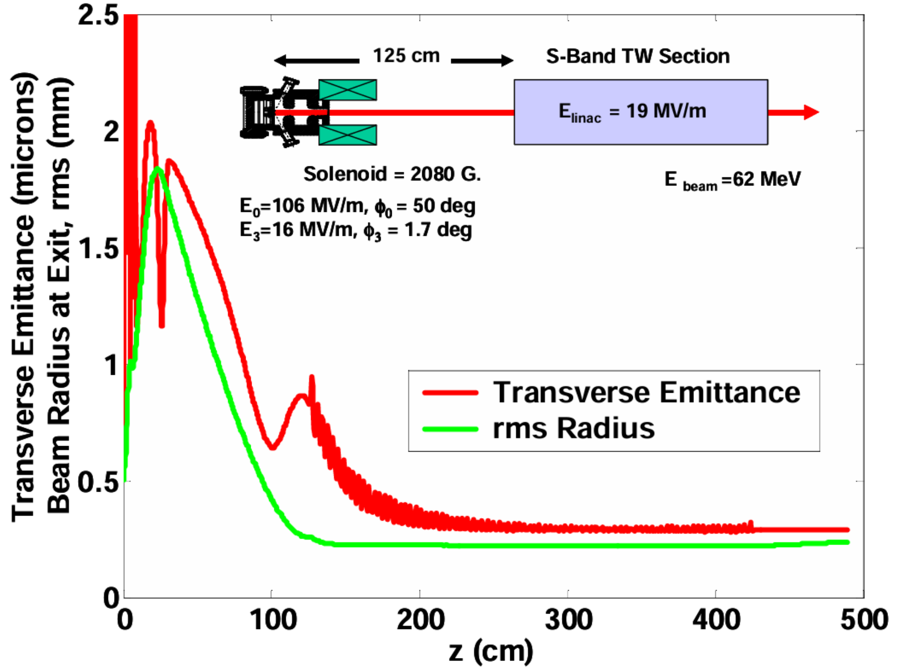
- Envelope equation

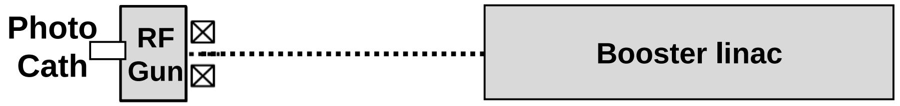
$$\sigma'' + K_r \sigma = \frac{I}{2I_0(\beta\gamma)^3\sigma} + \cancel{\frac{\epsilon_{n,\mathrm{th}}^2}{(\beta\gamma)^2\sigma^3}}$$

- Space charge dominated beam $\frac{I\sigma^2}{2I_0\gamma\varepsilon_n^2} \gg 1$
- Invariant condition $\sigma'' = 0$ inside the booster linac

$$\sigma'' = -\sigma_{match}\frac{\gamma'^2}{\gamma^2} + \frac{I}{2I_A\gamma^3\sigma_{match}} = 0 \qquad \sigma_{matched} = \frac{1}{\gamma'}\sqrt{\frac{I}{2I_A\gamma}}$$

  - The RF focusing and space charge defocusing is matched
  - The beam waist is at injection to the booster linac
  - The matched beam emittance decreases during linac acceleration





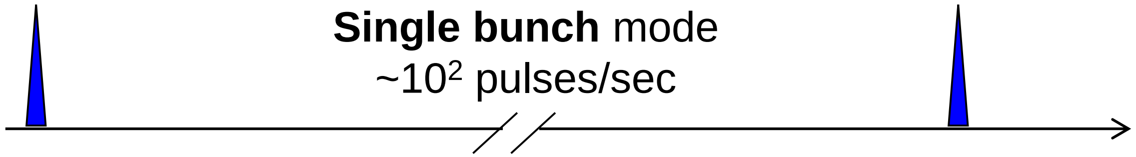
L. Serafini, PRE 55, 7565 (1997)

A brief overview on pulsed high brightness photoinjectors for FELs

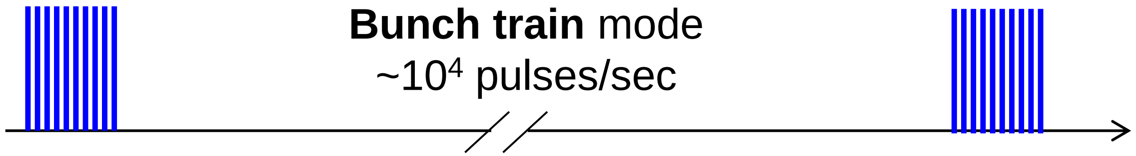
Pulsed photoinjector

Mature technology for X-ray FEL user facilities

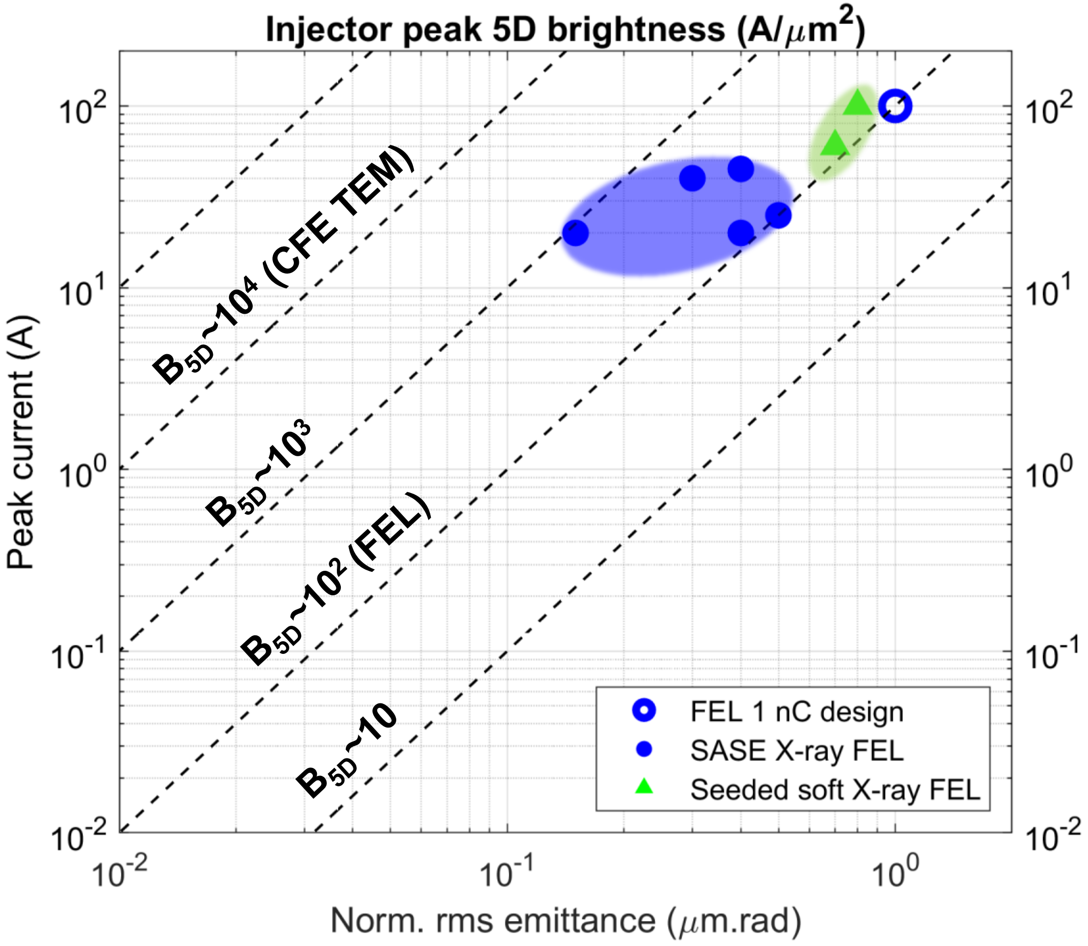
- Two injector modes
  - **S-band gun** injector facilities (LCLS/PAL/PSI/FERMI/SXFEL)



  - **L-band gun** injector facilities (FLASH/European XFEL)



	Charge (pC)	Peak (A)	Emit (µm.rad)	B_{5D} (A/µm²)
X-ray SASE FEL	200~400	20-45	0.15-0.5	100-900
Soft X-ray seeded FEL	500-600	60-100	0.7-0.8	122-156

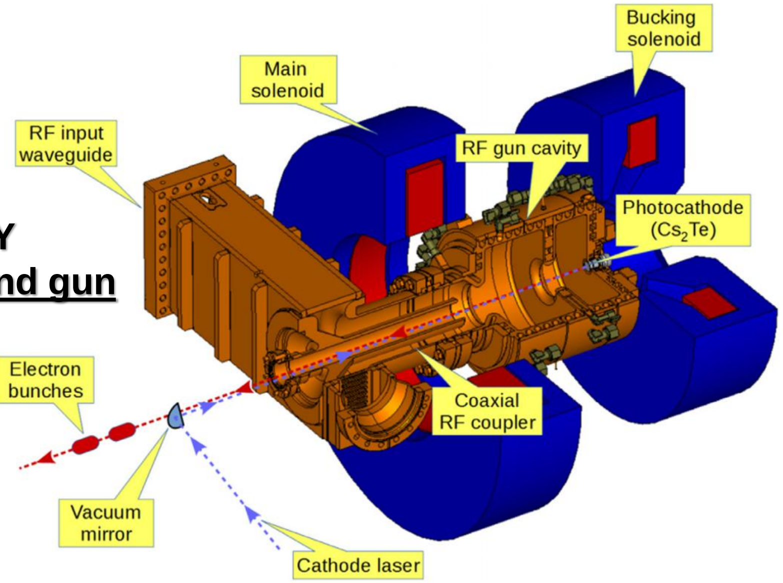


Pulsed photoinjector

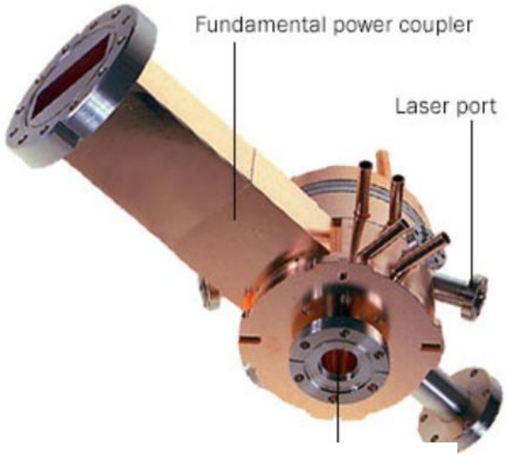
State of the art RF guns for X-ray FEL

	FEL facility	E_{cath} (MV/m)	f_{rep} (Hz)	Ek (MeV)	Cell #	Cath.
S-band 1-2 µs <1 kW	LCLS	115	120	5.5	1.6	Cu
	FERMI	110	100	5.2	1.6	Cu
	PAL	120	60	5.7	1.6	Cu
	SwissFEL	100	100	7	2.5	Cs_2Te
	SXFEL	105	10	5	1.6	Cu
L-band 650 µs 30-40 kW	FLASH	50	10	5.1	1.6	Cs_2Te
	XFEL	57	10	5.9	1.6	Cs_2Te

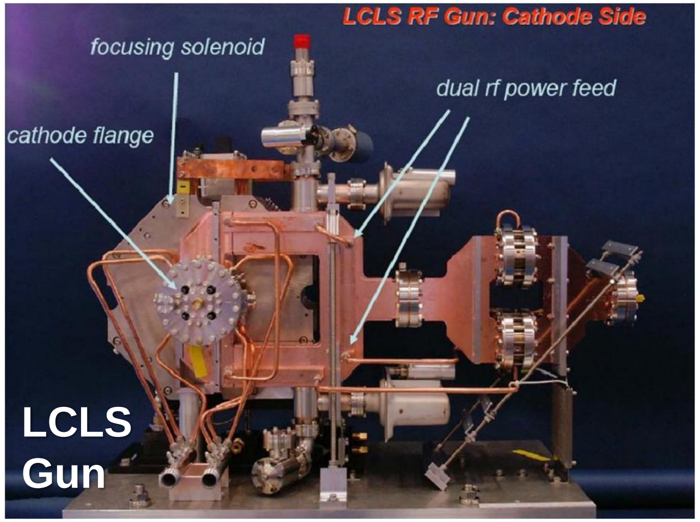
DESY
L-band gun

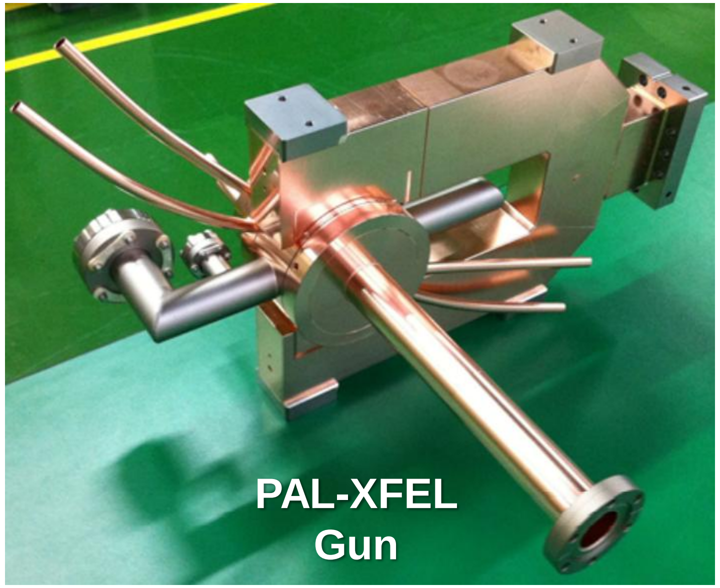


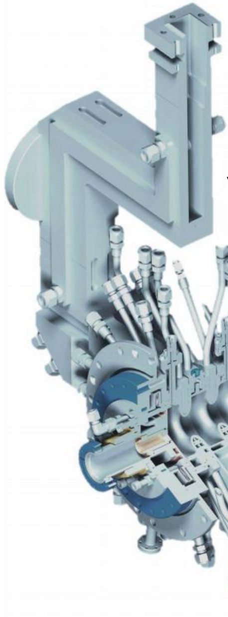
S-band RF gun, most widely used photoinjector



BNL/SLAC/UCLA gun





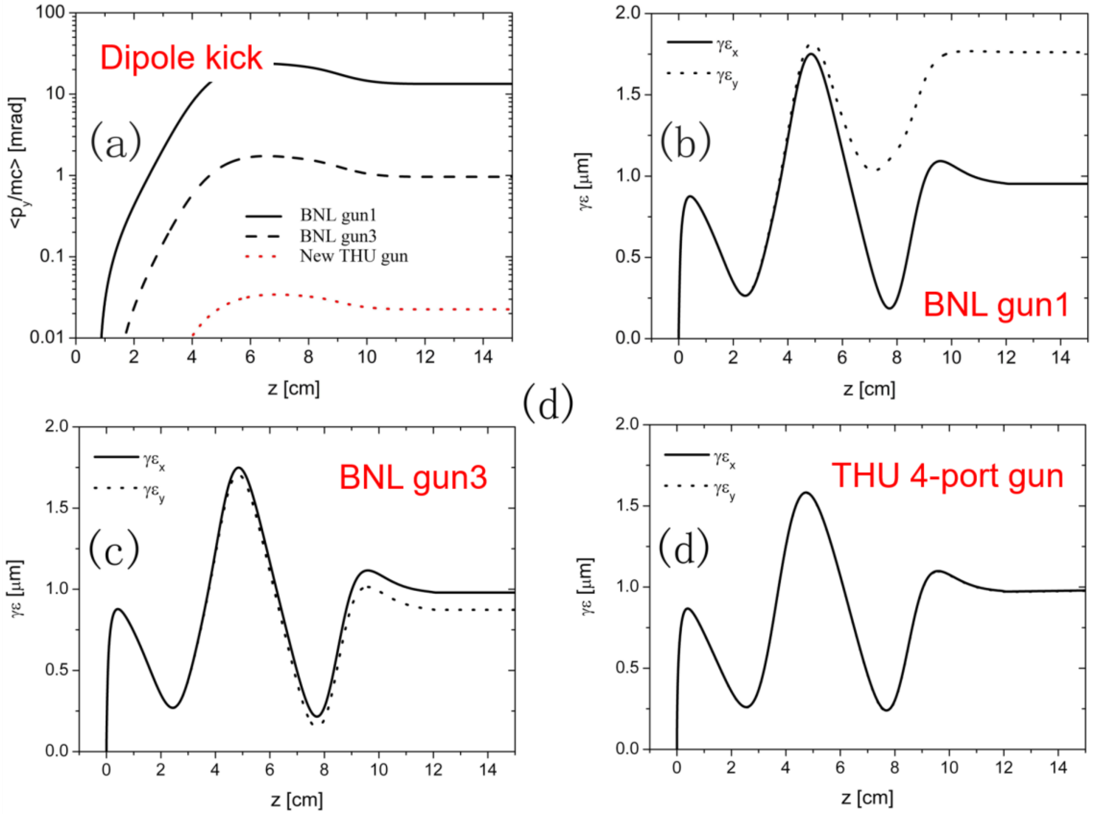


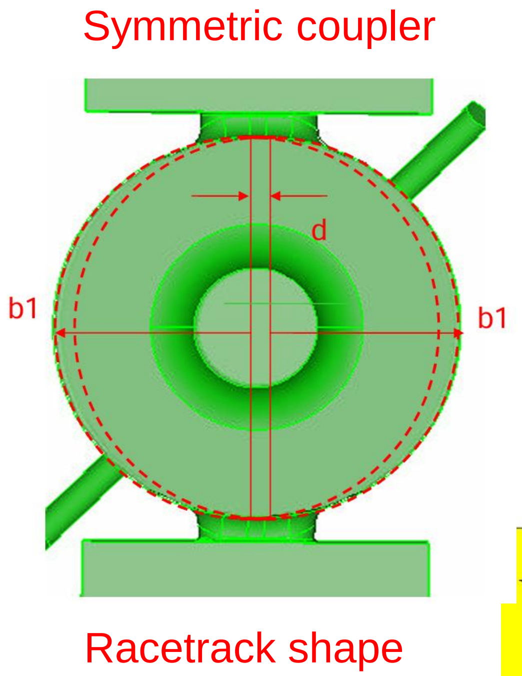
SwissFEL Gun

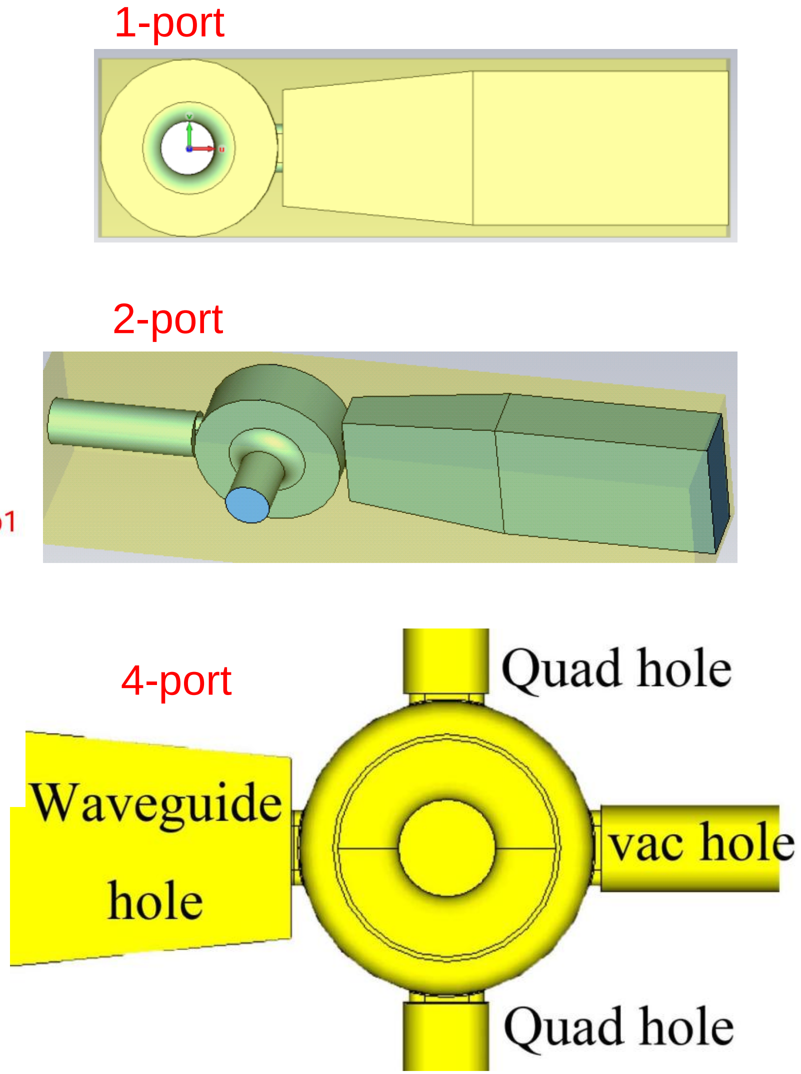
Pulsed photoinjector

Coupler kick optimization

- Coupler kick in RF guns





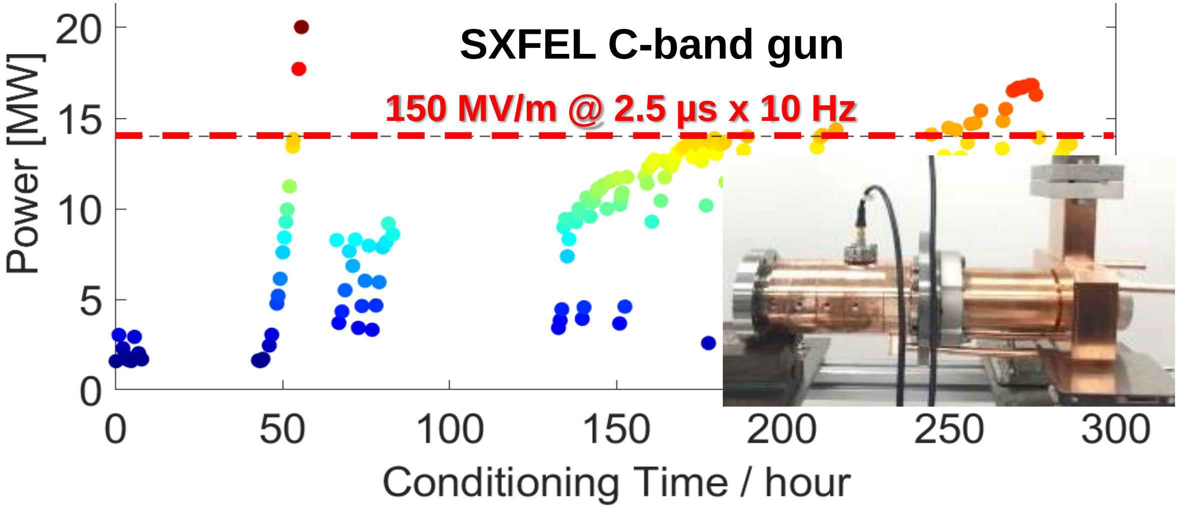


Pulsed photoinjector

Higher frequency → higher gun gradient

- X-band RF gun @SLAC/LLNL, ASU, Tsinghua
  - **SLAC/LLNL** (2001-now), Gun mark 0/1
  - 5.6 cell, **180-200 MV/m** x 110 ns x (10-60) Hz
  - B_{5D}: **~x10 @100 pC**, vs S-band (simulations)
  - **0.3 μm x 40 A @80 pC**, **~x1.6** than LCLS (measured)

- C-band RF gun @SwissFEL, INFN, SXFEL
  - Both SW and TW guns were studied.
  - SXFEL high power RF results
    - 3.6 cell SW gun, **150 MV/m** x 2.5 μs x10 Hz
    - B_{5D}: **~x4 @500 pC**, vs S-band (simulations)



Pulsed photoinjector

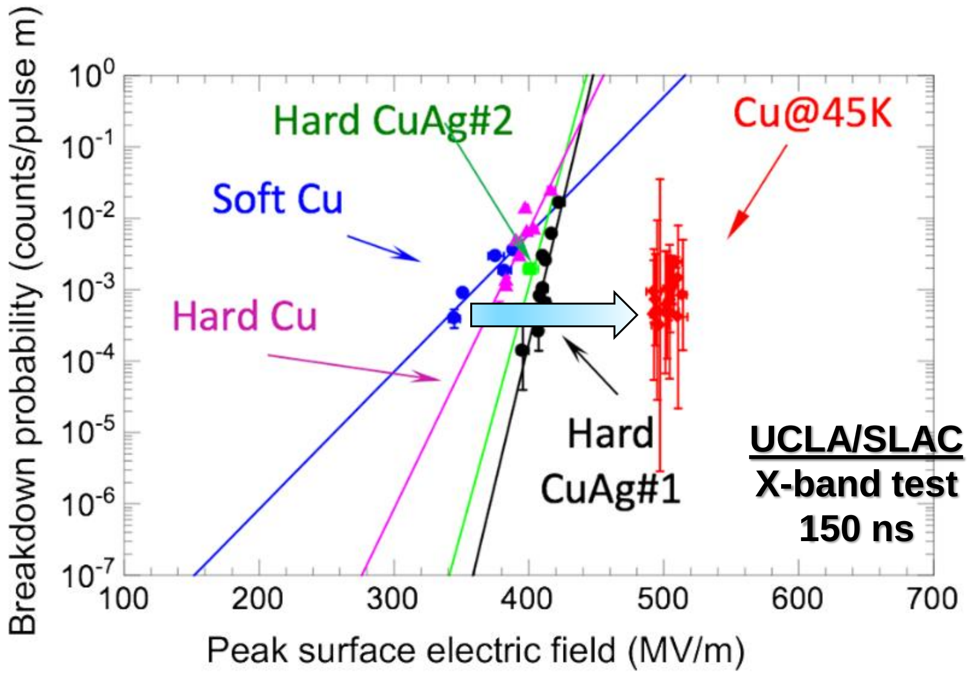
Room T → Cryo T NC gun

- Material @ cryo temperature → Lower BDR

- DESY proposal (V. Vogel et al)
    - 1.3 GHz DESY @20K → longer RF pulse
    - 1.3 GHz DESY @20K → 200 MV/m @3-5 µs

- UCLA proposal (J. Rosenzweig et al)
    - 1.6 cell **C band gun @27K**, UCLA/SLAC/LANL/INFN
    - **240 MV/m** x 0.3 µs x 100 Hz, **11 W RF heating**
    - B_{5D} **~x10 @100 pC**, than SwissFEL injector (simulations)
        - 100 pC, ~50 nm.rad @20 A (Simulation)

- R&Ds on cryo C-band guns are also ongoing at KEK/Nihon and SXFEL.



https://accphysem.desy.de/y2010/VVogel_ColdRFGun.pdf
J B Rosenzweig et al 2020 *New J. Phys.* **22** 093067

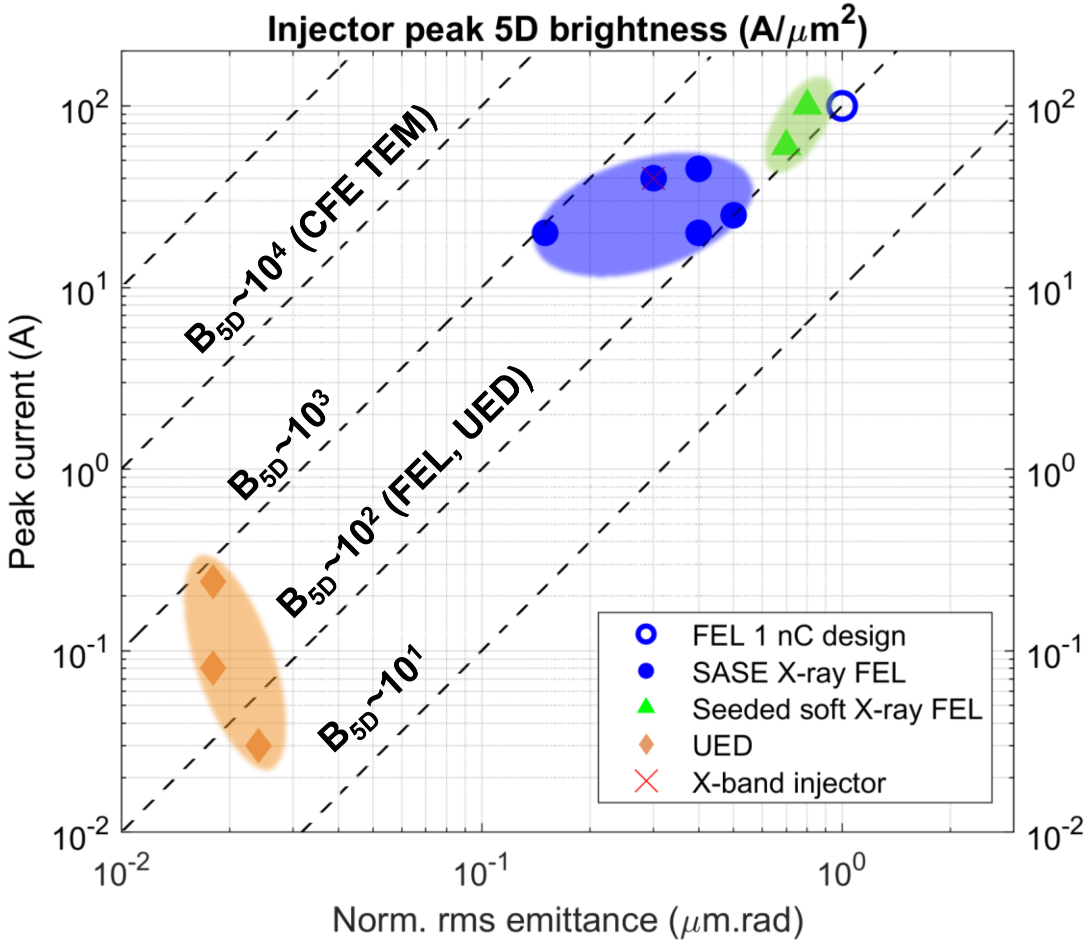
Pulsed photoinjector

Injectors developed for FELs benefits other applications

- Inverse Compton scattering based x-ray and gamma ray sources
  - Similar parameter space as X-ray FEL injector
- Ultrafast MeV electron diffraction and imaging

	Charge	Duration	ε_n (nm)	dp/p	B_{5D} (A/μm^2)
Diffraction	0.01-1 pC	0.1-1 ps	<100	$<10^{-2}$	10^2 -10^3
Single shot Imaging	>1 pC	10~100 ps	<10	**$\underline{<10^{-4}}$**	10^2 -10^3

  - Single shot imaging targeting 10 nm-10/100 ps resolution
    - not realized yet
    - Requires **B_{6D} $\underline{10^2\text{-}10^3}$ A/(keV*μm^2*rad^2)**
    - **B_{6D}** ~10^1 times higher than FEL injector



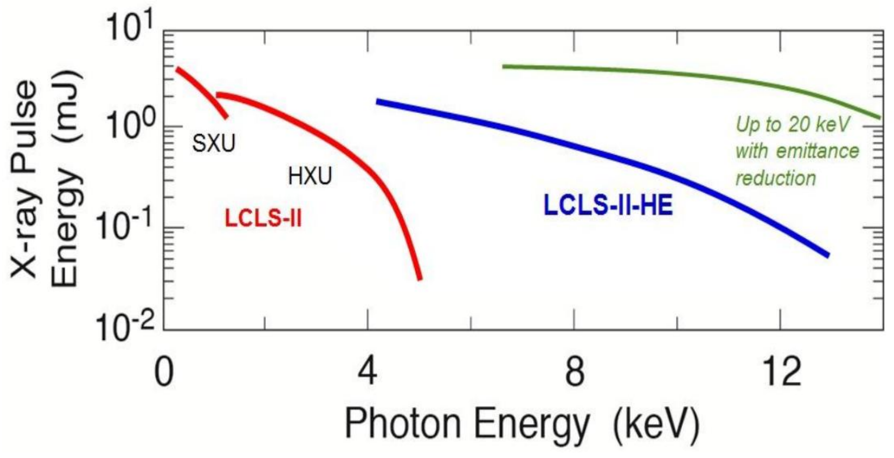
R. K. Li and P. Musumeci, *PRApplied* **2**, 024003 (2014)

A brief overview on CW photoinjector developments for ERL and FEL

CW photoinjector

Two frontiers

- CW X-ray FEL injector requests
  - LCLS-II/SHINE baseline: 100 pC, ε_n<**0.4 µm**, I_A~10 A
    - B_{5D}: >**62 A/µm²**
  - ε_n reduction to **0.1 µm** will help >20 keV lasing
    - B_{5D}: **10^3 A/µm²**



T.O. Raubenheimer, FLS2018, p6 (2018)

- ERL injector brightness requests
  - Injector for ERL based X-ray source
    - **77 pC**, ~**100 mA**, 5-15 MeV, ε_n<0.3 µm, σ_t<3 ps
    - Peak B_{5D}: **114 A/µm²**, comparable to FEL injector
  - Injector for ERL based EIC strong ion cooling
    - **1-1.5 nC**, **100~150 mA**, ε_n<5 µm
    - $\frac{I_{peak}}{\sigma_E} > \frac{20-150A}{15\ keV}$, i.e. **1.3~10 A/keV**
      - High longitudinal brightness
      - Comparable or better than typical FEL injector

E. Wang et,al *these proceedings*: TUPAB036
V. Livininenko *EIC workshop*, 7.Oct 2020

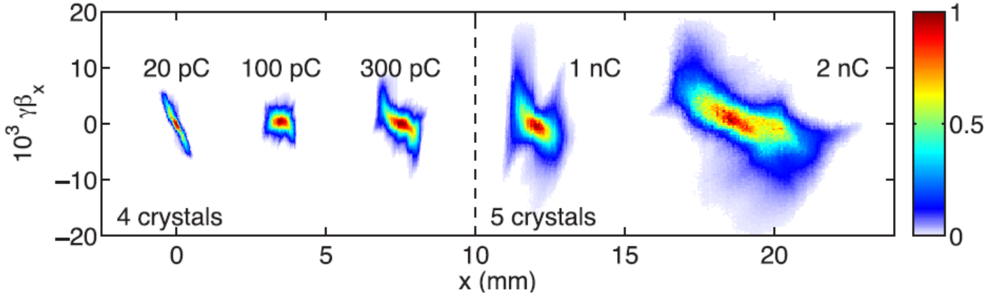
CW DC gun photoinjector for ERL applications

High average current and high peak brightness

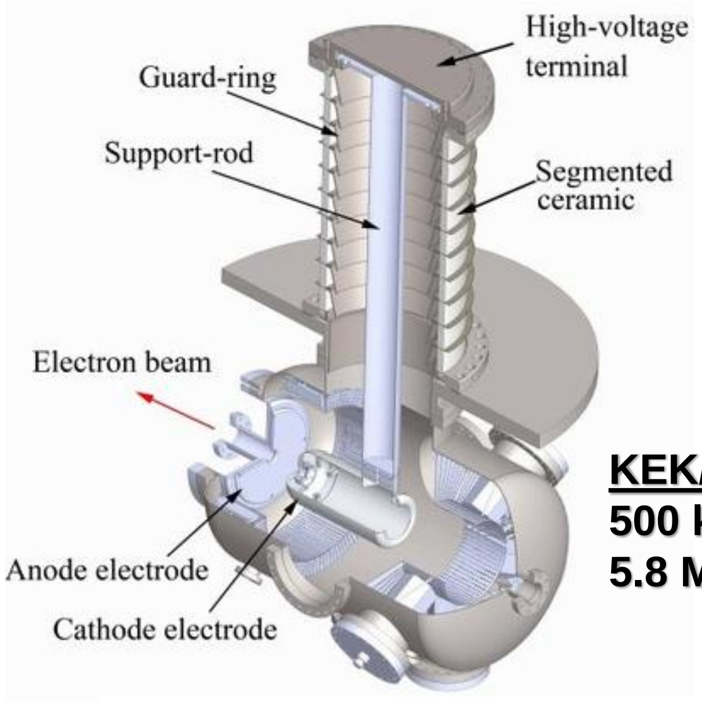
- CW photocathode DC gun injector demonstrations
  - **<1x10^{-11} torr**, compatible to high QE low MTE cathodes
  - **V_{gun} up to 500 kV**, **E_{cath}~5.8 MV/m**
  - **$I_{average}$ up to 65-75 mA, ~300 kW** beam power
  - **B_{5D} ~10^2 A/μm^2**, meets both FEL & ERL injector baseline requests

	Vgun (kV)	Ecath (MV/m)	Cathode	max I_{ave} (mA)	max E_k (MeV)
BNL-LEReC	375	~4	CsK_2Sb	14-20	1.6/2.0
Cornell	395	~4	NaKSb	65-75	~8
JLAB FEL	350	~4	GaAs	~10	~9
KEK ERL	500	5.8	GaAs	~1	~3

Cornell injector brightness measurements



A. Bartnik et al, *PRAB* **18**, 083401 (2015)



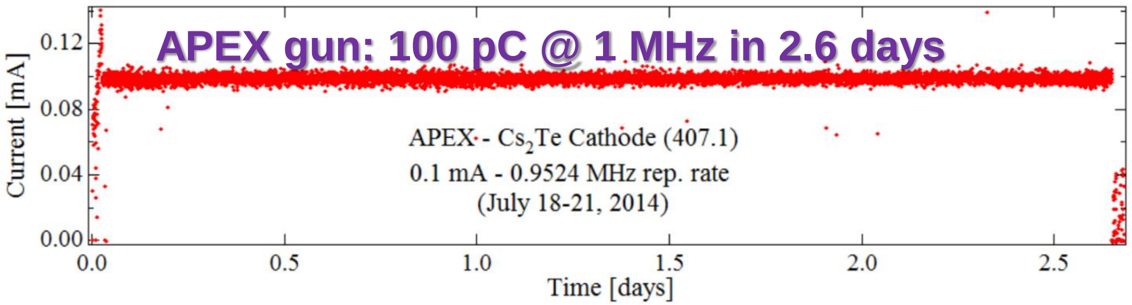
KEK/JAEA
500 kV gun
5.8 MV/m

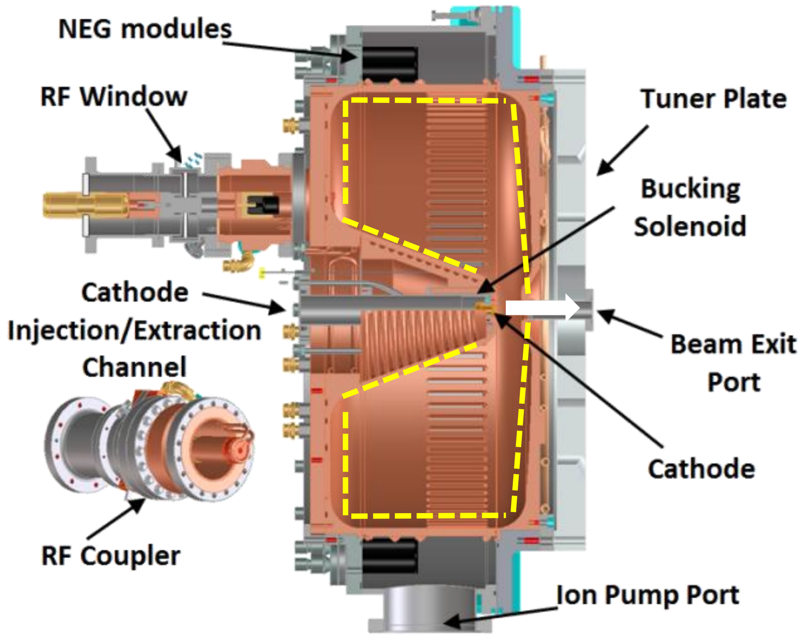
N. Nishimoriet al, *PRAB* **22**, 053402 (2019)

CW RF gun for FEL applications

NC VHF gun

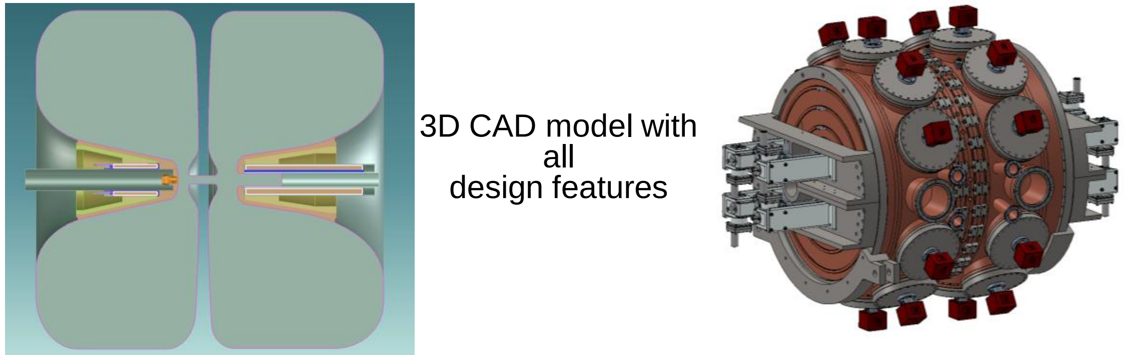
- LBNL, APEX gun, 187 MHz
  - CW RF (2012): **19.5 MV/m, 750 kV, 90 kW CW RF, with ~10^{-10} torr**
  - CW beam from Cs2Te (2014): **20-300 pC @ 1 MHz**
  - Brightness (2016): 20 pC, **<0.2 μm @6.5 A**





F. Sannibale et al, *PRAB* **15** 103501 (2012)
F. Sannibale et al, *RSI* **90** 033304 (2019)

- LBNL, APEX2 gun design (since 2016)



Parameters	1st cell	2nd cell	APEX
Frequency (MHz)	**162.5**	162.5	**185.7**
$E_{cathode}$ (MV/m)	**30**	N/A	**19.5**
Energy gain V (kV)	724	820	750
Power (kW)	**70.6**	85.4	88.5

CW RF gun for FEL applications

NC VHF gun

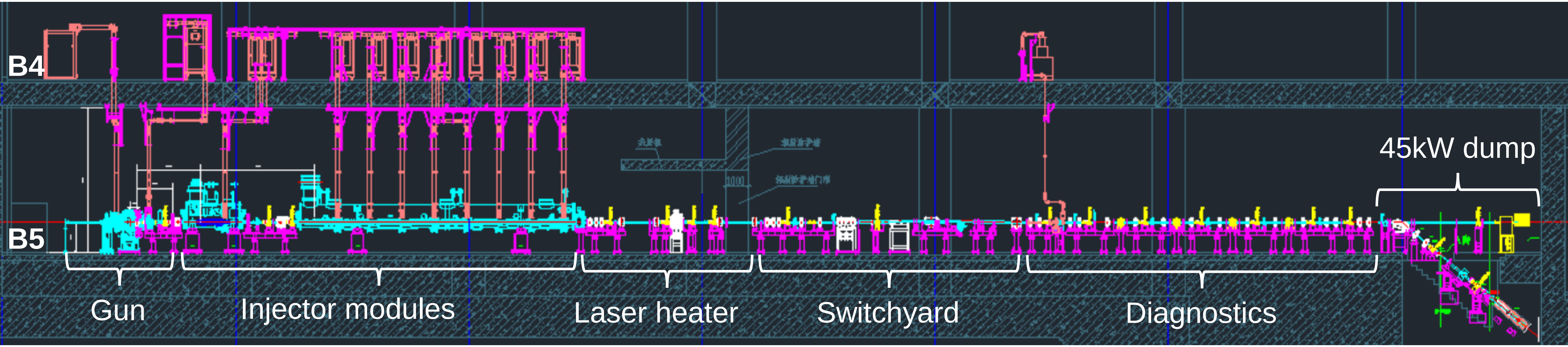
- Other CW VHF gun based on APEX design

	LCLS-II	SHINE	ZJLAB	Unit
Freq	1300/7	1300/6	1300/6	MHz
E_{cath}	~19	26	20	MV/m
E_k	700-750	750	750	kV
RF power	~90	~70	~70	kW
Beam current	0.1	0.1	3	mA

- Injector layout based on NC VHF gun


LCLS-II gun


SHINE gun

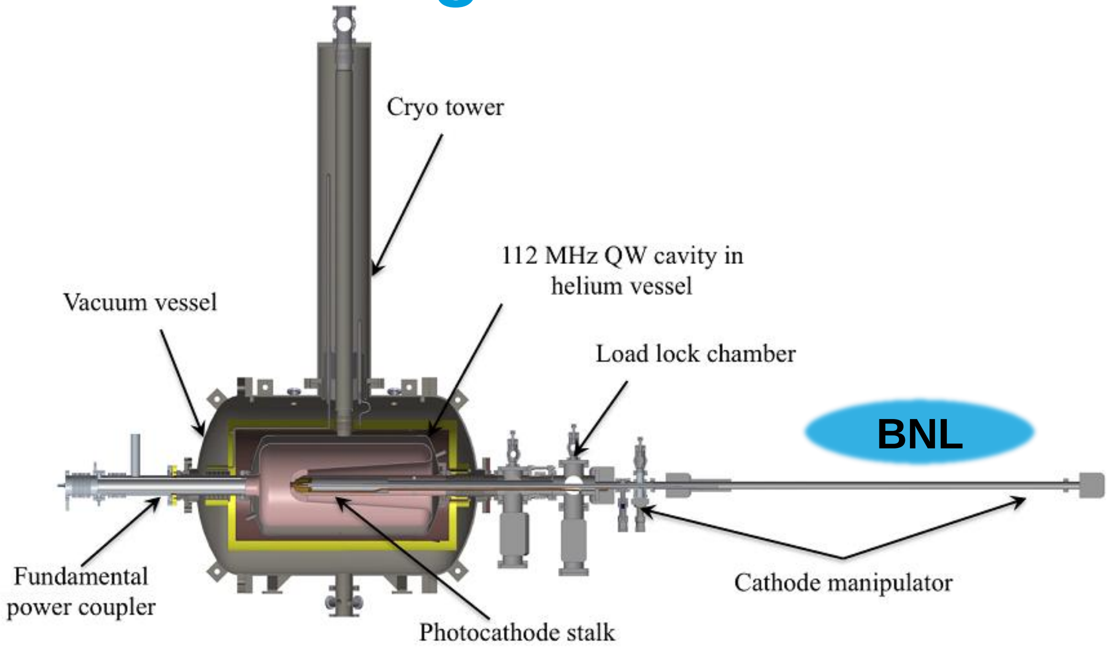


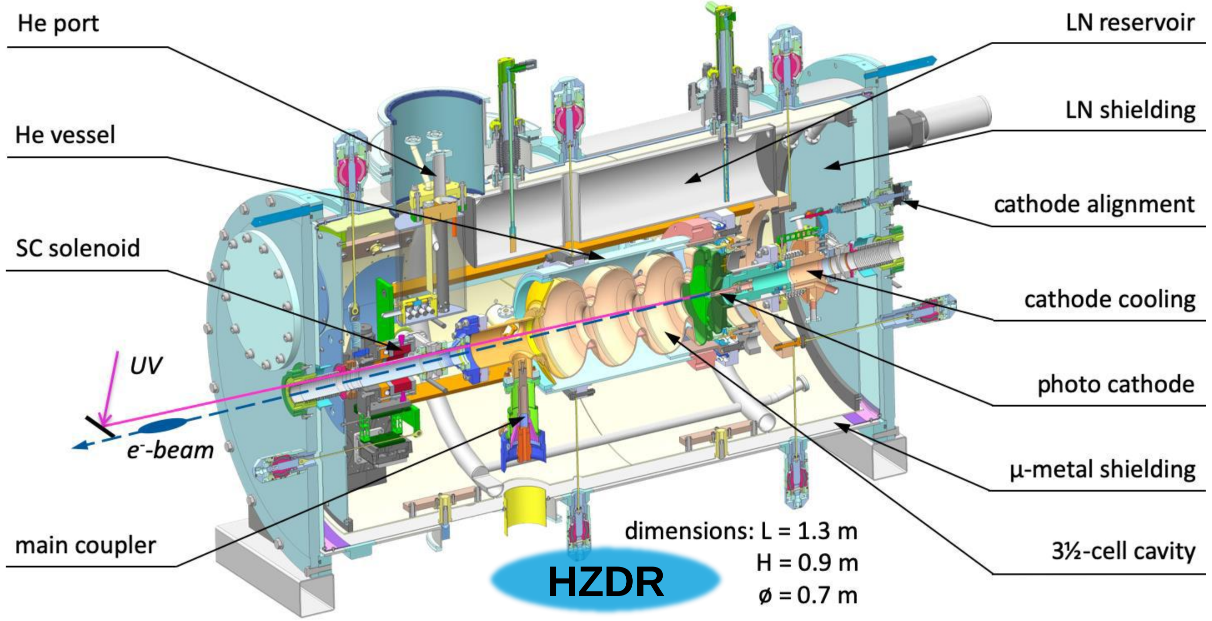
CW SC RF gun for FEL, ERL and hadron cooling

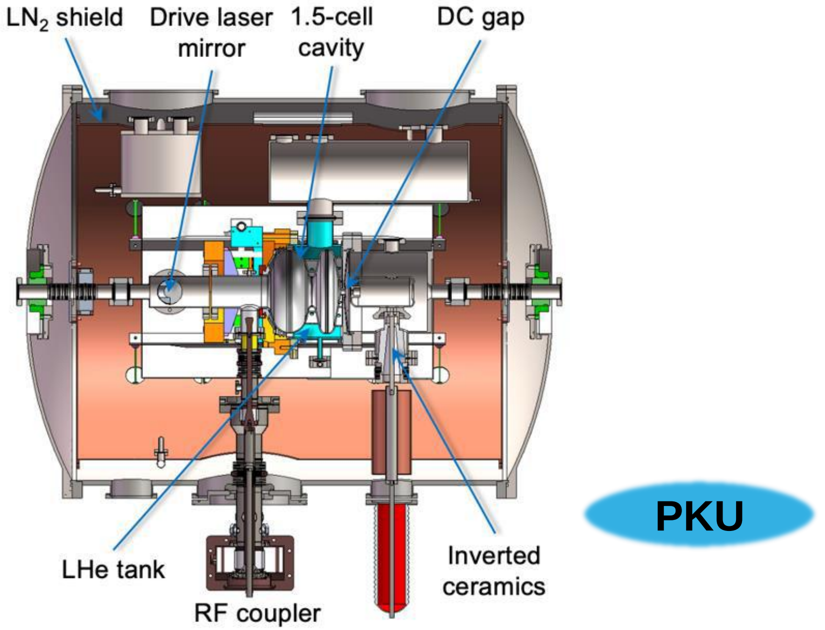
Current performance and challenges

- 3 guns in routine operation, 2 for user facilities

	Freq (MHz)	SC cavity	$E_{z,max}$ (MV/m)	E_{cath} (MV/m)	Ek (MeV)	Cathode	Gradient limit
HZDR	1300	3.5 cell TESLA	**20.5**	**12.2-14.5**	4	Mg, Cs2Te	Field emission
PKU	DC+1300	1.5 cell TESLA	**21**	**6**	2.2	Cs2Te	DC gap, Field emission
BNL	113	QWR	**18**	**13-18**	1.25	CsK_2Sb	Field emission





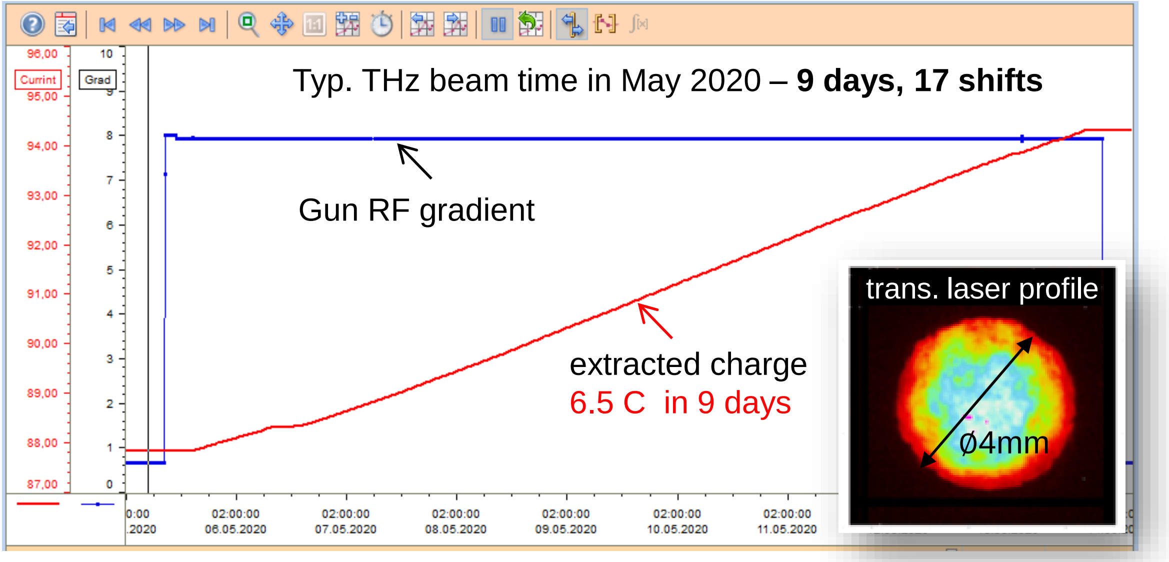


CW SC RF gun for FEL, ERL and hadron cooling

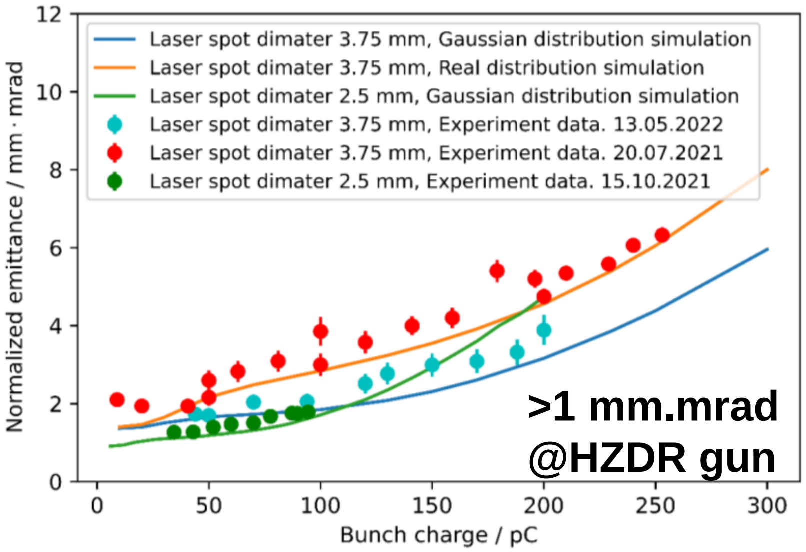
Current performance and challenges

- Stable routine operation for user facilities
  - HZDR gun, e.g. ~**1650 h** in 2020 for ELBE
  - BNL gun, e.g. **½ year** during RHIC run
    - Low emittance measured at BNL QWR gun

Example from **HZDR gun** 9-day user shift



- SC gun high gradient challenges
  - High QE cathode integration
    - Solved with RF choke or DC gap
  - High QE cathode field emission
    - Now 1-50 nA under E_{cath} 2.6 ~ 18 MV/m
  - Higher gradient
    - Surface cleaning improvement in progress

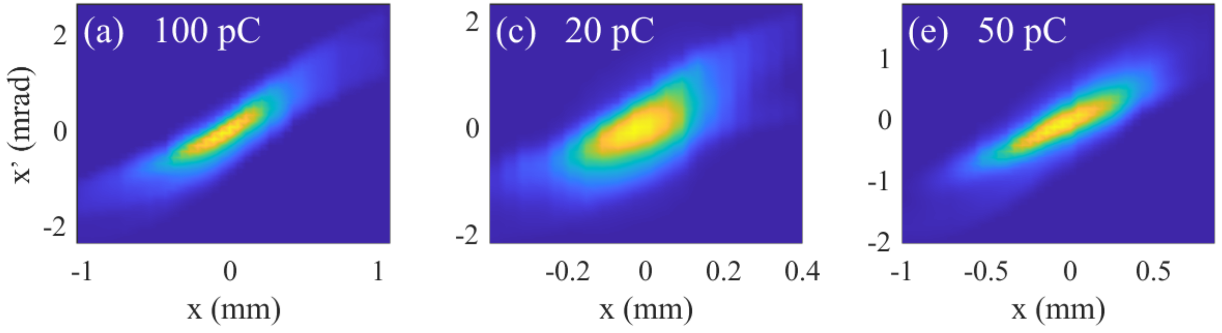


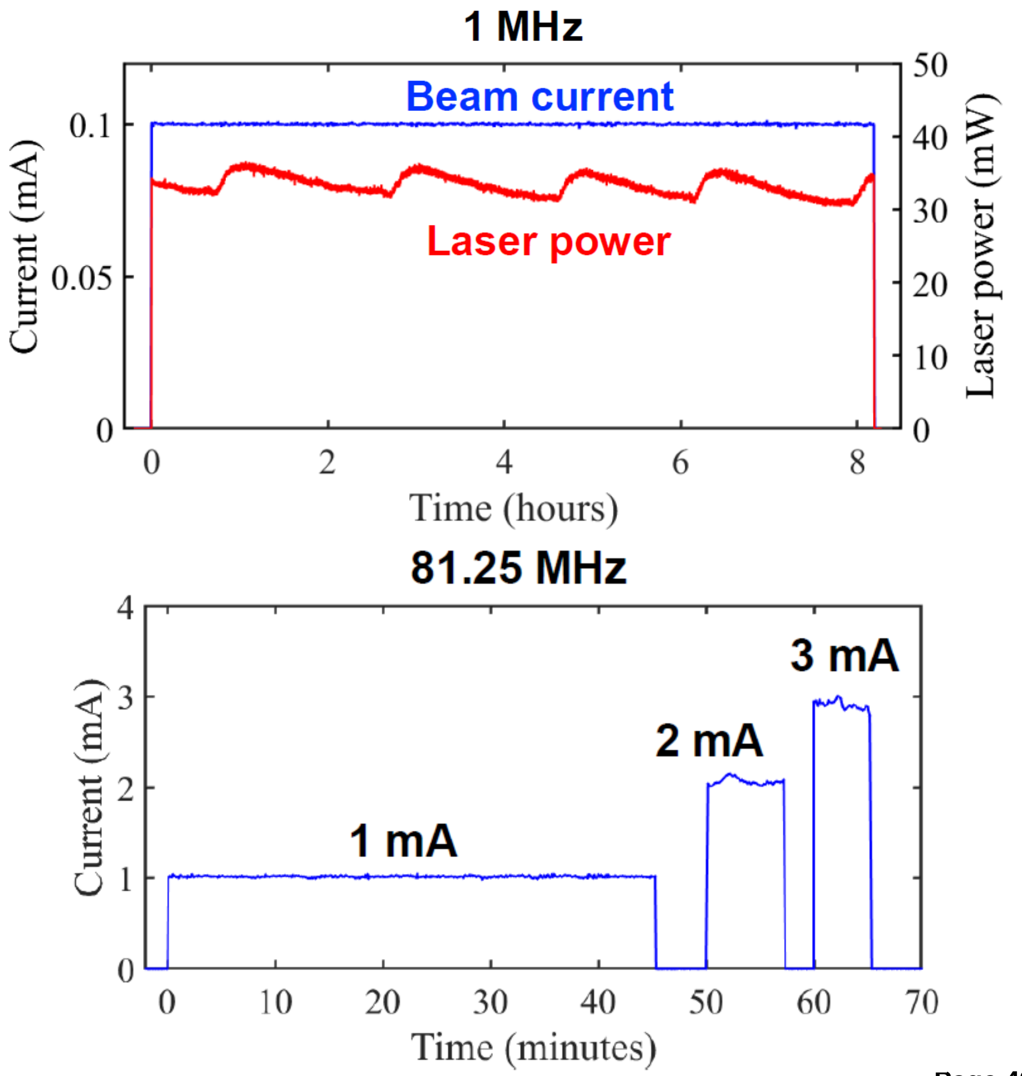
CW SC RF gun for FEL, ERL and hadron cooling

Current performance and challenges

- **PKU DC-SRF gun**
  - Demonstrates stable 1 mA operation with green cathode
  - Low emittance beam from 20 pC to 100 pC

Parameters	100 pC	50 pC	20 pC	Units
Cavity field (E_{max})	22.3	21.7	21.7	MV/m
Drive laser size (rms)	0.48	0.48	0.38	mm
Electron beam energy	2.42	2.35	2.35	MeV
Normalized emittance	0.54	0.40	0.28	mm-mrad
Core emittance	0.28	0.25	0.19	mm-mrad
Core fraction	70%	75%	77%	





CW injectors: 100 pC brightness improvements

Integration of low MTE cathode in higher gradient gun is the key

- **Cornell DC gun** injector demonstrates B_{5D} within LCLS-II baseline requirements.
- Current **NC VHF gun (~20 MV/m)** simulates ~x4 higher B_{5D} than DC gun injector with similar cathodes.
- Guns with **~30 MV/m and low MTE cathodes (≤0.6 µm.rad/mm)** predicts **~0.1 µm & ~10^3 A/µm^2.**

100 pC	DC	Normal conducting			Superconducting		Unit
	Cornell	LCLS-II	SHINE	DESY	SLAC	DESY	
Freq.	DC	1300/7	1300/6	1300/6	1300/7	1300	MHz
E_{cath}	**~4**	**~20**	**30**	**28**	**30**	**40**	MV/m
E_k	0.4	0.75	0.87	0.83	1.8	4	MeV
$\varepsilon_{th}/\sigma_l$	**0.52**	**0.6**	**0.6**	**0.5**	**0.6**	**0.5**	µm/mm
Buncher	Y	Y	Y	Y	Y	N	/
100% ε_n	0.38	0.19	0.11	0.12	0.11	0.15	µm
95% ε_n	**0.31**	**0.16**	**0.08**	**0.09**	**0.09**	**0.12**	µm
I_{peak}	**11**	**12**	**12**	**7.4**	**12**	**4.6**	A
H. δP_z	/	3.3	3.7	1.5	1.4	4.4	keV/c
B_{5D}	114	457	1829	1024	1387	319	A/µm^2

***Green are measurements**, **black and blue are simulations contributed from different groups.**

Photocathodes and laser shaping

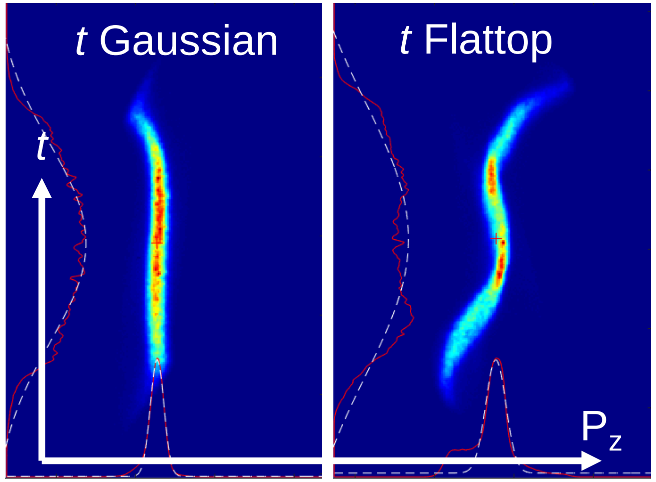
As important as a high gradient gun to reach high brightness

- Good photocathodes are critical
  - **Low MTE** is critical for low emittance
    - Dominating final emittance
  - **High QE** is important to reduce laser energy budget
  - **Life time**: improves operation reliability
    - Depends on QE, QE uniformity, dark current and MTE
    - Affected by vacuum, temperature, average current (density), gradient etc.

Typical	Cu	Mg	Cs2Te	Alkali antimonides	GaAs
Laser	UV	UV	UV	Green	IR/Green
QE	10^{-5}~10^{-4}	10^{-4}~10^{-3}	10^{-2}~10^{-1}	10^{-2}~10^{-1}	10^{-2}~10^{-1}
$\varepsilon_{th}/\sigma_l$	0.5-1	0.5-1	0.7-1	0.5-0.6	0.2~0.5
Vacuum	<10^{-9}	~10^{-10}	~10^{-10}	<10^{-10}	~10^{-11}
Life time	month ~ year			week ~ month	~week

D. H. Dowell et al., *NIMA*, 622, 685 (2010)

- Laser shaping affects both tran. & long. dynamics
  - **'Beer can' shape @ 1 nC** at FEL design stage → for emittance improvement.
  - **Real life, temporal Gaussian laser @ 0.25 nC**
    - FEL performance is comparable @0.25 nC vs flattop shaping in high gradient guns (pancake emission).
    - Flattop shaping effect in CW gun (cigar emission) is still to be studied.



250 pC
20 A beam
@PITZ

Summary

High brightness photoinjector is an enabling technology for many accelerator facilities.

- **Pulsed photoinjector (B_{5D} 10^3 ~ 10^2 A/µm^2)**
  - Room T **S/L-band** pulsed RF guns almost matured, B_{5D} dominated by emission brightness.
  - Ultra high gradient (**~200 MV/m**) guns are in R&D → B_{5D} 10^4 A/µm^2
- **CW photoinjector (B_{5D} ~ 10^2 A/µm^2)**
  - **DC guns** are **baseline for ERL**, high current **65-75 mA** and high brightness have been demonstrated.
  - **NC VHF guns (20-30 MV/m)** are **baseline for CW FELs**.
  - **SC guns** have high potential for both ERL and FEL applications, **many labs** are working together to push the technology to the next level.
- **The next photoinjector brightness frontiers**
  - Single shot UEM: **B_{6D} <u>10^2-10^3</u> A/(keV*µm^2*rad^2)**
  - CW XFEL: **B_{5D} ~<u>10^3</u> A/µm^2**, 0.1 µm @100 pC, 10 A
  - EIC strong hadron cooling: **100-150 mA, 1-1.5 nC, 1.3~<u>10</u> A/keV**

Summary

High brightness photoinjector is an enabling technology for many accelerator facilities.

- **Pulsed photoinjector (B_{5D} $10^3 \sim 10^2$ A/µm^2)**
  - Room T **S/L-band** pulsed RF guns almost matured, B_{5D} dominated by emission brightness.
  - Ultra high gradient (**~200 MV/m**) guns are in R&D → B_{5D} 10^4 A/µ
- **CW photoinjector ($B_{5D} \sim 10^2$ A/µm^2)**
  - **DC guns** are **baseline for ERL**, high current **65-75 mA** and high
  - **NC guns (20 MV/m)** are **baseline for CW FELs**, ~30 MV/m NC
  - **SC guns** have high potential for both ERL and FEL applications, technology to the next level.
- **The next photoinjector brightness frontiers**
  - Single shot UEM: $\mathbf{B_{6D}}$ **<u>10²-10³</u> A/(keV*µm²*rad²)**
  - CW XFEL: $\mathbf{B_{5D}}$ **~<u>10³</u> A/µm²**, 0.1 µm @100 pC, 10 A
  - EIC strong hadron cooling: **100-150 mA, 1-1.5 nC, 1.3~<u>10</u> A/**