High brightness SRF Gun Overview

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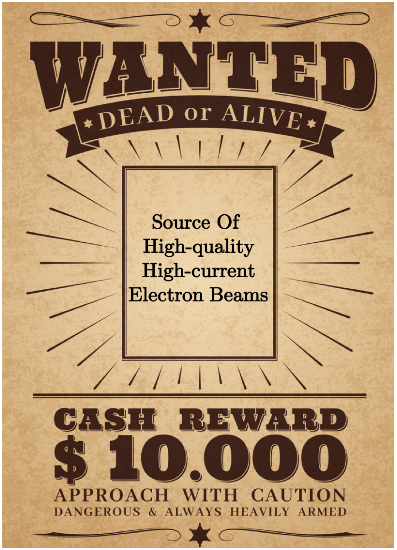
June 21, 2022

Contents

High-quality, high-current electron beams are needed!



- high-power X-ray and extreme ultraviolet (EUV) continuous wave (CW) free electron lasers (FELs)
- intense γ-ray sources
- coolers for hadron beams
- electron-hadron colliders.

Photoinjectors

DC guns

- \+ Easily provide CW e-beams
- − Low electric field
- − Short accelerating gap → limits maximal attainable charge

Normal-conducting RF (NCRF)

- \+ Well established
- ± Relatively low repetition rate with high accelerating gradient
- ± High repetition rate with low accelerating gradient

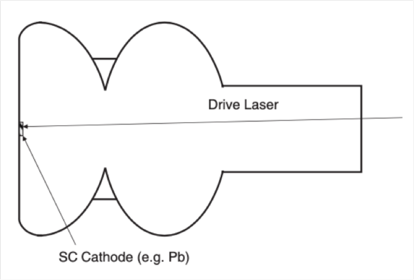
Superconducting RF (SRF)

- \+ Good vacuum inside Nb cavity at 2K/4K
- \+ Relatively high accelerating gradients
- \+ CW operation
- ? Are high-QE room-temperature cathodes compatible with the SRF environment?
- ? Can high-QE cathodes survive in an SRF cavity?
- ? Cryopumping?
- ? Dark current?

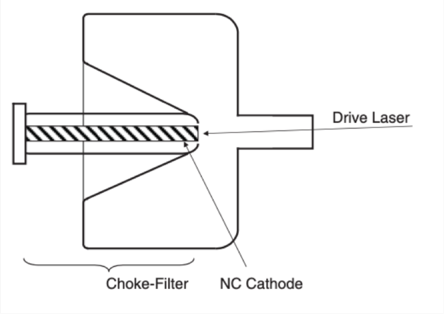
It is expensive and challenging—hence, there are very few operational SRF guns!

SRF photoinjectors—which one to choose[1]?

Elliptical cavity



Quarter Wave Resonator (QWR)

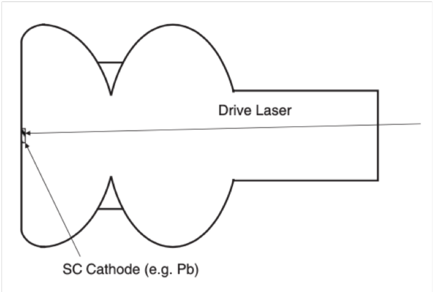


QWR operates at lower frequencies:

- \+ Relaxed cryostat temperatures
- \+ Reduced RF losses
- \+ Short accelerating gap compared to the wavelength → high transit time factor

SRF photoinjectors—which one to choose[1]?

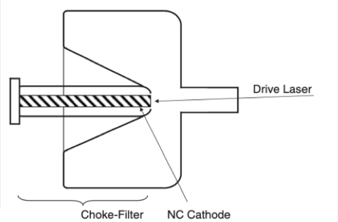
Cold cathode

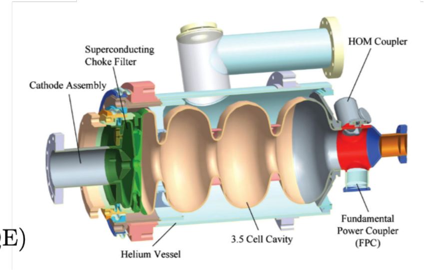


Cold cathodes:

- Usually have lower Quantum Efficiency (QE)
- Hard to replace

Warm cathode





Overview of existing SRF photoinjectors

As of now:

- 2 SRF guns in operation
- 4 SRF guns in R&D
- 1 SRF gun in plan

Different approaches are utilized:

- **DESY:** elliptical cavities with SC cathodes
- **HZDR, KEK, HZB:** elliptical cavities with NC cathodes in choke filter
- **PKU:** elliptical cavities with NC cathodes in DC module
- **BNL, SLAC:** QWR with NC cathodes and choke filter

Overview of existing SRF photoinjectors

	DESY	PKU	HZDR	KEK	HZB	BNL	SLAC
Cavity Type	1.6-cell elliptical	1.5-cell elliptical	3.5-cell elliptical	1.5-cell elliptical	1.4-cell elliptical	QWR	QWR
RF frequency [MHz]	1300	1300	1300	1300	1300	113	186
Operation temperature [K]	2	2	2	2	2	4	4
Field at cathode [MV/m]	40	6	14	23	24-27	15	30
Cathode	Pb	CsK_2Sb	Mg, Cs_2Te	CsK_2Sb	Cu or CsK_2Sb	CsK_2Sb	CsK_2Sb (?)
Laser wavelength [nm]	UV	519	262	532	521-523	532	532
Bunch charge [pC]	20-250	100	0-250	80	77	100-20000	100
Status	R&D	R&D	User Operation	R&D	R&D	Operation	In plan

Secrets of obtaining high-quality beams

Emittance of the beam extracted from a photoinjector depends on the value of the **electric field at the cathode at the moment of emission**, $E_{\rm em}$, and the **bunch shape**:

pancake-beam: $\varepsilon_n \propto \sqrt{q\frac{E_{MTE}}{E_{\rm em}}}$ **cigar-beam:** $\varepsilon_n \propto \frac{\sqrt{E_{MTE}}}{E_{\rm em}}\left(\frac{q}{\Delta t}\right)^{2/3}$

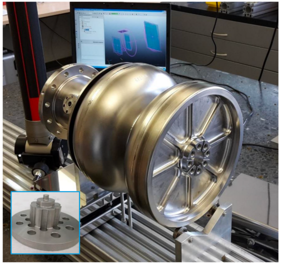
$E_{\rm em} = E_{\rm max}\sin(\phi)$

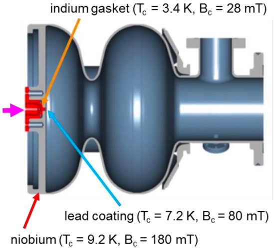
Phase of emission, ϕ, is selected to maximize the beam energy gain. It depends on the geometry of the RF cavity, accelerating gradient $E_{\rm acc}$, the RF frequency, and it is well described by a dimensionless parameter $\alpha = \frac{eE_{\rm acc}}{2mc\omega}$.

For HZDR: $\alpha = 0.7,\ \phi = 12.5^\circ,\ E_{\rm em} = (0.2 - 0.25)E_{\rm max}$
For BNL: $\alpha = 8.34,\ \phi = 78.5^\circ,\ E_{\rm em} \sim 0.98E_{\rm max}$

DESY: 1.3 GHz 1.6-Cell Cavity with SC Cathode

Status: R&D, high brightness source for CW XFEL

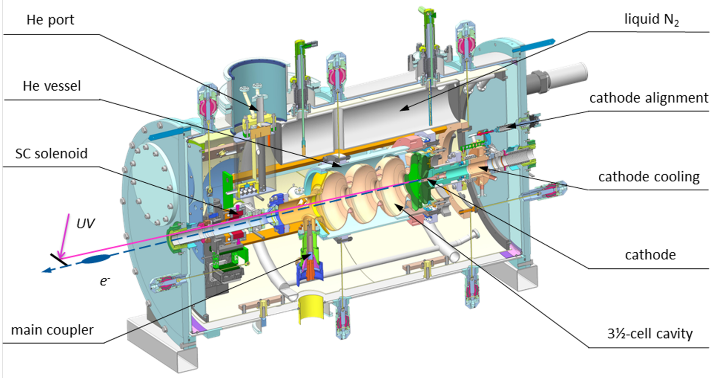




Parameter	Value
Rep. rate [kHz]	100 -1000
Bunch charge [pC]	20-250
Emittance [mm-mrad]	0.4-0.8
Beam energy [MeV]	> 3
Frequency [GHz]	1.3
Gradient [MV/m]	21
Field on cathode [MV/m]	40
Cathode	Pb, screwed to back wall

HZDR: 1.3 GHz 3.5-Cell Cavity with NC cathode & RF choke

Status: In user operation since 2019 for THz and Neutron generation



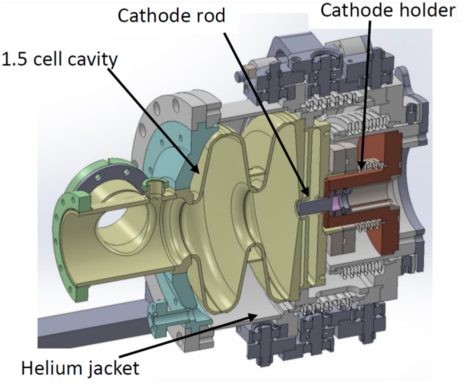
Parameter	Value
Rep. rate [kHz]	25-250
Bunch charge [pC]	0-250
Emittance [mm-mrad]	2-15
Beam energy [MeV]	4.5
Frequency [GHz]	1.3
Gradient [MV/m]	8
Field on cathode [MV/m]	14
Cathode	Cs_2Te on Cu

Further developments presently concentrate on:

- Improve cathode cooling
- Re-establish Cs_2Te for high bunch charge operation
- Study other cathode materials for SRF gun
- Establish a dedicated gun-lab

KEK: 1.3 GHz 1.5 Cell Cavity with NC cathode & RF choke

Status: R&D, high current beam for ERL



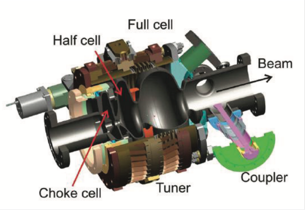
Parameter	Value
Rep. rate [GHz]	1.3
Bunch charge [pC]	80
Emittance [mm-mrad]	0.6
Beam energy [MeV]	2
Frequency [GHz]	1.3
Gradient [MV/m]	16
Field on cathode [MV/m]	23
Cathode	CsK_2Sb

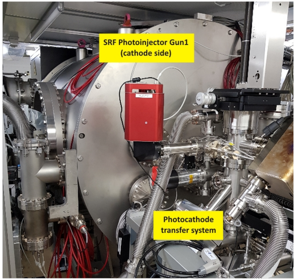
Next steps:

- Test with cathode rod in horizontal cryostat
- Beam test in horizontal test cryostat with small beam current (<500 keV, <1uA)

HZB: 1.3 GHz 1.4 Cell cavity with NC cathode & RF choke

Status: R&D, for bERLinPro ERL





Parameter	Value
Rep. rate [GHz]	N/A
Bunch charge [pC]	77
Emittance [mm-mrad]	<1
Beam energy [MeV]	3
Frequency [GHz]	1.3
Gradient [MV/m]	16
Field on cathode [MV/m]	24-27
Cathode	CsK_2Sb, NaK_2Sb

Next steps:

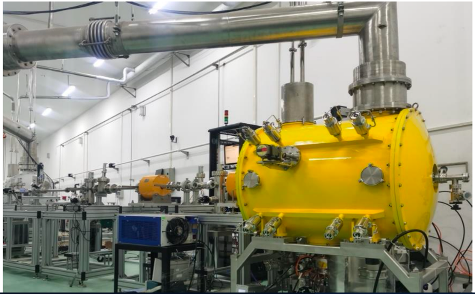
- Mid-2021 to check performance of gun cavity and RF system
- Beam operation with SRF gun and SRF booster in 2022
- Proof-of-concept in 2022+
- Full injector operation with Gun and Booster expected between late 2022 and 2023

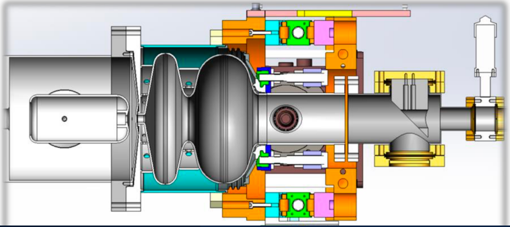
PKU: 1.3 GHz 1.5-Cell + NC cathode with DC gap

Status: R&D, injector test for CW XFEL

Parameter	Value
Rep. rate [MHz]	1
Bunch charge [pC]	100
Emittance [mm-mrad]	0.37
Beam energy [MeV]	2.8
Frequency [GHz]	1.3
Gradient [MV/m]	14
Field on cathode [MV/m]	6
Cathode	CsK_2Sb, Cs_2Te

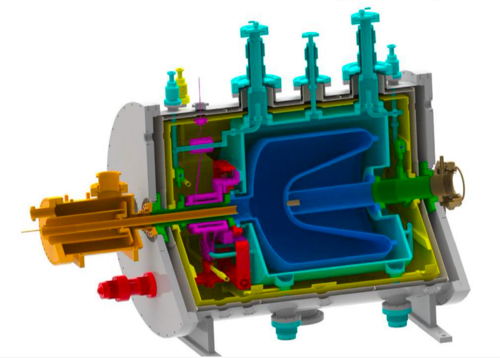
Highlight:
First beam from the PKU gun was generated on 04/29/2021





SLAC: 185.7MHz QWR gun with NC cathode & choke filter (?)

Status: Initial Planning, e-source for LCLS-II He

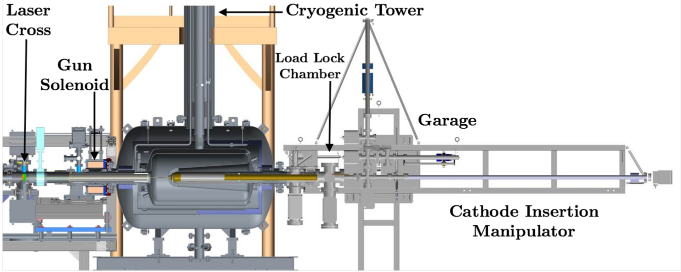


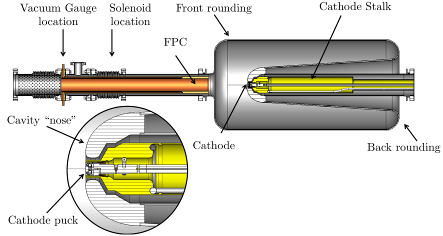
Parameter	Value
Rep. rate [MHz]	N/A
Bunch charge [pC]	100
Emittance [mm-mrad]	<0.1
Beam energy [MeV]	1.8
Frequency [MHz]	185.7
Gradient [MV/m]	20
Field on cathode [MV/m]	30
Cathode	CsK_2Sb (?)

BNL: 113MHz QWR gun with NC cathode & choke filter

Status: Routine operation, Coherent electron Cooling experiment

Parameter	Value
Rep. rate [kHz]	78
Bunch charge [pC]	0-20000
Emittance [mm-mrad]	0.3@100 pC
Beam energy [MeV]	1.25
Frequency [MHz]	113
Field on cathode [MV/m]	15
Cathode	CsK_2Sb

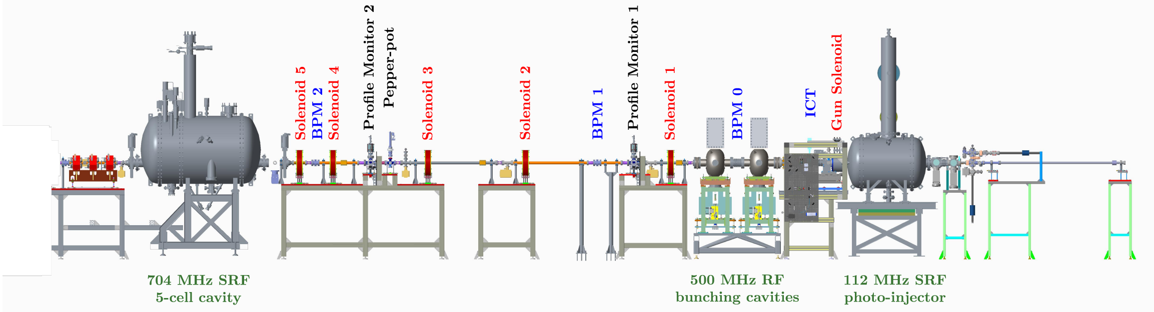




Highlights

- 1-2 months lifetime of high-QE CsK_2Sb cathodes
- dedicated procedure for the cavity start-up – no issues with multipacting
- 0.15 mm-mrad normalized RMS slice emittance measured for 100 pC bunches

Unexpected and Exciting Results: Very Low Transverse Emittance

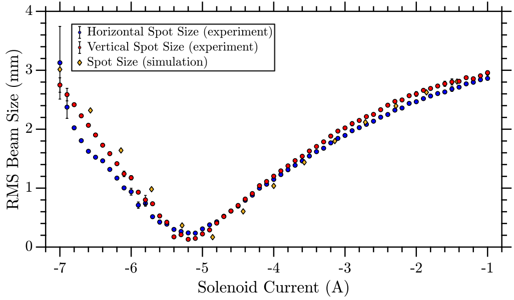


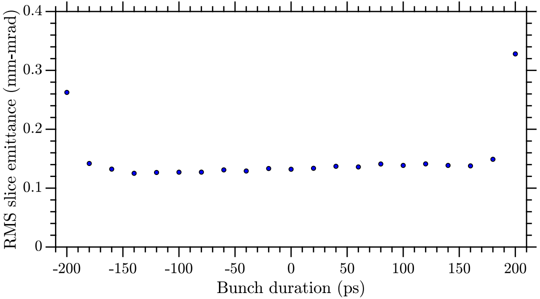
Normalized emittance for a 100 pC, 400 ps e-beam	
Projected emittance, mm-mrad	0.30
Slice emittance, mm-mrad	0.15

Normalized emittance for a 600 pC, 400 ps e-beam	
Projected emittance, mm-mrad	0.57
Slice emittance, mm-mrad	0.35

Transverse emittance from our SRF gun satisfies the requirements for a CW X-Ray FEL (0.4 mm-mrad for 100 pC bunches)!

Unexpected and Exciting Results: Very Low Transverse Emittance





Parameter	Units	LCLS II requirements	CeC SRF gun
Gun voltage	MV	0.75	1.25[1]
Charge per bunch	pC	100	100-10,000[1]
Average beam current @ 100 pC	mA	0.062	0.15[1]
Transverse RMS slice emittance @ 100 pC	mm-mrad	0.4	0.15[2]
Transverse RMS projected emittance @ 100 pC	mm-mrad	-	0.3[1]
Longitudinal RMS slice emittance @ 100 pC	keV·ps	3.3	0.7[2]
Quantum Efficiency	%	1	1-4[1]

[1]Measured value, [2]Extracted from simulations

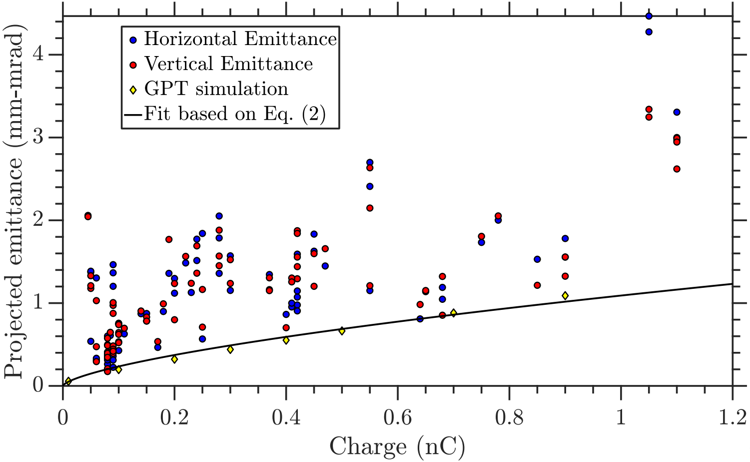
Emittance Measurements for a variety of settings during 2017-2018

Pancake-shaped bunch:

$$\varepsilon_n \propto \sqrt{q \frac{E_{MTE}}{E_{\text{em}}}} \quad (1)$$

Cigar-shaped bunch:

$$\varepsilon_n \propto \frac{\sqrt{E_{MTE}}}{E_{\text{em}}} \left(\frac{q}{\Delta t}\right)^{2/3} \quad (2)$$



BNL SRF gun: future plans

The collaboration between Stony Brook University, BNL, FNAL, and TJNAF is aiming to demonstrate:

- **High current SRF electron gun:** increase the average current of unpolarized electron beams to 100 mA.
- **Polarized SRF electron gun:** demonstrate sufficient lifetime of Cs_2Te-coated GaAs photocathode in the CeC SRF gun using 532 nm laser; generate and characterize polarized electron beams using 780 nm IR laser.
- **SRF electron gun performance restoration techniques:** simulate, design and build plasma processing system suitable for the 113 MHz gun geometry.

Conclusions

- SRF guns have demonstrated reliable performance in routine operation.
- Current designs have the potential to reach the high brightness requirement of modern XFELs and high average current for ERL.
- First tests of using an SRF gun as a polarized electron source are coming in the near future.
- There are still unanswered questions to be investigated:
  - Proper cathode solution is a key for the successful gun operation
  - Improved cavity gradient is pursued
  - High-QE long lifetime cathodes are a must
  - Effort on lowering the beam emittance: retracted cathode, higher field at the cathode.

Thank you for your attention

Special thanks:

- **CeC team:** V.N. Litvinenko, I. Pinayev, G. Wang, Y. Jing, J. Ma, K. Shih, Y.H. Wu
- **LLRF group:** G. Narayan, F. Severino, T. Hayes, K. Smith
- J. Tuozzolo[1], J.C. Brutus[1], S. Belomestnykh[3], C. Boulware[2], C. Folz[1], T. Grimm[2], P. Inacker[1], D. Kayran[1], G. Mahler[1], M. Mapes[1], T. Miller[1], T. Rao[1], J. Skaritka[1], Y. Than[1], E. Wang[1], B. Xiao[1], T. Xin[1], A. Zaltsman[1].

[1] Brookhaven National Laboratory, Upton, NY, USA
[2] Niowave Inc., Lansing, MI, USA
[3] Fermilab, Batavia IL, USA

For more details on the 113 MHz SRF gun refer to:

High-Brightness Continuous-Wave Electron Beams from Superconducting Radio-Frequency Photoemission Gun
I. Petrushina *et al.*
Phys. Rev. Lett. **124**, 244801 – Published 18 June 2020

Mitigation of multipacting in 113 MHz superconducting rf photoinjector
I. Petrushina, V. N. Litvinenko, I. Pinayev, K. Smith, G. Narayan, and F. Severino
Phys. Rev. Accel. Beams **21**, 082001 – Published 13 August 2018

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[12] I. Petrushina et al. "Mitigation of multipacting in 113 MHz superconducting rf photoinjector". In: *Physical Review Accelerators and Beams* 21.8 (2018), p. 082001.

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