Overview of Electron Source Development for High Repetition Rate FEL Facilities

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ACCELERATOR TECHNOLOGY & APPLIED PHYSICS DIVISION ATAP

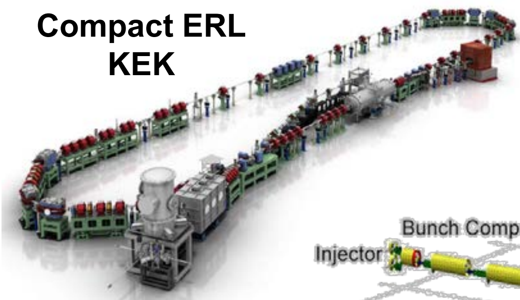
Outline

- Science Demand for High-Repetition Rate 4th Generation Light Sources
- Technology Implications Driven by the High-Rep. Rate Requirement
- The Need for High-Gradient and High-Energy High-Rep. Rate Guns
- Available Gun Technologies with Their Pros and Cons
- Performance Highlights
- Final Considerations and Future Needs

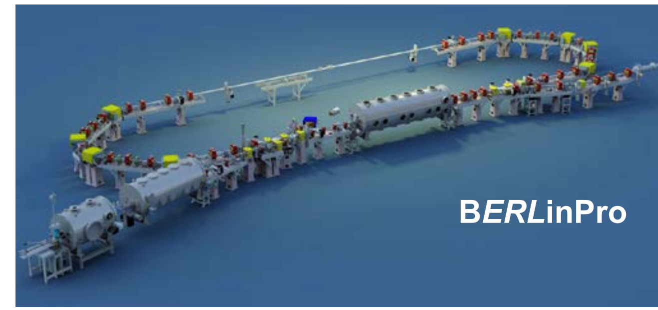
Science Driven Proposals/Projects!

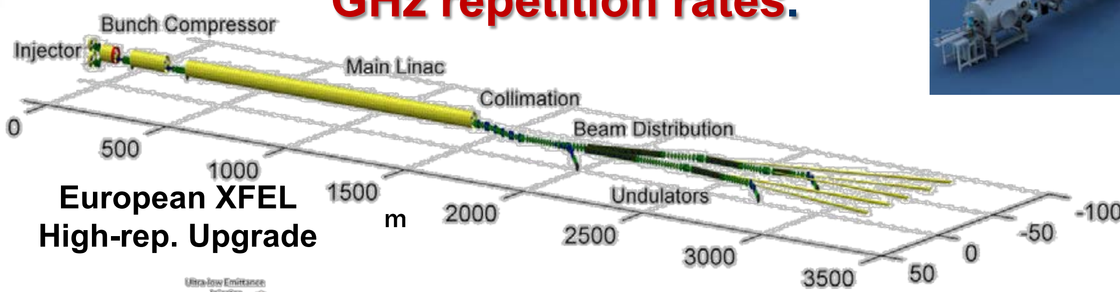
All operating 4th generation X-ray light sources are low repetition rate (< 120 Hz)
But science demand is pushing towards much higher repetition rates!

Compact ERL
KEK

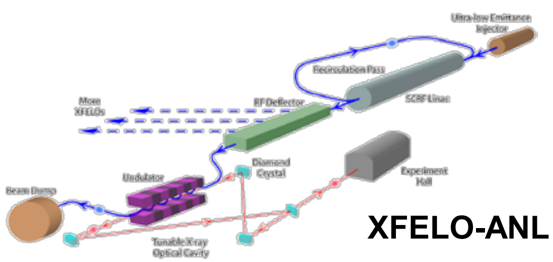


Proposed & in construction X-ray ERLs require the same beam quality at GHz repetition rates.



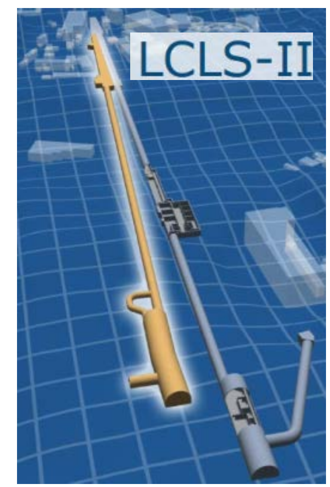


European XFEL
High-rep. Upgrade



XFELO-ANL

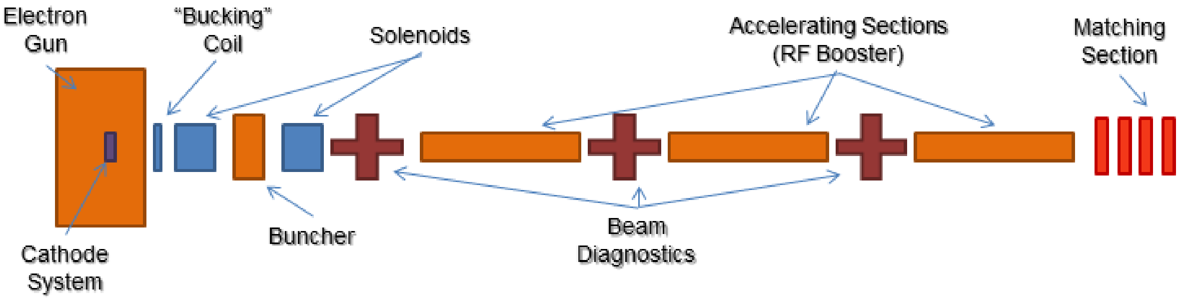
And proposed and under construction high-repetition rate X-ray FELs, FEL oscillators all require the similar beam quality at MHz repetition rates.



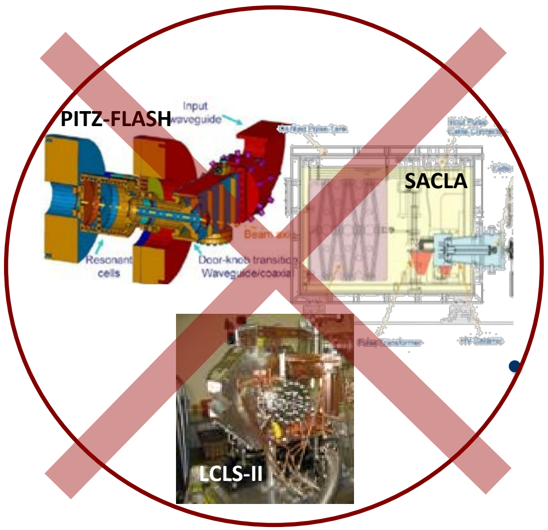
High repetition rate inverse Compton sources, UED, UEM, …

High-repetition rates high-brightness electron injectors are now required!

High Repetition Rate Technological Implications on the Injector



- High-repetition rates impose **superconductive accelerating cavities** in the RF booster to avoid unrealistic thermal losses.



- High-repetition rates require **high QE photo-cathodes** for realistic laser power requirements. Such cathodes are very reactive and susceptible to damage. **Demanding vacuum requirements for the gun.**

- Successful high-brightness low-repetition rate schemes such as NC high frequency (> 1.3 GHz) RF guns **cannot run at repetition rates >~ 10 kHz (excessive thermal load).**

A high-repetition rate high-brightness gun is a fundamental requirement!

What Does Define The Ultimate Performance of an FEL?

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

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

- The minimum obtainable value for ε_n defines the energy of the beam.

For X-Ray machines ($\lambda <\ \sim 1$ nm) and present gun performance that implies GeV-class electron beam energies obtainable by long and expensive linacs.

- Emittance appears also in the gain length for FELS. The smaller the emittance the shorter is the gain length

$$L_{Gain} \propto \left(\rho_{Pierce}\right)^{-1} \propto \gamma \left[\frac{\varepsilon_x}{I_p} \frac{1}{\lambda_u^2 K_u^2}\right]^{1/3}$$

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

$$\frac{\sigma_E}{E} <\sim \rho_{Pierce} \propto \frac{1}{\gamma}\left[\frac{I_p}{\varepsilon_x} \lambda_u^2 K_u^2\right]^{1/3} \approx 10^{-3}$$

- Achieving high FEL gain requires high ρ_{Pierce} → high peak currents (~ 1 kA) → hence high charge/bunch and short bunches.

→ FEL-based X-ray facilities requires high brightness accelerators. For a fixed charge, that translates in minimizing the emittance in all the planes.

The Emittance Game in the Injector

- It is well known that the ultimate brightness performance of a linac-based accelerator is set at the injector.

- Space charge forces that can generate emittance increase are strong in the injector and need to be properly controlled.

- The final transverse emittance at the injector output is given by:

$$\varepsilon_{nw} = \sqrt{\varepsilon^2_{nw\ Cathode} + \varepsilon^2_{nr\ Bz\ at\ Cathode} + \varepsilon^2_{nw\,Space\ Charge} + \varepsilon^2_{nw\,Optics\ \ Aberrations} + \varepsilon^2_{nw\ RF}} \qquad w = x, y$$

The optimization game in injectors consists in getting the cathode contribution term small and making all the other emittance contributions possibly negligible.

Cathode Emittance Contribution

• The **cathode thermal or intrinsic emittance** defines the emittance contribution associated to the cathode.

$$\varepsilon_{n\,Cathode} = \sigma_r \frac{\sigma_{p_r}}{mc} \quad \Rightarrow \quad \frac{\varepsilon_{n\,Cathode}}{\sigma_r} = \sqrt{\frac{\Delta E_C}{3mc^2}}$$

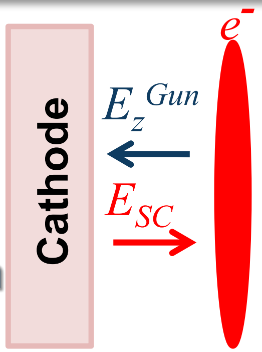
$$with \;\; \sigma_r \equiv rms \; beam \; size \; at \; the \; cathode$$

$$and \;\; \Delta E_C \equiv excess \; energy$$

In the "perfect" injector **the ultimate achievable minimal emittance is set by the thermal/intrinsic cathode emittance**

• Small cathode contributions to emittance can be obtained by the proper choice of the material (metal, semiconductor, …) and of the emission process (photo, field, thermal emission,…) but also by using **small beam sizes at the cathode**

Space Charge Limit and Gun Accelerating Gradient



• **During emission at the cathode**, the electric field E_{SC} due to the already emitted electrons shows opposite direction with respect to E_z^{Gun}, the accelerating field in the gun.

The **emission can continue until** E_{SC} **cancels** E_z^{Gun}.

The **max charge density that can be extracted by a given** E_z^{Gun} is known as the **'space-charge limit'** $\sigma_{SC\,MAX}$.

• Fixing charge, σ_{SC} is set by the bunch length and the transverse beam size. By setting the bunch length, a minimum transverse beam size σ_r^{min} is defined.

• By accounting that the emittance at the cathode is given by: The maximum brightness obtainable from a gun can be found.

$$\varepsilon_{n\,Cathode} \propto \sigma_r \sqrt{\Delta E_C}$$

For "pancake-beams" $\varepsilon_n^{\min} \propto \sigma_r^{\min} \sqrt{\Delta E_C} \approx \sqrt{\dfrac{Q\,\Delta E_C}{4\pi\,\varepsilon_0\,E_z^{Gun}}} \quad \Rightarrow B_{4D}^{\max} \propto \dfrac{Q/e}{\left(\varepsilon_n^{\min}\right)^2} \quad \Rightarrow \boxed{B_{4D}^{\max} \propto \dfrac{E_z^{Gun}}{\Delta E_C}}$

Bazarov, PRL 102, 104801 (2009)

Similarly for "cigar-beams" (long and transversely small beams) $\Rightarrow \boxed{B_{4D}^{\max} \propto \dfrac{\left(E_z^{Gun}\right)^{3/2} \sigma_\tau}{\sqrt{\sigma_r}\,\Delta E_C}}$

Filippetto, PRSTAB 17, 024201 (2014)

with σ_τ the bunch length

From these equations it is evident that a fundamental task for a high-brightness gun is to generate high accelerating gradients at the cathode

Space Charge Forces

Both transverse and longitudinal space charge forces that can jeopardize the beam brightness performance of an injector, scale with the inverse of the beam energy:

$$F_x = \left(1-\beta^2\right) qE_x \propto \frac{1}{\gamma^2} qE_x$$

$$F_y = \left(1-\beta^2\right) qE_y \propto \frac{1}{\gamma^2} qE_y$$

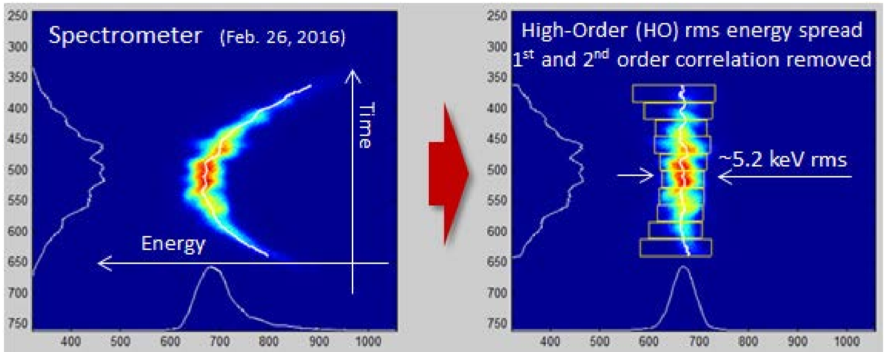
$$F_z = qE_z = \frac{1}{\gamma^2} \frac{q^2}{4\pi\varepsilon_0} \frac{1}{z^2}$$

By "quickly" accelerating the beam to relativistic energies it is possible to minimize the effects of space charge on brightness.

It is now evident that an additional fundamental task for a high-brightness gun is to generate high beam energies at its exit

It is not only Transverse Phase Space

- **FELs require heavy compression to achieve kA peak currents. Compression performance strongly depends from longitudinal phase space quality.**
- **While energy spread is usually artificially increased to mitigate microbunching instability in compressors, energy to longitudinal position correlations must be carefully controlled to avoid compression limitations.**
- **Linear & quadratic correlations can be compensated (linac dephasing, passive “dechirpers”, and harmonic cavities). Higher order correlations cannot be controlled and must be carefully minimized already at the injector/gun.**



- **Higher gradients and energies at the gun allow for a better control of such terms**

Once more, the pursue of higher accelerating gradients at the cathode and high beam energies at the gun exit are top priority goals for gun designers

TASK #1

TASK #2

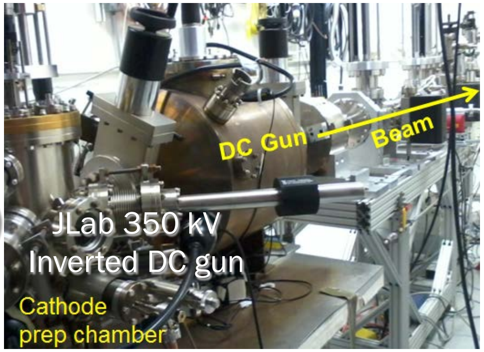
Requirements for a High-Repetition Rate x-ray FEL Gun

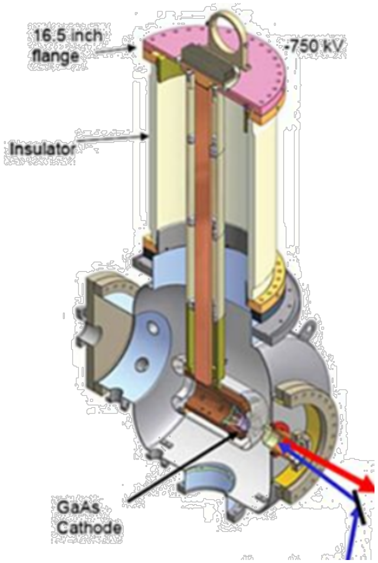
Besides the just mentioned two main tasks a high-brightness high-repetition rate electron gun has to satisfy additional requirements:

Repetition rate	~ MHz	
Charge per bunch	~ 10 – 500 pC	Different modes of operation
Normalized emittance	~ 0.1 – 0.7 μm	Lower value for lower charge
Beam energy at the gun exit	~ 0.5 – 3 MeV	For controlling space charge
Cathode electric field at photoemission	~ 10 – 40 MV/m	Maximum brightness limit; longitudinal phase space linearity.
Bunch length and shape control	From < 1 to ~ 60 ps	Space charge control; different modes of operation
Cathode/gun area magnetic field compatibility		Emittance compensation; (exotic modes)
Dark current at nominal gun energy	< ~ 100 nA	SRF quencing; rad. damage
Operational vacuum pressure	$\sim 10^{-10} – 10^{-9}$ Torr	High QE cathode lifetime
Loadlock cathode vacuum system		"Quick" cathode exchange
Reliability	High (>~98%)	Required for an user facility

DC Gun Technology

Pros:
- DC operation and GHz-class repetition rate capabilities
- DC guns reliably operated at ~ 400 kV, ongoing effort to increase the final energy to ~ 500 kV.
- Injector with DC gun demonstrated the capability of sub-micron emittances at several hundreds of pC, when a sufficient number of knobs are provided
- Highest current operation demonstrated
- Full compatibility with magnetic fields.
- Excellent vacuum performance
- Compatible with most photo-cathodes. (the only one operating GaAs cathodes)

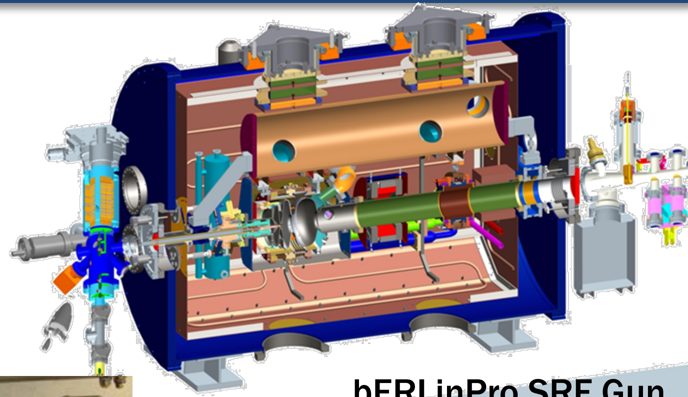




Cornell DC gun

Challenges:
- Beam energy approaching the limit of the technology
- Limited accelerating gradients at the cathode (up to ~ 10 MV/m)
- Developing and test new gun geometries (inverted geometry)

Superconducting RF Gun Technology


bERLinPro SRF Gun

Pros:

- Potential for high gradients. Demonstrated ~ 50 MV/m with super-conductive cathodes and ~ 20 MV/m with high QE cathodes.
- Several MeV beam energy demonstrated
- CW operation with GHz-class repetition rate capabilities
- Excellent vacuum performance.


DESY SRF Gun

Challenges:

- Overcome accelerating gradient degradation when cathodes are inserted (particulates creation by insertion mechanism?).
- Improve QE and QE lifetime of high QE semiconductor cathodes when used in the SRF structures
- Develop schemes compatible with emittance compensation (field exclusion, magnetic field induced quenching, …).

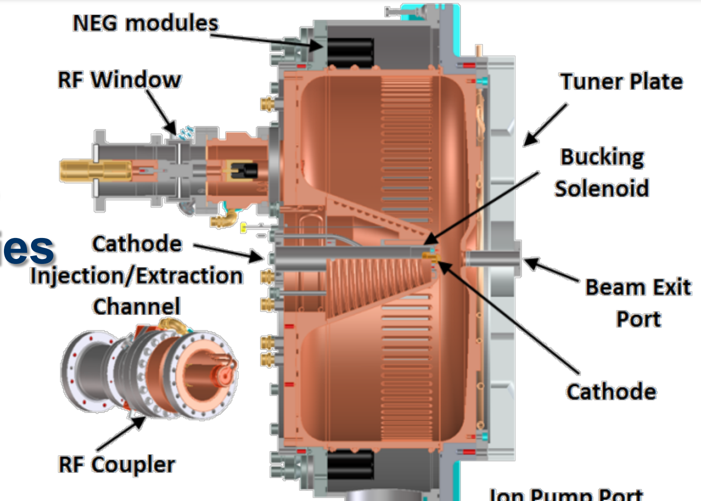
Low Frequency Normal Conducting RF Gun Technology

Pros:

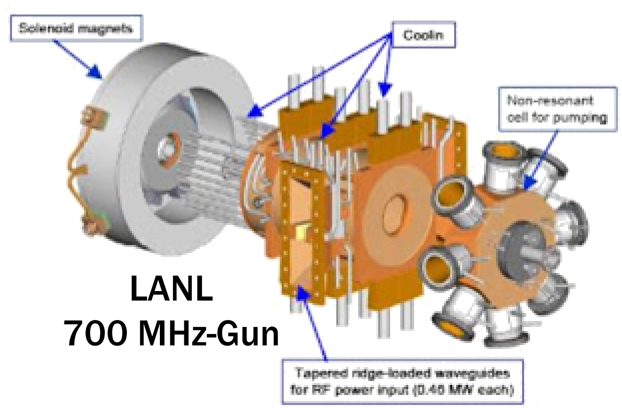
- Operate in CW mode
- For VHF frequency guns beam dynamics similar to DC but with much higher gradients and beam energies
- VHF frequency range version based on mature RF and mechanical technologies.
- Full compatibility with magnetic fields.
- Compatible with most photo-cathodes (demonstrated low pressure performance capability)
- VHF-Gun demonstrated high brightness performance for X-ray FELs

Challenges:

- High gradients and energies require high RF power



LBNL VHF-Gun



LANL 700 MHz-Gun

Hybrid DC-SRF Gun Technology

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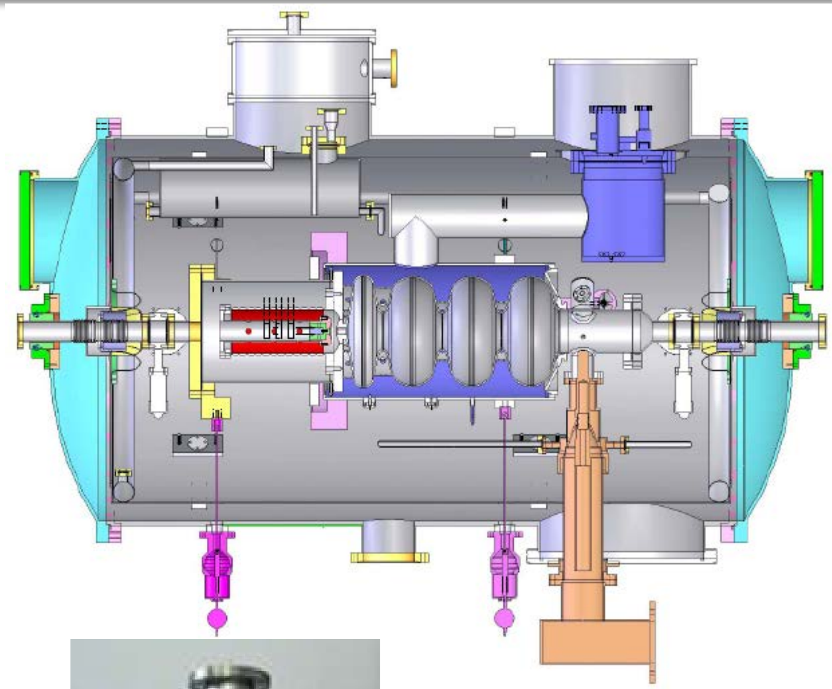
Pros:

- Brings the cathode out of the cryogenic environment
- Allows for a final beam energy higher than in DC guns
- Demonstrated mA-class current operation with semiconductor cathodes



Challenges:

- Gradient limitation in the DC part
- Increased system complexity

Peking University DC-SRF Gun

A (Incomplete!) List of Groups Developing High-Brightness High-Repetition Rate Gun

DC Guns

1. Cornell
2. Daresbury
3. JLab
4. JAEA
5. KEK

SRF Guns

1. BNL
2. DESY
3. HZB
4. JLab
5. KEK
6. Rossendorf
7. Winsconsin

NC RF Guns

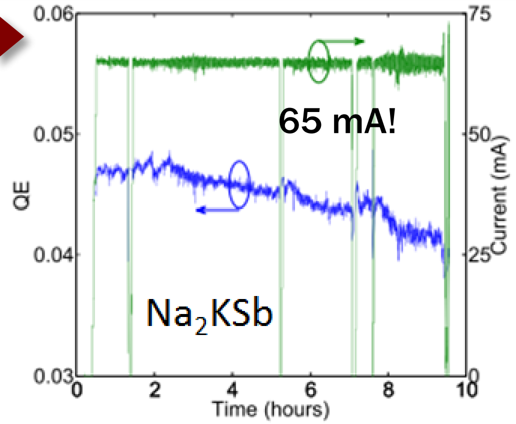
1. LANL
2. LBNL
3. SINAP

DC-SRF Guns

1. Peking University

DC Guns Accomplishment Highlights

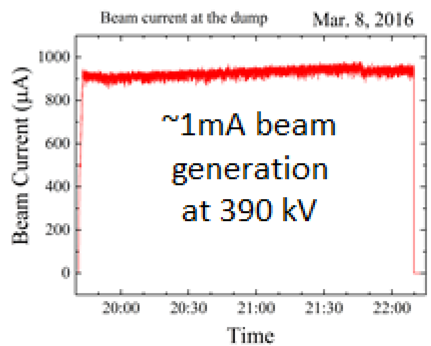
- **Cornell gun: delivered record high currents**

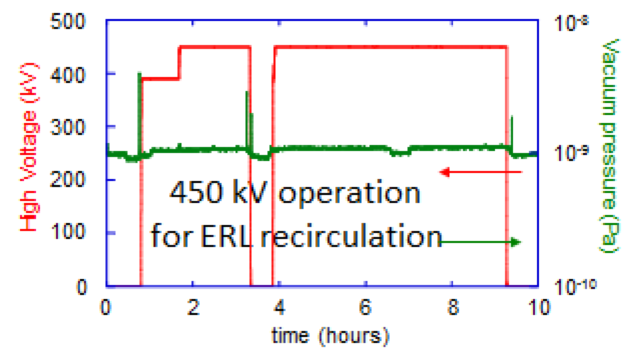


demonstrated LCLS-II beam quality needs @ ~ 400 keV

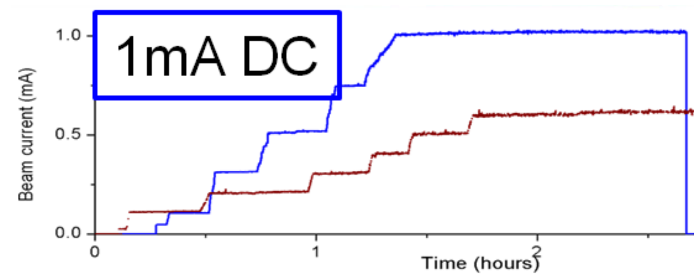
Q (pC)	I_{peak} Goal (A)	I_{peak} (A)	ε_n Goal (95%, μm)	ε_n (95%, μm)
20	5	5	0.25	H: 0.18, V: 0.19
100	10	11.5	0.40	H: 0.32, V: 0.30
300	30	32	0.60	H: 0.62, V: 0.60

- **KEK/JAEA DC gun:**
  ~1 mA with energy operation (390-450 keV) approaching 500 keV



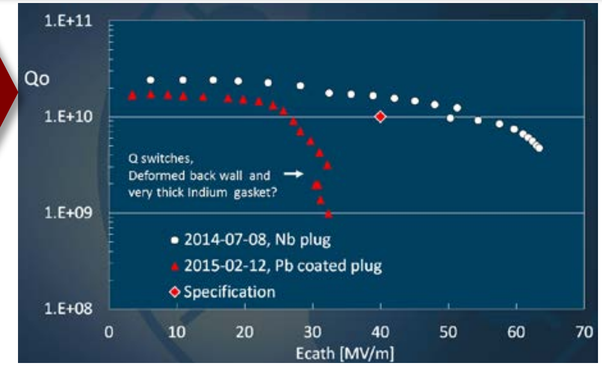


- **JLab new design inverted geometry delivered mA class beams approaching design energy of 350 keV (~325 keV)**

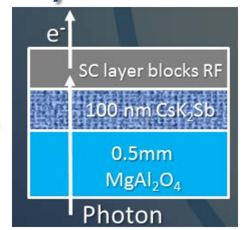


SRF Guns Accomplishment Highlights

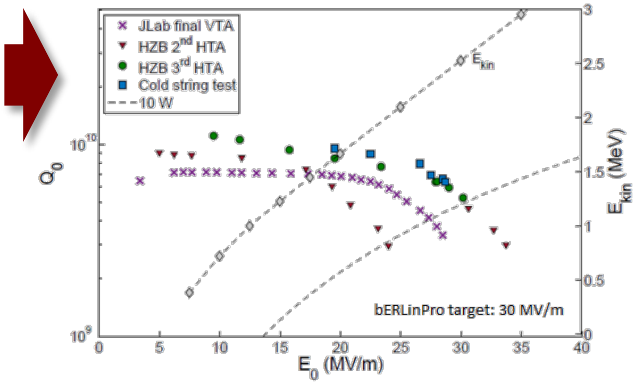
- DESY 1.3 GHz gun demonstrated ~50 MV/m at the cathode with Nb cathodes (~27 MV/m with Pb)



- KEK gun uses SC material layer and back illumination on their cathode to overcome warm cathode issues



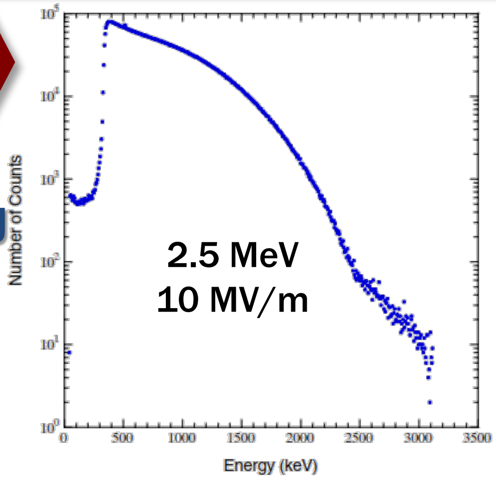
- HZB after first promising results with Gun 0 (~27 MV/m on Pb cathode) is getting ready to test Gun 1.



- HZRD 1.3 GHz confirmed many years of operation with warm cathodes and is planning for several upgrades and testing transverse focusing by HOMs
- Wisconsin 200 MHz gun generated beams at ~2.0MeV with ~20MV/m gradient with Cs_2Te cathode. Gradients up to 29MV/m were generated without cathode.
- BNL 113 MHz Gun, during CsK_2SB tests delivered high charges per bunch (3.7 nC), and 2 μm ε_n at 250 pC and 15 MV/m at the cathode.

NC RF Guns Accomplishment Highlights

- **Los Alamos 700 MHz demonstrated CW operation with ~800 kW RF power dissipated on the cavity wall.**

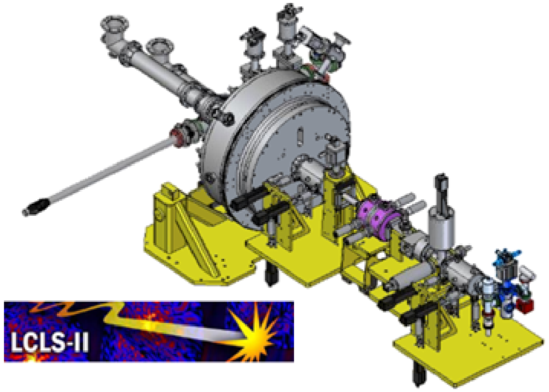


- **LBNL 186 MHz VHF-Gun demonstrated at APEX injector test facility all formal requirements for LCLS-II, including the generation of beams with the quality required to operate in high repetition rate X-ray FELs.**

Quantity	Required	Measured	Demonstrated
Charge per bunch [pC]	> 20	20-25	☺
Normalized emittance [μm]	< 0.25	~ 0.20*	☺
Bunch peak current [A]	> 5	5 - 9	☺
Energy Spread (H.O. whole beam) [keV]	< ~15	< 9**	☺

* After accounting for space charge contribution
** Value affected by space charge. Much smaller values at LCLS-II injector energies.

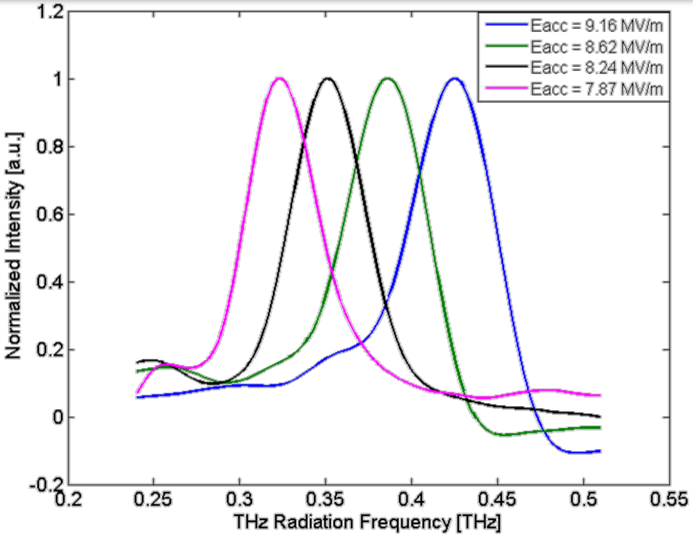
- **LBNL is fabricating a VHF-Gun (close version of the APEX gun) that will be driving the LCLS-II injector.**



- **A 250 MHz VHF-Gun was built at SINAP and underwent successful low power RF tests.**

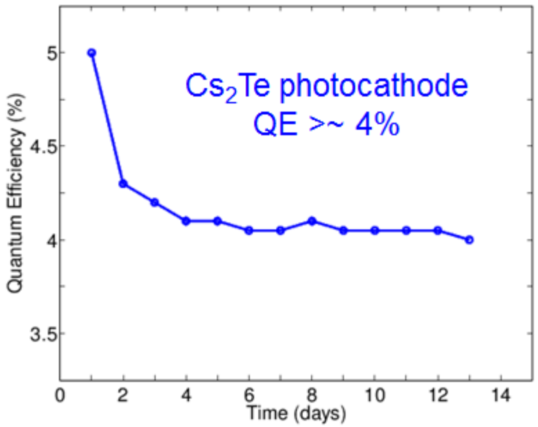
DC-SRF Guns
Accomplishment Highlights

- **3.5-cell gun fully commissioned entering in the users' time phase:**
  - **THz,**
  - **UED.**



- **Up to 1 mA on the macropulse (7% duty cycle at 81.25 MHz rep. rate)**

- **"Cesiation" before transfer in the cryomodule enhances Cs_2Te QE.**



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Performance Summary Table

Group	Technology	Cathode E_z at emission (goal)	Cathode E_z at emission (measured)	Beam energy (goal)	Beam energy (measured)	ε_n at charge (measured)	Current/ repetition rate (measured)
Cornell	DC	~6 MV/m	~5 MV/m	0.5-0.75 MeV	~0.4 MeV	~0.2μm/20pC ~0.3μm/0.1nC ~0.6μm/0.3nC	20-65 mA/ 1.3 GHz
Daresbury (JLab-type Gun)	DC	~3.3 MV/m	~3.1 MV/m	0.35 MeV	0.325 MeV	~5μm/50pC	~8μA/81.25MHz 100μs @ 20Hz
JAEA/KEK	DC	~6.7 MV/m	~6.7 MV/m	0.5 MeV	0.45-0.5MeV	~1.1μm/7.7pC	~1 mA/1.3GHz
JLab	Inverted DC	~4.5 MV/m	~3.9 MV/m	0.35 MeV	~0.3 MeV	To be measured	~1mA/DC
BNL	112 MHz SRF	22.5 MV/m	~15 MV/m	2 MeV	~1.2 MeV	~2μm/0.25nC	Up to 3.7nC
DESY	1.3 GHz SRF	~40 MV/m	~40MV/m Nb cath. ~22MV/m Pb cath.	3.7 MeV	To be measured	To be measured	To be measured
HZ Berlin (Gun 0.2)	1.3 GHz SRF	~9 MV/m	~10MV/m Pb cath.	2.3 MeV	2.5 MeV	1.9μm/mm rms Pb	Not available
HZ Rossendorf	1.3 GHz SRF	9 MV/m	~9 MV/m	4.5 MeV	~4.5 MeV	~0.3μm/3pC ~5μm/0.09nC	20μA/100kHz
KEK	1.3 GHz SRF	25 MV/m	To be measured	2 MeV	To be measured	To be measured	To be measured
Wisconsin	200 MHz SRF	40 MV/m	29MV/m no cath. 20 MV/m Cs_2Te	4 MeV	2.9MeV no cath. 2 MeV Cs_2Te	~1.5μm/0.1nC	Not available
LANL	700 MHz NC RF	~10 MV/m	~9.8MV/m	2.7 MeV	2.5 MeV	Not available	Not available
LBNL	186 MHz NC RF	19.5 MV/m	> 21 MV/m	0.75 MeV	> 0.8 MeV	~0.2μm/20pC	0.3 mA/1MHz
Peking University	DC SRF	5 MV/m	~2.6 MV/m	5 MeV	~3.4 MeV	~2μm/20pC	0.55mA/81.3MHz

Is the Present Performance of the Different Technologies Sufficient?

DC Guns have demonstrated FEL-class brightness and record high currents.
Several SRF Guns are demonstrating high gradient operation.
NC RF guns demonstrated FEL-class brightness and MHz repetition rate operation.

In other words, gun technologies have already demonstrated the gradients and the beam energies (and in some cases also the beam quality) required to operate present high-repetition rate X-ray FELs

Is the Present Performance Sufficient for Future Upgrades?

New proposals and upgrades (LCLS-II HE, MaRIE, …) require significantly lower transverse emittances to dramatically extend their photon spectra towards shorter wavelengths.

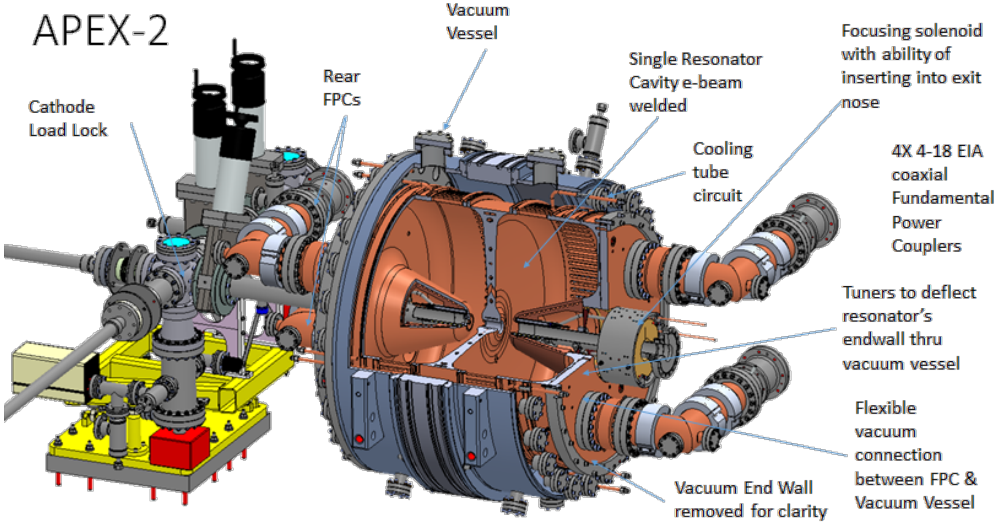
Electron sources capable of gradients at photoemission >~30 MV/m and energy >~1 MeV are now necessary.

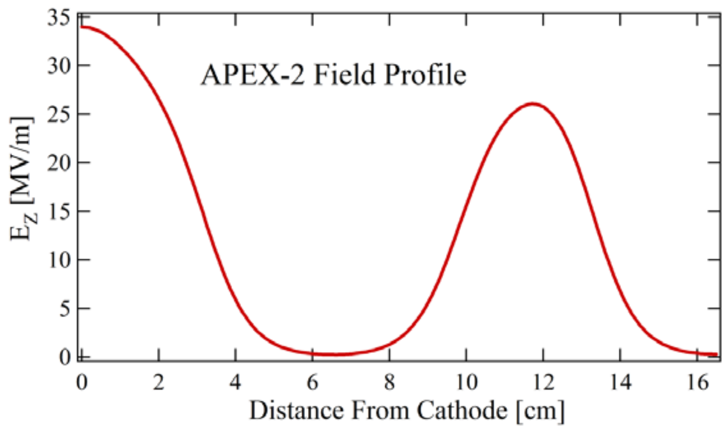
A recent DOE-BES sponsored workshop titled "*Future Electron Sources*" put together experts from around the world to define a pathway towards this enhanced performance.

The following tentative priority directions were defined (in arbitrary order):

- **Continue the R&D towards lower thermal emittance cathodes**
- **Continue the R&D on SRF gun to solve the present issues and achieve their nominal parameters.**
- **Extend the present NC low frequency RF gun schemes to generate higher gradients and beam energies**

APEX-2 the LBNL Answer to That Need





Parameter	APEX	APEX-2
Frequency [MHz]	186.7 (1300/7)	**162.5 (1300/8)**
Mode of operation	CW	**CW**
Launching field on cathode [MV/m]	19.5	**34**
Beam energy [MV]	0.75	**2**
Number of cells	1	**2**
RMS power per cell [kW]	85	**127**
Peak wall power density [W/cm^2]	22	**30**
Cavity inner radius [cm]	34.7	**47.5**
Cell length [cm]	35	**35**

(Incomplete) List of References

DC Guns

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That's It!

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