Higher Fields and Beam Energies in CW Room-Temperature VHF RF guns

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- Preamble
  - In the last decade, science demand pushed towards the development of CW 4th generation light sources requiring high-brightness CW guns.
  - Main ingredients for making a high-brightness high-repetition rate electron gun.
  - The present VHF-Gun, the CW room-temperature RF gun and its present performance.
- Upgrade paths towards a higher brightness VHF-Gun.

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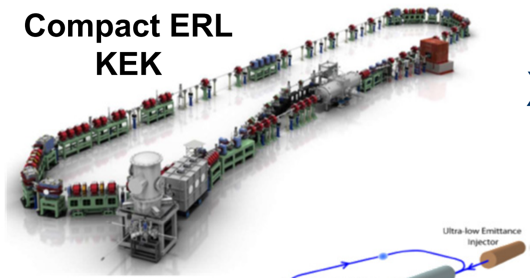
Science Driven Proposals/Projects!

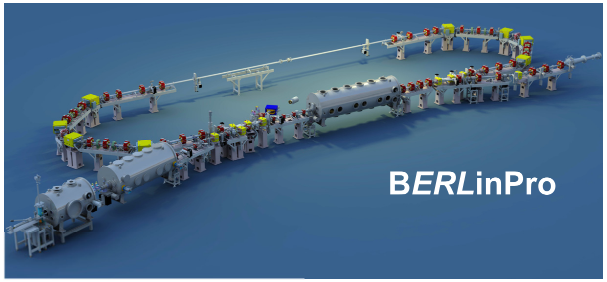
All operating 4th generation X-ray light sources are low repetition rate (< 120 Hz)

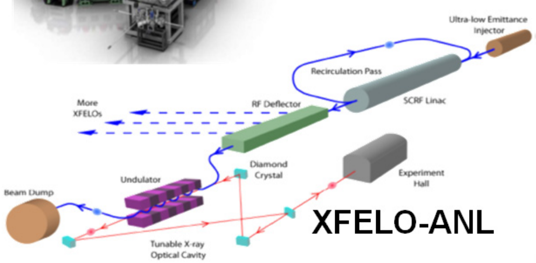
But science demand is pushing towards much higher repetition rates!

Compact ERL
KEK

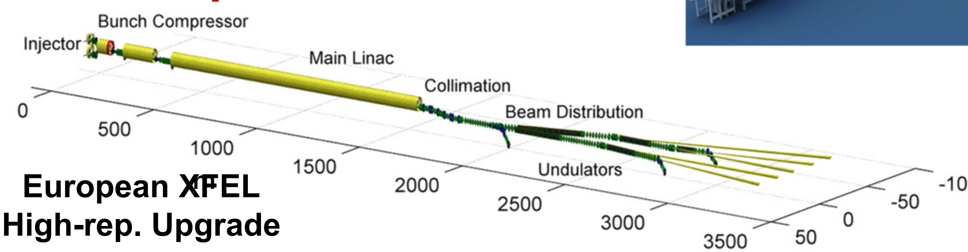


Proposed & in construction X-ray ERLs require the same beam quality at GHz repetition rates.

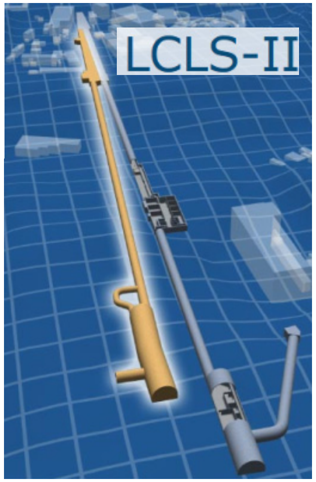




XFELO-ANL



European XFEL
High-rep. Upgrade



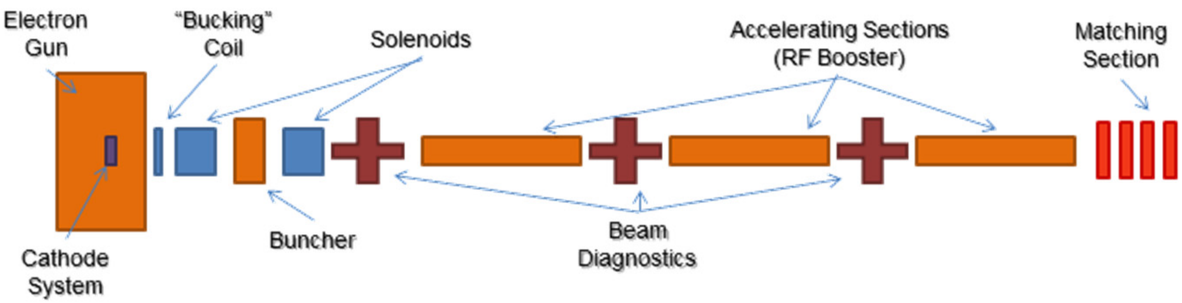
LCLS-II HE and Shanghai Coherent Light Facility (SCLF) recently approved!

And proposed/approved high-repetition rate X-ray FELs all require similar beam quality at MHz repetition rates.

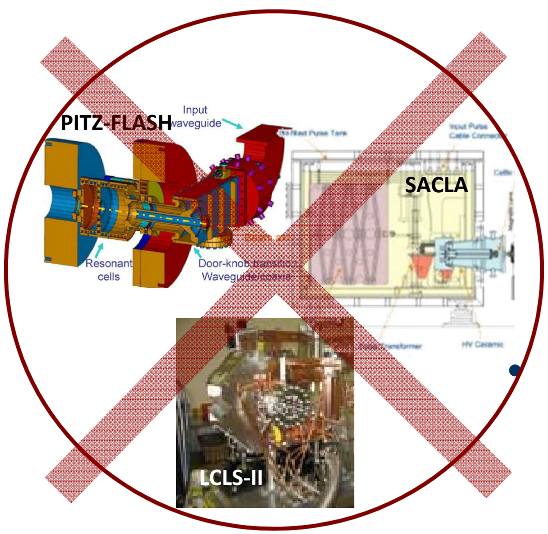
High repetition rate inverse Compton sources, UED, UEM, …

High-repetition rates (CW) high-brightness electron injectors are 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.**



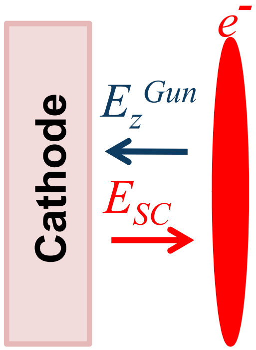
- **High-repetition rates require high QE photo-cathodes for realistic laser power requirements. Such cathodes are very reactive and susceptible to damage. Demanding vacuum requirements for the gun.**

- **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).**

New scheme high-repetition rate high-brightness guns are necessary!

Space Charge Limit and Gun Accelerating Gradient

- **During emission at the cathode, the electric field E_{SC} of the already emitted electrons limits the max charge density $\sigma_{SC\,MAX}$ that can be extracted by a given E_z^{Gun}.**



A consequence of this is that the maximum brightness that can be generated by a fixed field at the cathode is limited as well.

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

Bazarov, PRL 102, 104801 (2009)

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

Filippetto, PRSTAB 17, 024201 (2014)

with σ_τ the bunch length

Additionally, space charge forces that can dilute the emittance, scale with the inverse of the beam energy squared.
So a "quick" acceleration to higher energies is desired.

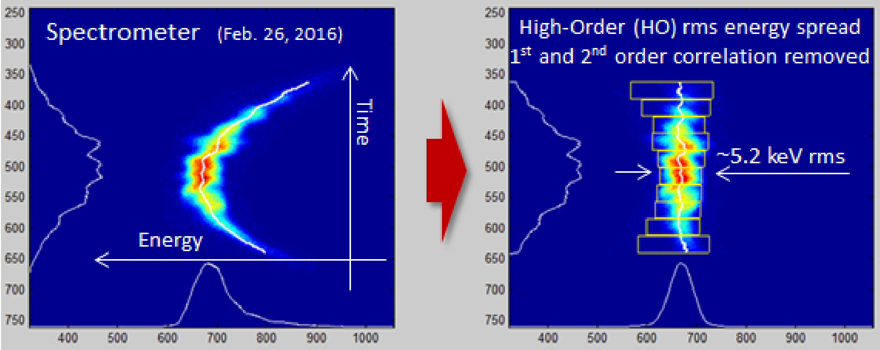
From these considerations, it is evident that high-brightness guns require <u>high accelerating gradients at the cathode</u> and <u>high output energies</u>

It is not only Transverse Phase Space

- **High-gain FELs require heavy compression to achieve kA peak currents. Compression performance strongly depends from longitudinal phase space quality.**

- **In particular, correlations in the longitudinal phase space 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.**

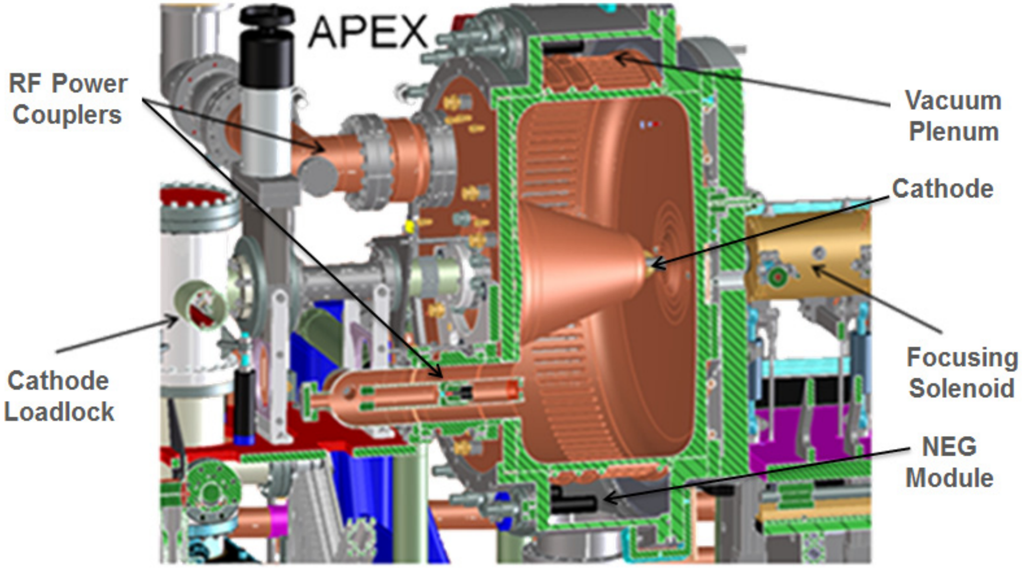


- **Higher gradients and energies at the gun allow for a better control of such terms**

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

The APEX VHF-Gun

The VHF-Gun, a normal-conducting scheme that satisfies all requirements.



J. Staples, F. Sannibale, S. Virostek, CBP Tech Note 366, Oct. 2006
F. Sannibale, et al., PRST-AB 15, 103501 (2012)
R. P. Wells, et al., Review of Scientific Instruments, 87, 023302 (2016)

Frequency	186 MHz (1.3 GHz/7 or 1.5 GHz/8)
Operation mode	CW
Gap voltage	750 kV
Field at the cathode	19.47 MV/m
Q_0 (ideal copper)	30887
Shunt impedance	6.5 MΩ
RF Power @ Q_0	87.5 kW
Stored energy	2.3 J
Peak surface field	24.1 MV/m
Peak wall power density	25.0 W/cm^2
Accelerating gap	4 cm
Diameter/Length	69.4/35.0 cm
Operating pressure	~ 10^{-10}-10^{-9} Torr

- At the VHF frequency, the cavity structure is large enough to withstand the heat load and operate in CW mode at the required gradients.
- Also, the long λ_{RF} allows for large apertures and thus for high vacuum conductivity.
- Based on mature and reliable normal-conducting RF and mechanical technologies.

APEX VHF-Gun Performance

Demonstrate capability of the VHF-Gun to reliably run in CW mode at the required cathode fields and energy (750 keV)
F. Sannibale, *et al*., PRST-AB **15**, 103501 (2012)

> 840 keV measured

Identify a cathode and demonstrate its capability to operate with sufficient lifetime (τ > 4 days - LCLS-II) at the required charge/bunch, rep. rate, and thermal emittance (<1 μm/mm required, ~0.7 μm/mm measured with Cs_2Te)
Filippetto, Qian, Sannibale, Appl. Phys. Letters **107**, 042104 (2015).

τ ~ 17 days Measured with Cs_2Te

Characterize and reduce dark current from the gun at the required level (< 400 nA @ 750 keV – LCLS-II)
R. Huang, *et al*., PRST-AB **18**, 013401 (2015)

~ 0.1 nA measured

Demonstrate the capability of APEX to operate with emittance and compression compatible with LCLS-II requirements and validate simulations.
In March 2016 a review of experts confirmed that all LCLS-II beam requirements were demonstrated and that simulations are reliable.

All parameters demonstrated

Is the Present Performance of the Different Technologies Sufficient?

The VHF-Gun has already demonstrated the fields at the cathode, beam energies and other parameters (vacuum, cathode lifetime) and ultimately the beam quality required to operate <u>present</u> high-repetition rate X-ray FELs.

Is the Present Performance Sufficient for Future Upgrades?

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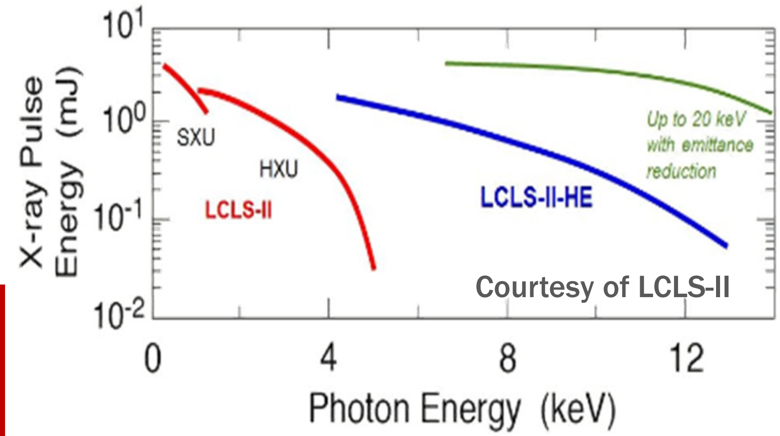
No!

New proposals/upgrades (LCLS-II HE, MaRIE, SCLF, …) would strongly benefit from lower emittances to extend their photon spectra to shorter wavelengths.

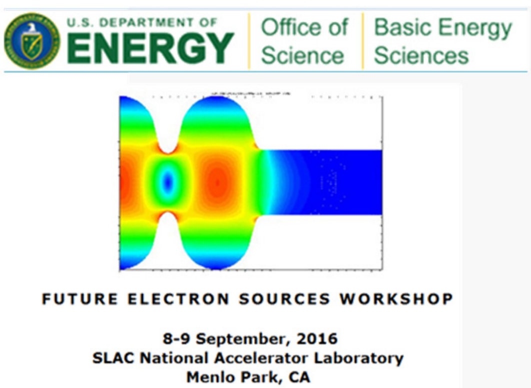


Electron guns capable of fields at photoemission >~30 MV/m and energy >~1 MeV are now necessary.

A recent DOE-BES workshop put together experts from around the world to define a pathway towards this enhanced performance.

Priority directions were established (arbitrary order):

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

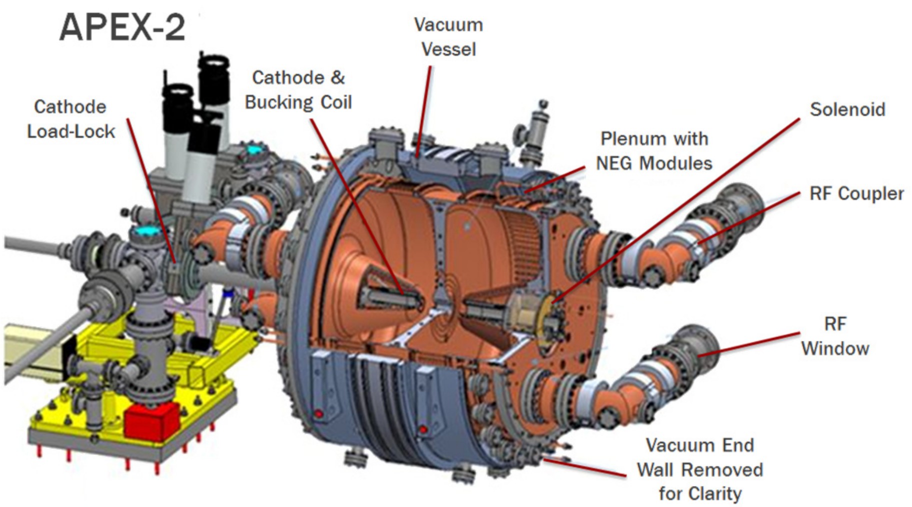


APEX-2 the LBNL Proposed Answer to That Need

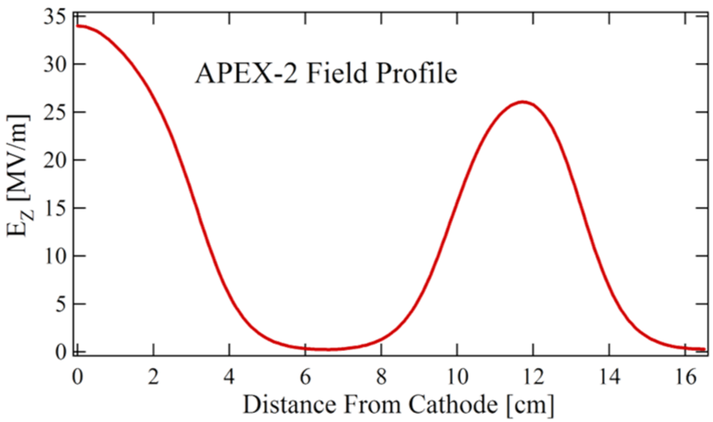
Based on APEX VHF-Gun successful performance.

APEX-2 fields and energies are comparable to those targeted by SRF guns with lower costs and complexity.

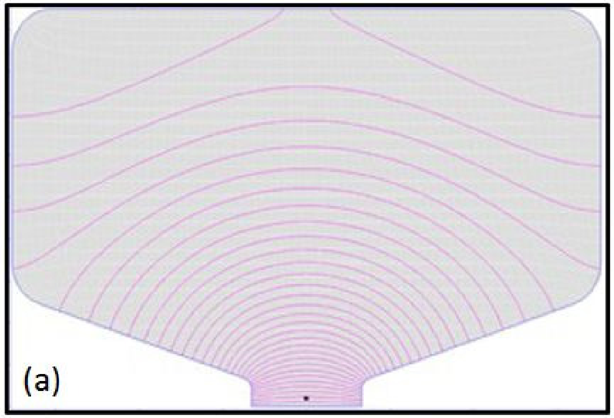
Parameter	APEX	APEX-2
Frequency [MHz]	186.7 (1300/7)	162.5 (1300/8)
Mode of operation	CW	CW
Launching field on cathode [MV/m]	19.5	34
Beam energy [MV]	0.75	2
Number of cells	1	2
RMS power per cell [kW]	85	127
Peak wall power density [W/cm^2]	22	30
Cavity inner radius [cm]	34.7	47.5
Cell length [cm]	35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



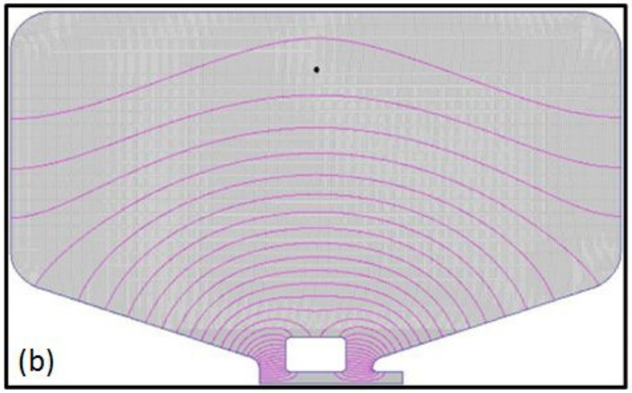
The two cells are decoupled and independently driven.



APEX-2 Alternate Designs

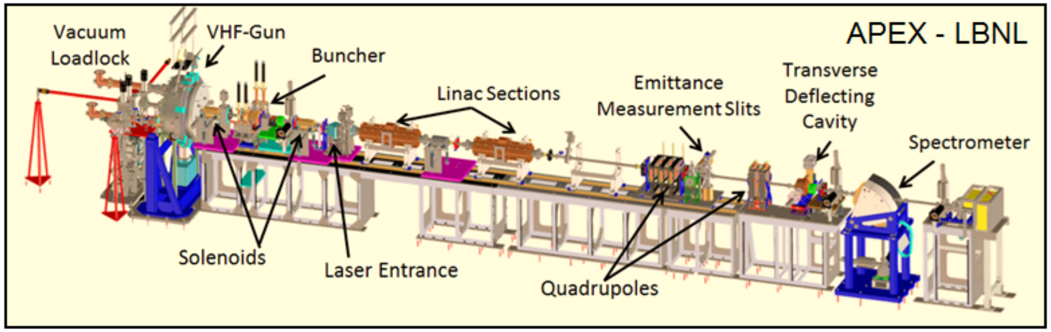


By removing the separation wall from the dual cell configuration, one obtains a layout with a large **Single-cell with dual nosecone** cavity.
Respect to the dual-cell version this option allows for same power to **higher output energies** but **lower fields at the cathode** .



The insertion of drift tube in the gap allows for recovering the field at the cathode and to make the cavity more efficient with a minor decrease of the output energy.
This **single-cell with drift tube** option allows for 35 MV/m at the cathode with a relatively small RF power requirement ~200 kW

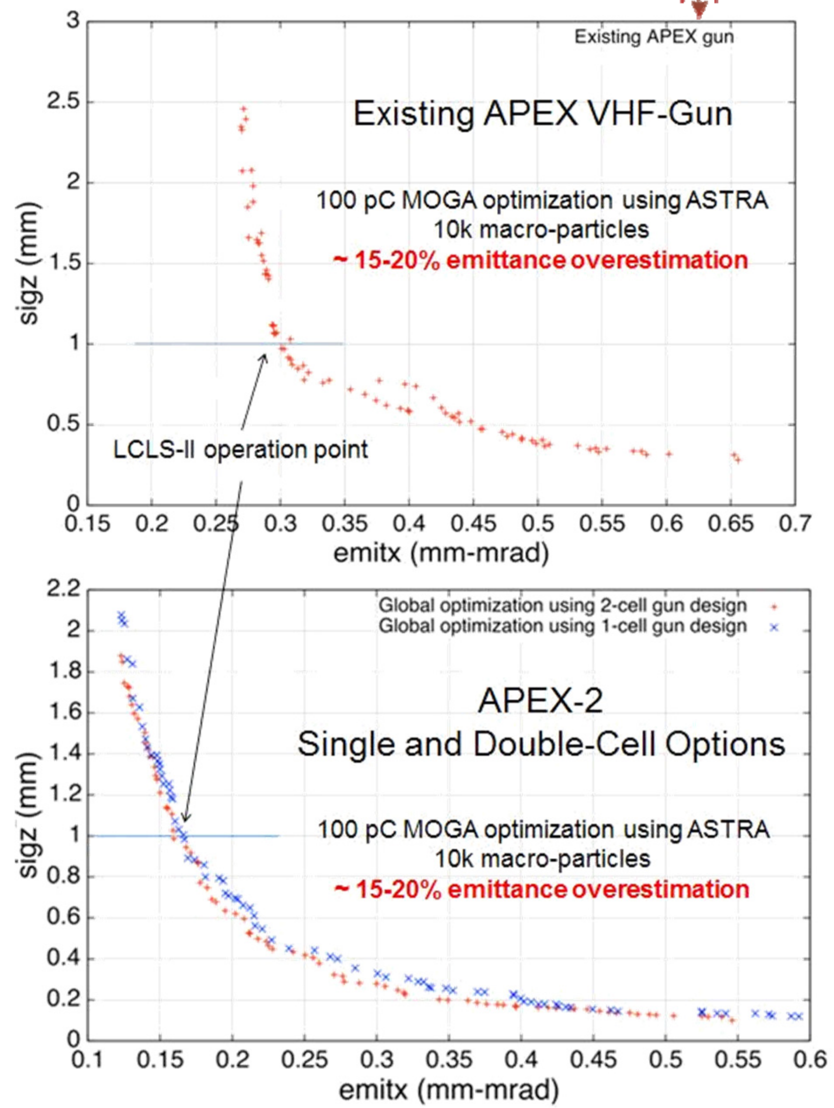
APEX-2 Performance Simulation



APEX-like layout used for simulations.

For a fixed field at the cathode the results do not depend on the gun geometry.

This initial simulations shows a 2-fold decrease in emittance (~0.13 µm at 100 pC) and hence the 4-fold brightness increase required by future applications.



Summary

- New proposed and upgraded versions of CW X-FELs would strongly benefit from the development of a higher brightness CW photo-injector.
- Initial studies at the conceptual level indicates that there are no evident show-stoppers to upgrade the VHF-Gun technology towards this new target.
- Several upgrade options are possible and further analysis and design work are necessary to bring such concepts from the conceptual to the fabrication level.

Thanks for the attention!