High-Brightness Electron Injectors for High-Duty-Cycle X-Ray Free Electron Lasers

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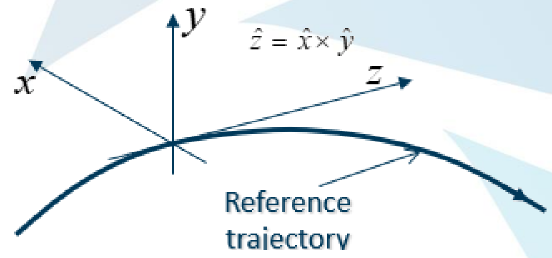
Outline

- Introduction
  - Brightness the ultimate parameter that defines the performance of a light source
  - The X-ray FEL brightness revolution and the X-ray FEL Dream
  - Science demand for high-duty-cycle (CW) high-repetition X-Ray FEL Dream
- FEL basics
- Ultimate FEL brightness performance already defined at the injector
- Injector requirements in linac-based high-duty-cycle X-FEL applications
- High-duty-cycle implications on X-FEL accelerators technology
- Examples of high-duty-cycle injectors existing and under development
- Injector requirements for future and upgraded high-duty-cycle X-FELs
- Conclusions

Brightness the Ultimate Particle Beam Parameter



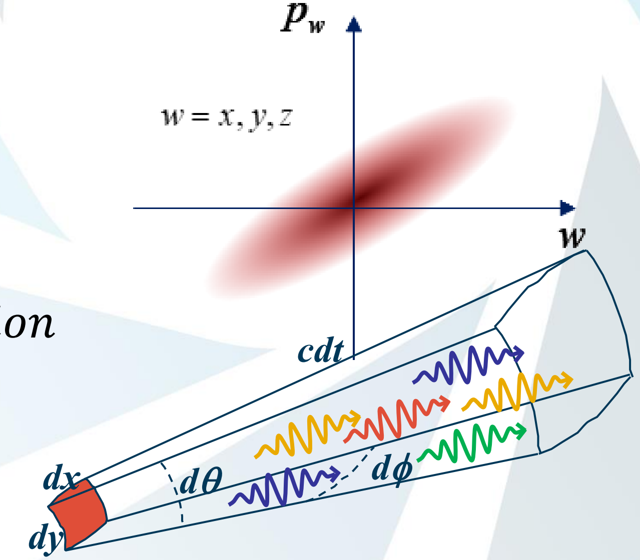
Brightness. The general definition of brightness is of a quantity proportional to the density of particles in the 6-D phase space defined by the 3 couples of conjugate variables $\{x, p_x\}$, $\{y, p_y\}$, $\{z, p_z\}$.

Brightness applies to any kinds of particles (photons, electrons, protons, neutrons, heavy ions, etc.).

Normalized emittance ε_n. Quantity proportional to the area occupied by the particles in the 2-D phase space plane.

$$\varepsilon_{nw} = \sigma_w \frac{\sigma_{pw}}{mc}$$

with $= x, y, z$ *and σ the distribution standard deviation*



Brightness is then defined as:
with N_p the number of particles in the bunched beam

$$B = \frac{N_p}{\varepsilon_{nx}\varepsilon_{ny}\varepsilon_{nz}}$$

When brightness is applied to beams propagating along a particular direction (we will assume z from now on) p_x and p_y are often replaced by the angular coordinates $x' = p_x/p_z = \tan\phi$ and $y' = p_y/p_z = \tan\theta$, and the conjugate couple z and p_z are often replaced by time t and energy E.

Geometric emittance ε:

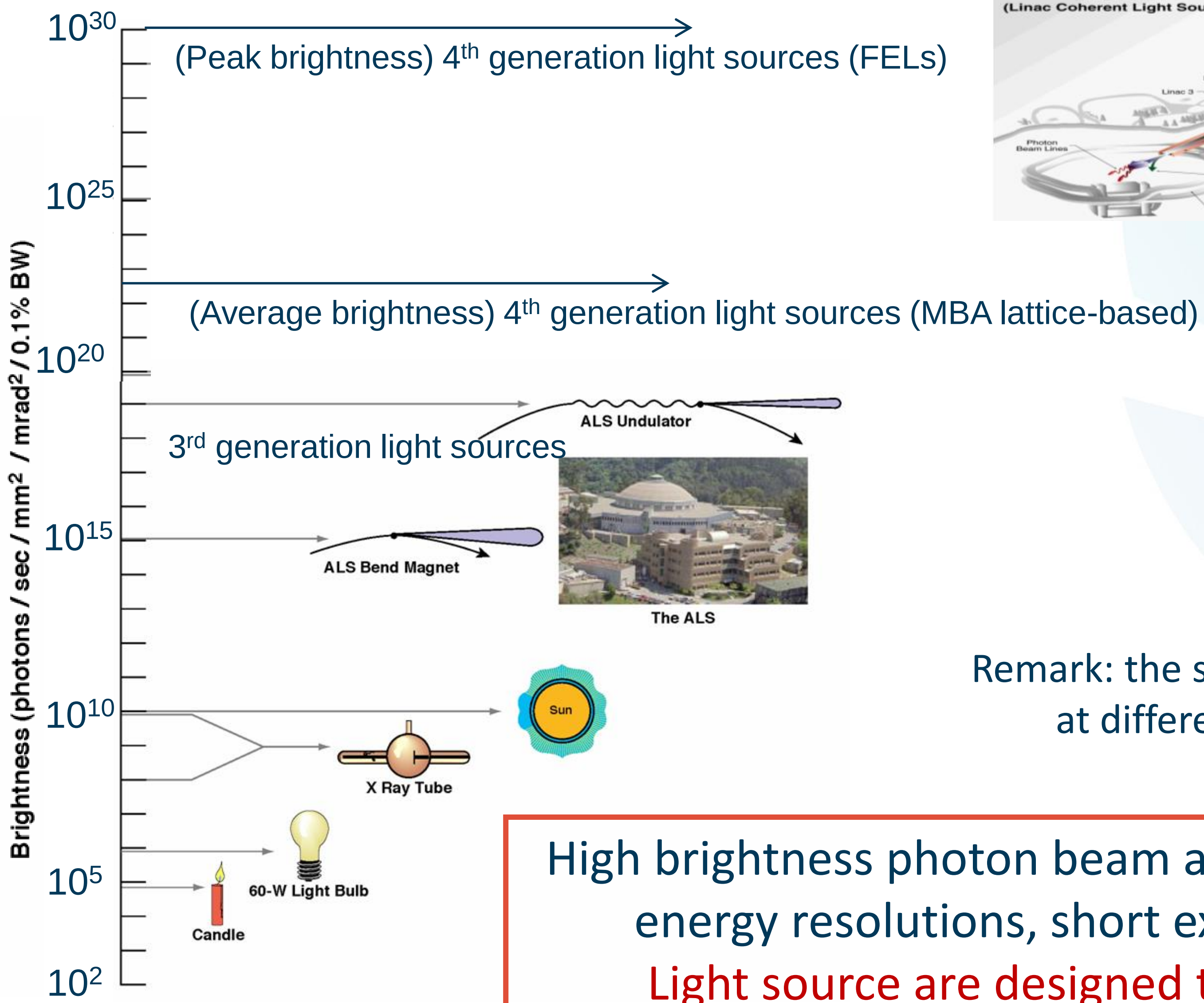
$$\varepsilon_w = \sigma_w \sigma_{w'}$$

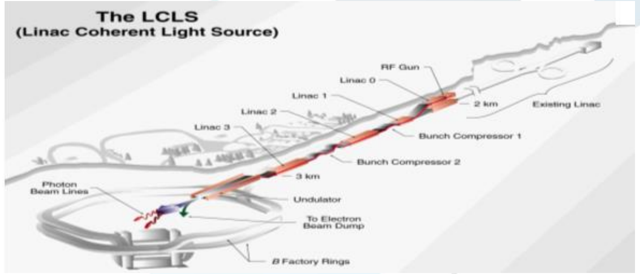
and

$$\varepsilon_{nw} = \beta\gamma\varepsilon_w$$

with $= x, y, z$

The X-FEL Peak Brightness Revolution





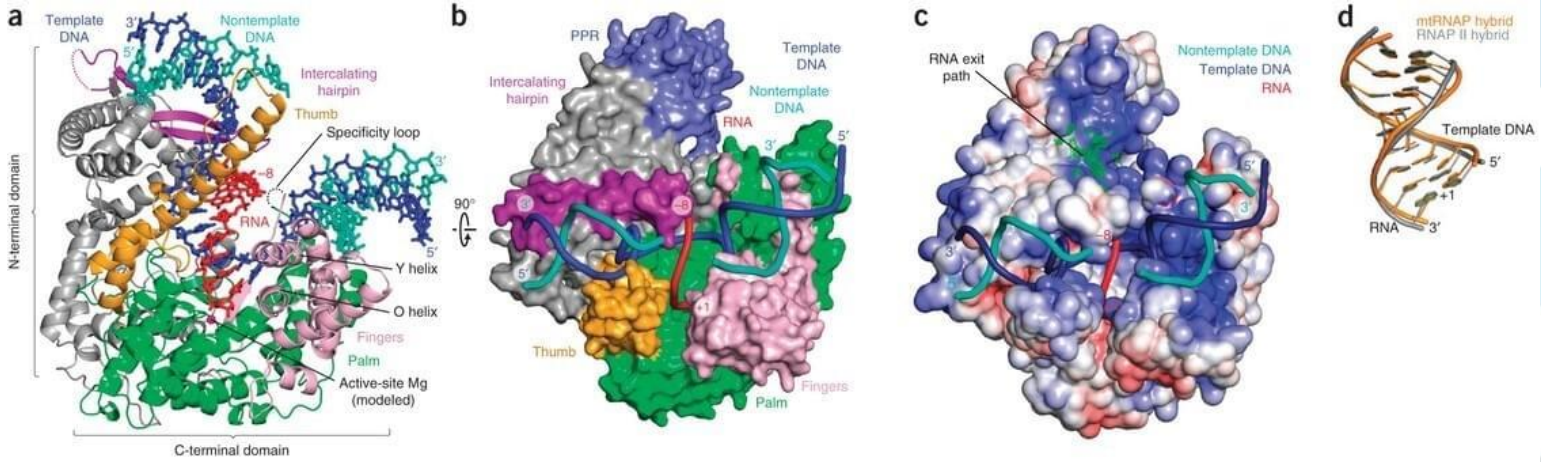
Started with the LCLS at SLAC in 2009

Remark: the sources are compared at different wavelengths!

High brightness photon beam allows for high spatial, temporal and energy resolutions, short experiment time and coherence.
Light source are designed to maximize such a parameter!

The X-Ray FEL Dream: Single-Shot, Single-Molecule, Lens-less Imaging

Capability of imaging complex molecules is of extreme importance for biology, medicine, catalysis, etc.



Diffraction techniques using X-rays already allows for 3D imaging of complex molecules in 3rd generation light sources, but due to the typically limited transverse coherence of such sources, it requires crystals where a large number of properly oriented molecules are aligned to get enough signal.

The problem is that not all molecules can be crystallized!

Single shot, single molecule, imaging requires a high-intensity, high-transverse coherence X-ray source!

X-Ray FELS have the potential of generating photons with such characteristics.
Not quite there yet though!

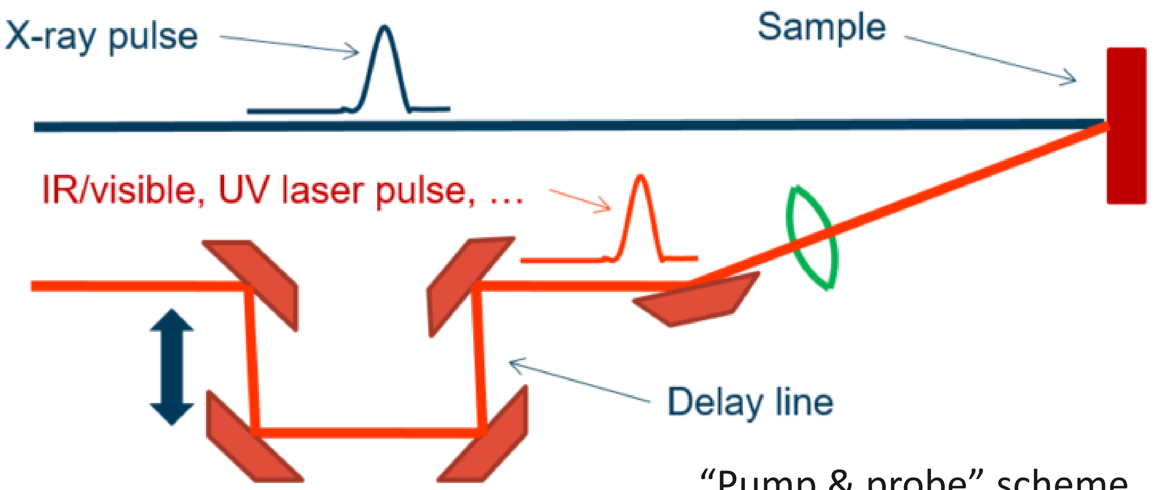
The X-Ray FEL Dream: Pump & Probe Experiments, "Movies"

Complex molecules, such as for example proteins, activate their functions by *folding*, so if we want to study these processes ➔ dynamic probing capabilities are also necessary!

An IR, visible, UV laser pulse "pumps" the sample in an excited state

A synchronized short X-ray pulse probes the sample with high time resolution.

A delay line allows to vary the arrival time of the laser pulse relatively to the X-ray pulse.



"Pump & probe" scheme

By varying the delay, it is possible to measure the excitation and the decay of the sample at different times. "Photograms" for a "movie" of the transition can be created!

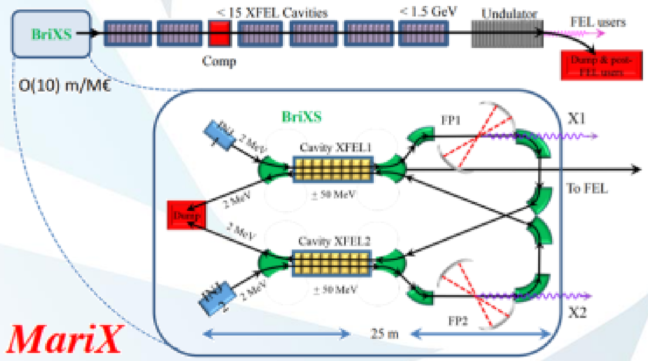
The time resolution of the experiment is defined by the length of the X-ray pulse and by the quality of the synchronization between the laser and X-ray pulses

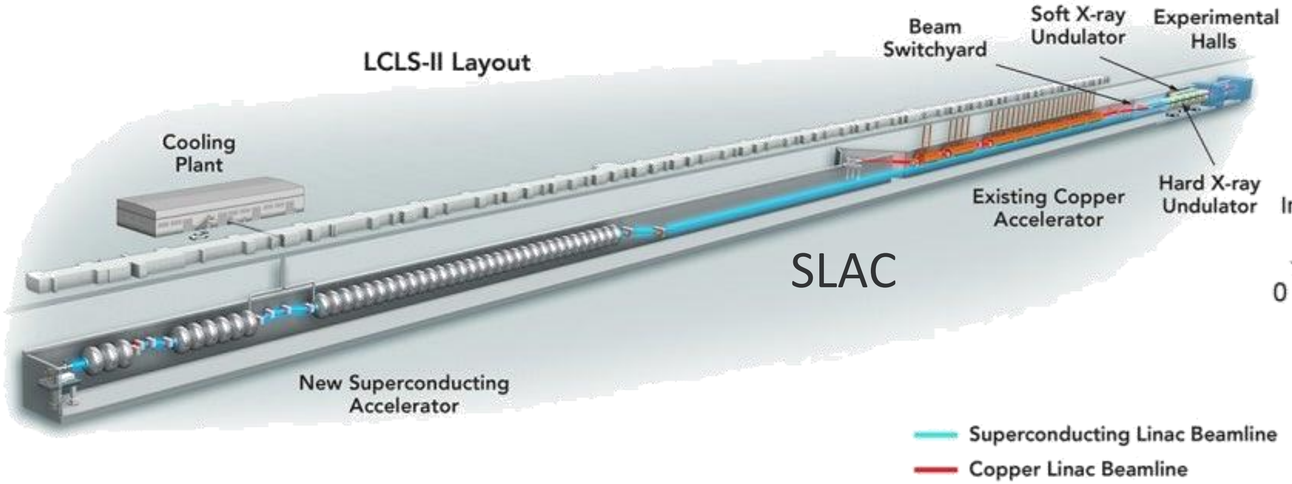
Pump and probe experiments with few fs time resolution have been demonstrated!

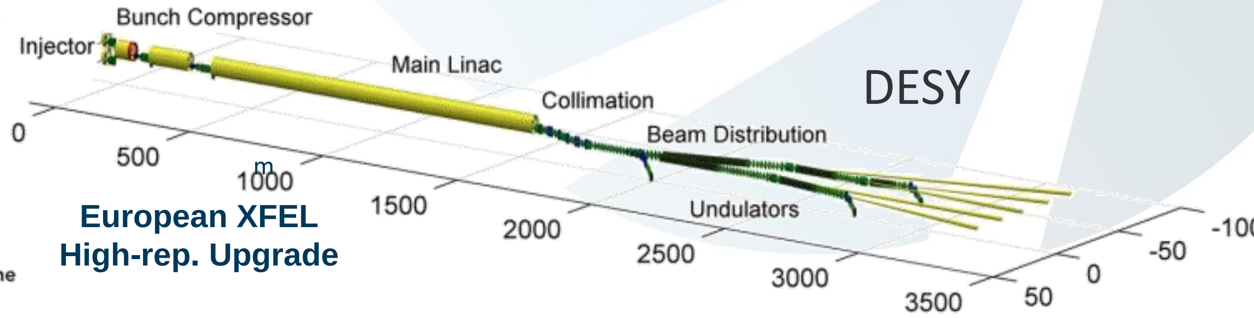
X-FELs Exist and Are producing Great Science, What Next?

All operating X-ray FELs are low repetition rate (< 120 Hz)
But science demand is pushing towards much higher repetition rates
(gas and droplet targets, high average brightness applications, multiple FELs fed by a single linac, etc.)!

To address this need, several proposed/approved X-ray FELs are targeting the same beam quality of the existing X-ray FELs but at MHz-class repetition rates.





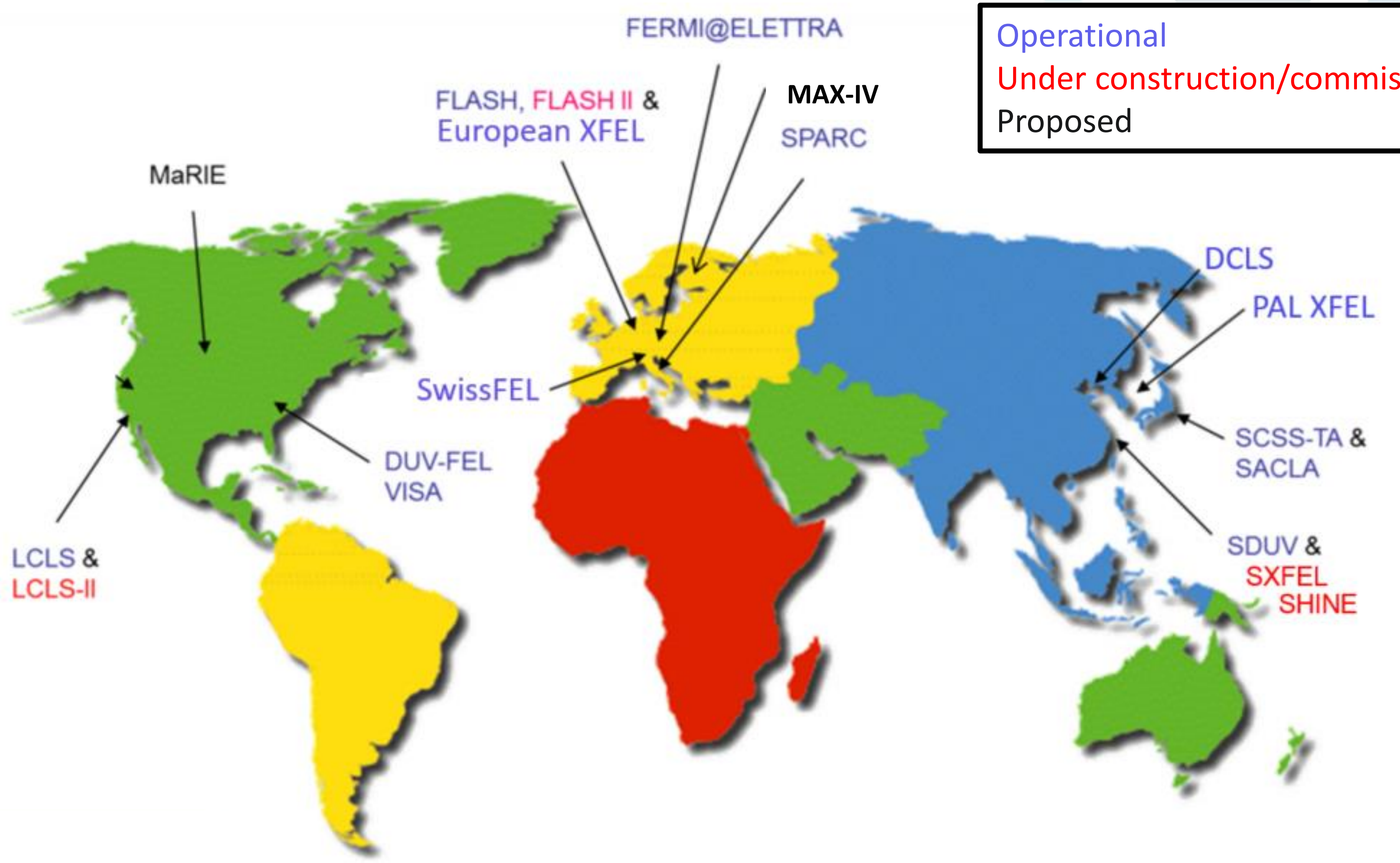


European XFEL
High-rep. Upgrade

LCLS-II at SLAC being commissioned and LCLS-II HE and SHINE in Shanghai approved!

Soft and Hard X-Ray FELs in the World

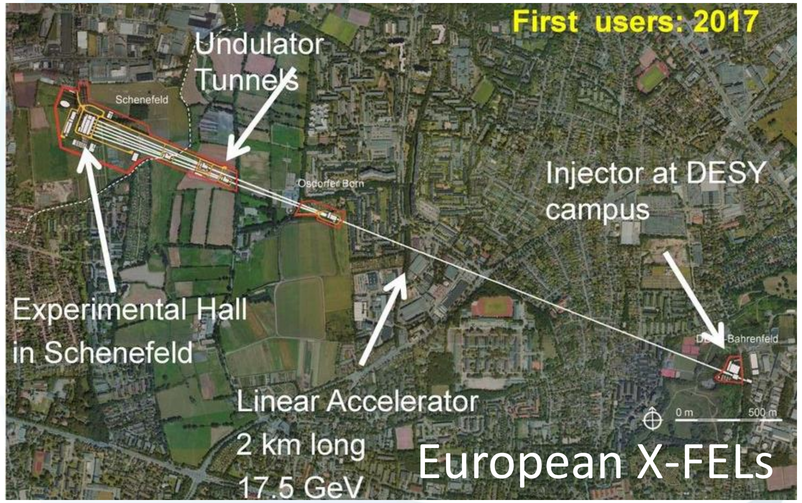
Operational
Under construction/commissioning
Proposed



Adapted from a talk by Zhentang Zhao in 2013

The Basic Ingredients for Building an FEL

- An accelerator capable of generating "high quality" electron beams at the proper energy:

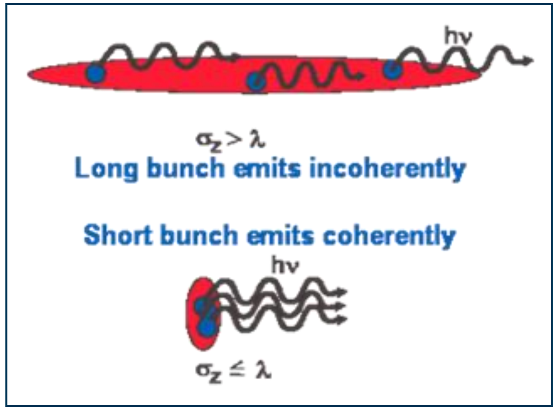


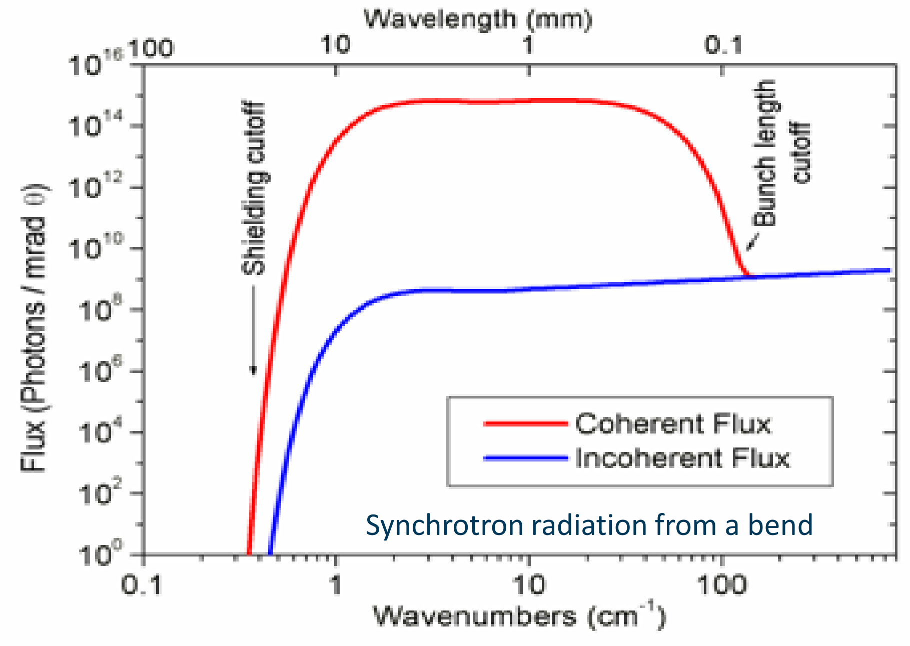
+

- Followed by one undulator
(by hundreds of meters undulator modules in reality):

- The electron beam is then sent through the undulator(s) to generate synchrotron radiation and …

Coherent Synchrotron Radiation (CSR) Basics





The power spectrum of the radiation from a bunch with N particles is given by:

$$\frac{dP}{d\omega} = \frac{dp}{d\omega}\left\{N\left[1-g(\omega)\right] + N^2 g(\omega)\right\}$$

Single particle power spectrum

$P_{SR} \propto N$
incoherent

$P_{CSR} \propto N^2$
coherent

CSR starts to be important for: $g(\omega) \geq 1/N$

$$g(\omega) = \left| \int_{-\infty}^{\infty} dz\, S(z) e^{i\omega\cos(\theta)z/c} \right|^2$$

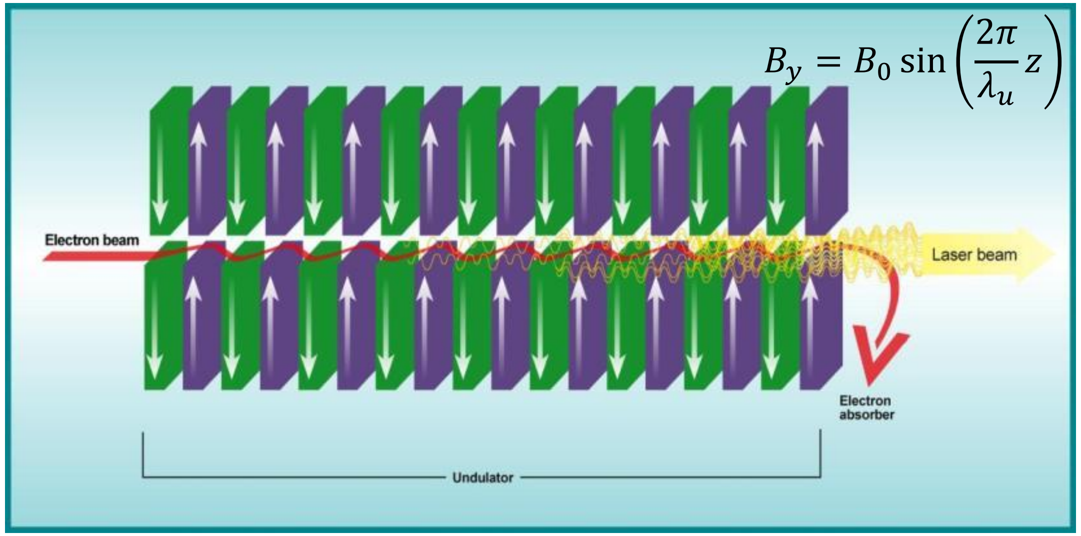
$0 \leq g(\omega) \leq 1$

$\theta \equiv$ *observation angle*

Bunch normalized longitudinal distribution

The CSR factor $g(\omega)$ determines the high frequency cutoff for CSR, while the vacuum chamber (shielding) defines the low frequency one.

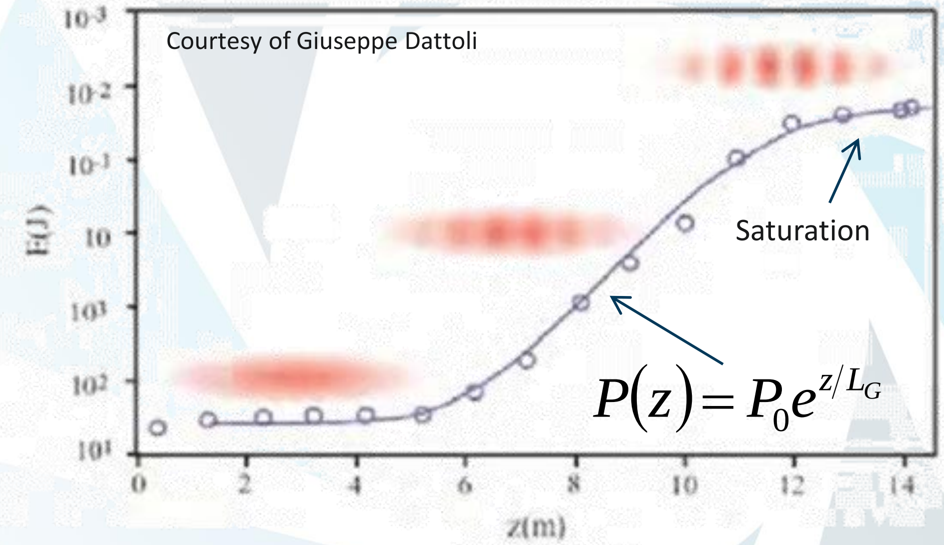
The Microbunching Process: How Coherence Is Created in FELs

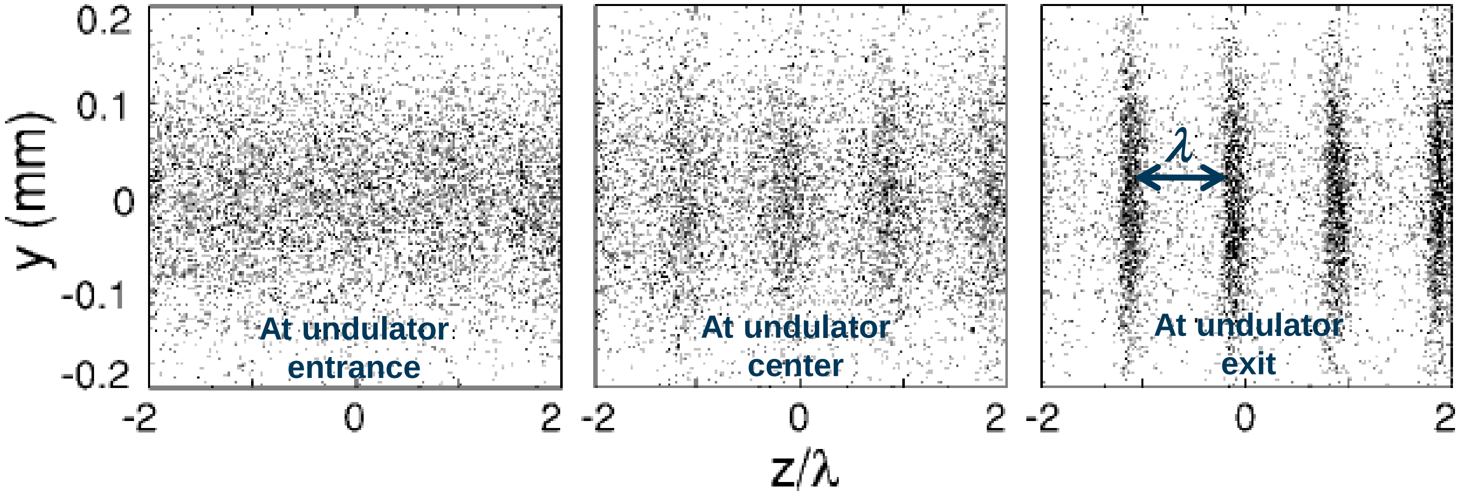


synchrotron radiation:

$$P_\perp = \frac{c}{6\pi\varepsilon_0} q^2 \frac{(\beta\gamma)^4}{\rho^2}$$

$$\rho = curvatureradius$$





$$\lambda = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2}\right)$$ Undulator resonance condition

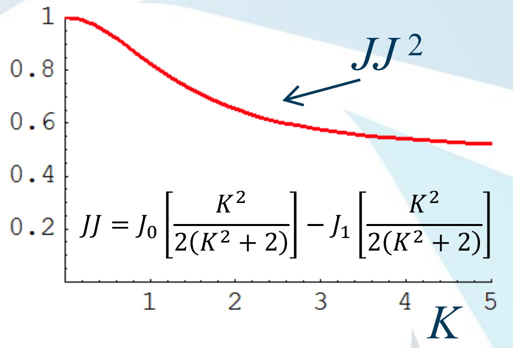
$$K = \frac{e}{2\pi m_0 c} \lambda_u B_0$$ Undulator parameter

FEL 1D Theory (neglects beam transverse size, diffraction and energy spread effects)

Pierce or FEL parameter

$$\rho = \frac{1}{\gamma}\left[\frac{1}{64\pi^2}\frac{I_e}{I_A}\frac{1}{\varepsilon_x\beta_x}\lambda_u^2 K^2 JJ^2\right]^{1/3}$$

J_0 and J_1 are Bessel functions, I_e the electron bunch peak current, I_A the Alfven current ($\sim 17\text{kA}$), ε_x the hor. geometric emittance, β_x the hor. beta function, K the undulator parameter and γ the beam energy in rest mass units. All quantities are measured at the undulator.



$$P(z) = P_0 e^{z/L_G} \quad L_G = \frac{\lambda_u}{4\sqrt{3}\pi\rho} \quad \textit{gain length}$$

$$N_G = \frac{L_G}{\lambda_u} = \frac{1}{4\sqrt{3}\pi\rho} \quad \textit{undulator periods per gain length}$$

$$L_S \approx 20 L_G = \frac{20}{4\sqrt{3}\pi}\frac{\lambda_u}{\rho} \approx \frac{\lambda_u}{\rho} \quad \textit{saturation length}$$

$$P_{Saturation} \approx \rho I_{beam} E_{beam[eV]} = \rho P_{beam}$$

$$\frac{\sigma_\gamma}{\gamma} = \frac{\sigma_E}{E} \lesssim \rho \quad \textit{energy spread condition}$$

The FEL Parameter can be maximized by:

- High electron bunch peak currents I_e (kA in XFELs)
- low geometric emittances ε_x (sub-nm)
- and small beta functions at the undulator β_x (few m)

K, λ_u and γ are not independent parameters, they play together to get the desired λ:

$$\lambda = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2}\right)$$

All these equations show that designing a powerful, efficient and compact FEL requires large ρ values

The Ultimate FEL Performance is Already Set at the Linac Injector

FELs generates transverse diffraction limited light pulses, so for an efficient lasing the transverse geometric emittance ε_w of the electron beam must be smaller than the photon diffraction limit:

$$\varepsilon_w \lesssim \frac{\lambda}{4\pi} \quad or \quad \varepsilon_{wn} \lesssim \beta\gamma \frac{\lambda}{4\pi} \approx \gamma \frac{\lambda}{4\pi} \quad \text{with} \quad w = x, y \qquad \begin{matrix} \lambda \sim 10^{-10}\ \text{m}, \\ \gamma \sim 1.6 \times 10^4\ (8\ \text{GeV}) \end{matrix} \rightarrow \varepsilon_{wn} \lesssim 0.13\ \mu\text{m}$$

Liouville Theorem states that in Hamiltonian systems, the normalized emittance is a motion invariant.
(Remark: the geometric emittance is an invariant only at constant energy)

A linac is with good approximation a Hamiltonian system and space charge forces within the bunch, are Hamiltonian forces as well.

That implies that the lowest normalized emittance that a linac can achieve is already set at its injector/gun.

This discussion shows how important for an X-FEL application to develop injectors/guns with low normalized emittance.

A lower normalized emittance allows for a lower energy linac and, as we saw earlier, for a larger ρ value.

Electron Beam Brightness

In general, the main goal for an FEL electron linac is to generate *short beams* with a *large number of electrons,* with almost the *same energy*, confined in a *small transverse spot*, and with *small divergence*. **In other words, the main task for an injector is to maximize the electron beam brightness**.

Electron Brightness: $$B = \frac{N_e}{\varepsilon_{nx}\varepsilon_{ny}\varepsilon_{nz}}$$

Where N_e is the number of electrons in the beam and ε_{nx}, ε_{ny} and ε_{nz} are the normalized emittances in each of the planes.

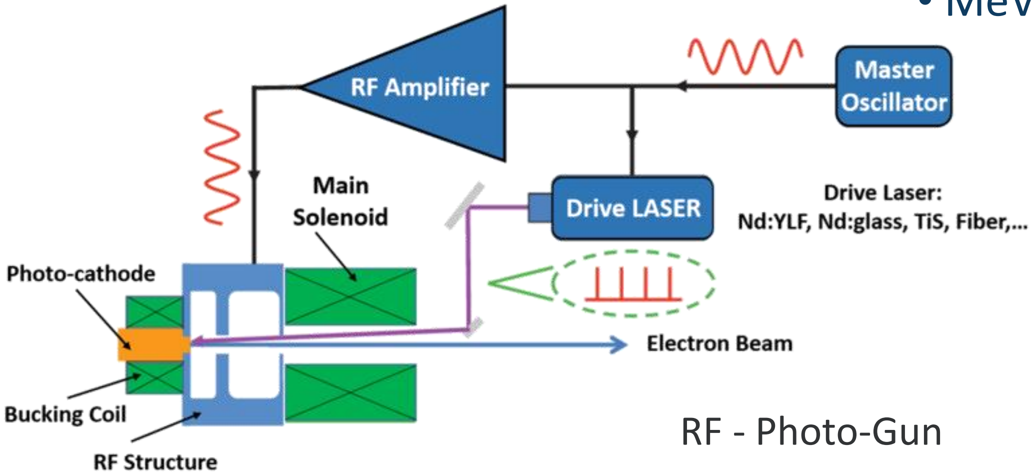
For a fixed charge per bunch, maximizing brightness translates in minimizing the emittance at the injector in each of the planes and preserving such an emittance along the downstream linac.

It is fair to say that the development of FELs widely relied on the invention of the RF photo-gun by J. S. Fraser, R. L. Sheffield in 1985, which for the first time allowed to generate electron beams with the brightness required by FELs.

The RF Photo-Gun

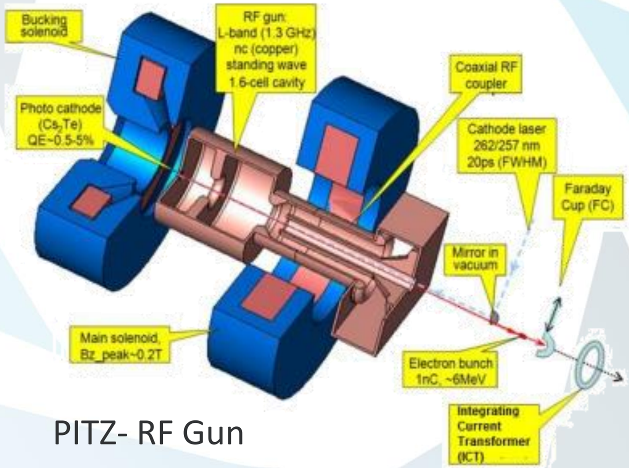
The RF Photo-Gun generates electrons by photo-emission and allows for:

- high accelerating fields at the cathode: 20 to 100 MV/m at the cathode
- control of the electron bunch 6D distribution by shaping the laser pulse
- control of the repetition rate
- MeV-class beam energies

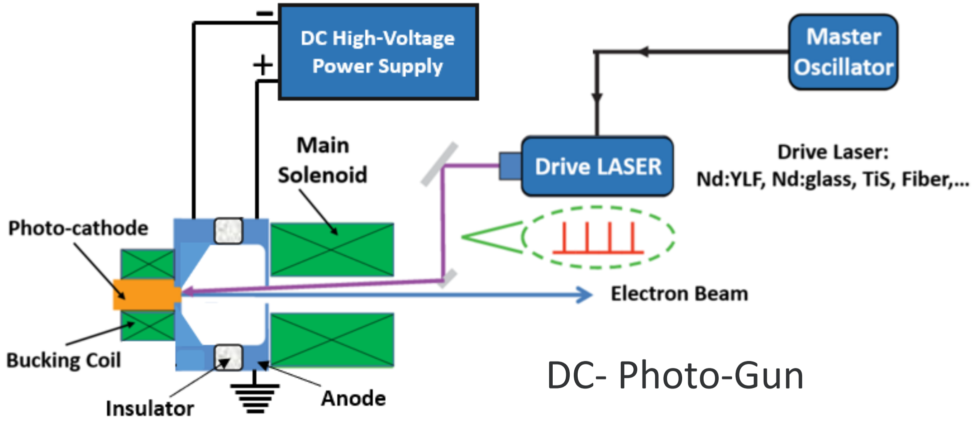


RF - Photo-Gun

The RF structure can be either normal or super conducting

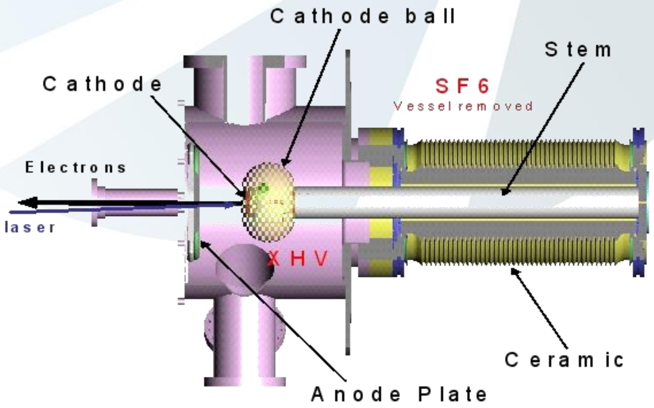


PITZ- RF Gun



DC- Photo-Gun

Same characteristics of the RF version but with lower accelerating fields and beam energies: < 10 MV/m and < 500 keV



ASTeC- DC Gun

The Transverse Emittance Game in Injectors

- In general, an electron linac is a nonlinear Hamiltonian system where the ultimate transverse brightness performance is set at the injector.

- For a given charge, the terms that affect the final transverse normalized emittance at the injector output and hence define its brightness performance, are:

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

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

- Let's now describe each of the terms in equation above.

Back to Emittance, an Additional Important Definition

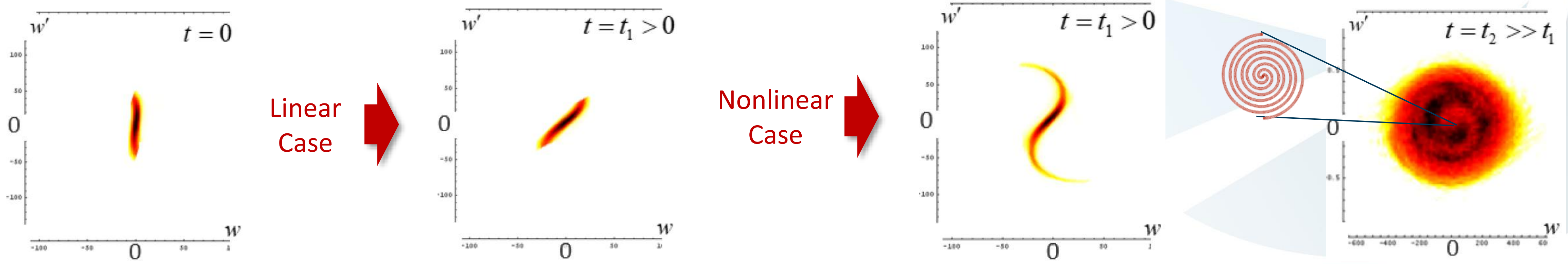
- It was previously mentioned that in Hamiltonian systems the normalized emittance is conserved.
- This is true even when the forces acting on the system are nonlinear (space charge, nonlinear magnetic and/or electric fields, …)

- This is not true in the case of the **rms emittance**:
In the presence of nonlinear forces, the rms emittance is not conserved

$$\varepsilon_{rms} = \sqrt{\langle w^2\rangle\langle w'^2\rangle - \langle w\, w'\rangle^2}$$

$w = x, y, z$

- Example: *filamentation*. Particles with different phase space coordinates, because of nonlinear forces, move with different "velocity" in the phase space.



The emittance according to Liouville is still conserved but the rms emittance calculated at later times increases.

In real applications, and in this talk equations, emittances are always rms (unless specifically mentioned).

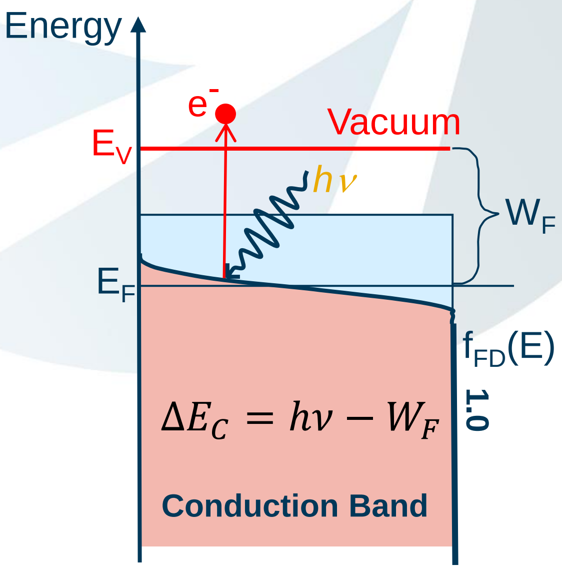
Cathode Emittance Contribution

$$\varepsilon_{nw} = \sqrt{\varepsilon^2_{n\,Cathode} + \varepsilon^2_{n\,Bz\,at\,Cathode} + \varepsilon^2_{n\,Space\,Charge} + \varepsilon^2_{n\,Optics\,Aberrations} + \varepsilon^2_{nw\,RF}}$$

- The cathode thermal (or intrinsic) emittance defines the emittance contribution associated with the cathode.

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

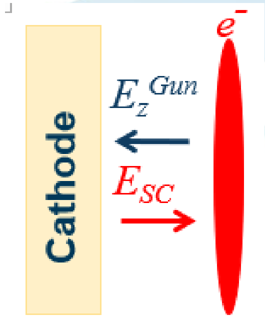
with $\sigma_r \equiv rms\ beam\ size\ at\ the\ cathode$
and $\Delta E_C \equiv electron\ excess\ energy$



- 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.

The Ultimate Brightness is already Set at the Gun

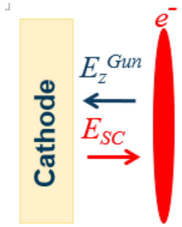
During emission at the cathode, the electric field E_{SC} of the already emitted electrons limits the max charge density $\sigma_{SC\,MAX}$ that can be extracted by a given E_z^{Gun}.



A consequence of this is that the maximum transverse brightness that can be generated by a given field at the cathode is limited. We can consider 2 regimes:

"Pancake-beams"

Bazarov *et al*., PRL 102, 104801 (2009)

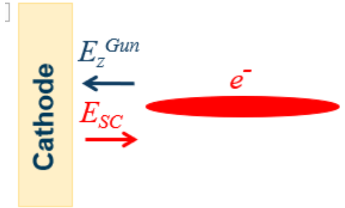


$$E_{SC} \approx \frac{\sigma_Q}{2\varepsilon_0}$$

$$\varepsilon_n^{\min} \propto \sigma_r^{\min}\sqrt{\Delta E_C} \approx \sqrt{\frac{Q\ \Delta E_C}{4\pi\,\varepsilon_0\,E_z^{Gun}}} \Rightarrow B_{4D}^{\max} \propto \frac{Q/e}{\left(\varepsilon_n^{\min}\right)^2} \Rightarrow B_{4D}^{\max} \propto \frac{E_z^{Gun}}{\Delta E_C}$$

Similarly, for "cigar-beams"

Filippetto *et al*., PRSTAB 17, 024201 (2014)



$$B_{4D}^{\max} \propto \frac{(E_z^{Gun})^{3/2}\sigma_\tau}{\sqrt{\sigma_r}\Delta E_C}$$

with σ_τ the bunch length

Additionally, after emission space charge forces in the bunch can degrade emittance. Such forces 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 high accelerating accelerating fields at the cathode and high output energies

Solenoidal Field at the Cathode

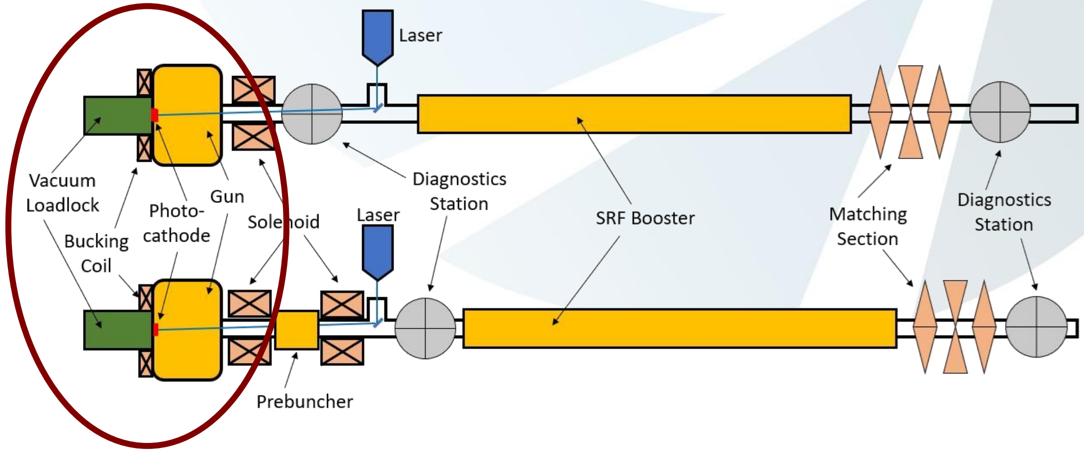
$$\varepsilon_{nw} = \sqrt{\varepsilon^2_{n\ Cathode} + \varepsilon^2_{n\ Bz\ at\ Cathode} + \varepsilon^2_{n\ Space\ Charge} + \varepsilon^2_{n\ Optics\ Aberrations} + \varepsilon^2_{nw\ RF}}$$

Solenoidal fields at the cathode plane during photoemission add an additional magnetic component to the transverse canonical momentum of the electrons, which is later converted to classical momentum when the electrons propagate to a region where the solenoidal field is zero (Busch's theorem).

This resulting extra momentum component is responsible for an emittance increase:

$$\varepsilon_{n\ Bz\ at\ Cathode} = \frac{e}{2mc}\sigma_r^2 B_z$$

Solenoidal fields at the cathode surface must be avoided.
In particular, fringe fields from the solenoid downstream of the gun must be compensated by the bucking coil (solenoid).



See for example, M. Reiser, Theory and Design of Charged Particle Beams (Wiley, 1994), p. 281.

Geometric and Chromatic Aberrations in Solenoids

The emittance term associated with solenoid aberrations indicates that the field of the main solenoid(s) can directly affect the emittance performance of the injector.

$$\varepsilon_{nw} = \sqrt{\varepsilon^2_{n\,Cathode} + \varepsilon^2_{n\,Bz\,at\,Cathode} + \varepsilon^2_{n\,Space\,Charge} + \varepsilon^2_{n\,Optics\,Aberrations} + \varepsilon^2_{nw\,RF}}$$

The magnetic field profile in this critical component must be designed to minimize its geometric and chromatic aberrations, which strongly depend on the transverse beam size:

$$\varepsilon_x = \kappa \alpha \sigma_x^4$$

with $\kappa = \sqrt{8}$ *for a Gaussian distribution and* $\alpha = \frac{1}{4}\left(\frac{e}{2mc\beta\gamma}\right)^2 \int \left(\frac{\partial B}{\partial z}\right)^2 dz$ → Geometric emittance increase due to solenoid geometric aberration

The chromatic aberration is consequence that the solenoid focal length depends on the beam energy: $\frac{1}{f} = \left(\frac{e}{2mc\beta\gamma}\right)^2 \int B_z^2 dz$

The normalized emittance contribution due to the chromatic aberration is

$$\varepsilon_{nx} = 2\frac{1}{f}\sigma_x\sqrt{\sigma_x^2 + x_0^2}\,\frac{\sigma_p}{mc}$$

Where x_0 is the beam offset from the solenoid center

This also implies that the optics that transports the electron beam to the solenoid, must be carefully designed to minimize the beam size inside the magnet. In particular, the distance between the cathode and the first solenoid needs to be minimized to avoid a large transverse expansion of the beam before entering the solenoid.

See for example: I. Bazarov, et al., Phys. Rev. ST Accel. Beams 14, 072001 (2011).

Transverse Emittance RF Dilution

$$\varepsilon_{nw} = \sqrt{\varepsilon^2_{n\,Cathode} + \varepsilon^2_{n\,Bz\,at\,Cathode} + \varepsilon^2_{n\,Space\,Charge} + \varepsilon^2_{n\,Optics\,Aberrations} + \varepsilon^2_{nw\,RF}}$$

- RF cavities generate the longitudinal electric field E_z to accelerate the particles. Due to Maxwell equations also a radial and an azimuthal fields exist:

$$E_r = -\frac{r}{2}\frac{\partial E_z}{\partial z}; \qquad B_\theta = \frac{r}{2c^2}\frac{\partial E_z}{\partial t}$$

- Such fields component generates a radial Lorentz force, which is stronger in the RF fringes, and that affects the transverse momentum of the particles

$$F_r = e\left(E_r - \beta c B_\theta\right)$$

- That generates an increase of transverse normalized emittance. For a Gaussian beam:

$$\varepsilon_{nr\,RF} = \frac{e}{2\sqrt{2}mc^4} E_0 \omega^2_{RF} \sigma^2_r \sigma^2_z$$

with e and m the electron charge and rest mass respectively, c the speed of light, $\omega_{RF}/2\pi$ the RF frequency, E_0 the accelerating field, and σ_r and σ_z the rms transverse and longitudinal beam sizes.

- For example, in a 1.3 GHz accelerating section with E_0 = 20 Mv/m, a beam with σ_r = 1 mm and rms bunch length of 10 ps will experience a normalized emittance increase of $\varepsilon_{nr\,RF} \sim 10^{-7}$ m.

K. J. Kim, *NIM*, **A275**, 201 (1989)

Space Charge Forces

$$\varepsilon_{nw} = \sqrt{\varepsilon^2_{n\ Cathode} + \varepsilon^2_{n\ Bz\ at\ Cathode} + \varepsilon^2_{n\ Space\ Charge} + \varepsilon^2_{n\ Optics\ Aberrations} + \varepsilon^2_{nw\ RF}}$$

- The intra-beam space charge forces that a particle in the beam experiences from the other particles in the beam is proportional to the beam charge density and to the inverse of beam energy measured in rest mass units.

For example, in the core of a Gaussian beam with charge density λ_q it can be found that:

$$F_x = q(E_x - \beta c B_y) = qE_x(1-\beta^2) \propto \lambda_q(1-\beta^2)x = \lambda_q \frac{1}{\gamma^2} x$$

$$F_y = q(E_y + \beta c B_x) = qE_y(1-\beta^2) \propto \lambda_q(1-\beta^2)y = \lambda_q \frac{1}{\gamma^2} y$$

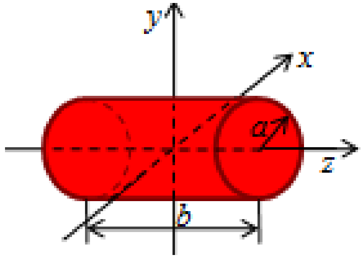
- The force dependence on the $1/\gamma^2$ term is actually quite general and shows that the transverse space charge forces become negligible for relativistic beams.

- Similarly to the transverse case, it can be shown that the $1/\gamma^2$ term is present also in the longitudinal space charge force expression and therefore such a force becomes negligible for relativistic beams as well.

$$F'_z = qE_z = \frac{q^2}{4\pi\varepsilon_0}\frac{1}{z^2} = \frac{q^2}{4\pi\varepsilon_0}\frac{1}{(\gamma z')^2} = \frac{1}{\gamma^2}\frac{q^2}{4\pi\varepsilon_0}\frac{1}{z'^2}$$

Emittance Compensation

$$\varepsilon_{nw} = \sqrt{\varepsilon^2_{n\ Cathode} + \varepsilon^2_{n\ Bz\ at\ Cathode} + \varepsilon^2_{n\ Space\ Charge} + \varepsilon^2_{n\ Optics\ Aberrations} + \varepsilon^2_{nw\ RF}}$$

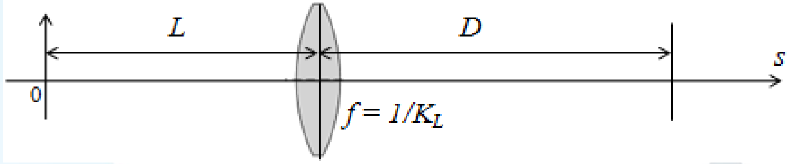


For a cylindrical beam with radius a, length b, linear charge density $\lambda_q(z)$ slow changing function of z, and uniform transverse charge density, Teng showed that:

$$for|z| << b \Rightarrow F_r(z) = \frac{e\lambda_q(z)}{2\varepsilon_0}\frac{1}{a^2\gamma^2}r$$

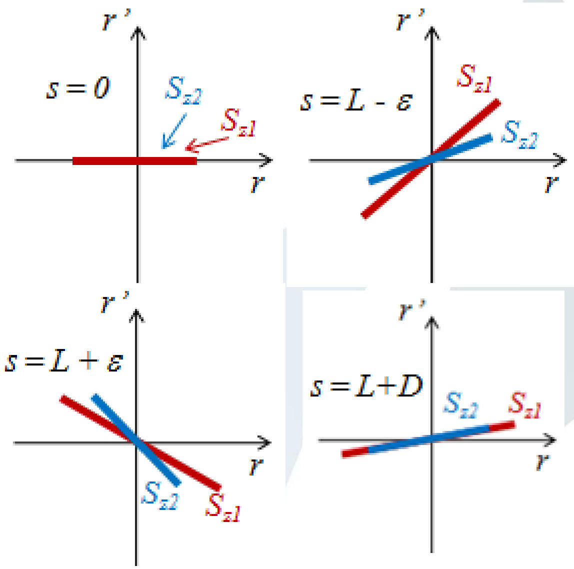
Linear transverse space charge force

We now divide the beam in longitudinal slices, and we want to propagate them from $s = 0$ to $s = L + D$ with a focusing element with focal length $1/K_L$ located at $s = L$.



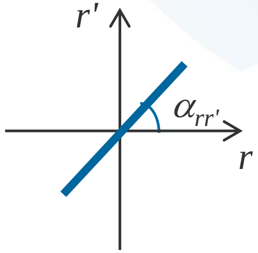
The space charge action over the drifts can be approximated by thin lens defocusing matrix and after some algebra and assuming $r'(z, s = 0) = 0$) we find for the beam slice located in z:

$$\begin{cases} r(z, s = L + D) = (1 - K_L D)r(z,0) + \dfrac{1}{2\beta^2}\dfrac{F_r(z)}{mc^2}[(L + D)^2 - K_L D L^2] \\ r'(z, L + D) = -K_L r(z,0) + \dfrac{1}{2\beta^2}\dfrac{F_r(z)}{mc^2}[2(L + D) - K_L L^2] \end{cases}$$



If we now set $K_L = \dfrac{2(L + D)}{D^2}$

$$\tan(\alpha_{rr'}) = \frac{r'(z, L + D)}{r(z, L + D)} = \frac{2(L + D)}{D(2L + D)}$$



The $\alpha_{rr'}$ slope in the phase space at $z = L + D$ does not depend on z or on $F_r(z)$ and is the same for all slices.
All slices are now aligned generating a projected emittance minimum!

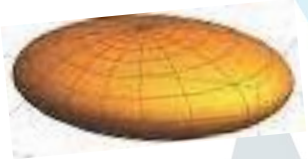
By placing an accelerating section in proximity of the minimum the emittance can be 'frozen' at its minimum value.

How Realistic is the Space Charge Linear Regime?

- Linear transverse space charge forces are generated by the Kapchinski-Vladimirski or K-V distribution, where the charge density is uniform on the surface of a hyper-ellipsoid in the 4D transverse phase space and zero elsewhere.

- In the longitudinal plane the Neuffer distribution plays a similar role generating linear space-charge forces by a parabolic linear longitudinal charge density.

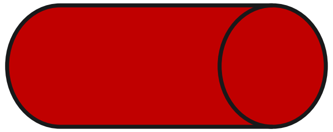
- In a more realistic case, the distribution that generates linear space charge forces is a **3D ellipsoidal beam with uniform particle density** inside and zero elsewhere.
  This distribution generates linear space charge forces in both transverse and longitudinal planes.



- Uniform ellipsoidal charge densities are experimentally pursued (with limited success so far) by shaping the laser in photocathode system, or by the so-called beam-blowout regime.

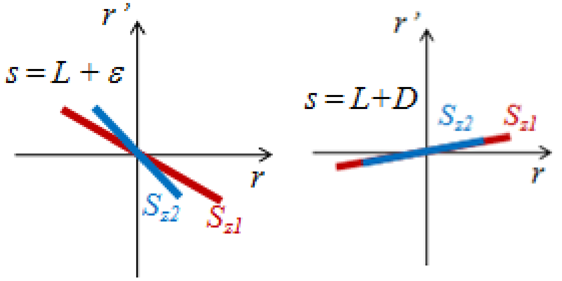
- In such a mode, a very short laser pulse (~100 fs) is sent on the cathode. The resulting 'pancake' of photo-emitted electrons is accelerated in the gun and simultaneously under the action of its own space-charge field evolves in a 3D uniform ellipsoidal charge distribution.
  This mode of operation has been experimentally demonstrated for charges per bunch smaller than ~100 pC.
  The blowout regime requires very high fields at the cathode and usually generates relatively high transverse emittances.

- A simpler distribution to generate is the uniform cylindrical distribution ("beer-can"), experimentally approximated by a laser pulse with a trapezoidal longitudinal distribution and a gaussian distribution truncated at 1 sigma in the transverse plane.

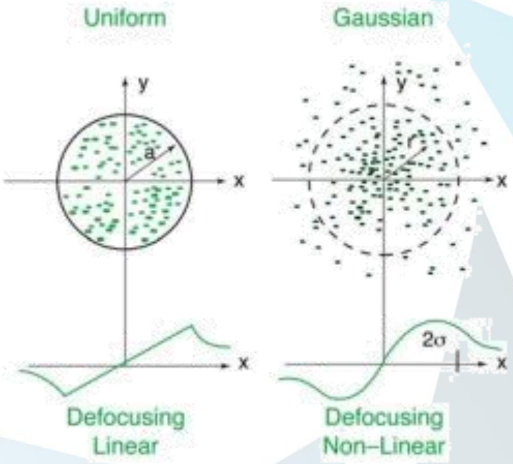


Bunch Length as a Knob for Controlling Space Charge Forces

• Space charge forces, which are stronger at the lower beam energies at the injector, can seriously affect the brightness performance of the injector by increasing the rms normalized emittance.



• The linear component can be controlled by the emittance compensation process, but the nonlinear part cannot!



• Space charge forces depends on the bunch charge density, the higher the latter the stronger the forces.

• Increasing the transverse size of the beam decreases charge density but also increases the thermal emittance at the cathode, so it must be used only with moderation .

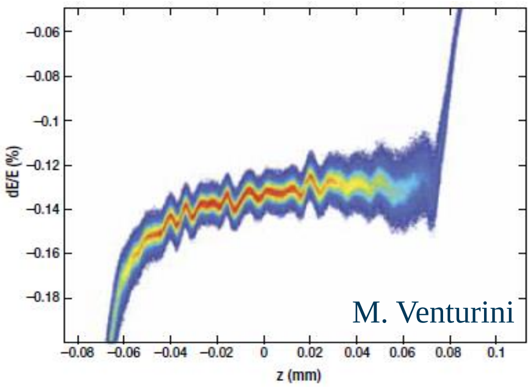
$$\varepsilon_{n\,Cathode} = \sigma_r \frac{\sigma_{p_r}}{mc}$$

• Increasing the bunch length is a better knob because, although it increases the longitudinal emittance, in most cases the FEL performance is marginally affected by it as long as the quality of the longitudinal phase space allows for the required compression in the linac.

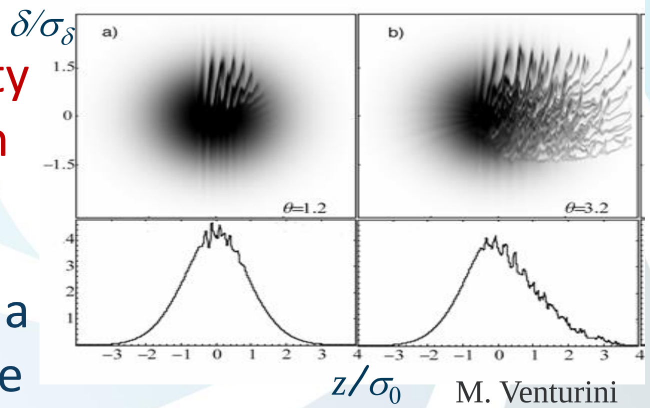
Longitudinal Phase Space: Bunch Length Compression

- In all FEL schemes the bunch length at the gun is longer than that required to generate the peak currents required at the undulator.

Longitudinal compression is then necessary and can be performed in the linac and /or in the injector.

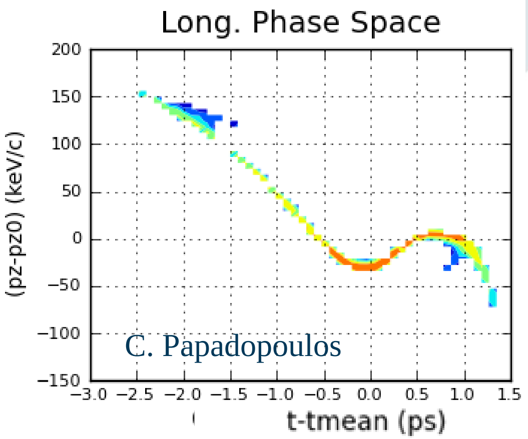


- Magnetic compressors such as chicanes or based on nonlinear optics can be subjected to microbunching instability (MBI) and to emittance growth due to coherent synchrotron radiation in case of high compression factors.



- MBI can be controlled by the so-called laser heater, where a laser modulates the beam energy in a chicane increasing the beam energy spread that prevents the onset of the instability.

- Excessive compression in the injector can also generate space charge induced transverse emittance increase and longitudinal phase space distortions making the final compression in the linac challenging.



- Methods for compressing the beam in the injector include a dedicated buncher section and/or the use of a technique referred as velocity bunching.

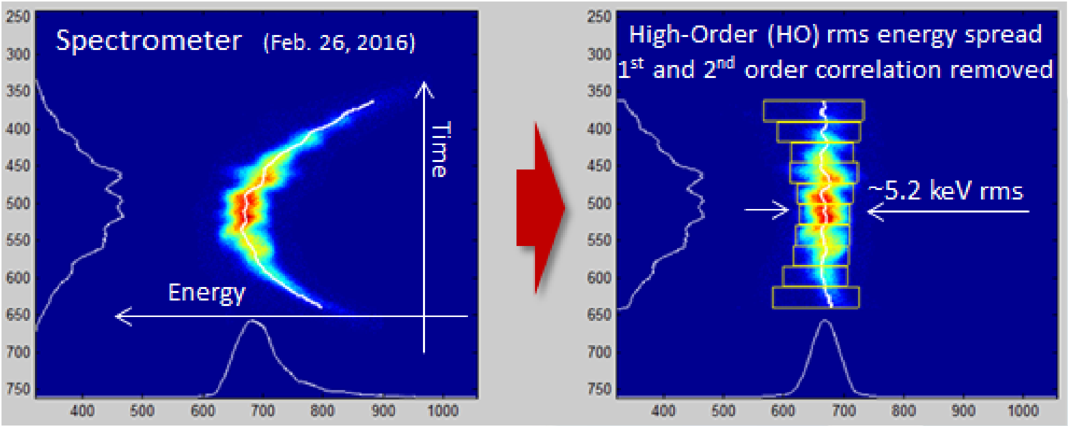
The Role of Longitudinal Phase Space Correlations

- High-gain X-FELs require heavy compression to achieve kA peak currents at the undulator. Compression performance strongly depends on 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", nonlinear optics and harmonic cavities).

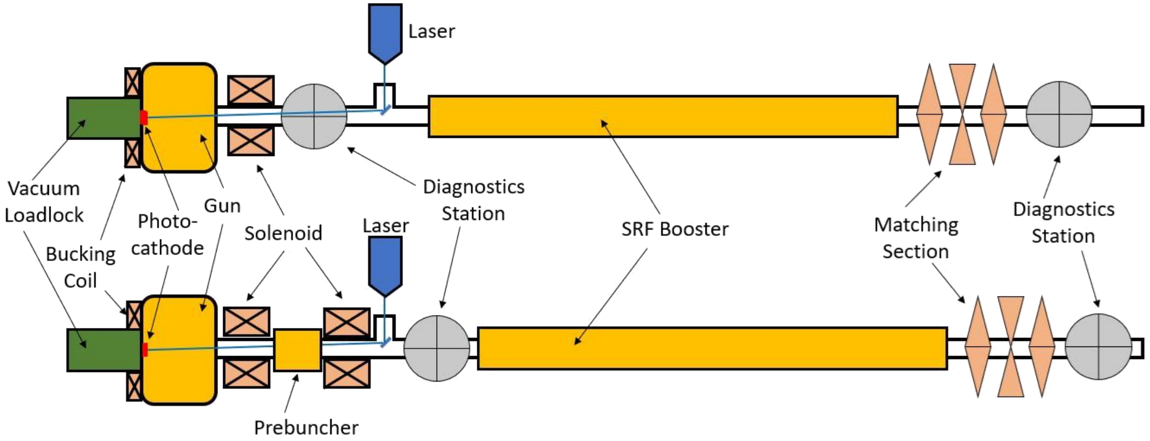
Higher order correlations cannot be controlled and must be carefully minimized already at the injector/gun.



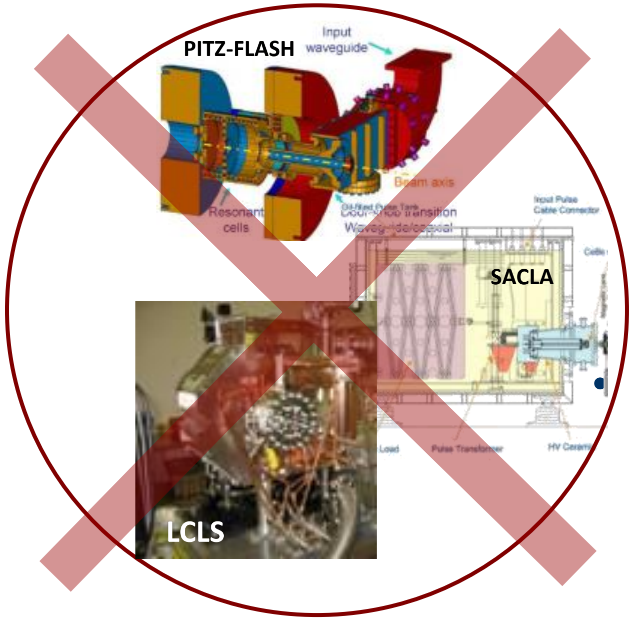
- Higher accelerating fields and energies at the gun allow for a better control of such terms

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

High-Duty-Cycle Technological Implications



- High-duty-cycles impose superconductive accelerating cavities in the RF booster and in the downstream linac to avoid unrealistic thermal losses.



- High-repetition rates require high quantum efficiency (QE ~10^{-2}) semiconductor photo-cathodes for realistic laser power requirements. The robust and stable metal cathodes used in low-duty-cycle X-FELs have low QEs (<~10^{-4}). Semiconductor cathodes are very reactive and susceptible to damage and require ultra low vacuum pressures in the gun and a vacuum loadlock system to swap cathodes without exposing them to air.

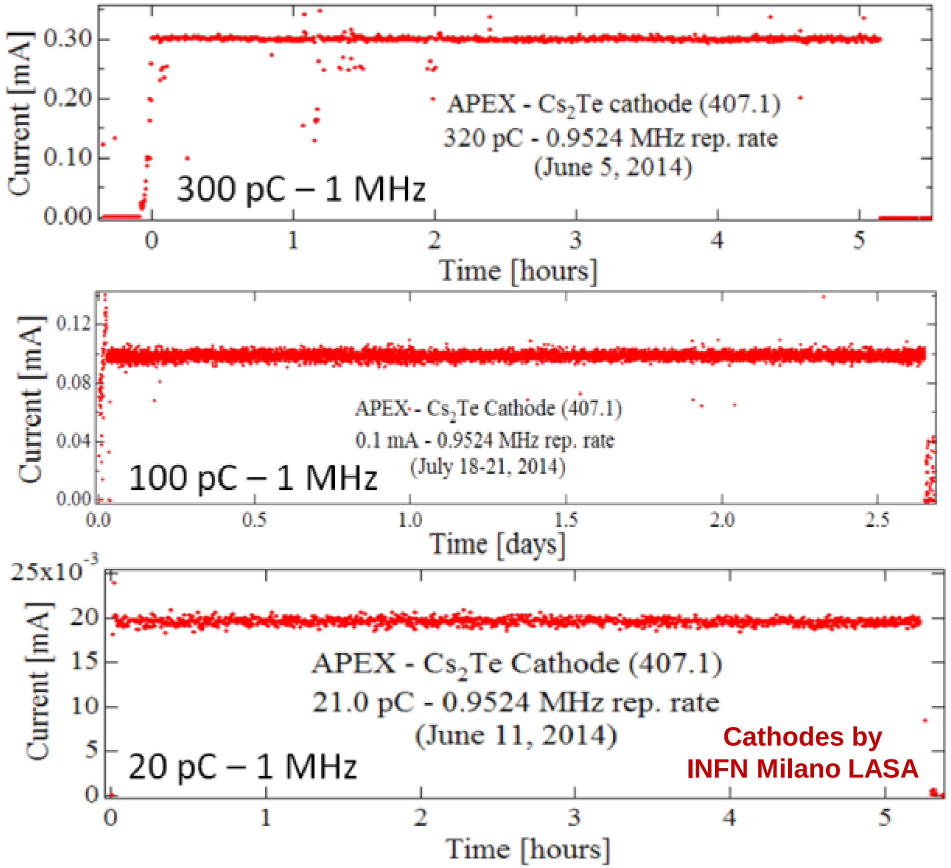
- The successful high-brightness low-duty-cycle RF guns, based on normal-conducting high frequency (GHz-class) RF and used in mostly of the presently operating X-FELs, cannot run at repetition rates > ~ kHz because of the excessive thermal load.

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

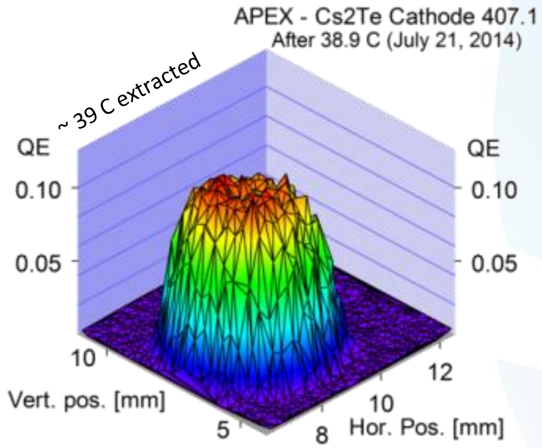
Requirements for a High-Repetition Rate x-ray FEL Gun

Parameter	Value
Duty cycle	From » 0.5 to 1
Repetition rate	Up to several MHz
Charge per bunch	From few tens to hundreds of pC
Electric field at the cathode during electron emission	> ~ 10 MV/m
R.m.s. bunch length at the cathode	From few ps to tens of ps
Normalized slice transverse emittance at the injector exit	From tens to hundreds of nm (Lower values for lower charges)
Normalized projected transverse emittance at the injector exit	As close as possible to the slice emittance value
Projected r.m.s. energy spread at the injector exit after energy/bunch-current correlations of order higher than 2 are removed.	From several keV to a few tens of keV (Lower values for lower charges)
Beam energy at the electron gun exit	> ~ 500 keV
Beam energy at the injector exit	~ 100 MeV
Peak current at the injector exit	From few tens to few hundreds of A (Lower values for lower charges)
Compatibility with magnetic fields in the cathode/gun region	Required by the emittance compensation process
Cathode type	High quantum efficiency (QE ~ 10^{-2}) photocathodes
Operational vacuum pressure in the electron gun	10^{-7} - 10^{-9} Pa (10^{-9} - 10^{-11} Torr)
Cathode replacement capability	Require a vacuum load-lock system to operate semiconductor cathodes
Maximum average dark current	< ~1 μA
Operation reliability	~ 99%

High QE Cathodes Required for Reasonable Laser Powers

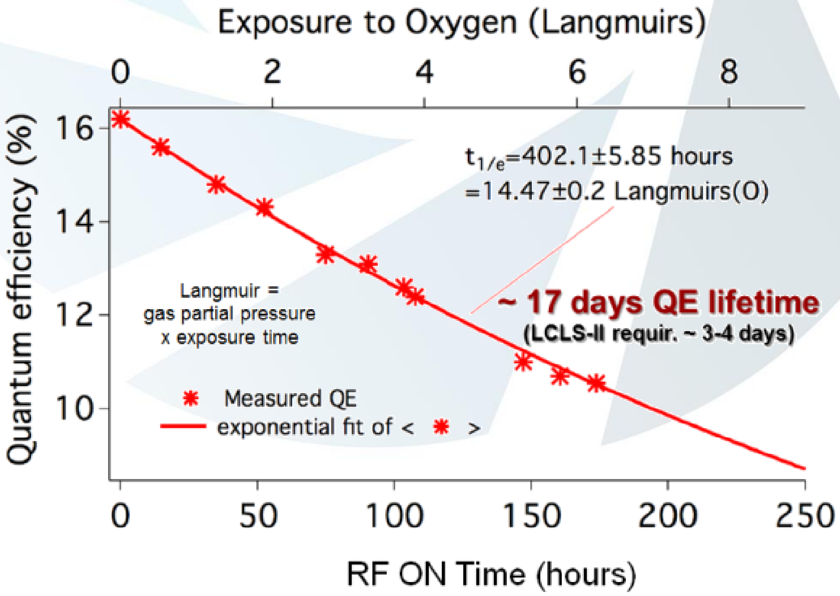


Thermal emittance ~0.7-0.8 μm/mm r.m.s.



No signs of either ion back-bombardment or of laser induced QE depletion after ~ 39 C extracted

The major QE degradation mechanism for Cs_2Te is oxidation. (A. di Bona, et al. JAP 80,1996).



Besides Cs_2Te, that photo-emits in the UV (~250 nm), several multi-alkali antimonides, as for example K_2CsSb, present percent level QEs and emits in the visible (~500 nm), have demonstrated a performance compatible with X-ray FELs.

Filippetto, Qian, Sannibale, Appl. Phys. Letters **107**, 042104 (2015).

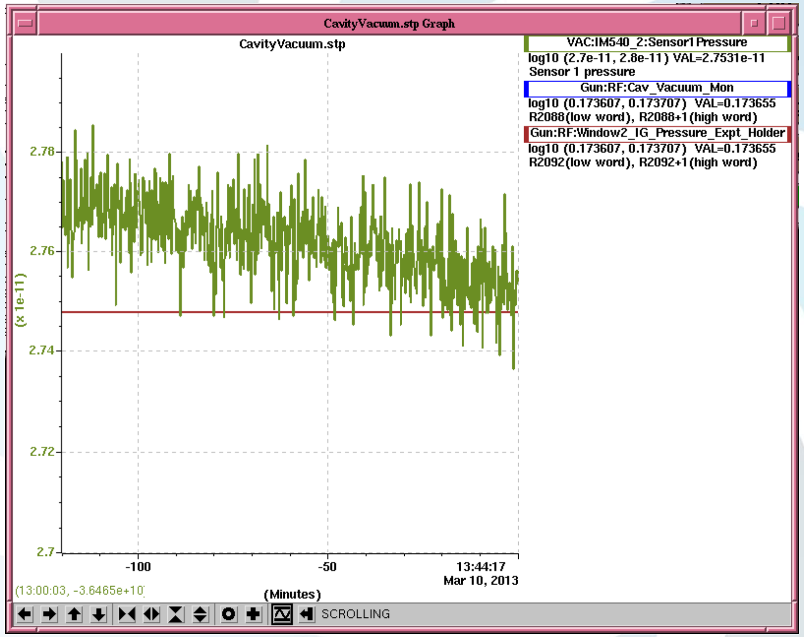
Vacuum

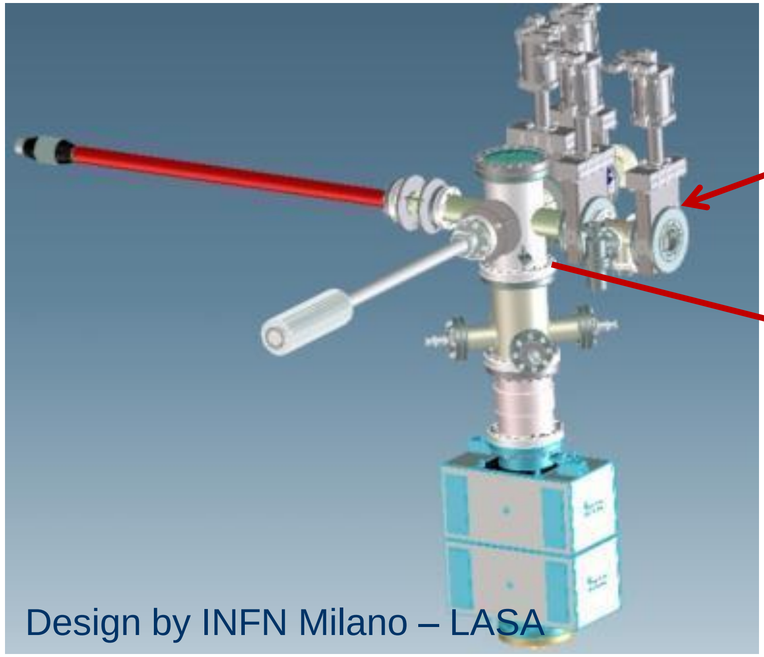
APEX VHF-Gun example:

Pressures in the gun without RF: 2 x 10^{-11} Torr

RGA measurement indicated partial pressures of H_2O, CO, CO_2 two-orders of magnitude smaller.

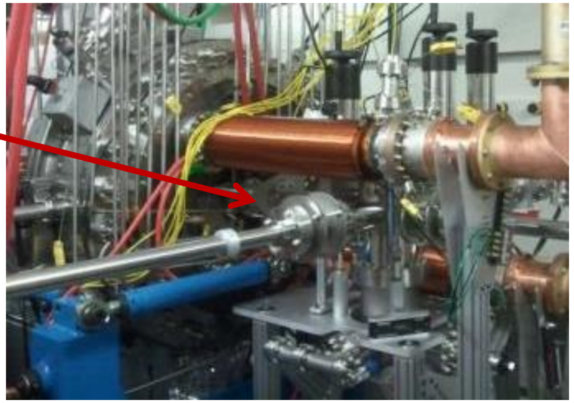
With RF at the nominal power the pressure rises to ~ 3 x 10^{-10} Torr

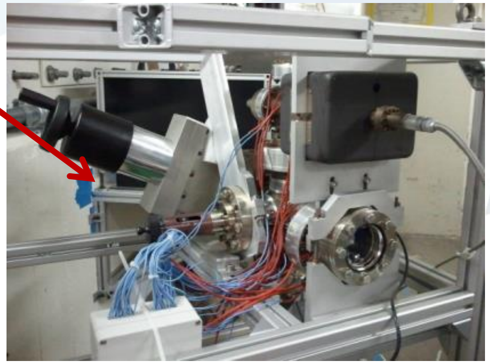




Design by INFN Milano – LASA

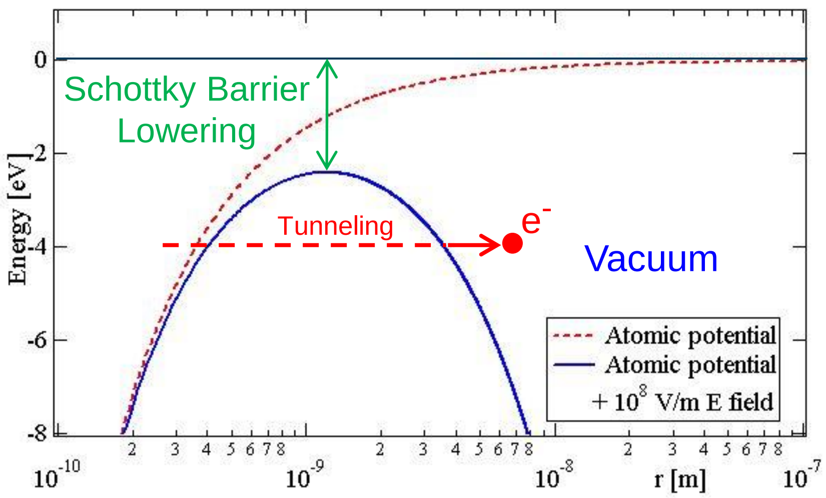
Vacuum "suitcase" compatible with airplane transportation (NEG pump)





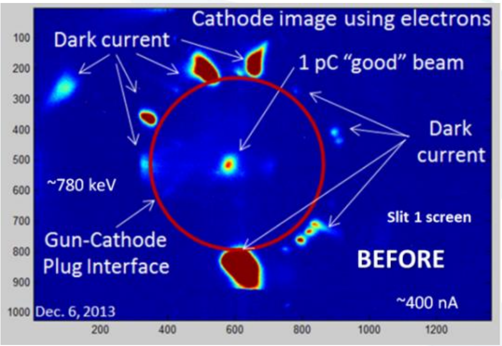
Dark Current

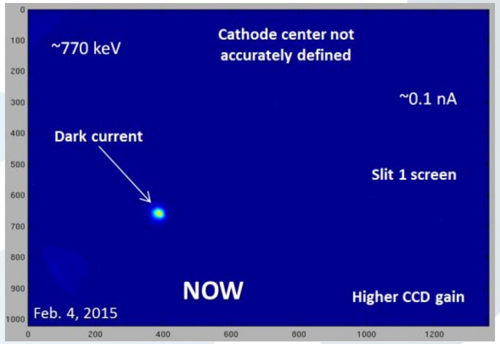
Dark current is generated by field emission from the accelerator parts exposed to high electric fields.



$$U_p = -\frac{1}{4\pi\varepsilon_0}\frac{e^2}{r} + e|\bar{E}|r \qquad |\bar{E}| = \text{constant} \qquad |\bar{E}| >\sim 10^8 \div 10^9\, V/m$$

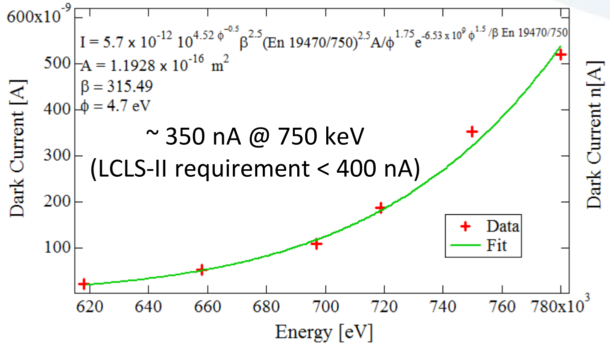
- Dark current can be relatively tolerated in low duty cycle accelerators but can represent a serious issue in accelerators running at high-duty-cycle or in continuous wave (CW) mode that can generate damage, quenching, and high radiation levels in the downstream accelerator.

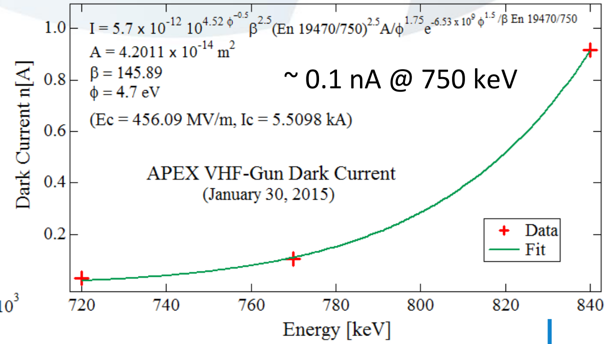




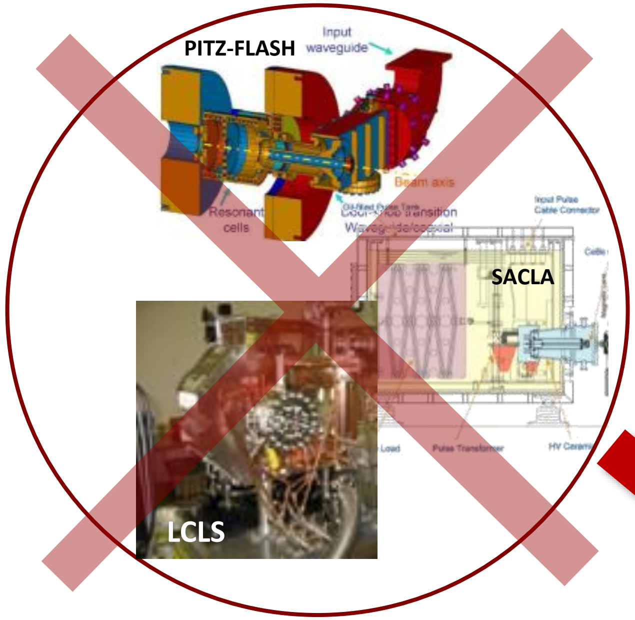
- While no definitive 'cure' for dark current exists, the best techniques known for minimizing it, should be used (surface finish, geometry, materials, material treatments…).

In particular, high accelerating fields in the cathode/gun area, which can potentially generate field emission, should be carefully evaluated in terms of dark current.

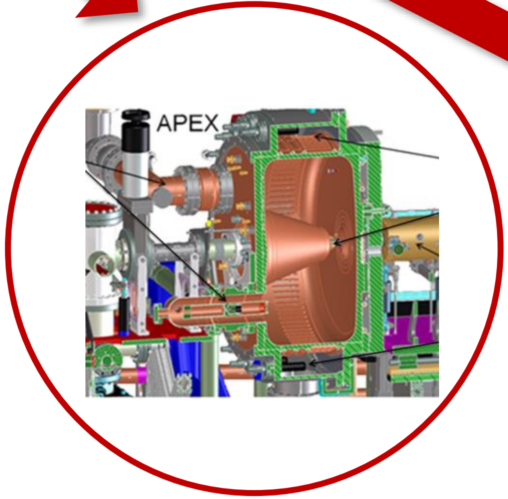




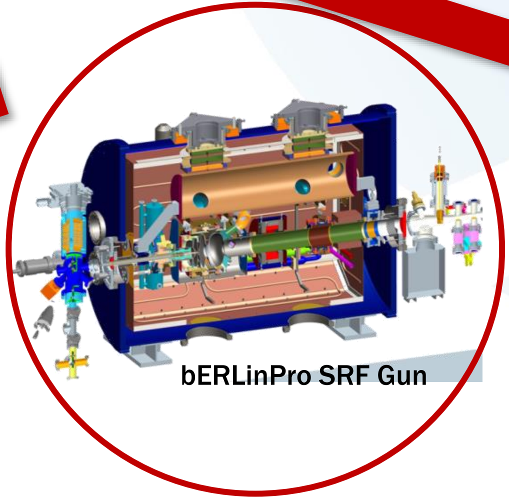
High-Duty-Cycle Photo-Gun Technologies



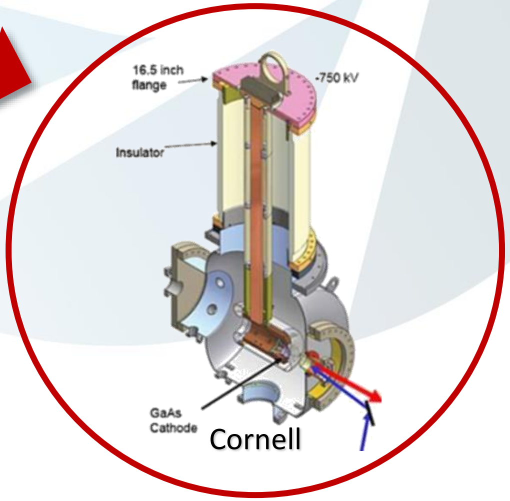
Normal-Conducting
GHz-class RF guns



Normal-Conducting
Low Frequency VHF RF Guns



Superconducting
RF Guns



DC Guns

A (Incomplete!) List of Groups Existing/Developing High-Brightness High-Repetition Rate Guns

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

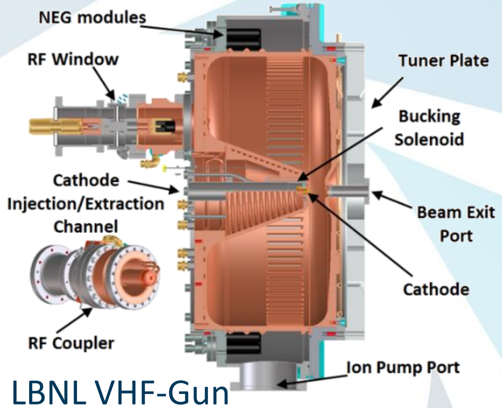
1. LANL
2. LBNL
3. SINAP

Low Frequency Normal Conducting (NC) RF Gun Technology

Basic idea: exploit the different scaling with RF between the power density dissipated on the RF structure walls and the voltage breakdown threshold:

$$\frac{dP}{dS} \propto f_{RF}^{5/2}$$

$$V_{BD} \propto f_{RF}^{1/2}$$



LBNL VHF-Gun

This favorable scaling allows to lower the RF frequency into the VHF, or "very high frequency" band (30-300 MHz), where the power dissipated on the gun permits CW operation, while the electric fields at the cathode are still high enough for a high brightness performance.

Pros:

- Operates in CW mode
- Beam dynamics similar to DC but at much higher gradients and beam energies
- Based on mature RF and mechanical technologies.
- Compatible with magnetic fields in the cathode/gun area.
- Capable of the vacuum performance required by semiconductor cathodes
- Demonstrated the high brightness performance required X-ray FELs

Cons:

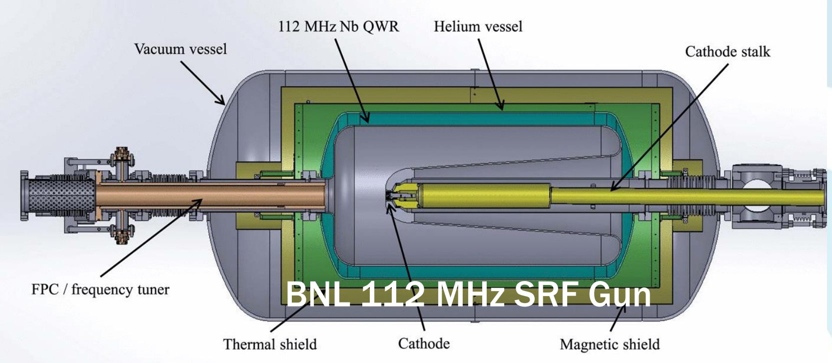
- High accelerating fields and energies require high RF power

Frequency	186 MHz
Operation mode	CW
Beam energy	750 kV
Field at the cathode	20 MV/m
Q_0	31,000
Shunt impedance	6.5 MW
RF Power @ Q_0	90 kW
Stored energy	2.3 J
Peak surface field	24. 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

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)

Superconducting RF (SRF) Gun Technology

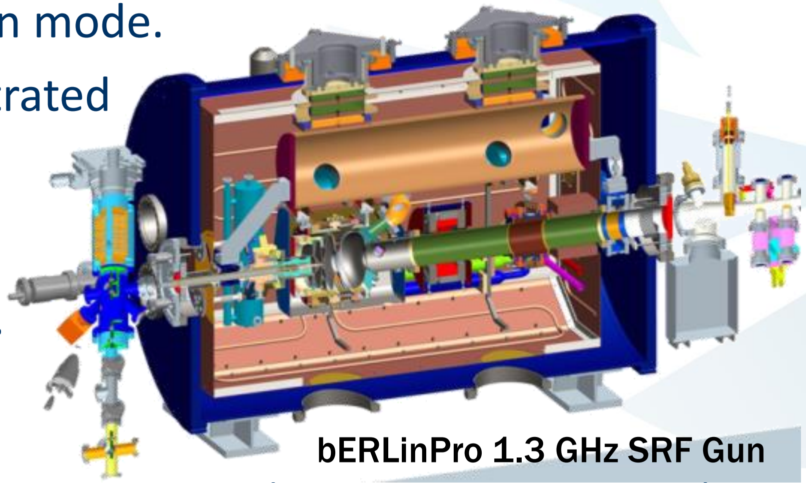
Since the first conception in 1998, several groups around the world are developing schemes where the gun RF structure is in superconducting niobium. Schemes use SRF structures resonating at GHz-class frequencies and at lower VHF frequencies.

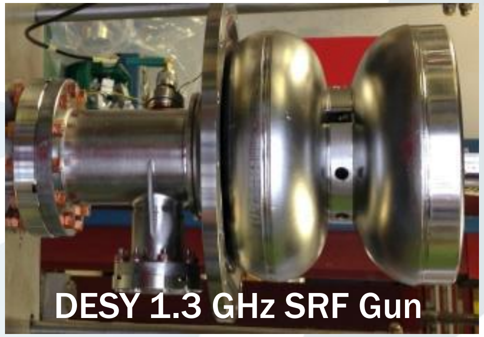


BNL 112 MHz SRF Gun

Pros:

- Excellent power efficiency operation at strongly reduced RF power
- Potential for high accelerating fields in XFEL operation mode.
- Compatibility with semiconductor cathodes demonstrated
- Few MeV beam energy demonstrated
- CW operation demonstrated.
- Excellent vacuum performance due to cryo-pumping.


bERLinPro 1.3 GHz SRF Gun

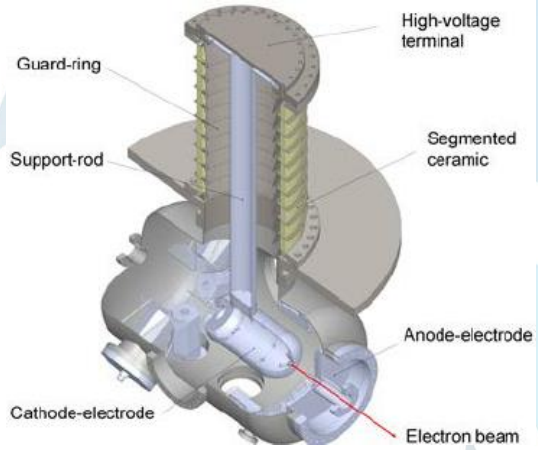

DESY 1.3 GHz SRF Gun

Challenges:

- Accelerating field degradation with cathodes insertion extraction (particulates creation).
- SRF field exclusion and maximum field limitations prevents to minimize the distance between the main solenoid and the cathode (important for beam dynamics)
- High-brightness performance required for driving an X-ray FEL not yet demonstrated

Direct Current (DC) Gun Technology

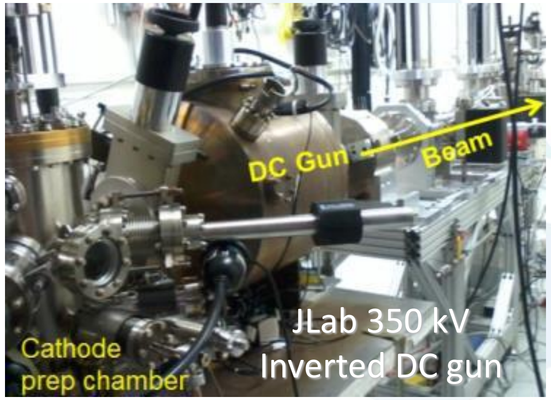
Electron guns based on DC schemes, are the work horse for many accelerator applications. In high-brightness high-duty-cycle applications, such as energy recovery linacs (ERLs) and source of polarized beams, they represent the only choice presently available.

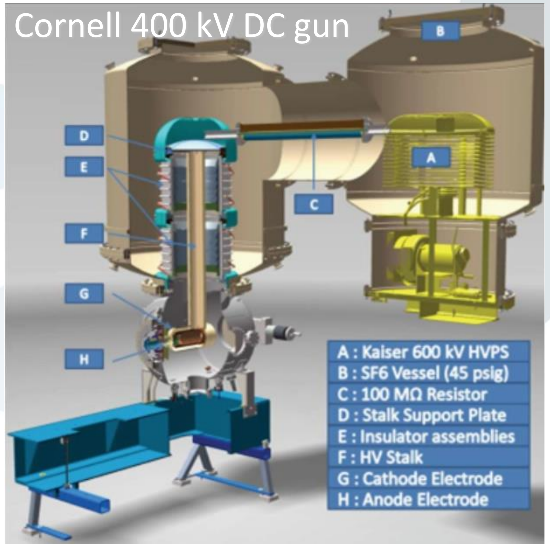


JAEA 500 kV DC Gun

Pros:

- DC operation and GHz-class repetition rate capabilities
- Demonstrated X-ray FEL quality in a complex layout injector
- Highest average current operation demonstrated
- Compatible with magnetic fields in the cathode gun area
- Excellent vacuum performance using NEGs inside the gun
- Compatible with most photo-cathodes.
  (the only one that operated GaAs cathodes for polarized beams)





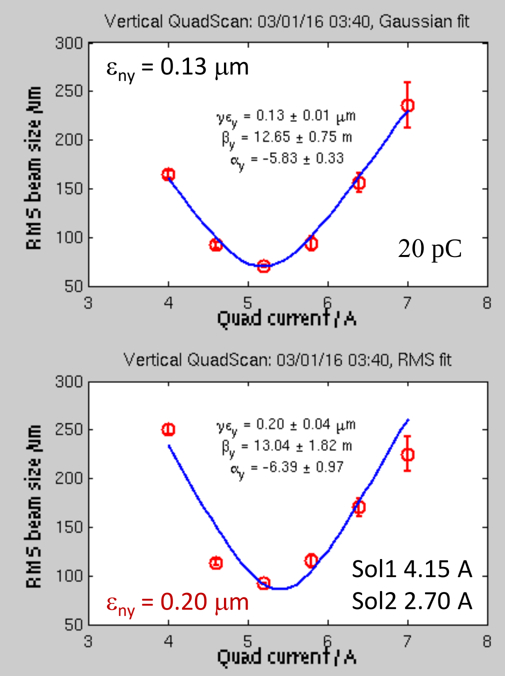
Challenges:

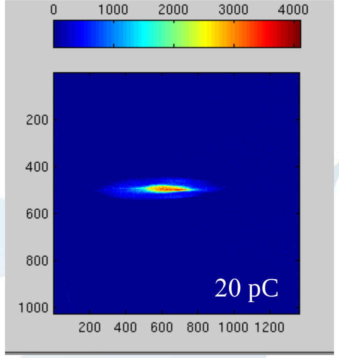
- Beam energy at the limit of the technology (field emission and insulator punctuation)
- Accelerating fields at the cathode limited to less than~ 10 MV/m
- Requires a complex injector configuration and low thermal emittance cathodes to deliver the X-ray FEL beam quality

NC RF Guns Accomplishment Highlights

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

Requirement		Result
Demonstrate reliably operation in CW mode at the required fields and energy (750 keV) F. Sannibale, *et al*., PRST-AB 15, 103501 (2012)	✓	> 840 keV measured
Demonstrate operation with sufficient lifetime (τ > 4 days) at the required charge/bunch, rep. rate, and thermal emittance (<1 μm/mm required, ~0.7 μm/mm measured with Cs_2Te) D. Filippetto, H. Qian, F. Sannibale, Appl. Phys. Letters 107, 042104 (2015).	✓	τ ~ 17 days Measured with Cs_2Te
Characterization and control of dark current to the required level (< 400 nA @ 750 keV – LCLS-II) R. Huang, *et al*., PRST-AB 18, 013401 (2015)	✓	~ 0.1 nA measured
Demonstrate APEX operation with emittance and compression required by one LCLS-II mode of operation. F. Sannibale, *et al*., Review of Scientific Instruments 90, 033304 (2019).	✓	All parameters demonstrated





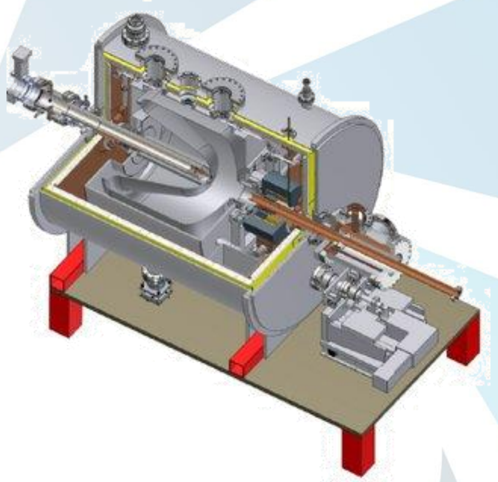
LBNL fabricated a second VHF-Gun (close version of the APEX gun) that is now driving the commissioning of the LCLS-II at SLAC.

All acceptance parameters achieved (F. Zhou, *et al*., Phys. Rev. Accel. and Beams **24**, 073401,2021).

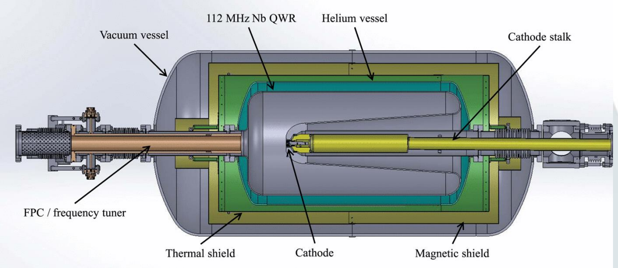
- A 250 MHz VHF-Gun is being built at SINAP for driving SHINE, the Shanghai X-ray FEL

SRF Guns Accomplishment Highlights

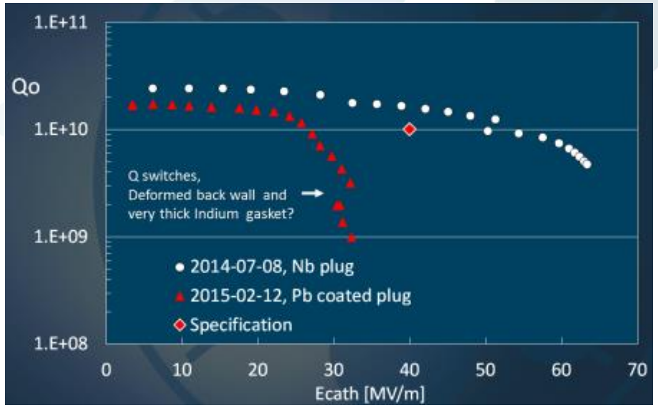
- Wisconsin 200 MHz SRF gun, achieved 20 MV/m at the Cs_2Te cathode without beam (corresponding to a beam energy of ~1.8 MeV) and also showed encouraging emittance values with 100 pC charge operating at a lower field at the cathode;



- BNL 112 MHz SRF operating with fields at the CsK_2Sb cathode of 18 MV/m and energy of 1.25 MeV at the gun exit, delivered 100 pC bunches with a promising emittance but with very long bunches (peak current at the injector exit was approximately 1 to 2 orders of magnitude smaller than required by X-ray FELs)



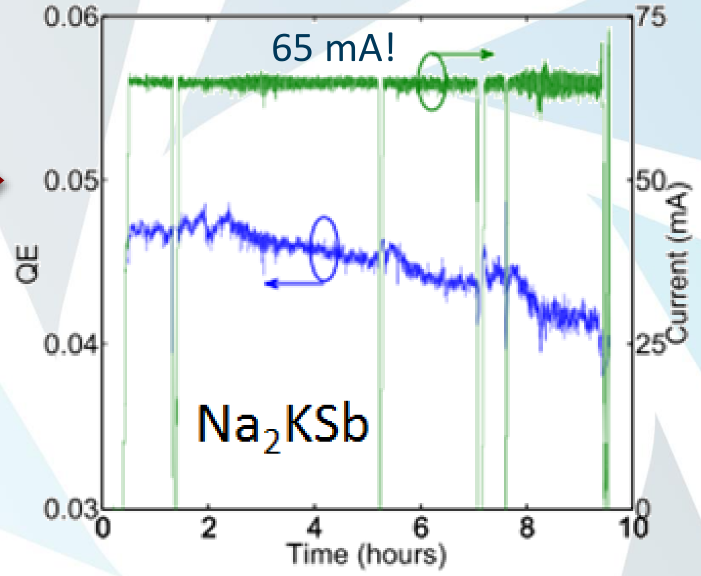
- DESY 1.3 GHz gun demonstrated ~50 MV/m at the cathode with low QE Nb cathodes (~27 MV/m with Pb)



- HZRD 1.3 GHz in Berlin, confirmed many years of operation with warm cathodes

DC Guns Accomplishment Highlights

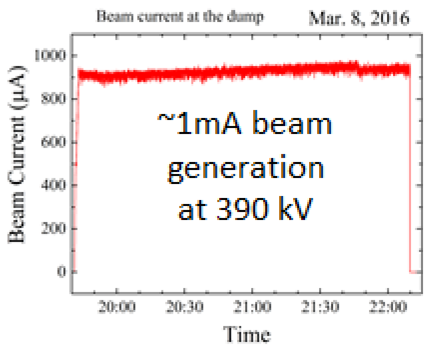
Cornell gun: delivered record high currents

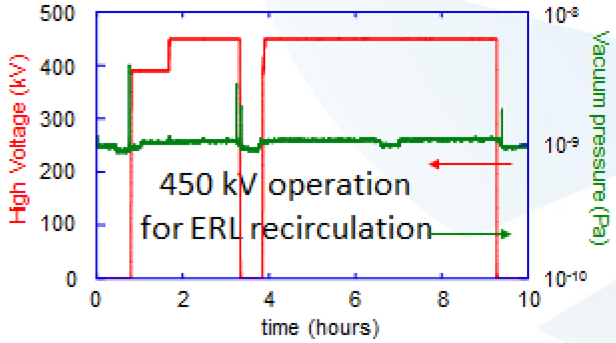


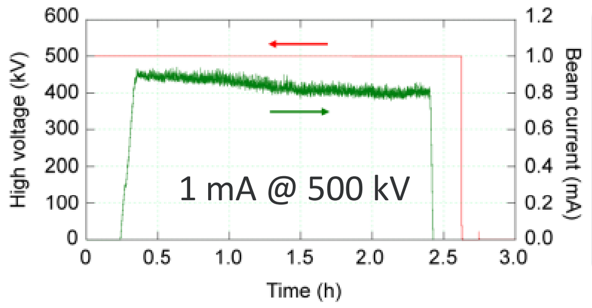
Demonstrated LCLS-II beam quality needs @ ~ 400 keV

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**

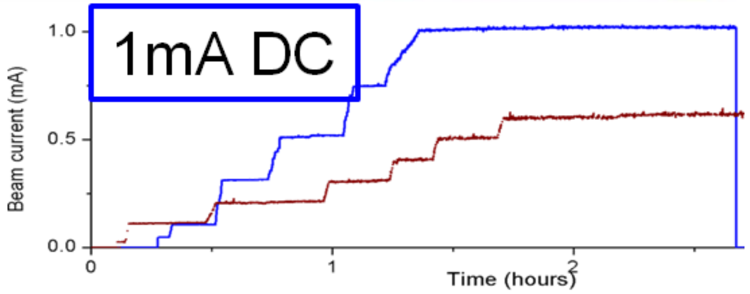
KEK/JAEA DC gun:
First DC gun to achieve 500 keV







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



Is the Present High-Duty-Cycle Guns Performance Sufficient?

Some of the high-duty-cycle gun technologies have already demonstrated, and others are approaching, the fields at the cathode, beam energies and the other parameters (vacuum, cathode lifetime) and ultimately the beam quality required to operate present high-repetition rate X-ray FELs.

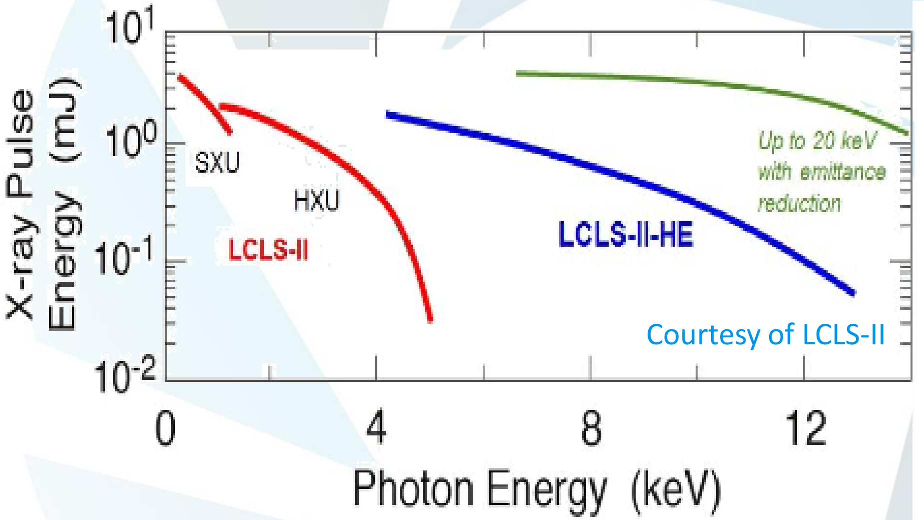
Is the Present Performance Sufficient for Future Upgrades?

Is the Present High-Duty-Cycle Guns Performance Sufficient?

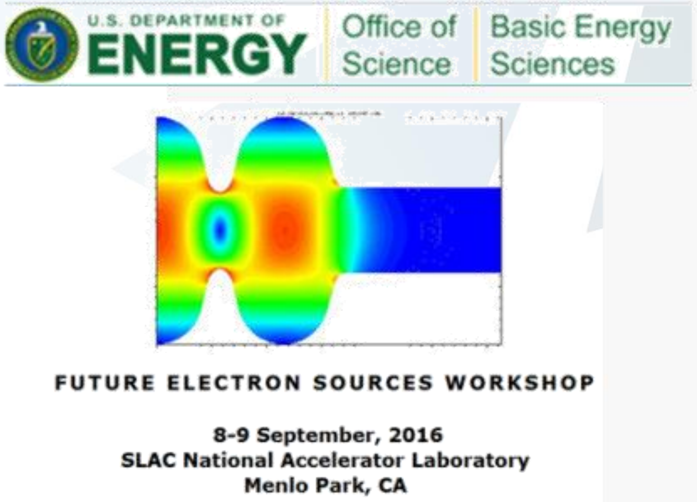
New proposals/upgrades (LCLS-II HE, MaRIE, SCLF, …) would strongly benefit from lower emittances to extend their photon spectra to shorter wavelengths.

No!

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



In 2016 a DOE-BES workshop put together experts from around the world to define a pathway towards this enhanced performance.



Priority directions were established (arbitrary order):

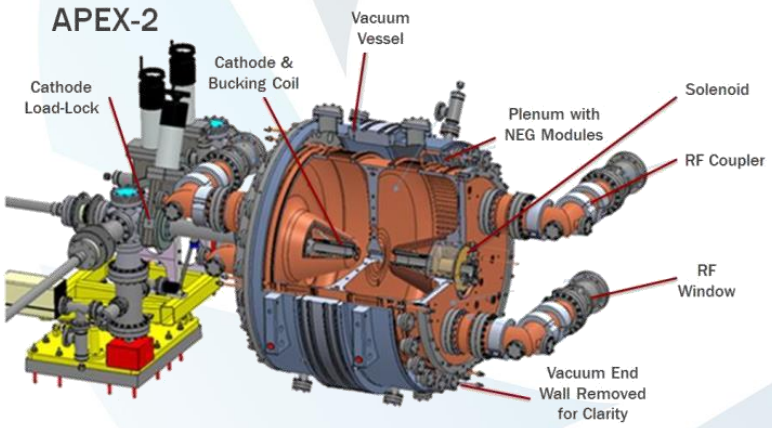
- Continue R&D towards lower thermal emittance cathodes
- Continue R&D on SRF gun to solve the present issues and achieve their nominal parameters.
- Extend the NC low frequency RF gun schemes towards higher accelerating fields and beam energies

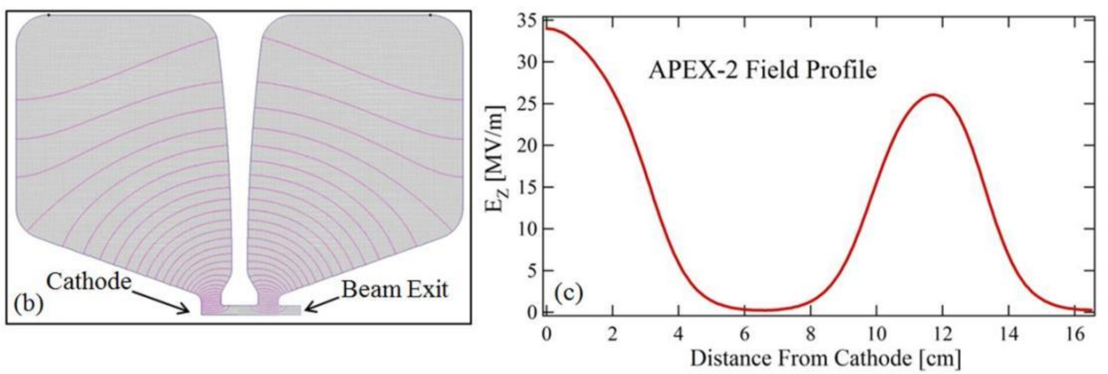
A Few Proposed Answers to That Need

A recent R&D activity for the development of an SRF gun for an upgrade of the LCLS-II HE project targets a design inspired by the Wisconsin 200 MHz SRF gun. The new gun is designed to generate a beam energy of 1.8 MeV and 30 MV/m fields at the cathode.

LBNL proposal is for APEX-2, an evolution of APEX with fields and energies comparable to those targeted by SRF guns R&D 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 reliable mechanical, vacuum, cathode load-lock, and RF schemes of APEX are reused in this new design.

The Main High-Duty-Cycle Technology Impact on Injector Beam Dynamics

• All present and proposed high-duty-cycle electron gun schemes show electric fields at the cathode during photo-emission significantly smaller than the ones in their low-duty-cycle counterparts: 20-40 MV/m vs. 60-80 MV/m

• Such fields forces to operate the injector in the “cigar” regime where relatively long bunches at the gun are used to control the effects of space charge forces that would severely degrade the brightness performance.

• Longer bunches lead to larger longitudinal emittances but this is tolerable in most of the X-ray FELs modes of operation.

• Longer bunches also requires more compression to achieve the several thousands A peak currents required at the FEL undulator.
Such compression must start already at the injector simultaneously to the emittance compensation process.

• This is a critical operation that must be performed in a way to minimize the emittance while preserving the quality of the longitudinal phase to allow for a smooth compression in the downstream linac.
Longitudinal phase space correlations of order greater than 2 are in particular dangerous and need to be minimized.

Conclusions

- High-duty-cycle X-ray FELs requiring high-brightness electron beams are a nowadays reality (LCLS-II, SHINE).
- The existing (and successful) RF photo-guns driving the present low-duty-cycle X-ray FELs cannot operate at high-duty-cycle.
- Groups around the world developed and are developing high-duty-cycle (CW) electron gun schemes capable of delivering beams with the required challenging performance.
- Different technologies are used, and some of them have already demonstrated, and others are approaching, the required performance.
- Proposals for new or upgraded CW X-FELs and other applications would strongly benefit from even higher brightness photo-injectors.
- R&D programs are being initiated and proposed to attack this new request..

Thanks for the Attention!

(Incomplete) 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	0.75 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	~0.5 MeV	To be measured	~1mA/DC
BNL	112 MHz SRF	22.5 MV/m	~18 MV/m	2 MeV	~1.25 MeV	~0.3µm/0.1nC	Up to 3.7nC
DESY	1.3 GHz SRF	~50 MV/m	~50MV/m Nb cath. ~27MV/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 With lower field	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

Space Charge Forces Downstream the Cathode

- Interaction between the electromagnetic field of the particles in a beam can be divided into two main categories:

  - Space charge forces or self-field forces: the force on a particular particle resulting from the combination of the fields from all other particles in the beam.
    Such a force is Hamiltonian and the lower order terms of it can be compensated.

  - Scattering (Boersch effect): a particle in the beam scatters (interacts) with another particle in the beam.
    This is a stochastic and hence non-Hamiltonian process, that generates an increase of the 'Liouville' emittance ('heating') that cannot be compensated.

- In a plasma (the beam is a nonneutral plasma), the Debye length λ_D represents the length beyond that the screening from the other particles in the plasma cancels the field from an individual particle.

$$\lambda_D = \left(\frac{\varepsilon_0 \gamma k_B T}{e^2 n} \right)^{\frac{1}{2}}$$

with n the electron density, k_B the Boltzmann constant, T the electron beam 'temperature' in the rest frame with $m\sigma_v^2 = k_B T$

If $\lambda_D < \sim n^{-1/3}$ = average electron distance ➡ scattering is prevalent

If $\lambda_D >> n^{-1/3}$ ➡ scattering can be neglected

For more info, see for example: Rieser, Theory and Design of Charged Particle Beams, Wiley, chapter 4.1.

Linear Space Charge Regime

• At the injector energies, the beam is not fully relativistic, and the space charge forces play a relevant role.

• In the case of linear space charge forces, the effect is that of a linear defocusing in both transverse planes, and an analytical expression for the rms beam envelope σ can be derived. In the case of cylindrical symmetric continuous beam:

$$\sigma'' + \sigma' \frac{\gamma'}{\beta^2 \gamma} + K_r \sigma - \frac{\kappa}{\sigma \beta^3 \gamma^3} - \frac{\varepsilon_n^2}{\beta^2 \gamma^2 \sigma^3} = 0 \qquad \kappa = \frac{I}{2I_0} \equiv perveance \qquad \frac{\partial f}{\partial z} = f'$$

where the second term on the LHS is the accelerating adiabatic damping, K_r is a linear focusing term (given for example by a solenoid), ε_n the normalized emittance, I the beam current and $I_0 \sim 17$ kA the Alfven current.

• In the case of a bunched beam, we previously saw that in its 'core' space charge forces are with good approximation linear, and the envelope equation above can be used for the core by replacing I with the beam peak current I_p.

• The envelope equation also shows that in the linear space charge case, a proper focusing can be used to compensate for space charge forces.

• A similar equation can be derived for the longitudinal beam envelope.

Longitudinal Emittance Dilution Terms

- As in the transverse case, also the longitudinal emittance is affected by RF and space charge dilution.

- The increase of the normalized longitudinal emittance due to RF is given by:

$$\varepsilon_{nz\,RF} = \frac{\sqrt{3}}{c^2}\left(\gamma_{exit} - 1\right)\omega_{RF}^2 \sigma_z^3$$

with e and m the electron charge and rest mass respectively, c the speed of light, $\omega_{RF}/2\pi$ the RF frequency, E_0 the accelerating field, and σ_r and σ_z the rms transverse and longitudinal beam sizes.

- Such a longitudinal emittance increase is mainly due to a quadratic energy/position correlation that can be removed by using a harmonic cavity or a nonlinear optics downstream in the linac.

- The increase of the normalized longitudinal emittance due to space charge is instead given by:

$$\varepsilon_{nz}^{SC} = \frac{\pi}{4}\frac{1}{\sin\varphi_0}\frac{2mc^2}{e\hat{E}_z^{RF}}\frac{I}{I_A} f\left(\frac{\sigma_x}{\sigma_z}\right) \quad with \;\; \varphi_0 \equiv emission\;\; phase \qquad f(A) = \frac{1}{1 + 4.5A + 2.9A^2}$$

- For example for a 1 nC, 10 ps bunch with a 1/3 aspect ratio, 120 MV/m field, emitted at 90 deg phase, the normalized emittance increase is ~ 15 μm.
- This is significantly larger than the cathode thermal emittance contribution of ~ 3 μm that a cathode with $\sigma_{pz}/mc \sim 10^{-3}$ would have for that beam transverse size.

K. J. Kim, NIM A275, 201 (1989

Boersch Effect

- After the emission from the cathode, the electron beam presents an isotropic distribution of temperatures

$$kT_{\perp i} = kT_{//i} = kT_i = m\sigma_v^2$$

- The subsequent acceleration does not affect the transverse temperature but dramatically decreases the longitudinal one:

$$kT_{//f} \approx \frac{\gamma_i^3}{\beta_f^2 \gamma_f^3} \frac{\left(kT_{//i}\right)^2}{mc^2}$$

- As a consequence, the longitudinal temperature becomes soon negligible, and Coulomb collisions start to reestablish the thermal equilibrium in the beam transferring momentum from the transverse to the longitudinal plane. This phenomenon is known as the Boersch effect.

$$T_{\perp f} \cong 2/3 T_{\perp i}\left(1 + 0.5 e^{-3t/\tau}\right) \qquad T_{//f} \cong 2/3 T_{\perp i}\left(1 - e^{-3t/\tau}\right)$$

$$\tau = \frac{4.44 \times 10^{20} \left(0.307\, kT_{\perp i}/mc^2\right)^{3/2}}{n \ln\left[5.66 \times 10^{21}\left(kT_{\perp i}/mc^2\right)^{3/2} n^{-1/2}\right]}$$

$$\sigma_E = \left(\frac{\beta_f^2 \gamma_f^3}{\gamma_i^3} mc^2\, kT_{//f}\right)^{\frac{1}{2}}$$

where k is the Boltzmann constant n the electron density, and i and f stay for 'final' and 'initial' respectively.

- For a 1 nC, 10 ps bunch with a 1/3 aspect ratio, kT_i 1 eV, the temperature relaxation time τ is ~ 300 ns (~ 100 m of accelerator!), but for a beam accelerated up to 1 MeV, 1 m downstream of the cathode, $\sigma_E \sim 600$ eV!

For example: Rieser, Theory and Design of Charged Particle Beams, Chapter 6.4.1, Wiley

Transverse Space Charge Forces

- It can be shown that for a beam with Gaussian linear charge density λ_C and for $|x| << \sigma_x$ and $|y| << \sigma_y$, (beam core) the transverse space charge fields are:

$$E_x = \frac{1}{2\pi\varepsilon_0}\frac{\lambda_C}{\sigma_x(\sigma_x+\sigma_y)}x, \quad E_y = \frac{1}{2\pi\varepsilon_0}\frac{\lambda_C}{\sigma_y(\sigma_x+\sigma_y)}y, \qquad B_x = -\frac{\mu_0}{2\pi}\frac{\lambda_C\beta c}{\sigma_y(\sigma_x+\sigma_y)}y, \quad B_y = \frac{\mu_0}{2\pi}\frac{\lambda_C\beta c}{\sigma_x(\sigma_x+\sigma_y)}x$$

Such space charge fields exert forces on the beam particles, and the intensity of such a forces are given by the Lorentz equation:

$$\vec{F} = q\left(\vec{E} + \vec{v}\times\vec{B}\right)$$

By comparing the previous relation, one finds:

$$B_x = -\frac{\beta}{c}E_y \qquad B_y = \frac{\beta}{c}E_x$$

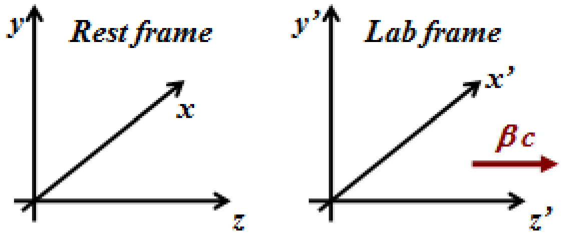
$$F_x = q\left(E_x - \beta c B_y\right) = qE_x\left(1-\beta^2\right) \propto \lambda_C\left(1-\beta^2\right)x$$

$$F_y = q\left(E_y + \beta c B_x\right) = qE_y\left(1-\beta^2\right) \propto \lambda_C\left(1-\beta^2\right)y$$

- The force dependence on the $(1-\beta^2) = 1/\gamma^2$ term is actually quite general and shows that the transverse space charge forces become negligible for relativistic beams.

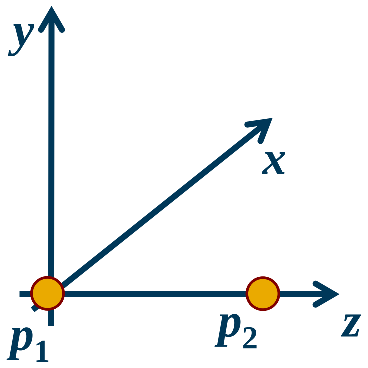
- The above equations also show that in the 'core' of the beam, the forces are linear in x and y. This implies that they can be compensated by linear focusing elements (solenoids, quadrupoles)

Longitudinal Space Charge Forces



The longitudinal component of the Lorentz force in the lab frame is given by:

$$F'_z = q\left[E_z + \frac{1}{1 - v_z\,\beta/c}\left[v_x\left(B_y + \frac{\beta}{c}E_x\right) - v_y\left(B_x - \frac{\beta}{c}E_y\right)\right]\right]$$



In the rest frame, two particles are resting as in the figure.

The field acting on p_2 due to p_1 is:

$$E_z = \frac{q}{4\pi\varepsilon_0}\frac{1}{z^2};\ E_x = 0;\ E_y = 0$$

$$\overline{B} = 0$$

Using this result in the previous expression:

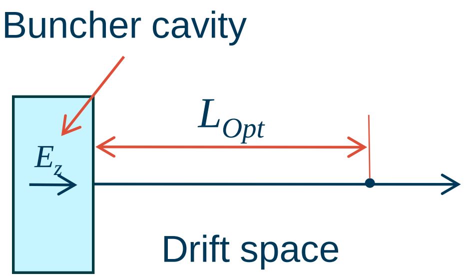
$$F'_z = qE_z = \frac{q^2}{4\pi\varepsilon_0}\frac{1}{z^2} = \frac{q^2}{4\pi\varepsilon_0}\frac{1}{(\gamma z')^2} = \frac{1}{\gamma^2}\frac{q^2}{4\pi\varepsilon_0}\frac{1}{z'^2}$$

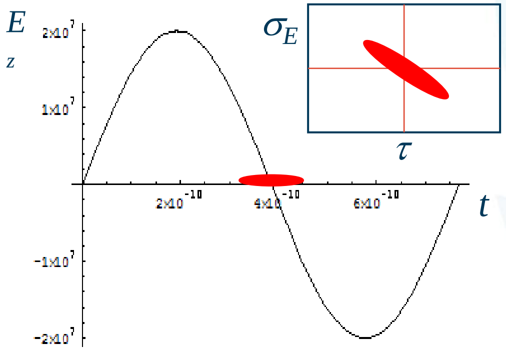
- Similarly to the transverse case, the $1/\gamma^2$ term shows that also the longitudinal space charge force becomes negligible for relativistic beams.

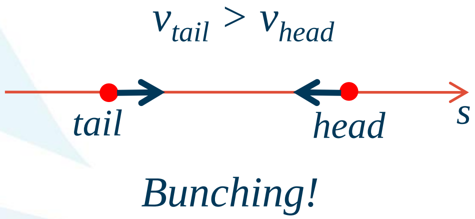
“Zero-Phase-Crossing” Buncher

One effective method to compress bunches when the beam is not fully relativistic consists in using a ‘buncher’ (or prebuncher) cavity.

In a buncher the most linear part of the RF field (‘zero phase crossing’) is used for creating an energy ‘chirp’ in the beam with no net acceleration of the bunch.







- It can be shown that the optimal bunching drift length L_{Opt} is given by:

$$L_{Opt} = mc^2 \gamma\left(\gamma^2 - 1\right) \frac{1}{\left.\frac{dW}{ds}\right|_{\varphi=\frac{\pi}{2}}}$$

where dW/ds is the particle energy variation per unit longitudinal displacement in the cavity.

- For an optimized pill box cavity (gap = $\beta\, \lambda_{RF}/2$) with electric field

$$E_z = \hat{E}_z \cos\left(\omega_{RF} t + \varphi\right) \Rightarrow \left.\frac{dW}{ds}\right|_{\varphi=\frac{\pi}{2}} = 2\beta \hat{E}_z$$

- For a non-relativistic beam and for λ_{RF} sufficiently long, to the linear energy chirp corresponds a linear velocity chirp, and the compression is symmetric.

For more relativistic beams the velocity chirp becomes non-linear and the compression asymmetric.

Velocity Bunching

Compressing more relativistic beams in the injector is still possible:

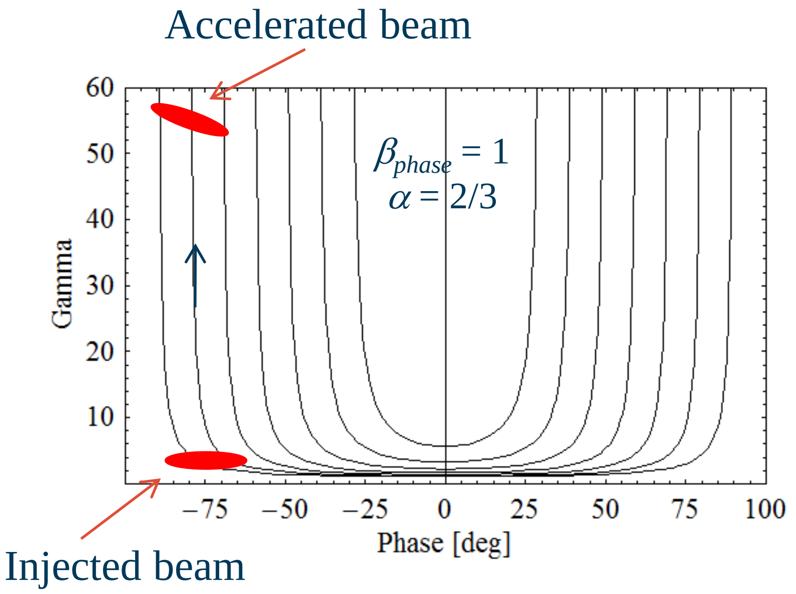
$$E_z = \hat{E}_z \sin(\omega t - kz - \psi_0) \quad with \quad \frac{\omega}{k} = c\beta_{phase}$$

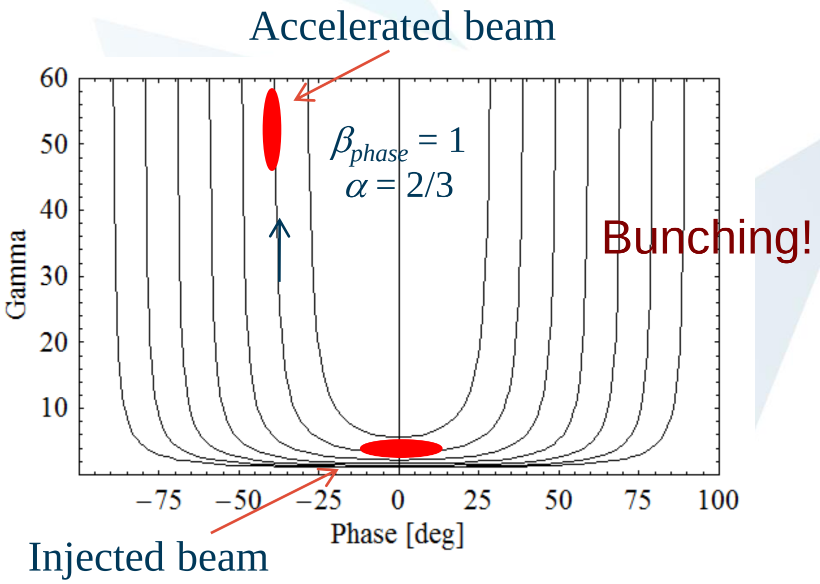
$$\begin{cases} \dfrac{d\varphi}{dt} = kc(\beta - \beta_{phase}) \\ \dfrac{dp}{dt} = -e\hat{E}_z \sin\varphi \quad with\ \varphi = \omega t - kz - \psi_0 \end{cases}$$

$$H = \gamma - \beta_{phase}\sqrt{\gamma^2 - 1} - \alpha\cos\varphi \quad with \ \alpha = \frac{e\hat{E}_z}{kmc^2}$$

$$and\ H \equiv constant$$

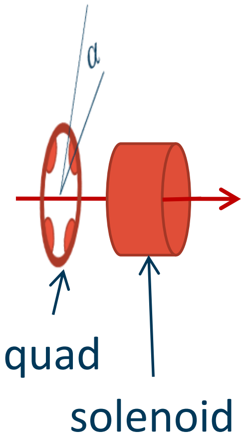
Particles trajectories in the γ, φ phase space



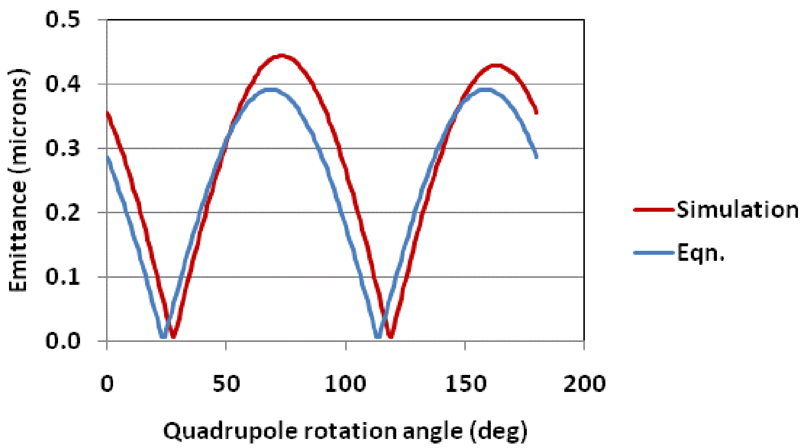


- The method can generate compression factors of more than 10 and can be used also with standing-wave accelerating sections.

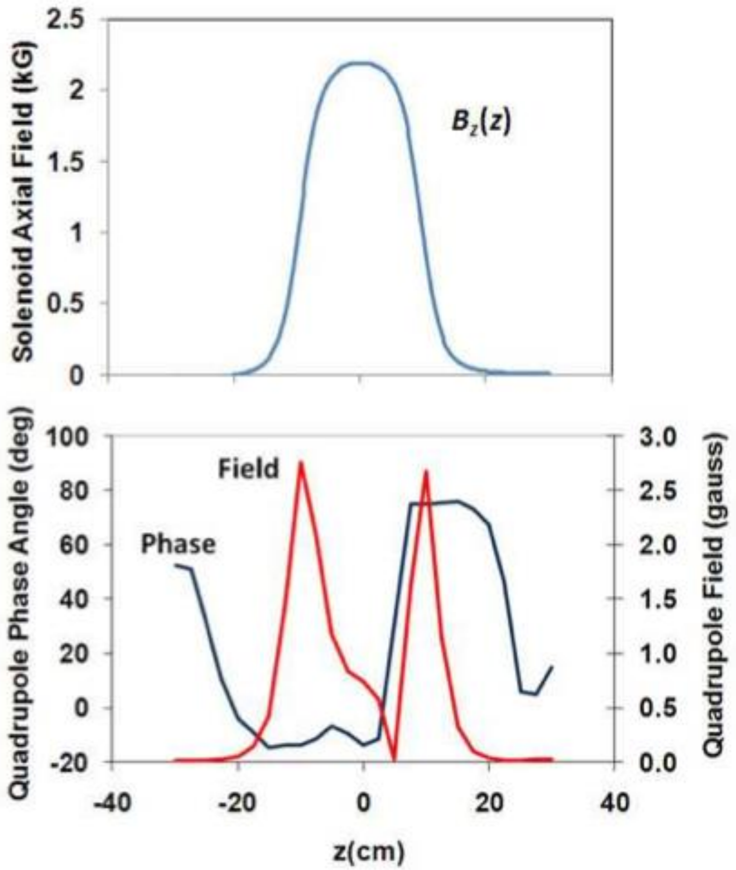
Aberrations due to Quadrupole fields due to lack of symmetry



$$\varepsilon_{x,qs} = \beta\gamma\sigma_{x,sol}\sigma_{y,sol}\left|\frac{\sin 2(KL+\alpha)}{f_q}\right|$$

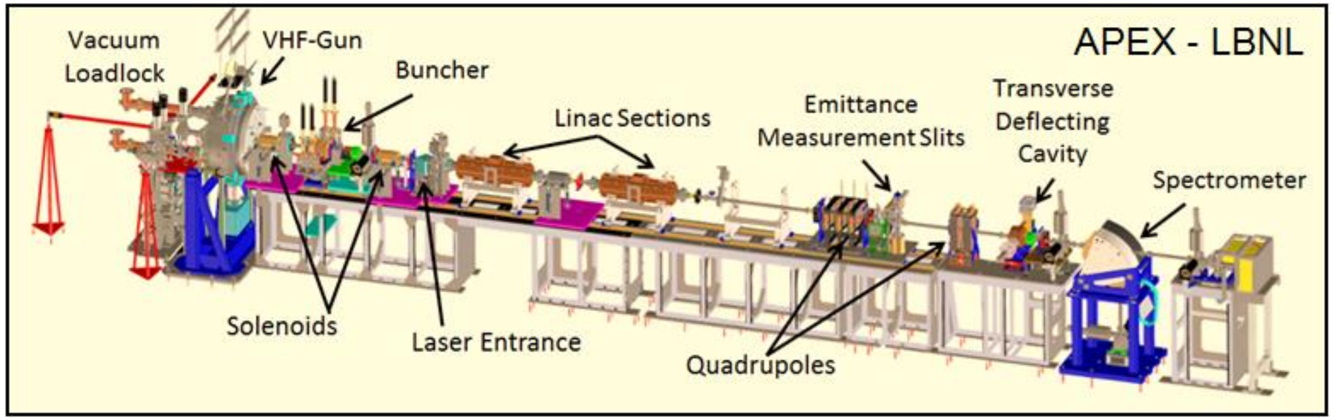


Measured magnetic fields, LCLS



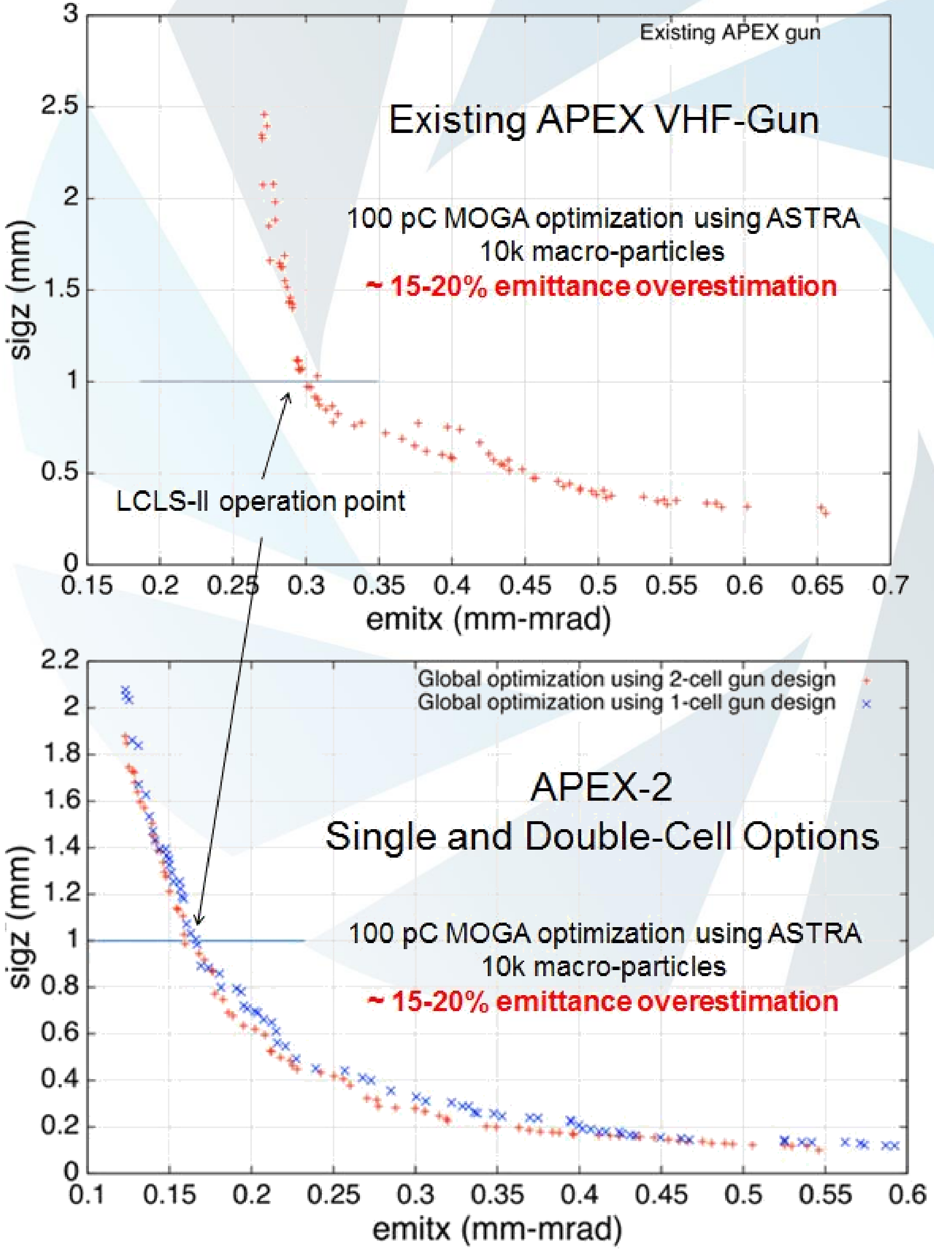
D.H. Dowell, Beam Physics At, Near and Far from the Cathode, Max Zolotorev's 70th Birthday,LBNL, nov. 2011

APEX-2 Performance Simulation



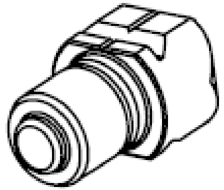
APEX-like layout used for simulations.

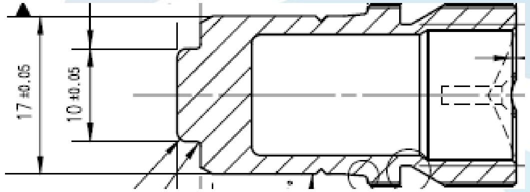
These initial simulations show a 2-fold decrease in emittance
(~0.13 μm at 100 pC)
and hence the 4-fold brightness increase required by future applications.

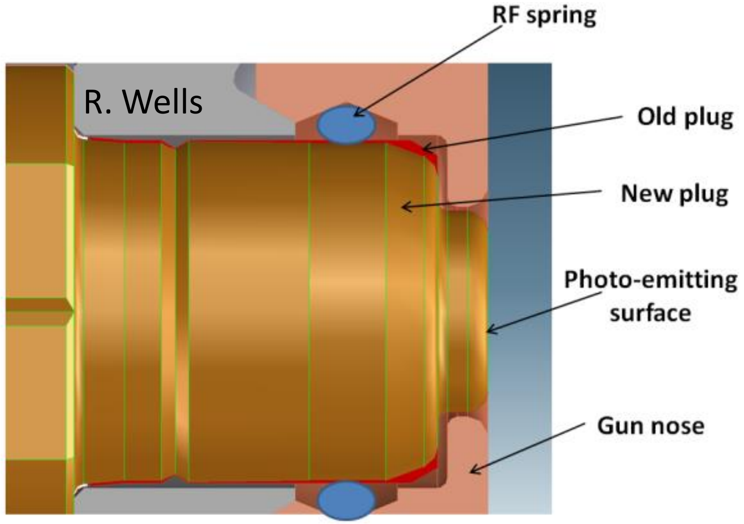


Cathode Plug

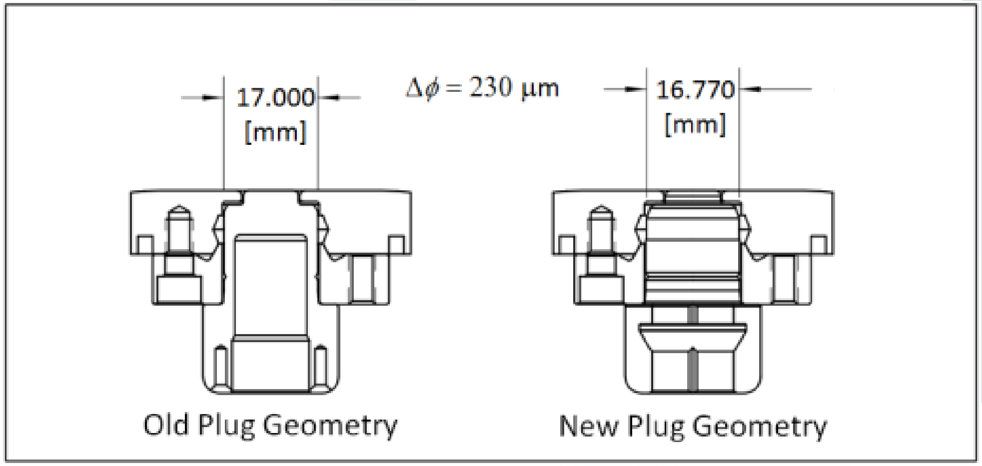
2nd generation: modified version of the INFN/FLASH plug for reducing field emission (used by FNAL and others).







Problems with the insertion/extraction operation damaging the RF spring pushed us to modify the cathode plug

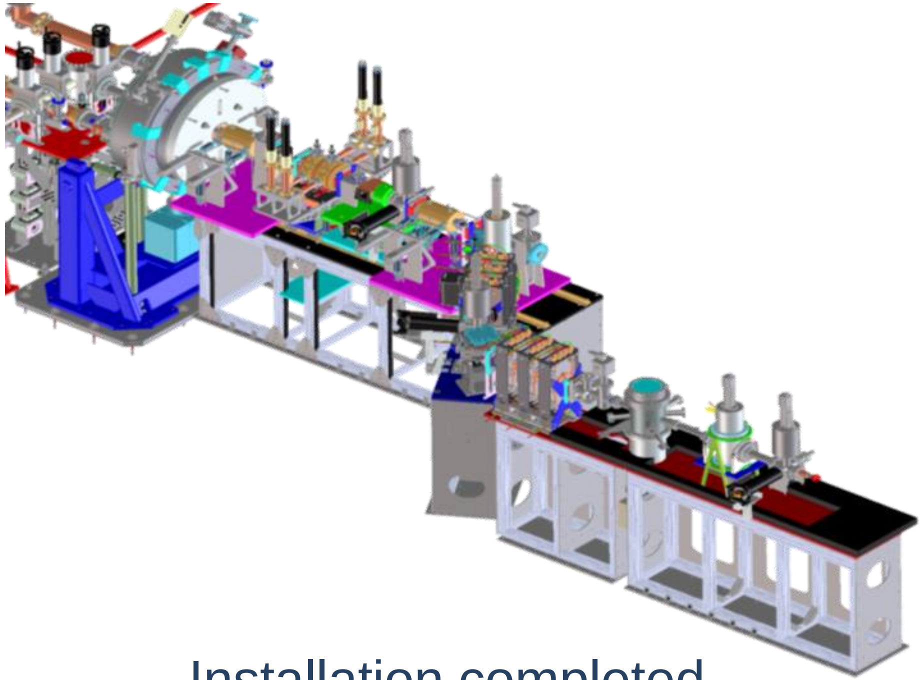


- Smaller "invitation" angle: 20º instead than 30º
- Slightly smaller diameter (-230 μm) at the RF spring contact
- Gold plated stainless steel RF spring with no discontinuity

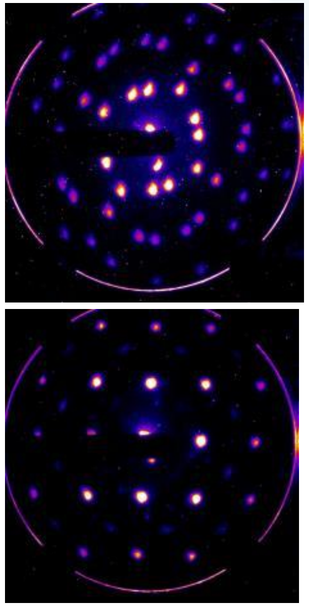
Any photocathode material deposited on a same geometry plug (usually in molybdenum) can be potentially tested at the VHF gun

HiRES, MHz-Class Repetition Rate UED at APEX

DOE Early Career
Award to
Daniele Filippetto



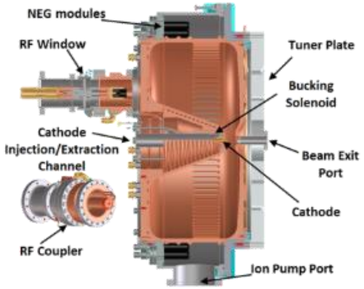
Installation completed.
First beam delivered in March 2017

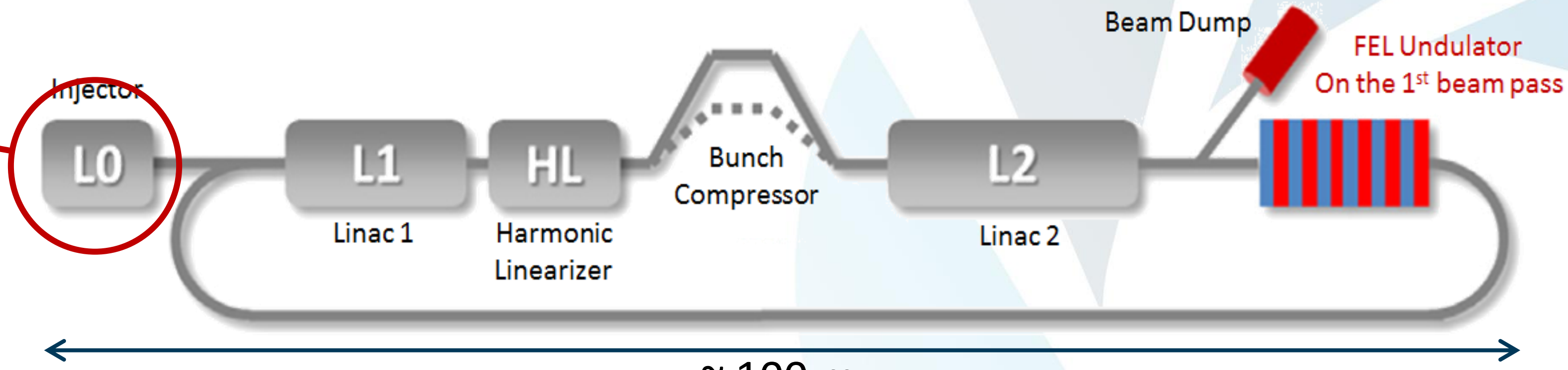


MHz repetition rate

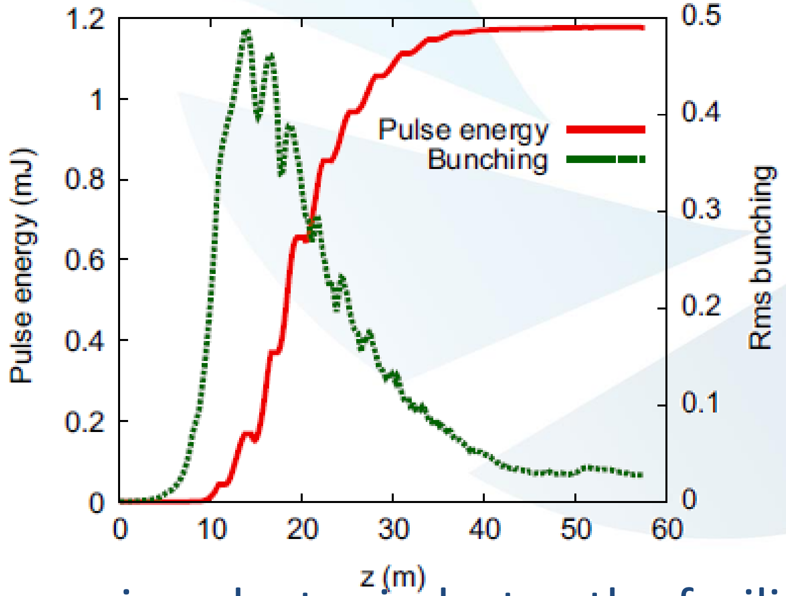
source properties	Science enabled
ultra-small pulses	atomic scale snapshots
high average flux	integrated measurements of weakly scattering processes
	matched to droplet injectors for biological sample replacement.
ultra-low charge pulses, high flux	weakly pumped systems
	unperturbed samples
	radiation sensitive materials

30 kW 13.5 nm EUV FEL with Energy Recovery





Energy at undulator	600 MeV
Bunch charge	300 pC
Inj. peak current	45 A
Inj. rms emittance	0.6 μm
Und. peak current	550 A
u-Period λ_u	18 mm
u-Parameter K (max.)	1
u-Length L_u	26 m
Gain length L_g	~0.5 m
Avg. beta functions $\beta_x = \beta_y$	5.3 m
FEL efficiency η	0.5%



For ~ 30 kW EUV, as presently required by the semiconductor industry, the facility has to operate at ~25 MHz repetition rate (~7.5 mA average current)

M. Venturini and G. Penn, *A non-conventional ERL configuration for high-power EUV FELs*, NIM A **795**, 219 (2015)

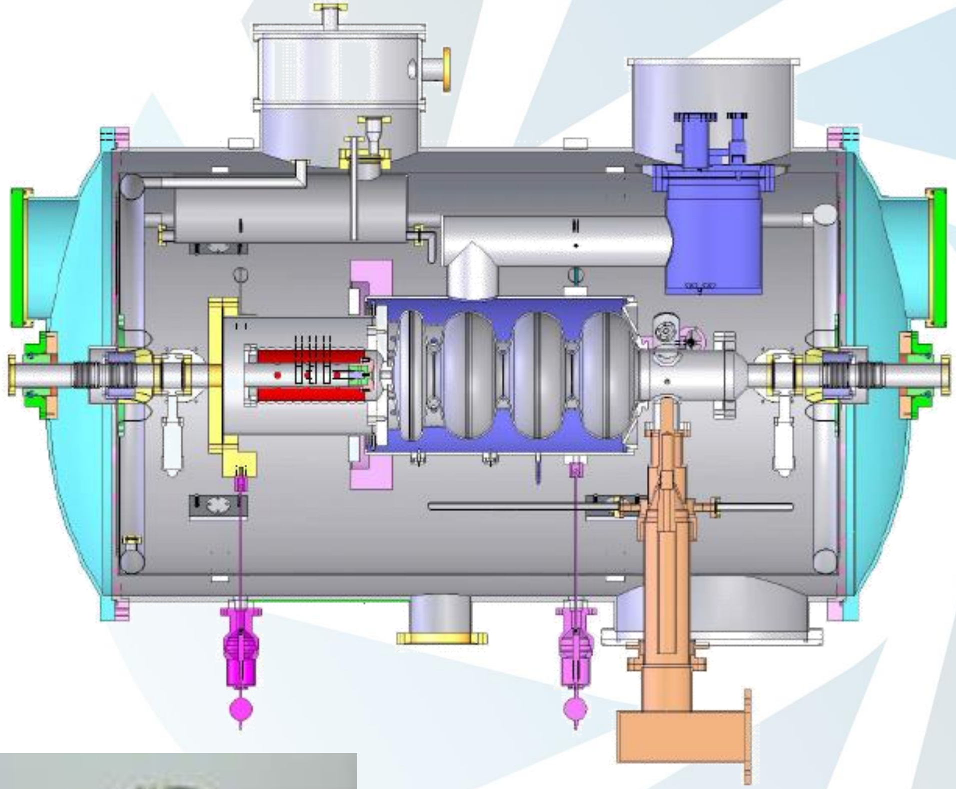
Hybrid DC-SRF Gun Technology

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:

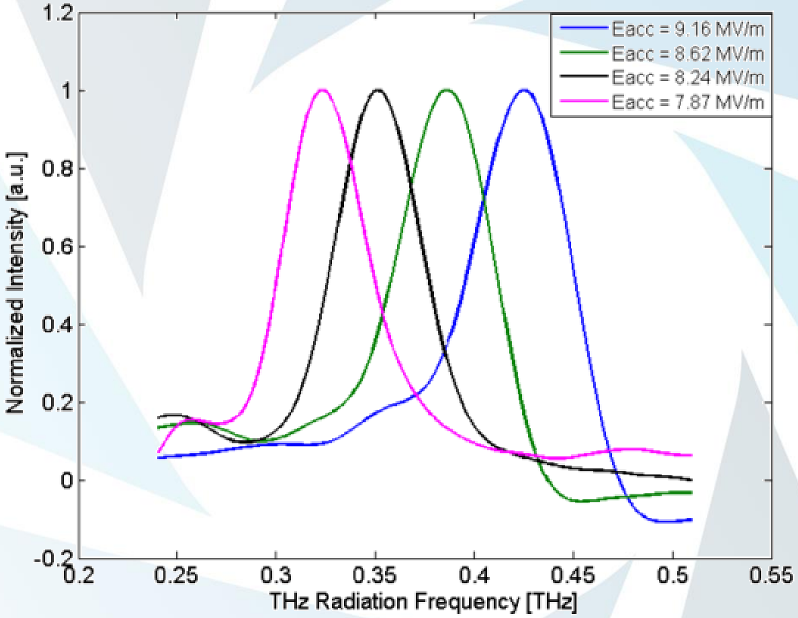
- accelerating field limitation in the DC part
- Increased system complexity



Peking University
DC-SRF Gun

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.