High brightness electron injectors for 4th generation light sources

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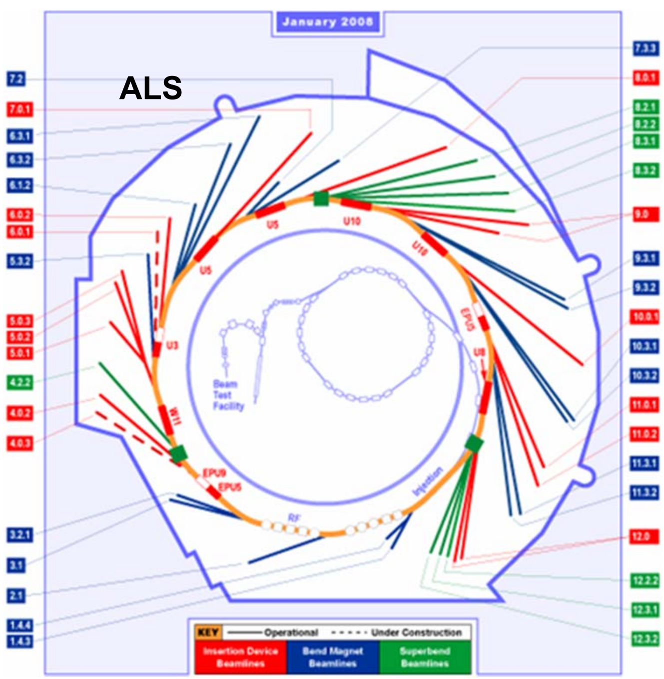
A lot of material for a talk!

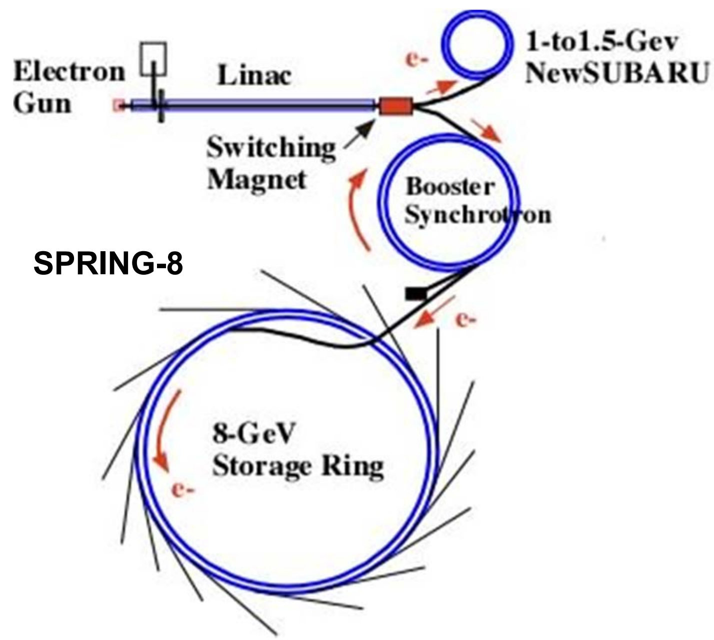
It forces to concentrate mostly in the explanation of main concepts and issues.

References will be given for those interested in a deeper insight.

The Role of the Electron Injector in Light Sources

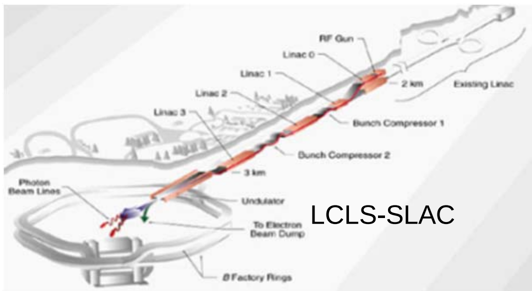
In 1st, 2nd and 3rd generation light sources, electron sources are part of the injector chain that typically includes a small linac and a "booster" ring.
The beam generated by the electron gun goes through the linac and is then accelerated and stored in the booster for a time long enough that the 6D beam phase-space distribution is fully defined by the characteristics of the booster and not of the electron source.

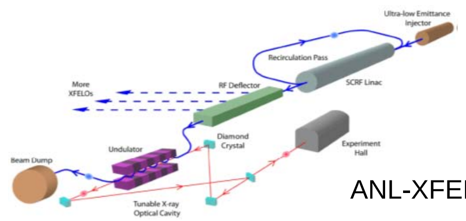




The Role of the Electron Injector in Light Sources

In linac based 4th generation light sources, such as free electron lasers (FELs) and energy recovery linacs (ERLs), the situation can be quite different. Indeed, in such a case, the final beam quality is set by the linac and ultimately by its injector and electron source.





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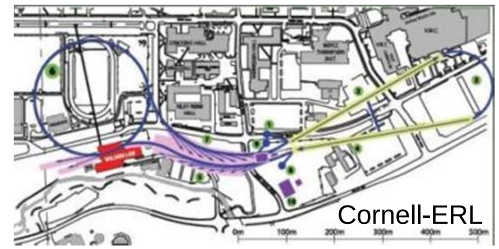
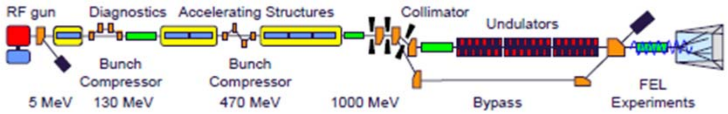
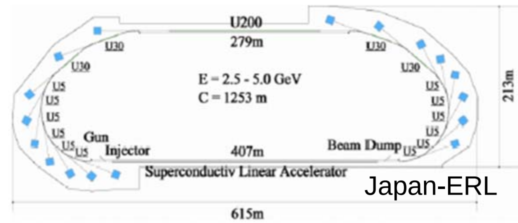


FLASH-DESY





In such facilities, the requirements for a large number of quasi-"monochromatic" electrons, concentrated in very short bunches, with small transverse size and divergence, translate into high particle density 6D phase-space, or in other words, in high brightness B:

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

with N_e the number of electrons per bunch and $\varepsilon_{nx,\ ny,\ nz}$ the normalized emittances for the planes x, y, and z

The brightness generated at the electron source represents the ultimate value for such a quantity, and cannot be improved but only spoiled along the downstream accelerator

X-Ray 4th Generation Light Sources, the Most Challenging Electron Injector Case

- 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 ($\gamma = E/mc^2$).

(with β the electron velocity in speed of light units, and assuming that an undulator with the proper period λ_u and undulator parameter K exist: $\lambda = \lambda_u / 2\gamma^2(1 + K^2/2)$)

- We will see later, that for the present electron gun technologies: $\varepsilon_n <\sim 1\ \mu\mathrm{m}$ for the typical $<\sim 1\ \mathrm{nC}$ charge/bunch.

For X-Ray machines ($\lambda <\sim 1\ \mathrm{nm}$) that implies GeV-class electron beam energy, presently obtainable by long and expensive linacs.

- Similar transverse emittance requirements apply also to ERLs.

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

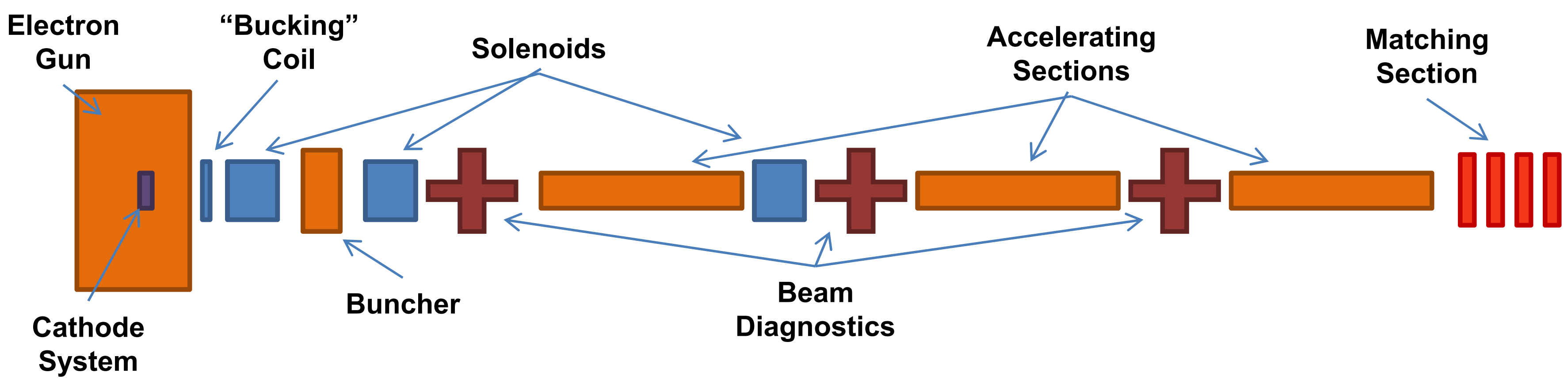
$$\frac{\sigma_E}{E} <\sim \rho_{Pierce} <\sim 10^{-3}$$

- Achieving the necessary FEL gain requires high peak current ($\sim 1\ \mathrm{kA}$), and hence high charge/bunch and short bunches.

- In both ERLs and FELs, high-time resolution user-experiments require extremely short X-Ray pulses (down to sub-fs) imposing the need for small and linear longitudinal emittances to allow for the proper compression along the linac.

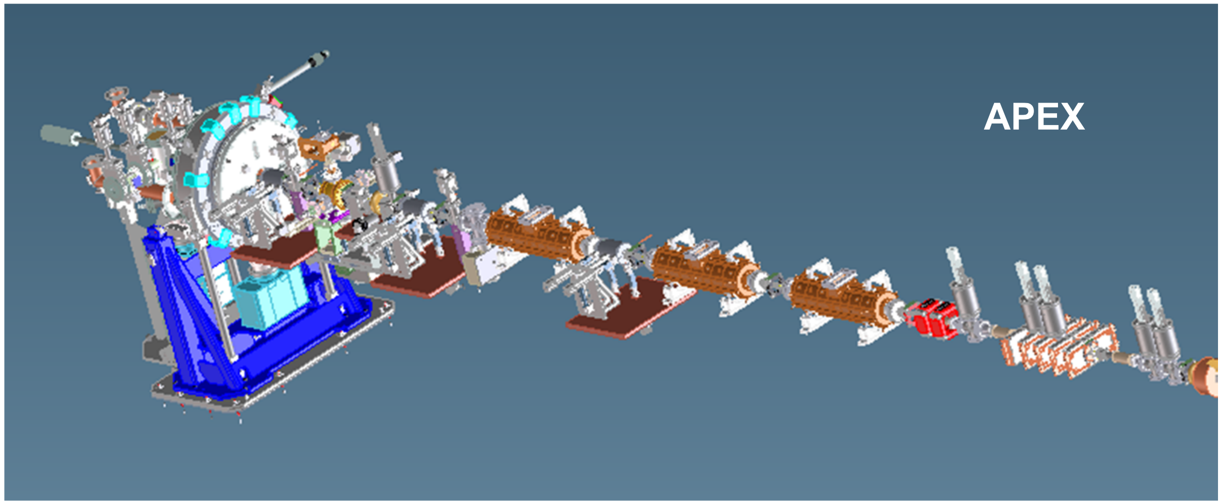
In summary, 4th generation X-Ray facilities challenge the performance of electron injectors. This talk from now on will focus on such a type of injectors

The Typical High-Brightness Injector Layout



Injector Sub-Systems:

- Cathode system
- Electron gun
- Focusing system
- Compression system
- Accelerating system
- Diagnostics system



More details later!

Requirements for the electron injector

Injector Requirement Summary Table

Repetition rate	from ~ 10 Hz to ~ 1 MHz (FELs) up to ~ 1GHz and beyond (ERLs)
Charge per bunch (depending on the operation mode)	from ∼ 1 pC to ∼ 1 nC
Normalized transverse emittance (slice)	sub 10^{-7} m to 10^{-6} m (from low to high charge/bunch)
Normalized longitudinal emittance	~ several μm at low charge outside the MBI regime
Beam energy at the gun exit (to control space charge effects)	$\gtrsim$ 500 keV
Beam energy at the injector exit	$\gtrsim$ 100 MeV
Accelerating electric field at the cathode (to overcome the space charge limit)	$\gtrsim$ 10-15 MV/m
Dark current	minimization is critical for high duty cycle injectors
Bunch length at the cathode (to control space charge effects and for different modes of operation)	from ∼ 100 fs to tens of ps
Peak current at the injector exit	tens of A in FEL's injectors
Compatibility with magnetic fields in the cathode and gun regions (for emittance compensation and/or exchange techniques)	
Operational vacuum pressure at the electron gun (compatible with damage-sensitive cathodes)	10^{-7} - 10^{-9} Pa ($\sim 10^{-9}$ - $\sim 10^{-11}$ Torr)
'Easy and fast' replacement of cathodes at the electron gun	
High reliability required to operate in an user facility	

up to several 100s mA average current (ERLs)

Brightness

Brightness: density of particles in the phase space.
I.e. number of particles per unit of phase space volume.

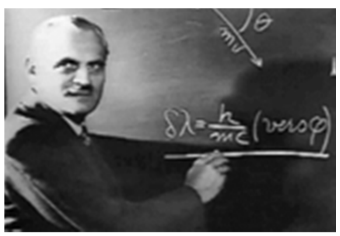
$$B = \frac{N}{\varepsilon_{nx}\varepsilon_{ny}\varepsilon_{nz}}$$

Heisenberg uncertainty principle: *"it is impossible to determine with precision and simultaneously, the position and the momentum of a particle"*. Applied to emittances:

$$\varepsilon_{nw} \geq \lambda_c / 4\pi \qquad w = x, y, z$$

$$\lambda_c \equiv Compton\ wavelength = h/m_0 c = 2.426\ pm\ \ for\ electrons$$

This can be interpreted as the fact that the phase space volume occupied by a particle is given by: $(\lambda_c/4\pi)^3$ = elementary phase space volume



Degeneracy Factor, δ: if the phase space is expressed in elementary phase space volume units, the brightness becomes a dimensionless quantity δ representing the **number of particles per elementary volume.**

$$\delta = B\left(\frac{\lambda_C}{4\pi}\right)^3$$

Because of the Pauli exclusion principle the **limit value of δ** is: infinity for bosons and **1 for non polarized fermions** (electrons). Quantum limited brightness for fermions.

High Brightness Electron Injectors?

Most of the edge electron beam applications (accelerators, free electron lasers, microscopes, ...) are limited by the performance of the electron source in:

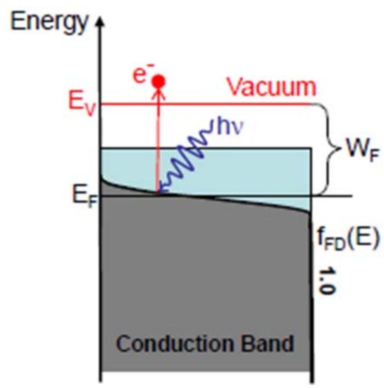
- Lowest emittance
- Smallest energy spread
- Highest brightness

Highest Degeneracy Factor δ

- Conv. thermionic: $\delta \sim 10^{-14}$
- SEM: $\delta < 10^{-14}$
- Photo-RF guns: $\delta \sim 10^{-11}$
- Field emission: $\delta \sim 10^{-5}$

The degeneracy factor inside a metal cathode is ~ 1.

!!!



How do we lose all of that?

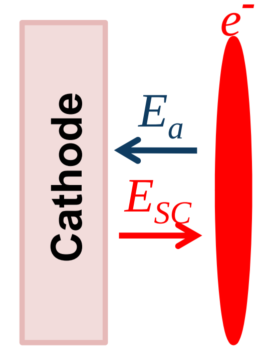
Extraction Mechanism

Coulomb interaction

ERLs and FELs require high charge/bunch sources for high photon flux. For those charges a $\delta \sim 10^{-11}$ is the best that can be presently obtained.

Beam Dynamics

Space Charge Limit



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

The **emission can continue until** E_{SC} **cancels** E_a.

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

• Assuming a '**pancake' beam** longitudinally thin and transversely wide (Gaussian) we can estimate the field due to space charge by:

$$E_{SC} \approx \frac{\sigma_{SC}}{2\varepsilon_0} \approx \frac{Q}{4\pi\varepsilon_0\sigma_r^2} \quad \Rightarrow \quad \boxed{\sigma_{SC}^{MAX} = \left(\frac{Q}{2\pi\sigma_r^2}\right)_{MAX} \approx 2\varepsilon_0 E_a} \quad \Rightarrow \quad \sigma_r^{\min} \approx \sqrt{\frac{Q}{4\pi\,\varepsilon_0 E_a}}$$

Q is the charge per bunch, σ_r the rms transverse beam size and ε_0 the vacuum permittivity.

• We will see later that the emittance at the cathode is proportional to σ_r and to a quantity $f(T_i)$ that depends on the cathode used and on the emission mechanism.

$$\varepsilon_n = \sigma_r\, f(T_i) \quad \Rightarrow \quad \varepsilon_n^{\min} = \sigma_r^{\min} f(T_i) \approx f(T_i)\sqrt{\frac{Q}{2\pi\,\varepsilon_0\,E_a}}$$

$$B_{4D}^{\max} \propto \frac{Q/e}{\left(\varepsilon_n^{\min}\right)^2} \approx \frac{2\pi\,\varepsilon_0\,E_a}{e\,f^2(T_i)}$$

Space charge limits the min emittance and the max brightness obtainable at the cathode for a given E_a. The brightness is also independent from charge.

Bazarov, PRL 102, 104801 (2009)

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 low 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.

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:

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

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:

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

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

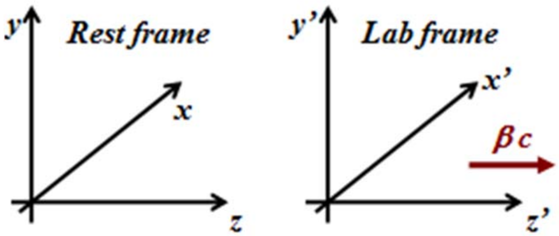
$$\boxed{F_y = q\left(E_y + \beta c B_x\right) = qE_y\left(1-\beta^2\right) \propto \lambda_C\left(1-\beta^2\right)y}$$

• 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**. This **implies that they can be compensated** by linear focusing elements (solenoids, quadrupoles)

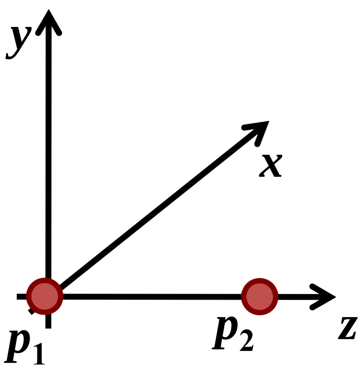
For more information, see for example: Wiedemann, Particle Accelerator Physics, Springer, 3rd edit., chapter 18.2.

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.**

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 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 $I_0 \sim 17\ \mathrm{kA}$ 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 replacing I with the beam peak current I_p**.

- **The envelope equation shows how in the linear space charge case a proper focusing can be used to control space charge forces**

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

For more info, see for example: Rieser, Theory and Design of Charged Particle Beams, Wiley, chapters 4 and 5.
J. D. Lawson, The Physics of Charged Particle Beams, 2nd ed., Oxford University Press, New York, 1988.

Is the Space Charge Linear Regime Realistic?

• **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 and a parabolic linear longitudinal charge density.**

• The best approximation of the above distributions, projected in the 3D spatial reference frame, is represented by 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, and no r.m.s. emittance increase.

• Uniform ellipsoidal charge densities are **experimentally** pursued by **shaping the laser in photocathode system**, or by the so-called **beam-blowout** regime.

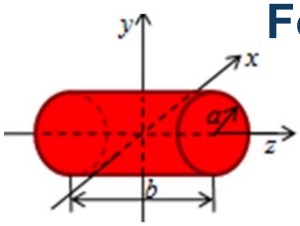
• In such a mode, that can be used with photo-cathode systems, a very short laser pulse (~100 fs) is sent on the cathode. The resulting ‘pancake’ of photo-emitted electrons is accelerated in the gun and simultaneously under the action of its own space-charge field evolves in a 3D uniform ellipsoidal charge distribution.

At the present time, this mode of operation has been experimentally demonstrated for charges per bunch smaller than ~few tens of pC

For more info, see for example: Rieser, Theory and Design of Charged Particle Beams, Wiley, chapters 4 and 5.

Beam-blowup, see: P. Musumeci, *et al*., Phys. Rev. Letters 100, 244801 (2008), and references in there.

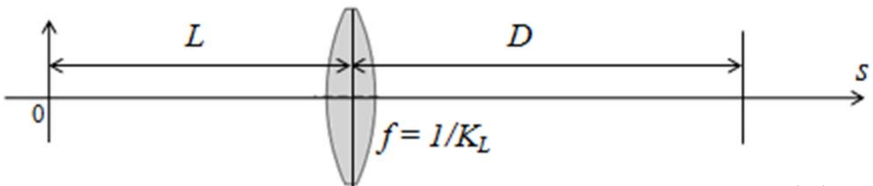
Emittance Compensation



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

Teng showed that:
$$for\ |z| << b \Rightarrow F_r(z) = \frac{e\lambda_C(z)}{2\varepsilon_0}\frac{(1-\beta^2)}{a^2}r$$

with $I = \lambda_C v_z = \lambda_C \beta c$ ➡
$$F_r(z) = \frac{e}{2c\varepsilon_0}\frac{1}{\beta\gamma^2}\frac{I(z)}{a^2}r = \frac{e}{2c\varepsilon_0}\frac{1}{\beta\gamma^2}J(z)\,r = K_{SC}(z)r$$

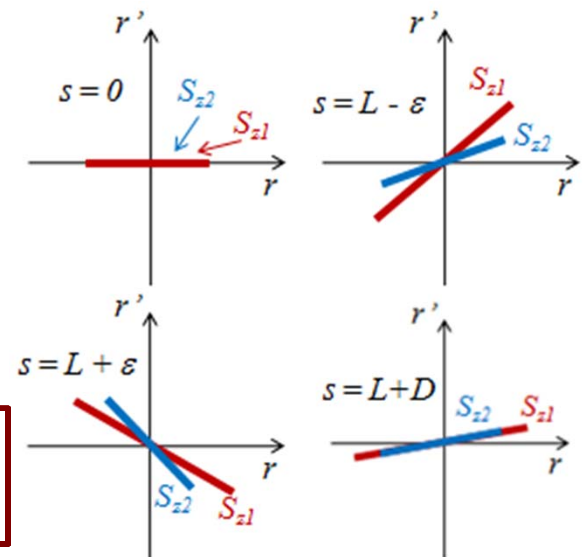


The transverse motion equations for the 'slice' at position z through the system are (assuming zero transv. emittance $r'(z,0) = 0$):

$$r(z, s = L + D) = (1 - K_L D)r(z,0) + \frac{1}{2\beta^2}\frac{F_r(z)}{mc^2}\left[(L+D)^2 - K_L D L^2\right]$$

$$r'(z, L + D) = -K_L r(z,0) + \frac{1}{2\beta^2}\frac{F_r(z)}{mc^2}\left[2(L+D) - K_L L^2\right]$$

If $K_L = \frac{2(L+D)}{D^2}$ ➡ $\boxed{\tan(\alpha_{rr'}) = \frac{r'(z,L+D)}{r(z,L+D)} = \frac{2(L+D)}{D(2L+D)}}$



The slope in the phase space is the same for all slices. Minimum of projected emittance

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

Emittance Compensation References

B. E. Carlsten, Nucl. Instr. and Meth. Phys. Res., Sect. A 285, 313 (1989).

L. Serafini, and J. B. Rosenzweig, Physical Review E 55, 7565 (1997).

The Final Injector Emittance

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

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

• The first term is often referred as the **cathode thermal or intrinsic emittance.**

Such emittance term is proportional to the beam size at cathode and to a momentum term defined by the emission process used

$$\varepsilon_{nw\ Cathode} = \sigma_w \frac{\sqrt{\langle p_w^2 \rangle}}{mc} \qquad w = x, y$$

The game in present injectors is to make all the emittance terms negligible respect to the cathode term.

• The 2nd term is due to the presence of solenoidal B_z field at the cathode (Palmer, *et al.*, PAC97, p. 2843)

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

• We already learned how to minimize the space charge term by removing the linear space charge contribution by the emittance compensation. The residual part is due to non linear space charge forces.

• The Beam Optics term is due to nonlinear components in the focusing and deflecting components along the injector. A proper design of such components can make this term negligible

• The last term is due to the RF fields along the injector

Transverse Emittance Dilution Due to 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 in the transverse normalized emittance**. For a Gaussian beam:

$$\varepsilon_{nr\,RF} = \frac{e}{2\sqrt{2}mc^4} E_0 \omega_{RF}^2 \sigma_r^2 \sigma_z^2$$

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)

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 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 σ_{pz}/mc ~ 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.**

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

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

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

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!**

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

Low & High Gun Gradient Regimes

• To preserve brightness, it is desirable to accelerate the beam as quickly as possible, thus 'freezing-in' the space charge forces, before they can significantly dilute the phase space.

• In the case of high repetition rate injectors, as it will be discussed later, technology limitations and/or or dark current mitigation, significantly reduces the peak accelerating gradients at the cathode with respect to those in pulsed low repetition rate systems.

• This situation can have a significant impact on beam dynamics.

• Space charge can be controlled by reducing the beam charge density, especially in the cathode region where the beam energy is small.

The use of larger transverse beam sizes at the cathode to reduce the density is carefully minimized because it increases the cathode thermal emittance.

• Instead, the bunch length is used, and longer bunches are required for lower gradients.

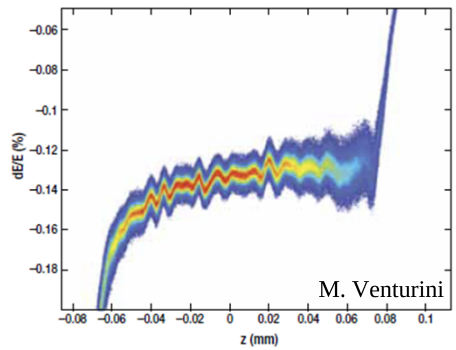
That increases the longitudinal emittance, but for most cases this is tolerable.

• As a consequence, in high repetition rate injectors, the bunch length at the cathode can be significantly longer than required at the FEL undulator entrance. This in turn necessitates relatively larger compression factors both at the injector and in the main linac.

Bunch Length Compression

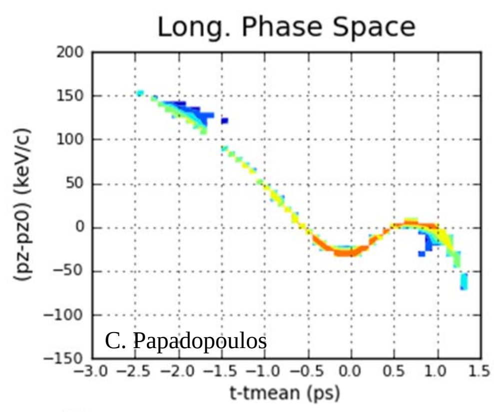
• In all FEL or ERL schemes the bunch length at the gun is longer than that required at the undulator position.

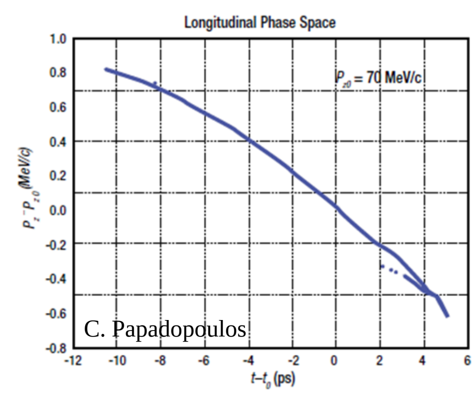
Longitudinal compression is then necessary and can be performed in the linac and /or in the injector and/or in the arcs in the case of ERLs.



• **Magnetic compressors** such as chicanes or arcs can be subjected to **microbunching instability** and to **emittance growth due to coherent synchrotron radiation** in the case of high compression factors.

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



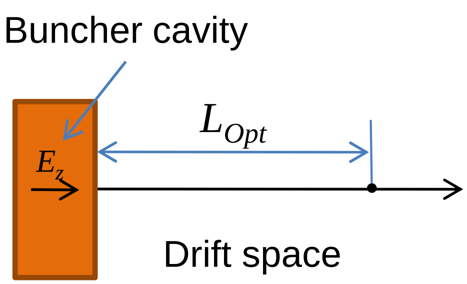


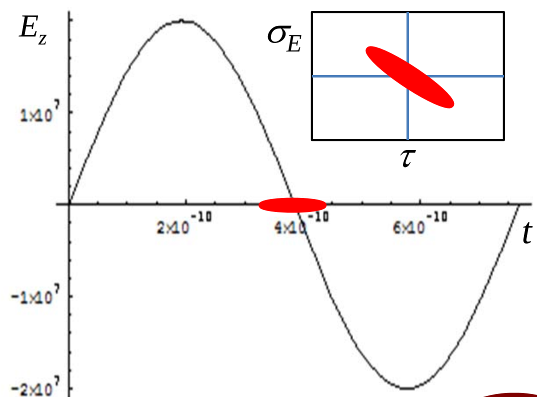
• The proper balance between these compression strategies must be found.

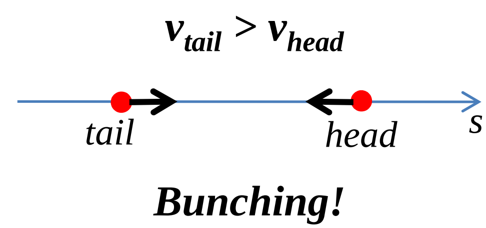
• Methods for compressing the beam in the injector include a dedicated **buncher** section and/or the use of a technique referred as **velocity bunching**.

"Zero-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 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:**

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

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**

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

- **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.

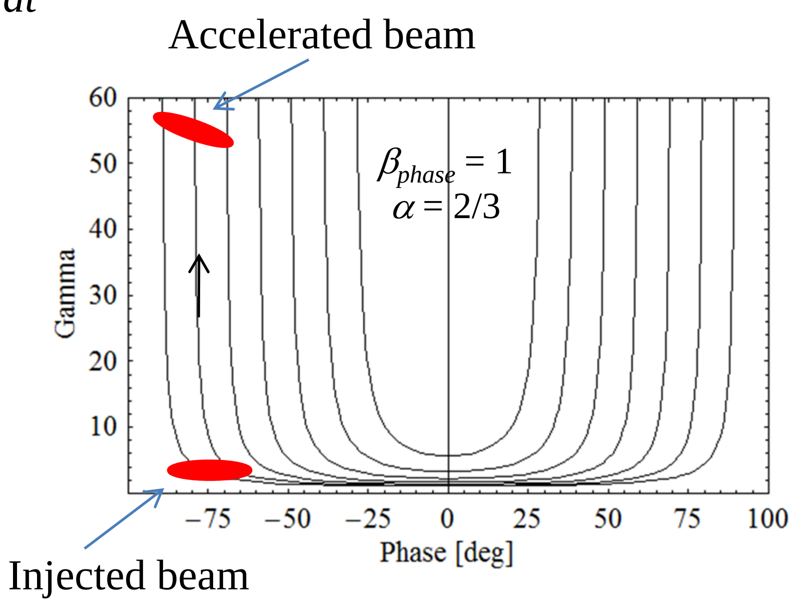
Compressing more relativistic beams in the injector is still possible:

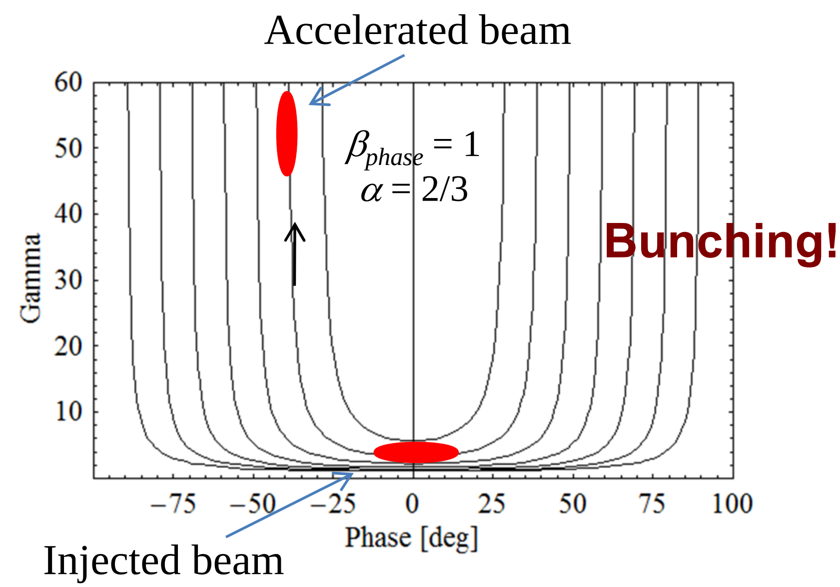
$$E_z = \hat{E}_z \sin(\omega t - kz - \psi_0) \quad with \quad \frac{\omega}{k} = c\beta_{phase}$$

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

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

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.**

- B. Aune and R. H. Miller, Report No. SLAC-PUB 2393, 1979.
- L. Serafini and M. Ferrario, AIP Conf. Proc. 581, 87 (2001).

Emittance Manipulation

- It should be clear now that **emittance** (in all its dimensions) is one of the **fundamental parameters** in present 4th generation light sources and that the major part of **the game for this parameter is played in the injector**.

- Schemes have been conceived and tested to generate **flat beams** in injectors, to match the requirements of linear colliders and diffraction limited x-ray sources based on spontaneous undulator radiation,

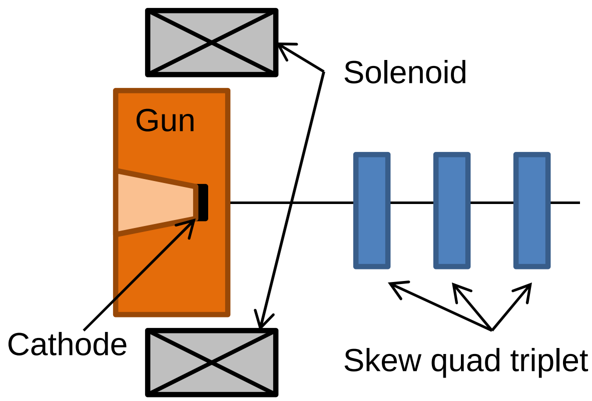
- or, to be used in combination with techniques that **exchange emittances** from one plane to another (typically from the longitudinal to the transverse) to best match the application requirements.

- The above are just particular applications of the more general concept of manipulating **eigen-emittances**, that are motion invariant quantities in the 6D phase space for linear Hamiltonian systems.

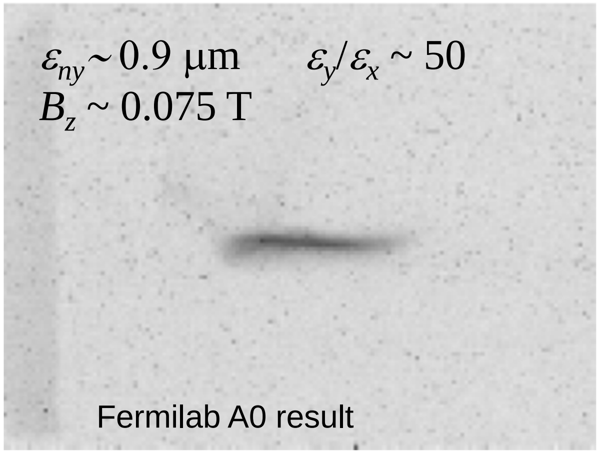
- Recently, compressor and "echo"-like schemes based on multiple emittance-exchange/flat-beam steps have been proposed.

Flat Beams

Flat beams from round beams at the cathode can be obtained by the following scheme:



• The presence of a solenoidal field at the cathode couples the transverse planes, and the skew triplet 'exploits' this correlation to generate the flat beam. It must be remarked that in the process the horizontal and vertical emittances are respectively increased and decreased with respect to their values at the cathode.



It can be seen that the emittance ratio is given by:

$$\frac{\varepsilon_x}{\varepsilon_y} = \frac{\varepsilon_{nx}}{\varepsilon_{ny}} = 1 + \frac{2\sigma_{r\,Gun}^2}{\beta_F^2 \sigma_{r'\,Gun}^2}$$

with the optical function:

$$\beta_F = \frac{2 p_Q}{e B_z} \quad with \quad p_Q \equiv \begin{matrix} momentum \\ at\ quad\ entrance \end{matrix}$$

If everything is linear:

$$\varepsilon_{nr} = \sqrt{\varepsilon_{nx}\varepsilon_{ny}}$$

Ya. Derbenev, "Adapting Optics for High Energy Electron Collider", UM-HE-98-04, Univ. Of Michigan, 1998.
R. Brinkmann, et al., "A Flat Beam Electron Source for Linear Colliders", TESLA-99-09.
D. Edwards et al., "The flat beam experiment at the FNAL photoinjector", Linac 2000, Monterey.
Ph. Piot, Y.-E Sun, and K.-J. Kim, Phys. Rev. ST Accel. Beams 9, 031001 (2006).

Eigen-Emittances

• Calculating the beam evolution through a generic beamline, where only linear fields are present, is in general a 6D problem.

• For a large number of cases, the motion in the different planes can be considered decoupled and one can deal with a 2D problem.

• In this 2D case the rms emittance is an invariant in each of the planes.

$$\varepsilon_{wrms} = \sqrt{\langle w^2\rangle\langle w'^2\rangle - \langle ww'\rangle^2} \qquad w = x, y, z$$

• In the general 6D case (including coupling between all planes) the concept of rms emittance can be generalized to produce three invariants (eigen-emittances). Such eigen-emittances are made out of second order moments of the beam distributions, and form a complete set.
In the uncoupled case, the eigen-emittances reduce to the 2D rms emittances.

• Schemes proposing to generate the proper correlations already at the cathode/injector and to manipulate the emittances between the planes to obtain at the linac exit the desired emittances have been proposed.

• The cases of flat beam and emittance exchange techniques presented before can be derived as particular applications of the 6D eigen-emittance theory.

G. Rangarajan, F. Neri, and A. Dragt, “Generalized emittance invariants” PAC1989.

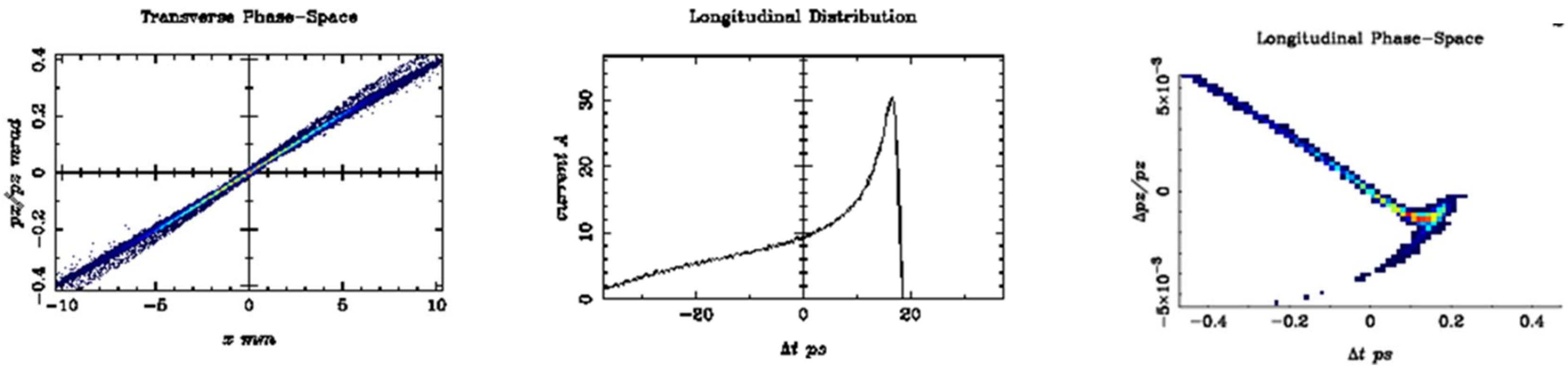
F. Neri, and G. Rangarajan, Phys. Rev. Letters 64, 1073, 1990.

Yampolsky, Carlsten, Ryne, Bishofberger, Russell, Dragt, arXiv:1010.1558 [physics.acc-ph] 7 Oct 2010

Real Non-Linear Injectors

• So far we have prevalently dealt with linear beam dynamics cases. But real injector components and space charge fields are generally nonlinear.

• Nonlinearities generates phase space filamentation, halos and non-Gaussian longitudinal tails in the beam.



• Filamentation generates rms emittance increase and can make compression difficult.

• Particles in the halo and tail of the beam can go out of the accelerator acceptance and can be lost generating radiation or causing undesired effects such as quenching in superconducting RF structures.
(particularly important in high duty cycle accelerator)

• In other words nonlinearities effects need to controlled and minimized.

Simulation Tools

At this point, we had the chance to realize how complex is beam dynamics in the presence of space charge, even in the linear regime.
As we just mentioned, if more realistic nonlinear problems are considered, the complexity increases even further and accurate evaluation can be pursued only by simulation tools.

Indeed, a number of simulation codes with space charge have been developed over the years to address the problem, and are heavily used in the design and optimization of high-brightness electron injectors.

An incomplete list of 'popular' codes include (alphabetical order):

- **ASTRA: free downloadable at http://www.desy.de/~mpyflo/**
- **GPT: commercial (http://www.pulsar.nl/gpt/)**
- **IMPACT-T: free, contact Ji Qiang (jqiang@lbl.gov),**
- **PARMELA: free, export limitations apply. http://laacg1.lanl.gov/laacg/services/**
- **…**

Multi-Objective Optimization

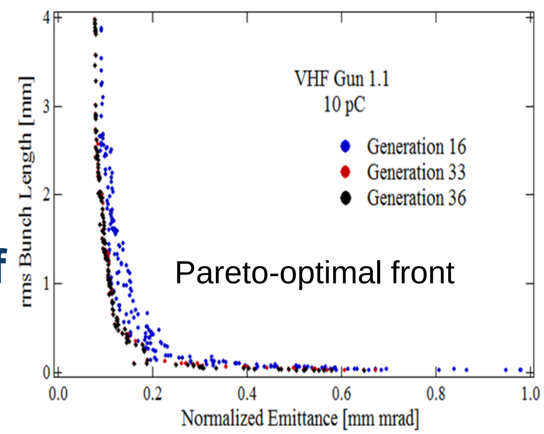
• The **design and optimization of an electron injector** requires the tuning of a **large number of knobs** targeting simultaneously **multiple objectives**. In other words is a **multi-objective optimization problem**.

• For example, for a given charge/bunch, transverse emittance and bunch length at the injector exit need to be minimized by tuning laser spot size and pulse length at the cathode, phase and electric field intensity for the buncher, field intensity of the emittance compensation solenoid, position, phase and field of the first accelerating section, …

• **Systematic scanning** of the multi-dimensional parameter space is **unrealistic** with existing computer power and more efficient method should be used.

• A notable example, is represented by **multi-objective genetic algorithms** (MOGA) that mimics the natural selection process.

• A population of possible solutions, is ranked towards the objective functions and a new generation of solutions is produced by 'mating' the highest ranking solutions. Random solution mutation is also applied. After a number of generations, the population of solutions converges to the so-called **Pareto optimal** front that represents the set of possible solutions trading-off between objectives. MOGA finds all the **globally optimal solutions** and allows for a ***a posteriori*** tradeoff selection.



Bazarov, I .V., and Sinclair, C .K., Phys. Rev. ST Accel. and Beams 8 034202 (2005).

Electron Injectors Sub-Systems

Cathodes

• Cathodes are obviously a fundamental part of electron sources. The gun performance heavily depends on cathodes

• The ideal cathode should allow for high brightness (have a low thermal/intrinsic normalized emittance, low energy spread, high current density) full control of the bunch distribution, and long lifetimes.

• In the lower charge regime the ultimate emittance performance of a linac is set by the cathode thermal emittance

• Photo-cathodes the most used in present injector schemes.

• Thermionic cathodes can in some cases, offer low thermal emittances but require complex compression schemes.
(CeB_6 at SCSS-Spring 8, XFELO-ANL)

• In high-repetition rates photo-sources high quantum efficiency photo-cathodes (QE>~ 1 %) are required to operate with present laser technology.

• Other cathodes under study (photo-assisted field emission, needle arrays, photo-thermionic, "photo-dispenser" diamond amplifiers, engineered cathodes, plasmonic, …)

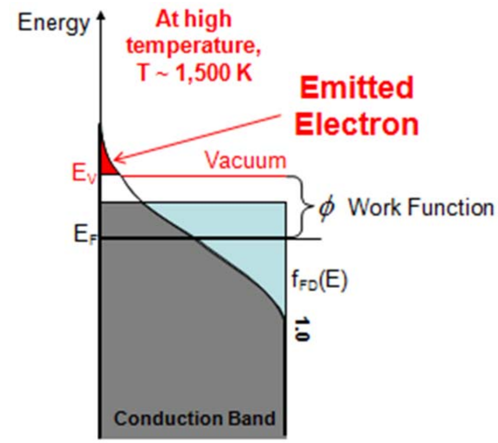
Cathode Parameters: Thermal/Intrinsic Emittance (Metals)

- **With the progress in electron guns, in many case is now the cathode thermal or intrinsic emittance, i.e. the cathode normalized emittance, to define the ultimate brightness performance of an injector.**

$$\varepsilon_n^i = \sigma_r \frac{\sigma_{p_r}}{mc}$$

$$\frac{\varepsilon_n^i}{\sigma_r} = \sqrt{\frac{k_B T}{mc^2}}$$

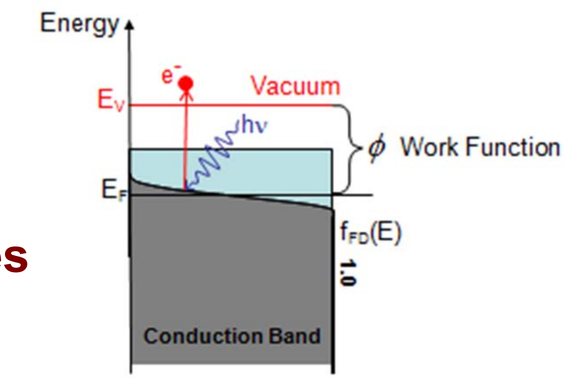
Thermionic cathodes



$$\frac{\varepsilon_n^i}{\sigma_r} = \sqrt{\frac{\hbar\omega - (\phi - \phi_{Schottky})}{3mc^2}}$$

$$\phi_{Schottky\ [eV]} = 3.7947 \times 10^{-5} \sqrt{E_{z\,[V/m]}^{Gun}}$$

Photo-cathodes



- **For uniform emission:** $\sigma_r = r/2$

- Dowell talk, EuroFEL Workshop Photocathodes for RF guns, Lecce, March 2011 (http://photocathodes2011.eurofel.eu/)
- D.Dowell, et al., NIMA 622, 685 (2010)

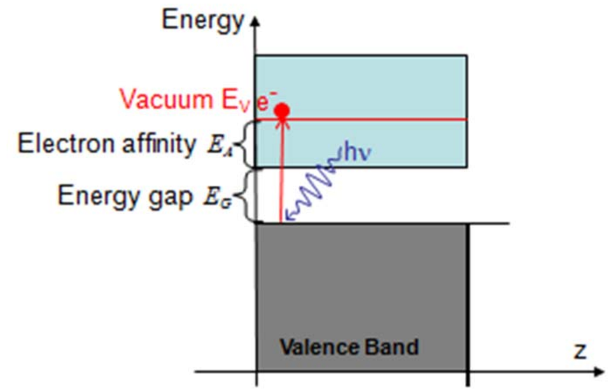
Cathode Parameters
Thermal/Intrinsic Emittance (Semiconductors)

- **Two cases can be distinguished:**

$$\frac{\varepsilon_n^i}{\sigma_r} = \sqrt{\frac{\hbar\omega - (E_G + E_A - \phi_{Schottky})}{3mc^2}}$$

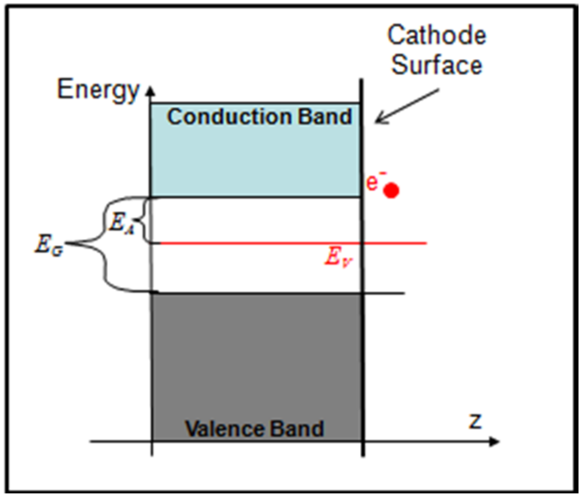
$$\phi_{Schottky\ [eV]} = 3.7947 \times 10^{-5} \sqrt{E_{z\,[V/m]}^{Gun}}$$

Positive electron affinity cathodes



$$\frac{\varepsilon_n^i}{\sigma_r} = \sqrt{\frac{k_B T}{mc^2}}$$

Negative electron affinity cathodes with electron-phonon scattering.
(Cesiated GaAs, Hydrogenated diamond)



Full thermalization happens only if the energy of the photon is close to the gap energy E_G.
In this regime the response time can be considerably longer.

- Dowell talk, EuroFEL Workshop Photocathodes for RF guns, Lecce, March 2011 (http://photocathodes2011.eurofel.eu/)
- D.Dowell, et al., NIMA 622, 685 (2010)
- Bazarov, et al., Journal of Applied Physics 103, 054901 (2008).

More Cathode Parameters

- Maximum **charge density** that can be extracted from a cathode is important when high charge/bunch are required with relatively small emittance:

$$J_{peak} = \frac{Q}{\pi r^2 \sigma_\tau} \sim 5\times 10^4 \; A/cm^2$$

Typical photocathodes
(pulsed emission)

$$\langle J \rangle \sim 50 \; A/cm^2$$

Thermionic: CeB_6, LaB_6
(continuous emission)

- **Lifetime**.
  - Chemical reactivity,
  - Robustness to ion/electron back-bombardment.

Sets operation vacuum pressure (from ~ 10^{-8} to ~ 10^{-12} Torr).

- Surface roughness, crystal domains, homogeneity, reflectivity, field enhancement, …

Complex physics, greatly not understood yet!

More Photo-Cathode Parameters

• The **Quantum Efficiency QE** is defined as the number of photo-emitted electrons per photon impinging on the cathode.

• The minimum **photon energy or wavelength** λ required for generating photo-emission from the cathode.

• The above parameters jointly with the required electron beam distribution define the characteristics of the laser system to be used for the photo-emission.

“Popular” Photo-Cathodes

METALS

Metal Cathodes	*Wavelength & Energy: λ_{opt} (nm), $\hbar\omega$(eV)*	*Quantum Efficiency (electrons per photon)*	*Vacuum for 1000 Hr Operation (Torr)*	*Work Function, ϕ_W(eV)*	*Thermal Emittance (microns/mm(rms))* Theory	Expt.
Bare Metal						
Cu	250, 4.96	1.4×10^{-4}	10^{-9}	4.6 [34]	0.5	1.0±0.1 [39] 1.2±0.2 [40] 0.9±0.05 [3]
Mg	266, 4.66	6.4×10^{-4}	10^{-10}	3.6 [41]	0.8	0.4±0.1 [41]
Pb	250, 4.96	6.9×10^{-4}	10^{-9}	4.0 [34]	0.8	?
Nb	250, 4.96	~2 10^{-5}	10^{-10}	4.38 [34]	0.6	?
Coated Metal						
CsBr:Cu	250, 4.96	7×10^{-3}	10^{-9}	~2.5	?	?
CsBr:Nb	250, 4.96	7×10^{-3}	10^{-9}	~2.5	?	?

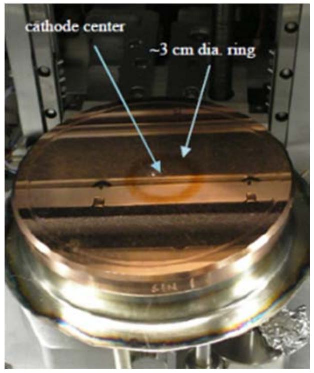
SEMICONDUCTORS

Cathode Type	*Cathode*	*Typical Wavelength, λ_{opt}(nm), (eV)*	*Quantum Efficiency (electrons per photon)*	*Vacuum for 1000 Hrs (Torr)*	*Gap Energy + Electron Affinity, E_A+E_G (eV)*	*Thermal Emittance (microns/mm(rms))* Theory	Expt.
PEA: Mono-alkali	Cs_2Te	211, 5.88	~0.1	10^{-9}	3.5 [42]	1.2	0.5±0.1 [35]
		264, 4.70	-	-	“	0.9	0.7±0.1 [35]
		262, 4.73	-	-	”	0.9	1.2 ±0.1 [43]
	Cs_3Sb	432, 2.87	0.15	?	1.6 + 0.45 [42]	0.7	?
	K_3Sb	400, 3.10	0.07	?	1.1 + 1.6 [42]	0.5	?
	Na_3Sb	330, 3.76	0.02	?	1.1 + 2.44 [42]	0.4	?
	Li_3Sb	295, 4.20	0.0001	?	?	?	?
PEA: Multi-alkali	Na_2KSb	330, 3.76	0.1	10^{-10}	1+1 [42]	1.1	?
	$(Cs)Na_2KSb$	390, 3.18	0.2	10^{-10}	1+0.55 [42]	1.5	?
	K_2CsSb	543, 2.28	0.1	10^{-10}	1+1.1 [42]	0.4	?
	$K_2CsSb(O)$	543, 2.28	0.1	10^{-10}	1+<1.1 [42]	~0.4	?
NEA	GaAs(Cs,F)	532, 2.33	~0.1	?	1.4±0.1 [42]	0.8	0.44±0.01 [44]
		860, 1.44	-	?	”	0.2	0.22±0.01 [44]
	GaN(Cs)	260, 4.77	-	?	1.96 + ? [44]	1.35	1.35±0.1 [45]
	GaAs(1-x)Px x~0.45 (Cs,F)	532, 2.33	-	?	1.96+? [44]	0.49	0.44±0.1 [44]
S-1	Ag-O-Cs	900, 1.38	0.01	?	0.7 [42]	0.7	?

In general, metal cathodes are more robust but present much lower QEs with respect to semiconductor cathodes

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

Examples of Photo-Cathodes & Lasers



Metal: Cu, … (used at LCLS for example)

- <~sub-picosecond pulse capability
- minimally reactive; requires ~ 10^{-8} Torr pressure
- low QE ~ 10^{-5}
- requires UV light (3rd or 4th harm. conversion from IR)
- for nC, 120 Hz reprate, ~ 2 W of IR required

PEA Semiconductor: Cesium Telluride Cs_2Te (used at FLASH for example)

- <~ps pulse capability
- relatively robust and un-reactive (operates at ~ 10^{-9} Torr)
- successfully tested in NC RF and SRF guns
- high QE > 5%
- photo-emits in the UV ~250 nm (3rd or 4th harm. conversion from IR)
- for 1 MHz reprate, 1 nC, ~ 10 W 1060nm required

NEA Semiconductor: Gallium Arsenide Cs:GaAs (used at Jlab for example)

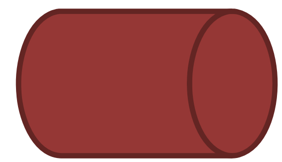
- tens of ps pulse capability with phonon damping
- reactive; requires UHV <~ 10^{-10} Torr pressure
- high QE (typ. 10%)
- Photo-emits already in the NIR,
- low temperature source due to phonon scattering
- for nC, 1 MHz, ~50 mW of IR required
- operated only in DC guns at the moment
- Allow for polarized electrons

Laser Pulse Shaping

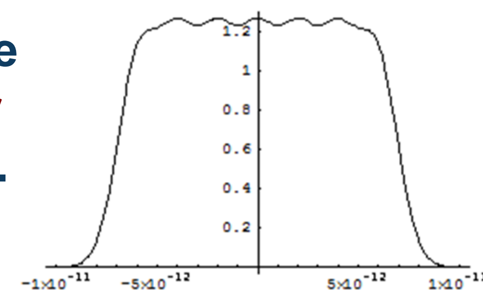
• In the beam dynamics section, we discussed the importance of the **beam distribution in controlling space charge effects.**

• The **3D ellipsoidal distribution with uniform charge density** represents the ideal case where space **charge forces are fully linear** and do not increase the rms normalized emittance.

• Generate such distribution is quite challenging, and in most cases, the so-called "**beer-can" with uniform charge density** represents a reasonable compromise.



• To generate a **longitudinal rectangular-like** distribution one can start with a **Gaussian short pulse, split it several lower intensity pulses and recombine them with the proper delay.**



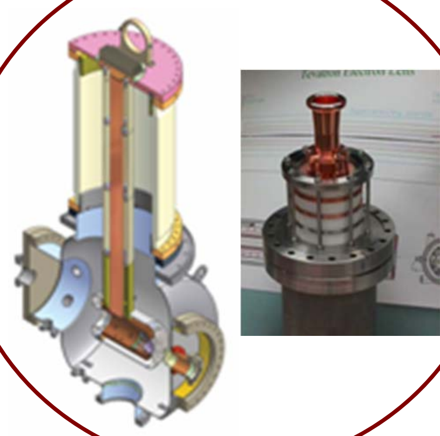
6 Gaussian pulses with σ_τ = 1 ps added with 2 σ_τ peak to peak distance

• The splitting/recombining can be done using conventional beam splitters and delay lines, or using a series of birefringent crystals of proper length.

• **Top-hat uniform transverse distributions** can be obtained by **expanding a transversely Gaussian beam and collimating** it through a sufficiently small **circular aperture** (simple but inefficient).

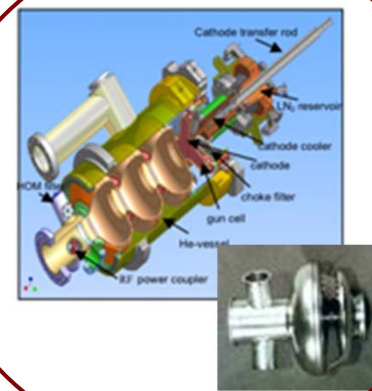
• **Nonlinear commercial focusing lens systems** can also be used but require excellent alignment and size matched Gaussian beams.

Principal Gun Technologies

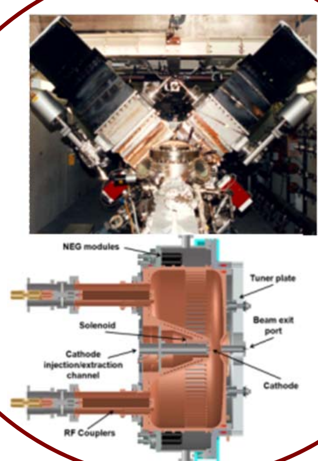


DC guns

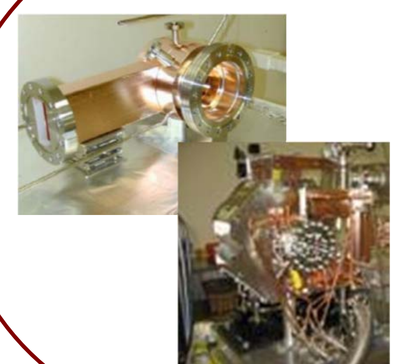
and hybrids



SC RF guns



Low freq. (<~ 700 MHz) NC RF guns

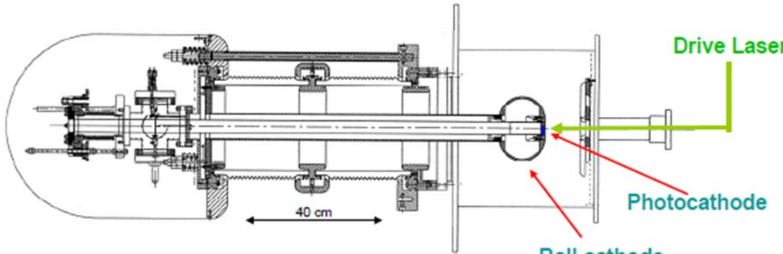


High freq.(> ~1 GHz) NC RF guns

DC Guns

Pros:

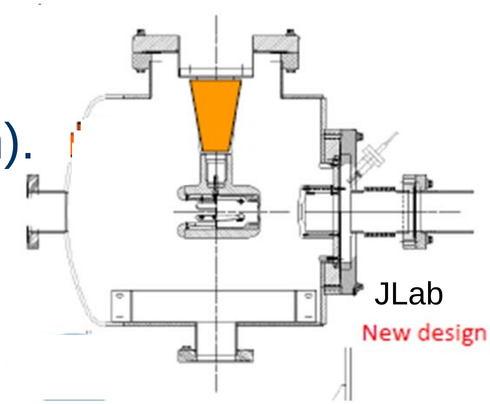
- DC operation
- DC guns reliably operated at 350 kV (JLAB) for many years, ongoing effort to increase the final energy (Cornell, Daresbury, Jlab, …).
- Extensive simulations (Cornell, …) "demonstrated" the capability of sub-micron emittances at ~ 1 nC, if a sufficient beam energy is achieved
- Full compatibility with magnetic fields.
- Excellent vacuum performance
- Compatible with most photo-cathodes. (The only one operating GaAs cathodes)



350 kV DC gun

Challenges:

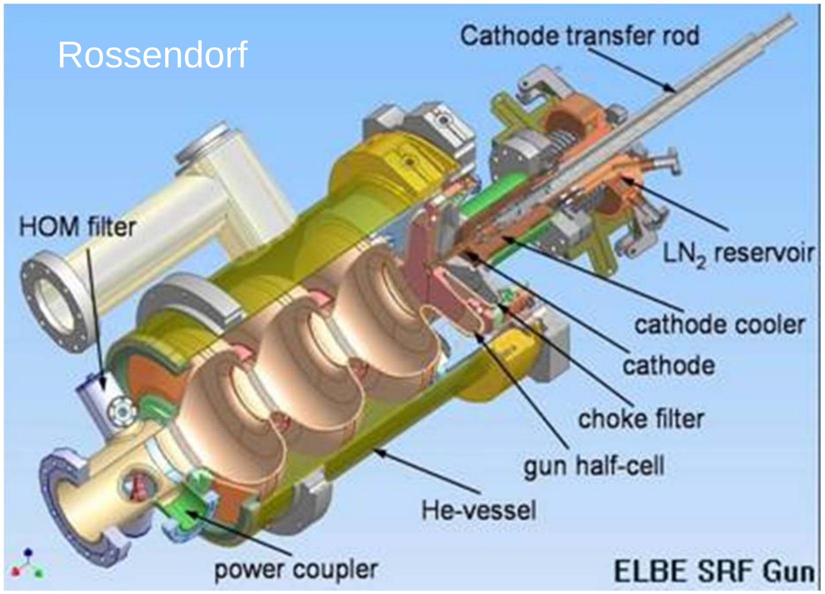
- Higher energies require further R&D and significant technology improvement (Promising results by JAEA DC Gun).
- In particular, improvement of the high voltage breakdown ceramic design and fabrication.
- Minimizing field emission for higher gradients (>~ 10 MV/m)



JLab

- Developing and test new gun geometries (inverted geometry, SLAC, JLab) Very interesting results from a "pulsed" DC gun at Spring-8.

Super-Conducting RF Guns



Pros:

- Potential for relatively high gradients (several tens of MV/m)
- CW operation
- Excellent vacuum performance.

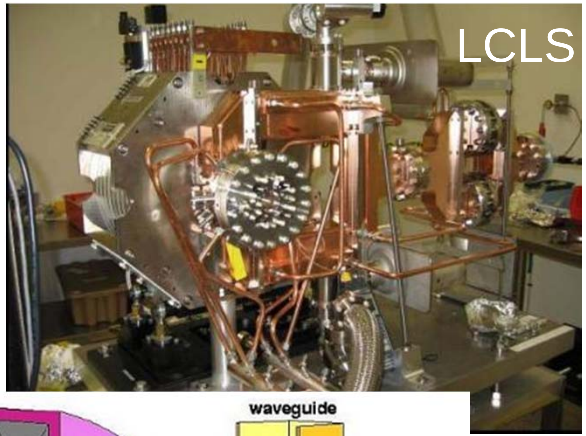
Challenges:

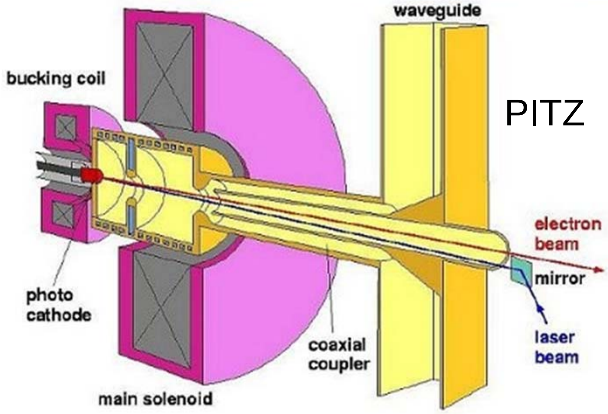
- Move technology from to a more "mature" phase. Significant progresses under way.
- Experimentally verify cathode compatibility issues (Promising results with Cs_2Te at Rossendorf, DC-SRF Peking approach)
- Develop and prove schemes compatible with emittance compensation (field exclusion, magnetic field induced quenching, …).

Normal Conducting L and S Band RF Guns (> ~ 1 GHz)

Pros:

- High gradients from ~50 to ~140 MV/m
- "Mature" technology.
- Full compatibility with magnetic fields.
- Compatible with most photocathodes
- Proved high-brightness performance. (LCLS and PITZ)





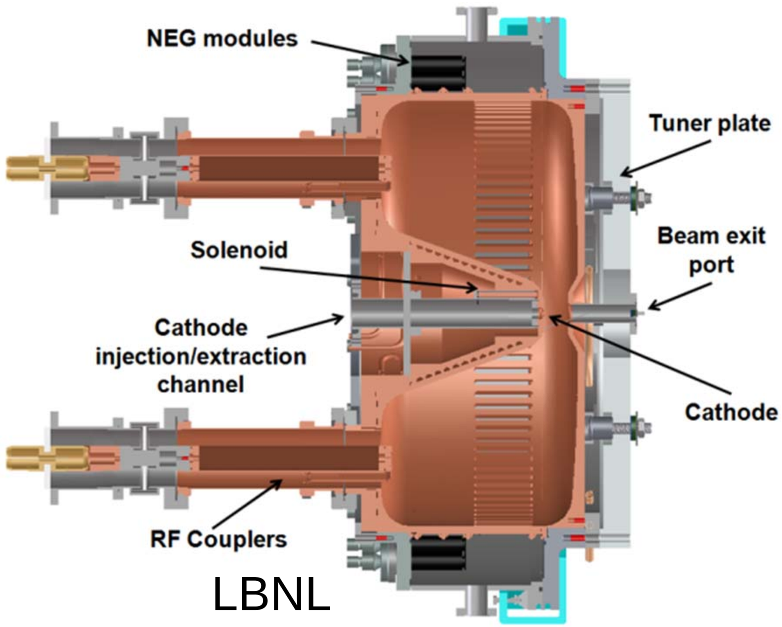
Challenges:

- High power density on the RF structure (~ 100 W/cm^2) limits the achievable repetition rate at high gradient to ~ 10 kHz.
- Relatively small pumping apertures can limit the vacuum performance.

Normal Conducting Low Frequency RF Guns

Pros:

- Can operate in CW mode
- Beam Dynamics similar to DC but with higher gradients and energies
- Based on mature RF and mechanical technology.
- Full compatibility with magnetic fields.
- Compatible with most photo-cathodes
- Potential for excellent vacuum performance.



Challenges:

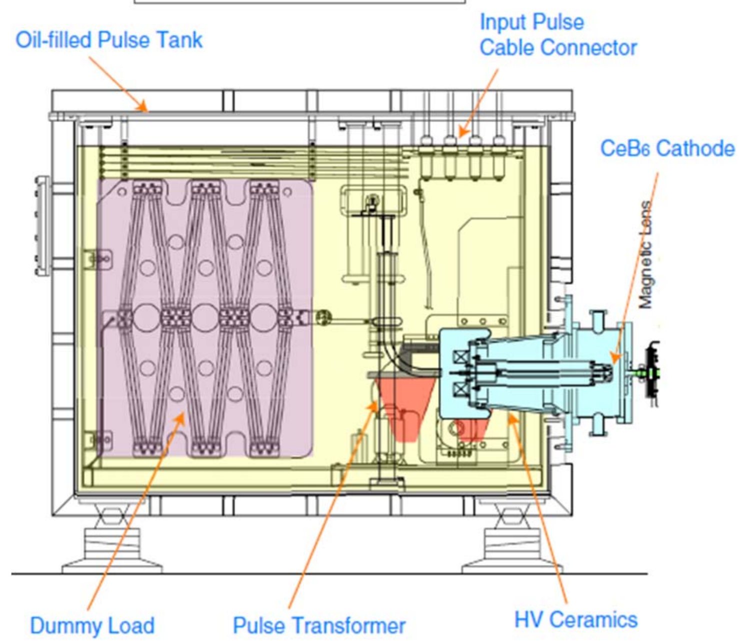
- Gradient and energy increase limited by heat load in the structure
- CW high brightness performance still to be proved
- Vacuum performance still to be proved

'Pulsed DC' Gun

Pros:

- Based on mature technology.
- The pulsed nature relaxes many of the DC gun issues
- Full compatibility with magnetic fields.
- Compatible with most photocathodes
- Proved high brightness performance with a 3 mm radius CeB_6 thermionic cathode.

SCSS 500 kV Electron Gun



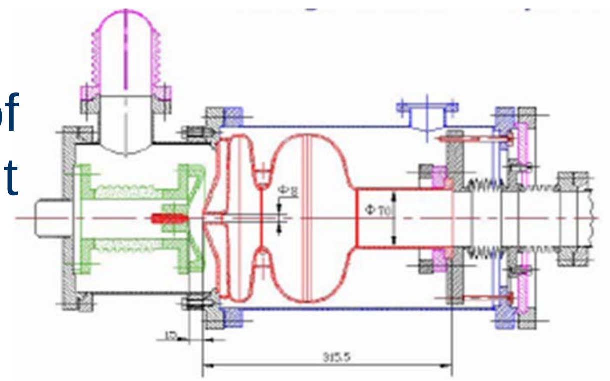
Challenges:

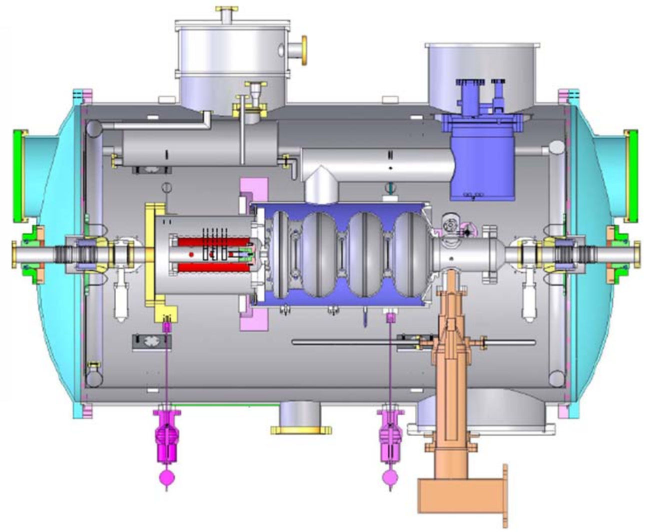
- Modulator technology limits maximum energy and repetition rate (~500 kV at 60 Hz presently, can it go to kHz?).
- Significant injector system complexity when used with thermionic cathodes ("adiabatic" compression requires chopper and multiple RF frequencies). Not integrated yet with photo-cathodes.

T. Shintake et al., PRST-AB 12, 070701 (2009)

Peking DC-SRF Gun

Pros:





- Brings the cathode out of the cryogenic environment
- Allows for a final beam energy higher than in DC guns
- 1.5 cell proof of principle already built. Second generation 3.5 cell under fabrication.

Challenges:

- Increased system complexity
- Gradient limitation in the DC part

Table 1: Parameters of the new photoinjector

2+1/2-cell cavity	
E_{acc}	15 MV/m
Drive laser	
Pulse length	10 ps
Spot radius	2 mm
Repetition rate	81.25 MHz
Electron bunch	
Charge/bunch	<60 pC
Energy	3.72 MeV
Energy spread (rms)	1.68%
Emittance (rms)	2.0 mm-mrad

Jiankui Hao, *et al*., SRF2009, p 205, Berlin, Germany

Additional References for Existing Gun Project (Incomplete List)

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- C. Limborg-Deprey, D. Dowell, J. Schmerge, Z. Li, and L. Xiao, RF Design of the LCLS Gun, LCLS TN-05-3, Feb. 2005.
- I. Bazarov, et al., in Proceedings of the 2009 Particle Accelerator Conf. , Vancouver, Canada, May 4-8, 2009, p. 683.
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- A. Arnold, et al., Nucl. Instrum. Methods Phys. Res., Sect. A 593, 57 (2008).
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- A. Fedotov,et al., BNL Collider-Accelerator AP Note: CA/ AP/307, 2008.
-T. Kamps, et al., in Proceedings of SRF'09, Berlin, Germany, September 20-25, 2009, p. 164.
- J.W. Lewellen, et al., in Proceedings of the 2008 FEL Conference, Gyeongju, Korea, August 24-29, 2008, p. 394.
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- J.Staples, F.Sannibale, S.Virostek, VHF-band photoinjector ,CBP Tech Note 366, 2006.
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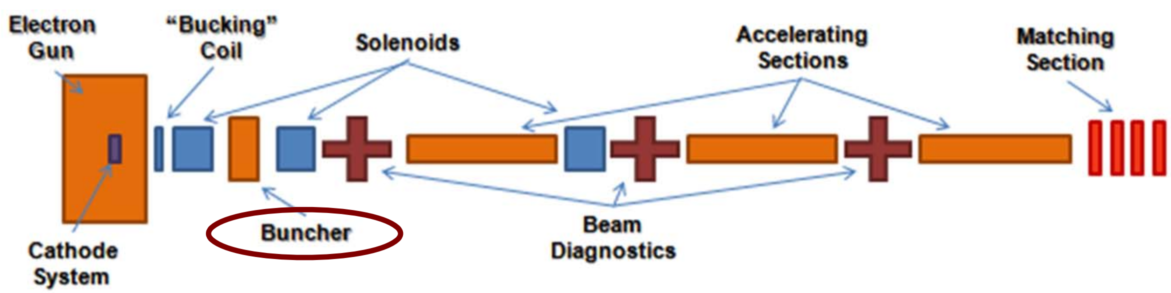
- F. Sannibale, et al., Status of the LBNL normal-conducting CW VHF electron photo-gun, in Proceedings of the 2010 FEL Conference, Malmo, Sweden, August 23-27, 2010.
- P. N. Ostroumov, et al., in Proceedings of the 2009 Particle Accelerator Conf., Vancouver, Canada, May 4, 2009, p. 461.
- A. Arnold and J. Teichert , "Overview on superconducting photoinjectors", Phys. Rev. ST Accel. Beams – February 2011 Volume 14, Issue 2
- M. Ferrario and T. Shintake , "High Performance Electron Injectors", Reviews of Accelerator Science and Technology (RAST), Volume: 3, Issue: 1 (2010).

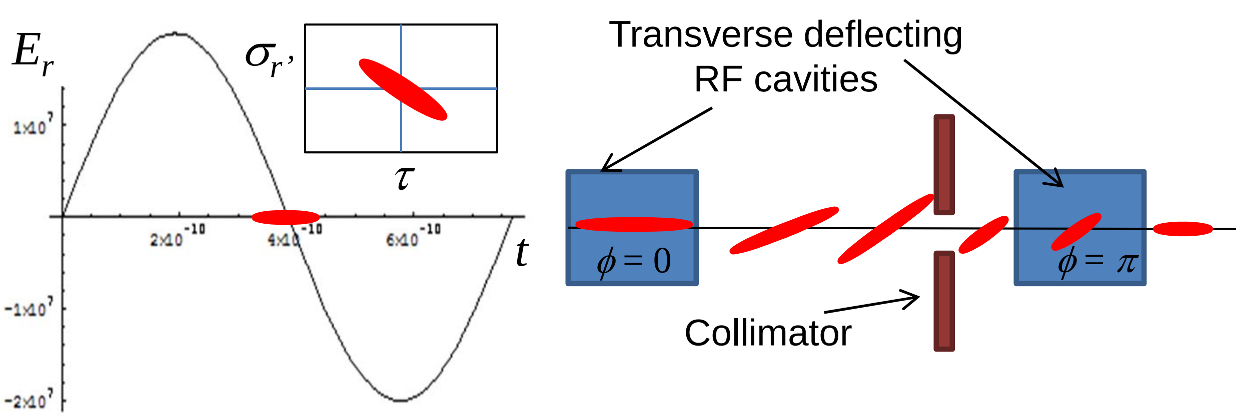
Bunching Systems

• The systems that allow to compress or define the bunch length in the injector are: **buncher**s, **choppers** and **"dephased" accelerating sections**.

• The operation principle of **bunchers** has been already explained earlier.
Bunchers are used when the **beam** out of the gun is **not extremely relativistic**.
Single or multi-cell, typically standing wave, cavities are used.
The frequency is often a sub-harmonic of the linac main frequency, for increasing the linearity of the bunching process.
Depending on the field intensity NC-RF or SC-RF is used.



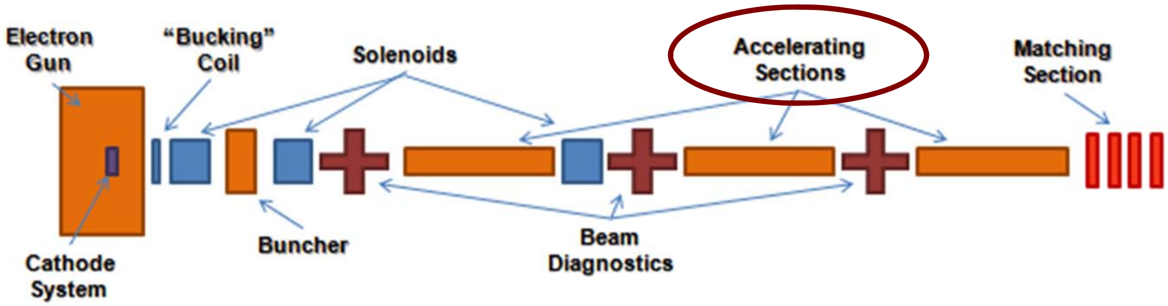
• **Velocity bunching** has been also discussed before, and requires de-phasing the RF in the first accelerating sections.



• An **RF chopper** system is used for example for reducing a continuous beam to a pulsed one.

Accelerating System

• The main task of the injector **accelerating system** (the first section of which is often referred as the "**RF Booster**") is to take the beam from the gun at the optimum of the emittance compensation process and to "quickly" accelerate it and "freeze" the compensated emittance.



• In the previous slide, we reminded that the RF booster can be also used for **velocity bunching**.

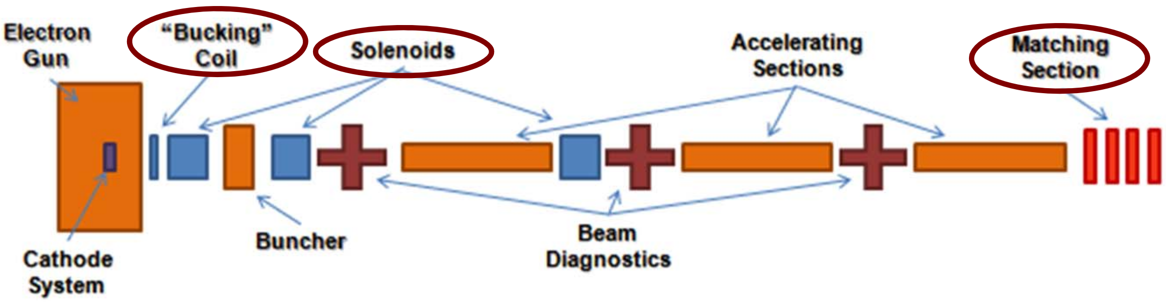
• The booster sections can be of **standing or travelling wave** type.

• The frequency can be a sub-multiple of the main linac RF for improving linearity during injector compression.

• The repetition rate defines the technology for the booster:
Normal-conducting pulsed systems for **repetition rate < ~ 1 kHz**
Super-Conducting Pulsed (train of bunches) and CW systems otherwise.

• **Accelerating gradients** are in the range of 10 – 50 MV/m for NC RF sections. Higher gradients correspond to higher frequencies (~500 MHz to ~5 GHz).
• For SRF the gradients range from ~ 10 to ~30 MV/m from frequencies going from ~ 500 MHz to ~ 1.5 GHz).

• The **"Bucking" coil** is used for cancelling undesired solenoidal fields on the cathode that would dilute emittance, or to couple the horizontal and vertical planes in flat-beam or emittance-exchange schemes.



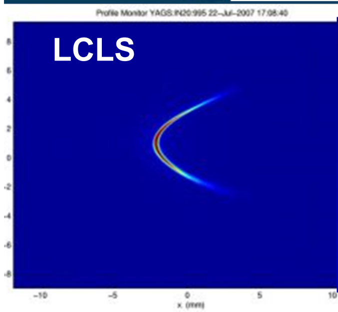
• **Steering coils** distributed along the injector allow to align the beam respect to the component centers.

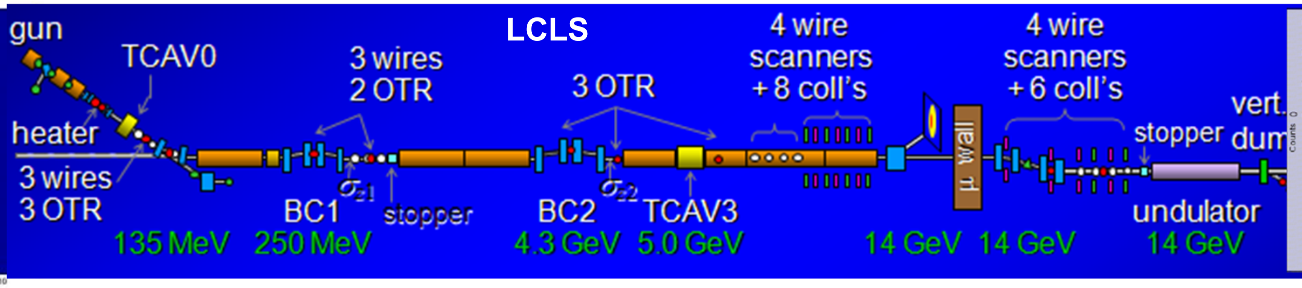
• The **solenoid**(s) performs the emittance compensation and controls the beam size along the injector. In same cases the solenoids wrap around the accelerating sections.

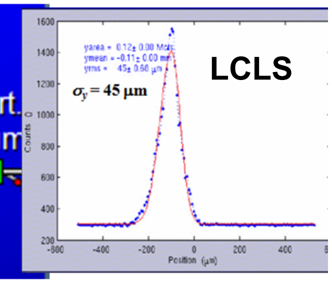
• **Correcting coils inside solenoids** showed a **dramatic effect** on the LCLS injector **emittance performance**. Steering coils and quadrupole correcting coils compensate for solenoidal field imperfections.

• At energies where space charge is negligible, it becomes cost effective to switch from the solenoid to a **quadrupole** based focusing system.

Beam Diagnostics







Beam Diagnostics is fundamental and necessary for the proper tuning and performance optimization of the injector.

There are a large number of such a systems, including:

- **Current and charge monitors.**
- **Transverse and longitudinal bunch distribution diagnostics.**
- **Energy and energy spread monitors**
- **Transverse and longitudinal phase-space diagnostics.**
- **Beam position monitoring**
- **Low Level RF System (lock and control different RFs and laser)**
- **Cathode and laser diagnostics.**

The description of such systems would require much more time and is beyond the scope of this lectures

Required R&D

• Pursue development of various electron source schemes

• The performance of an electron source is never fully characterized and demonstrated until the source is integrated in an injector

• Important to built R&D injector facilities that allow testing and optimization of:

• Emittance compensation and beam manipulation techniques, emittance exchange, velocity bunching, …

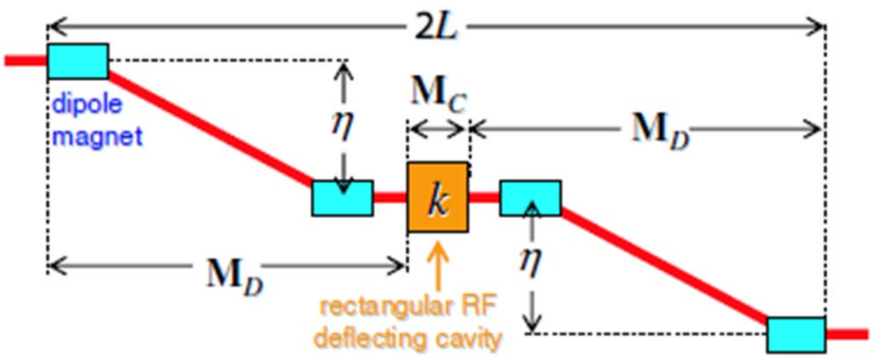
• Cathodes. Physics understanding, cathode test facilities capable of accepting all kind of cathodes, vacuum performance, load-lock, ….

• Beam diagnostics (especially when considering high repetition rate very low charge and very short bunches

Back-Up Viewgraphs

Emittance Exchange

In some applications (FELs in the microbunching instability regime or ERL modes where the longitudinal emittance is not very important) it can be convenient to exchange a smaller longitudinal emittance with a larger transverse emittance.



$$1 + k\eta = 0$$

$$k \equiv transverse\ kick\ strength$$
$$\eta \equiv transverse\ dispersion$$

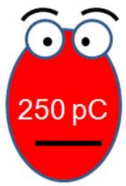
Several schemes have been proposed for exchanging the longitudinal with one of the transverse emittances (we will assume the horizontal plane in what follows). A dispersive section ('dogleg') is first used to create a correlation z-x, followed by a deflecting cavity that gives a transverse kick proportional to the particle z position, a second dogleg (as in the figure) removes undesired energy-position correlations generating a complete emittance exchange between x and z.

M. Cornacchia and P. Emma, Phys. Rev. ST Accel. Beams 5, 084001 (2002).
K.-J. Kim and A. Sessler, AIP Conf. Proc. No. 821 (AIP, New York, 2006), pp. 115–138.
P. Emma, Z. Huang, K.-J. Kim, P. Piot, Phys. Rev. ST Accel. Beams 9, 100702 (2006)

Charge per Bunch

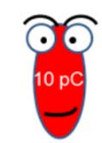
In order to exploit all the different modes of operation of ERLs and FELs, the injector must operate within a very broad range of charge/bunch.

- **For example, experiments in FELs and ERLs requiring large number of photons per pulse or very narrow transform limited photon bandwidth in seeded FEL schemes require longer bunches and hence higher charges per bunch that can approach the nC.**



- **The main operational mode for X-Ray FELs relies on a charge/bunch of a few 100s pC (~ 100 pC for ERLs), where a satisfactory tradeoff between the number of photons/pulse and a moderate transverse emittance increase at the injector due to space charge forces can be found.**

- **Smaller charges per bunch (from few tens of pC down to the pC) have being proposed as an alternative/complementary mode of operation. Because of the lower charge/bunch, space charge effects can be more efficiently controlled making electron guns capable of generating beams with smaller transverse and longitudinal normalized emittances. The resulting higher 6D brightness allows for shorter FEL gain lengths at a relatively moderate electron beam energy.**



In ERLs the low emittance potentially obtainable with few tens of pC charge/bunch allows for modes of operation with X-Ray pulse with full transverse coherence.

Emittance

We previously saw that the major objective for electron injectors is to maximize the brightness B

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

For a fixed charge/ bunch that translate in minimizing the emittance in each of the planes.

The normalized emittance in each plane is proportional to the area in the phase space occupied by the beam.

$$\varepsilon_{nw} = \sigma_w \frac{\sigma_{pw}}{mc} \qquad w = x, y, z$$

In Hamiltonian systems the normalized emittance is an invariant of motion.

For a constant energy beam, the geometric emittance is an invariant of motion and is defined (in the transverse plane) as:

$$\varepsilon_w = \frac{\varepsilon_{nw}}{\beta\gamma} = \sigma_w \frac{\sigma_{pw}}{\beta\gamma\, mc} = \sigma_w \frac{\sigma_{pw}}{p} = \sigma_w \sigma_{w'} \quad with \quad w = x, y \;\; and \quad w' = \frac{p_w}{p}$$

For a given set of particles (beam) the r.m.s. geometric emittance is defined as

$$\varepsilon_{wrms} = \sqrt{\langle w^2 \rangle \langle w'^2 \rangle - \langle w w' \rangle^2} \qquad w = x, y$$

The r.m.s. emittance is not conserved in the presence of nonlinear forces

Transverse Emittance

• Small normalized transverse emittances are extremely important in X-Ray FELs because the required matching between the small X-Ray photon emittance and the electron beam geometric emittance

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

can be achieved at lower beam energies
(assuming that undulators with the required period are feasible).

• Also, small emittances in SASE FELs allow for shorter gain lengths and thus for shorter undulators.

$$\rho_{Pierce}^{1D} = \frac{1}{\gamma}\left[\frac{1}{64\pi^2}\frac{I_e}{I_A}\frac{1}{\varepsilon_x \beta_x}\lambda_u^2 K^2 JJ^2\right]^{1/3}; \qquad \frac{1}{\rho_{Pierce}^{1D}} \approx \begin{array}{c} Number\ of\ undulator\ periods \\ required\ for\ saturation \end{array}$$

(3D effects add further dependence of the gain length on the geometric emittance)

• In ERLs high electron brightness translates directly into high photon brightness.

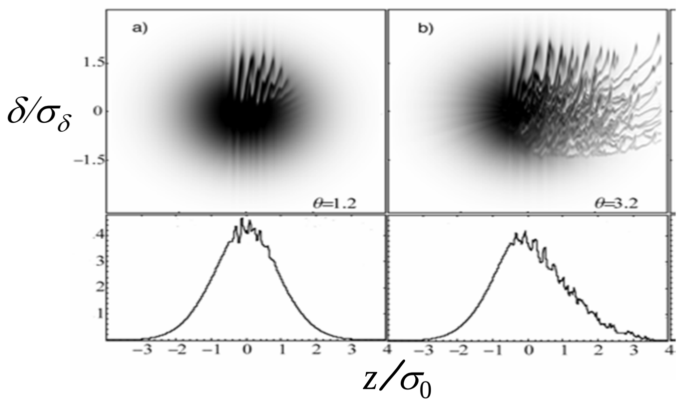
• These benefits are particularly important because they allow to effectively reduce the size and the cost of expensive X-Ray FEL and ERL facilities.

• The minimum achievable ε_n depends on the charge/bunch.
Indeed, at lower charges, it is possible to reduce the beam size at the cathode while still keeping under control space charge.
We will see later that smaller sizes at the cathode imply smaller emittances.

Longitudinal Emittance

• When discussing **longitudinal emittance** requirements for injectors, **two different cases need to be considered**.

• In the relatively high charge/bunch regime (**few hundreds of pC and above**), the rising of the **microbunching instability** (MBI) in linac magnetic compressors, forces to use 'heating' techniques (e.g. laser heating) to increase the uncorrelated energy spread and damp the instability. In this situation, the **longitudinal emittance at the injector exit is not relevant**.



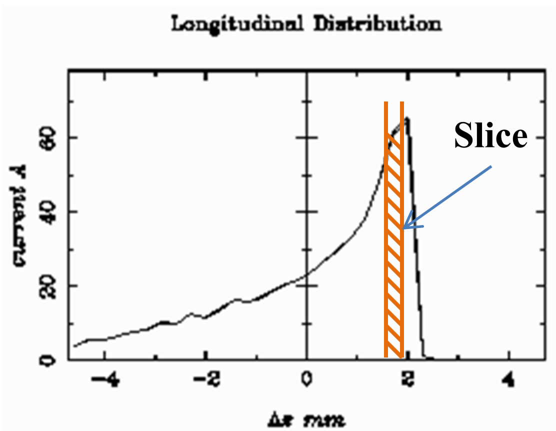
Simulation by Marco Venturini

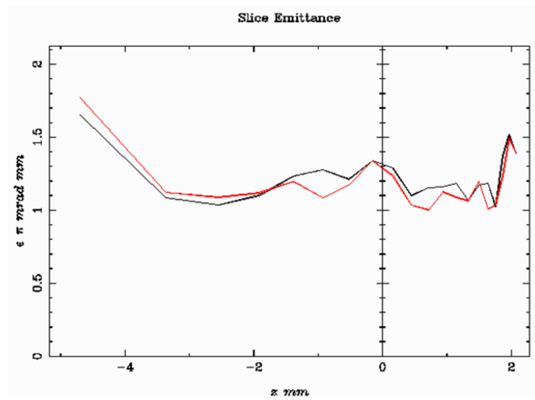
• **At lower charges per bunch**, MBI can be generally controlled and no beam heating is required anymore. Lower longitudinal emittances become now possible and available resulting in an increased 6D brightness and thus in a reduction of the FEL gain length.

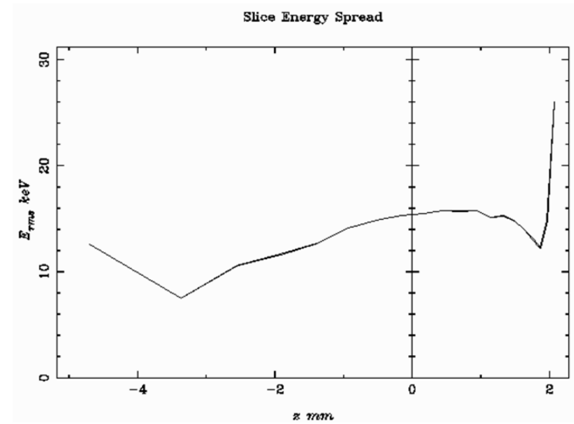
In this low charge regime, normalized longitudinal emittances in the µm range are desirable.

"Slice" and "Projected" Quantities

• An important remark: in an FEL, the **requirements** on beam parameters such as emittance, peak current and energy spread **need to be satisfied only in the longitudinal portion of the electron beam where lasing is desired.**







• The length of this region must be greater than the electron to photon slippage along one gain lenght, but it is ultimately defined by the FEL mode of operation, the experimental tolerances and the fluctuations of the relevant parameters.

• For example, in seeded FEL schemes, such a length must be longer than the seeding laser pulse convoluted with the total jitter between the electron and laser pulses. The term '**slice**' is usually associated with a beam quantity measured within this 'lasing' part of the beam (or to a fraction of it), while the term '**projected**' is referred to a property of the whole beam.

• On the contrary, **in ERLs are the projected characteristics** to be **important**

Energy

- **Most of the emittance increase due to space charge happens in the low energy part of the injector, the electron gun.**

- **Space charge effect intensity scales as γ^{-2} so higher energies at the gun are beneficial in minimizing such effects.**

- **Extensive simulation work and experimental evidence (Shintake gun) showed that an energy of at least ~500 keV is necessary to achieve the required beam quality within the charge/bunch range of interest.**

- **In a high brightness injector the final electron beam energy must be high enough to make residual space charge effects negligible. The actual value for such an energy depends on the bunch characteristics but it is typically found to be around 100 MeV or more.**

- Bazarov, I .V., and Sinclair, C .K., Phys. Rev. ST Accel. and Beams 8 034202 (2005).
- T. Shintake, et al., Phys. Rev. ST Accel. and Beams 12, 070701 (2009).

Accelerating Gradient at the Cathode

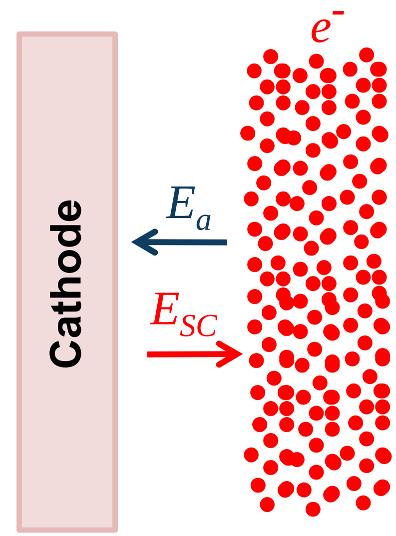
- **During emission at the cathode**, the electric field E_{SC} due to the already emitted electrons presents opposite direction with respect to E_a , the accelerating field in the gun.

  The **emission can continue until** E_{SC} **cancels** E_a.

  The **max charge density that can be emitted by a given** E_a is known as the '**space-charge limit**' and scales linearly with E_a.

  Higher gradients are required **to extract higher charge/bunch** and preserve beam quality.
  (1 nC bunch with $\varepsilon_{xn,\,yn} = 1$ mm requires $E_a > \sim$ 10-15 MV/m)

  More on the space-charge limit later in the lecture.

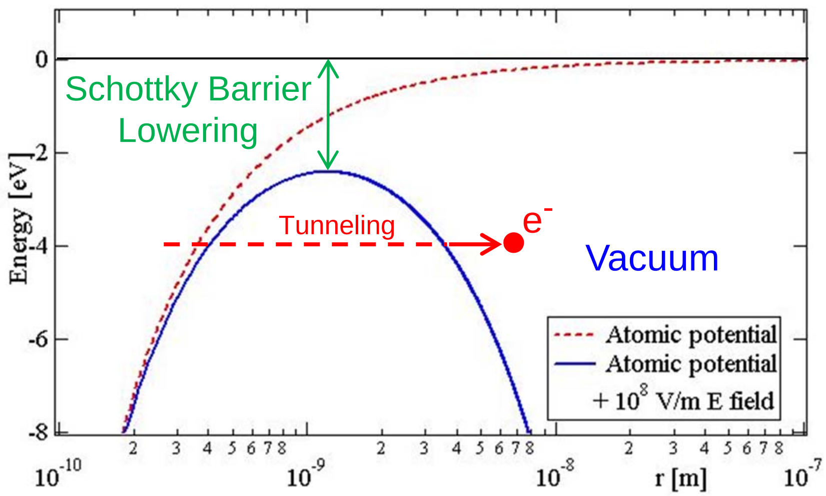


- Also, **larger gradients** allow for a '**faster' acceleration of the beam towards** higher energies **minimizing the deleterious effects of space charge** forces.

- There is a special mode of operation, the so-called '**beam blowout**' where a pancake like beam is emitted and evolves under the action of its own space charge forces.
  Such a mode of operation **requires relatively high gradients at the cathode**.
  More later in the lecture.

Dark Current

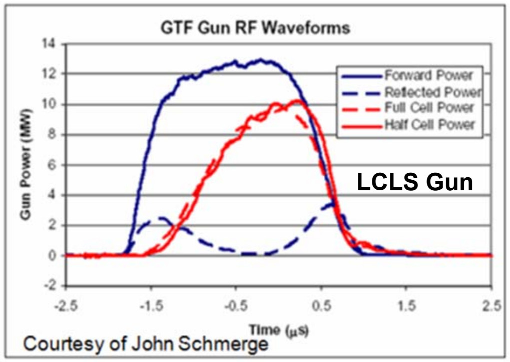
Dark current is mainly generated by field emission from the accelerator parts.



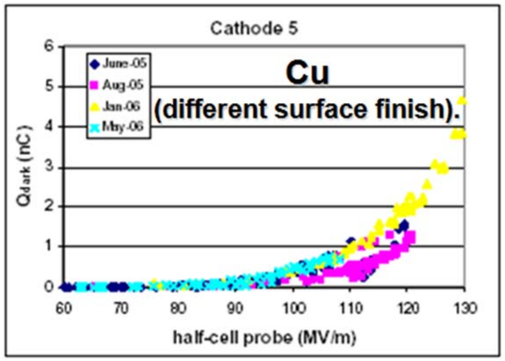
$$U_p = -\frac{1}{4\pi\varepsilon_0}\frac{e^2}{r} + e\left|\overline{E}\right| r$$

$$\left|\overline{E}\right| = \text{constant}$$

$$\left|\overline{E}\right| > \sim 10^8 \div 10^9\, V/m$$



• **Dark current can be relatively tolerated in pulsed injectors but can represent a serious issue in injectors running in continuous wave (CW) mode that can generate damage, quenching, and high radiation levels in the downstream accelerator.**



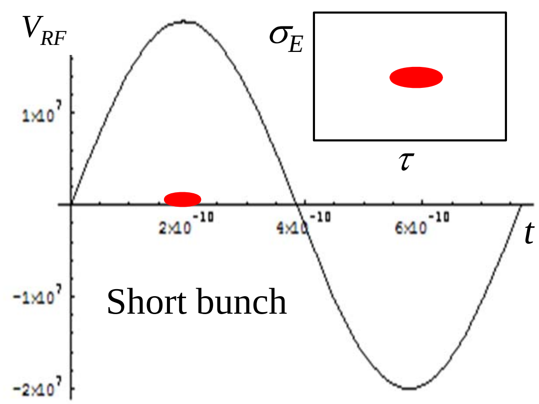
• **While no definitive 'cure' for dark current exists, the best techniques known for minimizing it should be used (surface finish, geometry, materials, …).**
In particular, high accelerating fields in the cathode/gun area, which can potentially generate field emission, should be carefully evaluated in terms of dark current.

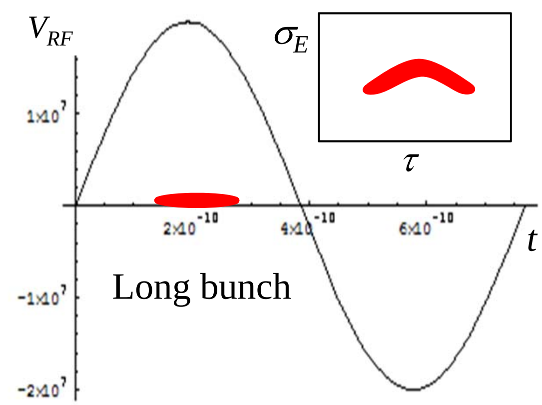
Bunch Length

- The **bunch length is an important knob for controlling the charge density** of the electron beam **and hence space charge effects** along the injector.

- In particular, **longer bunches at the cathode** can be used for mitigating space-charge induced emittance increase, especially when **relatively low accelerating gradients** at the electron gun are available.

- **Other factors** can also limit the **maximum bunch length**. For example, longer bunches sample more **RF nonlinearities** in the accelerating RF sections. Also as we will see later, **transverse emittance dilution due to RF** scales with the **square of the bunch length.**





- The capability of **controlling the longitudinal and transverse beam distributions** is **also important for the beam dynamics performance.**
- For this requirement, photo-cathode systems represents an appealing choice because they allow controlling the electron beam distribution by shaping the pulse of the laser used for the photoemission (more on cathode systems later).

Peak Current

• **FEL gain depends on the bunch peak current.**
For high-gain FEL schemes, values of up to 1 kA are typically required.

$$P(z) = P_0 e^{z/L_G} \qquad L_G = \frac{\lambda_u}{4\sqrt{3}\pi\rho^{1D}_{Pierce}} \quad gain\ \ length$$

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

• **Oscillator FEL schemes include storage cavities for the X-Ray pulses, and are usually operated in low-gain regime hence requiring smaller peak currents.**

• **Such high-peak currents are obtained by compressing the bunch length along the accelerator in several stages.**
Typical schemes include one or more magnetic chicanes in the linac, plus buncher systems and/or velocity bunching in the injector.

• **Typical peak currents required at the injector exit, compatible with reasonable compression factors in the downstream linac, are many tens of A.**

• **More on compression later in the lecture.**

Transverse Beam Size

Transverse emittance dilution due to RF scales with the square of the transverse rms size of the bunch.

(More later in the lecture).

• Larger beam sizes are more prone to sample regions with stronger nonlinearities in the transport channel potentially generating an increase of the transverse rms emittance.

• Larger beam sizes requires larger vacuum chamber cross-sections, larger bore magnetic components, making such parts bigger and more expensive.

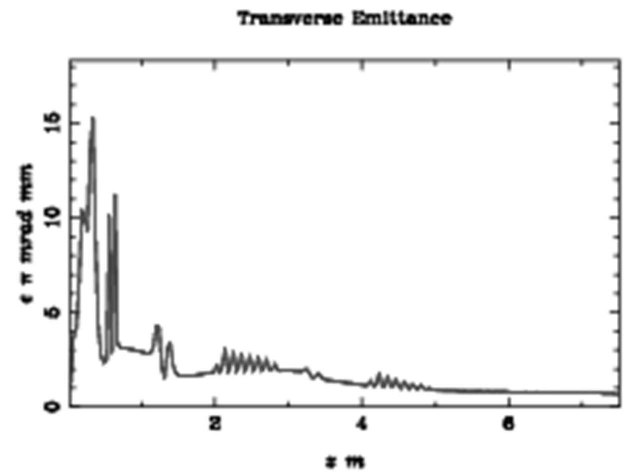
• The rms beam size inside the typical high brightness gun ranges from few hundreds microns up to few mm.

•The average beam size along the injector decreases linearly with the beam energy due to the geometric emittance scaling with energy.

Compatibility with Magnetic Field

- High-brightness injector schemes should be compatible with the application of magnetic fields in the cathode/gun area.

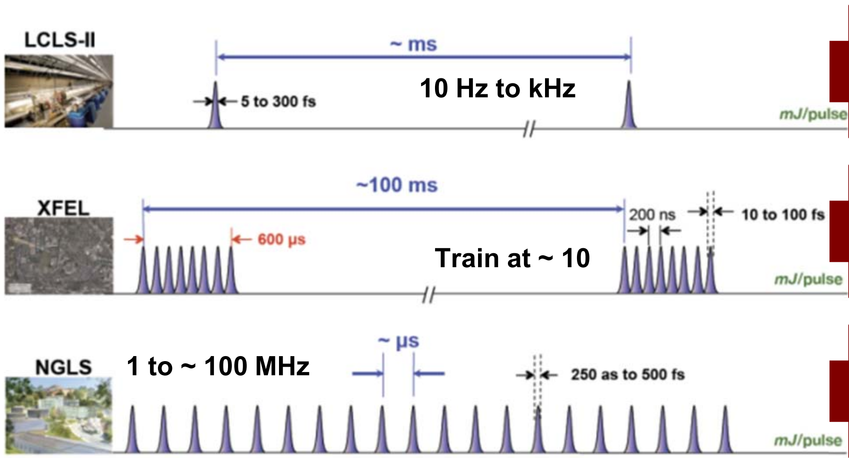
- Indeed, preserving the gun brightness along the injector requires techniques such as emittance compensation that requires magnetic fields in the gun region.
(More later in the lecture)



- Additionally, some of the proposed emittance exchange techniques requires the presence magnetic fields in the cathode region.
(More later in the lecture).

Repetition Rate

The repetition rate is a parameter that deeply impacts the technological choices for a 4th generation light source.
Indeed, it determines the injector and linac technologies and has a relevant impact on the facility cost, and also, as it will be discussed later, on the electron beam beam dynamics.

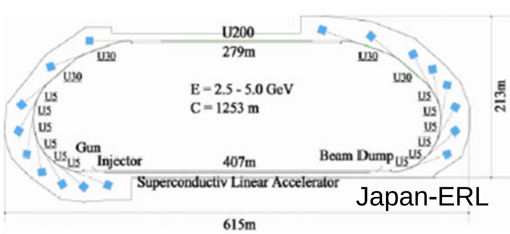


Normal-conducting linacs (S, C or X-Band); low repetition-rate gun.

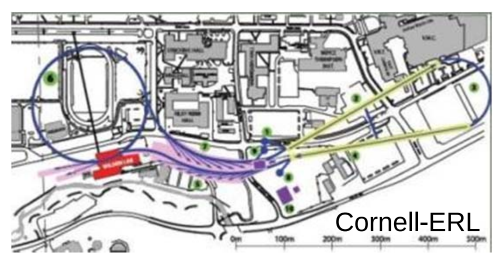
Normal or super-conducting linac; low repetition-rate gun.

Super-conducting linac; high repetition-rate gun.
(presently proposed XFEL ocillators requires ~ 1 MHz)

ERLs target 100s of mA average currents requiring GHz-class repetition rates



Japan-ERL



Cornell-ERL

and hence super-conducting linac and high repetition-rate gun.

Vacuum Performance

As it will be discussed later, the large majority of cathode systems used in high-brightness injectors are based on photo-cathodes.

In the low repetition-rate case, metal cathodes (mainly copper) have been extensively used because of their relatively simple preparation and robustness.

In the high repetition-rate case, metals cannot be used because of their low quantum efficiency QE in the 10^{-5} range (number of photo-emitted electrons per impinging photon), which would require unrealistically powerful lasers.

Higher QE materials, in the 10^{-2} range, are required in the high repetition-rate case.

Several materials have been already successfully developed and tested and many other promising candidates are under investigation.

Most of such materials are very reactive and/or their emitting surface is sensitive to damage by ion back-bombardment. Indeed, in order to achieve lifetimes compatible with the operation of a user facility, vacuum pressures ranging from 10^{-7} to 10^{-9} Pa (~10^{-9} to 10^{-11} Torr) are necessary (with even lower partial pressures for reactive residual gas molecules such as H_2O, O_2, CO_2).

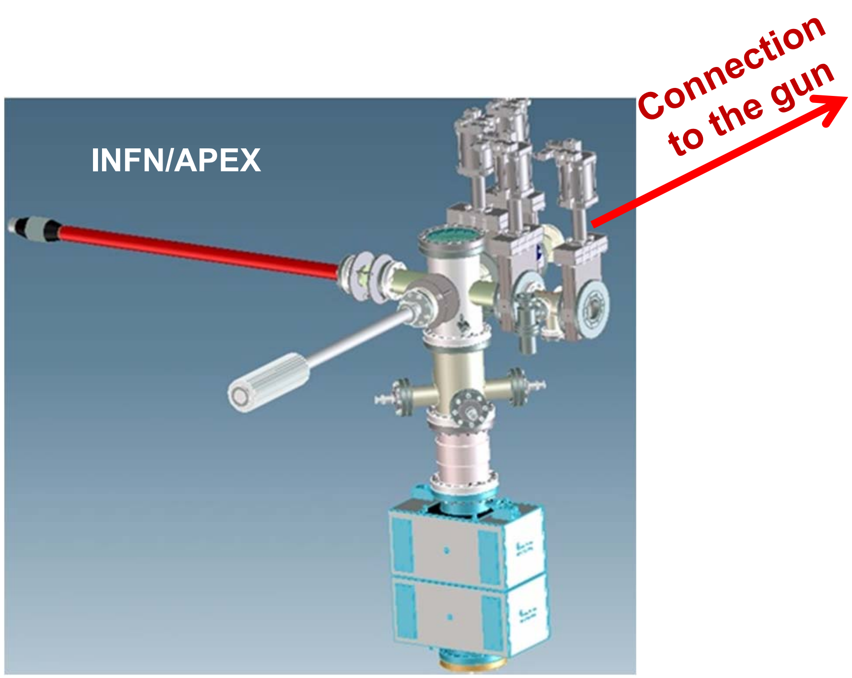
Reliability, Easiness of Operation

Independently from the gun/injector technology choice, the selected scheme should offer the required reliability and robustness to operate in an user facility and guarantee the proper continuity to the experimenters.

Also, replacement of parts with reduced lifetime should be performed as fast and efficiently as possible.

For example, in the case of delicate high-QE cathodes it is necessary to periodically replace and/or regenerate/activate the cathodes without breaking the vacuum pressure inside the gun.

To make that possible in a relatively straightforward and timely way, a vacuum load-lock system is usually required.

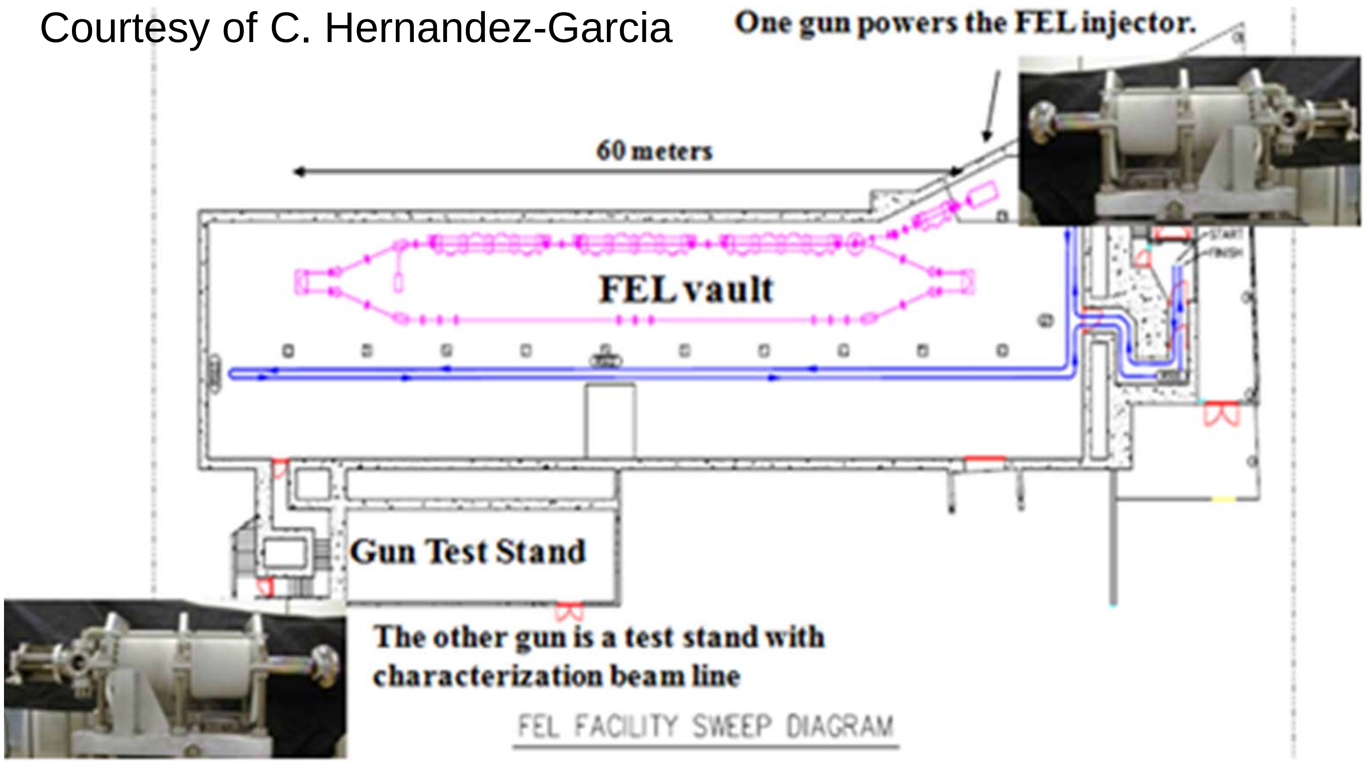


Gun - 4th Generation Light Source Matching

ERL	Up to hundreds of MHz reprate	DC gun, SC RF Gun, Low freq. NC RF Gun, DC-SRF Gun
	>~ 1 GHz reprate	DC gun, SC RF Gun, DC-SRF Gun
FEL	Reprate < ~ 10kHz	High freq. NC RF Gun, pulsed DC gun
	Up to hundreds of MHz reprate	DC gun, SC RF Gun, Low freq. NC RF Gun, DC-SRF Gun
XFELO	Few MHz reprate	Low freq. NC RF Gun with, DC guns, DC-SRF Gun

Jefferson Lab FEL DC Guns

Courtesy of C. Hernandez-Garcia

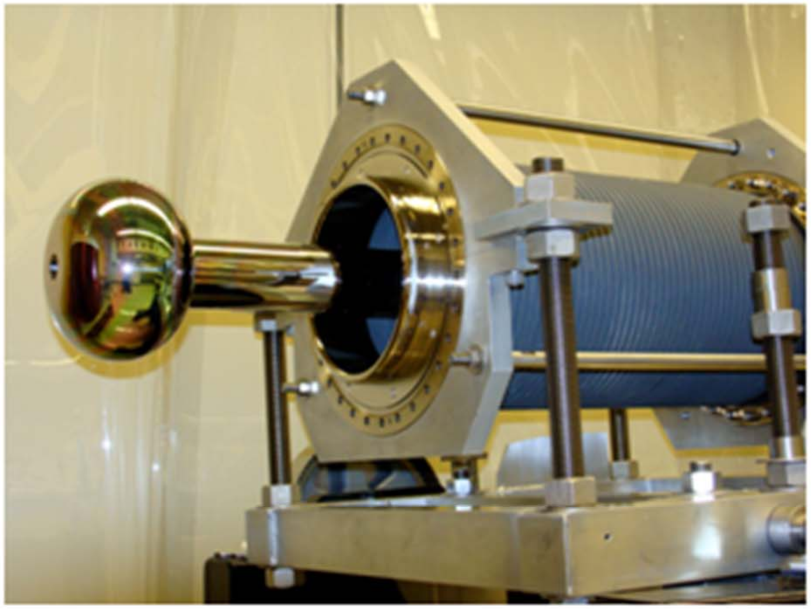


Between 2004 and 2007, operating at 350 kV, the FEL gun delivered over 7000 Coulombs and over 900 hours of beam time at 1-8.5 mA CW with a single GaAs wafer, which was activated into a photocathode a total of 9 times with an average of 6 re-cesiations per activation

Since Nov 2008, the FEL is operating a new photocathode at 325 kV (field emission limited) and close to 625 C and up to 4 mA CW has been already delivered

The Gun Test Stand gun was conditioned up to 485kV DC and demonstrated 1 nC beam at 375 kV in April 2008

Jefferson Lab

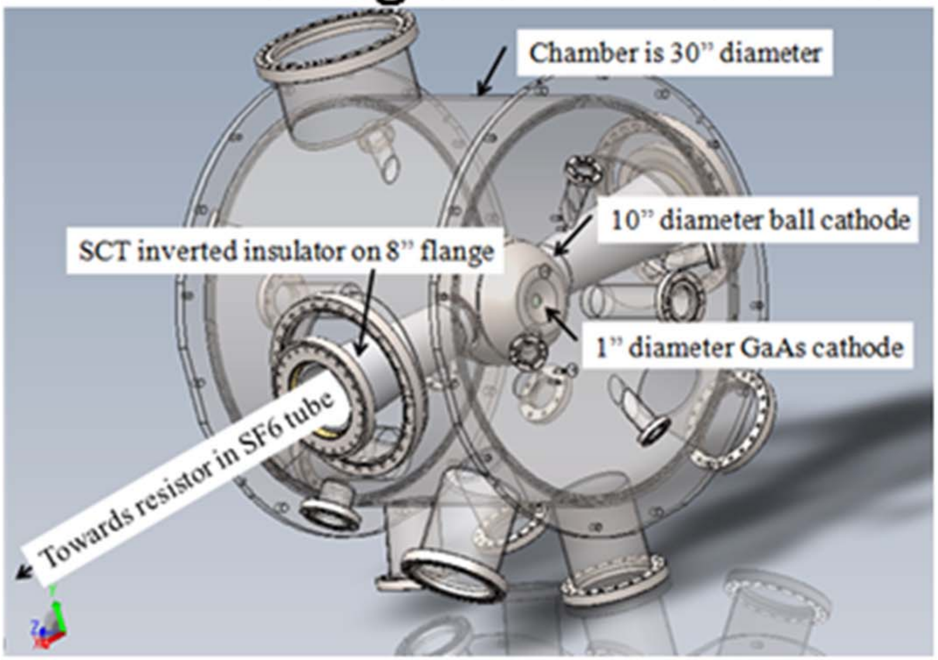


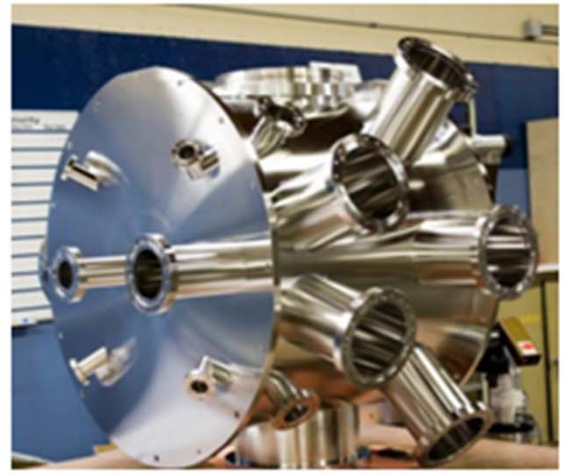
The GTS gun has been rebuilt with bulk resistivity insulator and is ready for installation

Courtesy of C. Hernandez-Garcia

Jlab Inverted DC Gun

The Jlab FEL is also developing a new gun using the inverted insulator concept





Vacuum chamber ready for delivery

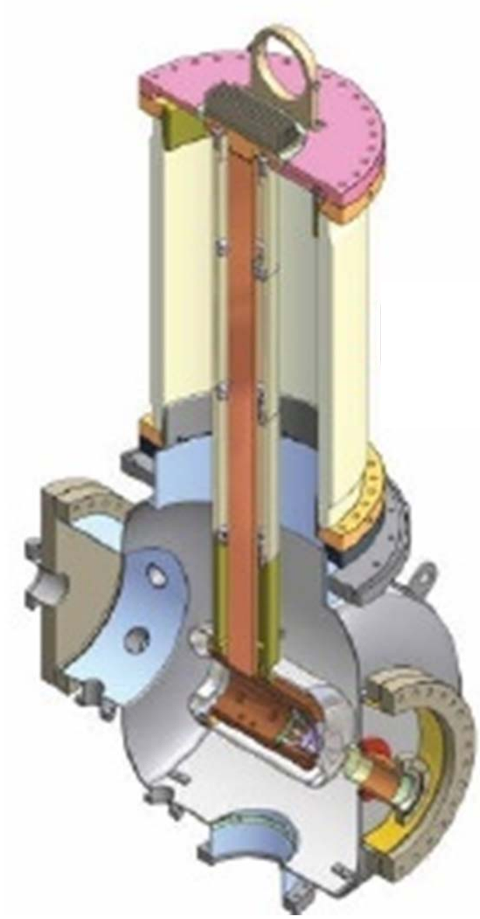
Cut-out of inverted insulator cathode design

Cut-out of ball cathode design

Courtesy of C. Hernandez-Garcia

Cornell DC Gun

- Present operation limited to ~ 250kV to limit field emission and minimize probability of field punctuation of the ceramic (750kV initial design).



Courtesy of I. Bazarov

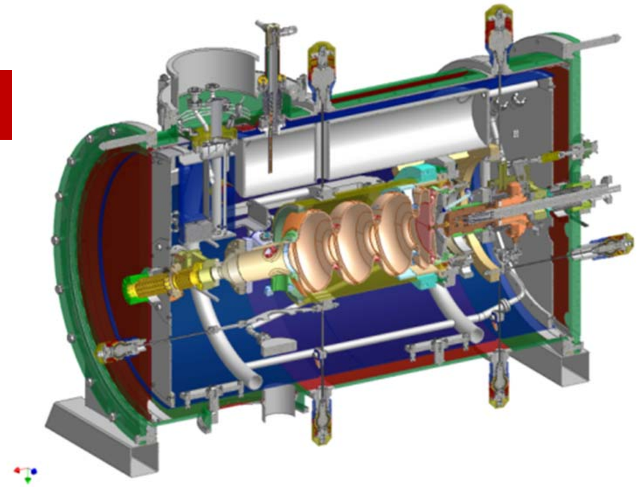
A new ceramic with bulk resistivity is being installed. Same ceramic material was used in Daresbury to get to over ~450kV.

The present gun was in beam operation for a number of years allowing for a rich experimental program.
For ensuring continuity of such program, the present and funded plan is to build a second DC gun (~500kV) as an R&D effort separated from the beam running.

BESSY-DESY-FZD-MBI SC RF Gun

Cs_2Te cathodes at 77 K, cavity at 2K,
QE ~ 10^{-3} (poor vacuum transfer chamber)

Gradient limited
by damaged cavity

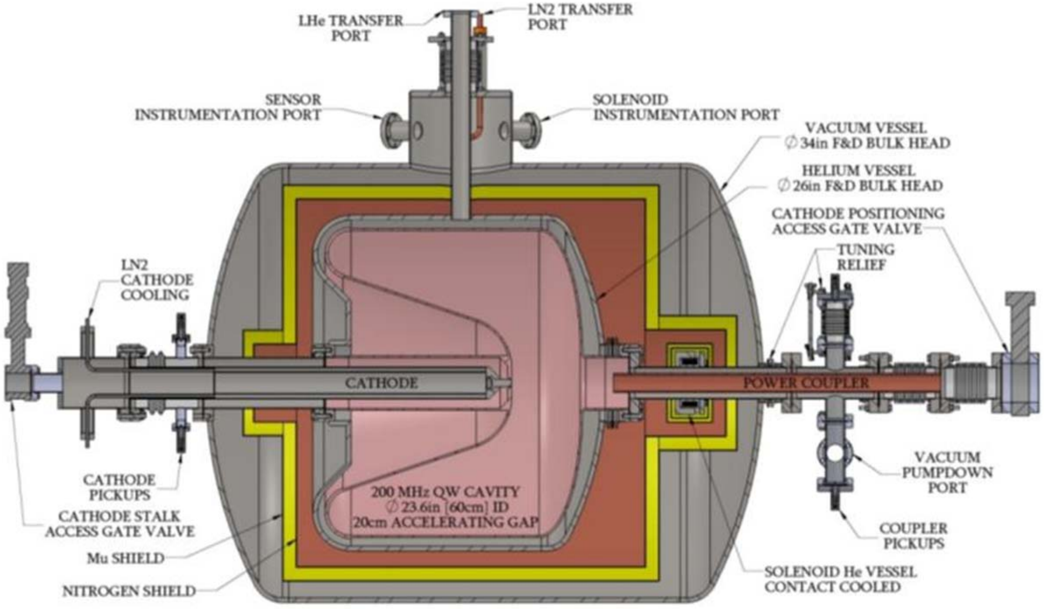


1.3 GHz TESLA-like cells.

J. Teichert et al., FEL08, Gyeongju, Korea p.467

parameter	present cavity			new "high gradient cavity"	
	measured ´08	ELBE	high charge	ELBE	high charge
final electron energy	2.1 MeV	3 MeV		≤9.5 MeV	
peak field	13.5 MV/m	18 MV/m		50 MV/m	
laser rep. rate	1 – 125 kHz	13 MHz	2 – 250 kHz	13 MHz	≤500 kHz
laser pulse length (FWHM)	15 ps	4 ps	15 ps	4 ps	15 ps
laser spot size	2.7 mm	5.2 mm	5.2 mm	2 mm	5 mm
bunch charge	≤ 200 pC	77 pC	400 pC	77 pC	1 nC
max. aver. Current	1 μA	1 mA	100 μA	1 mA	0.5 mA
peak current	13 A	20 A	26 A	20 A	67 A
transverse. norm. emittance (rms)	3±1 mm mrad @ 80 pC	2 mm mrad	7.5 mm mrad	1 mm mrad	2.5 mm mrad

The Wisconsin SRF 200 MHz Cavity



The WIFEL accelerator is required to supply each of the six FEL end stations simultaneously at up to a 1 MHz repetition

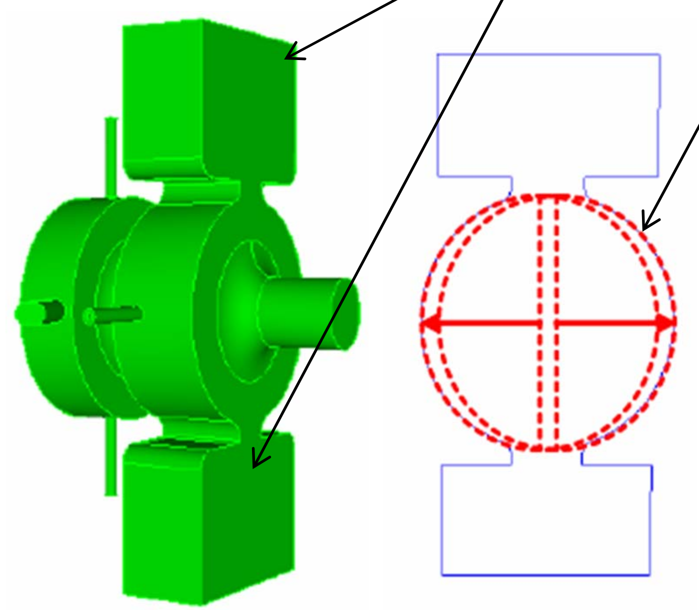
•Cs_2Te cathode, beam blow up regime 30 fs ~0.9 mm hemispherical transverse profile, 37 MV/m at cathode, 200 MHz SRF cavity, 5MeV final energy

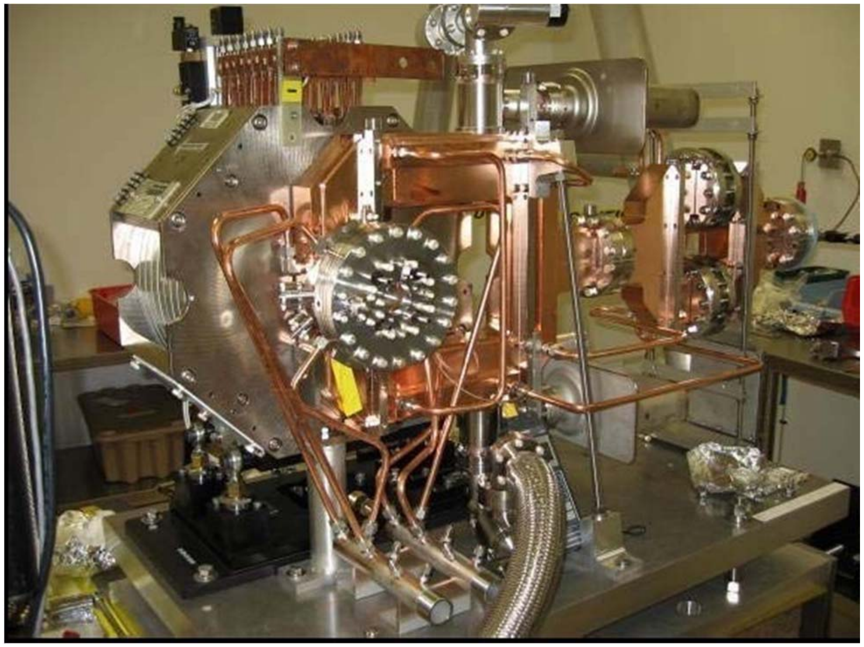
Pulse frequency, MHz	10
Charge per bunch, pC	200
Average current, mA	<2
I_{peak} at first bunch compressor, Amps	50
Peak field in gun, MV/m	41
σ_x at 100 MeV, mm	0.34
σ_z at 100 MeV, mm	0.34
Transverse ε at 100 MeV, mm-mrad	0.9
Longitudinal ε at 100 MeV, keV-mm	2.2

Courtesy of Robert Legg

SLAC NC S-Band RF Gun

Derived by the BNL-SLAC-UCLA design (S-Band).
Great care in minimizing dipolar and quadrupolar field components.





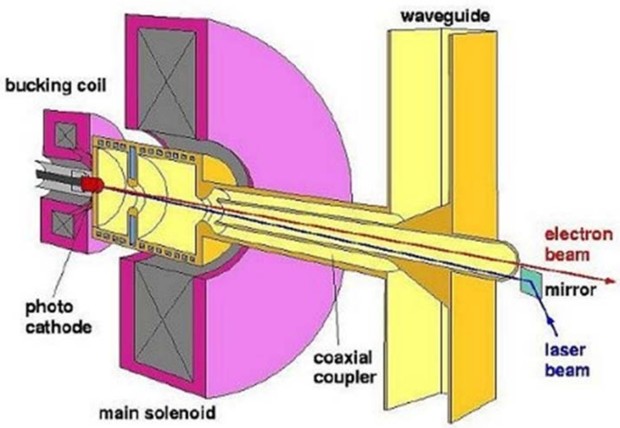
In operation

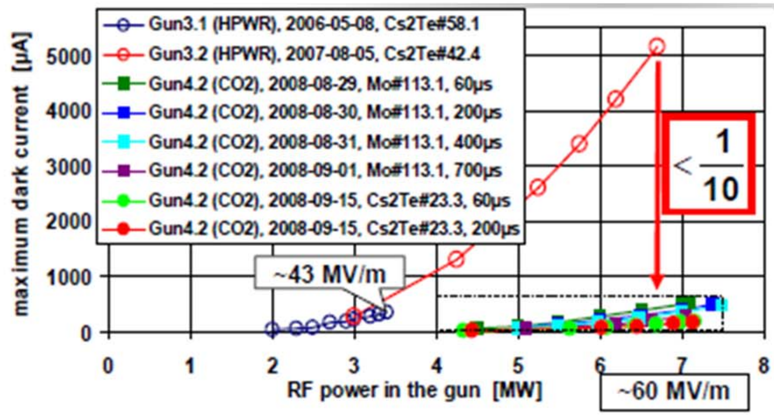
Up to date best performance

0.5 microns emittance at 250 pC
0.14 microns emittance at 20 pC

Courtesy of Dave Dowell

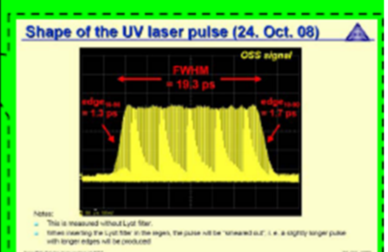
PITZ NC RF L-band Gun

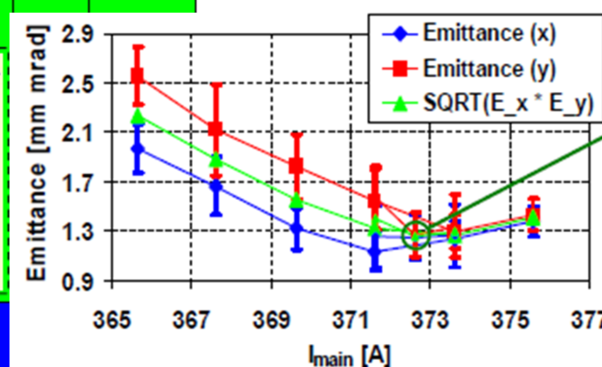




Surface cleaning techniques:
- HPWR: high-pressure water rinsing
- CO2: dry-ice cleaning, for details

- **Major reduction of dark current by CO2 snow cleaning**

	Rep. rate	Pulse train length	Individual pulse	Aver.current [mA] in train	Aver.current [mA] long term
achieved at PITZ	10Hz	200us, 1MHz (700us, 1MHz)	FWHM=18..19ps, rt≤2ps , 1nC FWHM=18..19ps, rt≤2ps , 1nC  Shape of the UV laser pulse (24. Oct. 08)	1 1	0.002 (0.007)
XFEL: to be achieved in 3 Years	10Hz	650us, 5MHz	FWHM=20ps, rt≤2ps		
possible in principle	10Hz 50Hz	1300us, 5MHz 1300us, 1300MHz	(?)FWHM=20ps, rt≤2ps(?), 1nC No pulse shaping, 77pC	5 100	0.065 6.5



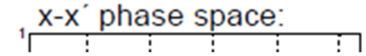
➔ for **~60 MV/m** we obtained

$\varepsilon_{x,n} = 1.25 \pm 0.19$ mm mrad
$\varepsilon_{y,n} = 1.27 \pm 0.18$ mm mrad @1nC

for 100 % RMS emittance !

➔ in good agreement with prediction from ASTRA

x-x´ phase space:

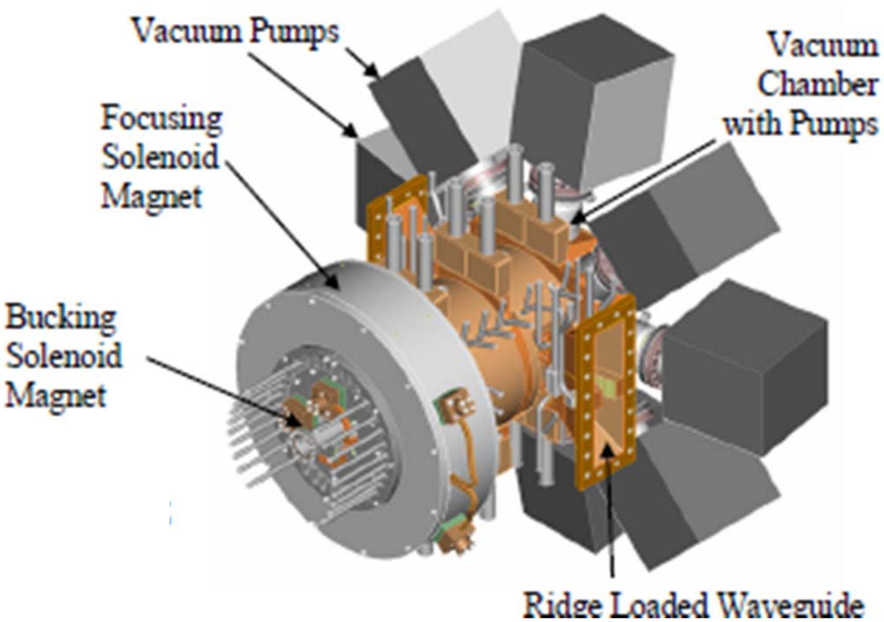


In operation

Courtesy of Frank Stephan

1.3 GHz Copper

LANL/AES NC CW 700 MHz Gun



Frequency	700	MHz
Energy	2.54	MeV
Current @ 33.3 MHz*	100	mA
Bunch Charge*	3	nC
Transverse Emittance	6	mm-mrad rms normalized
Longitudinal Emittance	145	keV-psec rms
Energy Spread	0.5	%
Bunch Length		psec rms

Courtesy of D. Nguyen and B. Carsten

700 MHz CW normal-conducting gun.

Hundreds of kW dissipated in the glidcop structure.

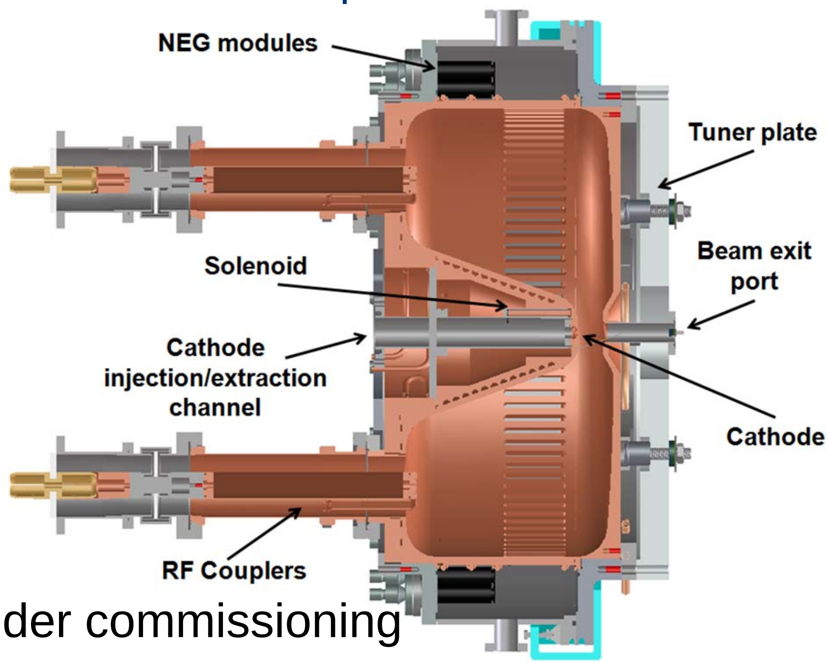
Part of a 100 mA injector for ~ 100kW IR FEL

RF conditioning successfully completed.

First beam tests soon

The LBNL CW NC VHF gun

The Berkeley normal-conducting scheme satisfies all the LBNL FEL requirements simultaneously.



Under commissioning

J. Staples, F. Sannibale, S. Virostek, CBP Tech Note 366, Oct. 2006

K. Baptiste, et al, NIM A 599, 9 (2009)

Frequency	187 MHz
Operation mode	CW
Gap voltage	750 kV
Field at the cathode	19.47 MV/m
Q_0	30887
Shunt impedance	6.5 MΩ
RF Power	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	69.4 cm
Total length	35.0 cm

- 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.
- 187 MHz compatible with both 1.3 and 1.5 GHz super-conducting linac technologies.