High brightness electron injectors for 4th generation light sources

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Contents

- Basics recap
- The role of electron sources and injectors in light source
- Requirements for electron sources and injectors
- Injector beam dynamics
- Injector components (additional material not presented during the lecture)

A lot of material for a single lecture!

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

References are given for those interested to a deeper insight.

Contents

- **Basics recap**
- The role of electron sources and injectors in light source
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- Injector beam dynamics
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From Single Particle to a Beam

• The number of particles per bunch in most accelerators can range between 10^5 to 10^{13}.

• Integrating the particle motion for such a large number of particles along accelerators with length ranging from few meters up to tens of kilometers can be a tough (impossible) task.

• Fortunately, *statistical mechanics* gives us very developed tools for representing and dealing with sets of large number of particles.

• Quite often, the statistical approach give us elegant and powerful insights on properties of the beam that could be hard to extract by approaching the problem using single particle techniques.

Phase Space Representation

In relativistic classical mechanics, the motion of a single particle is totally defined when, at a given instant t, the position r and the momentum p of the particle are given together with the forces (fields) acting on the particle.

$$\overline{r}_i = x_i\,\hat{x} + y_i\,\hat{y} + z_i\,\hat{z}$$

$$\overline{F} = F_x\,\hat{x} + F_y\,\hat{y} + F_z\,\hat{z}$$

$$\overline{p} = p_{xi}\,\hat{x} + p_{yi}\,\hat{y} + p_{zi}\,\hat{z}$$

It is quite convenient to use the so-called *phase space* representation, a 6-D space where the ith particle assumes the coordinates:

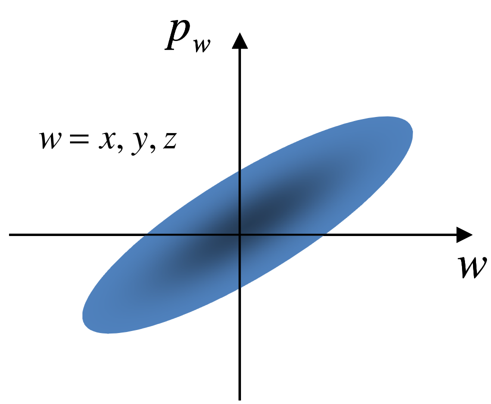
$$P_i \equiv \left\{ x_i, p_{xi}, y_i, p_{yi}, z_i, p_{zi} \right\}$$

In most accelerator physics calculations, the three planes can be considered with very good approximation as decoupled.
In this situation, it is possible and convenient to study the particle evolution independently in each of the planes:

$$\left\{ x_i, p_{xi} \right\} \qquad \left\{ y_i, p_{yi} \right\} \qquad \left\{ z_i, p_{zi} \right\}$$

Particles Systems & Ensembles

The phase space can now be used for representing particles:



The set of possible states for a system of N particles is referred as *ensemble* in statistical mechanics.

In the statistical approach, the particles lose their individuality. The properties of the whole system as a new individual entity are now studied.

The system is now fully represented by the density of particles f_{6D} and f_{2D} :

$$f_{6D}\left(x, p_x, y, p_y, z, p_z\right) dx\, dp_x\, dy\, dp_y\, dz\, dp_z \qquad f_{2D}\left(w, p_w\right) dw\, dp_w \qquad w = x, y, z$$

The above expressions indicate the number of particles contained in the elementary volume of phase space for the 6D and 2D cases respectively.

$$\int f_{6D}\, dx\, dp_x\, dy\, dp_y\, dz\, dp_z = N \qquad \int f_{2D}\, dw\, dp_w = N \qquad w = x, y, z$$

Important properties of the density functions can now be derived. Under particular circumstances, such properties allow to calculate the time evolution of the particle system without going through the integration of the motion for each single particle.

A system of variables q (generalized position) and p (generalized momentum) is Hamiltonian when exists a function $H(q, p, t)$ that allows to describe the evolution of the system by:

$$\frac{dq_i}{dt} = \frac{\partial H}{\partial p_i} \qquad \frac{dp_i}{dt} = -\frac{\partial H}{\partial q_i} \qquad \begin{aligned} \bar{q} &\equiv \{q_1, q_2, \ldots., q_N,\} \\ \bar{p} &\equiv \{p_1, p_2, \ldots., p_N,\} \end{aligned}$$

The function H is called Hamiltonian and q and p are referred as *canonical conjugate variables*.

In the particular case where q are the usual spatial coordinates $\{x, y, z\}$ and p their conjugate momentum components $\{p_x, p_y, p_z\}$, H coincides with the total energy of the system:

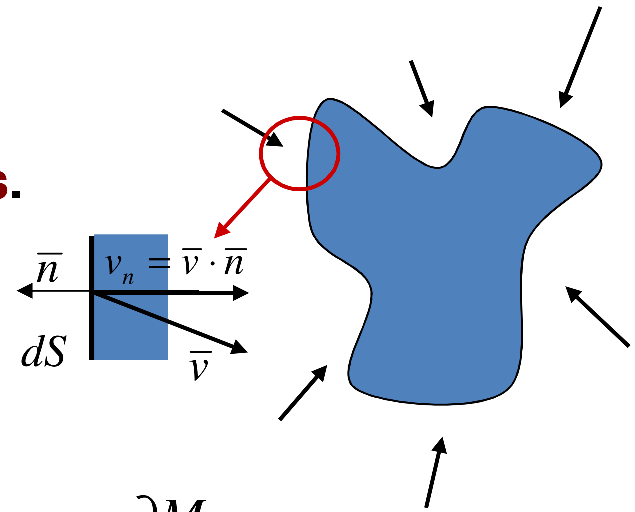
$$H = U + T = \text{Potential Energy} + \text{Kinetic Energy}$$

Non-Hamiltonian Forces:

- **Stochastic processes (collisions, quantum emission, diffusion, …)**
- **Inelastic processes (ionization, fusion, fission, annihilation, …)**
- **Dissipative forces (viscosity, friction, …)**

Mass Conservation → The Continuity Equation

If there is a flow of matter going in or out of a given volume, then the density inside the volume or the density must change in order to conserve the mass.



By indicating the density by ρ :

$$\rho(x, y, z, t)\, dx\, dy\, dz \equiv mass\ in\ the\ volume \quad dV = dx\, dy\, dz$$

$$dm = -\rho\, v_n dt\, dS = -\rho\, \bar{v} \cdot \bar{n}\, dS\, dt \;\Rightarrow\; \frac{dm}{dt} = -\rho\, \bar{v} \cdot \bar{n}\, dS \;\Rightarrow\; \frac{\partial M}{\partial t} = -\int_S \rho\, \bar{v} \cdot \bar{n}\, dS$$

But it is also true that:

$$M = \int_V \rho\, dV \;\Rightarrow\; \frac{\partial}{\partial t} \int_V \rho\, dV = -\int_S \rho\, \bar{v} \cdot \bar{n}\, dS.$$

But $\int_S \bar{F} \cdot \bar{n}\, dS = \int_V \nabla \cdot \bar{F}\, dV$

$$\Rightarrow\; \int_S \rho\, \bar{v} \cdot \bar{n}\, dS = \int_V \nabla \cdot \rho\, \bar{v}\, dV \;\Rightarrow\; \frac{\partial}{\partial t} \int_V \rho\, dV = -\int_V \nabla \cdot \rho\, \bar{v}\, dV$$

$$\Rightarrow\; \boxed{\frac{\partial \rho}{\partial t} + \nabla \cdot \rho\, \bar{v} = 0}$$

This expression, known as the continuity equation, is a consequence of the mass conservation law

Let us now use the continuity equation with our phase space.
For simplicity we will use a 2D distribution, but the same exact results apply to the more general 6D case.

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \rho \bar{v} = 0 \qquad \text{Let} \quad \rho \equiv f_{2D}(x, p_x) \quad \text{and} \quad \bar{v} \equiv \{\dot{x}, \dot{p}_x\}$$

$$\frac{\partial f_{2D}}{\partial t} + \nabla \cdot f_{2D}\bar{v} = \frac{\partial f_{2D}}{\partial t} + \frac{\partial(\dot{x} f_{2D})}{\partial x} + \frac{\partial(\dot{p}_x f_{2D})}{\partial p_x} = \frac{\partial f_{2D}}{\partial t} + \frac{\partial f_{2D}}{\partial x}\dot{x} + \frac{\partial f_{2D}}{\partial p_x}\dot{p}_x + f_{2D}\frac{\partial \dot{p}_x}{\partial p_x} + f_{2D}\frac{\partial \dot{x}}{\partial x}$$

But if our system is Hamiltonian ➡ $f_{2D}\frac{\partial \dot{x}}{\partial x} + f_{2D}\frac{\partial \dot{p}_x}{\partial p_x} = f_{2D}\frac{\partial^2 H}{\partial x \partial p_x} - f_{2D}\frac{\partial^2 H}{\partial x \partial p_x} = 0$

➡
$$\frac{\partial f_{2D}}{\partial t} + \nabla \cdot f_{2D}\bar{v} = \frac{\partial f_{2D}}{\partial t} + \frac{\partial f_{2D}}{\partial x}\dot{x} + \frac{\partial f_{2D}}{\partial p_x}\dot{p}_x = \frac{df_{2D}}{dt}$$

$$\frac{df_{2D}}{dt} = 0$$

Liouville Theorem: In Hamiltonian systems, the phase space density is an invariant of the motion. Or equivalently, the phase space volume occupied by the system is conserved.

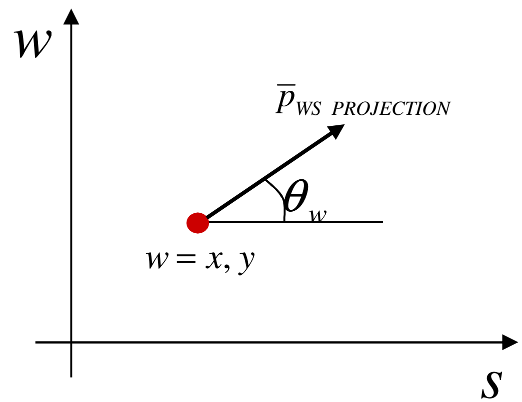
The Transverse Phase Space

For the transverse planes $\{x, p_x\}$ and $\{y, p_y\}$, it is usually used a modified phase space (sometimes referred as the *trace-space*) where the momentum components are replaced by:

$$p_{xi} \rightarrow x' = \frac{dx}{ds} \qquad\qquad p_{yi} \rightarrow y' = \frac{dy}{ds}$$

The physical meaning of the new variables:

$$x' = \frac{dx}{ds} = \tan\theta_x \qquad\qquad y' = \frac{dy}{ds} = \tan\theta_y$$



The relation between this new variables and the momentum (when $B_z = 0$) is:

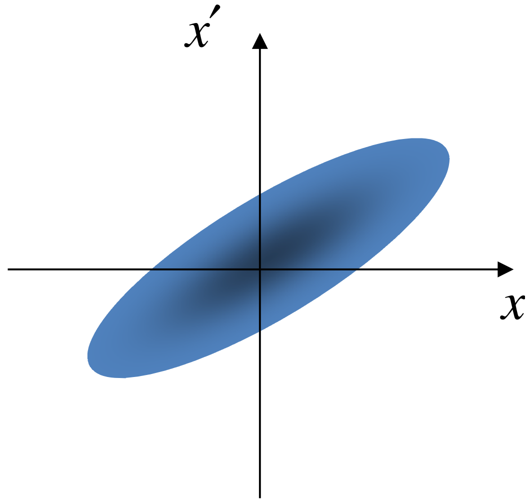
$$p_x = \gamma m \frac{dx}{dt} = \gamma m v_s \frac{dx}{ds} = \gamma \beta m c x'$$

$$p_y = \gamma \beta m c y'$$

$$where \quad \beta = \frac{v_s}{c} \quad and \quad \gamma = \left(1 - \beta^2\right)^{-1/2}$$

Note that x and p_x are canonical conjugate variables (CCV) while x and x' are CCV only if there is no acceleration (γ and β constant).

Definition of Emittance



We will consider the decoupled case and use the {w, w'} plane where w can be either x or y.

We define as emittance (often referred also as geometric emittance) the phase space area occupied by the system of particles, divided by π

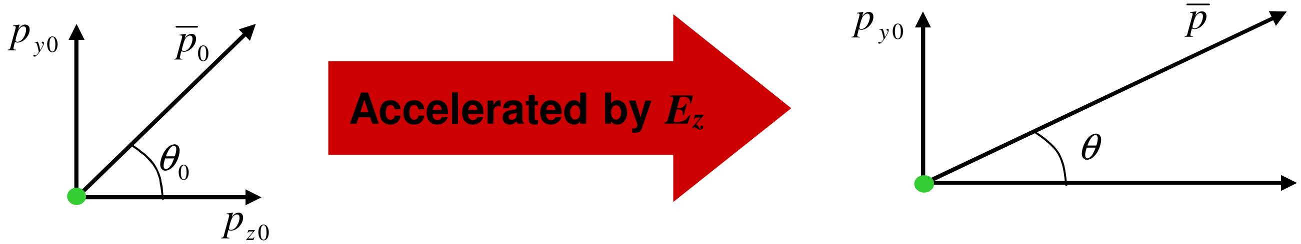
$$\varepsilon_w = \frac{A_{ww'}}{\pi} \qquad w = x, y$$

It can be shown that the quantities x' and y' are conjugate to x and y when $B_z = 0$ and in absence of acceleration. In this case, we can immediately apply the Liouville theorem and state that for such a system the emittance is an invariant of the motion.

This specific case is actually extremely important.
In fact, for most of the elements in a beam transferline, such as dipoles, quadrupoles, sextupoles, …, the above conditions apply and the emittance is conserved.

Emittance in the Presence of Acceleration

When the particles in a beam undergo to acceleration, β and γ change and the variables x and x' are not canonical anymore. Liouville theorem does not apply and the emittance is not conserved.



$$p_z = \sqrt{\frac{T^2 + 2Tmc^2}{T_0^2 + 2T_0 mc^2}}\, p_{z0}$$

$T \equiv kinetic\ \ energy$

$$y_0' = \tan\theta_0 = \frac{p_{y0}}{p_{z0}} = \frac{p_{y0}}{\beta_0 \gamma_0 mc} \qquad y' = \tan\theta = \frac{p_y}{p_z} = \frac{p_{y0}}{\beta \gamma mc} \qquad \frac{y'}{y_0'} = \frac{\beta_0 \gamma_0}{\beta \gamma}$$

It can be shown that in this case $\dfrac{\varepsilon_y}{\varepsilon_{y0}} = \dfrac{y'}{y_0'}$

$$\boxed{\beta \gamma \varepsilon_y = \beta_0 \gamma_0 \varepsilon_{y0}}$$

The last expression tells us that the quantity $\beta \gamma \varepsilon$ is a system invariant during acceleration. By defining the normalized emittance:

$$\boxed{\varepsilon_{nw} = \beta \gamma \varepsilon_w \qquad w = x, y}$$

Note that $\varepsilon_{nw} = \dfrac{p_w}{mc}\varepsilon_w \quad w = x, y$

We can say that the normalized emittance is conserved during acceleration.

In other words, the acceleration couples the longitudinal plane with the transverse one: the 6D emittance is still conserved but the transverse ones are not.

For the case of a real beam composed by N particles, we start calculating the second order statistical moments of its phase space distribution:

$$\langle x^2 \rangle = \frac{\sum_{n=1}^{N} x_n^2}{N} \cong \frac{\int x^2 f_{2D}(x,x')\,dx\,dx'}{\int f_{2D}(x,x')\,dx\,dx'} \qquad \langle x'^2 \rangle = \frac{\sum_{n=1}^{N} x_n'^2}{N} \cong \frac{\int x'^2 f_{2D}(x,x')\,dx\,dx'}{\int f_{2D}(x,x')\,dx\,dx'}$$

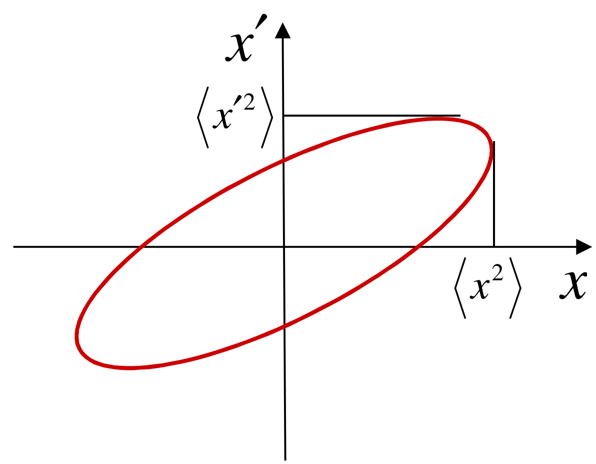
$$\langle x\,x' \rangle = \frac{\sum_{n=1}^{N} x_n x_n'}{N} \cong \frac{\int x\,x'\; f_{2D}(x,x')\,dx\,dx'}{\int f_{2D}(x,x')\,dx\,dx'}$$

We then define the **rms emittance** as the quantity:

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

This is equivalent to associate to the real beam an *equivalent ellipse* in the phase space with area $\pi\varepsilon_{rms}$ and equation:

$$\frac{\langle x'^2 \rangle}{\varepsilon_{rms}} x^2 + \frac{\langle x^2 \rangle}{\varepsilon_{rms}} x'^2 - 2\frac{\langle x\,x' \rangle}{\varepsilon_{rms}} x\,x' = \varepsilon_{rms}$$

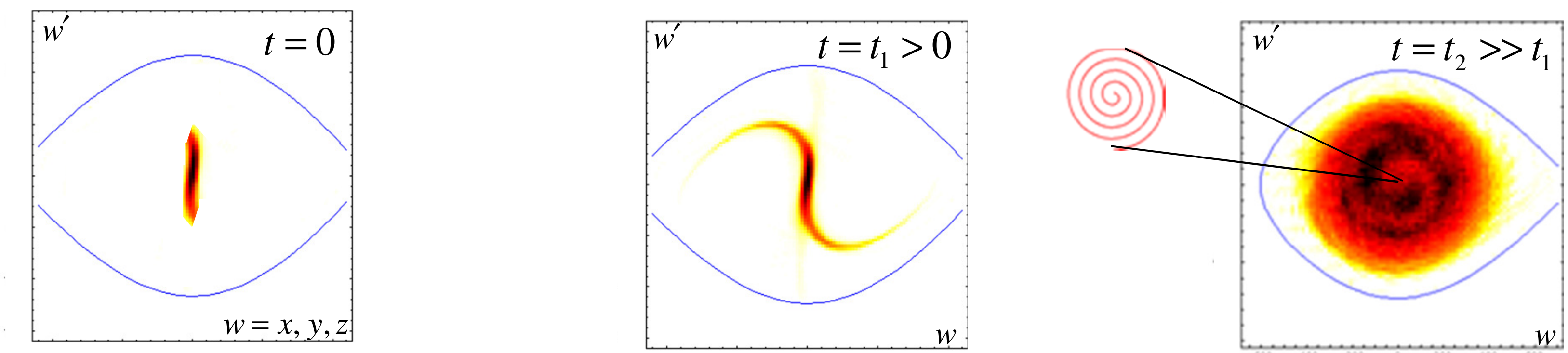


Nonlinear Forces and Filamentation

- In the case of a Hamiltonian system, as a consequence of the Liouville Theorem the 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

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



- In all these cases the emittance according to Liouville is still conserved.

But the rms emittance increases instead!

Brightness

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

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

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

For what previously discussed, in linear Hamiltonian systems brightness is a motion invariant.

In nonlinear Hamiltonian systems brightness can only decrease.

In non-Hamiltonian systems brightness can either increase or decrease.

In general the major goals for electron injectors is to generate *short beams* with a *large number of electrons,* all 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 beam brightness.

For a fixed charge per bunch that translates in minimizing the emittance in each of the planes.

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- Basics recap
- **The role of electron sources and injectors in light source**
- Requirements for electron sources and injectors
- Injector beam dynamics
- Injector components
- Challenges and required R&D

What is an Electron Injector?

The electron injector is the initial part of an accelerator (chain) where the electrons are generated and conditioned (at some level) to match the requirements of the following main accelerator.

The injector obviously initiates with an electron source, but where does it end?

Space charge forces play a central and in most of the cases a dominant role in limiting and spoiling the quality of an electron beam.

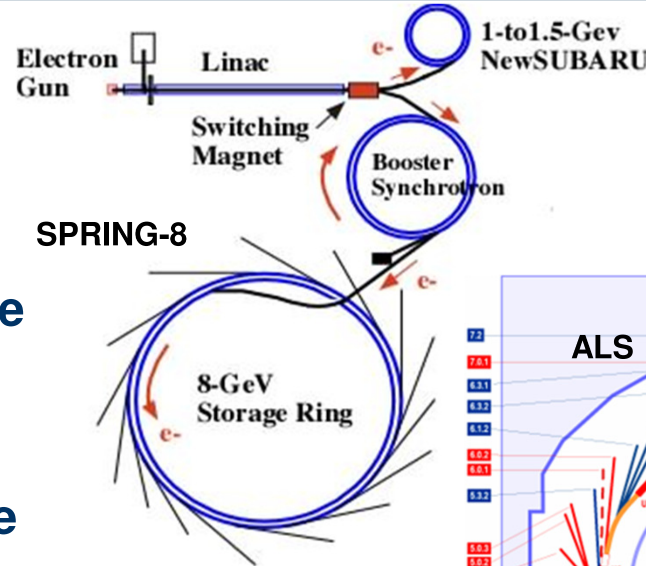
We will see that space charge forces scale inversely with the square of the beam energy.

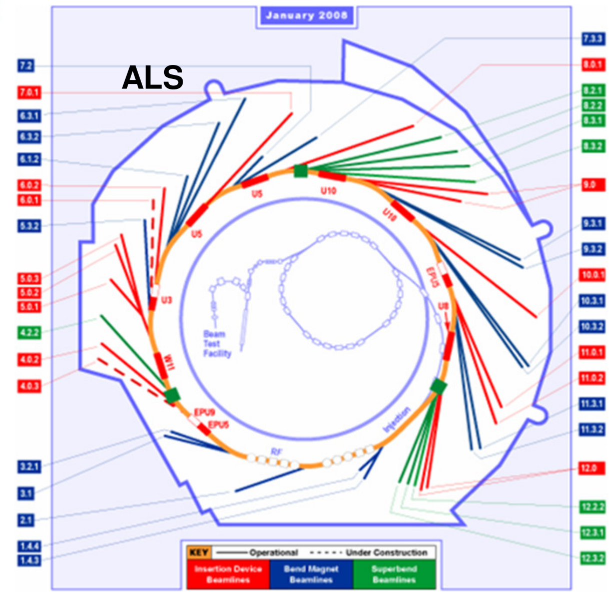
In the typical assumption, the injector should accelerate the electron beam up to energies sufficient to make space charge forces very small or preferably negligible and so "freeze" the beam brightness.

In other words, the ultimate beam quality (brightness) in a linac based accelerator is defined at the injector.

The Role of the Electron Injector in Light Sources

- *1st generation*: "parasitic" synchrotron radiation sources from dipoles in colliders.
- *2nd generation*: dedicated storage rings with light ports in dipoles
- *3rd generation*: dedicated storage rings with *insertion devices* (undulators, wigglers)
- *4th generation*: free electron lasers, energy recovery linacs…

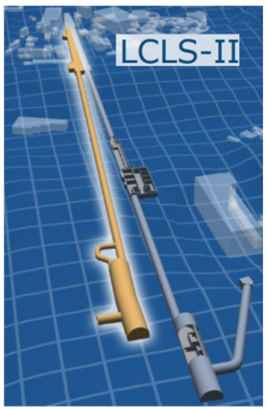


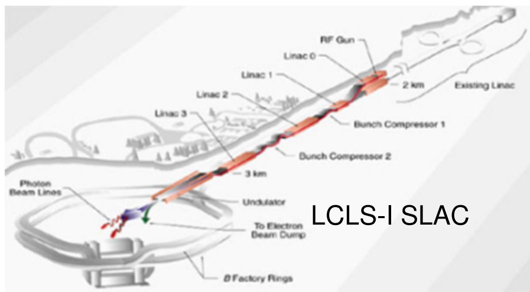


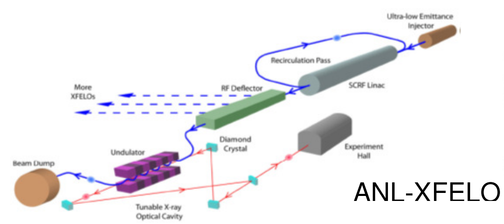
In 1st, 2nd and 3rd gen. light sources, electron sources are part of an injector chain that typically includes a small linac and a "booster/accumulator" ring. The beam generated by the electron gun goes through the linac and is then accelerated and stored in the booster for a time long enough that the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

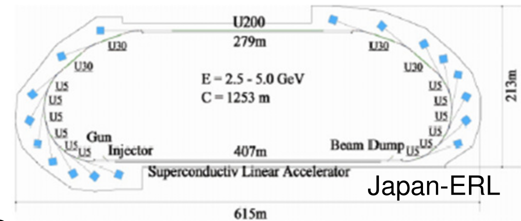
The Role of the Electron Injector in Light Sources

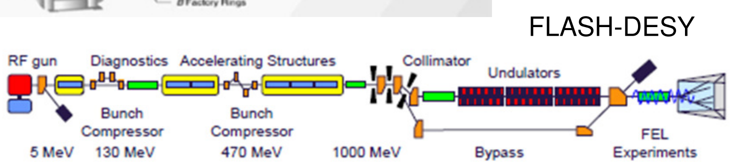
In linac based 4th generation light sources, such as free electron lasers (FELs) and energy recovery linacs (ERLs), the situation is quite different. In this machines, the final beam quality is defined already in the injector and ultimately in its electron source.

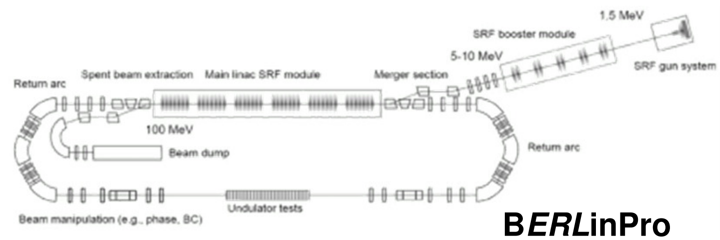












In such facilities, the requirements for a large number of quasi-"monochromatic" electrons, concentrated in very short bunches, with small transverse size and divergence, translate into high particle density 6D phase-space, or in other words, in high brightness B:

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

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.

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

- 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: $\lambda = \lambda_u / 2\gamma^2(1 + K^2/2)$)

- For the present electron gun technologies:

$\varepsilon_n <$ ~0.4 μm for the typical < ~300 pC charge/bunch.

For X-Ray machines ($\lambda <$ ~1 nm) that implies GeV-class electron beam energies 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 low energy spread as well

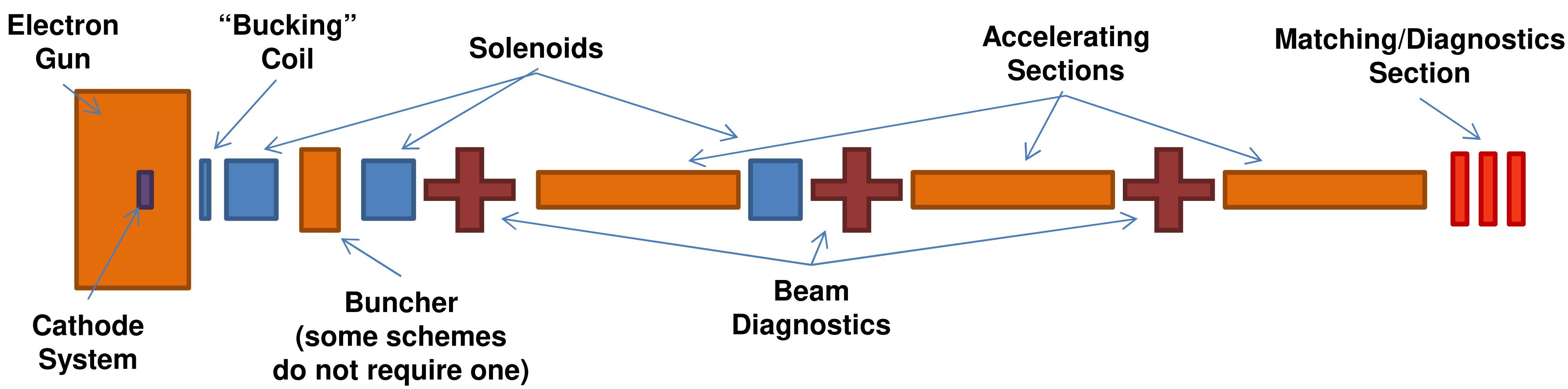
$$\frac{\sigma_E}{E} <\sim \rho_{Pierce} \propto \frac{1}{\gamma}\left[\frac{I_p}{\varepsilon_x}\lambda_u^2 K_u^2\right]^{1/3} \approx 10^{-3}$$

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

- 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.

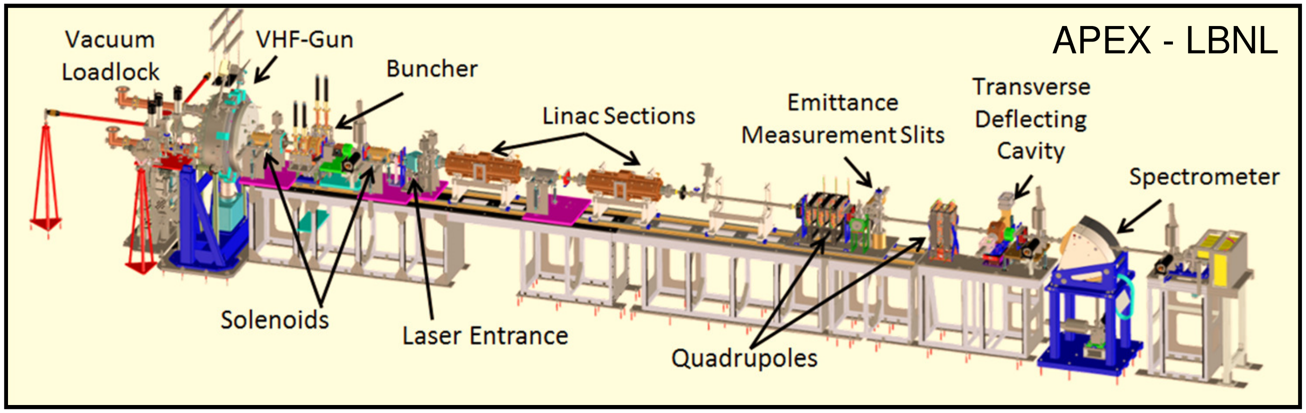
In summary, 4th generation X-Ray facilities challenge the brightness performance of electron injectors. We will from now on focus on such a type of injectors

The Typical High-Brightness Injector Layout



Injector Sub-Systems:

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



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Injector Requirement in 4th Generation Light Source

Repetition rate	up to ~1MHz/ 1GHz	X-FELs/ ERLs
Charge per bunch	~ 10 – 1000 pC	Different modes of operation
Normalized emittance	~ 0.1 – 1.0 μm	Lower values for lower charges
Beam energy at the injector exit	~100 MeV	Space charge force negligible
Beam energy at the gun exit	>~ 500 keV	For controlling space charge
Electric field at the cathode during emission	>~ 10 MV/m	Space charge limit; maximum brightness limit
Bunch length and shape control	From < ~1 to ~ 60 ps	Space charge control; different modes of operation
Relative energy spread		Compatible with $\sim 10^{-3}$ @ linac exit
Cathode/gun area magnetic field compatibility		Emittance compensation; (exotic modes)
Dark current at nominal gun energy	< ~ 1 μA	SRF quencing; rad. damage in high rep. rate facilities
Operational vacuum pressure	$\sim 10^{-10} – 10^{-9}$ Torr	High QE cathode lifetime in high rep. rate facilities
Loadlock cathode vacuum system		"Quick" cathode exchange in high rep. rate facilities
Reliability	High (>~99%)	Required for an user facility

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Injector Transverse Normalized rms 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 depends on te cathode properties and is referred as the **cathode thermal or intrinsic emittance**. It will be discussed in the next slide.

- The 2nd term is due to the presence of a solenoidal field B_z at the cathode (Busch's theorem; Palmer, *et al.*, PAC97, p. 2843) ➡ $\varepsilon_{nr\ Bz\ at\ Cathode} = \frac{e}{2mc}\sigma_r^2 B_z$

- The third term is due to the space charge term and the techniques to minimize it and to compensate for its linear part will be described.

- The Beam Optics term is associated with the geometric and chromatic aberrations in the magnetic and electromagnetic components along the injector.

- The last term is due to the presence of the time variable RF fields along the injector.

The optimization game in injectors consists in making all the emittance contributions possibly negligible with respect to the cathode one.

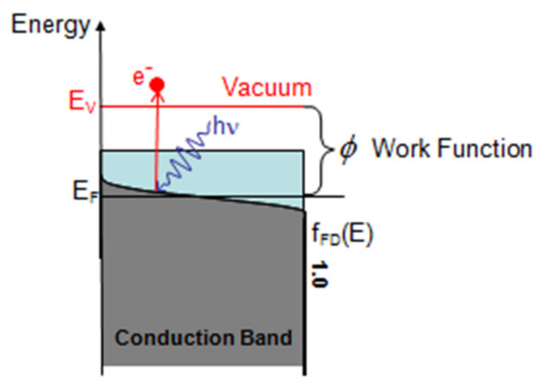
Cathode Thermal/Intrinsic Emittance

- The **cathode thermal or intrinsic emittance** (or we should more precisely say the cathode <u>normalized</u> thermal or intrinsic emittance) defines the emittance contribution associated to the cathode.
- Its value is defined by the cathode material and by the emission process.

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

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

Metal photocathode example:



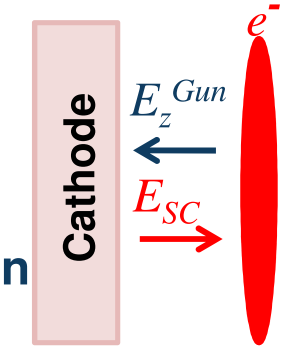
$$\frac{\varepsilon_{n\,Cathode}}{\sigma_r} = \sqrt{\frac{h\upsilon - (\phi - \phi_{Schottky})}{3mc^2}}$$

$$\phi_{Schottky\ [eV]} = 3.7947\times10^{-5}\sqrt{E_{z\,[V/m]}^{Gun}}$$

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

Space Charge Limit

- **During emission at the cathode, the electric field E_{SC} due to the already emitted electrons shows opposite direction with respect to E_z^{Gun}, the accelerating field in the gun.**
  The emission can continue until E_{SC} cancels E_z^{Gun}.
  The max charge density that can be estracted by a given E_z^{Gun} is known as the 'space-charge limit' $\sigma_{SC\,MAX}$.



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

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

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

- **We saw that the emittance at the cathode is proportional to σ_r and to the square root of the excess energy ΔE → $\varepsilon_n \propto \sigma_r \sqrt{\Delta E_C}$**

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

Bazarov, PRL 102, 104801 (2009)

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

Filippetto, PRSTAB 17, 024201 (2014)

with $\Delta\tau$ the bunch length

The max brightness is limited by E_z^{Gun} and by the cathode thermal emittance. For fixed E_z^{Gun}, cigar beams allow for higher brightness if larger longitudinal emittances are acceptable.

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**: 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:

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

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

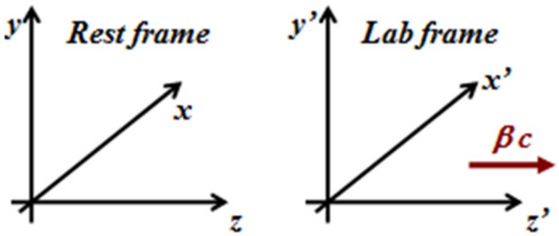
$$F_y = q\left(E_y + \beta c B_x\right) = qE_y\left(1-\beta^2\right) \propto \lambda_C\left(1-\beta^2\right)y$$

• The **force dependence on the** $(1 - \beta^2) = 1/\gamma^2$ term derived in this particular example 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)

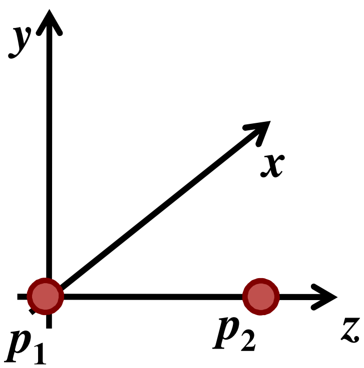
For more information, see for example: Wiedemann, Particle Accelerator Physics, Springer, 3rd edit., chapter 18.2.

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 dominant role** that if not controlled jeopardizes brightness.

- 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 a 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**

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.

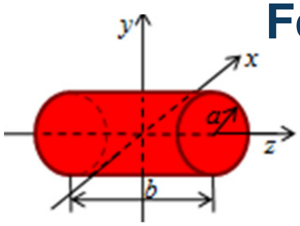
- The best approximation of the above distributions, projected in the 3D spatial reference frame, is represented by a 3D ellipsoidal beam with uniform particle density inside and zero elsewhere.
- This distribution generates linear space charge forces in both transverse and longitudinal planes, and no r.m.s. emittance increase.

- Uniform ellipsoidal charge densities can be experimentally pursued by shaping the laser in a 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 a cathode were high gradients are applied (~100MV/m). 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.

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

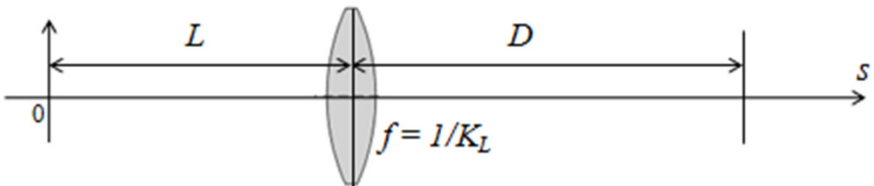


For a cylindrical beam with radius a, length b, linear charge density $\lambda_C(z)$ slow changing function of z, and uniform transverse charge density,

Teng showed that in the core of the beam:

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

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

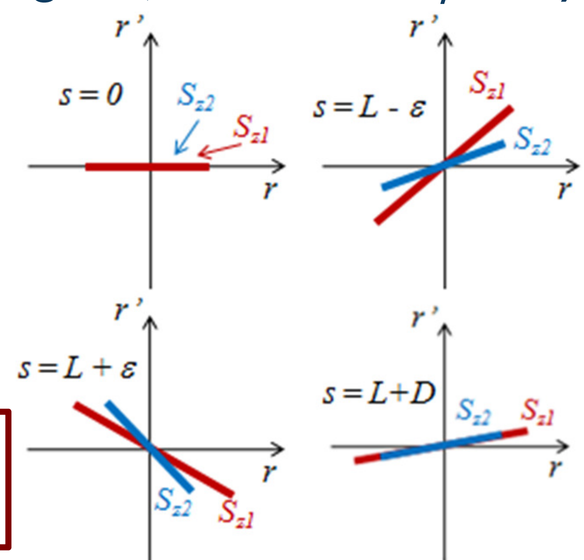


The transverse motion equations for a particle in the 'slice' at position z through the system are (assuming $r'(z,0) = 0$ and $\mathrm{d}F_r/\mathrm{d}s \sim 0$):

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

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

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



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).

Aberrations in the Electron Beam Optics

- Aberrations in axially symmetric (magnetic or electromagnetic) elements that arise from r^3 dependencies of transverse fields are commonly referred to as **geometric aberrations** (r^2 dependencies are not allowed by symmetry).
- **Chromatic aberrations** include for example focal length dependence on particle energy.
- Such aberrations can affect the slice and/or the projected emittances.

Example. Geometric and chromatic aberrations in solenoids.

$$\alpha = \frac{1}{4}\left(\frac{e}{2mc\beta\gamma}\right)^2 \int \left(\frac{\partial B_z}{\partial z}\right)^2 dz$$

$$B_r \cong -\frac{r}{2}\frac{\partial B_z}{\partial z} + \frac{r^3}{16}\frac{\partial^3 B_z}{\partial z^3}$$

$$\boxed{\varepsilon_x = \kappa \alpha \sigma_x^4} \quad with$$

$$\kappa = \begin{cases} \sqrt{8} \;\; Gaussian \\ \sqrt{200/147} \;\; Elliptical \\ \sqrt{8}/3 \;\; Uniform \end{cases}$$

$$\frac{1}{f_{sol}} = \left(\frac{e}{2mc\beta\gamma}\right)^2 \int B_z^2 dz$$

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

Aberrations can play a significant role especially in low charge bunches (< ~ tens of pC), where the space charge effects can be usually controlled, and aberrations and thermal emittance become the terms defining the final emittance value.

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

Transverse Emittance Dilution Due to RF

- RF cavities generate the longitudinal electric field E_z to accelerate the particles. Due to Maxwell equations and symmetry constraints also radial and azimuthal field components 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 (time-dependent defocusing effect)

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

- 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)

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- Basics recap
- The role of electron sources and injectors in light source
- Requirements for electron sources and injectors
- **Injector beam dynamics (longitudinal)**
- Injector components

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

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 (Gaussian case):

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

- For example for a 1 nC, 10 ps rms 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

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.

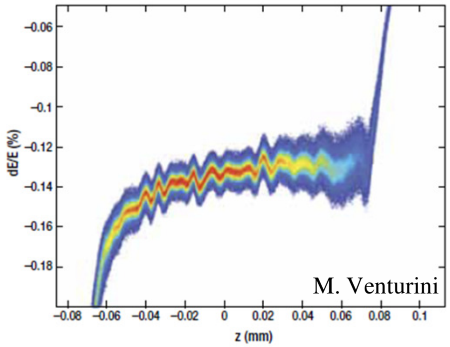
• Space charge can be controlled by reducing the beam charge density, especially in the cathode region where the beam energy is small.
The use of larger transverse beam sizes at the cathode to reduce the density is carefully minimized because it increases the cathode thermal emittance.

• 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.

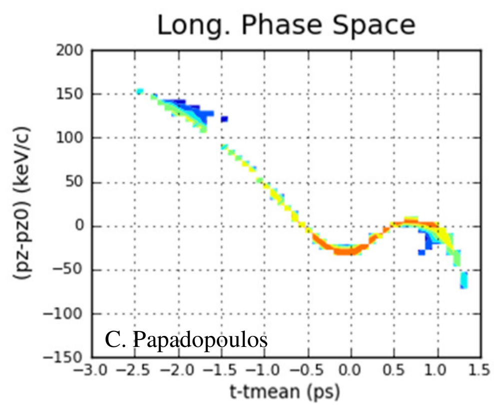
Bunch Length Compression

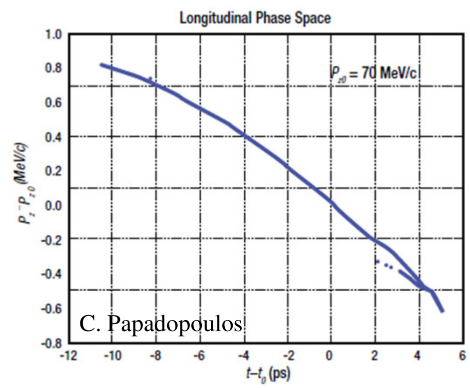
• In most 4th generation light source schemes, the bunch length at the gun is typically longer than that required at the undulator position. **Longitudinal compression** is then necessary and can be performed in the linac and /or in the injector and/or in the arcs in the case of ERLs.



• **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.

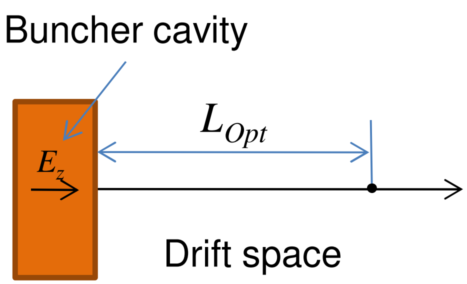


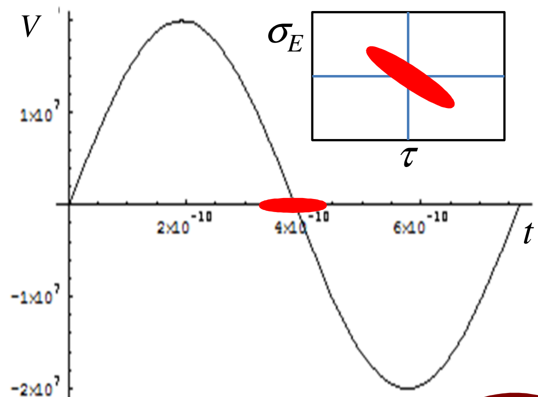


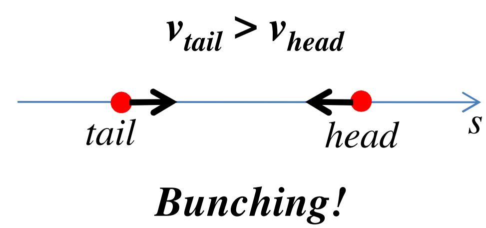
• The proper balance between these compression strategies must be found.

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

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:**

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

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:

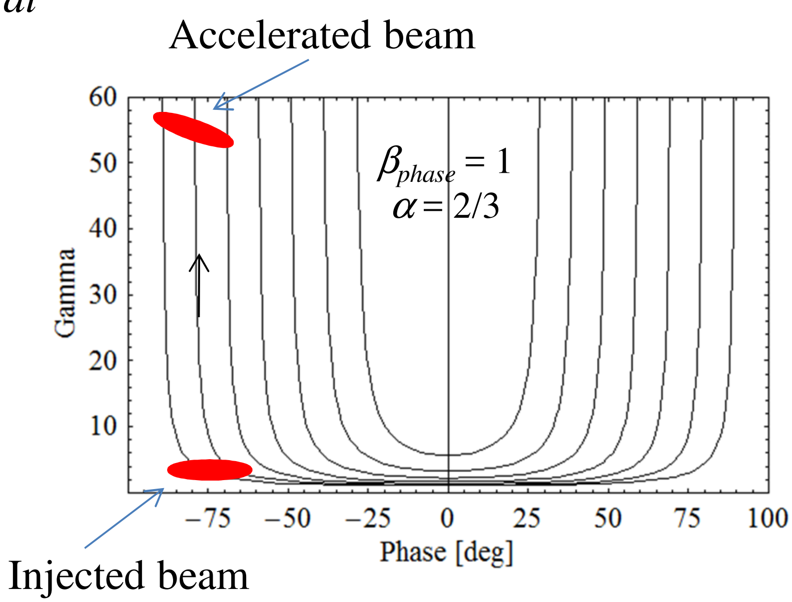
$$E_z = \hat{E}_z \sin(\omega t - kz - \psi_0) \quad with \quad \frac{\omega}{k} = c\beta_{phase}$$

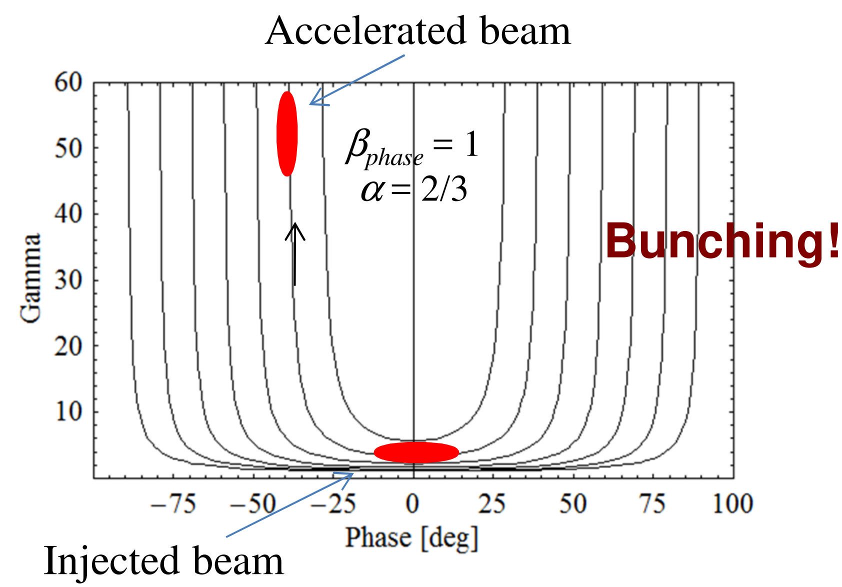
$$\begin{cases} \dfrac{d\varphi}{dt} = kc\left(\beta - \beta_{phase}\right) \\ \dfrac{dp}{dt} = -e\hat{E}_z \sin\varphi \quad with \;\; \varphi = \omega t - kz - \psi_0 \end{cases}$$

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

$$and \;\; H \equiv constant$$

Particles trajectories in the γ, φ phase space





- **The method can generate high compression factors, 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).

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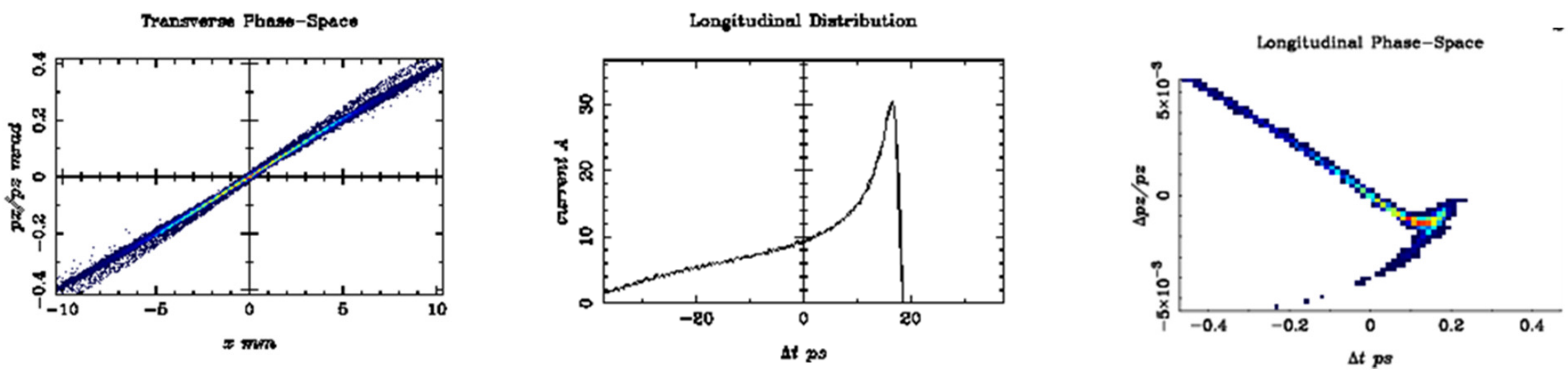
Real Non-Linear Injectors

• 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

During this lecture we got the appreciation of 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 and optimization can be pursued only by simulation tools.

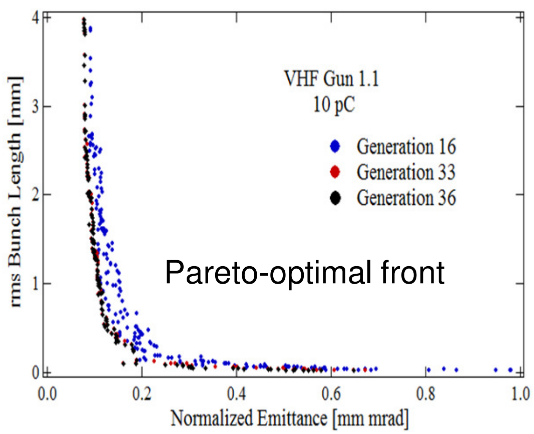
Indeed, a number of simulation codes with space charge have been developed over the years to address the problem, and are heavily used in the design and optimization of high-brightness electron injectors.

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).

Additional Material

Contents

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, …)

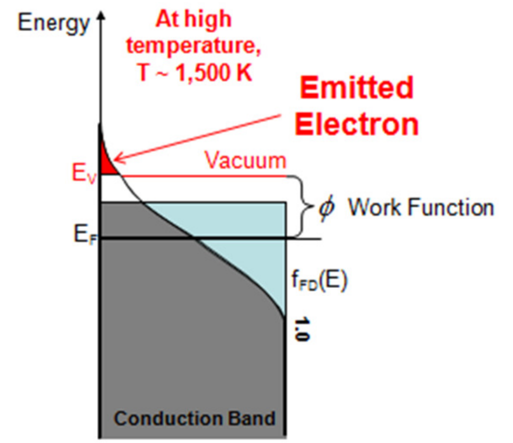
Cathode Parameters: Thermal/Intrinsic Emittance (Metals)

- 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.**

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

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

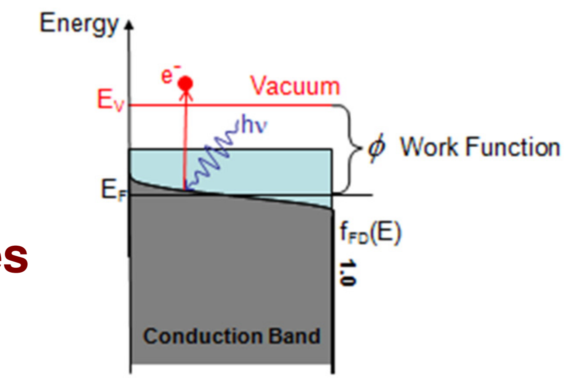
Thermionic cathodes



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

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

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)

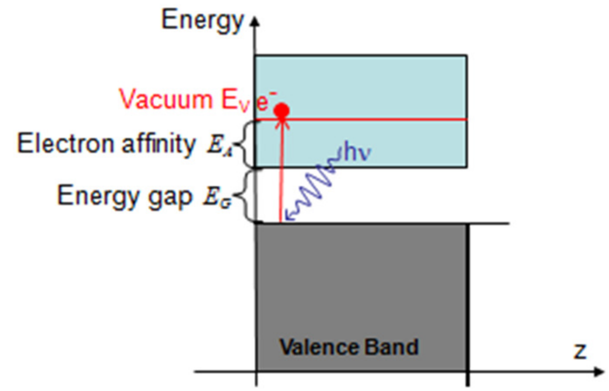
Cathode Parameters Thermal/Intrinsic Emittance (Semiconductors)

- **Two cases can be distinguished:**

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

$$\phi_{Schottky\ [eV]} = 3.7947\times10^{-5}\sqrt{E^{Gun}_{z\ [V/m]}}$$

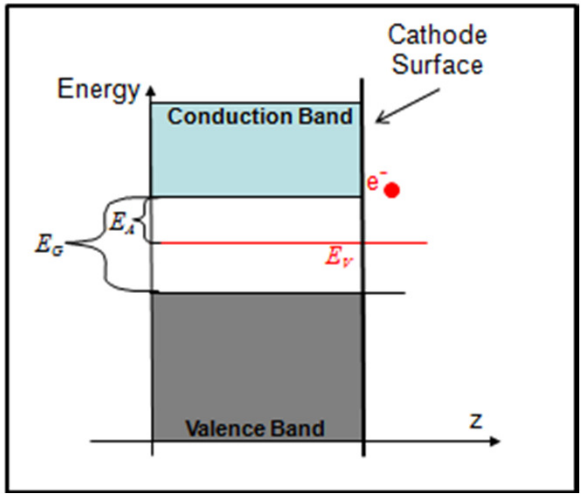
Positive electron affinity cathodes



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

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:

$$J_{peak} = \frac{Q}{\pi r^2 \sigma_\tau} \sim 5\times10^4 \;\; A/cm^2$$

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, in part 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.

LBNL

"Popular" Photo-Cathodes

Electron Injectors Tutorial
(F.Sannibale)

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	?	?

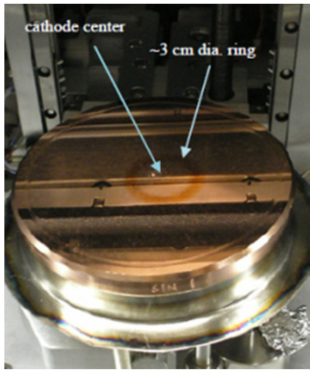
SEMICONDUCTORS

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, 5.88 264, 4.70 262, 4.73	~0.1 - -	10^{-9} - -	3.5 [42] " "	1.2 0.9 0.9	0.5±0.1 [35] 0.7±0.1 [35] 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, 2.33 860, 1.44	~0.1 -	? ?	1.4±0.1 [42] "	0.8 0.2	0.44±0.01 [44] 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



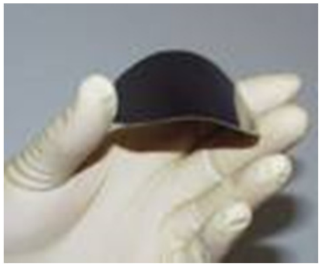
Metal: Cu, … (used at LCLS for example)

- <~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

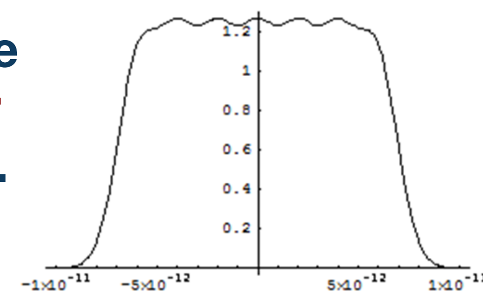
Laser Pulse Shaping

• 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.**



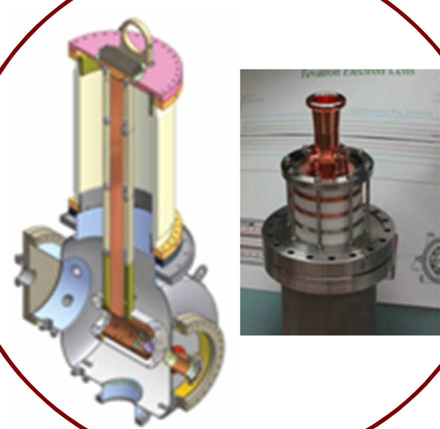
6 Gaussian pulses with σ_τ = 1 ps added with 2 σ_τ peak to peak distance

• 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).

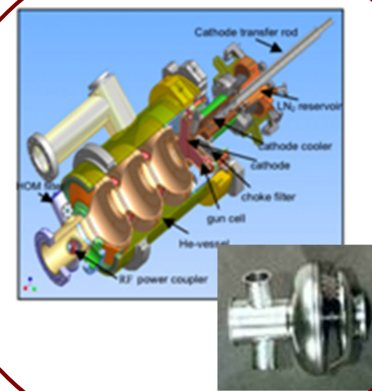
• **Nonlinear commercial focusing lens systems** can also be used but require excellent alignment and size matched Gaussian beams.

Principal Gun Technologies

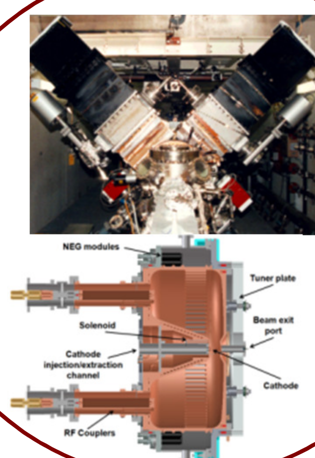


DC guns

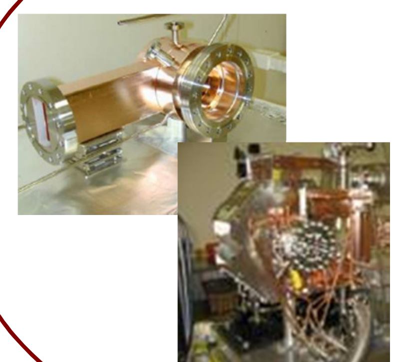
and hybrids



SC RF guns



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

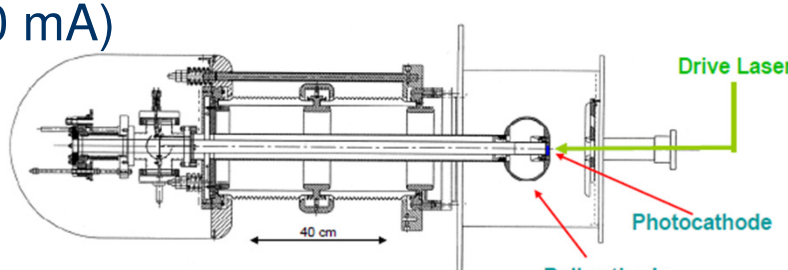


High freq.(> ~1 GHz) NC RF guns

DC Guns

Pros:

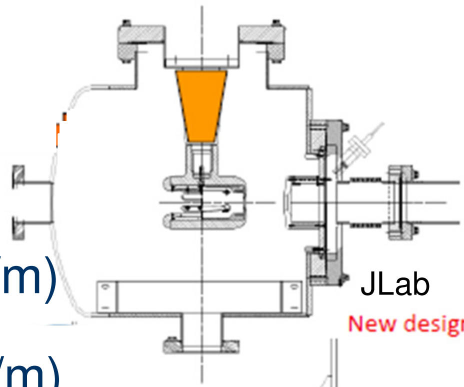
- DC operation and GHz-class repetition rate
- DC guns reliably operated at ~ 400 kV, ongoing effort to increase the final energy to ~ 500 kV (Cornell, JLab, JAEA, KEK, …).
- Injector with DC gun (Cornell, …) demonstrated the capability of sub-micron emittances at <~ 300 pC, if a sufficient number of knobs are provided
- High current operation demonstrated (~ 70 mA)
- Full compatibility with magnetic fields.
- Excellent vacuum performance
- Compatible with most photo-cathodes. (The only one operating GaAs cathodes)



350 kV DC gun

Challenges:

- Beam energy approaching the limit of the technology
- Limited accelerating gradients at the cathode (up to ~ 10 MV/m)
- Minimizing field emission for higher gradients (up to ~ 10 MV/m)
- Developing and test new gun geometries (inverted geometry, SLAC, JLab)

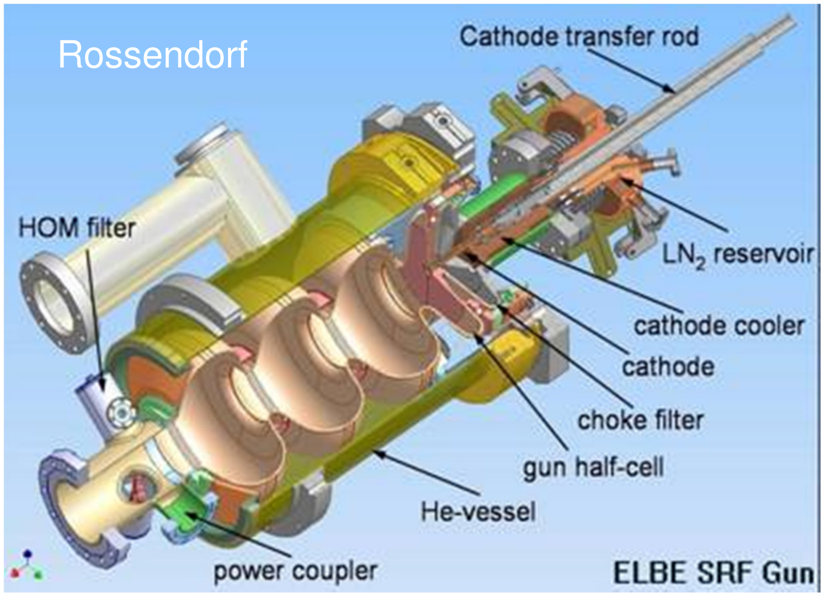


JLab
New design

Super-Conducting RF Guns

Pros:

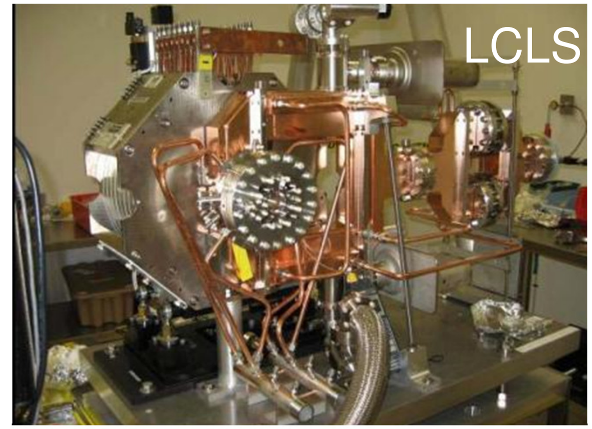
- Potential for relatively high gradients. Demonstrated ~ 40 MV/m with superconductive cathodes and ~ 20 MV/m with warm cathodes.
- CW operation with GHz-class repetition rate capabilities
- Excellent vacuum performance.

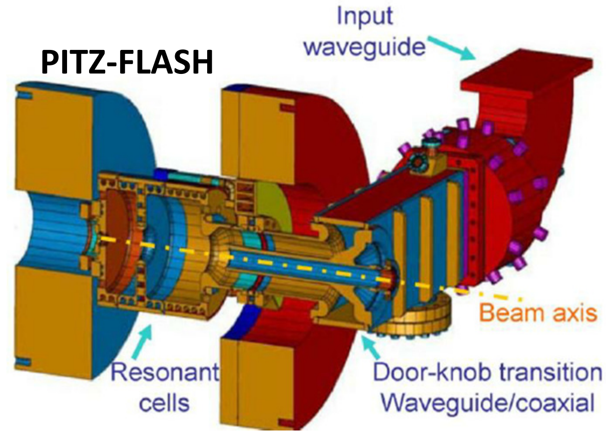


Challenges:

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

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





Pros:

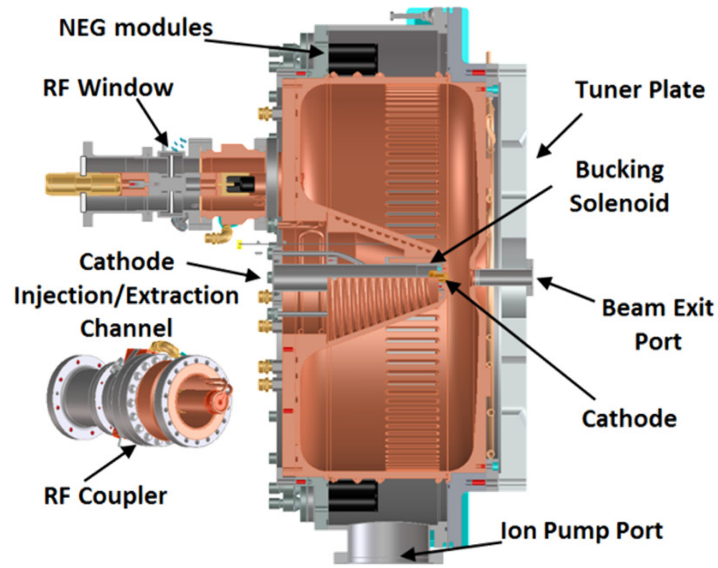
- High gradients from ~50 to ~140 MV/m
- "Mature" technology.
- Full compatibility with magnetic fields.
- Compatible with most photocathodes
- Proved high-brightness performance.

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:



- Operate in CW mode
- Beam Dynamics similar to DC but with much higher gradients and beam energies
- Based on mature RF and mechanical technology.
- Full compatibility with magnetic fields.
- Compatible with most photo-cathodes (demonstrated low pressure performance capability)
- Demonstrated high brightness performance as required by FELs

Challenges:

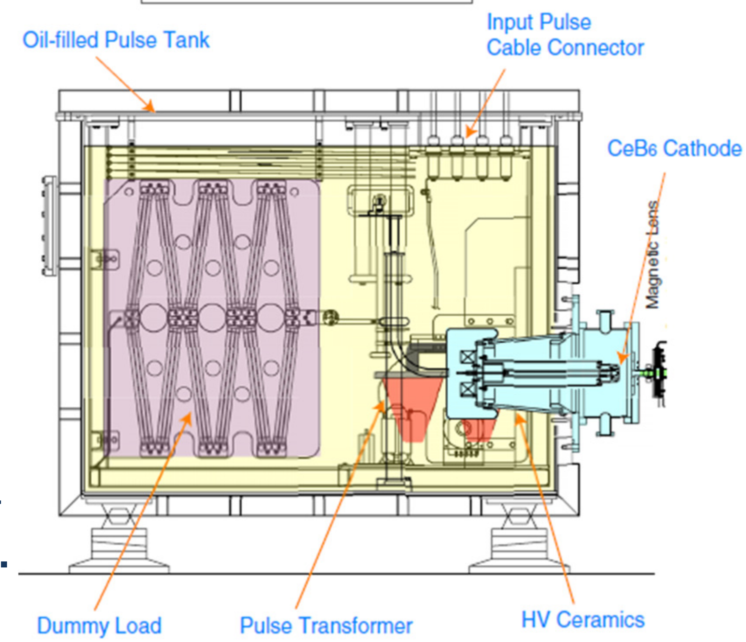
- High gradients and energies requires high RF power

‘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:

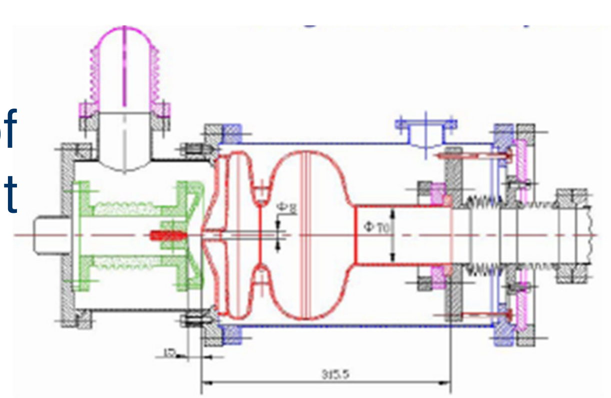
- Modulator technology limits maximum energy and repetition rate (~500 kV at 60 Hz presently, can it go to kHz?).
- Significant injector system complexity when used with thermionic cathodes (“adiabatic” compression requires chopper and multiple RF frequencies). Not integrated yet with photo-cathodes.

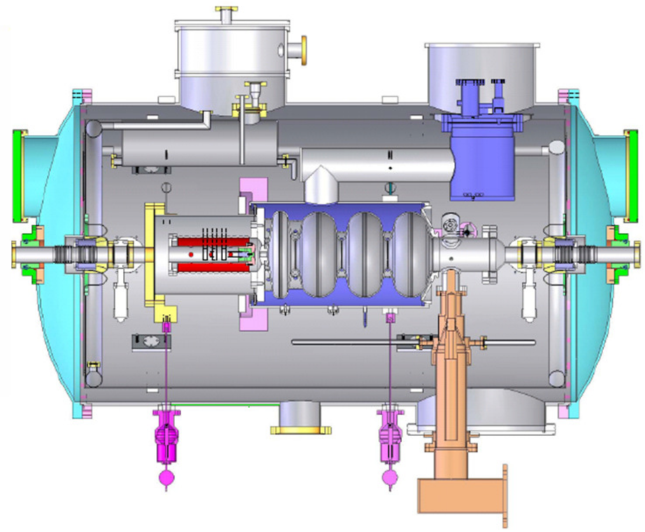
T. Shintake et al., PRST-AB 12, 070701 (2009)

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 and second generation 3.5 cell already built and in operation

Challenges:

- Increased system complexity
- Gradient limitation in the DC part

Table 1: Parameters of the new photoinjector

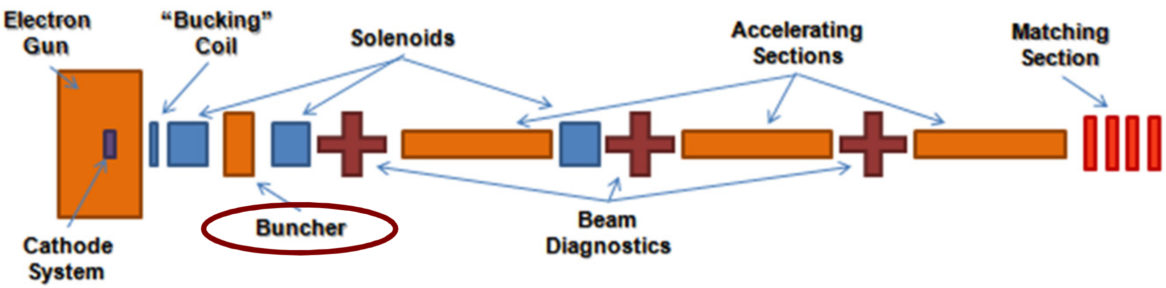
2+1/2-cell cavity	
E_{acc}	15 MV/m
Drive laser	
Pulse length	10 ps
Spot radius	2 mm
Repetition rate	81.25 MHz
Electron bunch	
Charge/bunch	<60 pC
Energy	3.72 MeV
Energy spread (rms)	1.68%
Emittance (rms)	2.0 mm-mrad

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

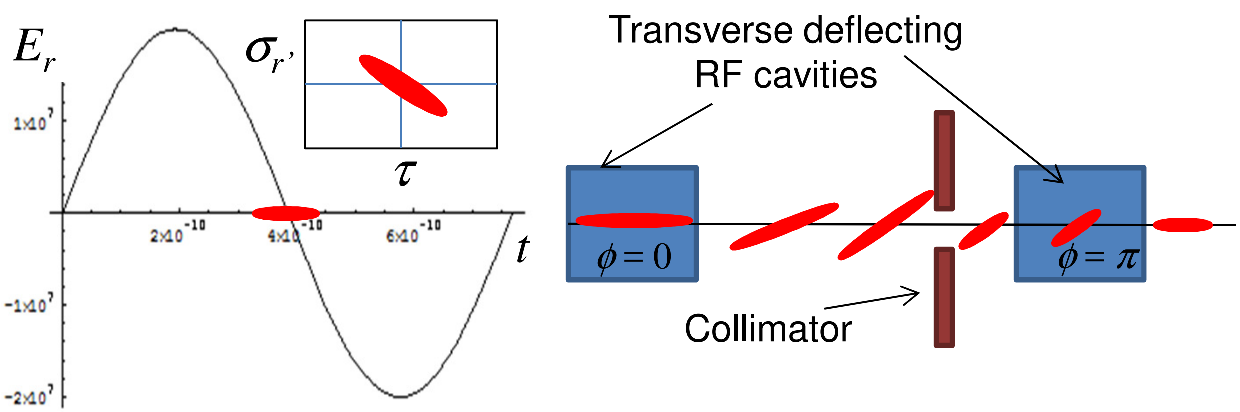
Bunching Systems

• The systems that allow to compress or define the bunch length in the injector are: **bunchers, 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.



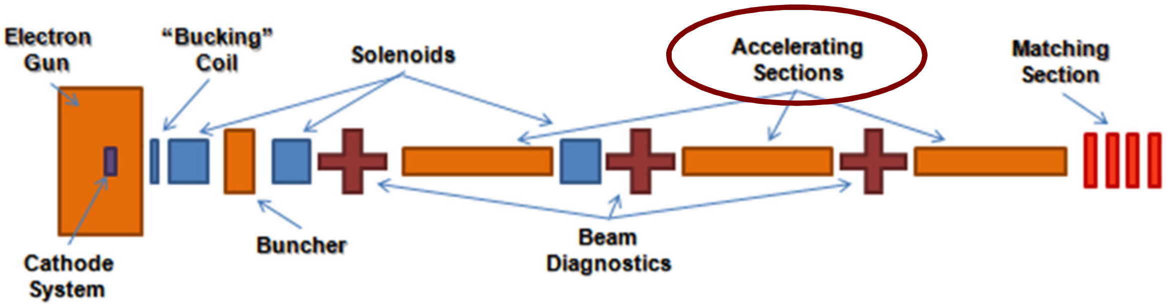
• **Velocity bunching** has been also discussed before, and requires de-phasing the RF in the first accelerating sections.



• 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.

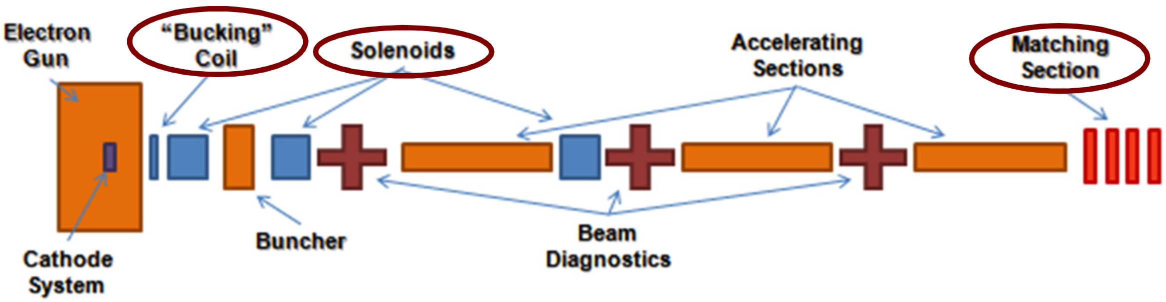
• The repetition rate defines the technology for the booster:
Normal-conducting pulsed systems for **repetition rate < ~ 1 kHz**
Super-Conducting Pulsed (train of bunches) and CW systems otherwise.

• **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).

Transverse Focusing System

• 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.

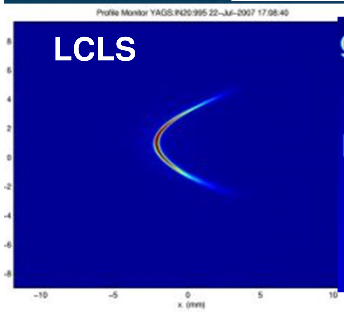


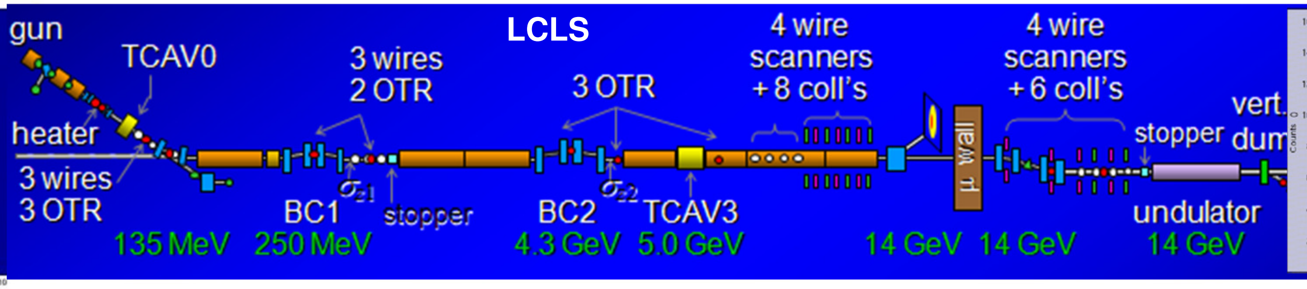
• Steering coils distributed along the injector allow to align the beam respect to the component centers.

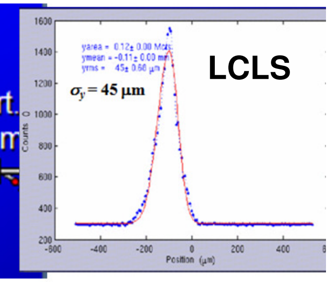
• The solenoid(s) performs the emittance compensation and controls the beam size along the injector. In same cases the solenoids wrap around the accelerating sections.

• 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 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 lecture

Contents

- Basics recap
- The role of electron sources and injectors in light source
- Requirements for electron sources and injectors
- **Injector beam dynamics (advanced concepts)**
- Injector components

Emittance Manipulation

- It should be now clear 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,

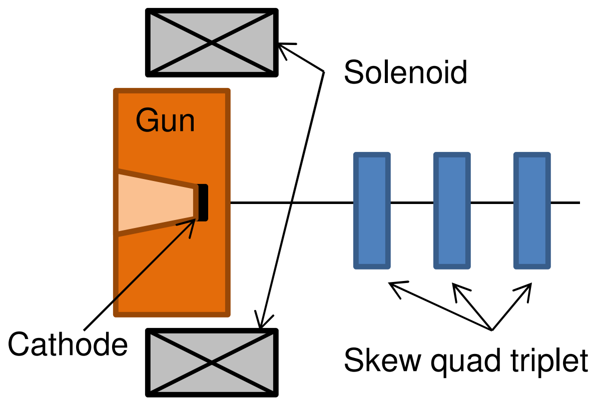
- or, to be used in combination with techniques that exchange emittances from one plane to another (typically from the longitudinal to the transverse) to best match the application requirements.

- 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.

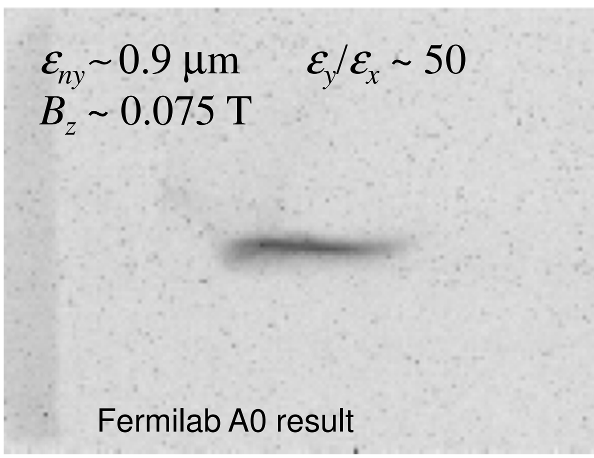
- Recently, compressor and "echo"-like schemes based on multiple emittance-exchange/flat-beam steps have been proposed.

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:

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

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.

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

• 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.

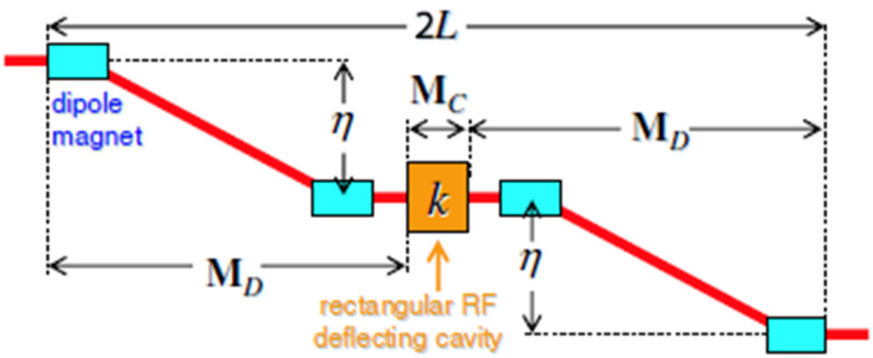
G. Rangarajan, F. Neri, and A. Dragt, "Generalized emittance invariants" PAC1989.

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

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.



$$1 + k\eta = 0$$

$$k \equiv transverse\ kick\ strength$$

$$\eta \equiv transverse\ dispersion$$

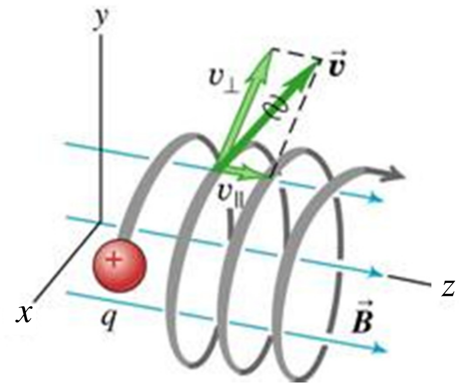
Several schemes have been proposed for exchanging the longitudinal with one of the transverse emittances (we will assume the horizontal plane in what follows). A dispersive section ('dogleg') is first used to create a correlation z-x, followed by a deflecting cavity that gives a transverse kick proportional 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)

Backup Slides

Emittance in the Presence of Bz

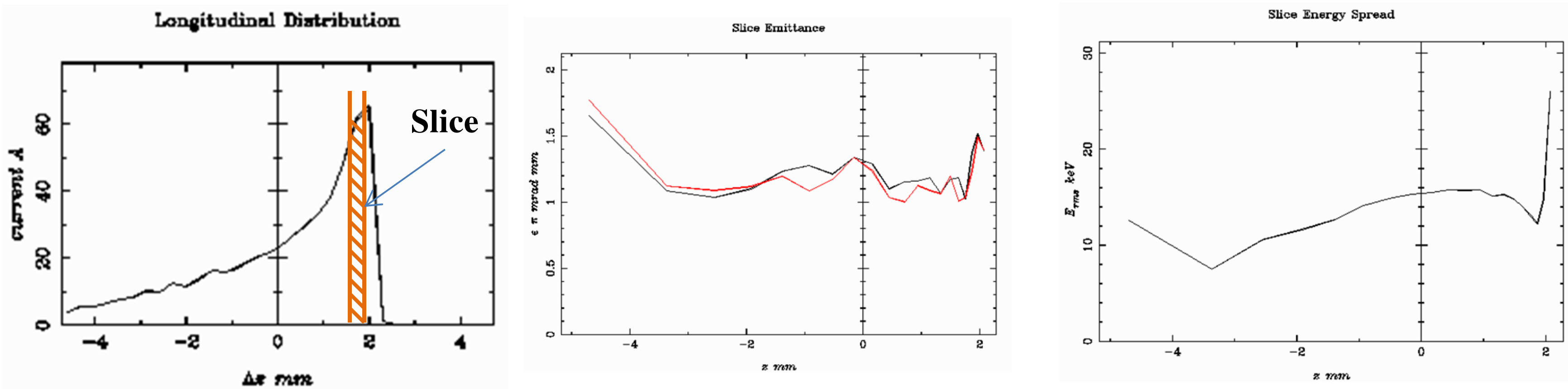
• When the B_z component of the magnetic field is present (solenoidal lenses for example), the transverse planes become coupled and the phase space area occupied by the system in each of the transverse planes is not conserved anymore.



• Anyway in this situation, the Liouville theorem still applies to the 4D transverse phase space where the ipervolume occupied by our system is still a motion invariant.

• Actually, if we rotate the spatial reference frame around the z axis by the *Larmor frequency* $\omega_L = qB_z / 2\gamma m_0$, then the transverse planes become decoupled again and the phase space area in each of the planes is conserved again.

• 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.**



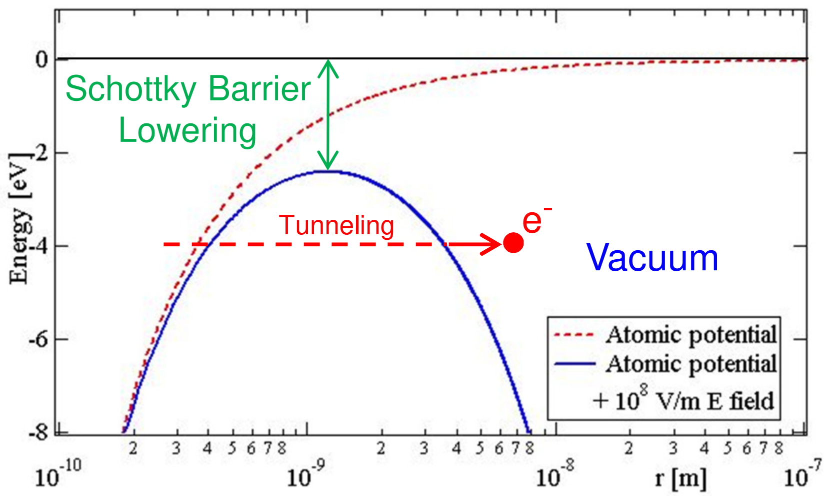
• The length of this region must be greater than the electron to photon slippage along one gain lenght, but it is ultimately defined by the FEL mode of operation, the experimental tolerances and the fluctuations of the relevant parameters.

• 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**

Dark Current

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

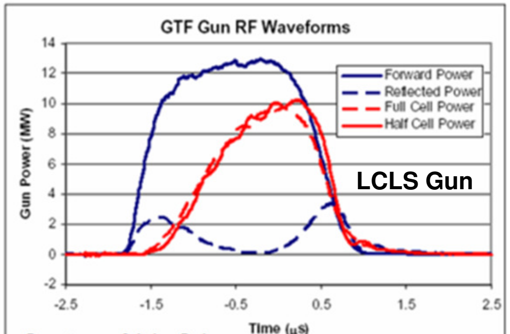


$$U_p = -\frac{1}{4\pi\varepsilon_0}\frac{e^2}{r} + e\left|\overline{E}\right| r$$

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

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

- **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.**



Courtesy of John Schmerge

- **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.**