RF Linac for High-Gain FEL

Photoinjectors

Dinh Nguyen, John Lewellen and Leanne Duffy
Los Alamos National Laboratory

US Particle Accelerator School
June 16-20, 2014

LA-UR 14-23995

III. Photoinjectors

1. Components of a Photoinjector
2. Photoemission
3. Intrinsic Emittance
4. Space Charge
5. Emittance Compensation
6. DC Gun
7. NCRF Gun
8. SRF Gun
9. Invariant Envelope
10. Booster

Components of a Photoinjector

A photoinjector has the following major components:

- **ELECTRON GUN** (either DC or RF) that accelerates electrons from rest
- **PHOTOCATHODE** that releases picosecond electron bunches when irradiated with the optical pulses from a modelocked laser
- **DRIVE LASER** to gate the emission of electrons from the photocathode
- **BOOSTER** to accelerate the electrons exiting the gun to sufficiently high energy to mitigate space charge emittance growth.
- **HV or RF SOURCE** such as a klystron to power the electron gun.

In this section, we focus on the generation of high-brightness beams in a photocathode electron gun. We briefly study three different designs of electron guns: **DC**, **normal-conducting RF** and **super-conducting RF**. We also explore the emittance compensation theory and how to match the electron beams into the booster to obtain minimum normalized emittance.

Technology Choices

Gun Technologies

- **DC Gun**
- **Normal-conducting RF Gun**
- **Super-conducting RF Gun**

Cathode Technologies

- **Thermionic cathodes**
- **Photocathodes**
  - **Metal**
  - **Semiconductor**

Booster Technologies

- **Normal-conducting Booster**
- **Super-conducting Booster**

What are the FEL wavelength and final electron beam energy?

What cathode gradient is needed to obtain the required normalized emittance?

What are the required bunch charge and repetition rate?

What is the photocathode intrinsic emittance at the laser photon energy (this determines the photoemission radius at the cathode)?

What is the electron beam's peak current exiting the booster (this and the final peak current determine the required bunch compression ratio) ?

Photoemission

Metal photocathodes

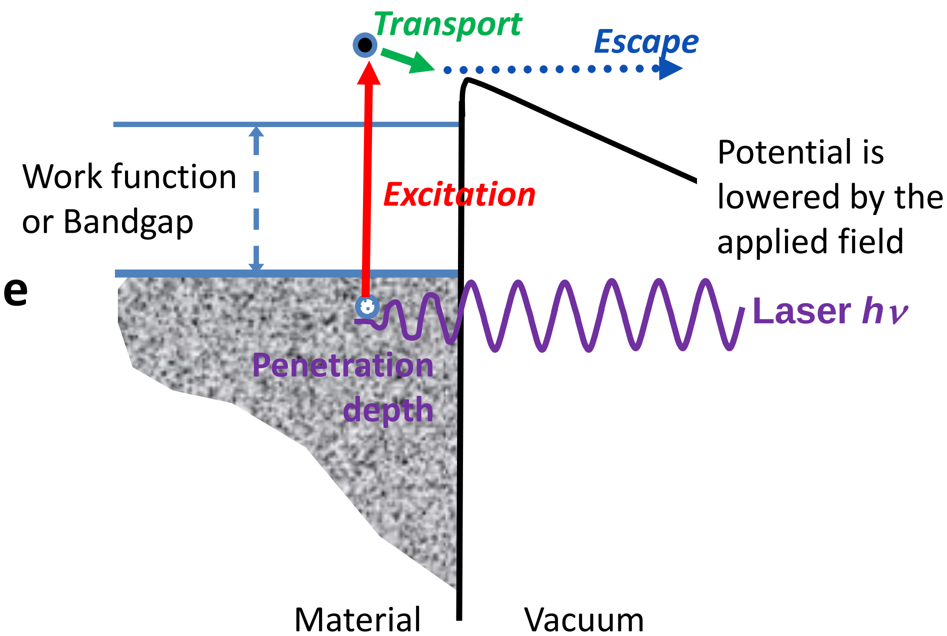
- Copper, magnesium, lead, niobium
- Require UV photons (>4.5 eV)
- $<10^{-4}$ quantum efficiency
- Short penetration depth (~14 nm)
- Prompt electron emission

Semiconductor photocathodes

- Cesiated antimonide, GaAs, telluride
- Require visible or UV photons
- $>10^{-2}$ quantum efficiency
- Long penetration depth (~μm)
- Delayed electron emission

Three steps of photoemission:

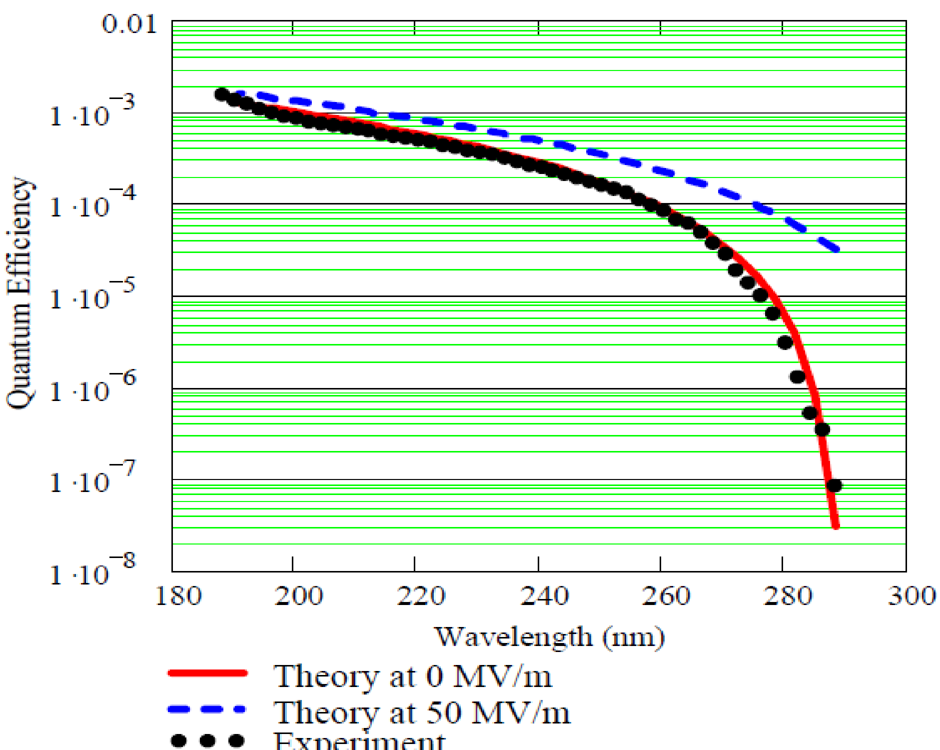
- **Electron excitation**
- **Electron transport to surface**
  - electron-electron scattering
  - electron-phonon scattering
- **Electron escape**
  - classical escape over the barrier



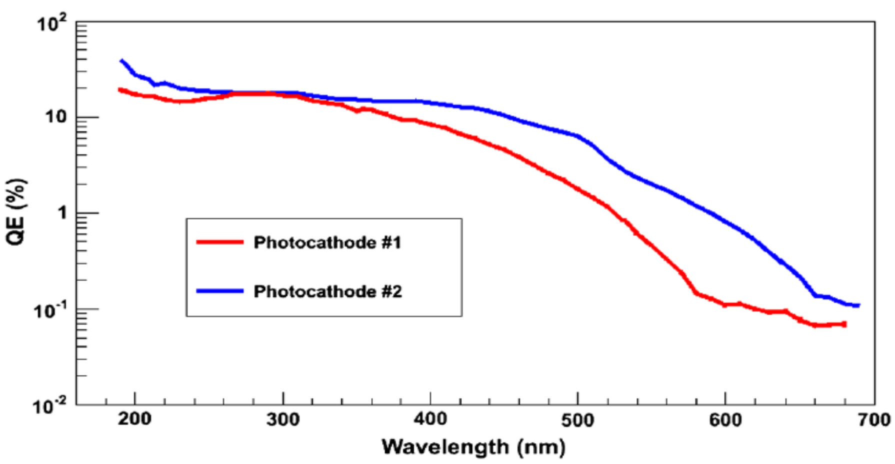
Quantum Efficiency

Quantum efficiency is defined as the number of electrons emitted divided by incident number of laser photons.

Cu photocathode Q.E. from Dave Dowell



K_2CsSb photocathode Q.E. BNL/Jefferson Lab



Electron bunch charge (in coulomb)

$$Q = \frac{W}{\hbar\omega} Q.E.$$

where W = laser pulse energy (J)

$\hbar\omega$ = photon energy (eV)

Intrinsic/Thermal Emittance

Intrinsic emittance depends on the residual transverse momentum of electrons upon escape from the cathode.

$$p_x = p_{total} \sin\theta \cos\varphi$$

$$p_{total} = \sqrt{2m_e\left(E + \hbar\omega\right)}$$

The normalized intrinsic emittance is proportional to photoemission radius by the angle ϑ, which is measured in μm/mm or mrad.

$$\varepsilon_{n,intrinsic} = \sigma_x \sqrt{\frac{\hbar\omega - \phi_{eff}}{3m_e c^2}} = \sigma_x \vartheta$$

For Cu cathode and 4.7 eV photons, the calculated angle ϑ is 0.45 mrad and measurements at SLAC yields an average ~0.7 mrad, presumably due to surface roughness. For K_2CsSb and 2.3 eV photons, the calculated angle is 0.36 mrad.

Image Charge at Cathode

Consider a slug of electrons with charge *q* being accelerated from rest by an applied electric field

Cathode field

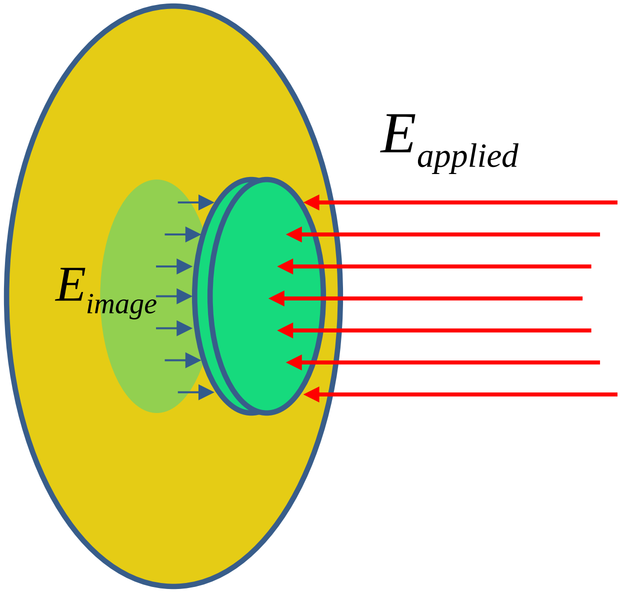
$$E_{cathode} = E_{applied} - E_{image}$$

Image charge field

$$E_{image} = \frac{q}{\varepsilon_0 A}$$

The applied field (gradient) is typically several times the image field which is set by the emission area. The emission radius is usually chosen to obtain a small intrinsic emittance.

$$\sigma_x = \frac{\varepsilon_{n,intrinsic}}{\vartheta}$$



LCLS gun with Cu cathode

Required ε_n = 0.5 μm for 0.25 nC

ϑ = 0.8 mrad for Cu

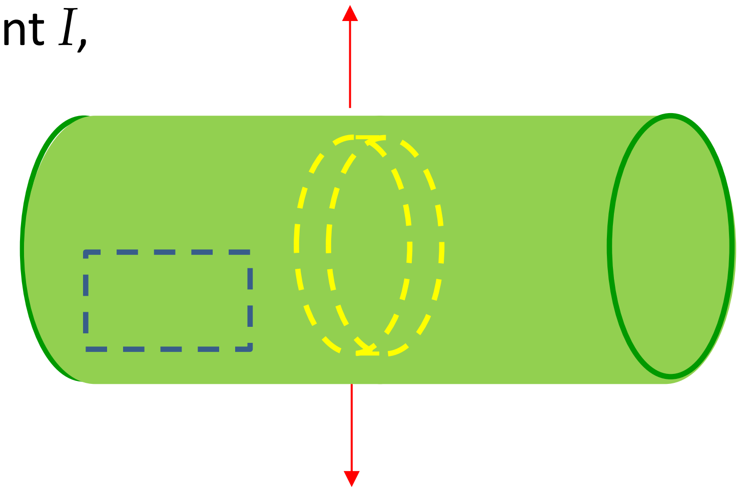
σ_x = 0.6 mm → r_0 = 1.2 mm

E_{min} = 7 MV/m

$E_{applied}$ ~ (120 MV/m)sinϕ

Transverse Space Charge

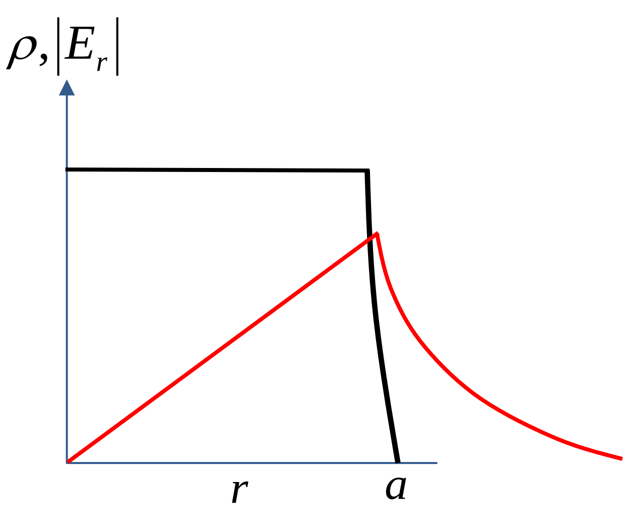
Consider a cylindrical electron bunch with current I, uniform charge and current density ρ and J.



$$\rho = \frac{I}{\pi a^2 \upsilon_z} \qquad J = \frac{Ir}{\pi a^2}$$

Transverse space charge fields for $r < a$

$$E_r = \frac{1}{2\varepsilon_0}\rho r \qquad B_\theta = \frac{\mu_0}{2} Jr = \frac{\upsilon_z}{c^2} E_r$$



Lorentz force

$$F_r = -e[E_r - \upsilon_z B_\theta] = -eE_r(1 - \beta^2)$$

$$F_r = -\frac{eE_r}{\gamma^2}$$

Transverse SC force scales with $1/\gamma^2$

Longitudinal Space Charge

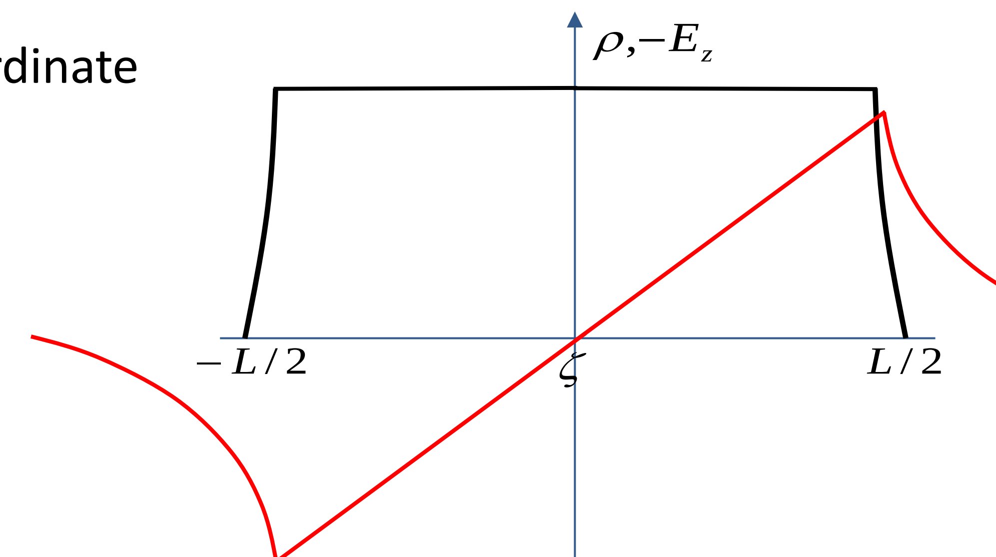
Longitudinal SC causes the beam to expand along the z direction and reduces its peak current

Longitudinal space charge fields for $|\zeta| < L/2$

$$E_z(\zeta) = \frac{\rho}{\gamma 2\varepsilon_0}\left[\sqrt{a^2+\gamma^2\left(\frac{L}{2}-\zeta\right)^2} - \sqrt{r^2+\gamma^2\zeta^2} - 2\gamma\left(\frac{L}{2}-\zeta\right)\right]$$

where ζ is the internal longitudinal coordinate

$$\zeta = z - \overline{\upsilon}_z t$$

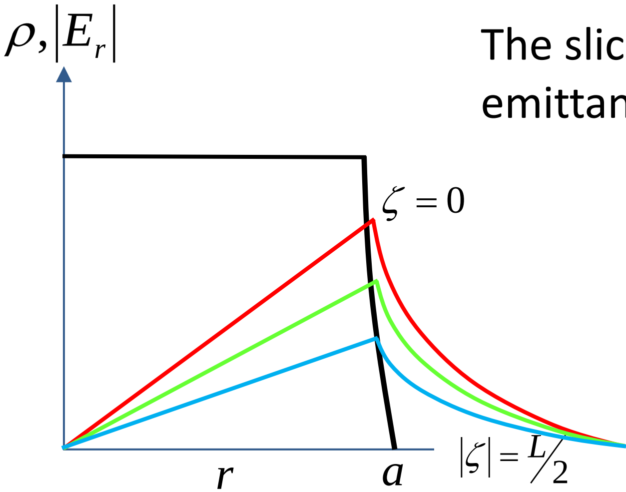


Due to mixing, the longitudinal (and transverse) SC depends on both ζ and *r*.

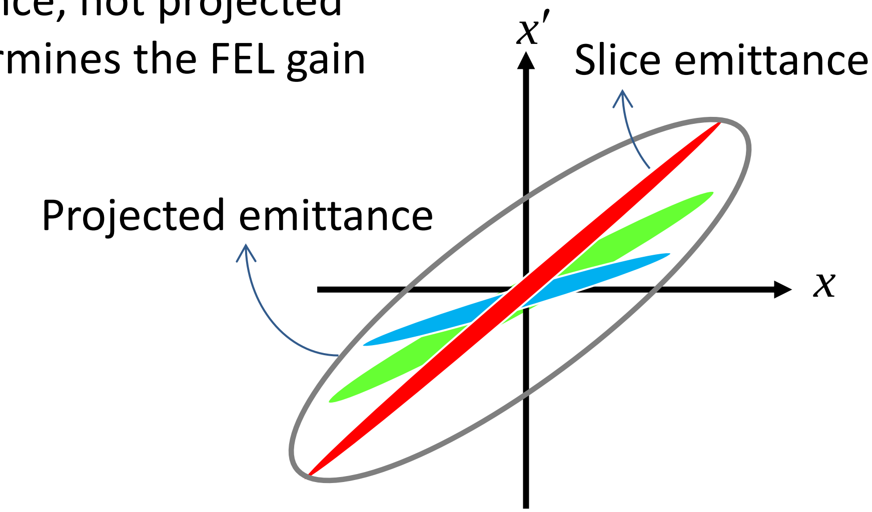
Longitudinal SC force scales with $1/\gamma$

Space-charge Emittance

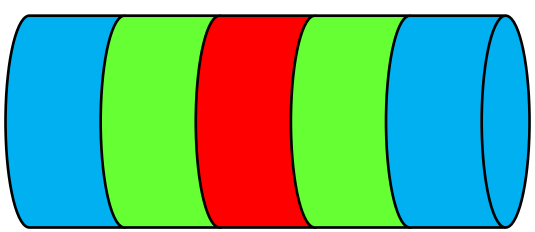
The slice emittance, not projected emittance, determines the FEL gain



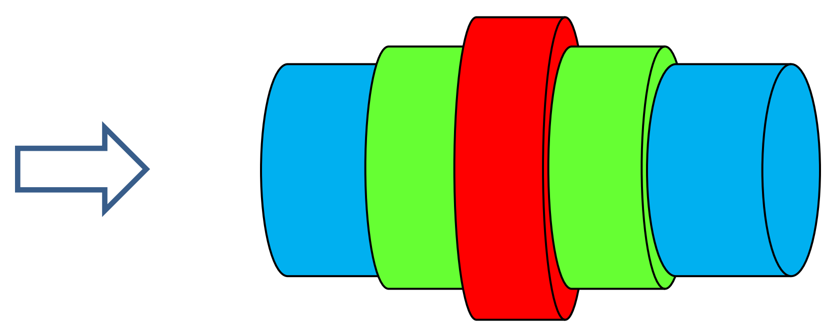
Transverse force is highest at $\zeta = 0$



Trace-space plots

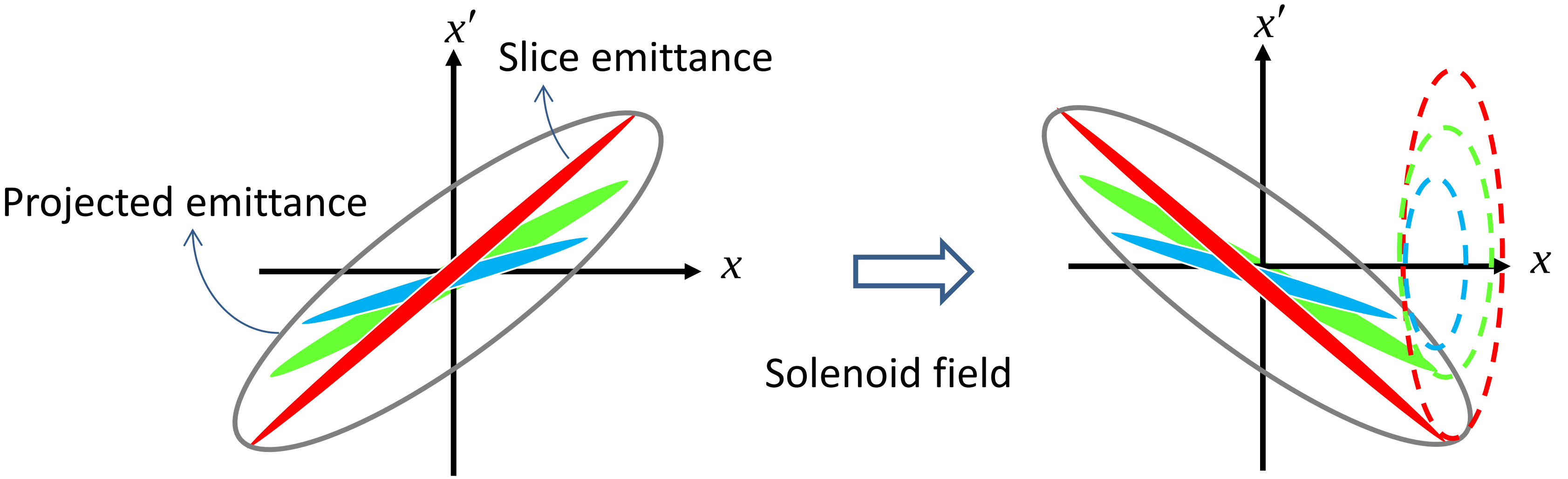


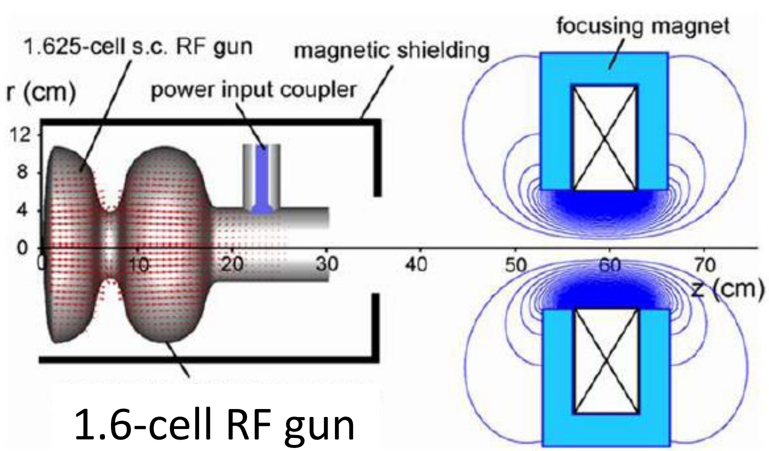
Initial bunch with 5 slices



Different slices expand radially at different rates

Emittance Compensation

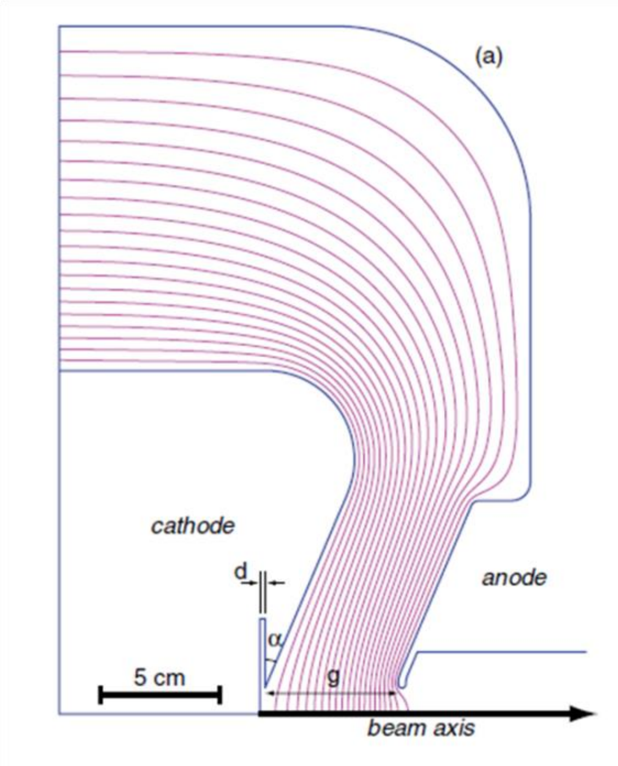




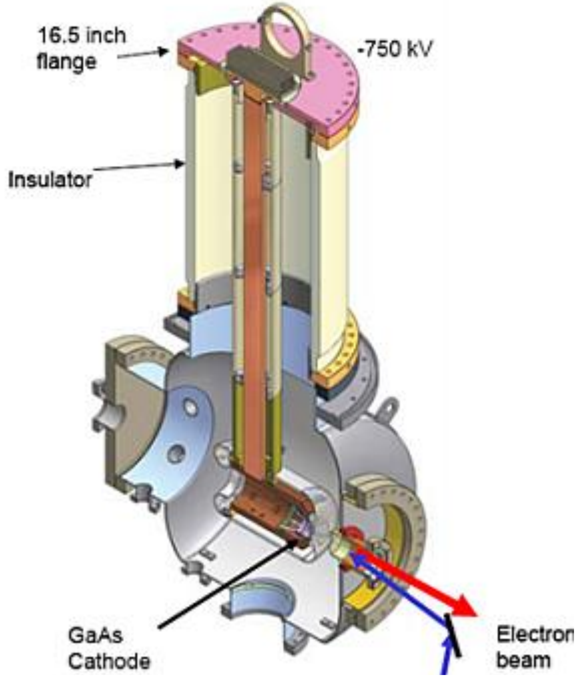
1.6-cell RF gun

Originally proposed by Carlsten and coined **Emittance Compensation**, the idea is to use a solenoid magnet to flip the trace-space ellipses and let them move in x-x’ space until the slices are aligned to form smaller projected emittance. Serafini and Rosenzweig later developed the emittance compensation theory based on plasma oscillation of the slices’ envelopes.

Cornell DC Gun

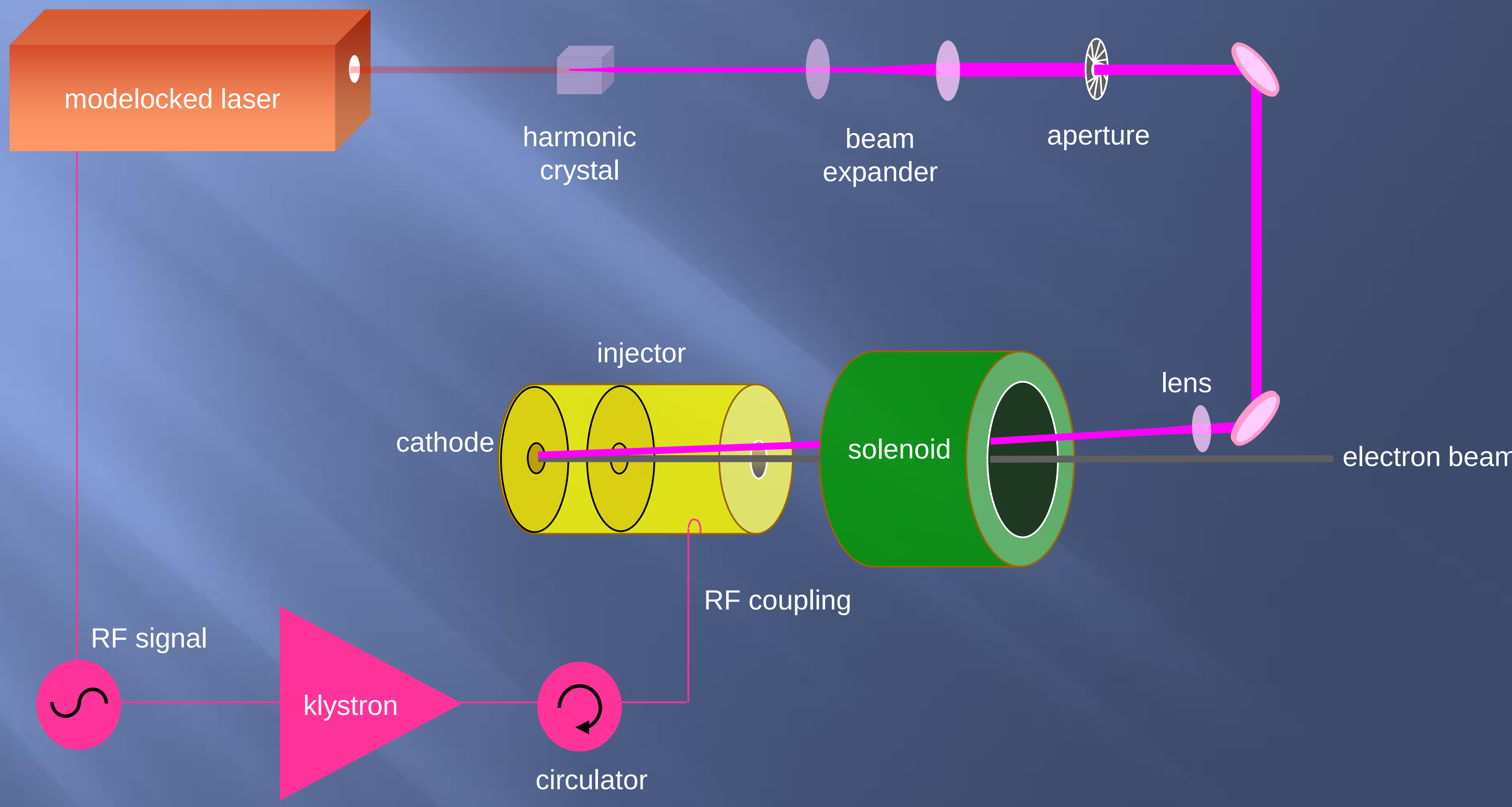


DC guns use a large ceramic insulator to stand off the high voltage between a cathode and an anode, creating accelerating gradients of a few MV/m.



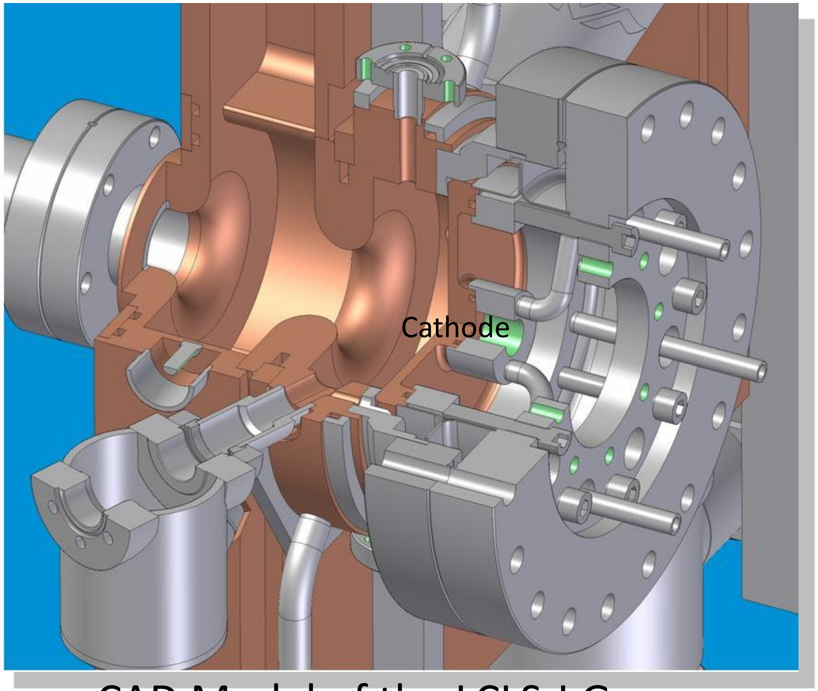
Cornell DC gun
Gradient = 5 – 10 MV/m
Gun exit energy = 0.35 MeV
GaAs and K_2CsSb photocathodes
Bunch repetition rate = 1300 MHz
Norm. rms emittance = 0.5/0.3 μm at 80 pC
Average current = 65 mA (at 50 pC)

Normal-Conducting RF Gun

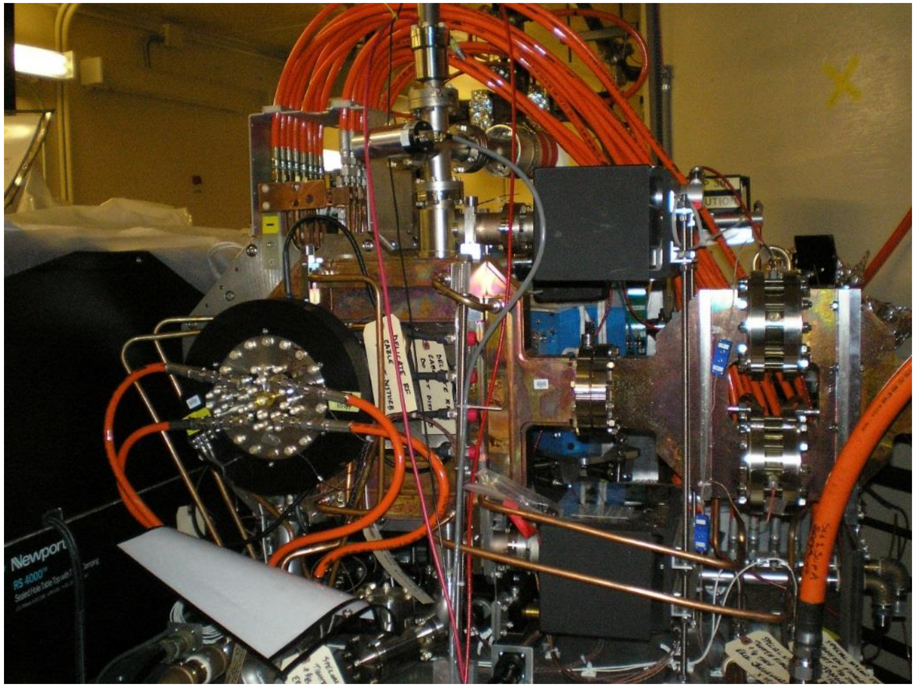


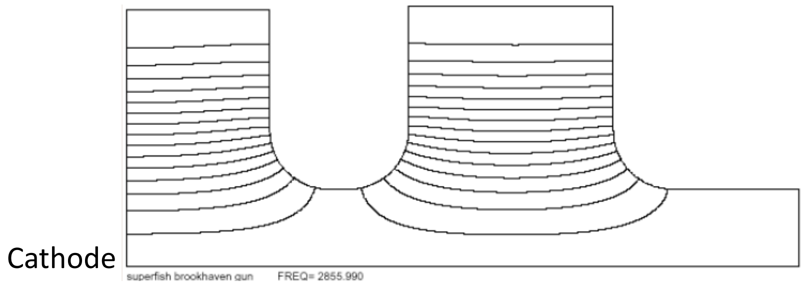
RF gun was invented by Fraser and Sheffield in the mid-1980s.
Pulsed NCRF guns can achieve accelerating gradients > 100 MV/m.

LCLS-I S-band Gun



CAD Model of the LCLS-I Gun

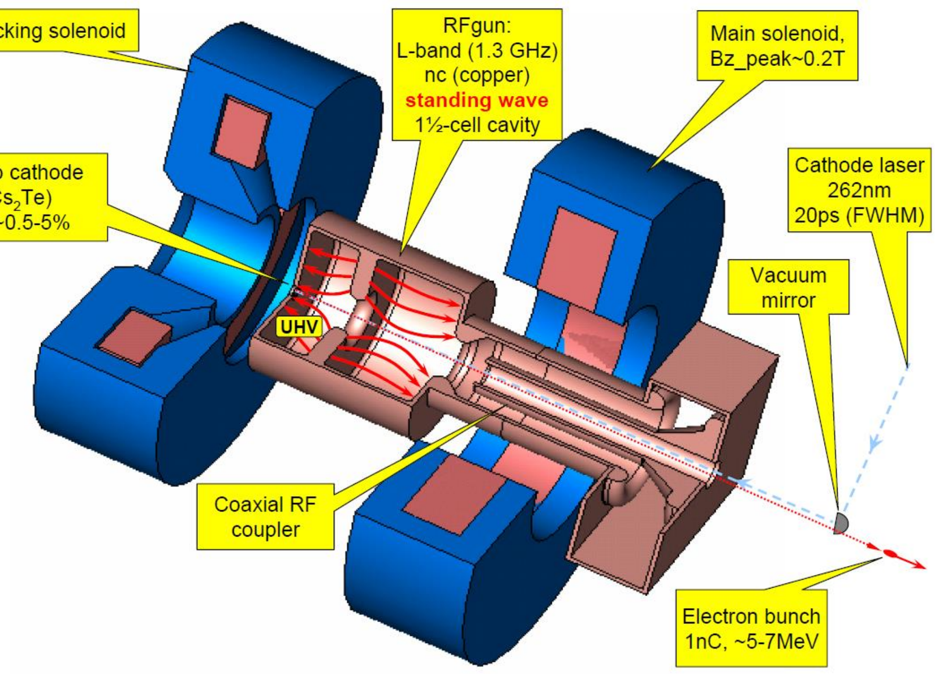


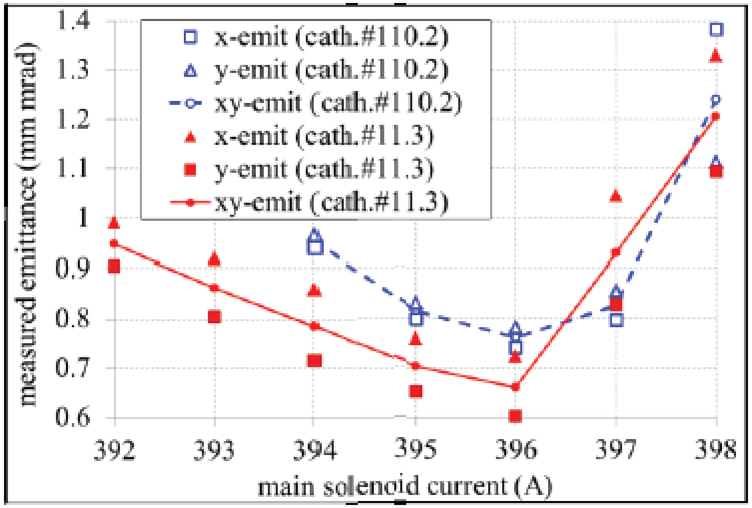


Superfish Model of the LCLS-I Gun

LCLS-I Gun (SLAC/BNL/UCLA)
Frequency = 2,856 MHz
Gradient = 120 MV/m
Exit energy = 6 MeV
Copper photocathode
Bunch repetition rate = 120 Hz
Norm. rms emittance = 0.4 μm at 250 pC
= 0.14 μm at 20 pC

PITZ L-band Gun



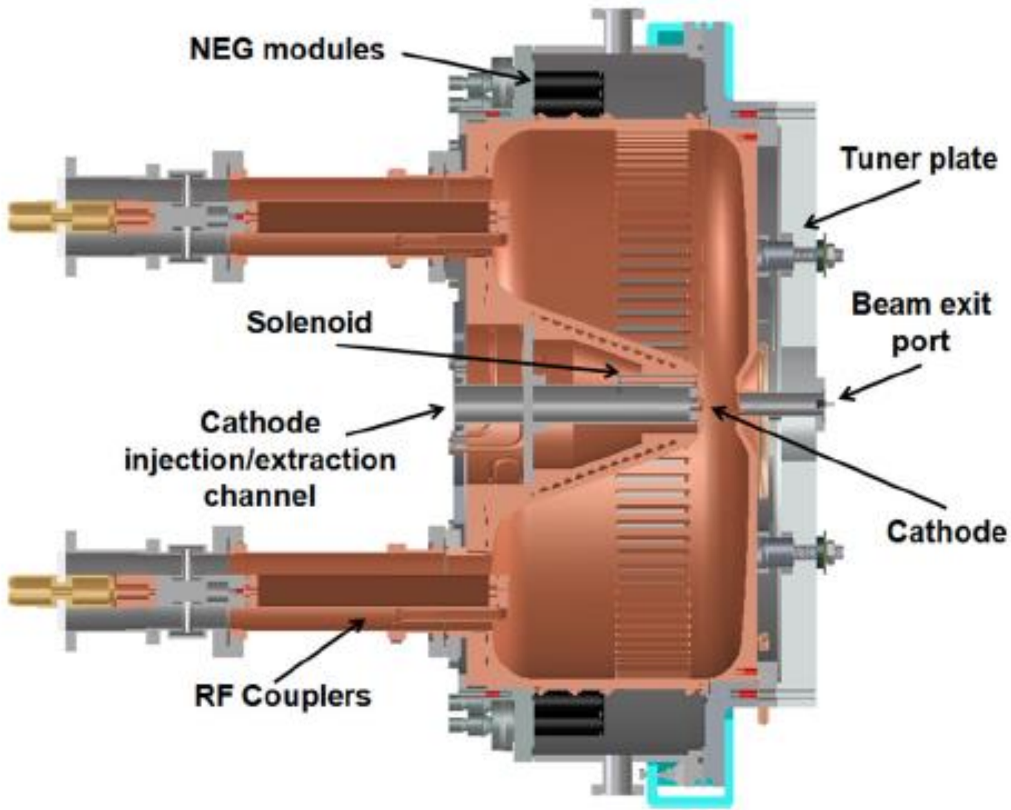


Parameters	FLASH	European XFEL
max. RF repetition rate	10 Hz	10 Hz
max. train length	800 µs	600 µs
bunch spacing	1 µs	0.2 – 1 µs

PITZ L-band Gun
Frequency = 1,300 MHz
Gradient = up to 60 MV/m
Exit energy = 6.5 MeV
Cs_2Te photocathode
800 bunches per macropulse
Normalized rms emittance
1 nC 0.70 µm
0.1 nC 0.21 µm

Reference: M. Krasilnikov, FEL2013, TUOANO-04 Talk

LBNL VHF Gun



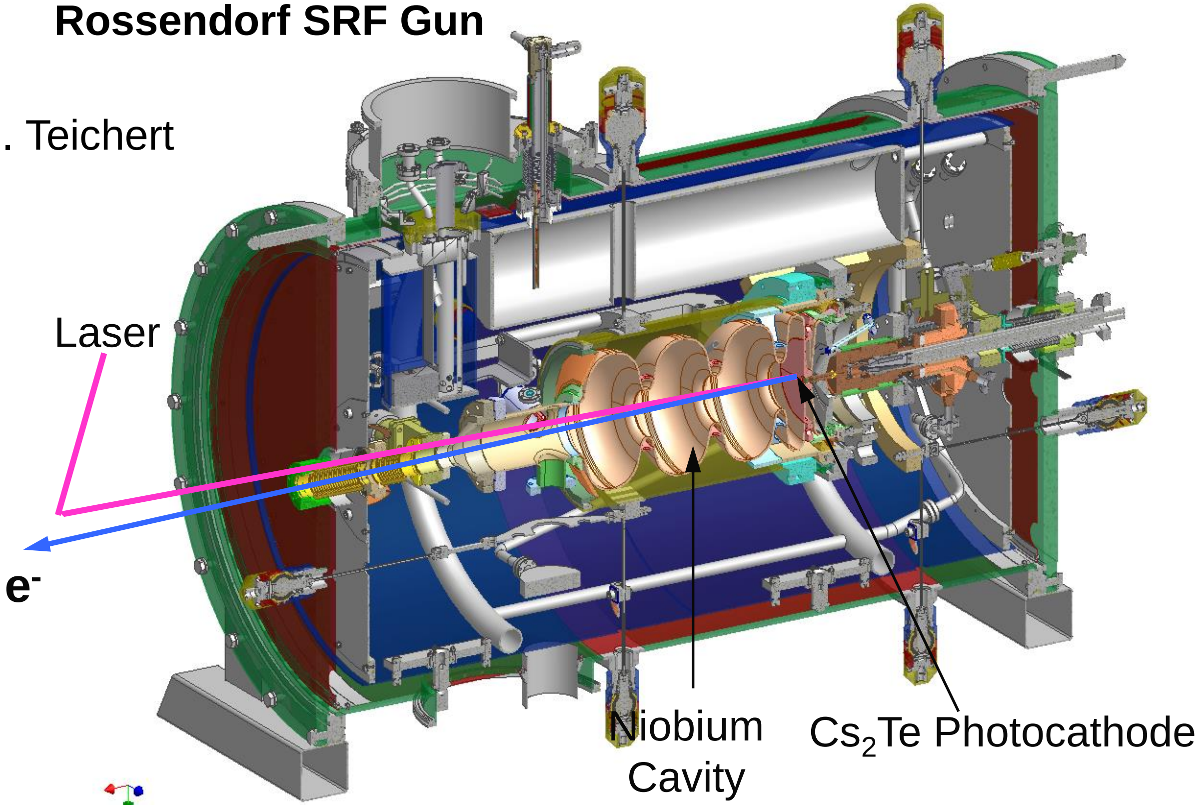
Frequency	186 MHz
Operation mode	CW
Gap voltage	750 kV
Field at the cathode	19.47 MV/m
Q_0 (ideal copper)	30887
Shunt impedance	6.5 MΩ
RF Power	100 kW
Stored energy	2.3 J
Peak surface field	24.1 MV/m
Peak wall power density	25.0 W/cm^2
Accelerating gap	4 cm
Diameter/Length	69.4/35.0 cm
Operating pressure	~ 10^{-11} Torr

The LBNL VHF gun has a co-axial quarter-wave geometry that resonates at low frequency (large structure) and thus reduces the power density on the cavity wall. The wall has vacuum pumping slots with NEG pumps to achieve ultrahigh vacuum.

Superconducting RF Gun

Rossendorf SRF Gun

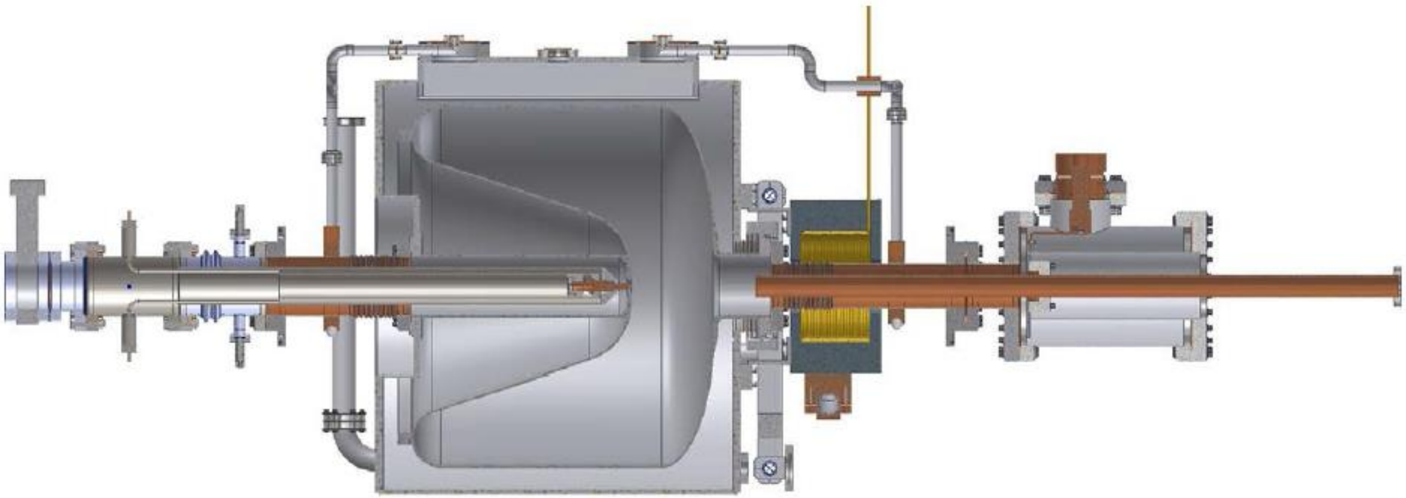
Courtesy of J. Teichert



Superconducting RF guns offer the benefit of very efficient use of RF power for operations at high bunch repetition but they require a helium cryostat and a liquid helium cryoplant. A 3.5-cell SRF gun has been tested with beams at FZD (Rossendorf).

Quarter-Wave Gun Design

Quarter-wave cavities have a smaller cross-section compared to full-wave (pill-box) cavities at the same frequency. QW designs of superconducting guns operate at frequencies below 500 MHz so they can be cooled with 4K atmospheric helium.



WiFEL (Wisconsin Free-Electron Laser) superconducting quarter-wave gun

Frequency = 199.6 MHz
Gradient < 45 MV/m
High Tc superconducting solenoid
Design beam energy = 4 MeV
Pulse repetition rate = 1 kHz up to a few MHz

Single Particle Equation of Motion

Rate of change in γ w.r.t. scaled distance ζ

$$\boxed{\frac{d\gamma}{d\zeta} = \alpha\left[\sin\phi + \sin\left(\phi + 2\zeta\right)\right]}$$

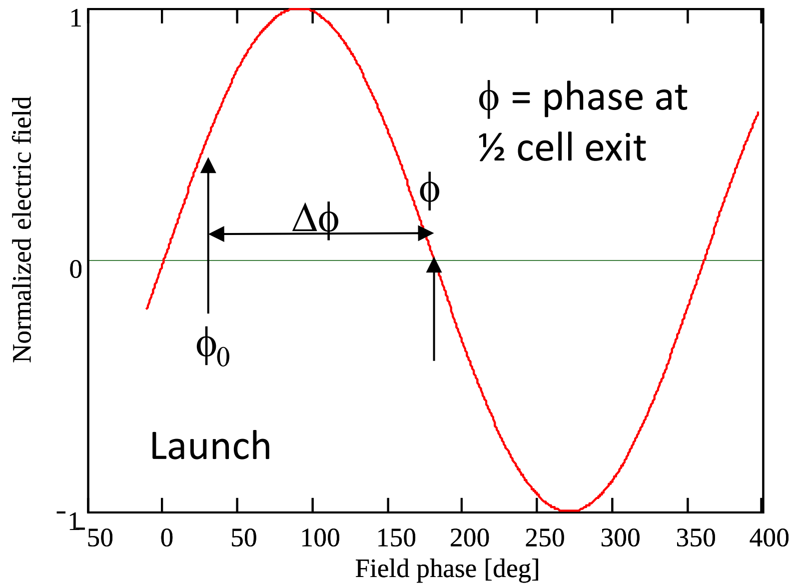
Rate of change in ϕ w.r.t. scaled distance ζ

$$\boxed{\frac{d\phi}{d\zeta} = \frac{\gamma}{\sqrt{\gamma^2 - 1}} - 1}$$

Scaled distance ζ $\quad \zeta = kz$

RF wave-number $\quad k = \frac{2\pi}{\lambda_{RF}}$

Dimensionless gradient $\quad \alpha = \frac{eE_0}{2km_e c^2}$



Typical values for an S-band gun

$$k = \frac{2\pi}{0.105m} \approx 60m^{-1}$$

$$\alpha = \frac{120MeV/m}{2k\left(0.511MeV\right)} \approx 2$$

Solution to EOM

Choose an approximate solution for γ (ignoring the 2nd sine term)

$$\tilde{\gamma}(\zeta) = 1 + 2\alpha\zeta \sin\phi_0$$

where ϕ_0 : injection phase. Plug the above into the phase equation and integrate

$$\phi(\zeta) = \frac{1}{2\alpha \sin\phi_0}\left[\sqrt{\tilde{\gamma}^2 - 1} - (\tilde{\gamma} - 1)\right] + \phi_0$$

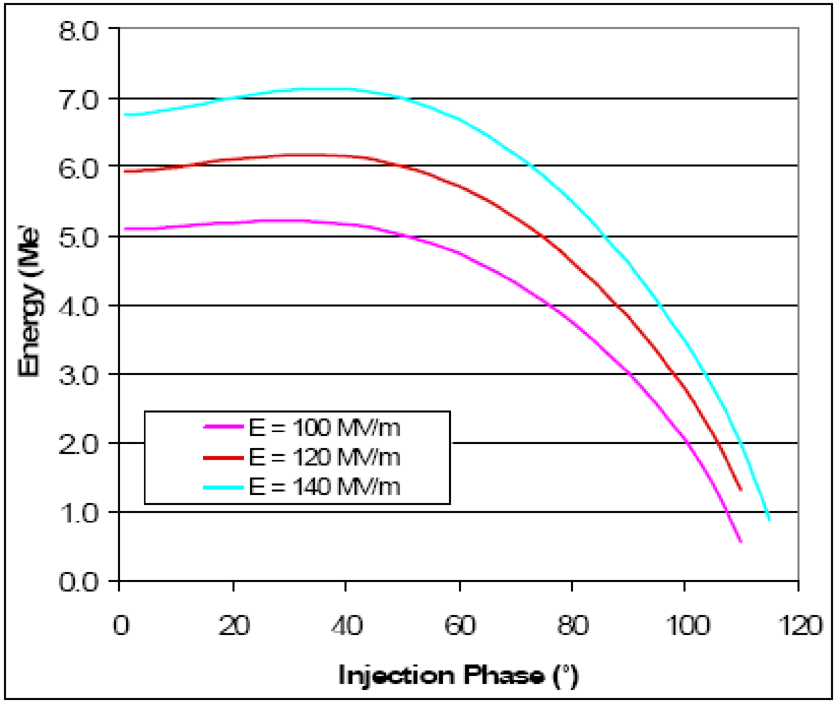
Insert the phase solution above into the energy equation and integrate

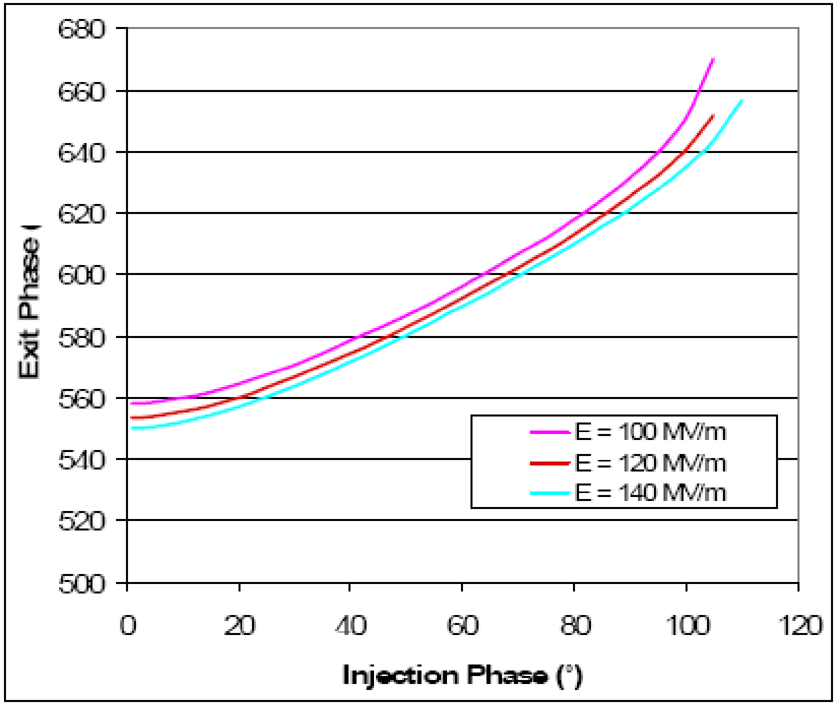
$$\gamma(\zeta) = 1 + \alpha\left[\zeta \sin\phi_0 + \frac{1}{2}(\cos\phi - \cos(\phi + 2\zeta))\right]$$

Select the injection ϕ_0 such that $\phi(\zeta) = \pi$ at $\zeta = \pi/2$ (end of the first ½ cell)

$$(\pi - \phi_0)\sin\phi_0 = \frac{1}{2\alpha}$$

Calculated Exit Energy and Phase





Beam energy at the exit of the LCLS 1½-cell gun is linearly proportional to cavity gradient. The exit energy is almost independent of the launch phase up to a launch phase of 50^{o}. The exit phase increases slowly with injector phase at small phases, but rises quickly if the injection exceeds 30 degrees.

Simulation Codes to Model RF Guns

RF and Magnet Design Codes: These codes model the gun cavities via time and frequency domain solvers, as well as designing the solenoid magnets.

- **SUPERFISH-POISSON:** free codes from LANL; 2D
- **HFSS:** commercial code from Ansoft; 3D
- **MicroWave Studio:** commercial code from CST; 3D

Particle Tracking Codes: These codes integrate the macroparticle trajectories under Lorentz forces, including space charge.

- **PARMELA:** particle tracking code from LANL; some export restrictions apply
- **ASTRA:** free parallel code from DESY
- **GPT:** Commercial code from Pulsar Physics

Particle-in-cell (PIC) Codes: These codes solve the Maxwell-Lorentz equations for particles in a 3D cell consistently. Very time-consuming and complex.

- **MicroWave Studio:** commercial code from CST
- **VORPAL**: plasma and PIC simulation code from Tech-X
- **MAGIC**: 2D and 3D PIC code

Equation of Motion with Space Charge (Self-Field) Defocusing

Self-field Lorentz force
$$F_r = -e\left[E_r - \upsilon_z B_\theta\right] = -\frac{eE_r}{\gamma^2}$$

$$F_r = \frac{eIr}{2\pi\varepsilon_0\gamma^2\beta c a^2} = \frac{d}{dt}(\gamma m \upsilon_r)$$

From geometric relation
$$\frac{d\upsilon_r}{dz} = \frac{1}{c}\frac{d\upsilon_r}{dt} = \beta^2\gamma^2 r''$$

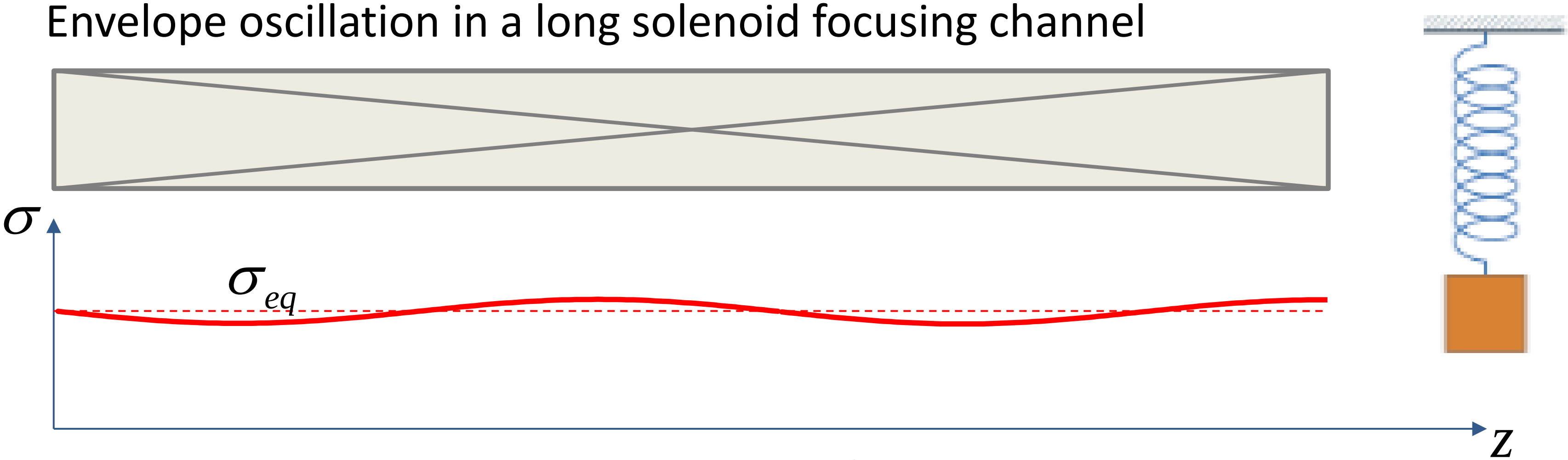
Equation of motion
$$r'' = \frac{F_r}{\beta^2\gamma^3 m_e c} = \left(\frac{e}{4\pi\varepsilon_0 m_e c^2}\right)\frac{2Ir}{\beta^3\gamma^3 a^2}$$

$$r'' = \frac{2I}{I_0\beta^3\gamma^3}\frac{r}{a^2} \qquad I_0 = 17kA$$

K is known as the generalized perveance
$$r'' = K\frac{r}{a^2} \qquad K = \frac{2I}{I_0}\frac{1}{\beta^3\gamma^3}$$

Solenoid Focusing

Envelope oscillation in a long solenoid focusing channel



Envelope equation
$$\sigma'' + k_B^2\sigma - \frac{\varepsilon^2}{\sigma^3} - \frac{K}{\sigma} = 0$$

Solenoid wave-number

$$k_B = \frac{eB_0}{2\beta\gamma m_e c}$$

Equilibrium solution for space-charge dominated beams (ignoring emittance)

$$\sigma_{eq} = \sqrt{\frac{K}{k_B^2}}$$

Paraxial Ray Equation & rms Envelope Equation

Assuming the particles are largely parallel to the beam axis, ignore second (r^2) and higher order terms. Paraxial ray equation for single particles:

$$r'' + \frac{\gamma'}{\beta^2\gamma} r' + k_B^2 r - \left(\frac{p_\theta}{\beta\gamma m_e c}\right)\frac{1}{r^3} - \frac{K}{a^2} r = 0$$

Acceleration damping

Focusing from an axial solenoid magnetic field

Canonical angular momentum due to magnetic field at cathode

Space charge defocusing

rms envelope equation

$$\sigma'' + \frac{\gamma'}{\gamma}\sigma' + k_B^2\sigma - \frac{\varepsilon^2}{\sigma^3} - \frac{K}{\sigma} = 0$$

where emittance has both the phase-space and angular momentum parts.

Invariant Envelope Equation

The slices rotates in x-x' space about an invariant envelope. The equation of invariant envelope rate of change with respect to z is given by

$$\boxed{\hat{\sigma}'' + k_f^2\hat{\sigma} - \frac{\varepsilon_n^2}{\hat{\sigma}^3} - \frac{\kappa}{\gamma^2\hat{\sigma}} = 0}$$

Definitions

$$\hat{\sigma} = \sigma\sqrt{\gamma}$$

$$k_f^2 = k_B^2 + \frac{3}{4}\left(\frac{\gamma'}{\gamma}\right)^2$$

$$\varepsilon_n = \gamma\varepsilon$$

$$\kappa = K\gamma^3 = \frac{2I}{I_0}$$

Space charge-to-emittance ratio

$$\xi = \frac{\kappa\sigma^2}{\gamma\varepsilon_n^2}$$

Solutions to invariant envelope equation

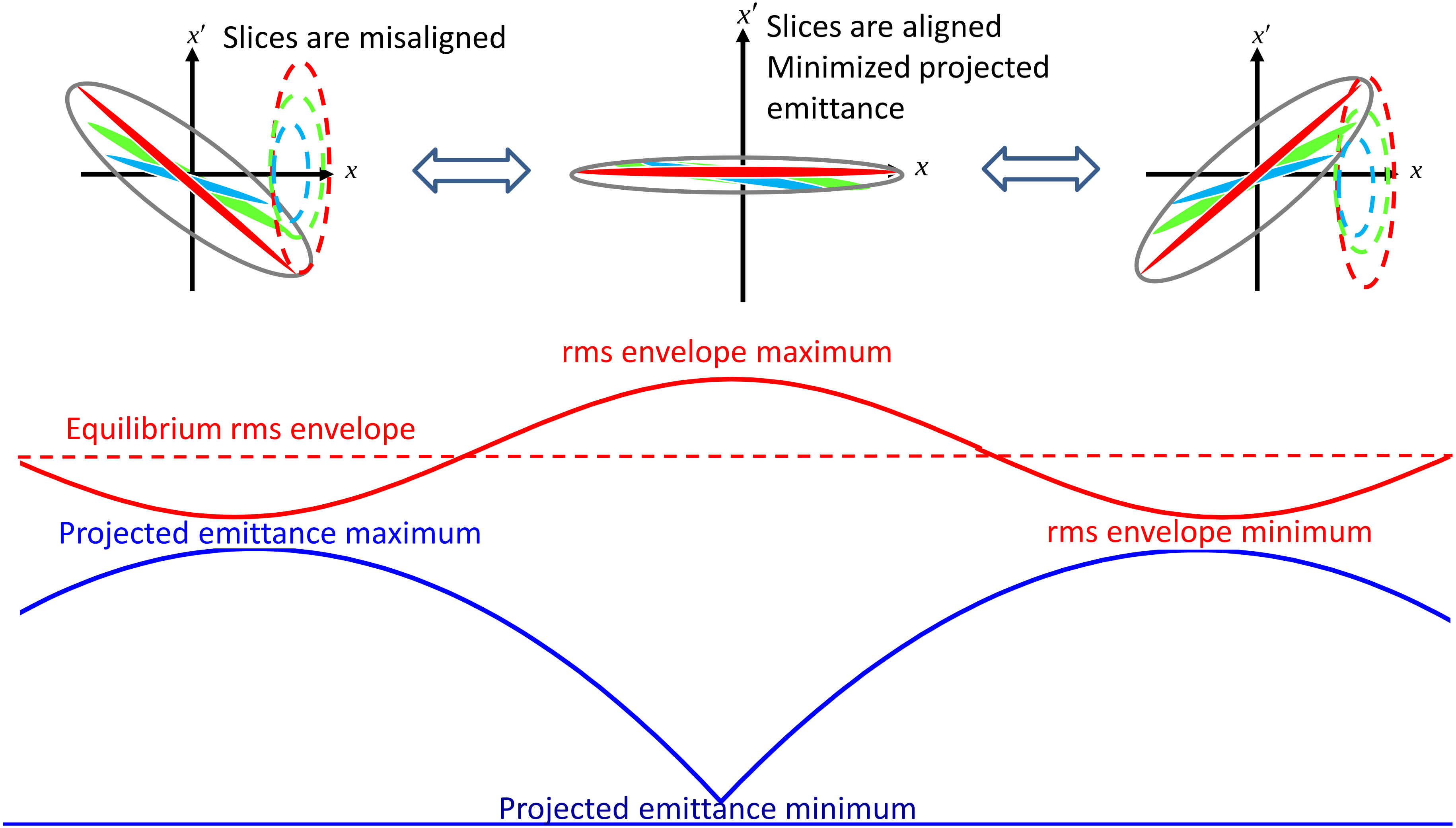
Space-charge dominated beams, $\xi > 1$

$$\hat{\sigma}_{SC} = \frac{1}{\gamma'}\left(\frac{4\kappa}{3}\right)^{\frac{1}{2}} \qquad \boxed{\sigma_{SC} = \frac{2}{\gamma'}\left(\frac{I}{3\gamma I_0}\right)^{\frac{1}{2}}}$$

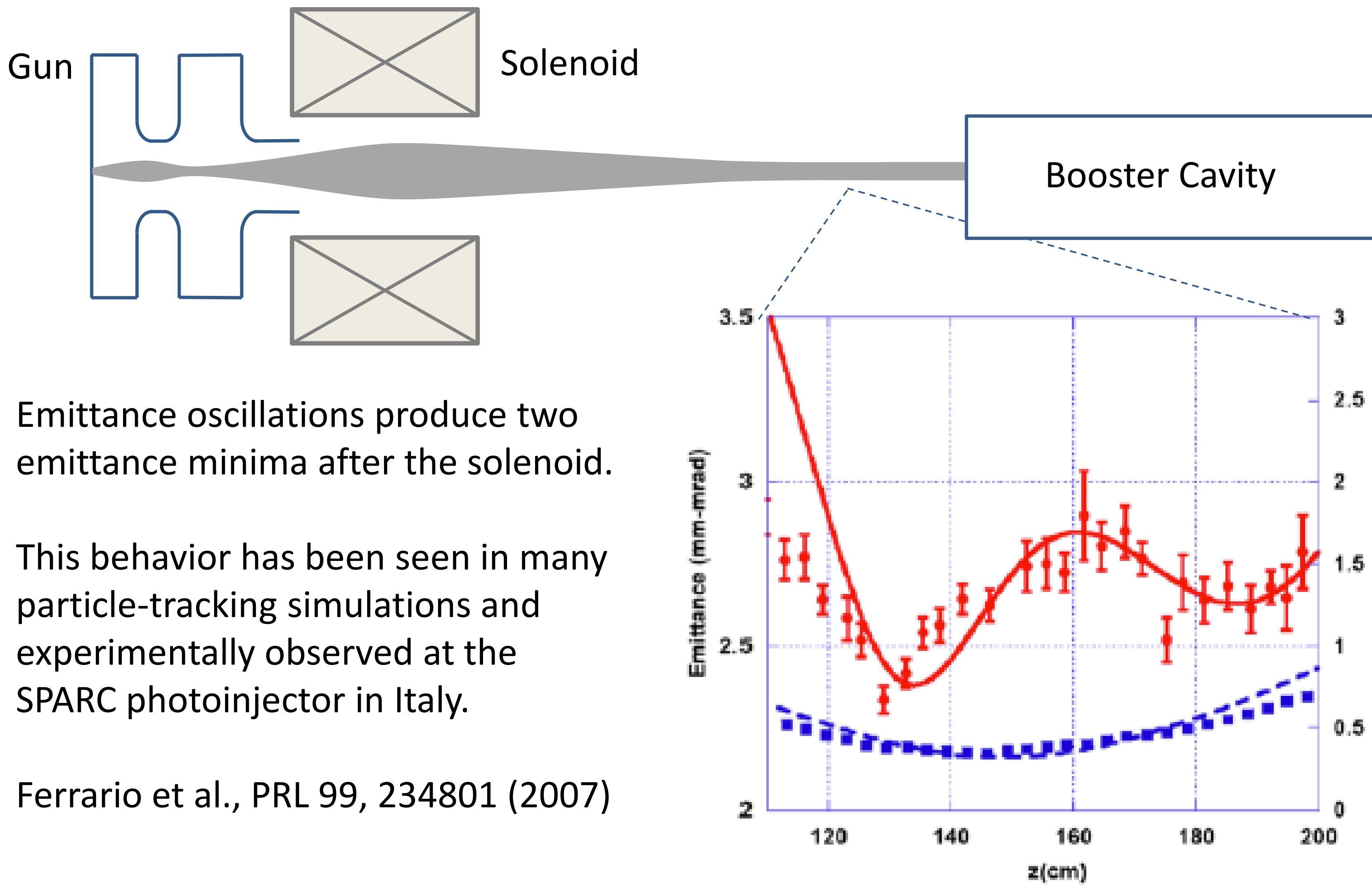
Emittance-dominated beams, $\xi < 1$

$$\hat{\sigma}_{emit} = \left(\frac{2\gamma\varepsilon_n}{\sqrt{3}\gamma'}\right)^{\frac{1}{2}} \qquad \boxed{\sigma_{emit} = \left(\frac{2\varepsilon_n}{\sqrt{3}\gamma'}\right)^{\frac{1}{2}}}$$

Envelope and Emittance Oscillation



Emittance Double Minima



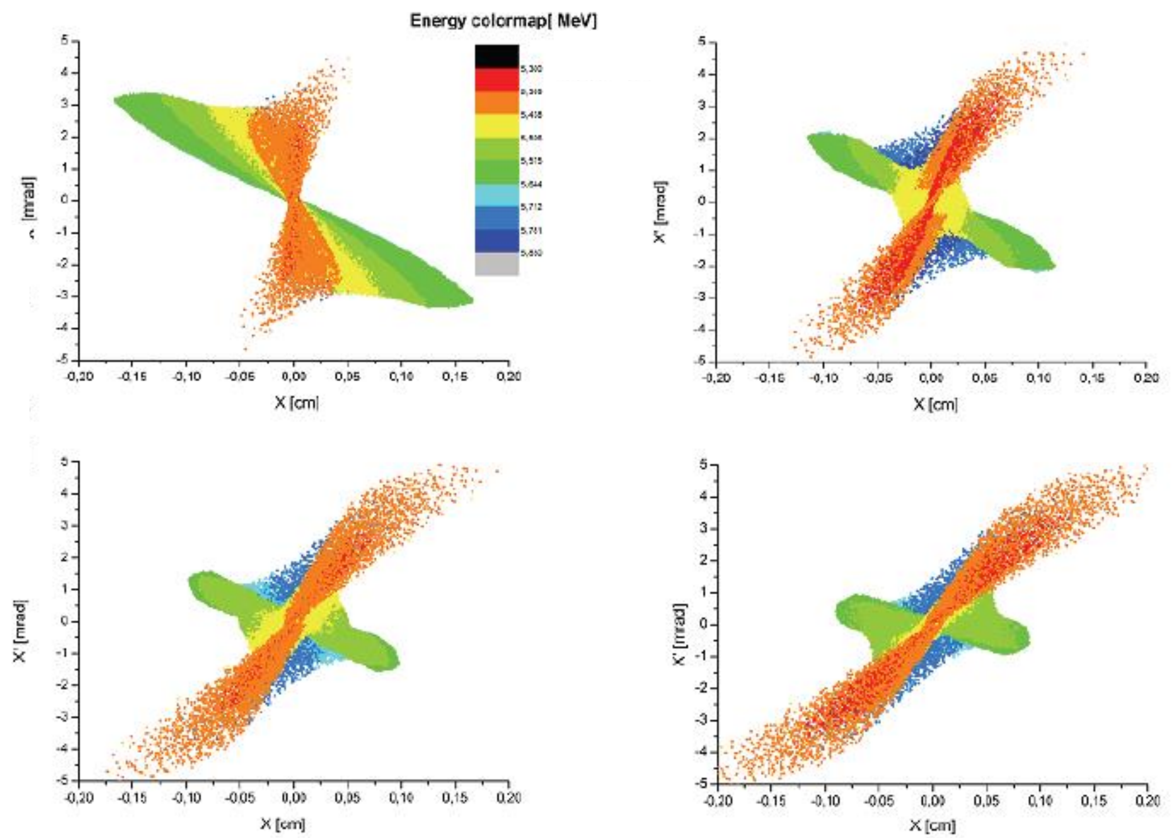
Emittance oscillations produce two emittance minima after the solenoid.

This behavior has been seen in many particle-tracking simulations and experimentally observed at the SPARC photoinjector in Italy.

Ferrario et al., PRL 99, 234801 (2007)

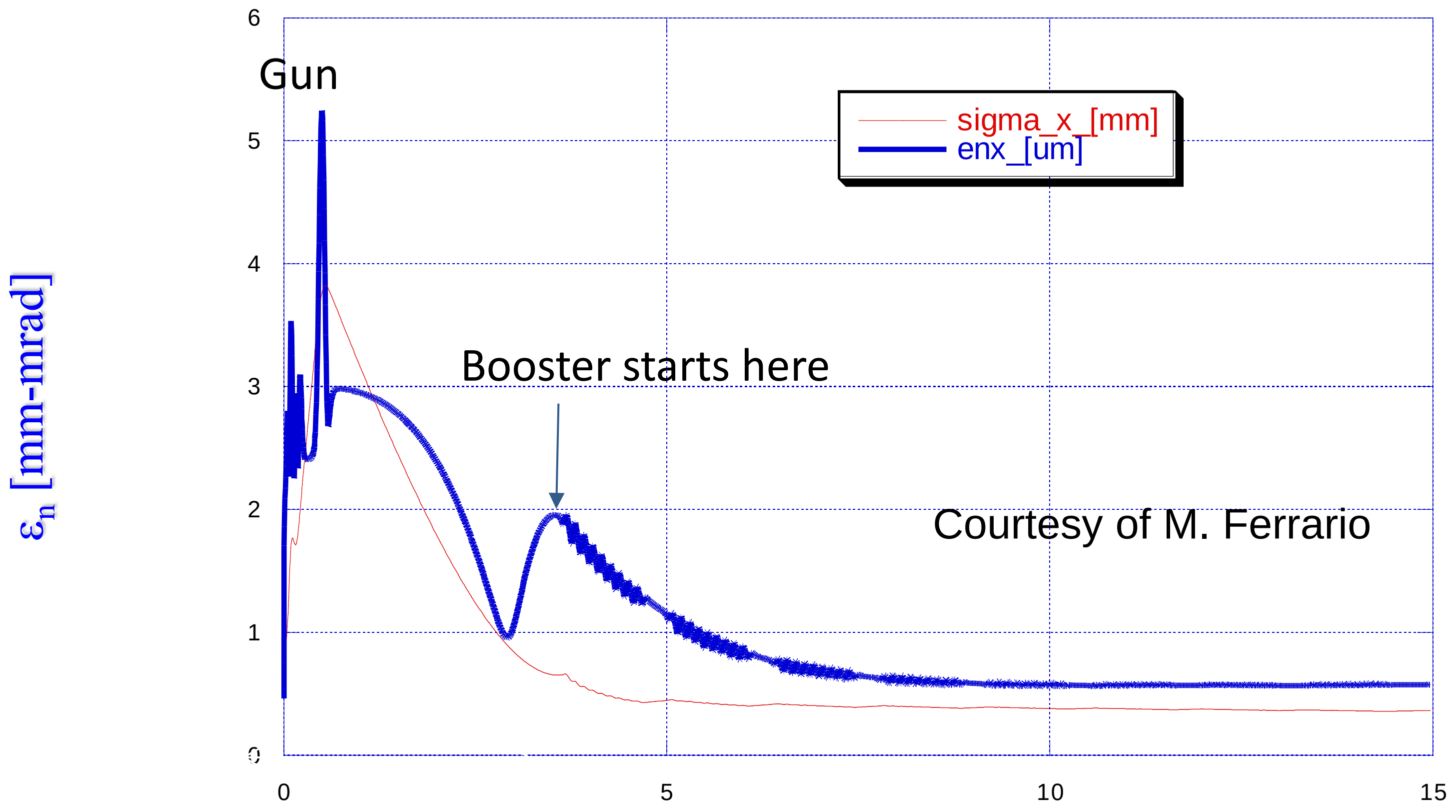
Explanation of Double Emittance Minima at Solenoid Focus

The slices have slightly different energies; the leading edge has higher energy (blue) and the trailing edge lower (red). The slices are not aligned, but the core (green) has the lowest phase space area in the two lower plots.



Matching into a Booster

Plots of normalized emittance (blue) and rms envelope (red) versus z



The beam is matched into the booster at z location where the normalized emittance has a local maximum (between two minima). Subsequent acceleration in the booster damps the emittance oscillation and freezes the second emittance minimum.

Summary

- The photoinjectors produce electron beams with exceptional brightness (peak current divided by emittance in x and y).
- The slice emittance determines the FEL gain.
- All three gun technologies (DC, NCRF and SCRF) are being considered for high-duty-factor XFEL operation.
- Emittance compensation has been used successfully to achieve very small projected emittance (high brightness).
- The Ferrario technique to match the beams into the booster freezes the final beam emittance at the second minimum.