Electron Injectors & Free-Electron Lasers

Bryant Garcia

Friday, June 17 2016. USPAS Fort Collins, Colorado

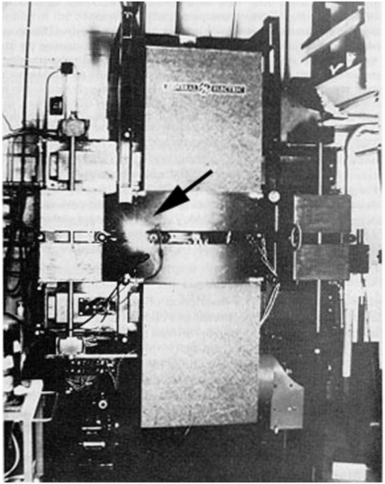
Electron Machine Basics – Why ?

- $m_e = 0.511 MeV/c^2$; $m_p = 938 MeV/c^2$; $m_p/m_e \approx 1835$!
- The beginning of the beamline: $E_{gun} \sim 1$MeV
  - Electrons are almost immediately relativistic
- This affects synchrotron radiation:

$$P_s \sim 1/m^4$$

- Electrons are often considered in *linear* machines because of this
- Differences in Radiation protection, beam dumps, etc. – won't cover

- Synchrotron Radiation discovered in 1947 at the 70 MeV GE synchrotron
- Originally a loss mechanism for electron synchrotrons ("On the maximal energy attainable in betatron", (1944))
- Spells the doom for (circular) electron machines as energy frontier devices but ...

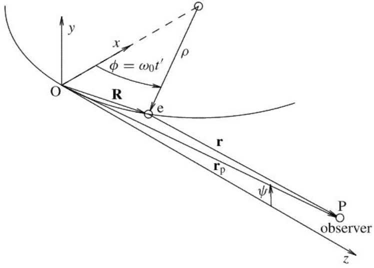


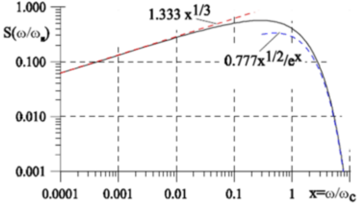
- A tough (but straightforward) EM calculation gives,

$$\frac{dW}{d\omega} = \frac{\sqrt{3}e^2}{4\pi\epsilon_0 c}\gamma\frac{\omega}{\omega_c}\int_{\omega/\omega_c}^{\infty} K_{5/3}(x)dx$$

$$\omega_c \equiv \frac{3}{2}\frac{c}{\rho}\gamma^3, \lambda_c = \frac{4\pi}{3}\frac{\rho}{\gamma^3}$$

- Wavelength spectrum peaked near λ_c
- $\gamma \sim 500$, $\rho \sim 10$m, $\lambda_c \sim 10$ nm! (but broad!)
- Enables the tunable production of high energy, BRIGHT photon pulses

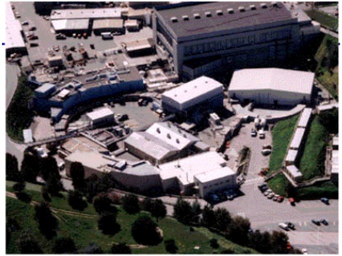




Brief Outline

- FEL physics
  - Insertion devices
  - High Gain FEL
  - SASE vs Seeded
- The Magnetic Chicane
  - Bunch compression
- Electron Injector / Gun
  - Photocathode guns
  - Focusing Solenoids
  - Compression stages
  - Emittance oscillation

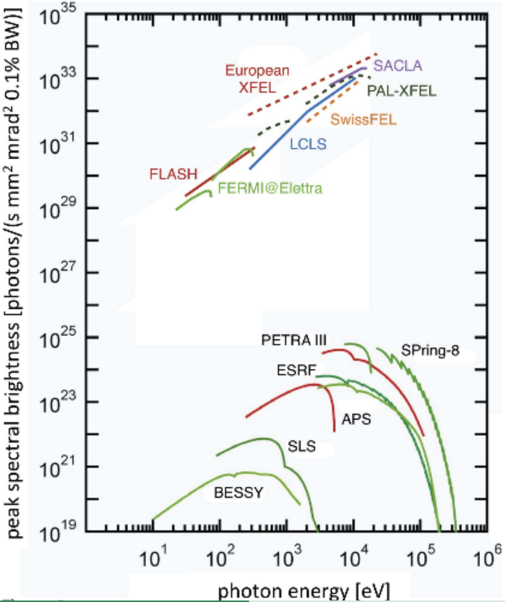
- 1st generation: Parasitic synchrotron radiation from high energy physics machines
- 2nd generation: Dedicated synchrotron machines for production of light
- 3rd generation: Evolved facilities with insertion devices, many beamlines
- 4th generation: Free-electron Lasers and Electron-recirculating linacs



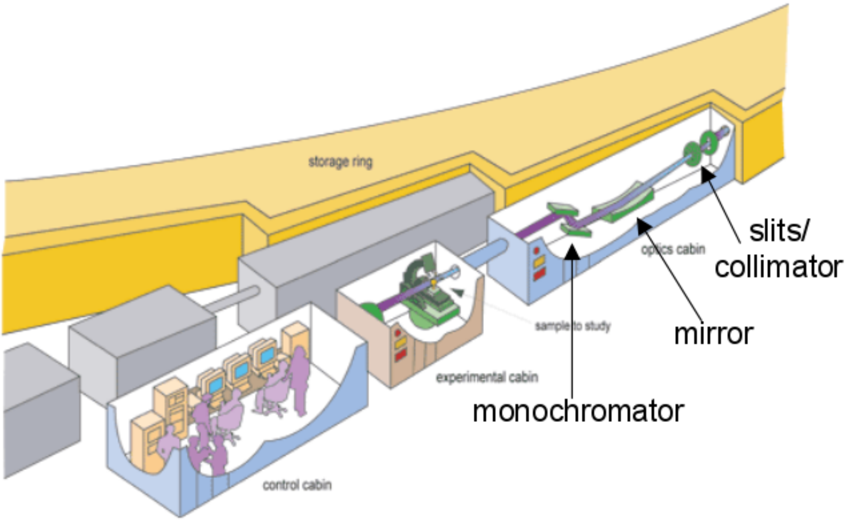
SSRL (SPEAR 2)

APS

The Spectral Brightness Race



The typical beamlines



The magnetic undulator

Series of alternating magnetic poles with periodicity λ_u, $K \equiv \frac{eB_0}{k_u mc}$

$$x(z) = \frac{K}{\gamma k_u} \cos k_u z$$

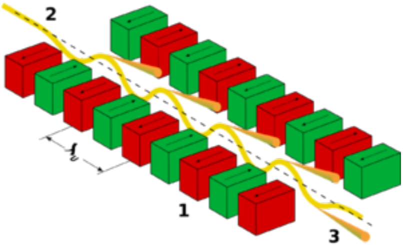
Lorentz transform to the beam rest frame: $k'_u = \gamma k_u$ or $\lambda'_u = \lambda_u / \gamma$

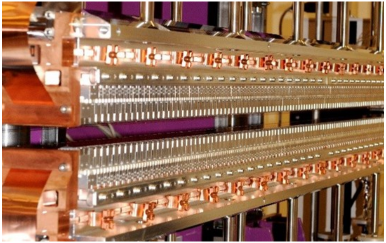
This is larmor radiation, and has wavelength λ'_u

In the lab frame, this radiation is *blueshifted* again by a factor of 2γ, so we expect lab radiation

$$\lambda_r \sim \frac{\lambda_u}{2\gamma^2} \text{ Estimate}$$

$$\lambda_r = \frac{\lambda_u}{2\gamma^2}\left(1 + K^2/2 + \gamma^2\theta^2\right) \text{ Reality}$$





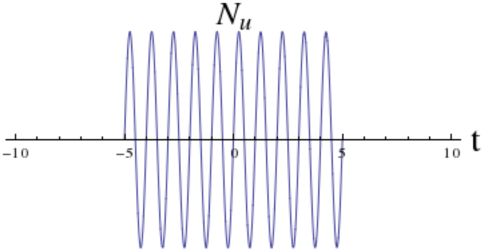
Undulator Radiation

The undulator radiation is then simply described as

$$E(t) = \begin{cases} E_0 e^{-i\omega_r t}, & -N_u\lambda_u/2c < t < N_u\lambda_u/2c \\ 0, & \text{otherwise} \end{cases}$$

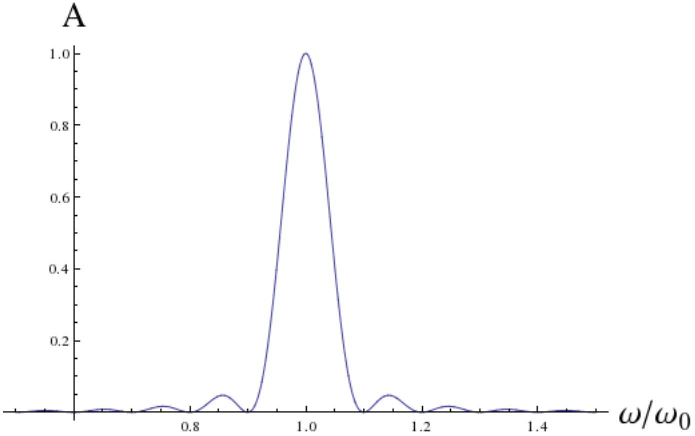
Frequency response is found via fourier transform ($T \equiv N_u\lambda_u/2c$)

$$F(\omega) = \int_{\infty}^{\infty} E(t)e^{i\omega t}dt = \int_{-T}^{T} E_0 e^{i(\omega-\omega_r)t}dt$$



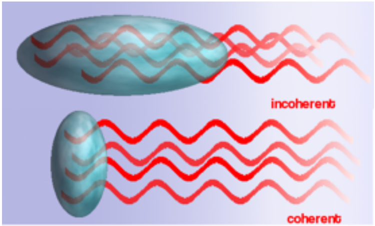
$$F(\omega) = 2TE_0 sinc(T(\omega - \omega_0))$$

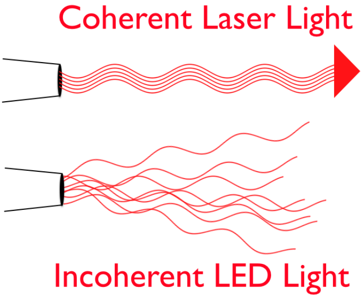
This spectrum has a FWHM $\Delta\omega = \omega_0 / N_u$



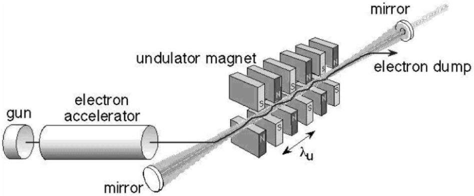
Coherent Radiation

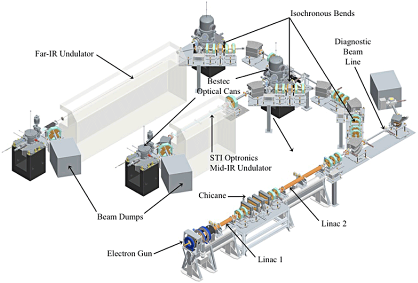
- Normally, electron radiation is *incoherent*, that is, the phase of each electron's emission is random.
- Incoherent power $P \approx N_e$.
- If the electron bunch has a size $< \lambda_r$, the phases are all roughly equal $\Rightarrow$ Coherent emission
- $P \sim N_e^2$ for Coherent emission ($\sim 10^9$!)



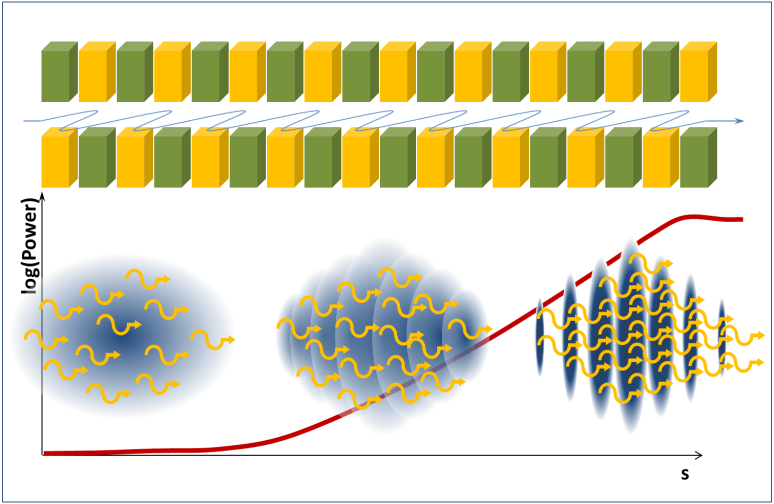


- We can achieve coherence through *low-gain* operation and a cavity, as in a traditional laser
- Can use low energy e beams to make Visible-Microwave radiation
- Requires *reflective optics* at the wavelengths of interest $\Rightarrow$ no X-rays





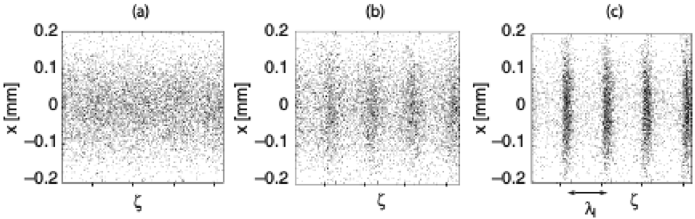
Another option is to have a very LONG undulator, and allow an instability to develop:



The LCLS Video

http://lcls.slac.stanford.edu/AnimationViewLCLS.aspx

- The radiated light becomes intense enough to back-react on the electron bunch
- The effect is to *bunch* the electrons up at the radiation wavelength



- The bunching ⇒ more coherent emission ⇒ stronger EM field ⇒ more bunching

[Video]

- The physics of the FEL process is all (basically) controlled by a single parameter ρ:

$$\rho = \frac{1}{2\gamma}\left(\frac{\hat{K}\lambda_u}{2\pi\sigma_b}\right)^{2/3}\left(\frac{I}{I_A}\right)^{1/3}$$

$$P_{\mathrm{sat}} = \rho\left(\frac{IE_b}{e}\right) = \rho P_{\mathrm{beam}}$$

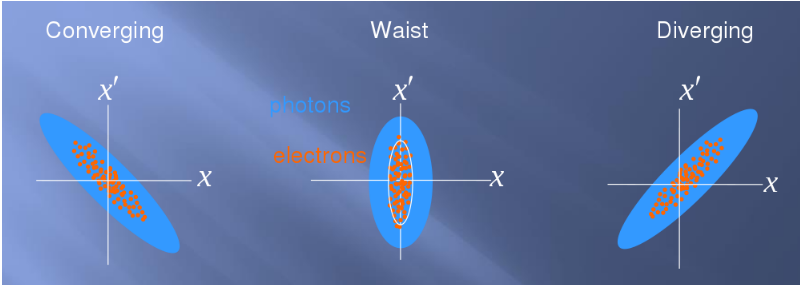
$$L_g = \frac{\lambda_u}{4\pi\sqrt{3}\rho}$$

- For reference, modern X-ray FELs have $\rho \sim 5 \times 10^{-4}$, λ_u ~cm. So $L_g \sim$ few meters.
- Turns out you need $\sim 20L_g$ to saturate $\Rightarrow$ very long undulators

To maintain *spatial* coherence, the phase space volume of the electrons should be less than the phase space volume of the photons:

$$\epsilon_{\text{electrons}} < \epsilon_{\text{photon}}$$

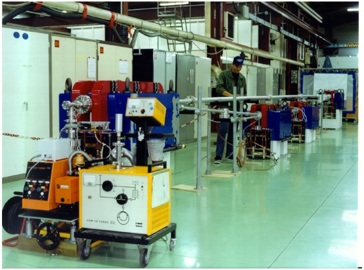
$$\epsilon_{\text{electrons}} < \frac{\lambda_r}{4\pi}$$

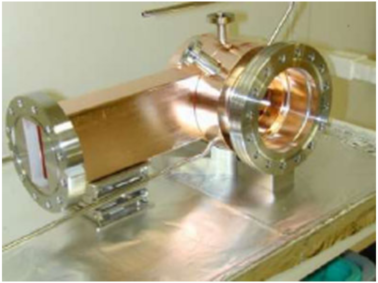


$\lambda_r \approx 1\text{nm} \Rightarrow \epsilon < 0.1\text{nm}$! This is very small!

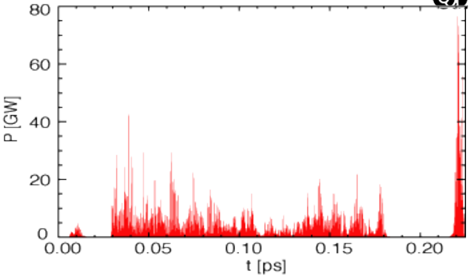
Storage rings have a natural emittance ~nm at best, so cannot be used for X-ray FELs $\Rightarrow$ linac sources

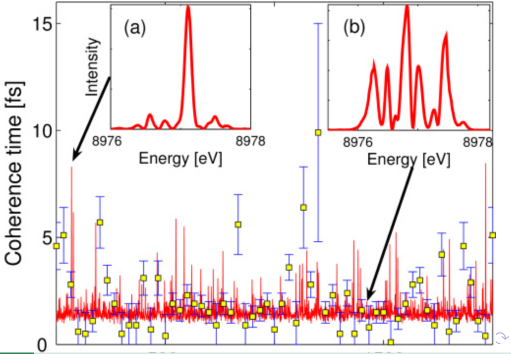
- Require very low emittance (for transverse matching)
- Require high energy electrons (for low λ_r)
- Require high peak current I/I_A (for high ρ)





- Random electron beam seeds the instability with *noise*
- Locations/size of lasing regions are stochastic
- Many spectral spikes, non-utilization of full electron beam
- *Spatially* but not *temporally* coherent radiation



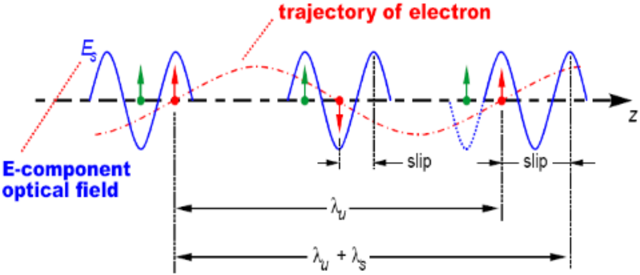


Coherence Length

The reason for the many spikes is that information is generally not propagated through the whole electron beam

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

This is also a *resonance* condition:

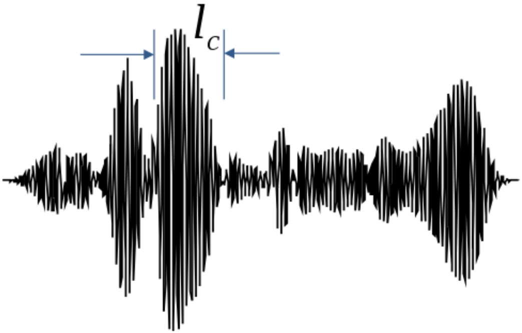


$$\frac{\lambda_u + \lambda_s}{c} = \frac{\lambda_u}{v_z} \iff \lambda_s = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2}\right)$$

The light slips forward by one radiation wavelength per undulator period

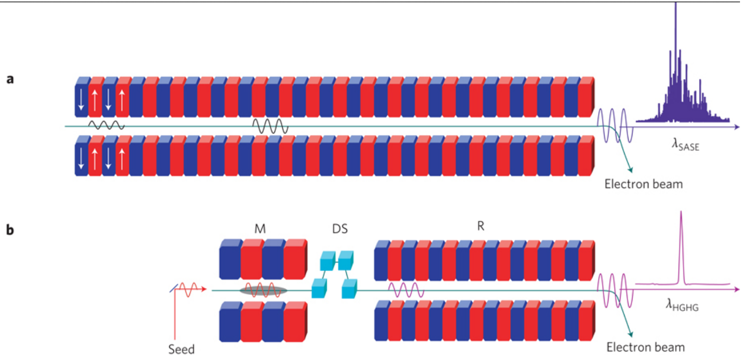
Coherence Length: Slippage in one gain length

$$L_c \approx \lambda_r / \pi\rho \ll l_{\mathrm{beam}}$$



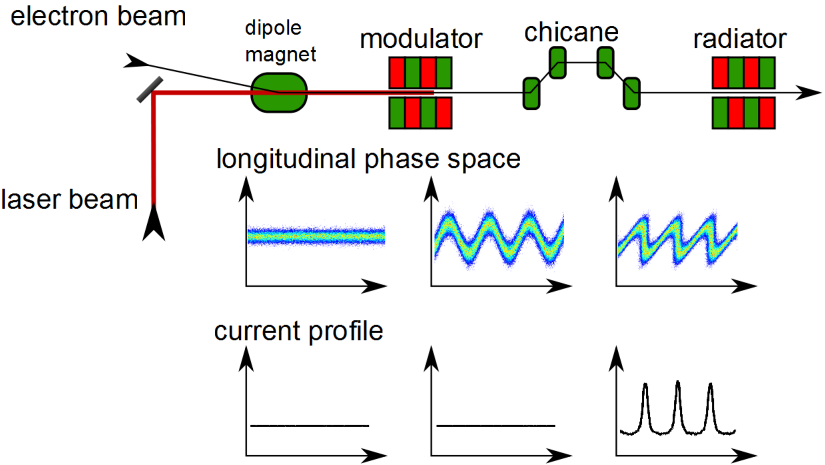
So the individual SASE spikes never have time to fully communicate

If we could introduce a coherent seed to the process, all areas of the beam would (ideally) radiate identically – Pure spectrum



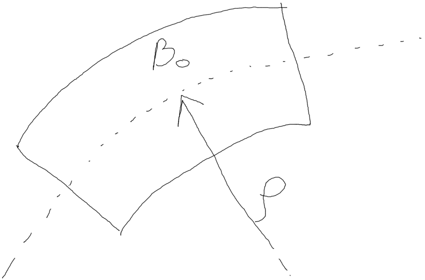
But how can we do this without the required lasers?

Use a conventional laser to create high harmonic density bunching (to seed the coherent emission)



- We've focused on transverse dynamics so far, but the need for peak current (and seeding) forces us to look in the longitudinal plane
- To compress, we need to be able to move particles longitudinally (R_{5i} transport components)

Consider a simple dipole magnet, bending in a radius ρ through an angle θ for the reference particle with momentum p.



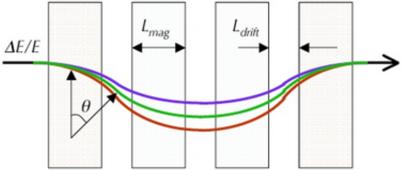
The result is that

$$ds/(\delta p/p) = \rho_0 \left(\theta - \sin\theta\right) - \frac{\rho_0 \theta}{\gamma^2}$$

- More energetic electrons travel a longer distance
- For relativistic particles $\gamma \gg 1$, they arrive *later* than their low energy counterpart $\Rightarrow$ prism!

Magnetic dipoles are longitudinally (as well as transversely) dispersing optics

Put 4 dipoles, to have the trajectory return to the straight path to form a chicane:



Higher energy particles travel a shorter distance ⇒ dispersing in longitudinal space:

$$ds/(\delta p/p) = 2\theta^2 \left(L_{\text{drift}} + \frac{2}{3} L_{\text{mag}}\right)$$

Note: Can use 2 dipoles if you desire a beamline shift (but horizontally dispersing)

Interim - The Magnetic Chicane

JLab Magnetic Chicane

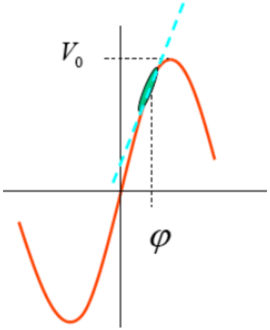
- Enter accelerating cavity off-crest to provide an energy-time(distance) correlation

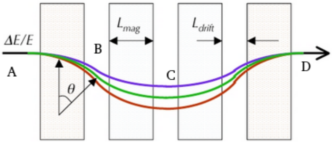
$$V(z) = V_0 \sin(k_0 z)$$

Where $k_0 = 2\pi/\lambda_{\rm RF}$ is the RF wavevector, so (assuming the bunch is ultra-relativistic and does not slip with respect to the RF wave)

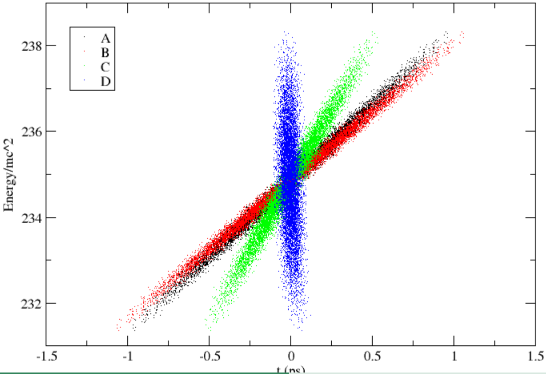
$$E(z) = E_0 + eV_0 \sin(k_0 z + \varphi)$$

$$\frac{dE}{dz} = eV_0 k_0 \cos(k_0 z + \varphi) \approx eV_0 k_0 \cos(\varphi)$$



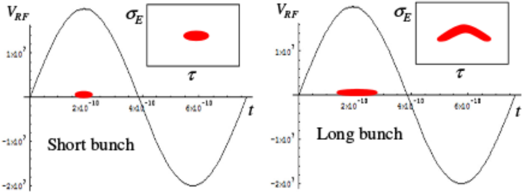


$$\sigma_{z,f} = (R_{56,O})\sigma_{\delta i} E_0/E$$



Non-linear complications

- For a bunch with comparable length to RF, the beam acquires quadratic curvature:



- 'Banana shape' limits compression
- Can use a harmonic cavity to correct the quadratic curvature term
- An infinite harmonic series $\Rightarrow$ a perfectly linear beam over ALL scales

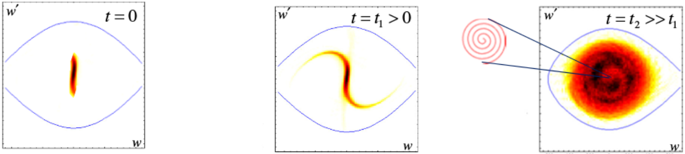
Electron Injectors

* Many slides taken/adapted from USPAS 2016 Course "Electron Injectors for 4th Generation Light Sources" F. Sannibale, D. Filipetto, C. Mitchell

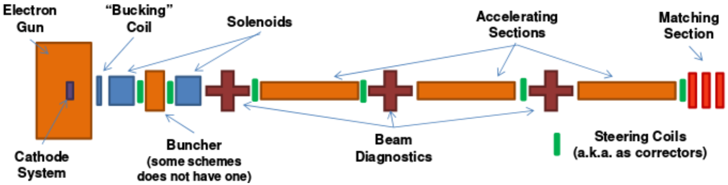
Electron Injector

- The electron injector is where the electrons are born and enter the accelerator environment
- Accelerator complex divided between ‘injector’ and 'accelerator’
    - Generally ‘injector’ ends when space charge forces are negligible
    - Space charge are beam self-forces, $\sim 1/\gamma^2$
- Space charge forces are in general *non-linear*, and can *increase* the rms emittance of the beam
- So the injector performance defines a limit for beam emittance

$$B = \frac{N}{\epsilon_{N,x}\epsilon_{N,y}\epsilon_{N,z}} \qquad \text{6-D Beam Brightness}$$

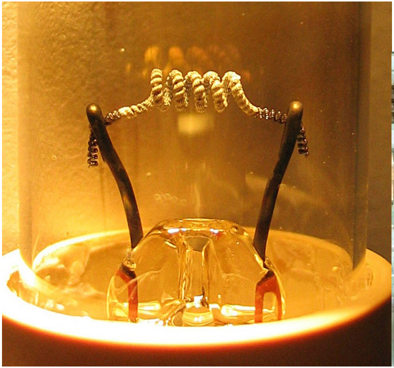


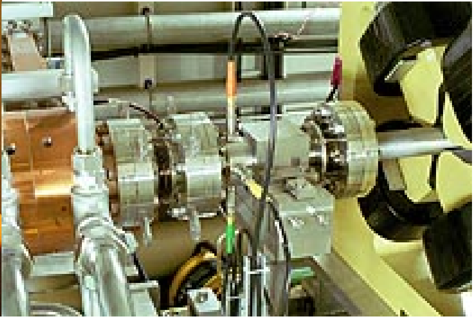
Electron Injector Subsystems



- Cathode system
- Gun
- Focusing Solenoids
- Buncher
- Accelerating systems
- Matching

- Hot filament simply emits electrons when heated
- Energy of electrons depends on temperature
- Electron distribution depends critically on cathode geometry
- CONTINUOUS (every RF Bucket) OPERATION



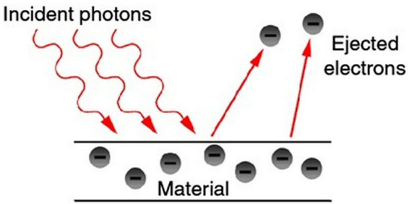


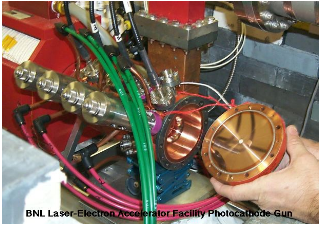
Photocathode

- Photocathodes: Laser impinges on material, photoelectric effect liberates electrons

$$E = \hbar\omega - \phi$$

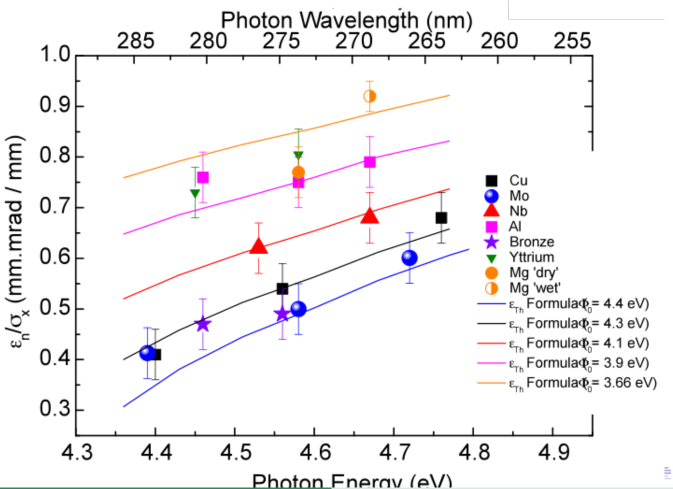
- Work function ϕ, and QE depend critically on material
- Requires laser system, usually in the UV (266nm)
- Fairly tunable via laser spot size, pulse duration. Prompt response.
- usually PULSED OPERATION



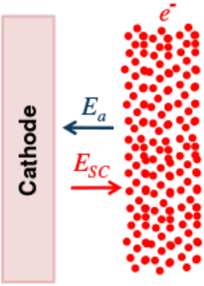

BNL Laser-Electron Accelerator Facility Photocathode Gun

Excess energy from the photons leads to increased electron (transverse!) velocity ⇒ increased emittance

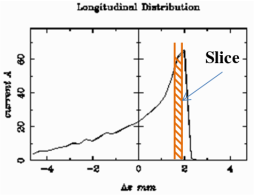
$$\epsilon \sim \sqrt{\hbar\omega - \phi + E_{\mathrm{schottky}}}$$

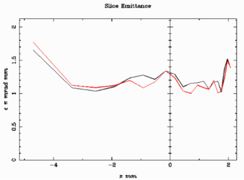


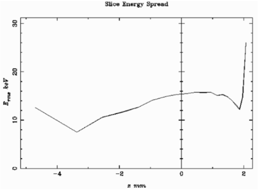
- FELs sensitive to peak current AND total beam power $\Rightarrow$ want a lot of charge, and high peak current
- Operational optimum usually found ~100s of pC/bunch
- Note: Can trade lower peak power for shorter gain length (generally)
- Space charge field defines maximum charge density extractable (Higher acc. field helps!)



The FEL physics ρ is generally sensitive only to the parameters in a local region 'slice' of the electron beam

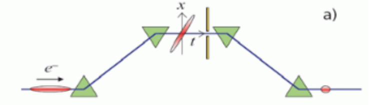


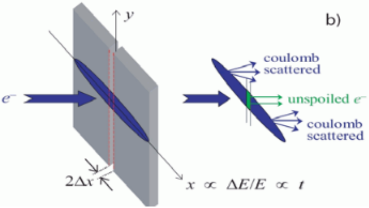


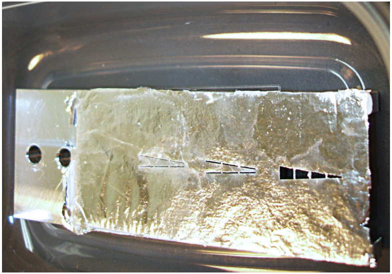


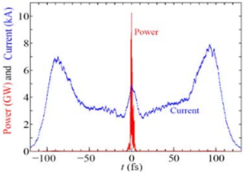
Length of slice is $\sim$ slippage length over the undulator $\sim N_u \lambda_r$
So we generally only require a *portion* of the electron beam to have good parameters out of the injector

- Can use this slice v. projected to lase on select portions of the beam
- Dispersive chicane + slotted foil picks out a *temporal* portion of the beam to preserve emittance
- Elaborate foils can be used to fully tune multiple pulses w/ durations and separations





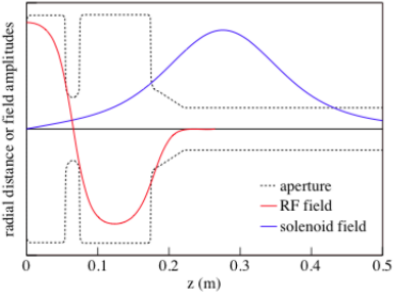




- Electrons emitted, need to capture them and accelerate quickly $\Rightarrow$ high gradient RF fields
- At this point, electrons are very non-relativistic, so they slip relative to the RF wave by a lot
- Need to adjust phase of RF for maximum acceleration gradient $\Rightarrow$ ride the wave

$$L_{\mathrm{acc}} = \frac{mc^2}{eE_0} < \lambda_{RF}$$

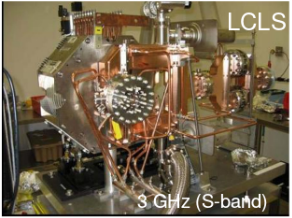
$\lambda_{RF} \sim \mathrm{mm} \Rightarrow E_0 \sim 50\text{MV/m !!!}$

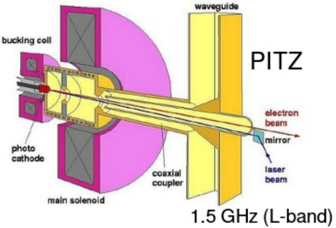


Normal Conducting High Frequency RF Guns

Pros:

- High gradients from ~50 to ~140 MV/m (20 – 60 MV/m at cathode during photo-emission
- "Mature" technology.
- Full compatibility with magnetic fields.
- Compatible with most photocathodes
- Proved high-brightness performance. (LCLS, PITZ, …)



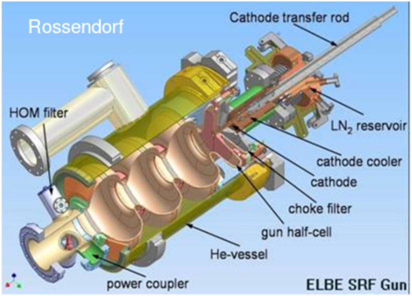


Areas for improvement:

- 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.

Pros:

- Potential for relatively high gradients (several tens of MV/m)
- CW operation
- Excellent vacuum performance.
- Promising results by several groups (Rossendorf, Wisconsin, HZB, BNL, ...)

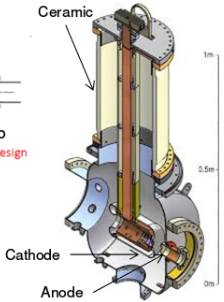


Areas for improvement:

- Move technology into a more mature phase. Significant progresses under way.
- Experimentally verify cathode/SRF compatibility issues (Promising results with Cs_2Te at Rossendorf, DC-SRF Peking approach). Develop higher QE super-conducting cathodes.
- Difficult emittance compensation (Meissner field exclusion, magnetic field induced quenching, ...).

Pros:

- DC operation
- DC guns reliably operate at 350~380 kV (JLAB, Cornell), ongoing effort to increase the final energy (Cornell, Daresbury, Jlab, JAEA, KEK,...).
- Simulations and recent results (Cornell) demonstrated the capability of sub-micron emittances at ~ 0.3 nC, with ~380 keV beam energies.
- Full compatibility with magnetic fields.
- Excellent vacuum performance
- Compatible with most photo-cathodes. (The only one operating GaAs cathodes)



Cornell 400 keV Gun

Areas for improvements:

- Higher energies require further R&D and significant technology improvement.
- In particular, improvement of the high voltage breakdown ceramic design and fabrication.
- Relative low gradients at the cathode <~ 10 MV/m
- Developing and test new gun geometries (inverted geometry, SLAC, JLab) Very interesting results from a “pulsed” DC gun at Spring-8.

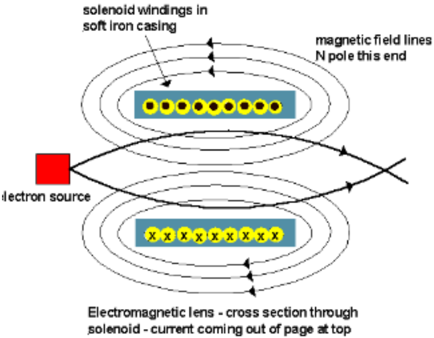
- Solenoids are capable of focusing *in both planes*

$$B_z(r,z) = B_z(z) - \frac{r^2}{4}B_z''(z)$$

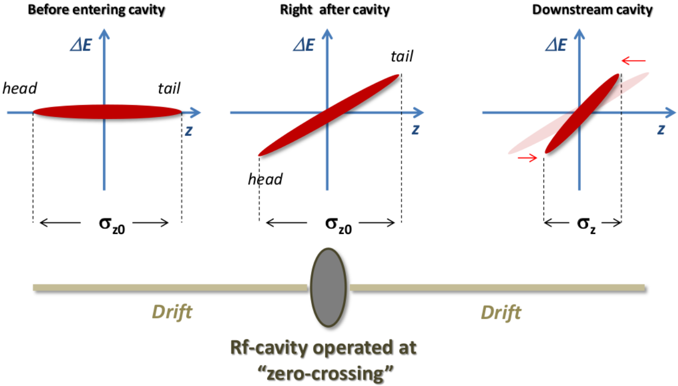
$$B_r(r,z) = -\frac{r}{2}B'(z) + \frac{r^3}{16}B_z'''(z)$$

$-\frac{r}{2}B'(z)$ induces a rotive velocity, which in turn focuses the beam in $r \Rightarrow$ both x and y!

- Useful for focusing and controlling the beam *quickly* in the low energy region



Low energy electrons streaked with a zero-phased RF cavity

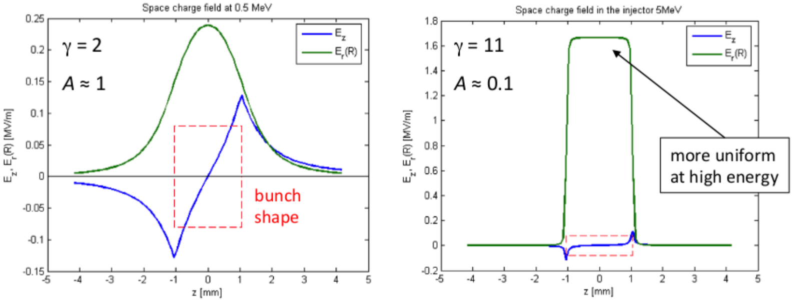


Recall in a drift

$$ds/(dp/p) = \frac{L}{\gamma^2}$$

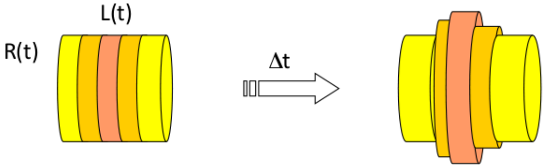
Effective compression at low energy!

Space charge electric field components E_z and E_r for a finite, uniform cylindrical bunch:



$$A = R/(\gamma L)$$

effect of space charge fields on the bunch over a time Δt



How will this affect the emittance of the beam?

Emittance Oscillation & Compensation

- The different longitudinal positions of the beam trace out different ellipses
- The projected result *looks* like an RMS emittance increase
- Focus and align them all, THEN 'freeze in' emittance via accelerating section