LINAC DESIGN FOR FELS

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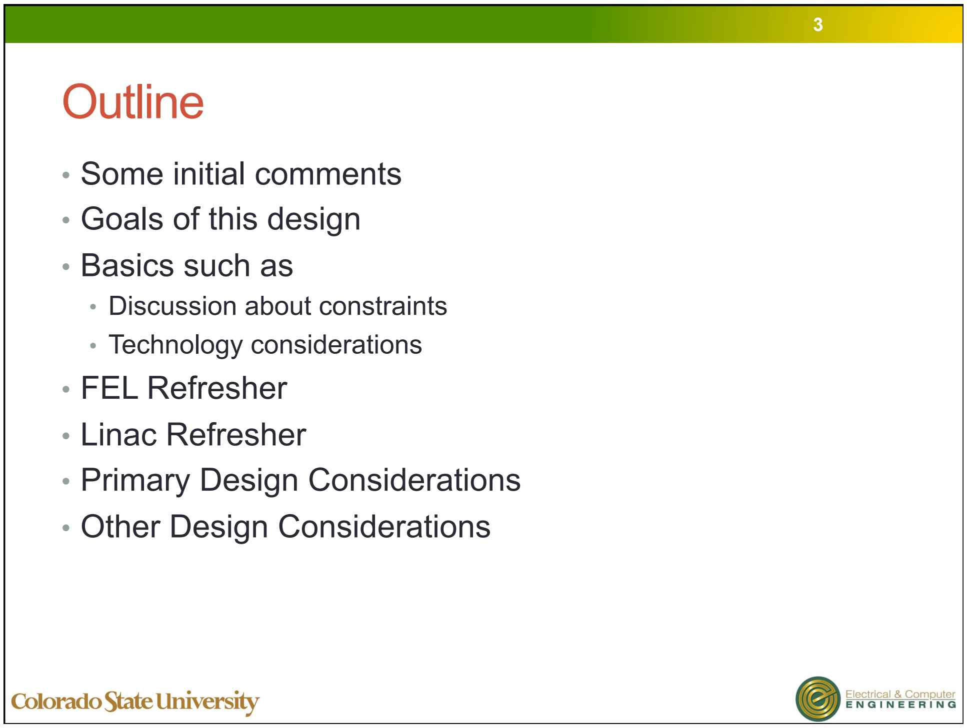
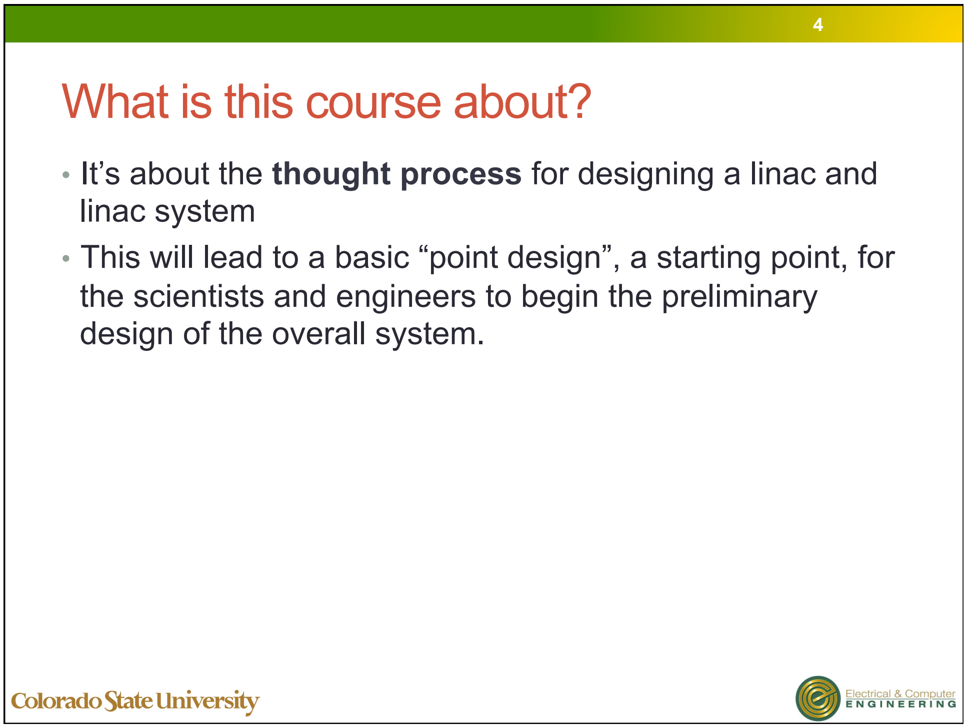
Synchrotron Radiation and Free-Electron Lasers
Erice, Italy 6 – 15 April 2011

INTRO



Outline

- Some initial comments
- Goals of this design
- Basics such as
  - Discussion about constraints
  - Technology considerations
- FEL Refresher
- Linac Refresher
- Primary Design Considerations
- Other Design Considerations



What is this course about?

- It's about the **thought process** for designing a linac and linac system
- This will lead to a basic "point design", a starting point, for the scientists and engineers to begin the preliminary design of the overall system.

As importantly, what this course is not

- It is not a course on how to design the details of a linac or the various items that make up a linac
- A course on linac optics
- A course on collective effects
- A course on how to engineer various components
- Etc.

What I Will Touch Upon

- What are the initial goals that we would like to achieve with the linac
- Some basics on FELs
- Some basics on linacs and linac systems
- The point design
  - Coming up with the initial concept of what you want to design
  - Proceeding through this design
  - Refining and iterating the design
- Ancillary Items
  - Buildings
  - Power and water needs
  - Cabling
  - Basics layout of infrastructure
  - Etc.

A few notes

- This is not (yet) a real design although it might look like a design for some other machine that you might have seen or know about.
- As always, designs take on the personality of the designer, i.e. there is no 1 perfect design. As such, these are my thoughts, and the compromises I have chosen to make reflect what I think might be best and these might not coincide with other's opinions. But, the point is to move forward with confidence… and with an open mind to new and useful ideas.
- I am certain there are some mistakes in what I will show today, but that's the way designs start. You just have to be both willing to expose possibly some of your weaknesses and also be willing to accept constructive criticism and then modify your design to make it even better.
- I might need more time than what is allocated. Then again, I might need less.

A Relevant Quote

> *When opening a University textbook, the undergraduate gets the impression that the subject concerned is a closed chapter. He is not likely to find openings for the discussion and understanding of problems still extant in the field. And yet, problems awaiting solution exist in every field*
>
> *Antonino Zichichi*

SOME GOALS OF THIS DESIGN

What should we build?

- The first question to ask is
  - Why are we building this?
    - It’s usually to provide a new light source for a broad user community.
    - It’s not necessarily because it is fun (although it is) or that we are trying to develop a broad range of new linac technologies.

What should we build?

- What does the user community want?
  - Below are my opinions
  - Up to 1100 eV photons at the fundamental wavelength (1.1 nm)
    - This is above highest Ni L-edge (and just above Cu L-edge) and allows one to readily explore all the important ferromagnetic materials
    - We will also assume that the FEL will be able to generate a significant amount of photons at the 5th harmonic, i.e. 5500 eV (0.23 nm)
  - > 10 kHz operations
    - Is this even possible?
      - Not a pulse train delivering 10 kpps, but true 10 kHz operation
      - Can it be done without SCRF?
        - Let's try anyway.
  - Multiple beam lines
    - Rate at individual beamlines programmable
    - Requires fast switching system

What should we build?

- What does the user community want?
  - Variable Autonomous Polarization
    - Use APPLE-type Undulators
  - Variable Autonomous Wavelength Control
  - Ultrashort pulses
    - 10s of fsec or better
  - Shot-to-shot Stability
    - Energy per pulse
    - Wavelength
  - Narrow, single-spike spectrum
  - (Note: The above two bullets might imply the need to seed)

What should we build?

- Some other considerations
  - We might not be able to simultaneously satisfy all user desires.
  - In fact we might never be able to satisfy some, but that’s OK.
  - It is probably is a good idea to design beamlines that are tailored for a specific wavelength range or set of optical properties rather than making all general purpose.
    - One could then move the experiment to the most appropriate station.
    - This can simplify the machine design and make for a source that has overall superior properties.
  - Seeding could be difficult at these wavelengths and repetition rates.
    - I will not concern myself with seeding at this time.
  - The real “new” goal is to achieve the high repetition rate with room temperature rf systems. That will be the primary focus of this design exercise.

What the Design Will Be

- I will go through the thought process of generating an initial rough design for a linac system that will be used to drive a single pass VUV to soft x-ray FEL
  - Up to 1.1 keV photons at the fundamental
  - 10 kHz operation if possible
  - Room temperature (i.e. not superconducting)
  - Compact and efficient (i.e. hopefully low cost)
- The design will draw upon other designs whenever possible, but will at the same time be unique.

SOME BASICS BEFORE PROCEEDING

Some Additional Possible Constraints

- Money
  - This amount available might be based upon the initial estimate.
  - It could be based on what the system will bear.
  - It might be based on what the sponsor has decided they will provide.
  - Contingency
    - Even with the best effort you should always (if possible) consider some sensible amount of contingency
- Real Estate
  - This could be defined by existing property boundaries.
  - It could be driven by costs
    - Many times the property is provided as an in-kind contribution
  - One must also be aware of the soil/geology conditions
- Existing Infrastructure
  - Power availability
  - Water availability

What to do

- Keep focus on the initial primary goals
  - Ignore some of these other possible constraints for the time begin, but keep them in the back of your mind.
  - You might find that your initial design meets all the essential constraints without need to compromise.
  - If not then compromise…or start all over if there is a real problem.
- Some of this designs goals will be
  - Keep the overall system short, compact
  - Try to keep the costs under control
    - I won't do a cost estimate, but will, when I think of it, point out where costs can be controlled.

Some Technology Considerations

- Obviously driven by the above constraints
- SC vs. Room Temperature RF accelerator (Big decision 1)
  - The typical choice for high pulse per second count is SC
    - The European XFEL
    - The Berkeley Next Light Source
    - i.e. common wisdom would say to design using a SC rf system
  - So we will choose a room temperature design just to be sporty
    - It is also considered to be the cheaper solution
      - Again, people will argue that point as well

Some Technology Considerations

- Type of Injector System to Use
  - Two primary types
    - Photocathode injector based systems
    - Thermionic cathode injector based systems
  - Need to consider
    - Emittance achievable
      - This has a direct impact on the final energy required
    - Repetition rate
    - Reliability
  - We'll leave this decision for little later
- Undulator Technologies
  - This also has a direct impact on the energy required
  - Again this decision will be left for a little later.

FEL REFRESHER

Undulator Magnets: Resonant Condition

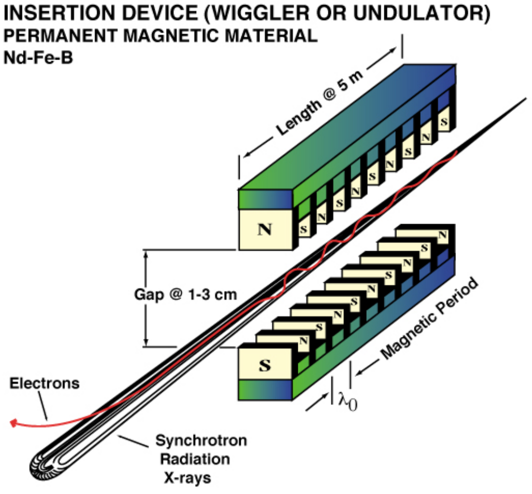
"Resonance" occurs when the light wavefront "slips" ahead of the electron by one optical period in the time that it took the electron to traverse the distance of one undulator period

$$\lambda_{rad} = \frac{\lambda_o}{2\gamma^2}\left(1 + K^2/2\right)$$

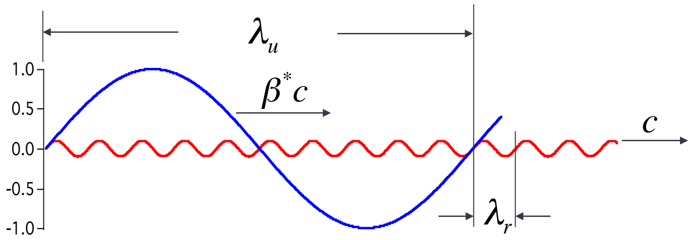
Where γ is the normalized electron beam total energy and

$K = 0.934\ \lambda_{rad}\,[\mathrm{cm}]\ B_{max}\ [\mathrm{T}]$

Is the normalized undulator field strength parameter



Simple Calculation of the "Resonant Wavelength"



$$t = \frac{\lambda_u}{\beta^* c}$$

$$\omega_r = \frac{2\pi}{\lambda_r} c$$

To be resonant the light should out race the electron by one optical wavelength λ_r (2π in phase) after the electron has traveled one full cycle, i.e. λ_u

$$\theta_r = k_r s - \omega_r t = -2\pi = 2\pi \frac{\lambda_u}{\lambda_r}\left(1 - \frac{1}{\beta^*}\right) \quad \Rightarrow \quad \lambda_r = \lambda_u\left(1 - \beta^*\right) \qquad \text{for } \beta^* \cong 1$$

Using

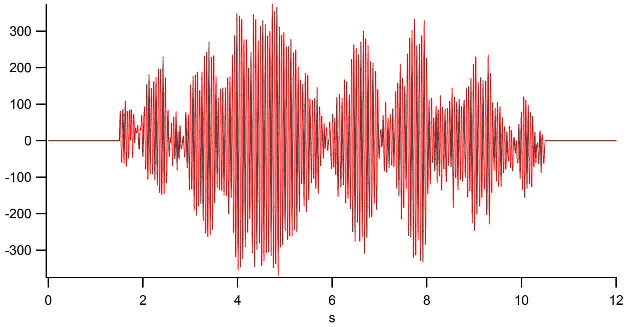
$$\beta^* = \frac{\bar{\dot{s}}}{c} = 1 - \frac{1}{2\gamma^2}\left[1 + \frac{K^2}{2}\right]$$

Gives the resonant wavelength $\lambda_r = \dfrac{\lambda_u}{2\gamma^2}\left[1 + \dfrac{K^2}{2}\right]$

Multiple Electrons

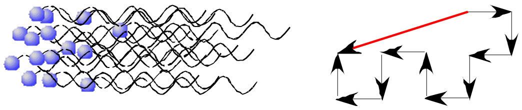
$$E_{tot}(t) = E_x(t)\sum_{j=1}^{N}\exp(i\phi_j)$$

Coherent sum of radiation from N electrons

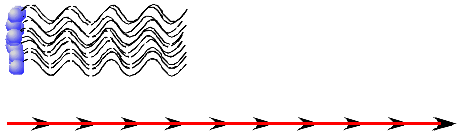


The light consists of several coherent regions, also referred to as spikes, randomly distributed over the pulse length of the electron beam.

Multiple Electrons



Incoherent Emission



Coherent Emission

If the electrons are independently radiating then the phase of their electric fields are random with respect to one another. The electric field then scale as the square root of the number of electrons and the power linearly with the number of electrons.

If the electrons are in lock synch and radiate coherently then the electric field grows linear with the number of electrons

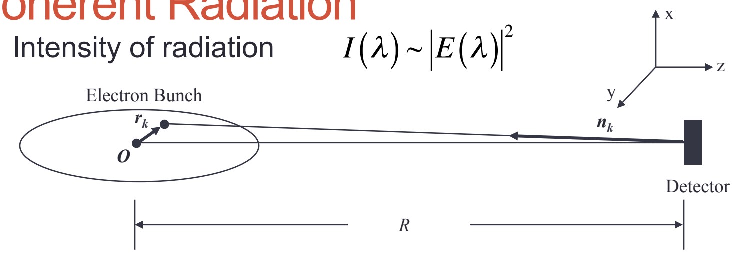
As power goes as the square of the field, if N is very large one can get an enormous gain in power emitted.

This is the essence of the Free-electron laser.

Coherent Radiation

Nodvick and Saxon, Phys. Rev. **96** (1954) 180.

- Intensity of radiation $I(\lambda) \sim |E(\lambda)|^2$



- The component of the electric field from an electron seen by the detector at wavelength λ is $$E_k(\lambda) = E_1(\lambda)e^{2\pi n_k \cdot r_k/\lambda}$$
- The total field of all electrons is $$E_{tot}(\lambda) = E_1(\lambda)\sum_{k=1} e^{2\pi i n_k \cdot r_k/\lambda}$$
- And the total intensity is

$$I_{tot}(\lambda) = I_1(\lambda)\left|\sum_{k=1}^{N} e^{2\pi i n_k \cdot r_k/\lambda}\right|^2 = I_1(\lambda)N + I_1(\lambda)\sum_{j\neq k}^{N} e^{2\pi i(n_k \cdot r_k - n_j \cdot r_j)/\lambda}$$

- The 1st is the incoherent term and the 2nd is the coherent

Coherent Radiation

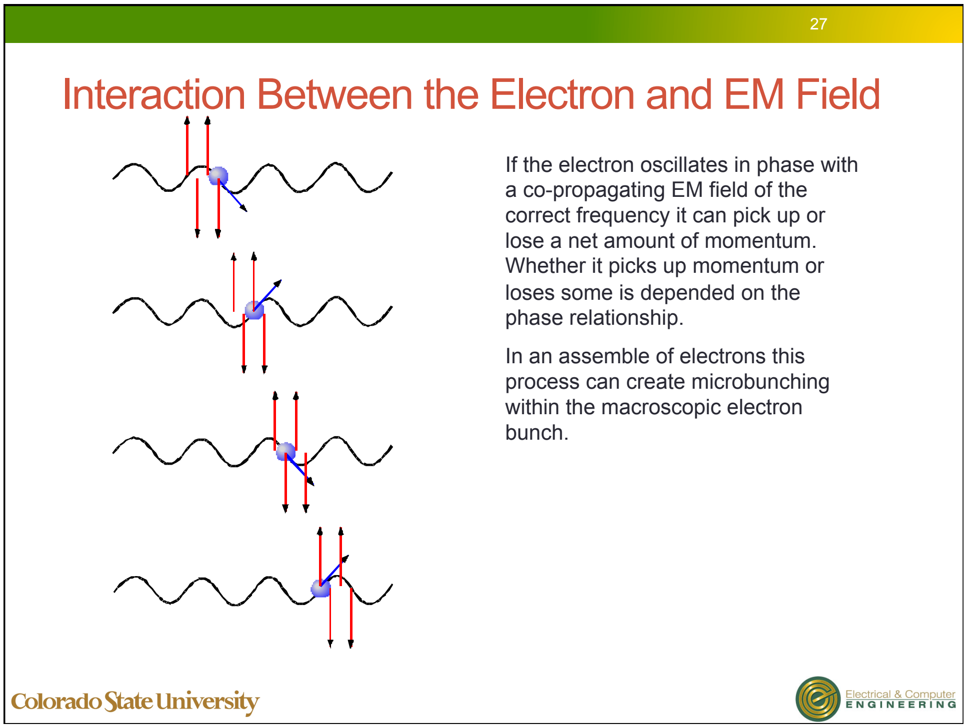
- Replace the sum with an integral and assume a normalized distribution symmetric about $r = 0$

$$I_{tot}(\lambda) = I_1(\lambda)\left[N + N(N-1)f(\lambda)\right]$$

$$I_{tot}(\lambda) = I_{inc}(\lambda)\left[1 + (N-1)f(\lambda)\right]$$

Where $I_{inc}(\lambda) = N\,I_1(\lambda)$ is the total incoherent intensity emitted by the bunch of N particles

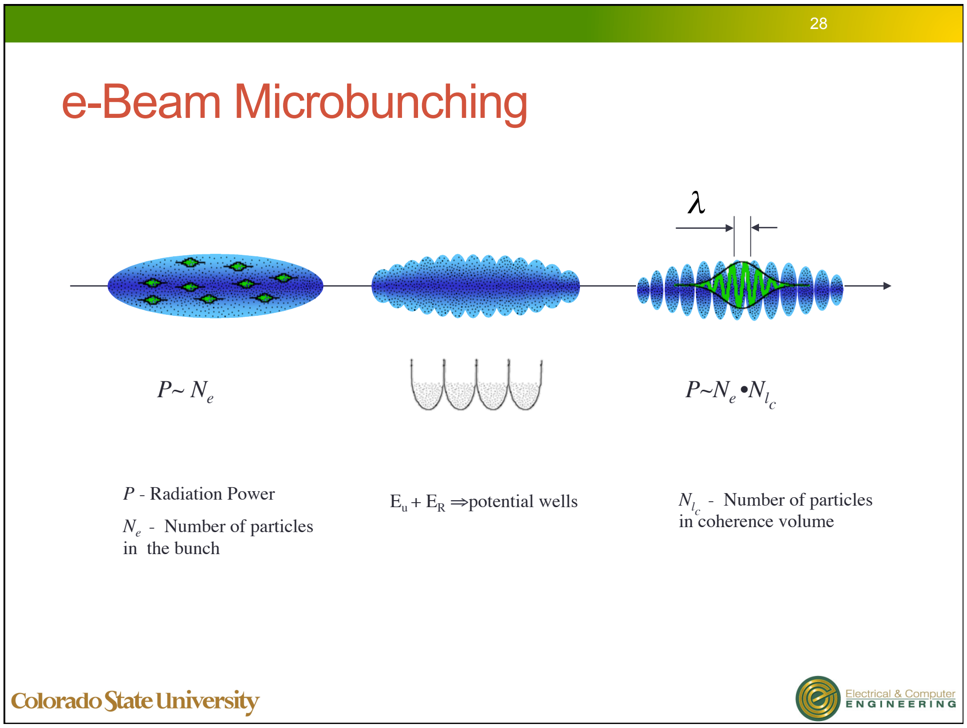
and $$f(\lambda) = \left|\int dz\, e^{2\pi i z/\lambda} S(z)\right|^2$$ is the form factor for the normalized bunch distribution $S(z)$. Here we have assumed that the detector is located at a distance much larger than the length of the electron bunch.



Interaction Between the Electron and EM Field

If the electron oscillates in phase with a co-propagating EM field of the correct frequency it can pick up or lose a net amount of momentum. Whether it picks up momentum or loses some is depended on the phase relationship.

In an assemble of electrons this process can create microbunching within the macroscopic electron bunch.



e-Beam Microbunching

$P\sim N_e$

$P\sim N_e \bullet N_{l_c}$

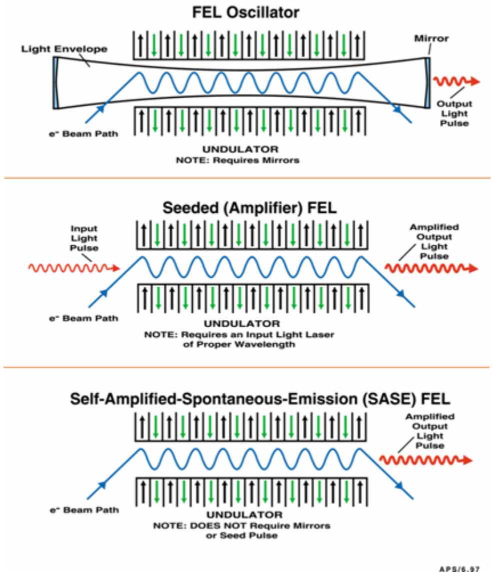
P - Radiation Power

N_e - Number of particles in the bunch

$E_u + E_R \Rightarrow$ potential wells

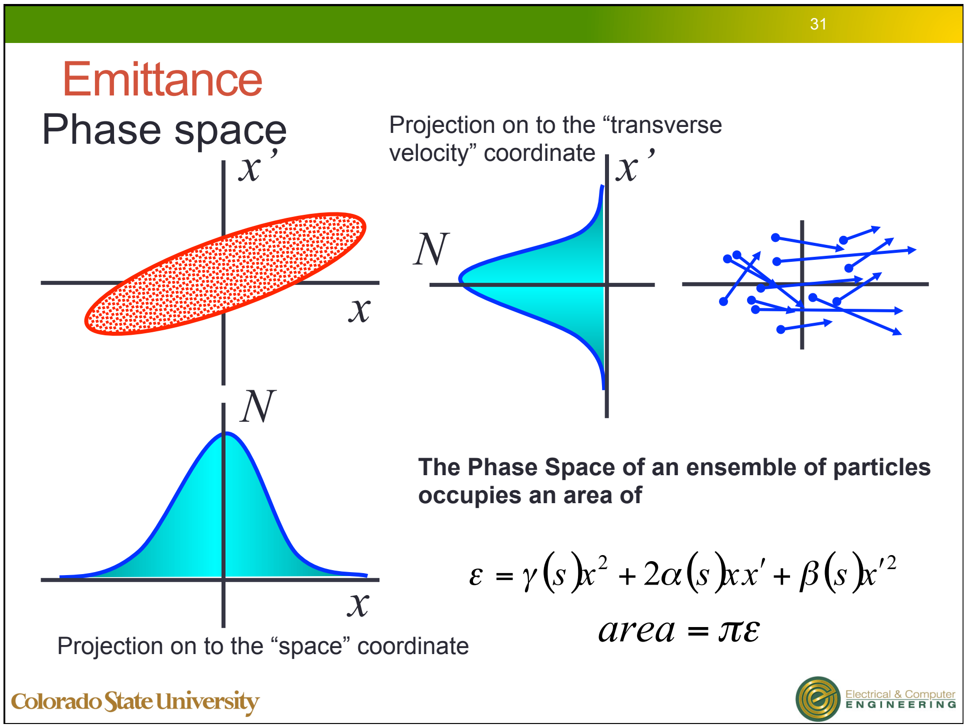
N_{l_c} - Number of particles in coherence volume

FEL Types: Oscillator, Seeded FEL, SASE



Beam Properties Required for Efficient FEL Action

- Good overlap of the electron beam with the optical beam
- Electron beam emittance better than the optical beam mode “emittance”
- Electron beam energy spread less than the width of the driving optical “rf bucket”



Emittance

Phase space

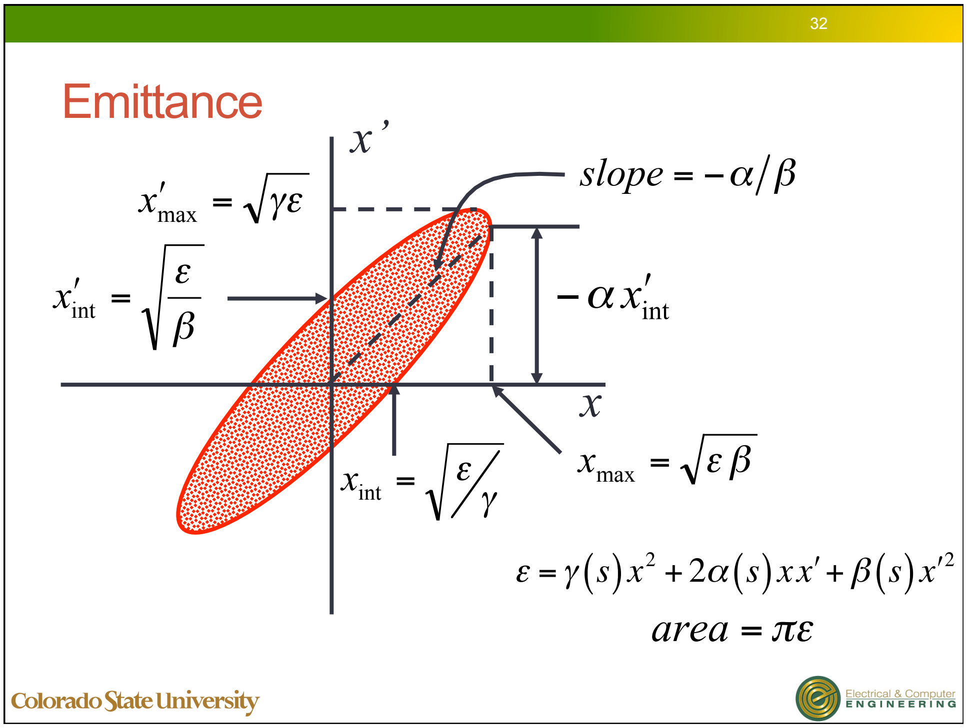
Projection on to the "transverse velocity" coordinate

Projection on to the "space" coordinate

The Phase Space of an ensemble of particles occupies an area of

$$\varepsilon = \gamma(s)x^2 + 2\alpha(s)xx' + \beta(s)x'^2$$

$$area = \pi\varepsilon$$



Emittance

$$x'_{\max} = \sqrt{\gamma\varepsilon}$$

$$x'_{\text{int}} = \sqrt{\frac{\varepsilon}{\beta}}$$

$$slope = -\alpha/\beta$$

$$-\alpha x'_{\text{int}}$$

$$x_{\text{int}} = \sqrt{\varepsilon/\gamma}$$

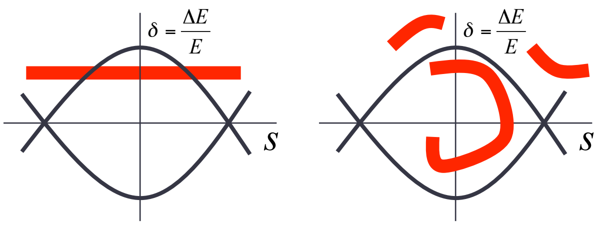
$$x_{\max} = \sqrt{\varepsilon\beta}$$

$$\varepsilon = \gamma(s)x^2 + 2\alpha(s)xx' + \beta(s)x'^2$$

$$area = \pi\varepsilon$$

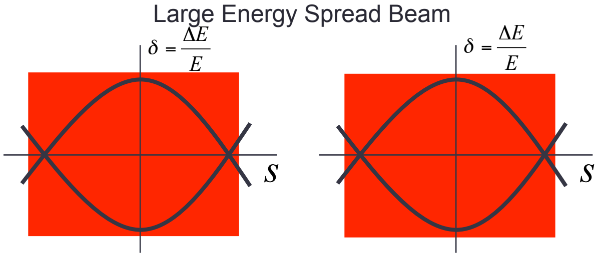
Energy Spread Effects

Small Energy Spread Beam



Favorable conditions to allow exchange of energy between the electron beam and the optical field

Large Energy Spread Beam



Unfavorable conditions. No net exchange of energy between the electron beam and the optical field

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Required Conditions

$$\varepsilon_n \le \gamma \frac{\lambda_r}{4\pi}$$

⇨ Want the beam emittance to be less than the optical mode Phase space size.

$$\frac{\Delta E}{E} \le \rho \approx \frac{1}{4}\left[\frac{1}{2\pi^2}\frac{I_{pk}}{I_A}\frac{\lambda_u^2}{\beta\varepsilon_n}\left(\frac{K}{\gamma}\right)^2\right]^{1/3}$$

⇨ The Pierce parameter, ρ, should be large and the beam energy spread should be smaller than ρ.

$$L_g < L_R \qquad L_R = \frac{2\pi\sigma_o^2}{\lambda_r}$$

⇨ The optical intensity should grow fast enough to counter diffraction loss.

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

⇨ Want a Minimum gain length so want ρ to be as large a possible. i.e Want large I_{pk} and a small beam emittance.

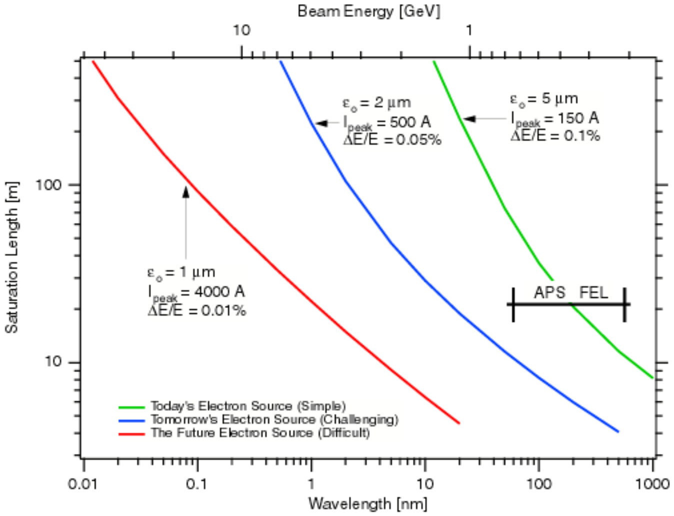
More Accurately and for a Planar Undulator

$$L_G^0 = \frac{\lambda_u}{4\pi\sqrt{3}\rho}$$ Gain Length

$$\rho = \left[\frac{I}{I_A} \frac{\gamma\lambda_r^2}{16\pi^2\sigma_{trans}^2} \frac{K^2}{\left(1+K^2/2\right)^2} \left[J_0\left(\frac{K^2}{4+2K^2}\right) - J_1\left(\frac{K^2}{4+2K^2}\right) \right]^2 \right]^{1/3}$$

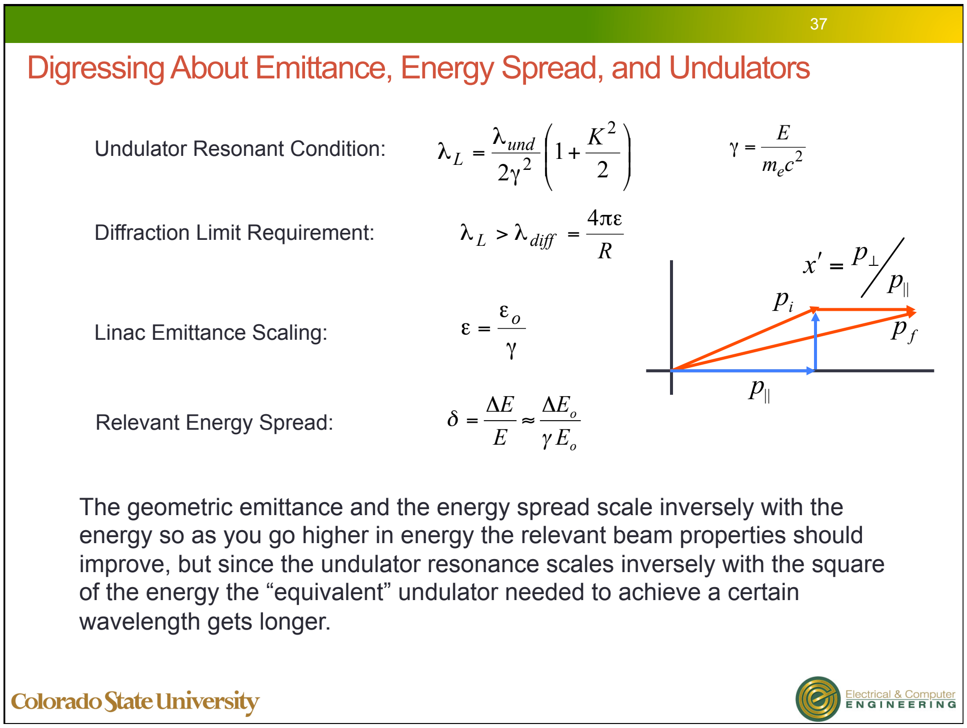
ρ is typically of the order 0.001 for visible and shorter wavelengths; therefore, the gain length is of the order of 100 undulator periods

Beam Requirements



An old slide circa 1998.

Difficult has now been achieved.



Digressing About Emittance, Energy Spread, and Undulators

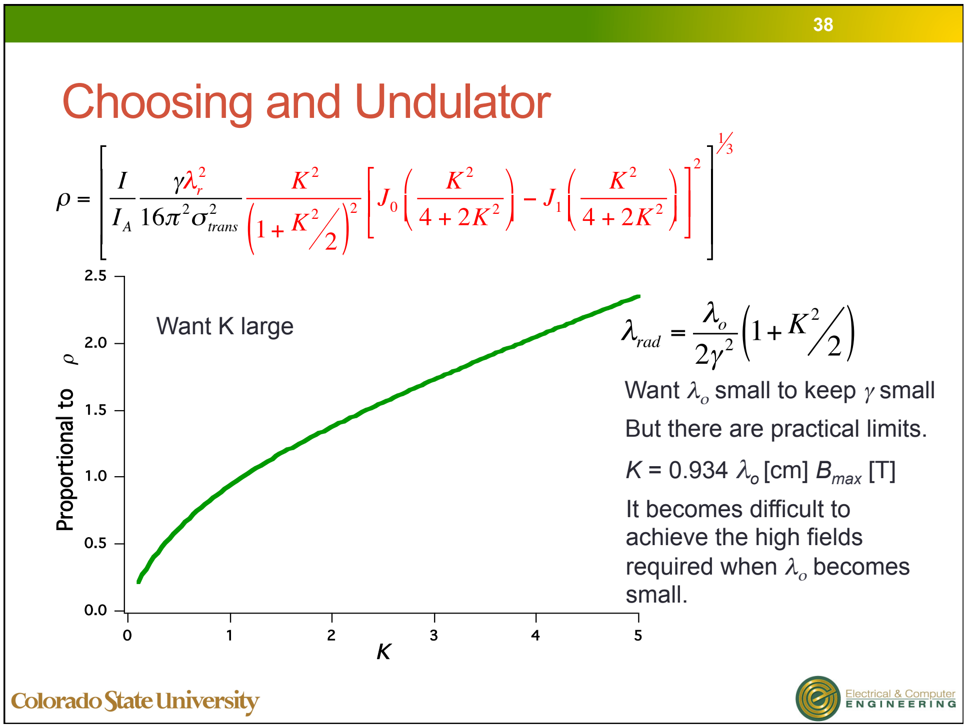
Undulator Resonant Condition: $\lambda_L = \frac{\lambda_{und}}{2\gamma^2}\left(1+\frac{K^2}{2}\right)$ $\gamma = \frac{E}{m_e c^2}$

Diffraction Limit Requirement: $\lambda_L > \lambda_{diff} = \frac{4\pi\varepsilon}{R}$

Linac Emittance Scaling: $\varepsilon = \frac{\varepsilon_o}{\gamma}$

Relevant Energy Spread: $\delta = \frac{\Delta E}{E} \approx \frac{\Delta E_o}{\gamma E_o}$

The geometric emittance and the energy spread scale inversely with the energy so as you go higher in energy the relevant beam properties should improve, but since the undulator resonance scales inversely with the square of the energy the “equivalent” undulator needed to achieve a certain wavelength gets longer.



Choosing and Undulator

$$\rho = \left[\frac{I}{I_A}\frac{\gamma\lambda_r^2}{16\pi^2\sigma_{trans}^2}\frac{K^2}{\left(1+K^2/2\right)^2}\left[J_0\left(\frac{K^2}{4+2K^2}\right)-J_1\left(\frac{K^2}{4+2K^2}\right)\right]^2\right]^{1/3}$$

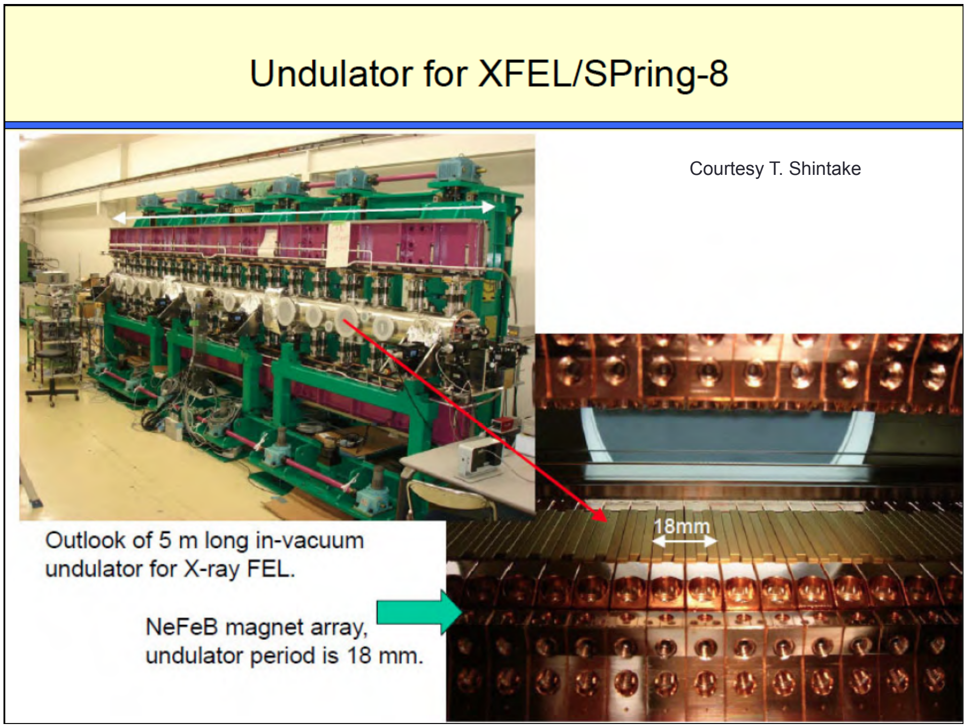
$$\lambda_{rad} = \frac{\lambda_o}{2\gamma^2}\left(1+K^2/2\right)$$

Want λ_o small to keep γ small

But there are practical limits.

$K = 0.934\ \lambda_o\,[\text{cm}]\ B_{max}\,[\text{T}]$

It becomes difficult to achieve the high fields required when λ_o becomes small.

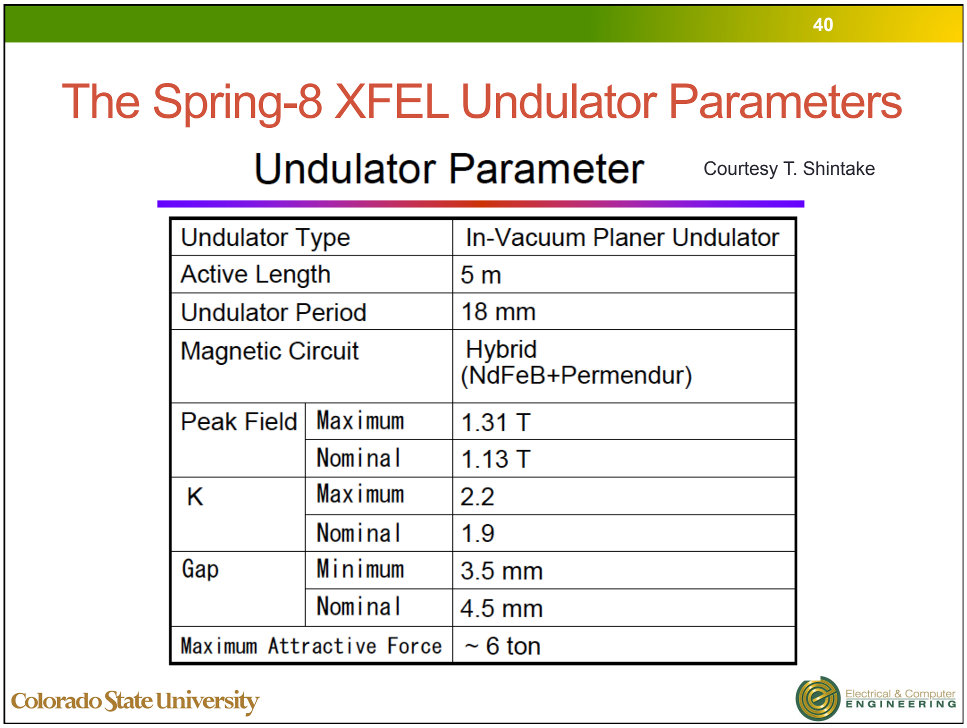


Undulator for XFEL/SPring-8

Courtesy T. Shintake

Outlook of 5 m long in-vacuum undulator for X-ray FEL.

NeFeB magnet array, undulator period is 18 mm.



The Spring-8 XFEL Undulator Parameters

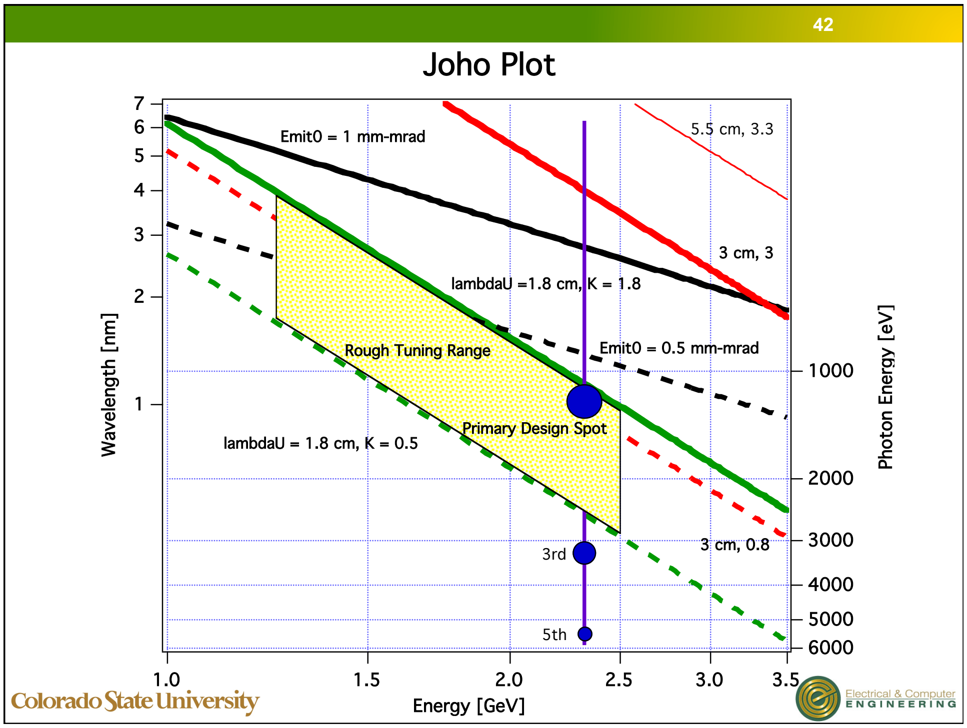
Undulator Parameter

Courtesy T. Shintake

Undulator Type		In-Vacuum Planer Undulator
Active Length		5 m
Undulator Period		18 mm
Magnetic Circuit		Hybrid (NdFeB+Permendur)
Peak Field	Maximum	1.31 T
	Nominal	1.13 T
K	Maximum	2.2
	Nominal	1.9
Gap	Minimum	3.5 mm
	Nominal	4.5 mm
Maximum Attractive Force		~ 6 ton

Undulator is ready for mass production.

T. Shintake@ SCSS & XFEL/SPring-8 2009



Joho Plot

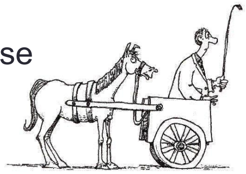
Colorado State University

Electrical & Computer ENGINEERING

Now we are getting somewhere with the design

- Linac Energy
  - We want a linac energy that is stable over the range 1.3 GeV to 2.5 GeV with a nominal working point energy of 2.3 GeV.
- Emittance
  - We will need a normalized emittance that is very good
  - i.e. ε_o < 1 mm-mrad. Assume 0.8 mm-mrad slice emittance.
- We will need an undulator with short period and relatively high *K* value.
  - 18 mm period, *K* roughly 1.8.
    - *K* is 1.75 to achieve with 2.3 GeV a photon energy of 1.1 keV.

Bunch length and energy spread

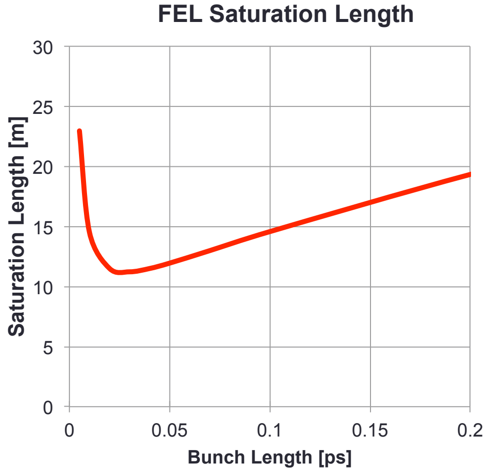


- Let's start by putting the cart before the horse
- Assume an initial longitudinal phase space
  - FWHM Bunch length = 0.7 psec
  - Energy Spread: $\sigma_{\Delta E/E}$ = 125 keV
  - The longitudinal emittance is thus ε_L = 87.5 keV-psec
  - This must be conserved.

Bunch length and energy spread

- Keeping the longitudinal emittance constant what is the optimal ratio of the bunch length to the energy spread.
  - I will show you how you can make this change in a minute.
- As simple spreadsheet calculation of the FEL performance helps here.
  - I have used the equations from M. Xie, "Design Optimization for X-ray Free Electron Laser Driven by SLAC Linac", Particle Accelerator Conference, 1995.

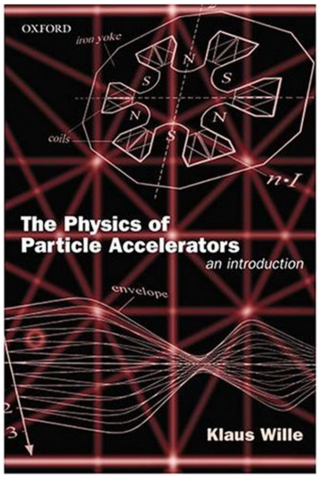
Bunch length and energy spread



- The optimum occurs when
  - Bunch length = 28 fs
  - Energy spread = 3.13 MeV
- That's a very short bunch with a very large energy spread!
- One will need to compress the beam a lot!
  - We'll do our best.

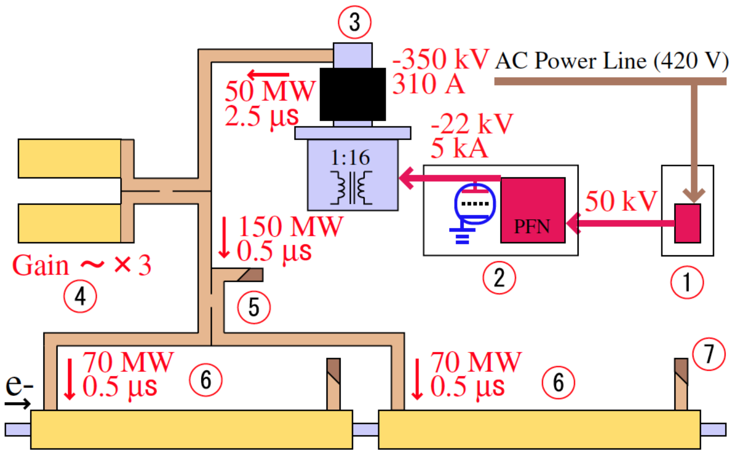
LINAC REFRESHER

Primary References

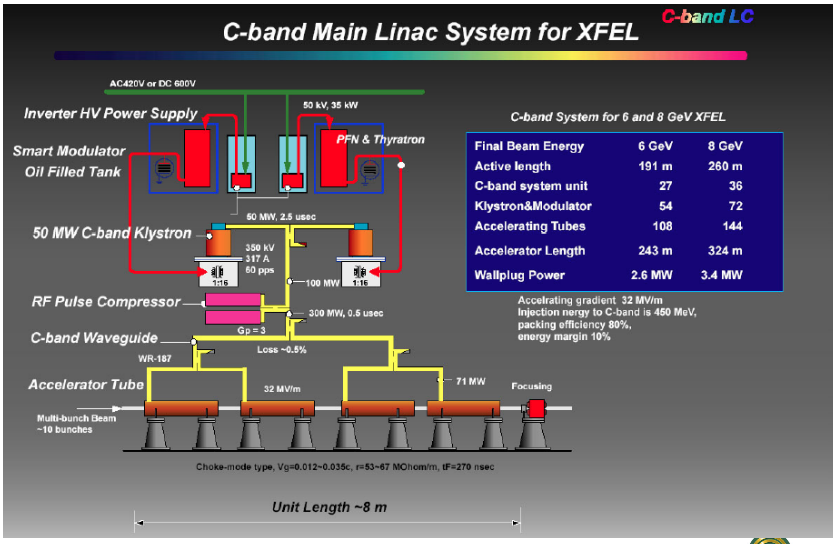


Example of the Basic Linac "Cell"

TSUMORU SHINTAKE *et al.*



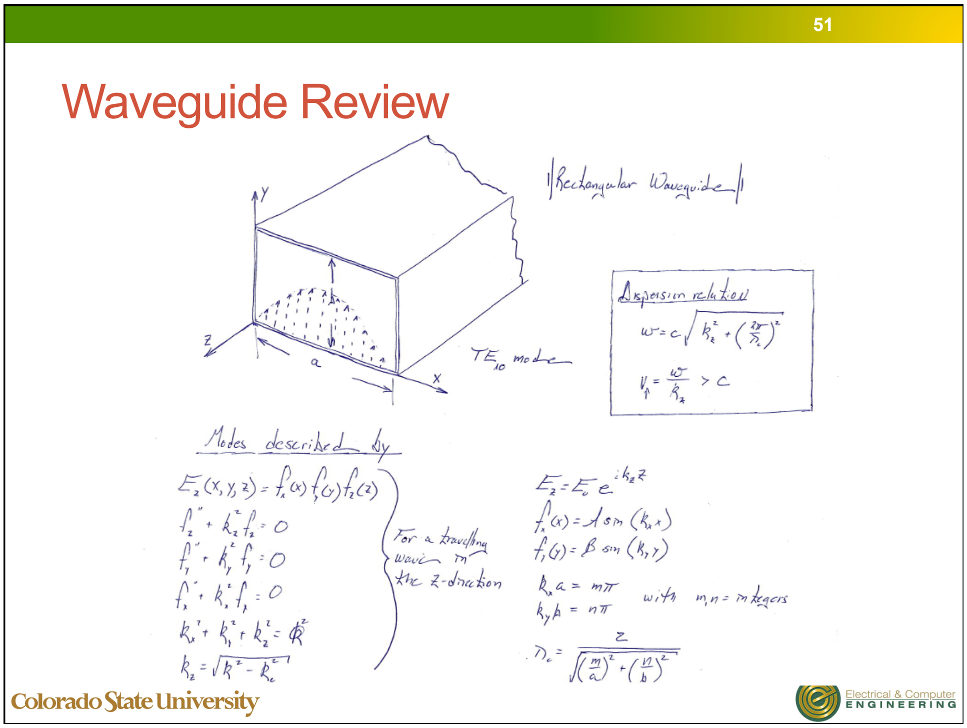
Alternate Example from SCSS CDR



C-band System for 6 and 8 GeV XFEL

Final Beam Energy	6 GeV	8 GeV
Active length	191 m	260 m
C-band system unit	27	36
Klystron&Modulator	54	72
Accelerating Tubes	108	144
Accelerator Length	243 m	324 m
Wallplug Power	2.6 MW	3.4 MW

Accelrating gradient 32 MV/m
Injection nergy to C-band is 450 MeV,
packing efficiency 80%,
energy margin 10%



Waveguide Review

||Rectangular Waveguide||

Dispersion relation

$$\omega = c\sqrt{k_z^2 + \left(\frac{2\pi}{\lambda_c}\right)^2}$$

$$v_p = \frac{\omega}{k_z} > c$$

Modes described by

$$E_z(x,y,z) = f_x(x) f_y(y) f_z(z)$$

$$f_z'' + k_z^2 f_z = 0$$

$$f_y'' + k_y^2 f_y = 0$$

$$f_x'' + k_x^2 f_x = 0$$

$$k_x^2 + k_y^2 + k_z^2 = k^2$$

$$k_z = \sqrt{k^2 - k_c^2}$$

For a travelling wave in the z-direction

$$E_z = E_0 e^{ik_z z}$$

$$f_x(x) = A \sin(k_x x)$$

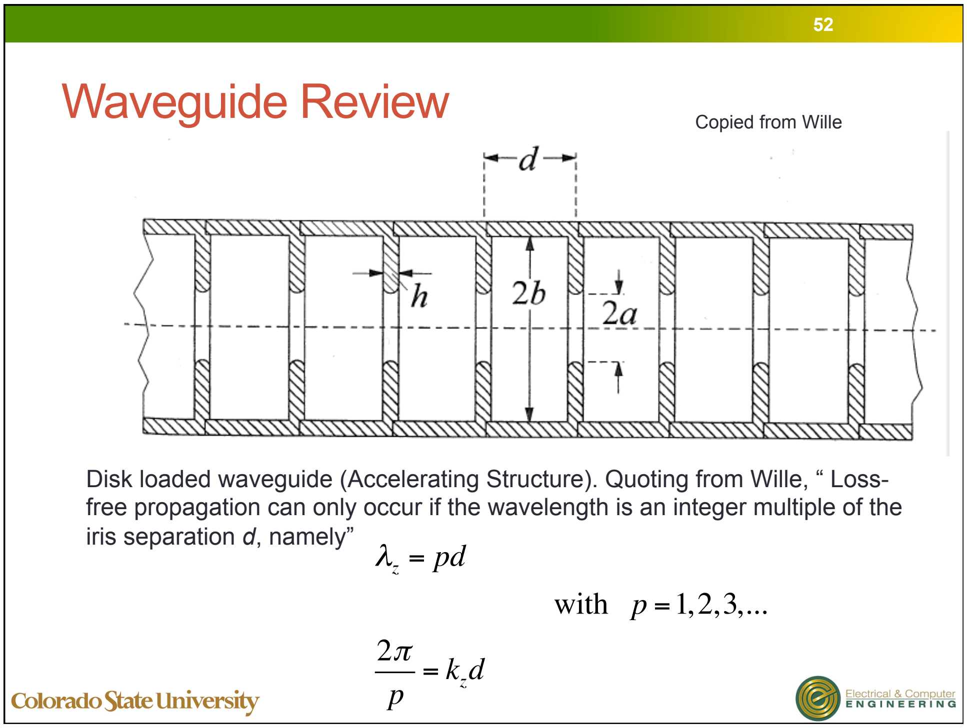
$$f_y(y) = B \sin(k_y y)$$

$$k_x a = m\pi$$

$$k_y b = n\pi$$

with $m,n =$ integers

$$\lambda_c = \frac{2}{\sqrt{\left(\frac{m}{a}\right)^2 + \left(\frac{n}{b}\right)^2}}$$



Waveguide Review

Copied from Wille

Disk loaded waveguide (Accelerating Structure). Quoting from Wille, “ Loss-free propagation can only occur if the wavelength is an integer multiple of the iris separation *d*, namely”

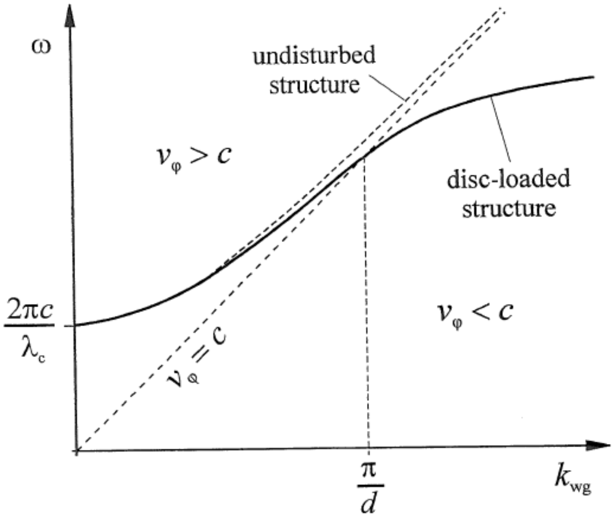
$$\lambda_z = pd$$

$$\text{with} \quad p = 1,2,3,\ldots$$

$$\frac{2\pi}{p} = k_z d$$

Waveguide Review

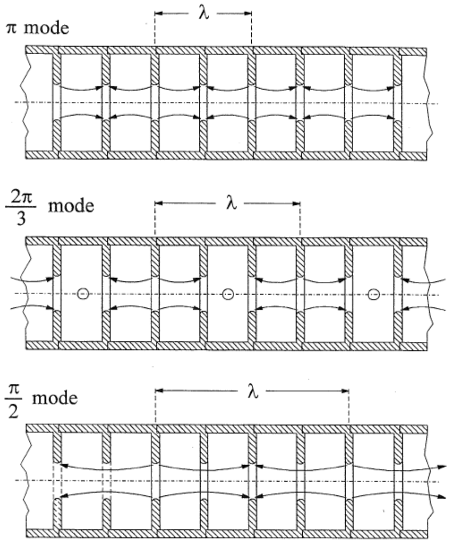
Copied from Wille



Waveguide Review

Copied from Wille

The most important modes



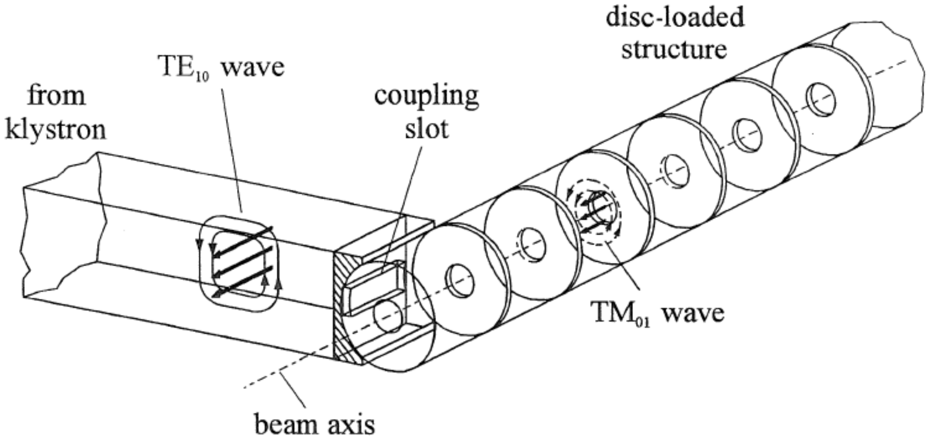
p = 2

p = 3
This is arguably the most commonly used.

p = 4

Waveguide Review

Copied from Wille



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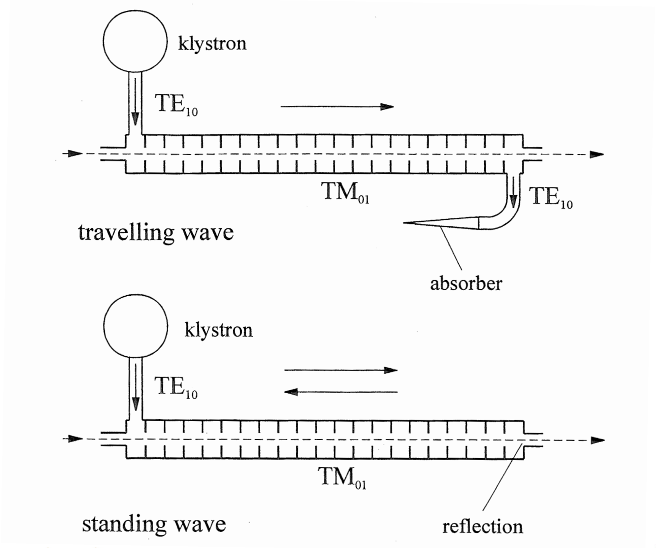
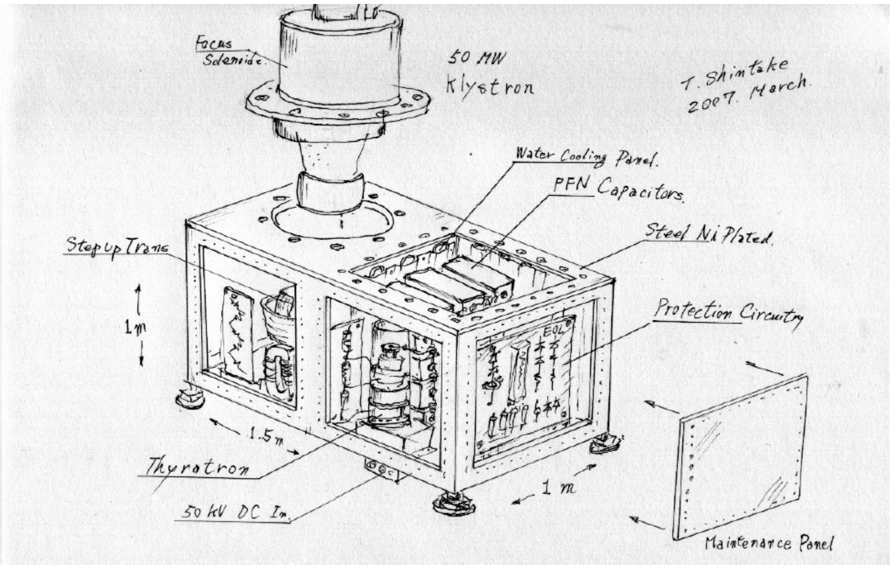
Waveguide Review

Copied from Wille



RF Power Generation: The Modulator



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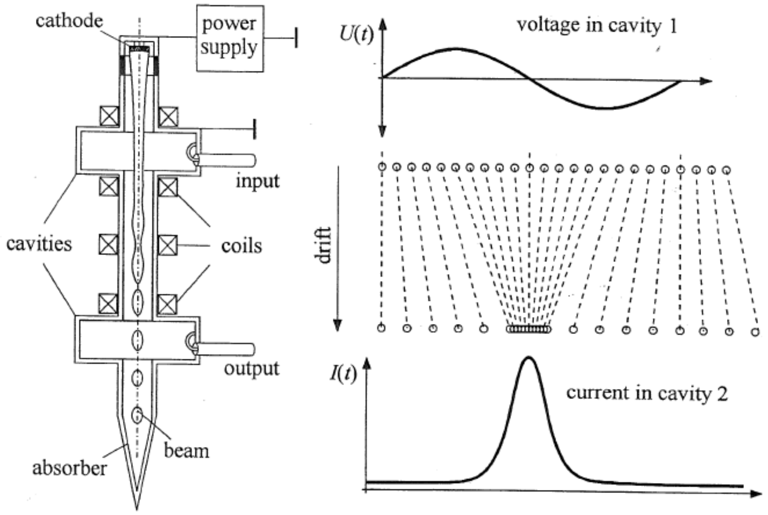
RF Power Generation: The Klystron



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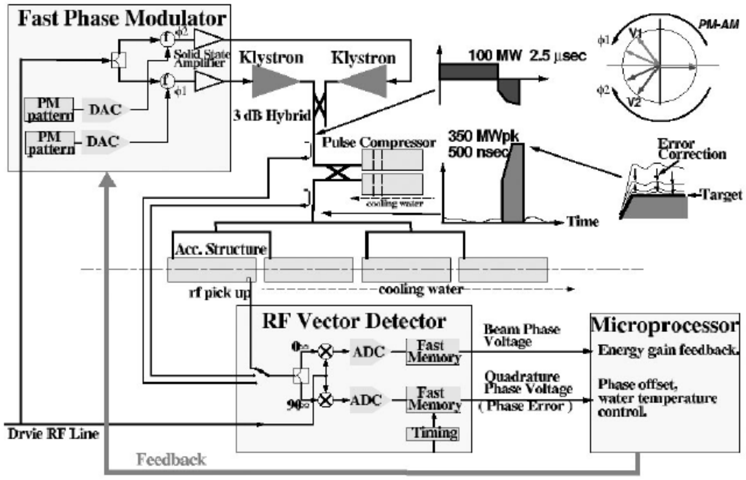
RF Power Generation: LLRF Control

From SCSS CDR



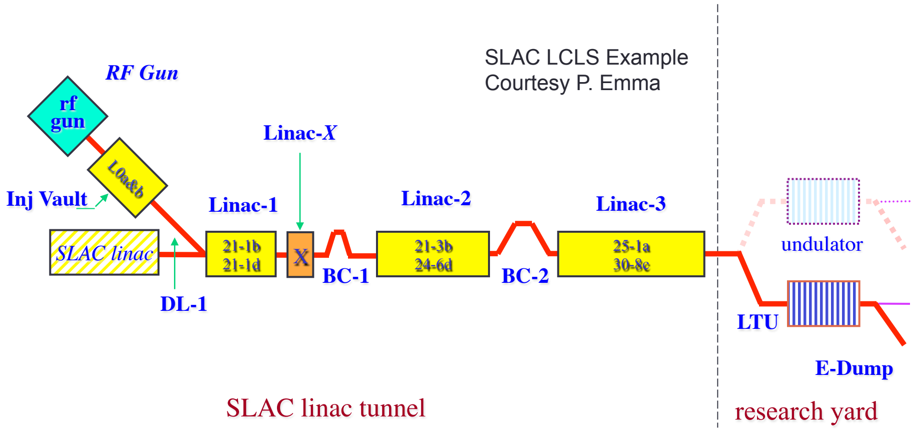
DESIGN CONSIDERATIONS

The Basics of a Linac to Drive and FEL

- Need
  - Low emittance injector
    - The lower the emittance, the lower the final beam energy (See Joho Plot)
  - High-gradient, high repetition rate accelerator
    - Keeps things compact
  - Short period, high efficiency undulator
    - Short wavelengths at low energies
  - Beam manipulation, monitoring, and controls
    - To tailor and monitor the beam properties

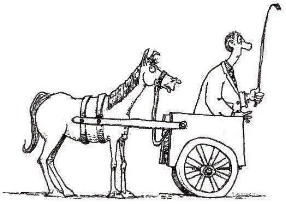
The Cartoons

- You've all seen them, but how do you get there from here?



SLAC LCLS Example
Courtesy P. Emma

Starting with a Vision



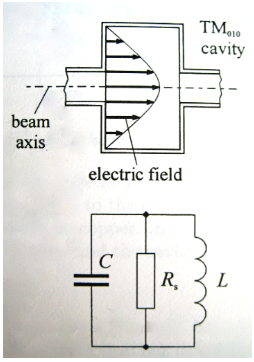
- Use a robust and simple injector system
  - I will choose to follow the work at Spring-8
  - Pulsed DC Thermionic injector system
- Want to minimize the overall length within reason but at the same time be able to operate at high repetition rates
  - Implies high shunt impedance, high gradient structures requiring low input power

---

Starting with a Vision: Choosing the Frequency

- Shunt impedance and voltage
  - The effective voltage generated across a cavity operating on resonance and being supplied with an average power of P_{RF} is

$$V_o = \sqrt{P_{RF} R_s}$$



  - Where R_s is the cavity shunt impedance
  - Two notes:
    - I have neglected for simplicity the transit time factor
    - Sometime you find a factor of 2 in the sqrt
      - Be careful

Copied from Wille

Starting with a Vision: Choosing the Frequency

- Scaling Laws
  - Using concepts from Wangler's book
    - Hold fixed the accelerating field E_o and the total energy gain ΔW so that the total structure length is fixed.
    - Scale all other dimensions as f^{-1}
  - The surface resistance
    - Note: there is still resistance in the superconducting case due to normal-conducting electrons at any finite temperature. (Imperfections have been neglected).

$$r_s \propto \begin{Bmatrix} f^{1/2} & Normal\ conducting \\ f^2 & Super\ conducting \end{Bmatrix}$$

Starting with a Vision: Choosing the Frequency

- Scaling Laws
  - RF Power Dissipation

$$P = \frac{r_s}{2}\int \left|\frac{B}{\mu_o}\right|^2 dA \propto \begin{Bmatrix} f^{-1/2} & Normal\ conducting \\ f & Super\ conducting \end{Bmatrix}$$

    - Higher frequency gives reduced power for normal conducting, but higher power for super conducting.
  - Q scales as

$$Q = \frac{\omega U}{P} \propto \begin{Bmatrix} f^{-1/2} & Normal\ conducting \\ f^{-2} & Super\ conducting \end{Bmatrix}$$

Starting with a Vision: Choosing the Frequency

- Scaling Laws
  - And the effective impedance per unit length scales as

$$R_{sEff} = \frac{(E_o T)^2 L}{P} \propto \left\{ \begin{array}{ll} f^{+1/2} & Normal\ conducting \\ f^{-1} & Super\ conducting \end{array} \right\}$$

    - Higher frequency gives higher shunt impedance for normal conducting, but lower for super conducting.

Starting with a Vision: Choosing the Frequency

- Scaling Laws
  - And finally the R_{sEff}/Q which is proportional to the energy gain achievable for a given stored energy is

$$\frac{R_{sEff}}{Q} \propto \left\{ \begin{array}{ll} f^{1} & Normal\ conducting \\ f^{1} & Super\ conducting \end{array} \right\}$$

    - Which is as expected as this figure of merit is geometry dependent and independent of surface properties.

The Injector: Choosing a system

- Rule: If you don't have good beam here you never will
- Requirements
  - Low emittance
  - High peak current
  - Low energy spread

Required for the FEL to function

- What I call "The Injector"
  - The electron source or "gun"
  - Initial 6-D phase space manipulation completed
  - Initial primary acceleration complete
    - i.e. Out of the space charge regime

$$F_r = q\left(E_r - vB_\theta\right) = qE_r\left(1-\beta^2\right) = {qE_r}/{\gamma^2}$$

$$F_r = mc\frac{d\left(\gamma\beta_r\right)}{dt} = \gamma mc\dot{\beta}_r \quad \text{or} \quad \frac{d^2r}{dt^2} = \frac{qE_r}{\gamma^3 m}$$

The Injector: Choosing the source

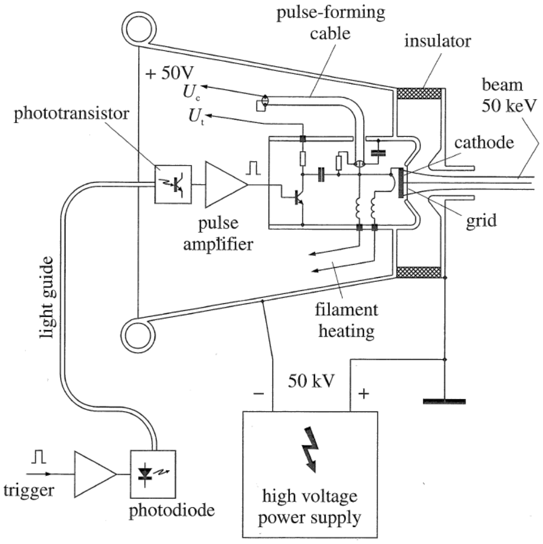
- Choices
  - RF-based or DC (pulsed) based
  - Photocathode-based or Thermionic-based (Examples)
    - RF Photocathode
      - LCLS, FLASH, FERMI
    - DC Photocathode
      - Jefferson Laboratory
    - RF Thermionic
      - Advanced Photon Source
    - DC (pulsed) thermionic
      - SCSS/XFEL

The Injector: Choosing the source

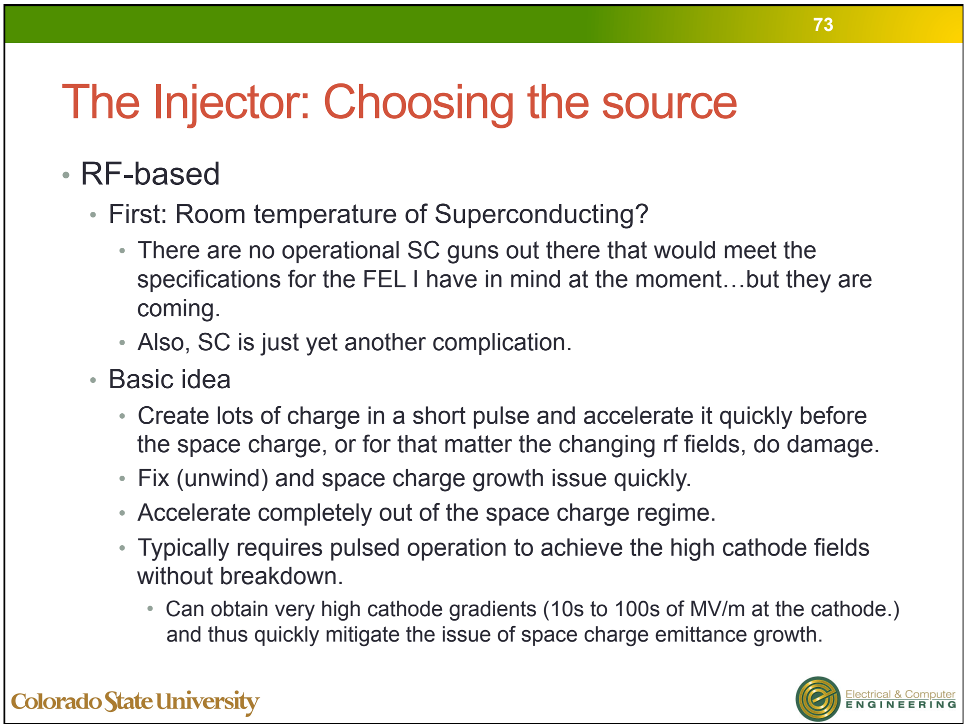
- DC-based
  - Stable (or is it?)
    - Will require pulsed operation for the beam to reach high enough energy off the cathode to avoid space charge issues.
    - Provides nice constant field for the duration of the beam emission and so simplifies the initial beam dynamics

$$\frac{d^2r}{dt^2} = \frac{qE_r}{\gamma^3 m}$$

The Basic Thermionic Electron Gun

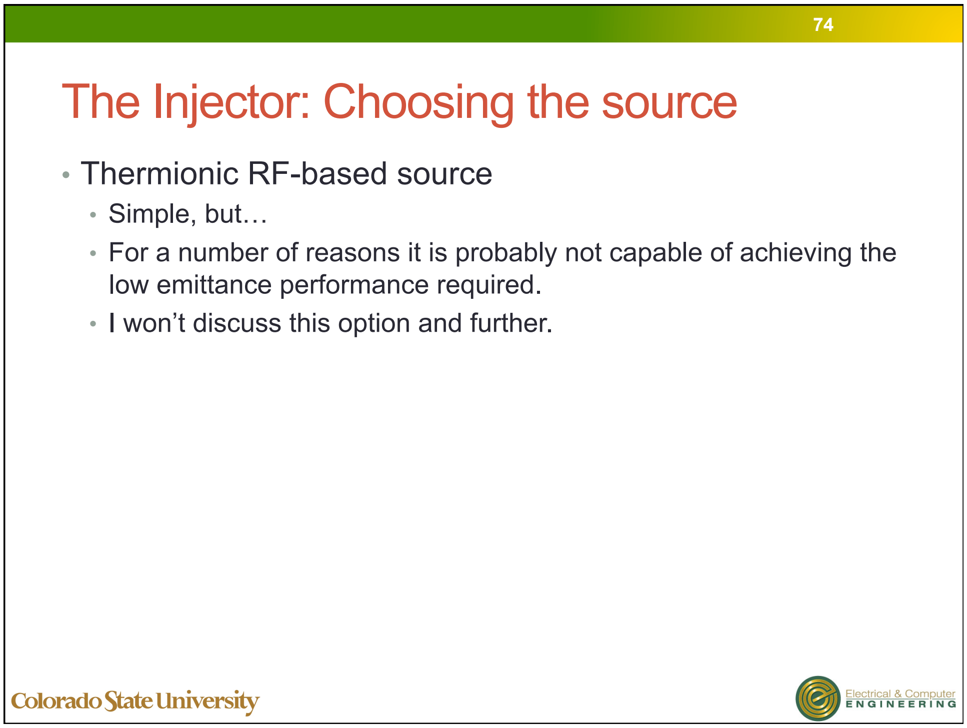


Copied from Wille



The Injector: Choosing the source

- RF-based
  - First: Room temperature of Superconducting?
    - There are no operational SC guns out there that would meet the specifications for the FEL I have in mind at the moment…but they are coming.
    - Also, SC is just yet another complication.
  - Basic idea
    - Create lots of charge in a short pulse and accelerate it quickly before the space charge, or for that matter the changing rf fields, do damage.
    - Fix (unwind) and space charge growth issue quickly.
    - Accelerate completely out of the space charge regime.
    - Typically requires pulsed operation to achieve the high cathode fields without breakdown.
      - Can obtain very high cathode gradients (10s to 100s of MV/m at the cathode.) and thus quickly mitigate the issue of space charge emittance growth.

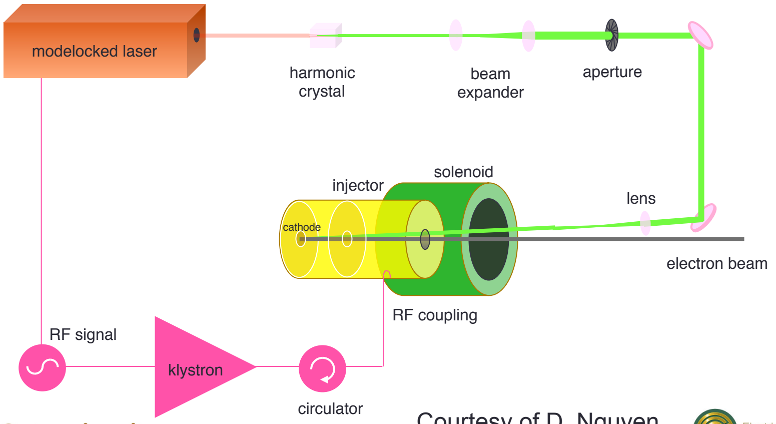


The Injector: Choosing the source

- Thermionic RF-based source
  - Simple, but…
  - For a number of reasons it is probably not capable of achieving the low emittance performance required.
  - I won't discuss this option and further.

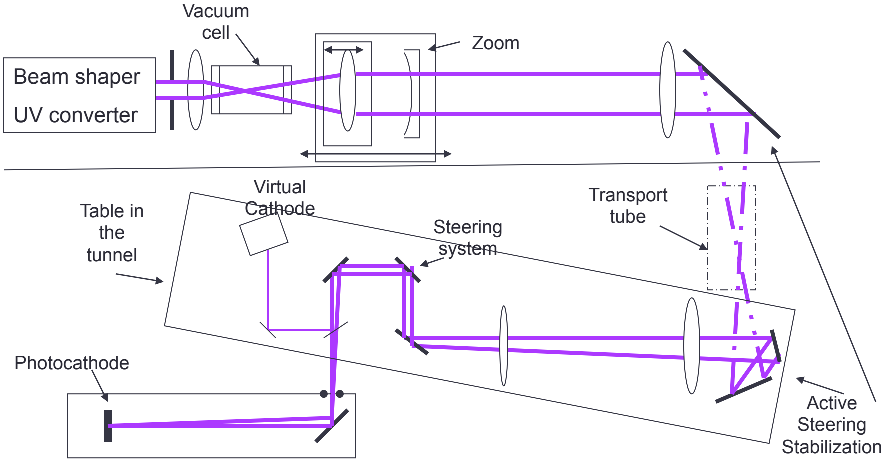
The Injector: Choosing the source

- RF Photocathode Version
  - Requires Laser
    - Complication



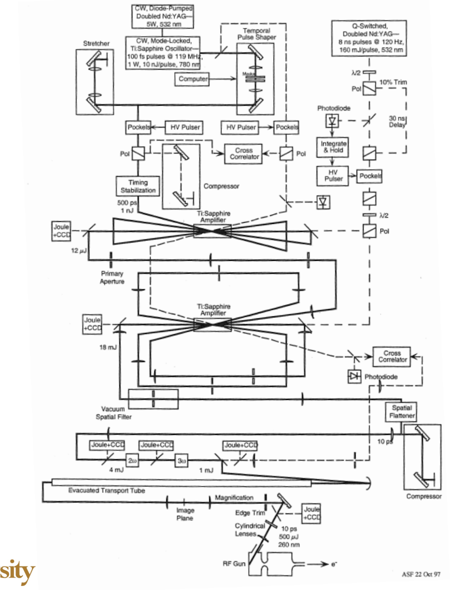
Courtesy of D. Nguyen

Generic Laser System Layout for Photocathode Systems



Courtesy of D. Nguyen

RF Photocathode Drive Laser



This was the original design for the drive laser of the LCLS. The figure is from the LCLS CDR.

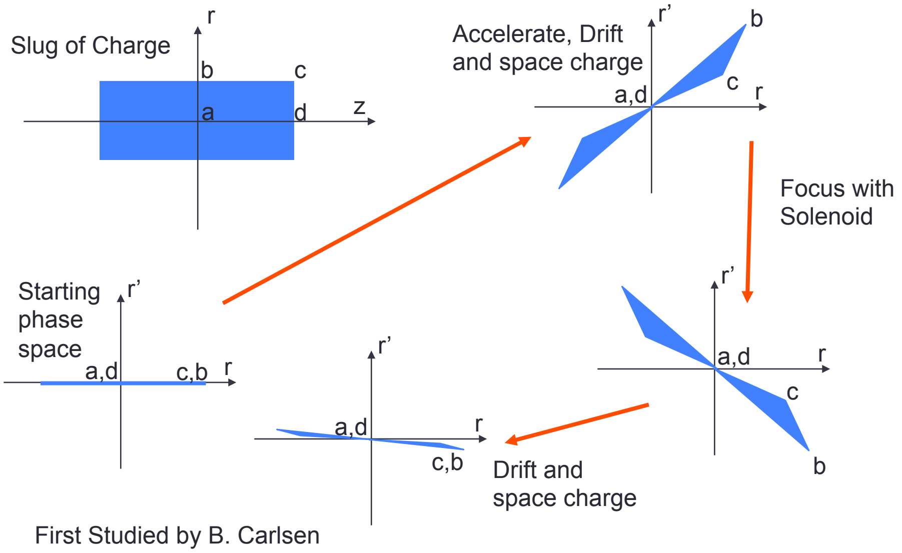
The Injector: Choosing the source

- Cathode Materials for RF Photocathode guns
  - Copper is chosen in many due to its resistance to the very high on axis fields at the cathode
    - Very low quantum efficiency
    - Due to the low QE the drive laser power becomes very high for high repetition rates
  - Some choose high QE cathodes such as Cs_2Te or GaAs or K_2CsSb
    - One needs to operate at lower on-axis fields
    - These are very susceptible to poor vacuum and can suffer short lifetimes before needing to be refreshed.
    - It's yet another complication.

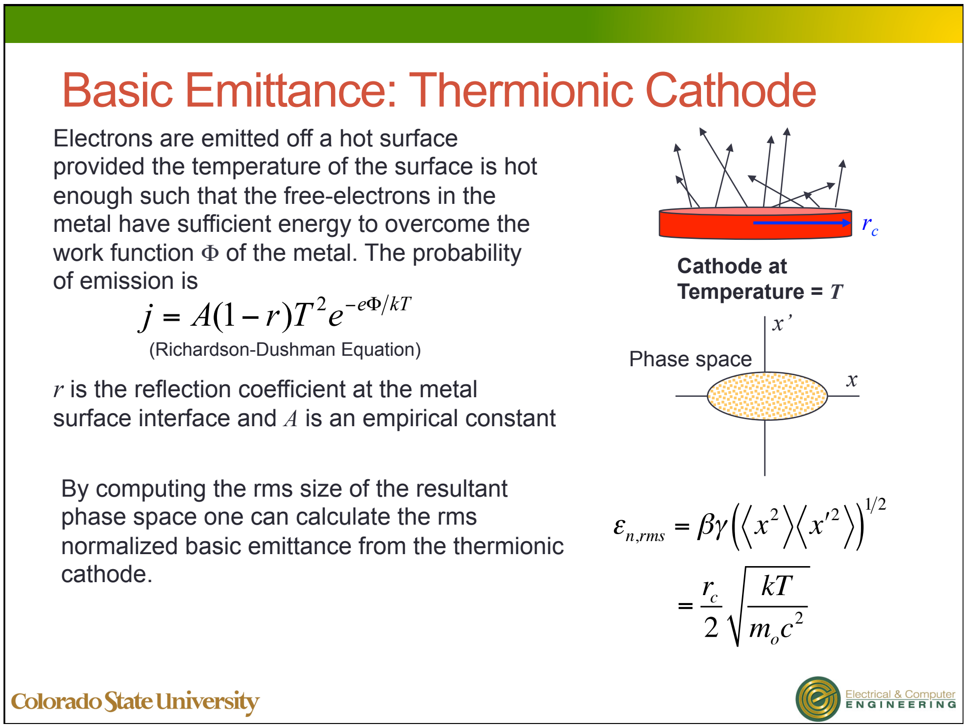
Effect of the Solenoid (as promised)

- The beam wants to diverge for 2 reasons
  - Space charge
    - The electron bunch coming off the cathode is very dense and wants to expand violently due to the electrostatic force
  - Divergent RF Fields within the RF gun
    - Anytime the electric field varies longitudinally there is a radial field
- The solenoid focuses the low energy beam radially
  - Beam enters the end radial field of the solenoid and gets a transverse kick $\nabla \cdot \vec{E} = 0 \quad \Rightarrow \quad \Delta r' \propto -r\, \partial E_z \big/ \partial z$
  - This new transverse motion crosses the longitudinal field and rotates inward or outward depending on the solenoid polarization
  - The particle is then closer in (assuming focusing) when passing through the end radial field at the opposite end of the solenoid and since it is further in the kick is less.
  - The result is a net transverse focusing

Digression on the Effect of Space Charge Compensation



First Studied by B. Carlsen



Basic Emittance: Thermionic Cathode

Electrons are emitted off a hot surface provided the temperature of the surface is hot enough such that the free-electrons in the metal have sufficient energy to overcome the work function Φ of the metal. The probability of emission is

$$j = A(1-r)T^2 e^{-e\Phi/kT}$$

(Richardson-Dushman Equation)

r is the reflection coefficient at the metal surface interface and A is an empirical constant

By computing the rms size of the resultant phase space one can calculate the rms normalized basic emittance from the thermionic cathode.

$$\varepsilon_{n,rms} = \beta\gamma\left(\left\langle x^2\right\rangle\left\langle x'^2\right\rangle\right)^{1/2}$$

$$= \frac{r_c}{2}\sqrt{\frac{kT}{m_o c^2}}$$

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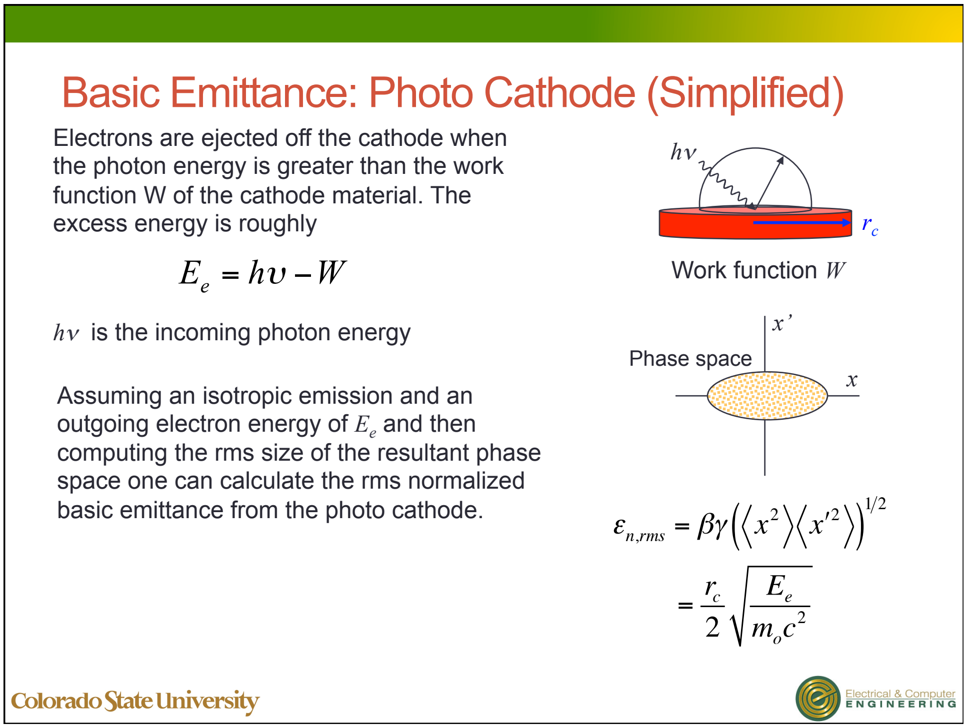

Basic Emittance: Photo Cathode (Simplified)

Electrons are ejected off the cathode when the photon energy is greater than the work function W of the cathode material. The excess energy is roughly

$$E_e = h\upsilon - W$$

$h\nu$ is the incoming photon energy

Assuming an isotropic emission and an outgoing electron energy of E_e and then computing the rms size of the resultant phase space one can calculate the rms normalized basic emittance from the photo cathode.

$$\varepsilon_{n,rms} = \beta\gamma\left(\left\langle x^2\right\rangle\left\langle x'^2\right\rangle\right)^{1/2}$$

$$= \frac{r_c}{2}\sqrt{\frac{E_e}{m_o c^2}}$$

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Basic Emittance: Some numbers

$r_c = 1\ mm$

$kT = 0.14\ eV \quad \approx 1400\ ^oC$

$W = 3\ eV$ Typical for a “red” metal such as copper

$h\upsilon = 4\ eV$ UV light such as the 3rd harmonic from a Ti:Sapphire system

$m_o c^2 = 0.511\ MeV$ Rest energy for electrons

$$\varepsilon_{n,rms}^{Thermionic} = 0.26\ mm \cdot mrad$$

$$\varepsilon_{n,rms}^{Photocathode} = 0.7\ mm \cdot mrad$$

The clear cathode of choice if one can use it.

Beyond Simple Basic Emittance

Take for example the photocathode

$\Phi_e = \Phi - \Delta$ This is the effective work function that has been lowered by the electric field on the cathode surface

$\Delta = e\sqrt{eE_c / 4\pi\varepsilon_o}$ E_c is the electric field on the cathode surface

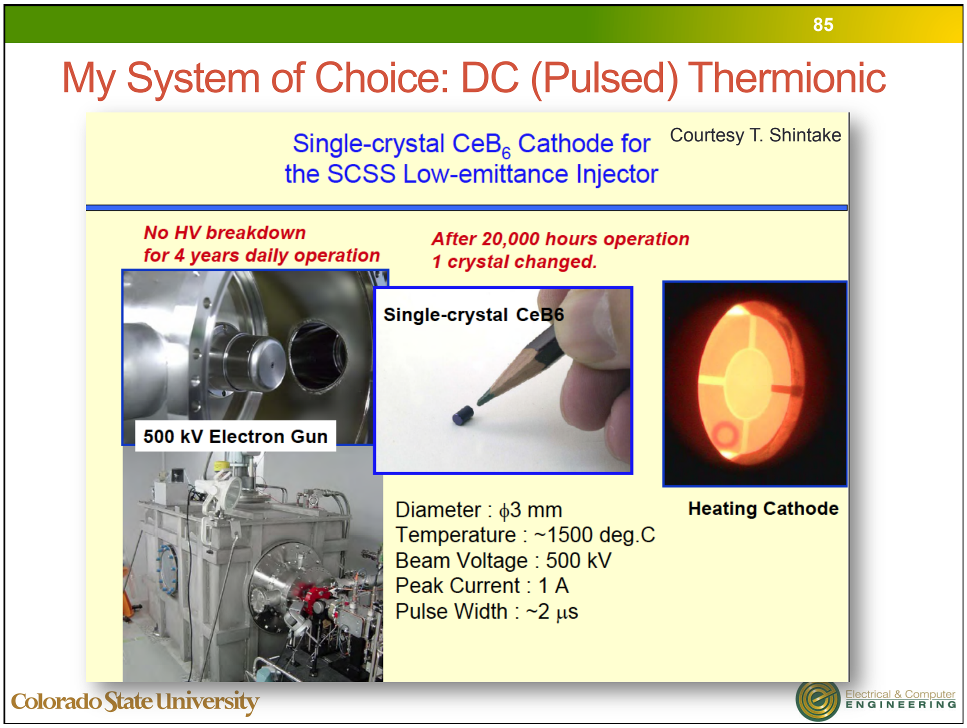
$$\varepsilon_{n,rms}^{therm} = \frac{r_c}{2}\sqrt{\frac{2E_{kin}}{m_o c^2}}\frac{1}{\sqrt{3}}\sqrt{\frac{2+\cos^3\varphi_{\max} - 3\cos\varphi_{\max}}{2(1-\cos\varphi_{\max})}}$$

Now a more complicated expression for the thermal emittance

$$E_{kin} = \varepsilon_F + h\omega$$

$$\varphi_{\max} = \arccos\left(\frac{\varepsilon_F + \Phi_e}{\varepsilon_F + h\omega}\right)^{1/2}$$

This treatment gives a lower value for the thermal emittance than the simple expression given earlier and is also more correct.



My System of Choice: DC (Pulsed) Thermionic

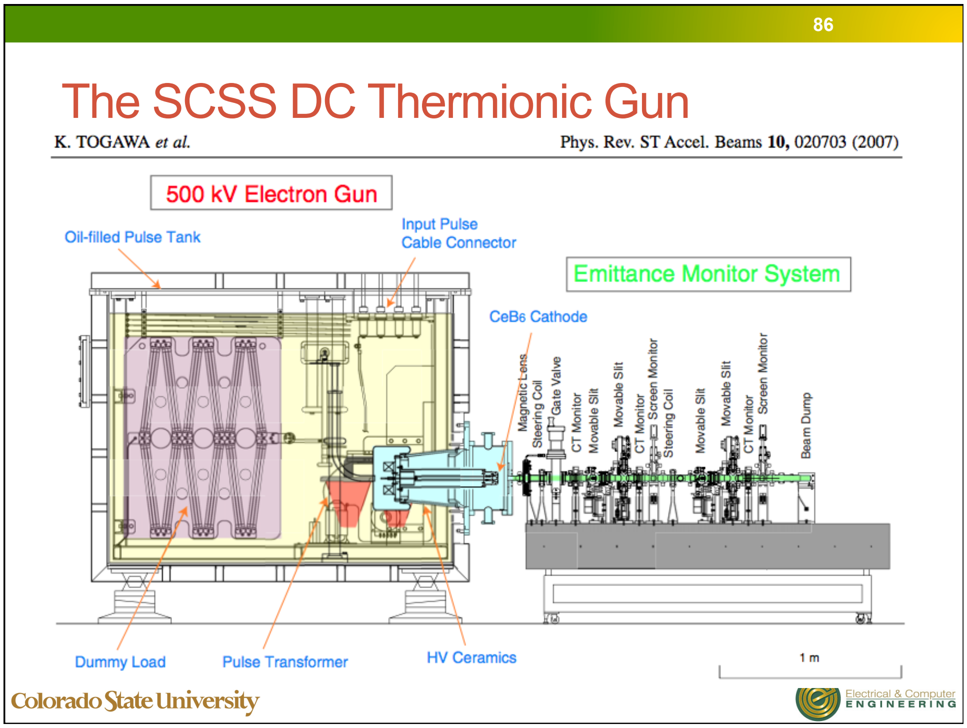
Single-crystal CeB_6 Cathode for the SCSS Low-emittance Injector

Courtesy T. Shintake

No HV breakdown for 4 years daily operation

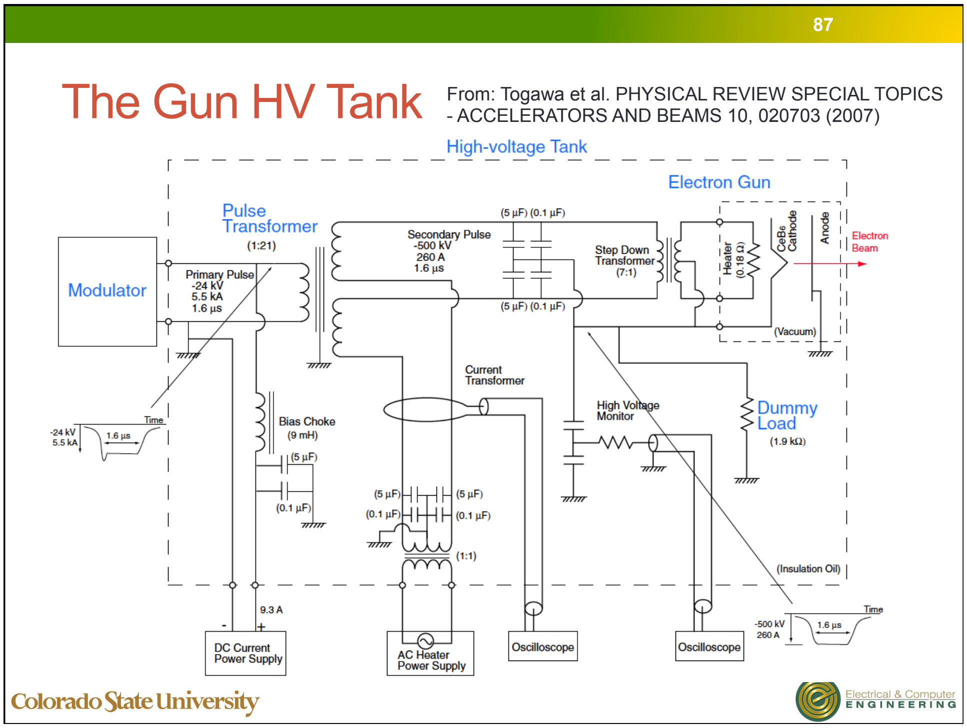
After 20,000 hours operation 1 crystal changed.

Diameter : ϕ3 mm
Temperature : ~1500 deg.C
Beam Voltage : 500 kV
Peak Current : 1 A
Pulse Width : ~2 μs



The SCSS DC Thermionic Gun

K. TOGAWA *et al.* Phys. Rev. ST Accel. Beams **10,** 020703 (2007)



The Gun HV Tank

From: Togawa et al. PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS 10, 020703 (2007)

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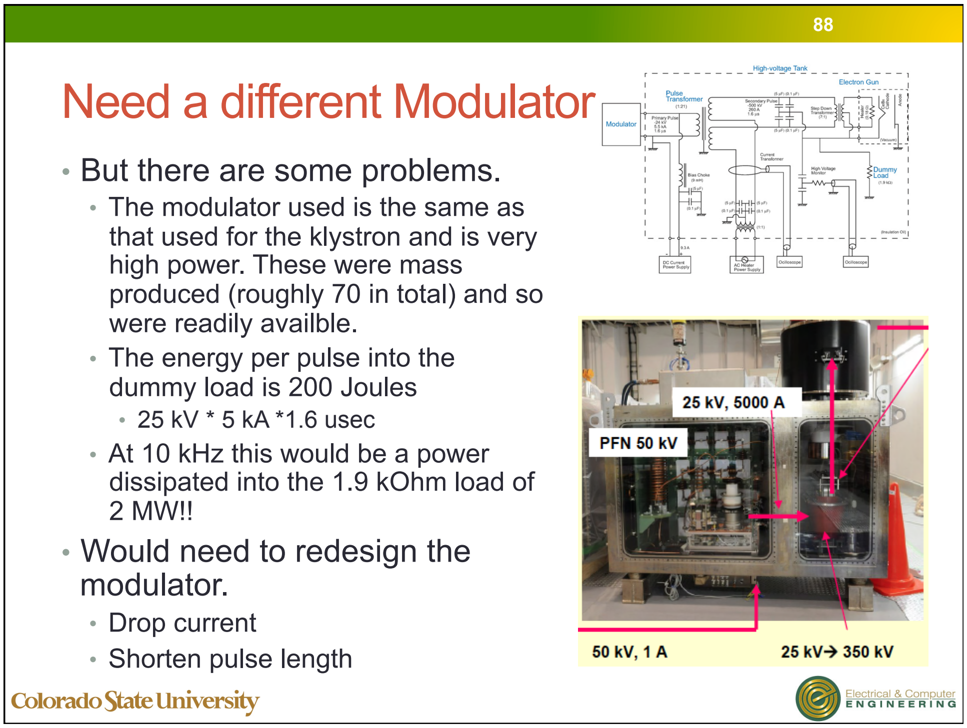

Need a different Modulator

- But there are some problems.
  - The modulator used is the same as that used for the klystron and is very high power. These were mass produced (roughly 70 in total) and so were readily availble.
  - The energy per pulse into the dummy load is 200 Joules
    - 25 kV * 5 kA *1.6 usec
  - At 10 kHz this would be a power dissipated into the 1.9 kOhm load of 2 MW!!
- Would need to redesign the modulator.
  - Drop current
  - Shorten pulse length

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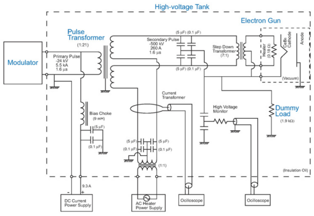
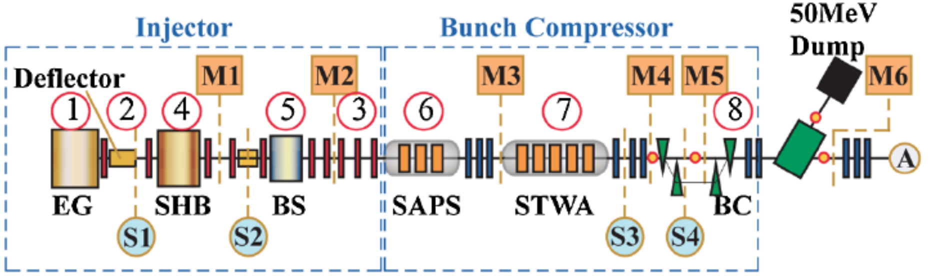
Need a different Modulator



- Lower current
  - Current out of the gun
    - 1 A at 500 kV.
    - This equates to an instantaneous power of 500 kW
    - The cathode to ground effective resistance is 500 kOhm (V/I)
    - Assume a dummy load of 500 kOhm for parallel resistance of 250 kOhm
    - The required current is then 2 A in the secondary
      - That's as opposed to the 260 A and so is a 130 fold reduction in power
- Shorter pulse length
  - For a single bunch that must be captured with a 1 nsec buncher system one only needs 1 nsec
    - Assume 160 nsec due to various things like stray capacitance and impedance
      - That's as opposed to 1.6 usec or a 10 fold reduction in power
- Power required if one uses a purpose-built modulator to operate at 10 kHz
  - 2 MW/260/10 = 770 W
  - Much better

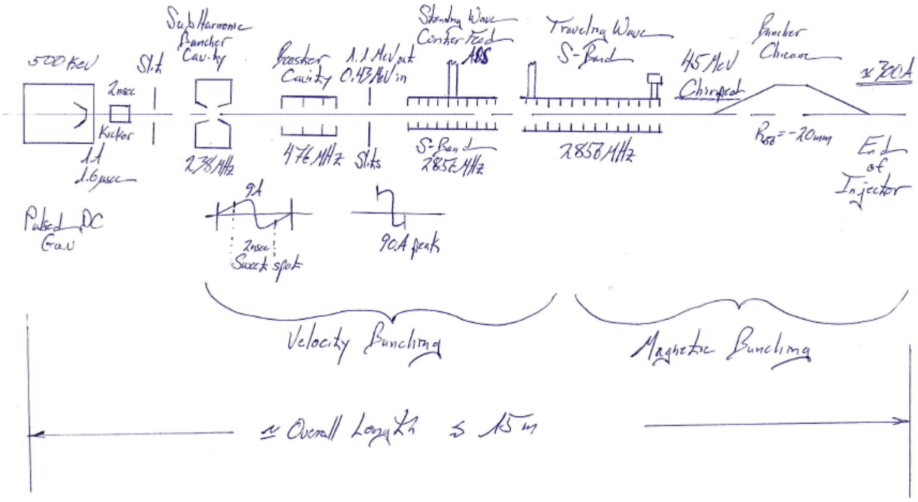
Basically Copy the SCSS Injector

From Shintake et al. PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS 12, 070701 (2009)



- Measured performance at the beam dump
  - 0.3 nC
  - 300 A peak, 0.7 psec FWHM, 125 keV energy spread
  - 0.7 mm-mrad normalized slice emittance

How it Works



Final Comments About the Injector

- There are still some problems to think through
  - Sub Harmonic Buncher, Booster, and S-band systems
    - These will still need to be designed to handle 10 kHz operations
    - I will not tackle this here.
    - Consider it a “homework problem”
    - I will certainly continue to think about it, but for now will assume that the problem is tractable.
- Where’s the Laser Heater?
  - It appears to not be needed for the thermionic source.
  - My guess is the drive laser for the photocathode source together with the very high space charge at the cathode for these sources creates micro density modulations that drive longitudinal space charge instabilities etc. etc.
  - No laser heater simplifies things yet again.

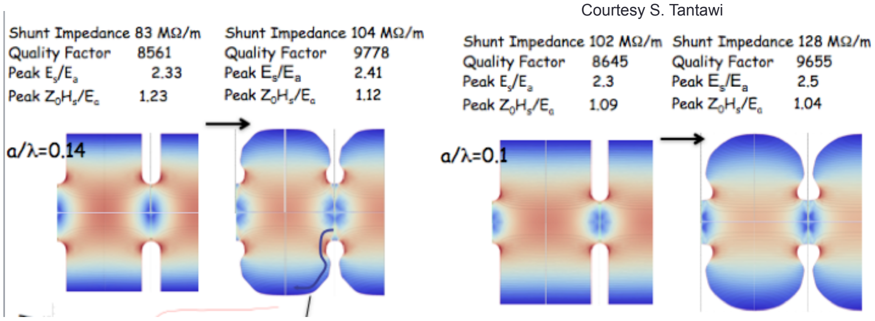
The Accelerator Frequency Choice

- What's available out there (sort of)
  - S-band (2856 MHz), C-band (5712 MHz) and X-band (11.424 GHz)
- X-band
  - Although the technology is not widely available…yet…there are many laboratories interested and there is a lot of research and testing that has been done.
  - It provides the highest shunt impedance (based on scaling laws) and so will make for the shortest linac
  - Choose X-band and see where it leads.
  - Note: Others are thinking about this as well. I certainly am not the first.

X-Band: What's "Available"

- SLAC is the most advanced in this technology
  - Have produced 80 MW klystrons capable of operation at roughly 100 Hz
  - Have produced structures capable of supporting near 80 MV/m
  - But that is not exactly what I need.

Courtesy S. Tantawi



Scaling to High Frequencies

- What I really need
  - First note: the voltage across a cavity is proportional to the square root of the power, i.e. the voltage does not drop so rapidly as does the power.
  - Assume I can build a 1.3 MW X-Band klystron that operates at 10 kHz
    - If I compare this to the 80 MW at 100 Hz that's a little more than 60% of what was proven 10 years ago, i.e. it should be possible.
  - Run this into a SLED (I will describe this later) to boost the power up to 4 MW and split this between two 0.6 m X-band TW cavities.

$$V_{gain} = \sqrt{P_{rf} l r_s}$$

  - For P_{rf} = 2 MW, l = 0.6 m and r_s = 10^8 Ohms/m one gets 11 MV per cavity, i.e. 18 MV/m, i.e. pretty darn good. (at 1 MW it is 13 MV/m)
  - I need the special purpose modulator (a challenge but not impossible) and an X-band structure with high shunt impedance (probably straight forward).

Discussion of Impact by X-band Choice

- The Iris Size in Small
  - At low energy will the beam fit comfortable
  - The wakefields will be large, can one control them?
- Power feed
  - 1 klystron/1 structure, 1 klystron/2 structures, 1 klystron/4 structures
  - The trade off is in cost and space
    - The cost increases for rf power as the number of structures per klystron decreases, but the overall length decreases. One needs to weight these against each other.
    - More klystrons also means tighter packing of components such as the klystrons and modulators and could mean increasing the width and height of the klystron gallery.
- Et cetera
  - For every decision comes many other opportunities to make yet more decisions.

What is a SLED?

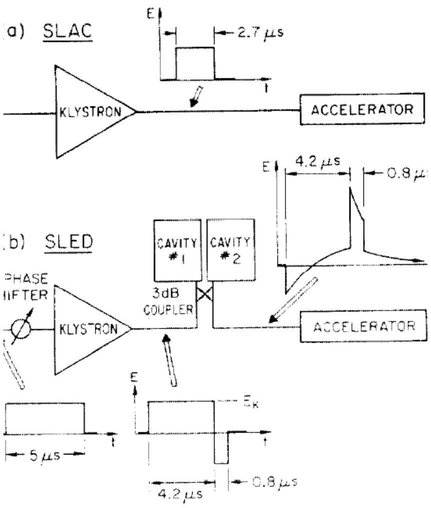
- Send and power to and store energy in high Q resonant cavities.
- Used that stored energy, together with the klystron power to greatly increase the peak power sent to the accelerator thereby increasing the available accelerating potential.
- Factors of 3 in peak power are typical and readily achieved.
- These are an integral part of this design.

IEEE Transactions on Nuclear Science, Vol.NS-22, No.3, June 1975

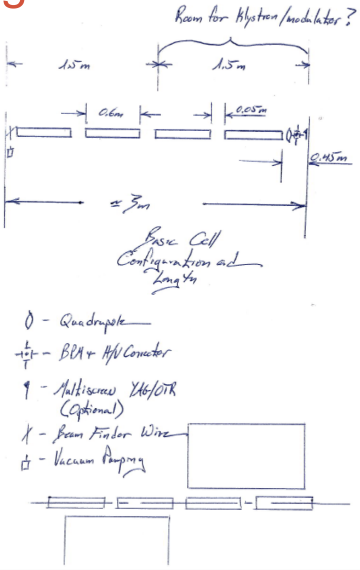
RECENT PROGRESS ON SLED, THE SLAC ENERGY DOUBLER*

Z. D. Farkas, H. A. Hogg, G. A. Loew, P. B. Wilson

Stanford Linear Accelerator Center
Stanford, California, 94305



Rough Estimate of Length



2.5GeV - 0.045GeV = 2.455GeV

Rough Estimate of Length

Common items

Injector ≈ 15m

Bunch Compressors ≈ 15m x 2

End of Linac ≈ 15m

60m

Case A: 1Klystron/2structures

18MV/m ⇒ 43MV/Girder

$\frac{2455}{43}$ = 57 Girders (114 Power Systems)

57x3m = 171m

Total = 171 + 60 = 231m

Case B: 1Klystron/4structures

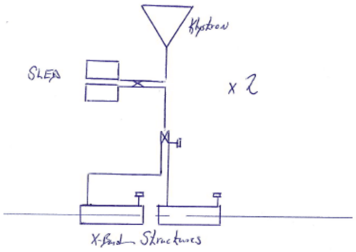
13MV/m ⇒ 30MV/girder

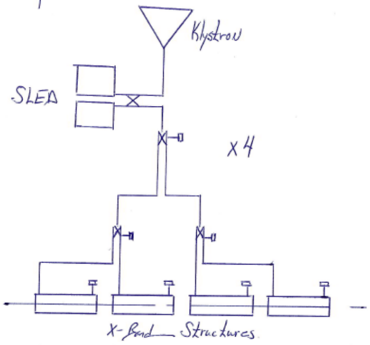
$\frac{2455}{30}$ = 82 girders

Total = 82x3 + 60 = 306

306 m

2 vs 4 Comparison





- Will achieve higher gradients for a given klystron
- Will require ≈ 30% more RF power systems and power
- Will be ≈ 40% shorter
- Will require tighter integration in klystron gallery
- Provides easier tuning

- Requires fewer RF power systems overall
- But requires ≈ 40% more RF structures and overall length
- Simplifies installation in the klystron gallery
- More difficult to get all the phases correct
- Less costly to run and maintain

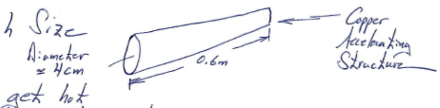
Rough Check of Power to Structure

- Assume Klystron characteristics

Pulse Duration	2 μsec	(SLED fill time ≈ 1.4 μsec)
Power Output	1.3 MW	
Rep Rate	10 kHz	

$$\langle P \rangle = (1.3\,\text{MW})(2\,\mu\text{sec})(10\,\text{kHz}) = 26\,\text{kW}$$

- Case A: 1 Klystron / 2 structures
  $\Rightarrow \simeq 13\,\text{kW}/\text{Structure}$
- Case B: 1 Klystron / 4 structures
  $\Rightarrow \simeq 6.5\,\text{kW}/\text{structure}$
- Basic Structure Rough Size



Case A could get hot and be difficult to cool

The Basic X-Band Structure

- Choose TW
  - Generally more efficient and suitable for SLED
- Make a simple design
  - Single bunch only
  - Scale from SLAC S-band structures
    - $2\pi/3$, simple iris coupled pillbox design
    - Constant gradient

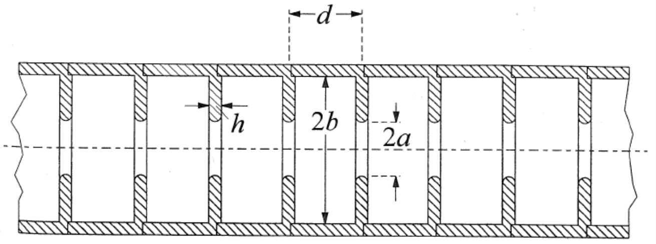
$b \simeq 1.05\text{cm} \rightarrow 0.95\text{cm}$

$a \simeq 3.3\text{mm} \rightarrow 2.3\text{mm}$

$h \simeq 1.3\text{mm}$

$d = \lambda_0/3 \simeq 8.75\text{mm}$

See Wangler § 3.11 for a nice analysis of the periodic iris-loader waveguide



The Basic X-Band Structure

- Determining the length
  - In a TW structure the power drops like
    $$\frac{dP_w}{dz} = -2\alpha_0(z)P_w$$
  - The power at the end of the structure is
    $$P_L = P_0 e^{-2\tau_0} \quad \text{where} \quad \tau_0 \equiv \int_0^L \alpha_0(z)\,dz$$
  - A particle on crest gain on energy of
    $$\Delta W = 2\sqrt{r_s P_0 L(1-e^{-2\tau_0})}$$
  - The fill time of the structure is
    $$t_f = \tau_0 \frac{2Q}{\omega} = L/V_g \qquad V_g \text{ is the group velocity}$$
  - We would like the fill time to be short so that things work well with the SLED but we want also to use the power efficiently

The Basic X-Band Structure

- SLAC chose for their S-band structure $\tau_0 = 0.57$
- Here we will choose $\tau_0 = 1$

$$\Rightarrow \cancel{\tau}\, t_f = (1)\left(\frac{2\,(9000)}{2\pi\,(11.4\times10^9)}\right)\text{sec} = 250\,\text{nsec}$$

Note: SLED fill time is $\simeq 1.4\,\mu\text{sec}$

From the cavity parameters one calculates

$V_g \simeq$ ~~0.048~~ $0.008c$

$$\underline{\underline{L}} = V_g t_f = \left(3\times10^8\,\tfrac{m}{sec}\right)(250\,\text{nsec})(0.008) = \underline{\underline{60\,\text{cm}}}$$

- Note: With $\tau_0 = 1$ $e^{-2} = 0.14$ i.e. 14% of the power goes into the load and 86% is used to generate the accelerating potential.

Rough Estimate of Total Power Needed for RF

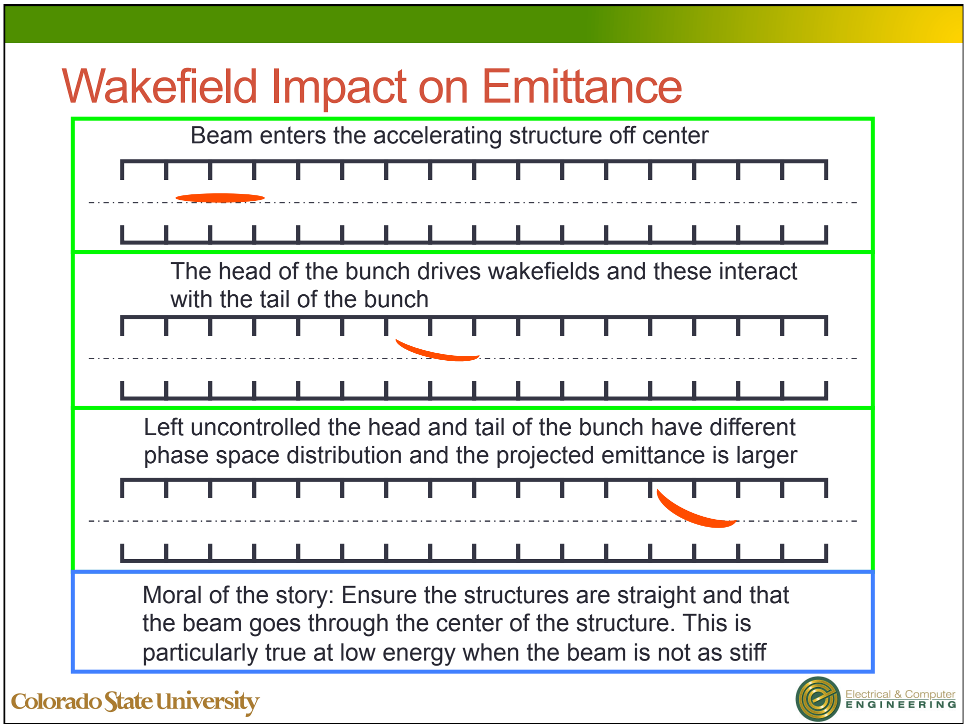
- Klystron Power
  - Output = 1.3 MW, Duration = 1.4 usec, Rep rate = 10 kHz
  - Assume 60% efficient
  - Average power required from modulator
    - 1.3 MW/0.6 * 1.4 usec * 10 kHz = 35 kW
      - Note: 26 kW of that goes to the accelerating structures
- Modulator Power
  - Assume 90% efficiency
  - Average power for the modular = 35 kW/0.9 = 39 kW
- Using 1 klystron per 4 cavities
  - Requires 79 power stations to reach 2.5 GeV
  - 79 * 0.039 MW = 3.1 MW
- Injector
  - No more than 0.1 MW
- Total power needed to generate the beam and RF ~ 3.2 MW

Other Major Power Needs

- Water Plant
  - Need to cool various system and supply all the water needs
  - Roughly 1 MW for a system this size
- Basic building power and HVAC needs
  - Roughly 0.8 MW for a system this size
- Magnet Systems
  - Roughly 1 MW for a system this size
- Total approximate power required for the facility
  - 4 to 5 MW which is really not all that bad for the repetition rate
- Spoiler
  - In some areas ordinances are in place requiring that you have installed enough power to power all installed equipment at 100%. Then the number jumps up significantly.

Wakefield control

- The problem
  - For the same reason that we like the x-band structures, high shunt impedance, they also present a problem, emittance growth due to the strong wakefields.



Wakefield Impact on Emittance

Beam enters the accelerating structure off center

The head of the bunch drives wakefields and these interact with the tail of the bunch

Left uncontrolled the head and tail of the bunch have different phase space distribution and the projected emittance is larger

Moral of the story: Ensure the structures are straight and that the beam goes through the center of the structure. This is particularly true at low energy when the beam is not as stiff

Wakefields Control

- Build the structures straight and true

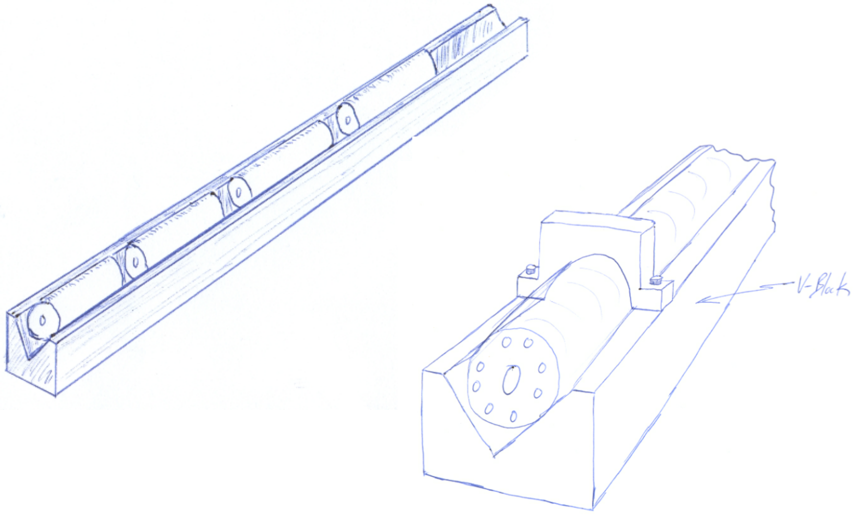
Courtesy T. Shintake

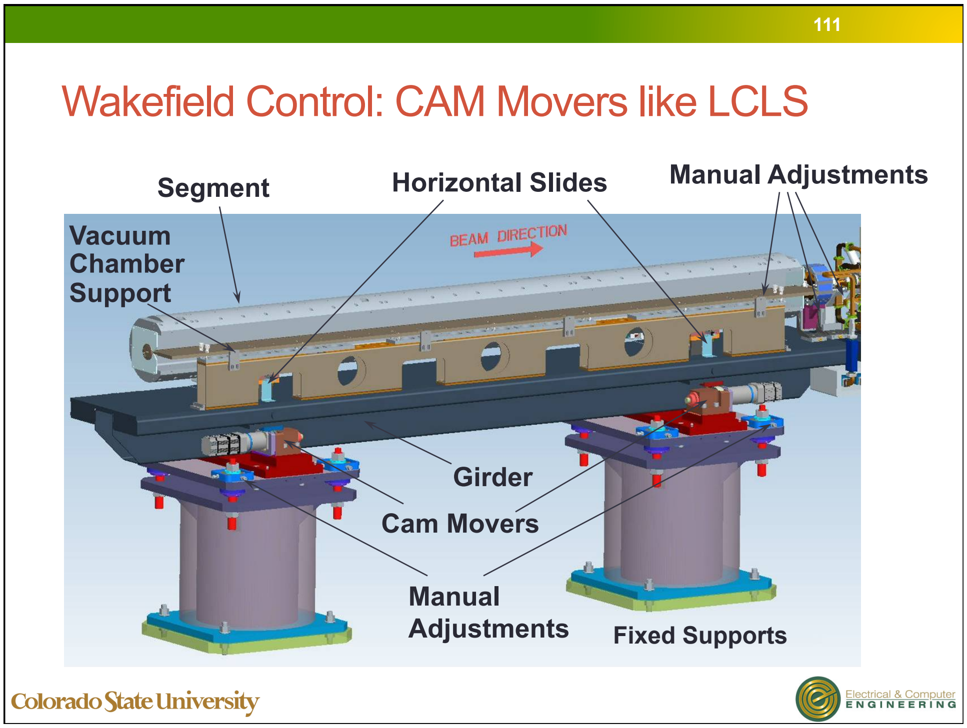
Mass Production of C-band Accelerator
at MITSUBISHI Heavy Ind. 2007 ~ 2009

Wakefield Control

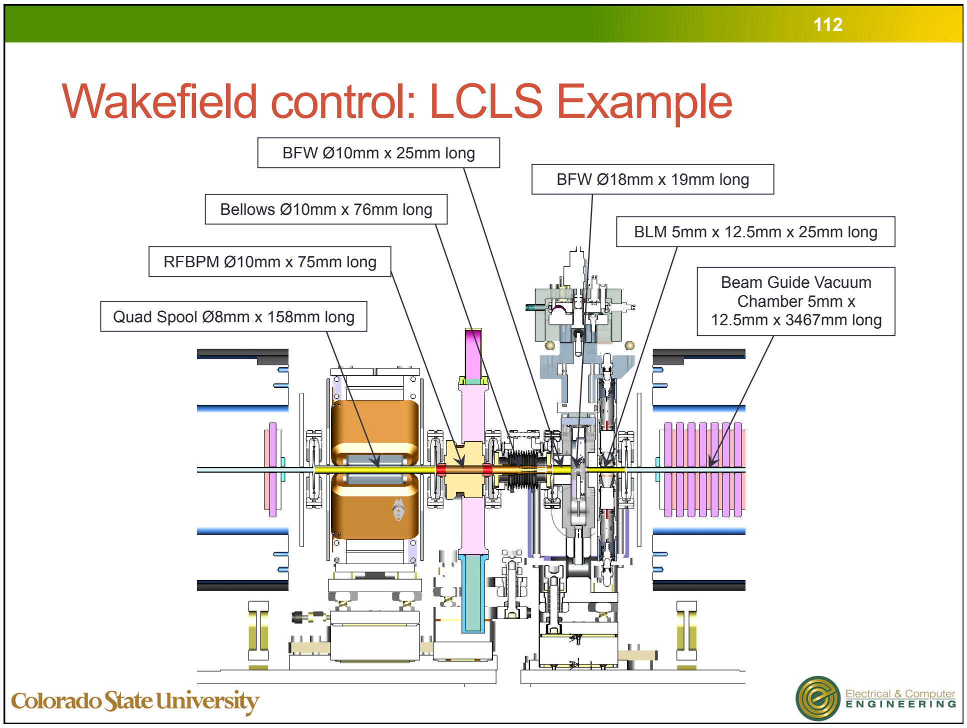
- Align and position them perfectly
  - Fiducialize accurately all components
  - Place 4 accelerating structures on a V-block support/girder
  - Install all other equipment on the girder with the aid of a coordinate measurement machine (1 to 2 micron accuracy)
  - Install girder in tunnel on precision CAM mover system (1 to 2 micron accuracy)
  - Use beam position monitor on one end and beam finder wire on the other end to precisely position the girder with respect to the beam
  - This is what was done for the LCLS undulator system

Wakefield Control: Use of V-Block



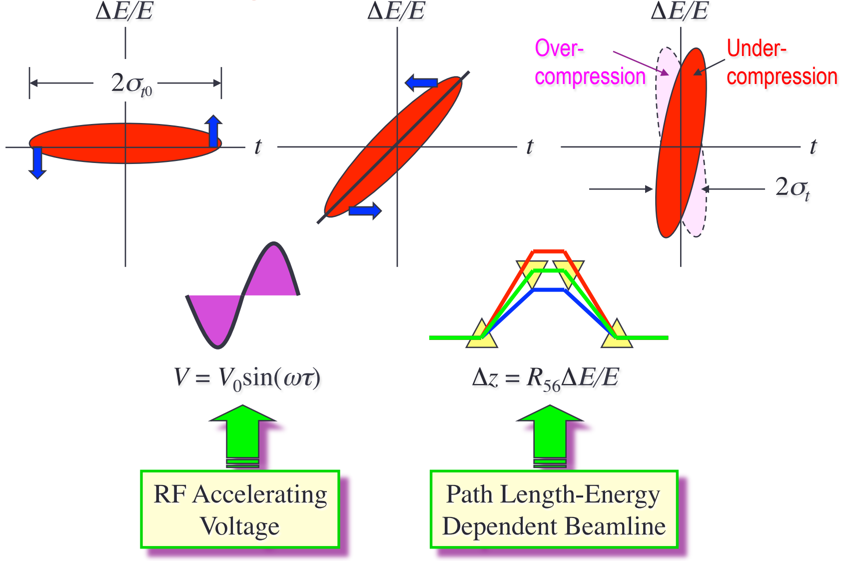


Wakefield Control: CAM Movers like LCLS



Wakefield control: LCLS Example

Compressing the Electron Bunch



$V = V_0 \sin(\omega\tau)$

$\Delta z = R_{56} \Delta E/E$

RF Accelerating Voltage

Path Length-Energy Dependent Beamline

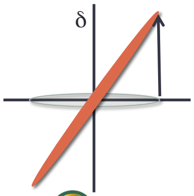
Drawings from P. Emma SLAC/LCLS

Bunch Compression

- Where does one place the bunch compressor chicane?
  - Would like to compress the bunch as soon as possible to mitigate the rf curvature effects
  - Need to also mitigate space charge $SC \propto 1/\gamma^2$
  - As was seen before one can and should compress a lot for the best FEL performance (for this case).
- Decide to use two compressors
  - Compress a bit to start early on
  - Then compress as much as one can in the final bunch compressor

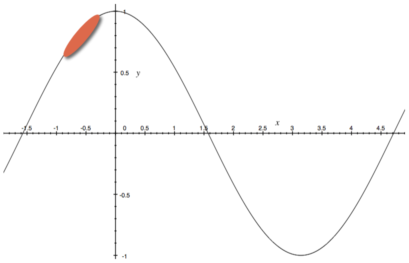
1st Bunch Compressor

- Compress by a factor of 4 to start
  - This was chosen because the beam coming out of the injectors is 0.7 ps FWHM long. That is 2.9 degrees which is long enough to see the curvature of the RF
  - 2.9/4 = 0.7 degrees at x-band
  - For space charge reasons would like to wait until the energy is 2 times what is it was at the injector, i.e. > 90 MeV
- How much do you chirp the beam?
  - Energy spread of the beam at the injector was 125 keV
  - Conserving phase space I want 500 keV to compress by a factor of 4



1st Bunch Compressor

- Need to both get the beam up to energy and put the required chirp on the beam.
- To be safe with space charge place BC1 at 200 MeV
  - This also buys tuning flexibility



$$\Delta E_{beam} = qV_L l \cos\phi_c \qquad \frac{\Delta E_{chirp}}{\phi_1} = -qV_L l \sin\phi_c$$

$$\phi_c = \tan^{-1}\frac{-\Delta E_{chirp}}{\phi_1 \Delta E_{beam}}$$

Using

$\Delta E_{chirp} = 0.5$ MeV $\quad \Delta E_{beam} = 105$ MeV (150 MeV at BC1)

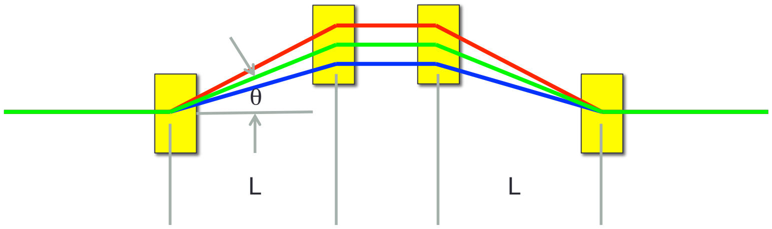
$\phi_1 = 0.025$ rad (half of the 0.7 ps FWHM)

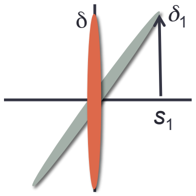
$V_L = \left(13\ \mathrm{MV}/m\right)70\% = 9.1\,\mathrm{MV}/m$ where I have provided overhead for tuning. One gets

$\boxed{\phi_c = -0.188 \text{ rad } (-11^{\circ}) \text{ and } l = 12 \text{ m}}$

This implies using 20 x-band sections or 5 girders prior to the BC1 chicane.

What Does the BC Look Like?





$$s_1 = R_{56}\,{}^{\Delta E}\!/_{E} = R_{56}\delta_1$$

$$R_{56} = \frac{s_1}{{}^{\Delta E}\!/_{E}}$$

In our current case

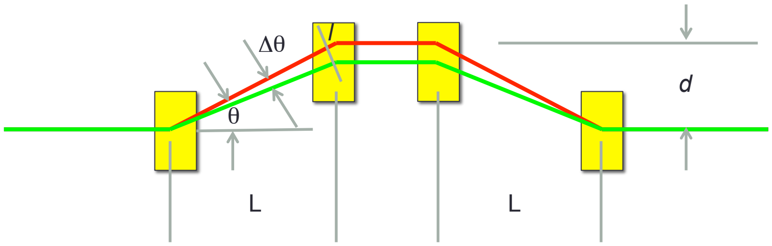
$\tau_1 = 0.35$ psec

$s_1 = -105\ \mu\text{m}$

$\delta_1 = \frac{0.5\ \text{MeV}}{150\ \text{MeV}} = \frac{1}{300}$

$R_{56} = -31.5$ mm

Rough Estimate of θ and R_{56}



$$\frac{\Delta\theta}{\theta} = \frac{-\Delta p}{p} \approx \frac{-\Delta E}{E} = -\delta$$

$$l \approx L\Delta\theta\theta = -L\delta\theta^2$$

$$R_{56} \approx \frac{2l}{\delta} = -2L\theta^2$$

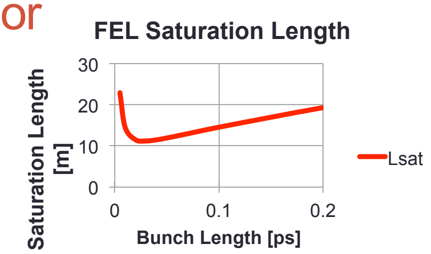
If L = 1.5 m R_{56} = -31.5 mm

$$\theta = \left[\frac{-R_{56}}{2L}\right]^{1/2} = 0.1\ \text{rad}\ \left(5.9^\circ\right)$$

$d \approx 15$ cm

These are very reasonable numbers

A 2nd Bunch Compressor



- Bunch as much as possible
  - Higher peak currents.
    - Better FEL performance
  - Less problems with rf curvature
  - Less problems with wakefields
- How much do we dare compress?
  - Current bunch length after BC1
    - 175 fsec FWHM
  - For optimal FEL performance need to compress to 28 fsec FWHM
    - i.e. compress by a another factor of 6.25
    - Is this possible or desirable?

A 2nd Bunch Compressor

- Where should it be placed?
  - Place it at as low an energy as possible
    - This helps mitigate wake field effects, rf curvature effects and reduces the integrated strength of the BC dipoles.
- The Choice
  - Compress by a factor of 2
    - For space charge reasons the BC2 should be installed at an energy above 212 MeV, but will occur automatically as the gradient is not sufficient to apply that amount of chirp in such a short distance.
    - The minimum number of sections/girders needed is

$$l \ge \frac{\Delta E}{\phi_1}\frac{1}{qV_l} = \frac{2*0.5\text{ MeV}}{0.0063\text{ rad}}\frac{1}{q*13\text{ MV}/\text{m}} = 12.2\text{ m}$$

$$\frac{12.2\text{ m}}{0.6\text{ m}} = 20\text{ sections or 5 girders}$$

A 2nd Bunch Compressor

- The Choice (Continued)
  - Use 3 times the number of structures needed only chirp the beam
    - 15 girders at 31 MeV per girder is 465 MeV so target 700 MeV as the energy for the second bunch compressor
    - From before

$$s_1 = R_{56} \Delta E / E = R_{56}\delta_1 \qquad \phi_c = \tan^{-1}\frac{-\Delta E_{chirp}}{\phi_1 \Delta E_{beam}} = \tan^{-1}\frac{-1\ \text{MeV}}{0.0062\ \text{rad}\ 550\ \text{MeV}} = -0.29\ \text{rad}\ \left(-17^\circ\right)$$

$$R_{56} = \frac{s_1}{\Delta E / E}$$

$$\tau_1 = 0.087\ \text{psec}$$

$$s_1 = -26\ \mu\text{m}$$

$$\delta_1 = \frac{1\ \text{MeV}}{700\ \text{MeV}} = \frac{1}{700}$$

$$R_{56} = -18.4\ \text{mm}$$

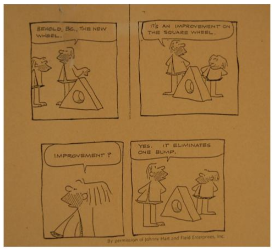
OK, but now what?? Need to still design the BC2

A 2nd Bunch Compressor

- Assume we use the identical bunch compressor as BC1 but allow *L* to vary.
  - This minimizes redesign of many thing and so simplifies our task
  - Make the following assumption
    - Dipole strengths at BC1 vs BC2
      - BC2 strength is 3 times BC1
        - Change power supply current but assure not saturated
  - Energy difference
    - 150 MeV vs 700 MeV = factor of 4.7
  - Implies
    - θ chicane = 0.1 rad *3/4.7 = 0.064 rad (3.7°)

$$L = \frac{-R_{56}}{2\theta^2} = \frac{0.0184\ \text{m}}{2 * \left(0.064\ \text{rad}\right)^2} = 2.25\ \text{m}$$

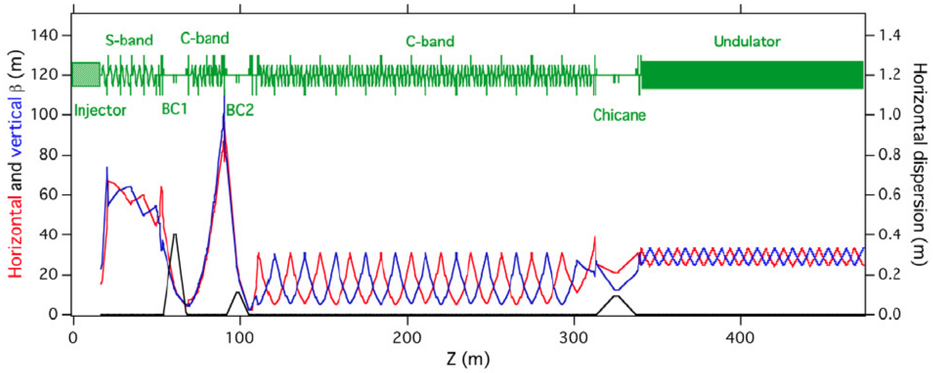
    - Again all perfectly reasonable.



Remember the cave man engineer

Focusing the Beam Along the Linac

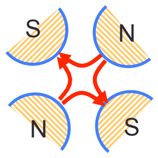
- One needs to control and focus the beam along the length of the linac.
  - A quadrupoles

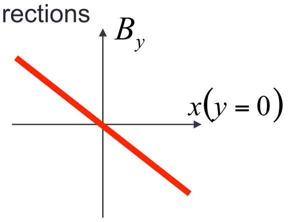


Beam Focusing

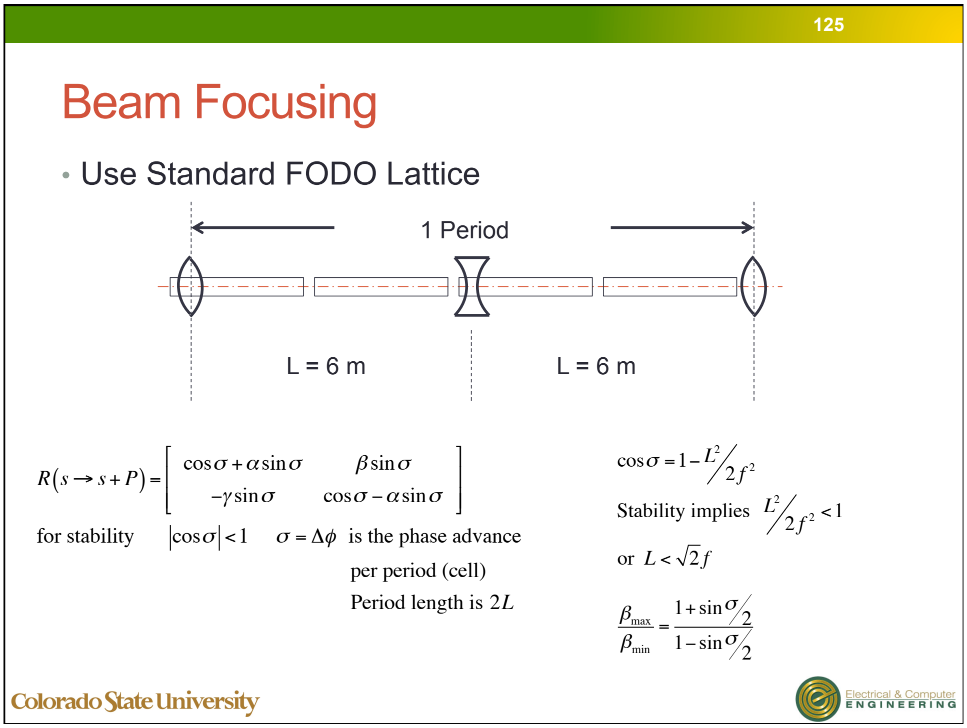
- Periodically need to focus the electron beam
  - Quadrupole: A magnetic element similar to an optical lens, but…
  - Whereas a lens can be made to radially, a quadrupole focuses in on pland and defocuses in the other
  - A properly contrived “lattice” of quadrupoles can be made to, on average, focus simultaneously in both directions

$$\frac{1}{f} = \frac{\int_0^{L_q} \frac{\partial B_y}{\partial x} dl}{B\rho}$$





$B\rho$ is referred to as the beam rigidity and is proportional to the momentum (~300 MeV = 1 Tm for electrons)



Beam Focusing

- Use Standard FODO Lattice

$$R(s \to s+P) = \begin{bmatrix} \cos\sigma + \alpha\sin\sigma & \beta\sin\sigma \\ -\gamma\sin\sigma & \cos\sigma - \alpha\sin\sigma \end{bmatrix}$$

for stability $|\cos\sigma| < 1$ $\sigma = \Delta\phi$ is the phase advance per period (cell)

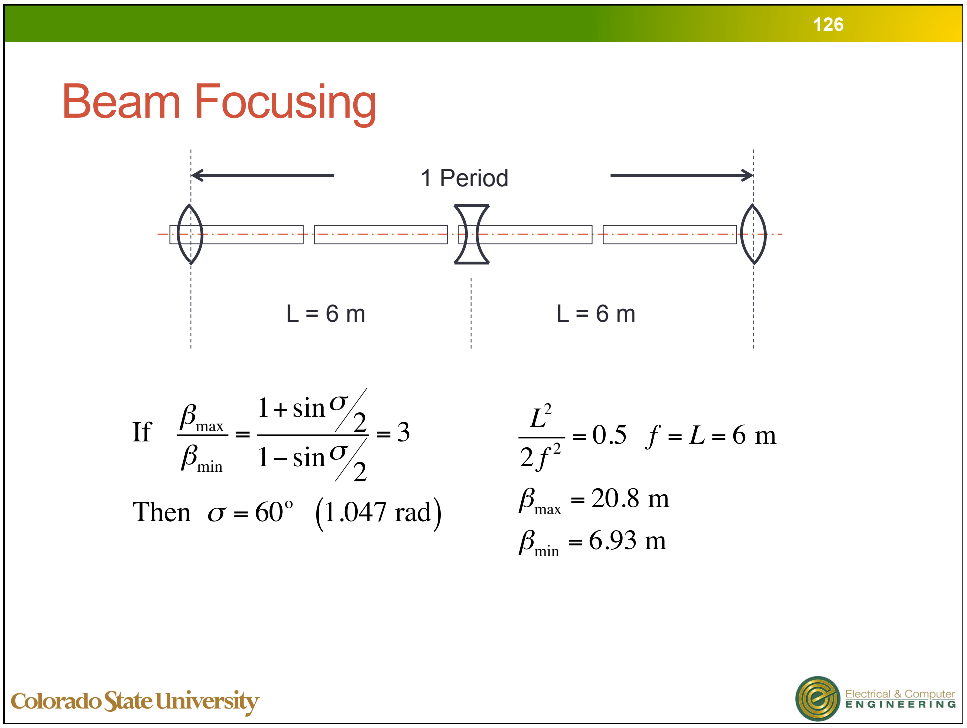
Period length is $2L$

$\cos\sigma = 1 - L^2/2f^2$

Stability implies $L^2/2f^2 < 1$

or $L < \sqrt{2}f$

$$\frac{\beta_{\max}}{\beta_{\min}} = \frac{1+\sin\sigma/2}{1-\sin\sigma/2}$$



Beam Focusing

If $\dfrac{\beta_{\max}}{\beta_{\min}} = \dfrac{1+\sin\sigma/2}{1-\sin\sigma/2} = 3$

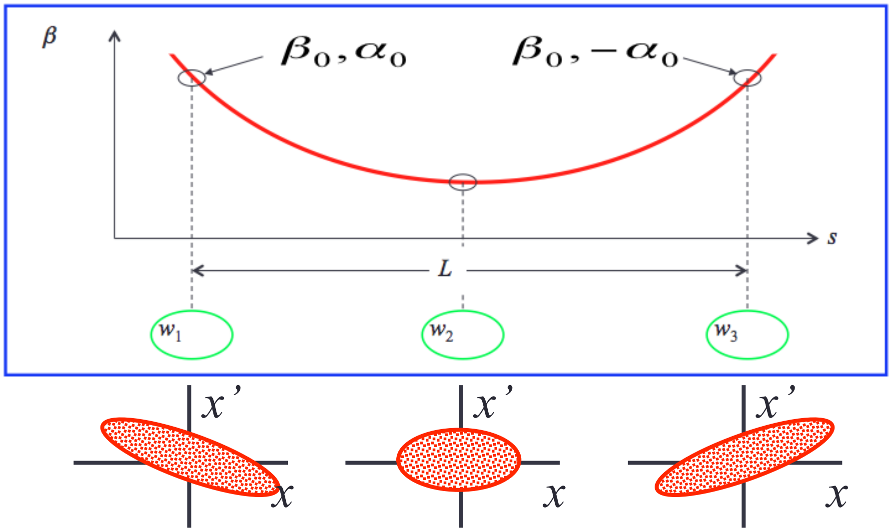
Then $\sigma = 60^\circ$ (1.047 rad)

$\dfrac{L^2}{2f^2} = 0.5$ $f = L = 6$ m

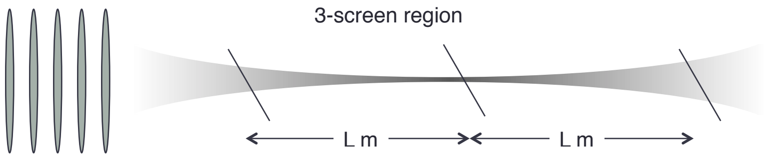
$\beta_{\max} = 20.8$ m

$\beta_{\min} = 6.93$ m

Propagation of Phase Space in Free Space



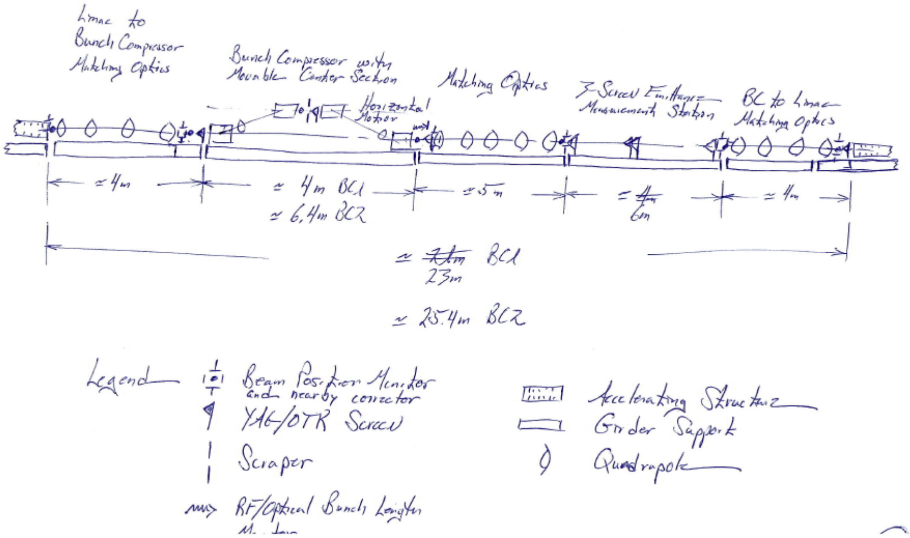
Emittance & Matching



- Obtain the Twiss parameters
- Calculate mismatch:
- Correct quadrupole strengths
- Repeat until $\delta_m \sim 1$

$$\delta_m = \frac{1}{2}\left(\beta_o\gamma_m - 2\alpha_o\alpha_m + \beta_m\gamma_o\right)$$

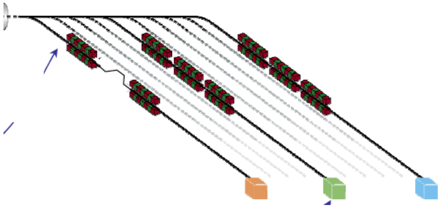
Bunch Compressor Region Layout



Exhaustion Sets In With Plenty More to Do

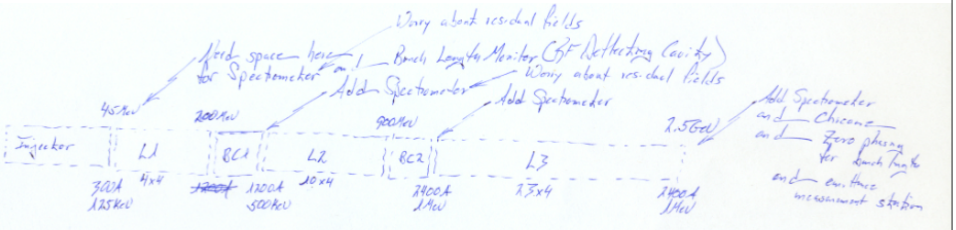
What Have We Got?

- Key Features (Unique Features) of This Design
  - Very High Repetition Rate
  - Normal conducting, i.e. not superconducting
  - Use of a Pulsed DC Gun
  - No Laser Heater
  - Use of X-Band Accelerator
  - Relatively Compact, all things consic
    - Could be argued…and should
- Overall Length
  - Just a bit over 300 m
- Capability
  - 10 kHz operation
    - Ability to service MANY beamlines
      - If one had 100 beamlines and all were operating and being provided equal time each would have 100 Hz operation and near full autonomous tuning
  - 1.1+ keV fundamental operation with a 2.3 GeV beam



From J. Corlett LBNL and NGL CDR

Where I Was a Week Ago



Grand Total 4x37 X-band Systems

Structures per group

Groups

2 Bunch Compressors

2 S-Band Systems (I have not sorted this out, Nor will I here)

1 Pulsed DC Thermionic Gun System

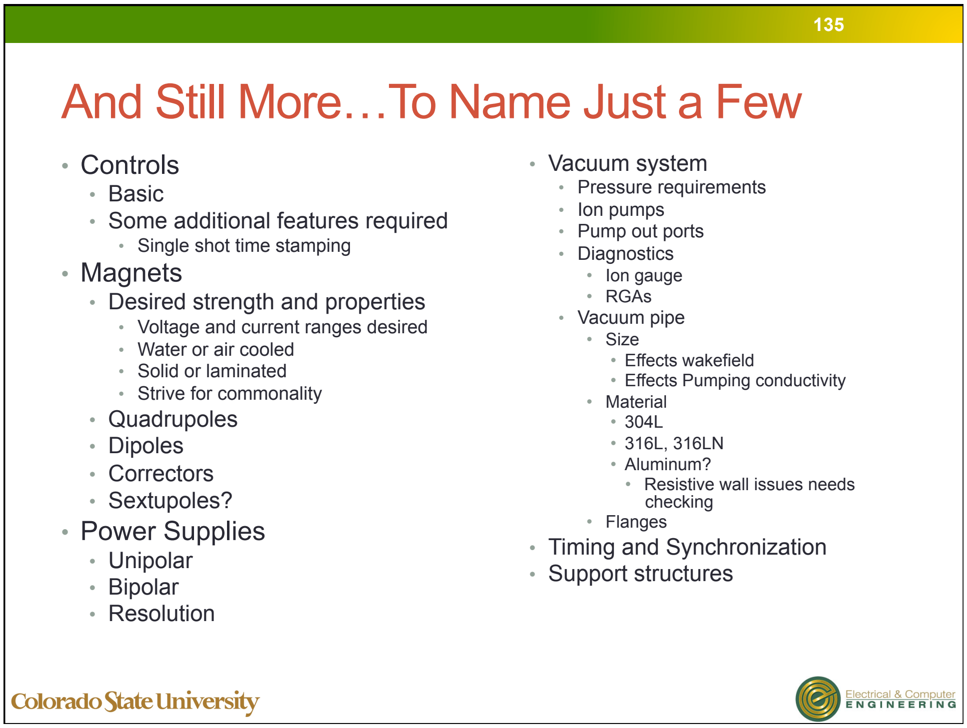
- Moral of the Story
  - Things evolve constantly

But There is Still Lots More to Think About

- Ancillary Systems
  - Buildings and Infrastructure
    - Floor
    - Radiation Enclosure
    - Power System
      - Primary Site Feed
      - Secondary distribution to main switch boxes
      - Local panel distribution
      - Distribution dictated by overall design, safety requirements and operational needs
    - Waters Systems
      - Primary Site Feed
      - Secondary Distribution
      - Tertiary local distribution and control
      - Distribution dictated by overall design, safety requirements and operational needs

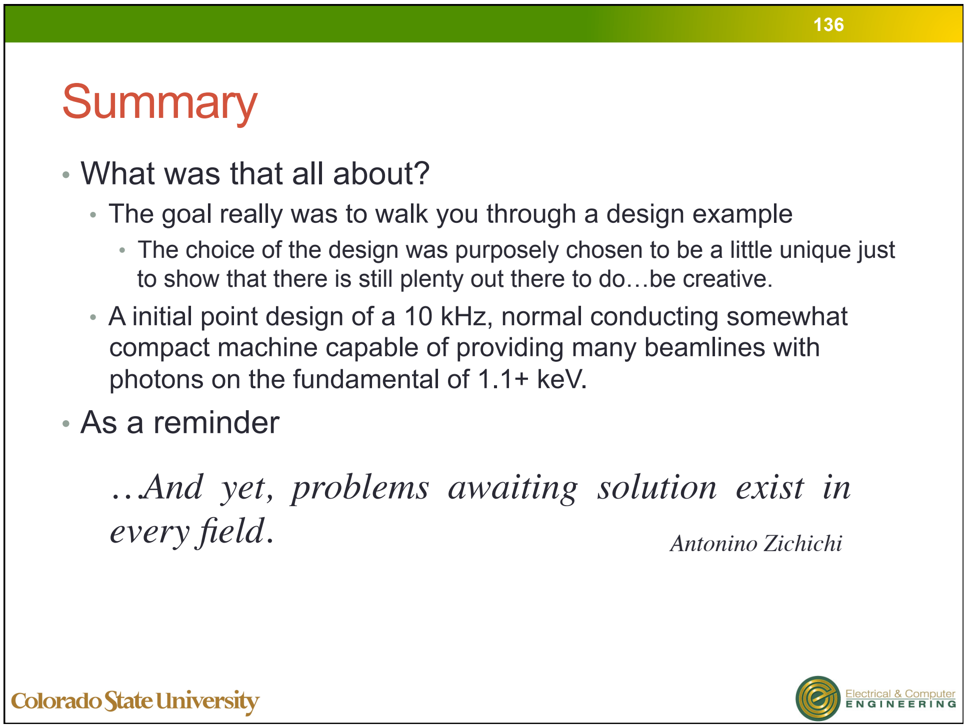
And Still More

- Other major systems
  - Diagnostics
  - BPMs
    - Striplines
    - Buttons
    - Cavities
  - Screens
    - YAG
    - Chromox
    - OTR
  - Wire scanners
  - Charge monitors
  - RF Deflecting cavities
  - Spectrometer
  - Bunch Arrival Monitor
  - EO sampling system
  - CSR monitor
  - Coherent signal bunch length monitor



And Still More…To Name Just a Few

- Controls
  - Basic
  - Some additional features required
    - Single shot time stamping
- Magnets
  - Desired strength and properties
    - Voltage and current ranges desired
    - Water or air cooled
    - Solid or laminated
    - Strive for commonality
  - Quadrupoles
  - Dipoles
  - Correctors
  - Sextupoles?
- Power Supplies
  - Unipolar
  - Bipolar
  - Resolution
- Vacuum system
  - Pressure requirements
  - Ion pumps
  - Pump out ports
  - Diagnostics
    - Ion gauge
    - RGAs
  - Vacuum pipe
    - Size
      - Effects wakefield
      - Effects Pumping conductivity
    - Material
      - 304L
      - 316L, 316LN
      - Aluminum?
        - Resistive wall issues needs checking
    - Flanges
- Timing and Synchronization
- Support structures



Summary

- What was that all about?
  - The goal really was to walk you through a design example
    - The choice of the design was purposely chosen to be a little unique just to show that there is still plenty out there to do…be creative.
  - A initial point design of a 10 kHz, normal conducting somewhat compact machine capable of providing many beamlines with photons on the fundamental of 1.1+ keV.
- As a reminder

> *…And yet, problems awaiting solution exist in every field.*
>
> *Antonino Zichichi*