The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific and
Cultural Organization

IAEA
International Atomic Energy Agency

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Advanced School on Synchrotron and Free Electron Laser Sources and their Multidisciplinary Applications

7 - 25 April 2008

FEL Machine Physics

Stephen V. Milton
SINCROTRONE
TRIESTE
ITALY

FEL-Machine Physics

8 April, 2008
ICTP

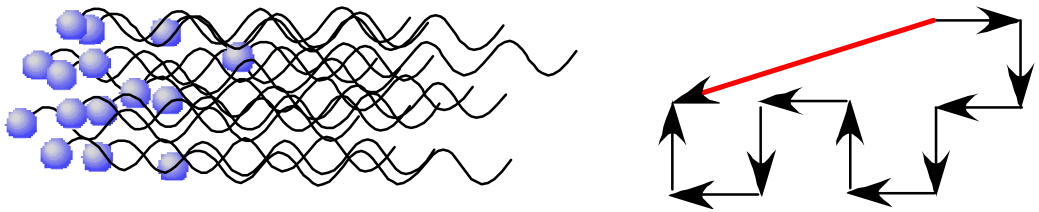
Stephen V. Milton

Sincrotrone Trieste, S.C.p.A.

Overview

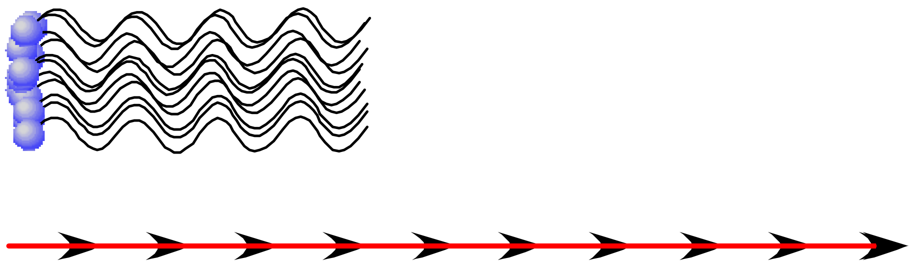
- The FEL Process
- FERMI@Elettra
- Major Systems
- Some Actual Measurements
- Summary

Coherence



Incoherent Emission

If the electrons are independently radiating light then the phase of the their electric fields are random with repect ot one another and the electric field scale as the square root of the number of electrons



Coherent Emission

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

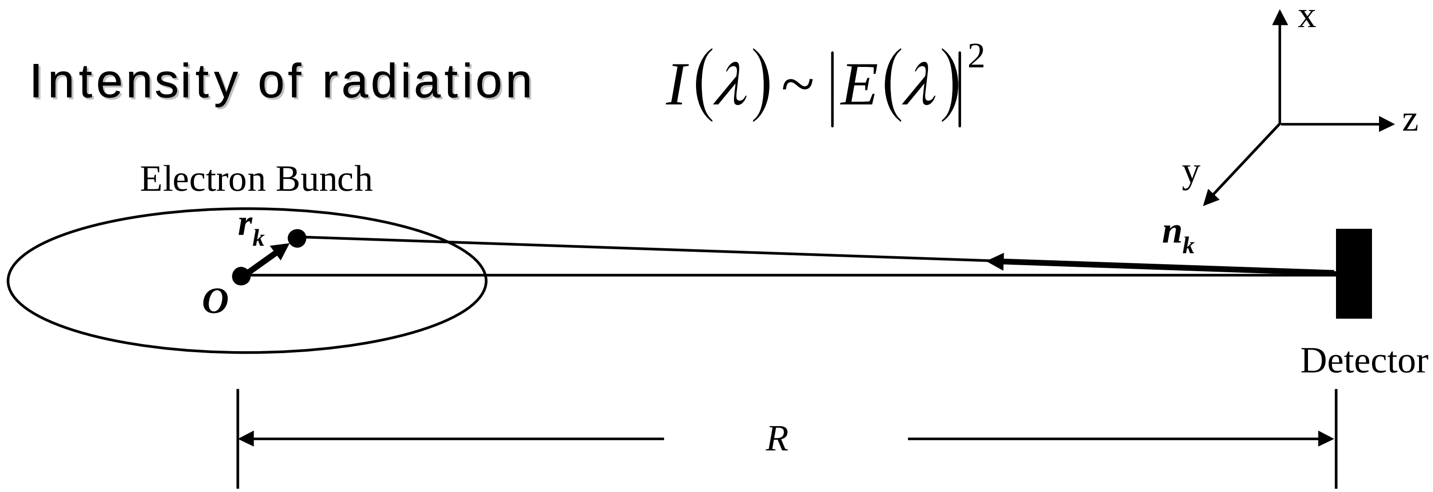
The power goes as the square of the field and if N is very large one can get an enormous gain in power emitted.

This is the essence of the Free-electron laser.

Coherent Radiation

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

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



- The component of the electric field from an electron seen by the detector at wavelength *l* is

$$E_k(\lambda) = E_1(\lambda) e^{2\pi n_k \cdot r_k / \lambda}$$

- The total field of all electrons is
- And the total intensity is

$$E_{tot}(\lambda) = E_1(\lambda) \sum_{k=1} e^{2\pi i n_k \cdot r_k / \lambda}$$

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

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

Undulator Magnets: Resonant Condition

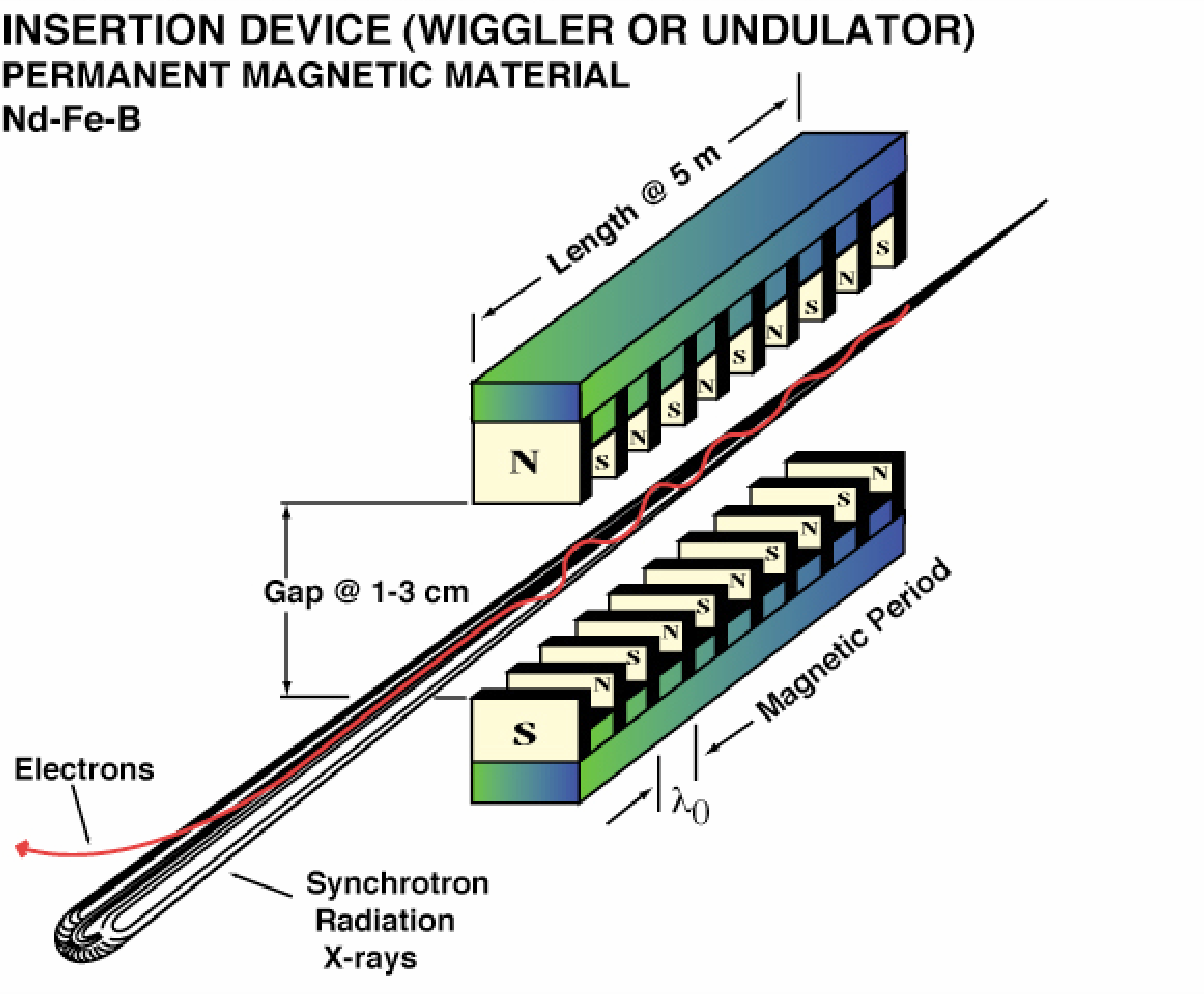
"Resonance" occurs when the light wavefront "slips" ahead of the electron by one optical period in the time that it took the electron to traverse the distance of one undulator period

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

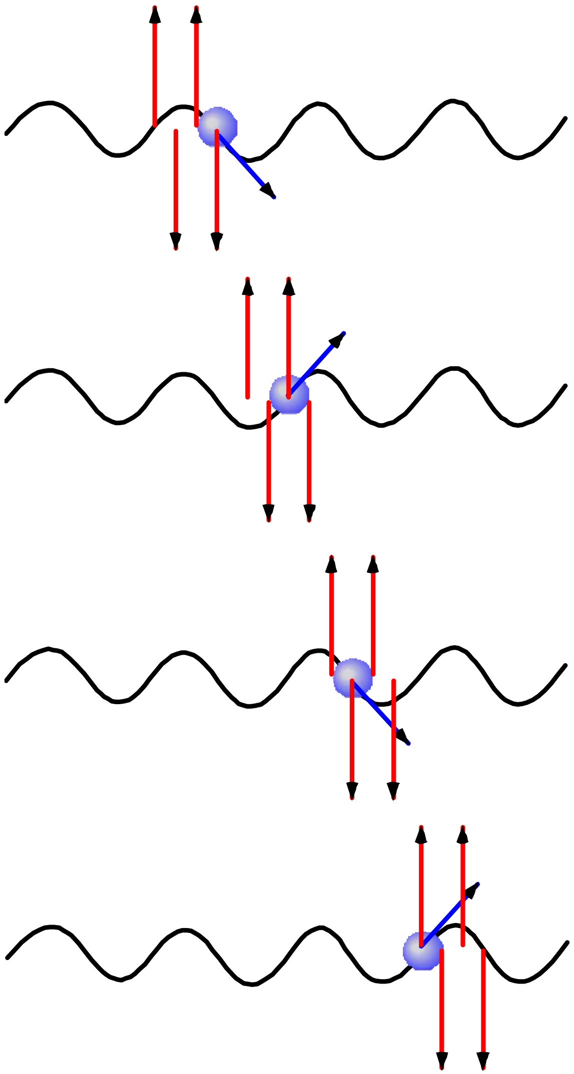
Where γ is the normalized electron beam total energy and

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

Is the normalized undulator field strength parameter



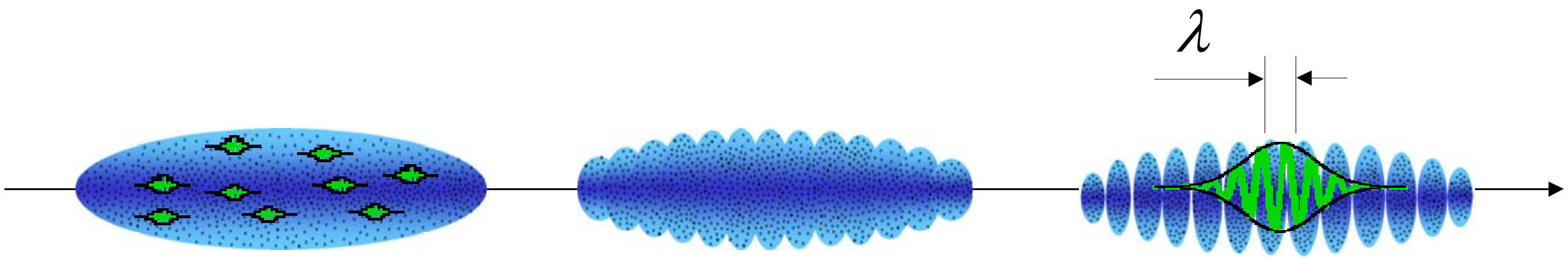
Interaction Between the Electron and EM Field



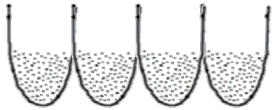
If the electron oscillates in phase with a co-propagating EM field of the correct frequency it can pick up or lose a net amount of momentum. Whether it picks up momentum or loses some is depended on the phase relationship.

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

e-Beam Microbunching



$P \sim N_e$



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

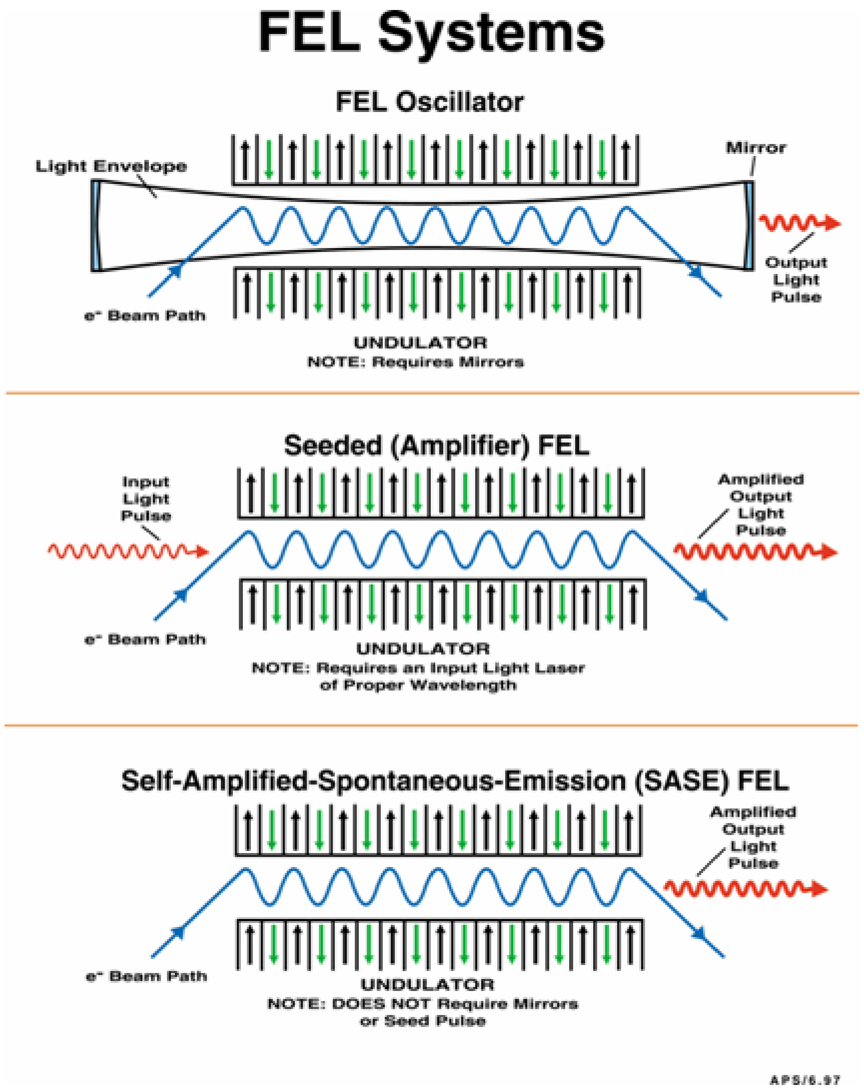
P - Radiation Power

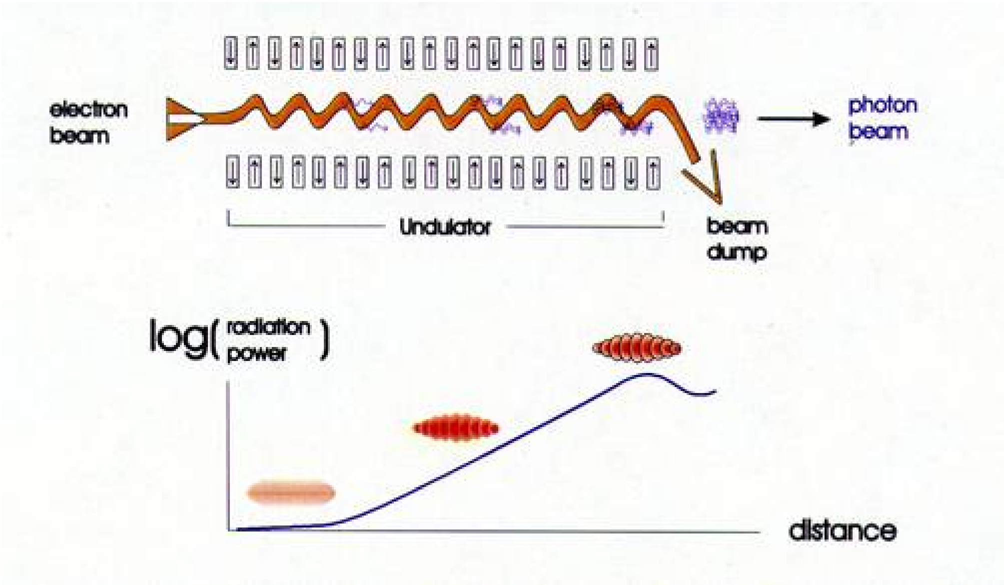
N_e - Number of particles in the bunch

$E_u + E_R \Rightarrow$ potential wells

N_{l_c} - Number of particles in coherence volume

Oscillator, Seeded FEL, SASE





Electrons are bunched under the influence of the light that they radiate.The bunch dimensions are characteristic of the wavelength of the light.

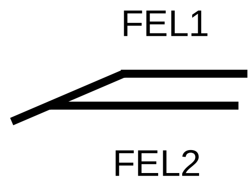
Excerpted from the TESLA Technical Design Report, released March 2001

FERMI@Elettra System

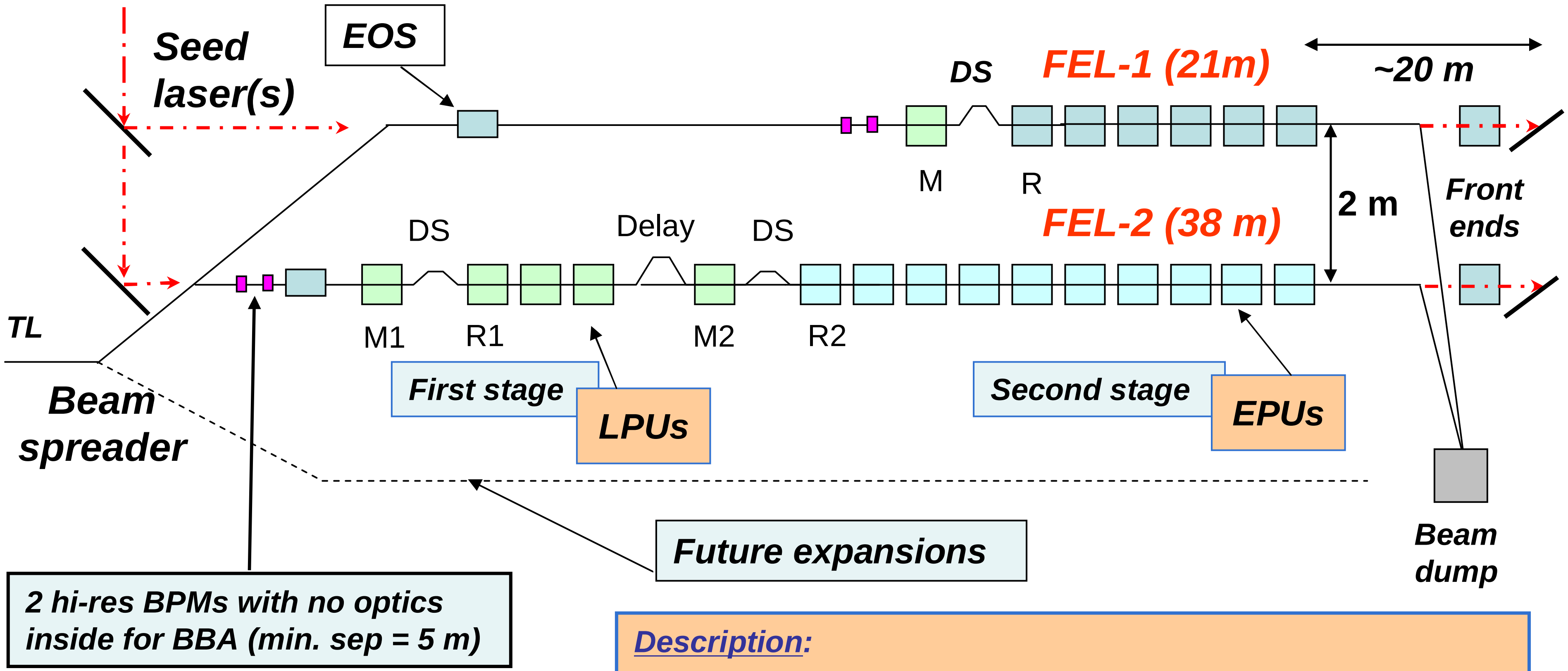
The beam source for the FERMI@Elettra FEL is a linac

- Photocathode RF Gun
- Accelerating Structures
- Various Beam Manipulation Systems
  - Emittance compensating Solenoid, Laser Heater, Longitudinal phase space linearizer, Bunch Compressors
- FEL Region

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.



Conceptual layout of the FELs, transport line, spreader and beam dump

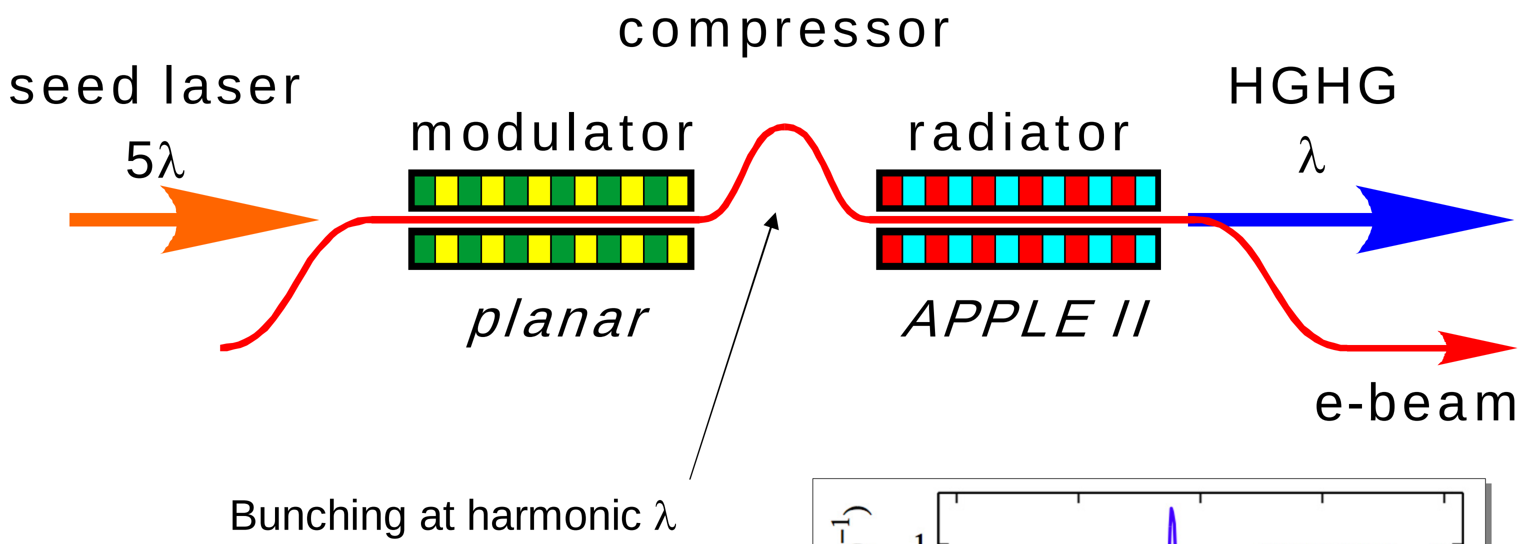


FEL-2 Configurations
- Fresh bunch
- Whole bunch
- HHG seeding

Description:

- *undulator axis separated by 1 m*
- *transverse/energy collimation incorporated*
- *space for matching optics, BPMs, EOS, other diag.*
- *small angles to CSR effects: ~ 6 deg total*

High Gain Harmonic Generation - HGHG



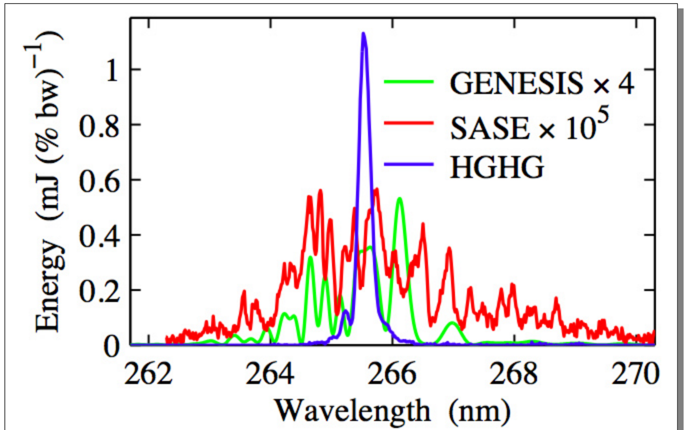
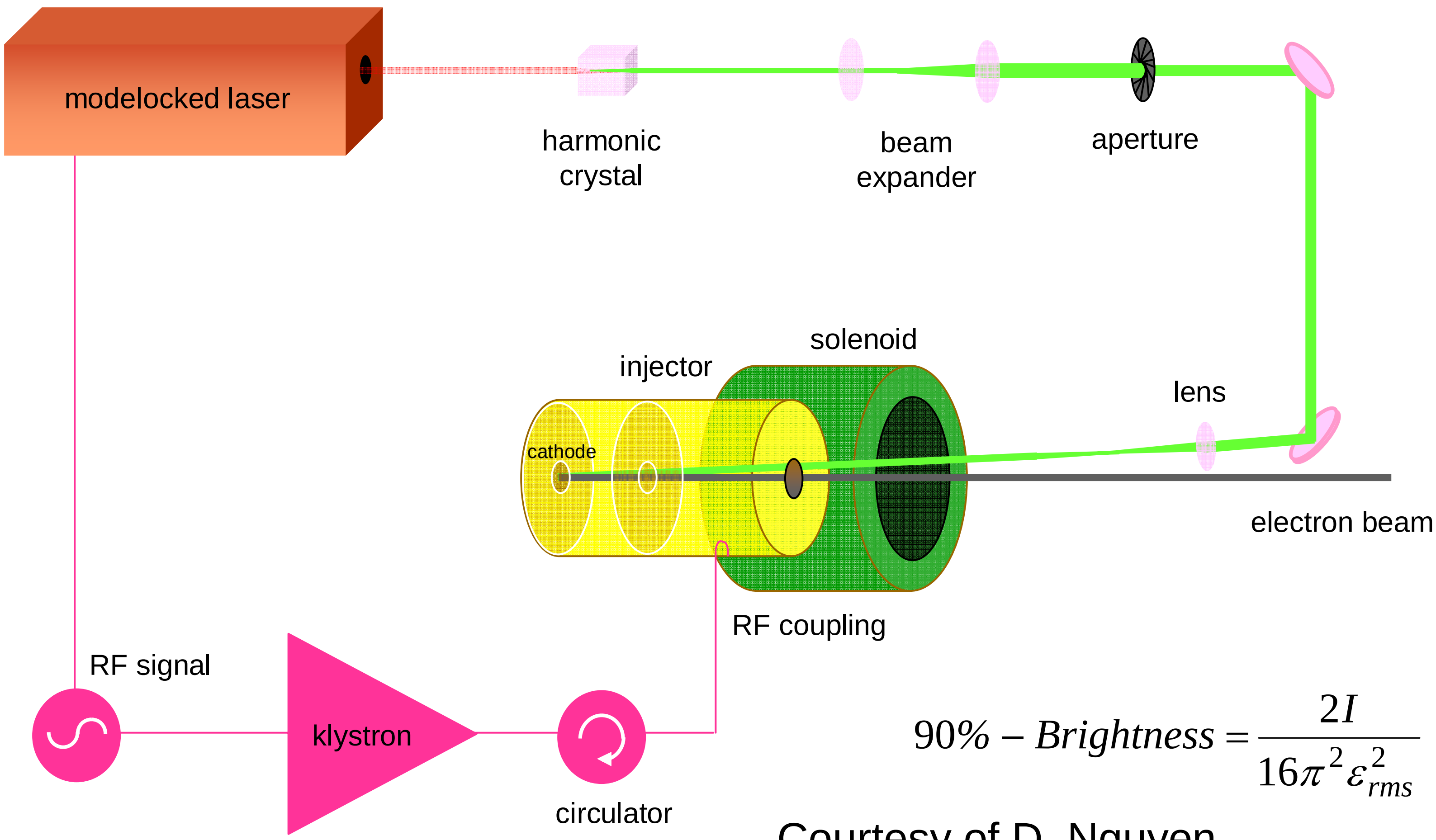


FIG. 4: Single shot HGHG spectrum for 30 MW seed (blue), single shot SASE spectrum measured by blocking the seed laser (red) and simulation the SASE spectrum after 20 m of NISUS structure (green). The average spacing between spikes in the SASE spectrum is used to estimate the pulse length.

More compact and fully temporally coherent source, control of pulse length and control of spectral parameters.

Li-Hua Yu
DUV-FEL

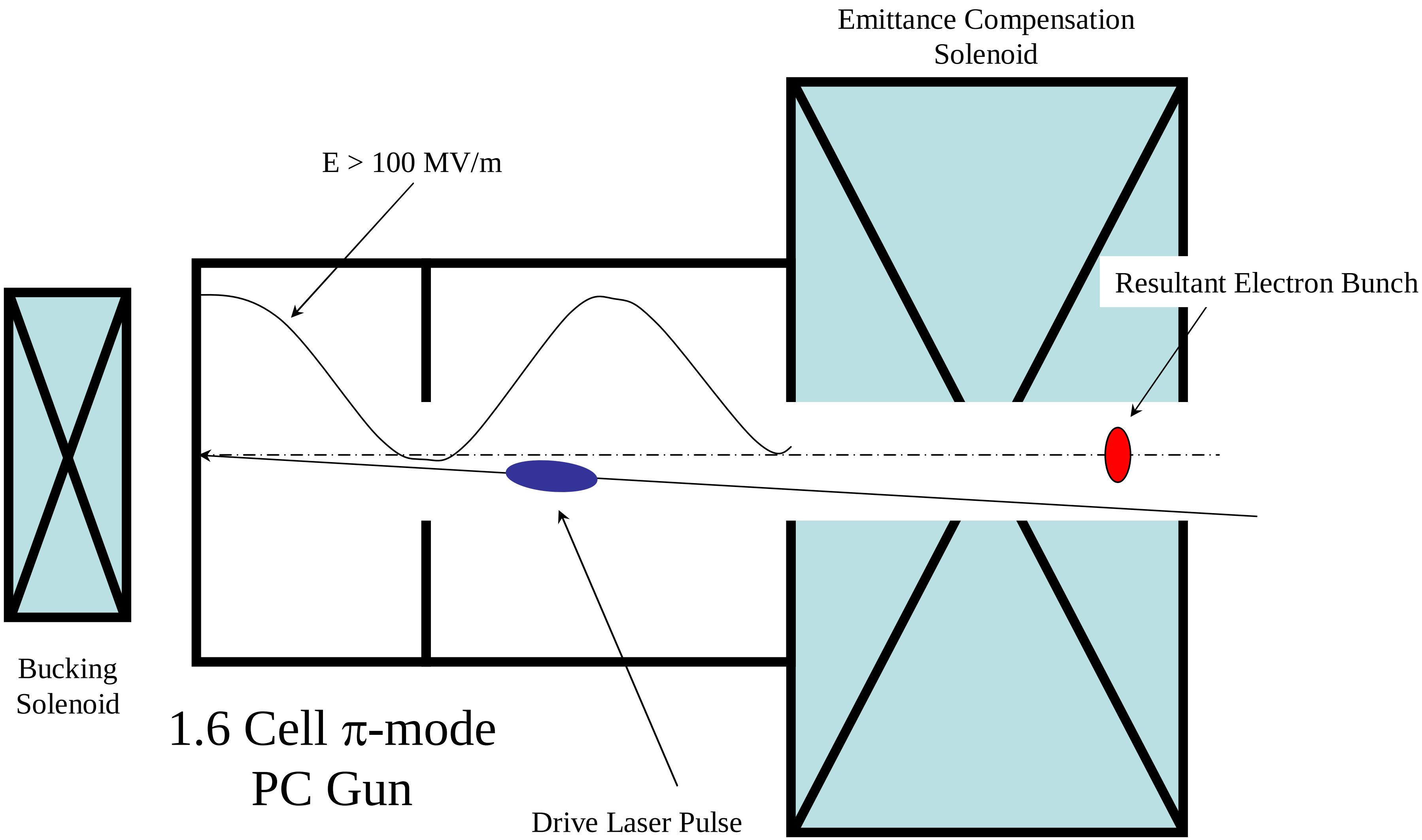
Schematic of a Photoinjector



$$90\% - Brightness = \frac{2I}{16\pi^2 \varepsilon_{rms}^2}$$

Courtesy of D. Nguyen

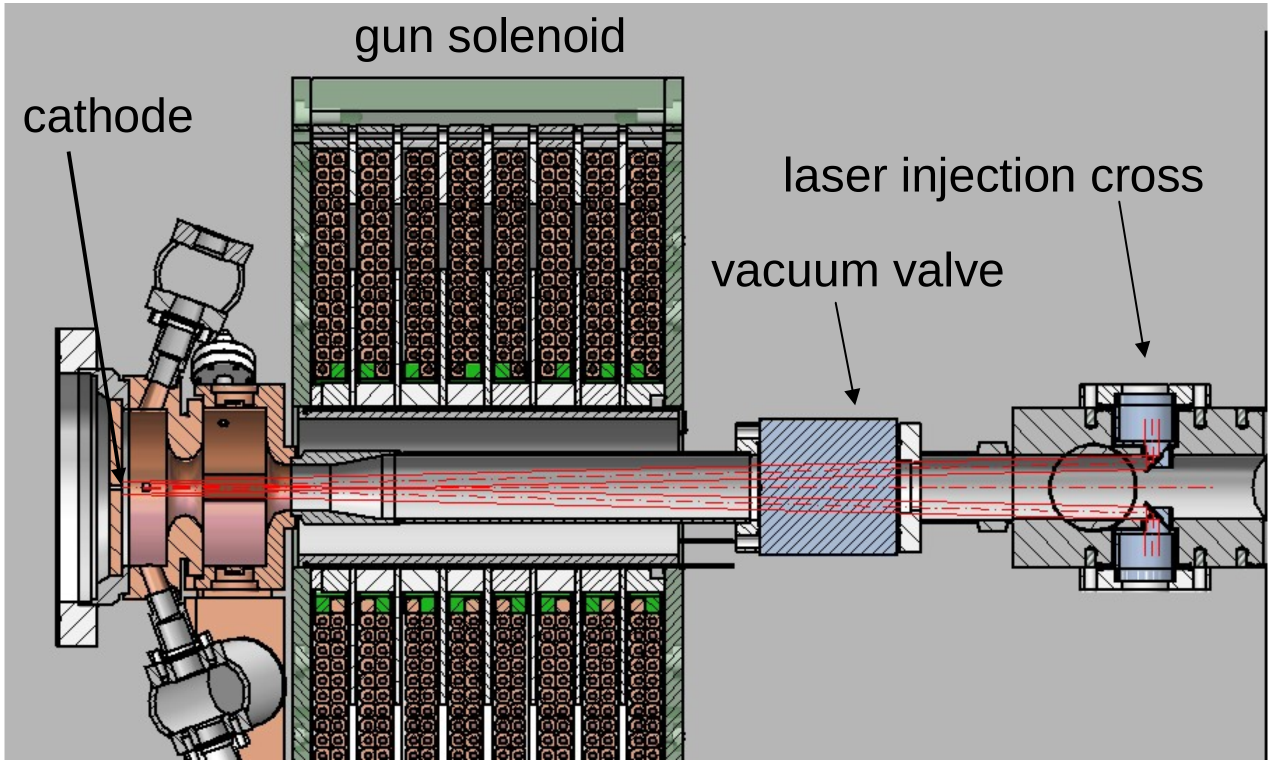
Basics Photocathode RF Gun



More Details

Grazing incidence optics add risk to laser shaping.

Wakes from dual in-vacuum mirrors tolerable.



Drawing compliments of R.F. Boyce & T. Osier

Effect of the Solenoid

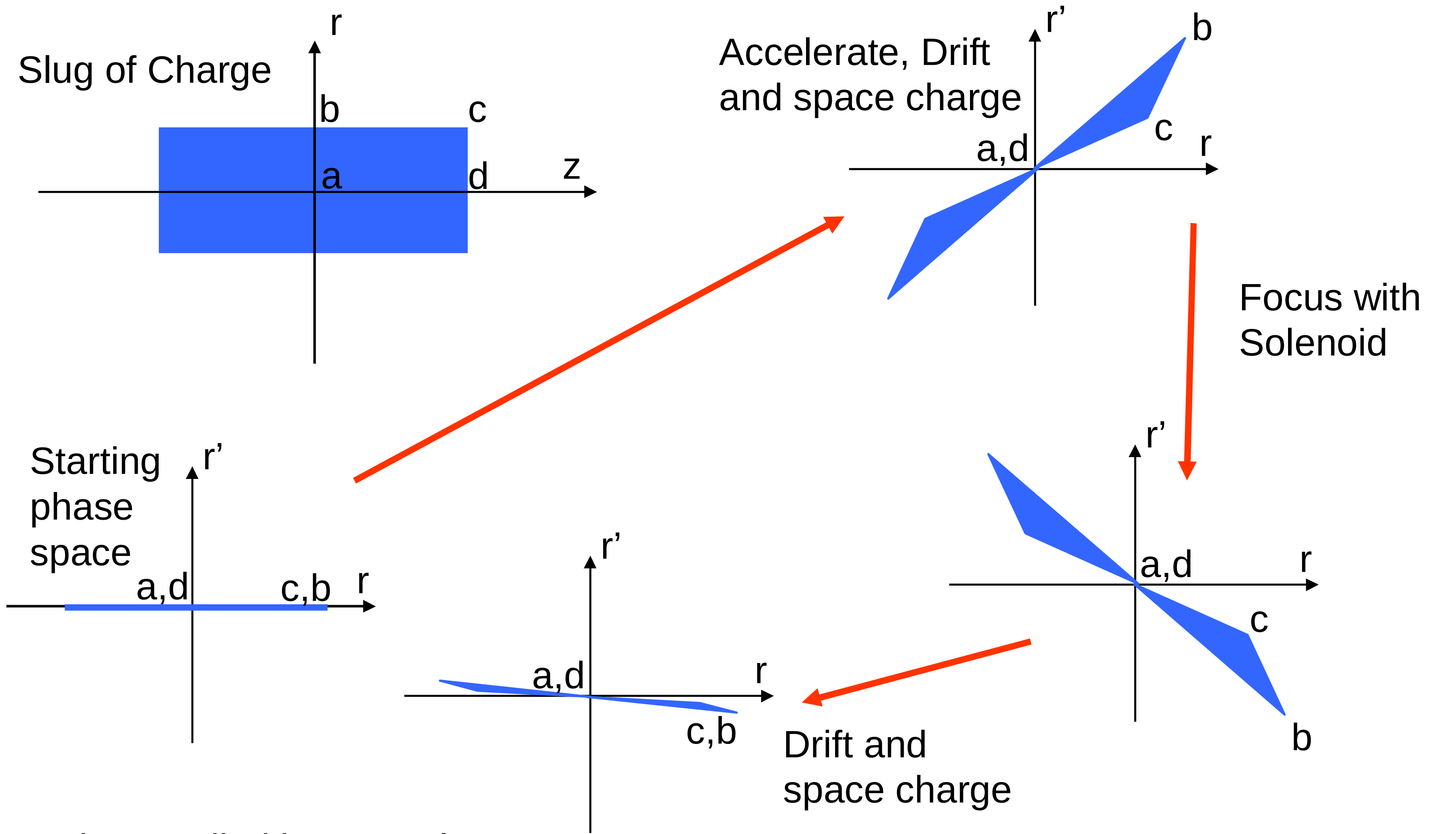
The beam wants to diverge for 2 reasons

- 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
    - $\nabla \cdot \vec{E} = 0 \quad \Rightarrow \quad \Delta r' \propto -r \, \partial E_z / \partial z$

The solenoid focuses the low energy beam radially

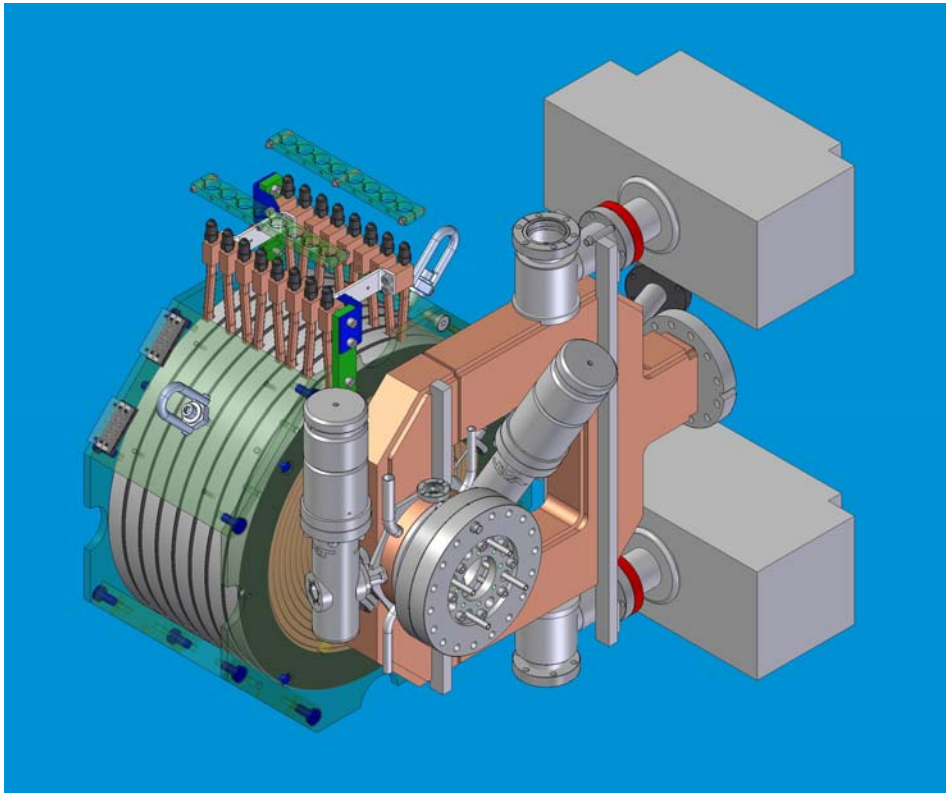
- Beam enters the end radial field of the solenoid and gets a transverse kick
- This new transverse motion crosses the longitudinal field and rotates inward or outward depending on the solenoid polarization
- The particle is then closer in (assuming focusing) when passing through the end radial field at the opposite end of the solenoid and since it is further in the kick is less.
- The result is a net transverse focusing

Space Charge Compensation

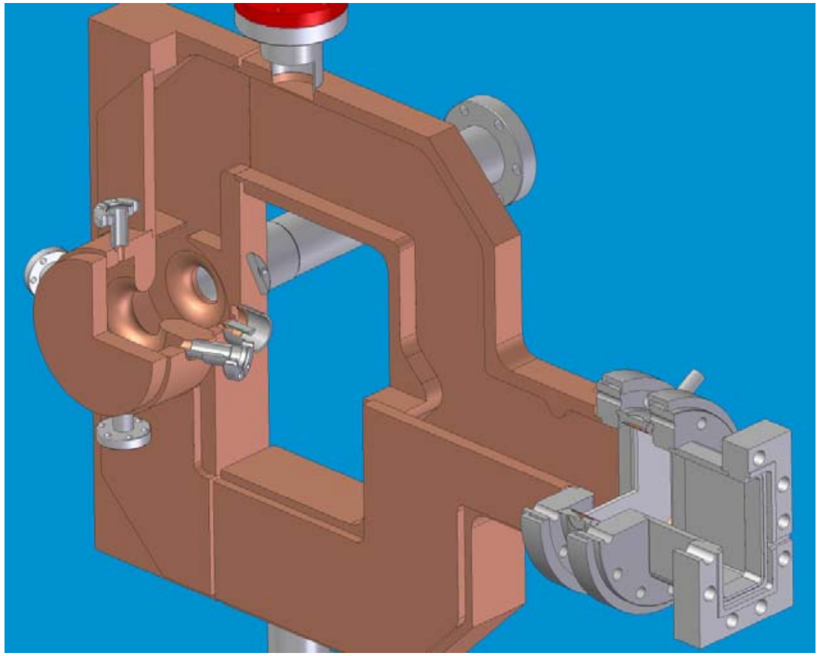


First Studied by B. Carlsen

PC Gun and Solenoid

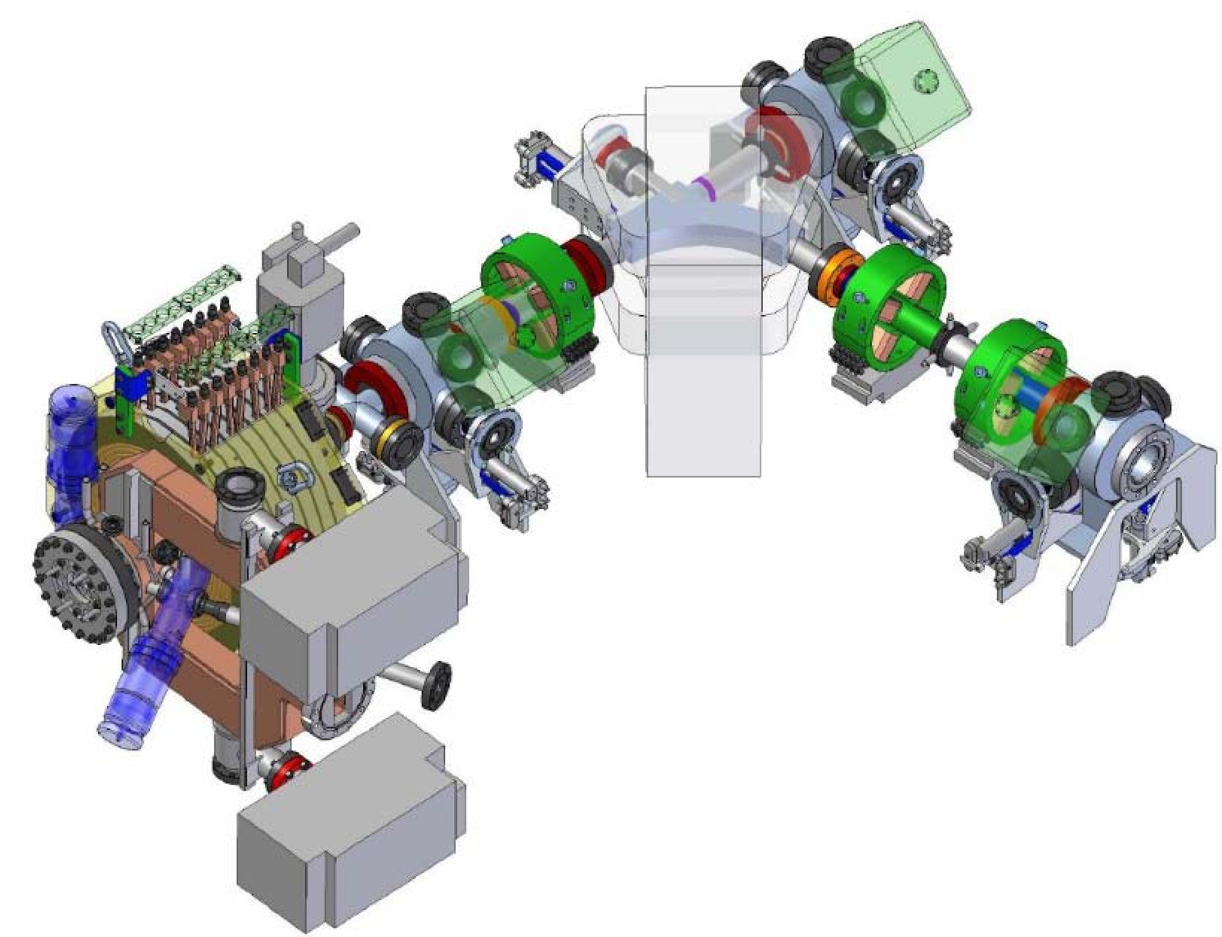


Complicated “Dual Feed” design used to partially symmetrize the RF field. Unsymmetric fields lead to emittance growth



Courtesy of E. Jongewaard

PC Gun Region in the LCLS



Acceleration Using Linear Accelerators

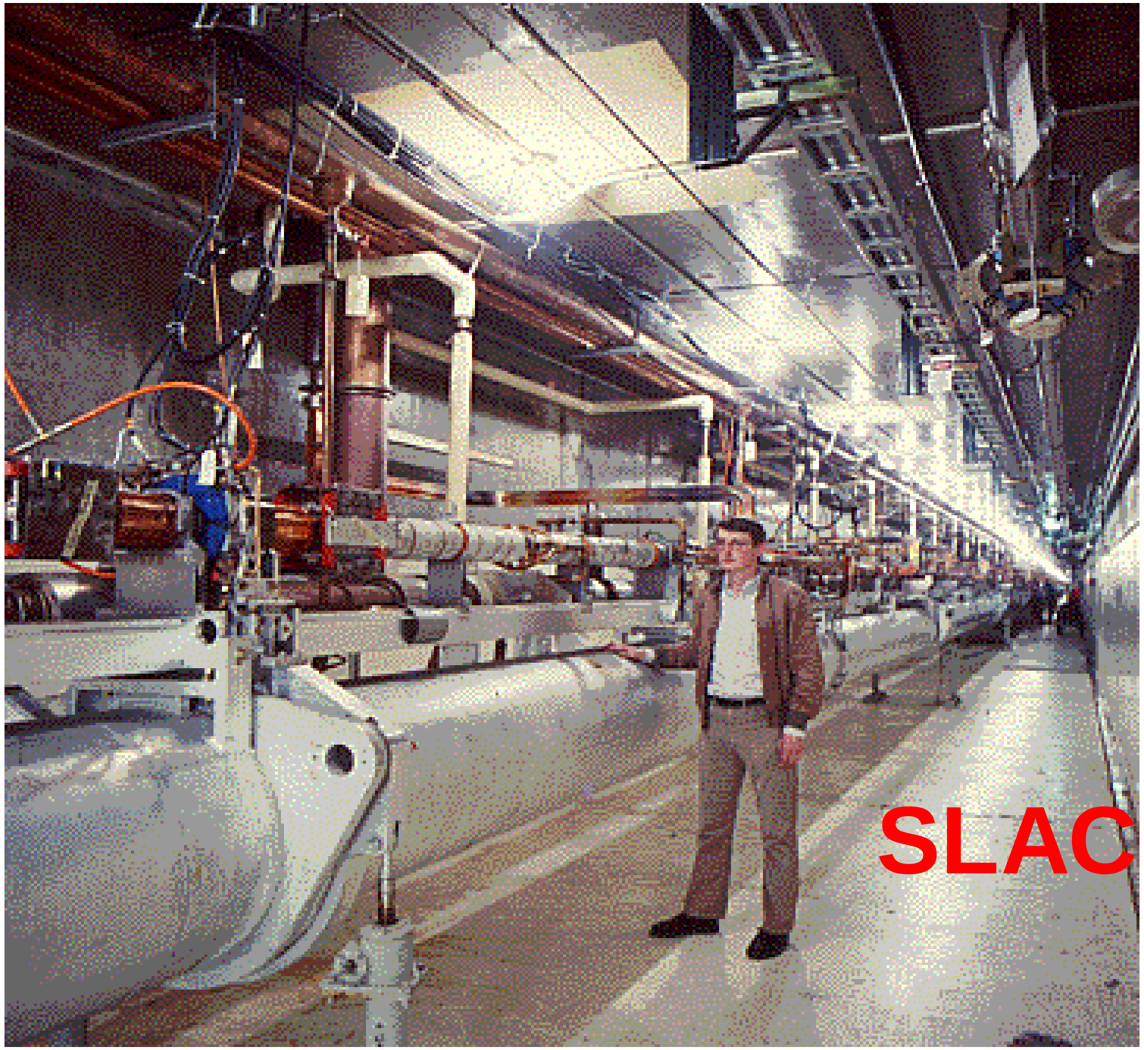
Accelerators come in a number of varieties

- Traveling wave $E(z,t) = E_0 \sin(kz - \omega t) \quad \omega/k = c$
  - A waveguide is load such that the phase velocity of the rf wave is c – the speed of light
- Standing wave $E(z,t) = E_0 \sin(kz)\sin(\omega t)$
  - The forward and backward traveling wave conspire to make a wave that is fixed in space but oscillates in time
- Normal Conducting
  - Typically operated in pulsed mode
  - Can achieve very high accelerating gradients
  - Limited in duty factor due to resistive wall heating
- Superconducting
  - Can be operated CW
  - Can be very efficient
  - Limited in accelerating gradient, but there is continual progress on this front
  - Complec

Typical frequencies

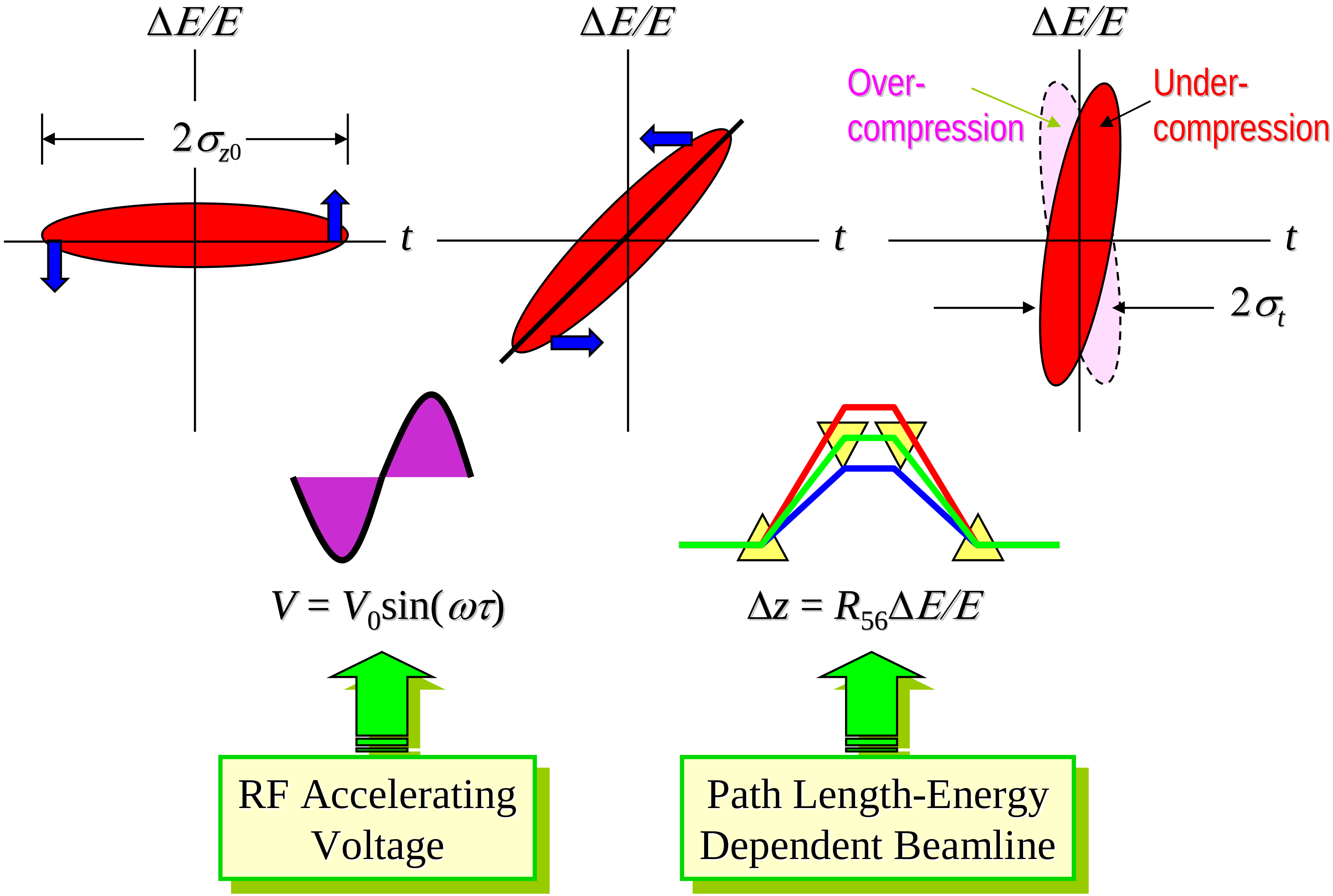
- 100 MHz → 9 GHz

A BIG Normal Conducting Linac



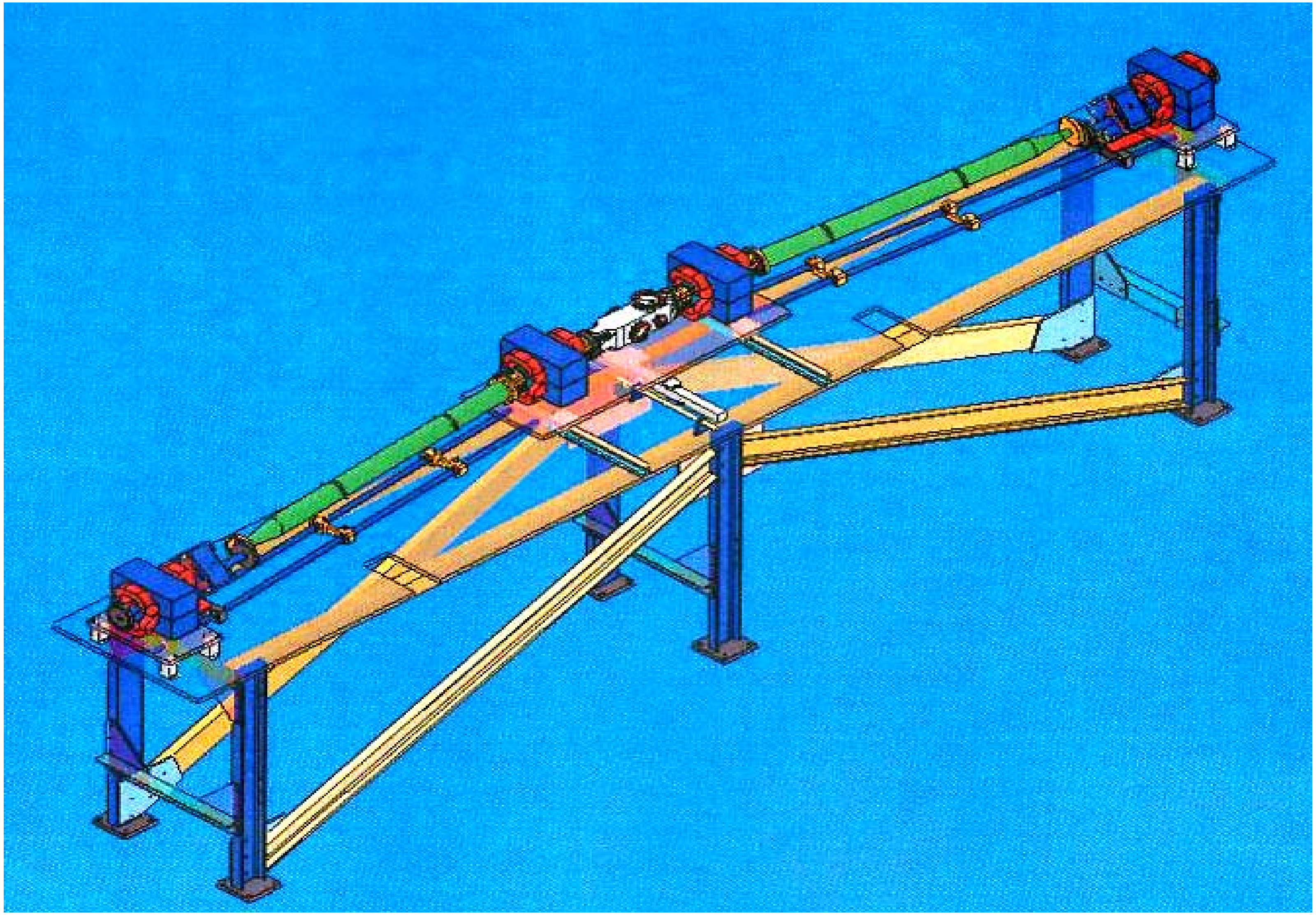
SLAC Linac

Electron Bunch Compression

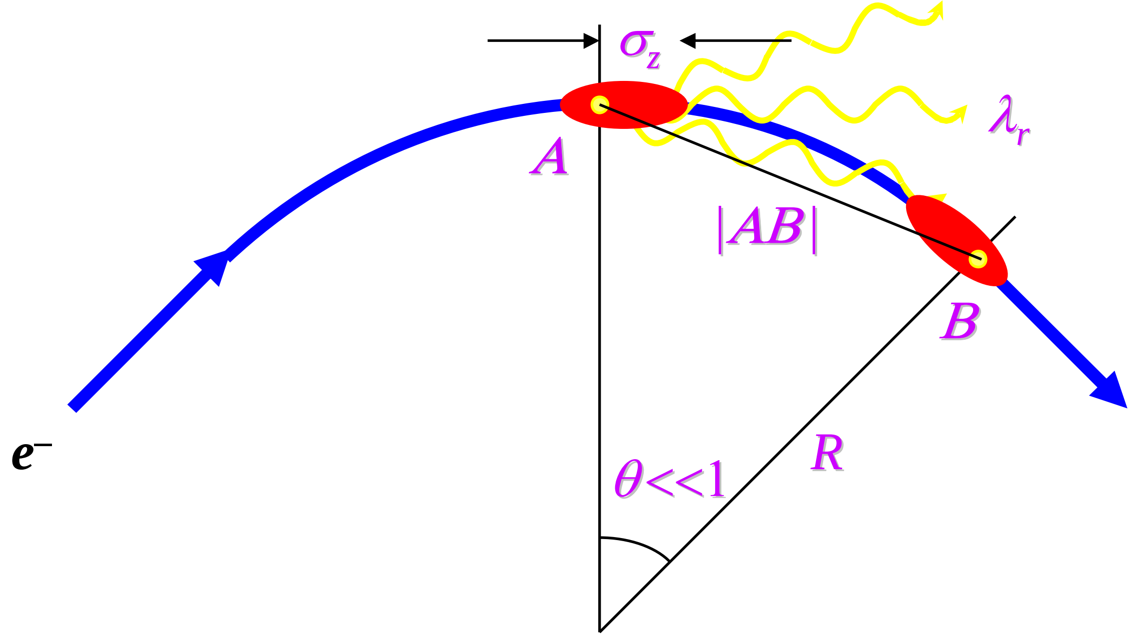


Drawings from P. Emma SLAC/LCLS

Bunch Compressor Design



Coherent Synchrotron Radiation (CSR)



Coherent radiation for: $\lambda_r >> \sigma_z$

...from Derbenev, et. al.

Free space radiation from bunch tail at point ***A*** overtakes bunch head, a distance *s* ahead of the source, at the point ***B*** which satisfies...

$$s = \text{arc}(AB) - |AB| = R\theta - 2R\sin(\theta/2) \approx R\theta^3/24$$

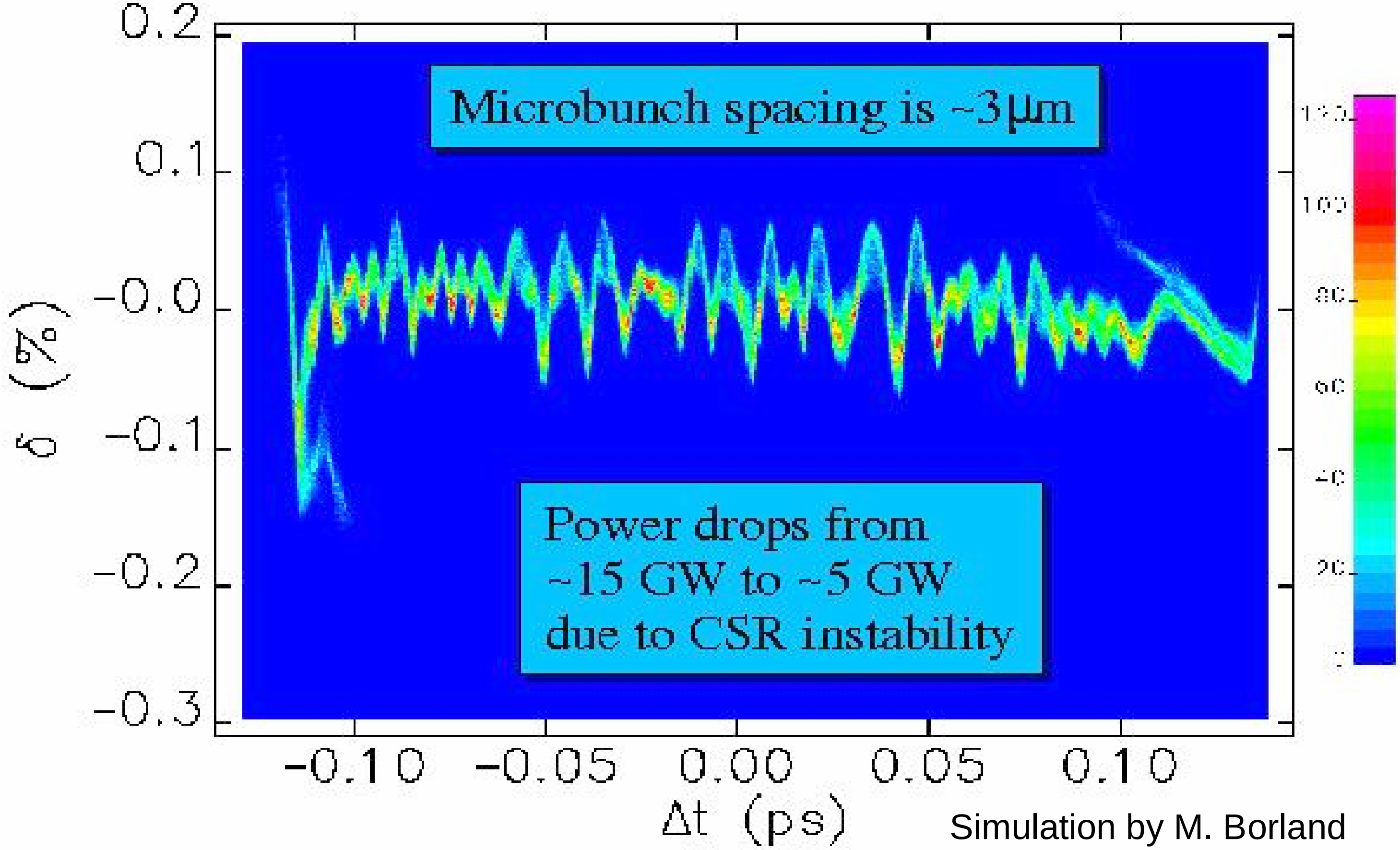
and for $s = \sigma_z$ (rms bunch length) the overtaking distance is...

$$L_0 \equiv |AB| \approx (24\sigma_z R^2)^{1/3}, \quad (\text{ LCLS: } L_0 \sim 1\text{ m})$$

Drawings from SLAC/LCLS

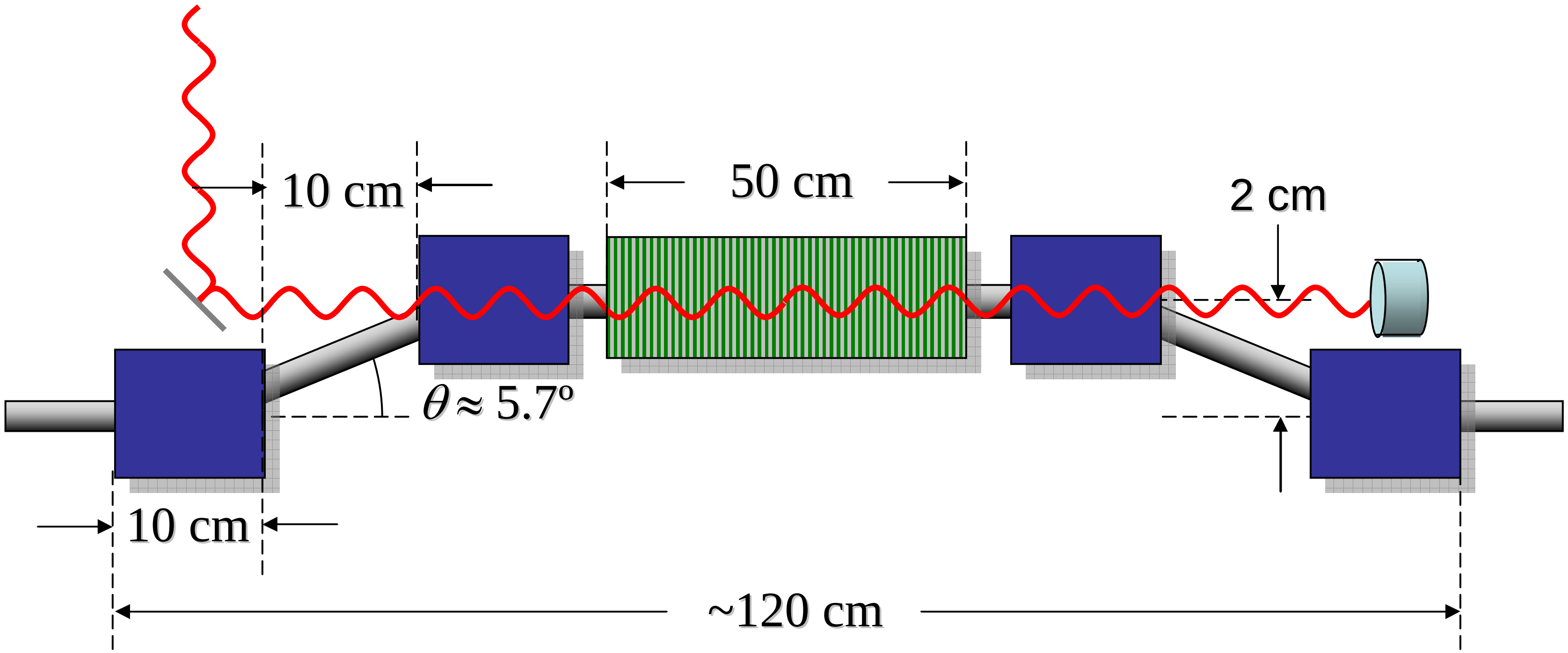
CSR Microbunching Instability

06Dec00 Design



Simulation by M. Borland

Laser Heater System



- Laser heater replaces SC wiggler to suppress beam instabilities
- Uses a small portion of the drive laser IR beam
- Cost and Schedule in Baseline

Slide compliments
of P. Emma

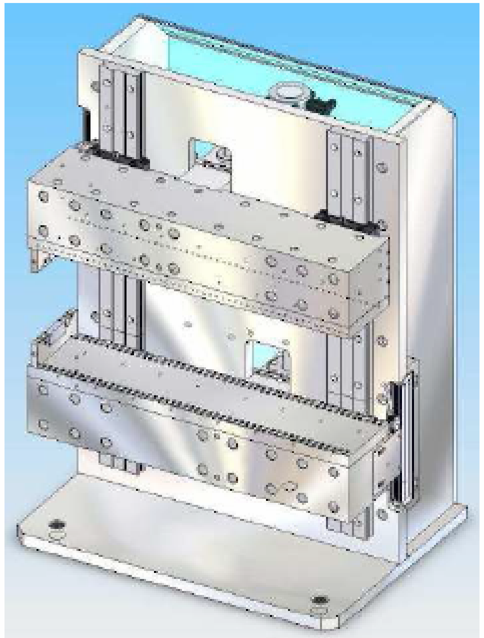
Undulator Construction

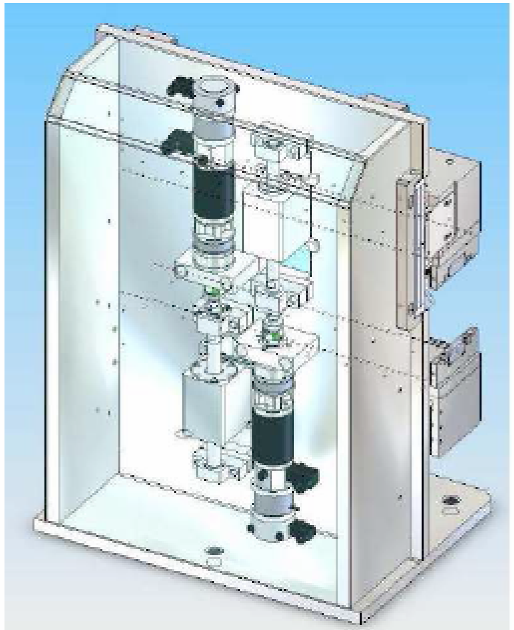
3 basic types

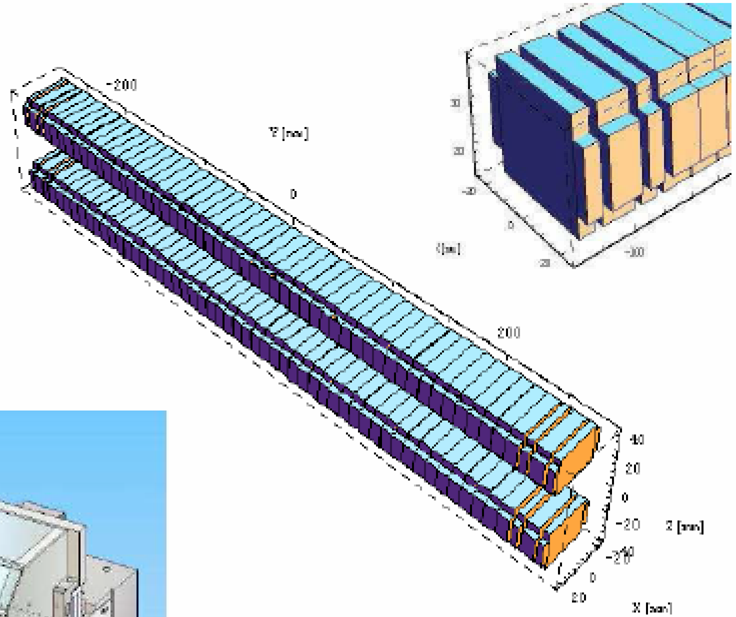
- Electromagnet
  - One uses electrical current and iron to shape the magnetic field
  - One controls the strength by varying the current in the conductor
  - This can be either normal conducting or superconducting
  - Issues
    - *Consumes lots of power*
    - *Complex*
    - *Difficult to measure and tune the superconducting variety*
      - » *Difficult to get probe in*
- Pure Permanent Magnet
  - Here one uses nothing but permanent magnet blocks configured to achieve the sinusoidal field
  - Issues
    - *Complex magnetic arrangement*
- Hybrid
  - Here one uses permanent magnets to power the field and high permeability poles such as those made of vanadium permendur to shape the magnetic field
  - Gap variation is used to control the field strength
  - Relatively simple
  - Most widely used today

Undulator Design

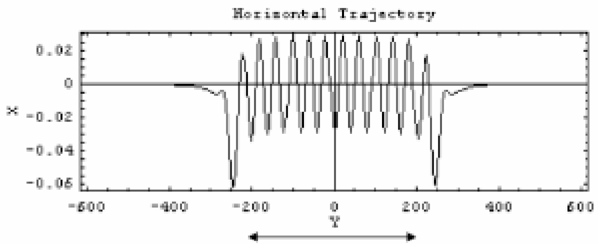
- Detailed magnetic design
- Magnetic blocks specifications
- Required mechanical tolerances
- Proposed mechanical system
- Control system requirements







Design validated by FEM analysis



~ 10 ÷ 11 "effective" periods

Minimum operational magnetic gap	24 mm
Maximum operational magnetic gap	32 mm
Full open gap (field switch off mode)	> 130 mm
Stay-clear aperture[5]	80 x 22 mm

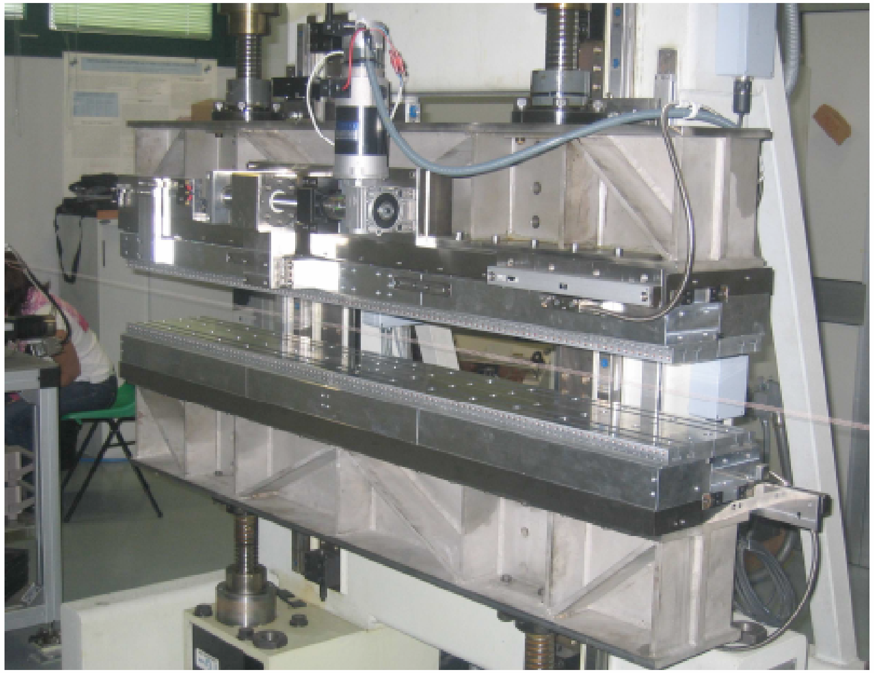
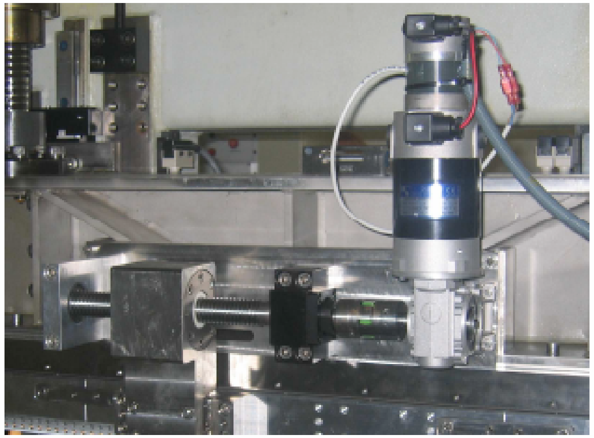
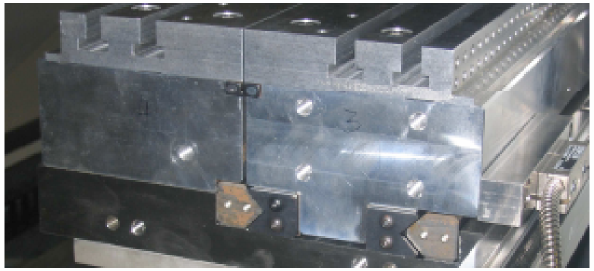
MAC meeting, 24/9/2007

B. Diviacco

Undulator Construction

EPU prototype

- FEL-2 radiator parameters (5 cm period, APPLE-II structure), L=1.5 m
- Use an existing support structure, retrofitted with new phase adjustment mechanics

Motivations: Evaluate quality of the purchased magnetized NdFeB blocks

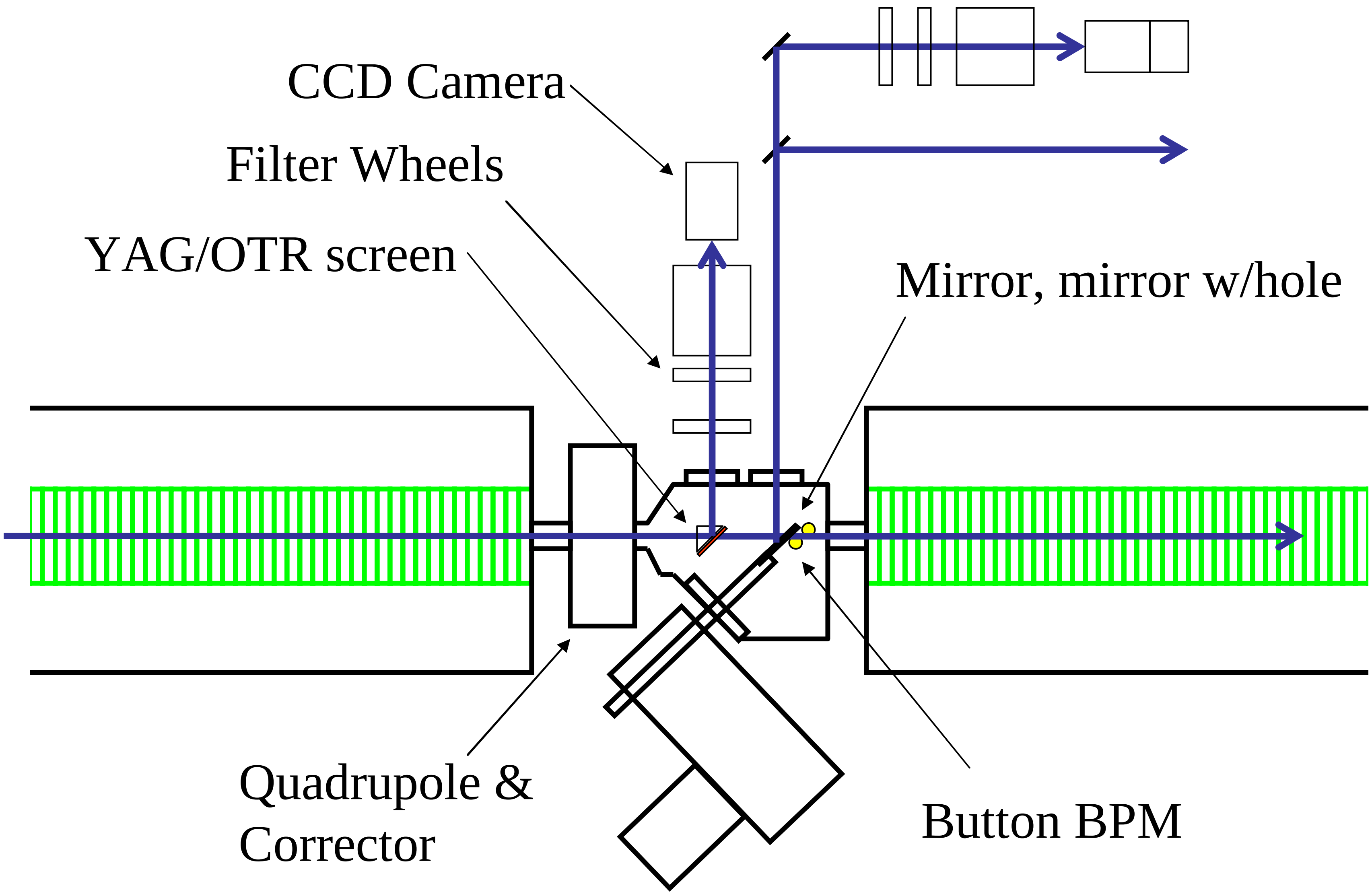
Address small-gap issues arising from magnetic in-homogeneities

Training of the new personnel hired for the mechanical design

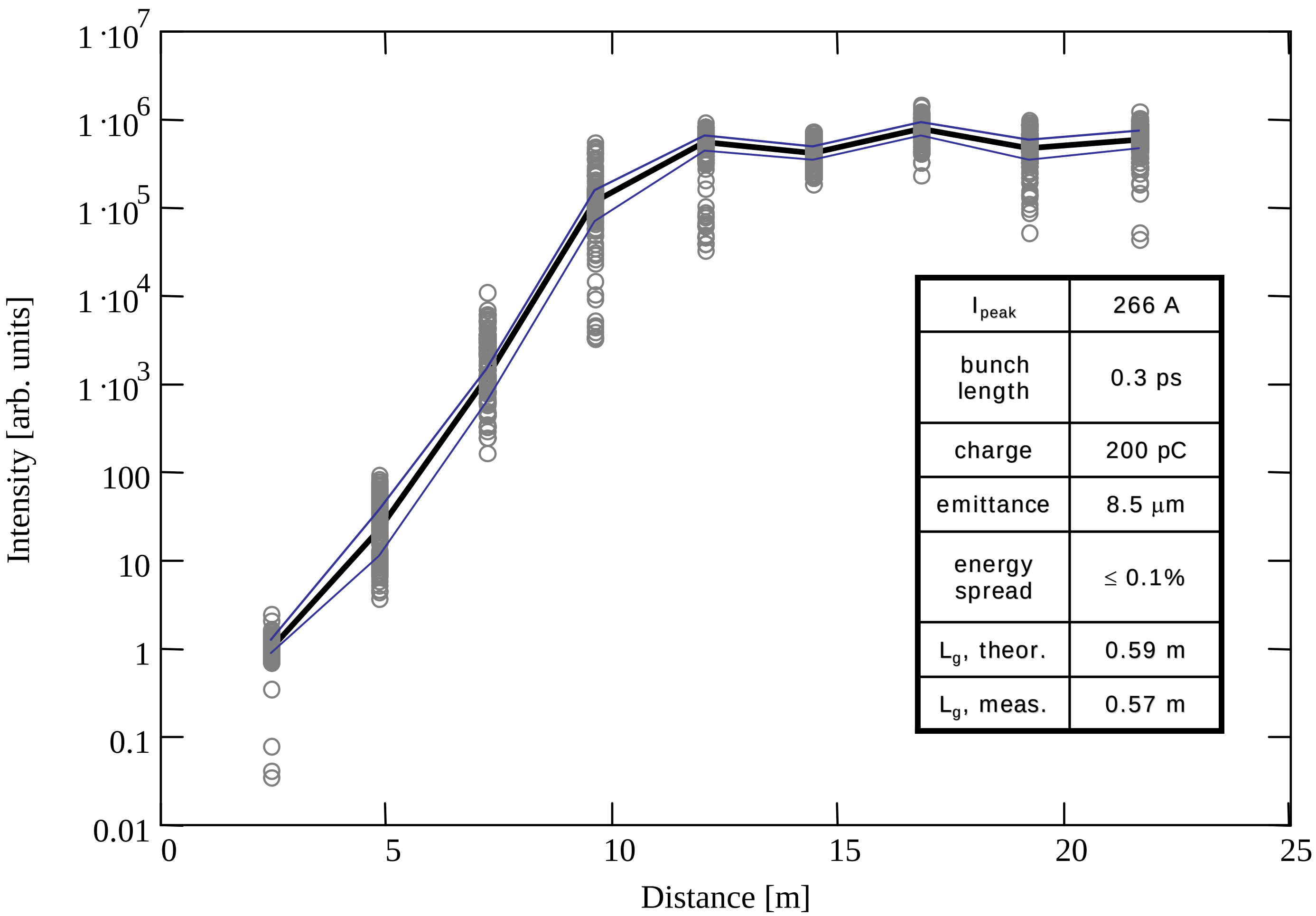
MAC meeting, 24/9/2007

B. Diviacco

Undulator Line Diagnostics

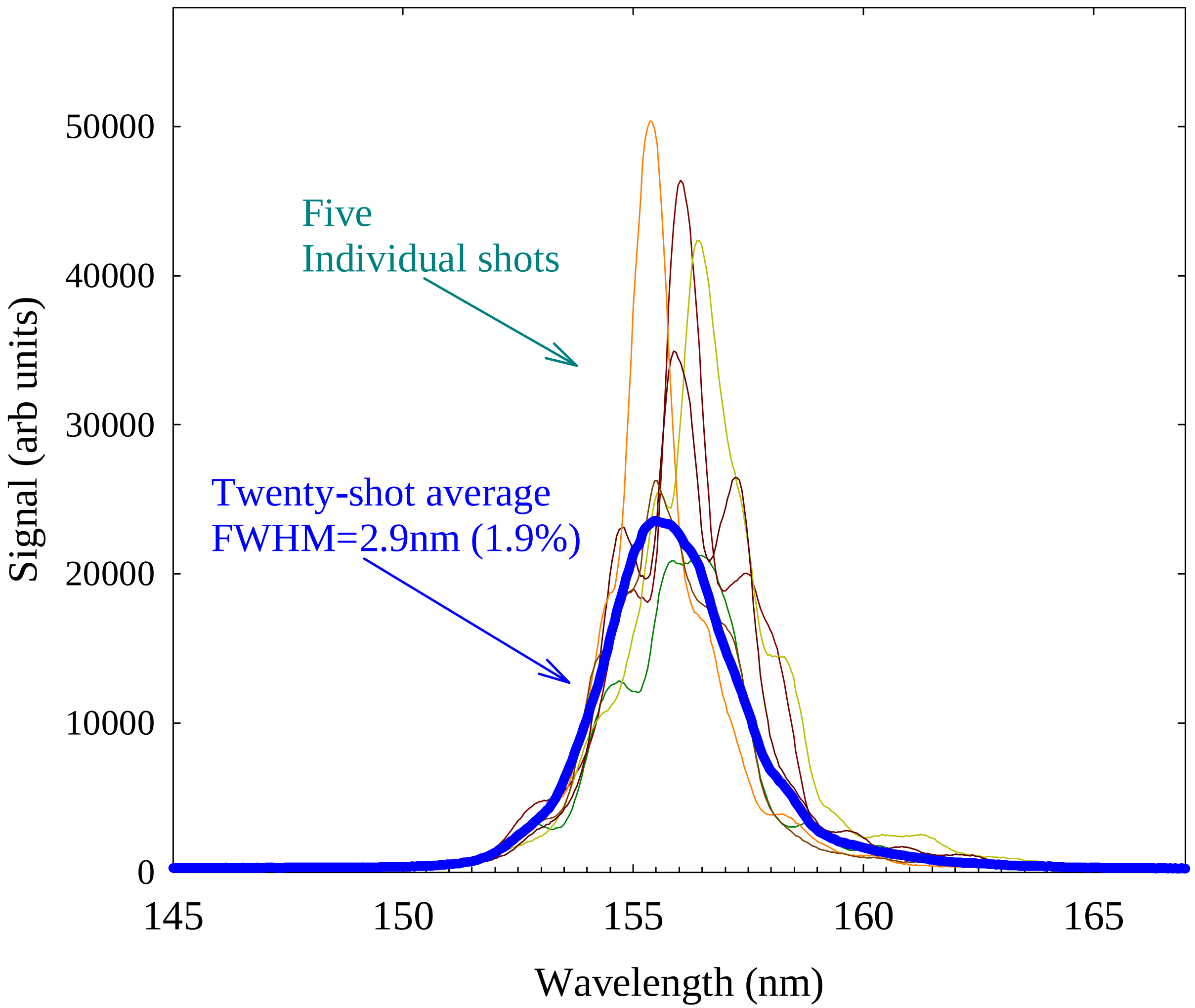


Intensity vs. Distance: Gain



I_{peak}	266 A
bunch length	0.3 ps
charge	200 pC
emittance	8.5 μm
energy spread	≤ 0.1%
L_g, theor.	0.59 m
L_g, meas.	0.57 m

Spectral Measurments: SASE



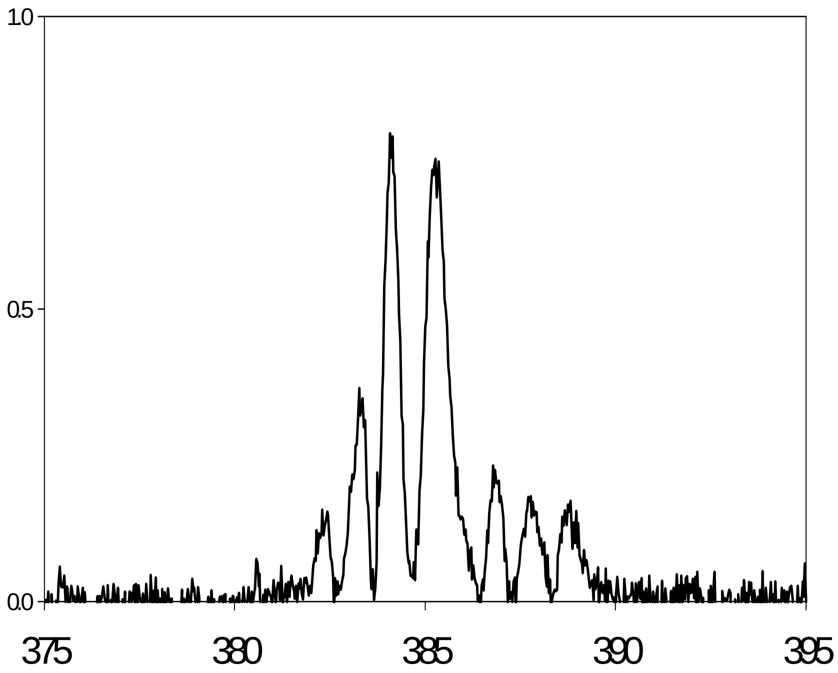
Pulse Length
~ 200 -> 300 fs FWHM

Energy/Pulse
~ 10 microJoules
(This should be near 100 and is under investigation)

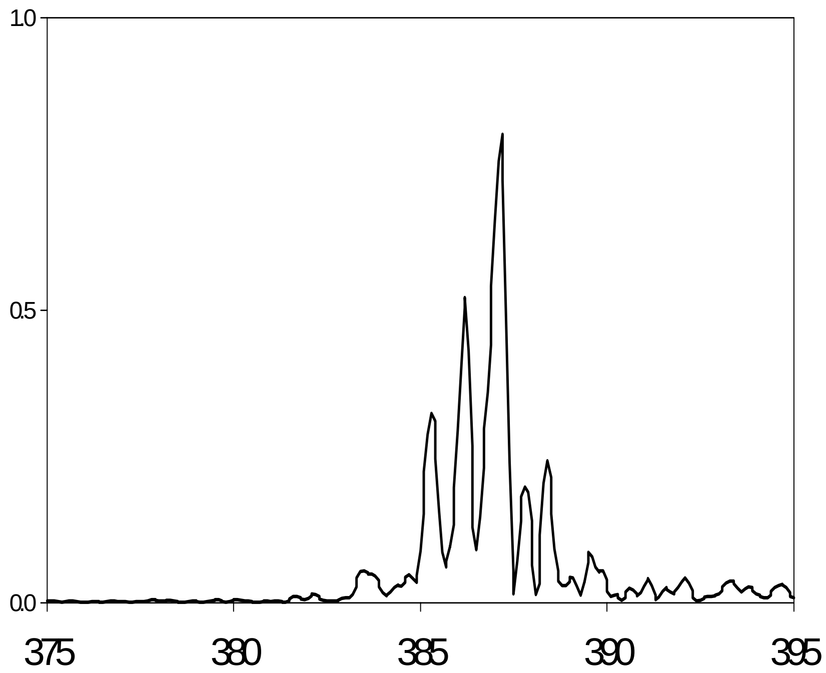
SASE Spectra – 385 nm

VLD2 (4.8 m)

Measurement



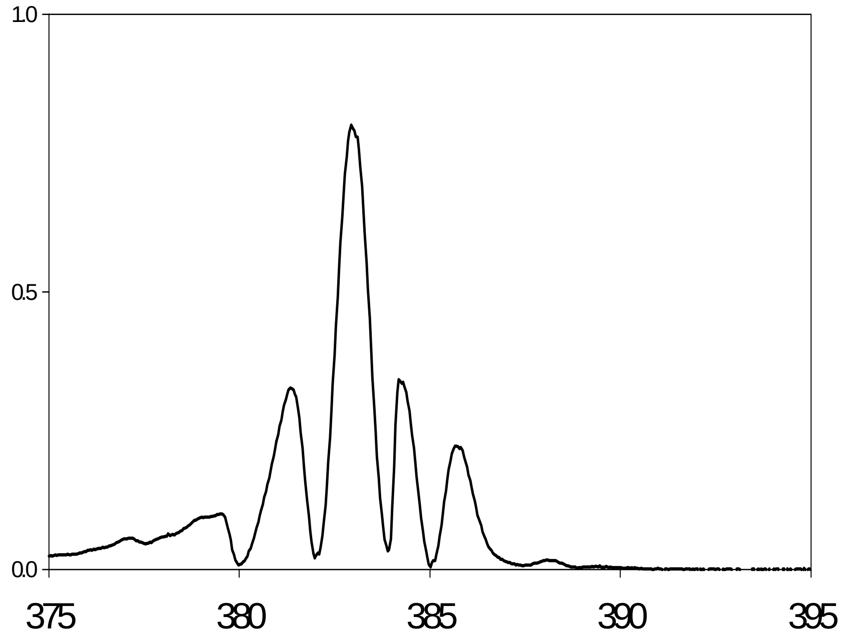
Simulation



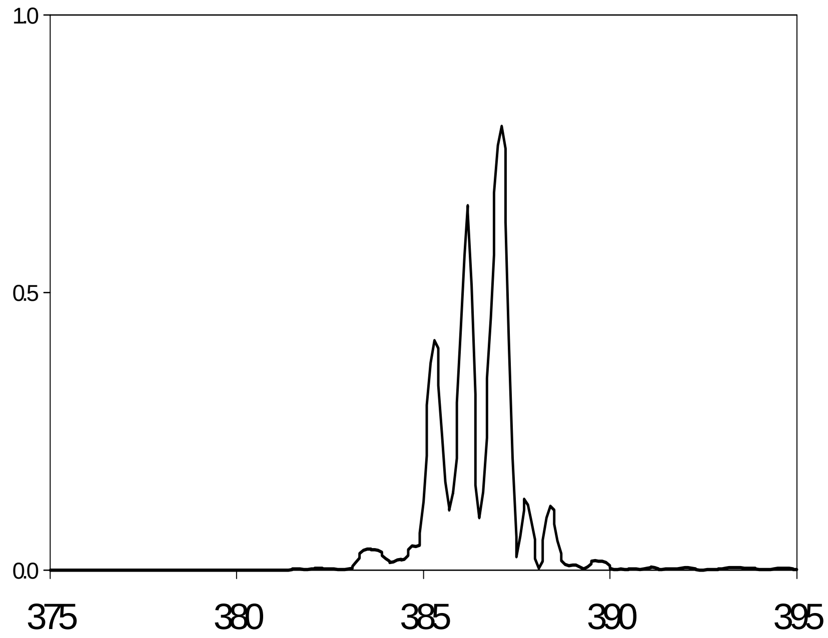
SASE Spectra – 385 nm

VLD3 (7.2 m)

Measurement



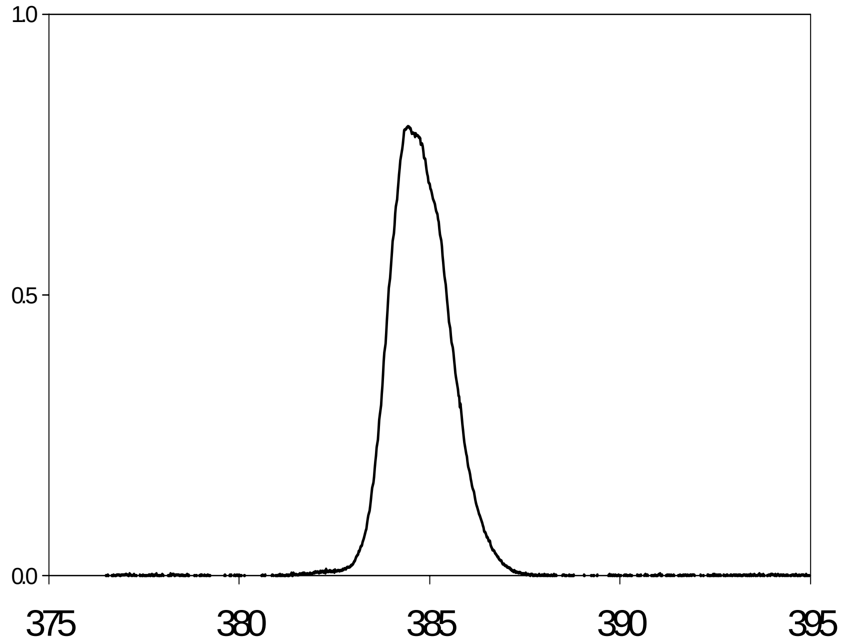
Simulation



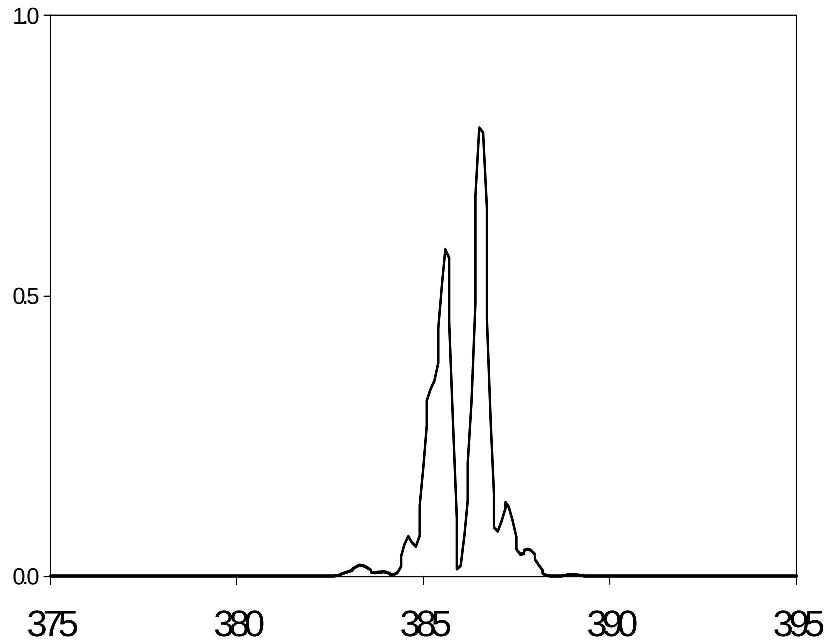
SASE Spectra – 385 nm

VLD5 (12 m)

Measurement



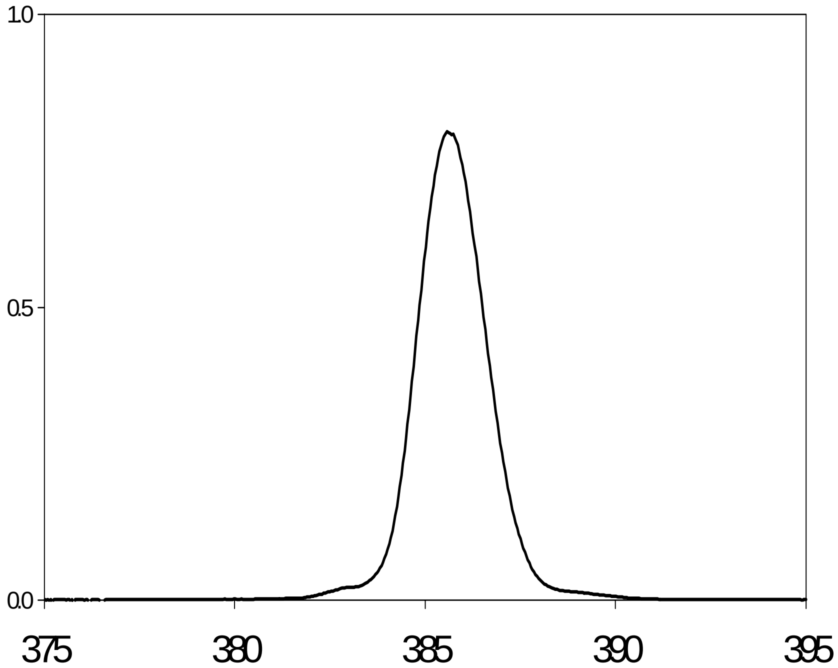
Simulation



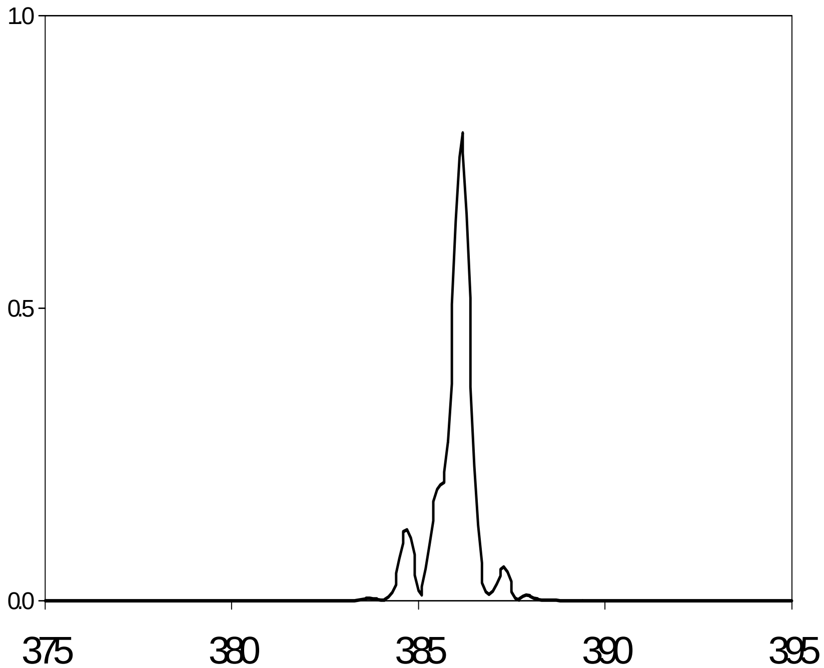
SASE Spectra – 385 nm

VLD7 (16.8 m)

Measurement



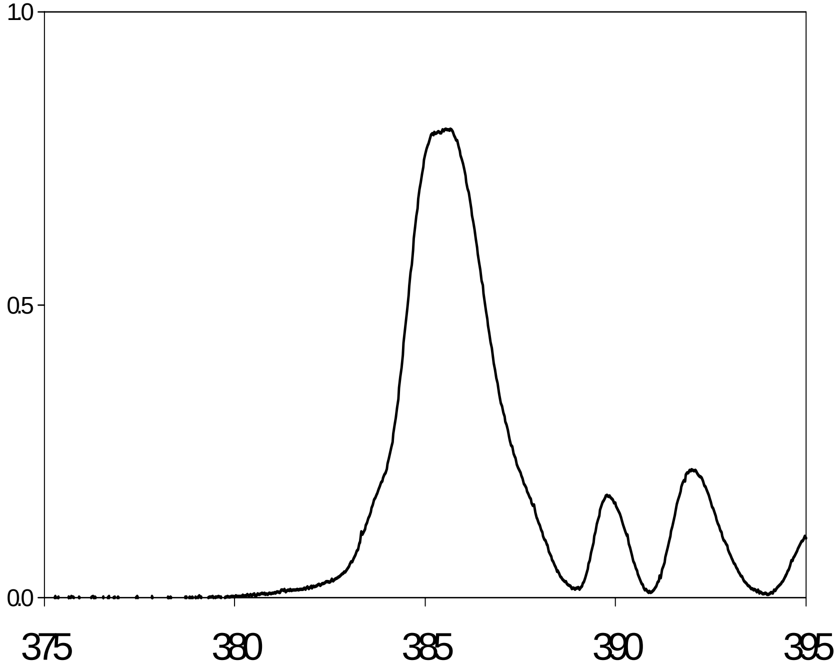
Simulation



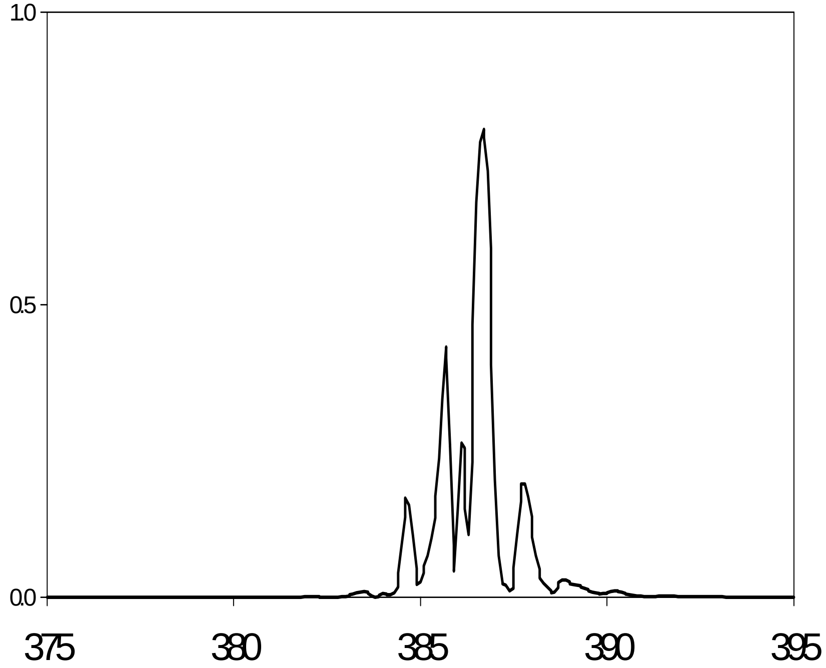
SASE Spectra – 385 nm

VLD9 (21.6 m)

Measurement



Simulation



SASE Spectra – 385 nm

Single shot spectra

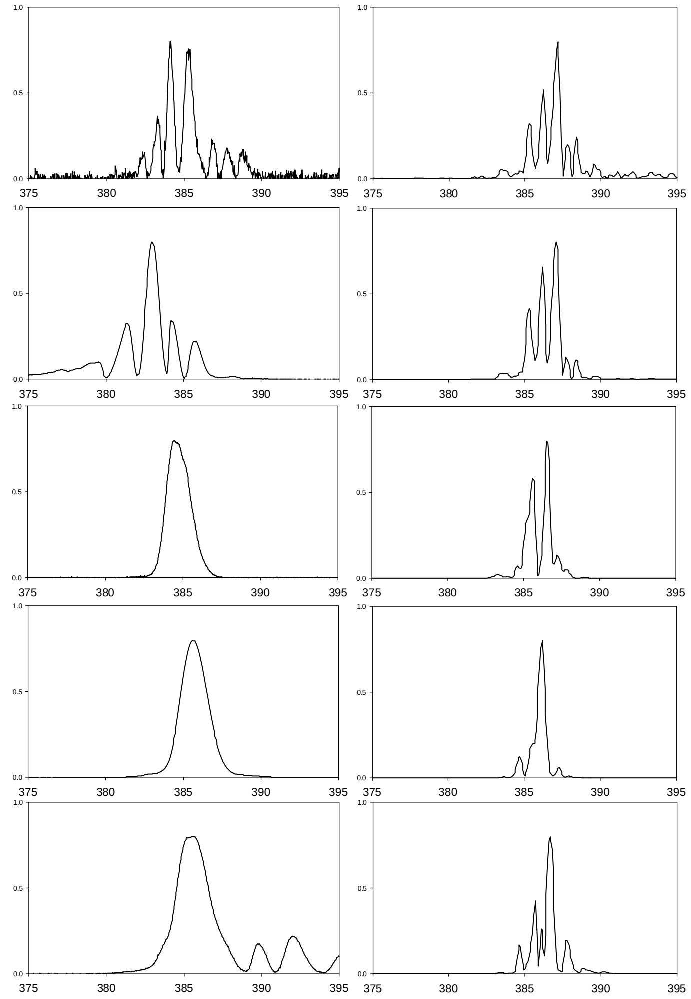
VLD2 (4.8 m)

VLD3 (7.2 m)

VLD5 (12 m)

VLD7 (16.8 m)

VLD9 (21.6 m)



Optical Transition Radiation

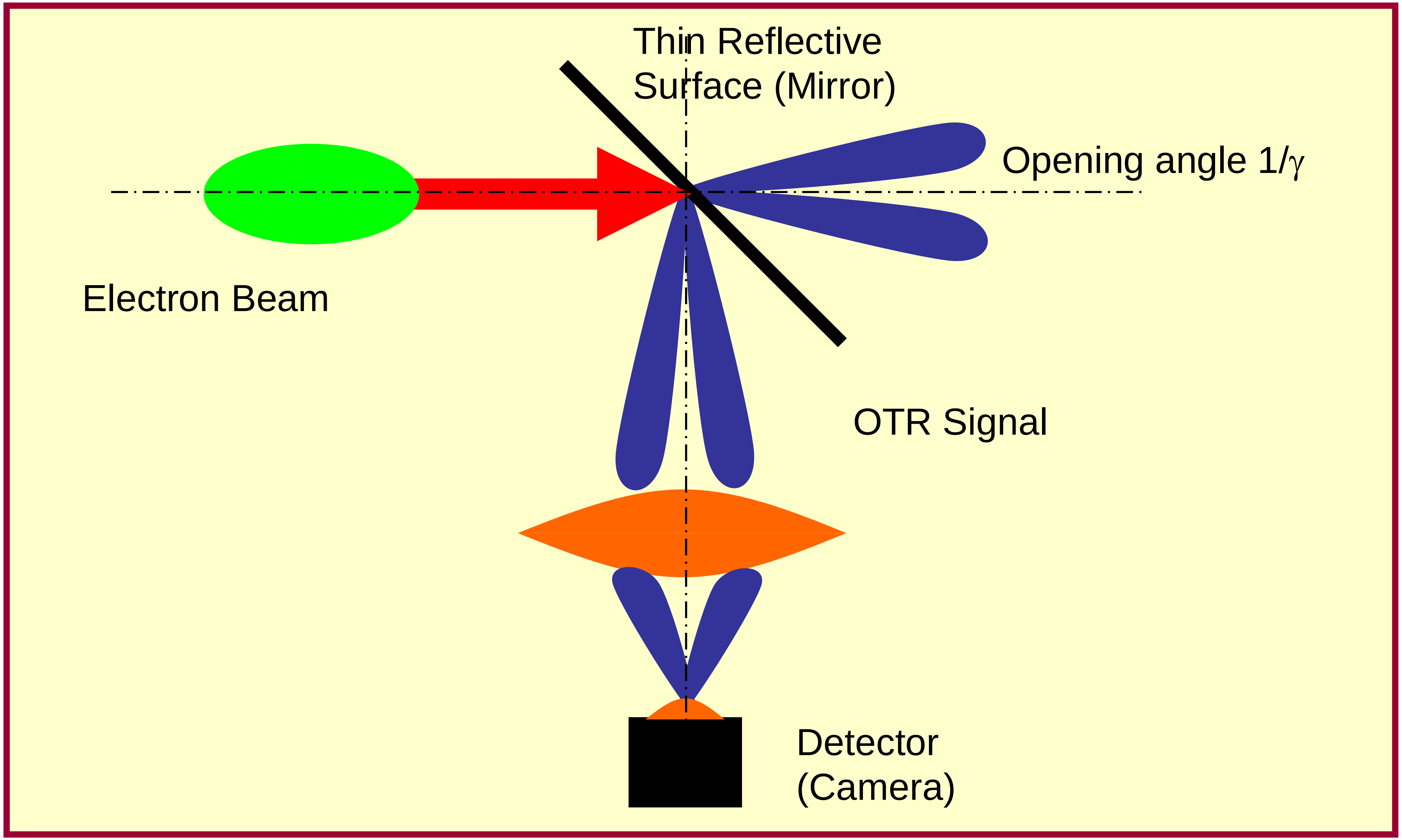
OTR

- When an electron crosses through a reflective surface OTR is generated
- OTR is basically a transient reflection of the electron
  - When the image charges in the reflective surface accelerate towards the electrons radiation is produced

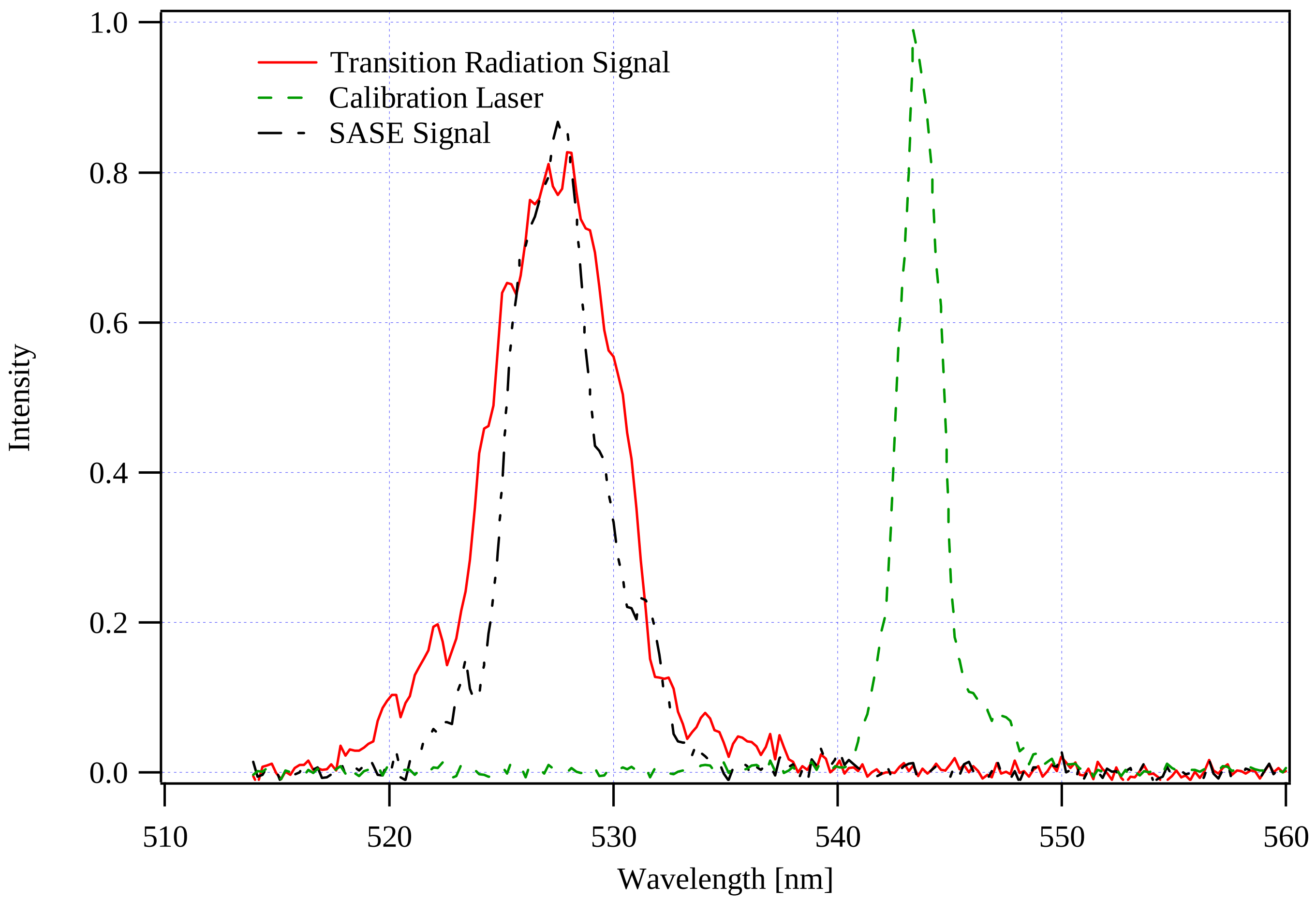
Coherent OTR

- If there is microbunching within the electron bunch and this microbunching has a distinct period then coherent OTR can be generated at the wavelength of the microbunching
  - This provides a unique way of validating that the bunch is lasing and the FEL is performing as designed

Optical Transition Radiation



Proof of Microbunching



Summary

To Build a Free-Electron Laser

- Source of High Quality Electrons
- Acceleration Sufficient to Achieve the Wavelength Desired
- Additional Beam Manipulation Systems
- Undulators
- Diagnostics, Controls Systems, etc.

Why?

- FELs can provide a laser-like source (transversely and longitudinally) that are infinitely tunable down to x-ray wavelengths and have peak intensities many, many order magnitude available from any other existing source.

Sincrotrone Trieste

- Currently building a seeded FEL system that when operational will provide a unique light source capable of wavelengths from 100 nm down to 10 nm and perhaps even lower.