Short Pulse Capabilities of the Linac Coherent Light Source

- LCLS Description
  - Facility
  - Performance Goals
- Short Pulses
  - Compression
  - Selective Deflection
  - Chirp-pulse self seeding
  - Spoiling
  - Heating, 800nm bunching

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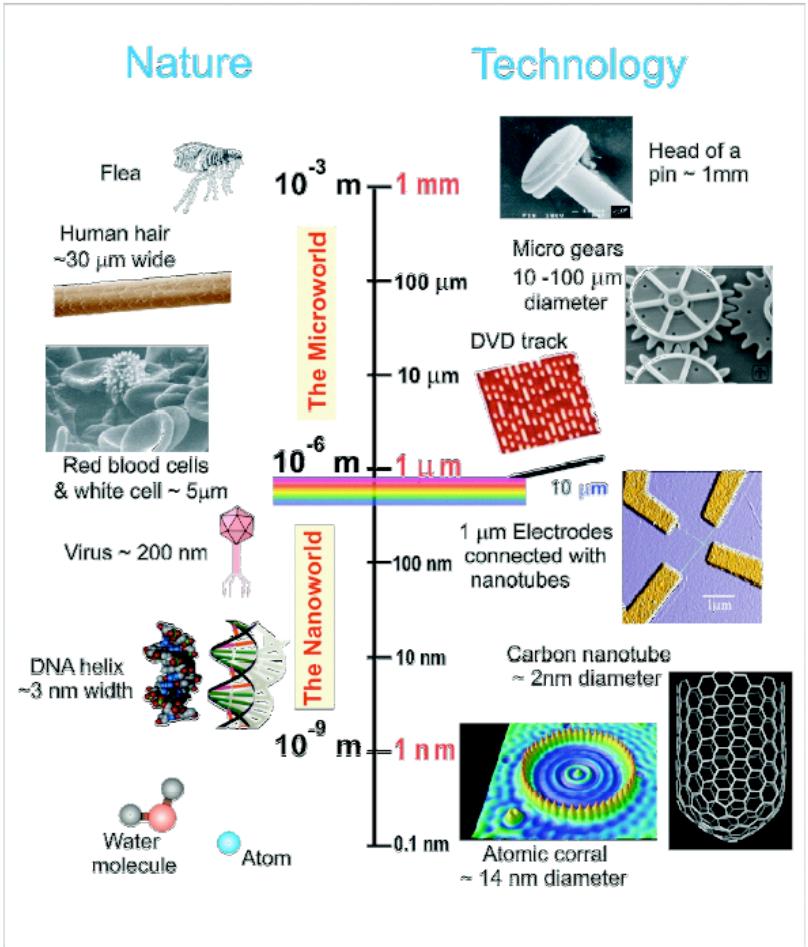
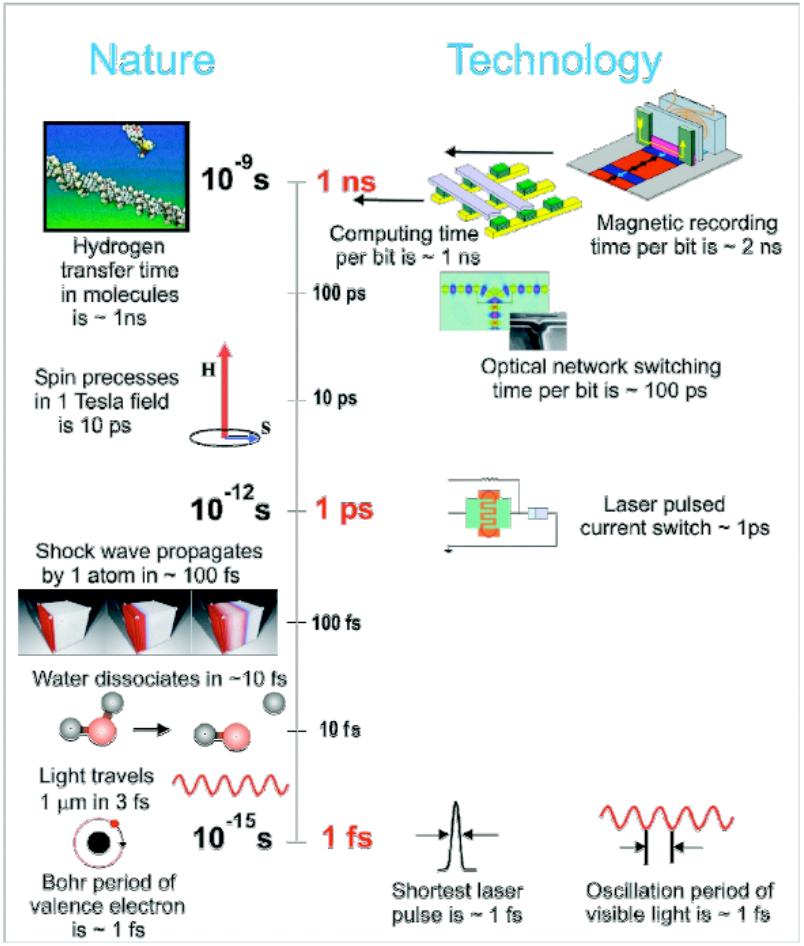
The World's First Hard X-ray Laser

Ultra-Small



Ultra-Fast



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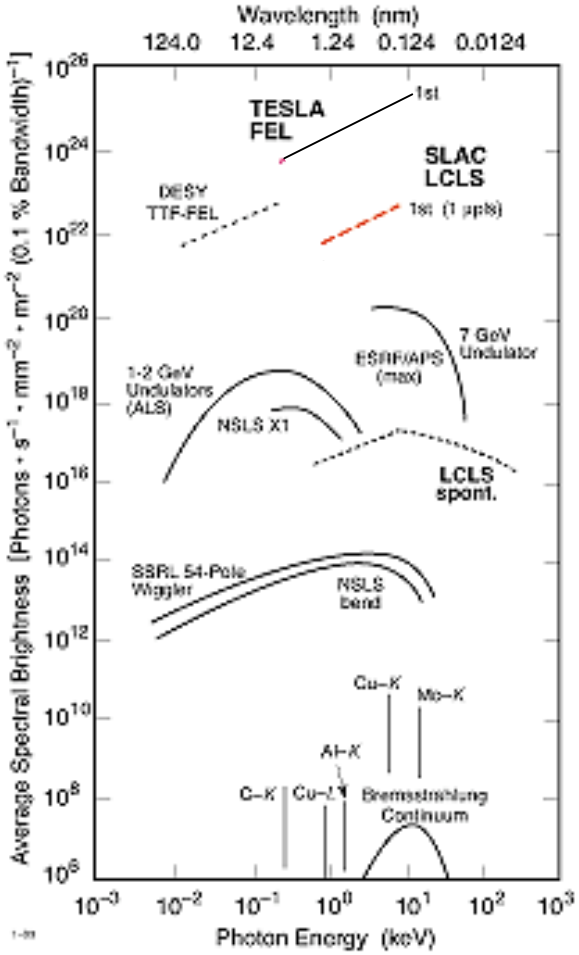
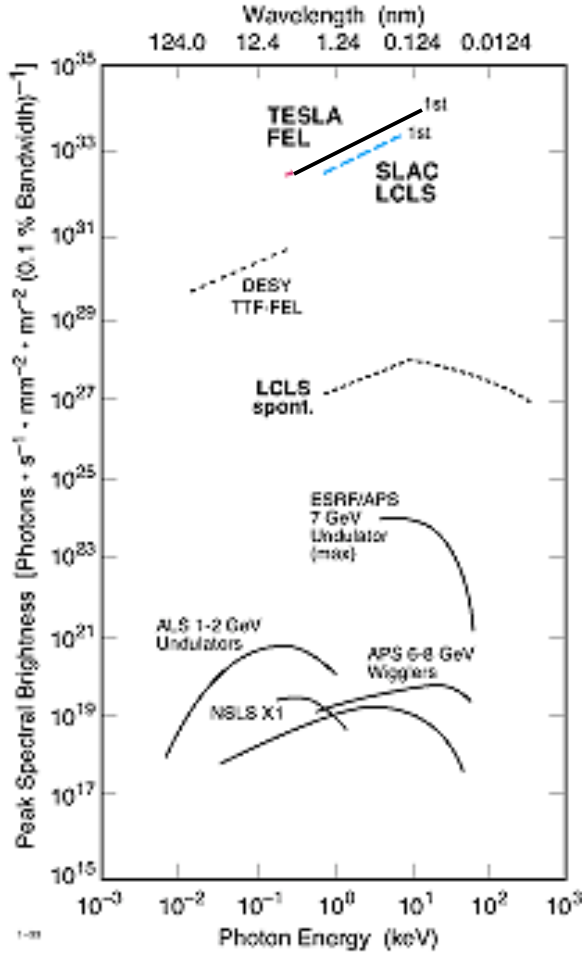
Capabilities

Spectral coverage: 0.15-1.5 nm





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Capabilities

Spectral coverage: 0.15-1.5 nm

To 0.5 Å in 3rd harmonic

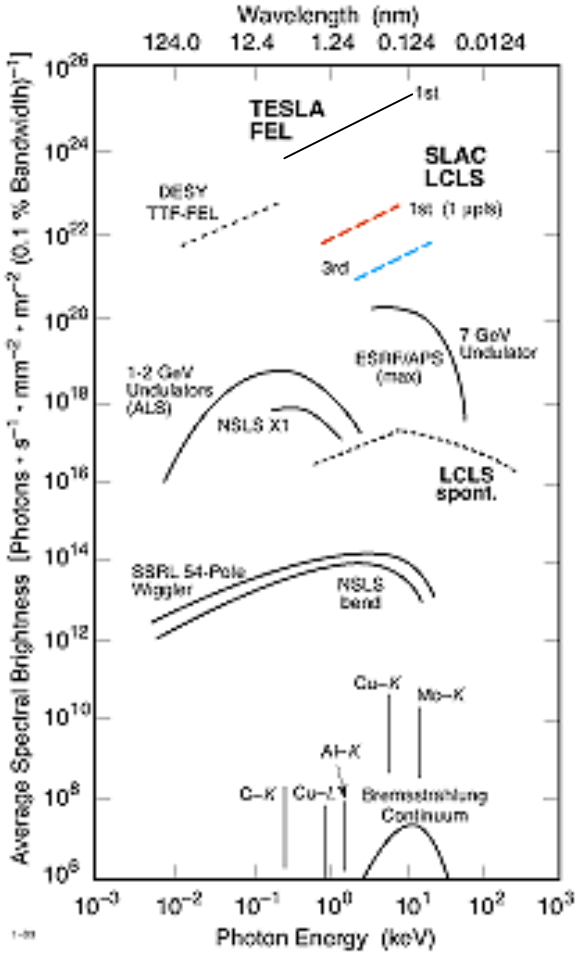
Peak Brightness: 10^{33}

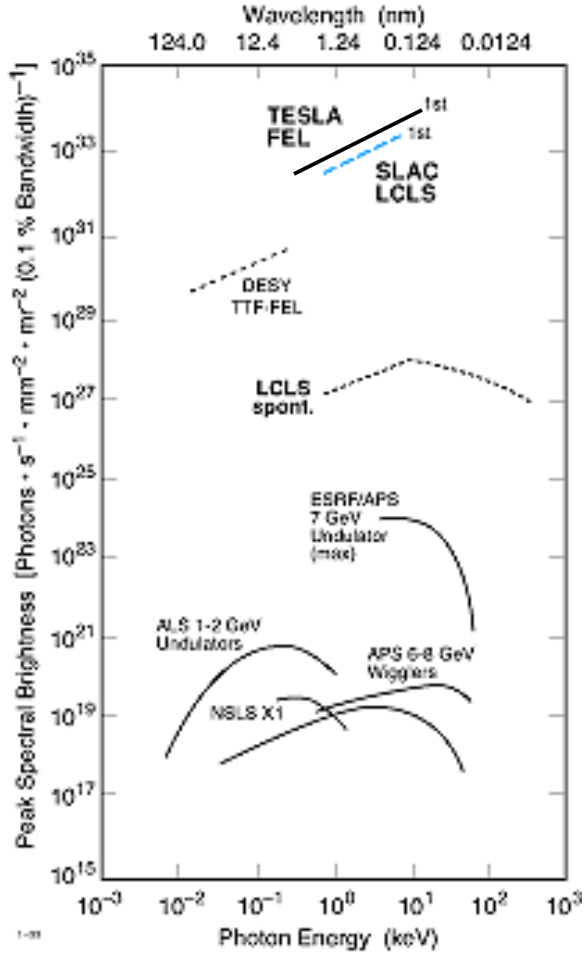
Photons/pulse: 10^{12}

Average Brightness: 3 x 10^{22}

Pulse duration: <230 fs

Pulse repetition rate: 120 Hz





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Capabilities

Spectral coverage: 0.15-1.5 nm

To 0.5 Å in 3rd harmonic

Peak Brightness: 10^{33}

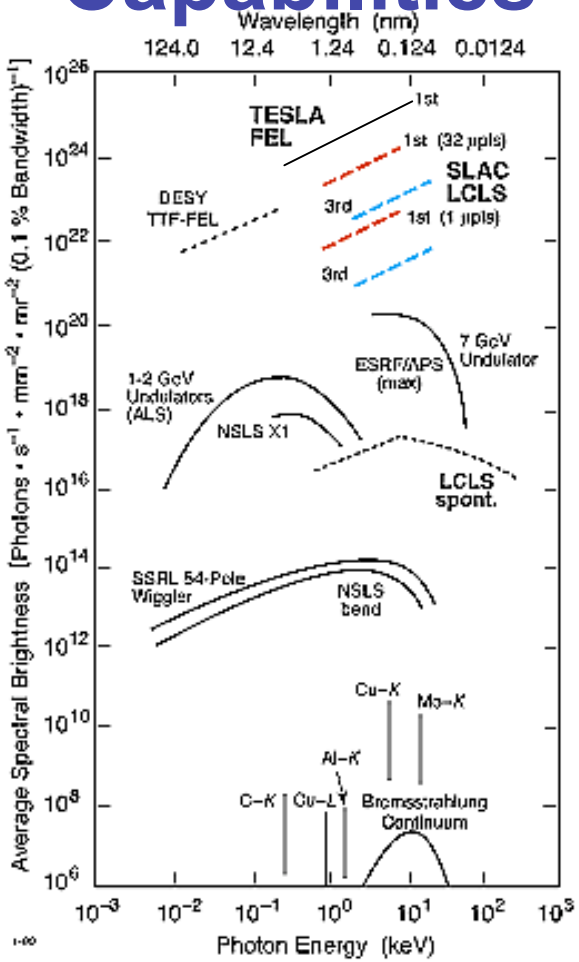
Photons/pulse: 10^{12}

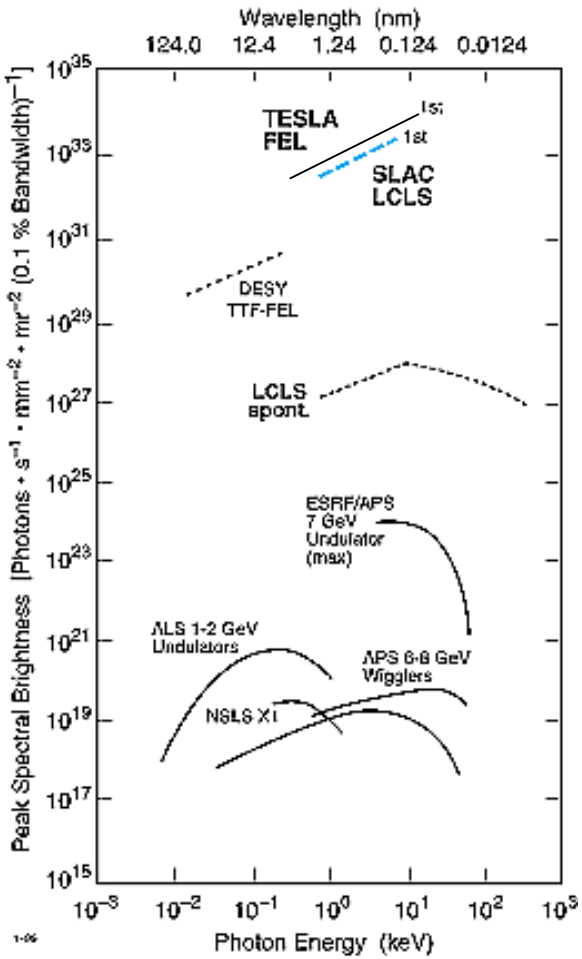
Average Brightness: 3 x 10^{22}

Pulse duration: <230 fs

Pulse repetition rate: 120 Hz

Upgrade – more bunches/pulse





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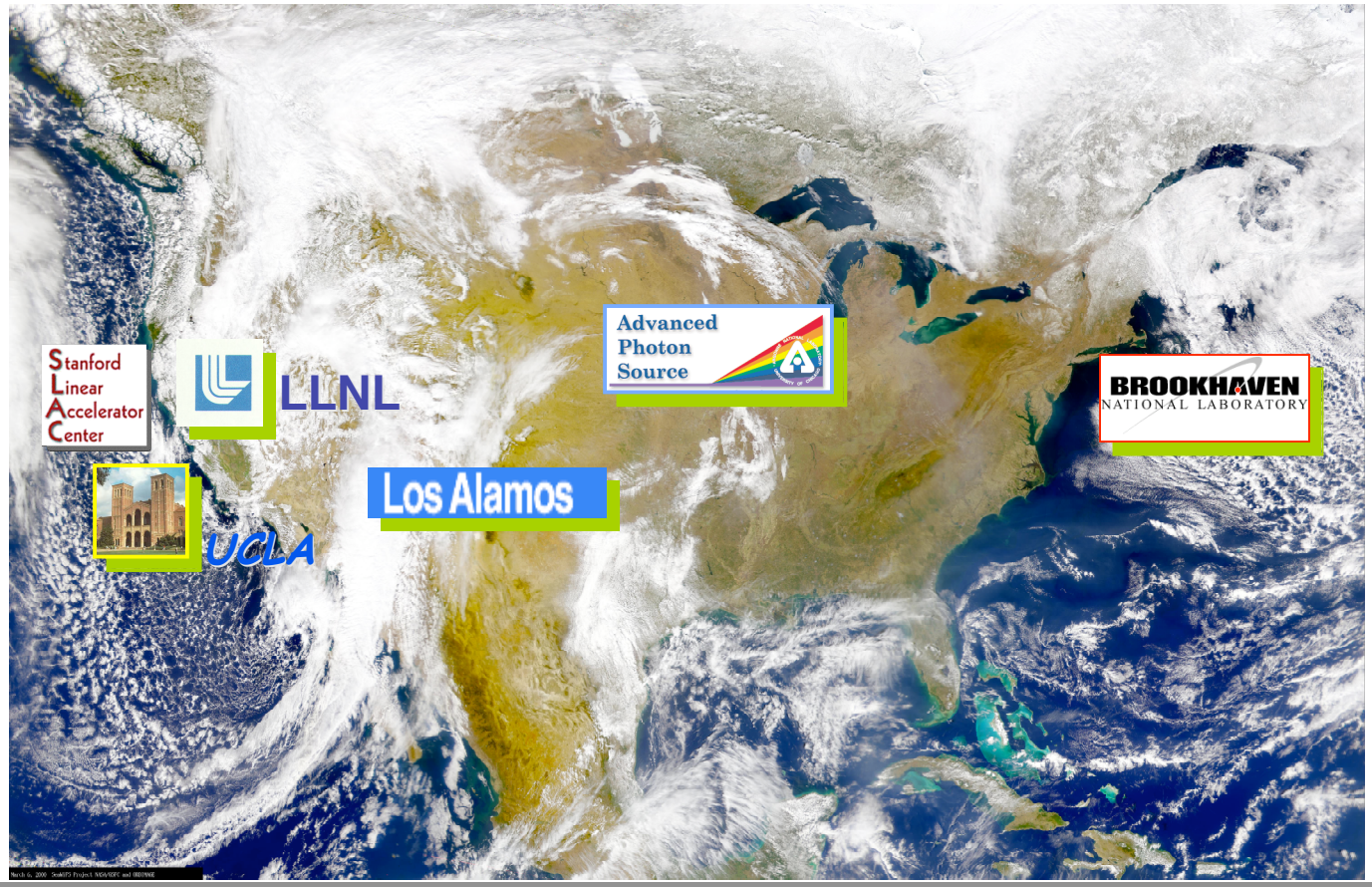
LCLS R&D Collaboration

FEL Theory, FEL Experiments, Accelerator R&D, Gun Development, Undulator R&D



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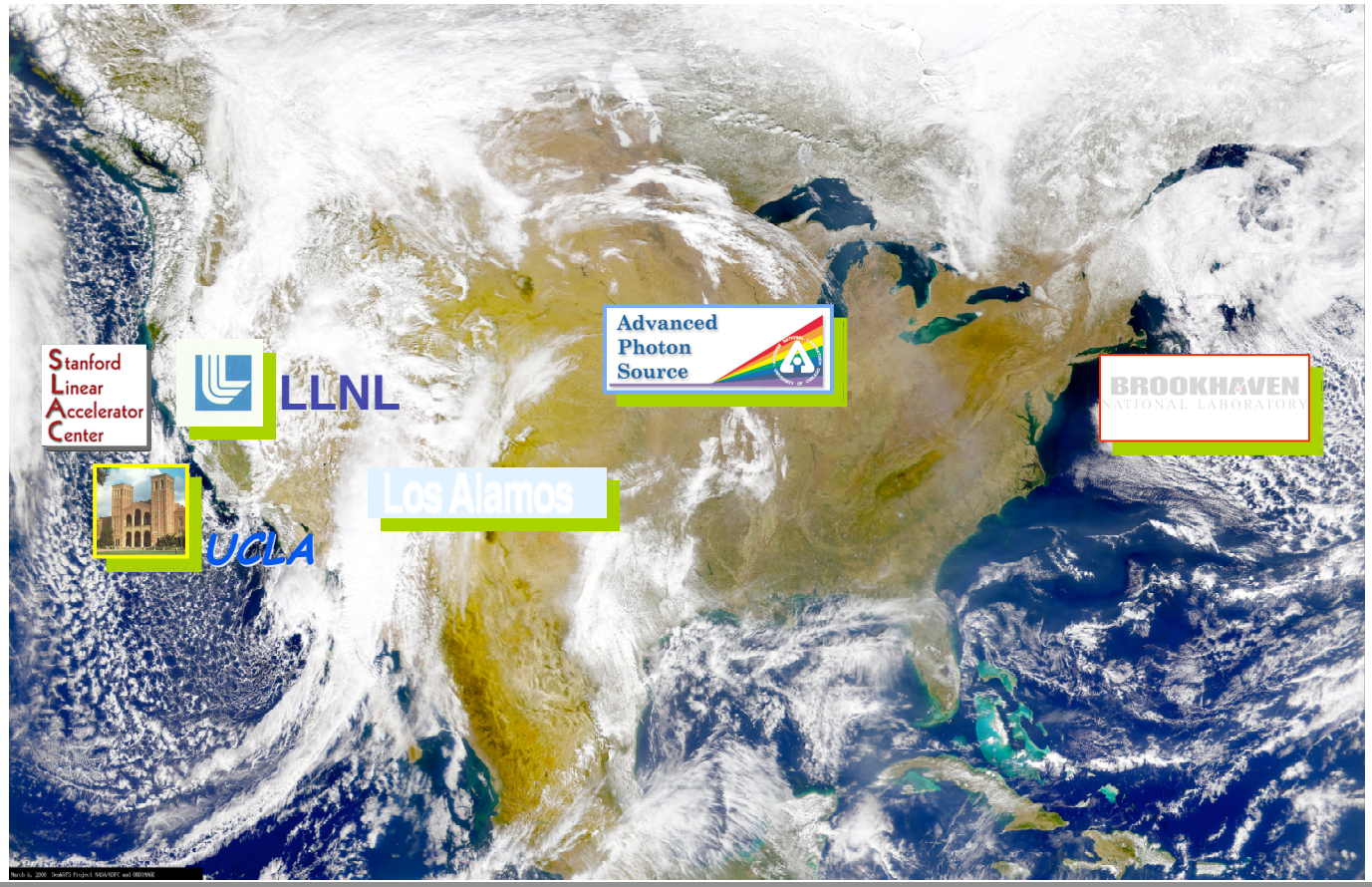
LCLS Construction Collaboration

Project Management Responsibilities Delegated to Partner Labs



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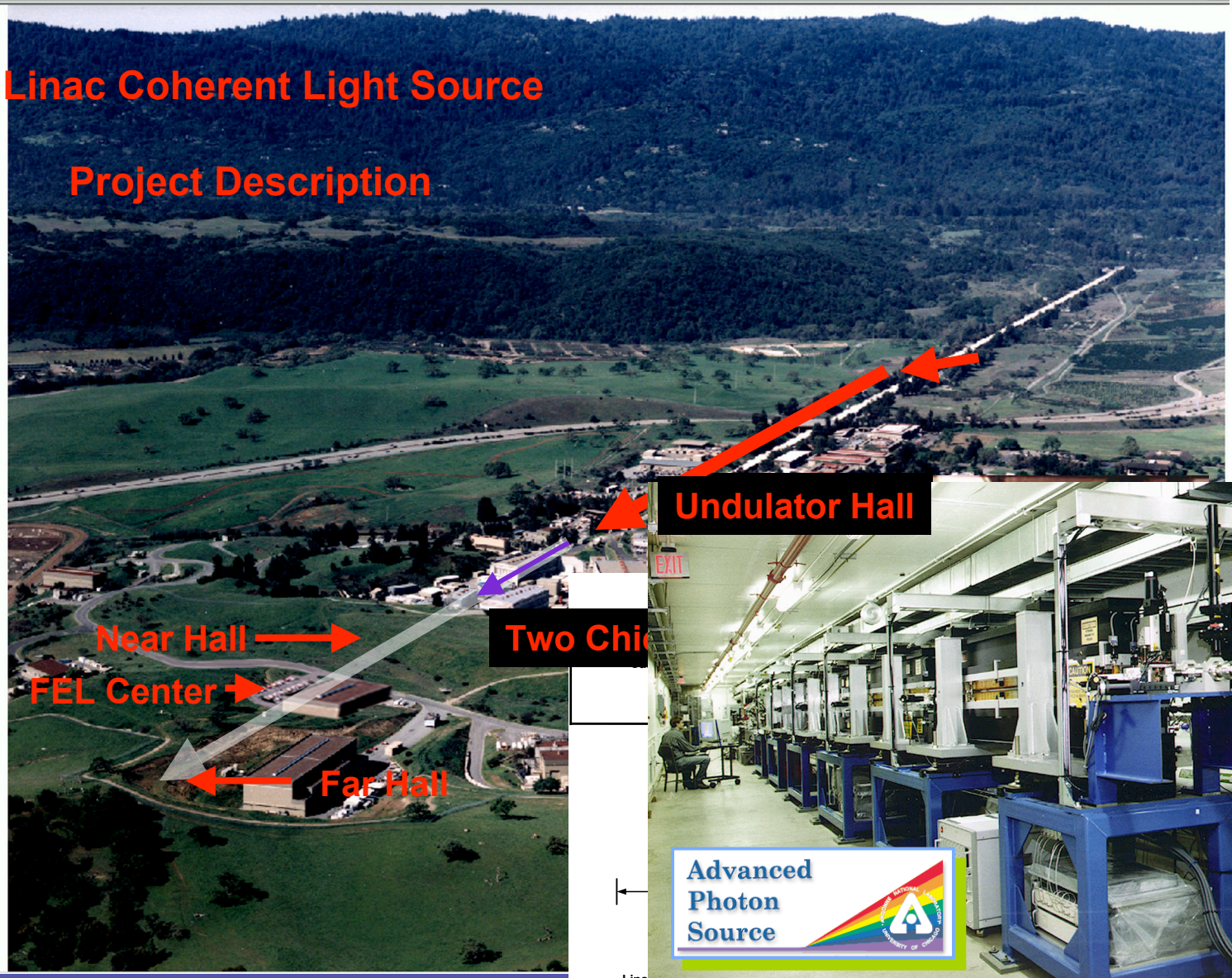
Linac Coherent Light Source

Project Description



Lina

Linac Coherent Light Source

Photon Beam Handling Systems

LLNL

- *X-ray Transport, Optics and Diagn*
  - *Front end systems – attenuators, shutters, diagnostics*
  - *Optics – the prerequisites for LCLS experiments*
- *X-ray endstation systems Hutches, Personnel Protection*
  - *Computer facilities for experiments*
  - *Laser for pump/probe experiments*
  - *Detectors matched to LCLS requirements*

Essential Infrastructure for the LCLS Experimental Program

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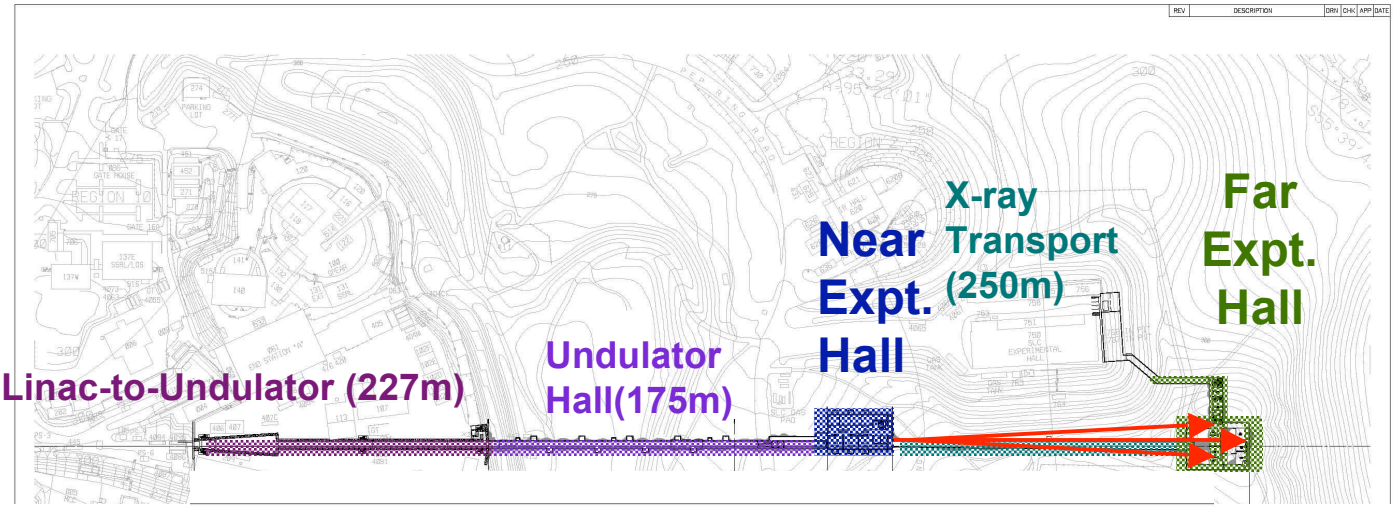

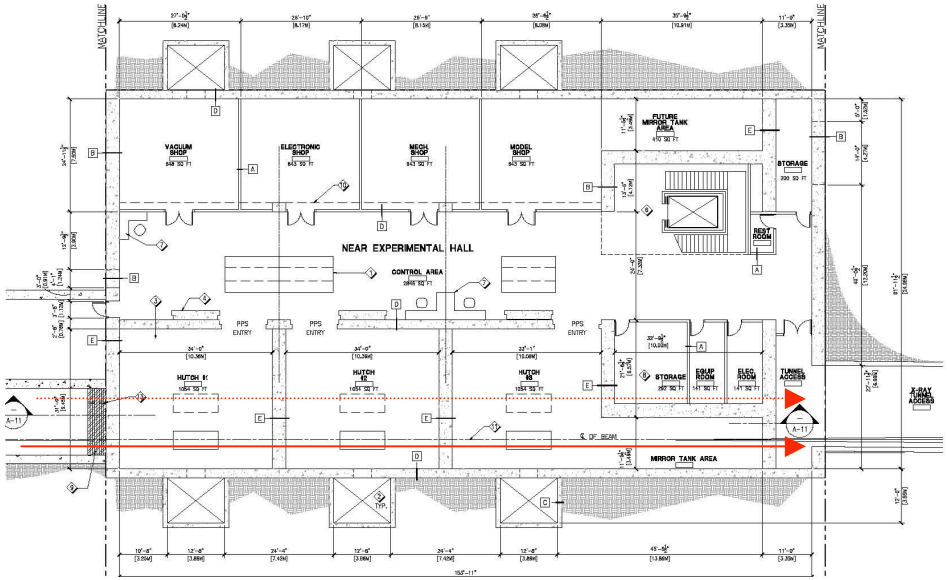

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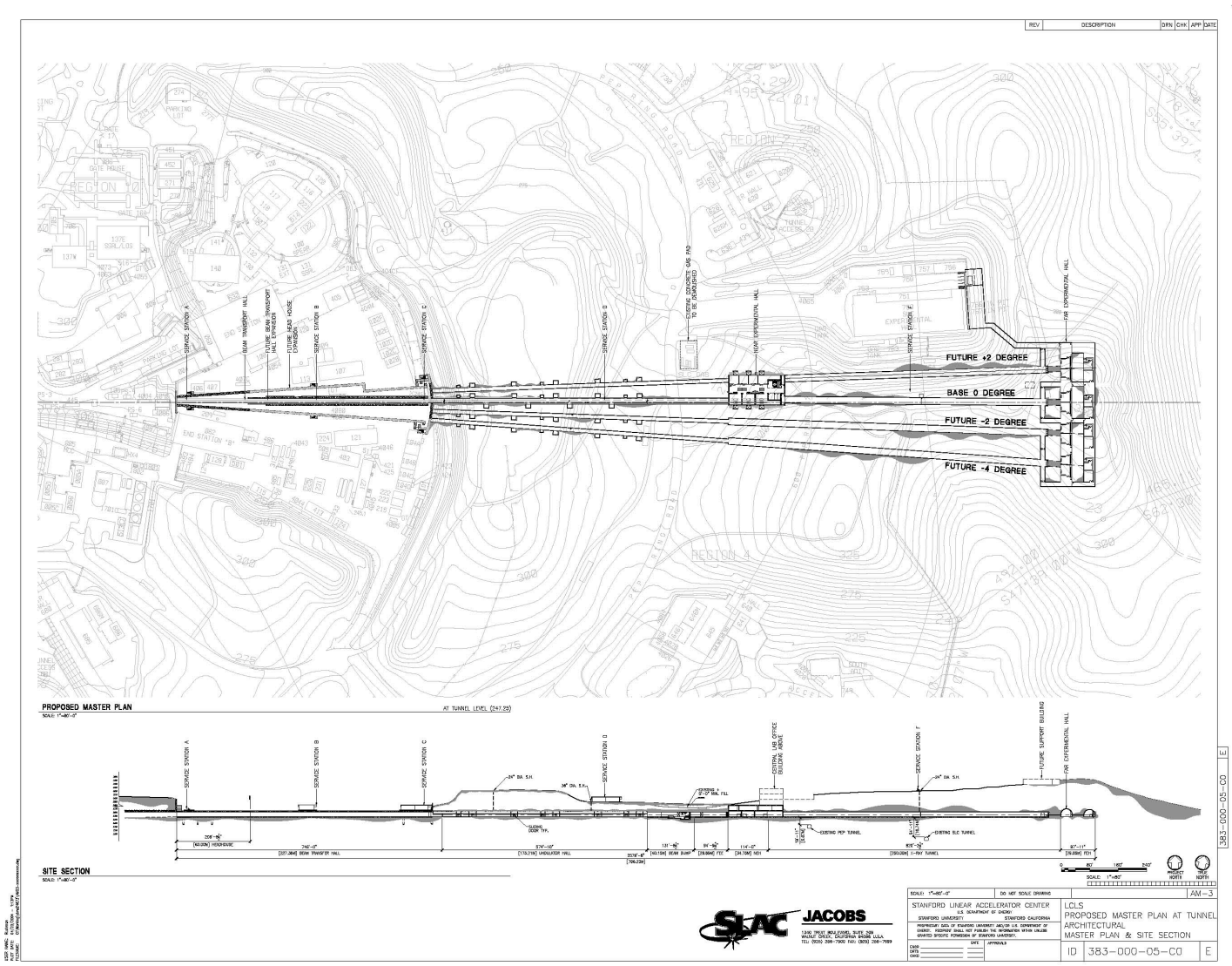

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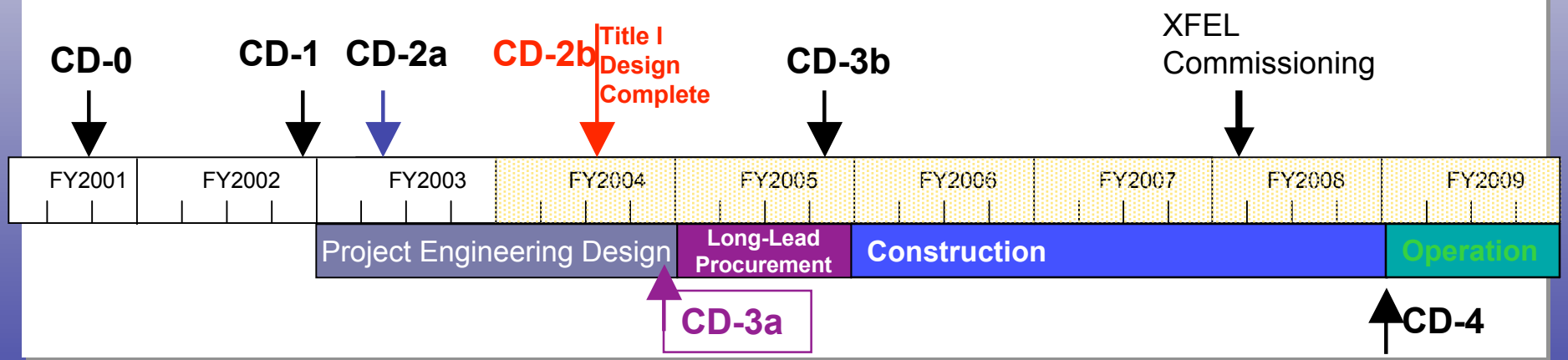
LCLS - Estimated Cost, Schedule

- *$273M Total Estimated Cost*
- *$315M Total Project Cost*
  - **FY2005** Long-lead purchases for injector, undulator
  - **FY2006** Construction begins
  - **FY2007** FEL Commissioning begins
  - ***September 2008*** Construction complete – operations begins



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Machine Flexibility

Courtesy Paul Emma

77 fs rms

Operation at 0.2 to 1.0 nC and constant 87-m saturation length at 1.5 Å

Bunch charge ?	0.2	0.4	0.6	0.8	1.0	nC
Initial bunch length (rms)	491	619	709	780	840	?m
Final bunch length	14.2	20.7	23.1	23.6	23.1	?m
Slice emittance required	0.60	0.74	0.89	1.04	1.20	?m
Peak current required	1.11	1.52	2.03	2.66	3.40	kA
linac-1 rf phase	-33.1	-34.6	-27.5	-32.4	-38.1	deg-S
linac-2 rf phase	-27.2	-40.6	-41.9	-42.0	-43.2	deg-S
linac-3 rf phase	-8.2	-7.6	-10.0	-9.7	-9.4	deg-S
R_{56} of BC1	-47.7	-45.9	-60.4	-47.7	-36.6	mm
R_{56} of BC2	-33 .1	-20.6	-22.5	-23.1	-22.2	mm
energy spread in BC1	0.91	1.18	0.98	1.31	1.77	%
energy spread in BC2	0.14	0.29	0.43	0.58	0.76	%
bunch length after BC1	62	80	119	157	193	?m
rms gun ? t_0 ? 10% ? $_z$	4.8	9.0	3.9	5.4	3.3	psec
rms gun ? t_0 ? 0.05% ? E/E_0	1.9	1.4	1.7	1.0	0.70	psec
rms ? Q/Q ? 10% ? $_{pk}$	9.5		6.0		5.4	%

47 fs rms

in/output beam

linac setup

jitter

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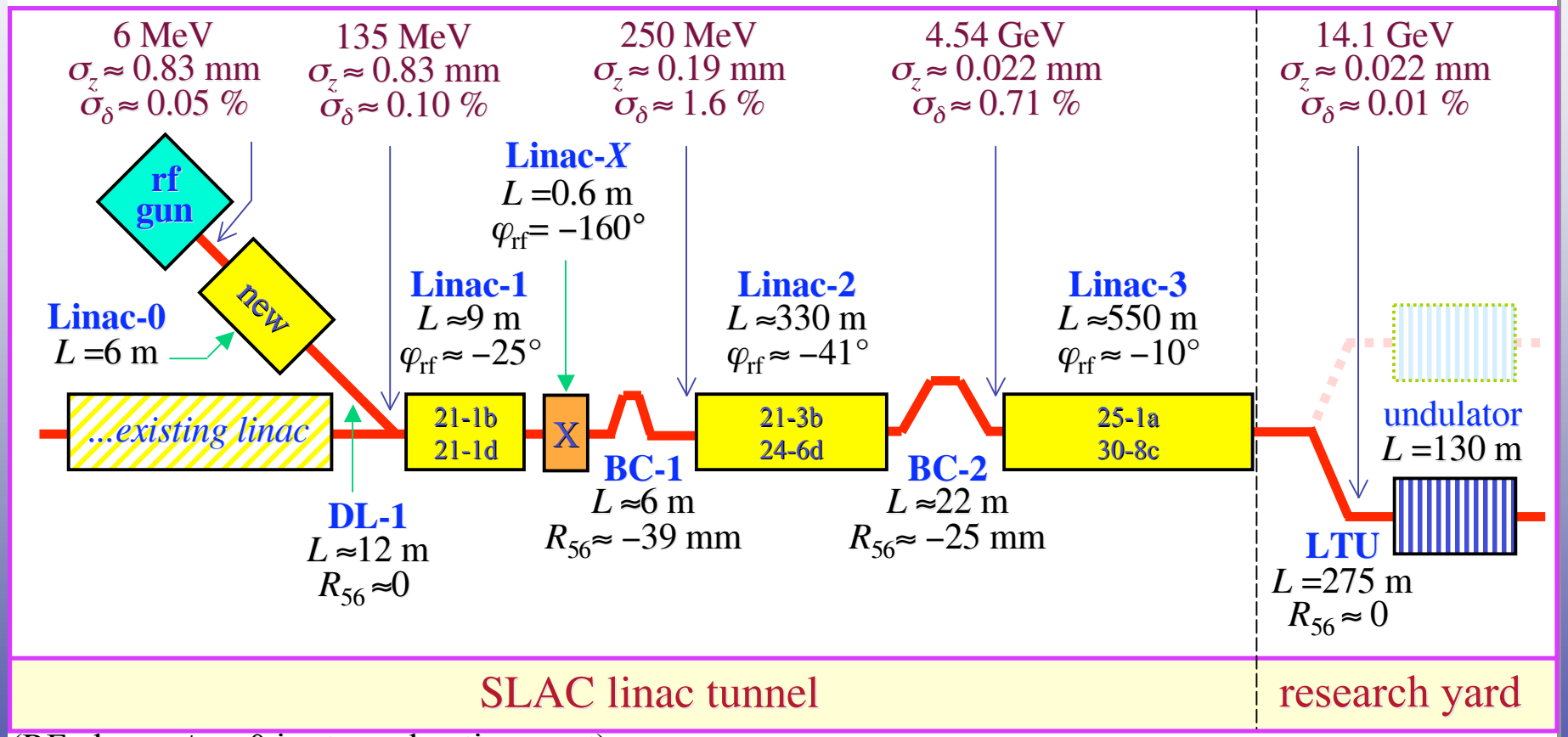
LCLS has 2 bunch compressors

Single bunch, 1-nC charge, 1.2-μm *slice* emittance, 120-Hz repetition rate…



(RF phase: $\phi_{rf} = 0$ is at accelerating crest)

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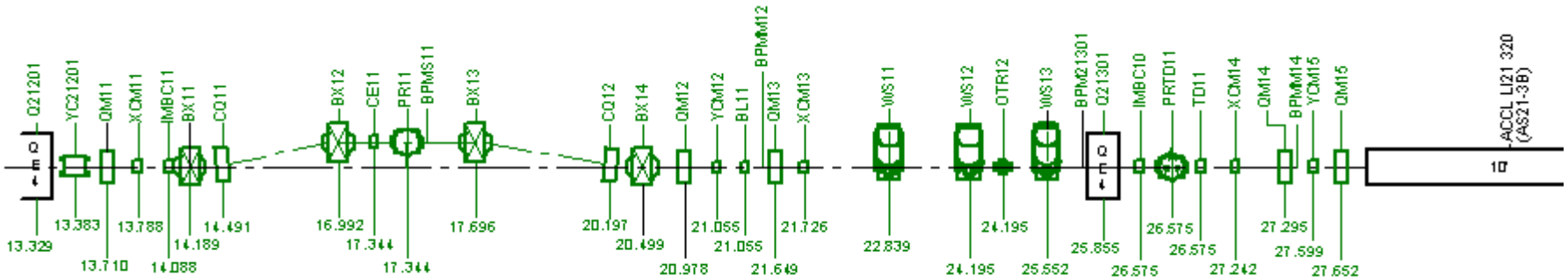
LCLS Linac BC1 Subsystem



Parameter Description	Symbol	Value	Unit
Initial to final electron energy	E	250	MeV
Initial and final bunch length (rms)	σ_z	830 - 190	μm
Active length of system	L	6.3	m
Relative energy spread of e^- bunch (rms)	σ_E/E	1.6	%
Bend angle of chicane dipoles	$\lvert\theta_B\rvert$	4.82	deg
Nominal $\lvert R_{56}\rvert$ (and operational range)	$\lvert R_{56}\rvert$	39 (15 to 65)	mm
Length of chicane dipoles	L_B	20.32	cm

- Linac Sector 21-2a to 21-3a
- Compresses a single 1-nC, 830-μm long (rms) electron bunch, at a repetition rate of 120 Hz, at 250 MeV to an rms length of 190 μm.

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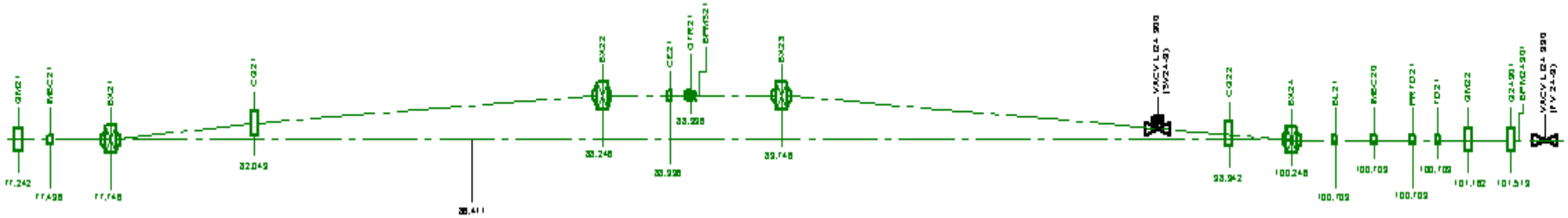
LCLS Linac BC2 Subsystem



Parameter Description	Symbol	Value	Unit
Nominal electron energy	E	4.54	GeV
Initial and final bunch length (rms)	σ_z	190 - 22	μm
Active length of system	L	22.5	m
Relative energy spread of e^- bunch (rms)	σ_E/E	0.7	%
Bend angle of each chicane dipole	$\lvert\theta_B\rvert$	1.98	deg
Nominal $\lvert R_{56}\rvert$ (and operational range)	$\lvert R_{56}\rvert$	25 (10 to 50)	mm
Length of chicane dipoles	L_B	50	cm

- Linac Sector 24-7a to 24-8d.
- compress a single 1-nC, 195-μm long (rms) electron bunch, at a repetition rate of 120 Hz, at 4.54 GeV to an rms length of 22 μm

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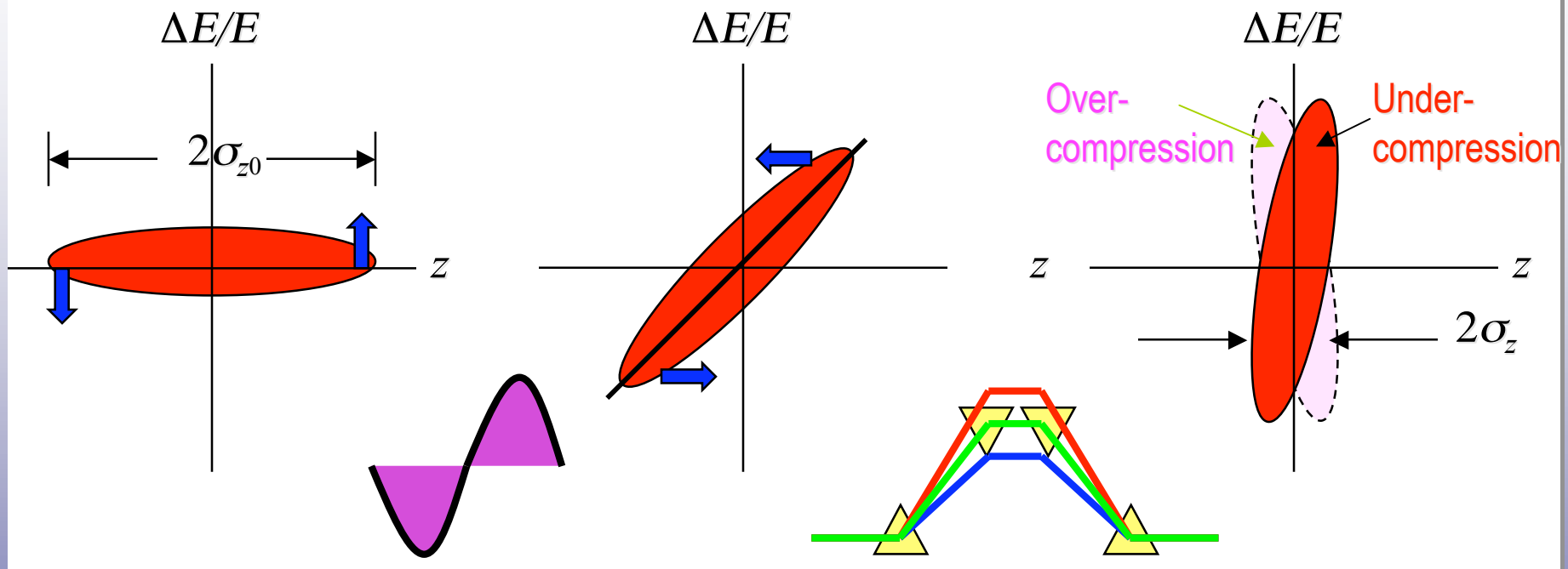
Magnetic Bunch Compression



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

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

RF Accelerating Voltage

Path Length-Energy Dependent Beamline

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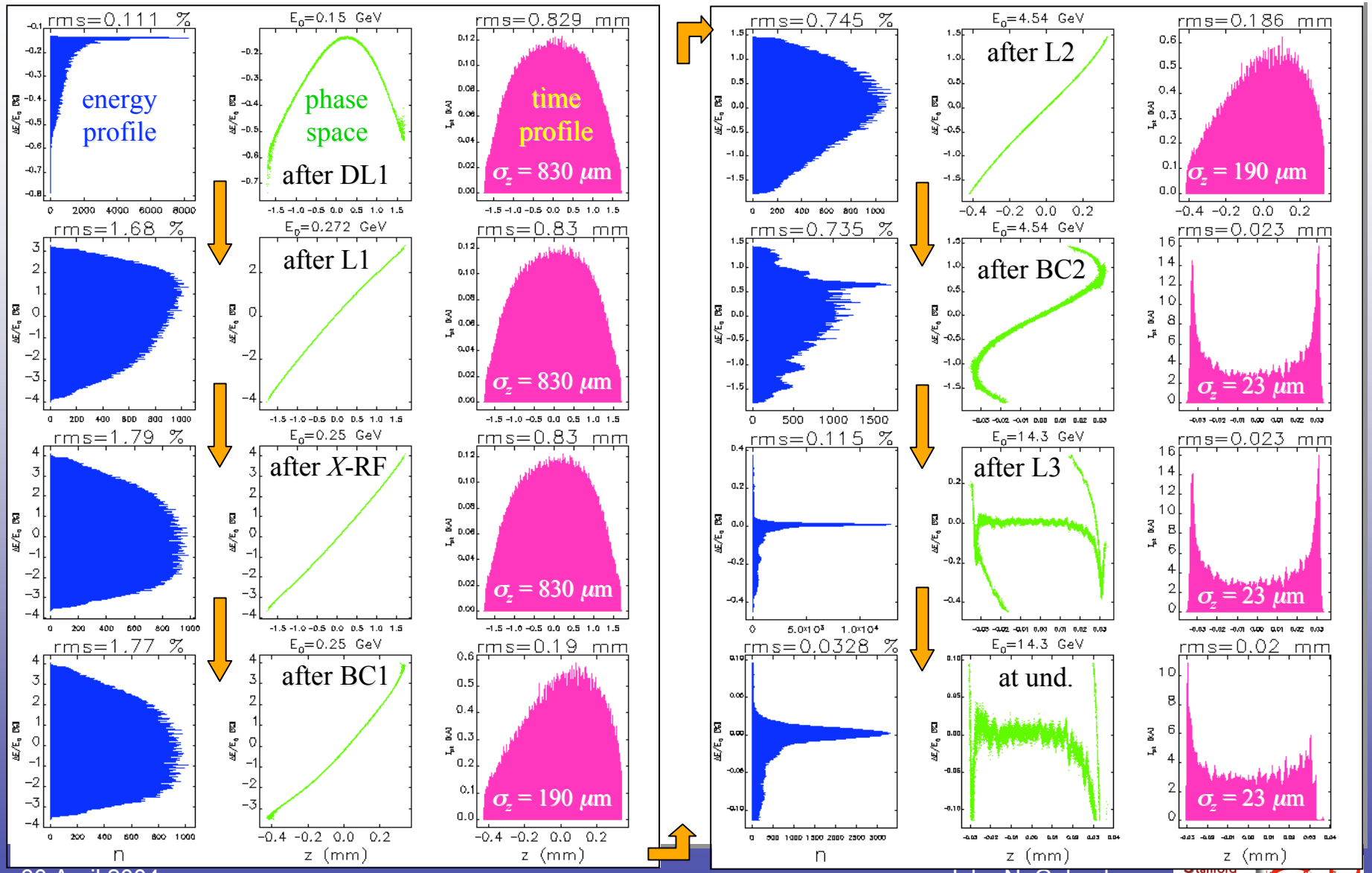

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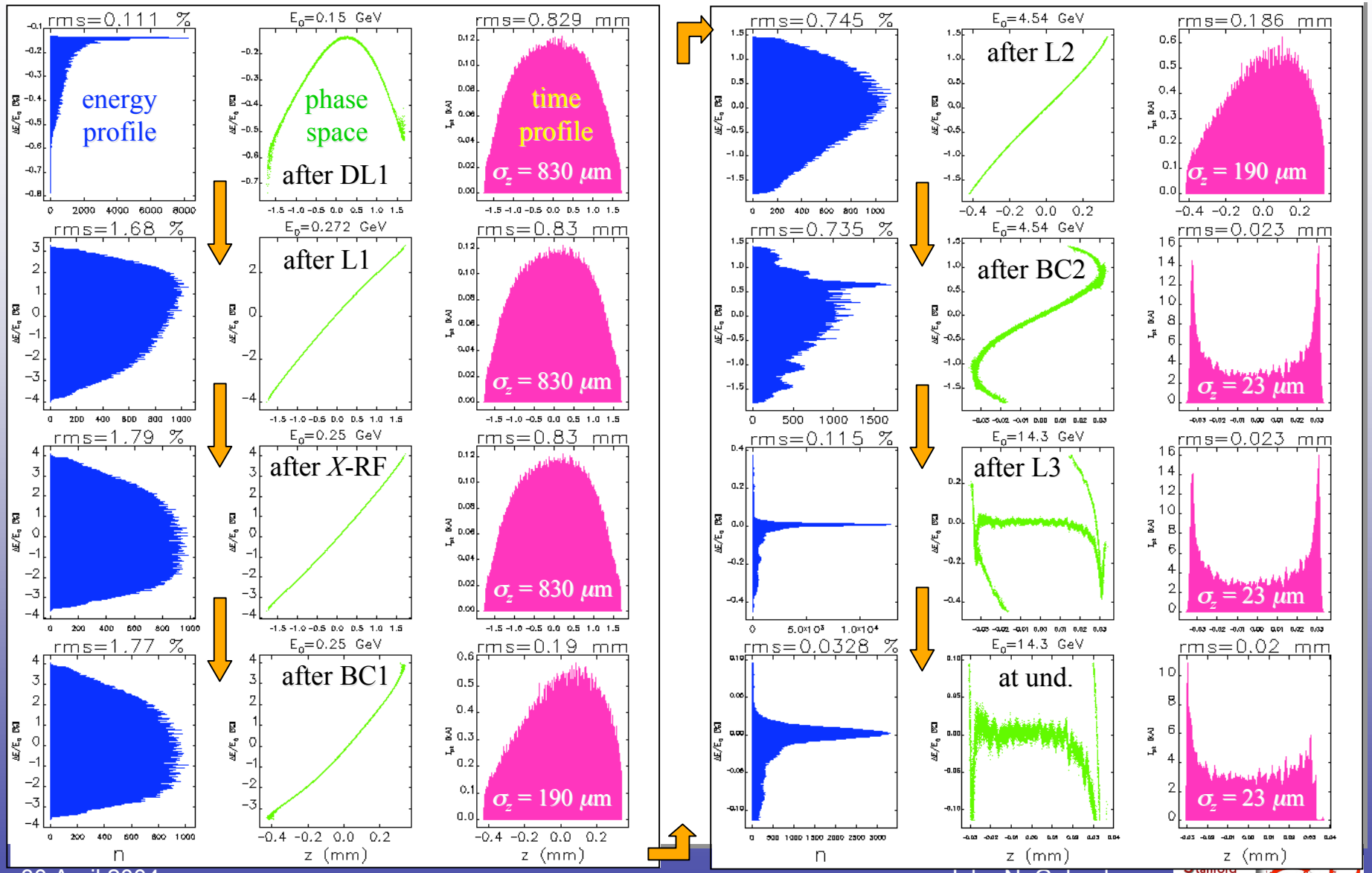

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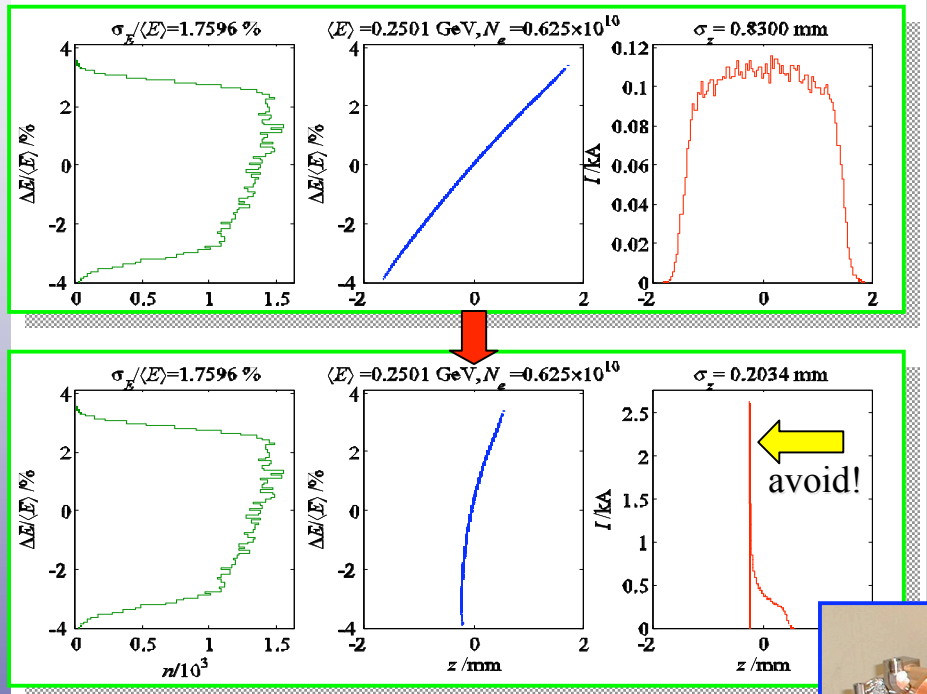
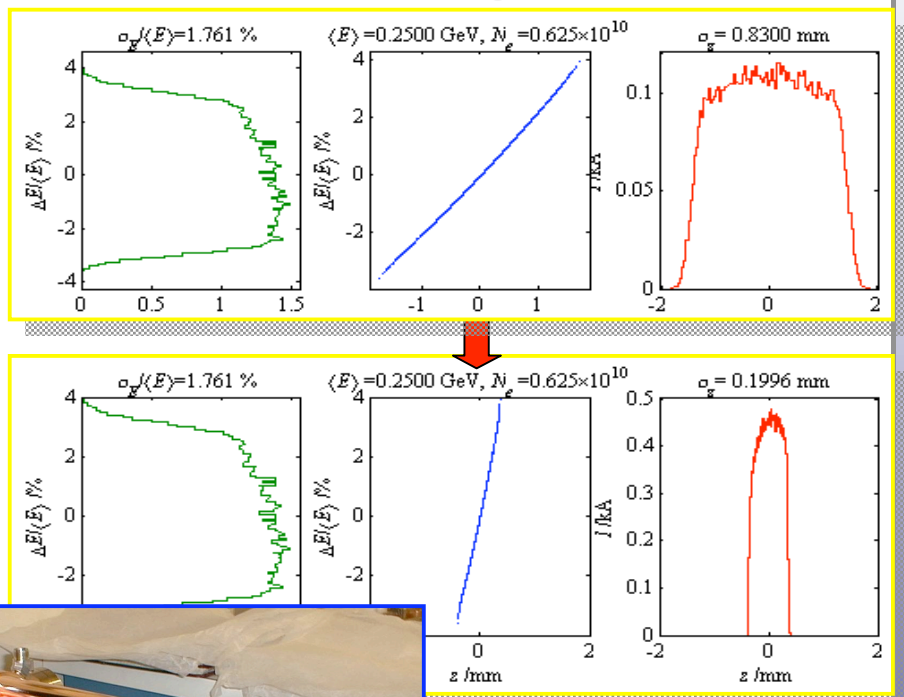
X-band RF used to Linearize Compression (f = 11.424 GHz)

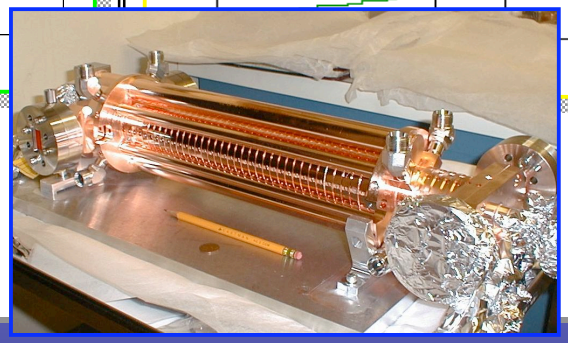
S-band RF curvature and 2nd-order momentum compaction cause sharp peak current spike



X-band RF at decelerating phase corrects 2nd-order and allows unchanged z-distribution



$$eV_x = \frac{E_0\left[1-\frac{1}{2\pi^2}\frac{\lambda_s^2 T_{566}}{R_{56}^3}\left(1-\sigma_z/\sigma_{z_0}\right)^2\right]-E_i}{\left(\lambda_s/\lambda_x\right)^2-1}$$



0.6-m section, 19 MV available at SLAC (200-μm alignment)

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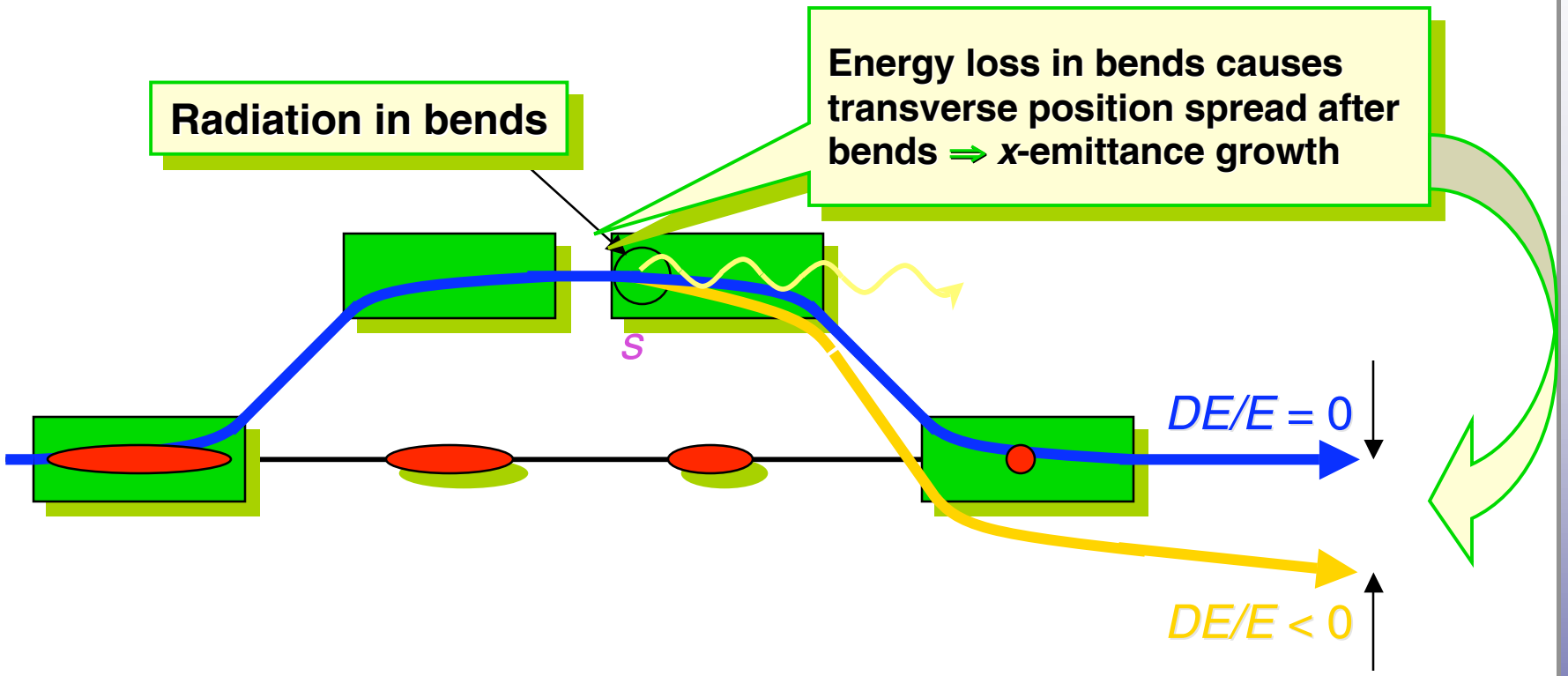
Coherent Synchrotron Radiation



CSR Effects → Emittance Growth

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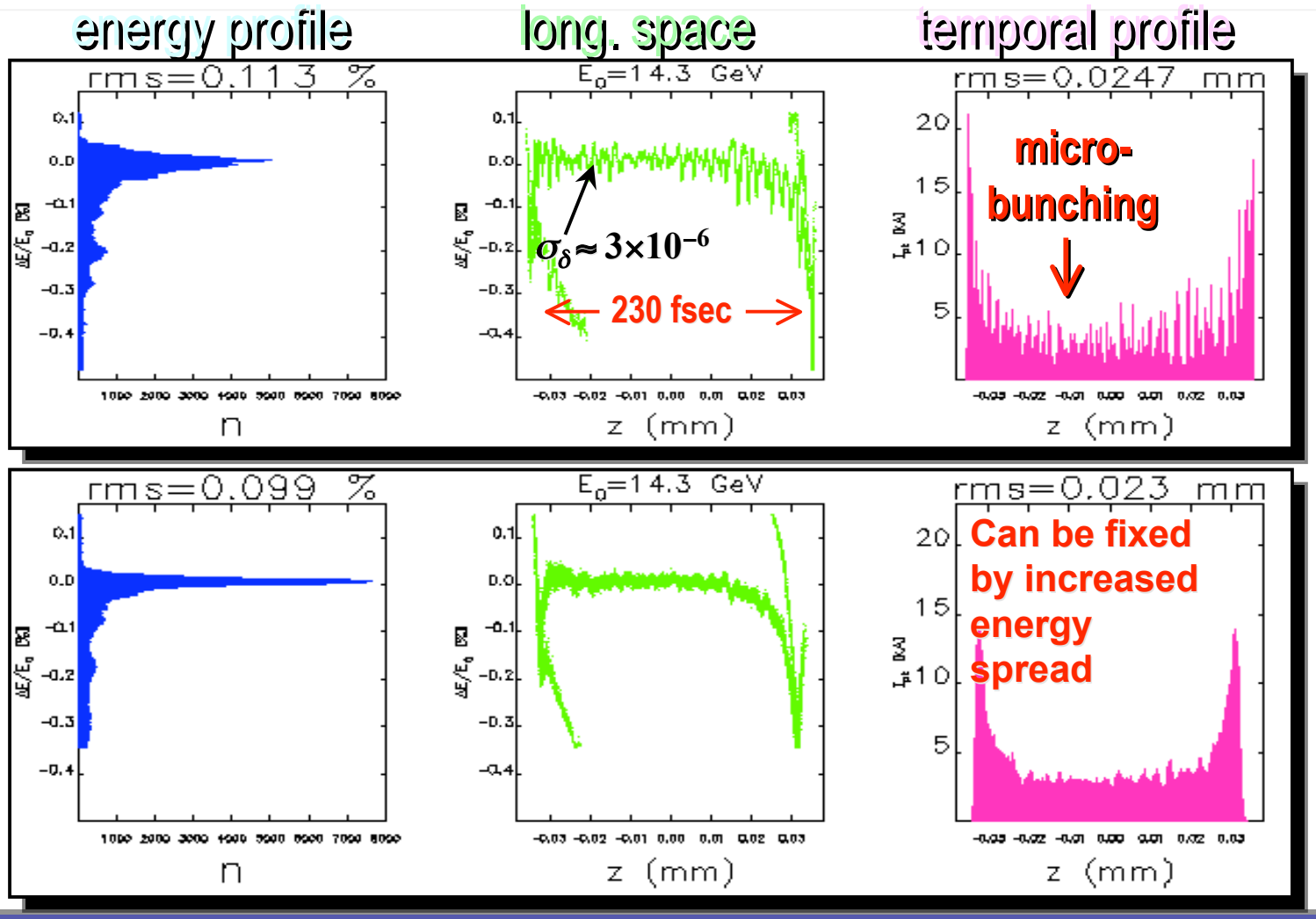
Greater compression risks CSR instability



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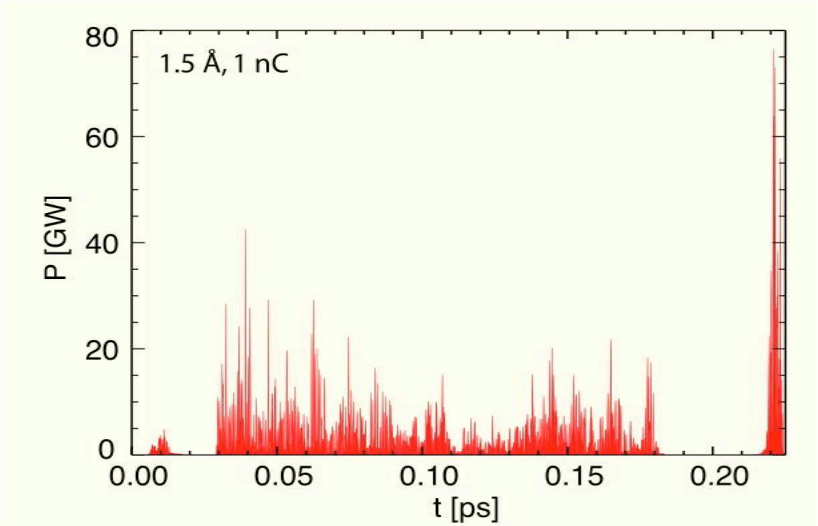
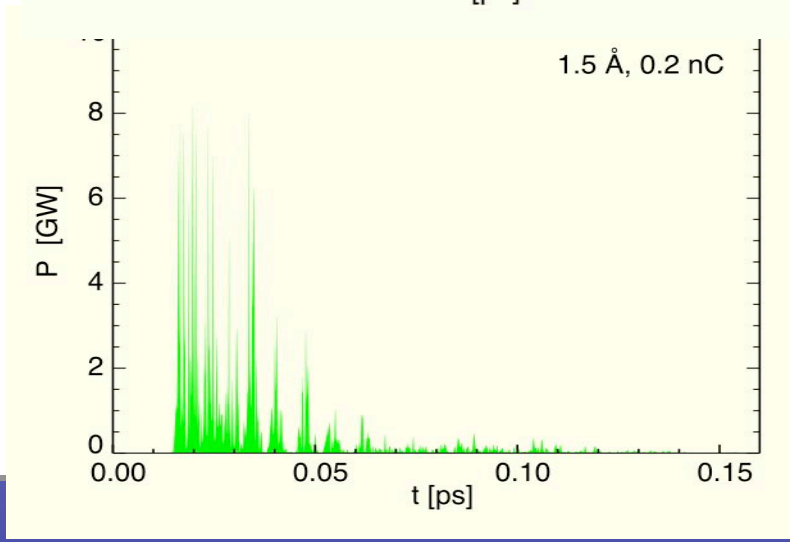
Power Profile Highly Sensitive to z-Dependence of Electron Beam Parameters

Power Profile



Profile similar for entire wavelength range.



Gaps in profile due to z-dependence of
- **Undulator wakes**
- **emittance**
- **energy spread**

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Timing Control of a ~30 fs LCLS Pulse Can Be Implemented Using a Deflecting Cavity

- *A scheme has been proposed for* spatially chirping *the LCLS pulse, making use of a deflecting cavity incorporated in its design. The authors describe the scheme as "a very straightforward way to produce SASE x-ray pulses with fwhm duration of* ***~30 fs****, which are ~7-times shorter than the LCLS electron bunch length. The method uses an S-band RF deflecting structure already included in the LCLS design (although not optimally located for this purpose). It may be possible to push this method to* ***~10 fs*** *fwhm depending on aperture restrictions."[*
- P. Emma and Z. Huang, "Femtosecond X-Ray Pulses from a Spatially Chirped Bunch in a SASE FEL", 2003 Free Electron Laser Conference, Tsukuba, Japan, August 2003, SLAC-PUB-10294
- *The timing stability of these ~30 fs pulses will be determined by* the stability of the deflecting cavity alone*, rather than the stability of the rest of the SLAC linac. How stable can a single cavity be made? Based on estimates by the LUX design team for a similar system,* ***~10 fs timing stability*** *could be achieved in the LCLS.*
- Corlett, *et al*., "Techniques for Synchronization of X-ray pulses to the Pump Laser in an Ultrafast X-ray Facility", 2003 Particle Accelerator Conference, http://accelconf.web.cern.ch/accelconf/p03/PAPERS/WPPB001.PDF

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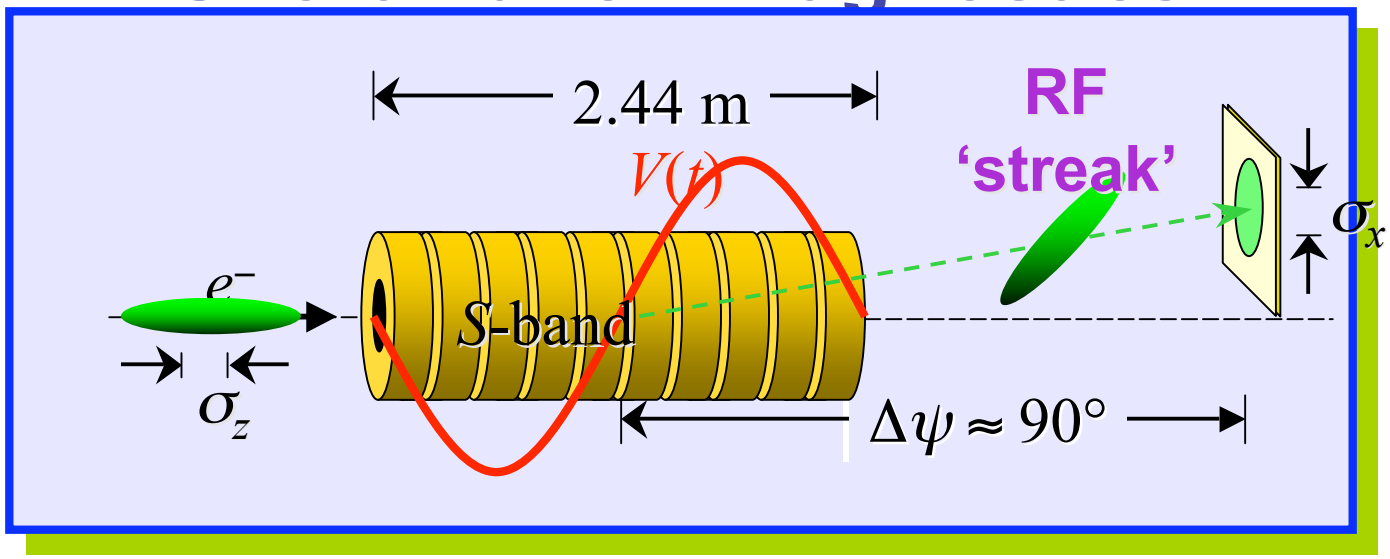
Short Bunch Diagnostics

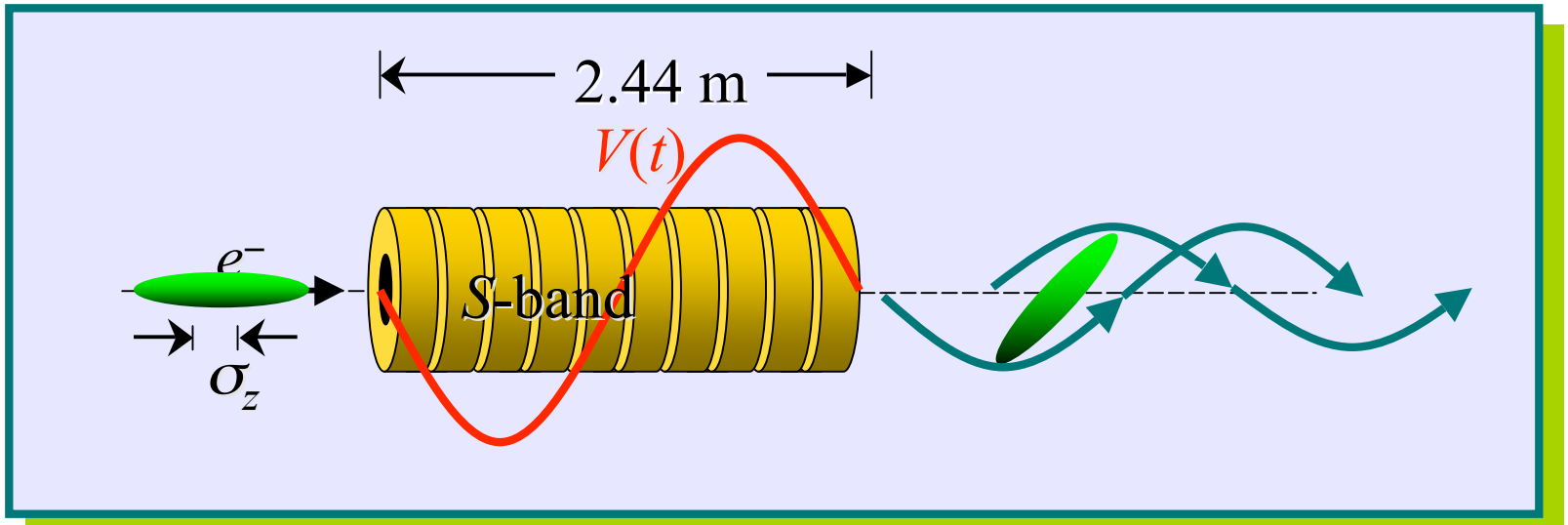
P. Emma,
J. Frisch,
P. Krejcik,
G. Loew,
X.-J. Wang



Turning the SLAC linac into a streak camera

Induced Betatron Oscillation Kills SASE

P. Emma,
J. Frisch,
P. Krejcik,
G. Loew,
X.-J. Wang



Only a fraction of a millimeter oscillation will turn off the SASE

Timing of the undisturbed portion of the bunch is determined by the phase of the deflecting cavity

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LCLS R&D Has Established the Feasibility of Self-Seeding[9]

Two-Stage Chirped-Beam SASE-FEL for High Power Femtosecond X-Ray Pulse Generation

C. Schroeder*, J. Arthur†, P. Emma†, S. Reiche*, and C. Pellegrini*

This option for shorter-pulse operation, down to 30 fs, is comparable to the deflecting cavity approach mentioned earlier. However the "two-stage chirped beam" approac offers a very significant additional feature: it can produc a "transform-limited" (full temporal coherence) x-ray pul

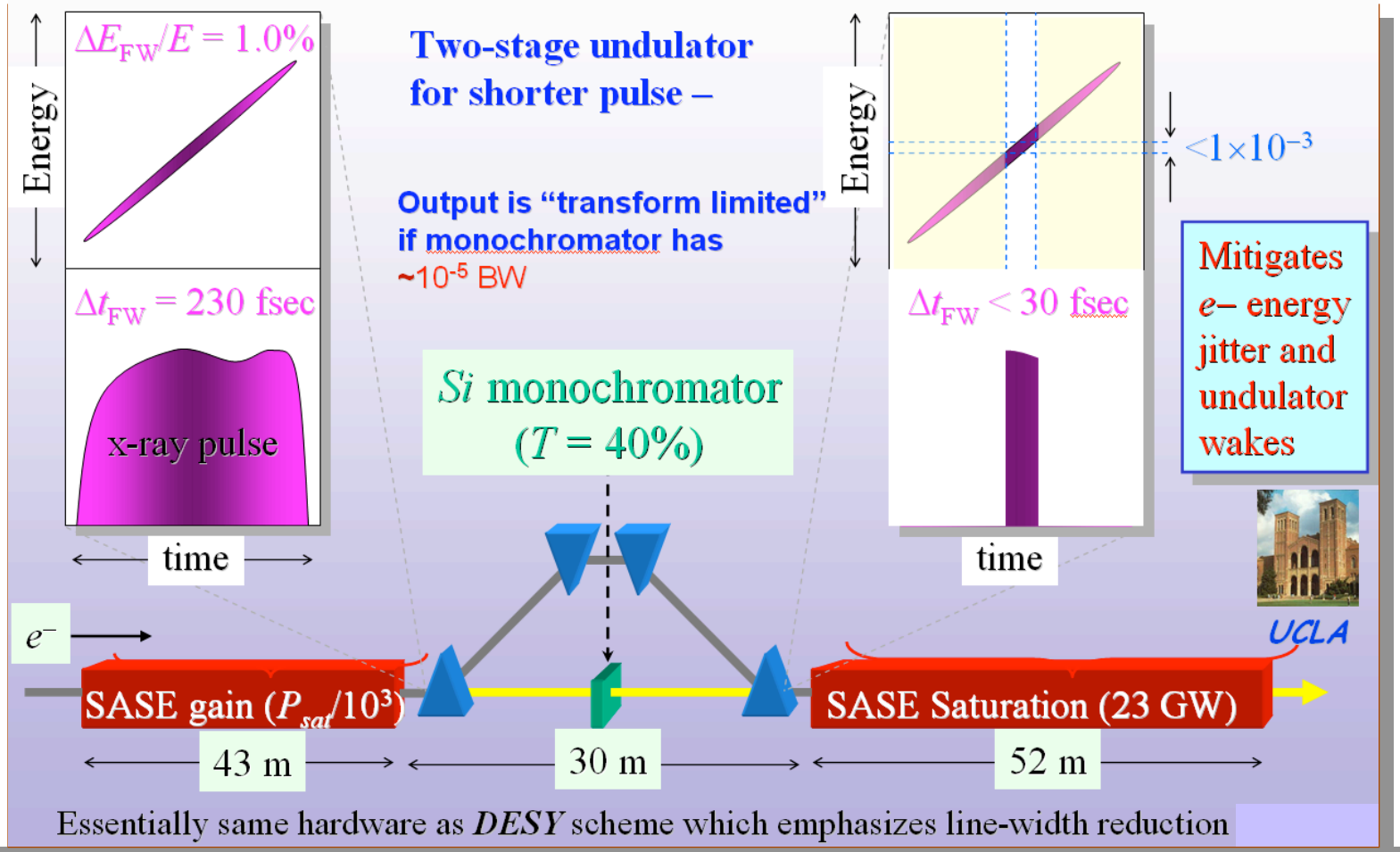
The same hardware may be used to produce 100-200 fs transform-limited pulses with greatly enhanced brightne

This option is envisioned as an early operations-era upgr of the LCLS.

†Stanford Linear Accelerator Center
*UCLA

UCLA

Two-Stage Chirped-Pulse Seeding in the LCLS



Essentially same hardware as *DESY* scheme which emphasizes line-width reduction

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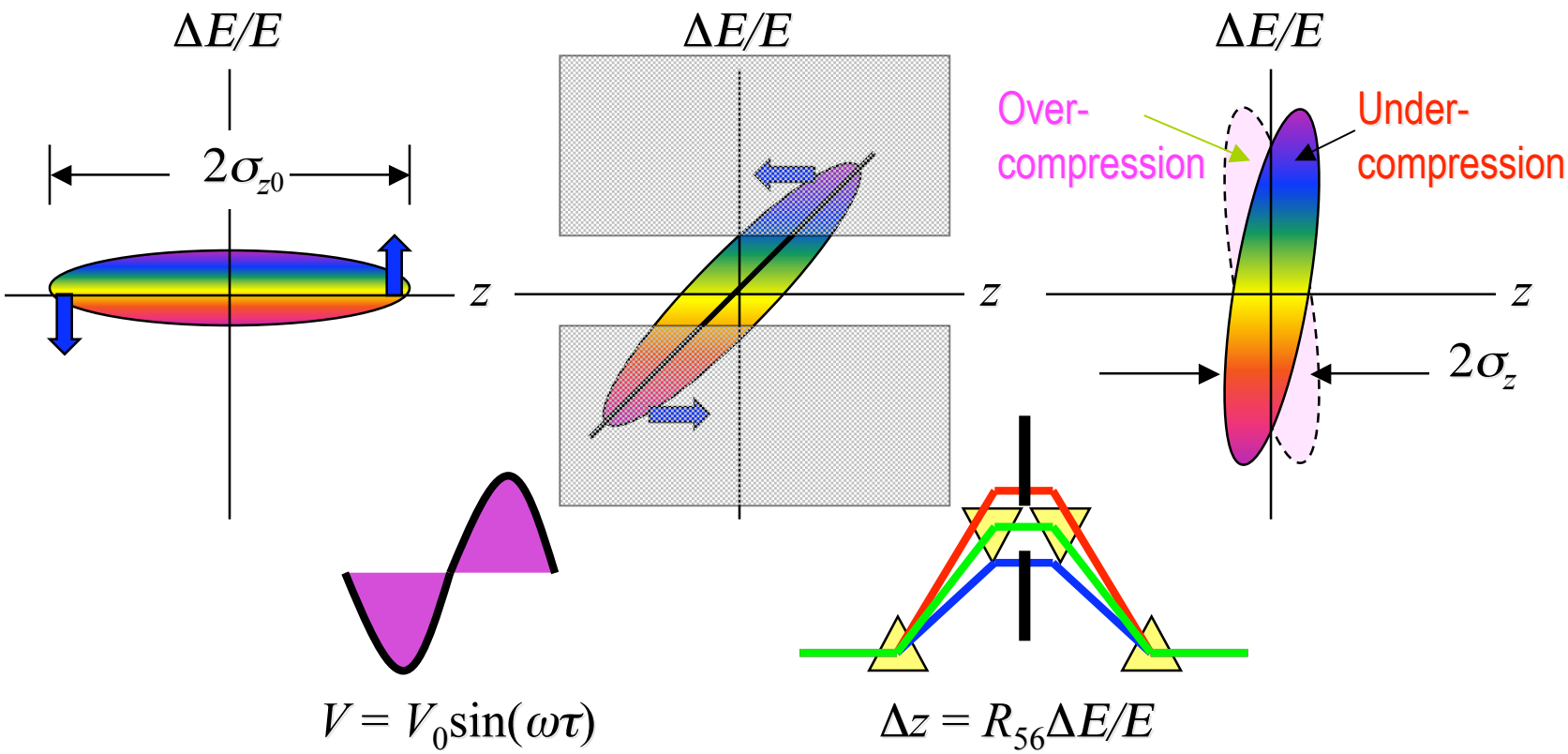
Spoiling – P. Emma, et al. SLAC-PUB-10002, 2003



RF Accelerating Voltage

Path Length-Energy Dependent Beamline

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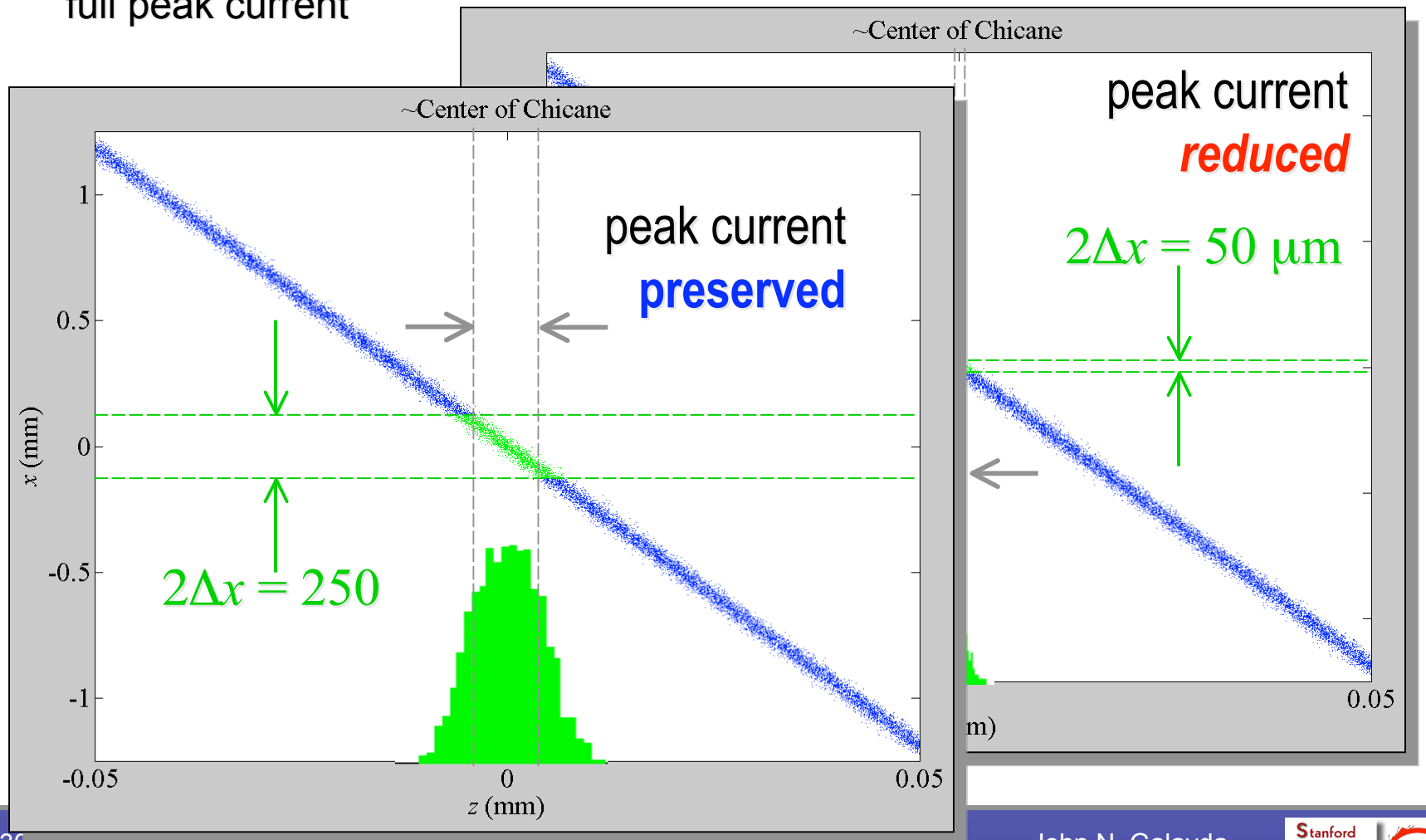
Choose slot for shortest e^- pulse, while retaining full peak current



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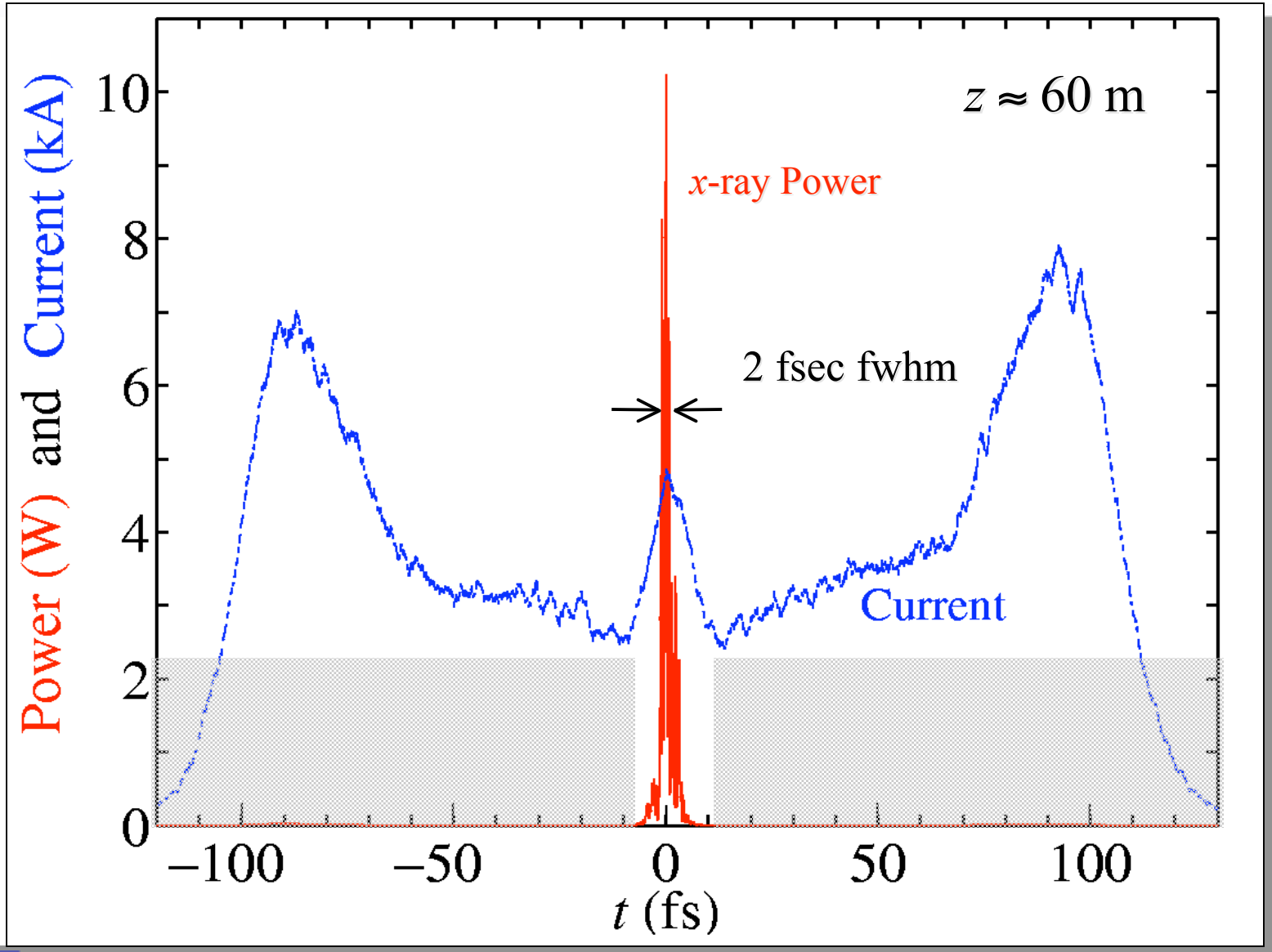

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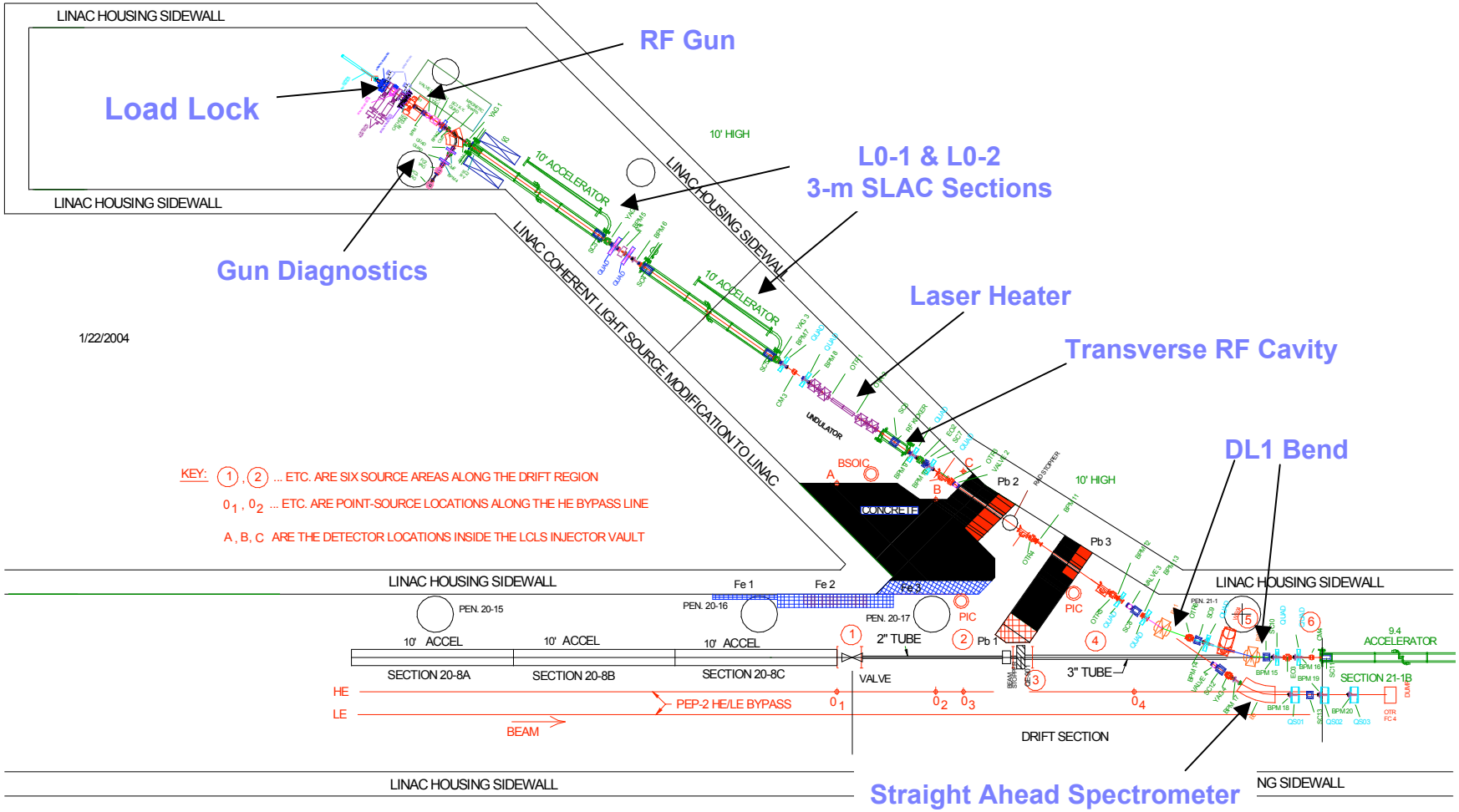
LCLS Injector Configuration



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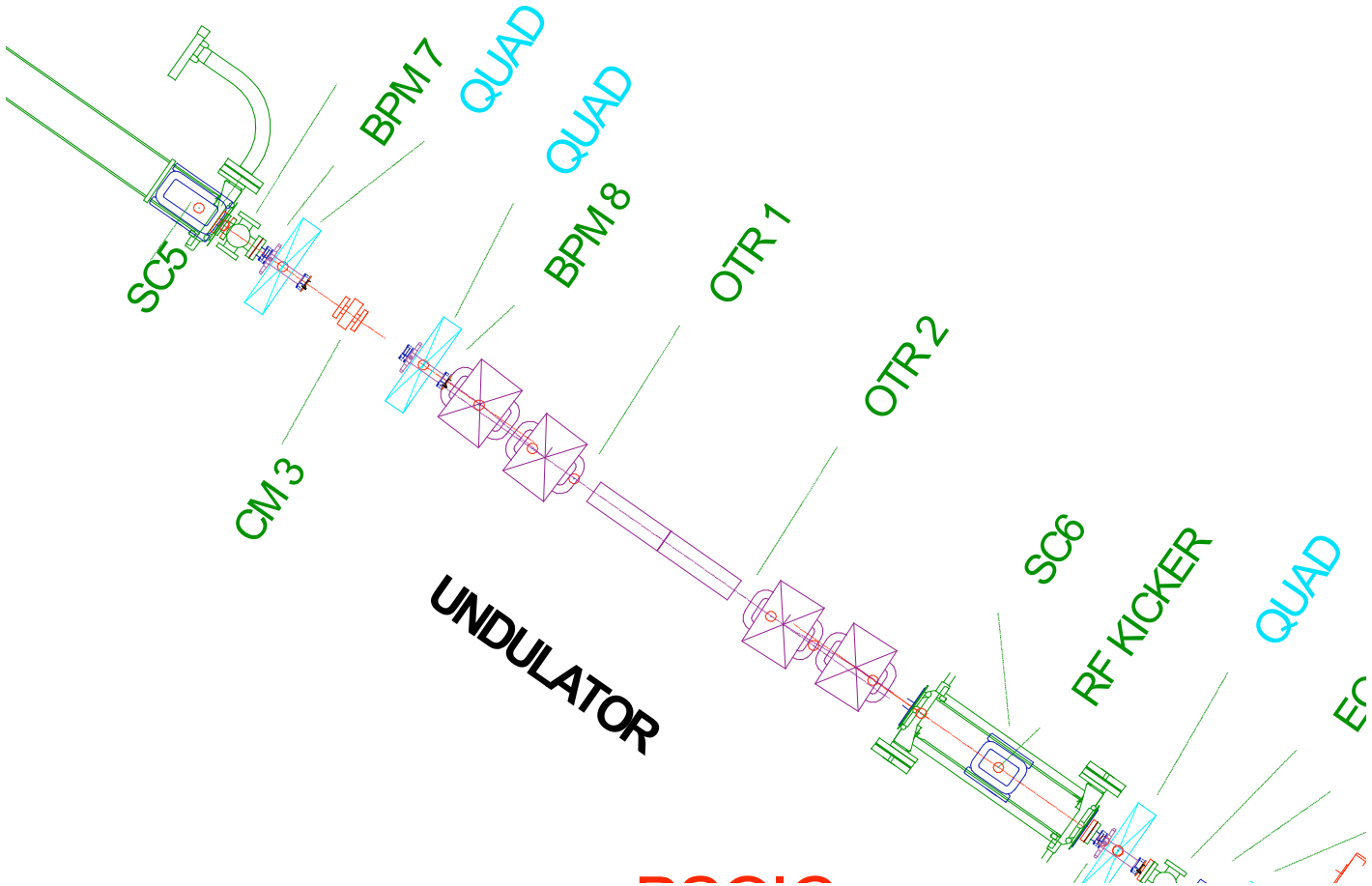
WBS 1.2.15 Laser Heater



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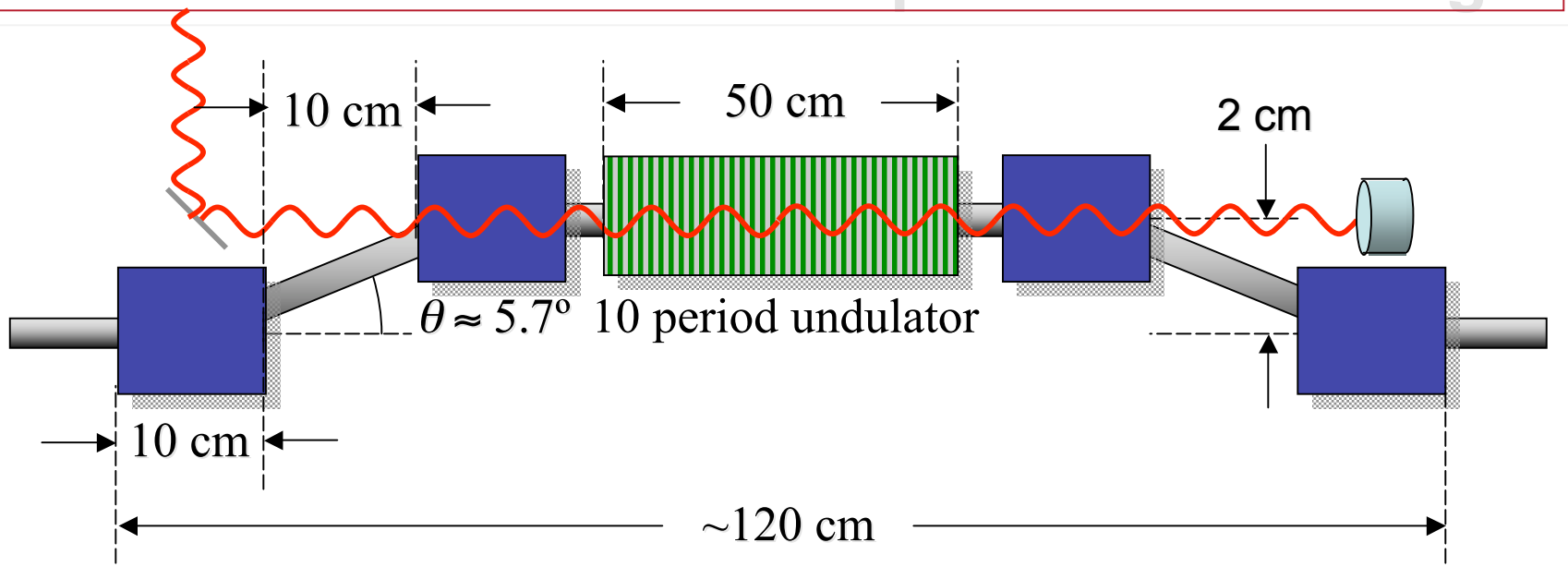
Laser Heater – Same Principle as ALS Slicing



- Laser-electron interaction in an undulator induces rapid energy modulation (at 800 nm), to be used as effective energy spread before BC1 (3 keV➔ 40 keV rms)

- Inside a weak chicane for easy laser access, time-coordinate smearing (Emittance growth is completely negligible)

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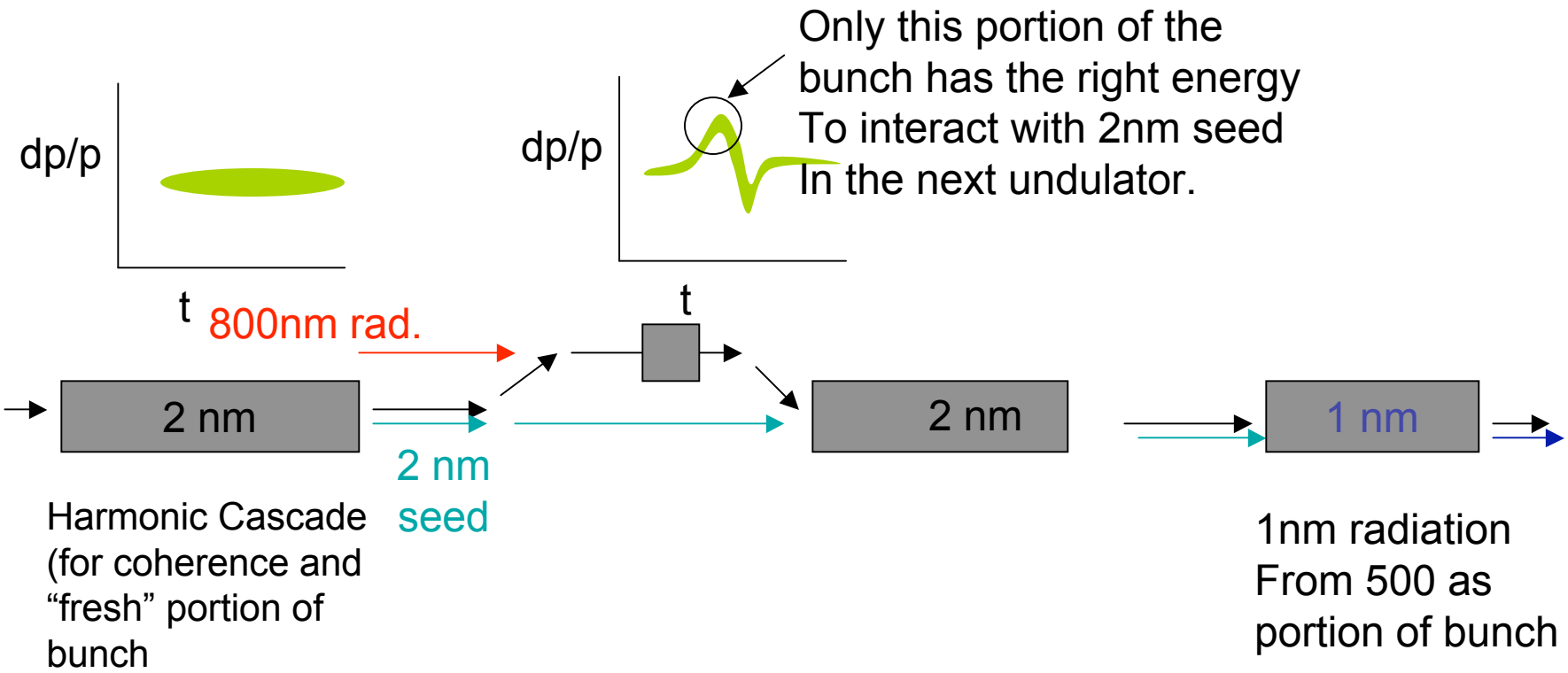
Highly Localized Control of Energy Within Bunch Used to Restrict FEL output to short duration

- Zholents, Fawley, LBNL-54084



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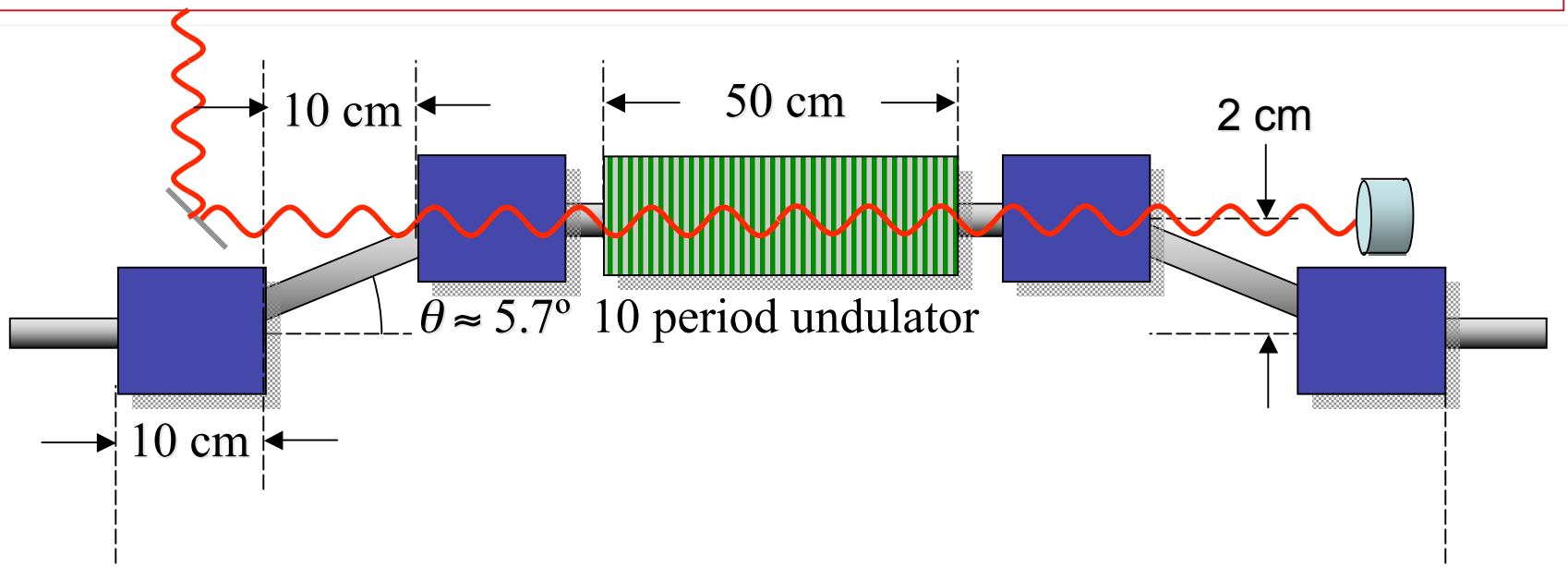
An 800nm modulator looks like a laser heater



- Modulation in the **10 MeV** range is possible-

•Zholents, Fawley, Z. Huang and P. Emma are considering the possibility of producing :20kA microbunches in the LCLS beam by this means; this could result in LCLS reaching saturation at 1.5 Angstrom after traversing as little as 30m of undulator. Saturation at 1.5 Angstroms in the LCLS with an input emittance of 2 mm-mrad looks like it might be possible.

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Conclusions, Speculations

- Adjustment of bunch compression can push LCLS current pulse to <100 fs
- Nonlinear current distributions and wake fields cut the pulse length further, but a pedestal remains
- Kill the pedestal with a laser heater?
- RF deflector can turn off SASE in all but 30 fs of bunch
  - Phase of one RF cavity determines timing, jitter
- Chirped pulse self-seeding gets down to 30 fs, with enhanced or even full temporal coherence
- Selective "spoiling" of the emittance with a foil can shorten the pulse to femtosecond range
- 800nm modulation of current by (separate) interaction with laser and undulator can produce a *series* of sub-fs, ~20,000A current pulses
  - Keyed to laser phase
  - This is attractive because higher peak current means shorter gain length

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End of Presentation

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