Roadmap Towards Hard X-ray FELs

John N. Galayda, SLAC

October 30, 2003

- **Challenges, Initiatives**
  - Electron Source
  - Compression
  - Undulator
  - Optics
  - Timing
  - Detectors

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FEL R&D for synchrotron radiation user facilities

- *Jefferson Lab energy recovery FEL*
  - *3 micron to UV, high average power*
- *Brookhaven National Lab Deep-UV FEL*
  - *Externally seeded, High-Harmonic Generation, to 50 nm*
  - *Brookhaven Accelerator Test Facility laid foundation(gun, HGHG)*
- *Argonne National Lab LEUTL*
  - *SASE, 100nm to 50 nm*
- *Stanford Linear Accelerator Center LCLS*
  - *14 GeV electron beam*
  - *SASE FEL, 0.8-8 keV*

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20-Year BES Facilities Roadmap Workshop

February 22-24, 2003

Doubletree Hotel and Executive Meeting Center
1750 Rockville Pike
Rockville, MD 20852

- **Proposals greater than $50M, to Department of Energy**
- **FEL-related proposals:**
  - **Linac Coherent Light Source at SLAC**
  - **LUX facility at Lawrence Berkeley National Lab**
    - **Recirculating linac, 2.4 GeV; HGHG to 1 keV**
  - **"Green Field" FEL (no site specified)**
- **Prioritization by US DOE on 10 November 2003**

20-Year BES Facilities Roadmap Workshop

February 22-24, 2003

Doubletree Hotel and Executive Meeting Center
1750 Rockville Pike
Rockville, MD 20852

- **Recognition of importance of accelerator R&D for light sources**
- **Recognition of importance of educating accelerator experts**
  - **Labs to develop a roadmap for R&D/Education**

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Greenfield FEL Wish List

- *Spectral coverage to 30 keV in first harmonic*
  - *Comparable to large 3rd generation facilities*
  - *One could argue for 60 keV*
- *X-ray pulse ~10^{12} photons*
- *Pulse duration – 100 femtosec to 100 attosec*
- *Narrow spectrum $\Delta\omega/\omega < 10^{-6}$, coherence control*
- *Multiple undulator facility*
  - *About 10 FEL undulator beamlines*
- *1-10 kHz rate at undulator*

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Development of SC Undulators

Advantages

- *SC helical ID represent the shortest possible SASE FEL amplifier*
- *SC ID has an intrinsic capability of tuning of the wavelength*
- *SC helical ID delivers lowest heat load on optical components*
- *SC ID utilizes the same technology as a primary particle source – SC Linac*

Challenges

- *Stringent requirements for quality of the magnetic field for long periodic SC magnets*
- *Reliability of the long SC ID in respect to the interaction with the powerful x-ray source*
- *Extremely high level tolerances for mechanical and vacuum systems*
- *Incorporating compatible diagnostics of electron beam and x-rays*

Solution

- *Extensive prototyping is required. But technical challenges for critical elements of the SC undulator line could be solved in the period of three years with adequate funding.*

Linac Coherent Light Source recommendation:

- *Essential for exploring future science using intense femtosecond coherent X-ray beams*
- *DoE Critical Decision 0 and 1 have been approved*

Recommend continued strong support

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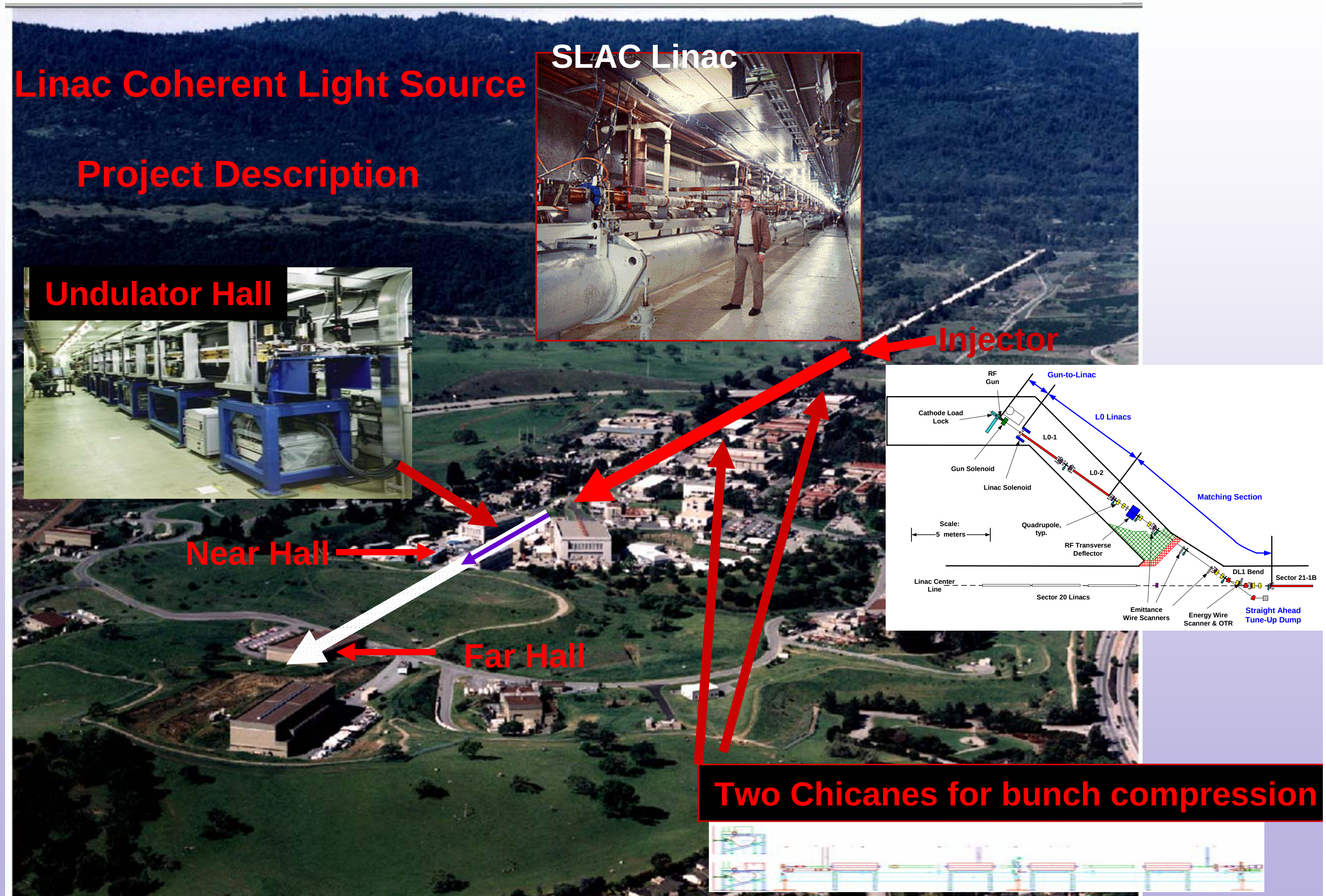

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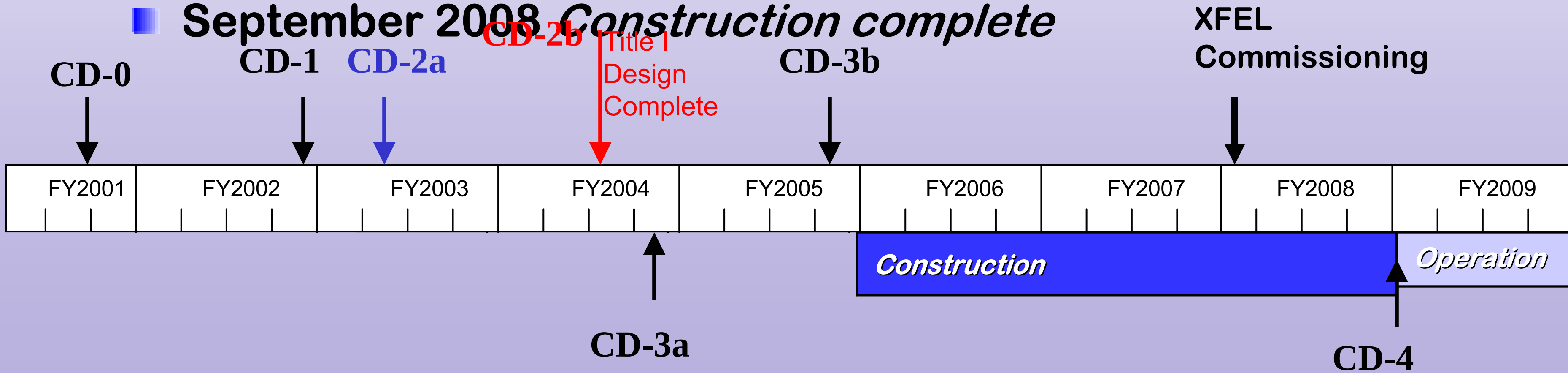
Estimated Cost, Revised Schedule

- ***$200M-$240M Total Estimated Cost range***
- ***$245M-$295M Total Project Cost range***
  - *FY2005* *Long-lead purchases for injector, undulator*
  - *FY2006* *Construction begins*
  - *January 2008* *FEL Commissioning begins*
  - September 2008 *Construction complete*



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Capabilities

Spectral coverage: 0.15-1.5 nm

To 0.5 Å in 3rd harmonic

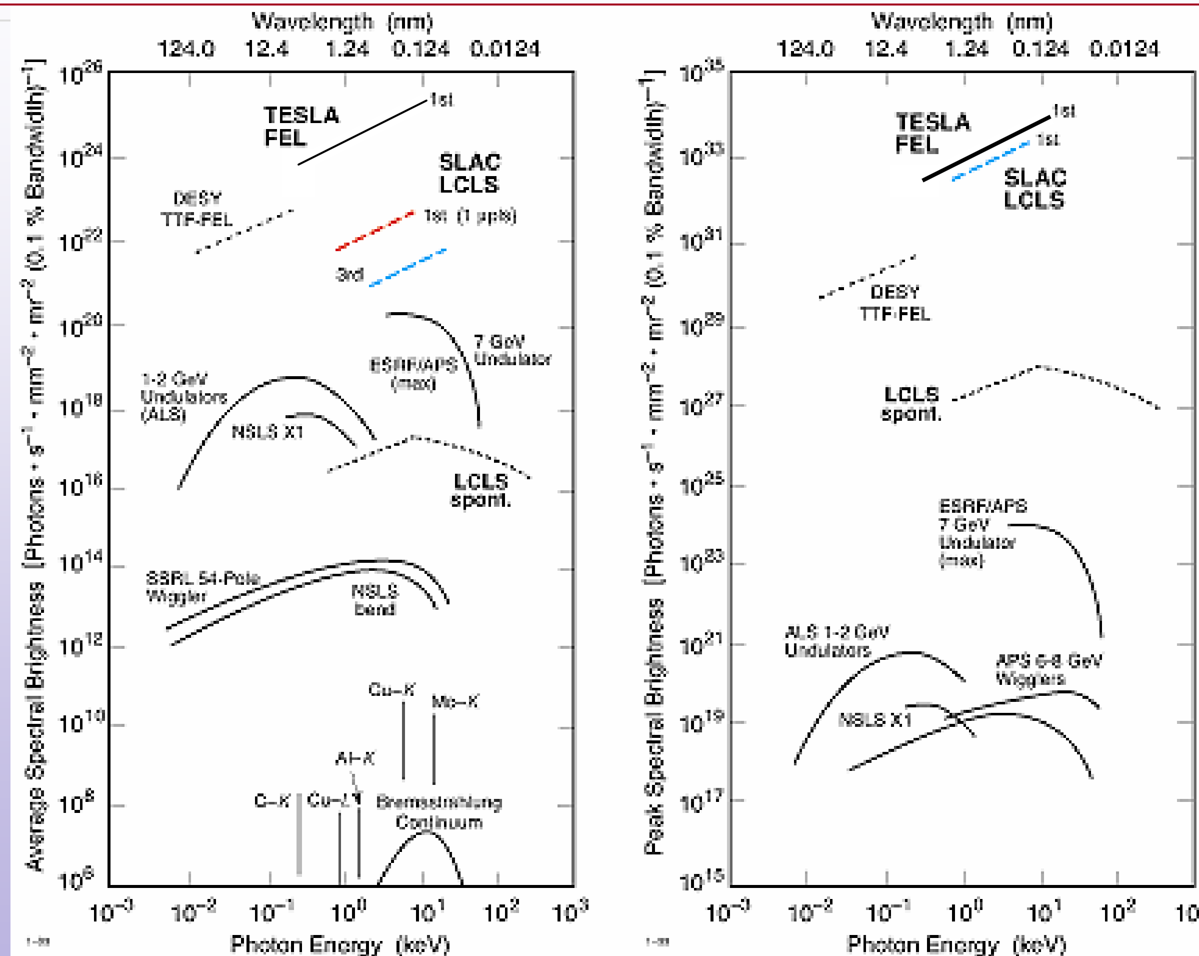
Peak Brightness: 10^{33}

Photons/pulse: 10^{12}

Average Brightness: 3×10^{22}

Pulse duration: <230 fsec

Pulse repetition rate: 120 Hz



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Common Challenges for X-ray Free-Electron Lasers

- *High- brightness sources of electrons*
- *Challenges of Bunch Compression*
- *X-ray optics*
- *X-ray diagnostics/control for timing and pulse length*

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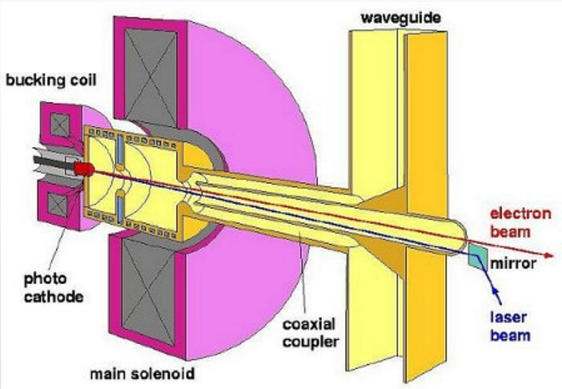
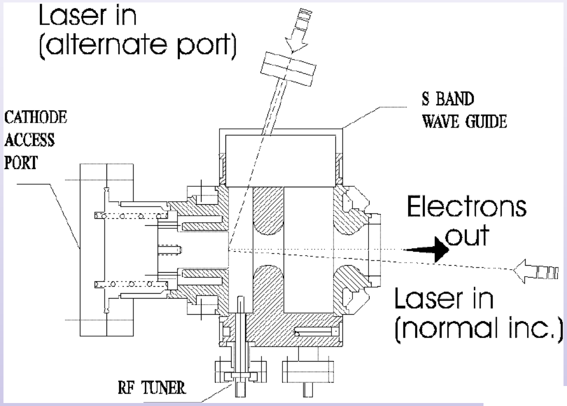
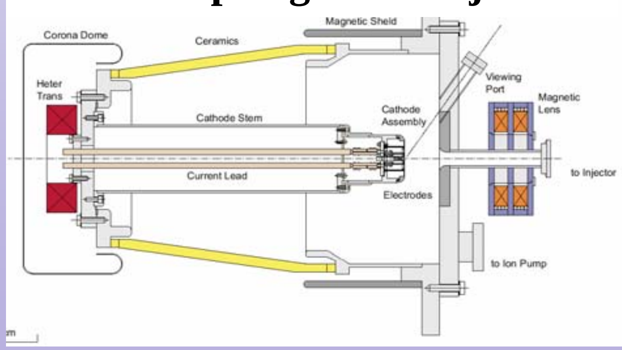
Common Challenge- High Brightness Electron Sources





500 kV Spring-8 DC Injector



- Photocathode
- Laser
- Numerical techniques for gun design
- Verification with experiment
- Diagnostic Techniques

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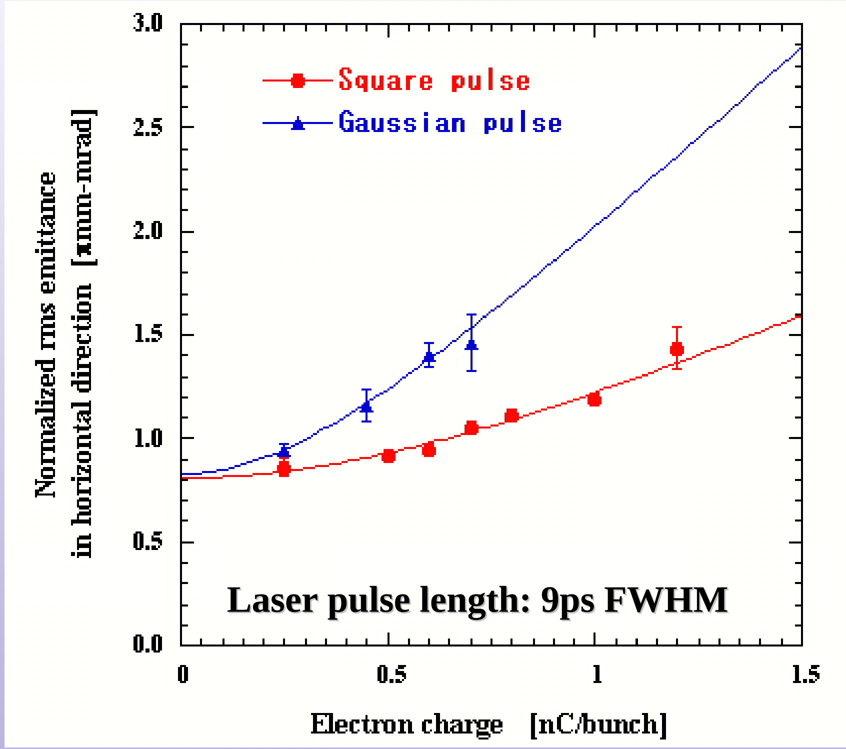
Record Emittances @ Sumitomo SHI + FESTA



$$\varepsilon_n = \sqrt{(a' Q)^2 + b'^2}$$

	a'	$b' = \sqrt{\varepsilon_{rf}^2 + \varepsilon_{th}^2}$
	πmm-mrad/nC	πmm-mrad
Gaussian(9ps)	1.85±0.13	0.83±0.05
Square (9ps)	0.92±0.05	0.81±0.03

The reduction of the linear space-charge emittance for the square pulse shape: ~50%.

Courtesy of F. Sakai

Emittance measurements for gaussian and square laser pulse shapes

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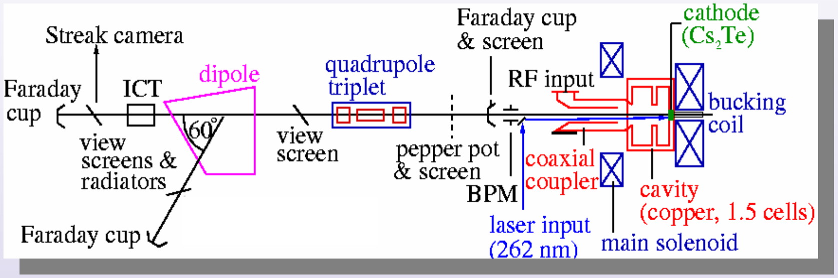
Meeting the Challenge - Gun Testing Facilities

PITZ



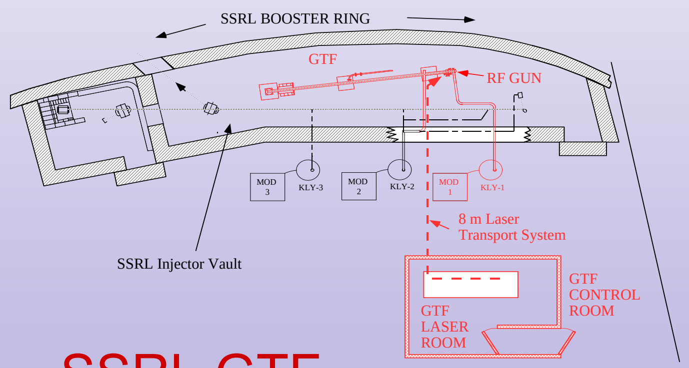
More facilities at

- ATF at Brookhaven,
- ANL Gun Test Facility,
- VESTA,
- …

Thorough characterization of existing designs

Many concepts to be explored:

- **Multi-cell gun**
- **2-frequency gun**
- **Overmoded gun**
- **Hybrid DC/RF gun**
- **Needle Cathode**
- **Other cathodes**



SSRL GTF

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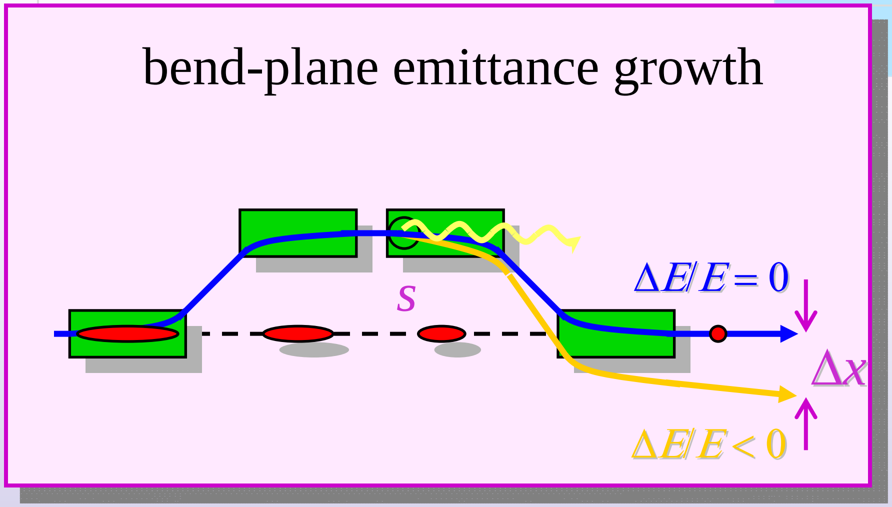
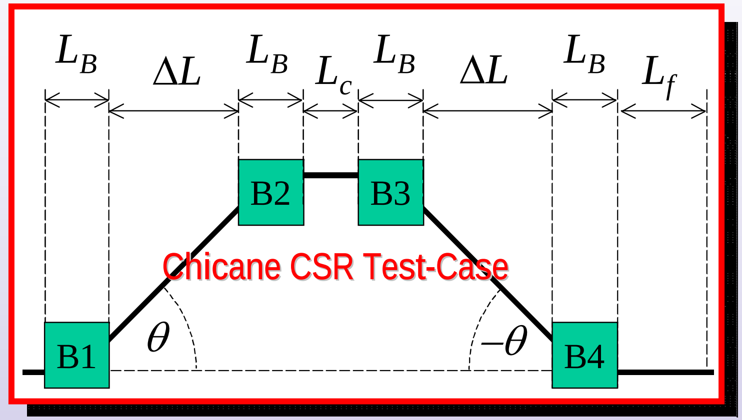
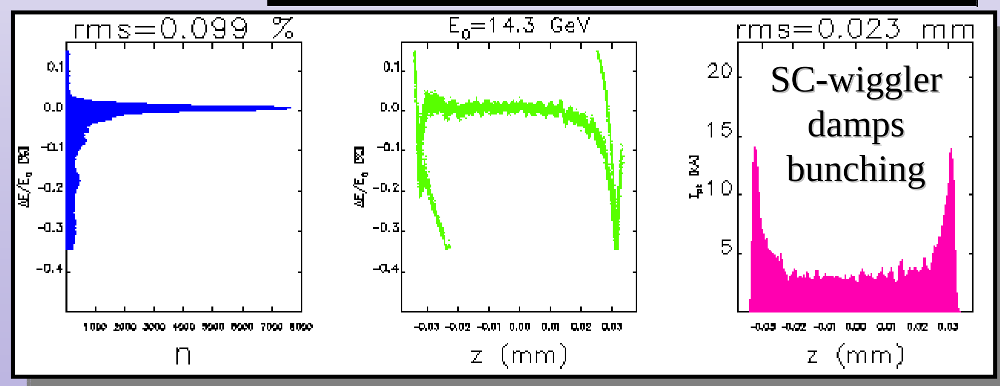
Common Challenge – Coherent Synchrotron Radiation



CSR workshop 2002

January 14-18, 2002 at DESY-Zeuthen (Berlin, GERMANY)





Coherent Synchrotron Radiation

- Theory
- Numerical computations:
  - ANL, SLAC, TESLA, JLAB, ENEA
- Experiment
- Short, high current bunches

S. Heifets, S. Krinsky, G. Stupakov, SLAC-PUB 9165, March 2002

Z. Huang, K. J. Kim, PRSTAB 5 074401(2002)

E. Saldin, et al. TESLA-FEL 2002-2 (submitted to NIM)

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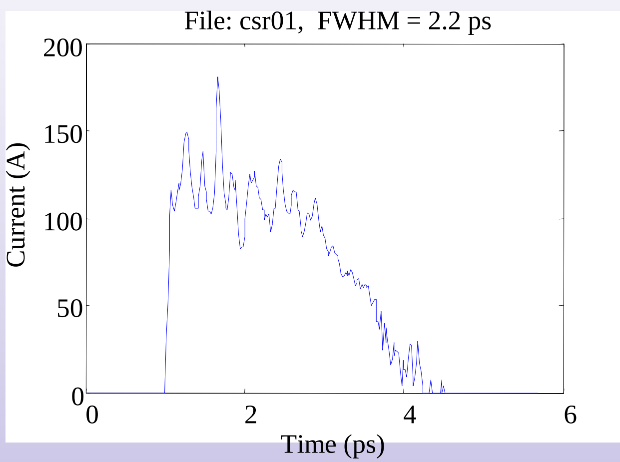
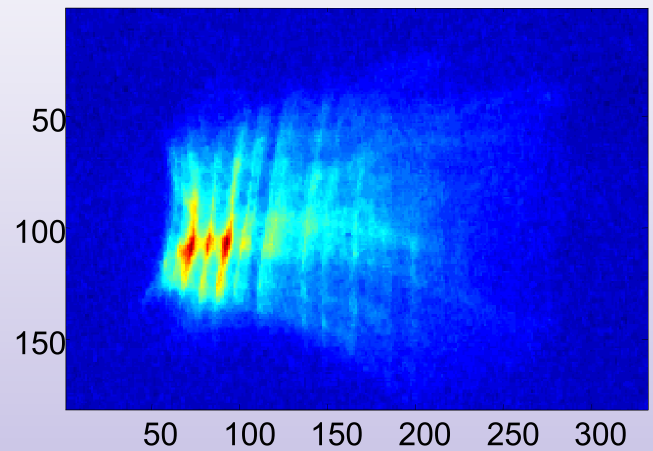
Common Challenge- Longitudinal Space Charge Effects

Saldin/Schneidmiller/Yurkov, TESLA-FEL-2003-02





BNL SDL Observations

ICFA Future Light Sources Sub-Panel

Mini Workshop on Start-to-End Simulations of X-RAY FELs

August 18-22, 2003 at DESY-Zeuthen (Berlin, GERMANY)

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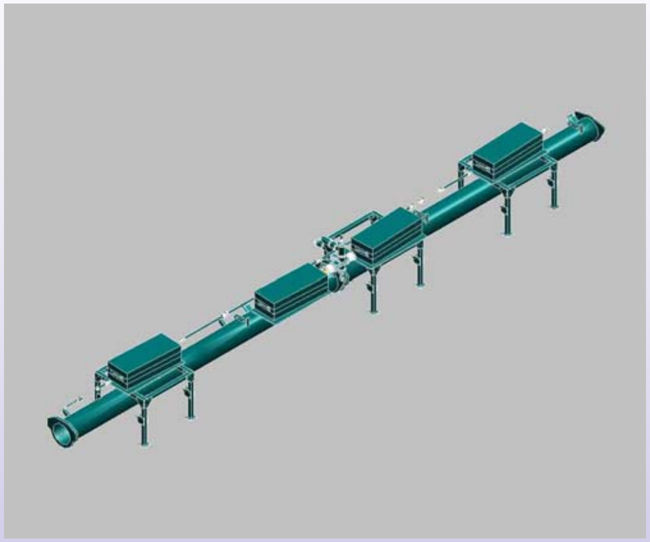
Meeting the Challenge - Testing Bunch Compression

- CLIC Test Facility
- TTF
- LEUTL
- SDL
- SPPS
- VISA



- Countermeasures – Not as easy to test
    - Careful control of gun laser characteristics
    - Laser Heating, leading to Landau damping
    - Superconducting wiggler (at high energy)

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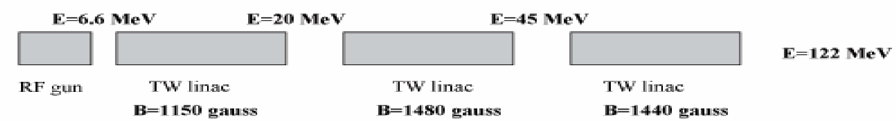
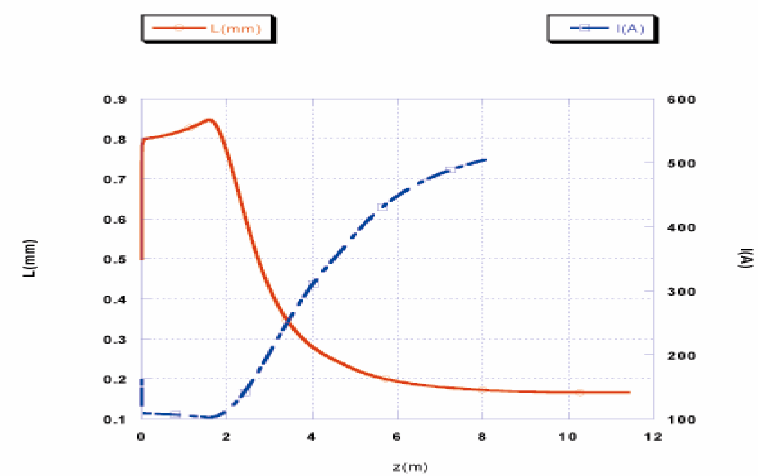
SPARC Project

PRELIMINARY LAYOUT



Ipeak=500 A
En=0.6 π mm mrad
ΔE/E= ± 2.25%

First Parmela Simulation of RF Compressor



C. Ronsivalle

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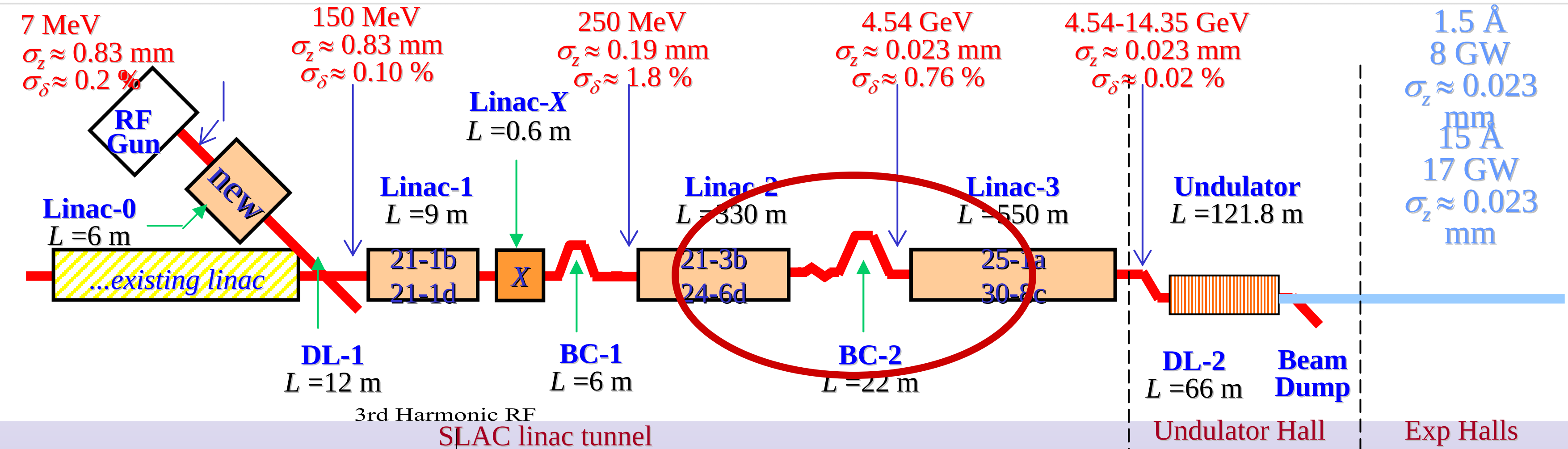
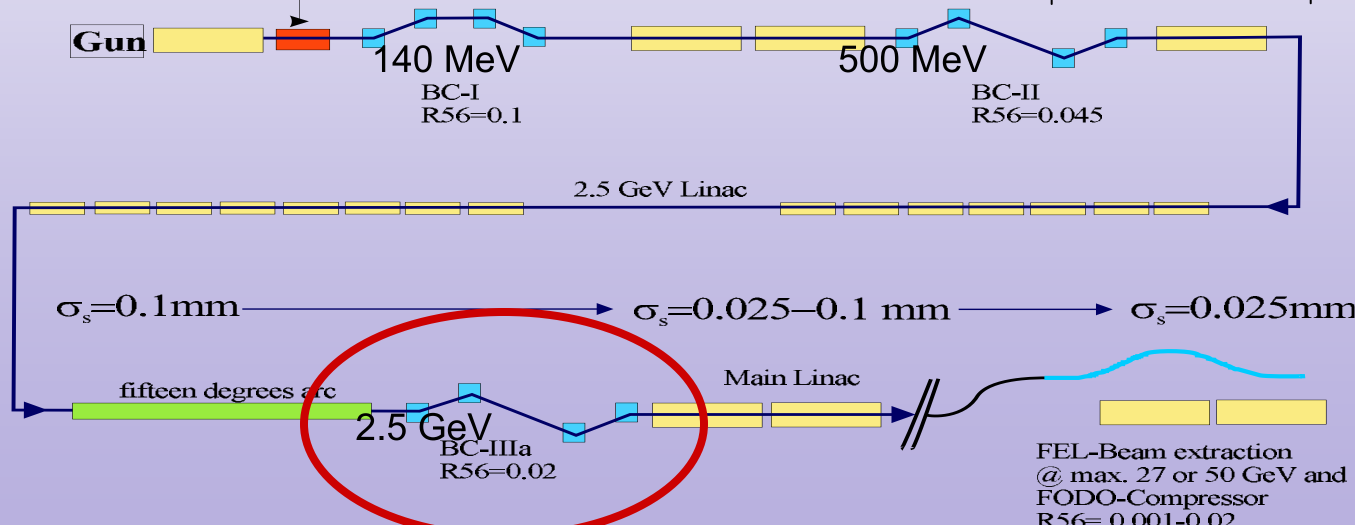
Final Stages of Compression are at High Energy





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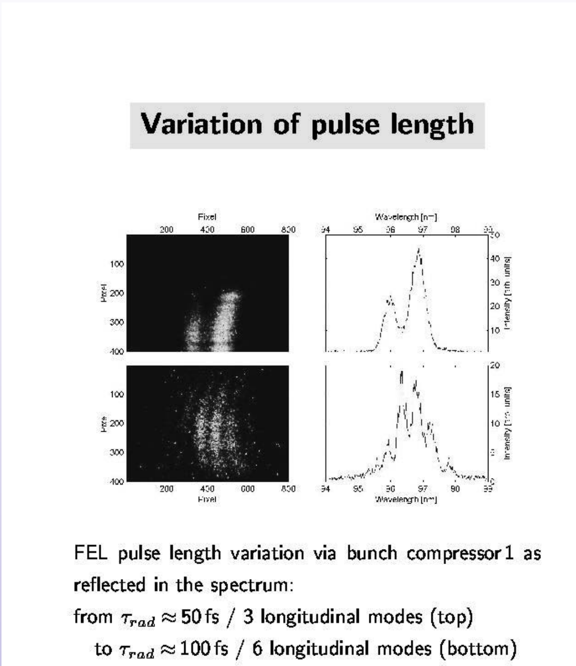
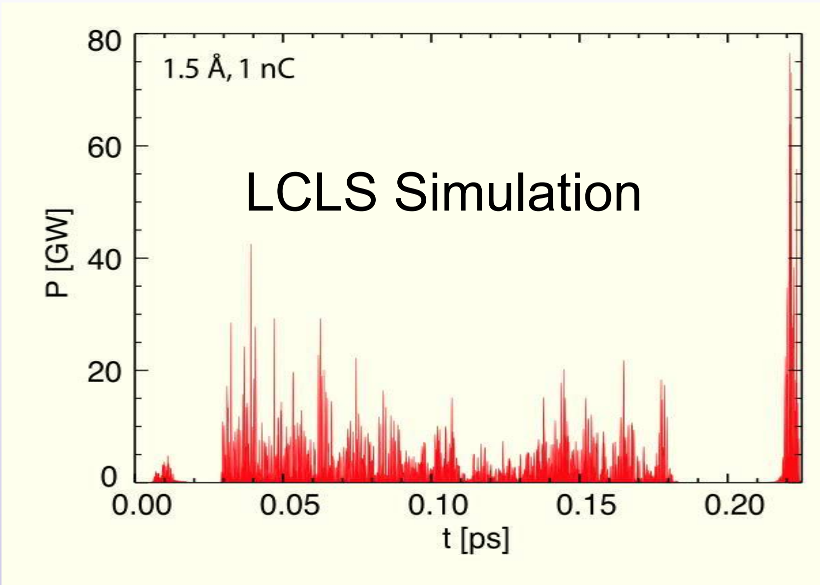
Common Challenges – SASE



TTF x-ray pulse length data



The FEL wants to make shorter pulses

How to measure and control SASE pulse length-

Is <1 fs possible?

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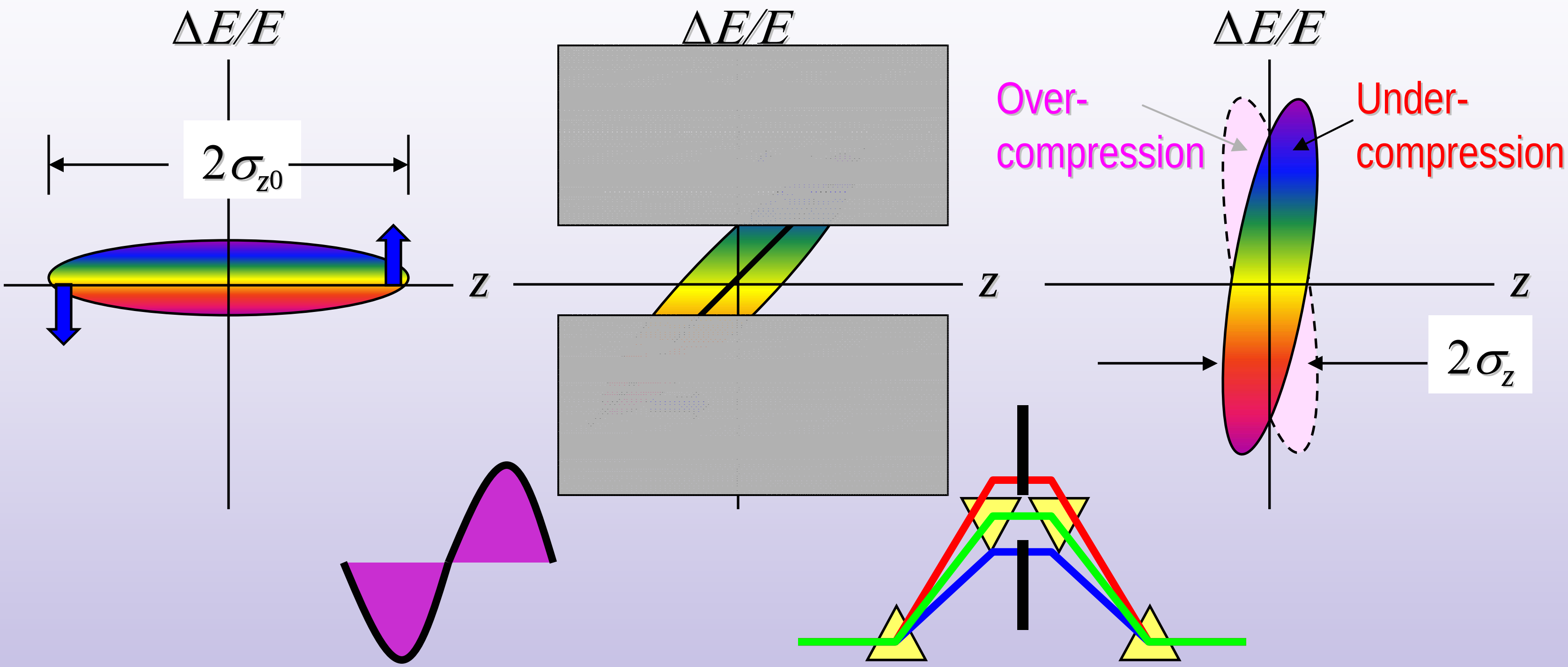
Bunch Compression



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

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

RF Accelerating Voltage

Path Length-Energy Dependent Beamline

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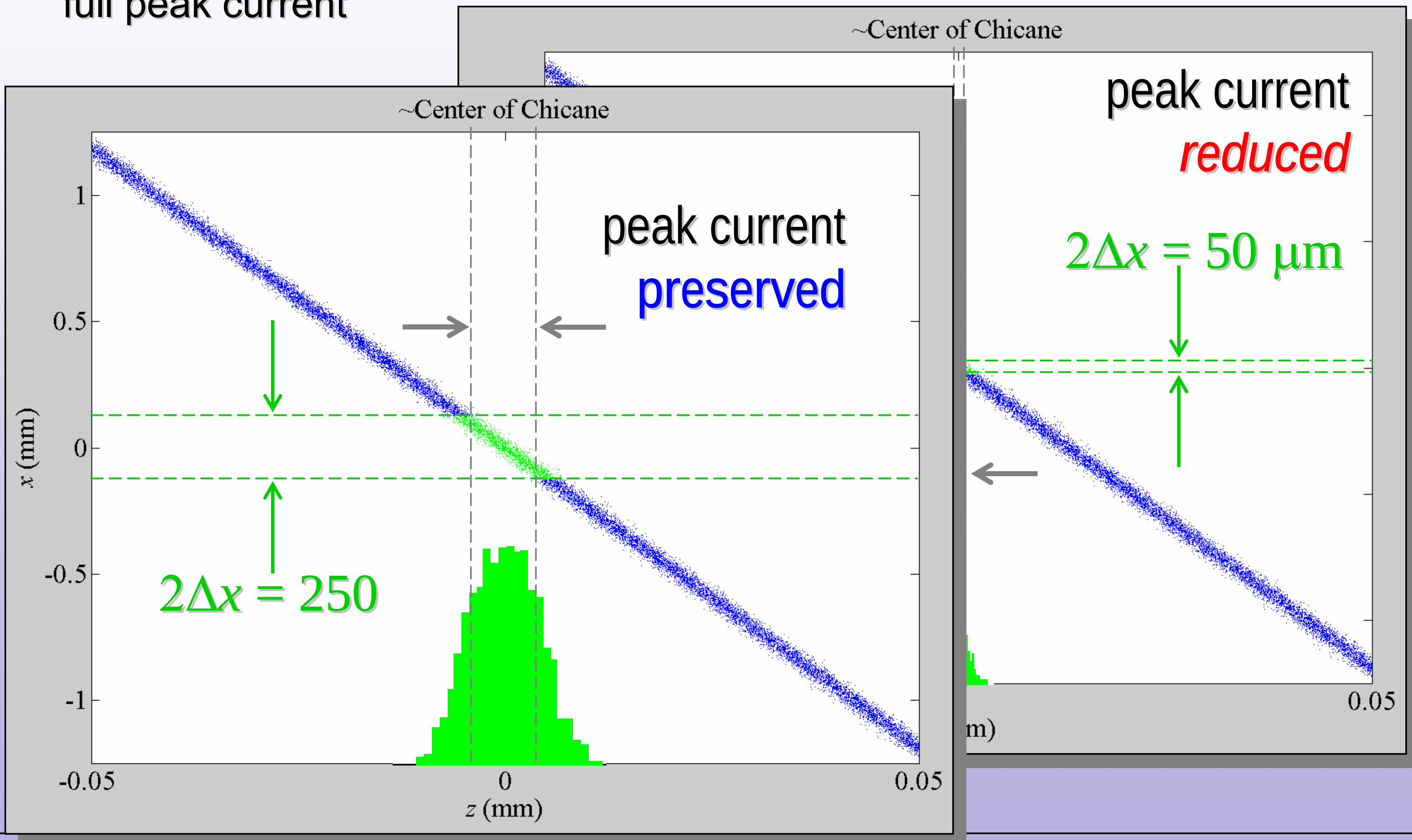
Choose slot for shortest e^- pulse, while retaining full peak current



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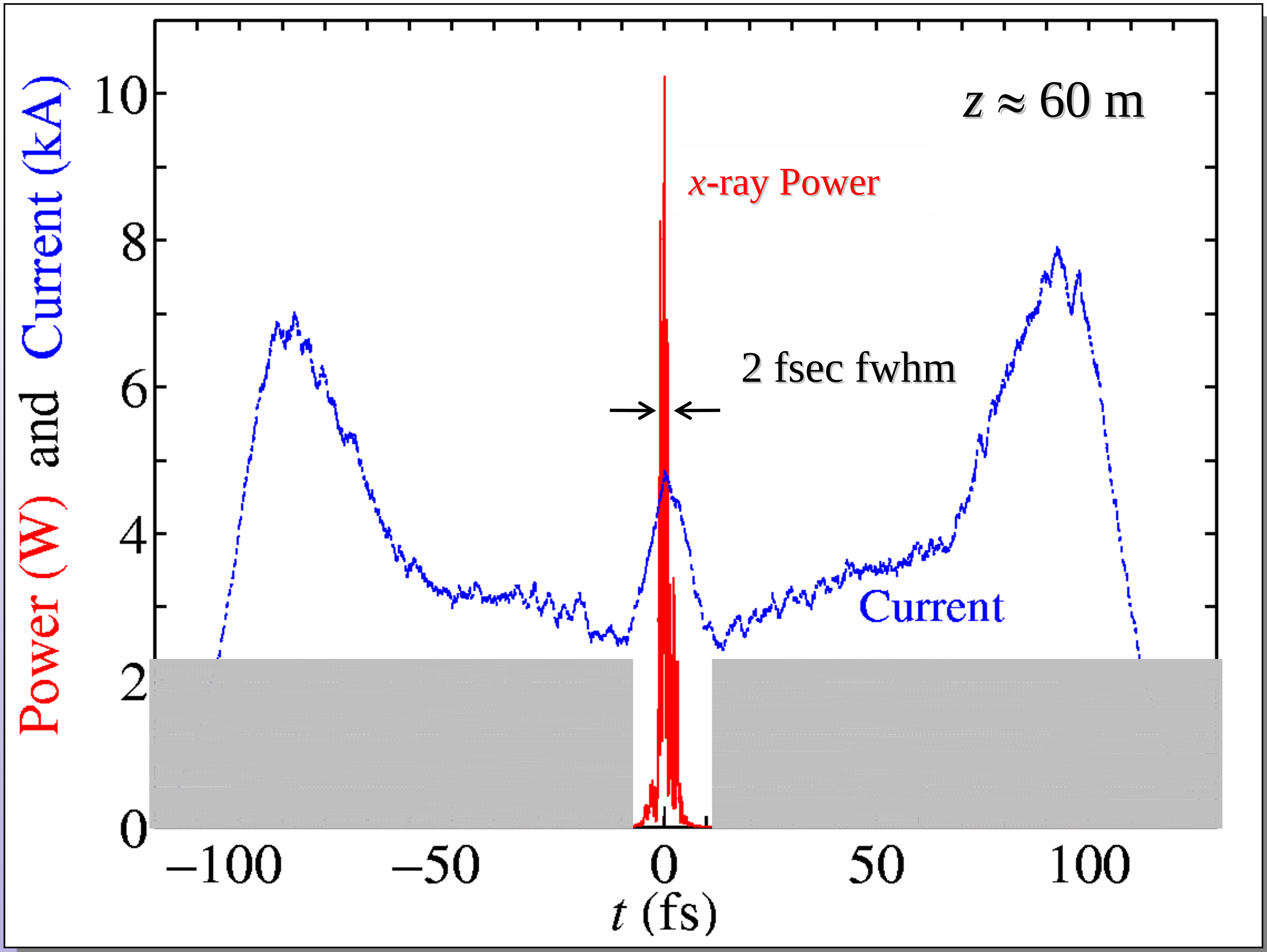

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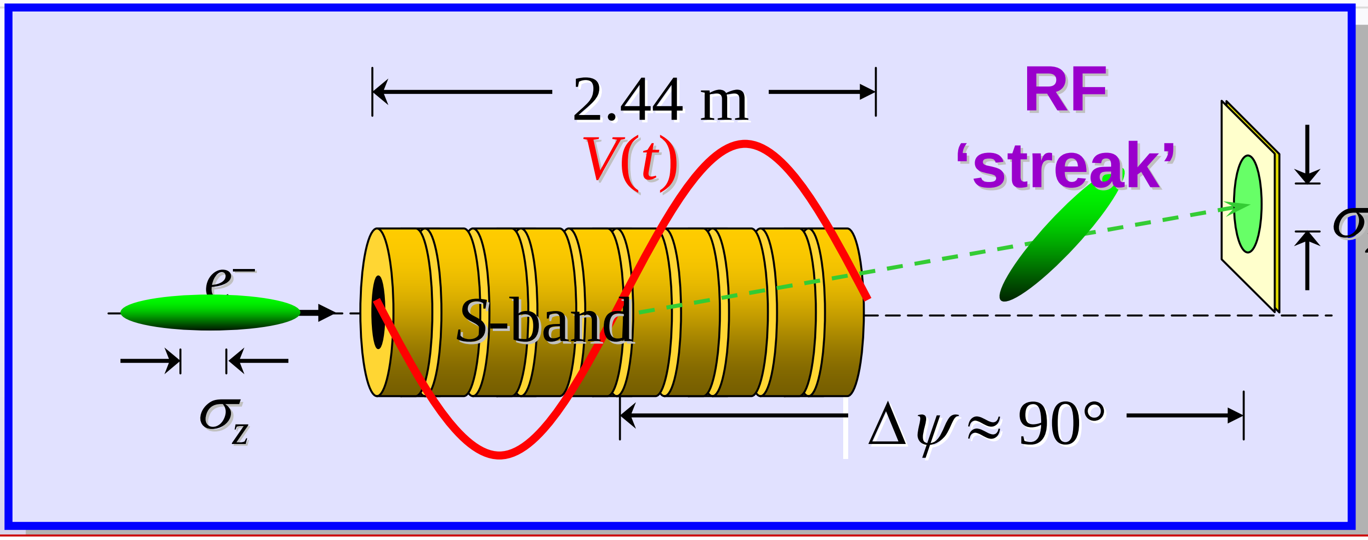
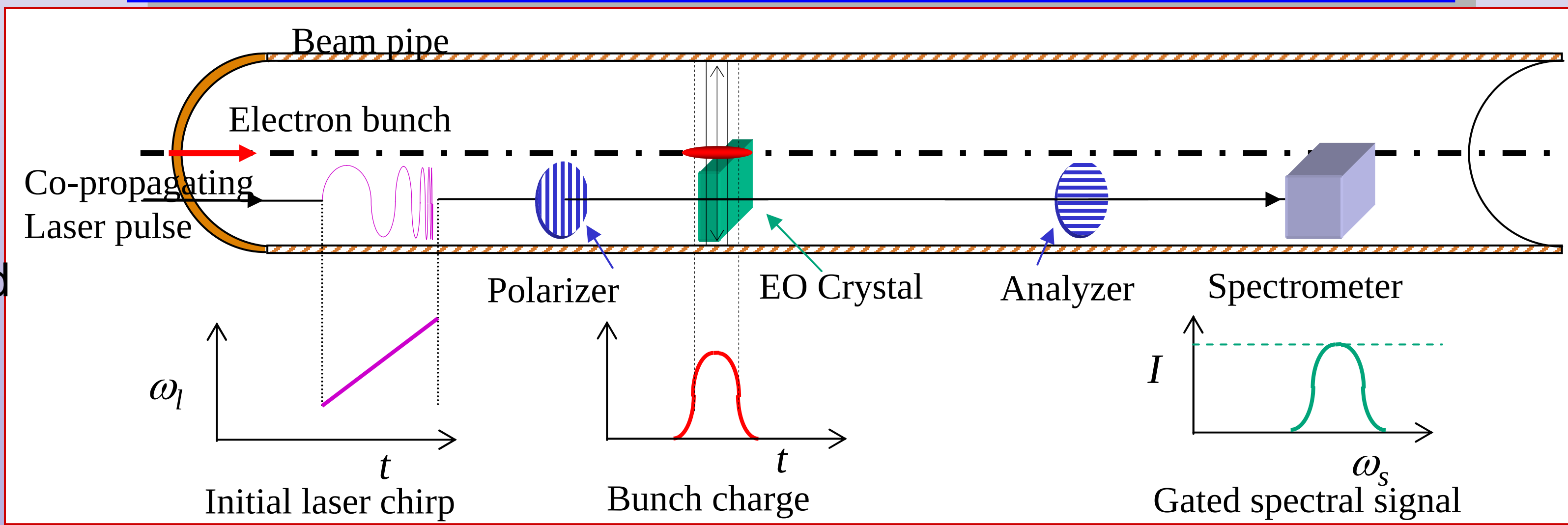
Short Bunches and Diagnostics

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

Tested at SLAC



Added to TTF-II



Added To SPPS

Tested at TTF

Meeting the Challenge- Testing Optics, X-ray Diagnostics, Timing

Sub-Picosecond Pulse Source, TTF

Direct Measurement of x-ray pulse duration, timing

Damage to Optics

Focusing, split/delay while preserving short pulse

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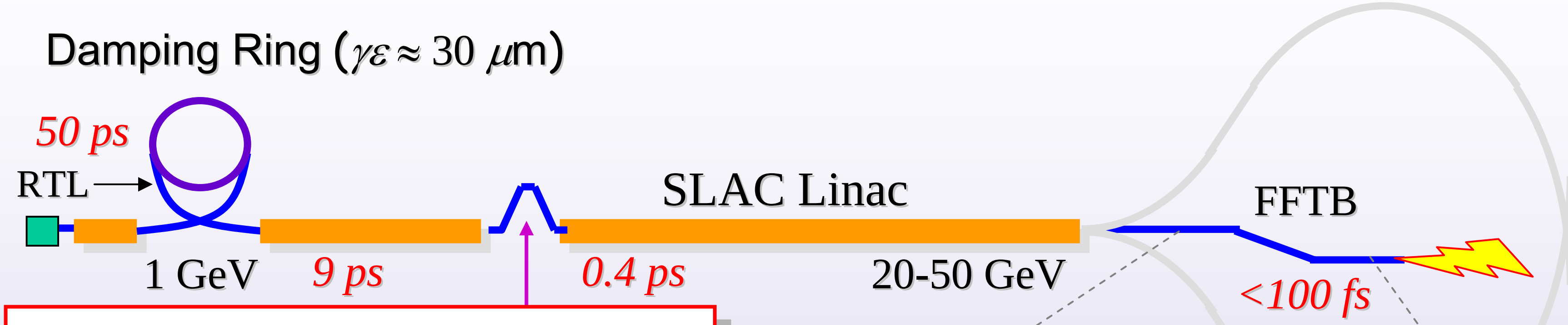
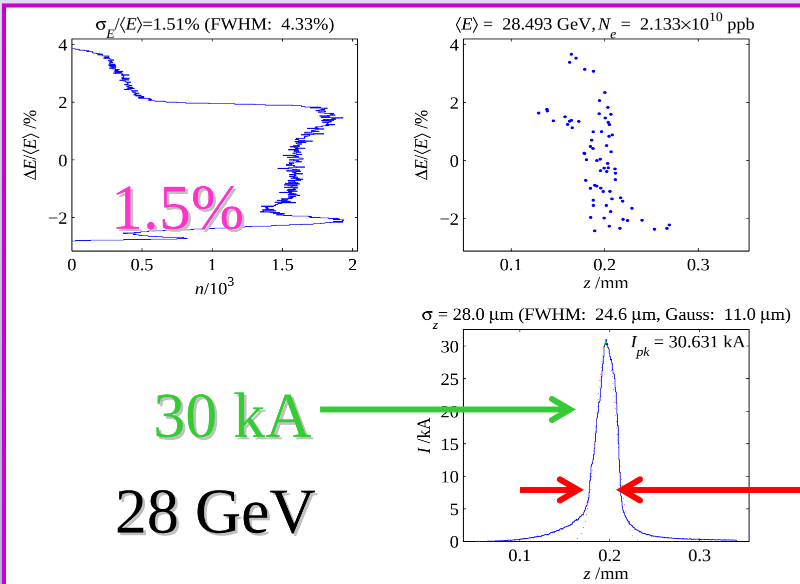
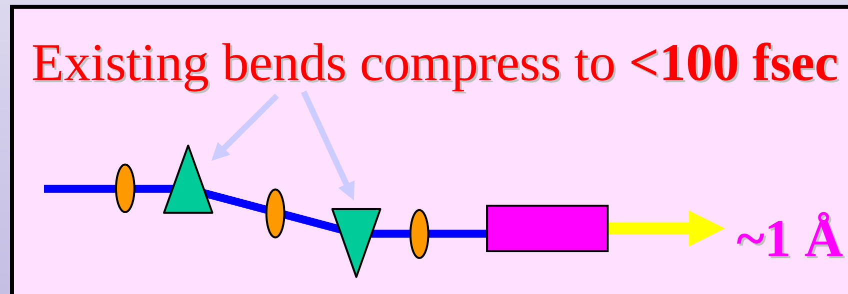
Short Bunch Generation in the SLAC Linac



Add 12-meter chicane compressor in linac at 1/3-point (9 GeV)





80 fsec FWHM

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SPPS Performance based on Advanced Photon Source Wiggler A

Parameters	*Values*	*Units*
Electron beam energy	28	Gev
Horizontal emittance	$9.1\text{x}10^{-10}$	π m-rad
Vertical emittance	$1.8\text{x}10^{-10}$	π m-rad
Beam current	30,000	Amperes
Photon pulse length, FWHM	80	fsec
Repetition rate	30	Hz
Fundamental photon energy	8.3	[keV]
Peak Brightness	4.0×10^{24}	ph/s,mm^2,mr^2,0.1%bw
Average Brightness	9.7×10^{12}	ph/s,mm^2,mr^2,0.1%bw
Peak spectral flux	3.6×10^{20}	ph/s,0.1% bw, all angles
Average spectral flux	8.6×10^{8}	ph/s,0.1% bw, all angles
Output photons per pulse	2.9×10^{7}	ph/0.1% bw, all angles

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SPPS Collaboration: Institutional Members

APS Argonne Nat'l Lab
BioCARS
Copenhagen Univ.
DESY
NSLS Brookhaven Nat'l Lab
SLAC/SSRL
UC Berkeley
Univ. of Michigan
Univ. of Uppsala

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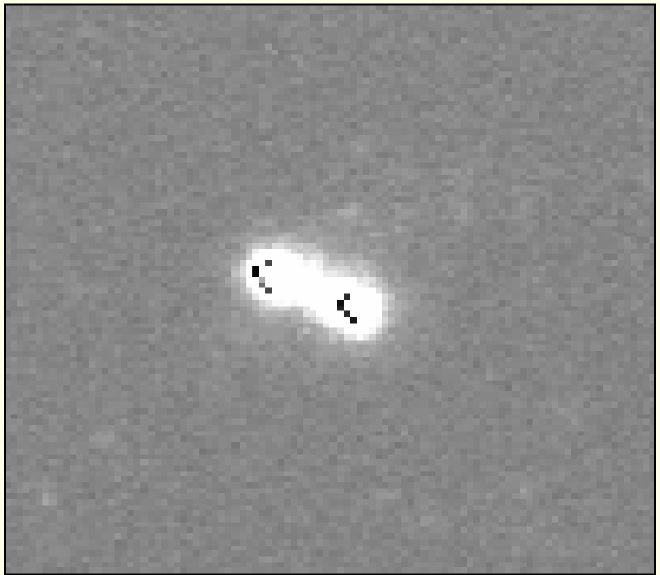
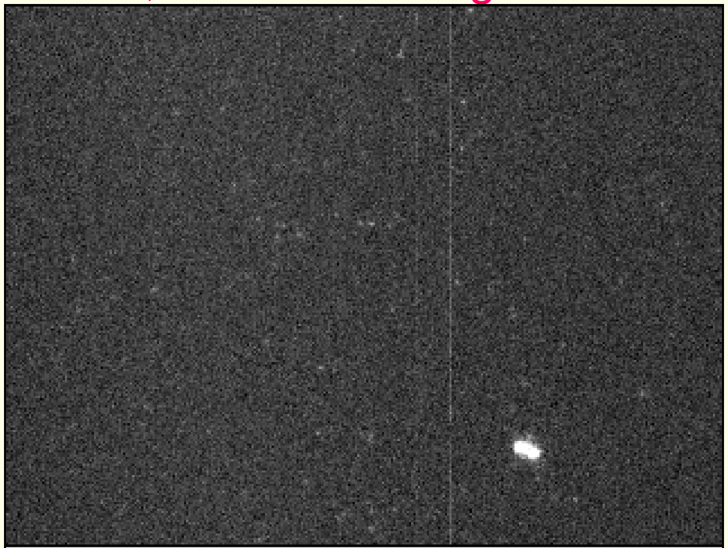
Single pulse exposures

- ***Probing the rocking curve***
- ***18 steps: $\Delta\Phi$=-1.0° to $\Delta\Phi$=+0.4°***
- ***Single exposures***
- ***gated CCD, 62 ms***



rc1x1.avi

Intensity fluctuations
90 exposures @ 10 Hz,
gated CCD, 62 ms
$\Delta\Phi$=0, Max. of rocking curve



rock00.avi

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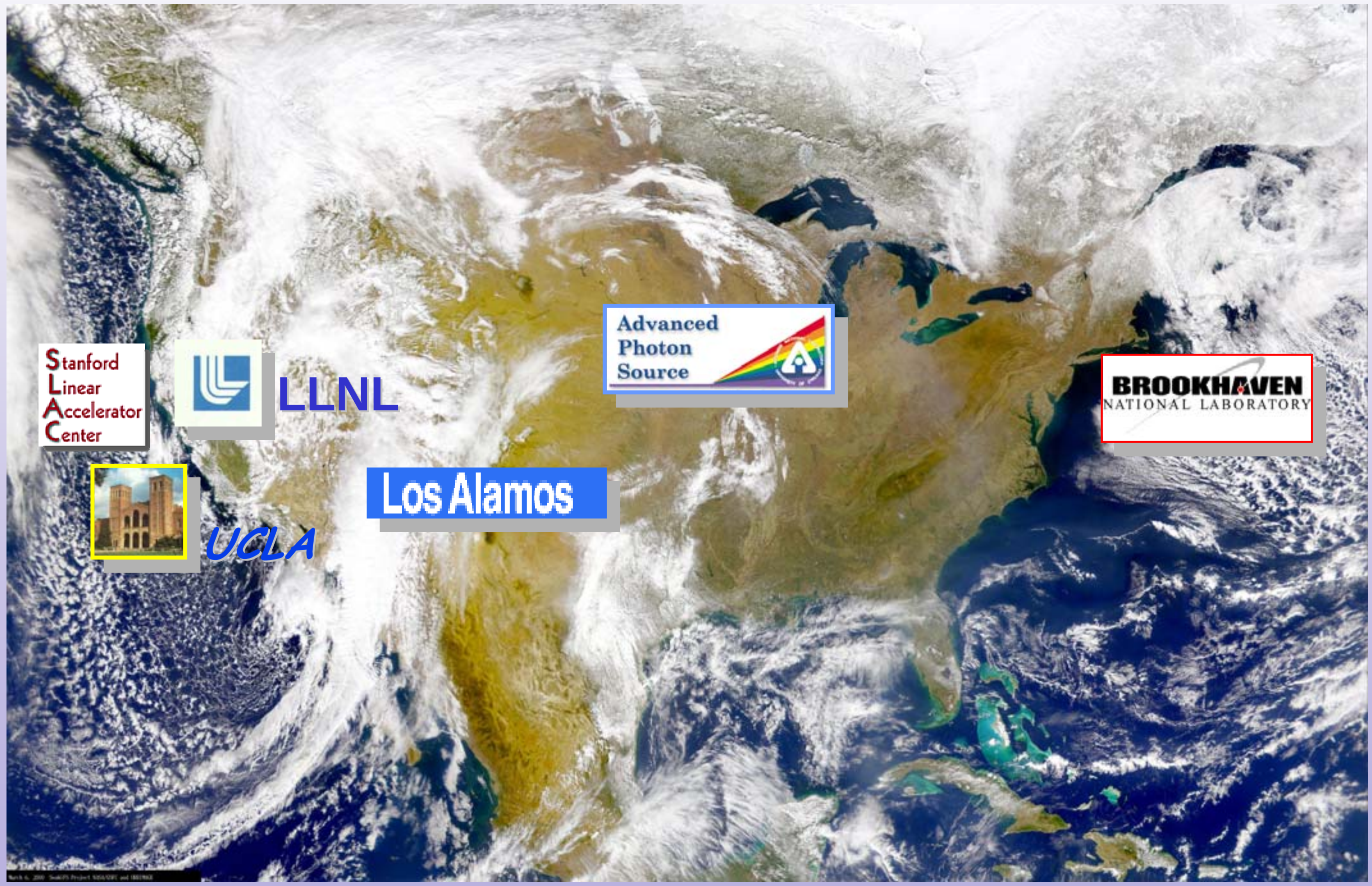
LCLS R&D Collaboration

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



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LCLS Construction Collaboration

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

SLAC:Accelerator Systems, Experiment Stations, Buildings

ANL:Undulator Systems

LLNL:X-ray High Power Optics

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Collaborative research agreements with

- TESLA XFEL Lab – Bunch Compression, X-ray Optics
- INFN Frascati SPARC FEL project- Laser & Gun R&D

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SLAC-DESY/TESLA FEL Collaboration

- ***1 November SLAC/DESY FEL Collaboration Workshop***

Albrecht Wagner	Hermann Schunck	Ray Orbach	Jonathan Dorfan
Director DESY	Ministry of Science/Education	DOE Office of Science	Director SLAC

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Detectors and X-ray Optics

- *Fastest time-resolving detectors (streak cameras) currently have time resolution of about 500 fs. Also limited by poor quantum efficiency for x-rays. Further R&D could push the resolution down to 100 fs.*
- *Many fast experiments can use pump/probe, where time resolution depends on pump and probe durations, allowing a variety of slow detectors to be used. R&D on x-ray optics such as pulse splitters and delay lines will benefit this approach.*
- *Nearly all sub-picosecond pulse diagnostics, including measurement of pulse length and calibration of pump/probe system, require correlation methods that detect overlap of two pulses with femtosecond precision. R&D on such methods in the x-ray range has hardly begun.* This is the most critical development area for FEL scientific applications.
- *High FEL pulse intensity invites the use of large area detectors to collect all data in a single shot. High data rates, high dynamic range, and low noise are all required. Existing x-ray CCD detectors will not suffice; R&D into other technologies, such as pixel array detectors, is needed.*

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Summary

- *LCLS project a near-term priority in US FEL R&D Roadmap*
- *Potential for great progress with existing FEL/e-beam test facilities, particularly in gun R&D*
- *Great opportunities for accelerator development when the first generation of hard x-ray FELs are built*

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End of Presentation

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