



# Compact X-Ray FELs Using High-Brightness Beams *Cheaper, Better, Faster*

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FEL Miniworkshop  
August 5-6 2010

$$B_N = \frac{N_e}{\epsilon_{nx} \epsilon_{ny} \epsilon_z} = \frac{N_e}{\epsilon_{nx} \epsilon_{ny} \sigma_z \sigma_\gamma}$$

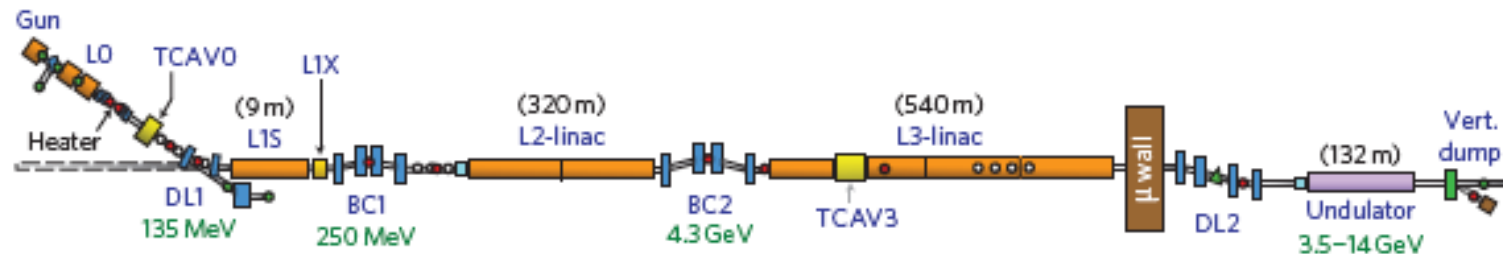


Figure 1 | LCLS machine layout. Layout from the electron gun to the main dump, with two bunch compressors, BC1 and BC2, and a 132-m-long undulator.

# Why are we here?

## **Compact (cheap) X-Ray FELs Using High-Brightness Beams**

Thursday August 5, 2010 — Friday, August 6, 2010

Recent advances in RF gun design and operation indicate that low charge bunches can be produced with high brightness electron beams. Can (or have?) we expect to simultaneously reach parameters

1–10 pC bunch charge

Transverse emittance  $\sim 1-3 \cdot 10^{-7}$  m

Longitudinal emittance  $\sim 1-10$  keV-ps.

If so: high brightness

reduces the energy needed to satisfy the FEL emittance constraint,  
coupled with small enough longitudinal emittance, we can reach the X-ray regime with  
substantially lower electron energy:

Issues that we will discuss:

- 1) Can wigglers be constructed reliably with sub-centimeter periods?
- 2) Can high-brightness bunches be accelerated, compressed, and transported without degradation?
- 3) Can particle (and radiation beams) propagate through small-gap wigglers for many gain-lengths?
- 4) What are the consequences of short bunch FEL operation (longitudinal coherence, reduced gain, seeding)



# FEL considerations

Emittance and energy spread constraints

$$\frac{\epsilon_n}{\gamma} < \frac{\lambda}{4\pi} \quad \frac{\Delta\gamma}{\gamma} \leq \rho_{3d}$$

$$\lambda = \frac{\lambda_w (1 + a_w^2)}{2\gamma^2}$$

Six dimensional beam brightness:

Conserved (ignoring scattering, nonlinearity/mismatch, CSR, wakefields...)

Determines scale for FEL gain

$$B_N = \frac{N_e}{\epsilon_{nx} \epsilon_{ny} \epsilon_{zn}} = \frac{N_e}{\epsilon_{nx} \epsilon_{ny} \sigma_z \sigma_\gamma}$$

FEL Equations scale with the 'brightness length'

$$\frac{1}{L_B k_w} = \frac{2a_w^2}{(1+a_w^2)} \frac{\gamma^2}{k^2} r_{cl} B_N = \frac{2a_w^2}{(1+a_w^2)} \left( \frac{E_e}{E_v} \right)^2 r_{cl} B_N$$

Optimum growth rate scales linearly with brightness

At fixed brightness and photon energy:

*optimum growth rate is inversely quadratic in beam energy*

*Difficulty for EM wiggler---requires large power for wiggling and sufficient length for gain.*

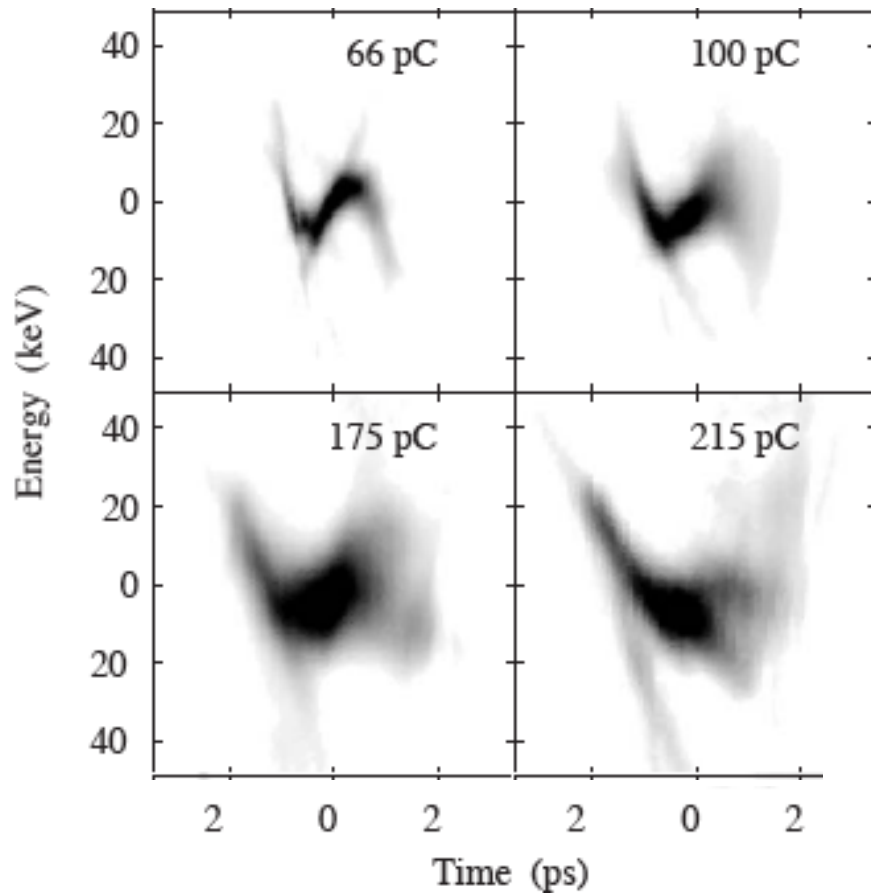
**Emittance criteria can always be satisfied (in theory) by throwing away (judiciously) some charge.**

**This may move you closer to the optimum, but will not increase it.**

$$B_N \sim \frac{I}{\epsilon_{nx} \epsilon_{ny} \sigma_\gamma} \quad \frac{\Delta\gamma}{\gamma} \leq \rho_{3d}$$

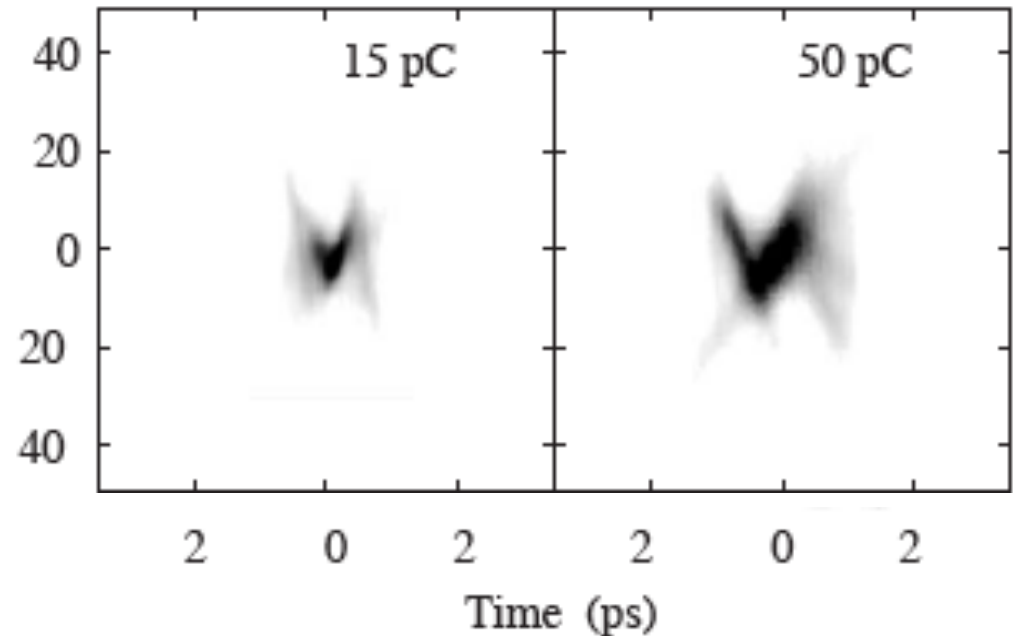
- Push towards short bunch low charge FELs requires **high brightness bunches** (bunches need to be compressed to get high current, and compression leads to energy spread increase).  
Avoid CSR, heaters, etc. Gain longitudinal coherence.
- Now combine this with a factor of **~10 increase in longitudinal brightness** from cathodes can potentially make a big difference in FEL design (opening up short wavelength wiggler options)
- Low charge → low emittance → satisfy wavelength requirement at lower energy → require short wavelength wiggler for resonance.
- Compression to get high current → need low energy spread to satisfy longitudinal thermal spread constraint → need to increase longitudinal brightness.
- Sub-cm wavelength wigglers

# Real world distributions



- Devil is the details.
- Measurement and instrumentation
- Control
- Wakefields in undulators

(Loos, et al. NIM 2004)



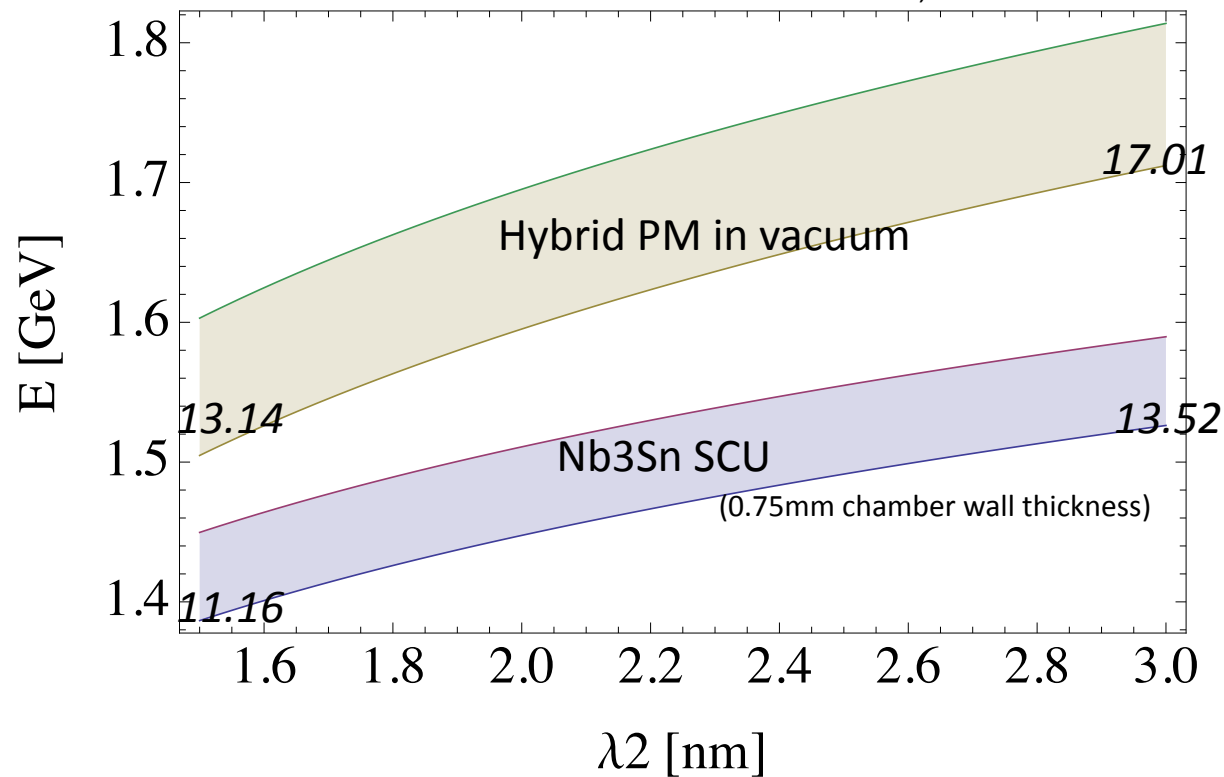
		NGLS	typical	brightness	brightness
			x5; 20ps	X5; 10ps	
Beam Parameters	UNITS				
Energy	MeV	2400	800.00	800.00	800.00
FWHM	psec	0.3	0.01	0.02	0.01
emitN	micron	0.8	0.10	0.10	0.10
Ipeak	A	1000	500.00	250.00	500.00
sigE	MeV	0.100	3.00	0.30	0.60
beta	m	10.00	4.20	4.20	4.20
Q	nC	0.300	0.005	0.005	0.005
emitG	nm-rad	0.170	0.064	0.064	0.064
sig_eta	%	0.004	0.375	0.038	0.075
sigx	micron	41.3	16.4	16.4	16.4
sigxp	microrad	4.1	3.9	3.9	3.9
gamma		4696.7	1565.6	1565.6	1565.6
emit_long	KV-ps	30.00	30	6	6
Undulator Parameters					
lambdaU	mm	24.00	5.00	5.00	5.00
is_planar	boolean	TRUE	FALSE	FALSE	FALSE
aw		0.9156	0.4201	0.4201	0.4201
Bpeak	T	0.578	0.900	0.900	0.900
FEL calculations					
lambda	nm	1.000	1.2	1.2	1.2
rho		7.29E-04	7.36E-04	5.84E-04	7.36E-04
rho_effect		5.64E-04	3.90E-06	2.96E-04	2.12E-04
Lg 1D	m	1.51	0.31	0.39	0.31
Lg 3D	m	2.0	58.9	0.78	1.08
Psat 1D	GW	1.75	0.29	0.12	0.29
Psat 3D	GW	1.68	0.00	0.05	0.04
Lsat	m	37.7	520.2	13.6	18.2
Lsatb	m	34.3	1295.3	13.2	19.5
Pbeam	TW	2.4	0.4	0.2	0.4

## Physics and technical capabilities, current and projected

- Lower energy beams → lower costs
- Lower energy beams → higher technical risk,
  - High brightness beams: creation, propagation.
  - Short wavelength wigglers: magnet technology, beam propagation
  - Short bunch FEL operation: Trade-offs (bunch length, charge, gain length); generation of THz with short bunch (synchronization);
  - Instrumentation, diagnostics

# Impact of undulator technology on beam energy selection

Assume vacuum gap 4-5mm;  $K_{min}=0.8$  (yields  $\lambda_2, \lambda_1=1\text{nm}$  in all cases)



# A Few Questions

What can be achieved with cm to few mm wavelength wigglers? Where does performance breakdown for different technology options?

What determines limits on beam brightness? How high can we go?

What are the best gun results to date? Is there a need for more detailed measurements? Are new diagnostics needed? How do gun results translate to beam at the wiggler for various brightness and bunch charge combinations?

Factor of 5-10 increase in longitudinal brightness (assuming reduced emittance scaling as  $\sim\sqrt{Q}$ ) from guns can potentially make a significant difference in FEL design.

Is this an achievable goal for an aggressive R&D plan (say, 5 years) properly coordinated between the labs? Improved performance benefits all programs. What is required to demonstrate success: individual components or, e.g., a 100MeV test facility?

What are the key unknowns for short bunch FEL operation?

Outside our scope—but critical---the photon pulse structure and the users.

"Mini-Workshop" on  
**Compact X-Ray FELs Using High-Brightness Beams**

Thursday August 5, 2010 — Friday, August 6, 2010

Conference room of Building 71, LBNL

Berkeley, CA, USA

*Program (as of 8/2/2010)*

**Thursday Aug. 5**

**Morning**

- 9:00 Welcome  
9:05 **J. Corlett**, *Overview of X-Ray FEL R&D at LBNL*  
9:20 **J. Wurtele**, *Towards lower energy X-Ray FELs*  
9:40 **F. Sannibale**, *Gun R&D at LBNL*  
10:20 – 10:30 Coffee Break  
10:30 **J. Bisognano**, *Gun R&D at Wisconsin*  
11:10 **J. Lewellen**, *The NPS SRF gun*  
11:50 **R. Lindberg**, *Thermionic -based injector R&D at ANL*  
12:15 Discussion  
12:30 – 2:00 PM Lunch Break

**Afternoon**

- 2:00 **C. Pellegrini**, *Ultra fast x-ray FELs for pump probe experiments*  
2:40 **D. Xiang**, *Experimental demonstration of the echo-enabled harmonic generation technique at SLAC*  
3:10 – 3:20 Coffee Break  
3:20 **P. Emma**, *Beam brightness measurements in the LCLS injector*  
4:00 **D. Dowell**, *Unresolved emittance issues of the LCLS gun*  
4:40—5:00 Discussion

## Friday Aug. 6

### Morning

- 9:00 **Y. Ding**, *Low-charge beam operations at LCLS*  
9:30 **J. Frisch**, *Low-charge beam diagnostics*  
10:00 **Z. Huang**, *Single-shot method for measuring fs bunches in LCLS*  
10:30 – 10:50 Coffee Break  
10:50 **J. Byrd**, *Timing & Synchronization*  
11:20 **A. Zholents**, *Novel scheme for bunch compression*  
12:00 **E-S. Kim**, *Beam dynamics in a linac for PAL-FEL*  
12:30 – 2:00 PM Lunch Break

### Afternoon

- 2:00 **G. Penn**, *Lasing of 1-10pC beams*  
2:40 **S. Prestemon**, *Short-period undulator technology*  
3:20 – 3:30 Coffee Break  
3:30 **G. Stupakov**, *Wakefield effects in small gap undulators*  
4:00 **J. Wu**, *Wakefield measurements at LCLS*  
4:30 – 5:00 Closing Discussion