Introduction to Free Electron Lasers (Part 2)

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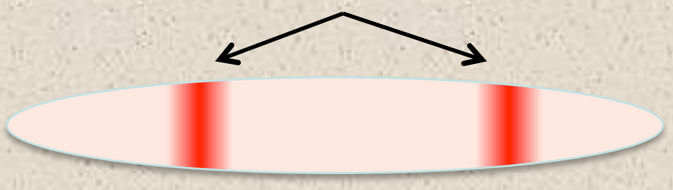
Intro to SASE FELs

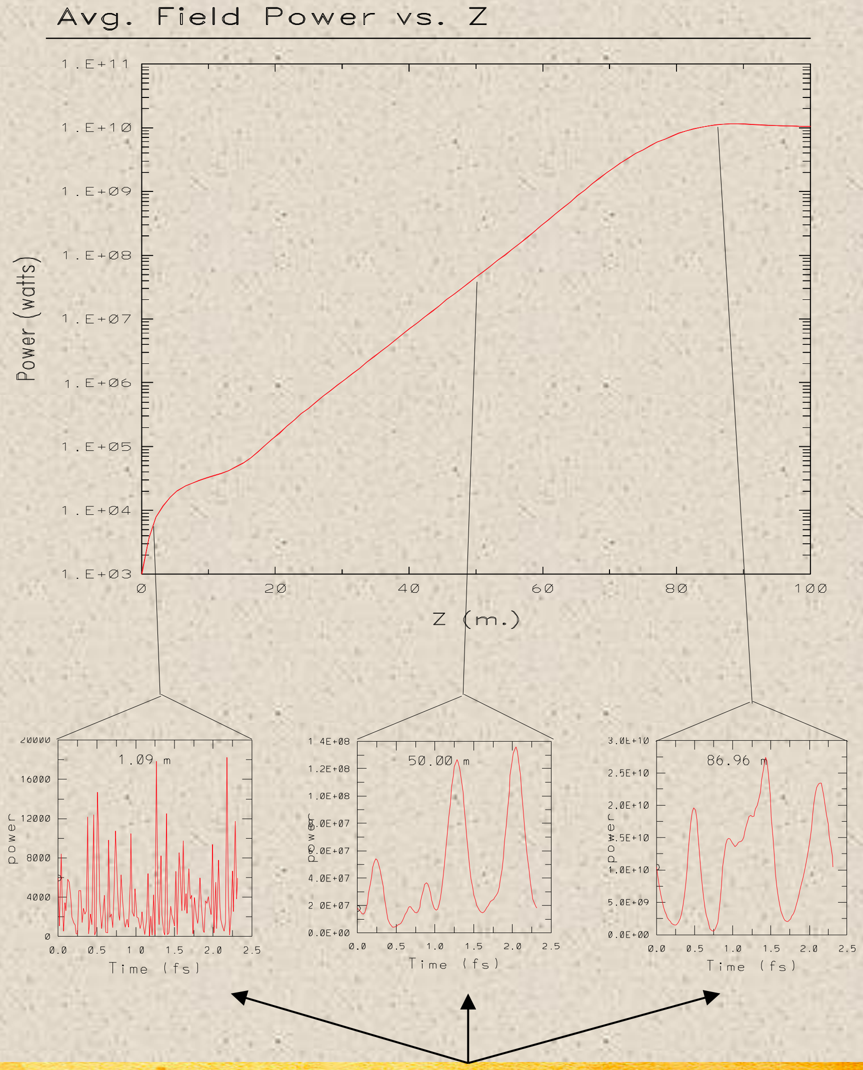
Implications of shot noise:

Different slices don't communicate



Each slice lases independently!

Upshot: SASE FELs have complicated temporal structure



1 % of X-Ray Pulse Length

The Linac Coherent Light Source

LCLS accelerator parameters:

Electron energy range	2.5-15.8 GeV
Electron charge	20-250 pC
Slice emittance (normalized)	0.2-0.4 um
Electron pulse length	~5-500 fs
Peak current	1-3 kA
Initial slice energy spread	1-2 MeV
Electron energy jitter	0.04-0.07 %
Undulator period	3 cm
Number of undulator periods	3000
Gain length	1.5-3 m

LCLS Parameters

LCLS X-ray performance:

Parameter	Value
Photon energy range (fundamental)	0.3-11.2 keV
Photon wavelength range	0.11-4 nm
Typical pulse energy	2 mJ
Typical number of photons	$10^{12} – 10^{13}$
Bandwidth (non-seeded)	0.1-0.5 %
Pulse length	<10-400 fs
Focused beam size	100 nm – 50 um

Realities of building an XFEL

$$\boxed{\varepsilon_x < \frac{\lambda_r}{4\pi}}$$

emittance < radiation wavelength

→ $\gamma\varepsilon$ < 1 µm

Undulator strength

Peak current

Beam energy

FEL parameter

$$\boxed{\rho = \left[\frac{1}{16\pi^2}\frac{I}{I_A}\left(\frac{K[\mathrm{JJ}]}{1+K^2/2}\right)\frac{\gamma\lambda^2}{\sigma_x^2}\right]^{1/3} > \sigma_E}$$

Energy spread

Beam size

Need high energy, high peak current, low emittance, and small energy spread

➔ Need bright beam both transversely and longitudinally

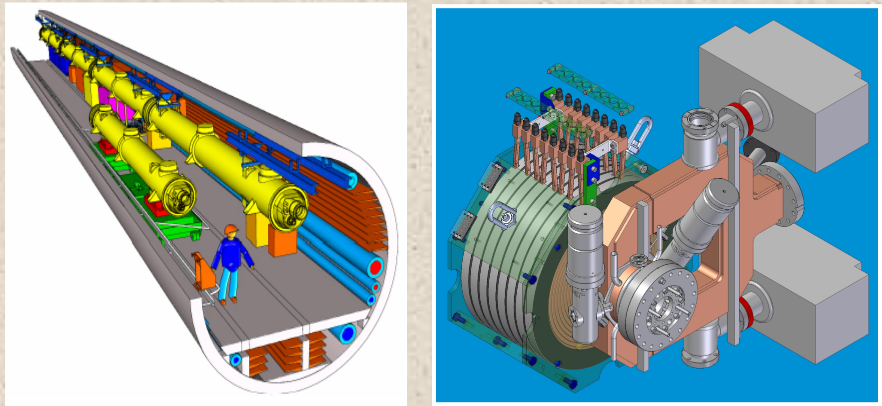
Slide from P. Emma

Realities of building an XFEL

Storage ring

~~$\sigma_z \approx 5$ mm,~~
~~$\sigma_E/E \approx 0.1\%$ (10 MeV),~~
~~$\gamma\varepsilon_z = \sigma_z\sigma_E/mc^2 \approx$ **100 µm**~~
~~$\varepsilon_x \sim \gamma^2$~~

Linac



$\sigma_z \approx 1$ mm,
$\sigma_E/E \approx 0.001\%$ (100 keV),
$\gamma\varepsilon_z = \sigma_z\sigma_E/mc^2 \approx$ **0.2 µm**
$\varepsilon_x \sim 1/\gamma$

Slide from P. Emma

Realities of building an XFEL

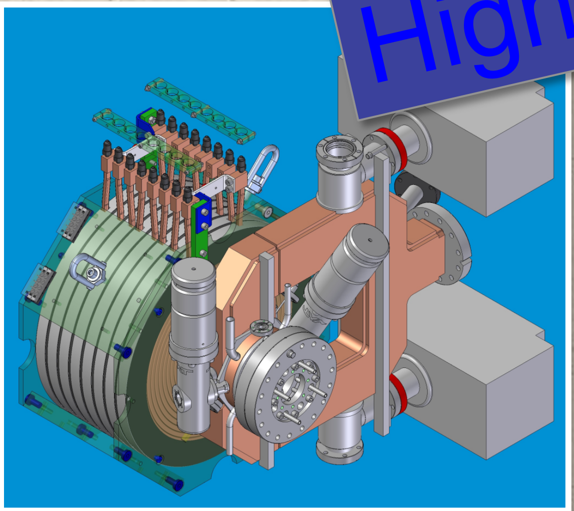
Radio Frequency Photo-Cathode Gun

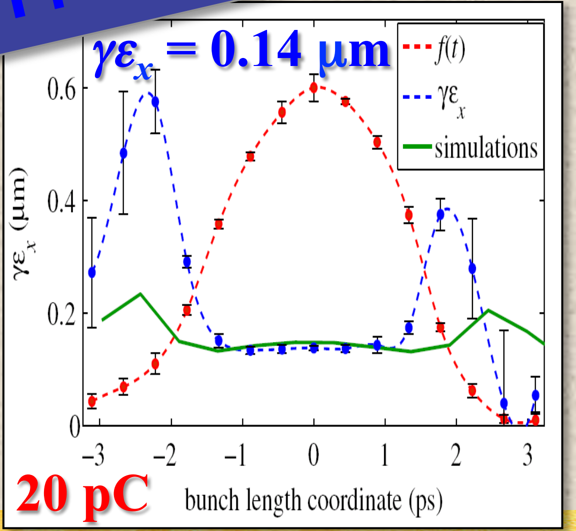
UV laser → electron emission from cathode

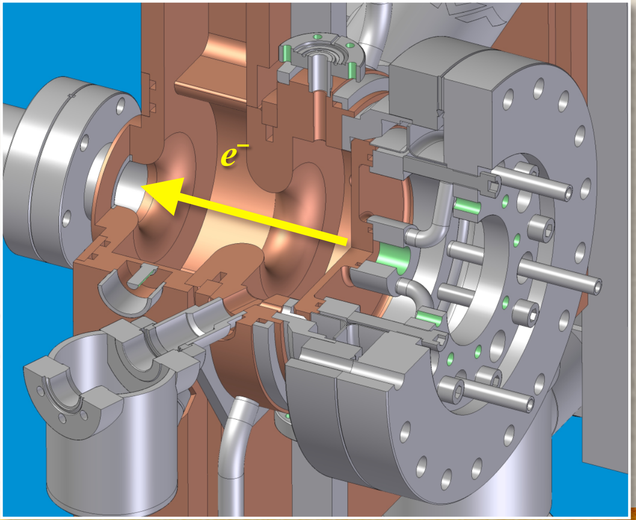
RF (GHz) accelerates before space-charge g

Produces very bright e^- beam

High Transverse Density



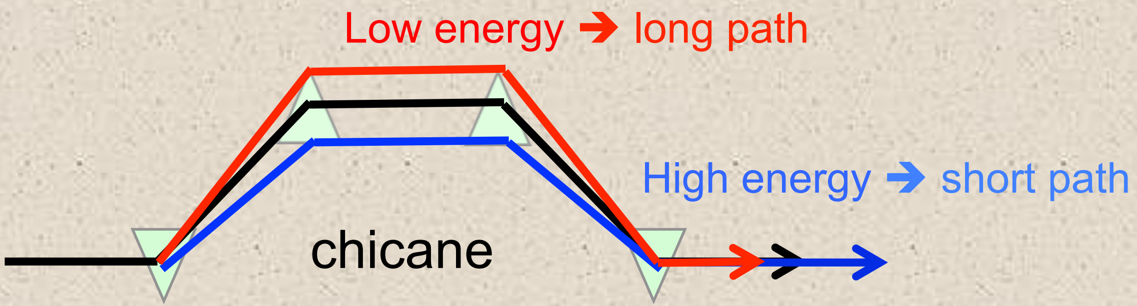


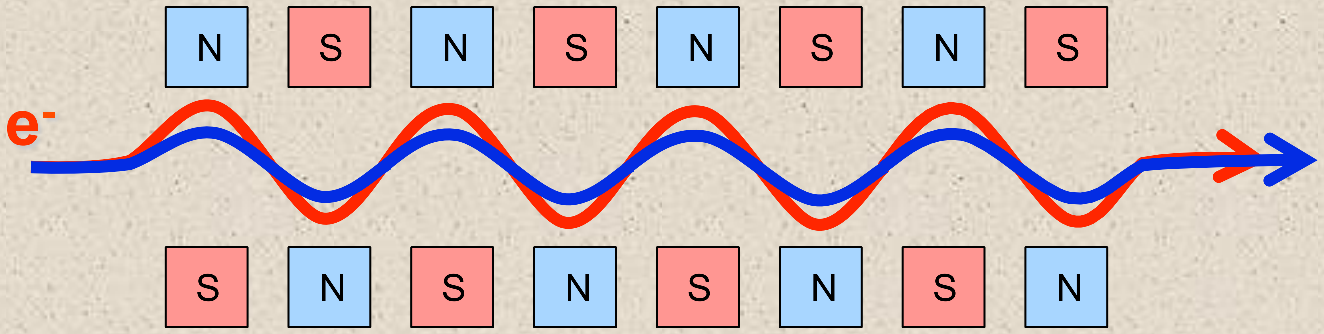


Slide from P. Emma

Realities of building an XFEL

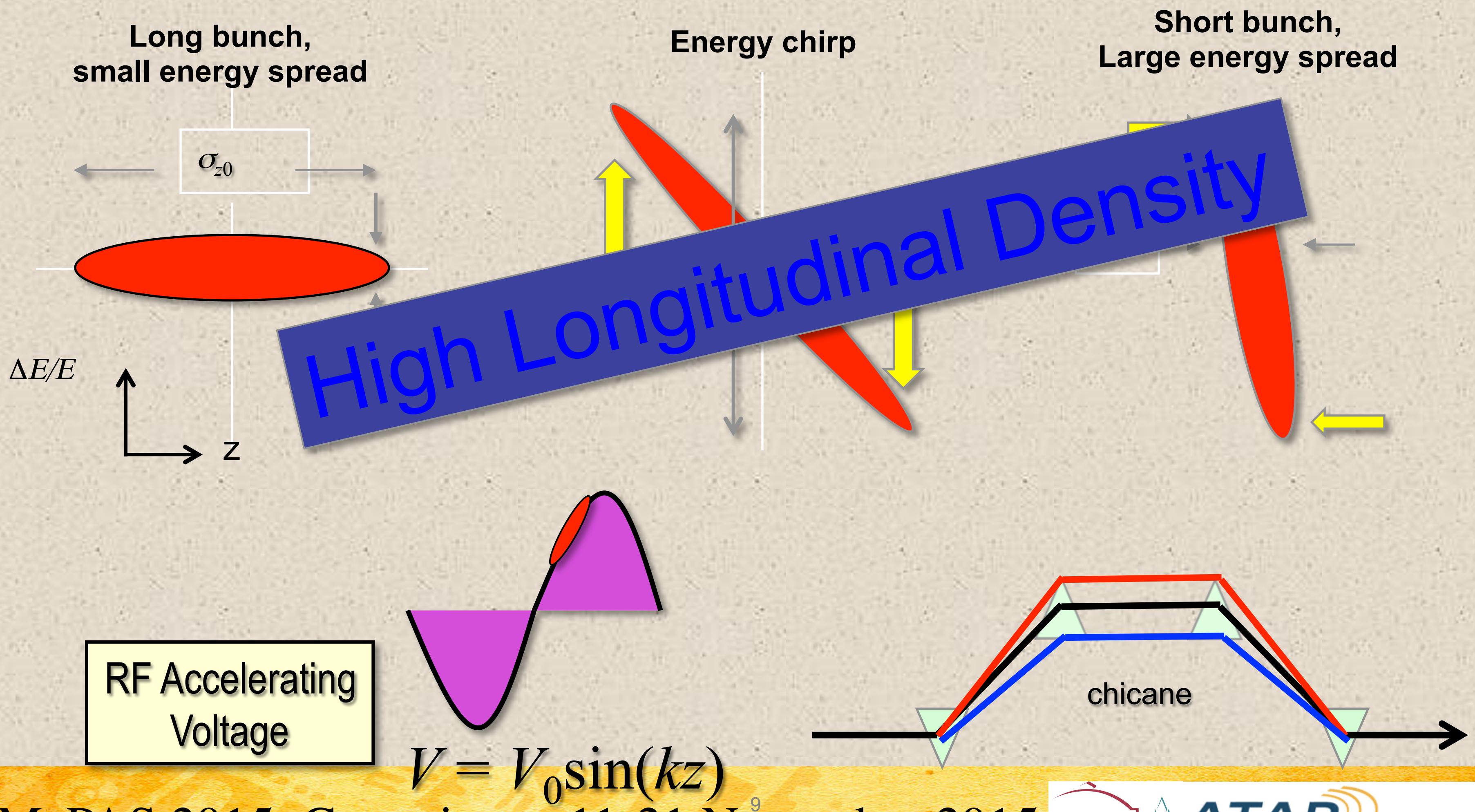
Dispersion in accelerators





Realities of building an XFEL

Bunch Compression



High Longitudinal Density

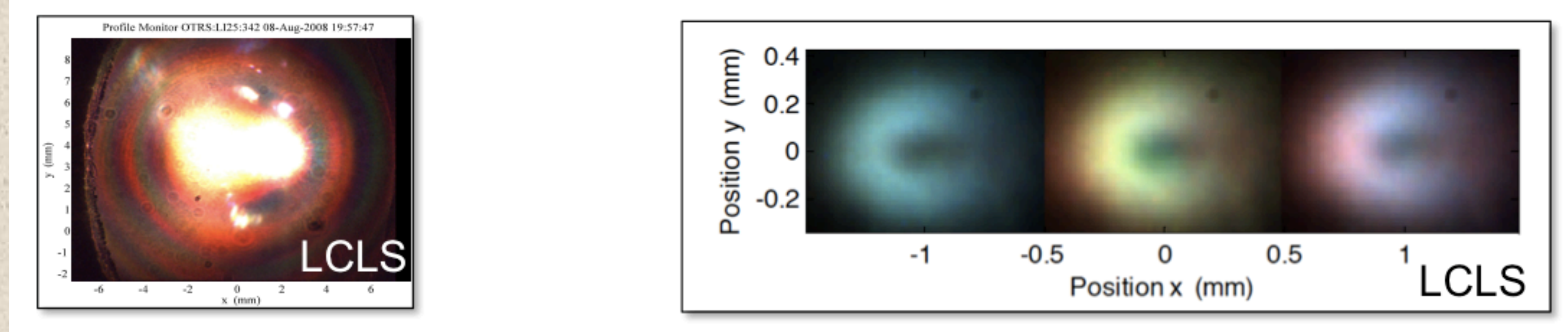
RF Accelerating Voltage

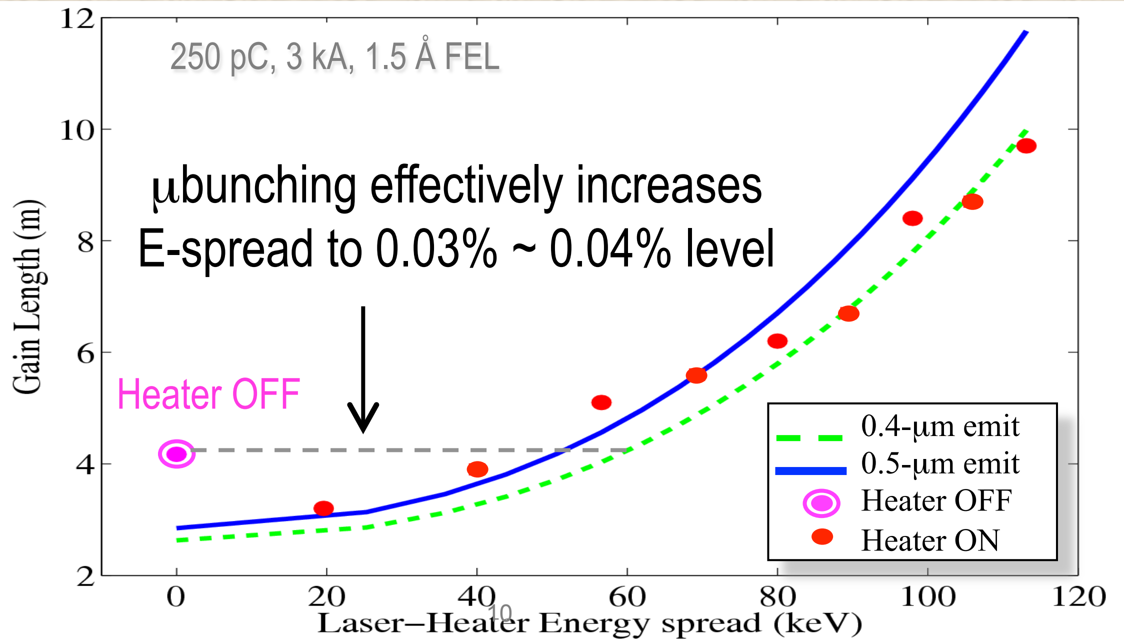
$$V = V_0 \sin(kz)$$

Slide from P. Emma

Measurements

Microbunching Instability

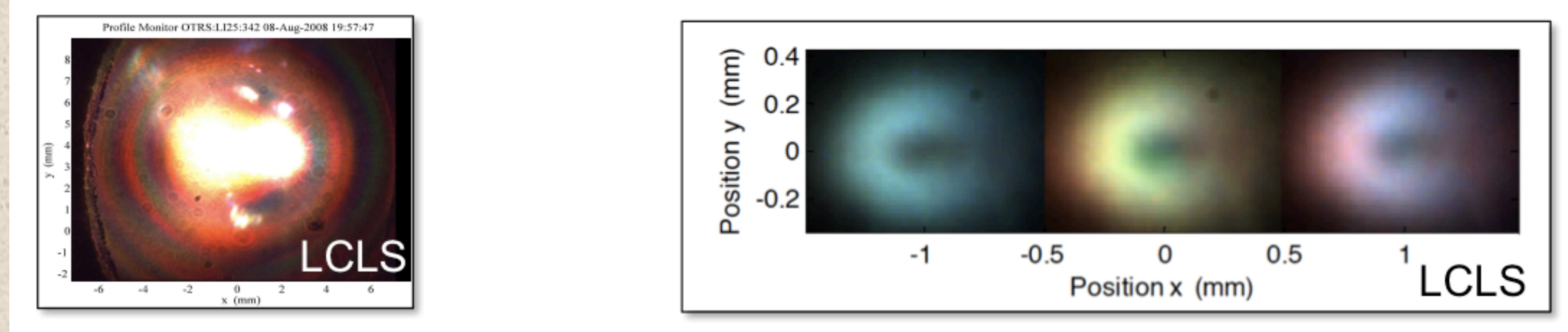


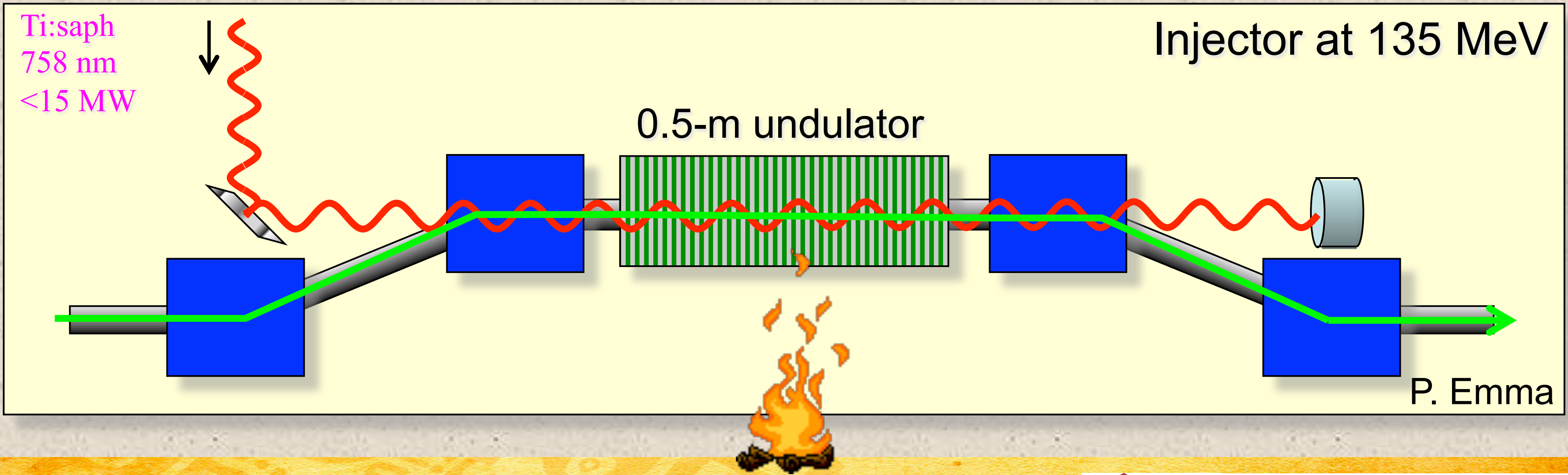


μbunching effectively increases E-spread to 0.03% ~ 0.04% level

Measurements

Microbunching Instability





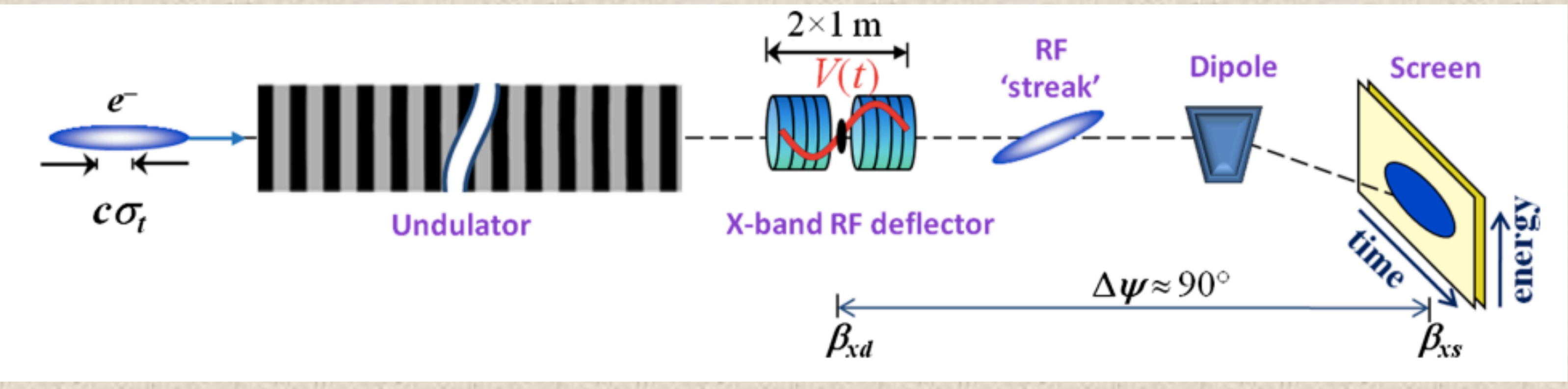
P. Emma

'Laser heater' suggested by Saldin et al., NIMA, 2004; independently by J. Galayda

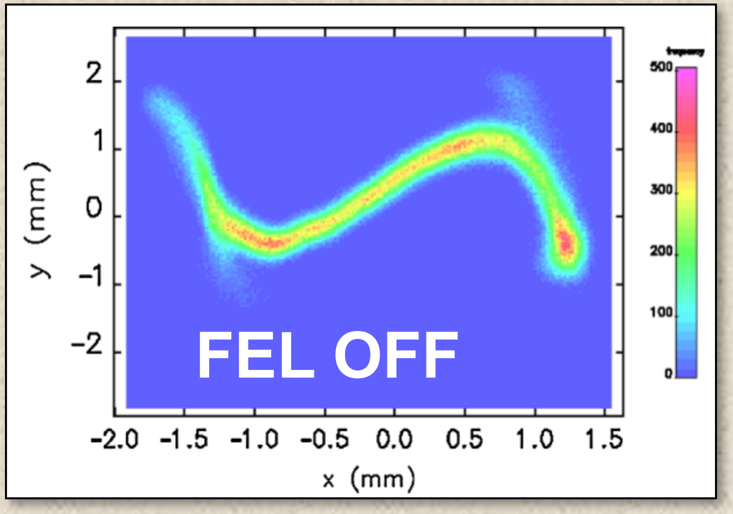
LCLS design study: Z. Huang et al, PRST 2004 (chicane suggested by T. Smith)

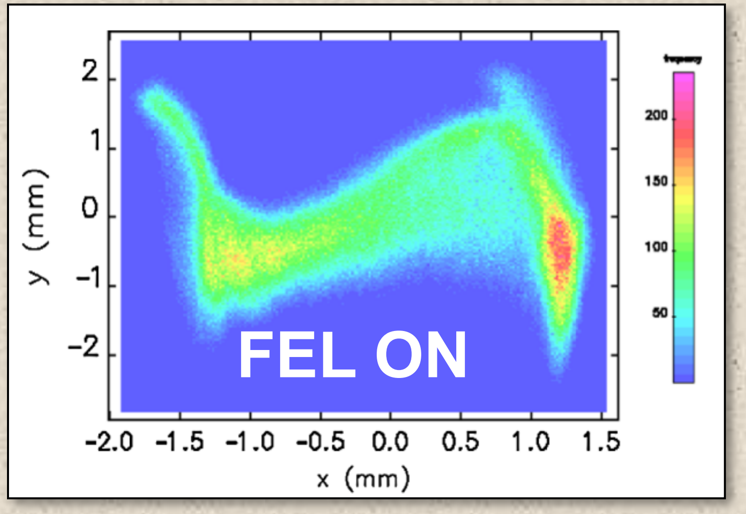
Measurements

X-Band Transverse Cavity



Energy



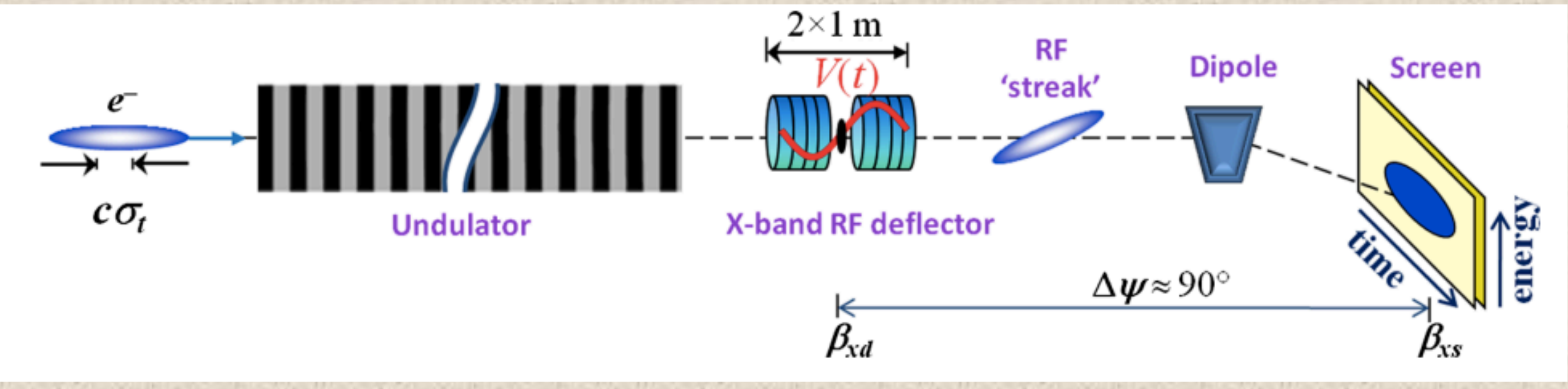


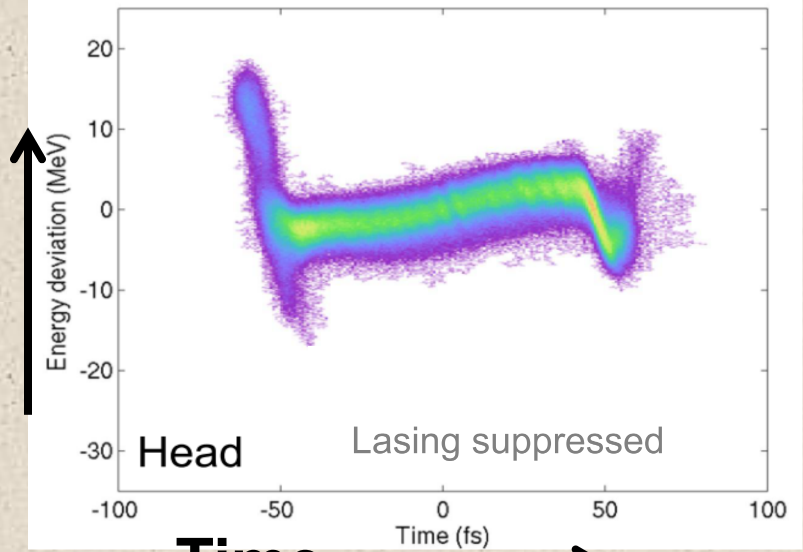
Time

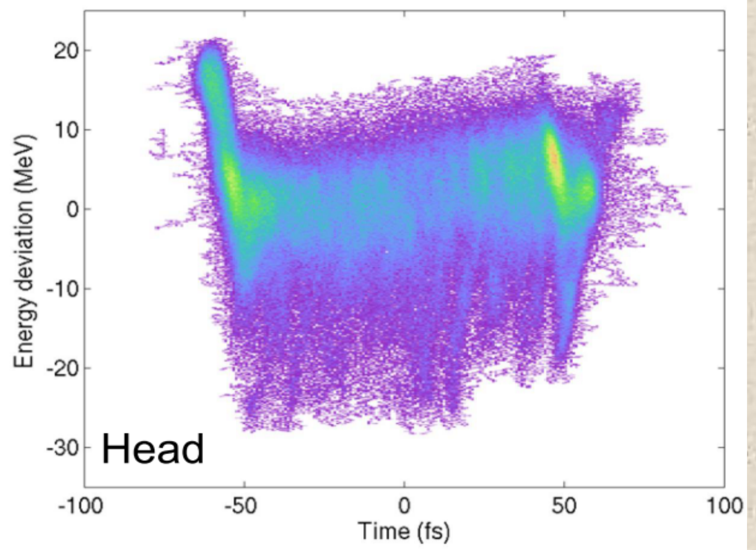
Y. Ding et al., PRSTAB 2011

Measurements

X-Band Transverse Cavity







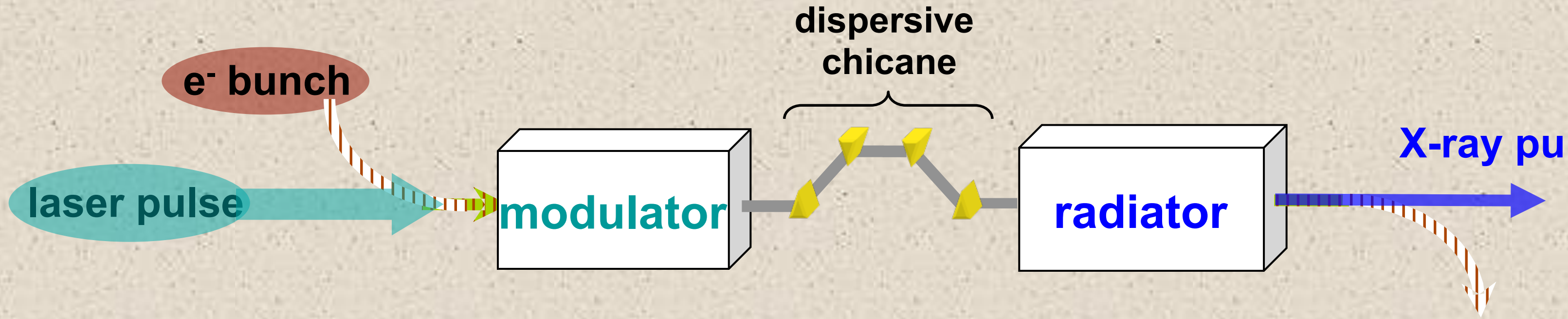
Energy

Time

Y. Ding, P. Krejcik

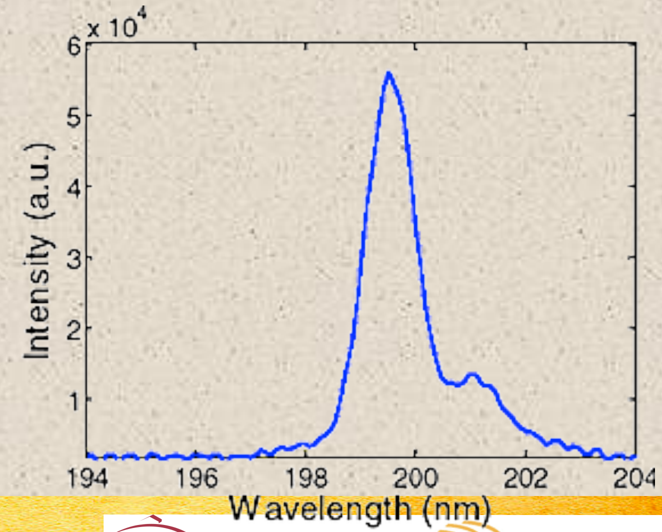
Full phase coherence requires a laser seed

High-gain harmonic generation (HGHG)



$$\lambda_{laser} = \lambda_{x-ray}^{modulator} = \frac{\lambda_{undulator}^{modulator}}{2\gamma^2}\left(1+\frac{K^2}{2}\right)$$

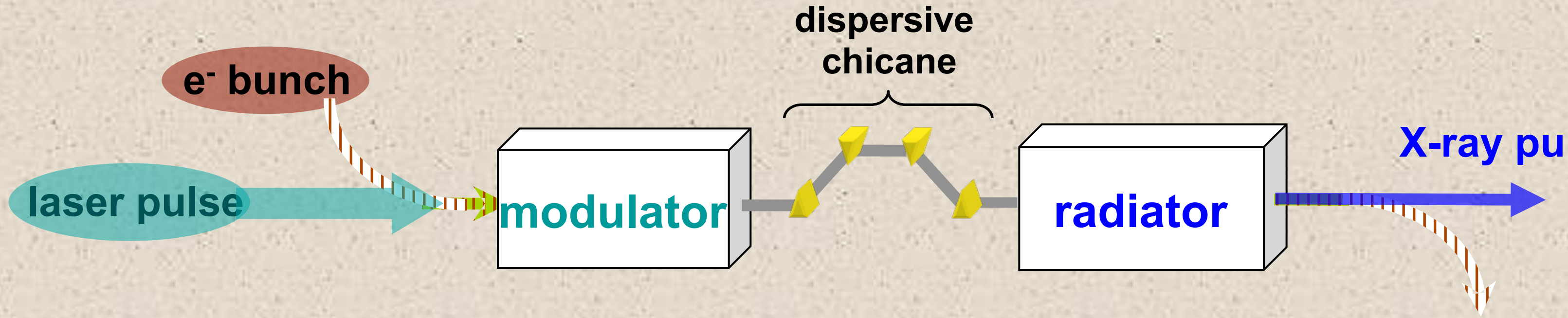
$$\lambda_{x-ray}^{radiator} = \frac{\lambda_{x-ray}^{modulator}}{n} = \frac{\lambda_{undulator}^{radiator}}{2\gamma^2}\left(1+\frac{K^2}{2}\right)$$



L.-H. Yu et al, Science 289 932-934 (2000)
L.-H. Yu et al, Phys. Rev. Let. Vol 91, No. 7, (2003)

Csonka 1980; Kincaid 1980; Bonifacio 1990; L.-H. Yu 1990

HGHG makes harmonics of optical laser seed



e$^-$ bunch

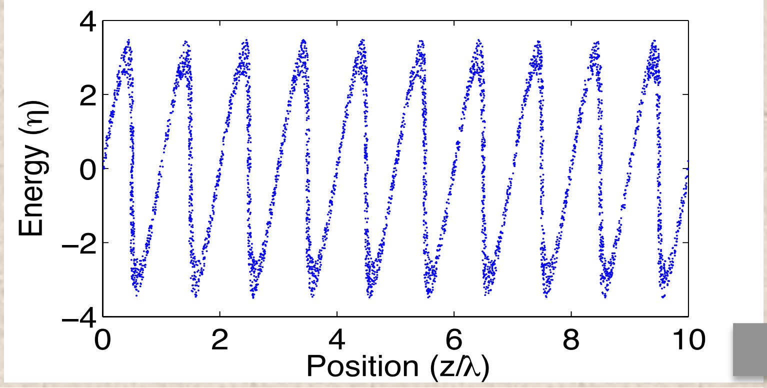
laser pulse

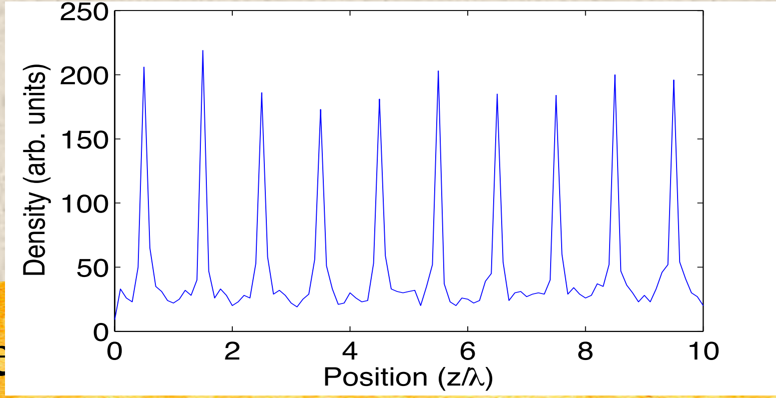
modulator

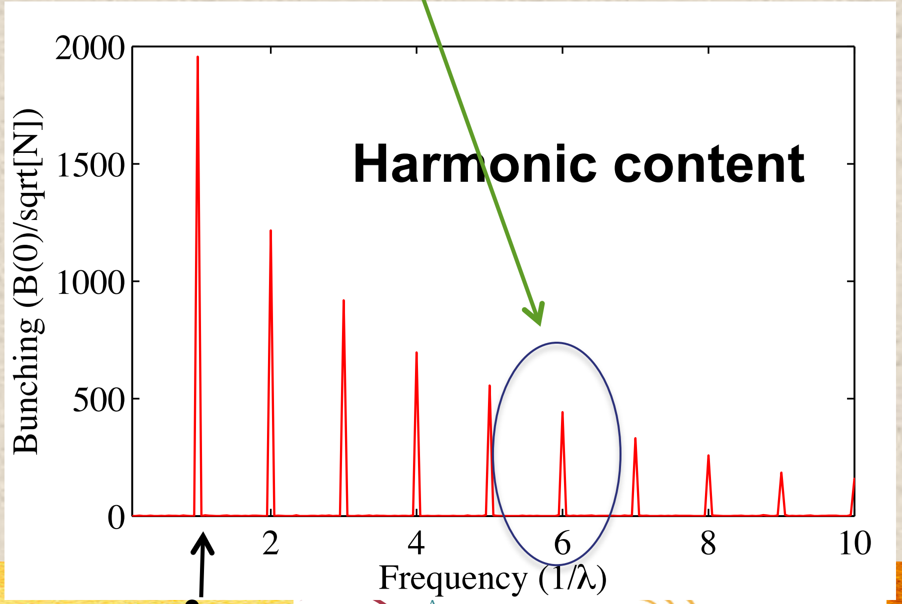
dispersive chicane

radiator

X-ray pulse







Harmonic content

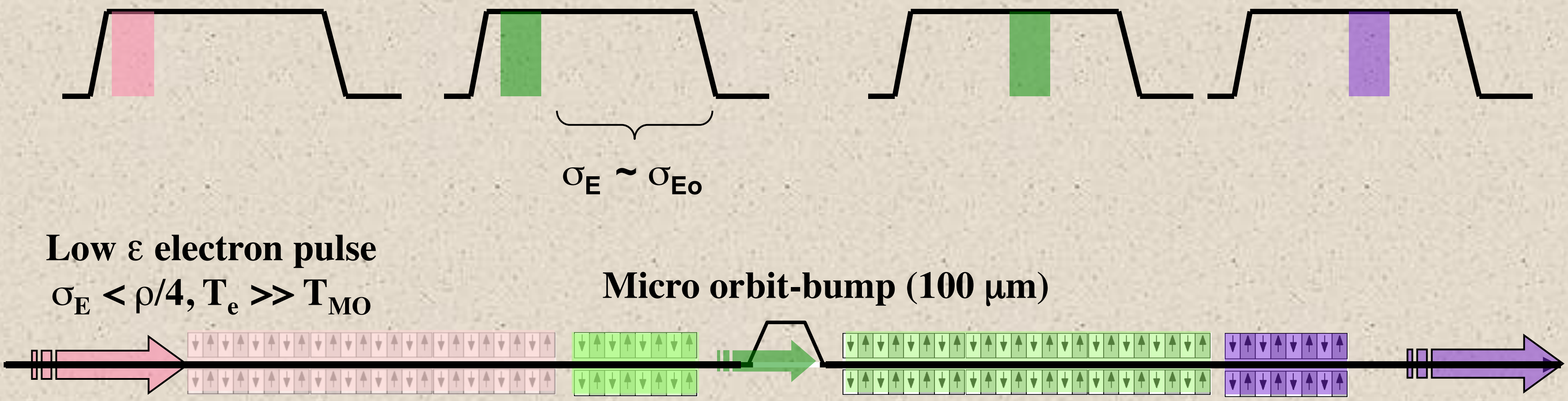
λ_L

FERMI proposal: Multiple-stage, Super-Radiant

Harmonic Cascade Amplifier

Requirements:

Position of optical pulses in electron pulse



$\sigma_E \sim \sigma_{Eo}$

Low ε electron pulse

$\sigma_E < \rho/4$, $T_e >> T_{MO}$

Micro orbit-bump (100 μm)

MO pulse
$T_e >> T_{MO}$
$P_{MO} > 100\, P_{shot}$

FEL amplifier
$L_W < L_{SAT}$

3rd - 5th
Harmonic
radiator
$P_{HG} \sim P_{MO}$

3 - 5th harmonic
FEL amplifier
$L_W < L_{SAT}$

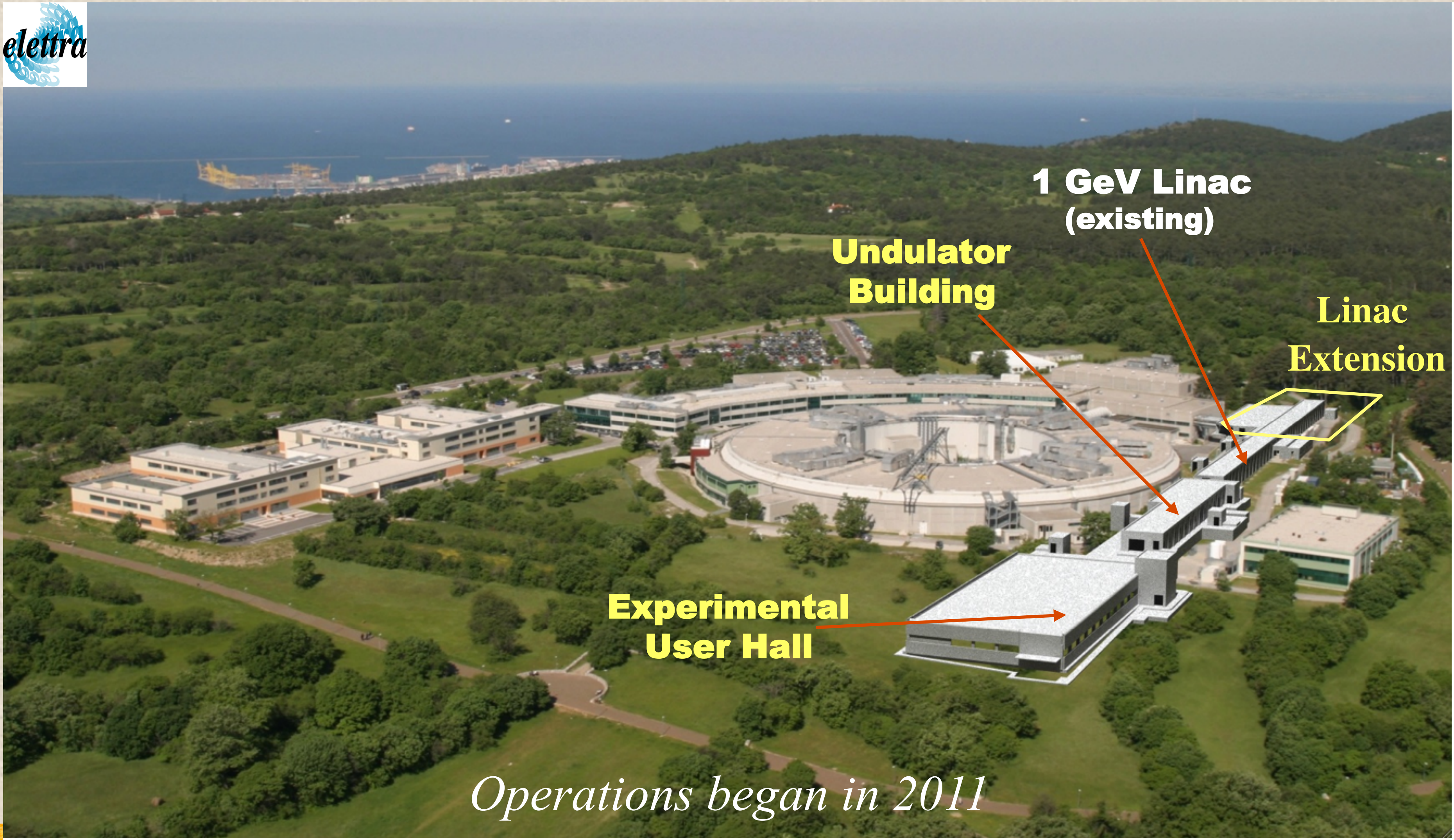
3rd - 5th
Harmonic
radiator
$P_{HG} \sim P_{MO}$

FEL scheme for generation of precisely timed pulses of 10^8 - 10^{12} photons/pulse over range of 20 - 2 nm

Barletta & Bonifacio, 2003

FERMI @ Elettra: a seeded, HGHG cascade

Photon energy range 20 eV to 600 eV, fully coherent



Operations began in 2011

Self-Seeding

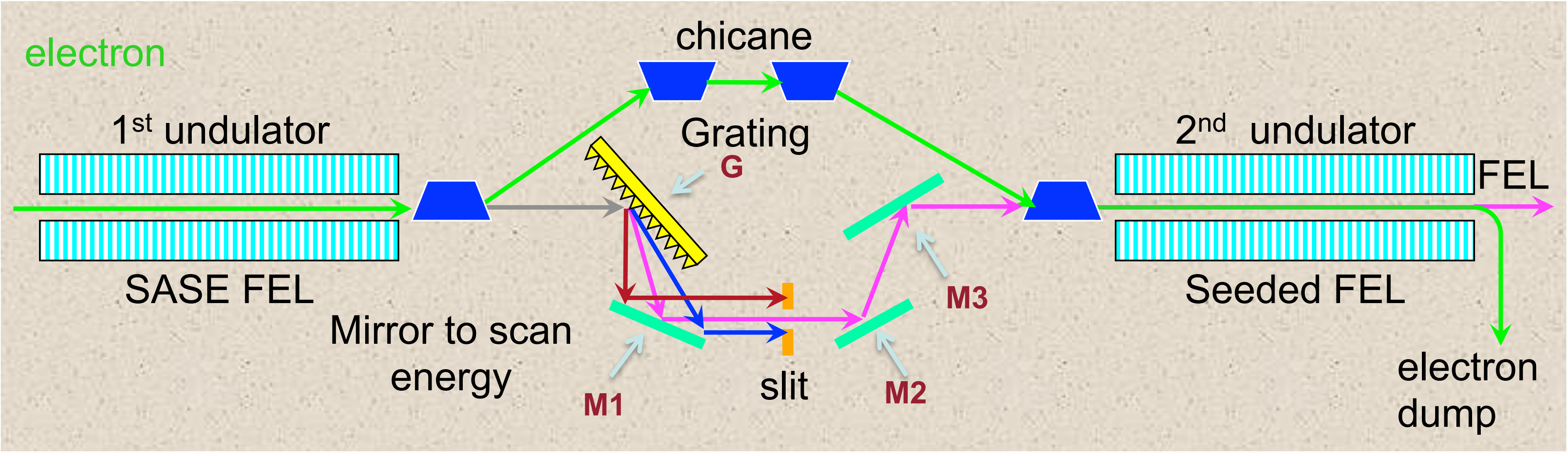
Self-Seeding: First half of FEL seeds second half

Two components:

a) Monochromator makes narrow-bandwidth seed

b) Chicane resets electron bunch

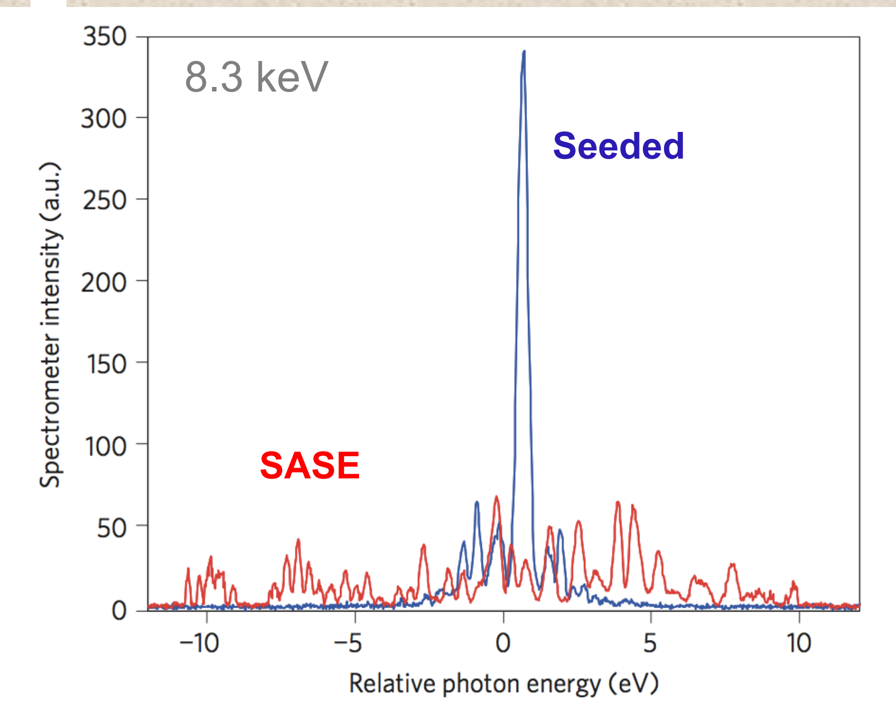
Soft X-ray Self-Seeding Design

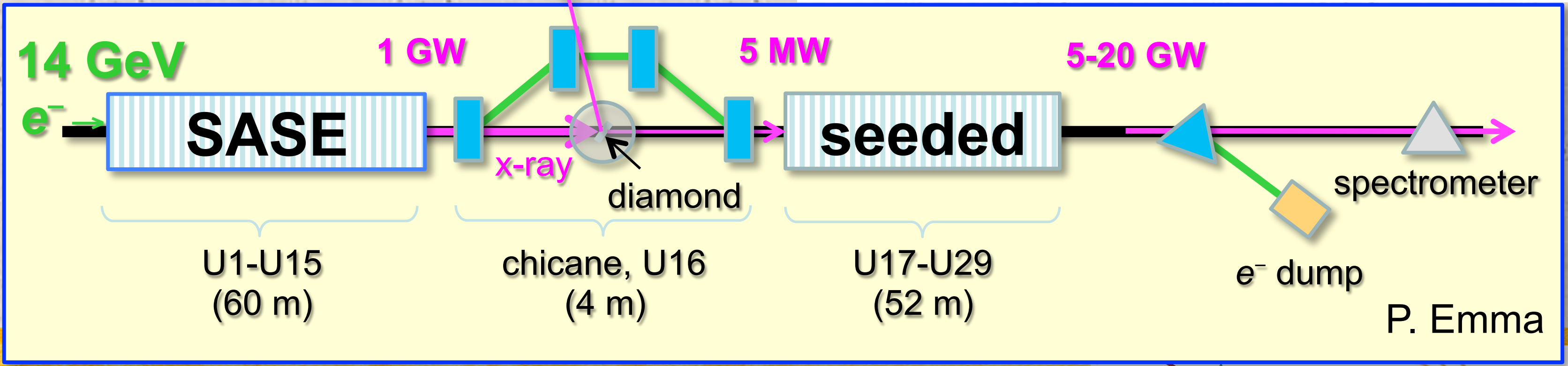


Seeded FELs

Self-Seeding: Hard X-rays

Diamond Bragg reflection produces monochromatic wake



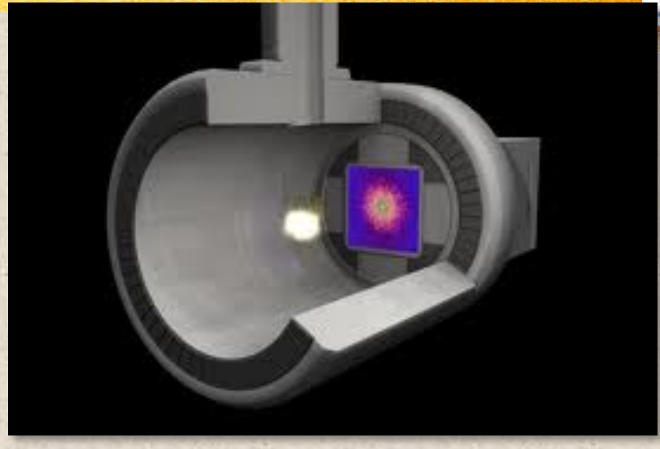


P. Emma

TeraWatt FELs

XFEL dream:
Single molecule imaging

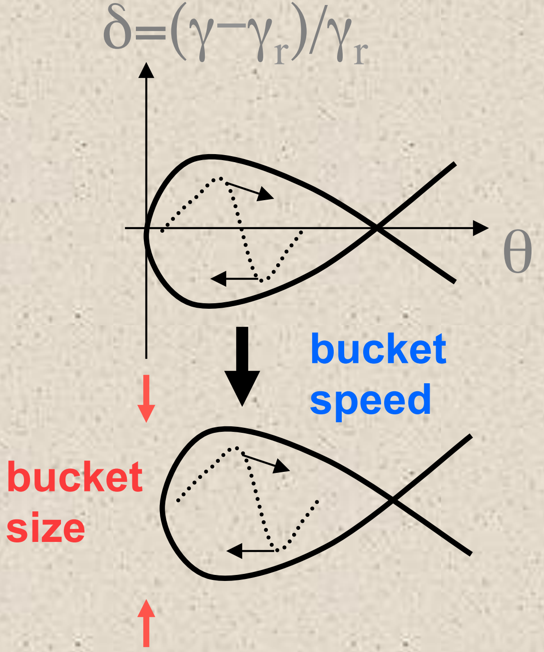
…but need TW FEL!!



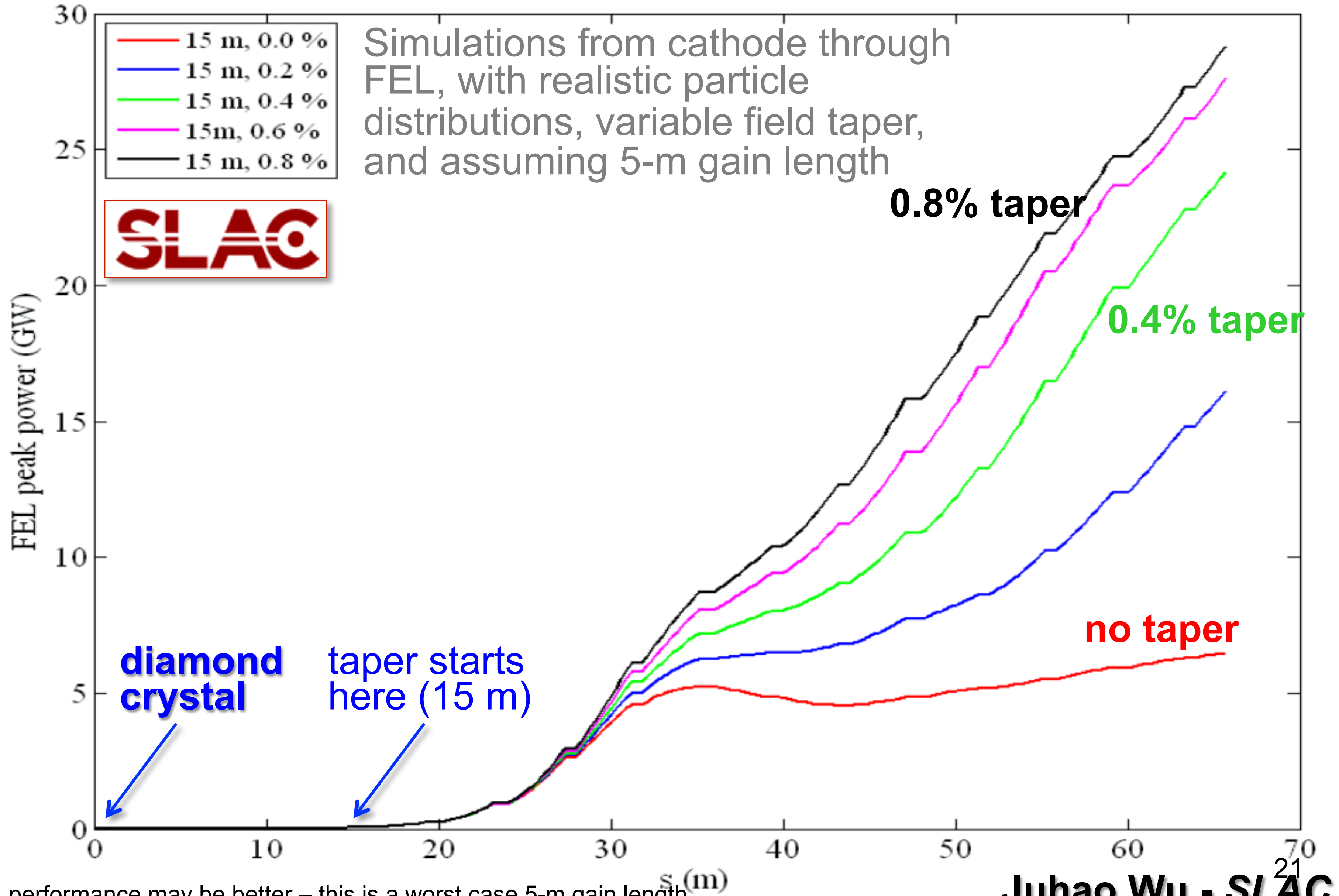
LCLS currently saturates around 10 GW

1. Bunching maximal
   ➔ exponential growth ends
2. e- energy drops
   ➔ Resonant frequency changes

$$\lambda_{sat} = \lambda_u \frac{[1+\overset{\text{Offset with drop in K}}{K^2}/2]}{2(\underbrace{\gamma_0-\Delta\gamma}_{\text{Energy drops}})^2} > \lambda_1$$



Tapering the Undulator allows further lasing



Simulations from cathode through FEL, with realistic particle distributions, variable field taper, and assuming 5-m gain length

0.8% taper

0.4% taper

no taper

diamond crystal

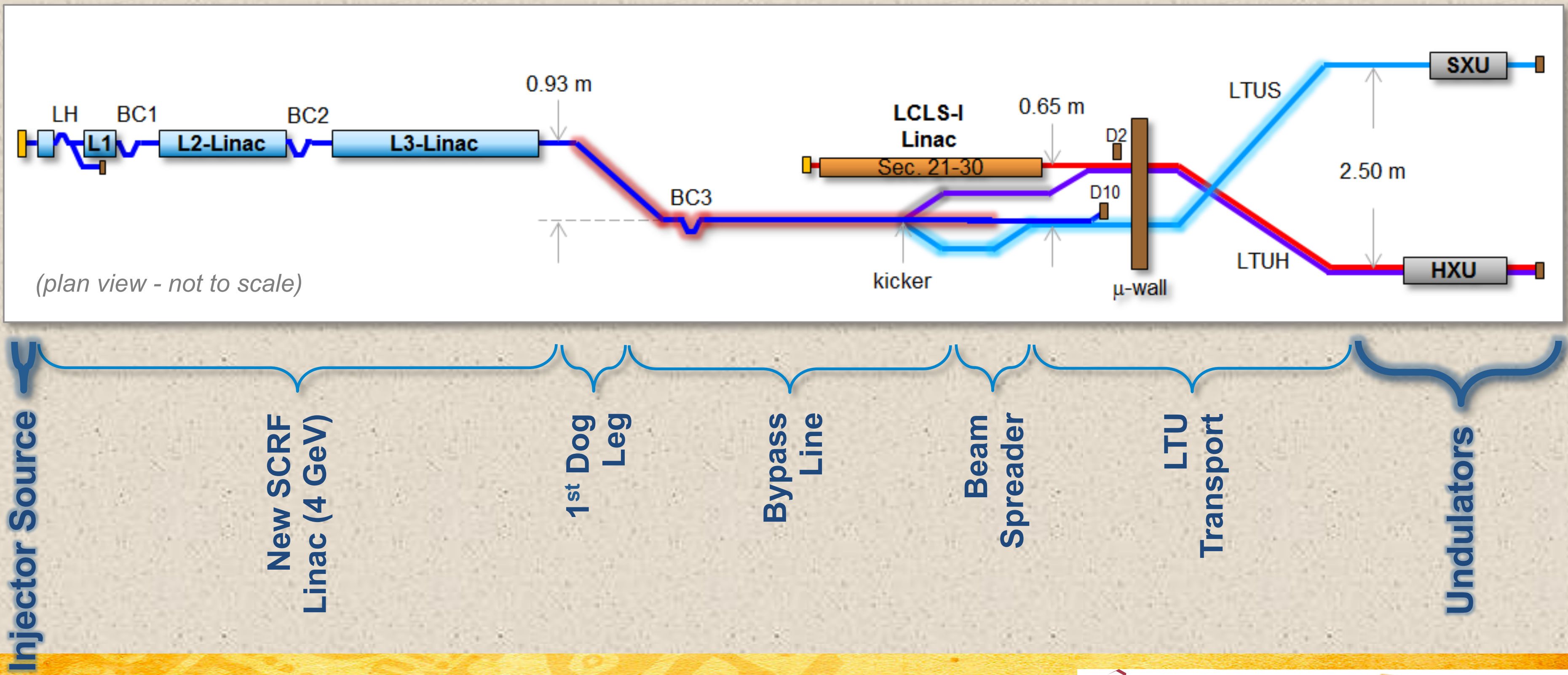
taper starts here (15 m)

performance may be better – this is a worst case 5-m gain length

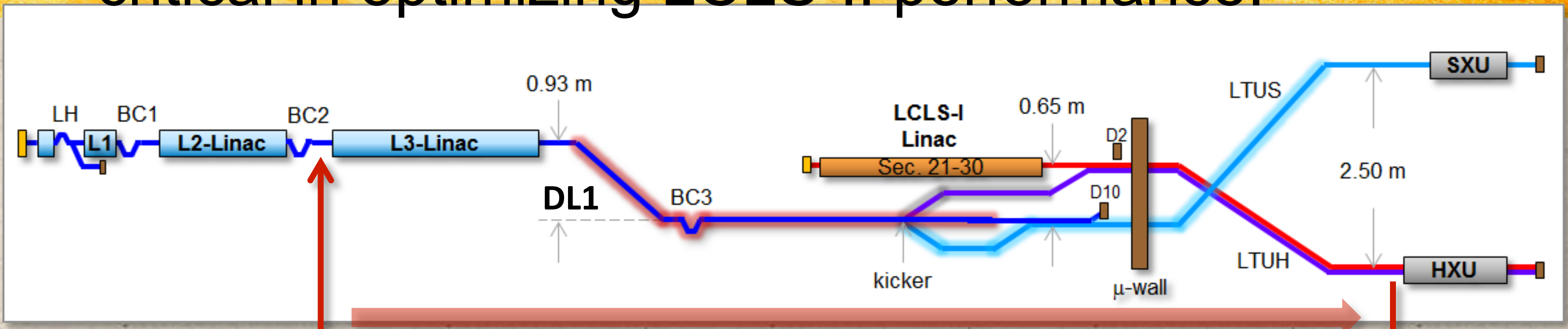
Juhao Wu - *SLAC*

Major effort to increase average FEL power

- The best way to increase average power is to increase repetition rate. The only way to do this is to use a superconducting linac.
- LCLS-II is a high average power FEL photon science facility under construction at SLAC
- Unique capabilities derive from CW high repetition rate and high brightness electron bunches, superconducting accelerator, and two tunable undulator lines and delivering CW ultrafast X-ray pulses of very high brightness over a broad energy spectrum

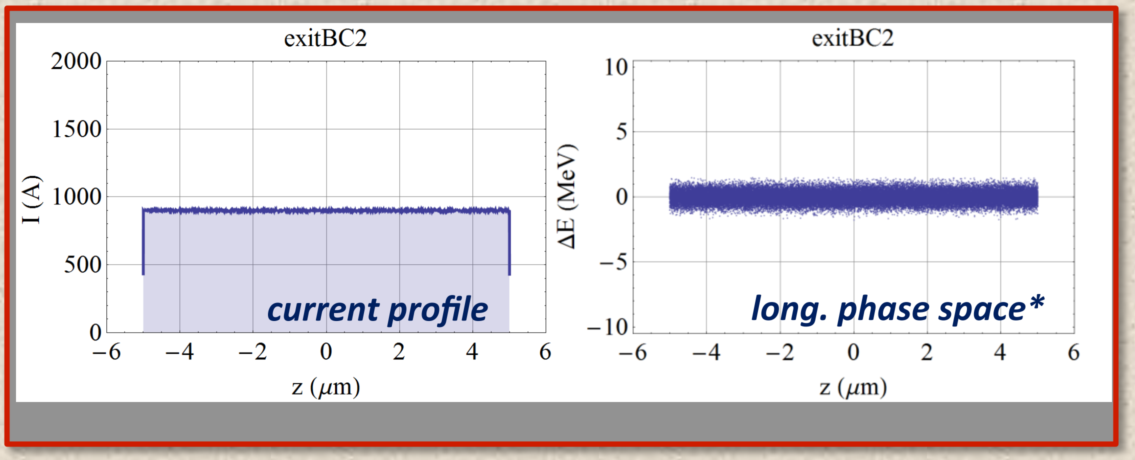


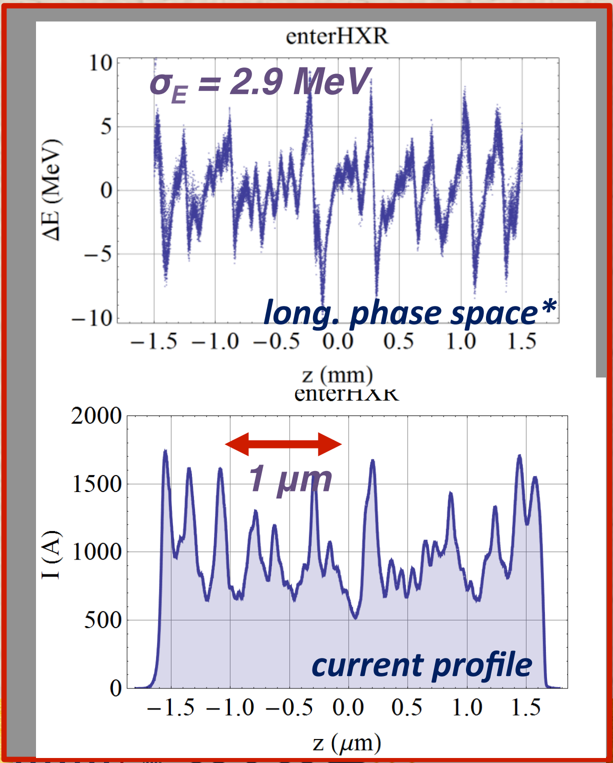
Modeling and control of the microbunching instability are critical in optimizing LCLS-II performance.



Start simulation with smooth beam model at exit of BC2

Beam as observed at HXU FEL is strongly microbunched



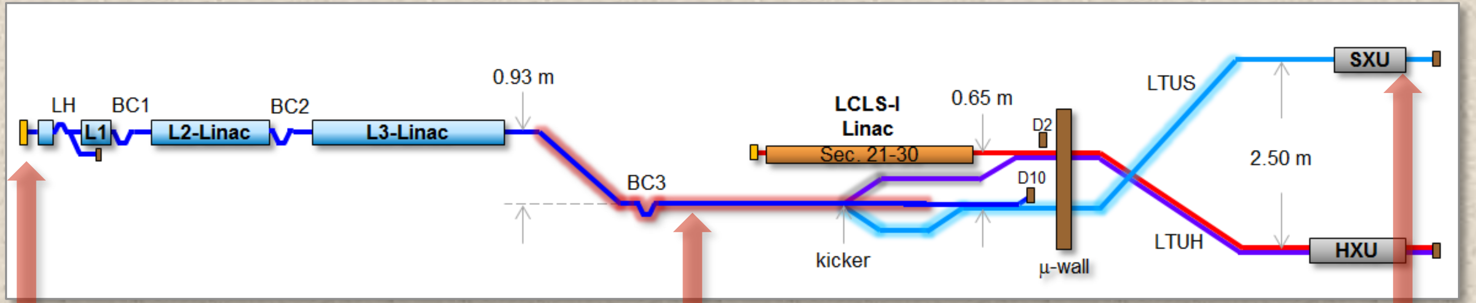


- Macroparticle simulation of **flat-top** model beam with **gaussian** uncorrelated energy spread at exit of BC2
  - representing short section of **Q = 100 pC** bunch with Laser Heater turned on.

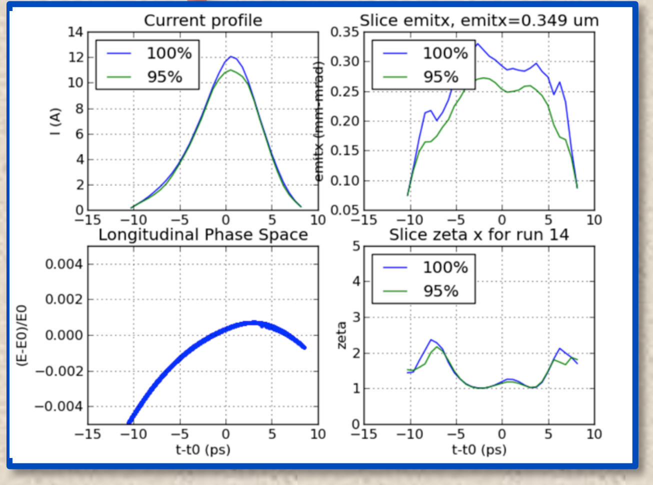
- Microbunching on **sub-μm scale** develops through the first dogleg (DL1) and the transport section between μ-wall and FEL.

High-resolution, multi-physics, start-to-end modeling tools critical to modern FEL design.

LCLS-II baseline

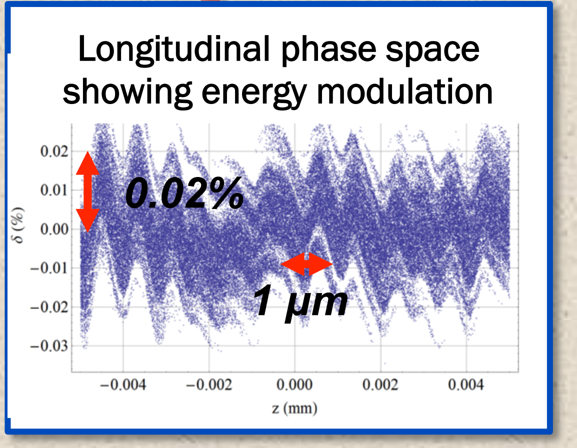


4 GeV



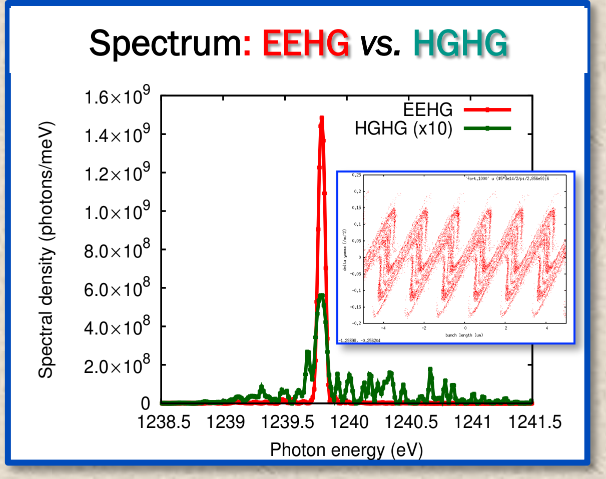
Global optimization of the APEX-based LCLS-II injector design

Longitudinal phase space showing energy modulation



Compression schemes and microbunching (µBI) in the LCLS-II linac

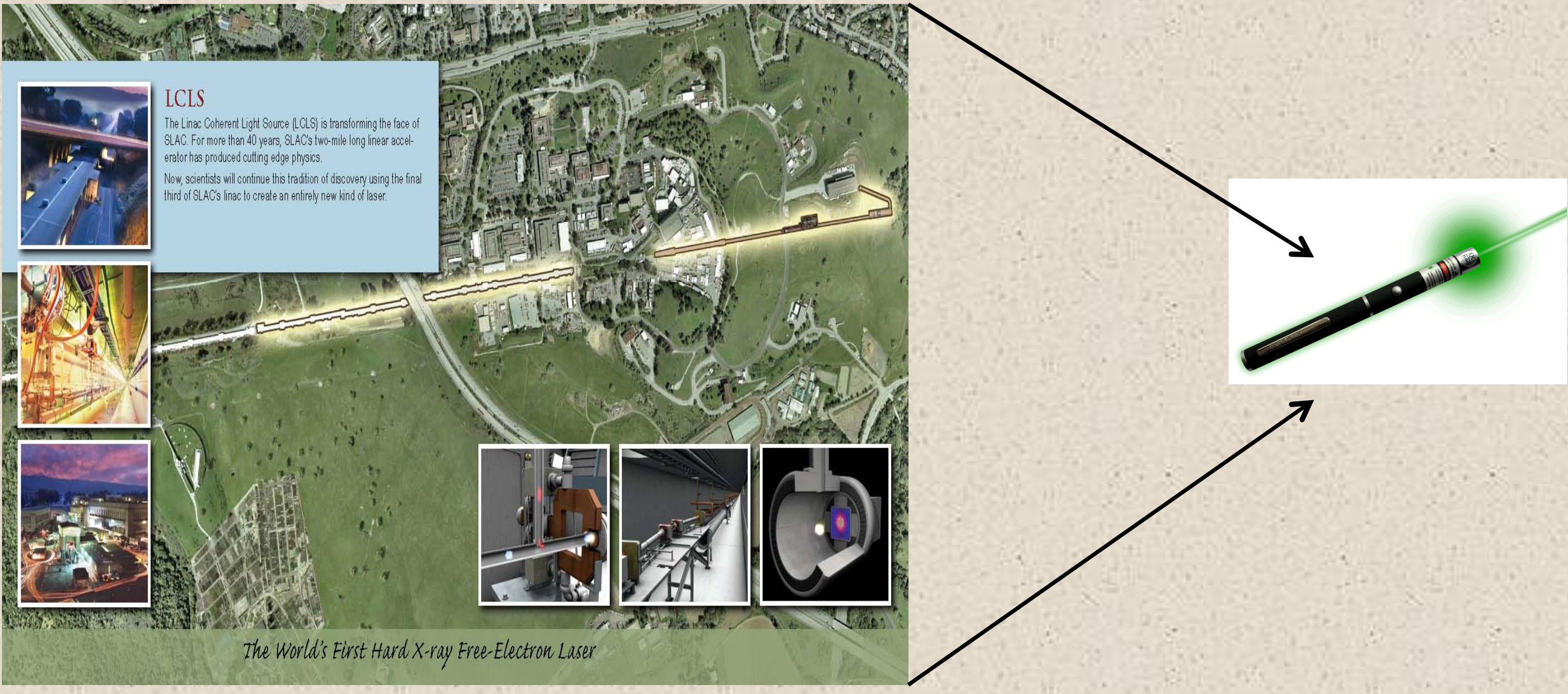
Spectrum: EEHG *vs.* HGHG



Exploration of seeded FEL options (Echo, 2-stage HGHG, self-seeded); sensitivity to µBI

Compact FELs

Grand challenge in FELs: Miniaturize the X-ray laser!



LCLS

The Linac Coherent Light Source (LCLS) is transforming the face of SLAC. For more than 40 years, SLAC's two-mile long linear accelerator has produced cutting edge physics.

Now, scientists will continue this tradition of discovery using the final third of SLAC's linac to create an entirely new kind of laser.

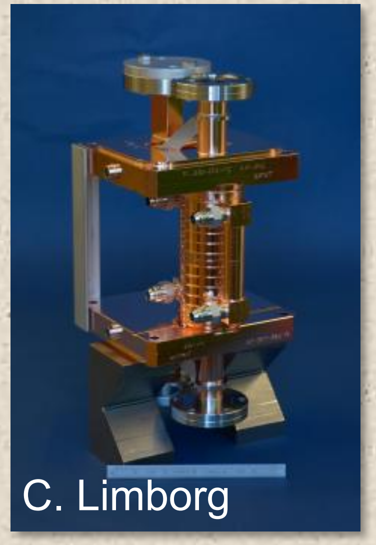
The World's First Hard X-ray Free-Electron Laser

Compact FELs

Path to a Miniature X-ray FEL: Miniaturize the Accelerator

Small step:
X-band guns, accelerators

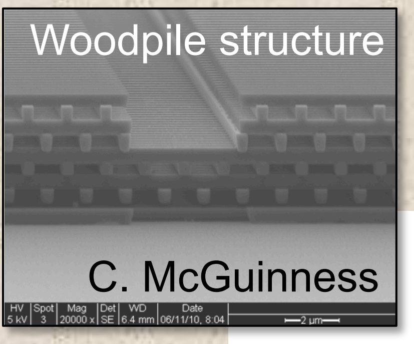
C. Limborg



C. Limborg

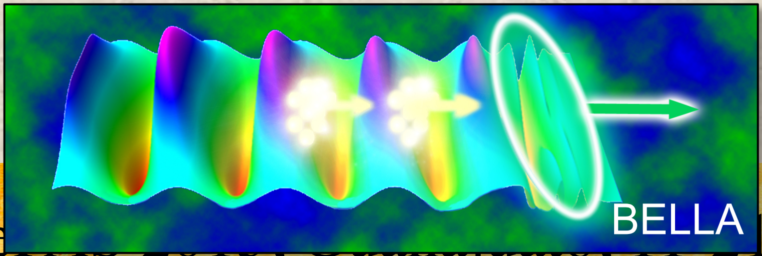
Big step:
Novel acceleration methods

e.g. Laser wakefield
and dielectrics:

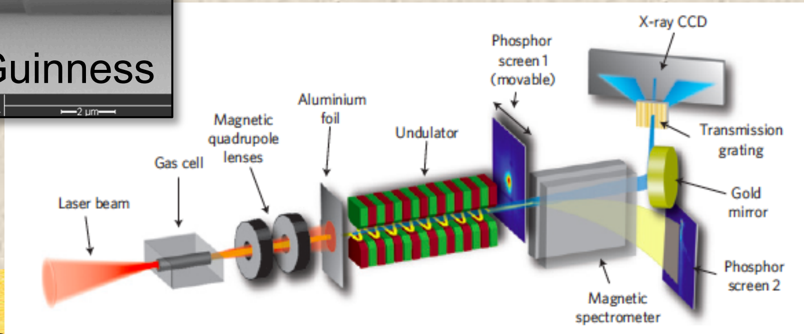


Woodpile structure

C. McGuinness



BELLA

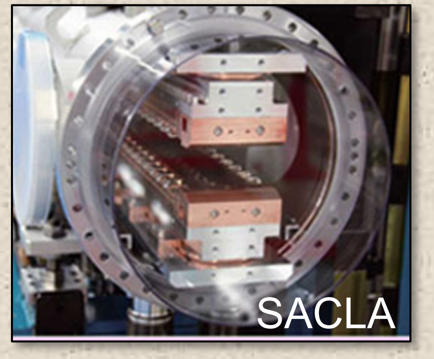


M. Fuchs et al., Nature 2009

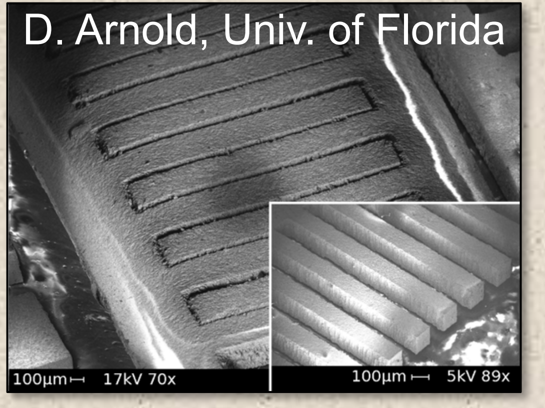
Compact FELs

Path to a Miniature X-ray FEL: Miniaturize the Undulator

Smaller periods:

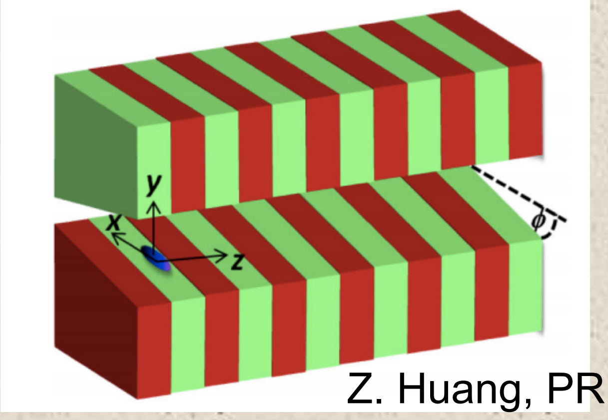


In vacuum


D. Arnold, Univ. of Florida

Micromachining

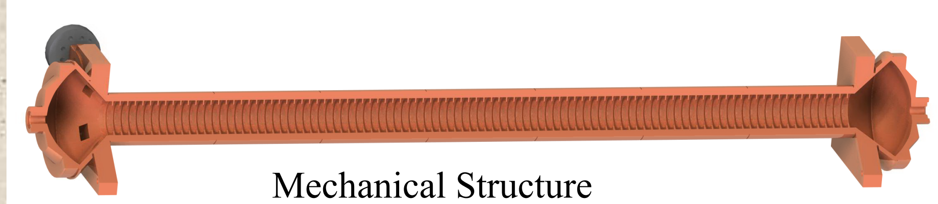
Undulators for compact accelerators:

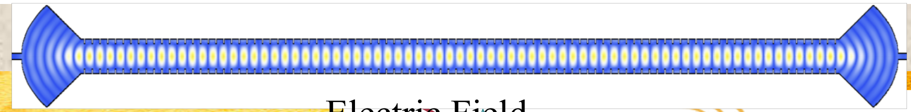


Z. Huang, PRL 2012

Transverse Gradient Undulator

Electromagnetic undulators


Mechanical Structure


Electric Field

LPA advances have triggered FEL applications
Efforts across the globe underway

Last decade: LPAs have matured

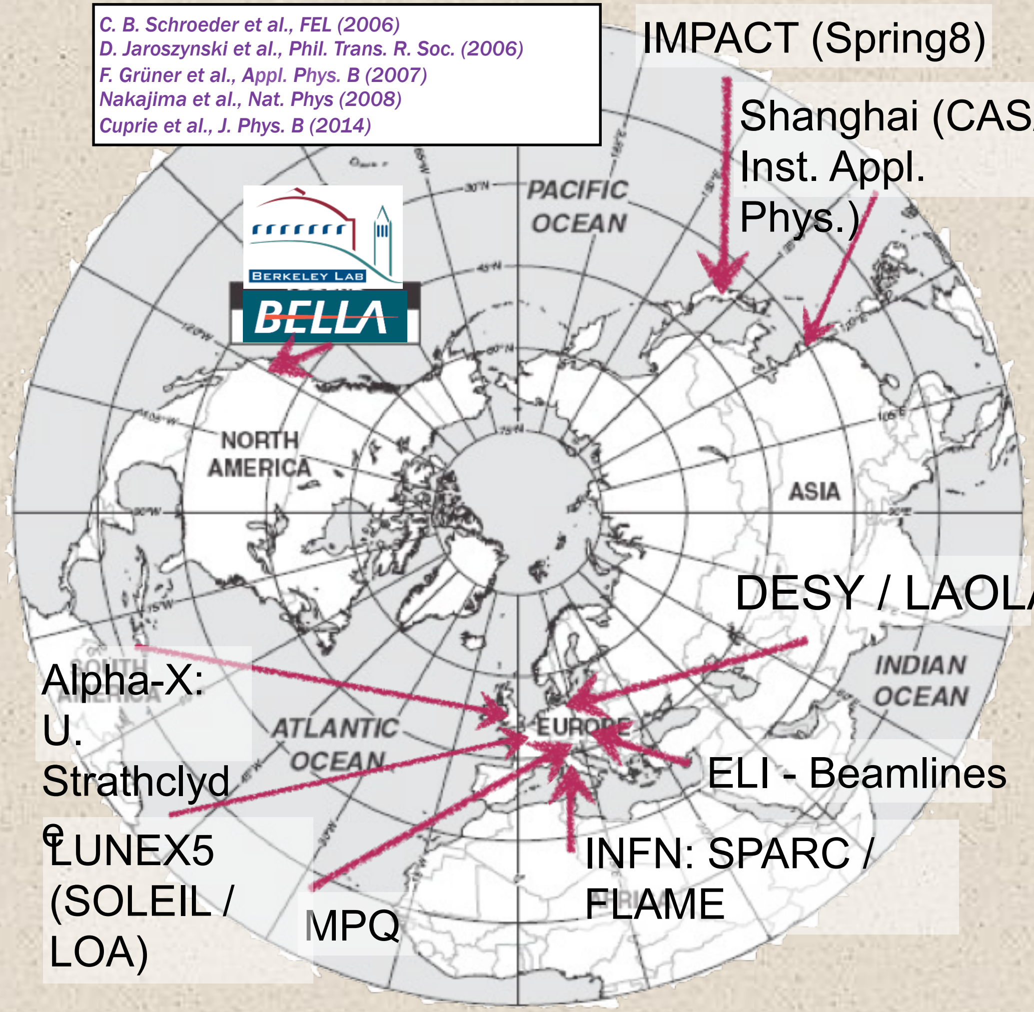
- High peak-current (>kA)
- Ultra-short (few-fs)
- sub-GeV to multi-GeV energies
- Excellent emittance
- Stability improvements

→Compact Free Electron Laser (coherent X-rays)

→Few femtosecond

→High peak power

→Hyper-spectral synchronization



C. B. Schroeder et al., FEL (2006)
D. Jaroszynski et al., Phil. Trans. R. Soc. (2006)
F. Grüner et al., Appl. Phys. B (2007)
Nakajima et al., Nat. Phys (2008)
Cuprie et al., J. Phys. B (2014)

IMPACT (Spring8)

Shanghai (CAS
Inst. Appl.
Phys.)

DESY / LAOL

Alpha-X:
U.
Strathclyde

LUNEX5
(SOLEIL /
LOA)

MPQ

ELI - Beamlines

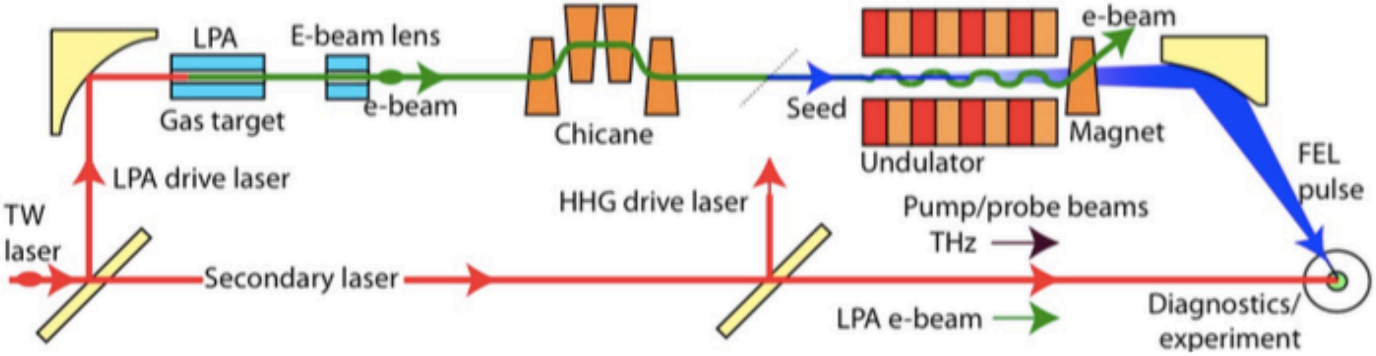
INFN: SPARC /
FLAME

LPA-FEL benefits from intrinsic synchronization and hyper-spectral capabilities

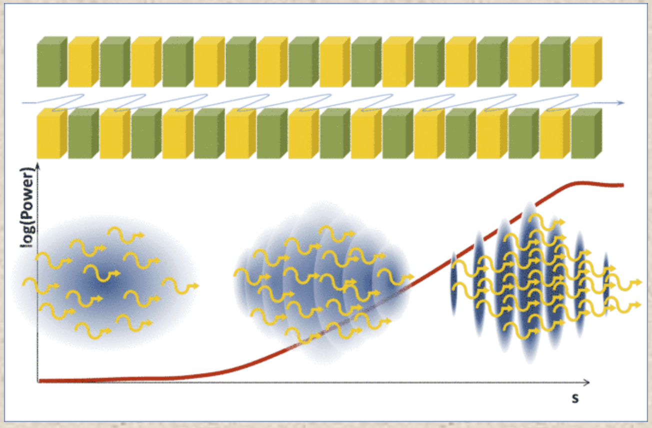
Potential advantages of LPA-driven FEL

- Small facility footprint: ultra-compact accelerator producing fs, kA e-beams
- Hyper-spectral source for pump-probe
  - e-beam ions, high-field THz (CTR), hard x-rays (betatron radiation), gamma-rays (Thomson scattering)
- Ultra-short durations
- Intrinsically small timing jitter (sub-fs)
- Layout flexibility

Schematic of LPA-driven (seeded) FEL for pump-probe AMO experiments

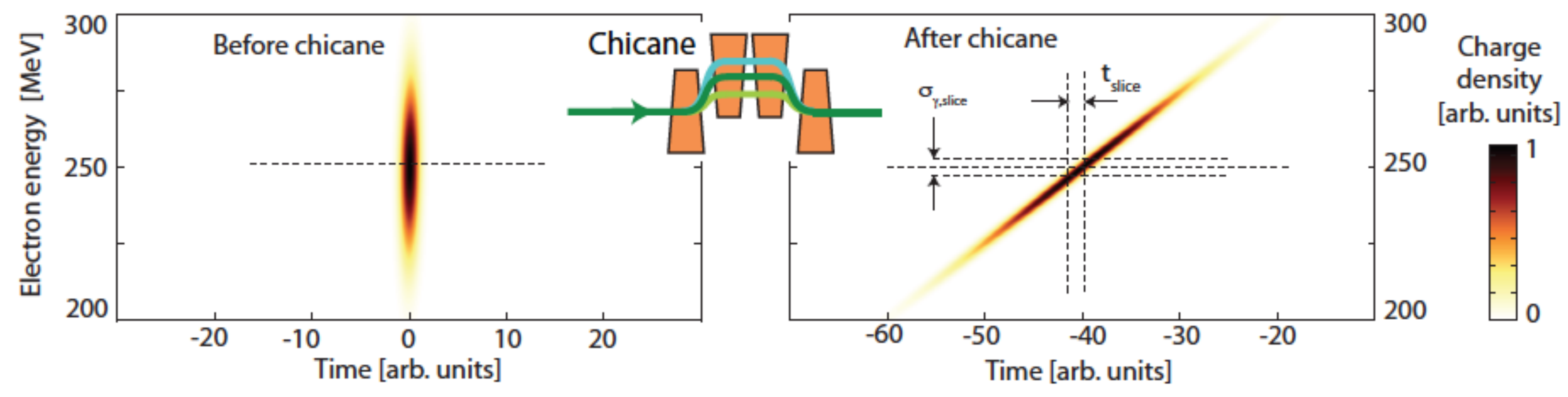


LPA electron beam subject to stringent requirements



Key requirements

- Sub-% ΔE/E required for lasing slice
- Disperse/stretch electron beam
- Charge 2-3 pC/MeV
- Beam size: ~10-µm-level over several meters (low emittance or additional transport)

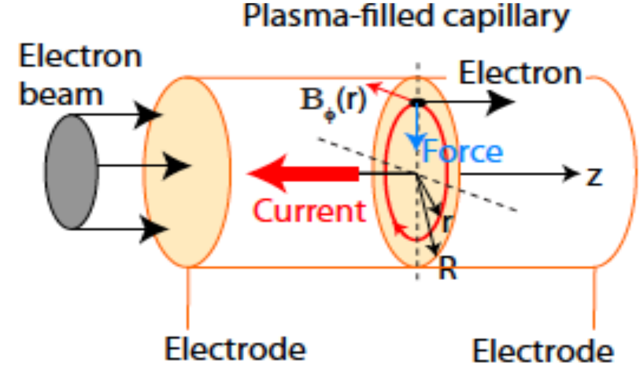


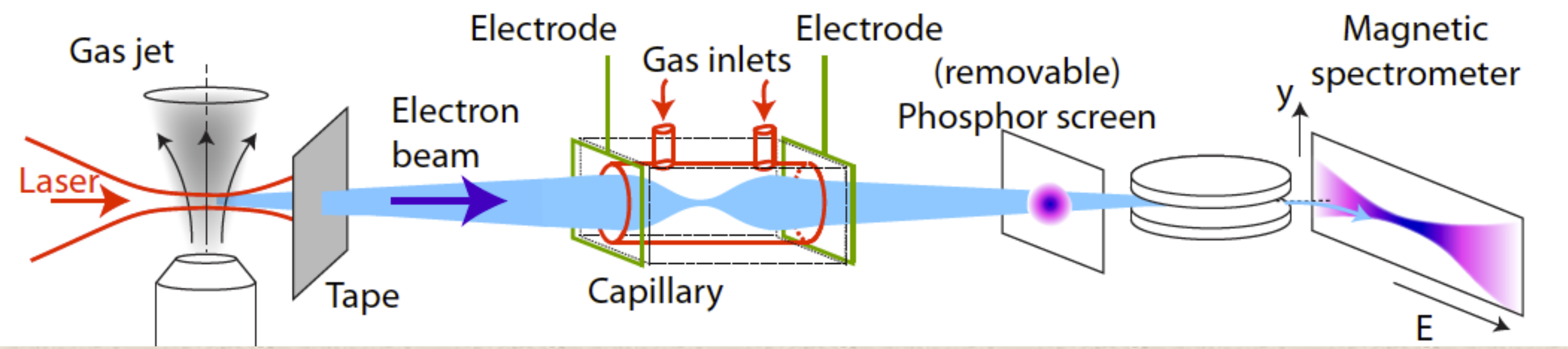
Capillary-discharge active plasma lens provides compact focusing

Active Plasma Lens

- Introduced 1950s (ion beams)
- Symmetric focusing
- Tunable
- Gradients >3000 T/m
- Rely on negligible wakefields

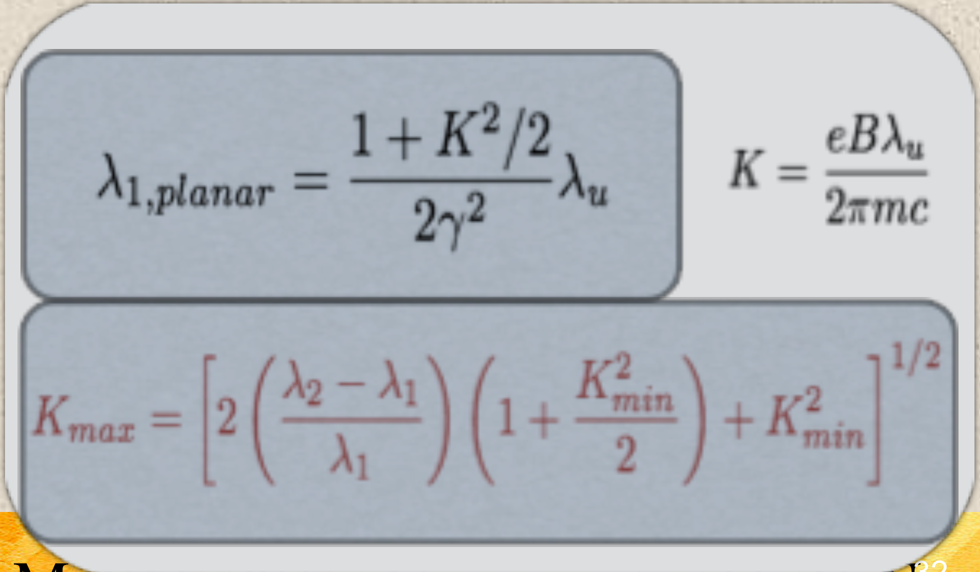
Panofski *et al*. RSI 1950
van Tilborg *et al*. PRL **115**, 184802 (2015)





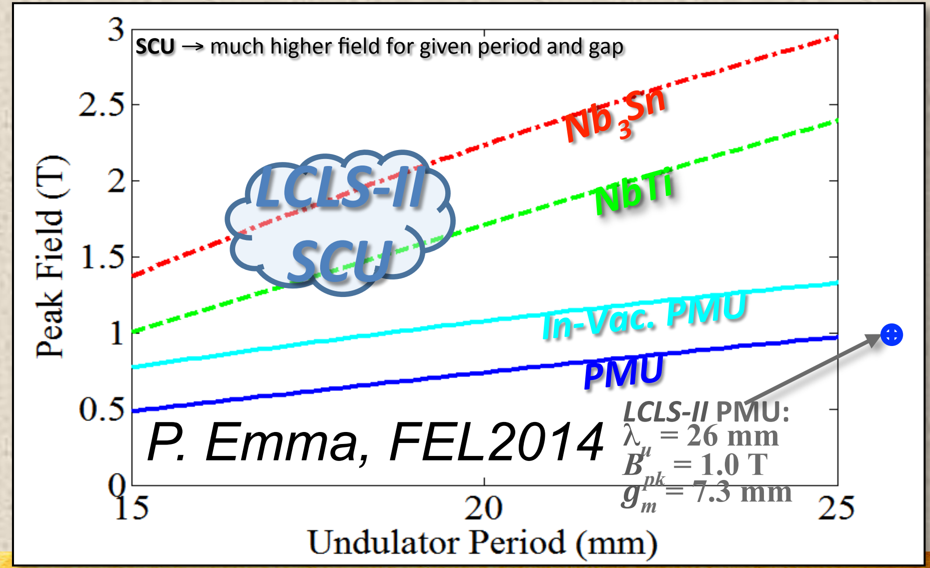
Superconducting Undulators

- SCUs can provide the best performance characteristics for X-ray facilities
  - High-field, short-period devices provide spectral range with shortest FEL footprint, lowest beam energy
  - Fine trajectory and phase-shake correction provides requisite field quality and access to harmonics (minimize errors through fabrication tolerances and field correction scheme)
- Various types of facilities can benefit from the development of SCU technology
  - FEL facilities
  - FELs based on advanced accelerator concepts
  - Storage ring facilities



$$\lambda_{1,planar} = \frac{1+K^2/2}{2\gamma^2}\lambda_u \qquad K = \frac{eB\lambda_u}{2\pi mc}$$

$$K_{max} = \left[2\left(\frac{\lambda_2-\lambda_1}{\lambda_1}\right)\left(1+\frac{K^2_{min}}{2}\right)+K^2_{min}\right]^{1/2}$$

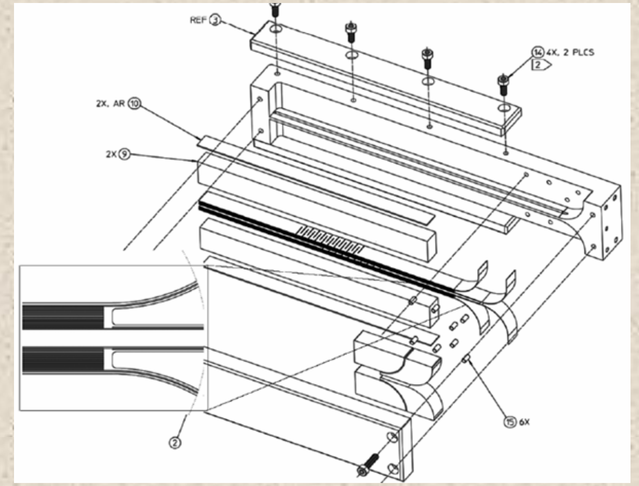


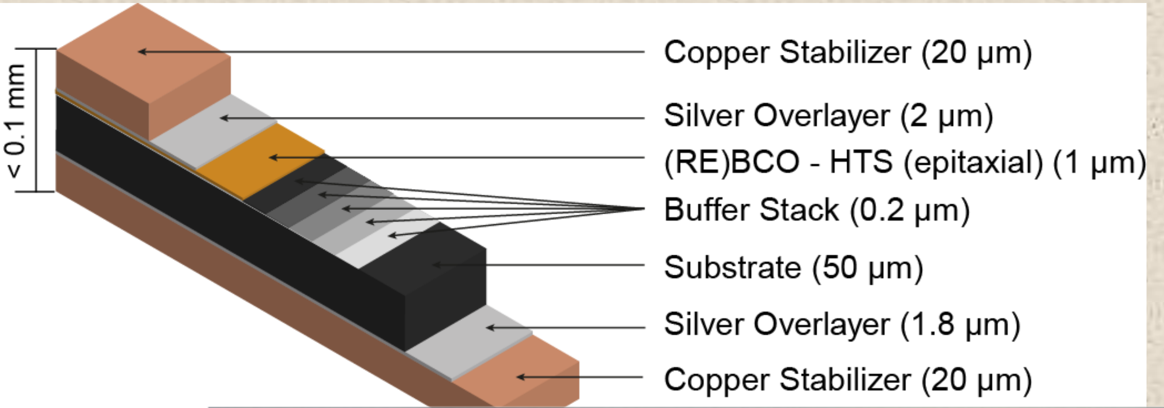
P. Emma, FEL2014

LCLS-II PMU:
λ_u = 26 mm
B_{pk} = 1.0 T
g_m = 7.3 mm

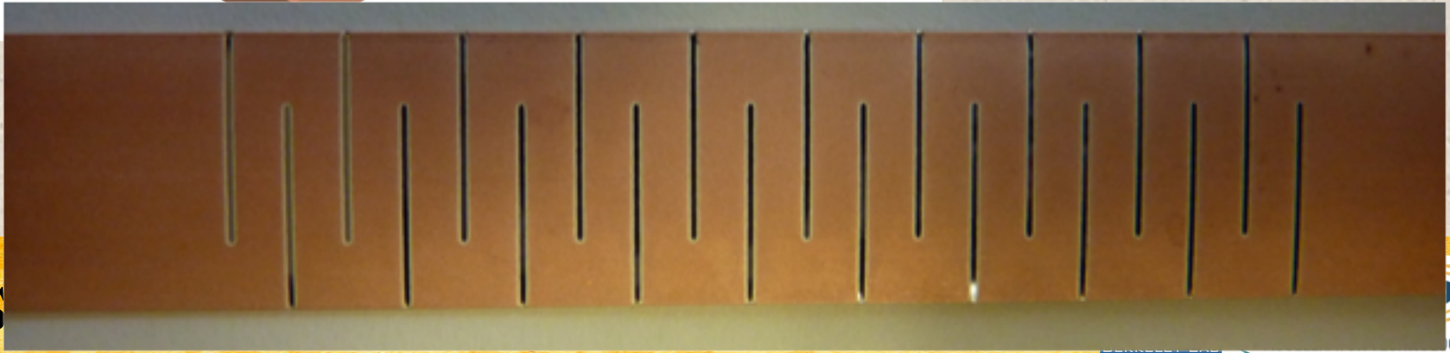
YBCO Tape Undulator could reach <10 mm period

- Commercial tape from SuperPower Inc.
- Masks designed for photolithography process
- Chemical etching used to remove Copper, Silver, and YBCO layers where desired
- Solderable thin film heaters were developed for efficient and reliable fabrication
- Laser cutting is used to separate joint section





Copper Stabilizer (20 µm)
Silver Overlayer (2 µm)
(RE)BCO - HTS (epitaxial) (1 µm)
Buffer Stack (0.2 µm)
Substrate (50 µm)
Silver Overlayer (1.8 µm)
Copper Stabilizer (20 µm)



FEL References

References:

K.-J. Kim and Z. Huang, FEL lecture note, available electronically upon request (zrh@slac.stanford.edu)

Saldin, Schneidmiller, Yurkov, The Physics of Free Electron Lasers (Springer, 1999), more SASE but much more technical