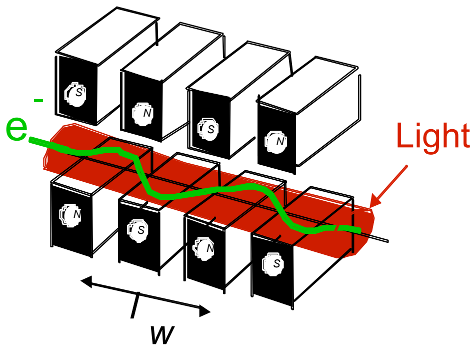
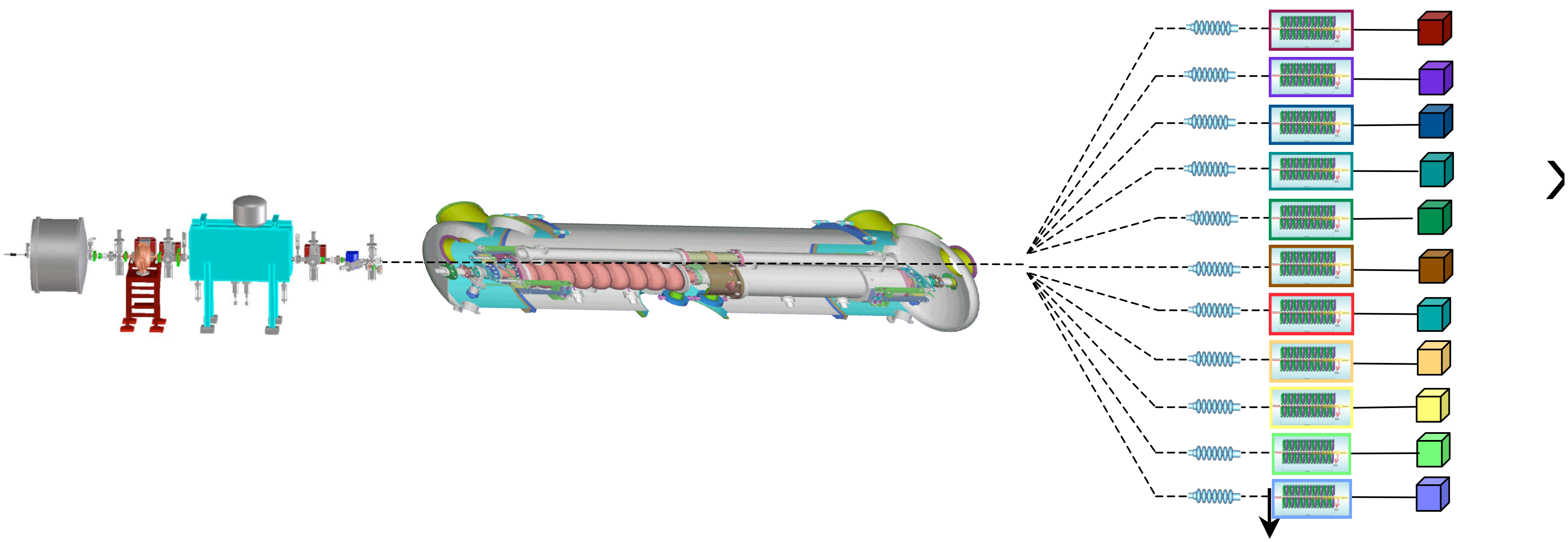
# X-Ray Free Electron Lasers

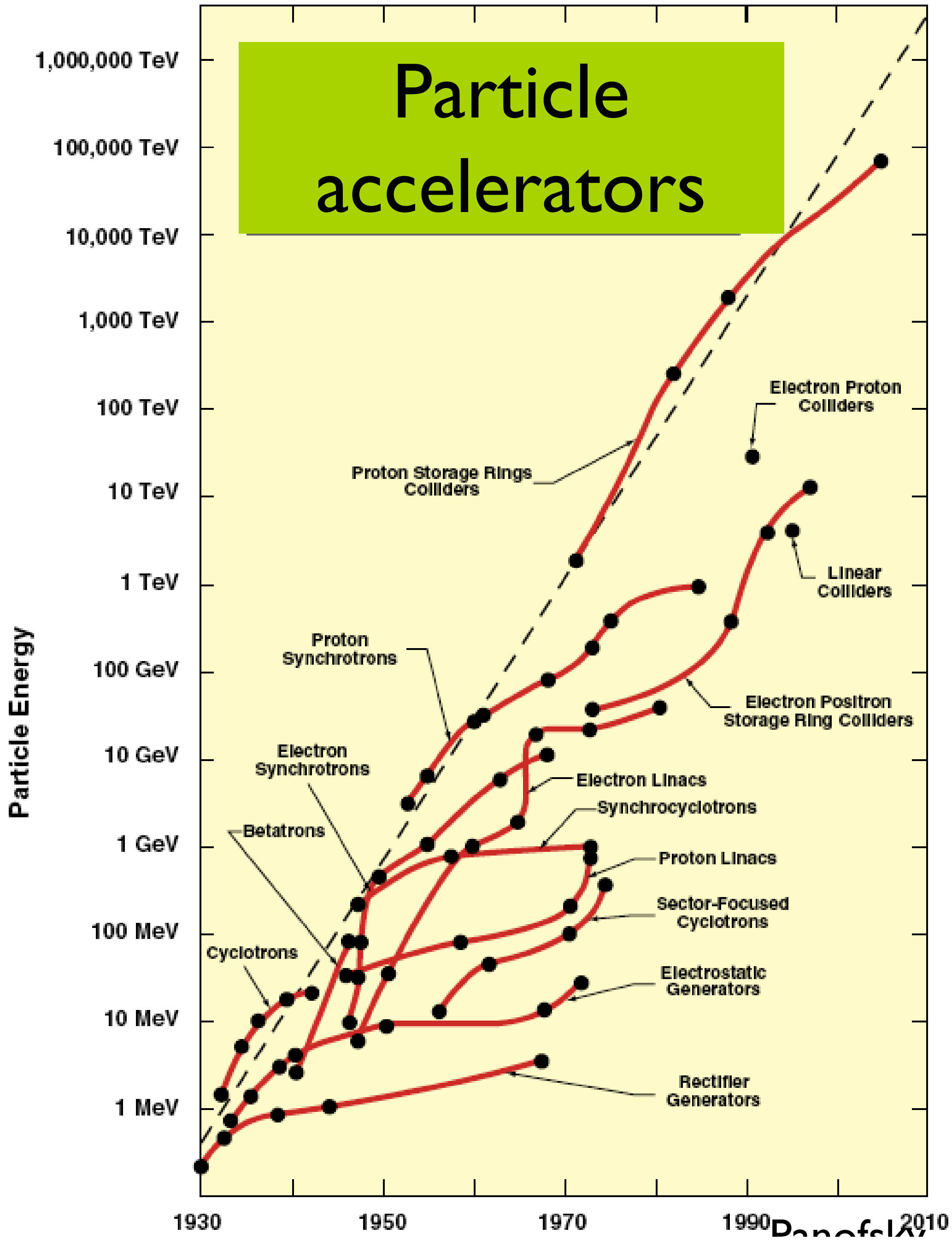
J.S. Wurtele
UCB and LBNL



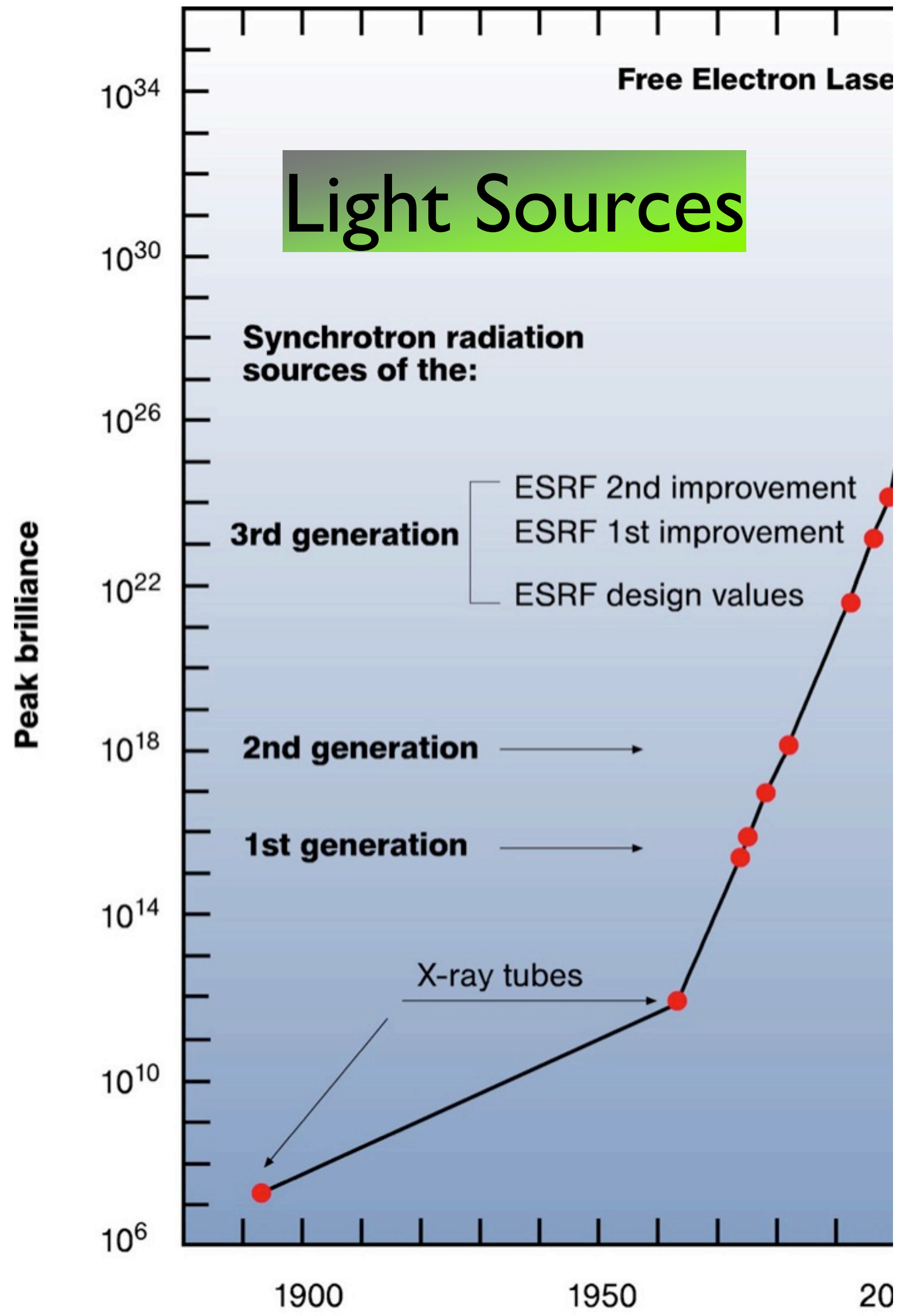

Davidson Symposium
PPPL
June 12, 2007



# Two Livingston Plots




Panofsky



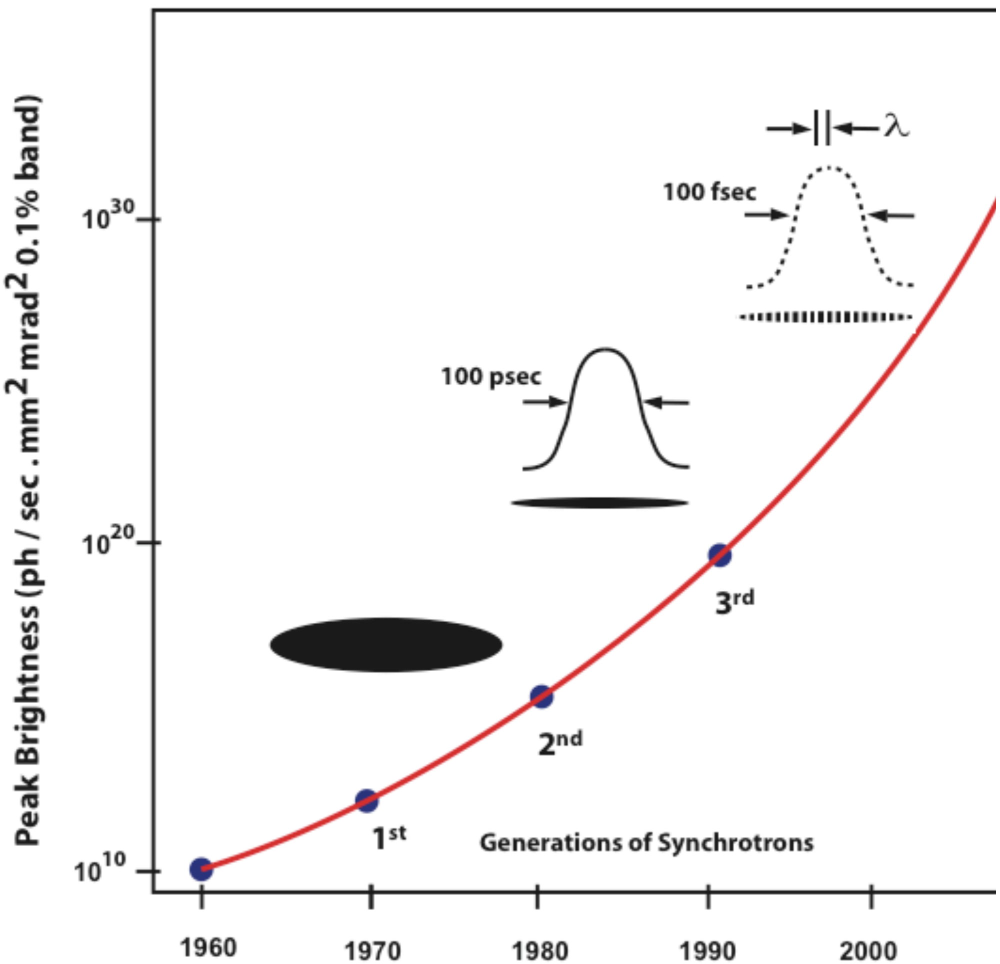
# Evolution of synchrotron radiation sources

## X-Ray FELs

**Goals:**

- High average flux
- High peak power
- Temporal coherence
- Spatial coherence
- Attosecond pulses
- Synchronization
- Flexibility

- Implications (current technology): Large machines, GeV Energies
- Critical Physics
  - Optical manipulation of phase space
  - High brightness beam generation and preservation
  - Wiggler technology

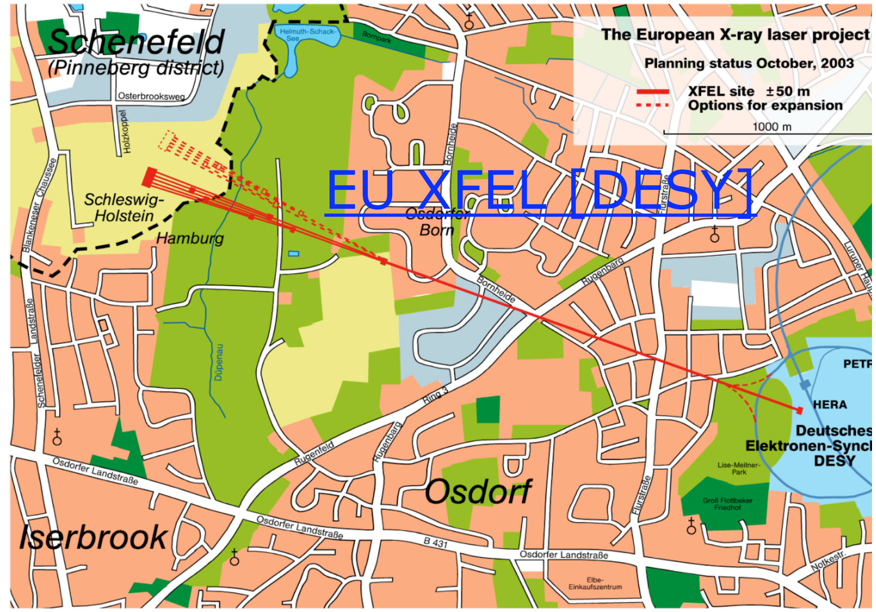


# X-ray sources expand

JAPAN [SPRING 8]


Fig. 2 Proposed site for XFEL machine at SPring-8.

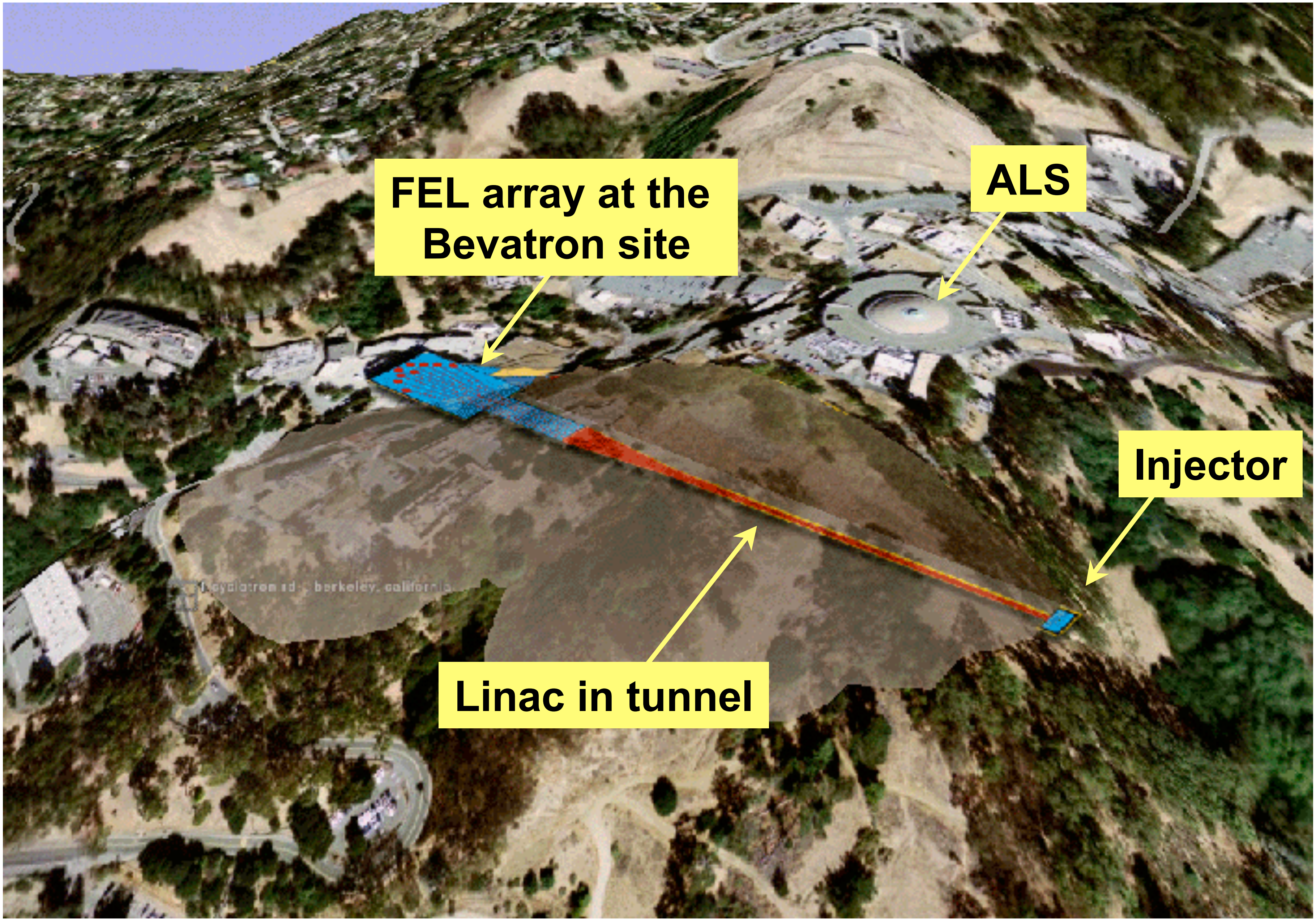
EU XFEL [DESY]




LCLS [SLAC] FEL

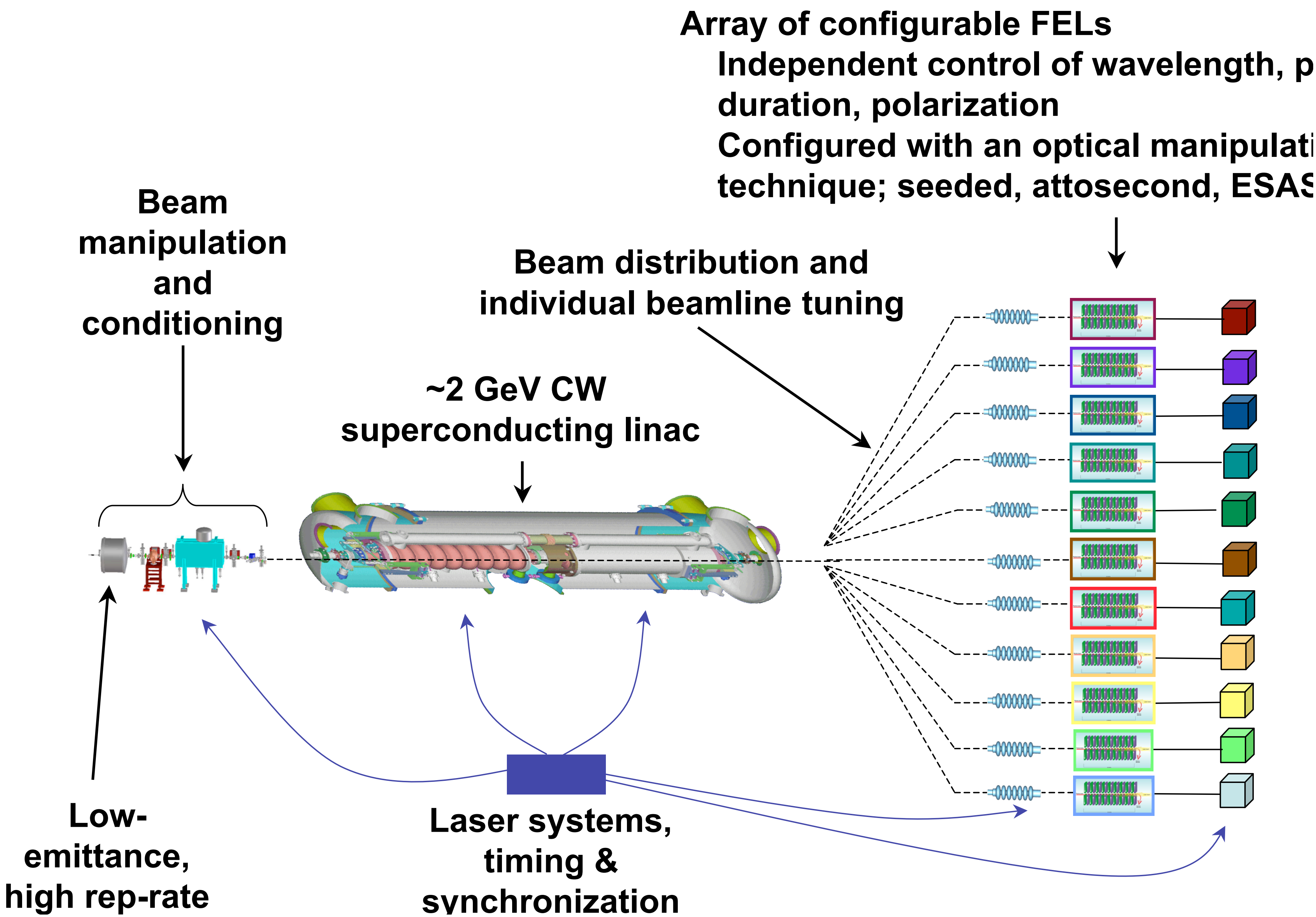
| | |
|---|---|
| Current | ~3.5kA |
| Energy | ~13.6GeV |
| Repetition rate | ~120Hz |
| Peak X-Ray Power | ~8GW |
| | |

# Vision for a future LBNL light sour

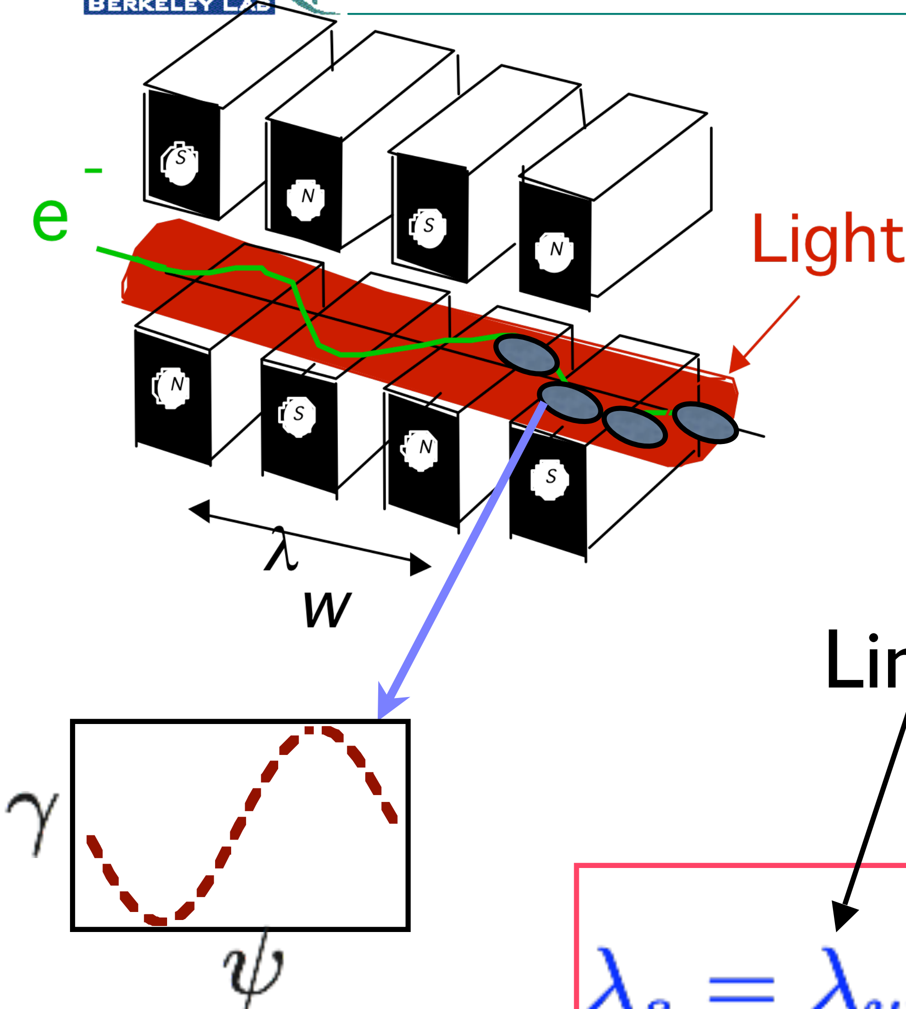


# Vision for a future light source facility at LBN

## A HIGH REP-RATE, SEEDED, VUV — SOFT X-RAY FEL ARRAY



# FEL BASICS




$$\frac{d\gamma}{dz} = \frac{q\vec{E}\cdot\vec{v}}{mc^2 v_z}$$

$$\psi = (k_s + k_w)z - \omega$$

$$v_z = \frac{\omega_s}{k_s + k_w}$$

Limits

$$\lambda_s = \lambda_w \frac{1+\gamma^2\beta_\perp^2}{2\gamma^2}$$

Spread in this term is harmful!

# What drives X-ray FELs towards large energy electron beams?

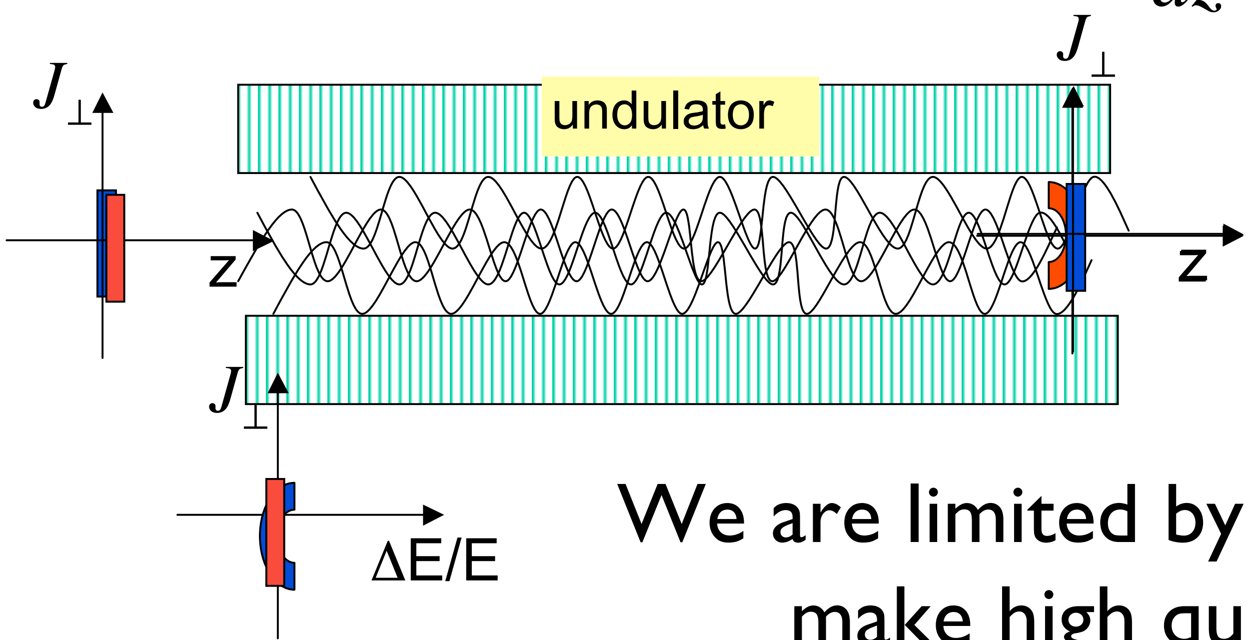
1. Coherent emission--bunching at X-ray wavelengths

2. Limits on our ability to create and propagate high brightness electron beams

3. Limits on our ability to build short wavelength wiggler

# Dephasing from transverse motion

$$\frac{d\psi}{dz} = 2k_w \frac{\gamma - \gamma_r}{\gamma_r} +$$

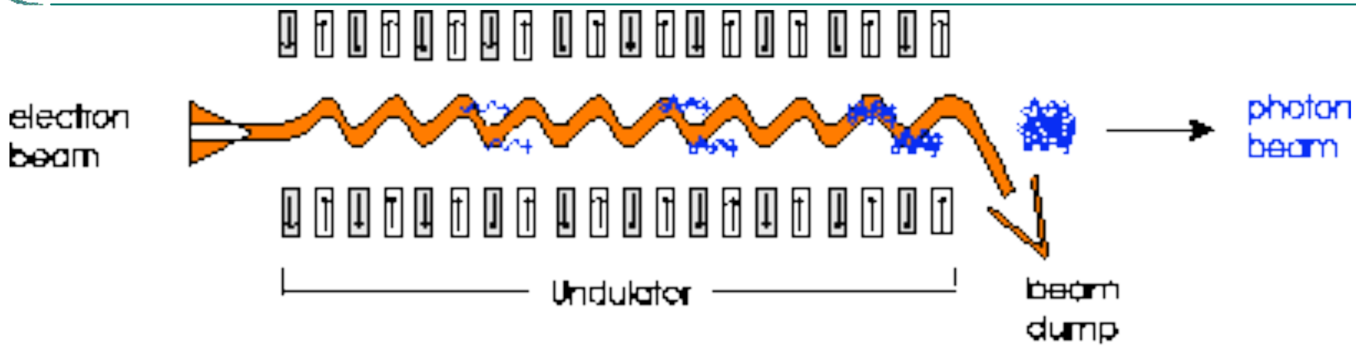



We are limited by our inability t
make high quality beams

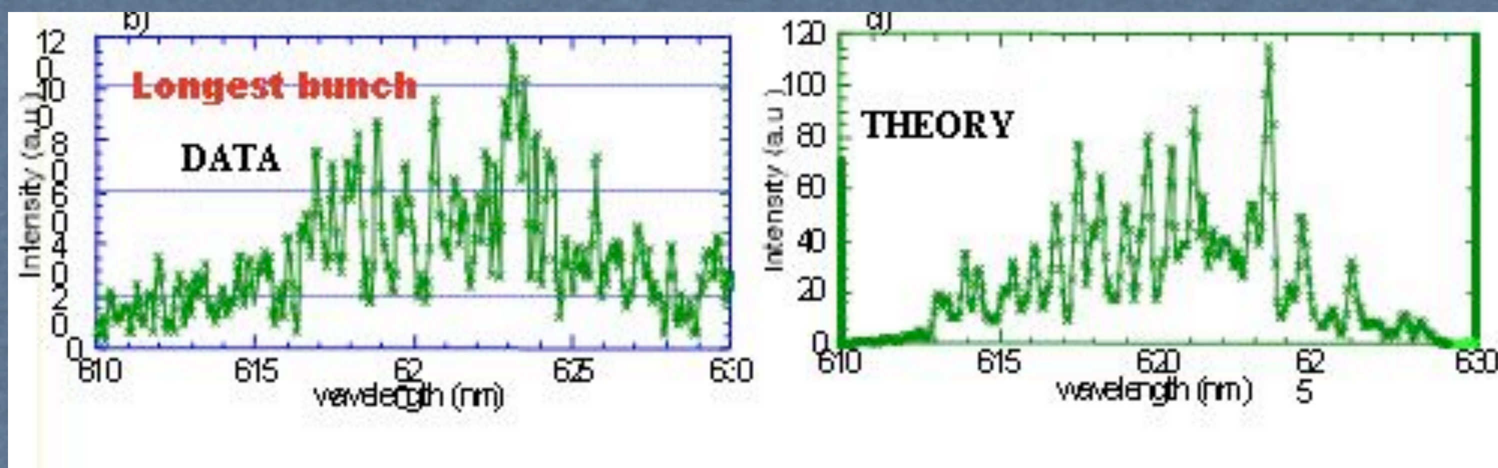
**with conditioning**

- allows relaxed emittance requirement in FEL-
-but we do not know how to produce required conditioning in a practical system (yet)

# SASE FEL: amplification of fluctuations




Single pass synchrotron radiation spectrum (Catravas, et al, @BNL/ATF,)



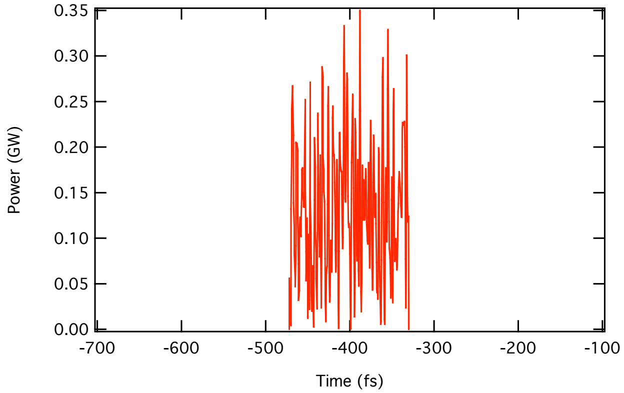

SASE spectrum and temporal shape has spikes--
poor longitudinal coherence

# Seeded FEL

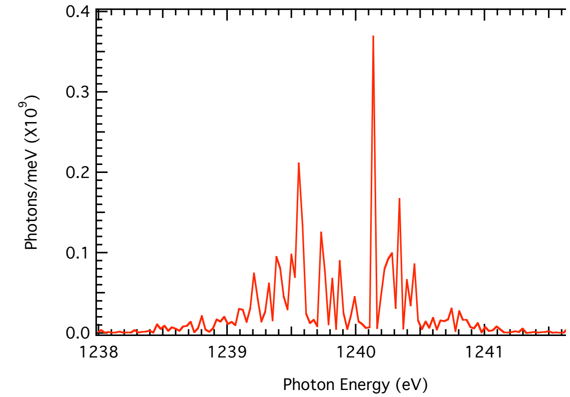
## ENHANCED CAPABILITIES FOR CONTROL OF X-RAY PULS

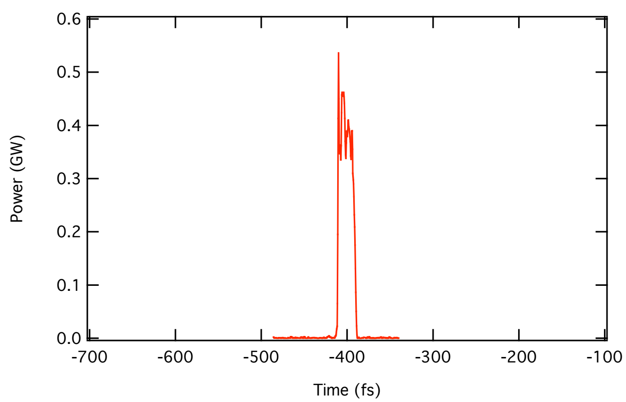
### Pulse profile

### Spectrum

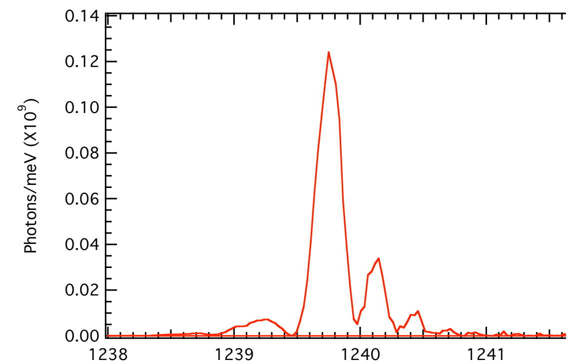



**SASE**



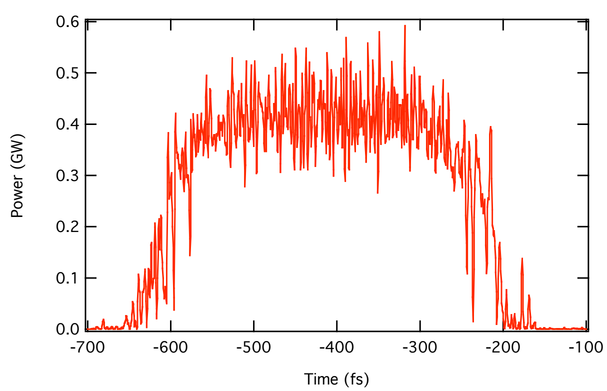




**25 fs seed**



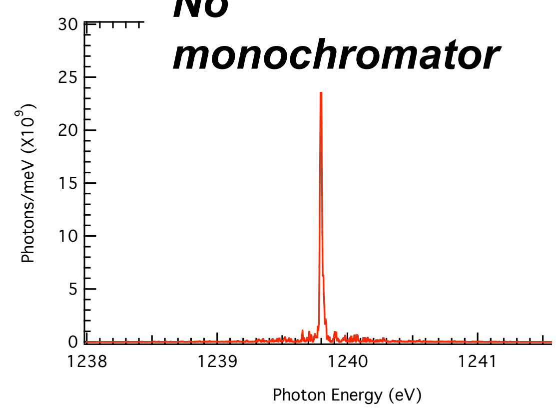

**Seeded FEL close to**

**transform limit**




**500 fs seed**

***No monochromator***



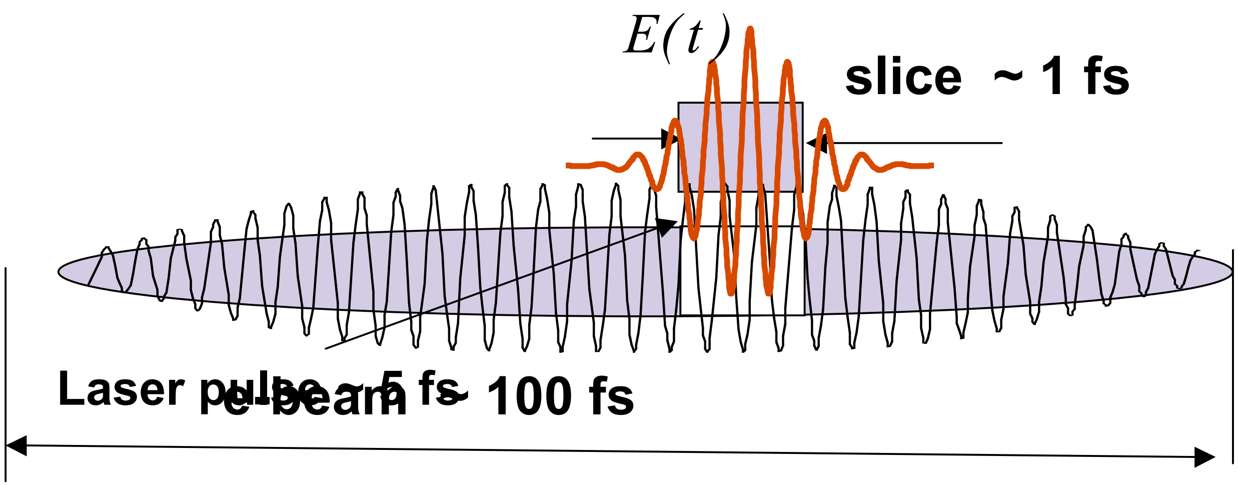
# Phase space manipulation

Manipulate beam phase space can have many advantages:

- Enhanced gain
- Seeding radiation pulse for harmonic cascades
- Attosecond pulses
- Synchronization
- Relax beam quality constraints (conditioning)
- Lower energy for given wavelength

Many of these ideas are realized by laser interactions with the electron beam prior to the radiation generation. Sor examples…

# Lasers manipulate longitudinal phase spa during interaction in wiggler

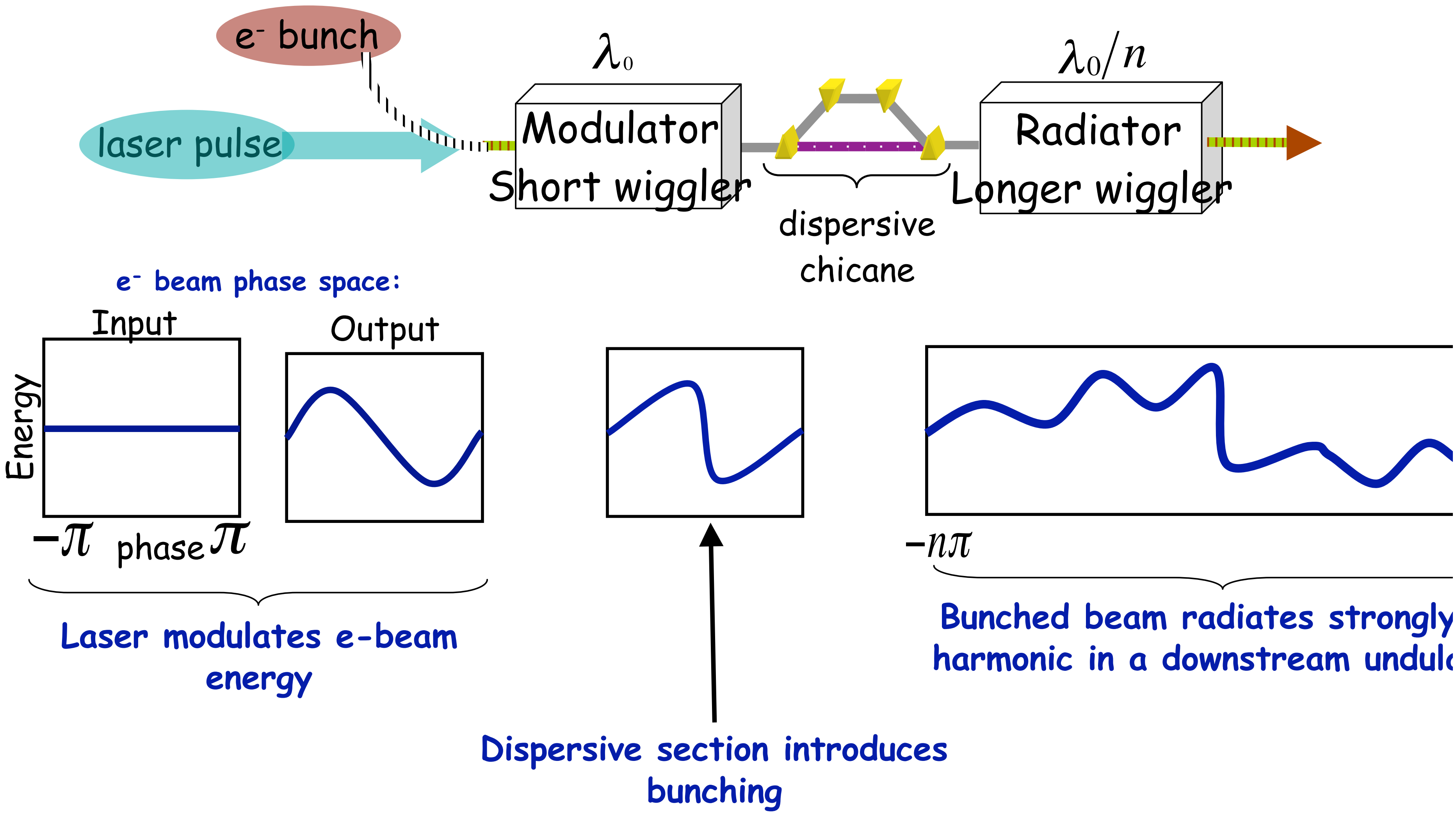



Harmonic cascade see

This cartoon is realized by manipulation of beam phase space with short pulse lasers. The idea is to condition and select specific slices of electrons to radiate differently (in direction, frequency, intensity, *etc.). For synchrotron sources this has already been accomplished:* Zholents & Zoloterev (1996); Schoenlein, et al, 2000; Khan, Part. Acc. Conf. 2005. For FEL see Zholents et al (2003-2007)

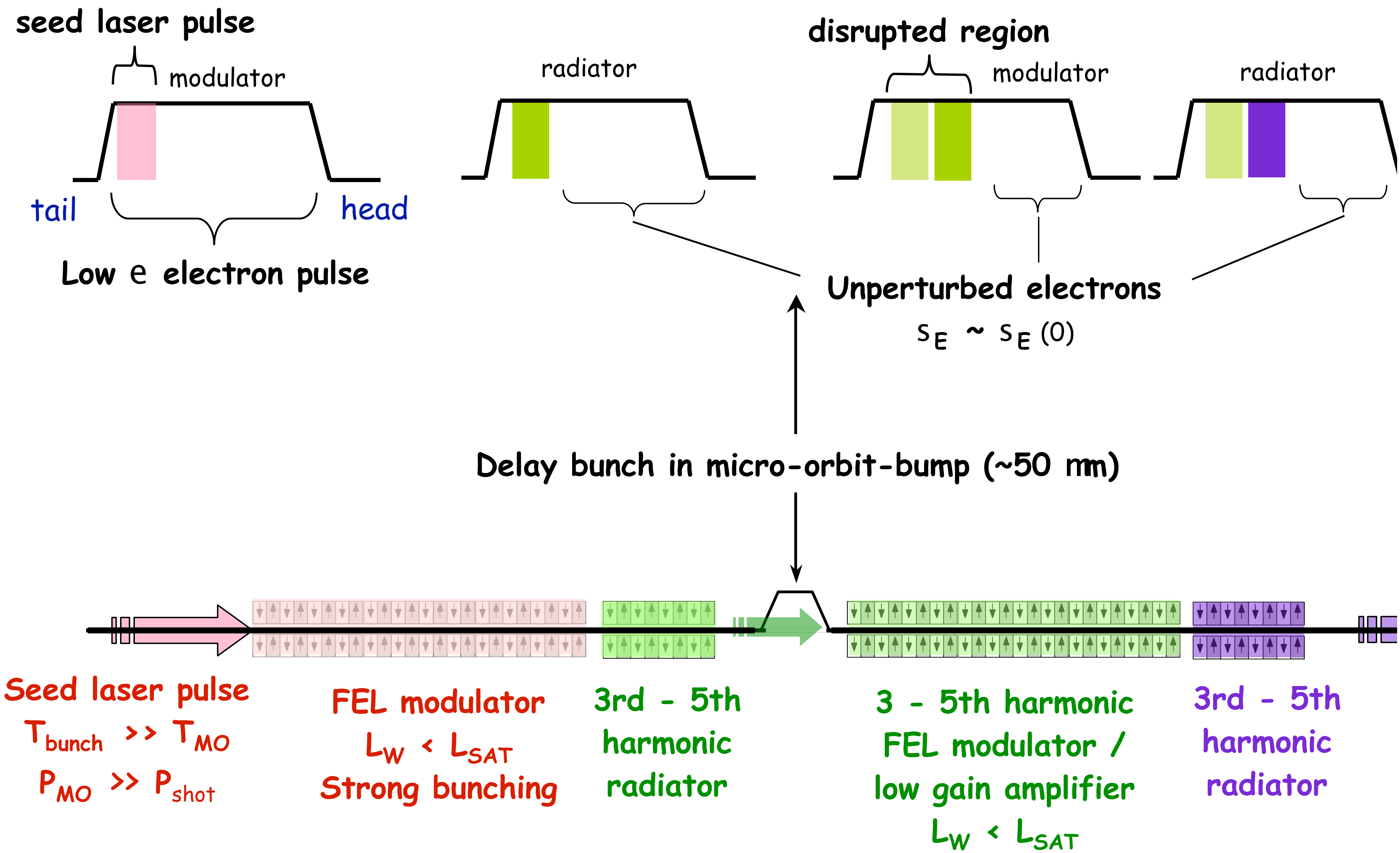
# High Gain Harmonic Generation (HGHG) – seed with a laser pulse and radiate at a harmonic

## Extends energy reach, lower power




L.-H. Yu et al, Science 289 932-934 (2000)

# Cascaded harmonic generation scheme



# HHG laser seed--an alternative to harmoni cascades

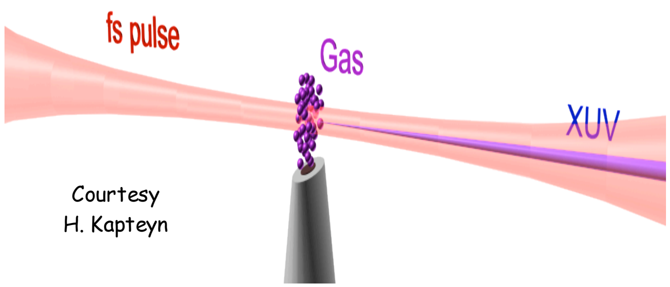
Example with seed at 30 nm, radiating in the water window
First stage amplifies low-power seed with "optical klystron"
More initial bunching than could be practically achieved with a single modulato
Output at 3.8 nm ($8^{th}$ harmonic)

100 kW
l =30 nm

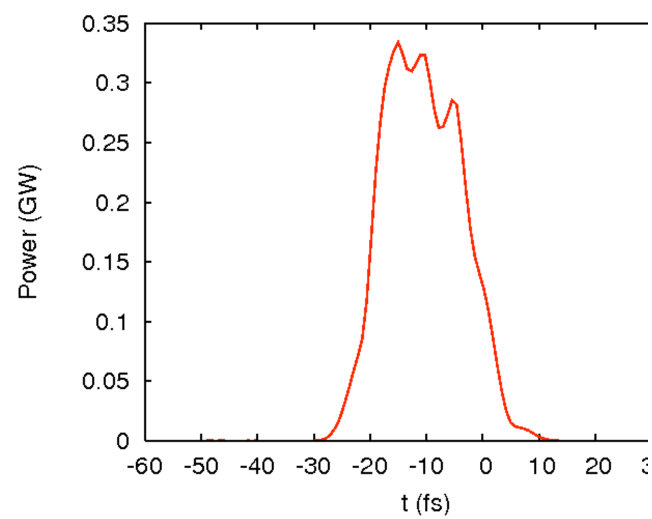
1 GeV beam
500 A
1.2 micron emittance
75 keV energy spread

| Modulator | Modulator | Radiator |
|---|---|---|
| 30 nm, L=1.8 m | 30 nm, L=1.8 m | 3.8 nm, L=12 |

**300 MW output at 3.8 nm ($8^{th}$ harmonic) from a 25 fs FWHM seed**

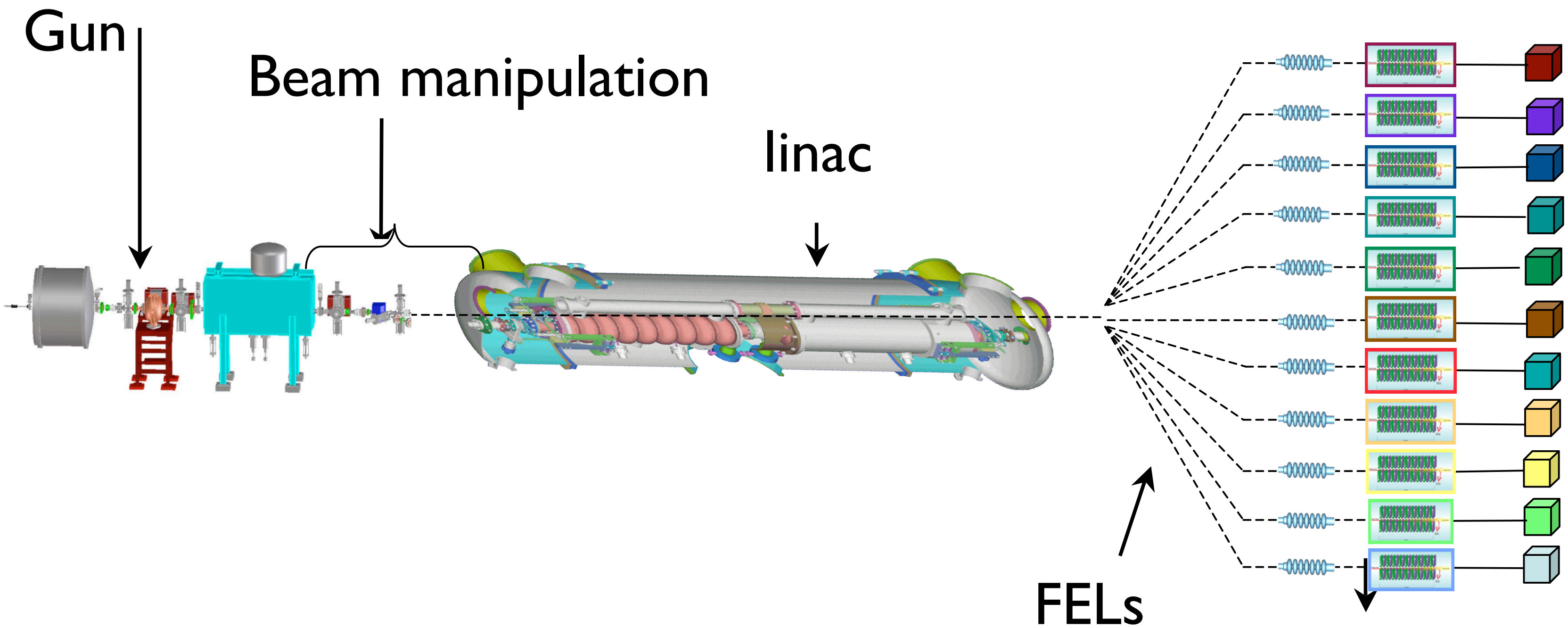



Courtesy
H. Kapteyn




Or, X-ray laser seed

Gullans et a




FEL performance is governed by beam brightness:

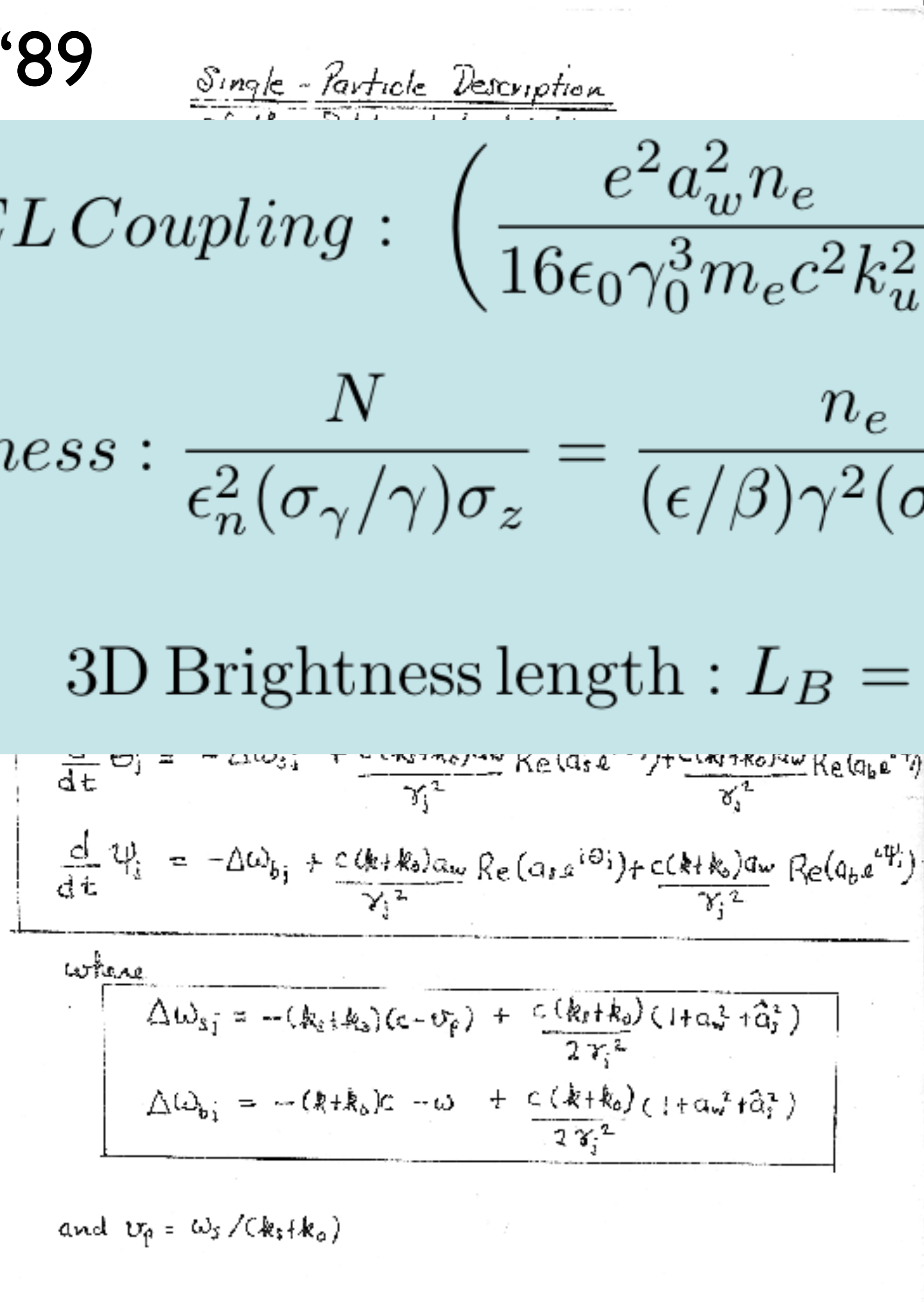
*Brightness = # electrons/6D-phase space volume*

This number will NOT get larger---

determined by gun physics and emittance

or energy spread can grow through various instabilities

# RCD circa '89



Single-Particle Description

$$\frac{d}{dt}\theta_j = -\Delta\omega_{sj} + \frac{c(k_s+k_0)a_w}{\gamma_j^2} Re(a_s e^{i\theta_j}) + \frac{c(k_s+k_0)a_w}{\gamma_j^2} Re(a_b e^{i\psi_j})$$

$$\frac{d}{dt}\psi_j = -\Delta\omega_{bj} + \frac{c(k+k_0)a_w}{\gamma_j^2} Re(a_s e^{i\theta_j}) + \frac{c(k+k_0)a_w}{\gamma_j^2} Re(a_b e^{i\psi_j})$$

where

$$\Delta\omega_{sj} = -(k_s+k_0)(c-v_p) + \frac{c(k_s+k_0)}{2\gamma_j^2}(1+a_w^2+\hat{a}_j^2)$$

$$\Delta\omega_{bj} = -(k+k_0)c - \omega + \frac{c(k+k_0)}{2\gamma_j^2}(1+a_w^2+\hat{a}_j^2)$$

and $v_p = \omega_s/(k_s+k_0)$

$$FEL\,Coupling: \left(\frac{e^2 a_w^2 n_e}{16\epsilon_0\gamma_0^3 m_e c^2 k_u^2}\right)^{1/3}$$

$$Brightness: \frac{N}{\epsilon_n^2(\sigma_\gamma/\gamma)\sigma_z} = \frac{n_e}{(\epsilon/\beta)\gamma^2(\sigma_\gamma/\gamma)}$$

$$\text{3D Brightness length}: L_B = \frac{Br_{cl}}{k_r}$$

Gullans et al

# Many people within LBNL contribute to new light sou

Walter Barry
Dan Bates
Ken Baptiste
Ali Belkacem
John Byrd
Chris Celata
Chris Coleman-Smith
John Corlett
Stefano DeSantis
Larry Doolittle
Roger Falcone
Bill Fawley
Graham Fleming
Miguel Furman
Tom Gallant
Mike Greaves
Steve Gourlay
Michael Gullens
Gang Huang
Zahid Hussein

Preston Jordan
Jerry Kekos
Janos Kirz
Jim Krupnick
Slawomir Kwiatkowski
Steve Leone
Derun Li
Steve Lidia
Steve Marks
Bill McCurdy
Pat Oddone
Howard Padmore
Emanuele Pedersoli
Gregg Penn
Dave Plate
Ilya Pogorelov
Ji Qiang
Alex Ratti
Ina Reichel
David Robin

Kem Robinson
Glenna Rogers
Rob Ryne
Fernando Sannibale
Bob Schoenlein
Andy Sessler
Kiran Sonnad
John Staples
Christoph Steier
Jean-Luc Vay
Marco Venturini
Will Waldron
Weishi Wan
Russell Wells
Russell Wilcox
Jonathan Wurtele
Sasha Zholents
Mike Zisman
Max Zolotorev