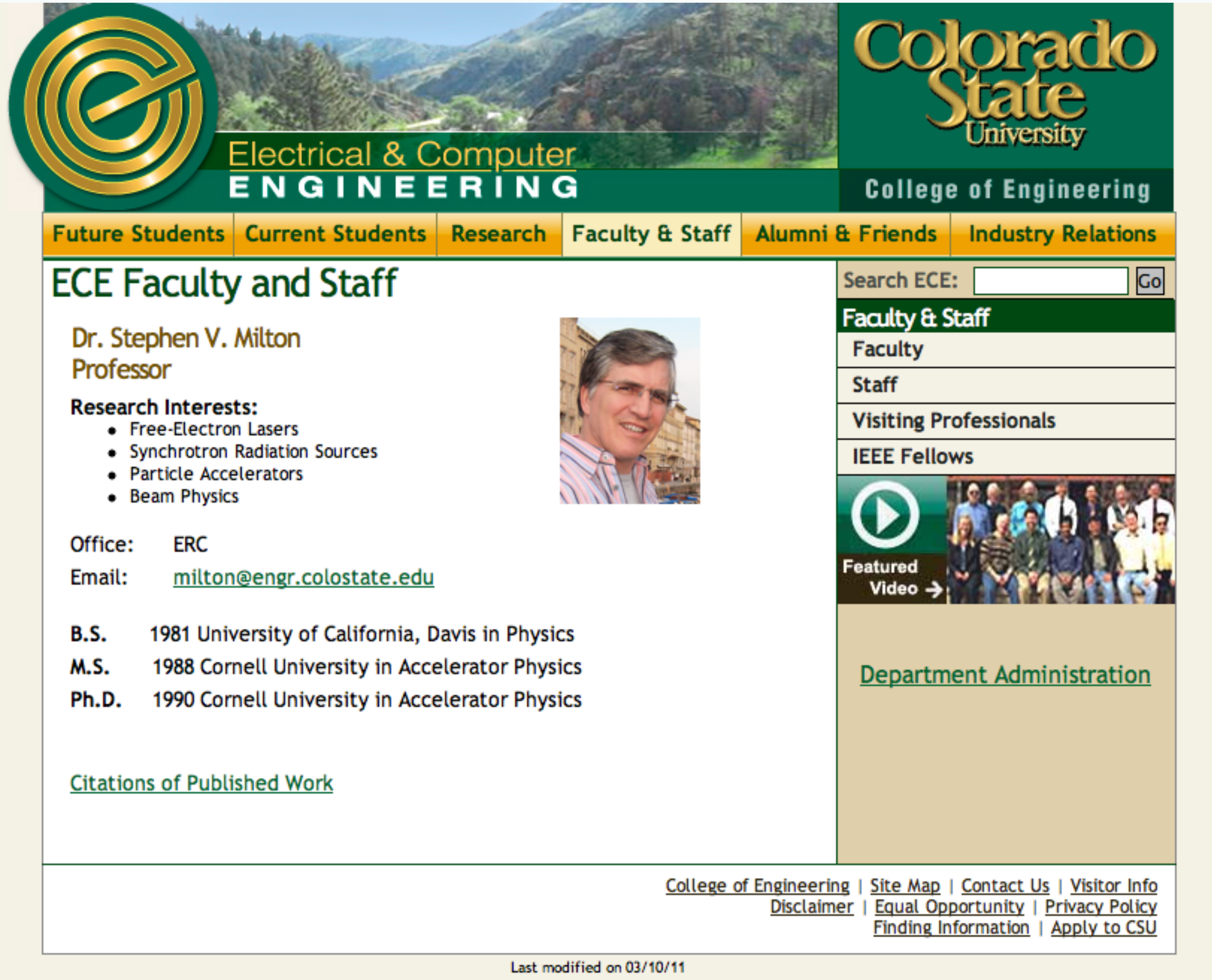
Seeded FELs

International Linear Collider School
Whistler BC
Stephen Milton, Colorado State University
5 Nov. 2015



ECE Faculty and Staff

Dr. Stephen V. Milton
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Research Interests:
- Free-Electron Lasers
- Synchrotron Radiation Sources
- Particle Accelerators
- Beam Physics

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B.S.	1981 University of California, Davis in Physics
M.S.	1988 Cornell University in Accelerator Physics
Ph.D.	1990 Cornell University in Accelerator Physics

Citations of Published Work

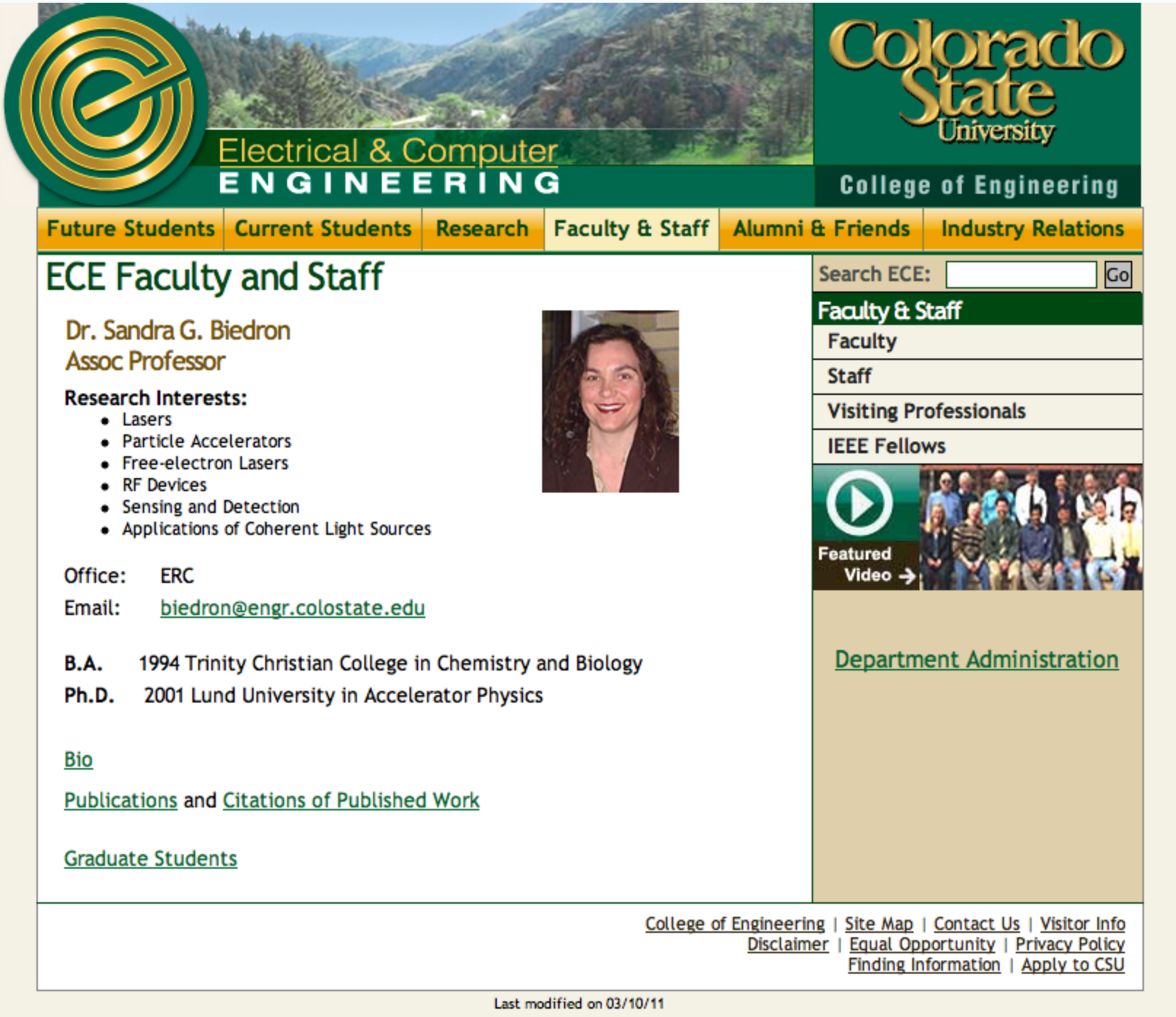
Last modified on 03/10/11

Fort Collins, Colorado

WINNER
Top 100 rank: 6
Population: 141,000
Unemployment: 7.4%

COURTESY: FORT COLLINS/RYAN BURKE

Bikers and beers. In most parts of the country, those two elements may be reasons to move elsewhere. But in the foothills of Colorado's Front Range, bikers mean cyclists: Fort Collins has 29 miles of well-used trails.
As for beers, this town has become a high-end microbrew mecca. New Belgium Brewery (maker of Fat Tire) is based in this entrepreneurial town, and competitors are moving in.



ECE Faculty and Staff

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- RF Devices
- Sensing and Detection
- Applications of Coherent Light Sources

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Bio

Publications and Citations of Published Work

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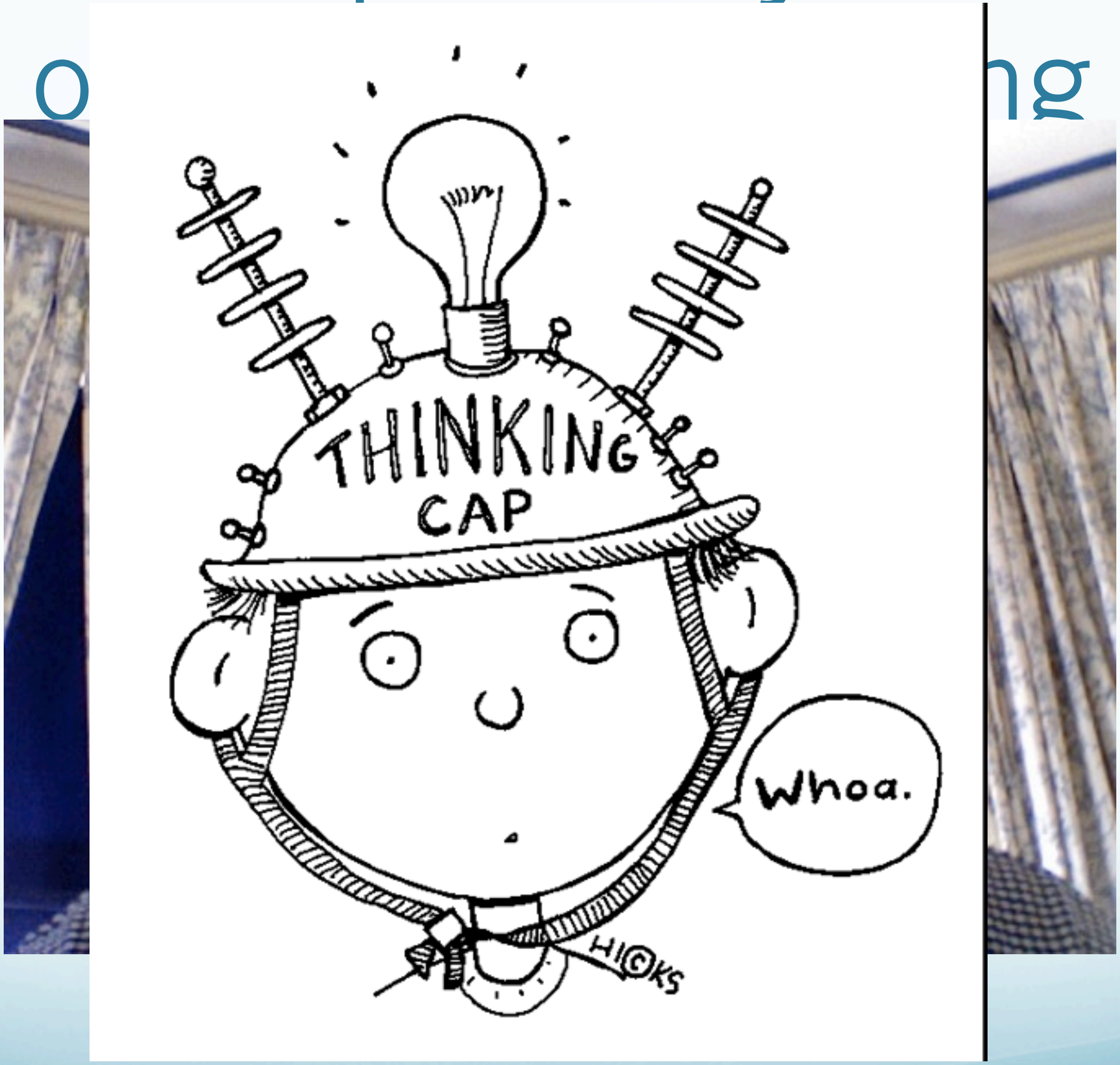
Your now probably look like o ng

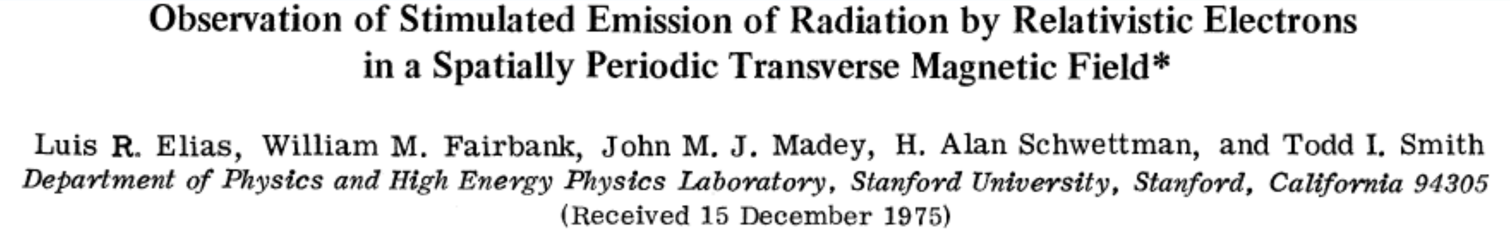


The Plan

- A little background
  - History
  - Where we are
- SASE
  - Why
- Seeding Advantage
- Seeding Techniques
- Technicalities

FIRST “modern” free-electron laser

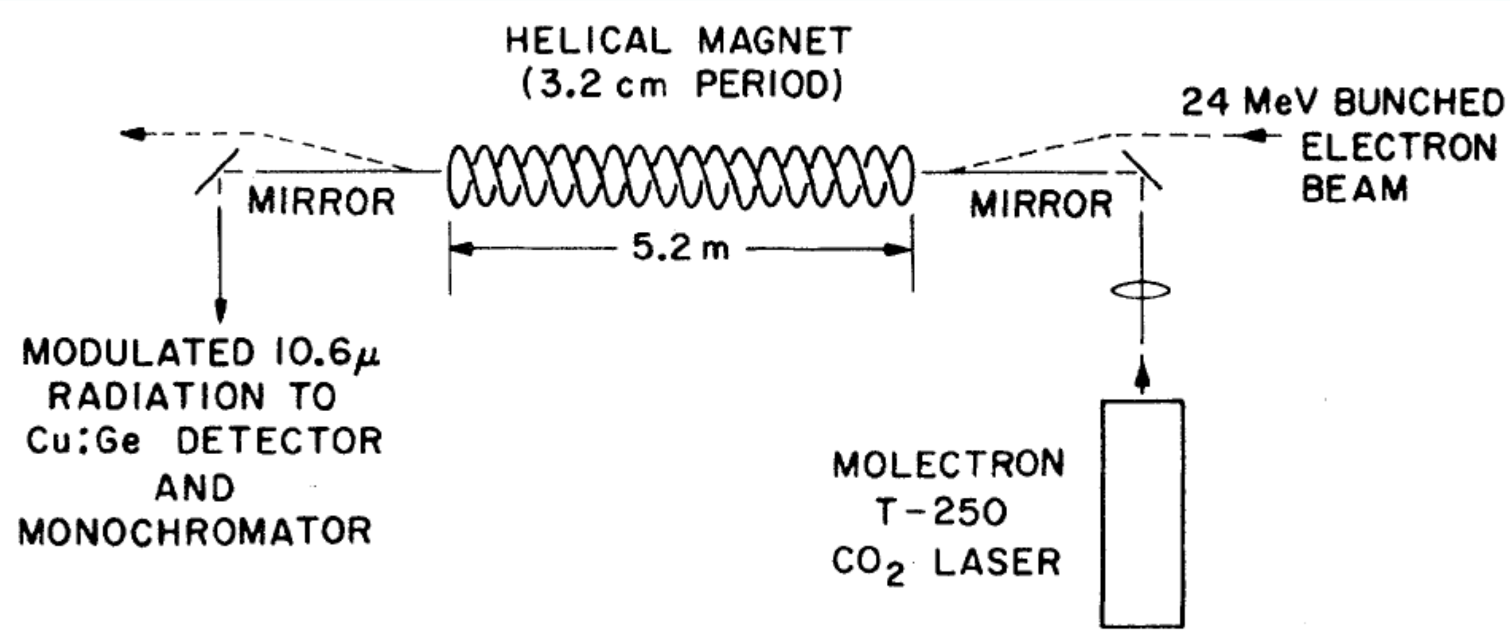
relativistic doppler shift, amplifier system



Observation of Stimulated Emission of Radiation by Relativistic Electrons in a Spatially Periodic Transverse Magnetic Field*

Luis R. Elias, William M. Fairbank, John M. J. Madey, H. Alan Schwettman, and Todd I. Smith
Department of Physics and High Energy Physics Laboratory, Stanford University, Stanford, California 94305

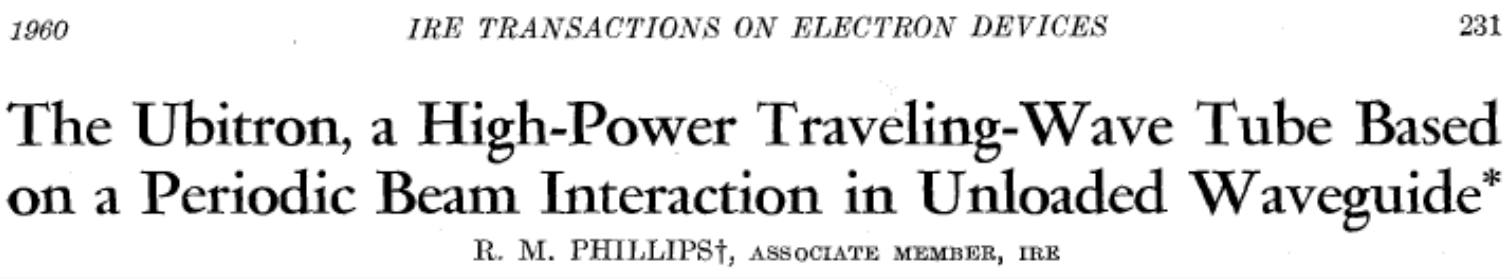
(Received 15 December 1975)



Elias et al., PRL 36, 717 (1976)

Ubitron: first free-electron laser

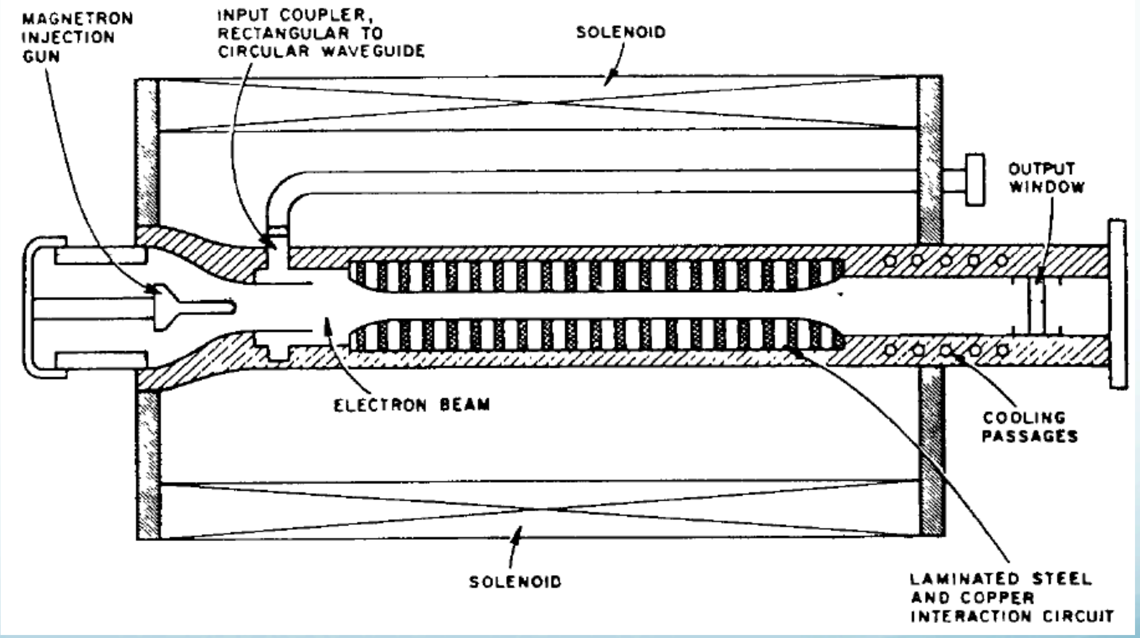
“non-relativistic” free-electron laser generating microwaves

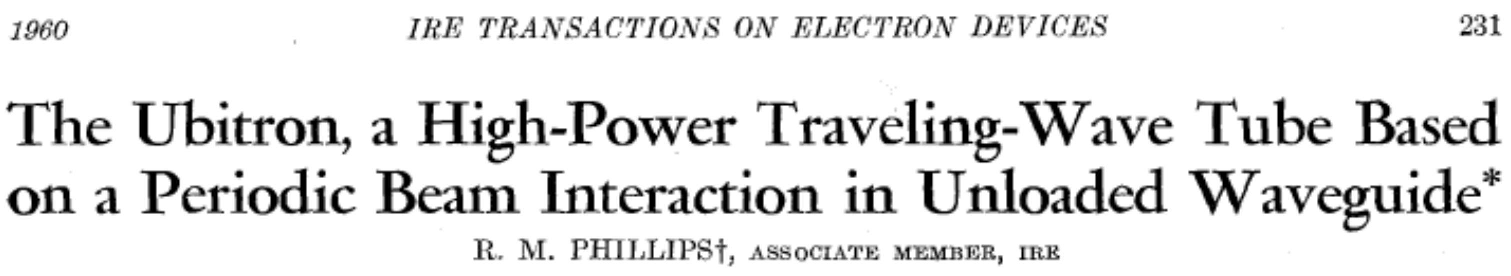


1960 *IRE TRANSACTIONS ON ELECTRON DEVICES* 231

The Ubitron, a High-Power Traveling-Wave Tube Based on a Periodic Beam Interaction in Unloaded Waveguide*

R. M. PHILLIPS†, ASSOCIATE MEMBER, IRE





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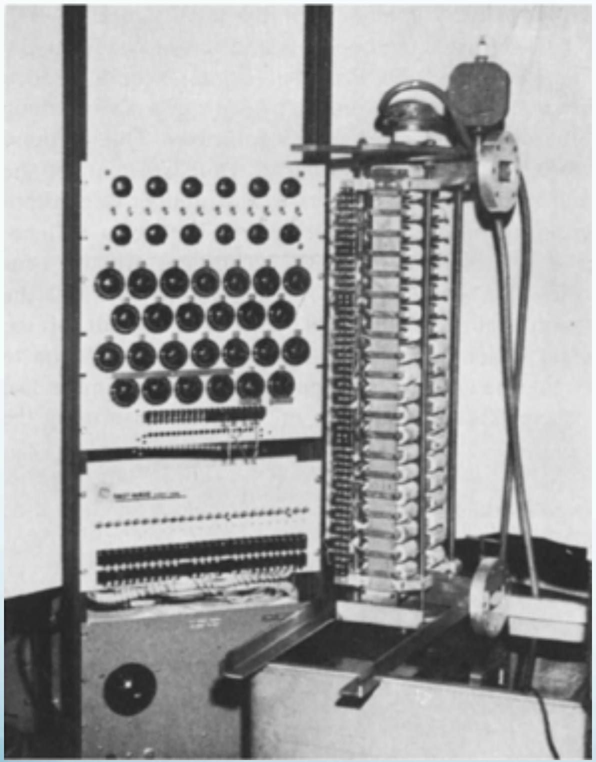
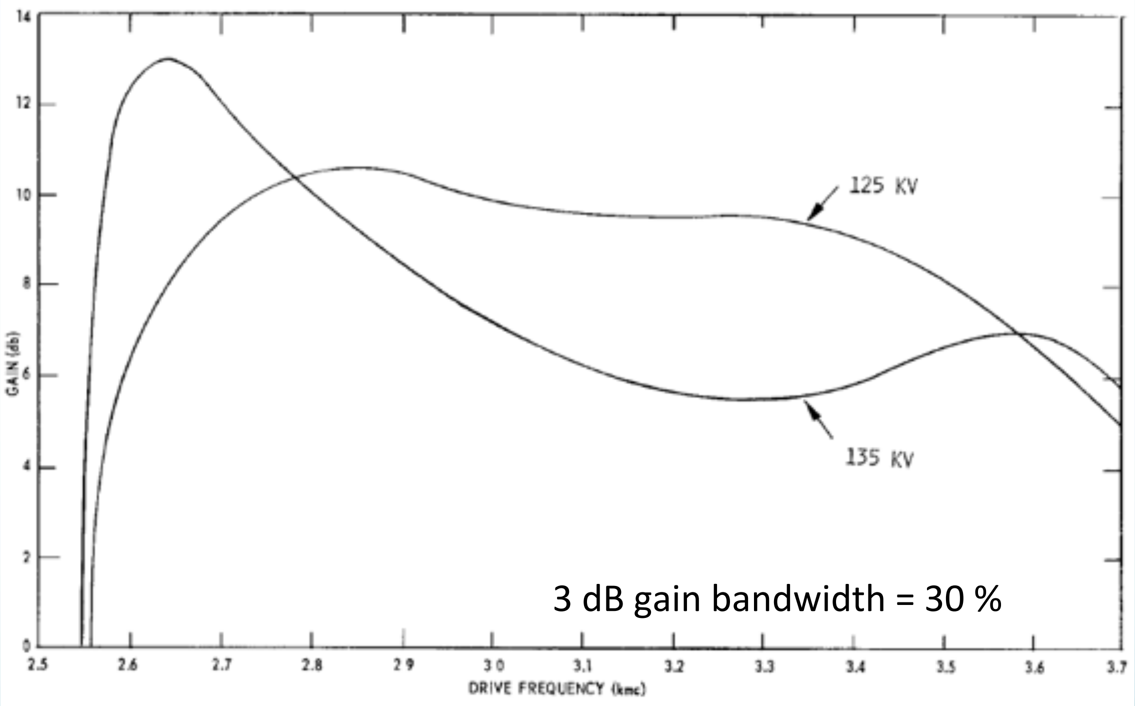
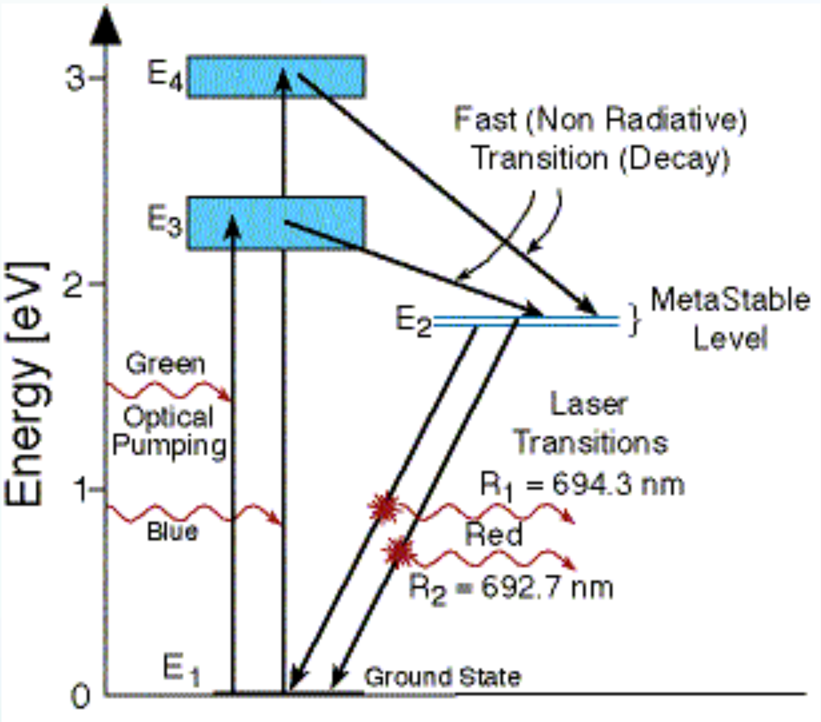
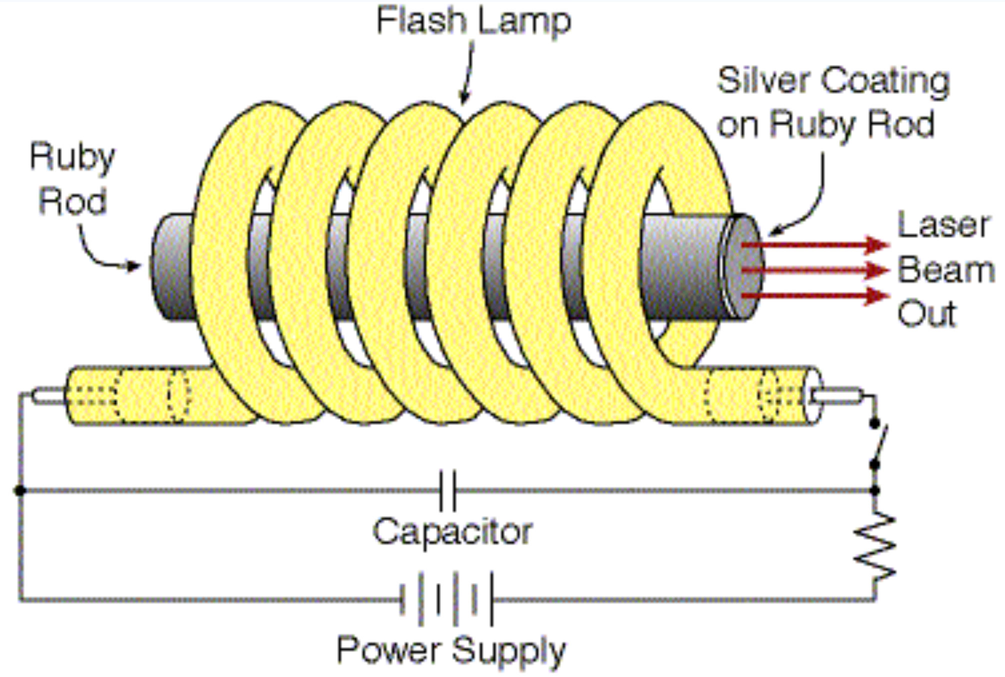




3 dB gain bandwidth = 30 %

The Classical Laser





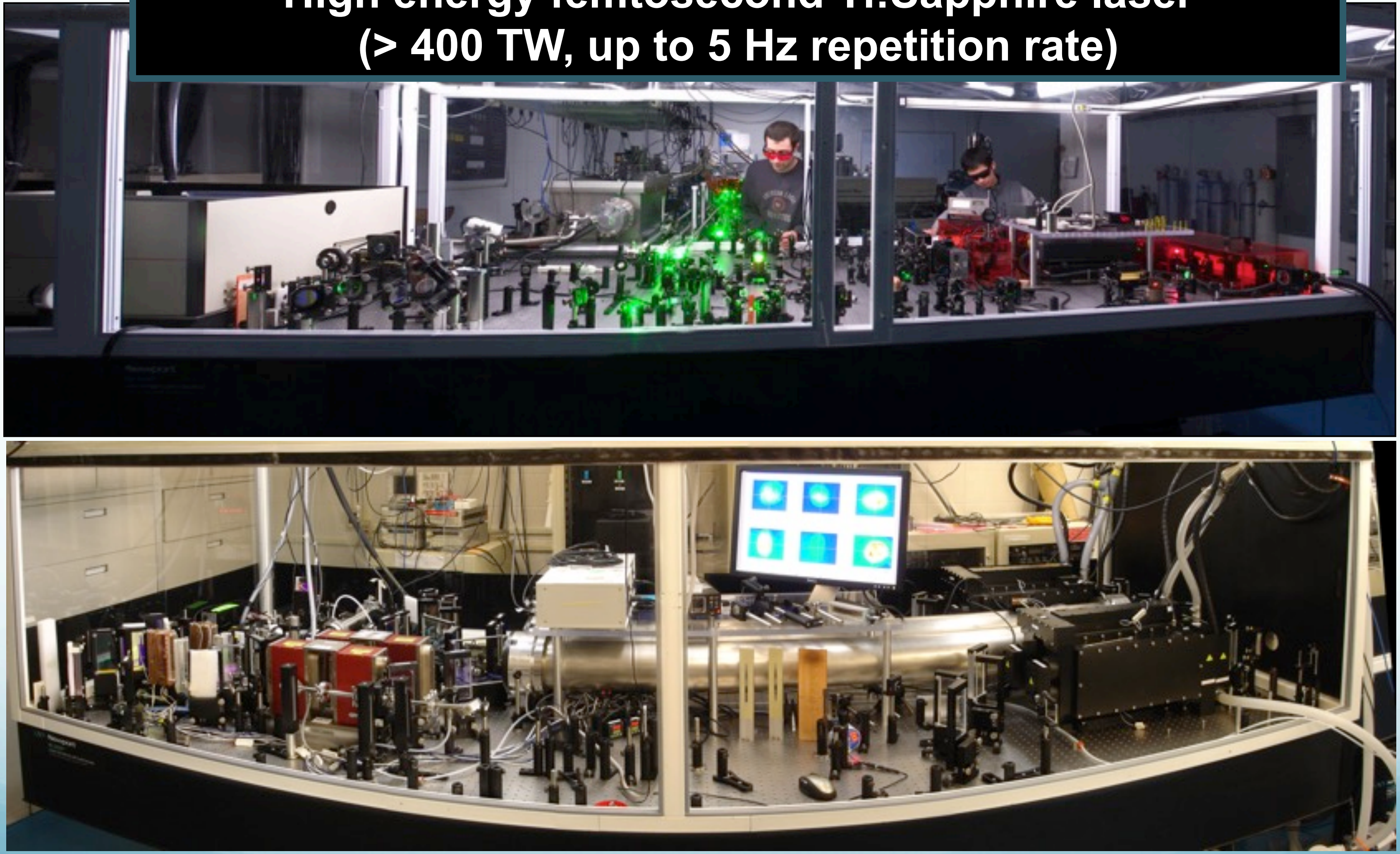
The early classical lasers generated mostly ASE (amplified spontaneous emission), but with the addition of mirrors and longer lasing times (longer flash lamp pulses), the pulse quickly cleaned up temporally and provide near complete temporal coherence. The classical oscillator configuration.

The Classical Laser

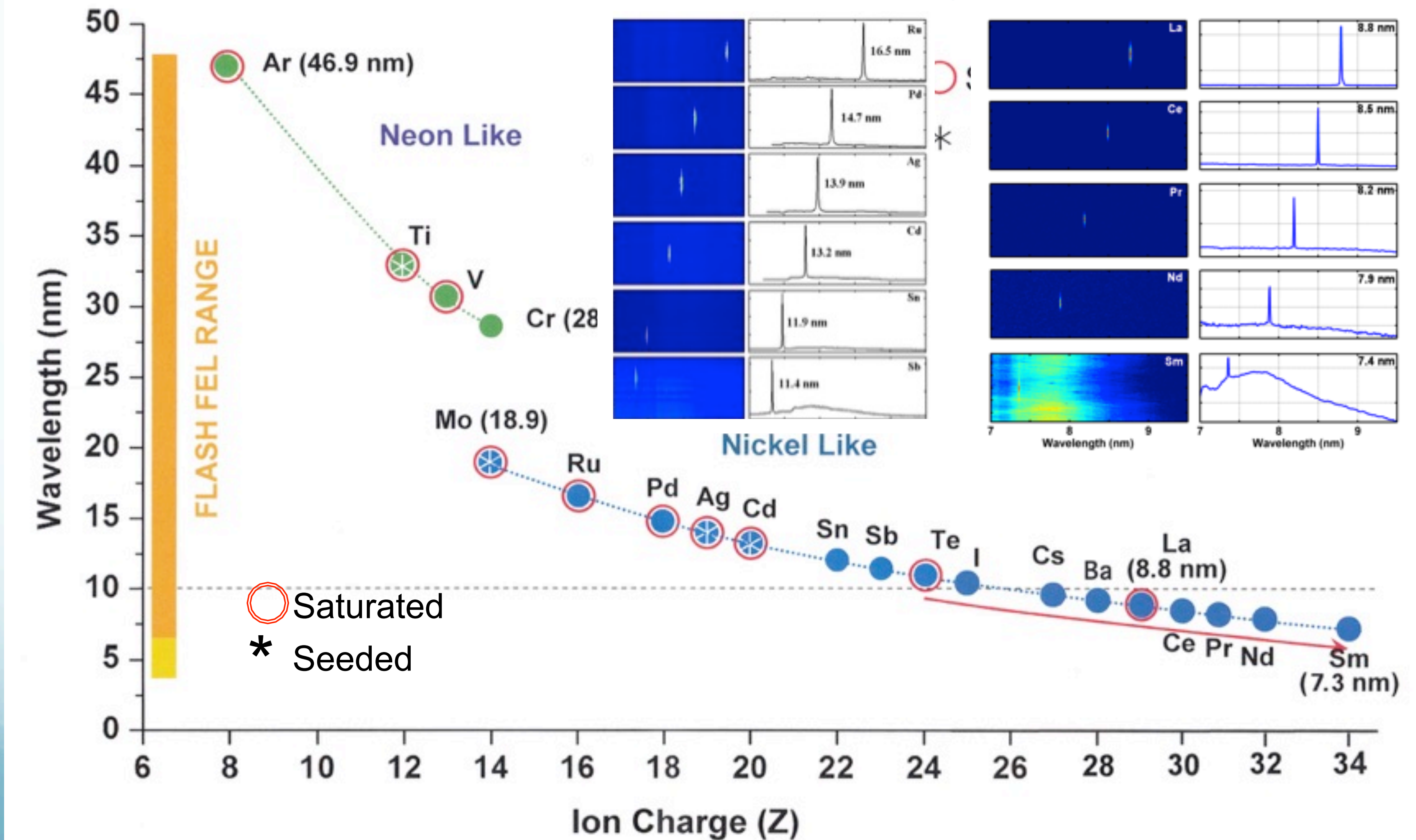
- For the atomic lasers to work one needs to first raise the atom or molecule to an excited state.
- Producing lasing action directly at UV wavelengths or beyond becomes increasingly difficult as one needs to pump the atom up to might higher excited states.
- Current records are in the 5nm-10nm range using Nickel-like atomic states generated in high-Z elements from high temperature, high-density plasmas created with very powerful lasers.

CSU Laser Lab 1 System

High energy femtosecond Ti:Sapphire laser
(> 400 TW, up to 5 Hz repetition rate)

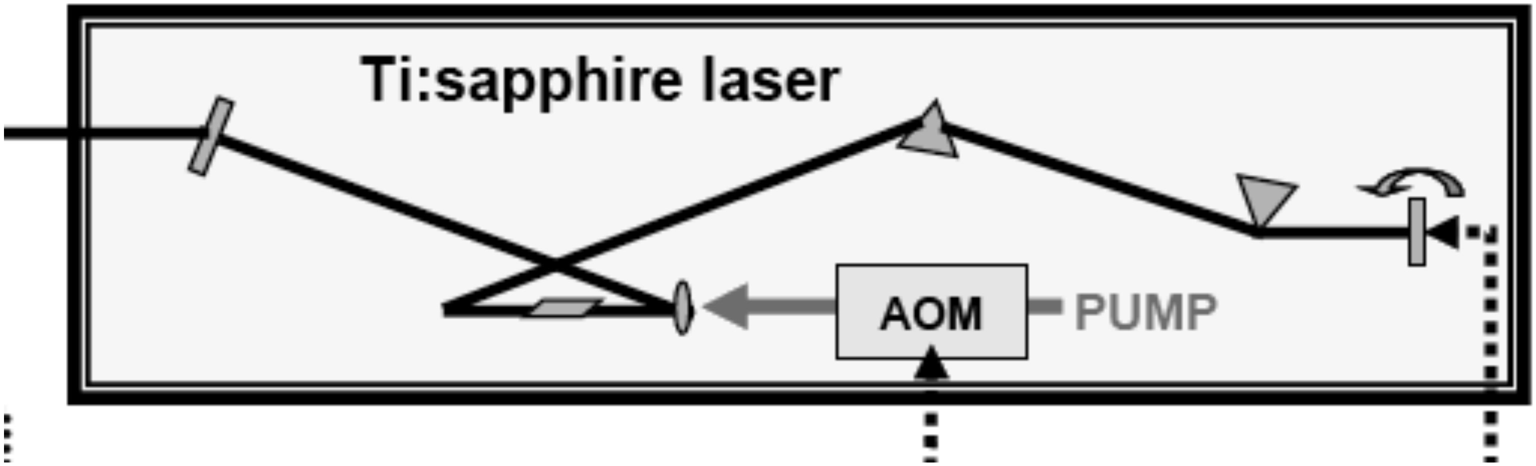


Primary Laser Lab Purpose: Generation of secondary radiation from the extreme ultraviolet to x-rays



D. Alessi et al. Phys. Rev X, 1, 021023, (2011)

Example:Ti:Sapph MLL



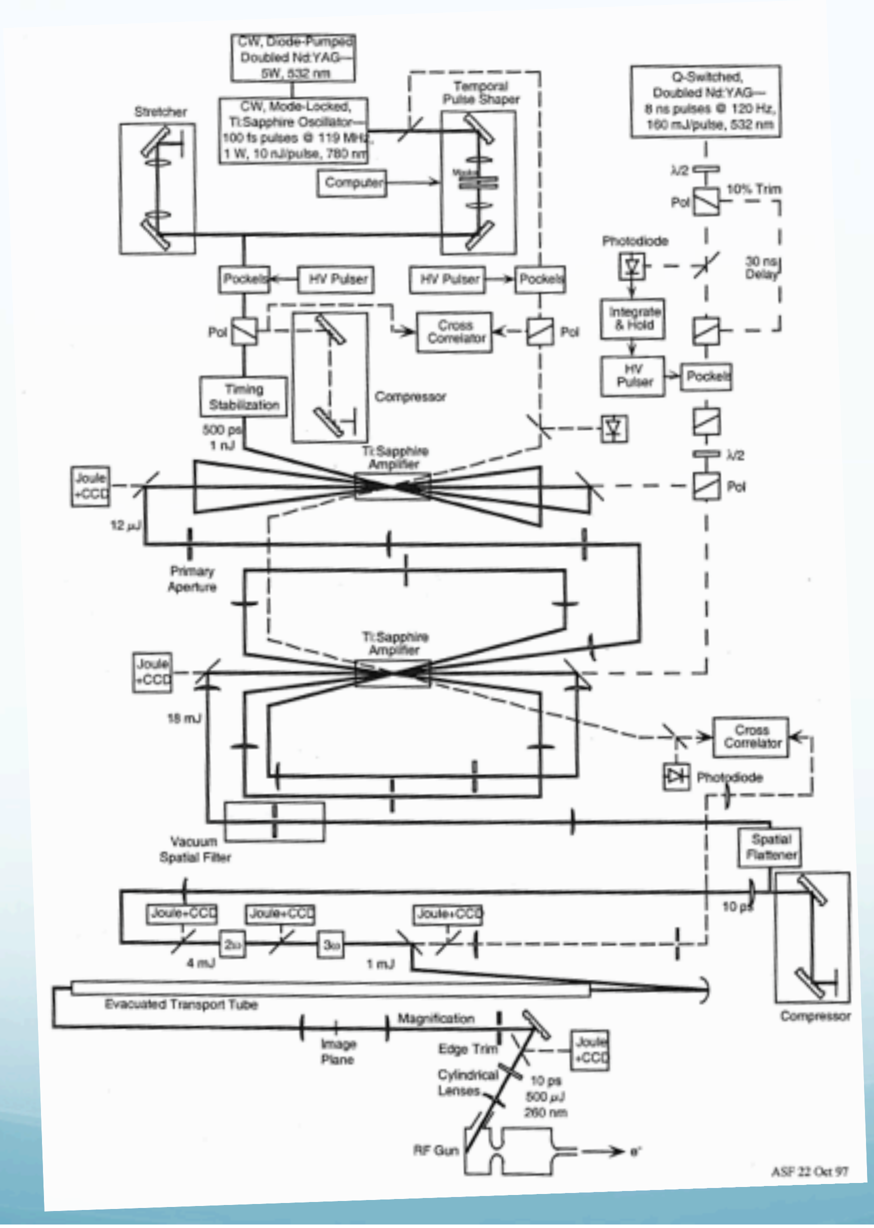
Repetition rate given by round trip travel time in cavity. Modulated by piezo adjustment of cavity mirror.

Passive mode locking achieved by properties of nonlinear crystal

Modern commercial designs include dispersion compensation in optics

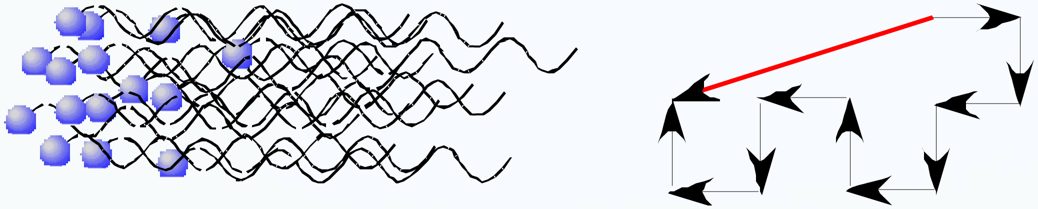
Comb spectrum allows direct link of microwave frequencies to optical frequencies

RF Photocathode Drive Laser

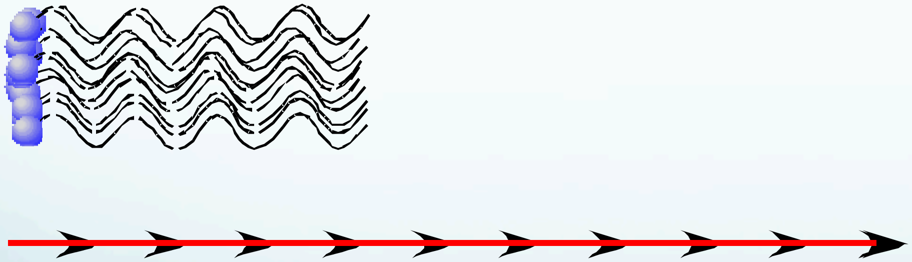


This was the original design for the drive laser of the LCLS. The figure is from the LCLS CDR.

Multiple Electrons



Incoherent Emission



Coherent Emission

If the electrons are independently radiating light then the phase of the their electric fields are random with repect ot one another and the electric field scale as the square root of the number of electrons

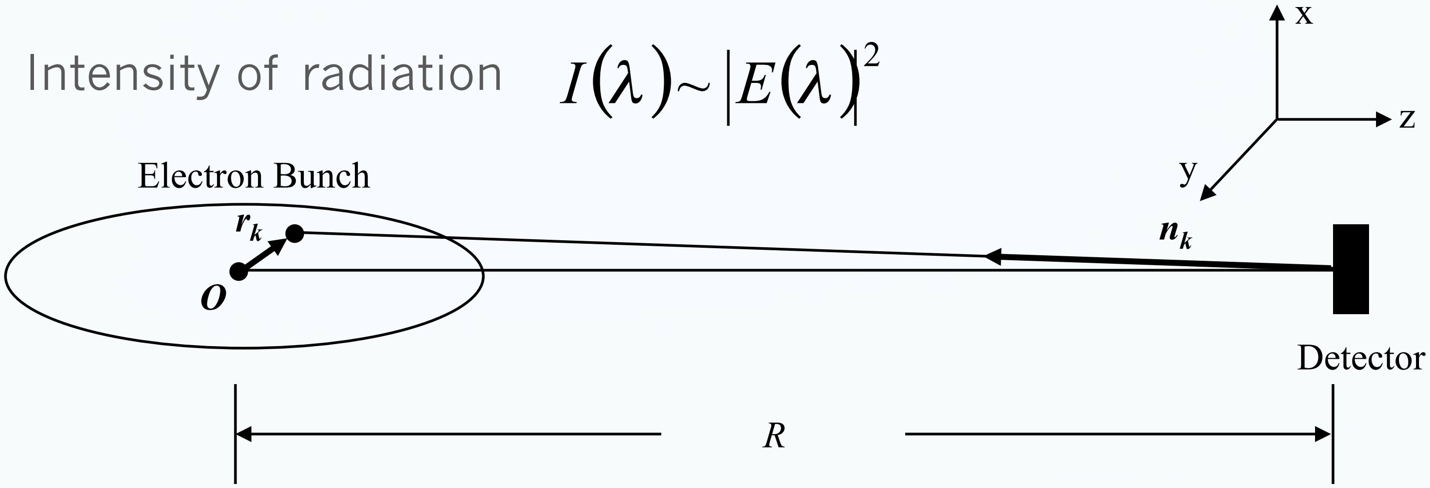
If the electrons are in lock synch are radiate coherently then the electric field grows linear with the number of electrons

The power goes as the square of the field and if N is very large one can get an enormous gain in power emitted.

This is the essence of the Free-electron laser.

Coherent Radiation

- Intensity of radiation $I(\lambda) \sim |E(\lambda)|^2$



- The component of the electric field from an electron seen by the detector at wavelength λ is

$$E_k(\lambda) = E_1(\lambda) e^{2\pi\, n_k \cdot r_k / \lambda}$$

- The total field of all electrons is

$$E_{tot}(\lambda) = E_1(\lambda) \sum_{k=1} e^{2\pi i\, n_k \cdot r_k / \lambda}$$

- And the total intensity is

$$I_{tot}(\lambda) = I_1(\lambda) \left| \sum_{k=1}^{N} e^{2\pi i\, n_k \cdot r_k / \lambda} \right|^2 = I_1(\lambda) N + I_1(\lambda) \sum_{j \neq k}^{N} e^{2\pi i (n_k \cdot r_k - n_j \cdot r_j)/\lambda}$$

- The 1^{st} is the incoherent term and the 2nd is the coherent

Nodvick and Saxon, Phys. Rev. **96** (1954) 180.

Coherent Radiation

- Replace the sum with an integral and assume a normalized distribution symmetric about $r = 0$

$$I_{tot}(\lambda) = I_1(\lambda)\left[N + N(N-1)f(\lambda)\right]$$

$$I_{tot}(\lambda) = I_{inc}(\lambda)\left[1 + (N-1)f(\lambda)\right]$$

Where $I_{inc}(\lambda) = N\,I_1(\lambda)$ is the total incoherent intensity emitted by the bunch of N particles

and $f(\lambda) = \left|\int dz\, e^{2\pi i z/\lambda} S(r)\right|^2$ is the form factor for the normalized bunch distribution $S(r)$. Here we have assumed that the detector is located at a distance much larger than the length of the electron bunch.

Various Form Factors

- For a gaussian bunch

$$S(z) = \exp\left[-\left(z/\sigma_z\right)^2\right] \Big/ \pi^{1/2}\sigma_z$$

$$f(\lambda) = \exp\left(-\alpha^2/2\right) \qquad \alpha = 2\pi\sigma_z/\lambda$$

- For a uniform rectangular distribution

$$S(z) = 1/\left(2\sigma_z\right), \qquad |z| < \sigma_z,$$

$$= 0, \qquad otherwise$$

$$f(\lambda) = \left[\left(\sin\alpha\right)/\alpha\right]^2$$

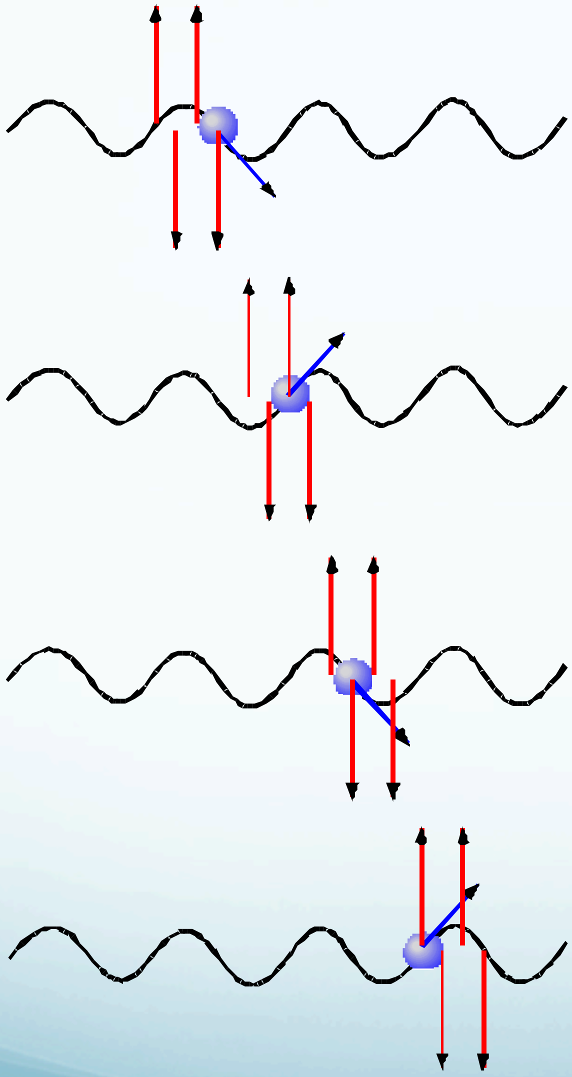
- For an ellipsoidal distribution

$$S(r) = 3\Big/\left(4\pi\sigma_\rho^2\sigma_z\right), \quad \left(z/\sigma_z\right)^2 + \left(\rho/\sigma_\rho\right)^2 \le 1,$$

$$= 0, \qquad otherwise$$

$$f(\lambda) = 9\left[\left(\sin\alpha\right)/\alpha - \cos\alpha\right]^2 / \alpha^4$$

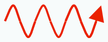
Interaction Between the Electron and EM Field

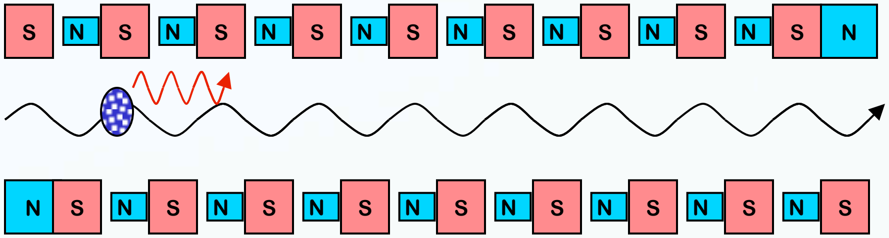


If the electron oscillates in phase with a co-propagating EM field of the correct frequency it can pick up or lose a net amount of momentum. Whether it picks up momentum or loses some is depended on the phase relationship.

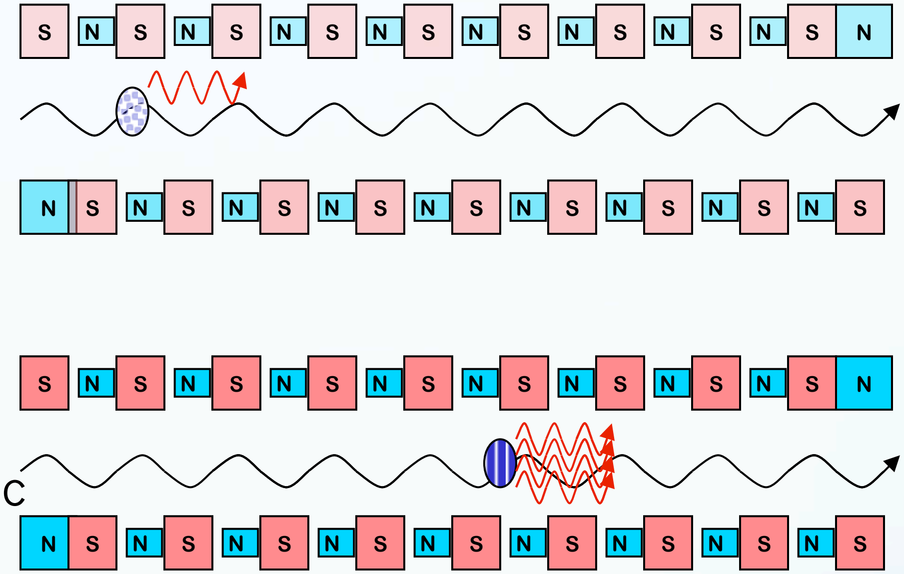
In an assemble of electrons this process can create microbunching within the macroscopic electron bunch.

Self-Amplified Spontaneous Emission (SASE)

An intense, highly collimated electron beam  travels through an undulator magnet. The alternating north and south Poles of the magnet force the electron beam to travel on an approximately sinusoidal trajectory, emitting synchrotron radiation  as it goes.

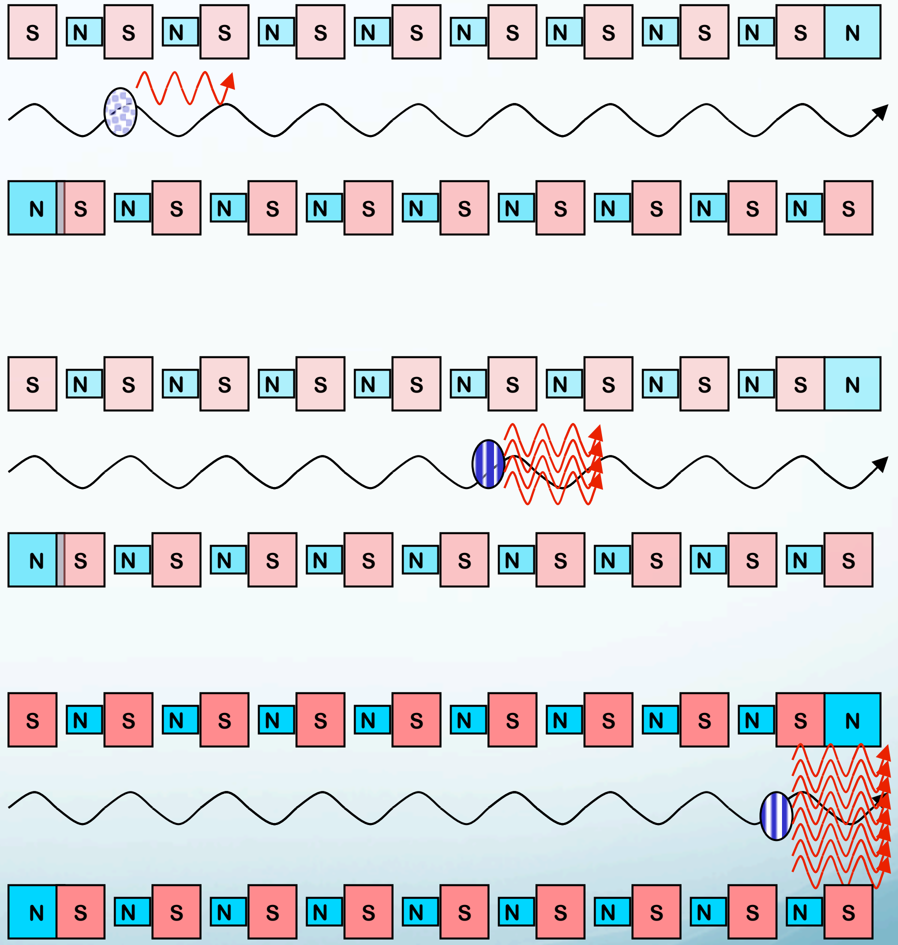


Self-Amplified Spontaneous Emission (SASE)



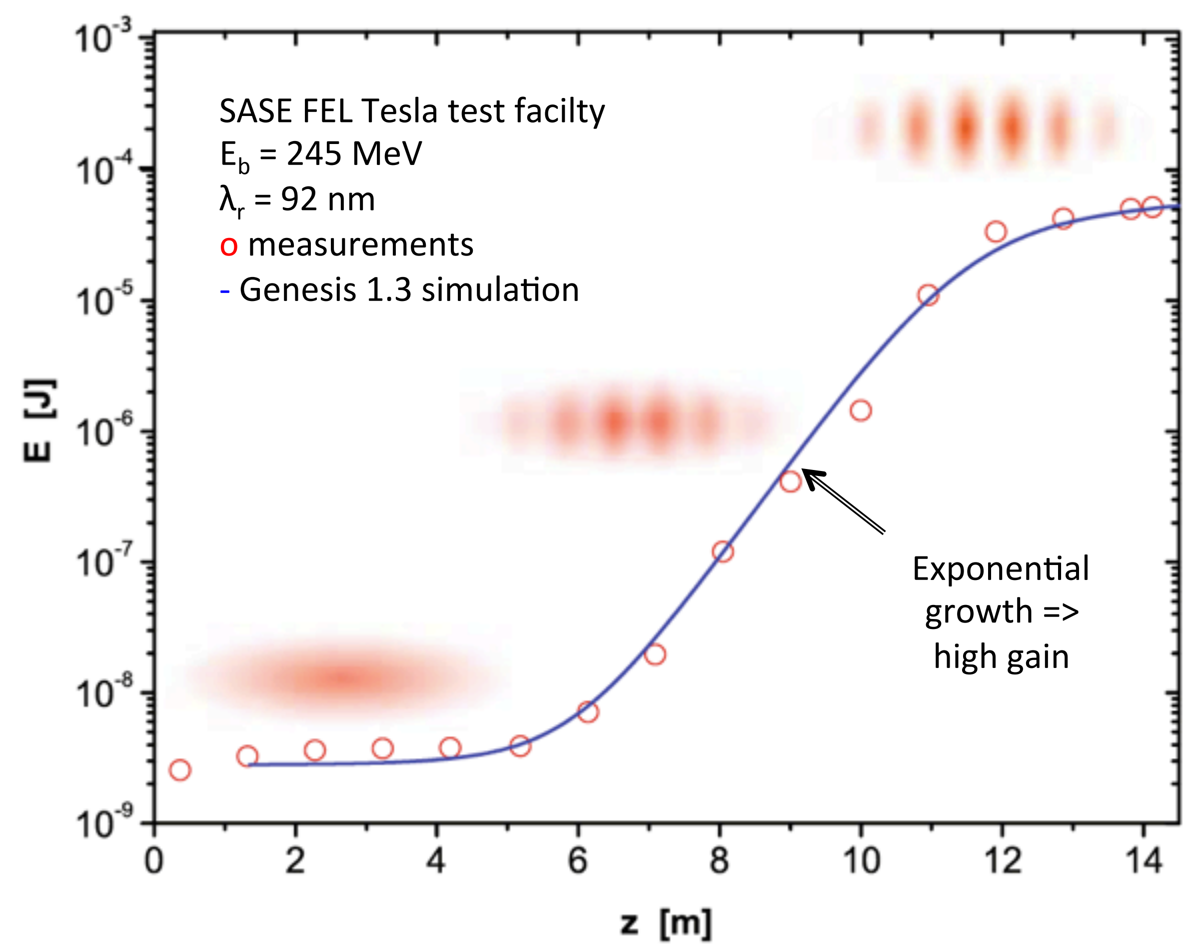
The electron beam and its synchrotron radiation are so intense that the electron motion is modified by the electromagnetic fields of its own emitted synchrotron light. Under the influence of both the undulator and its own synchrotron radiation, the electron beam begins to form micro-bunches,  separated by a distance equal to the wavelength of the emitted radiation.

Self-Amplified Spontaneous Emission (SASE)



These micro-bunches begin to radiate as if they were single particles with immense charge. The process reaches *saturation* when the micro-bunching has gone as far as it can go.

Example of growth in a SASE FEL

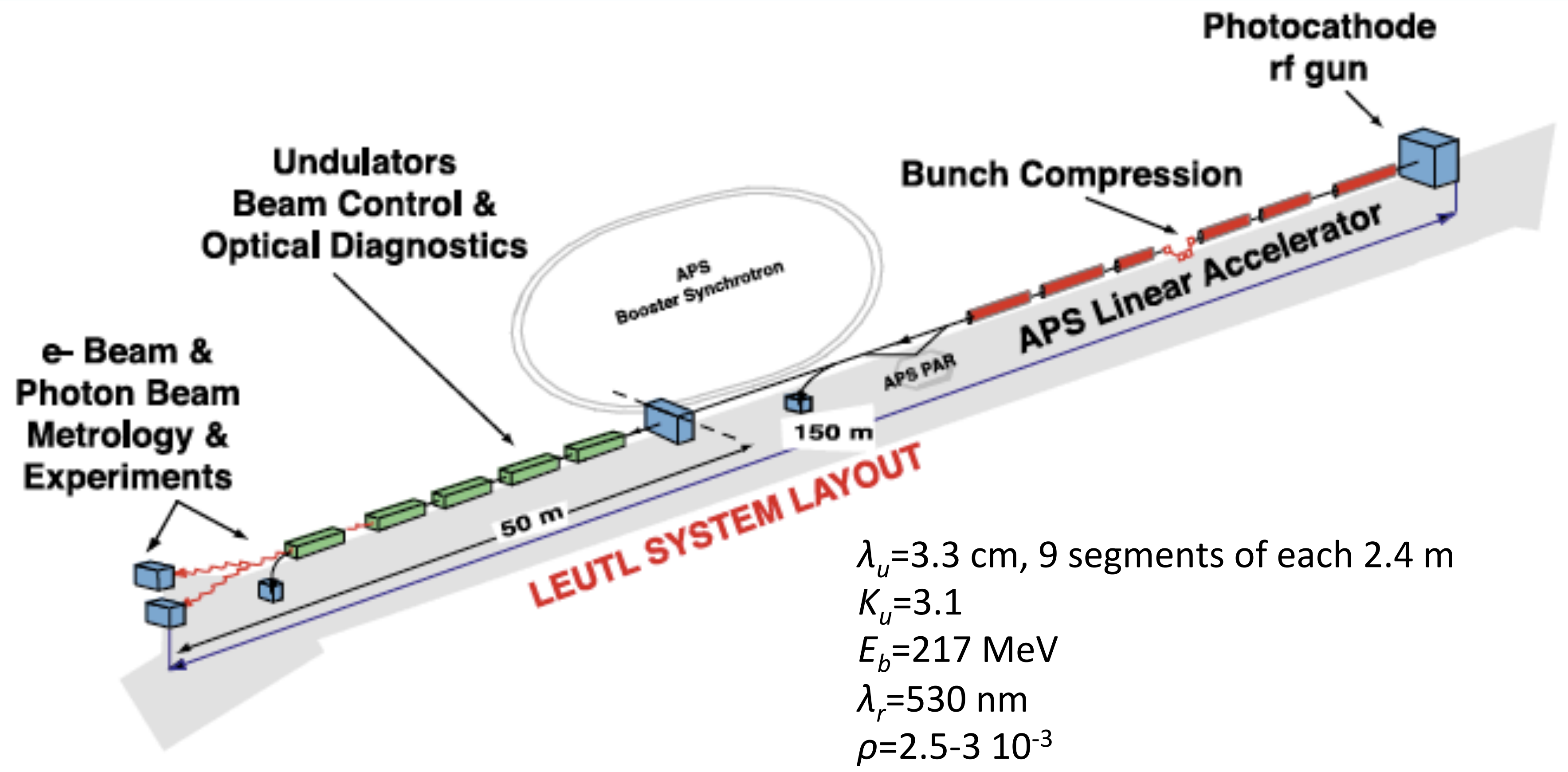


SASE FEL Tesla test facilty
E_b = 245 MeV
λ_r = 92 nm
o measurements
- Genesis 1.3 simulation

Exponential
growth =>
high gain

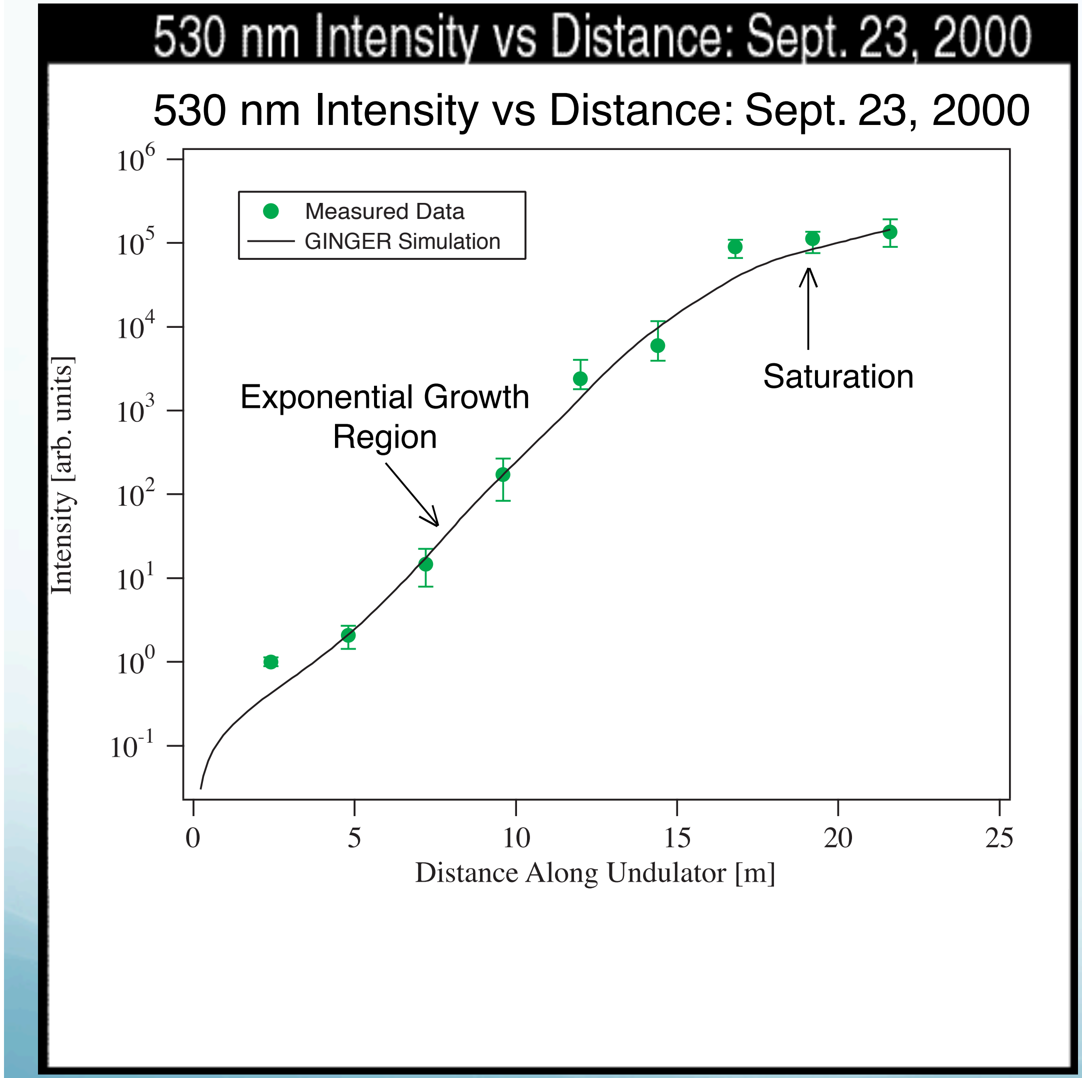
V. Ayvazyan et al., PRL **88**, 104802, 2002

First to saturate

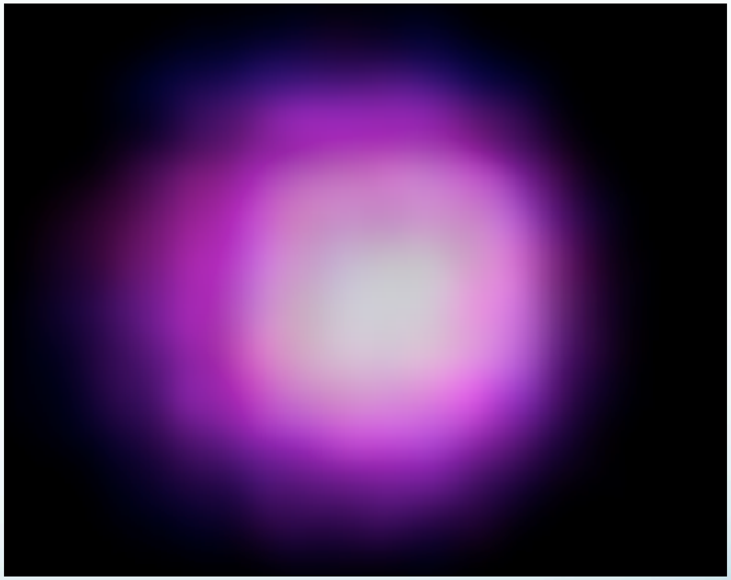


λ_u=3.3 cm, 9 segments of each 2.4 m
K_u=3.1
E_b=217 MeV
λ_r=530 nm
ρ=2.5-3 10^{-3}
I_b=600 A @ t_b=0.19 ps (Q_b=0.3 nC)

First SASE FEL to Saturation

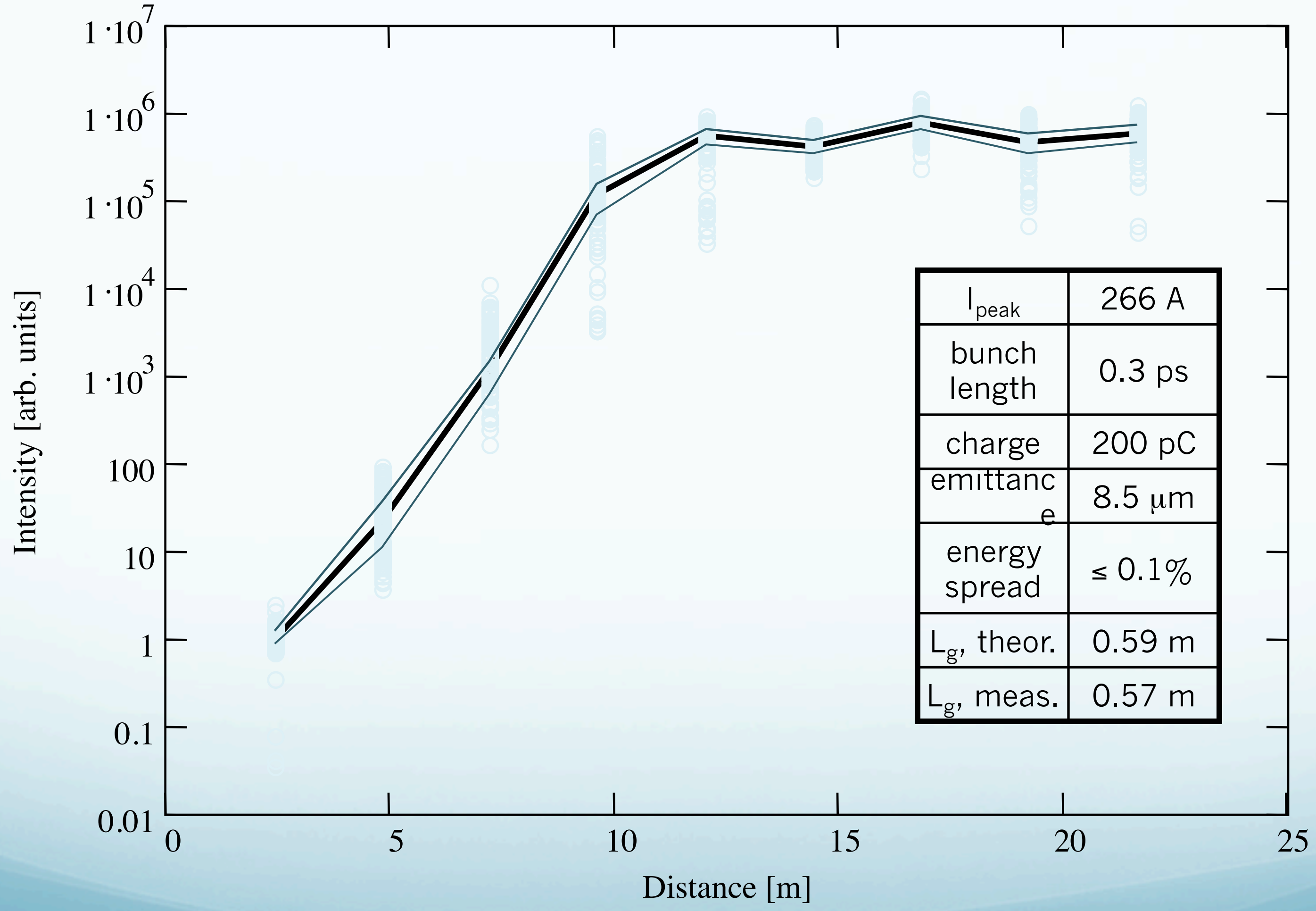


Flash of UV light (385 nm) near saturation. The expected wavelength as a function of angle (radial offset) is clearly seen. The darker "lines" are from shadows of secondary emission monitors in the vacuum chamber.



S. Milton et al., Science, Vol. 292, Issue 5524, 2037-2041 (2001)

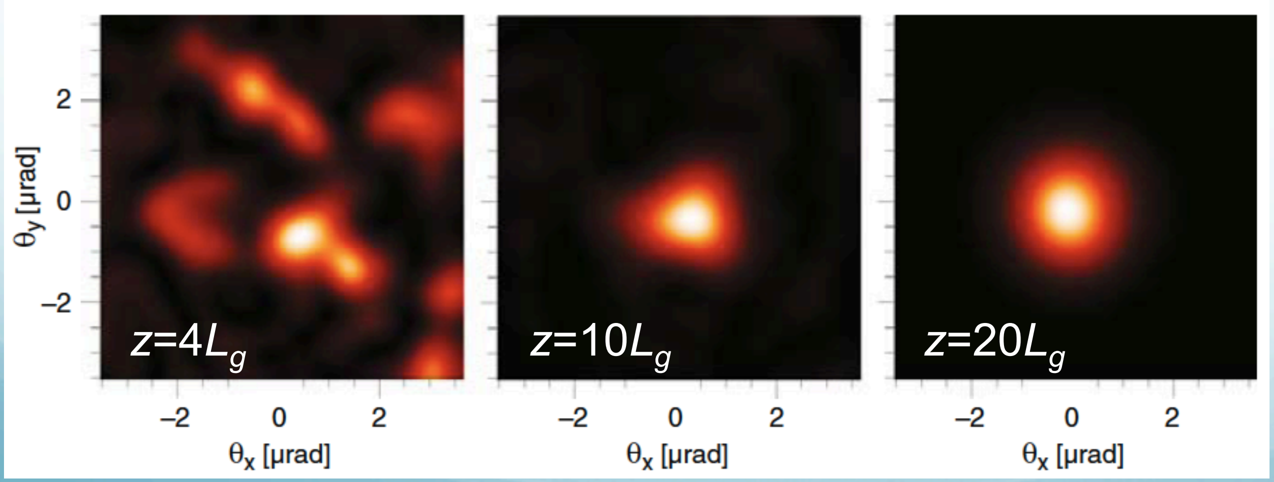
Optical Intensity vs. Distance: Gain



I_{peak}	266 A
bunch length	0.3 ps
charge	200 pC
emittance	8.5 μm
energy spread	≤ 0.1%
L_g, theor.	0.59 m
L_g, meas.	0.57 m

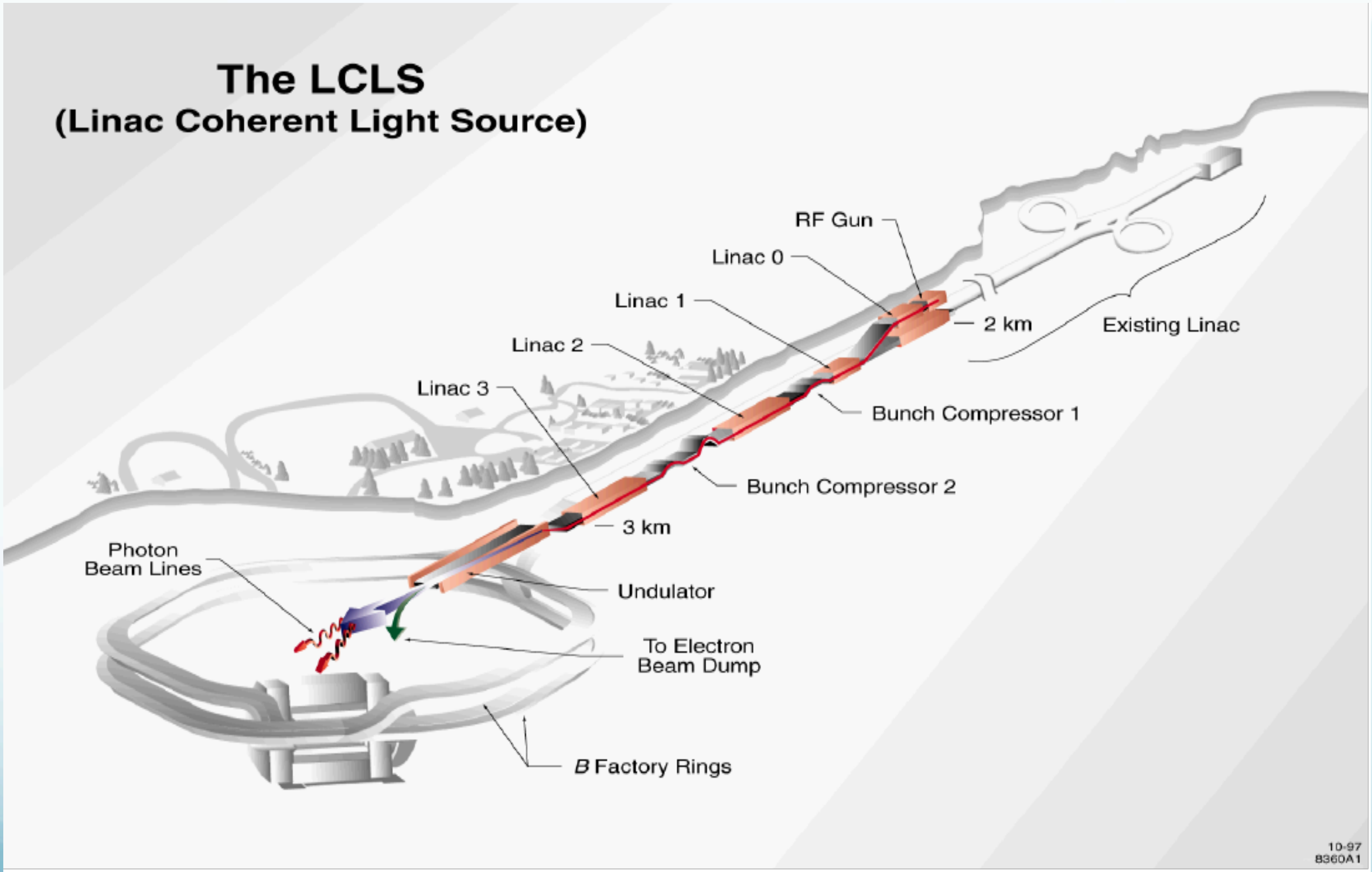
Transverse coherence in SASE FELs

- Fundamental Gaussian TEM_{00} mode has highest on-axis intensity
- Higher order TEM_{mn} modes extend to larger radial distances and may even vanish on axis
- The higher overlap of the TEM_{00} mode with the electron beam ensures a higher growth rate and will increasingly dominate the laser field
- Near saturation the TEM_{00} mode will usually dominate and the FEL radiation will show a high degree of transverse coherence



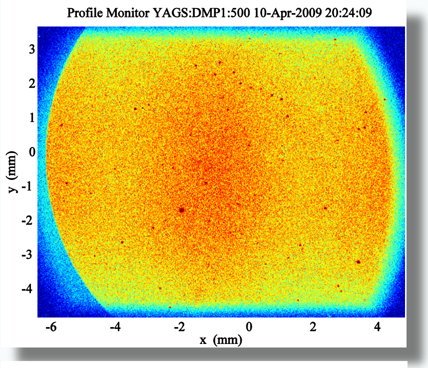
Genesis 1.3 simulation
(courtesy S. Reiche)
LCLS, Stanford, USA
L_g=5 m

LCLS: AN X-RAY LASER @ 1.5 Å

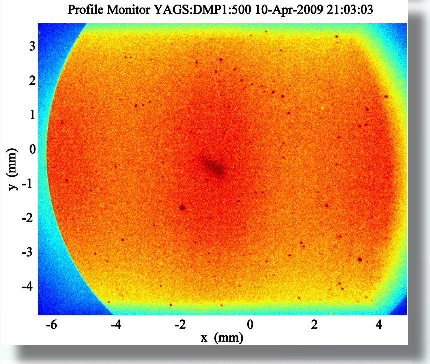


10 April 2009!

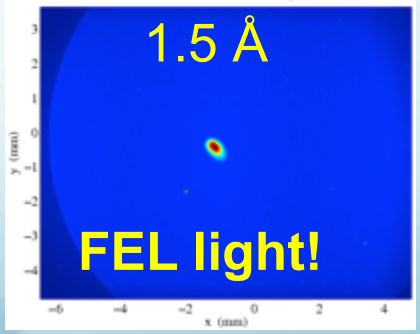
- 21 undulators available
  - reduce peak current from 3 kA to 0.5 kA
  - insert undulator section at a time
    - correct orbits
    - observe spontaneous emission:



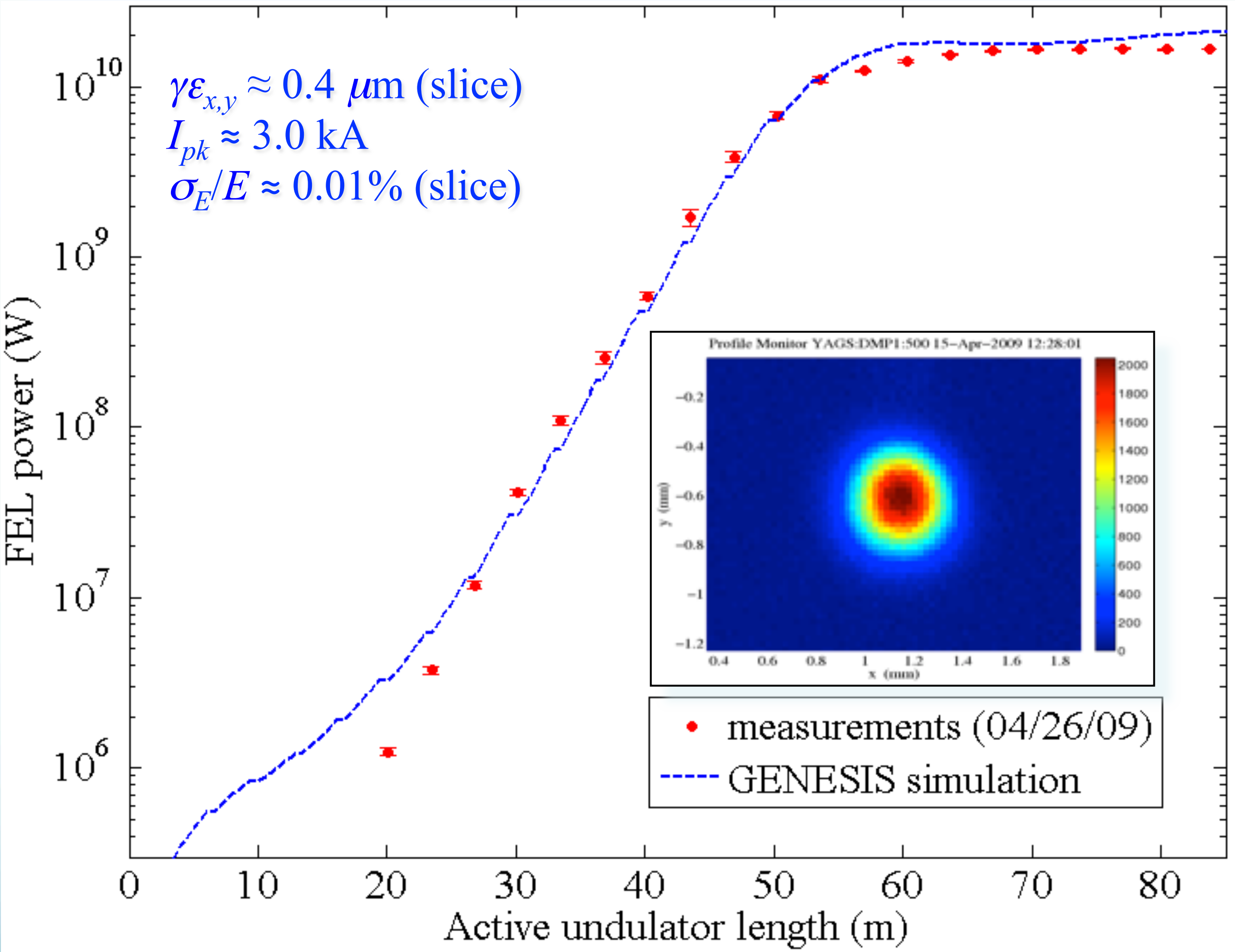
- after 10 undulators a small spot started to form at the centre of the screen:



- insert remaining undulators and slowly increase peak current to full 3 kA:

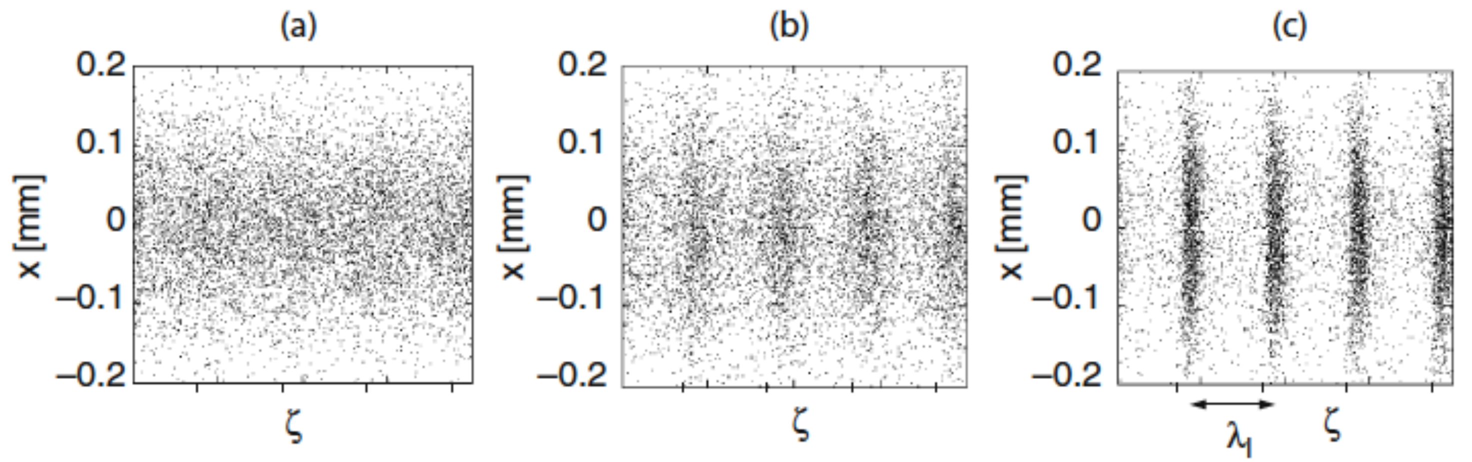


Courtesy Paul Emma & LCLS commissioning team



Courtesy Paul Emma & LCLS commissioning team

Growth in a SASE FEL



Initial distribution

Beginning of bunching

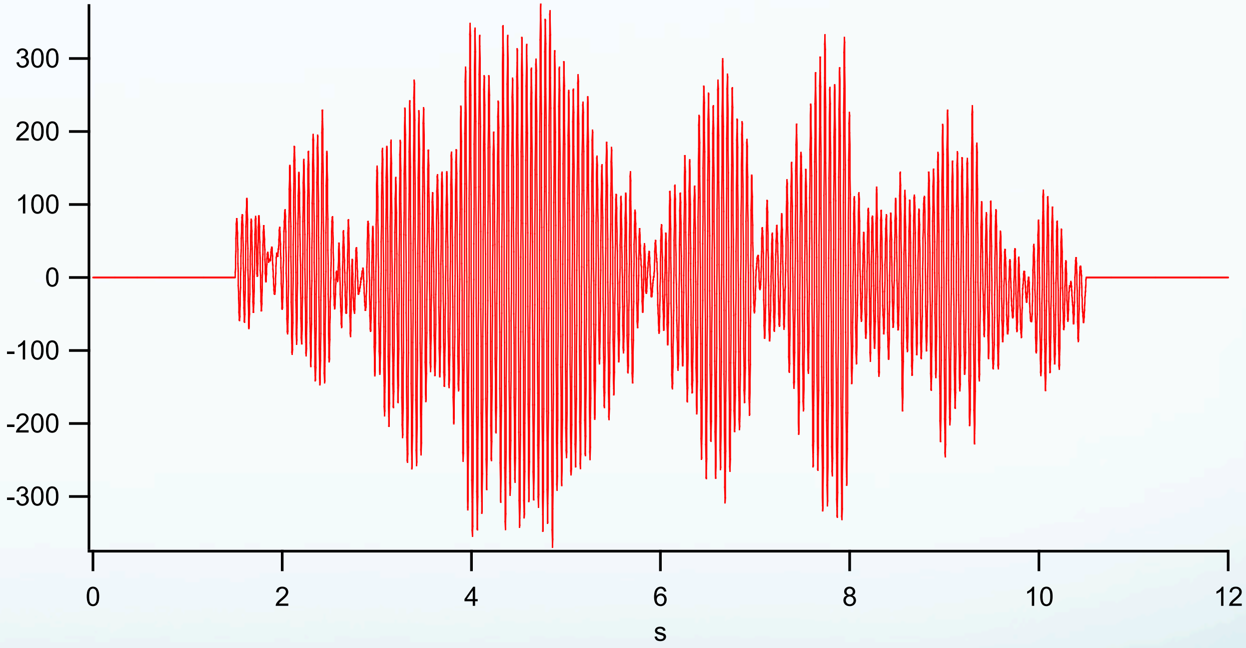
Fully bunched at laser wavelength

(courtesy of Sven Reiche)

The Start of Microbunching

$$E_{tot}(t) = E_x(t)\sum_{j=1}^{N}\exp(i\phi_j)$$

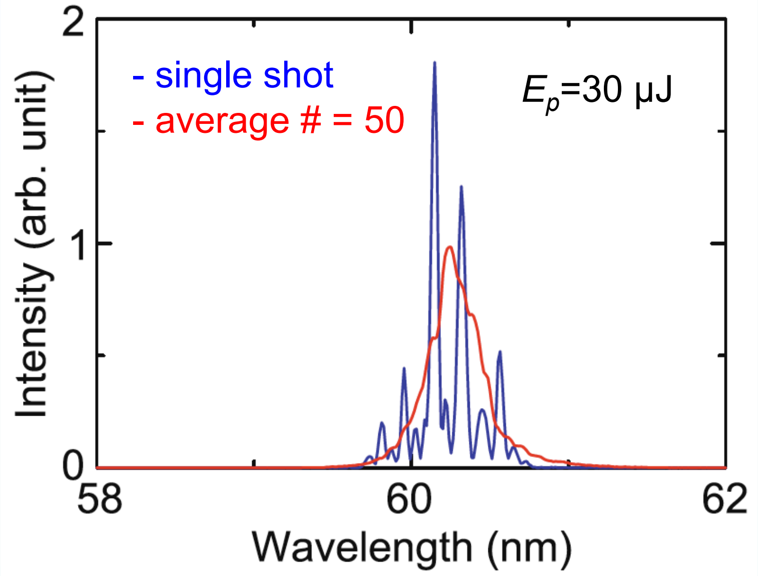
Coherent sum of
radiation from N electrons



The SASE light consists of several coherent regions, also known as spikes, randomly distributed over the pulse length of the electron beam.

Stochastic nature of SASE light

- Electrons produce spontaneous undulator radiation in first section of a long undulator and this acts as seed for remainder
- Alternatively, the random distribution of electrons in the bunch result in “white noise” in the density distribution.
  - thus some “pre-bunching” at radiation wavelength that seeds the FEL.
- Both views describe the same physics.



SASE FEL spectrum as measured at SCSS (test accelerator for Japanese XFEL project).

courtesy M. Yabashi, H. Tanaka

Stochastic nature of SASE light

- Coherence time τ_{coh}: time over which correlation exists in the light pulse

$$\boxed{\tau_{coh} \approx \frac{\sqrt{\pi}}{\sigma_w}}$$

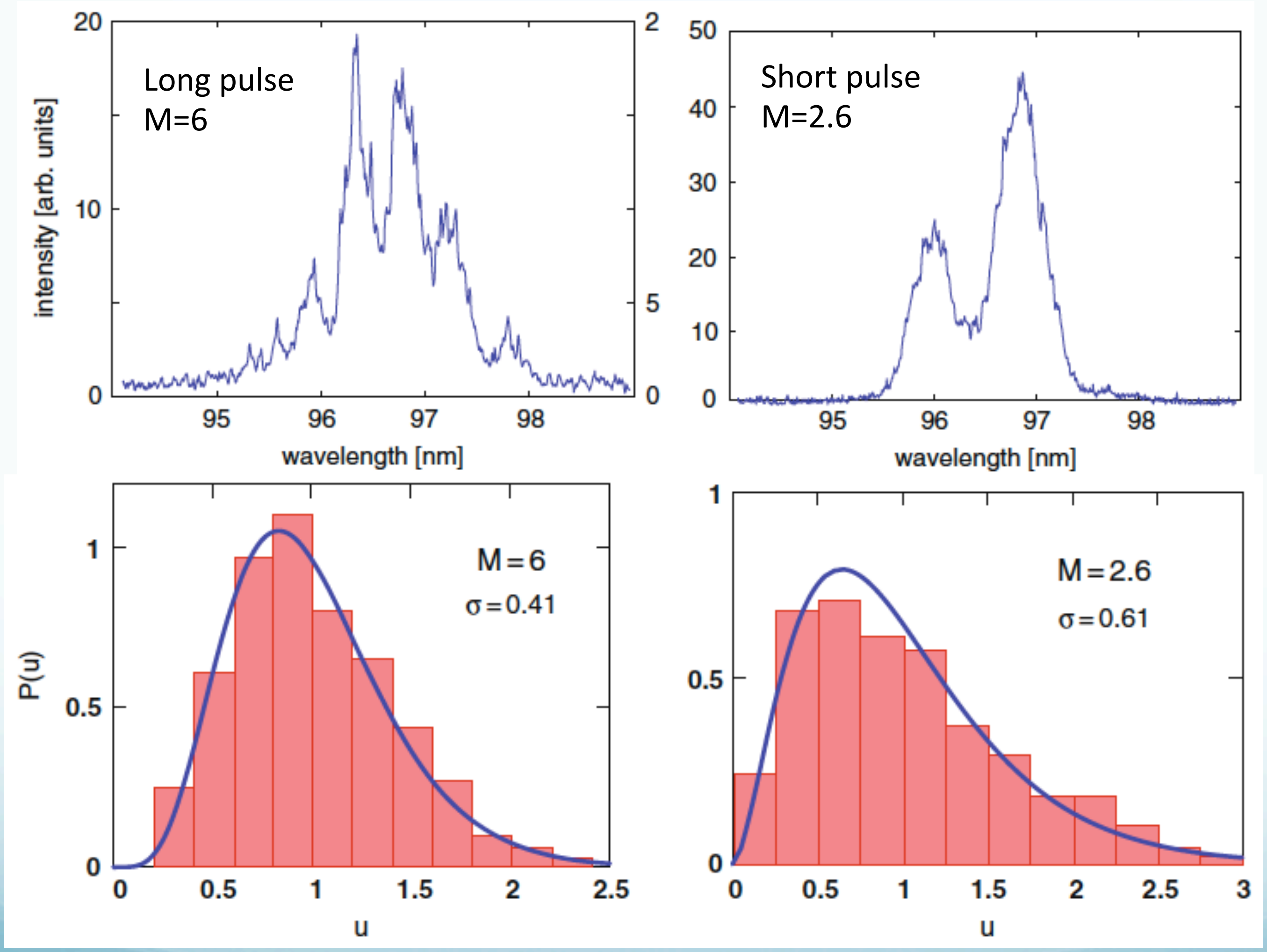
$$\sigma_w = \sigma_w(z) = 3\sqrt{2}\rho\omega_r\sqrt{\frac{L_g}{z}}$$

rms Power bandwidth (is larger at beginning of undulator)

- Consider a "flat-top" electron bunch of duration T$_{b,}$ then $M = \frac{T_b}{\tau_{coh}}$ independent wave packets can evolve. These are also called "longitudinal modes".
- Let $u = \frac{W_r}{\langle W_r \rangle}$ be the SASE pulse energy normalised to the average pulse energy, then in the exponentional gain regime the variance of *u* is given by

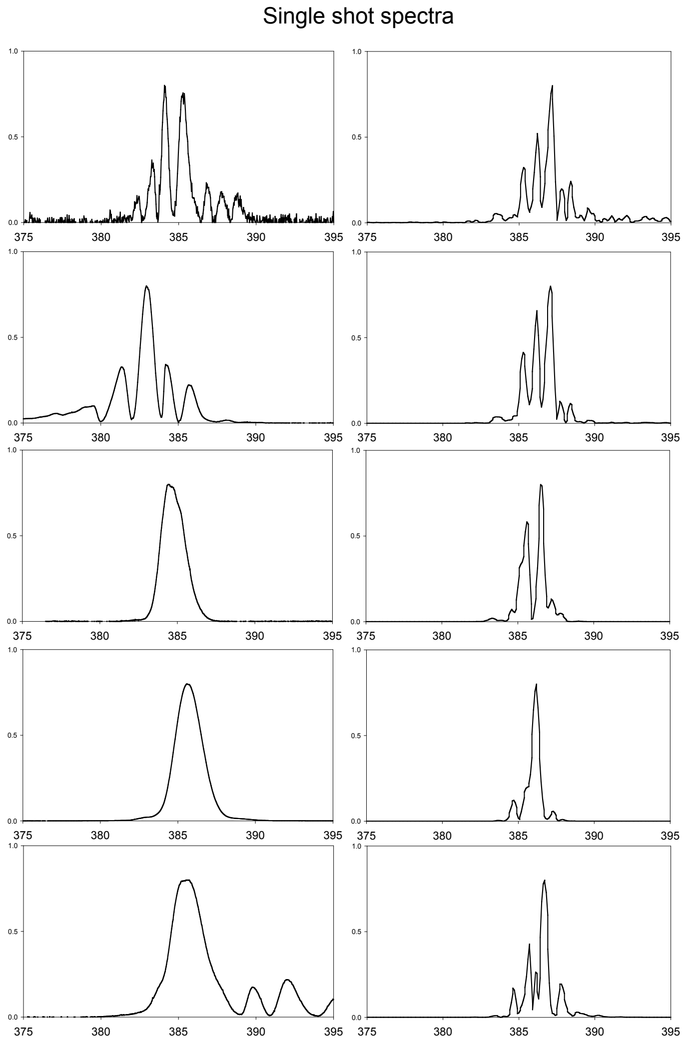
$$\boxed{\sigma_u^2 = \frac{1}{M}}$$

Stochastic nature of SASE light



Ayvazyan, V., et al. Eur. Phys. Journ. D **20**, 149 (2002)

SASE Spectra – 385 nm


Single shot spectra

VLD2 (4.8 m)

VLD3 (7.2 m)

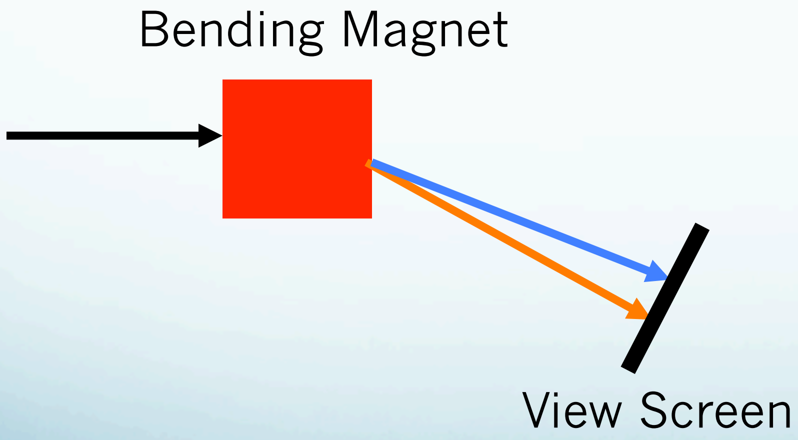
VLD5 (12 m)

VLD7 (16.8 m)

VLD9 (21.6 m)

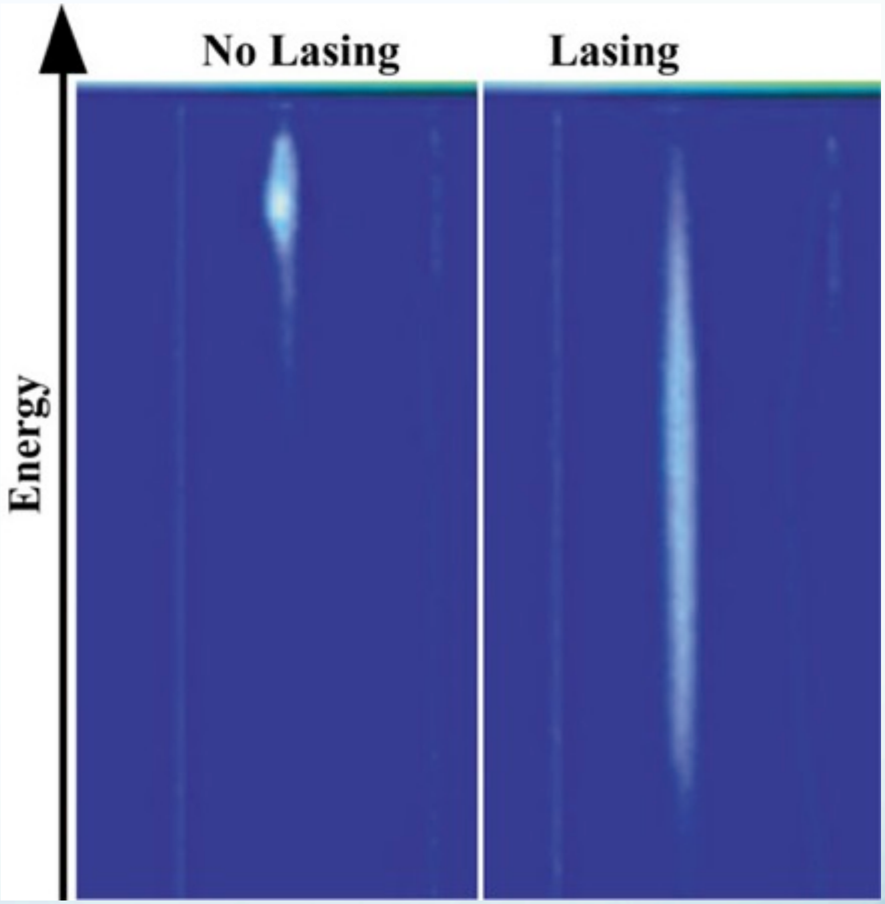
Measured Beam Energy Spectra

- During lasing the beam energy spread is significantly larger than periods of no lasing.
- The centroid energy also drops.
- This is a good tuning aid.

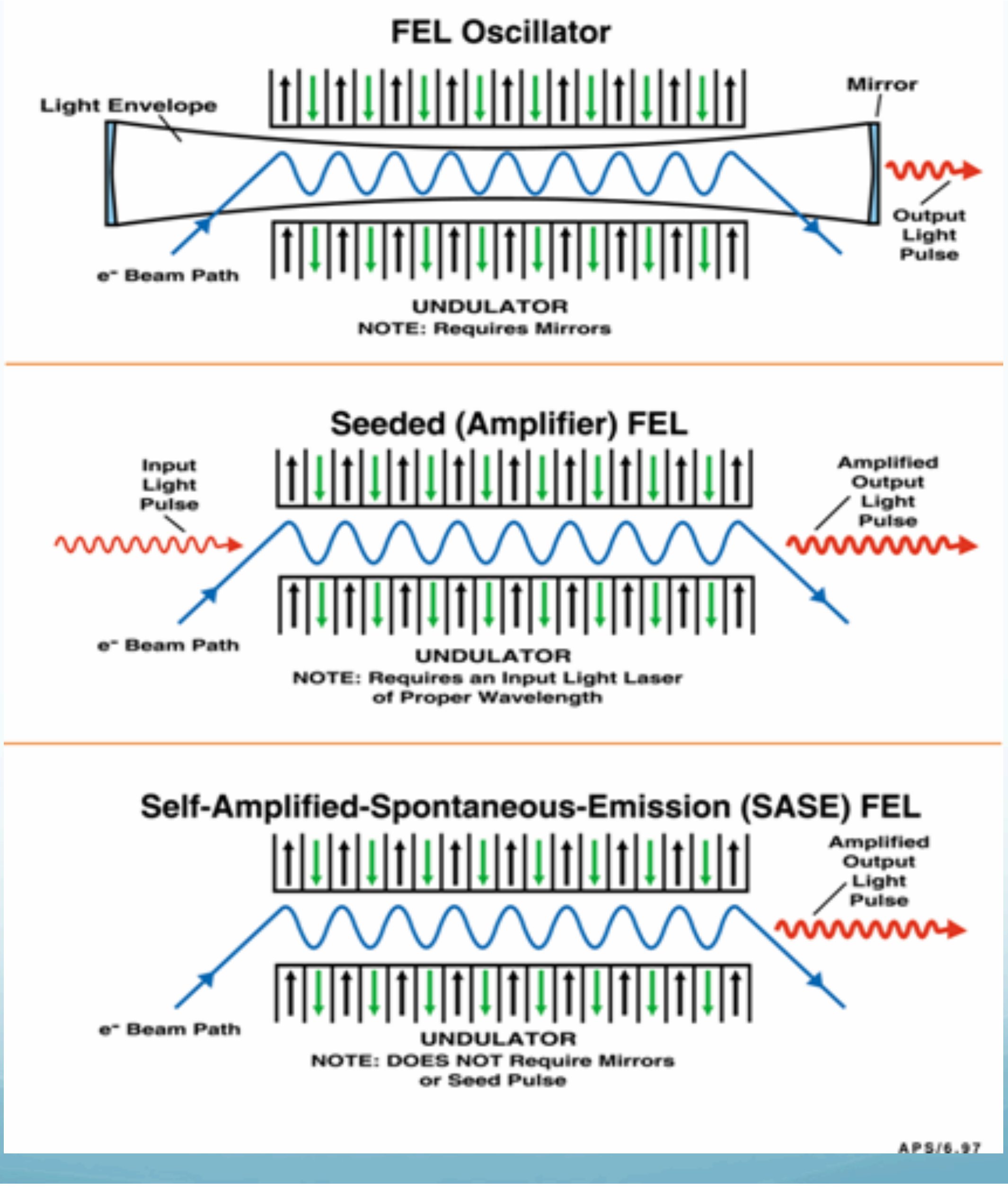


Bending Magnet

View Screen



FEL Types: Oscillator, Seeded FEL, SASE



Benefits of a Seeded FEL

A “seed” laser controls the distribution of electrons within a bunch:

- Very high peak flux and brightness (comparable to SASE FELs)
- Temporal coherence of the FEL output pulse
- Control of the time duration and bandwidth of the coherent FEL pulse
- Close to transform-limit pulse provides excellent resolving power without monochromators
- Complete synchronization of the FEL pulse to the seed laser
- Tunability of the FEL output wavelength, via the seed laser wavelength or a harmonic thereof
- Reduction in undulator length needed to achieve saturation.

Giving:

- Controlled pulses of 10-100 fs duration for ultrafast experiments in atomic and molecular dynamics
- Temporally coherent pulses of 500-1000 fs duration for experiments in ultrahigh resolution spectroscopy and imaging.
- Future possible attosecond capability with pulses of ~100 as duration for ultrafast experiments in electronic dynamics

Advantage of Seeded FELs

In Comparison to SASE FELs seeded FELs can offer the improvement:

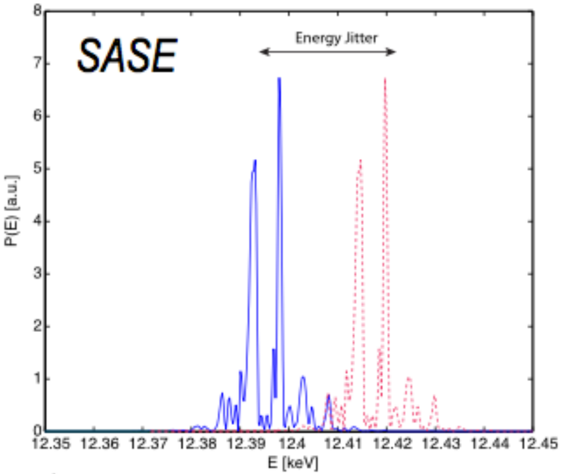
1. **Control/Improvement of the Longitudinal Coherence**
2. **Improved Brilliance**
3. **Energy Stability of FEL Output Pulse**
4. **Spectral Stability at Selected Frequency**
5. **Synchronization with External Source (Pump-Probe)**
6. **Ability to Increase FEL Efficiency with Taper**
7. **FEL becomes shorter**

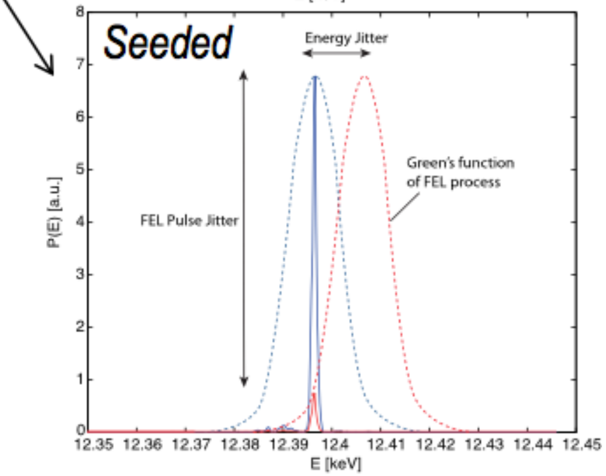
Slide Courtesy of Sven Reiche

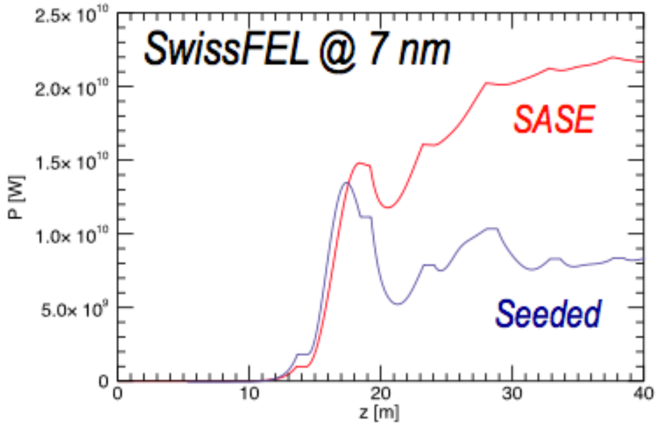
Disadvantage of Seeded FELs

FEL Performance gets more sensitive to electron beam fluctuation:

SASE FEL	Seeded FEL
Energy Jitter shifts central wavelength but keeps photon number almost unchanged	Huge fluctuation in output power when energy jitter becomes comparable to FEL bandwidth
FEL performance unchanged from arrival time	Temporal overlap problems unless seed signal is longer
Power growth flattens at saturation with a slight growth	Post Saturation Oscillation of FEL power







Slide Courtesy of Sven Reiche

Synchronization to External Seed Signal

Seed pulse must be shorter than electron bunch length

Otherwise FEL pulse length is defined by electron bunch length, including bunch arrival jitter

Seed pulse must be longer than cooperation length

Pulse will be stretched by FEL process. Identical performance than single spike SASE operation

Goal is mutual exclusive to maximum brilliance

Maximum brilliance is given by bunch length and requires a seed signal longer than bunch length

Slide Courtesy of Sven Reiche

Arrival time jitter must be less than bunch length

Otherwise there is a chance of missing overlap. Bunch will laser in SASE mode

Shot Noise and Seeding Efficiency

$$P_{sn} = \frac{3\sqrt{4\pi}\rho^2 P_{beam}}{N_\lambda \sqrt{\ln(N_\lambda / \rho)}} \propto \frac{\gamma}{\sqrt{a - \ln\gamma}}$$

Towards shorter wavelengths the typical beam energy increases and the shot noise signal gets larger

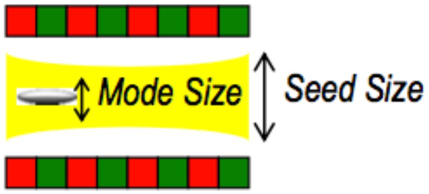
Example: 5 nm @ 2 GeV → P_{sn} ~ 100 W

(N_λ: #electrons/wavelength, ρ: FEL Parameter)

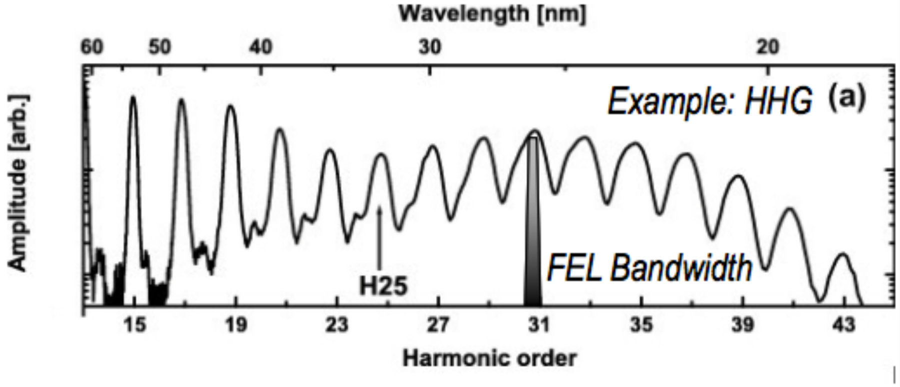
Coupling to Growing Mode

$$P = \frac{P_0}{9} e^{z/L_g}$$

Coupling to FEL Mode



Matching FEL Bandwidth

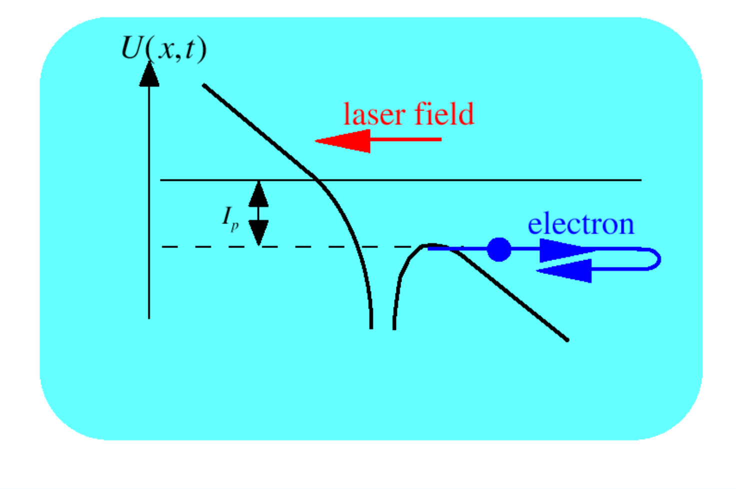


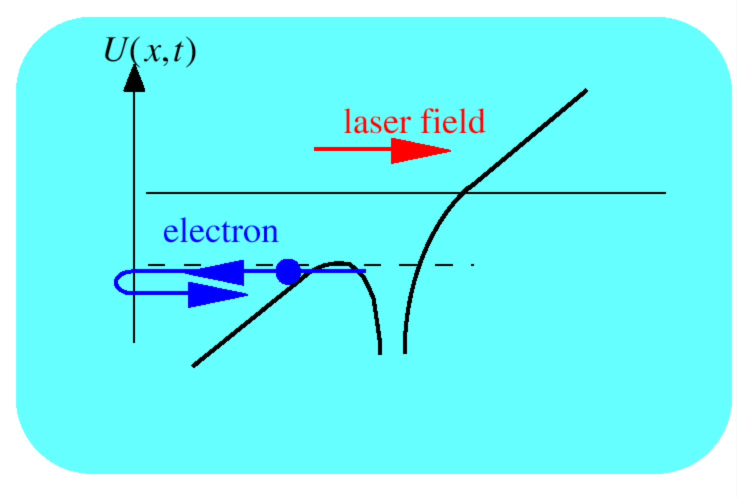
Seed Power	**x**	**Transport Loss**	**x**	**Growing Mode**	**x**	**FEL Mode**	**x**	**Bandwidth**	**>**	**Contrast**	**x**	**Shot Noise**
		<10%		11%		<50%		10-100 %		>10		

$P_{seed} > 2000\ P_{sn}$

Slide Courtesy of Sven Reiche

High Harmonic Generation



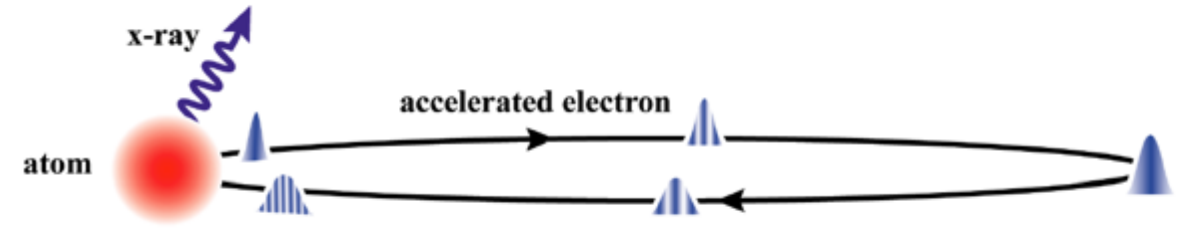


$$h\upsilon_{cutoff} = I_p + 3.2U_p$$

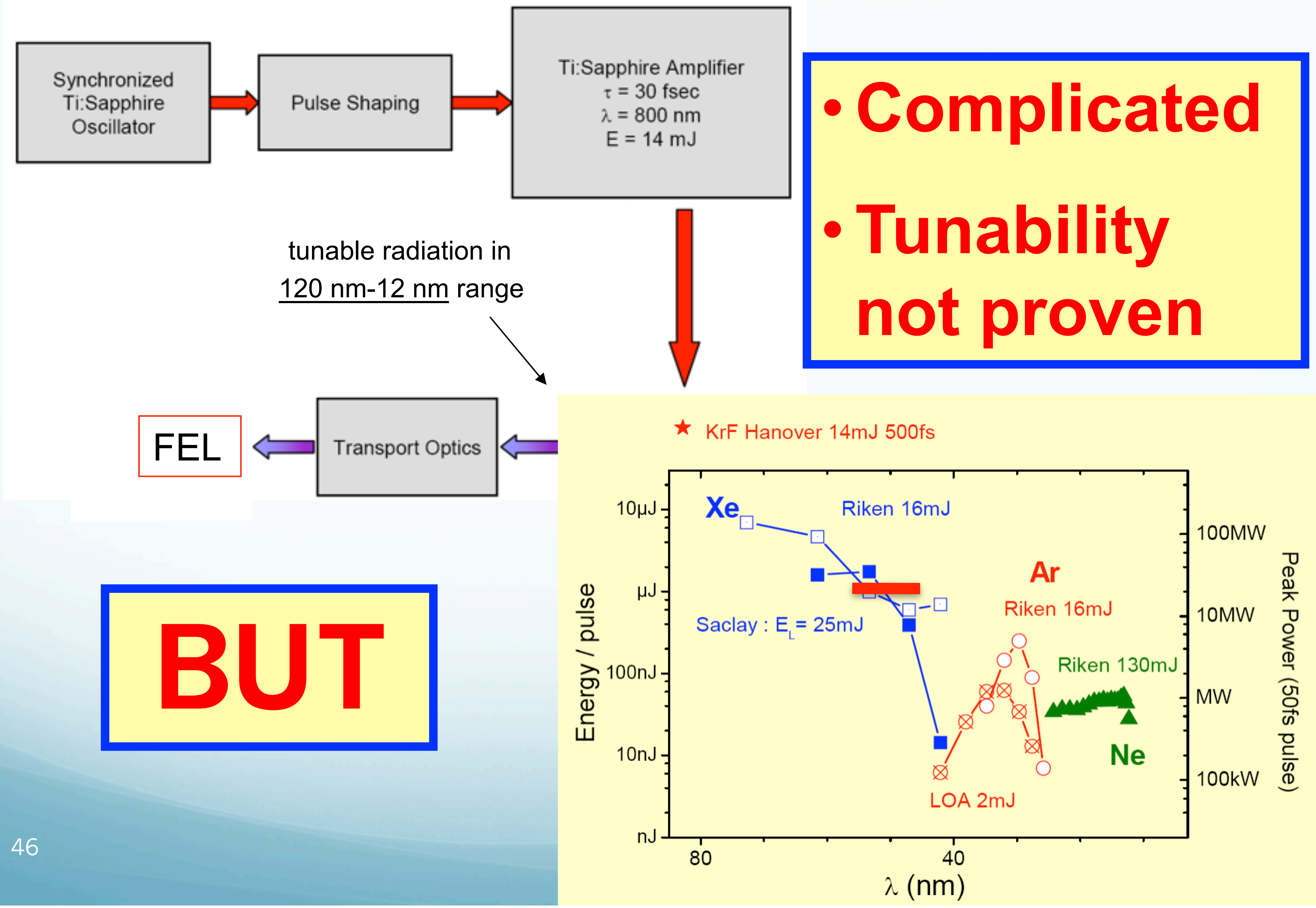
ionization potential of atom

$U_p \approx I_L \lambda^2$ quiver energy of e^-

$\varphi_{x\text{-}ray} \approx \varphi_{Laser}$ and I_{Laser}



Seeding with an HHG Source?



Synchronized Ti:Sapphire Oscillator

Pulse Shaping

Ti:Sapphire Amplifier
τ = 30 fsec
λ = 800 nm
E = 14 mJ

tunable radiation in
120 nm-12 nm range

Transport Optics

FEL

- **Complicated**
- **Tunability not proven**

BUT

More Comments About an HHG Seed

- Direct Seeding Option
  - But now one is limited to the wavelength cutoff of the HHG system
    - 10 nm perhaps a little shorter.
    - 10 kw to 100 kw
      - Too low for HGHG seed
- Pulse length
  - Tends to be on the order of 10 fs to 20 fs, even shorter if needed, but difficult to make significantly longer.

Seeded HHG Source

A “problem” with using a HHG source as a seed is that the power is not that high.

The “problems” with using a plasma laser are the timing stability, pulse duration, and longitudinal coherence.

Combined however they could make an ideal seed for future FELs.

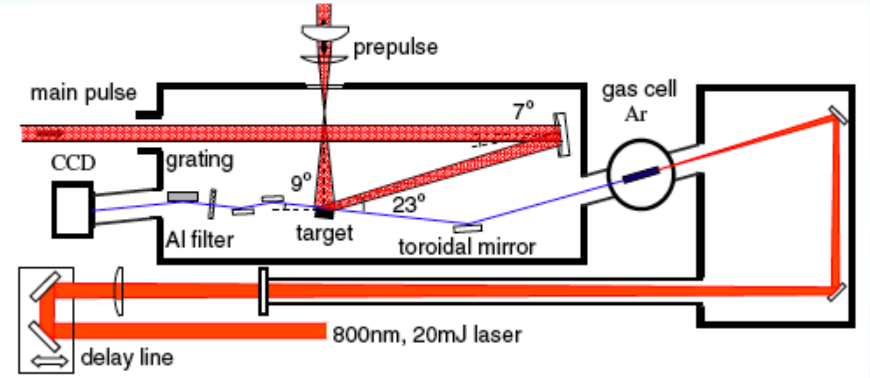


FIG. 1 (color online). Schematic representation of the seeded soft-x-ray-laser amplifier based on a grazing incidence pumped plasma.

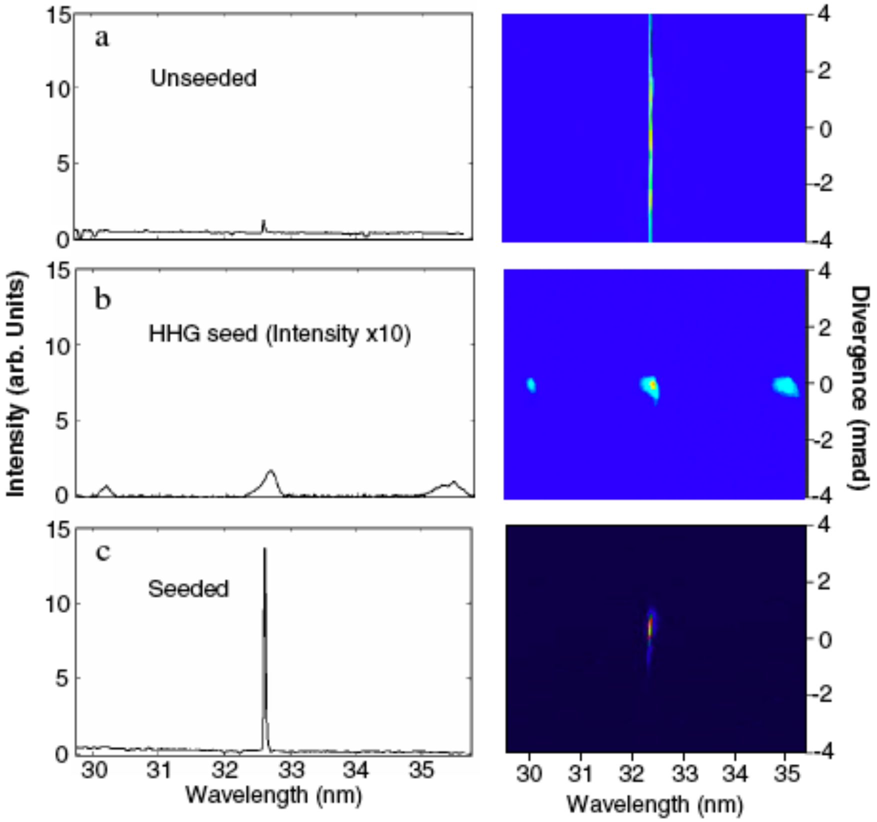
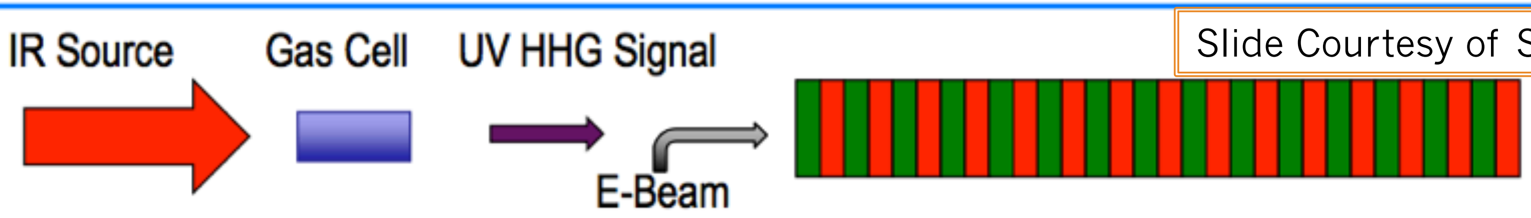


FIG. 2 (color online). Spectra illustrating the relative intensity and beam divergence for the (a) unseeded 32.6 nm soft-x-ray-laser amplifier, (b) high harmonic seed pulse, and (c) seeded soft-x-ray-laser amplifier. The length of the plasma amplifier is 3 mm. The intensity scale of the seed pulse is magnified by 10 times.

Wang et al., Phys. Rev Lett. **97** 123901 (2006)

High Harmonic Generation (HHG) Seeding

Slide Courtesy of Sven Reiche

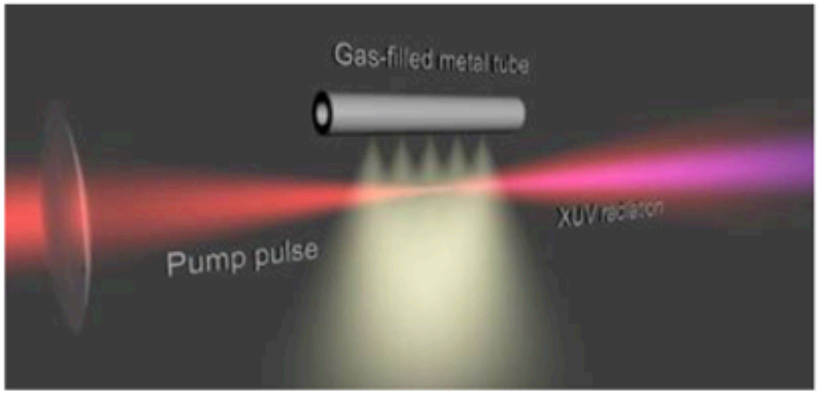


IR Source

Gas Cell

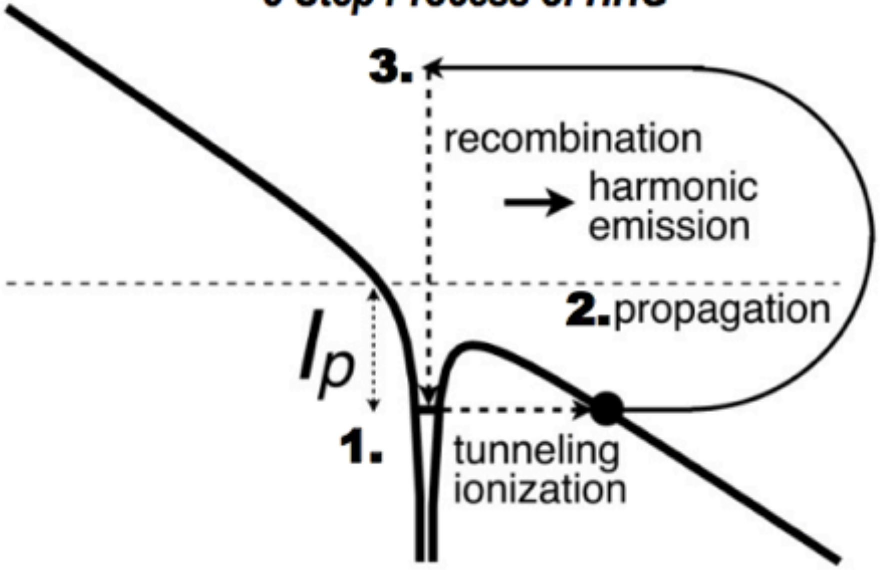
UV HHG Signal

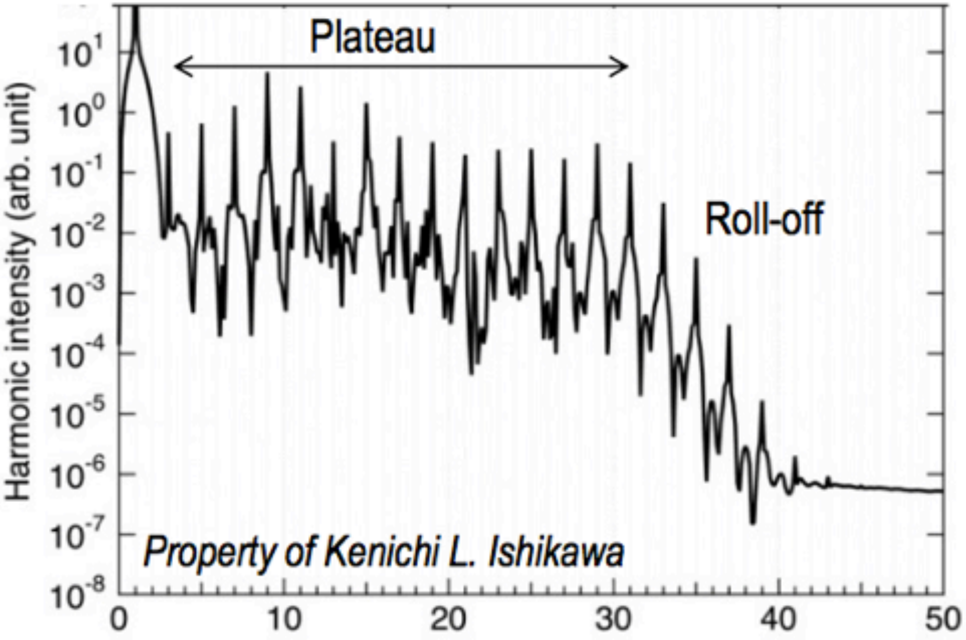
E-Beam



- 3 step process in noble gases
- High energetic photons, phase locked to drive laser
- Coherence properties inherited from drive laser
- Limited to short pulses due to ionization of gas

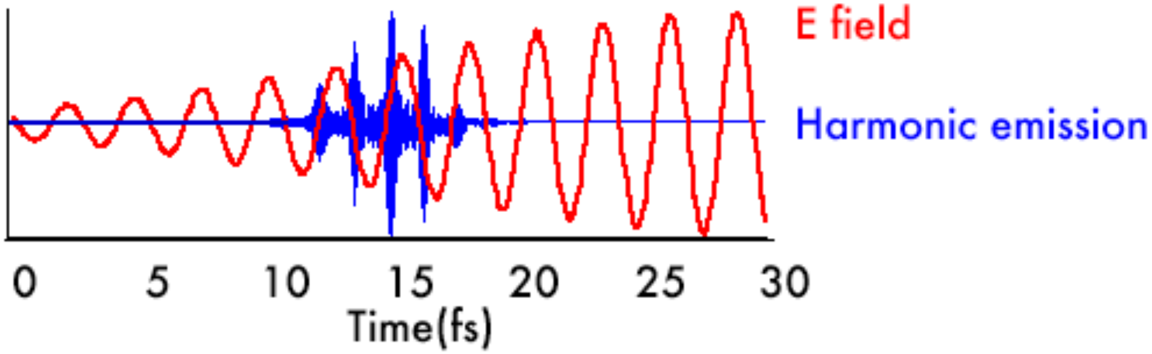
3 Step Process of HHG





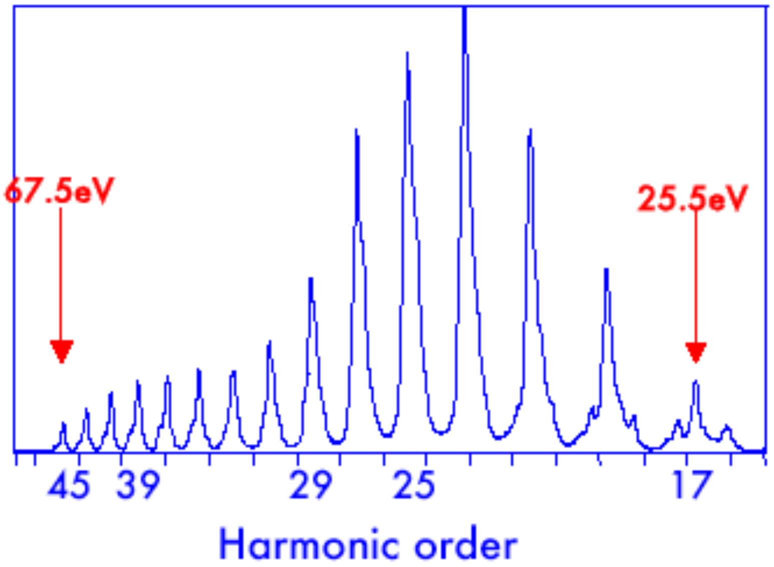
Property of Kenichi L. Ishikawa

time



I. Christov et al, PRL 78, 1251, (1997)

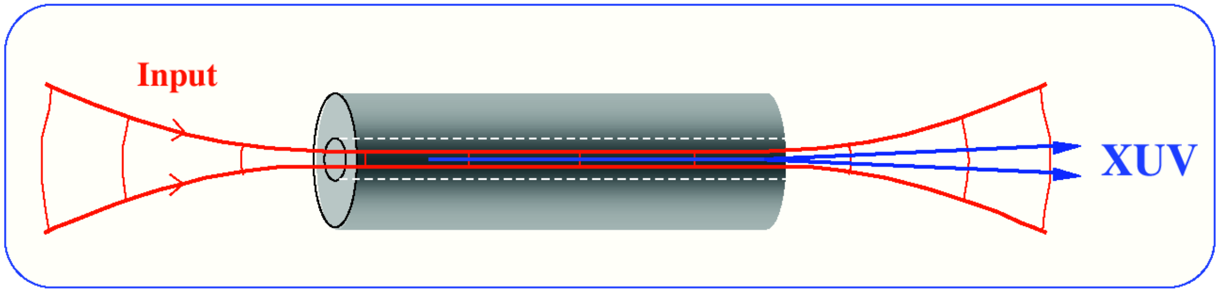
frequency



J. Zhou et al, PRL 76(5), 752-755 (1996)

Phase-matched frequency conversion in waveguides:

C. Durfee et al., Optics Letters 22, 1565 (1997)
A. Rundquist, et al, Science, vol. 280, pp. 1412-1415 (1998)



- Waveguide creates plane-wave geometry
- Waveguide can control the phase velocity ($v_p = \omega/k$)

$$k = \frac{2\pi}{\lambda}\left(1 + P\delta(\lambda) - \frac{1}{2}\left[\frac{u\lambda}{2\pi a}\right]^2 - \frac{1}{2}\frac{N_e r_e \lambda^2}{\pi}\right)$$

vacuum **gas** **waveguide** **ionization**

Proof-of-Principle Experiment

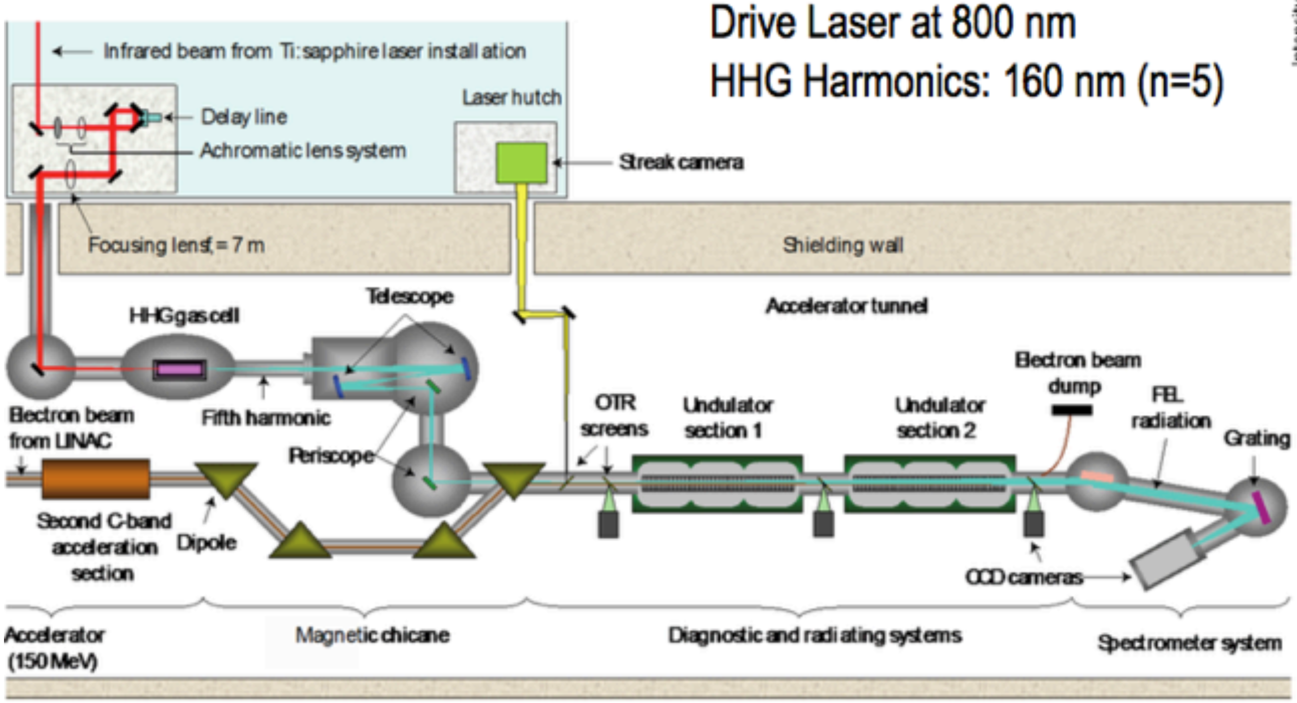
Slide Courtesy of Sven Reiche

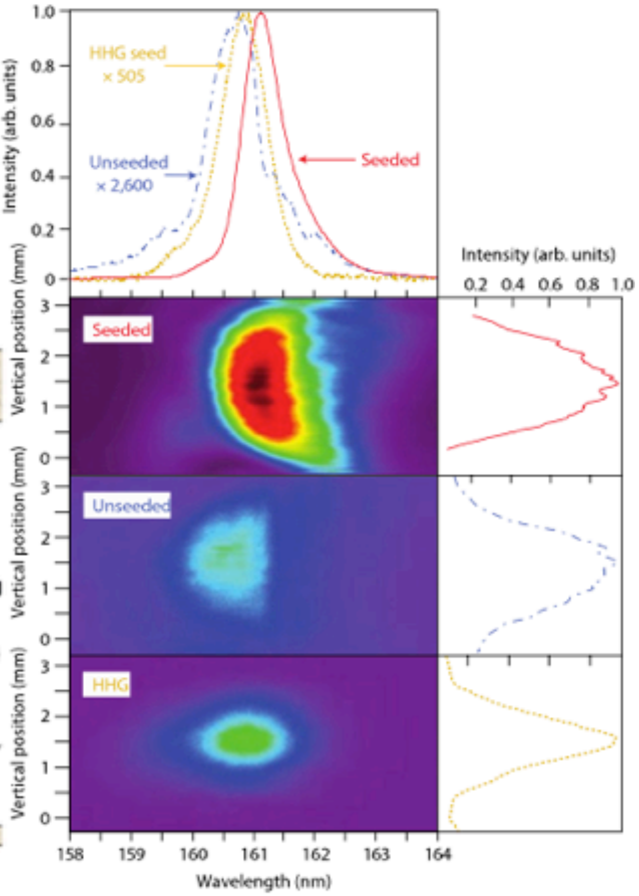
G. Lambert et al, Nature Physics Vol. 4 (2008) 296

Test Injector at SCSS (Spring 8)

Drive Laser at 800 nm

HHG Harmonics: 160 nm (n=5)





HHG Seed is amplified by a factor of about 500

SASE signal is 2600 times weaker than seeded FEL(good contrast of seed to shot noise)

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Comments on HHG Seeding

Slide Courtesy of Sven Reiche

HHG sources as seeds for FEL have been demonstrated at various experiments with the current record of 39 nm [*C. Lechner, et al, Proc of FEL Conference 2012*]

However further progress requires significant R&D in the source development:

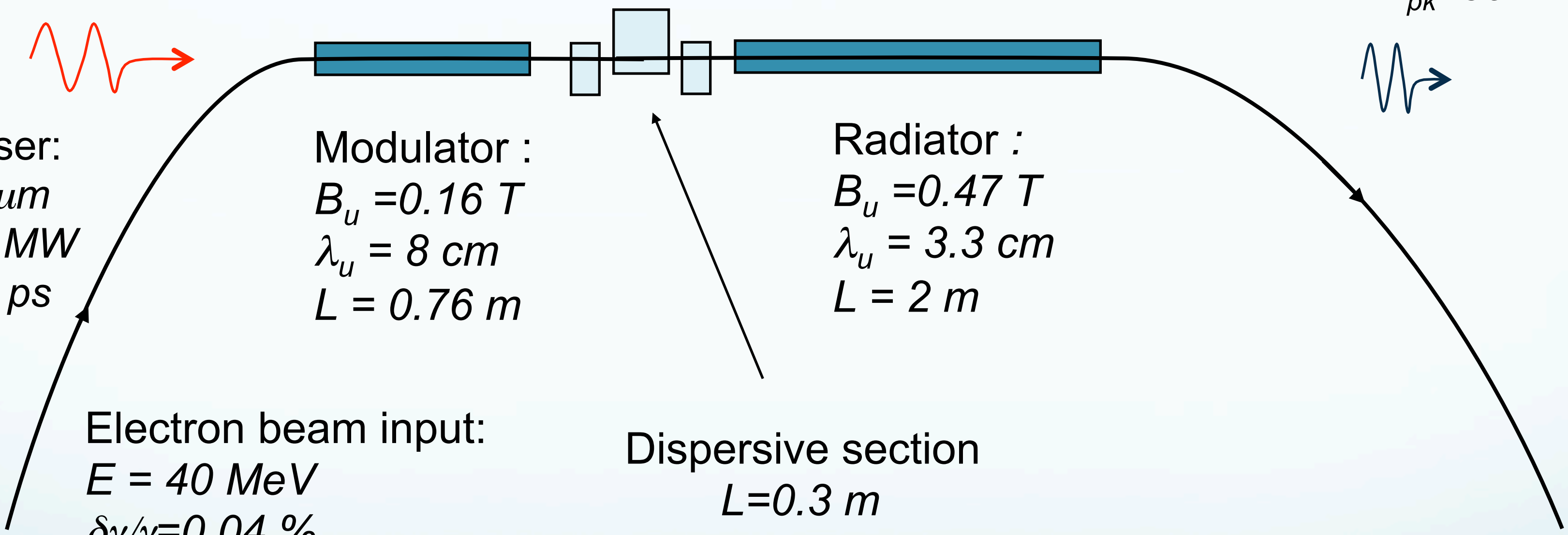
- Decrease the wavelength (extending the plateau of the HHG process)
- Increase the efficiency of HHG process to overcome increasing shot noise power
- Control/preserve the phase front and mode content of the HHG source
- Control the bandwidth of a given harmonic to match FEL bandwidth

Wavelengths below 20 nm difficult to achieve

Best for sync FEL pulse to external signal

Very little increase in brightness
(Single-spike SASE might be better alternative)

HGHG



Seed laser:
λ=10.6 μm
P_{pk}=0.7 MW
t_p = 300 ps

Modulator :
B_u =0.16 T
λ_u = 8 cm
L = 0.76 m

Radiator :
B_u =0.47 T
λ_u = 3.3 cm
L = 2 m

2nd harmonic:
λ= 5.3 μm
P_{pk}=35 MW

Electron beam input:
E = 40 MeV
$\delta\gamma/\gamma$=0.04 %
I_{pk}=110 A
t_p = 6 ps

Dispersive section
L=0.3 m

Output is

$2 \cdot 10^7 P_{spont.}$

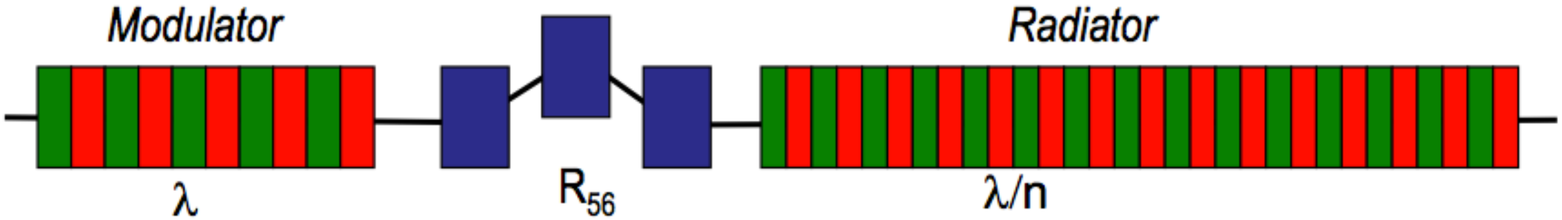
$2 \cdot 10^6 P_{SASE}$

High Gain Harmonic Generation (HGHG)

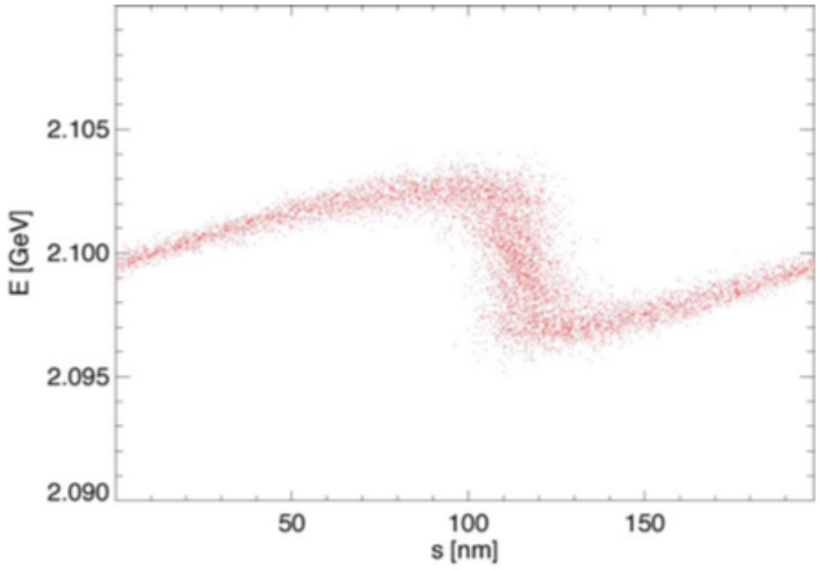
- Induced energy modulation at longer wavelength is changed into rich harmonic current content after compression with a chicane.
- To avoid smearing out the energy modulation must be larger than intrinsic energy spread
- A selected harmonic is picked up with a succeeding undulator.

Slide Courtesy of Sven Reiche

Theory: L.-H. Yu, Science 289 (2000) 932



Phase Space at Radiator Entrance



Bunching:

$$b_n = J_n\left(\frac{n}{\lambda}R_{56}\frac{\Delta E}{E}\right)e^{-\frac{1}{2}\left(\frac{n}{\lambda}R_{56}\frac{\sigma_E}{E}\right)^2}$$

$$\Longrightarrow \quad \Delta E \approx n\cdot\,\sigma_E$$

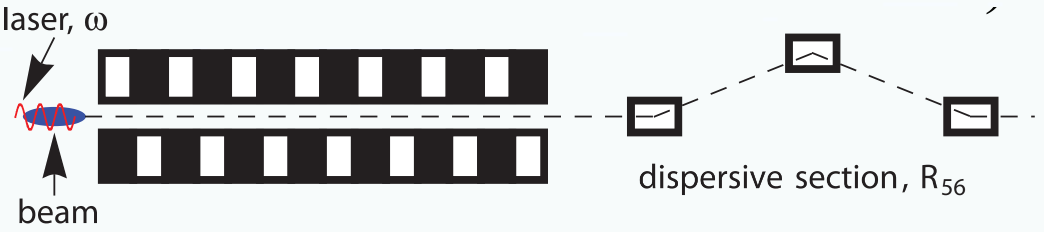
Limit:

$$\frac{\Delta E}{E} = \frac{n\sigma_E}{E} < \rho$$

Calculating the Bunching Coefficient

Follow directly G. Stupakov who in turn followed L-H. Yu.

Assume an initial Gaussian beam energy distribution with the variance σ_E and use the variable $p = (E-E_0)/\sigma_E$ for the dimensionless energy deviation of a particle. The initial distribution function of the beam, normalized by unity, is $f(p) = N(2\pi)^{-1/2}e^{-p2/2}$, where N is the number of particles per unit length of the beam.

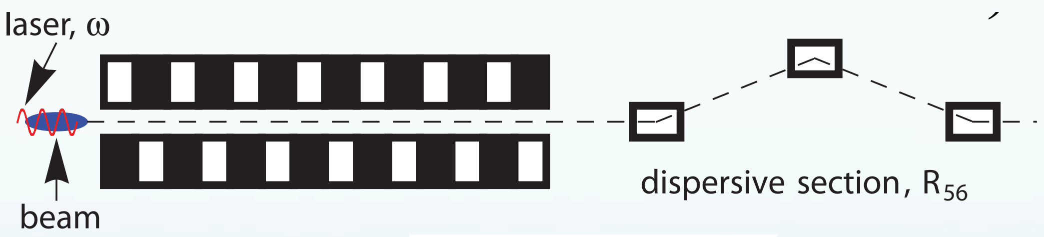


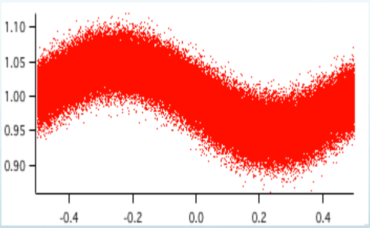
E_0 interacts with a laser beam of frequency ω in a short undulator (called a modulator) with the resonant frequency tuned to ω.

Calculating the Bunching Coefficient

Follow directly G. Stupakov who in turn followed L-H. Yu.

After passage through the undulator, the beam energy is modulated with the amplitude ΔE, so that the final dimensionless energy deviation p' is related to the initial one p by the equation $p' = p + A\sin(\kappa z)$, where $A = \Delta E/\sigma_E$, $\kappa = \omega/c$, and z is the longitudinal coordinate in the beam. The distribution function after the interaction with the laser becomes $f(z, p) = (2\pi)^{-1/2} \exp[-(p - A \sin \xi)^2/2]$ where we now use the dimensionless variables $\xi = \kappa z$.





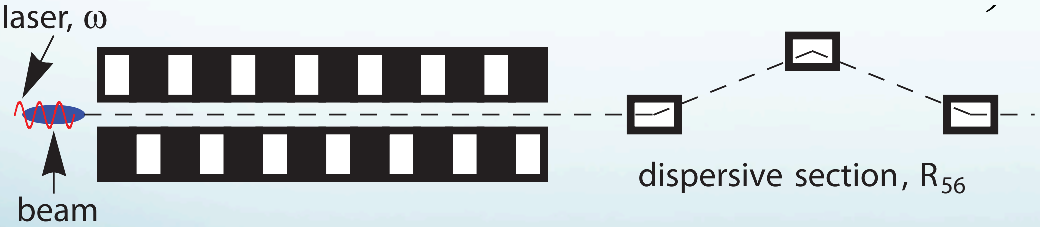
Calculating the Bunching Coefficient

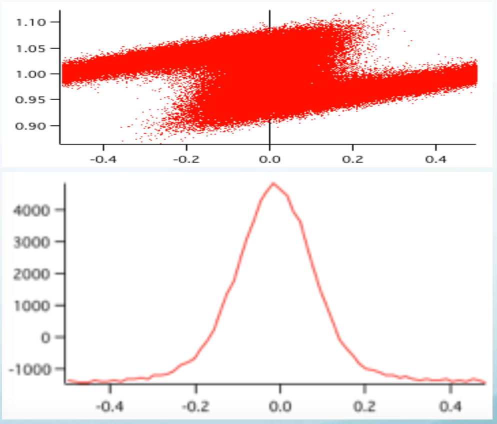
Follow directly G. Stupakov who in turn followed L-H. Yu.

Sending then the beam through a dispersive system with the dispersive strength R_{56}, converts the longitudinal coordinate z into z′ ,
$z' = z + R_{56} p \sigma_E / E_0$, and makes the distribution function

$$f(\zeta, p) = \frac{N}{\sqrt{2\pi}} \exp\left[-\frac{1}{2}\left(p - A\sin(\zeta - Bp)\right)^2\right]$$

where $B = R_{56} \kappa \sigma_E / E_0$.





Calculating the Bunching Coefficient

Follow directly G. Stupakov who in turn followed L-H. Yu.

Integration of f over p gives the distribution of the beam density N as a function of the coordinate ξ,

$$N(\zeta) = N_0 \int_{-\infty}^{\infty} dp f(\zeta, p)$$

Noting that this density is a periodic and even function of ξ one can expand it into Fourier series

$$\frac{N(\zeta)}{N_0} = 1 + \sum_{k=1}^{\infty} b_k \cos(k\zeta)$$

where the coefficient b_k is the amplitude of the harmonic k. Calculations with the function (previous page) give an analytical expression for b_k [Yu].

$$|b_k| = 2\, e^{-\frac{1}{2}B^2k^2} |J_k(ABk)|$$

where J_k is the Bessel function of order k.

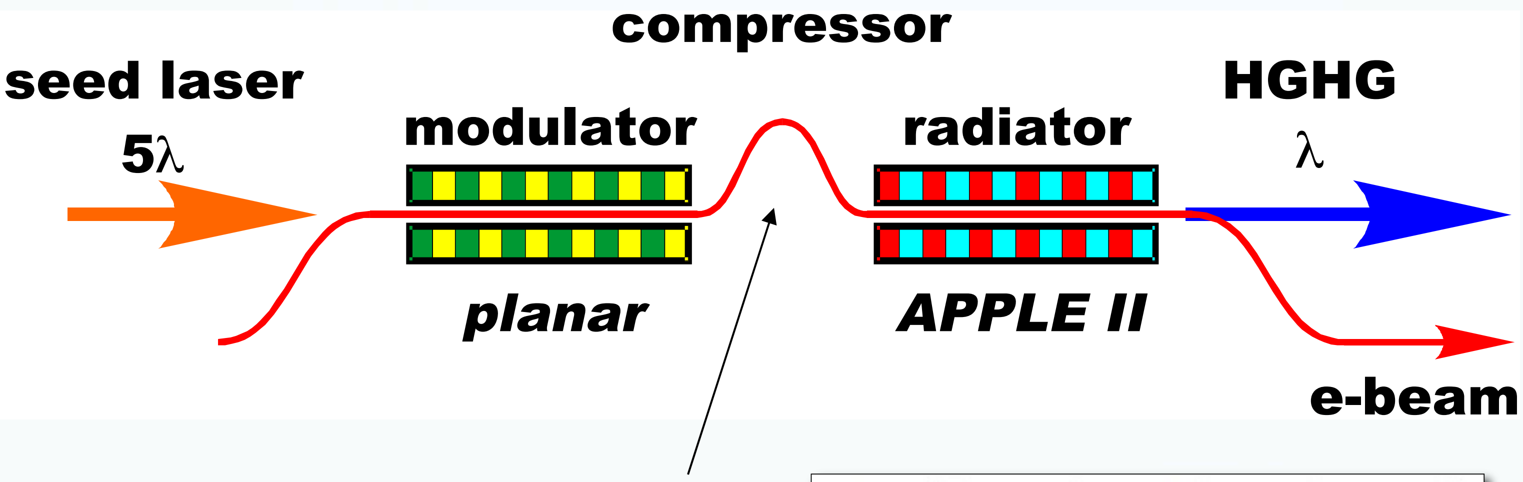
Calculating the Bunching Coefficient

Follow directly G. Stupakov who in turn followed L-H. Yu.

$$|b_k| = 2\, e^{-\frac{1}{2}B^2k^2}|J_k(ABk)|$$

Note: b_k drops off dramatically as k increases and the mater is even worse of $B = R_{56}\,\kappa\,\sigma_E/E_0$ is large. This was one of the motivating factors for Stupakov to develop the echo enabled scheme.

High Gain Harmonic Generation - HGHG



Bunching at harmonic λ

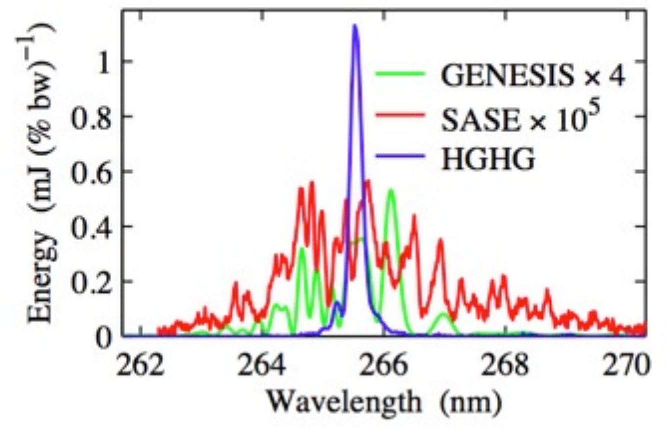


FIG. 4: Single shot HGHG spectrum for 30 MW seed (blue), single shot SASE spectrum measured by blocking the seed laser (red) and simulation the SASE spectrum after 20 m of NISUS structure (green). The average spacing between spikes in the SASE spectrum is used to estimate the pulse length.

More compact and fully temporally coherent source, control of pulse length and control of spectral parameters.

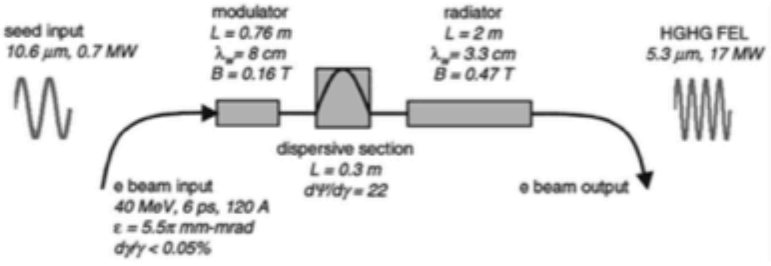
Li-Hua Yu
DUV-FEL

HGHG Experiments

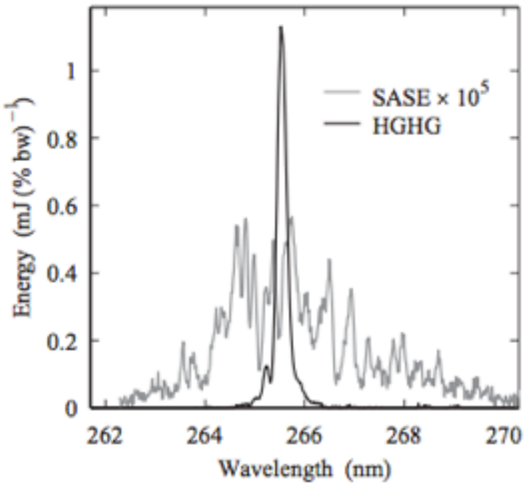
Slide Courtesy of Sven Reiche

Proof-of Principle Experiment (SDL)

A. Doyuran et al, PRL 86 (2001) 5902

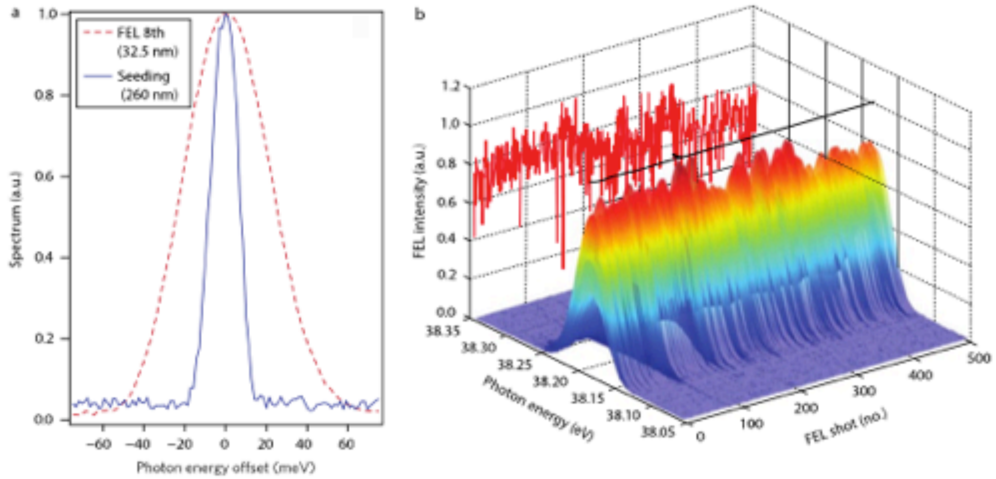


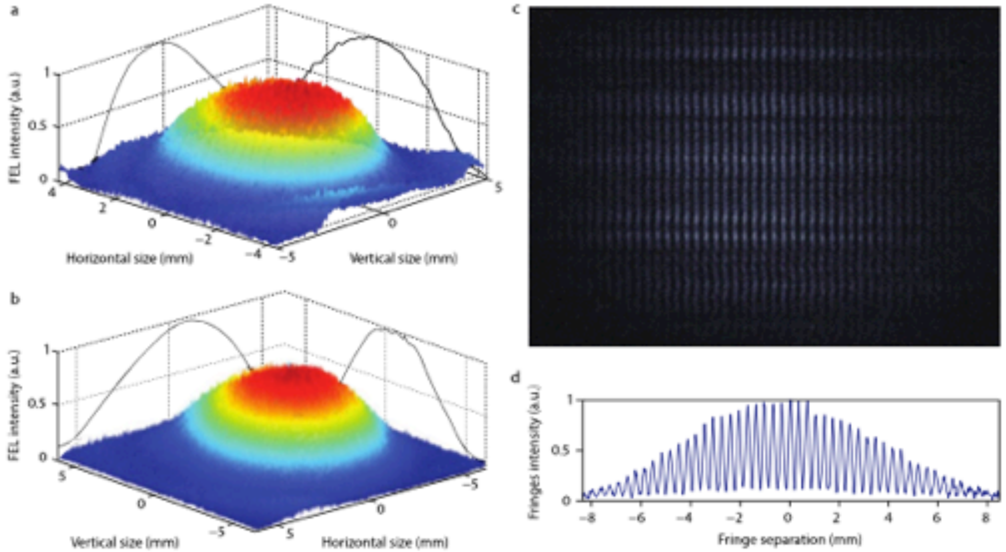
L.-H. Yu et al, NIMA 528 (2004) 436



FERMI @ Elettra – User Facility based on HGHG

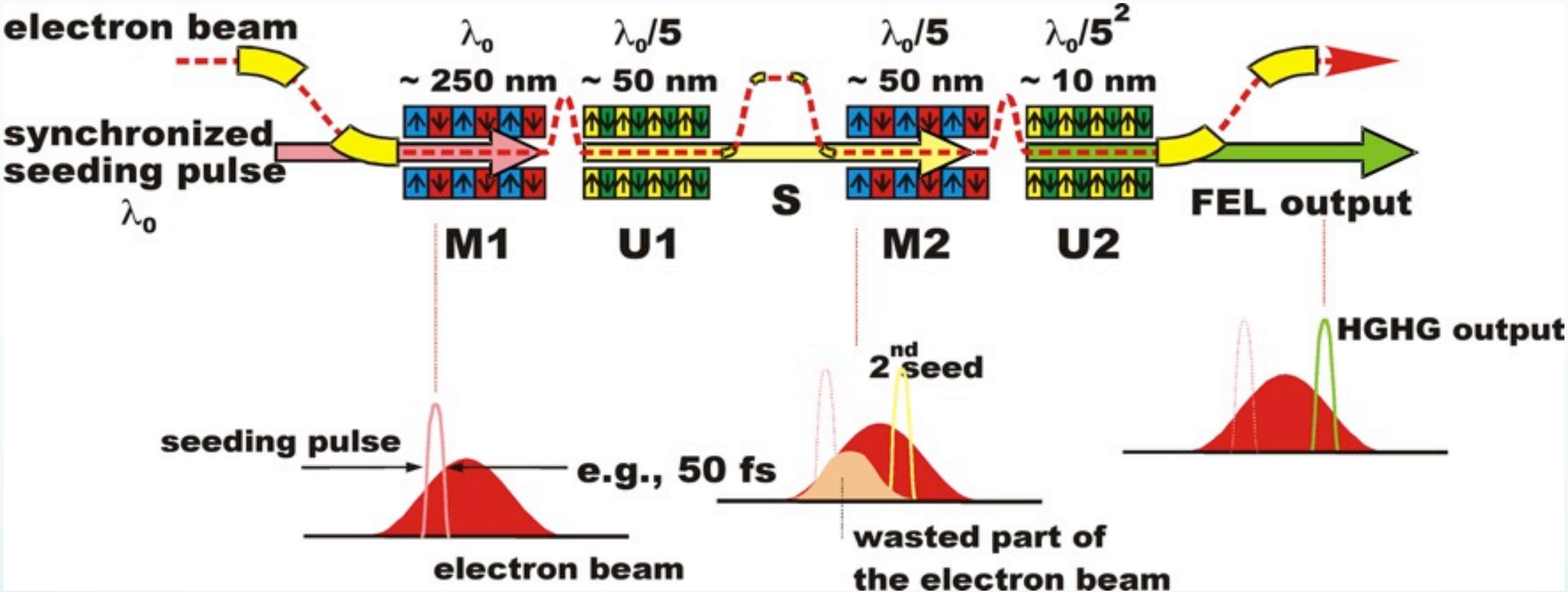
E. Allaria et al, Nature Photonics. 6 (2012) 699





Cascaded HGHG

2-Stage cascade HGHG



Here one upconverts the frequency by a very large amount. In this example by 25.

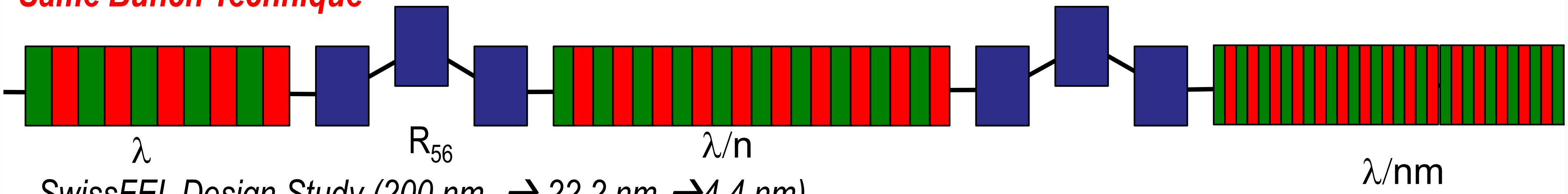
But at a price…complexity.

If only the seed wavelength were shorter…

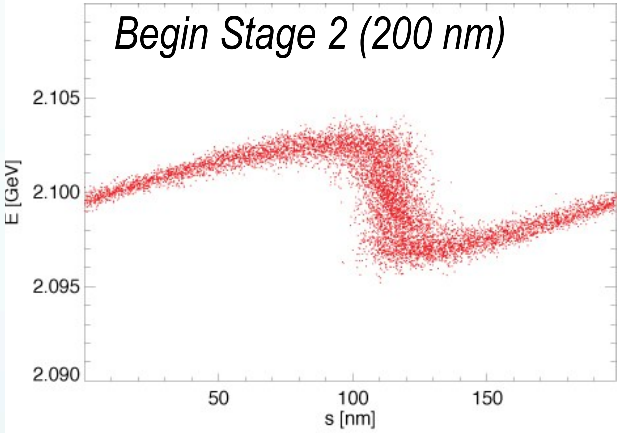
Cascading HGHG

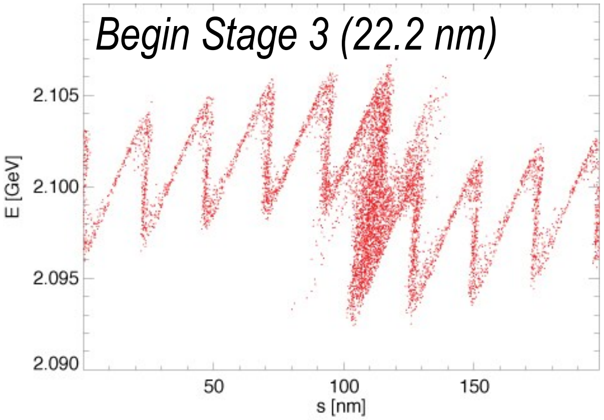
Slide Courtesy of Sven Reiche

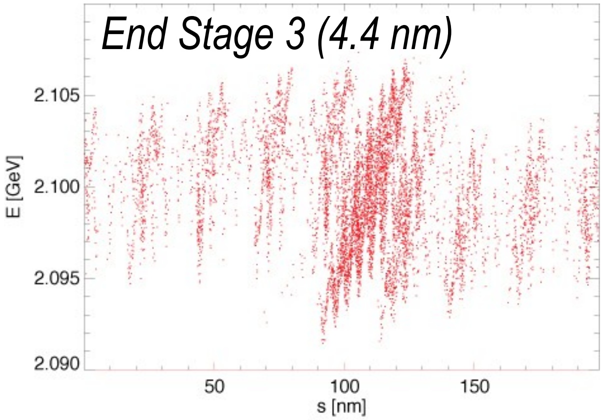
Same Bunch Technique



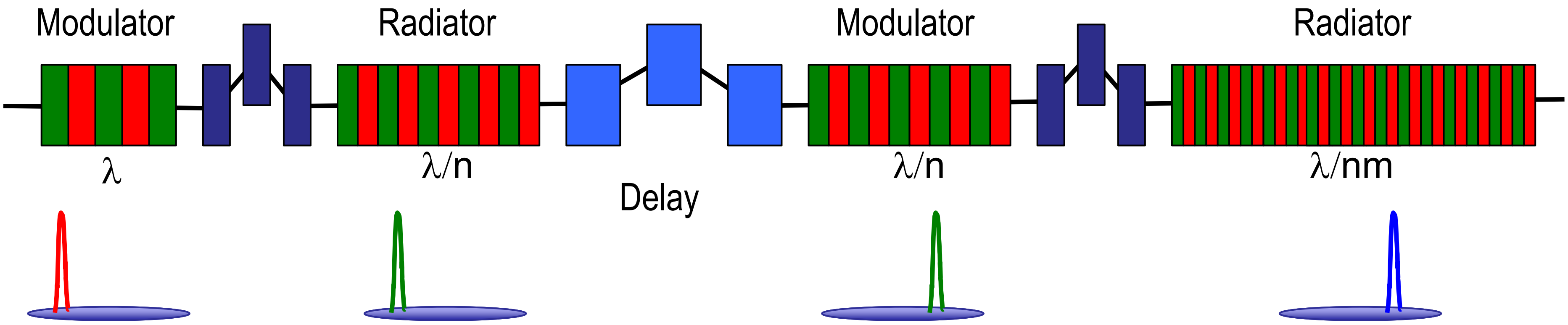
SwissFEL Design Study (200 nm → 22.2 nm →4.4 nm)


Begin Stage 2 (200 nm)


Begin Stage 3 (22.2 nm)


End Stage 3 (4.4 nm)

Fresh Bunch Technique (e.g. FEL II at FERMI@Elettra)



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Comments on HGHG

Slide Courtesy of Sven Reiche

Strong progress in the last year mostly due to the success of FERMI. Wavelengths down to 4 nm have been achieved.

However an HGHG FEL cannot be optimized much for pulse energy:

- Only fresh bunch feasible for cascades due to the tremendous sensitivity of same bunch cascades
- Long bunches reduces the current and thus the saturation power
- Only a subsection of the bunch contribute to the final radiation stage (similar to HHG seeds)
- Energy spread of initial beam has to be less than in SASE case, limiting the use of laser heaters in the injector and machine.

Wavelengths down to 1 nm seems feasible

Good for sync FEL pulse to external signal

Not optimized for pulse energy.

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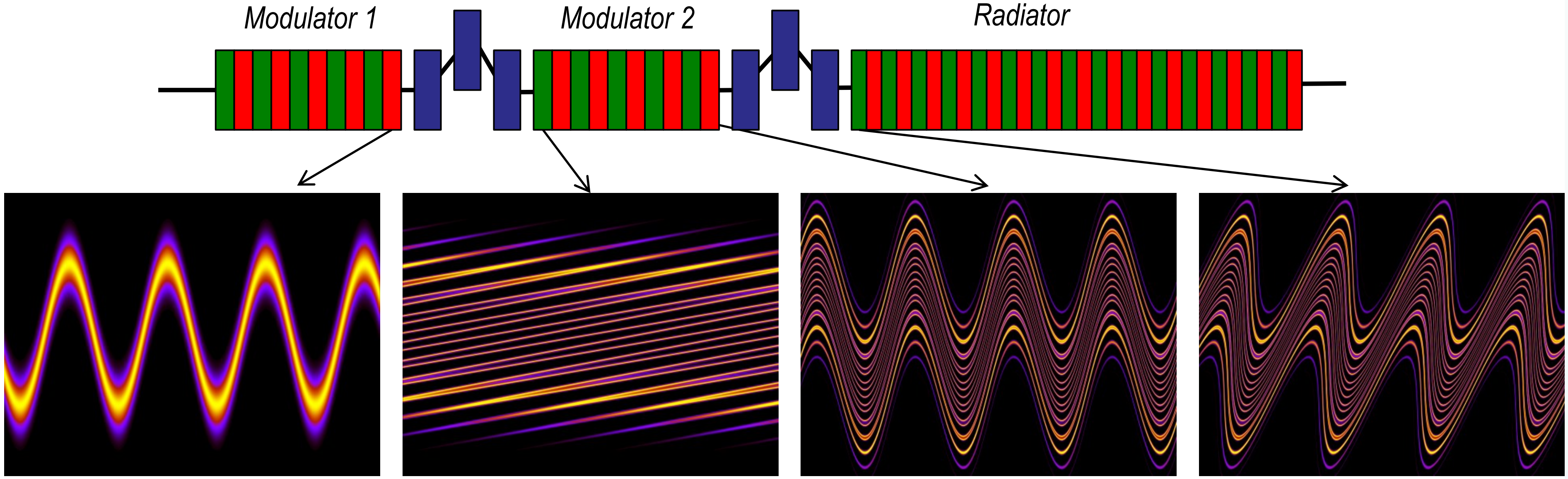
Echo-Enabled Harmonic Generation

Slide Courtesy of Sven Reiche

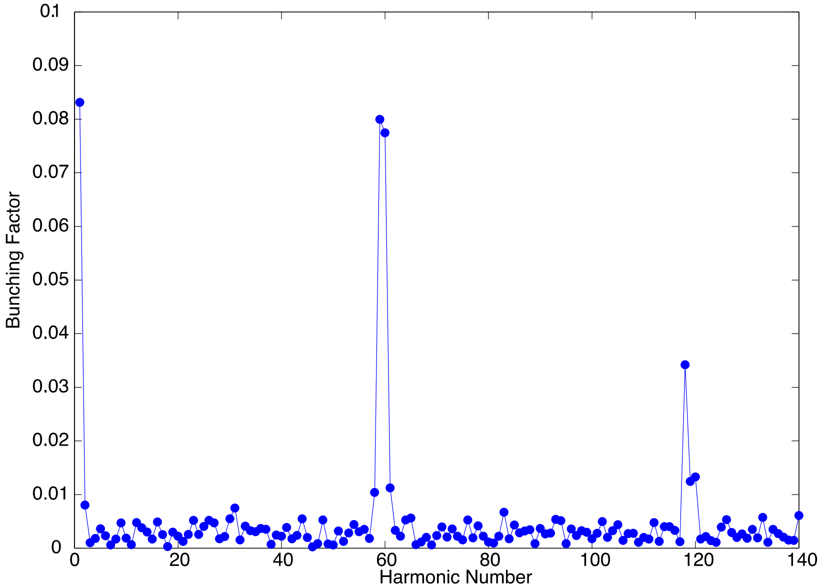


Basic Idea [*D. Xiang and G. Stupakov, PR STAB 12 (2009) 030702*]:

- First stage: Modulation and overcompression to generate energy bands
- Second stage: HGHG principle but spacing of bands defines harmonics

High efficiency for bunching

$$b_{\max} = \frac{0.39}{m^{1/3}}$$



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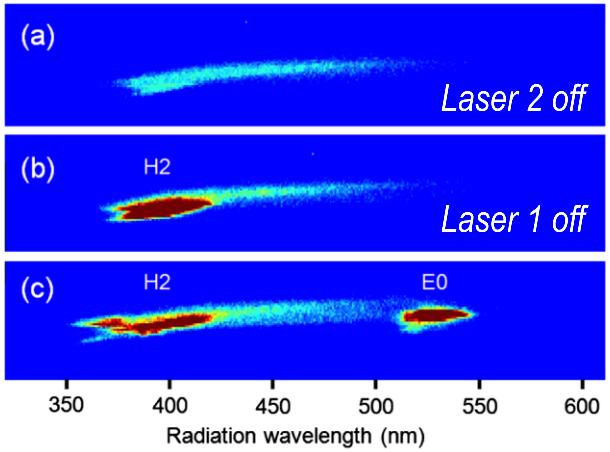
Experiments for EEHG

Slide Courtesy of Sven Reiche

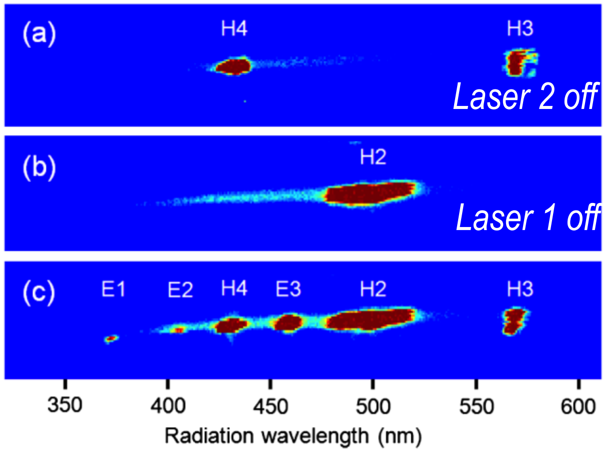
[D. Xiang et al PRL 105 (2010) 114801]

λ_1= 759 nm, λ_2 = 1590 nm

Little Chirp



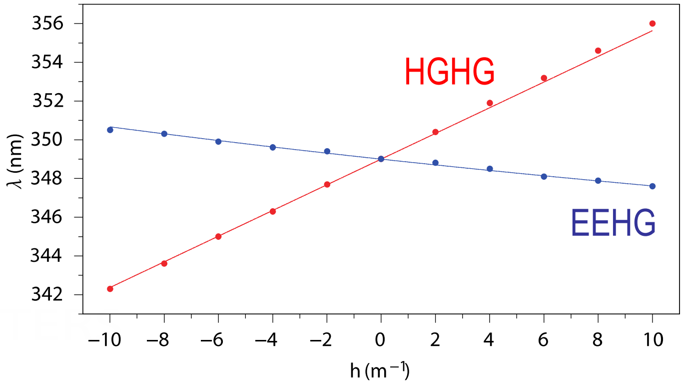
Strong Chirp

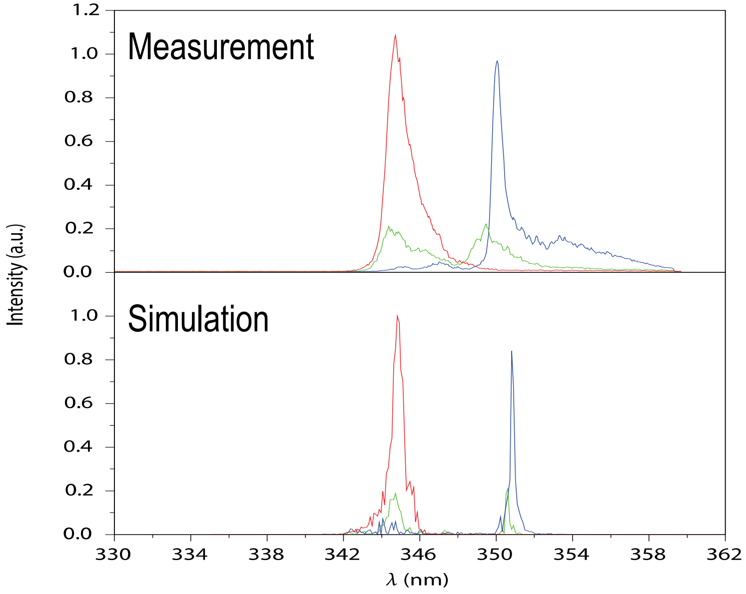


[Z.T. Zhao et al Nature Photonics 6 (2012) 360]

λ_1= 1047 nm, λ_2 = 1047 nm

Wavelength vs chirp





Wavelength Limit of EEHG

Slide Courtesy of Sven Reiche

Although scaling towards shorter wavelength is promising, there are practical reasons for the higher harmonic numbers:

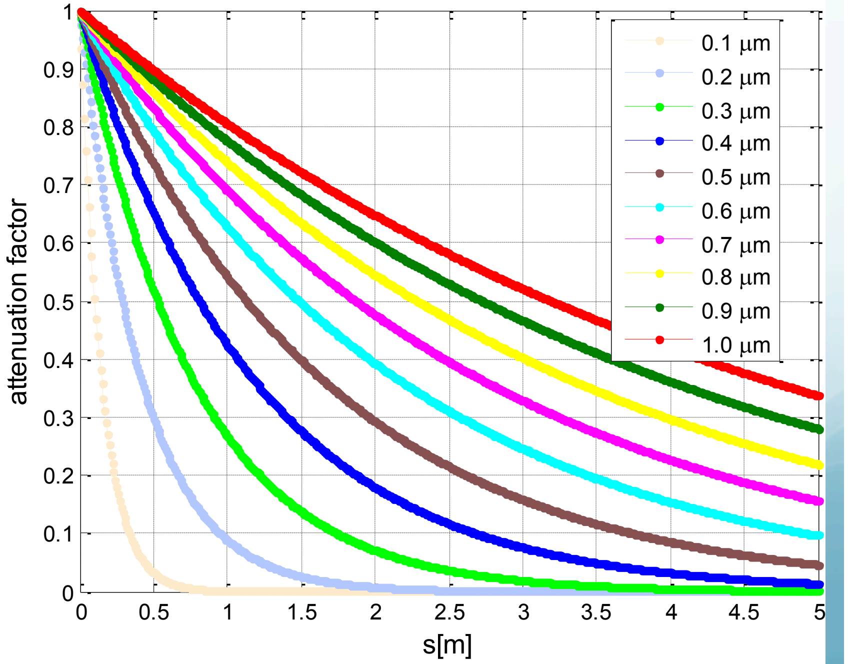
- Total width of energy modulation is limited by FEL process ($\Delta\gamma/\gamma<\rho$)
- Number of lines defines harmonic *m* with an average line spacing of $\delta\gamma/\gamma < \rho/m$
- Hyperfine structure can be blurred out by:
  - Quantum Fluctuation of the incoherent emission in modulator and chicane
    - Favors low magnetic field and long chicanes
  - Intrabeam scattering [G. Stupakov, FEL 2011]
    - Favors compact chicanes

Wavelength limit at about 1 nm

Good control of electron chirp

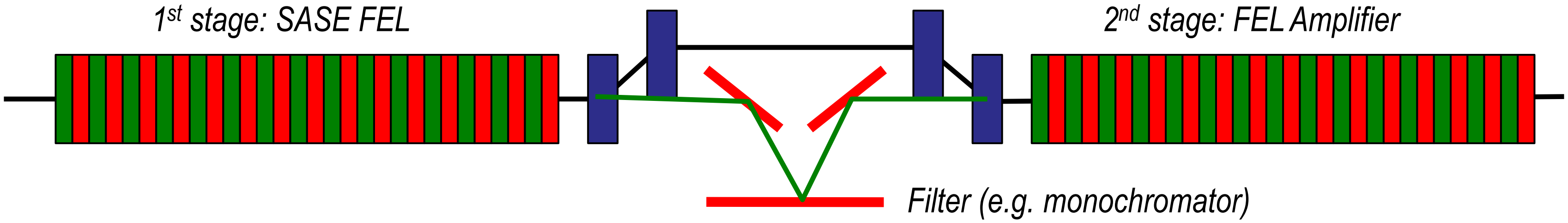
1st chicane can lengthen bunch

Dependence of IBS on emittance @ 1 nm



Slide Courtesy of Sven Reiche

Self-Seeding



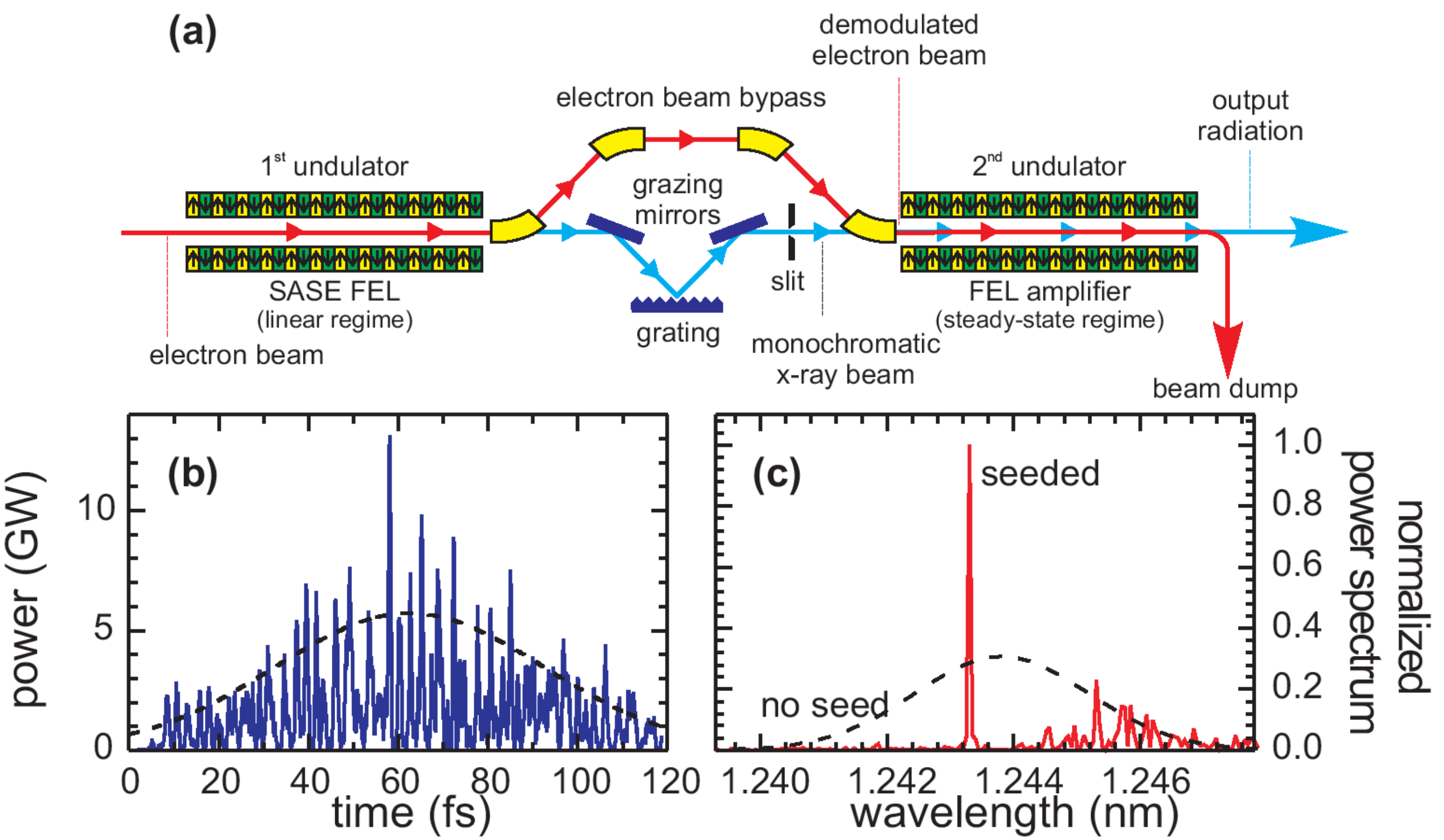
Basic Idea:

- 1st stage operates as SASE FEL, but stopped before saturation
- Radiation is filtered, introducing longitudinal coherence
- Delay of radiation field is matched with delay electron beam with a magnetic chicane. The chicane removes also any induced bunch, removing the imprint of SASE in the bunch (quasi fresh bunch)
- Beam and radiation are overlapped in a second stage, operating as an FEL amplifier.

First proposed for soft X-ray FEL FLASH *[J. Feldhaus et al, Opt. Comm 140 (1997) 341]* but never realized due to the strong delays in the photon and electron path.

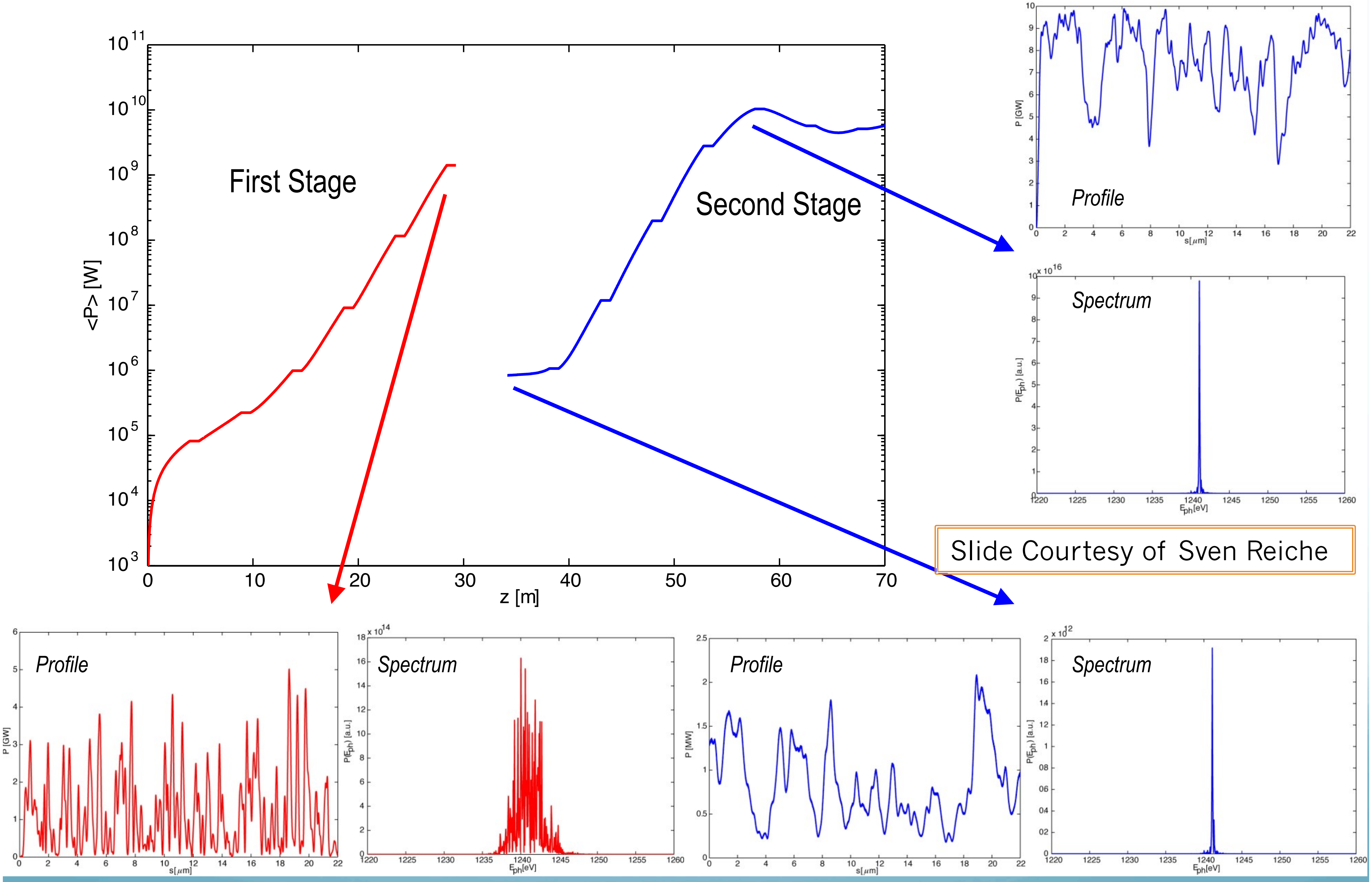
Idea brought up again for hard X-ray [*G. Geloni, Jour. Of Modern Optic 58:16 (2011) 1391*], using the transmission around the stop band of a Bragg reflection (see next slide).

More compact design for soft X-ray [*Y. Feng, LCLS*] makes self-seeding feasible for longer wavelength



Top: Basic scheme of a two-stage FEL [16] providing full longitudinal and transverse coherent light, see text for details. Bottom: GENESIS simulation of the two-stage FEL employing a 3 kW seed in the second undulator.

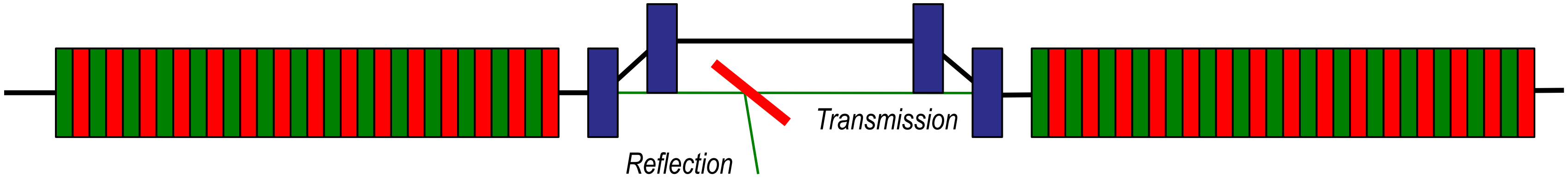
Example Performance for SwissFEL at 1 nm



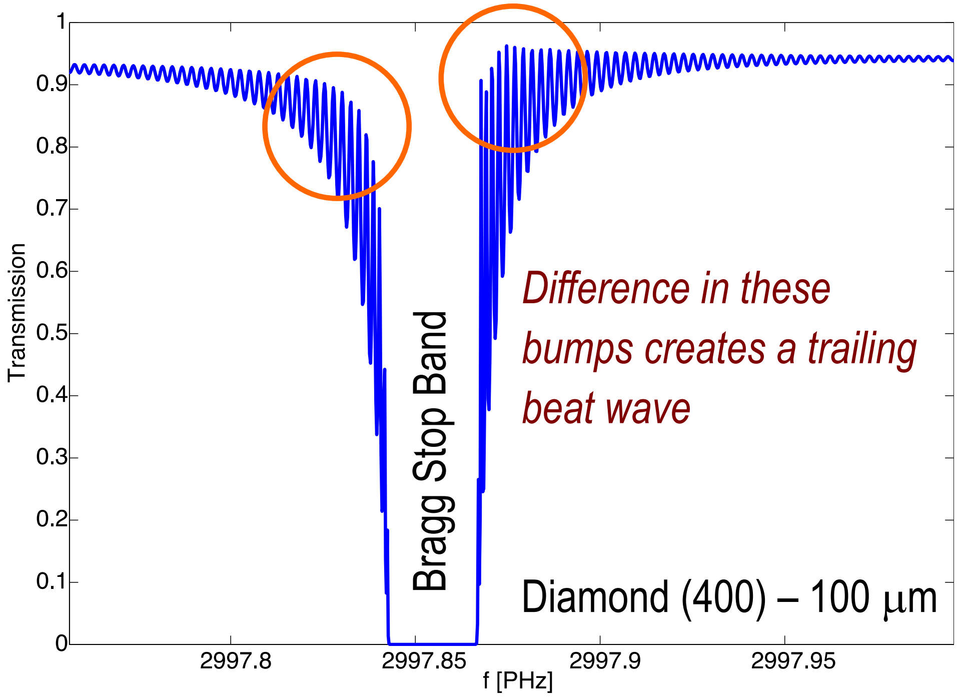
Slide Courtesy of Sven Reiche

Self-Seeding for Hard X-rays

Slide Courtesy of Sven Reiche



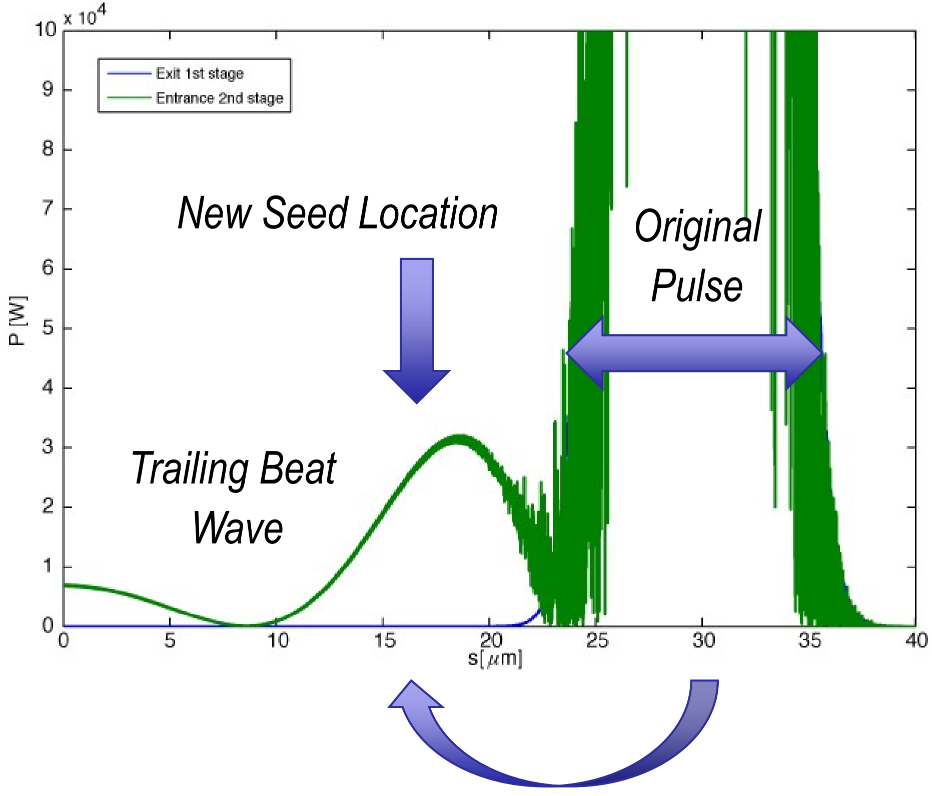
Transmission



Difference in these bumps creates a trailing beat wave

Diamond (400) – 100 μm

Time Profile of Radiation Pulse



New Seed Location

Original Pulse

Trailing Beat Wave

Bunch Delay by Chicane

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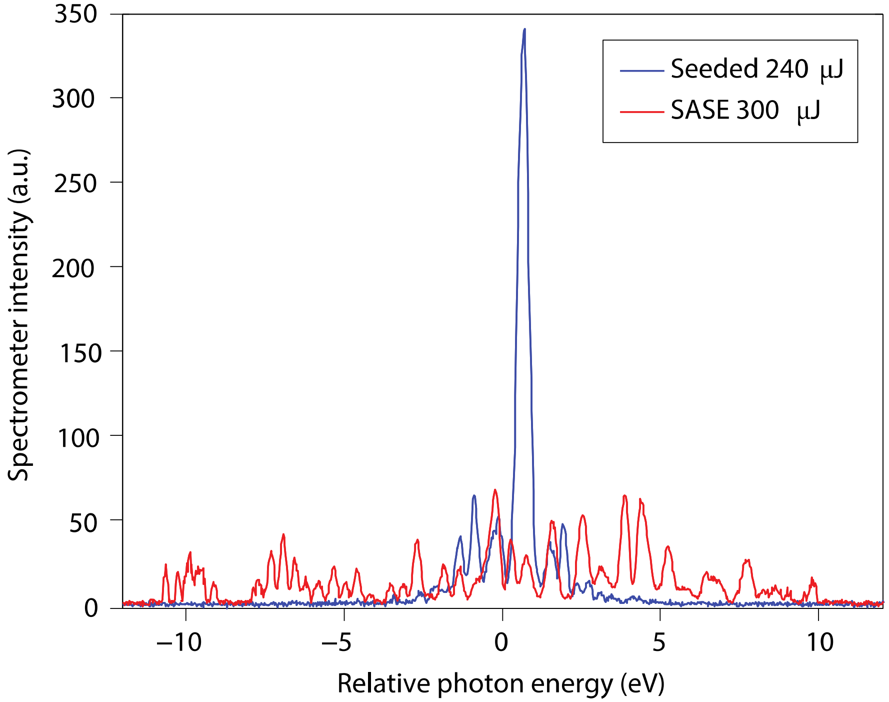
Proof-of Principle Experiments

Slide Courtesy of Sven Reiche

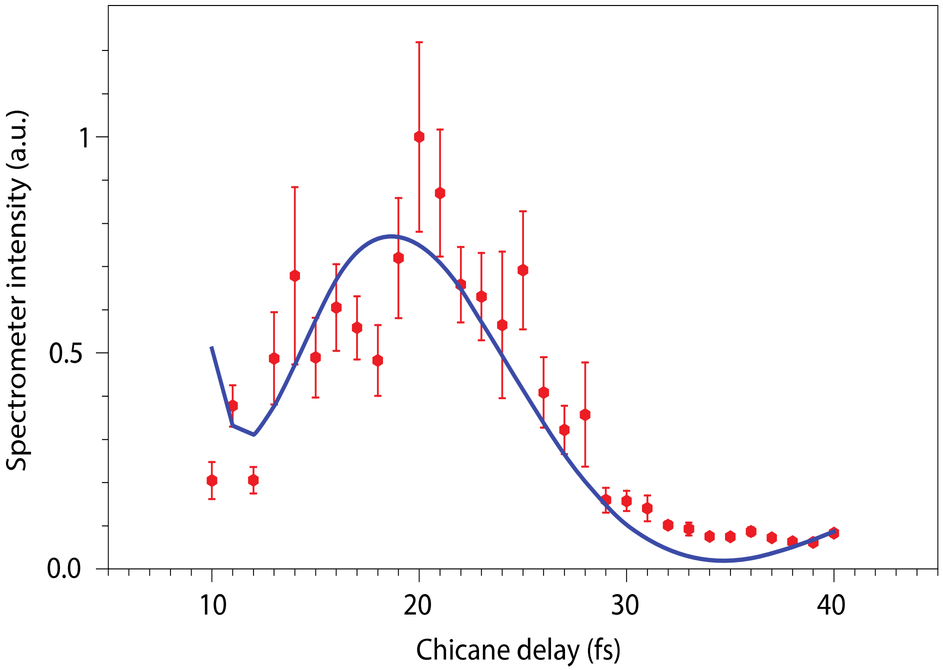
Hard X-ray Self-seeding done at LCLS for 8 keV [*J. Amann et al, Nature Photonics 6 (2012) 693*]

- Wavelength: 1.5 nm
- Diamond Crystal, using (400) reflection
- Reduction of Bandwidth by factor 40 observed
- Output energy very sensitive to electron energy jitter

Single-Shot Spectrum



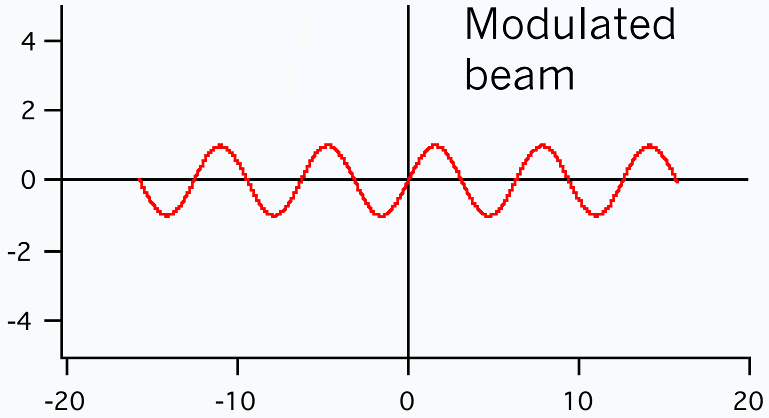
Electron Bunch Delay



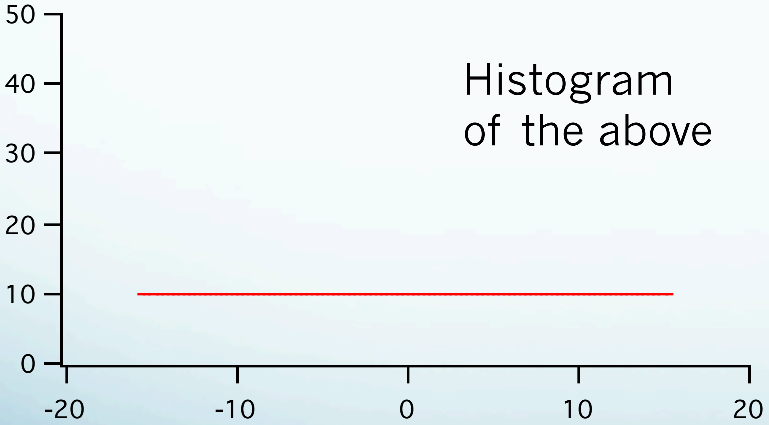
Wavelength Shifting

- Basic Idea
  - Modulate in energy at a fixed wavelength the electron bunch
  - Compress the bunch and create a density modulation at a different wavelength than the seed
  - Remove any unwanted energy chirp
  - Pass the beam through an undulator tuned to the new wavelength
- Advantages
  - Allows one to seed with a well controlled fixed source
  - Allows one to set up the major part of the system and then leave untouched

Wavelength Shifting: Graphically

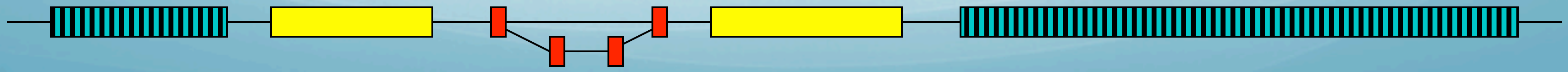


Imprint an energy modulation onto the beam. This is identical to the first step in HGHG, i.e. combine an electron bunch with a laser seed pulse within the field of an undulator resonant at the seed wavelength.

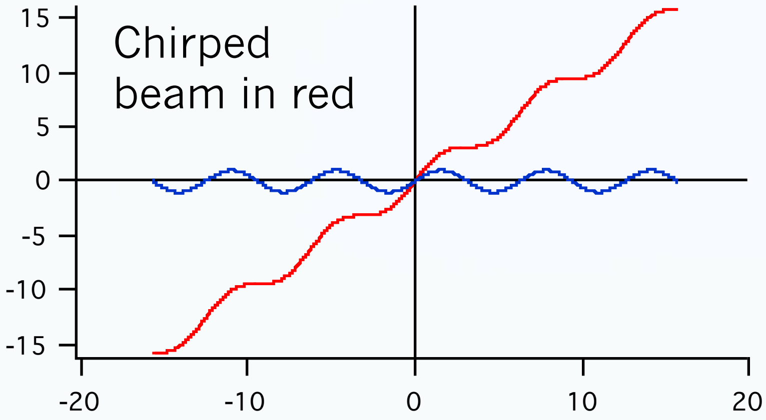


At this point there is no density modulation on the beam and so the beam is not yet suitable for coherent emission

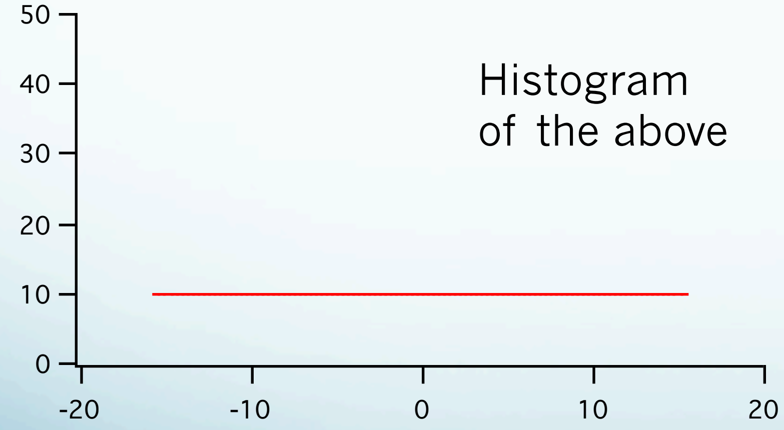
Modulator Undulator



Wavelength Shifting: Graphically

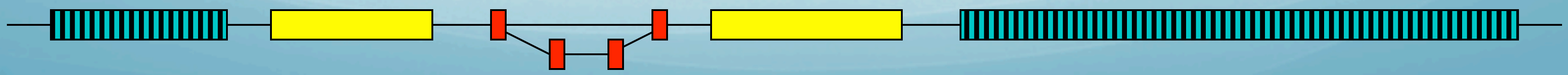


Now pass the beam through an accelerator and add a correlated energy spread to the imprinted beam.

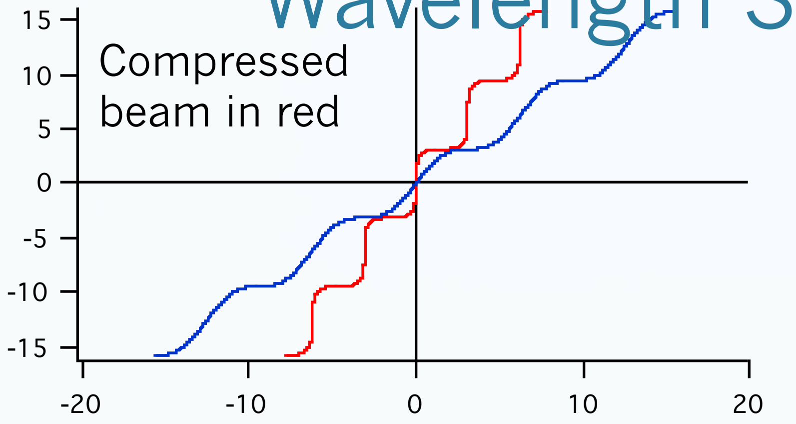


At this point there is still no density modulation on the beam and so the beam is still not yet suitable for coherent emission.

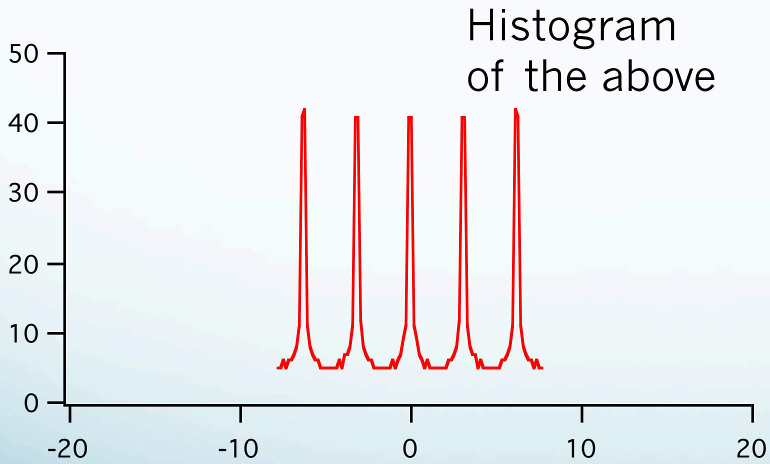
Accelerator one



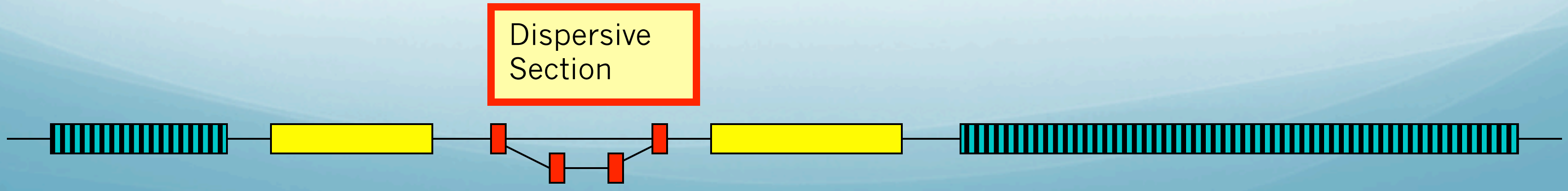
Wavelength Shifting: Graphically



The beam now is passed through a chicane and the high energy tail of the beam catches up with the low energy head of the beam.

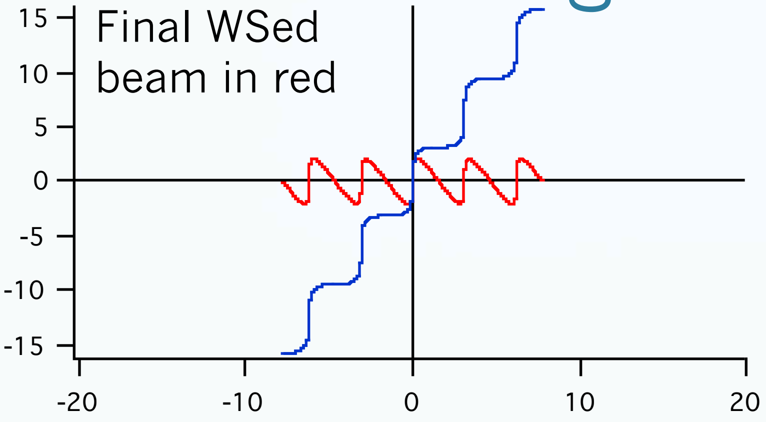


Done correctly there is now a significant density modulation on the bunch, but now it is at a different wavelength than the seed. This wavelength is dependent on the seed wavelength and the depth of the initial modulation. The beam is now ripe for coherent emission.

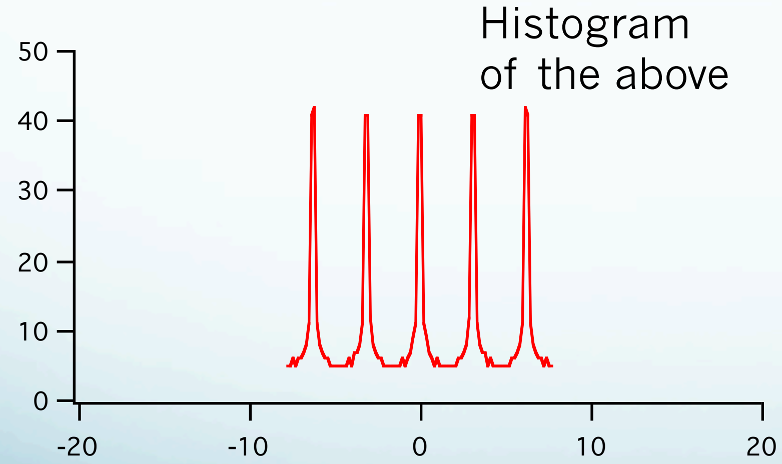


Dispersive Section

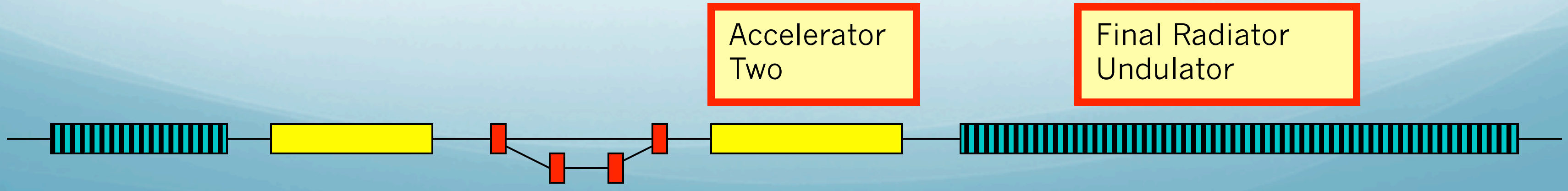
Wavelength Shifting: Graphically



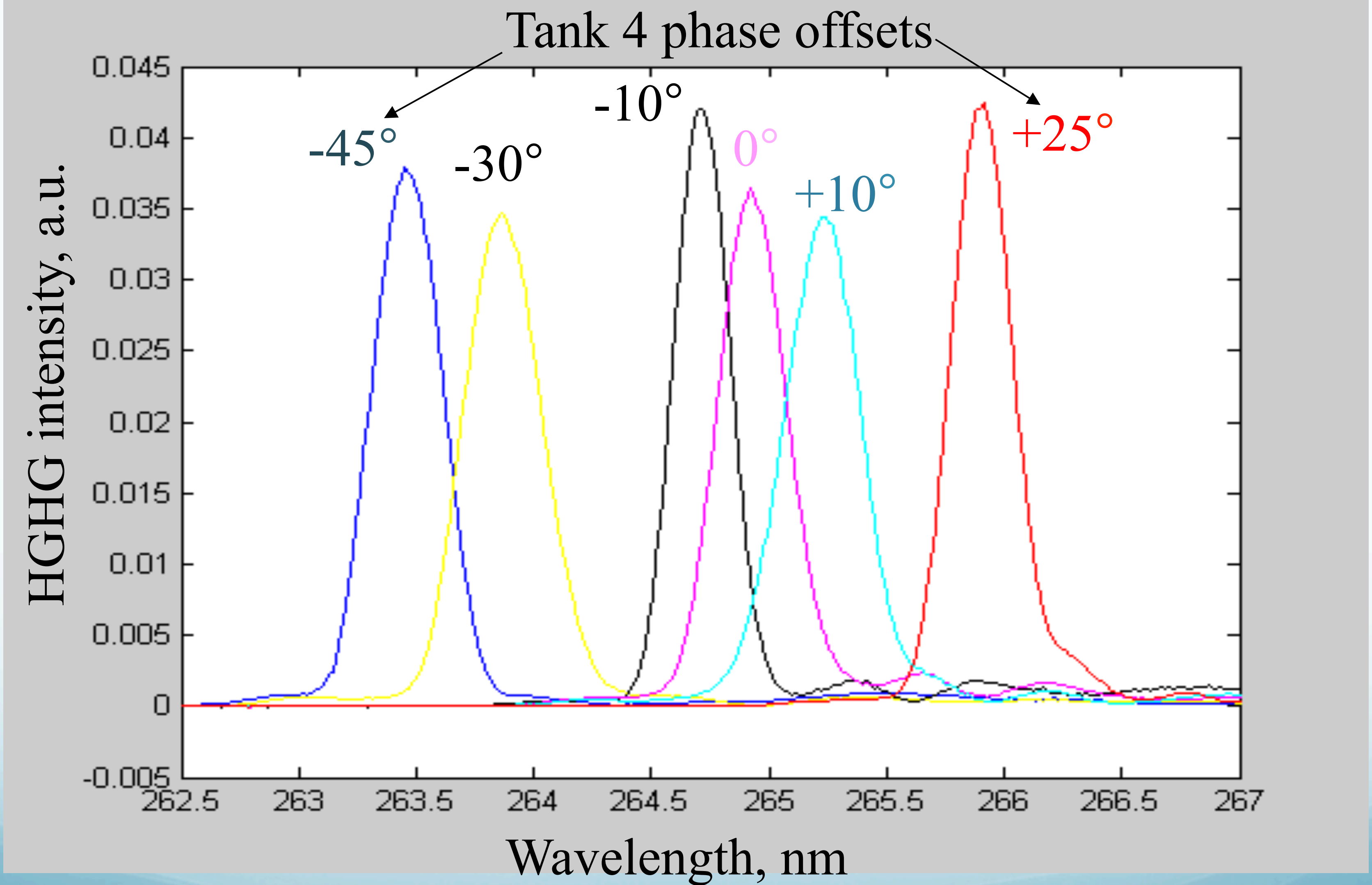
A second accelerator running off crest is used to remove the energy chirp. Note some of this energy chirp could be left on the beam for further use in compressing the optical pulse duration.



The beam is now ideally bunched at the new desired wavelength. All that was needed in addition to that needed for HGHG are two additional accelerating structures.



Wavelength Shifting Experiment BNL



T. Shaftan, et al.

Attosecond X-rays

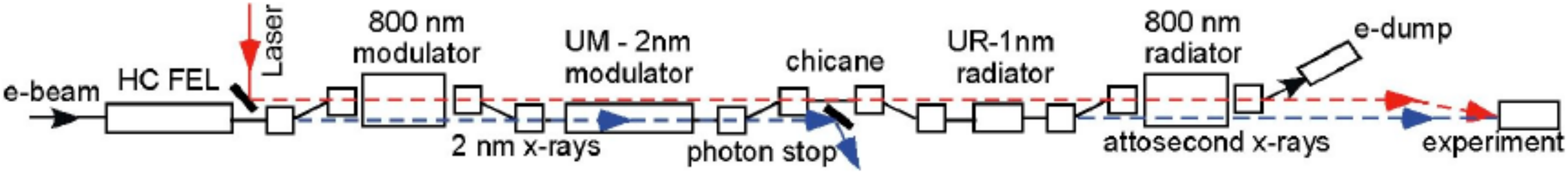


Figure 1: A schematic of the components involved in attosecond **x**-ray pulse production.

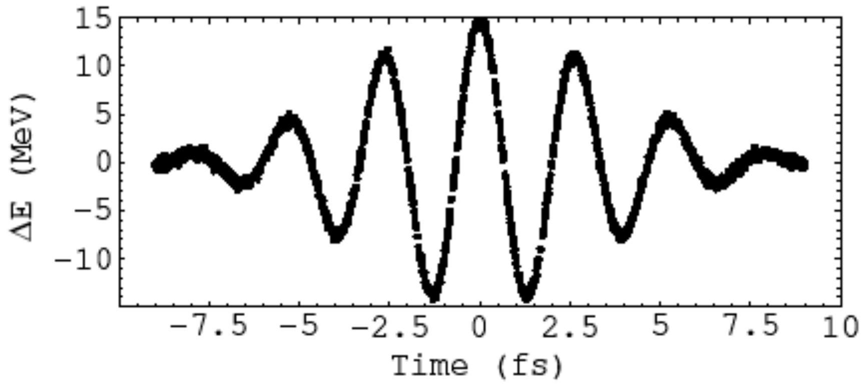


FIG. 2: The calculated energy modulation of the electrons along the electron bunch produced in the interaction with a few-cycle, 800-nm laser pulse in the wiggler magnet presuming an instantaneous electron beam energy spread $\sigma_E = 0.3$ MeV.

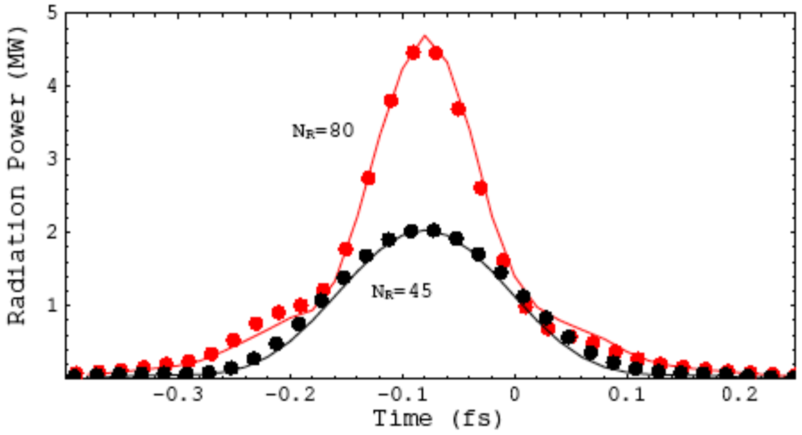


FIG. 4: (Color) Predicted attosecond pulse power at 1-nm wavelength from a radiator with $N_R = 80$ (top line) and $N_R = 45$ (bottom line) using Eq. (7). Both curves were normalized to the peak intensity of the $N_R = 80$ simulation results (dots).

A.A. Zholents, W.M. Fawley, Phys. Rev. Lett., 92, 224801 (2004); LBNL-54084Ext, (2003).

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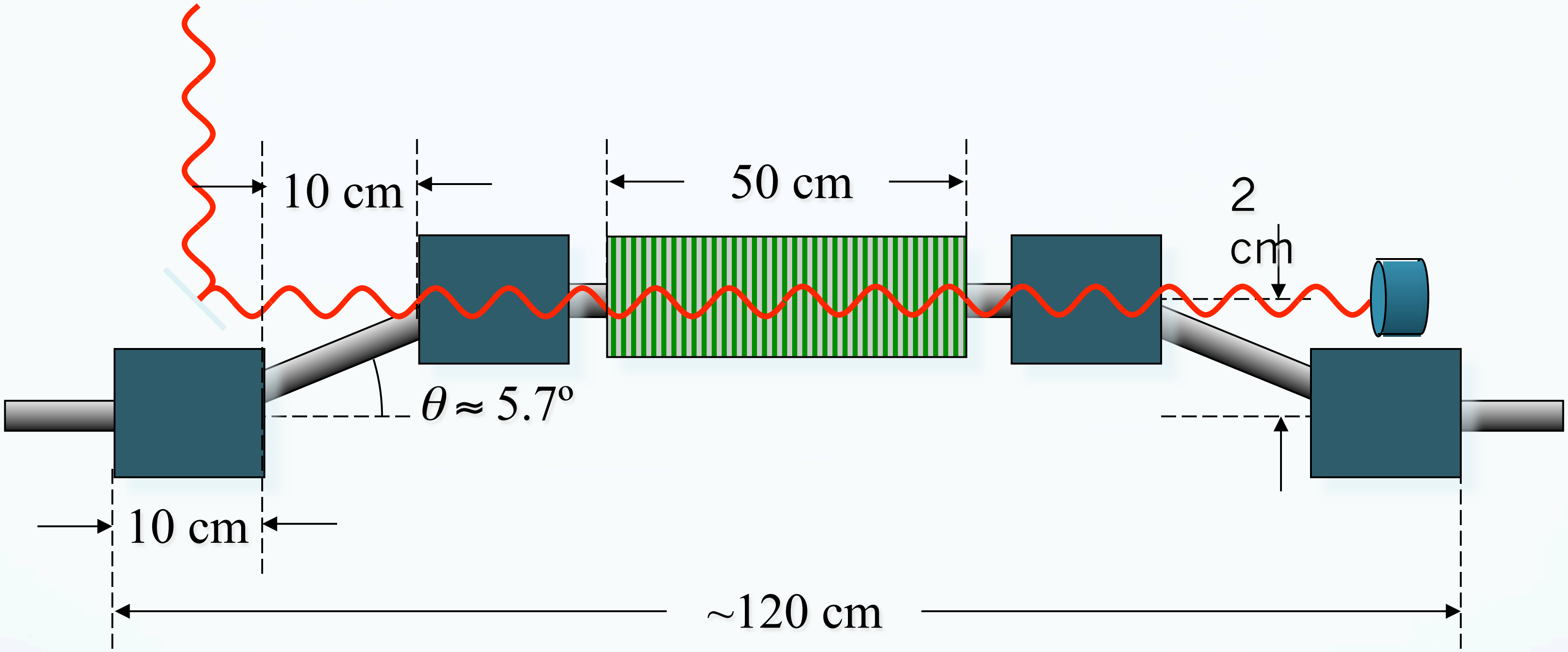
Comparison and Summary

Slide Courtesy of Sven Reiche

Method	Direct Seeding (HHG)	HGHG Cas. or EEHG	Self-Seeding
Wave Length Limit	>20 nm	> 1nm	> 0.1 Å
Synchronization	Good	Good	None
Brilliance	Similar to SASE (penalty from seed BW)	Slightly better (penalty from lower current)	Much better than SASE
Pulse Length	~10 fs	10 – 100 fs	As electron bunch
Signal-to-Background	Poor	Moderate - Good	Excellent
Complexity	Moderate (excluding source)	High	Moderate
Electron Beam Requirement	Arrival time and energy stability	Arrival time and energy stability, lower energy spread	Energy stability
Undulator Length	Slightly less than SASE FEL	Comparable and longer than SASE FEL	50% longer than SASE FEL

Laser Heater System: Add energy spread (IFEL)

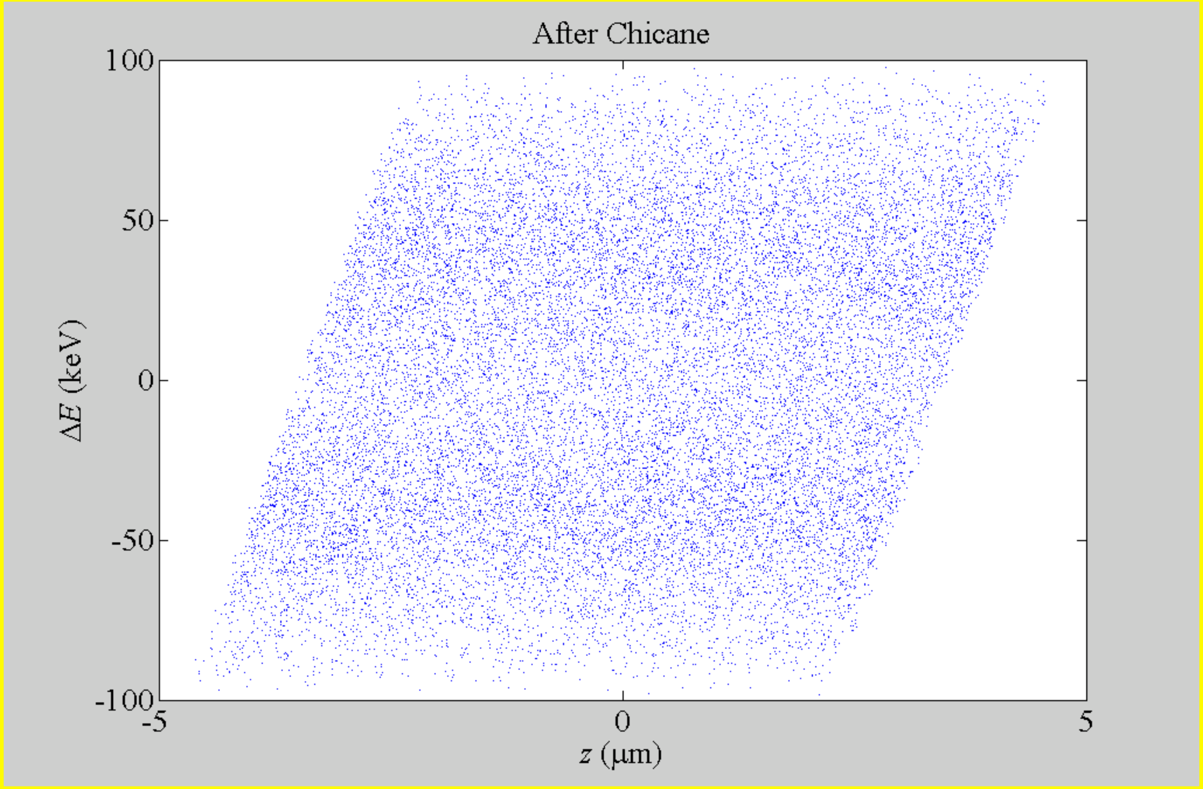


- Laser heater replaces SC wiggler to suppress beam instabilities
- Uses a small portion of the drive laser IR beam
- Cost and Schedule in Baseline

Slide compliments
of P. Emma

Laser Heater Effect on Beam

- Laser Heater increases the uncorrelated energy spread from ~5keV to more than 50keV to suppress beam instabilities.
- Studies show Laser Heater is more effective than SC Wiggler in controlling instabilities.



$P_0 = 2$ MW
$w_0 = 400\ \mu m$
$\sigma_x \approx 200\ \mu m$
$\sigma_y \approx 200\ \mu m$

Slide complements of P. Emma

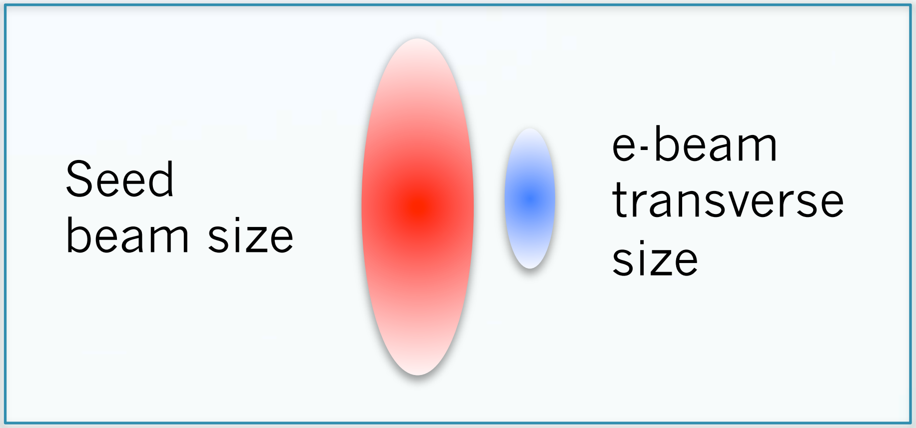
Overlap

- Transverse
  - Size
  - Position
- Timing
- Beam to beam signal overlap
- Energy overlap

Summary: Lots of things need to be right for seeding to work.

Transverse Overlap of Beams

- Transverse overlap
  - Seed beam smaller than the e-beam size
    - Doesn't make much sense as one wants to seed the fill transverse size of the e-beam
  - Seed beam the same size as e-beam
    - Not necessarily ideal
    - Outer edges of e-beam do not get the full effect of seeding
    - Sensitivity to beam to beam relative motions

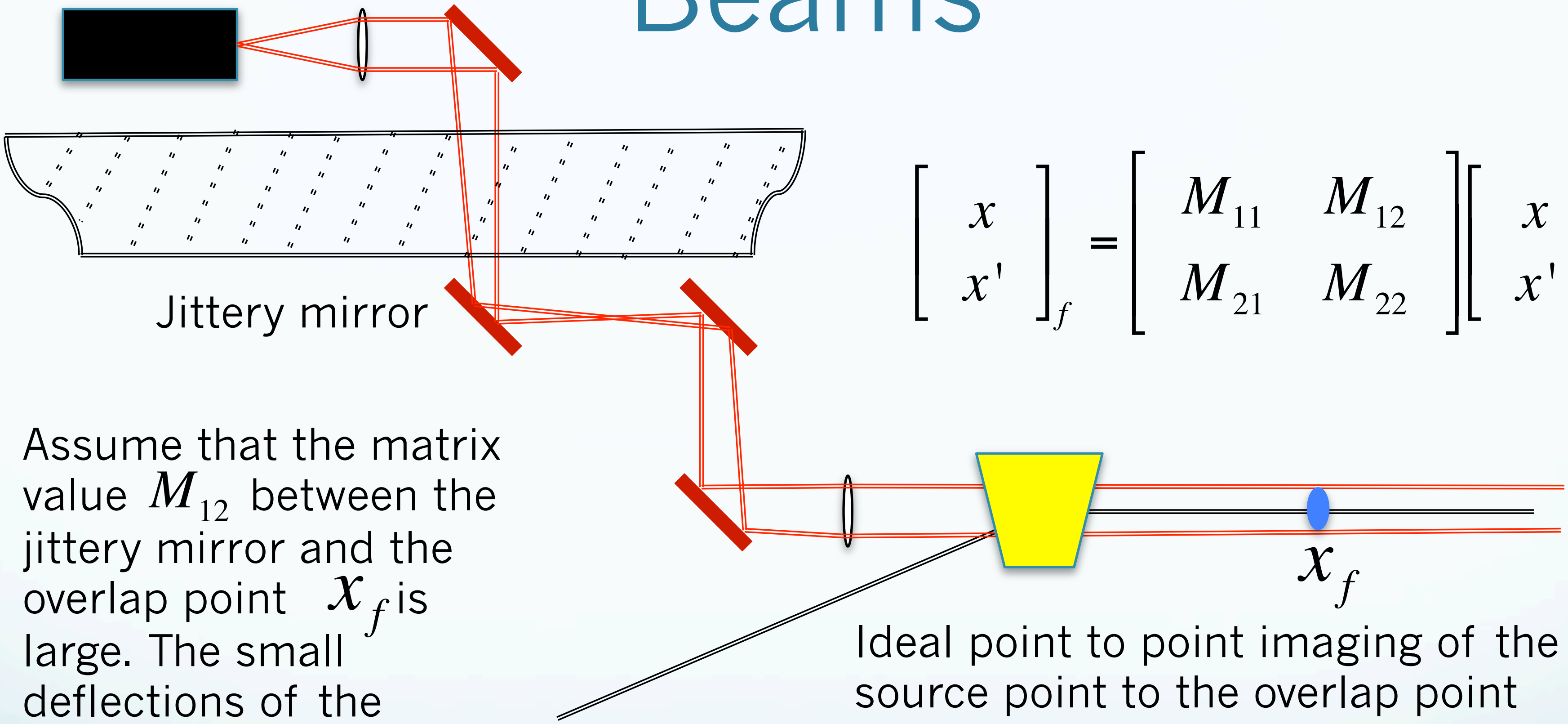


Seed beam size

e-beam transverse size

  - Seed beam larger than the e-beam size
    - Good it not too much larger
      - Too much larger and the power density goes
    - Reduces somewhat the sensitivity to beam to beam relative motion

Transverse Overlap of Beams



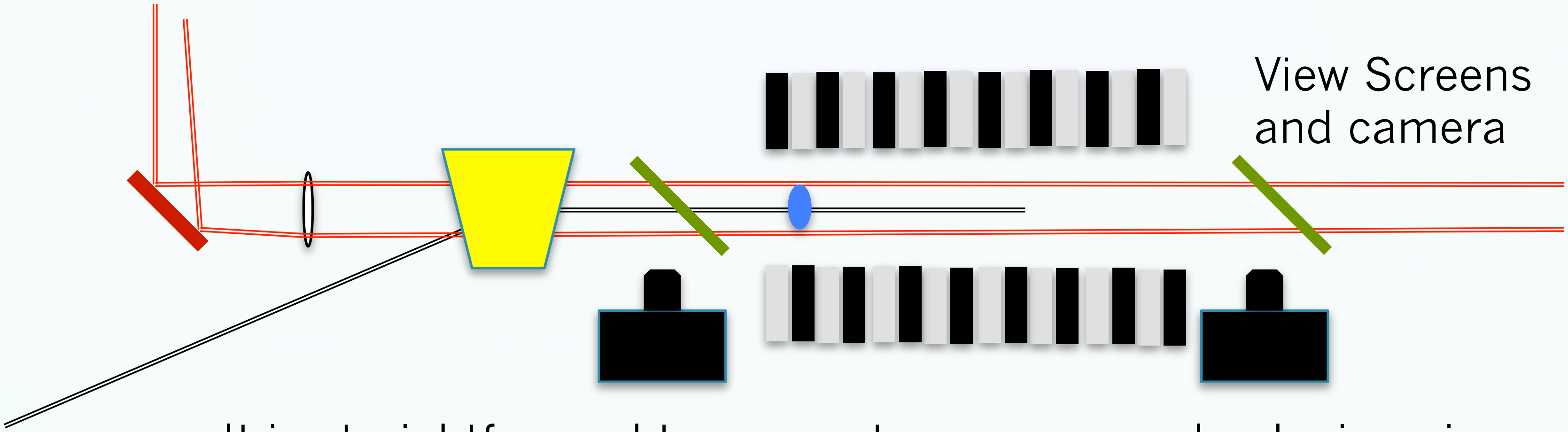
$$\begin{bmatrix} x \\ x' \end{bmatrix}_f = \begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix} \begin{bmatrix} x \\ x' \end{bmatrix}_i$$

Assume that the matrix value M_{12} between the jittery mirror and the overlap point x_f is large. The small deflections of the mirror result in large transverse offsets at the overlap point.

Ideal point to point imaging of the source point to the overlap point would be good as this reduces the problem of the mirror jitter.

One must take care in the design of the optical transport system.

Transverse Overlap of Beams



It is straightforward to ensure transverse overlap by imaging the e-beam and seed beam at two positions on a jointly used imaging system.

One needs to ensure that the system can image both beams within its dynamic range and that one does not do the imaging in a manner that might compromise the undulator with excessive radiation.

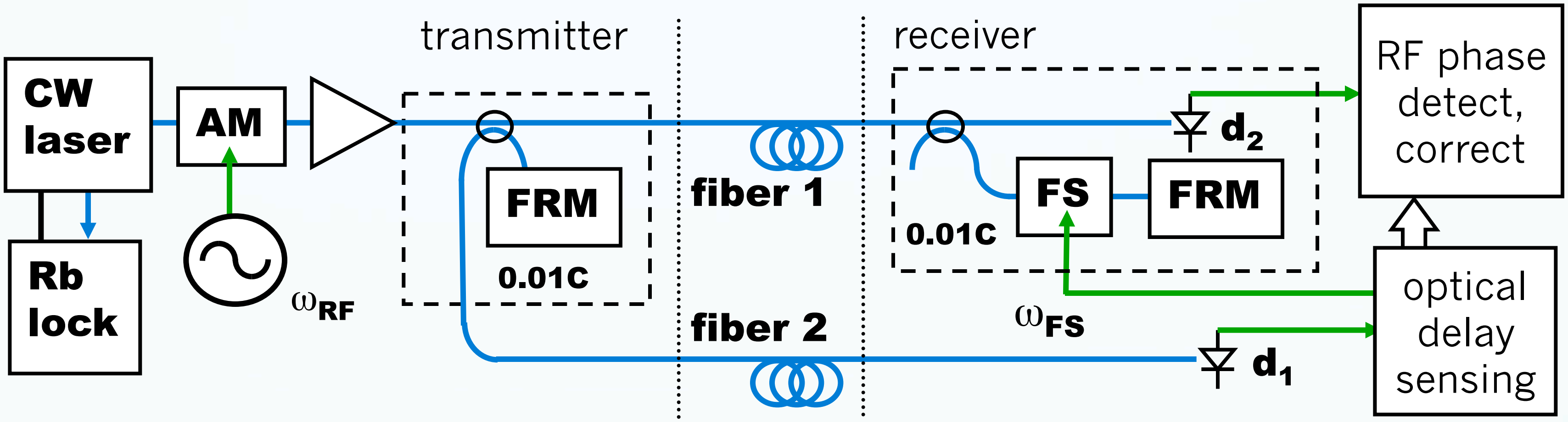
This same system is used for both position and size checks.

Timing and Synchronization

- Many sources of error here
  - Drive laser timing – Timing jitter at the cathode
  - Electron beam energy fluctuations
    - Driven by rf system amplitude and phase fluctuations coupled to pulse compressor delay times
  - Seed signal arrival time
  - Seed and e-beam pulse lengths
  - Even wakefields coupled to peak current fluctuations coming from compressor errors and can cause problems.
  - Et cetera

Summary: If you knew any better you would not even attempt this.

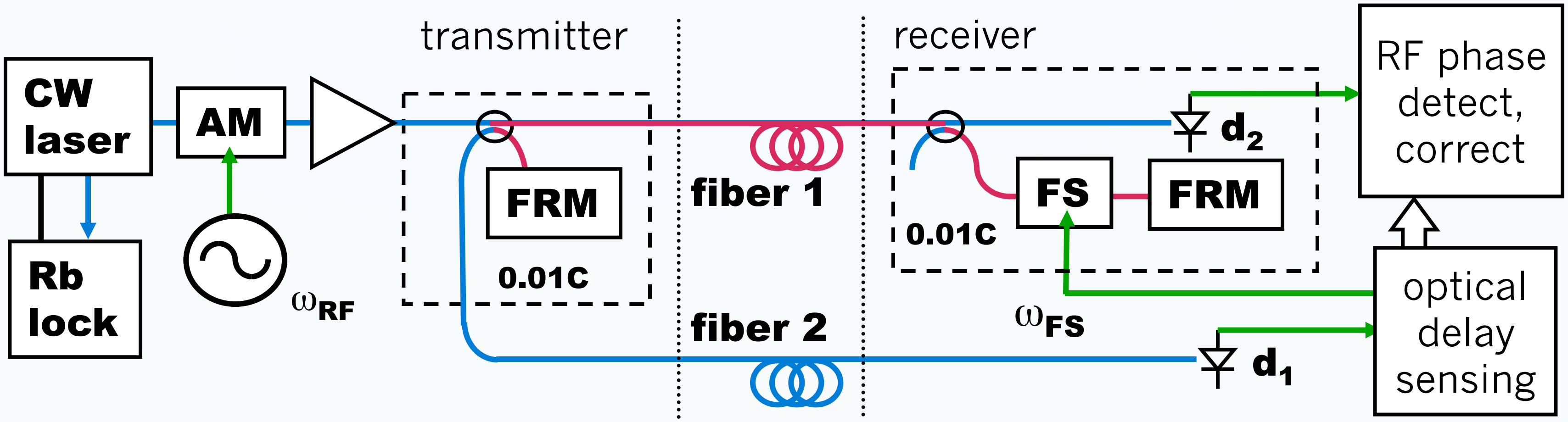
Schematic of one link



- FRM is Faraday rotator mirror (ends of the Michelson interferometer)
- FS is optical frequency shifter
- CW laser is absolutely stabilized
- Transmitted RF frequency is 2856 MHz
- Detection of fringes is at receiver
- Signal paths not actively stabilized are temperature controlled

Courtesy R. Wilcox and J. Byrd

Schematic of one link



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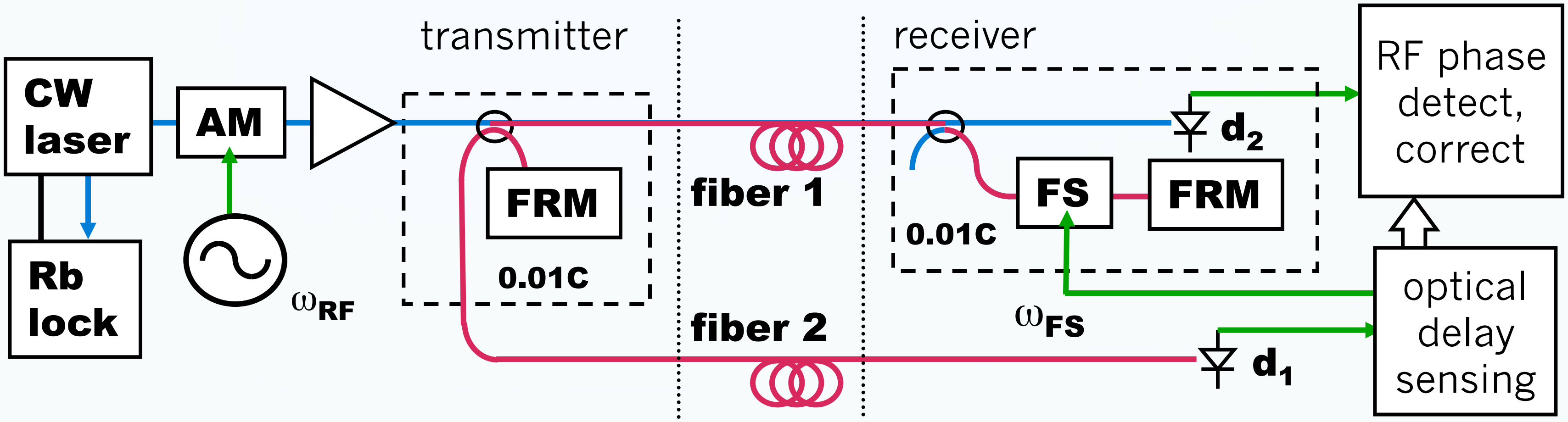

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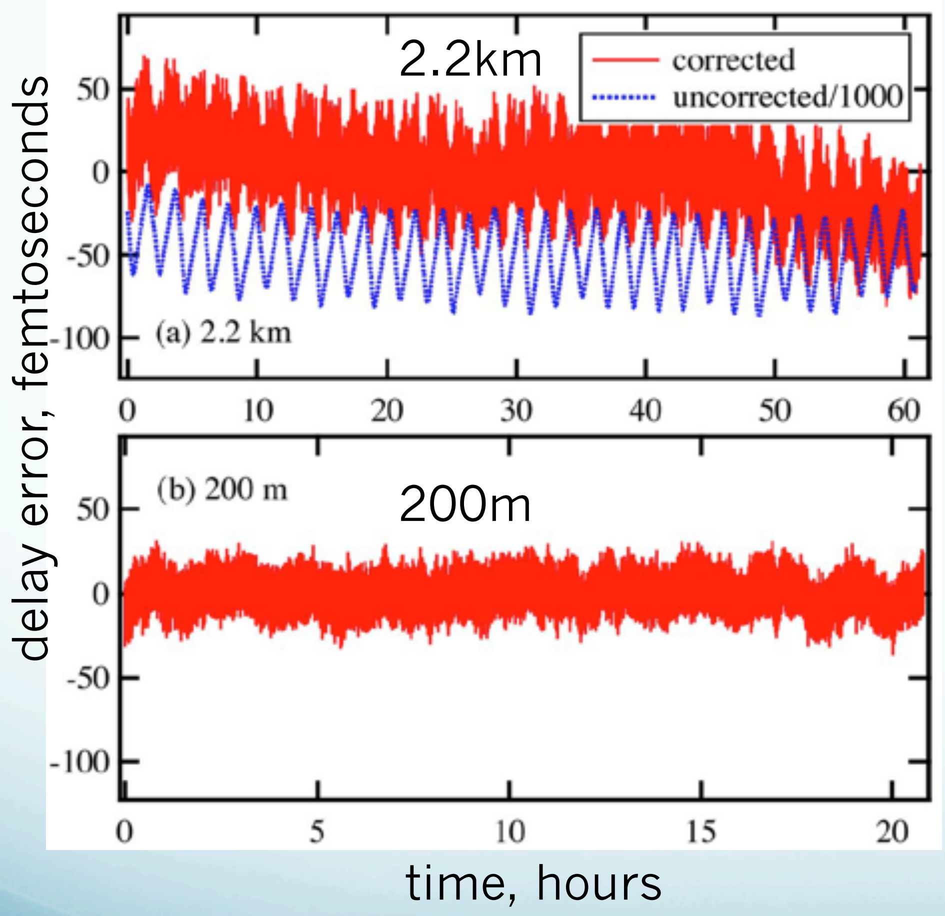
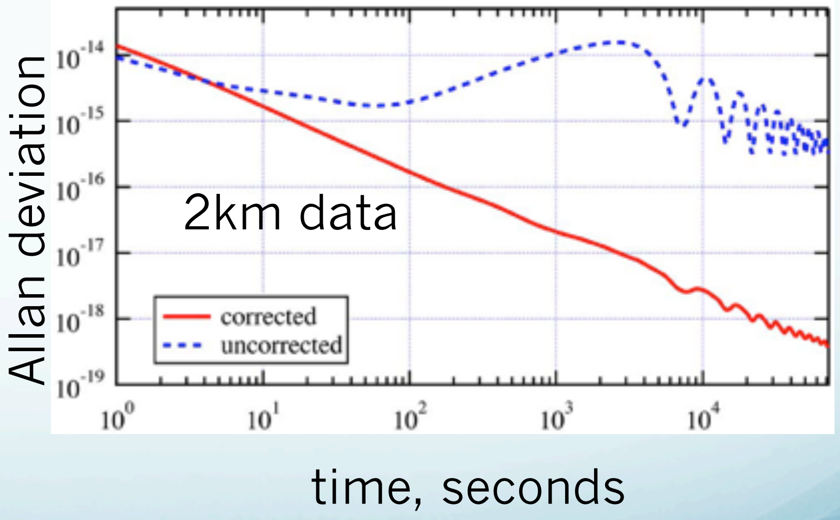
Courtesy R. Wilcox and J. Byrd

Dual-channel results

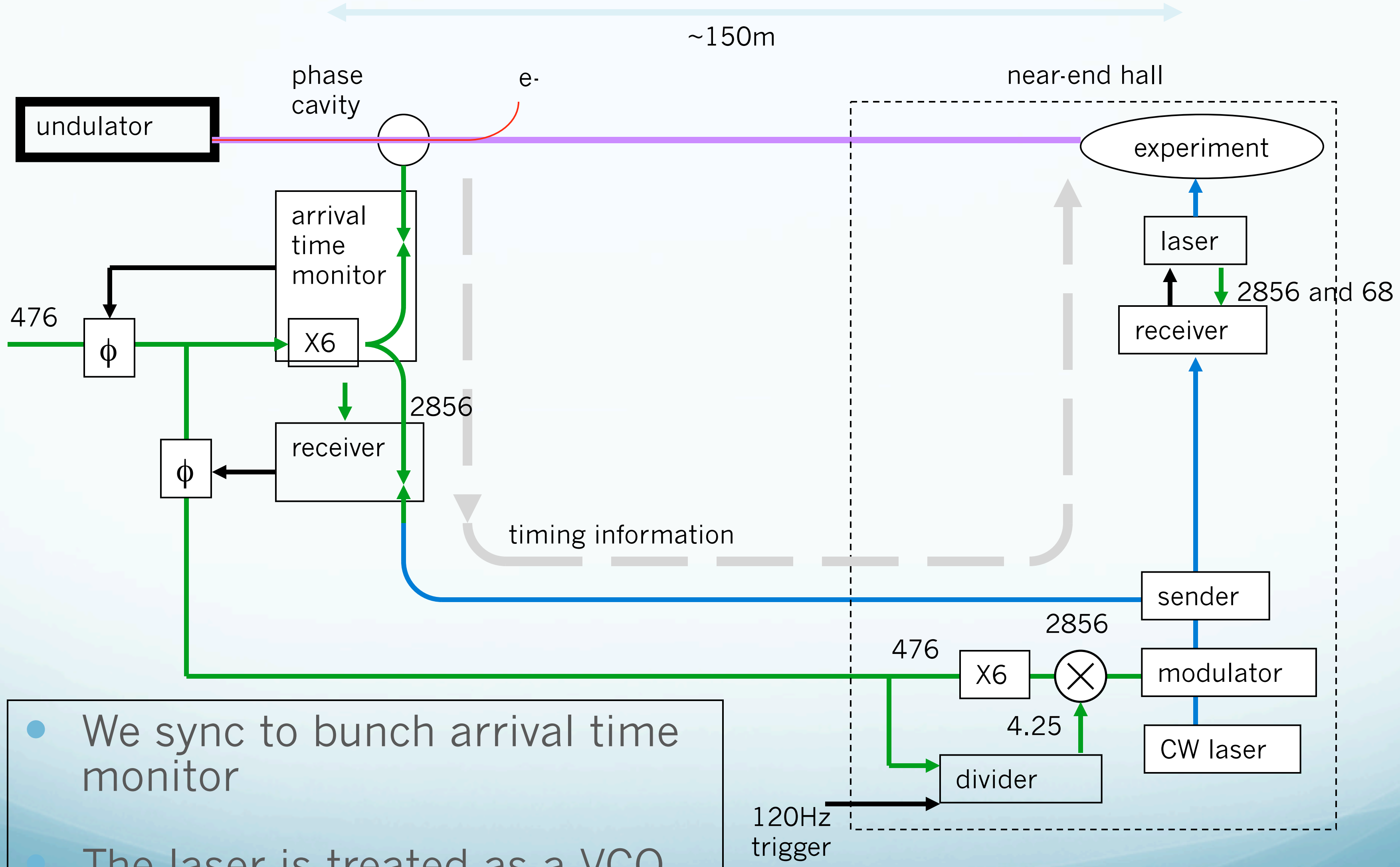


- 1kHz bandwidth
- For 2.2km, 19fs RMS over 60 hours
- For 200m, 8.4fs RMS over 20 hours
- 2-hour variation is room temperature



Courtesy R. Wilcox and J. Byrd

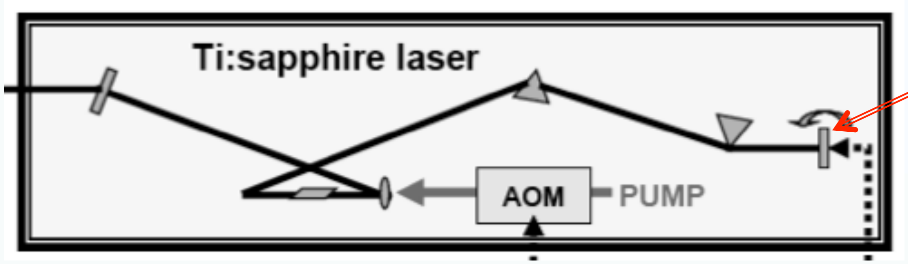
LCLS timing scheme



- We sync to bunch arrival time monitor
- The laser is treated as a VCO

Courtesy R. Wilcox and J. Byrd

Other Errors



Assume this mirror vibrates back and forth at, say, 10 Hz and with an amplitude of say 10 nm. Also assume that the cavity pulse frequency is 100 MHz.

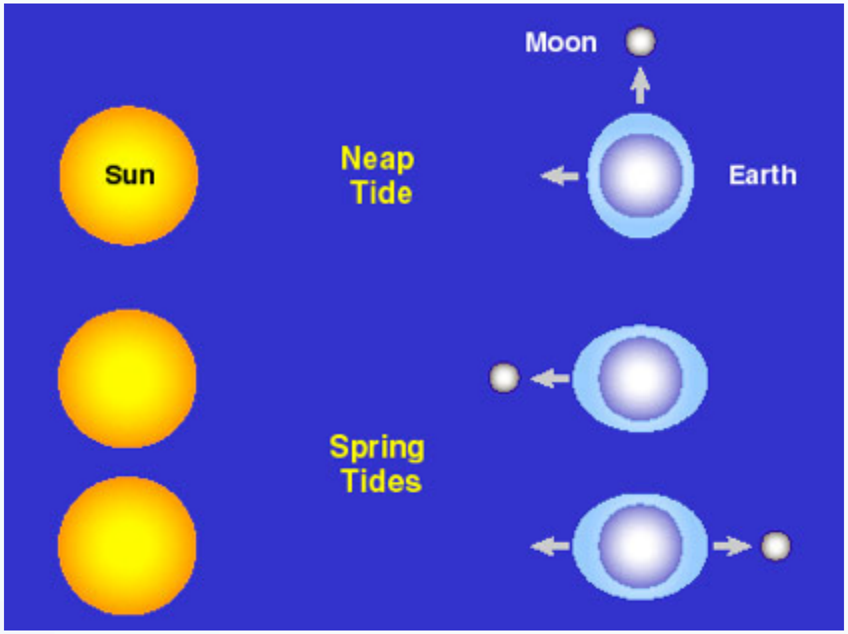
10 nm in time at the speed of light is equal to (300 nm = 1 fs), 33 as.

But at 100 MHz this small timing error accumulates.

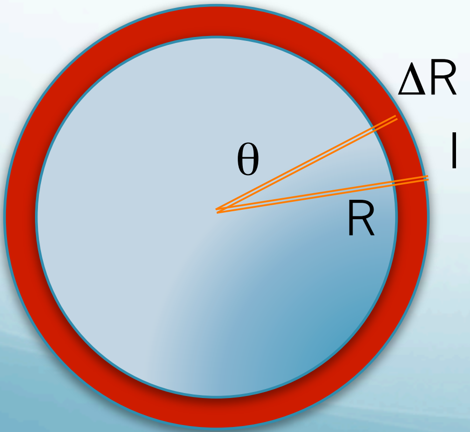
$$\Delta t_{error} = \frac{1}{10\,\mathrm{Hz}} 100\,\mathrm{Mhz} \times 33\,\mathrm{as} = 330\,\mathrm{fs}$$

So even if I have perfect synchronization between various systems a small vibration of the seed or cathode drive laser could ruin everything.

Other Errors



The Earth is constantly subjected to tidal forces. You may not know it, but the land bulges outward at 30 cm every 12 hours.



$$l = R\theta \longrightarrow \Delta l = l\frac{\Delta R}{R}$$

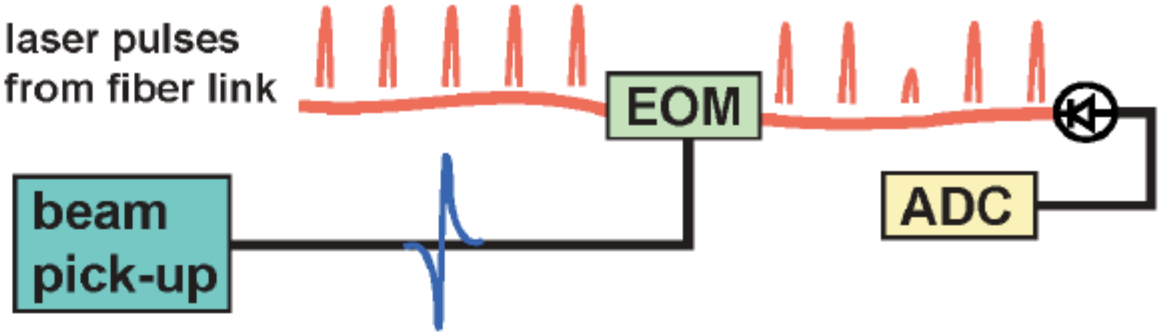
$R \approx 6.4 \times 10^6\,\mathrm{m}$ Radius of Earth

$l \approx 2.2\,\mathrm{km}$ Approx. length of the LCLS

With these $\Delta l = 100\,\mu\mathrm{m}$

or $\Delta t = 330\,\mathrm{fs}$!!

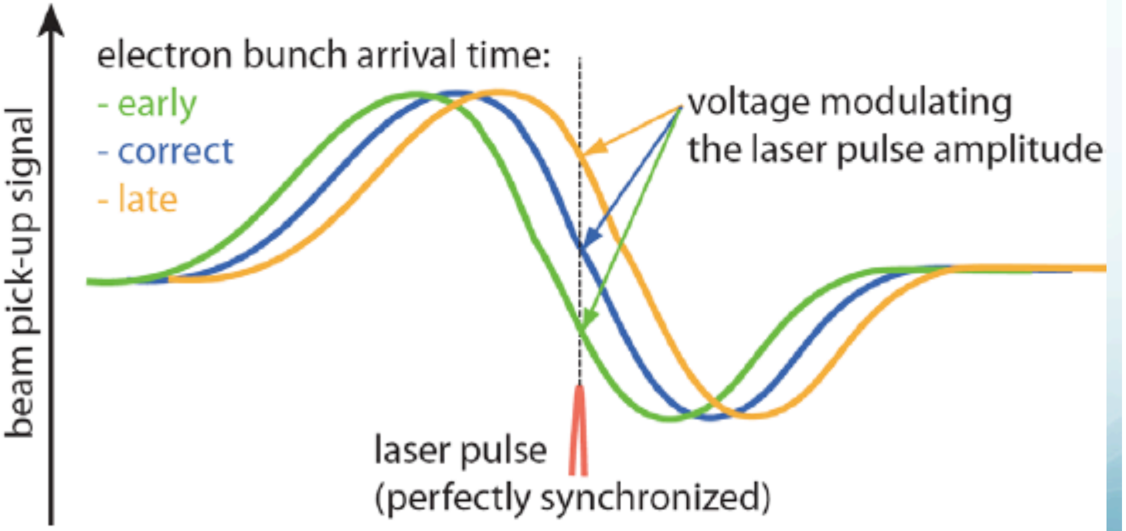
Example: Beam Arrival Time Monitor using MLL pulses



A laser pulse samples the zero-crossing of a beam induced pick-up signal.

Variations of the bunch arrival-time result in a modulation of the laser pulse energies.

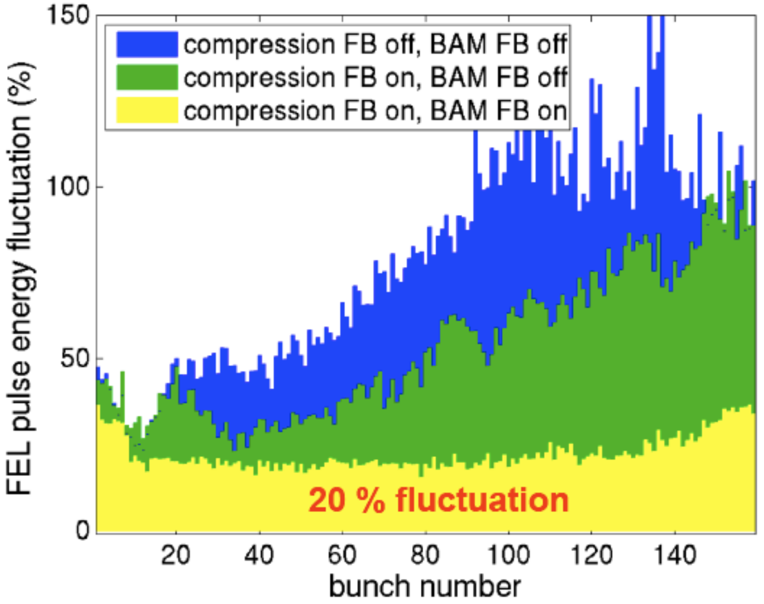
By measuring the energies of single laser pulses, the bunch arrival time can be deduced.

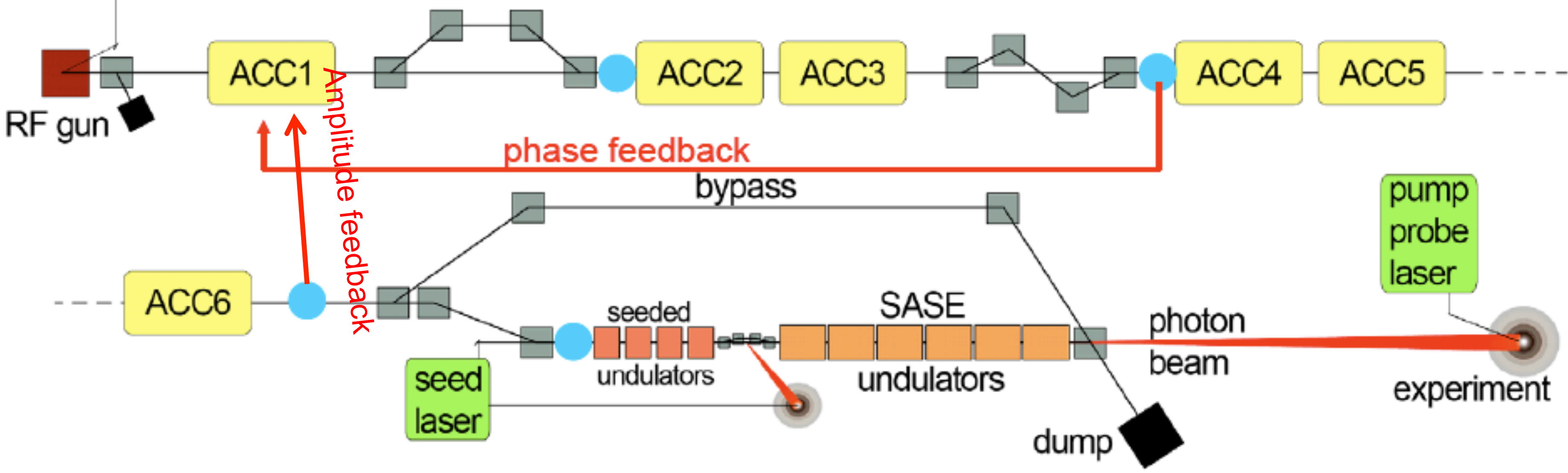


- Florian Loehl, et al., PRL 104, 144801 (2010)

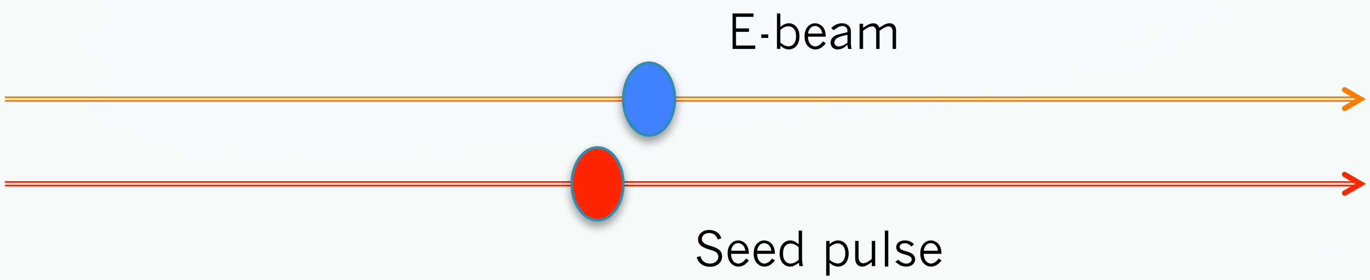
Use arrival time and bunch length to stabilize FEL output

- Coherent THz signal used as relative bunch length monitor
- BAM used for time (energy) jitter





Overlapping in time



E-beam

Seed pulse

Most people use a BAM and fast photodiode to get close and then just scan. It is real painful work.

This is one of the things that make self-seeding so much more attractive.

Energy Errors

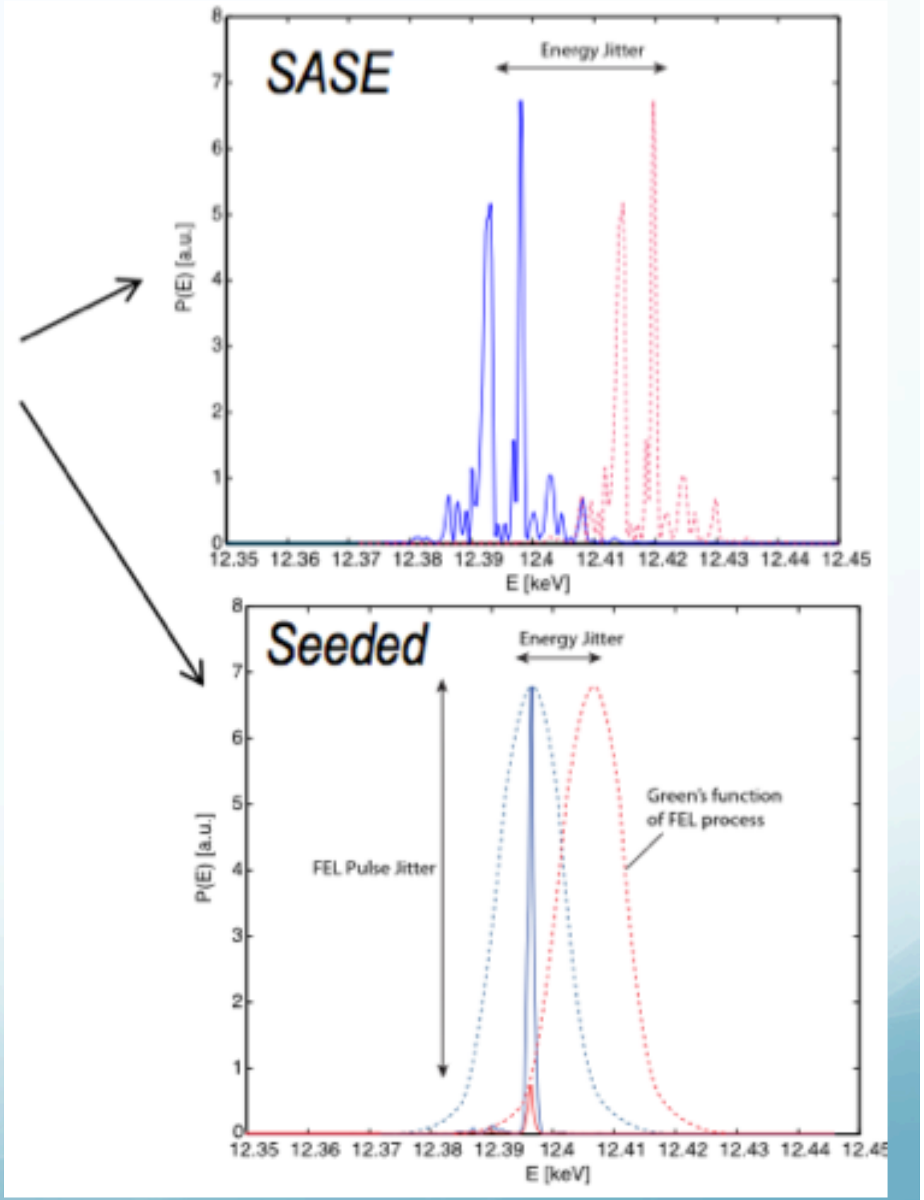
One needs to get the relationship

$$\lambda = \frac{\lambda_u}{2\gamma^2}\left[1 + {K^2}\big/{2}\right]$$

To well within the gain bandwidth of the FEL for the seeding to be stable and work well.

This is readily done by either changing the laser wavelength (OPAs can do this) or by changing slightly the beam energy.

Energy
Offsets
(Errors)



Summary

- Seeding FELs is a hot topic
  - One one hand we are still way behind our atomic colleagues, or the other we are doing things they have never had to do before.
- There are many methods that people have developed to seed FELs
  - Some have been tried while many others are waiting their turn
  - I picked only a representative few examples
- Even with a good seed there are many technological challenges in order to use it.

Thanks

- Many thanks go to a number of people that have helped my gather all these slides. In particular I want to thank both Sandra Biedron and Sven Reiche, who I have drawn from heavily.