Beyond 3rd Generation: Overview

NSF Workshop on Light Source Facilities
Lawrence Livermore National Laboratory
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S. Krinsky
BNL

Fourth Generation Sources

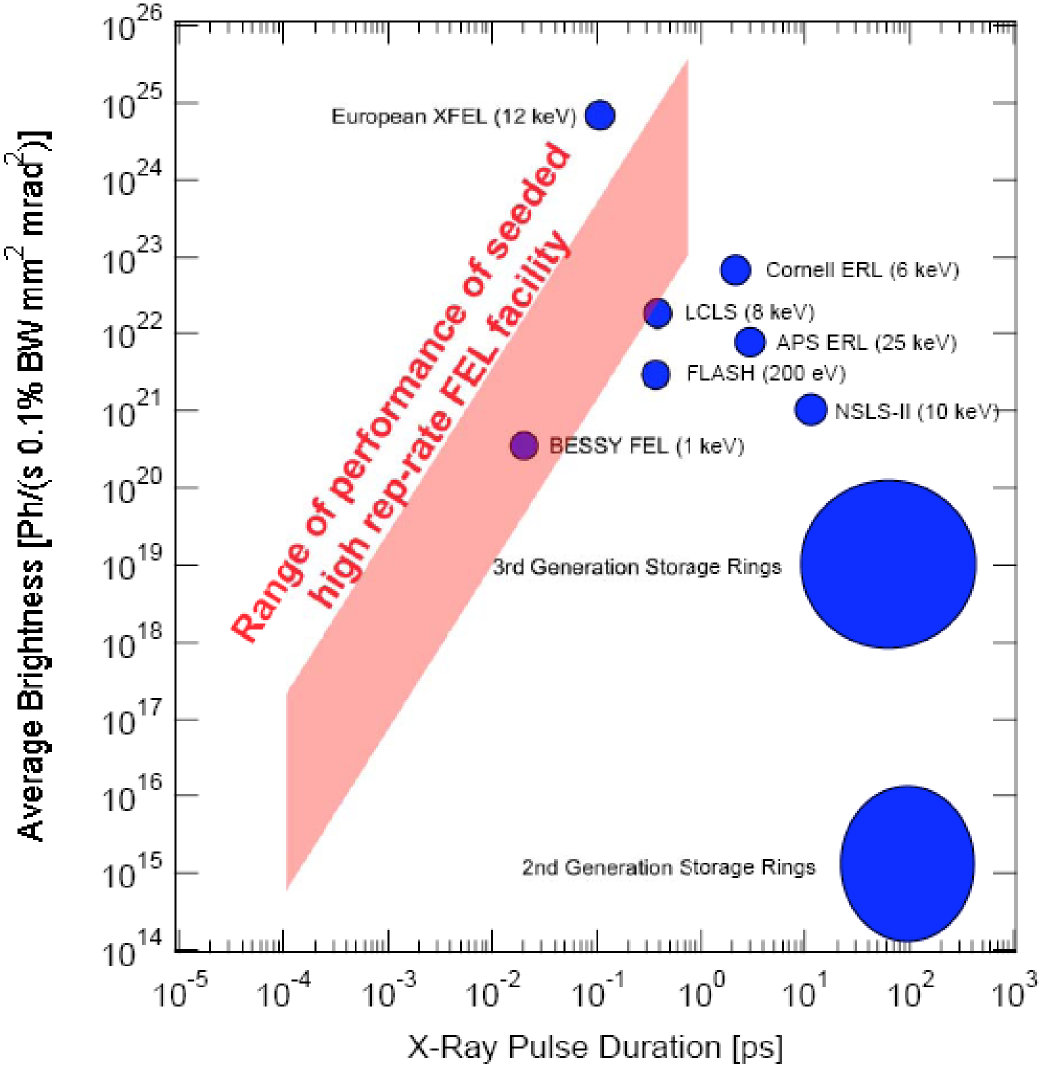
Continuous Sources

- Storage Ring
- Energy Recovery Linac

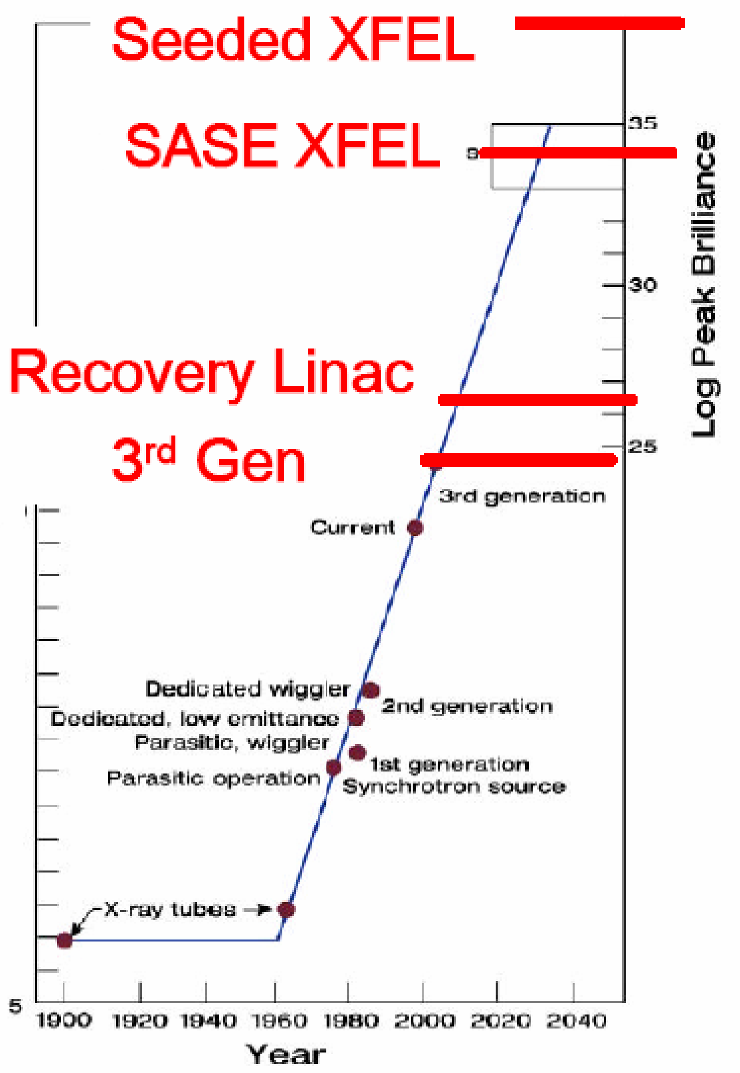
Pulsed Sources

- Self-Amplified Spontaneous Emission
- Seeded Free-Electron Laser

Light Source Development



Courtesy J. Corlett



Courtesy D. Moncton

Fourth Generation Storage Ring

Horizontal emittance determined by equilibrium between radiation damping and quantum fluctuation: $\varepsilon_H \sim \gamma^2 / M_{Cell}^3$

Small emittance (~30pm)→ large circumference (>2km) and small dispersion → strong chromaticity sextupoles → Limited dynamic aperture & energy acceptance→ short lifetime & difficult injection

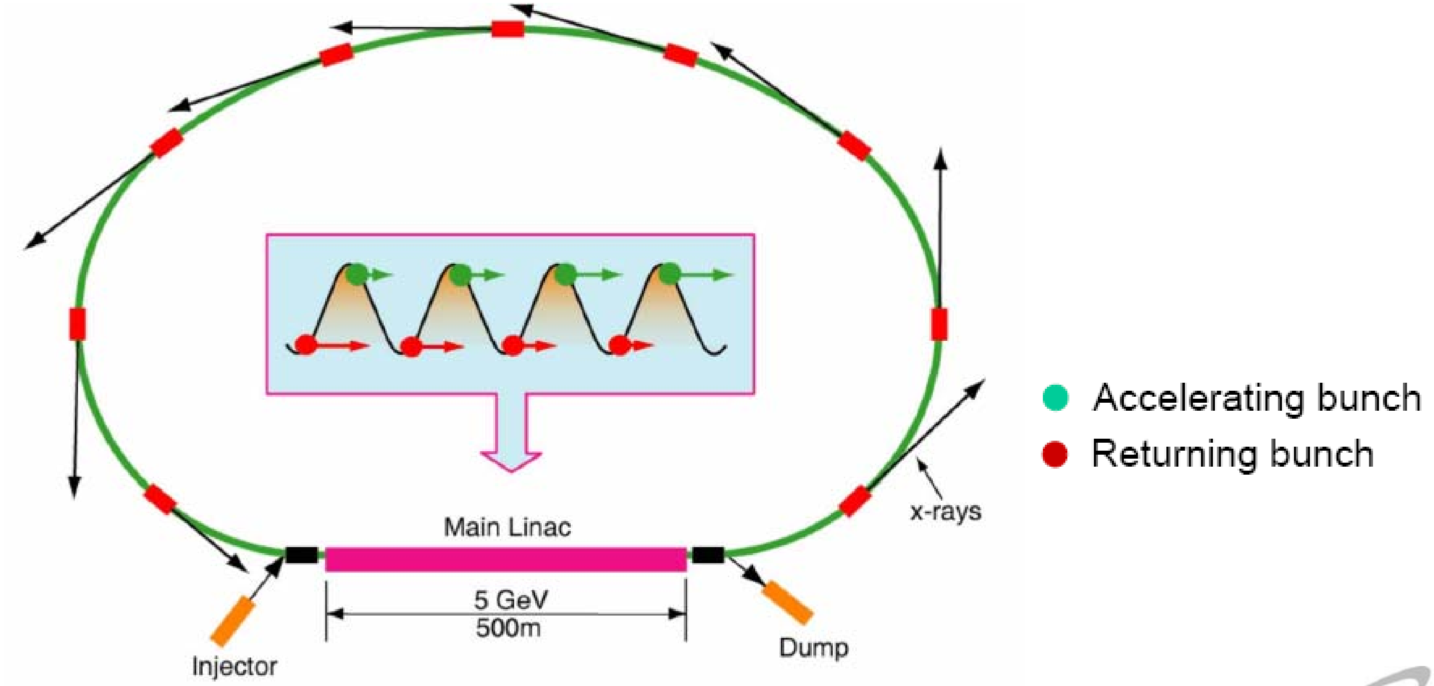
One possibility is to have an accumulator ring and the storage ring and transfer the beam periodically (few minutes) via on-axis injection

Energy Recovery Linac

Superconducting linac: after use the electron beam is re-circulated through the linac at decelerating phase returning energy to the RF cavities

Emittance is determined by the normalized emittance of the electron source

$$\varepsilon = \varepsilon_n / \gamma$$



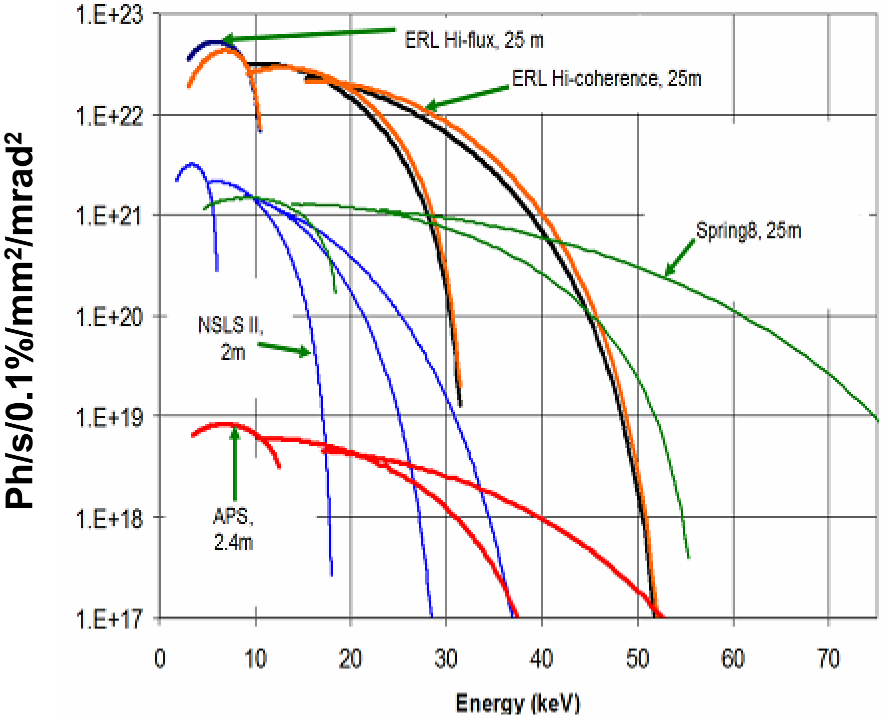
Cornell Energy Recovery Linac (ERL)

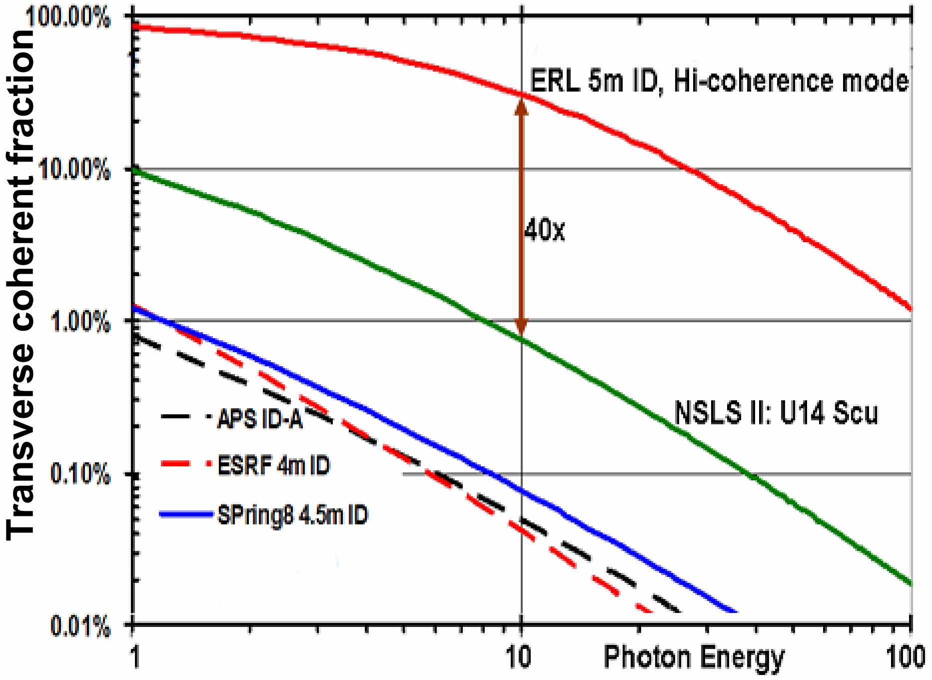
Modes	Hi-flux	Hi-Coherence
Energy (GeV)	5	5
Current (mA)	100	25
Bunch Charge (pC)	77	19
Repetition Rate (MHz)	1300	1300
Geom. Emittance, both Horiz. & Vert. (pm)	30	8
RMS Bunch Length (fs)	2000	2000
Relative electron energy spread (x10-3)	0.2	0.2

- ERL hi-brightness mode for coherence applications
- A few micron diameter electron source size – good for intense, possibly one nm diameter, hard x-ray beams.
- Bunch compression allows pulses < 50fs.

Courtesy S. Gruner

Cornell Energy Recovery Linac (ERL)

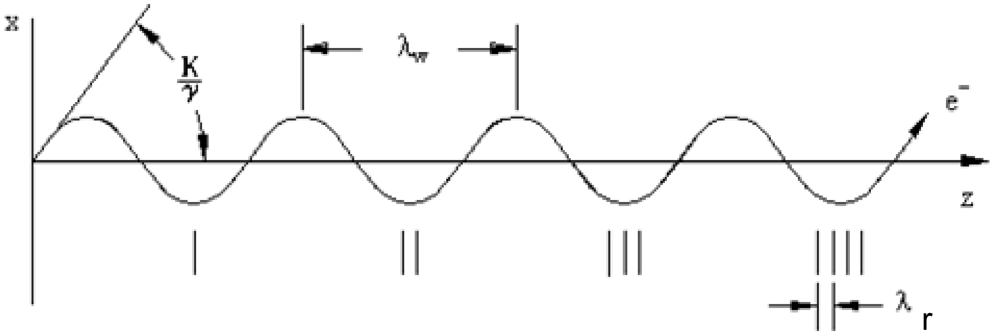




Key technical challenges

- development of low emittance, high average current electron source
- transport of the electron beam while maintaining the small emittance
- achieve level of stability now routine in storage rings

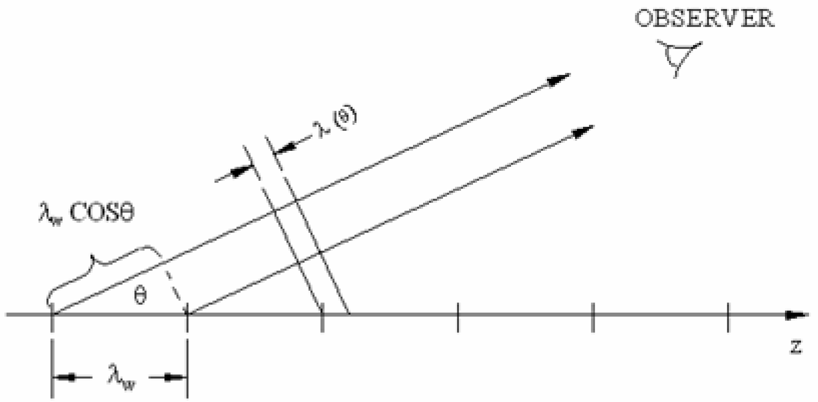
Undulator Radiation



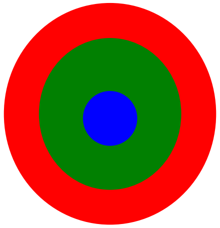
$$\lambda_r = \frac{\lambda_w}{2\gamma^2}\left(1+\frac{K^2}{2}\right)$$

$$\frac{\Delta\lambda}{\lambda_r} = \frac{1}{N_w}$$

$$\ell_{coh} = \lambda^{2.} / \Delta\lambda = N_w \lambda$$



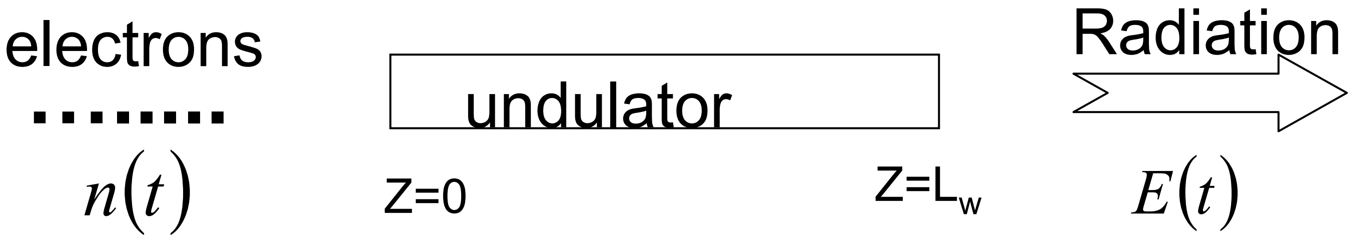
$$\lambda_r(\theta) = \frac{\lambda_w}{2\gamma^2}\left(1+\frac{K^2}{2}+\gamma^2\theta^2\right)$$



$$\frac{\Delta\lambda}{\lambda_r} = \frac{\gamma_0^2\theta_w^{\ 2}}{1+K^2/2} = \frac{1}{2N_w}$$

$$\theta_w = \sqrt{\frac{\lambda_r}{L_w}}$$

Coherent Emission



electrons

$n(t)$

undulator

Z=0

Z=L_w

Radiation

$E(t)$

t_j : arrival time of j^th electron at z=0

$$\tilde{E}(\omega) = \tilde{E}_1(\omega)\sum_{j=1}^{N_e} e^{i\omega t_j}$$

$$I(\omega) \cong I_1(\omega)\left[N_e + N_e\left(N_e - 1\right)\left|\int dt\, n(t)\, e^{i\omega t}\right|^2\right]$$

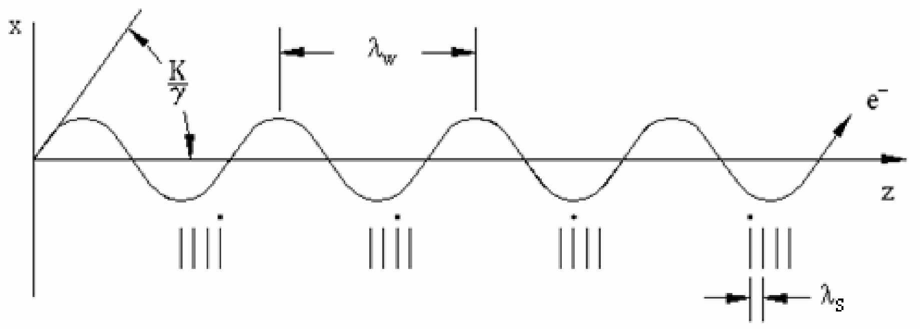
Incoherent emission

Coherent emission

Coherent emission is important when electrons are bunched on scale of the radiation wavelength

Energy Modulation of Electron Beam

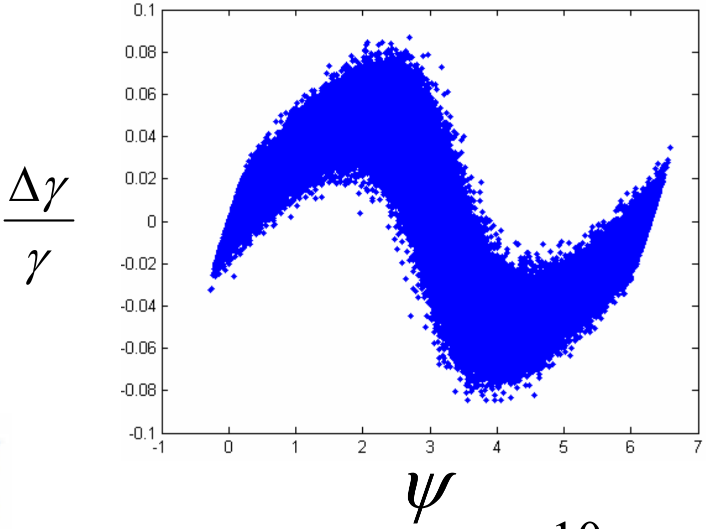
At resonance, while traversing one period of the undulator, the electron falls one radiation wavelength behind the EM-wave



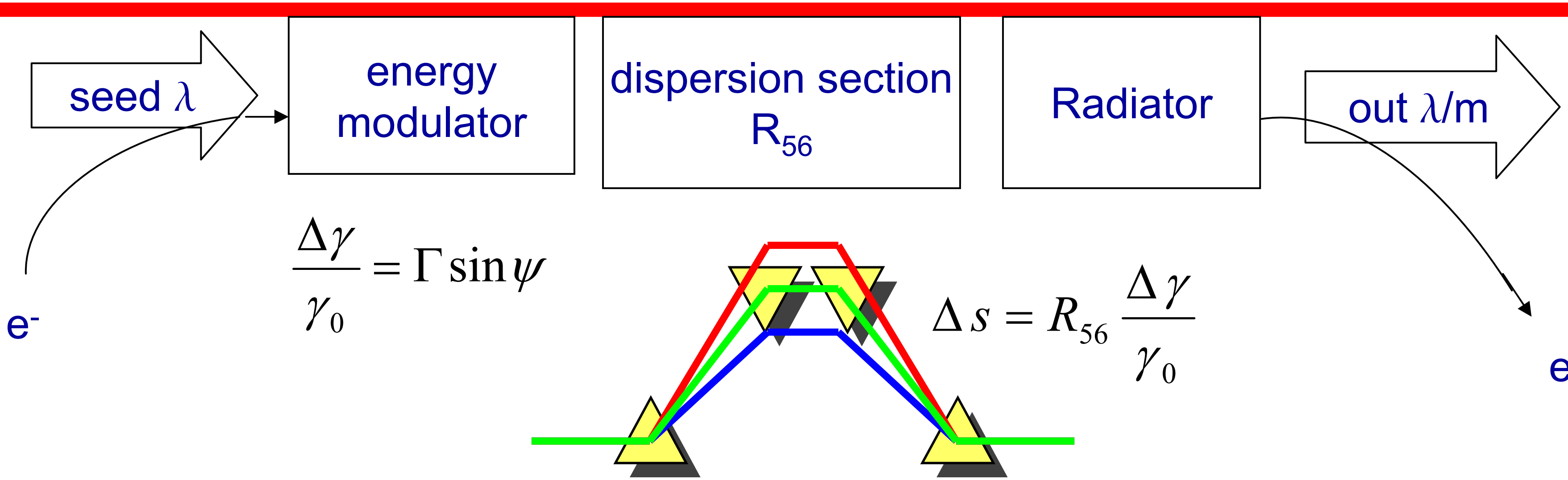
$$\frac{1+K^2/2}{2\gamma_r^2}\lambda_w = \lambda_s$$

$$\Delta\gamma = \Gamma \sin\psi$$

ψ =Phase of electron relative to EM-wave

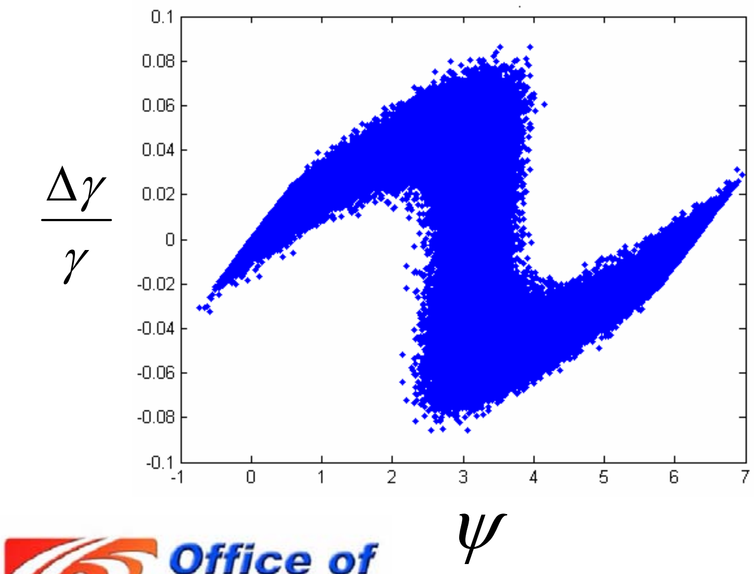


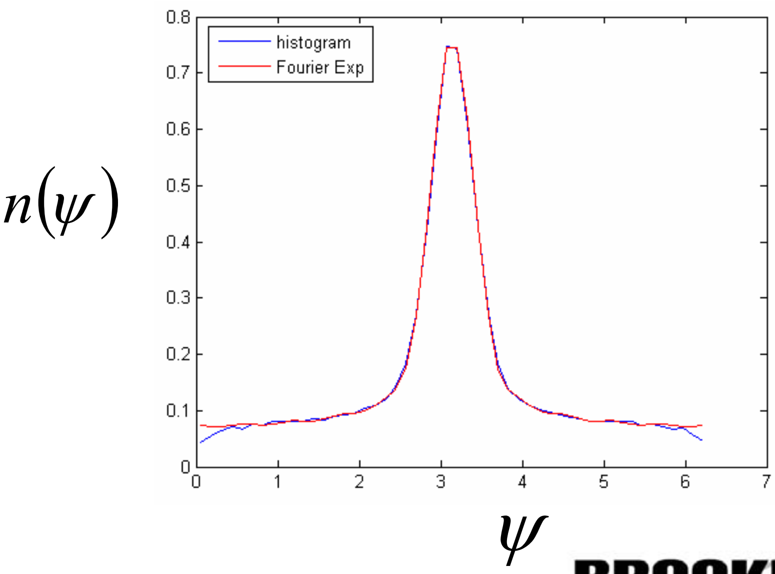
Optical Klystron



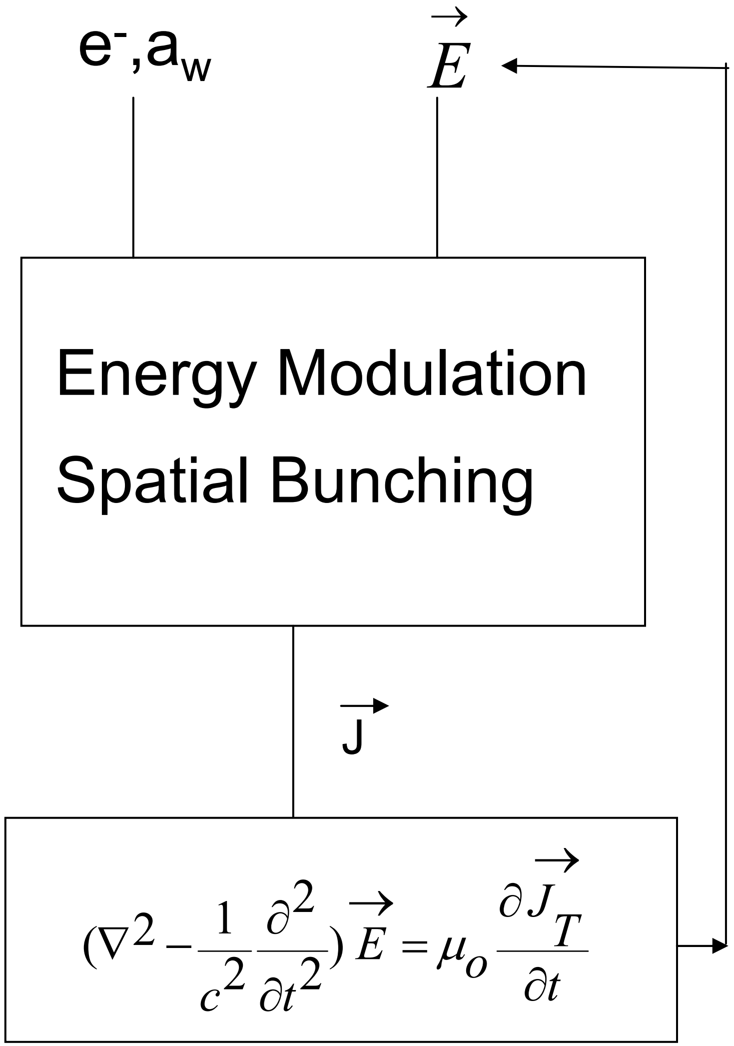
$$\frac{\Delta\gamma}{\gamma_0} = \Gamma \sin\psi$$

$$\Delta s = R_{56}\frac{\Delta\gamma}{\gamma_0}$$





FEL Amplifier



e^-, a_w

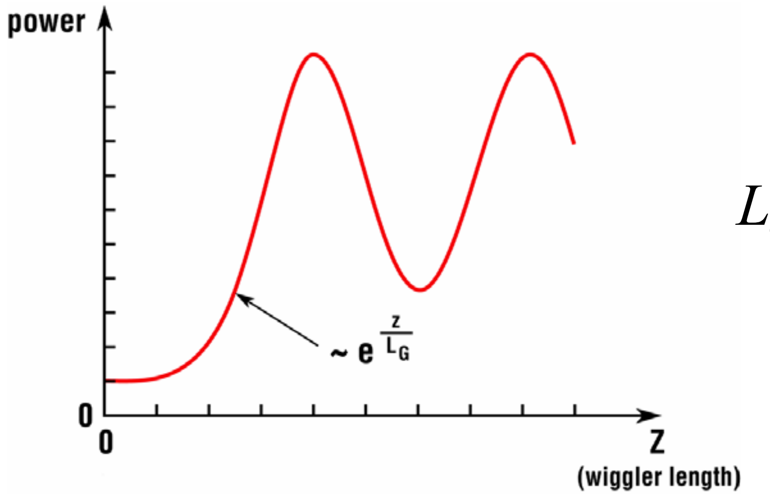
$\vec{E}$

Energy Modulation

Spatial Bunching

$\vec{J}$

$$\left(\nabla^2 - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\right)\vec{E} = \mu_o \frac{\partial \vec{J}_T}{\partial t}$$



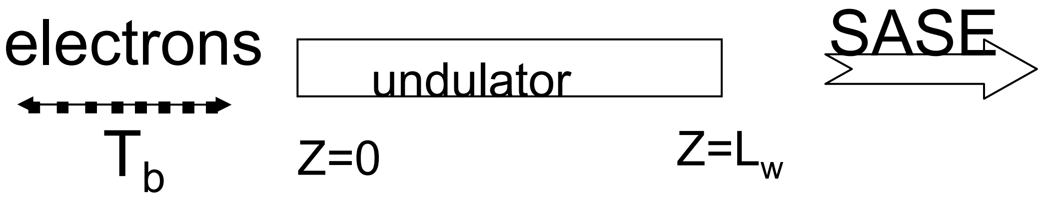
$$L_G \cong \frac{\lambda_w}{4\pi\,\rho}$$

$$(2\rho)^3 = \frac{\lambda\,\lambda_w}{\pi\ Area\ \gamma}\ \frac{(K^2/2)[JJ]^2}{1+K^2/2}\ \frac{I_e}{I_A}$$

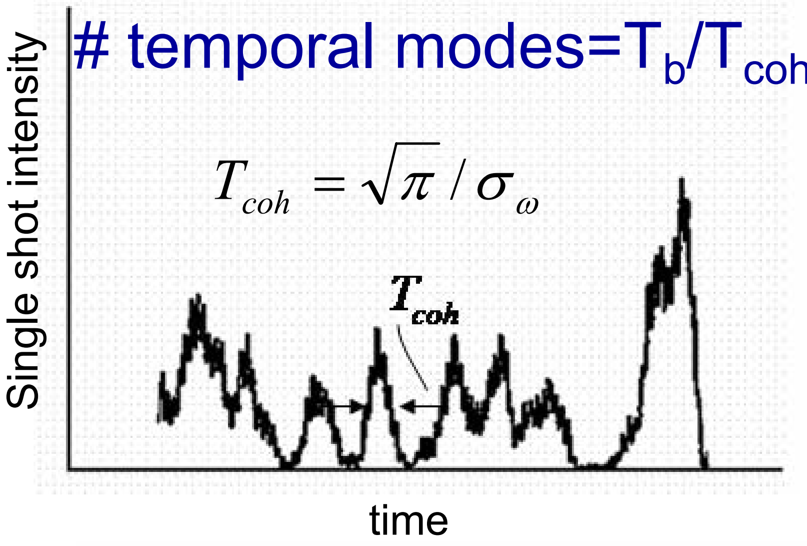
$$\frac{\sigma_\gamma}{\gamma} < \rho \qquad \varepsilon = \frac{\varepsilon_n}{\gamma} \sim \frac{\lambda}{4\pi}$$

$$P_{sat}(GW) \cong \rho\, I_e(Amp)\, E(GeV)$$

SASE: Single Transverse Mode, Many Longitudinal Modes

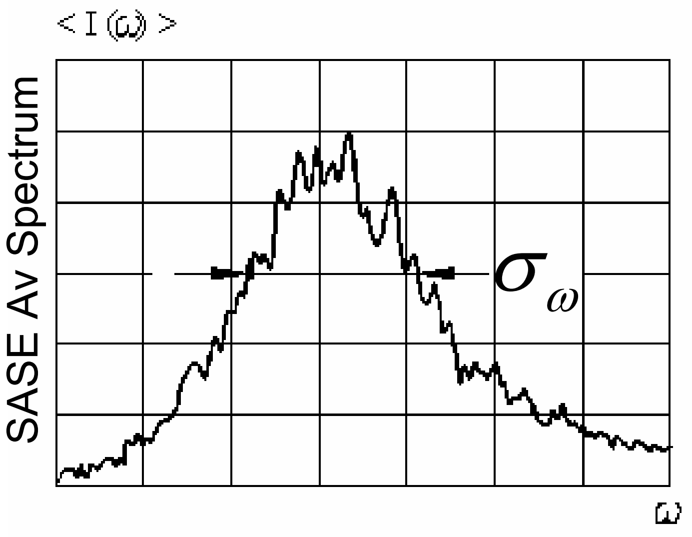


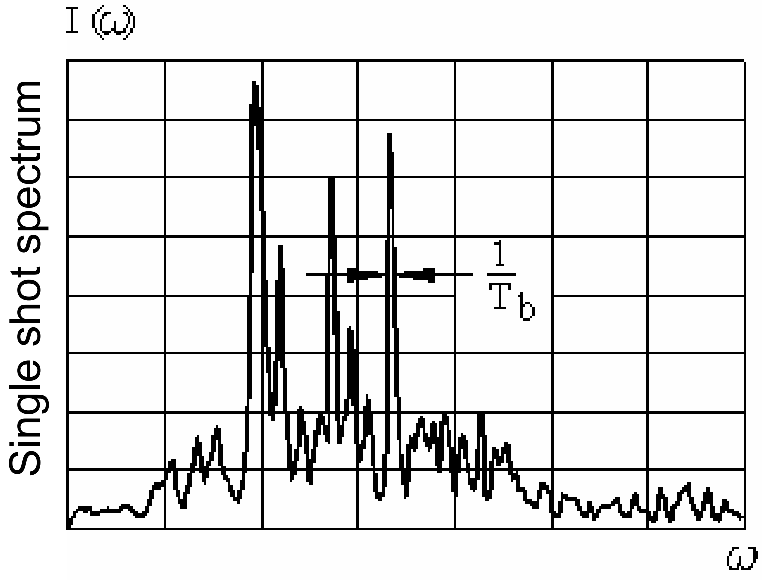
$$\frac{dP_{av}}{d\omega} \cong \left[\left(\frac{dP}{d\omega} \right)^{seed} + \left(\frac{dP}{d\omega} \right)^{Noise} \right] \frac{1}{9} e^{-\frac{(\omega-\omega_r)^2}{2\sigma_\omega^2}} e^{\frac{z}{L_G}}$$



\# temporal modes=T_b/T_{coh}

$$T_{coh} = \sqrt{\pi} / \sigma_\omega$$

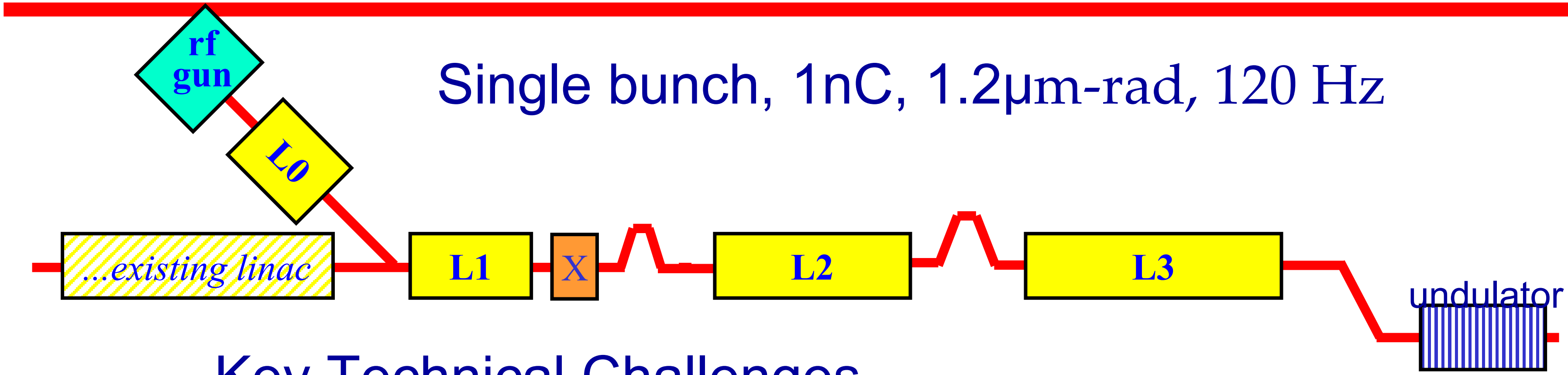




Difficulty increases as output wavelength decreases

	100 nm	0.15 nm (LCLS)	0.1 nm(XFEL)
Energy (GeV)	.3	14	20
Peak Current (Amp)	500	3400	5000
N. Emittance (mm-mrad)	3	1.2	1.4
Energy Spread (%)	.05	.01	.005
Undulator Length (m)	15	120	170
Pierce Parameter	2×10^{-3}	5×10^{-4}	

LCLS



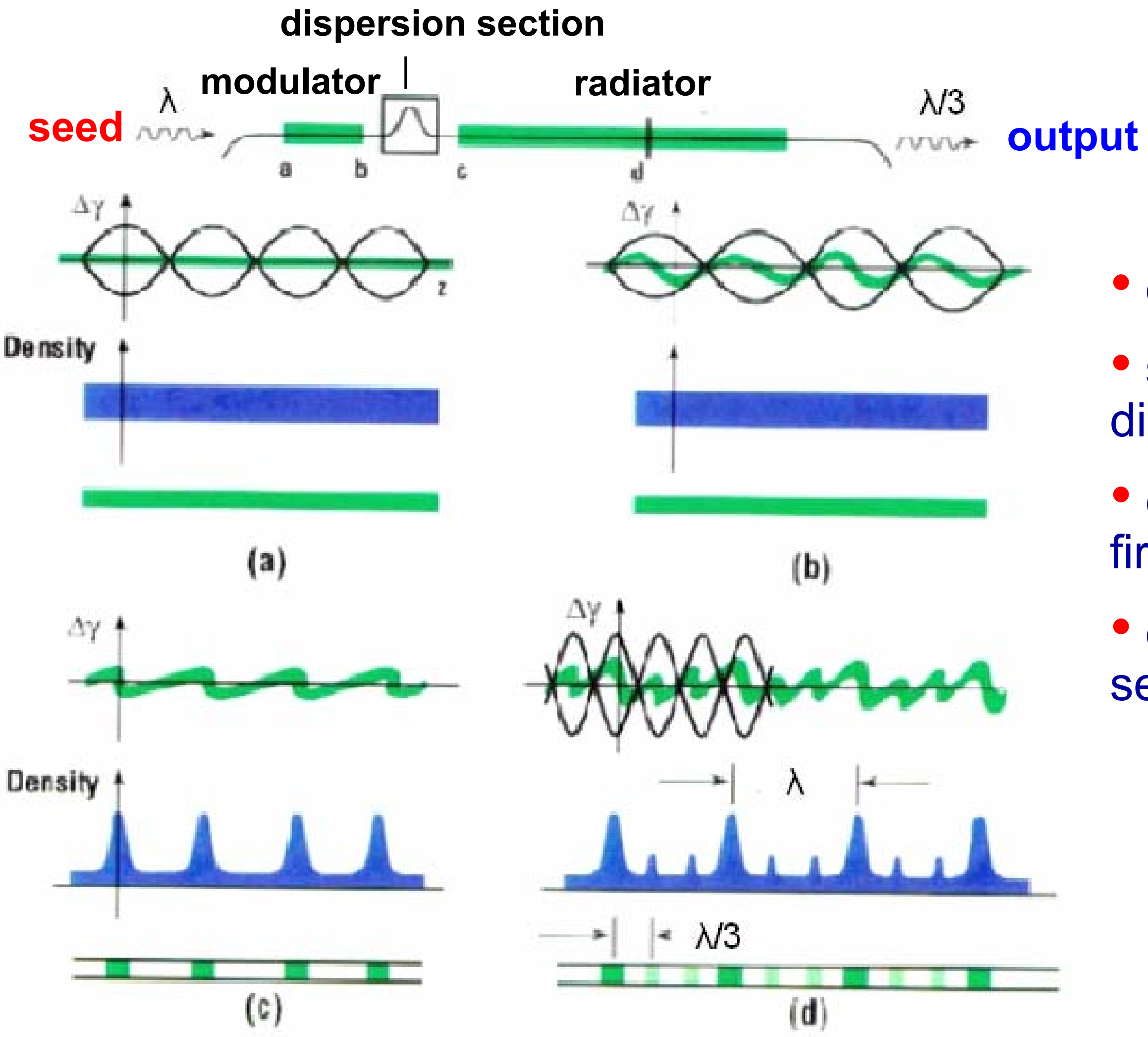
Single bunch, 1nC, 1.2μm-rad, 120 Hz

Key Technical Challenges

- Photo-injector (project has achieved excellent results)
- Bunch compression and transport through maintaining e-beam brightness
- Controlling wakefield effects
- Trajectory through long undulator
- Production of fs pulses

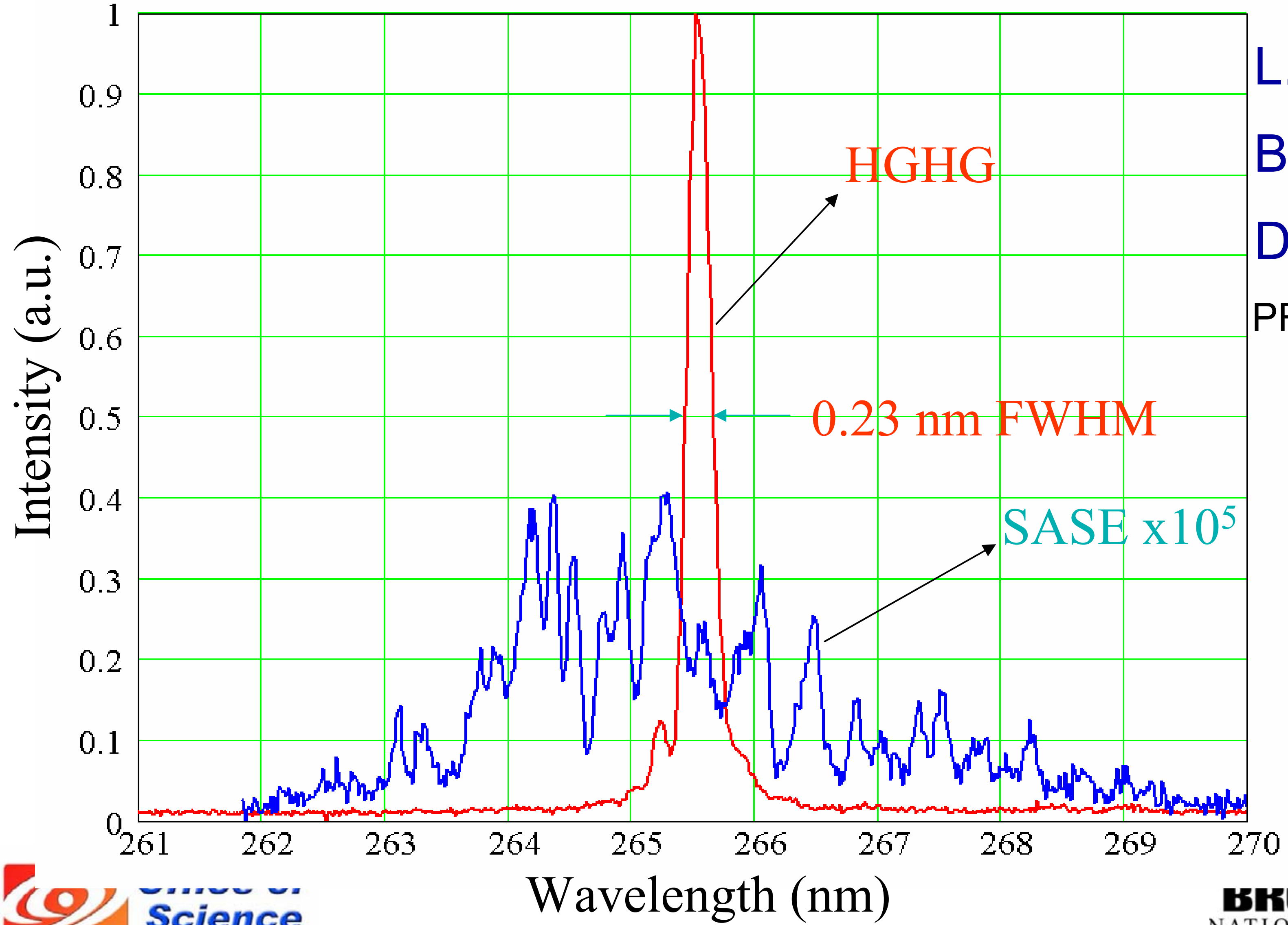
High-Gain Harmonic Generation (HGHG)

Using seed one can achieve full temporal coherence



- energy modulation
- spatial bunching in dispersion section
- coherent emission in first part of radiator
- exponential gain in second part of radiator

Spectrum of HGHG (800nm→266nm) and unsaturated SASE under the same electron beam condition



L.H. Yu et al

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DUV-FEL

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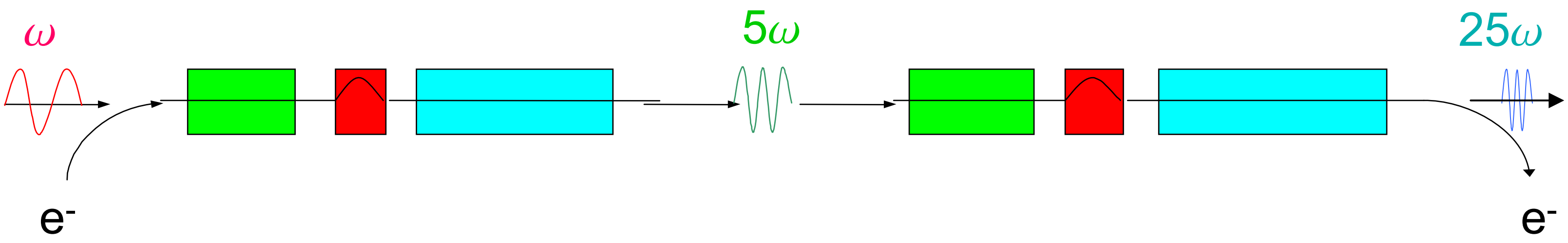
Cascaded HGHG

Use output of one HGHG stage as input to next

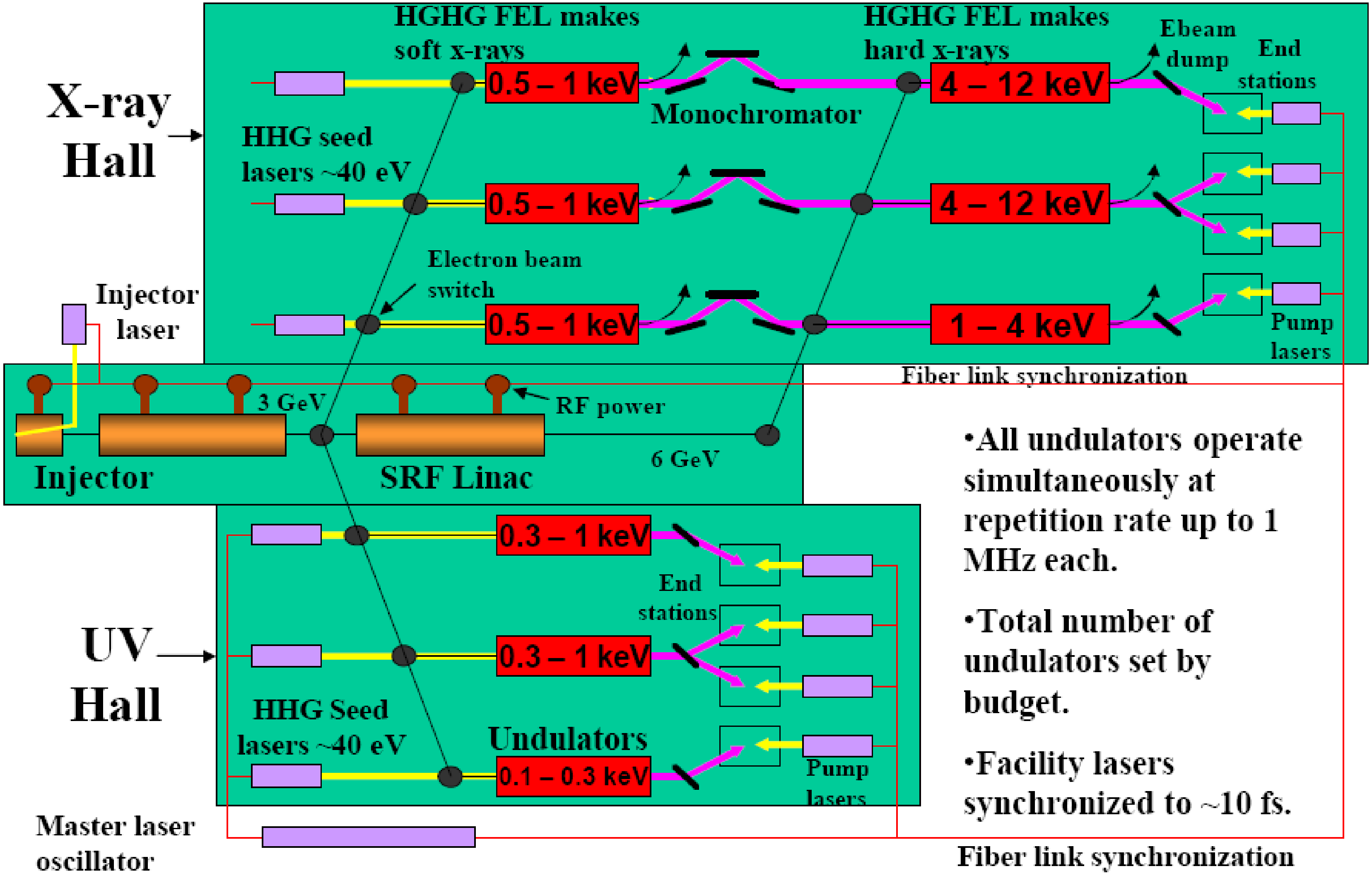


Key Technical Challenges

- Development of short wavelength seed laser
- Synchronization of lasers
- Demonstration of cascading
- Tunable output wavelength

(Shaftan & Yu have demonstrated scheme to vary output wavelength with constant seed wavelength)

A Seeded X-Ray FEL User Facility



- All undulators operate simultaneously at repetition rate up to 1 MHz each.
- Total number of undulators set by budget.
- Facility lasers synchronized to ~10 fs.

Performance Goals

source	# trans. modes	# long. modes	photons/ pulse	pulses/ second
ERL	1-2	10^4	10^6	10^9
LCLS	1	10^3	10^{12}	10^2
XFEL	1	$<10^3$	10^{12}	10^4
SXFEL	1	1	$>10^{11}$	10^6

Based on table from D. Moncton