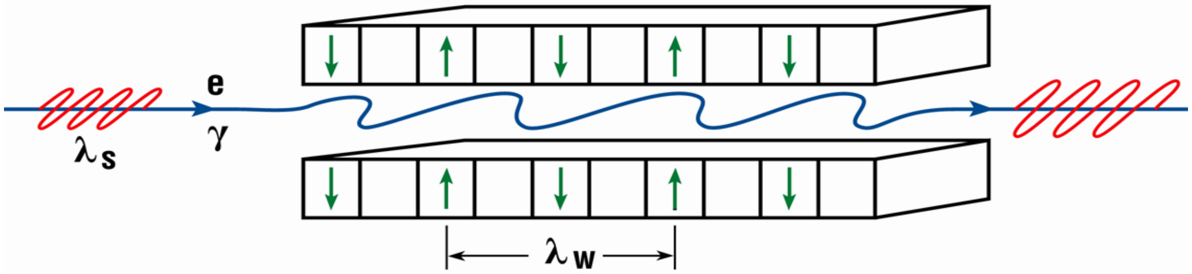
R&D Towards
X-ray Free Electron Laser

Li Hua Yu
Brookhaven National Laboratory

1/23/2004

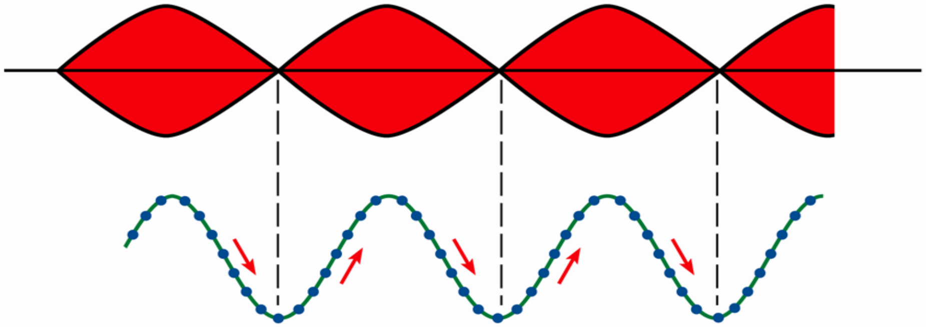
FEL Principle

J. Maday *et. al.* (1976)

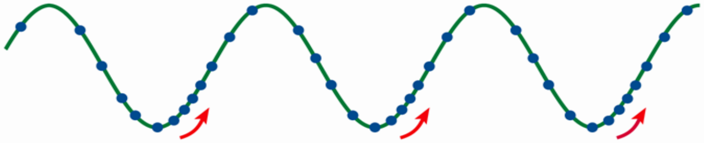


in a moving frame (resonance frame)

standing wave

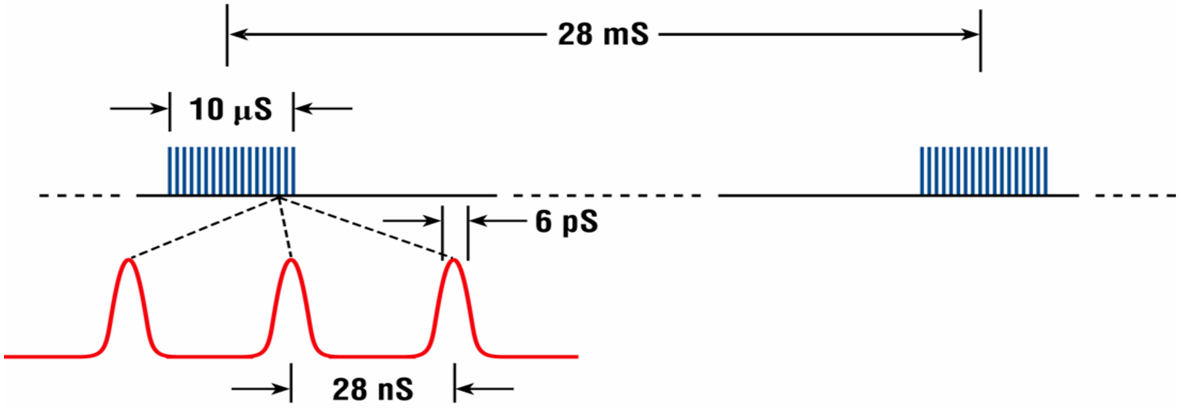


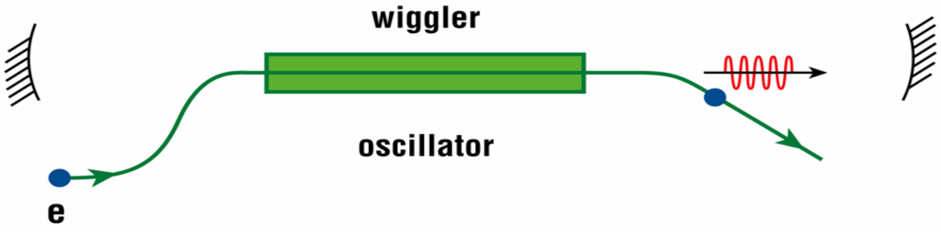
electron move faster than resonance frame

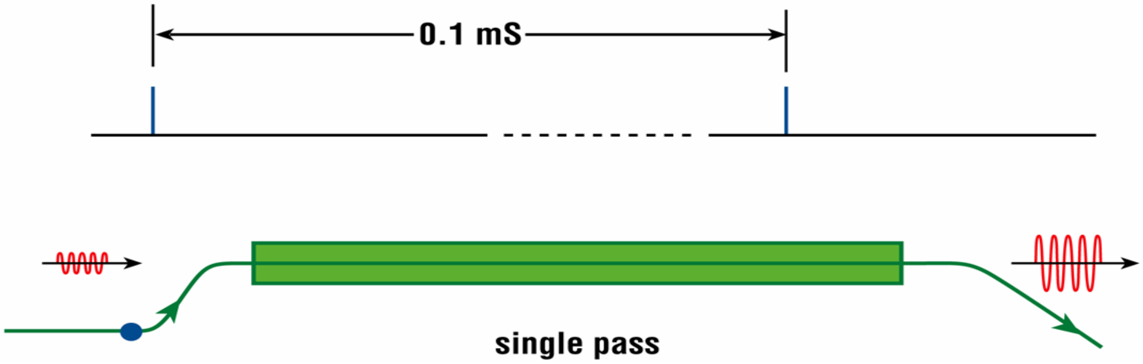


microbunching
e-beam lose energy in average

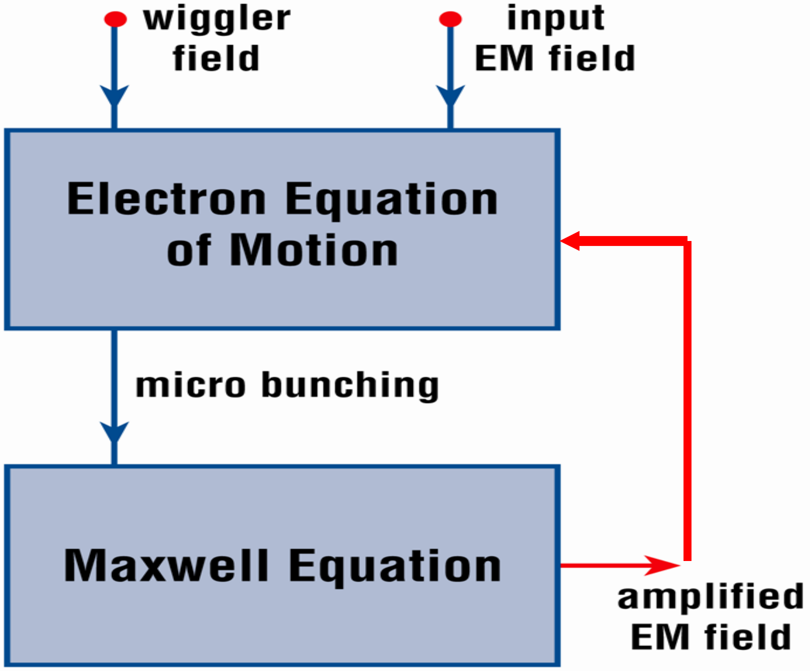
Time Structure and Different FEL Configurations







High Gain FEL – Exponential Growth



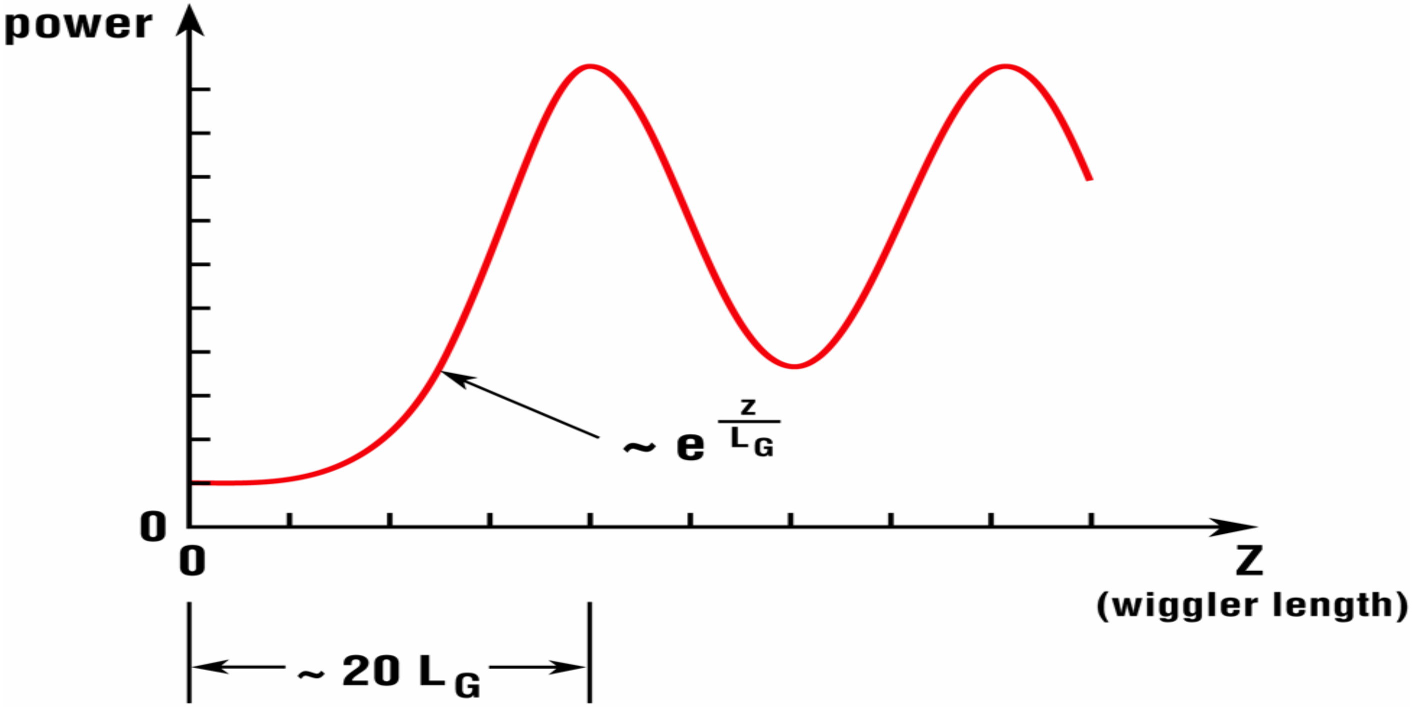
1D Theory: exponential growth, proposes SASE

Self Amplified Spontaneous Emission

Saldin et al. (1982)
Bonifacio, Pellegrini et al. (1984)

Gain Length

(Length power increases by a factor of e)



Saturation Length ~ 20 L_G

Beam quality requirement: Scaling Function of Gain

L.H.Yu, S.Krinsky, R. Gluckstern PRL. 64, 3011 (1990)

$$\frac{\lambda_w}{L_G D} = G\left(\frac{\varepsilon_n}{\gamma \lambda_s}, \frac{\sigma_\gamma}{\gamma D}, \frac{\lambda_w}{\lambda_\beta D} \right)$$

Electron beam energy γ   Current I_0

Wavelength: $\lambda_s = \frac{\lambda_w}{2\gamma^2}(1 + a_w^2)$ ($a_w \sim 1$)

Emittance ε (transverse phase space size = beam size*angular spread)

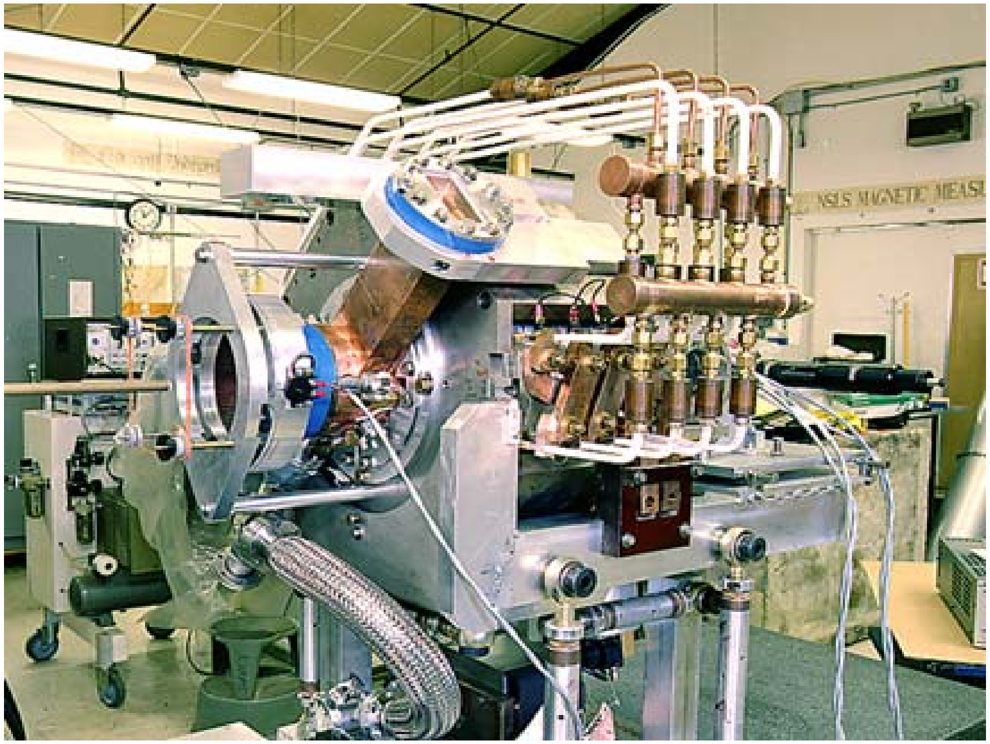
$$\gamma \propto 1/\sqrt{\lambda_s} \quad , \quad I_0 \propto 1/\sqrt{\lambda_s} \quad ,$$

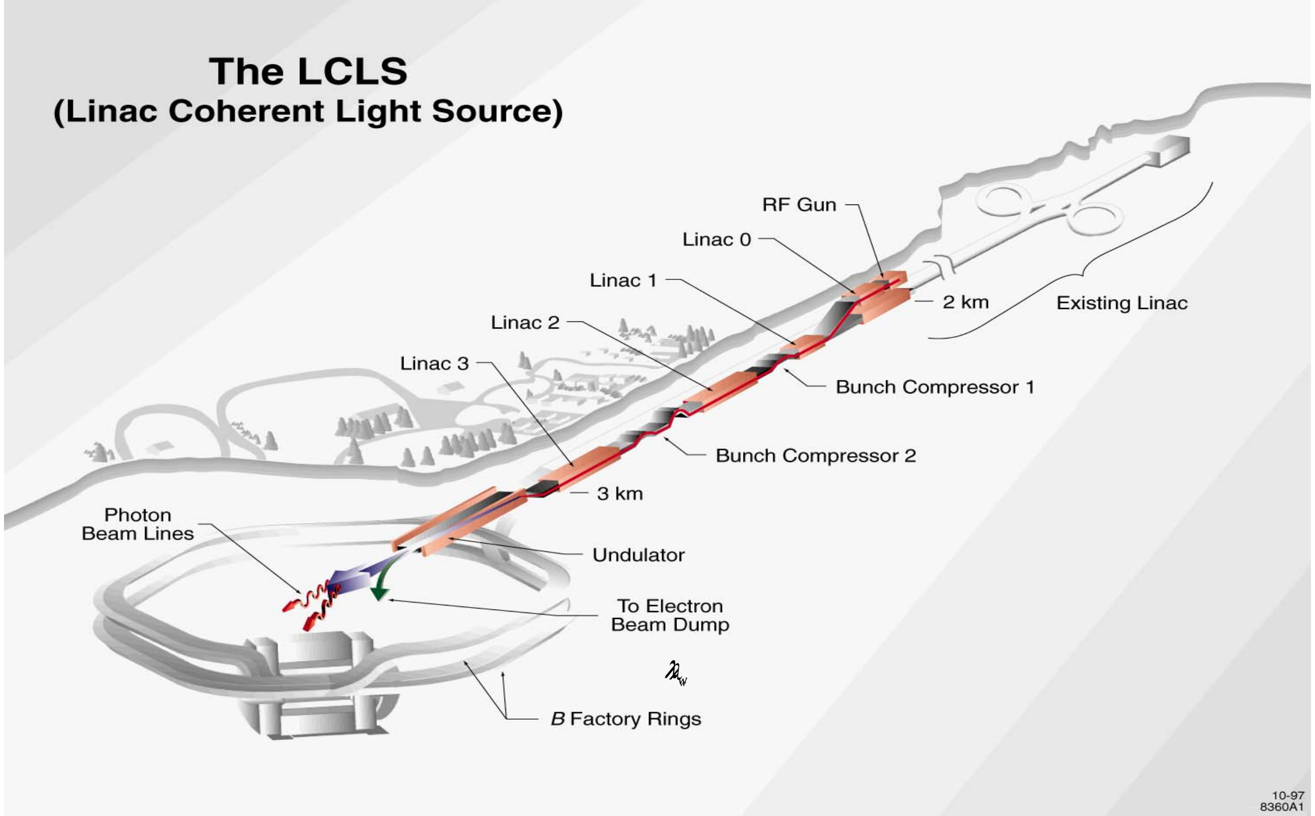
Scaling:

$$\varepsilon_n \propto \sqrt{\lambda_s}$$

The weak square root scaling is favorable for going to short wavelength

The development of Photocathode RF Gun (R. Schefield, 1985) with Emittance Compensation Solenoid (B. Carleston) makes it possible to consider high gain X-ray FEL because it provides high brightness beam





LCLS (SLAC) Proposal

Wavelength	λ	1.5 Å
Electron energy	γ	14.35 GeV
Norm. emittance (rms)	ε_n	1.5 π mm mrad
Peak current	I_0	3,400 A
Wiggler Period	λ_w	3 cm
Gain Length	L_G	5.8 m

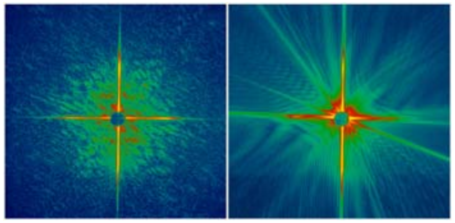
Courtesy: Max
Cornaccia

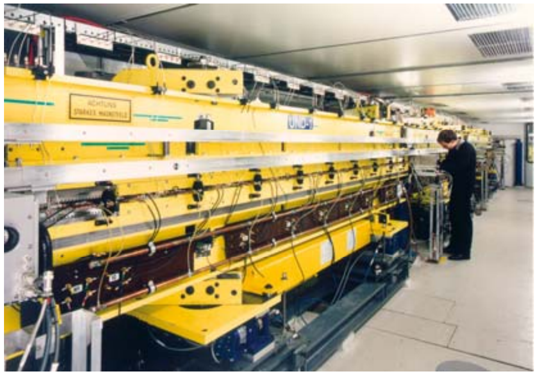
& Schedule

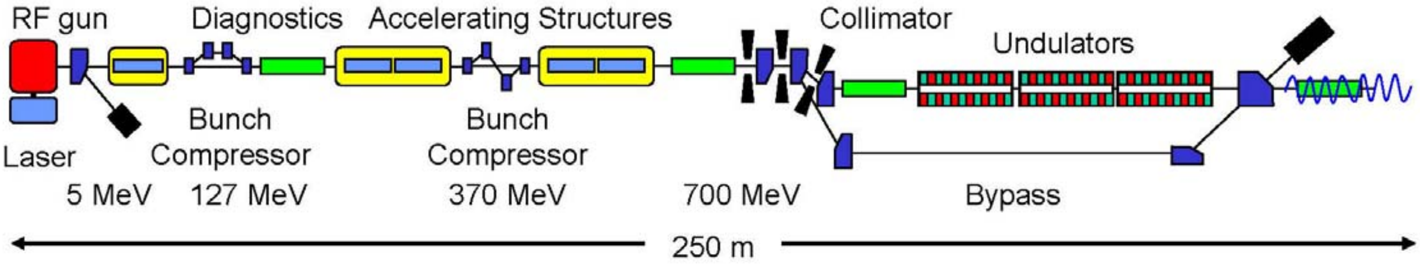
Schedule:

1999 - 2002	Research and Development
2003 - 2006	Project Engineering Design
2005	Long-Lead Procurement
2006 - 2008	Facilities Construction, Startup
2009	Start Operations

Cost: The Linac Coherent Light Source makes use of the last 1/3 of the Two-Mile Linac at the Stanford Linear Accelerator Center, reducing the cost of construction by more than $300,000,000.

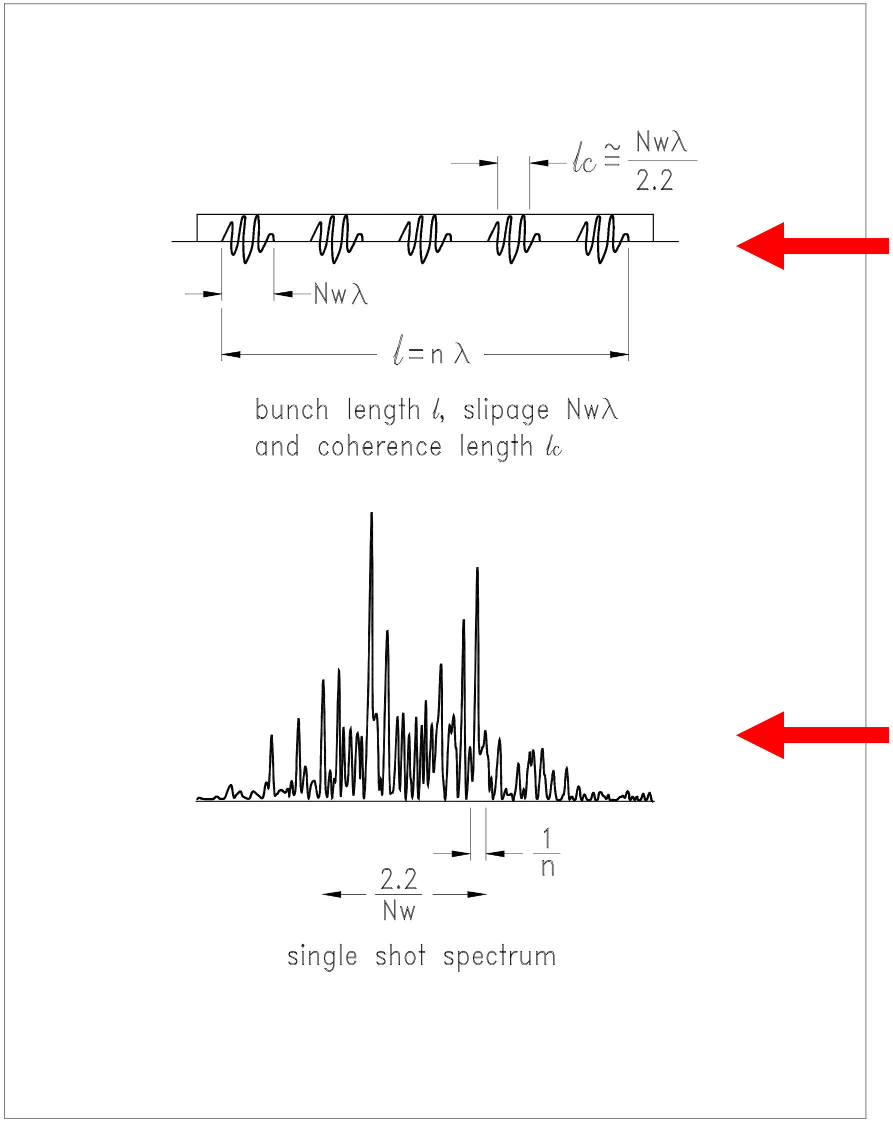






Free-electron laser at DESY delivers highest power at at wavelengths between 13.5 and 13.8 nanometers with an average power of 10 milliwatts and record energies of up to 170 microjoules per pulse.

SASE spectrum is not coherent

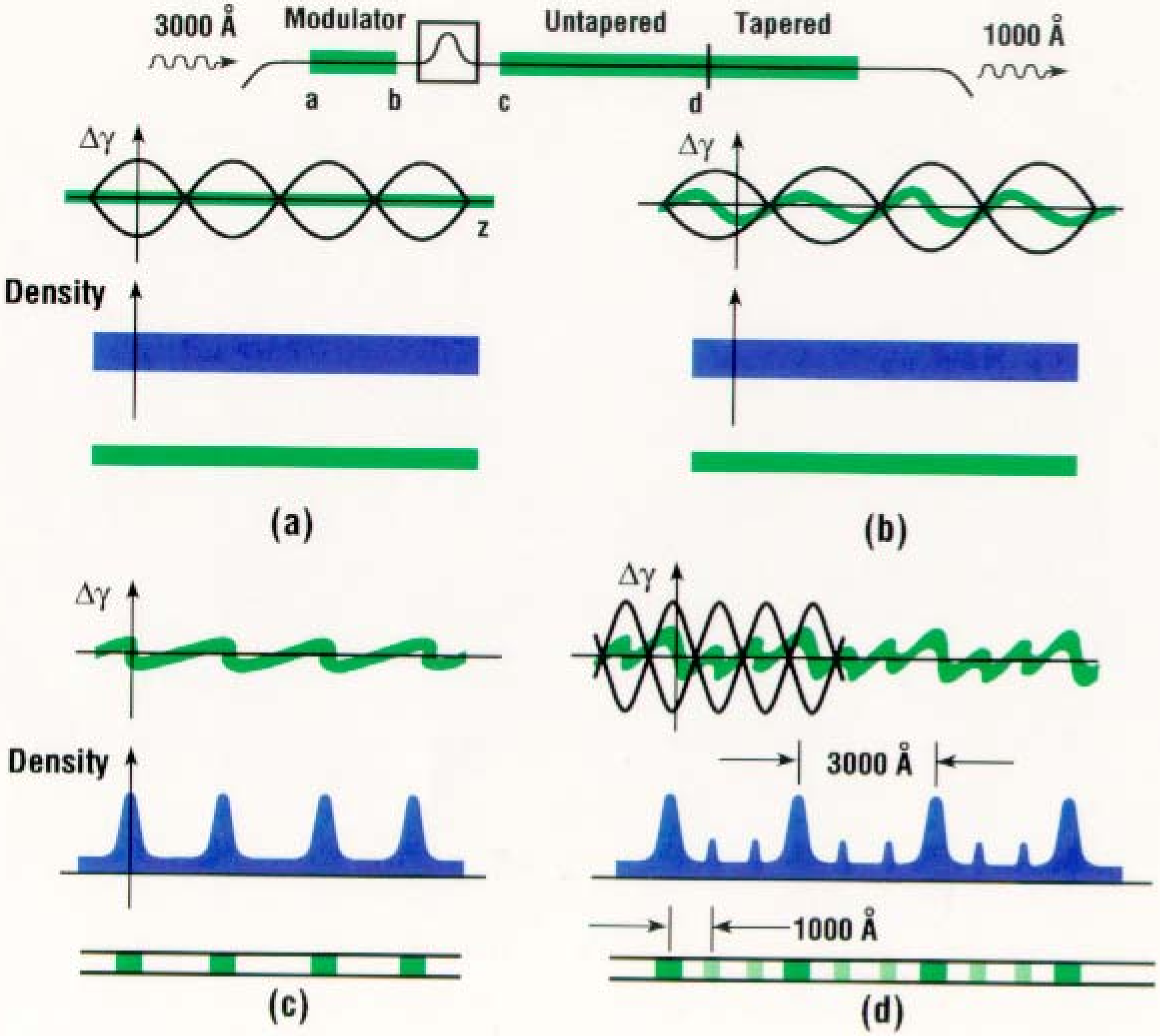


Train of pulses with
independent phase

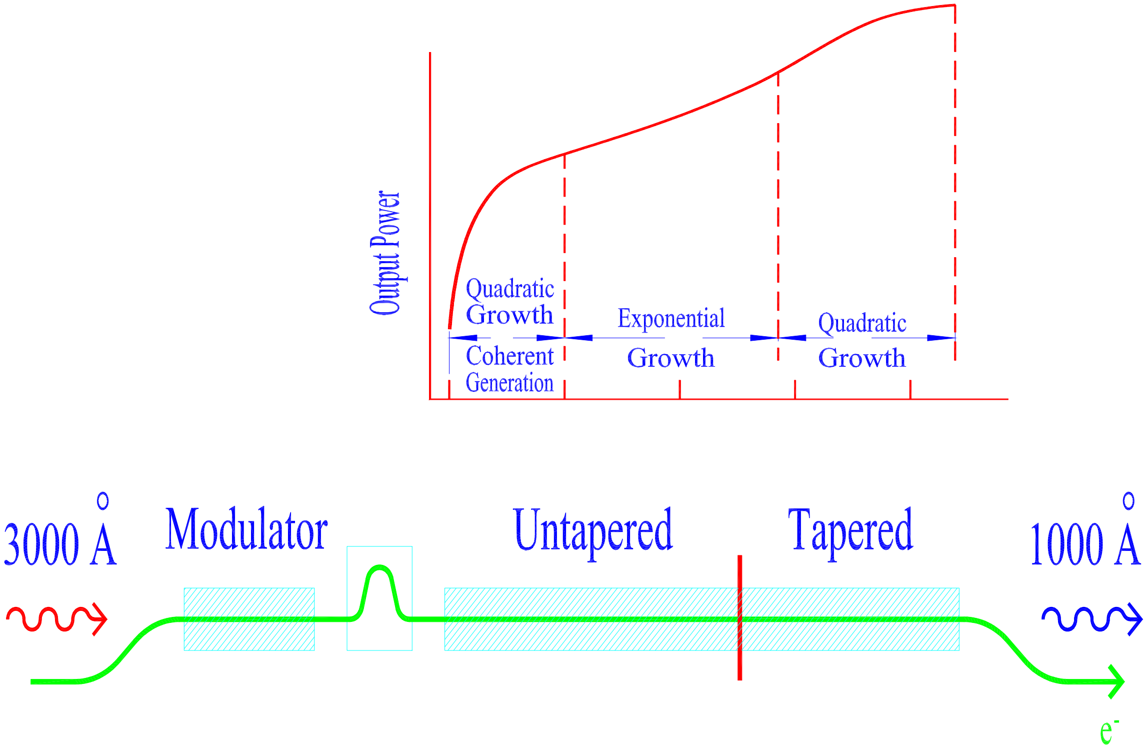
Spectrum consists spikes

with 100% fluctuation

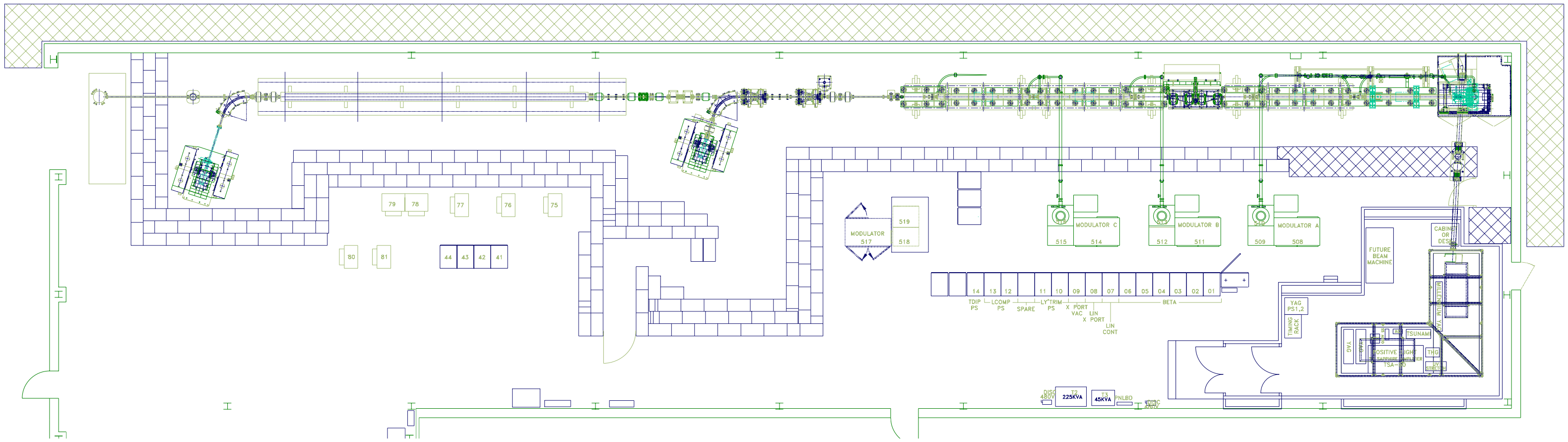
High Gain Harmonic Generation (HGHG) for coherence and stability



HIGH GAIN HARMONIC GENERATION (HGHG)



DUVFEL Configuration



DUVFEL using NISUS wiggler

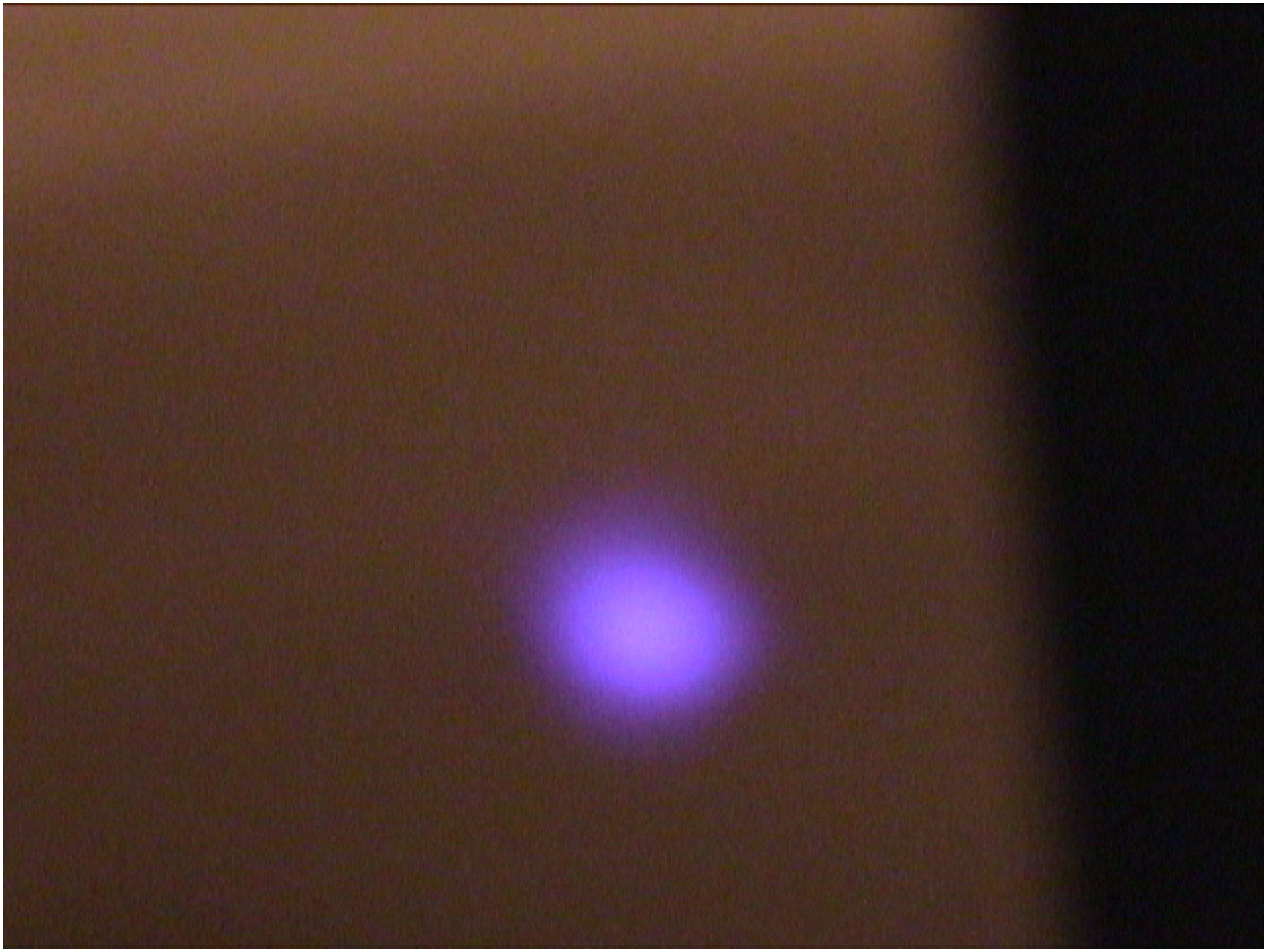
Step 1. SASE at 400 nm

Step 2. direct seeding at 266nm

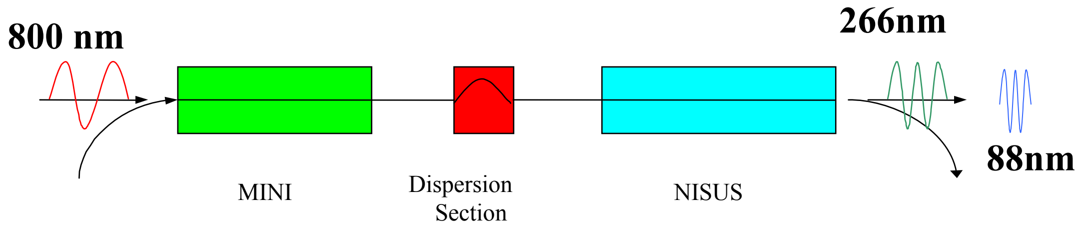
Step 3. HGHG 800nm → 266 nm

BROOKHAVEN
NATIONAL LABORATORY

Camera image after exit window



HGHG Experiment

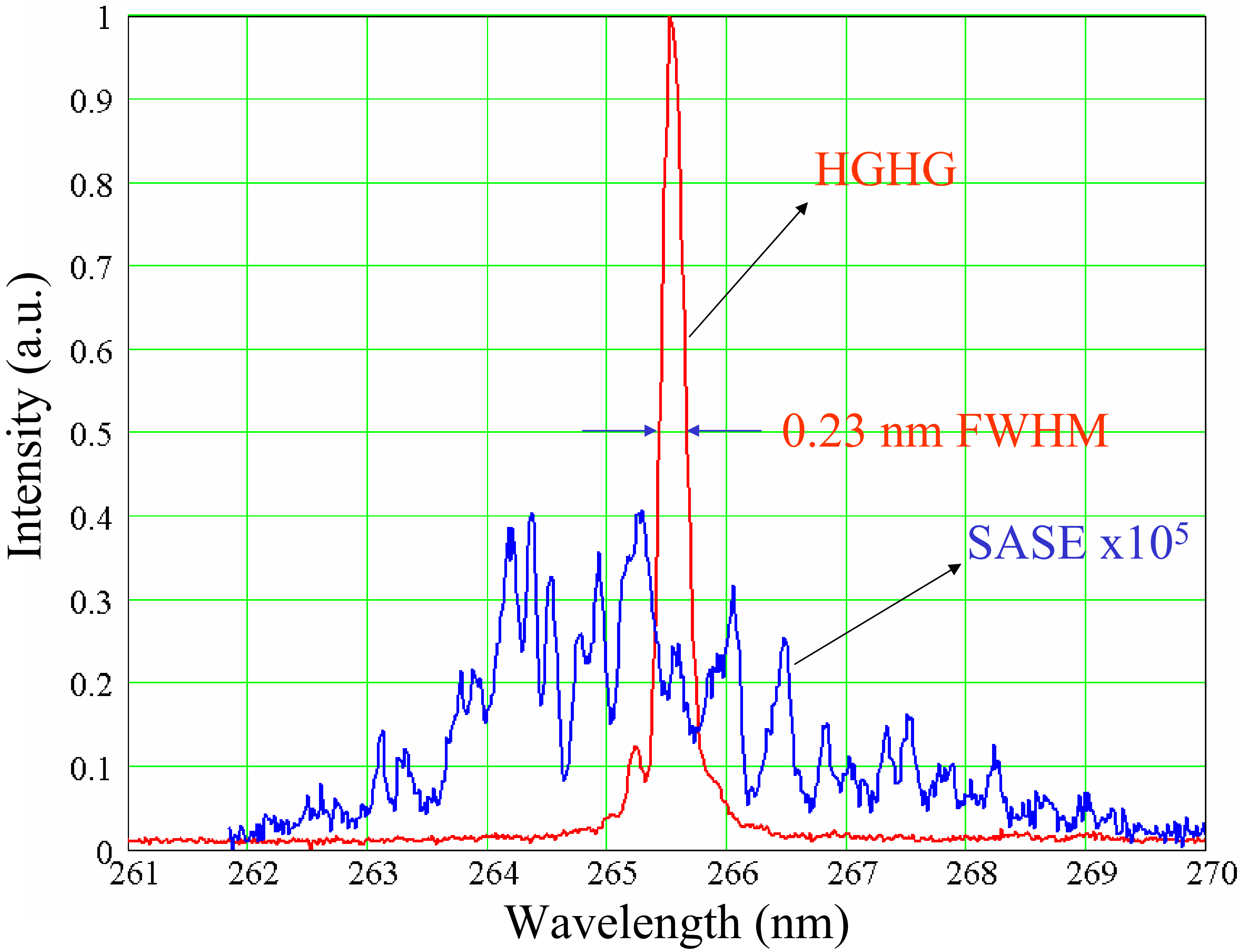


HGHG from 800 nm→266 nm,
Output at 266 nm: ~ 120μJ,
e-beam: 300 Amp, 3 mm-mrad,
Energy 176MeV

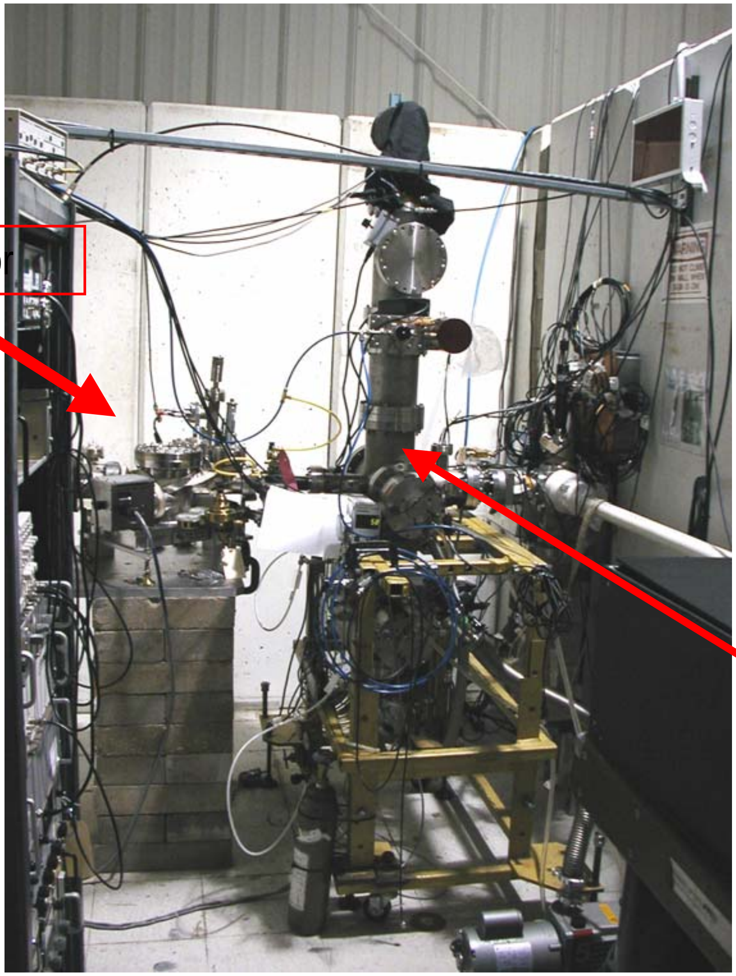
Output at 88 nm ~ 1 μJ
On-going Experiment Application in Chemistry

L.H.Yu et al **PRL** 91 074801-1 (2003)

Spectrum of HGHG and SASE at 266 nm under the same electron beam condition

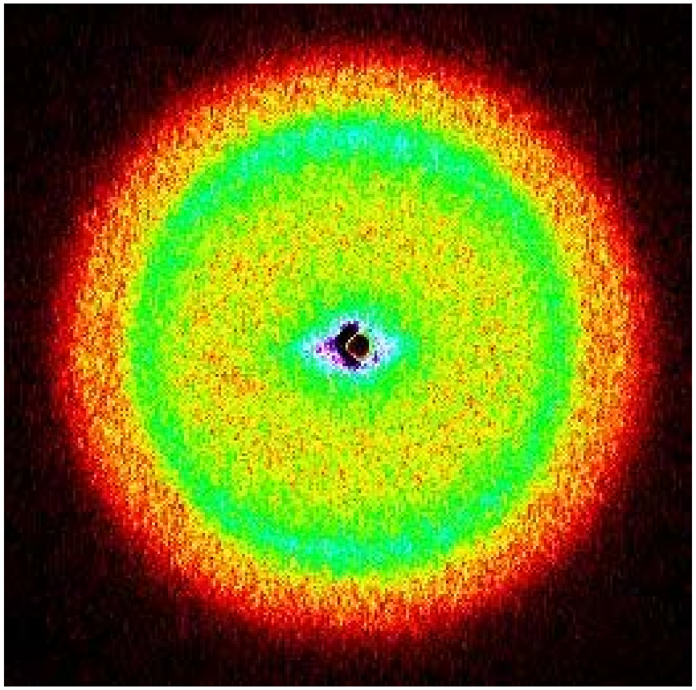


Harmonic at 89 nm is used in Ion pair imaging experiment

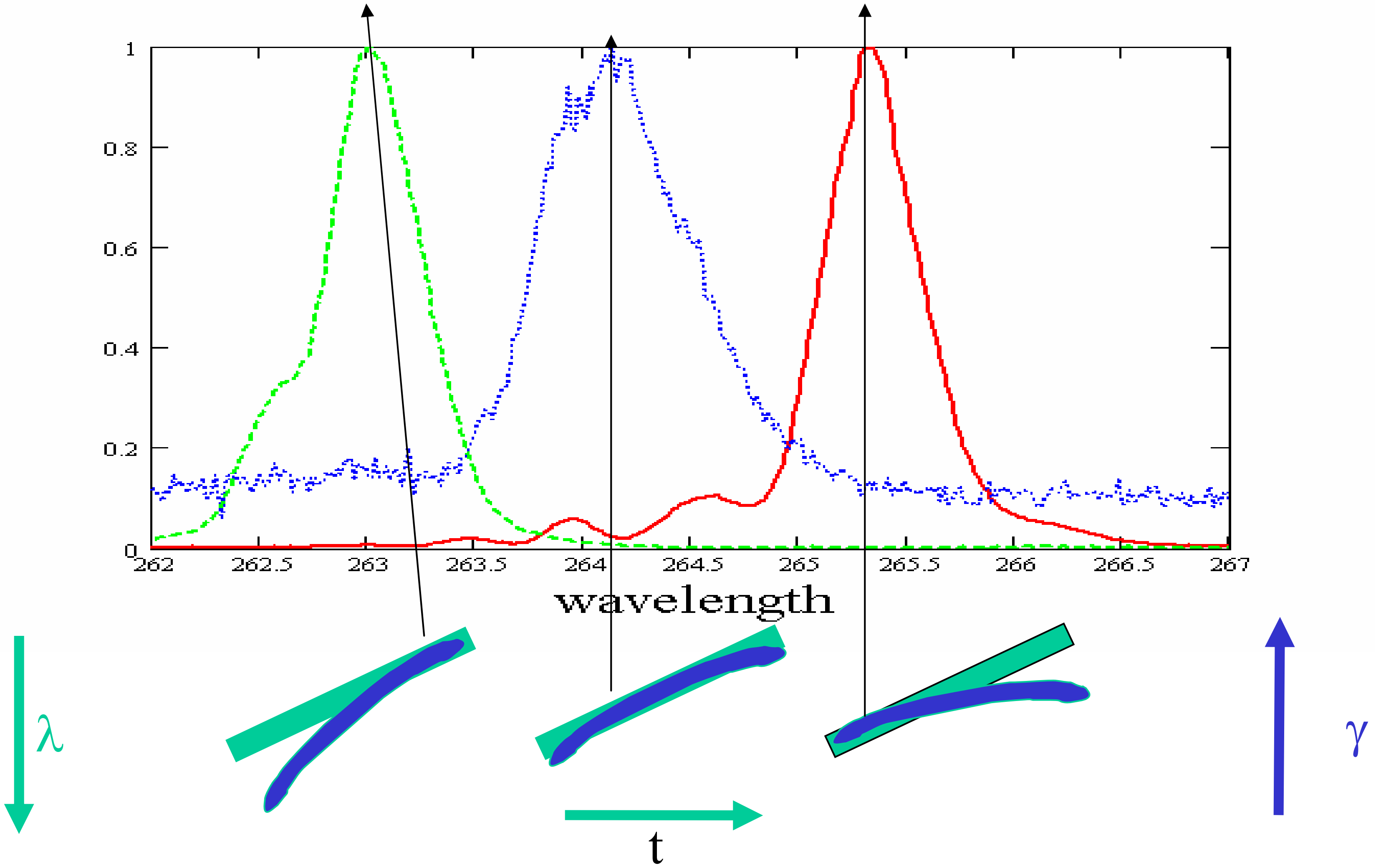


Monochromator

Ion Pair Imaging station



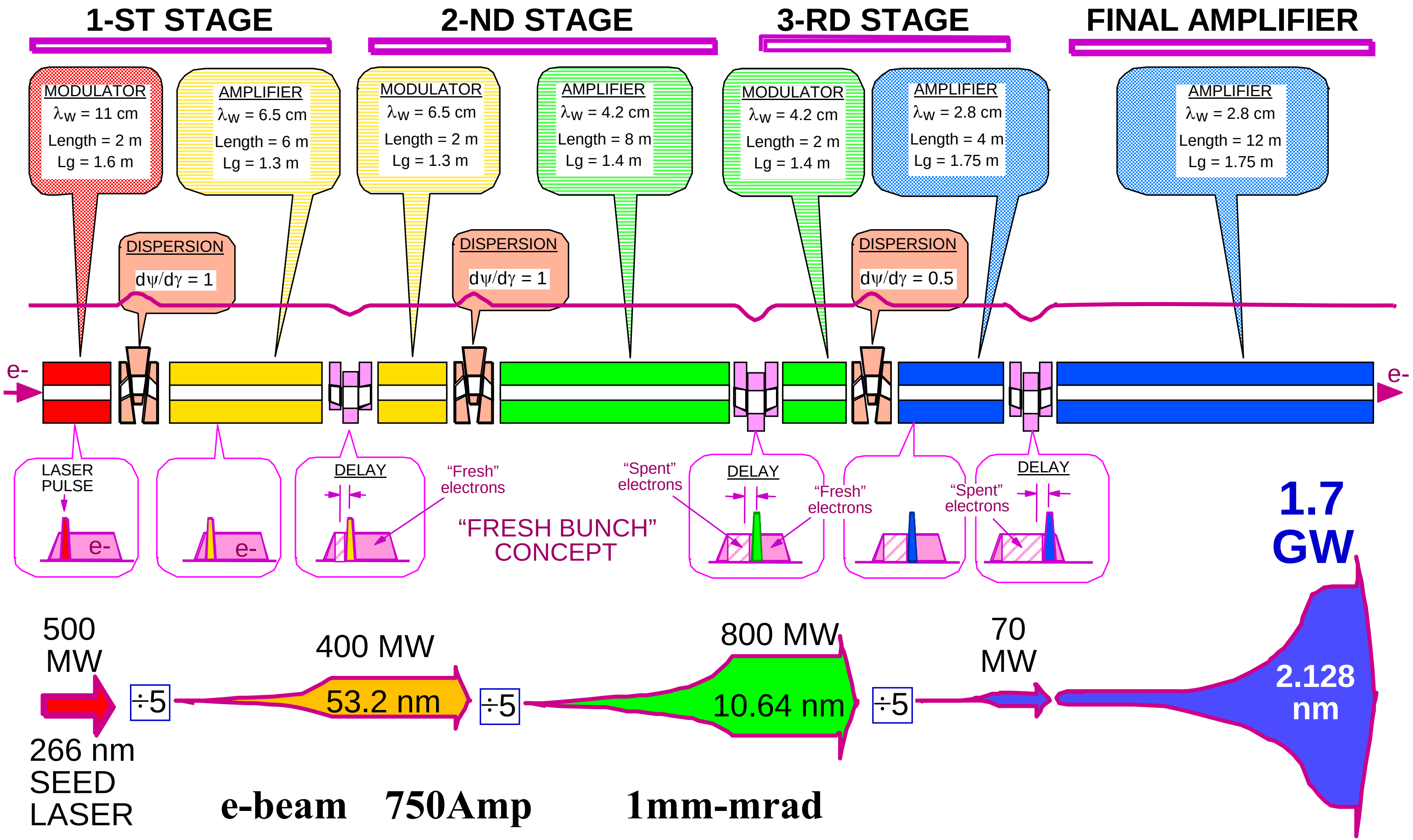
CPA (Chirped Pulse Amplification) HGHG Spectra



Interpretation of 3 sets of measurements: effect of RF curvature; the second matched e-beam chirp to seed chirp

R&D Towards Cascading HGHG: One of the Earlier Calculated Schemes

A Soft X-Ray Free-Electron Laser



1-ST STAGE

MODULATOR
λ_W = 11 cm
Length = 2 m
Lg = 1.6 m

DISPERSION
$d\psi/d\gamma = 1$

AMPLIFIER
λ_W = 6.5 cm
Length = 6 m
Lg = 1.3 m

2-ND STAGE

MODULATOR
λ_W = 6.5 cm
Length = 2 m
Lg = 1.3 m

DISPERSION
$d\psi/d\gamma = 1$

AMPLIFIER
λ_W = 4.2 cm
Length = 8 m
Lg = 1.4 m

3-RD STAGE

MODULATOR
λ_W = 4.2 cm
Length = 2 m
Lg = 1.4 m

DISPERSION
$d\psi/d\gamma = 0.5$

AMPLIFIER
λ_W = 2.8 cm
Length = 4 m
Lg = 1.75 m

FINAL AMPLIFIER

AMPLIFIER
λ_W = 2.8 cm
Length = 12 m
Lg = 1.75 m

e-

e-

LASER PULSE

e-

e-

DELAY

"Fresh" electrons

"FRESH BUNCH" CONCEPT

"Spent" electrons

DELAY

"Fresh" electrons

"Spent" electrons

DELAY

1.7 GW

500 MW

266 nm SEED LASER

÷5

400 MW

53.2 nm

÷5

800 MW

10.64 nm

÷5

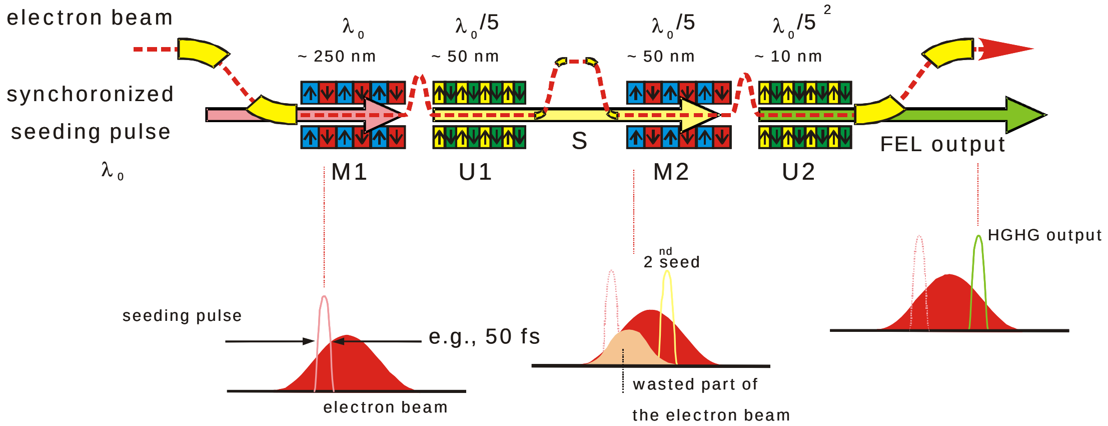
70 MW

2.128 nm

e-beam 750Amp 1mm-mrad

2.6GeV $\sigma_\gamma/\gamma = 2\times10^{-4}$ **total** $L_w = 36$m

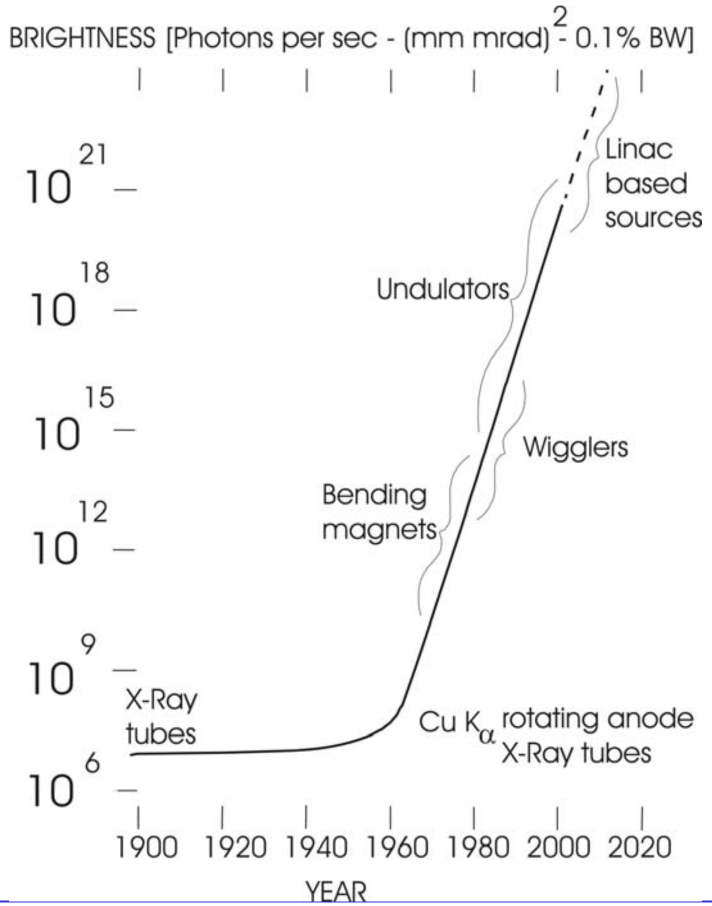
FEL at ELETTRA of Trieste

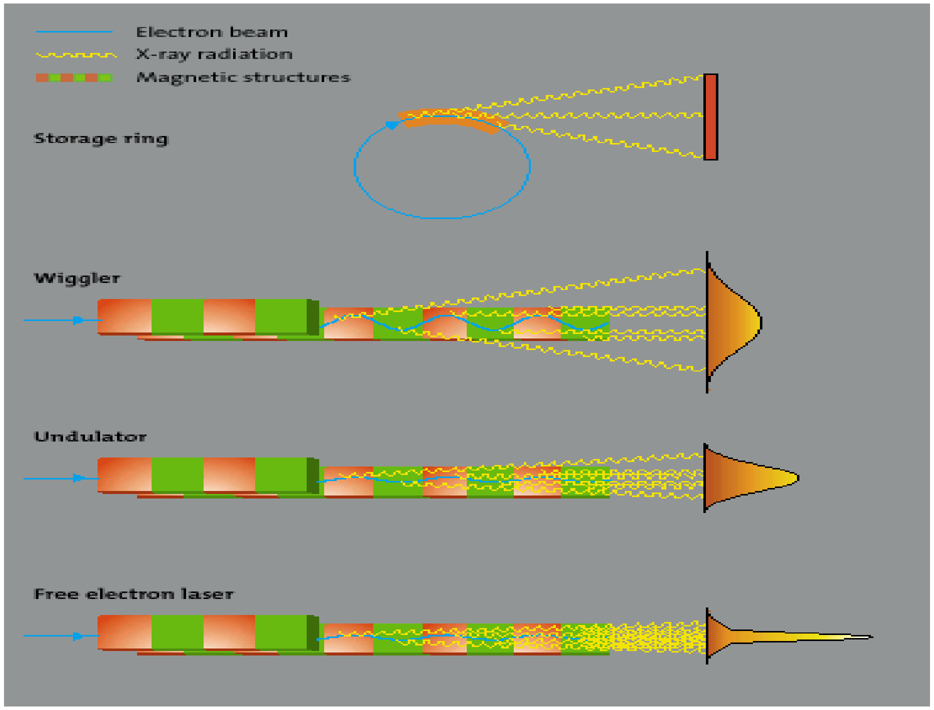


FEL at 1 GeV

	FEL-1		FEL-2		
Wavelength Target	100	40	40	10	nm
	10	31	25	124	eV
Electron Beam Energy	0.70		0.55	1.00	GeV
Bunch Charge	1.0		1.0		nC
Peak Current	0.8		2.5		kA
Bunch Duration (rms)	500		160		fs
Energy Spread (rms)	0.5		1.0		MeV
Normalized Emittance	2.0		1.5		$\times 10^{-6}$ m
Undulator Period	52		36.6		mm

Introduction





- Ultrahigh Spatial Resolution
- Microscopy
- Coherent X-ray Scattering

Coherent time:

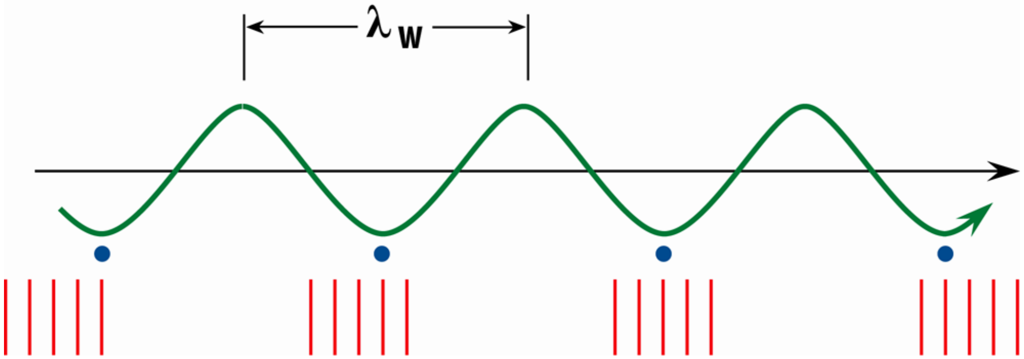
$$\tau \approx \hbar / kT \approx 100 \quad fs$$

Resonance Condition

$$(C - v_{\parallel}) \frac{\lambda_w}{v_{\parallel}} = \lambda_s$$

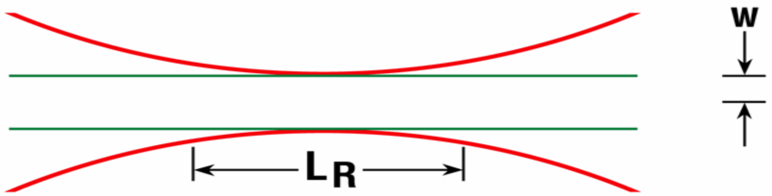
$$\frac{1 + a_w^2}{2\gamma_0^2} \lambda_w = \lambda_s$$

$$a_w = \frac{eA_w}{mC} \sim 1 \quad \text{(scaled vector potential)}$$



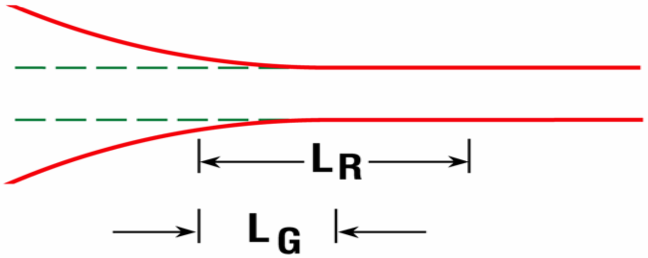
Diffraction and Optical Guiding

G. Moore, Nucl. Ins. Meth. A239, 119 (1985)
Scharleman, Sessler, Wurteli, PRL, 54, 1925 (1985)

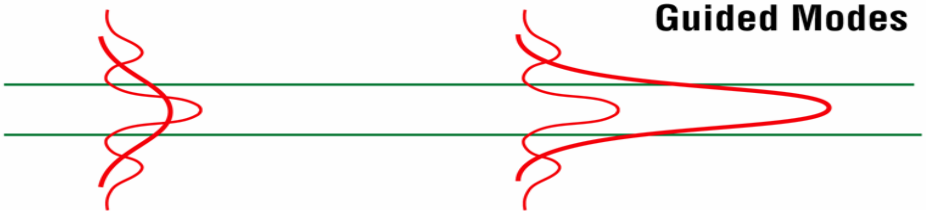


Rayleigh Range

$$L_R = \frac{\pi w^2}{\lambda_s}$$



$$\frac{L_R}{L_G^{1D}} >> 1 \longrightarrow \text{1 - D Theory}$$



Guided Modes

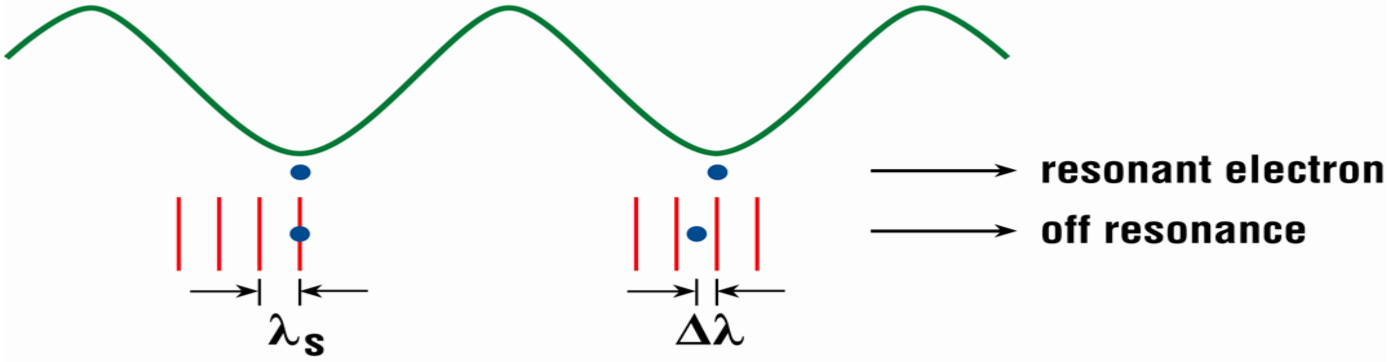
Effects of Electron Beam Quality

energy spread **degrades coherent bunching**

$$\lambda_s = \frac{\lambda_w}{2\gamma_0^2}(1 + a_w^2)$$

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

$$\therefore \frac{\Delta\lambda}{\lambda} = 2\frac{\Delta\gamma}{\gamma}$$



Emittance

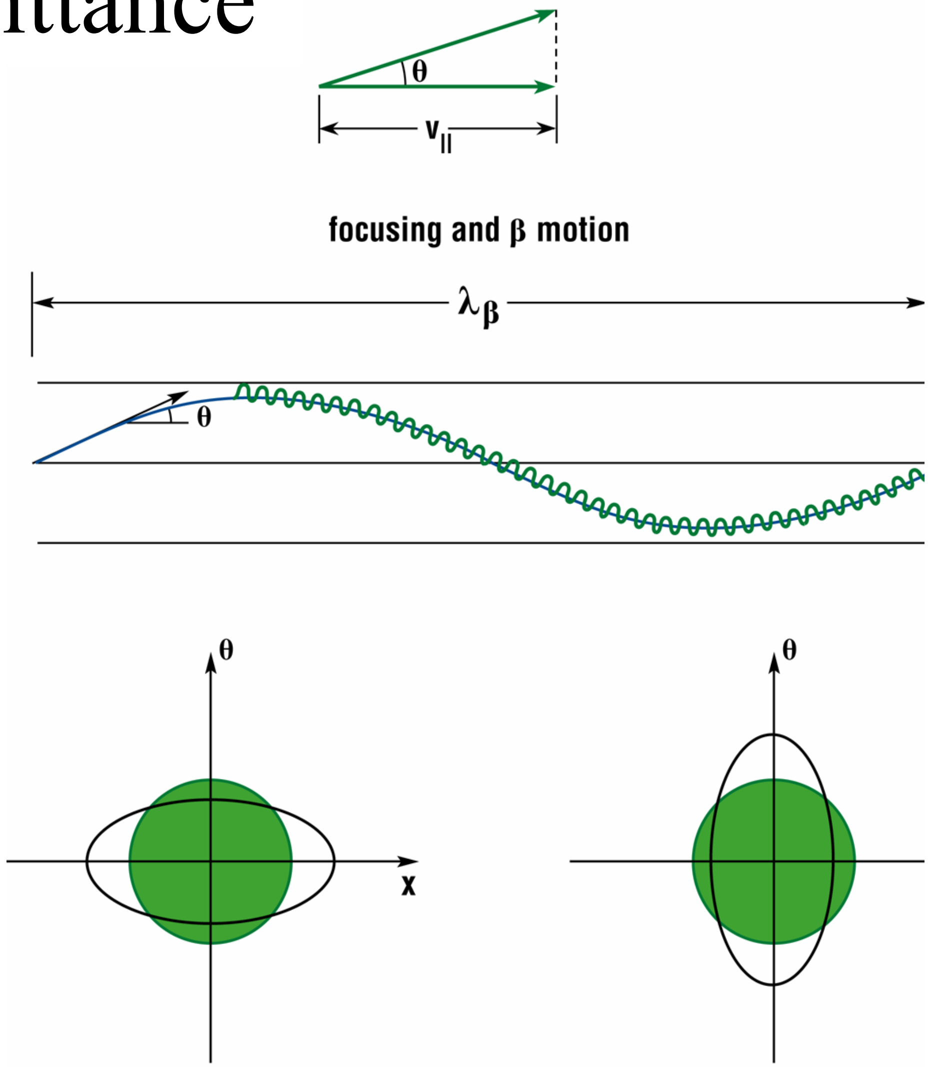
- Angular spread ❑ also degrades micro-bunching

- Strong focusing reduces beam size but increases angular spread

- Emittance ♏

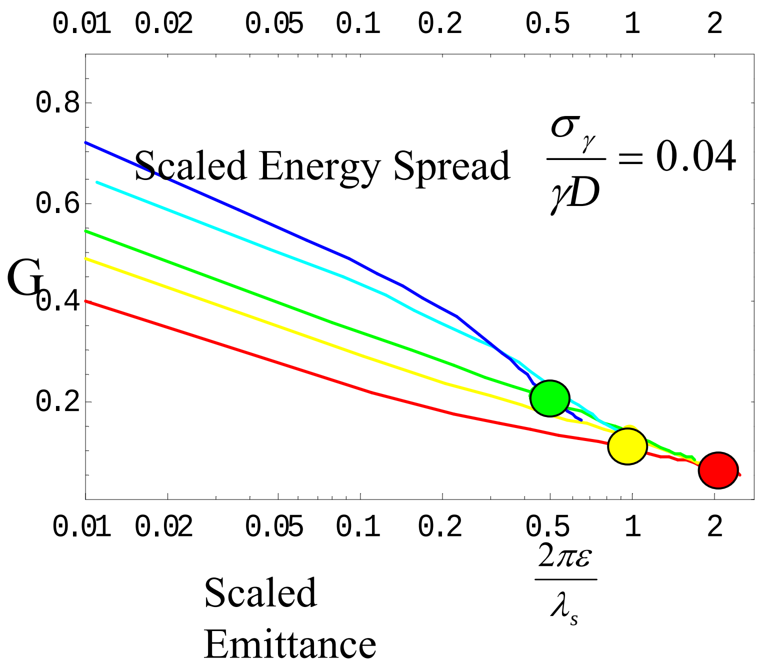
  ~ beam size×angular spread

- Requirement on ♏: $\varepsilon < \dfrac{\lambda_s}{4\pi}$



Emittance ε ~ phase space area

$\varepsilon_n = \gamma\varepsilon$ (invarient during acceleration)



On the scaled function plot, operating points do not change very much even though wavelength changes several orders of magnitudes

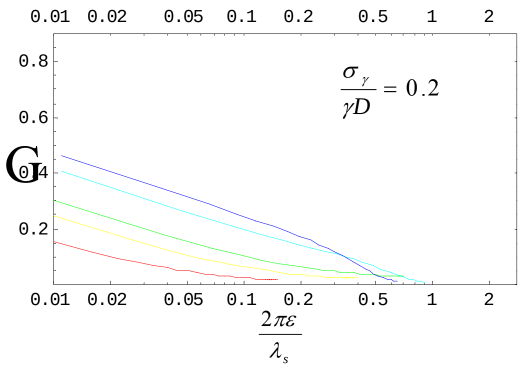
Scaled Focusing $\frac{k_\beta}{k_w D}$

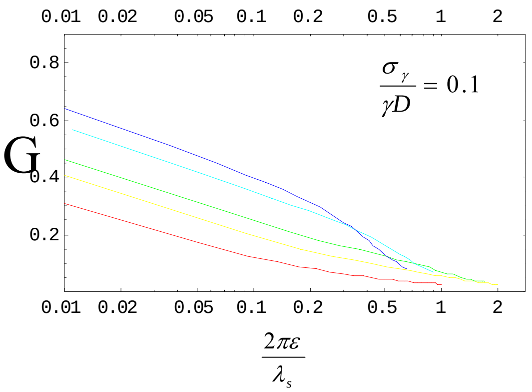
- 1. 0.5
- 0.15
- 0.08
- 0.03

🟢 DUV(BNL)(100nm)

🟡 TTF (DESY)(6nm)

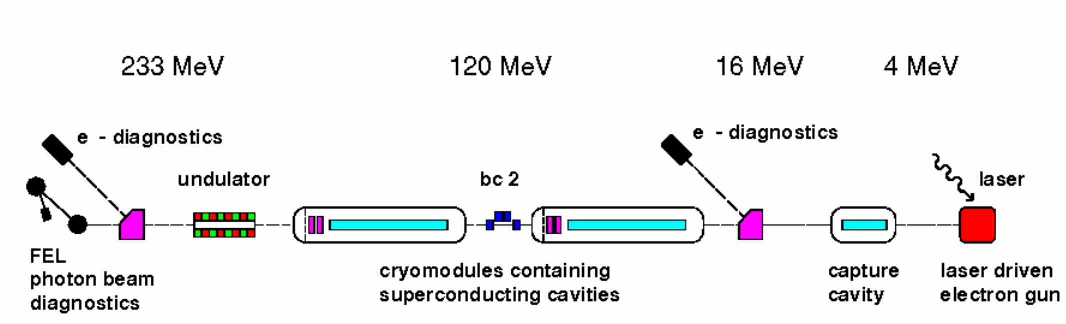
🔴 LCLS(SLAC)(0.15nm)



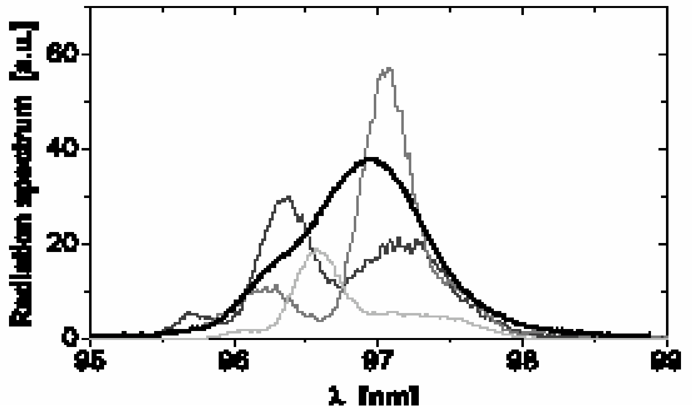


A series of SASE experiment confirming the Theory

- LANL, UCLA: 15 μm (1999)
- APS: Luetle 0.4 μm (2000-2001)
- BNL, SLAC, UCLA: 0.8 μm (2001)
- DESY: 0.1 μm (2002)
- BNL: UVFEL 0.266 μm (2002)



Schematic of DESY SASE experiment at 100 nm

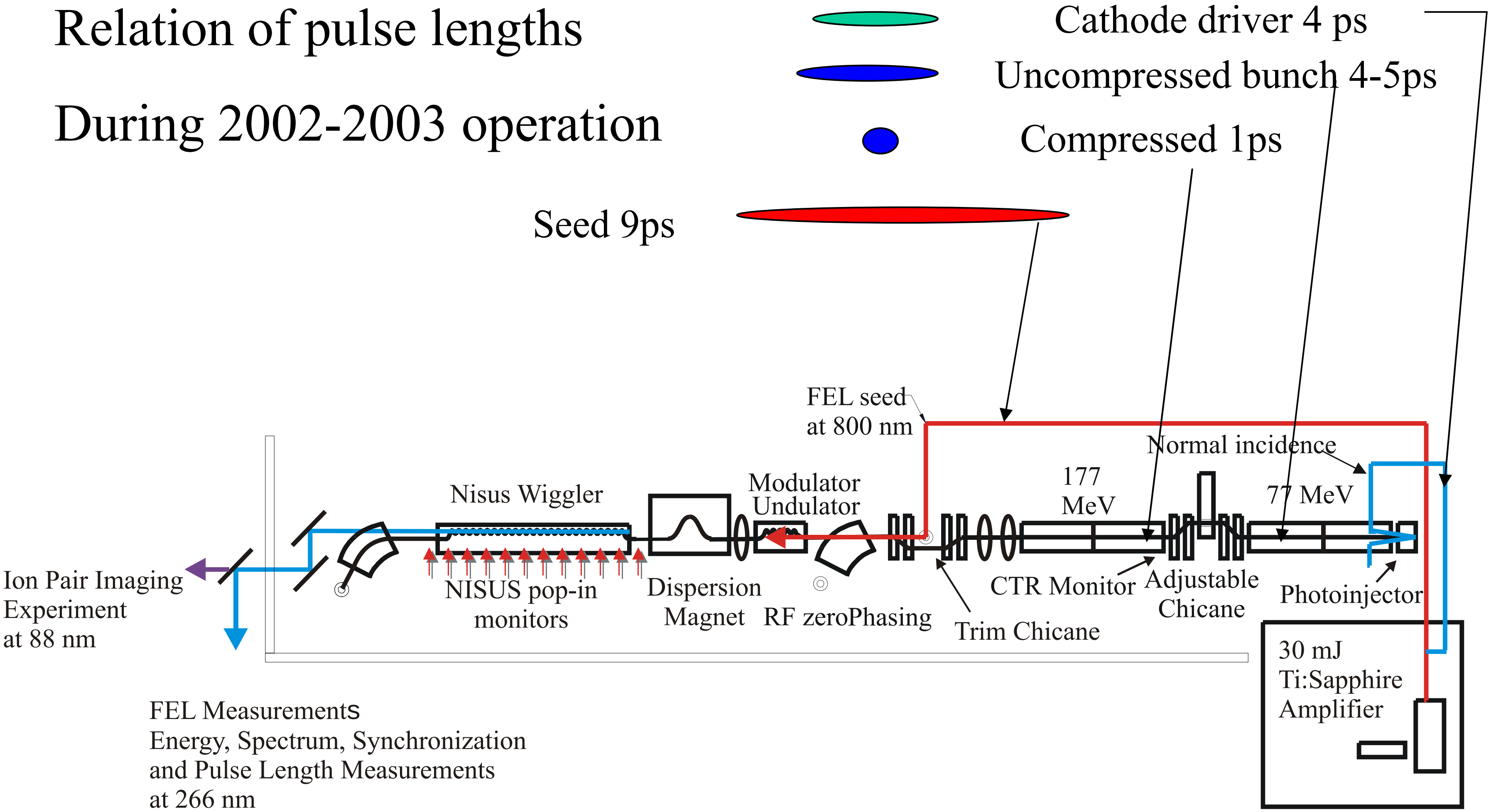


Single shot and average SASE spectrum
showing fluctuation and spikes

Deep UV Free Electron Laser at SDL

Relation of pulse lengths

During 2002-2003 operation



FEL Measurements
Energy, Spectrum, Synchronization
and Pulse Length Measurements
at 266 nm

NISUS Undulator Parameters

- Period $\lambda_w = 3.9$ cm
- Length 10 m
- Canted poles provide horizontal focusing and reduce vertical focusing
- 4-wire focusing provide tuning ability to reach equal focusing Natural focusing: betatron wavelength $\lambda_\beta = 20$ m
- Because focusing is not strong, also because period 3.9 cm is large, gain length is far from optimized.

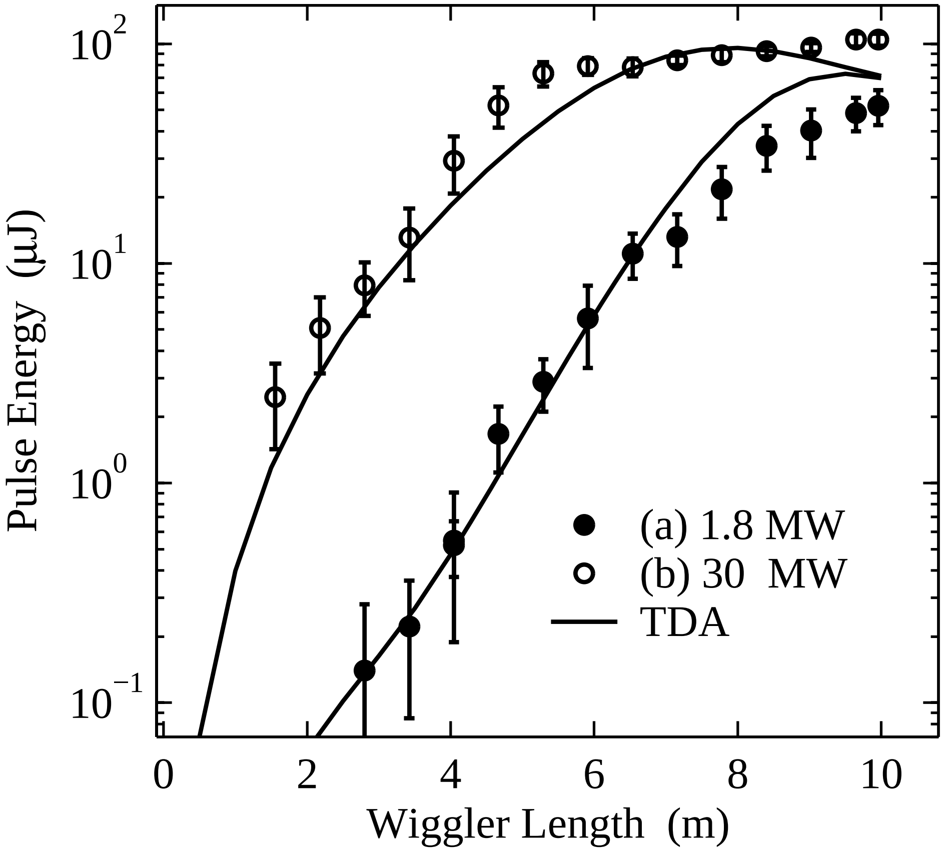
FEL gain length

- Simulation: HGHG reaches saturation at 400 nm with current

  $I_0 = 300$ amp, emittance $\varepsilon_n = 5$ mm-mrad, energy spread

  $\sigma_\gamma / \gamma = 1.5\times10^{-3}$, gain length $L_G = 1.1$ m
- We do not expect SASE saturation, because we have only 10 gain length
- SASE in February 2002 : $L_G = 0.9$ m

Two sets of data compared with Simulation



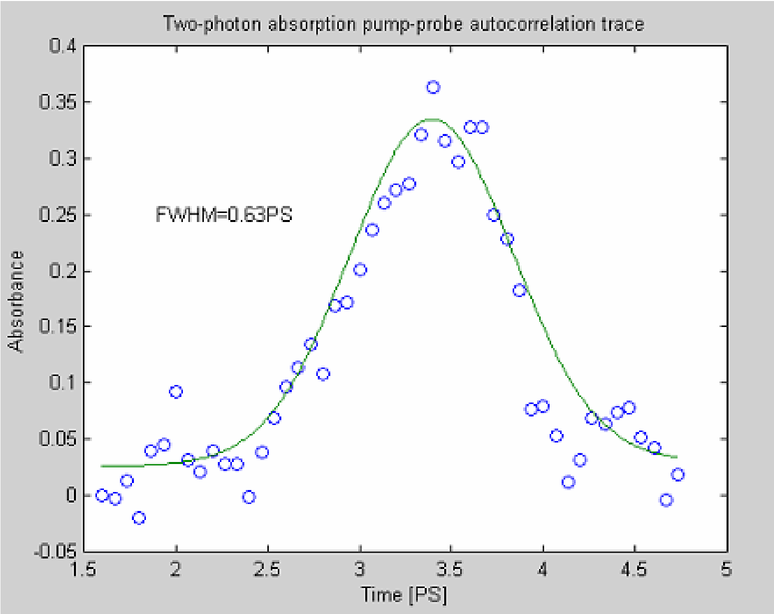
current 300 Amp, energy spread $\sigma\gamma/\gamma = 1\times10^{-4}$, dispersion $d\psi/d\gamma = 8.7$

(a) **12/11/02 Model**: P_{in}=1.8MW pulse length 0.6 ps, slice emittance 2.7 mm-mrad

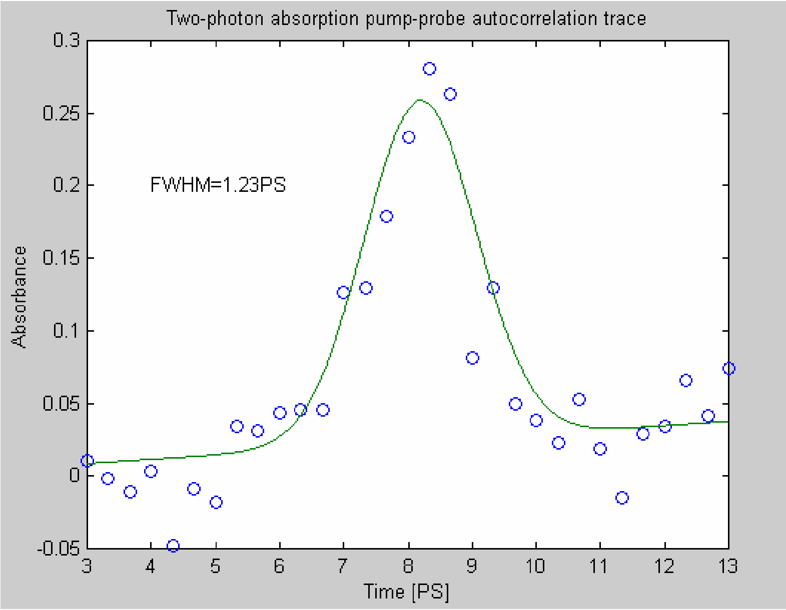
(b) **3/19/03 Model**: P_{in}=30MW pulse length 1 ps, projected emittance 4.7 mm-mrad

Whole bunch contributes to the output

Autocorrelation Pulse Length Measurement



(a)



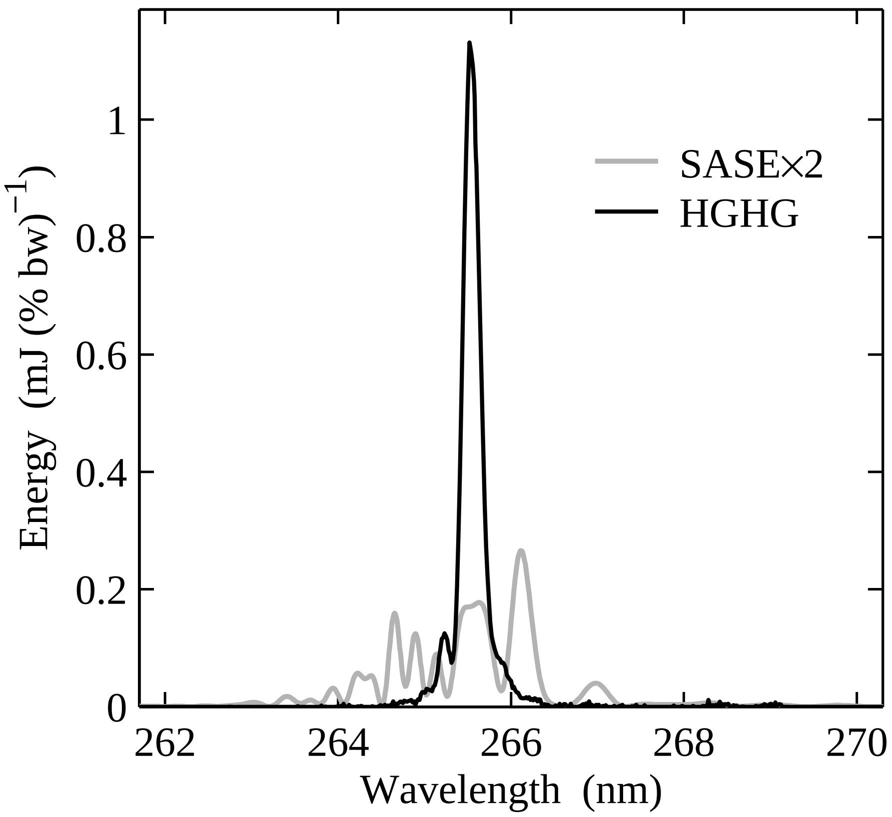
(b)

current 300 Amp, energy spread $\sigma\gamma/\gamma = 1\times10^{-4}$, dispersion $d\psi/d\gamma = 8.7$

(a) **12/11/02 Model**: P_{in}=1.8MW pulse length 0.6 ps, slice emittance 2.7 mm-mrad

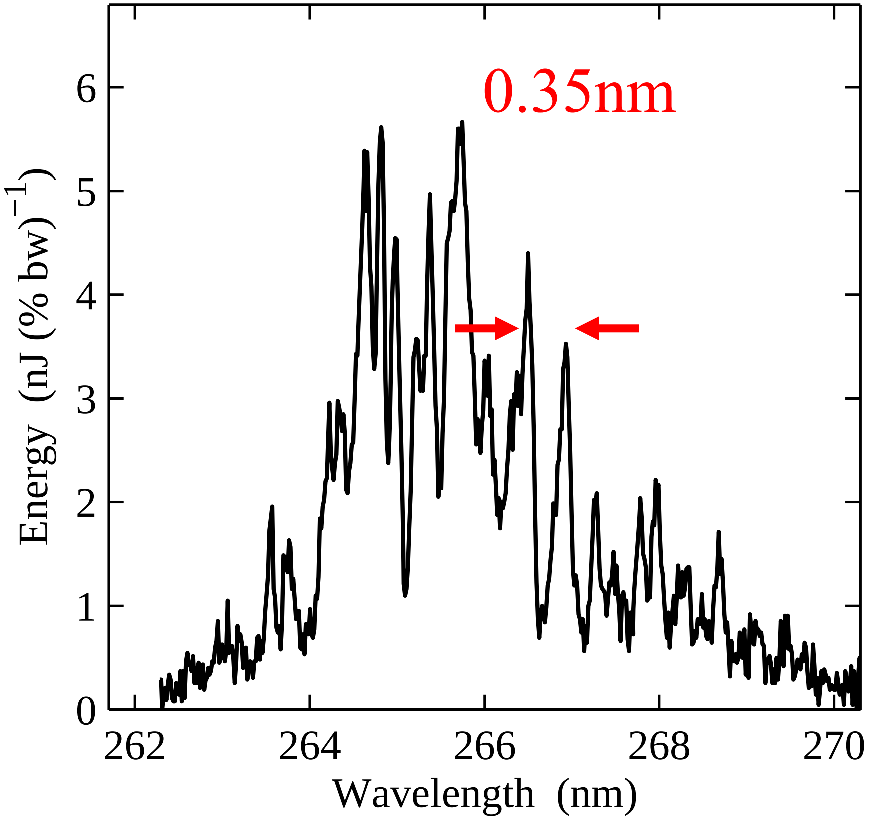
(b) **3/19/03 Model**: P_{in}=30MW pulse length 1 ps, projected emittance 4.7 mm-mrad

Whole bunch contributes to the output



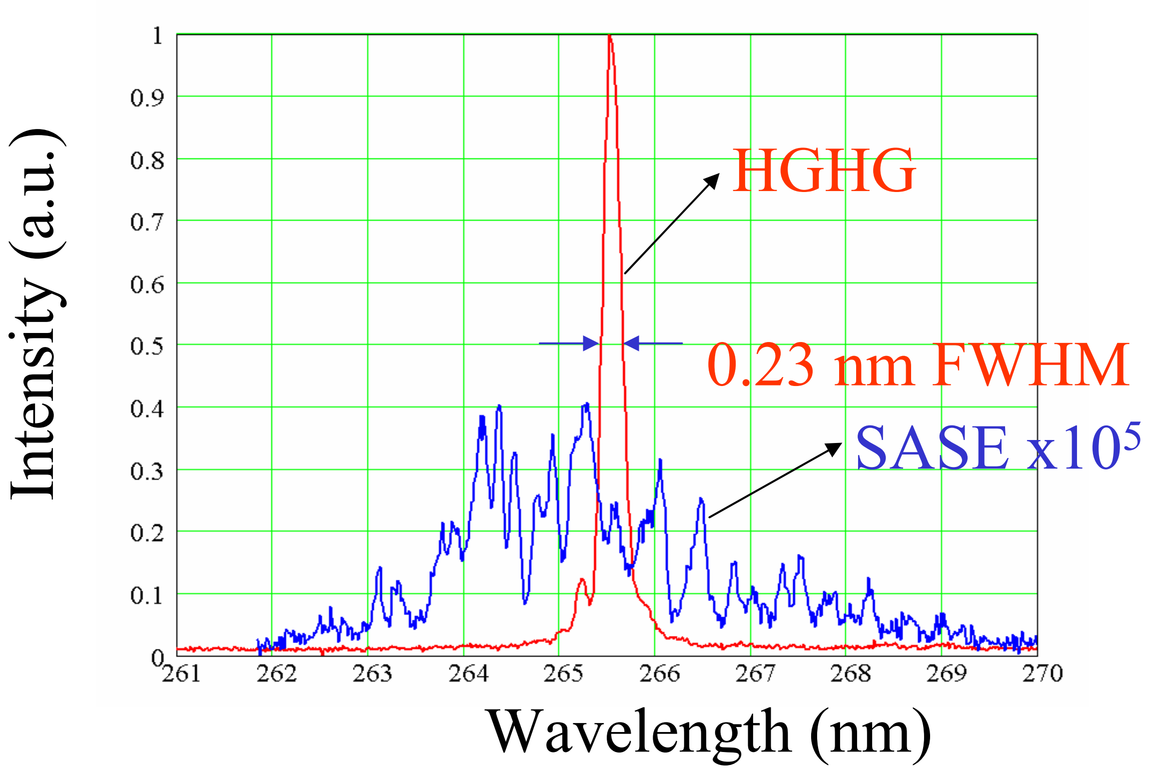
If NISUS were increased to 20 m, the SASE would be saturated. The gray line is a Genesis Simulation.

Average spacing between peaks in SASE spectrum also gives pulse length 1ps



$$T_b = \frac{\lambda^2}{0.64\ \ c\Delta\lambda} = \frac{(266nm)^2}{0.64 \times 3 \times 10^8 m/s \times 0.35nm} \approx 1ps$$

S.Krinsky
(2001)



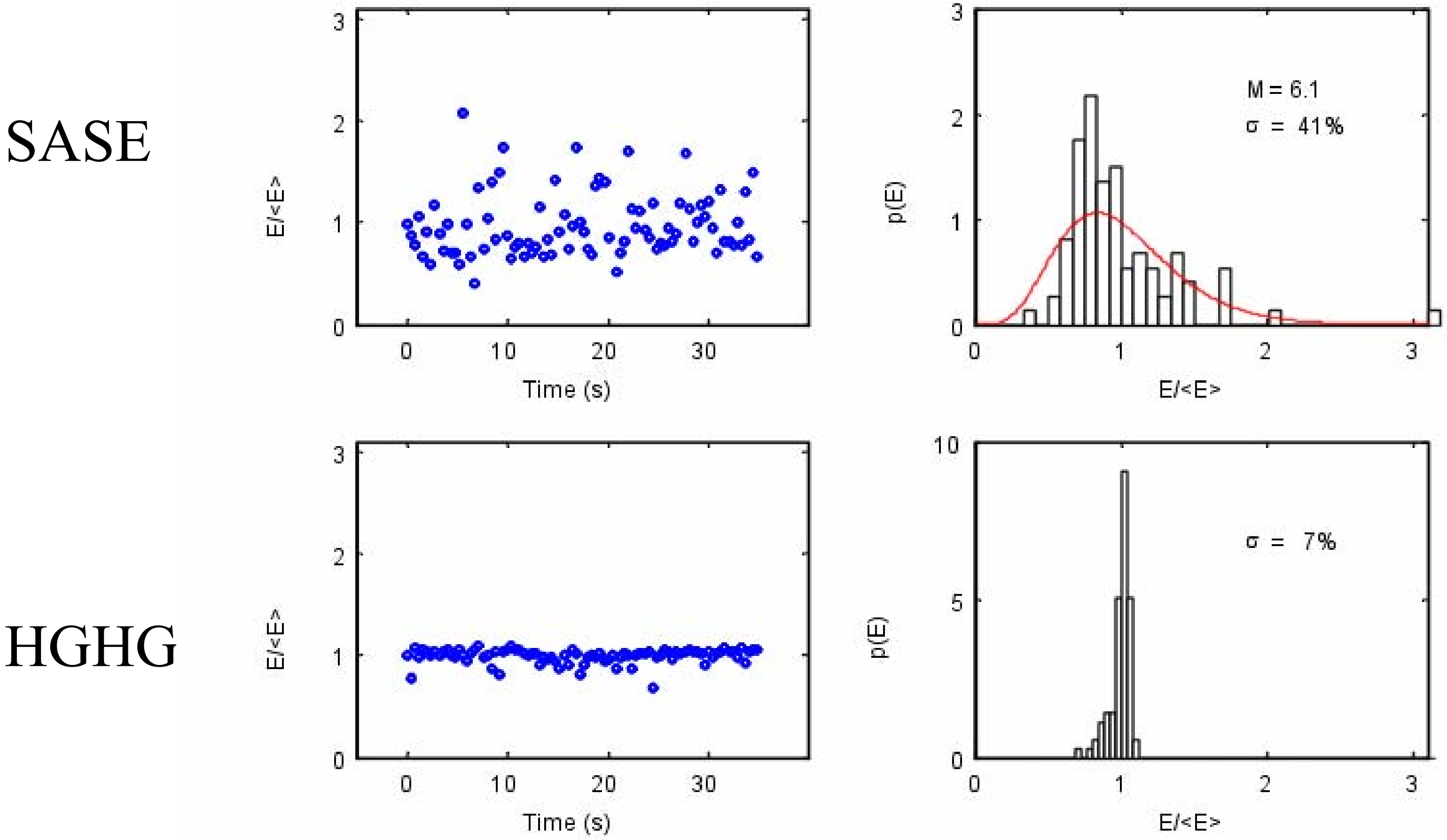
For a flat-top 1ps pulse the bandwidth is

$$\Delta\lambda = \frac{\lambda^2}{\tau c} = \frac{(266nm)^2}{1ps \times 3 \times 10^8 m/s} \approx 0.23nm$$

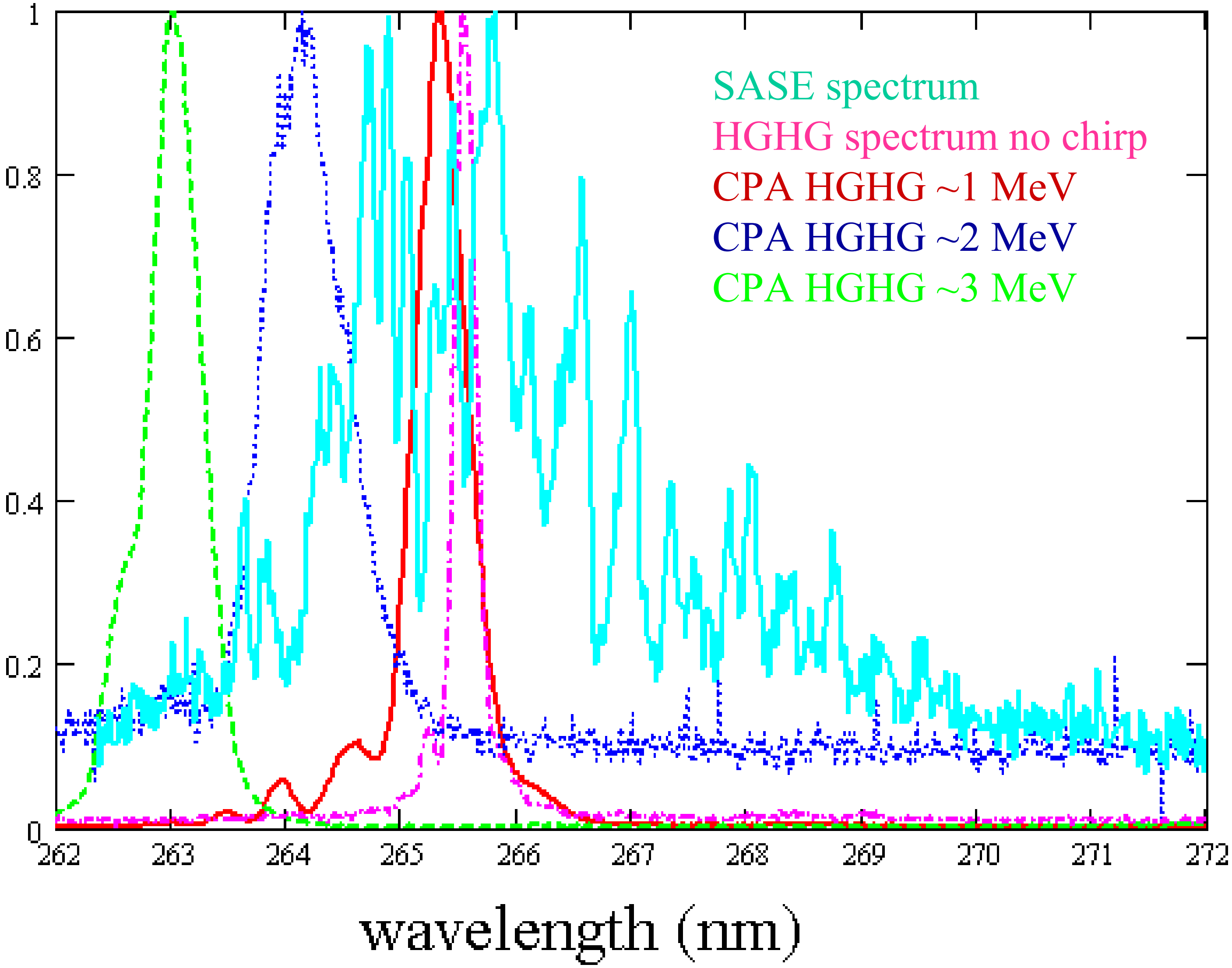
HGHG output is nearly Fourier transform limited

Shot to Shot Intensity Fluctuation

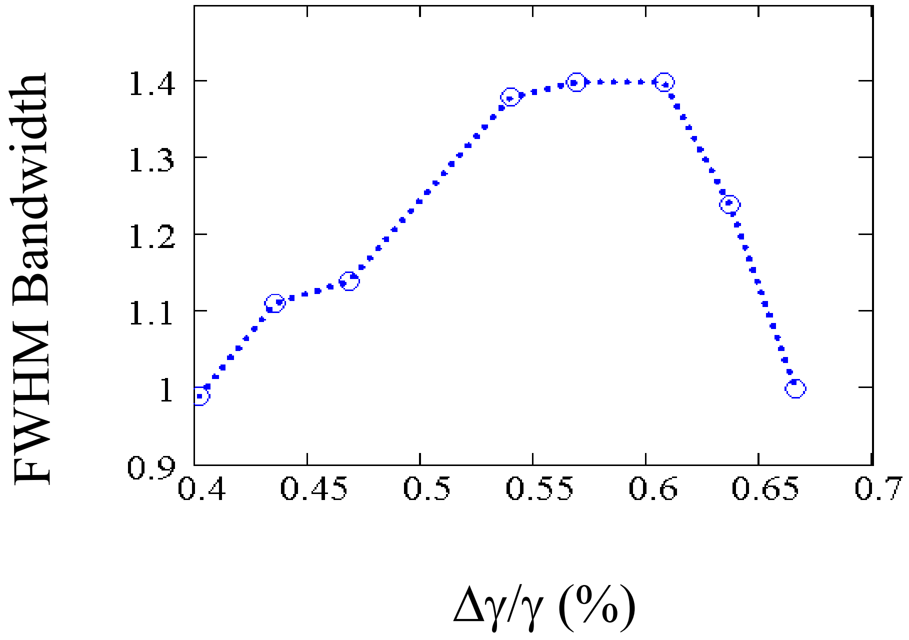
Shows High Stability of HGHG output



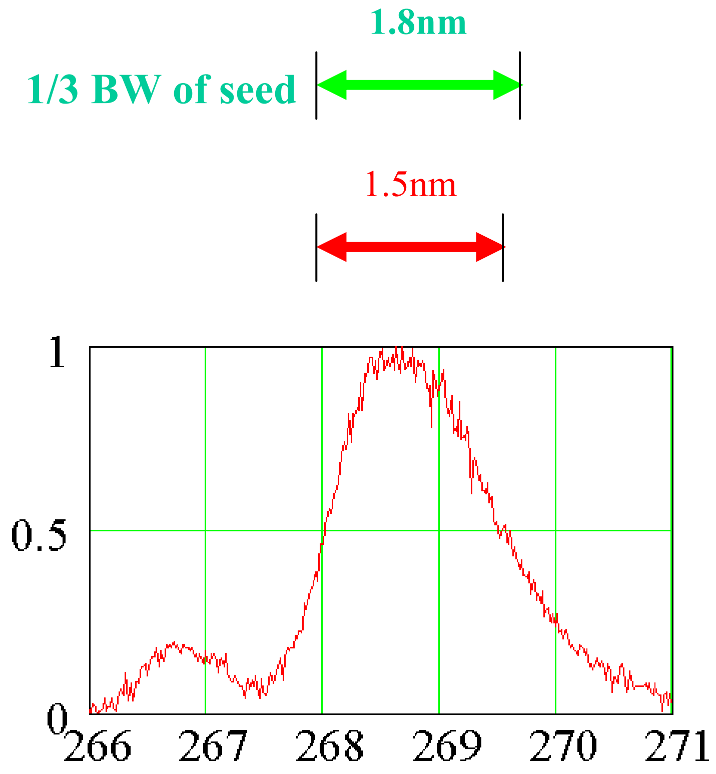
Chirped and Unchirped HGHG spectra



Bandwidth vs Chirp



Seed bandwidth is 5.5 nm currently, thus 1.8 nm is expected at third harmonic.

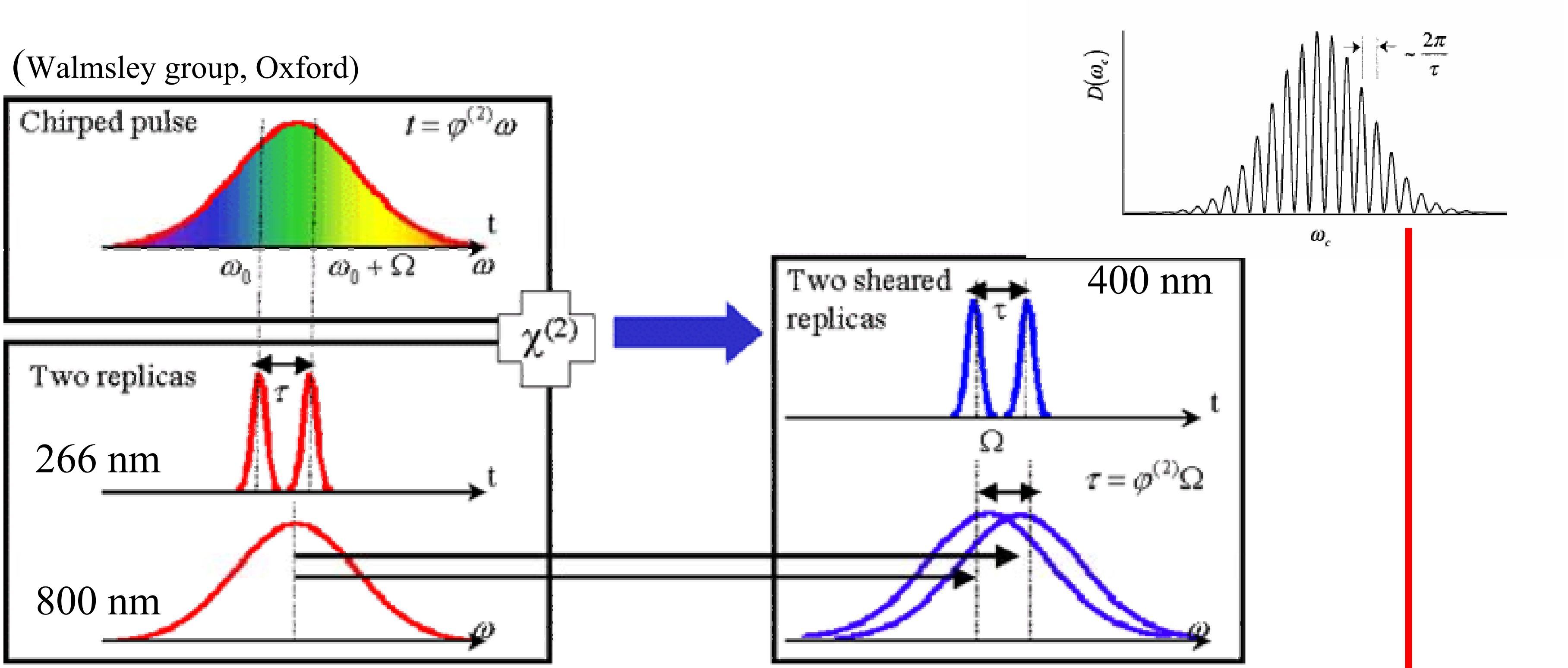


Spectrum at Δγ/γ = 0.62 %

- **Next: measurement of phase distortion**
- **CPA: expected pulse length > 50fs (B. Sheehy, Z. Wu)**
- **R&D: CPA at 100 nm?**

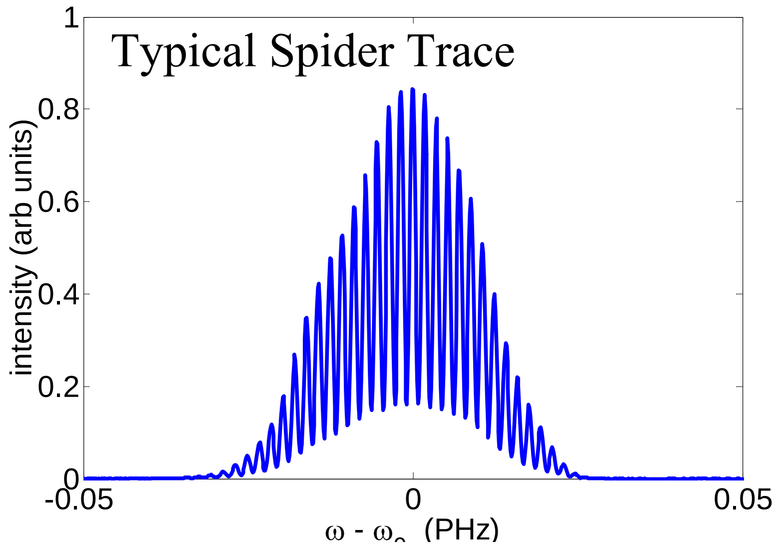
Measuring the spectral phase: SPIDER
(Spectral Interferometry for Direct Electric-Field Reconstruction)

(Walmsley group, Oxford)



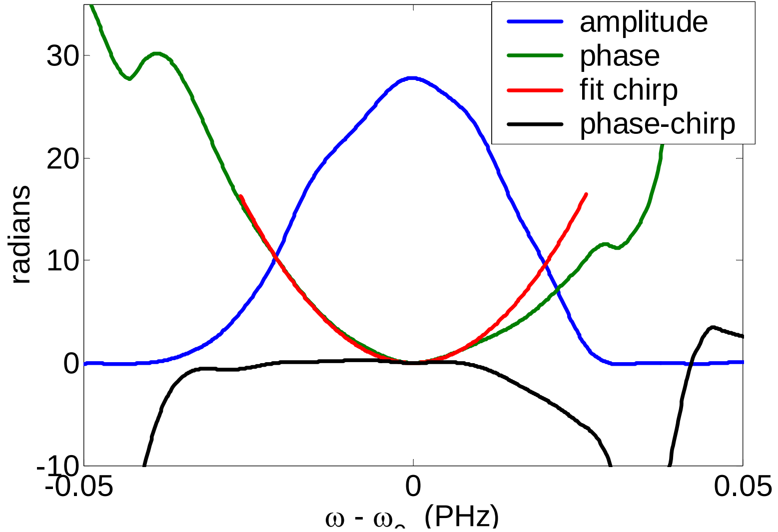
$$\begin{aligned} D(\omega_c) &= |\tilde{E}(\omega_c - \Omega)|^2 + |\tilde{E}(\omega_c)|^2 \\ &\quad + 2|\tilde{E}(\omega_c - \Omega)\tilde{E}(\omega_c)|\,\underline{\cos[\phi_\omega(\omega_c - \Omega)} \\ &\quad \underline{- \phi_\omega(\omega_c) - \tau\omega_c}]. \end{aligned}$$

Spidering a laboratory 266 nm source (B. Sheehy, Z. Wu_)

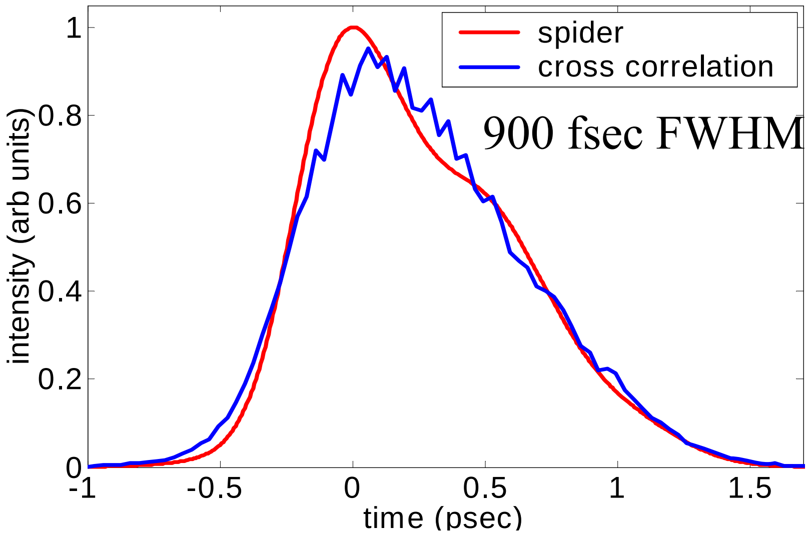


- •Undercompress a 100 femtosecond 800 nm Ti:Sapph chirped-pulse-amplification system
- • Frequency-triple in BBO to 266 nm(spoil phase matching to create an asymmetry in the time profile)
- • Compare scanning multi-shot x-correlation of the 266 nm and a short 800 nm pulse with the average reconstruction, convolved with 250 fsec resolution of the x-correlator

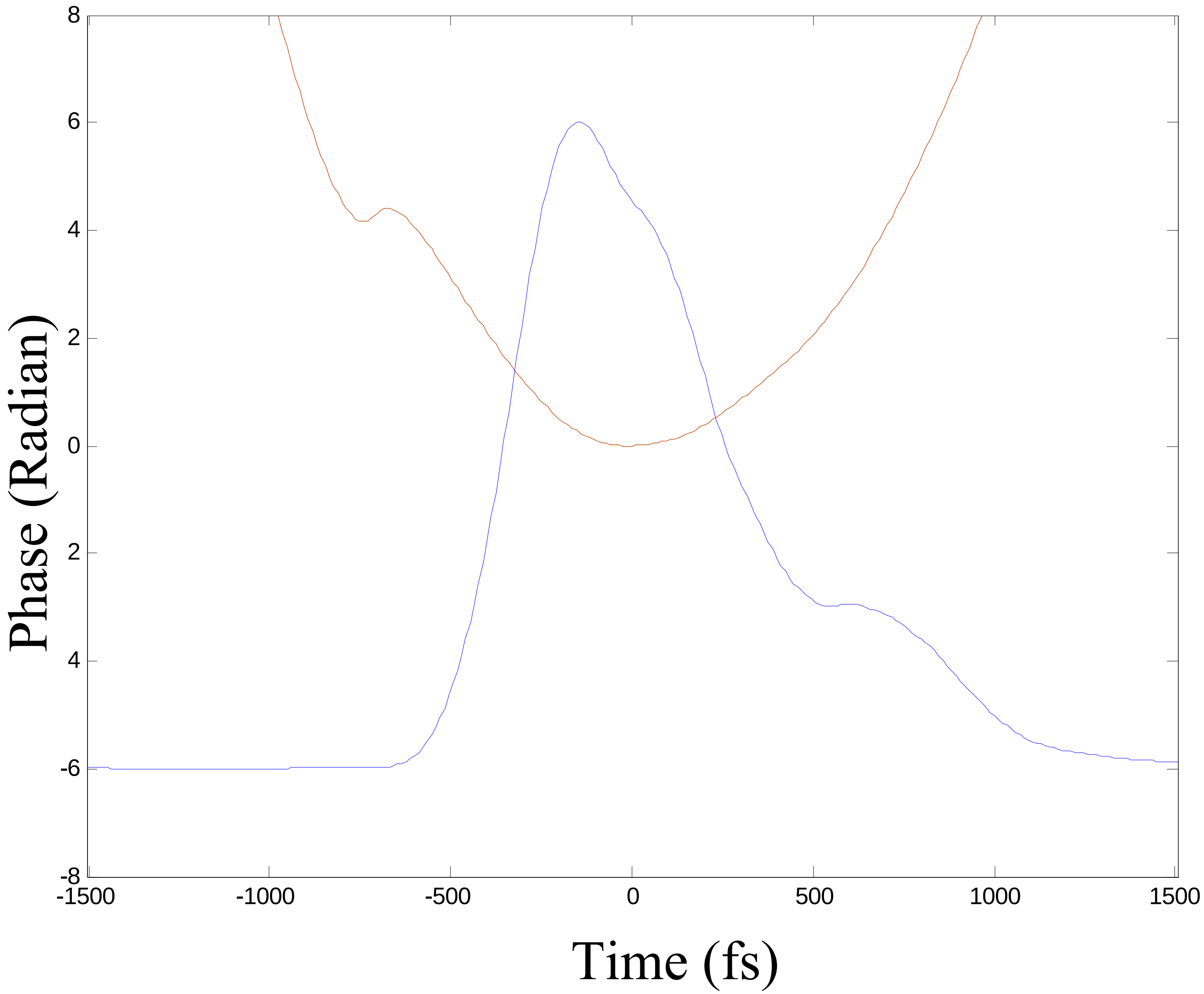
Reconstructed phase and amplitude



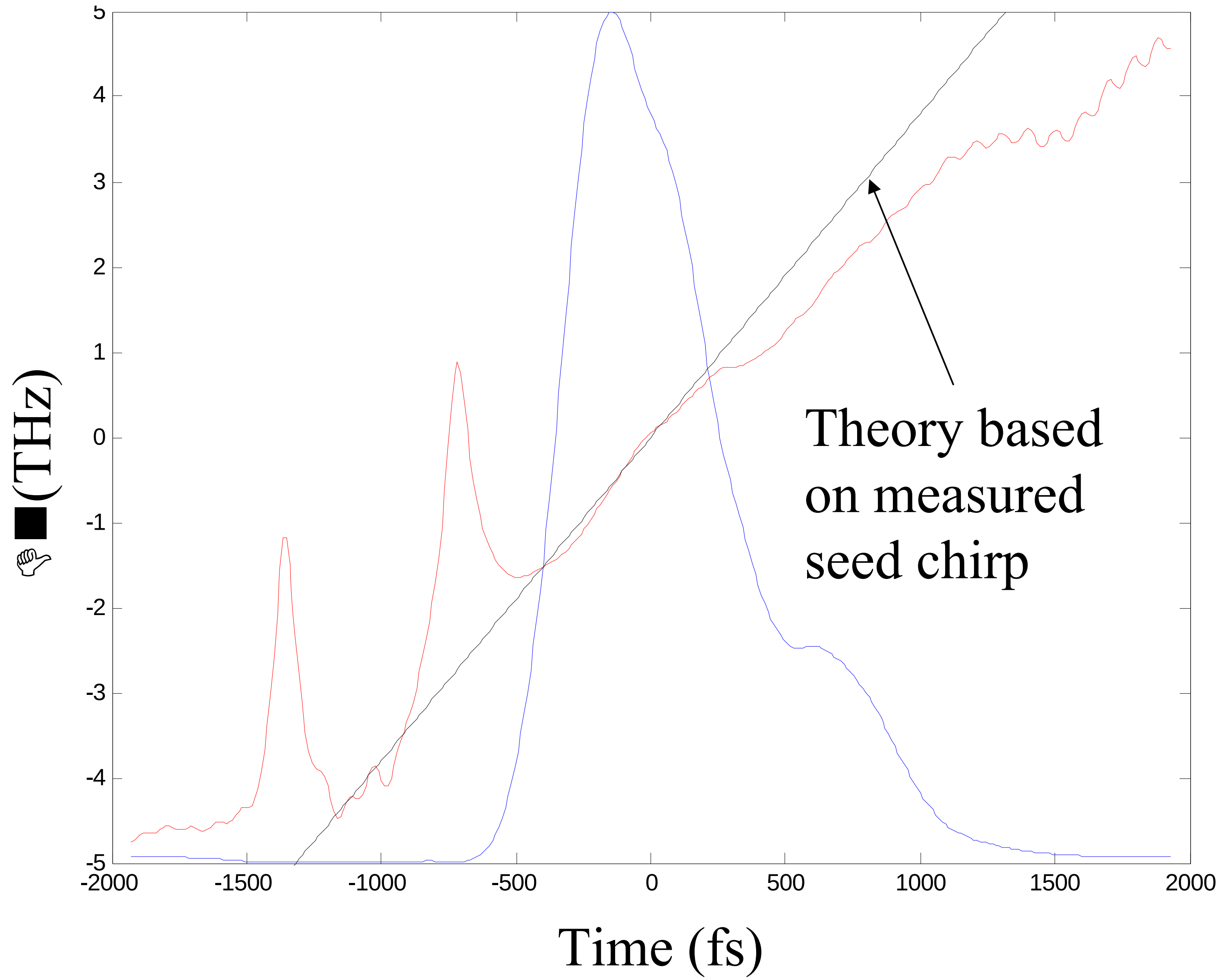
Comparison with x-correlation



Preliminary Data of SPIDER for a chirped HGHG
Phase and amplitude vs. time

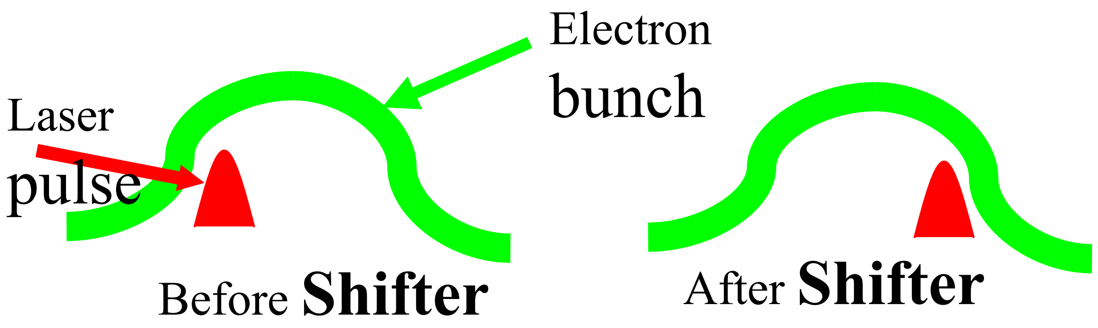


Preliminary Data of SPIDER for a chirped HGHG
Frequency change vs. time (electron beam energy chirp unmatched)



Theory based on measured seed chirp

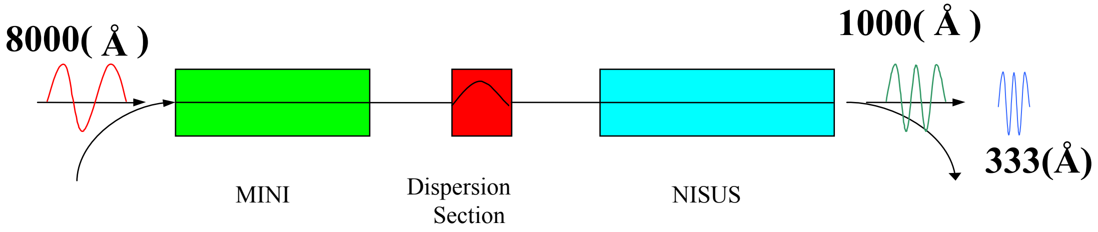
Fresh Bunch Technique



Technical issues:

- Time jitter of seed << electron bunch length
- Reduce number of stages: higher harmonic,
  smaller local energy spread
- Shorter seed laser pulse

Energy Upgrade for 100 nm Output
8’th Harmonic Generation



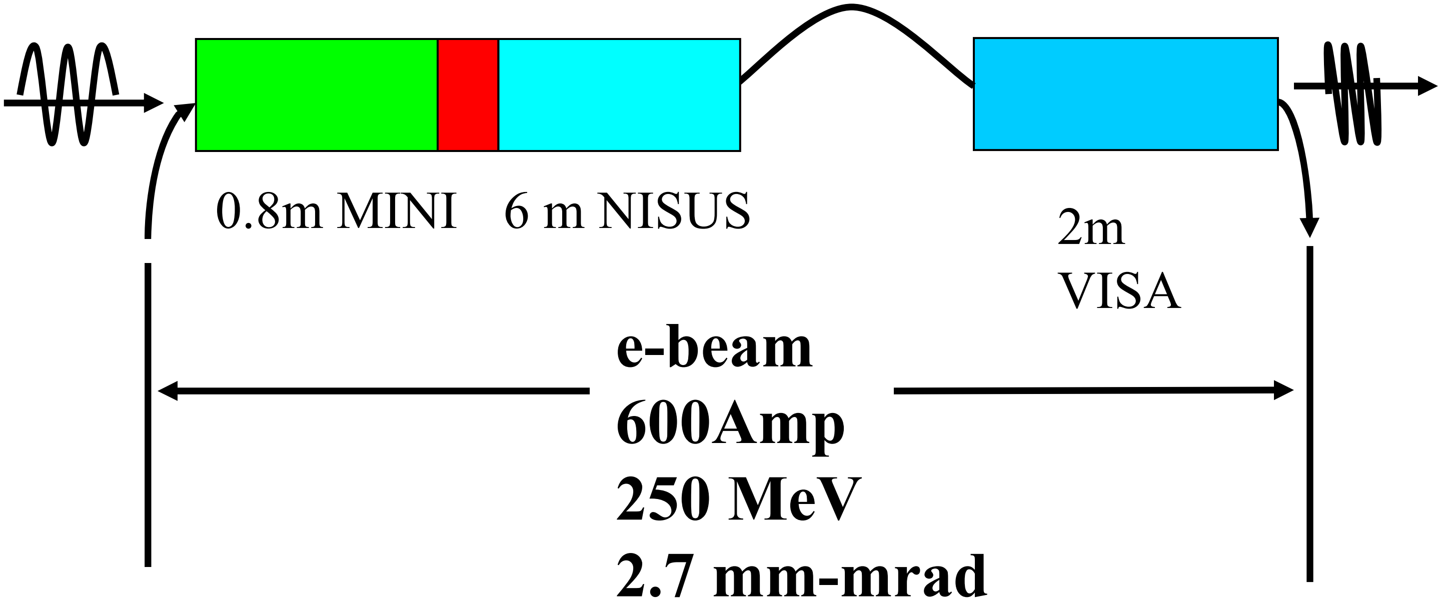
HGHG from 800 nm→100 nm,
Output at 100 nm: ~0.1mJ,
e-beam: 300 Amp, 3 mm-mrad,
Linac Upgrade: Energy 300MeV

Cascading HGHG for Shorter Wavelength

P_{in}=1.5 MW
266nm

56 MW
133nm

P_{out}=140 MW
66.5 nm



0.8m MINI
6 m NISUS

2m
VISA

e-beam
600Amp
250 MeV
2.7 mm-mrad
$\sigma_\gamma / \gamma = 1.\times 10^{-4}$

Pulse length ~ 0.5ps → 70μJ
Range: 50 nm—100nm