Narrow Linewidth X-ray Generation

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Topics

1. Motivation
2. High Harmonic Generation (HHG) seed properties and synchronization
3. Noise propagation in a harmonic cascade
4. Initial numerical studies

Presenting data from recent "Workshop on Physics of Seeded Free Electron Lasers" held at MIT in June.

Proceedings at http://mitbates.mit.edu/xfel/conference.htm

See also poster MOPOS56

Seeded Single-Pass FEL Facility

•Fully coherent milli-Joule pulses at kHz rates

•Wavelength range from 200 nm to 0.1 nm

•30 or more independent beamlines using SCRF

The Scientific Impact

Femtosecond pulse duration

Full transverse coherence

Milli-volt bandwidths

Full quantum degeneracy

High electric field

Chemistry

Biology

Condensed Matter Physics

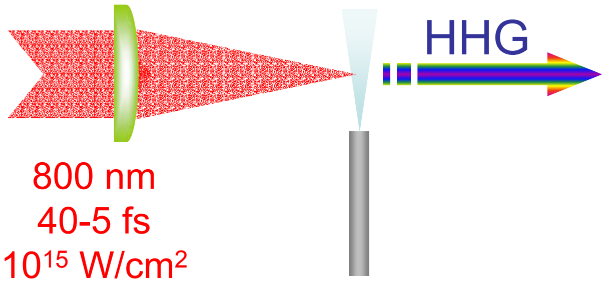
Materials Science

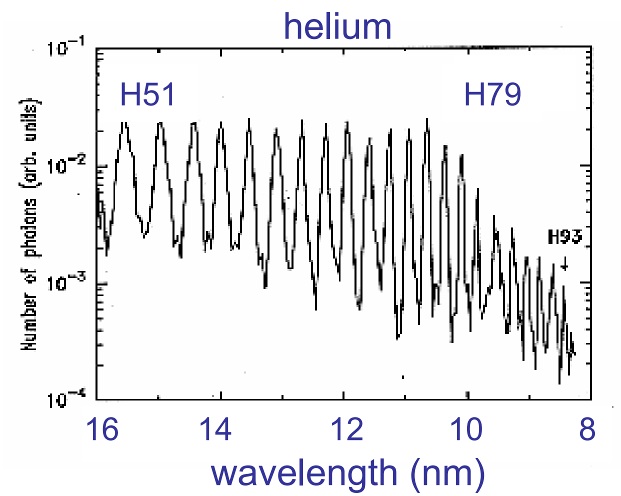
Atomic Physics

Fundamental Physics

Engineering Applications

HHG Seed Generation in a Gas Jet





- intense laser-atom interaction produces a comb of harmonics.
- harmonics result from the field driven electron energy
- cutoff energy law: $I_p + 3U_p$
- ponderomotive energy: $U_p \propto \lambda^2 \, I$

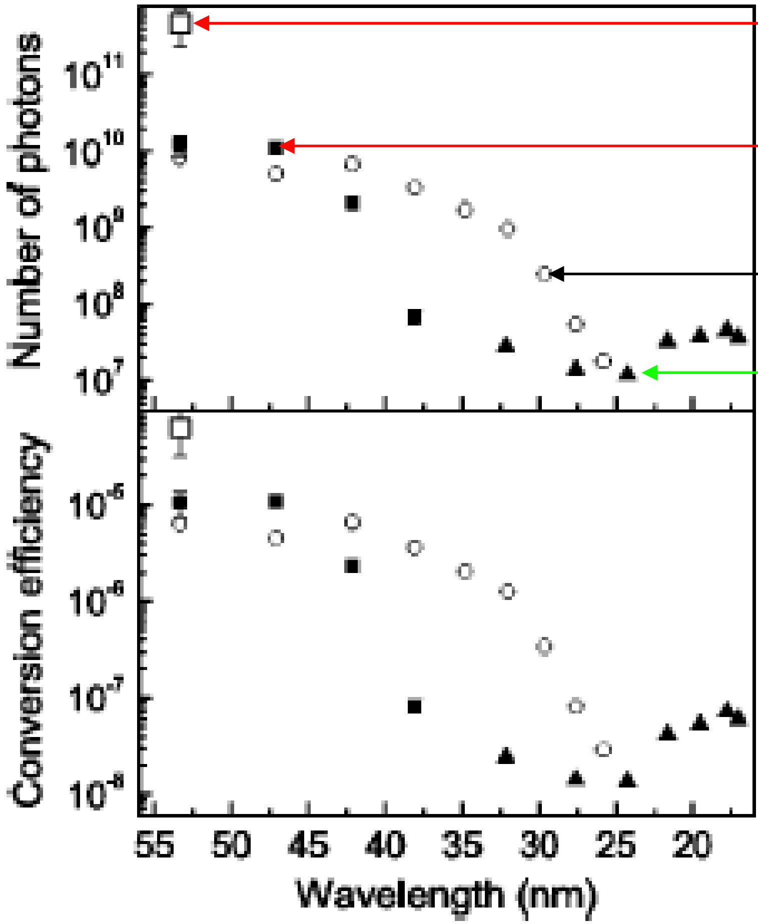
wavelength knob

intensity knob

Courtesy of L. DiMauro, OSU and BNL

HHG Efficiency in EUV

J.-F. Hergott, PRA 66, 021801, (2002); E. Takahashi, PRA 66, 021802, (2002)



Xe: optimized, 1-2μJ @ 55 nm
10μJ @ 70 nm

Xe

Ar

Ne

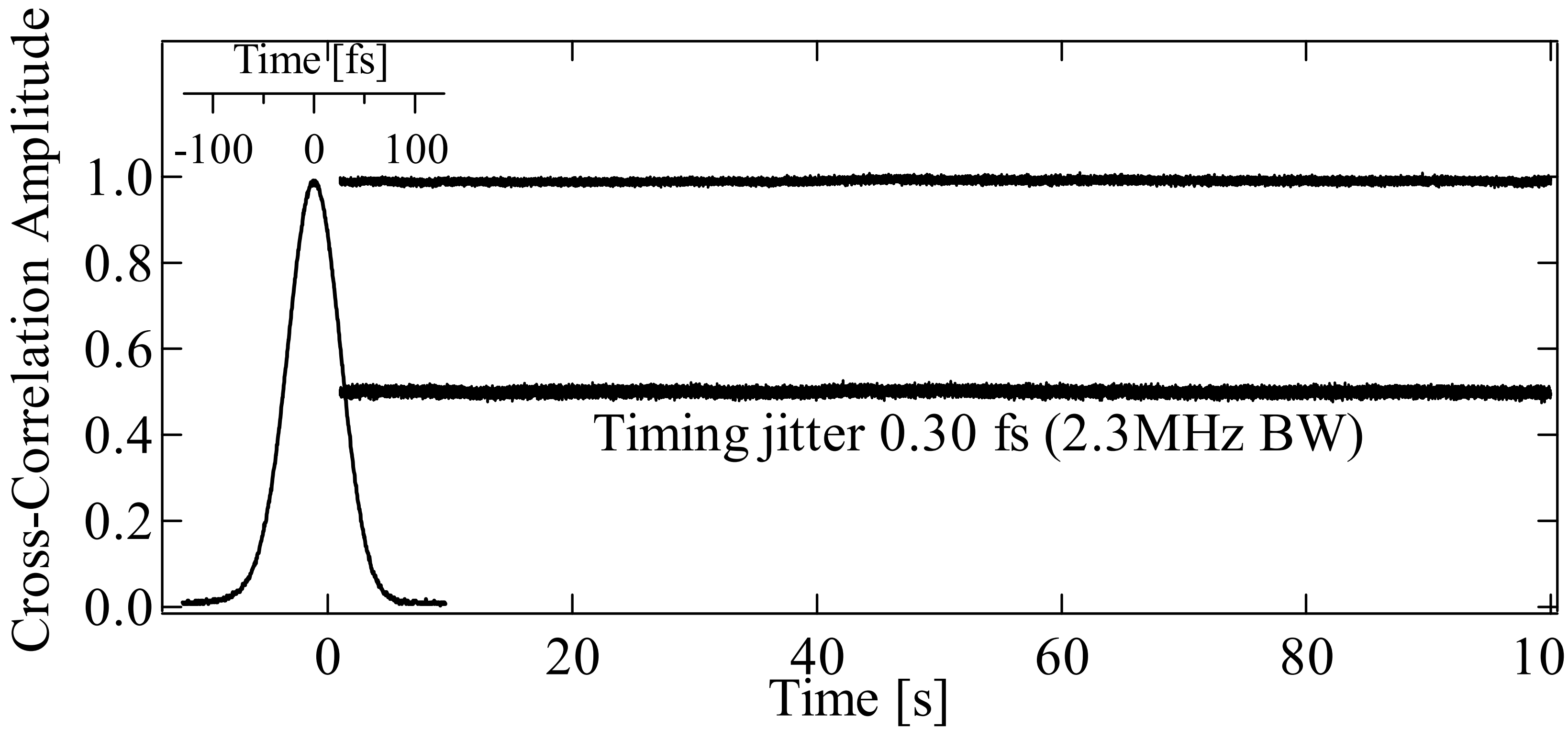
Laser Source:
Ti:sapphire

27 mJ, 60 fs
@ 800 nm

1μJ /100 fs = 10 MW @ 55 nm

Courtesy of F. Kaertner, MIT

Laser Synchronization

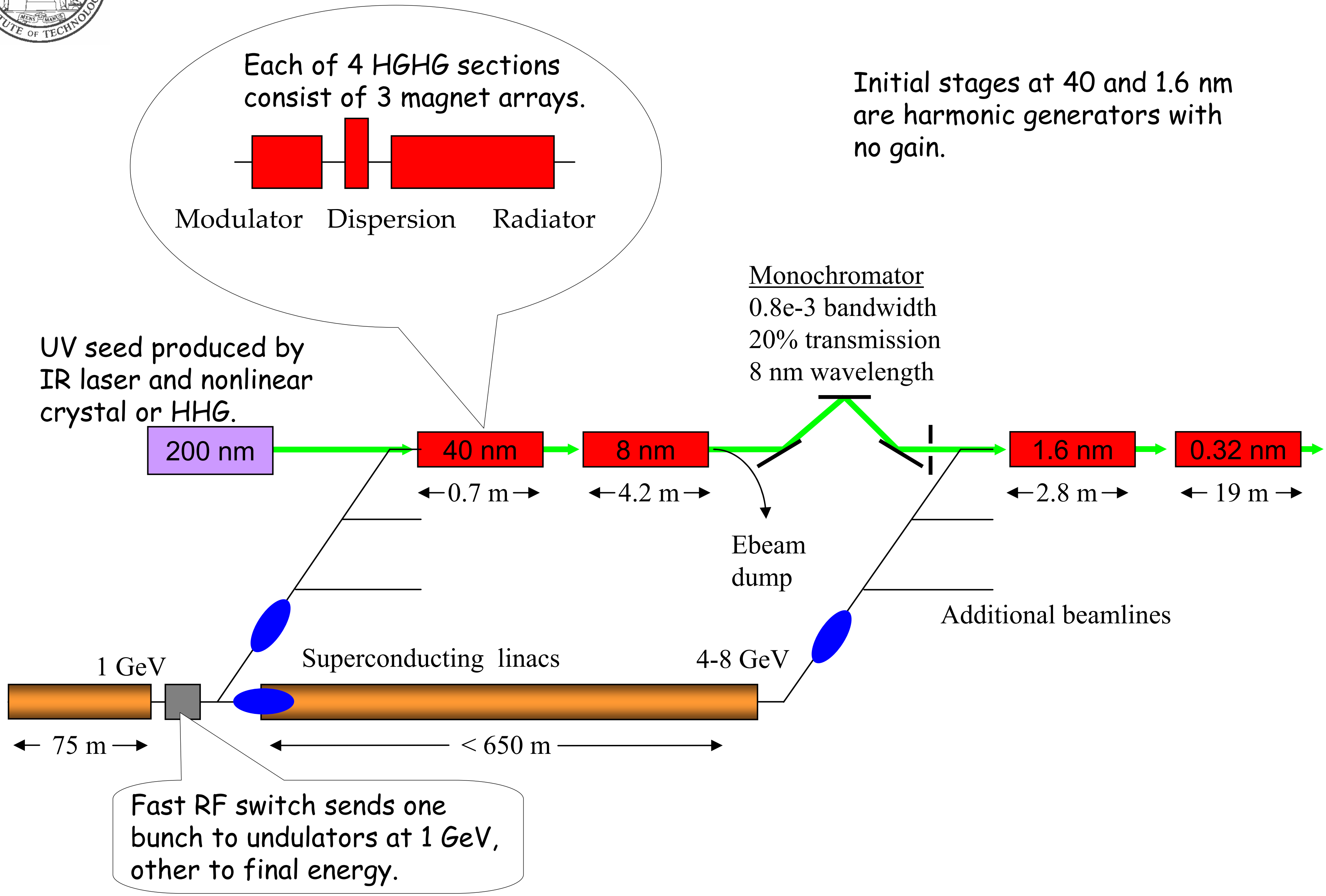


The residual out-of-loop timing-jitter measured from 10mHz to 2.3 MHz is 300 attosec (one tenth of an optical cycle)

See talk TUAOS03 by J.-W. Kim, MIT for details

Harmonic Generation Cascade

Initial stages at 40 and 1.6 nm
are harmonic generators with
no gain.



Ratio of noise/signal for modulator

$$\left(\frac{P_n}{P_s}\right)_h = \frac{h^2}{P_L}\frac{d^2P}{d\omega d\Omega}\Delta\Omega\Delta\omega \equiv$$

Ratio of noise to signal at h^{th} harmonic of modulator

Very sensitive to harmonic number

Bandwidth depends on experiment design

$$\approx \frac{h^2\pi^2}{P_L}\frac{r_e}{\lambda_1}\frac{mc^2}{e} I N_u \quad \frac{\Delta\omega}{\omega_1}$$

Set high seed power

- Following method of Z. Huang presented at MIT workshop

Scaling of Bandwidth

$$\Delta\omega \approx \frac{\omega_1}{N_{u1}} \approx 0.1\,\omega_1$$

Natural bandwidth of spontaneous emission

$$\Delta\omega \approx \rho\,\omega_1 \approx 0.01\,\omega_1$$

SASE bandwidth if modulator is a high gain device

$$\Delta\omega \approx \Delta\omega_{mono} \approx 0.001\,\omega_1$$

Bandwidth set externally by monochromator

Ratio of noise/signal for radiator

$$\left(\frac{P_n}{P_s}\right)_h = \frac{(1/N_e)\Delta\omega_n}{J_h^2(hD\Delta\eta)\,\Delta\omega_s}$$

$\Delta\omega_s = 2\pi c/L_b$ Transform-limited signal bandwidth

$\Delta\omega_n$ Noise bandwidth set by experiment design

$J_h^2(hD\Delta\eta)$ Bessel function $J \leq 0.3$

$\Delta\eta = \Delta\gamma/\gamma$ Energy spread (require $\Delta\gamma \geq h\sigma_\gamma$)

Require $\Delta\gamma \geq h\sigma_\gamma$ and dispersion D $\approx 1/(\Delta\eta)$ for optimal bunching ($J^2 \approx 0.1$)

Example

Consider 1 nC of charge in 1 ps seeded by 280 nm laser and radiating at 7th harmonic (40 nm).

Transform-limited bandwidth is $0.9 \times 10^{-3}\ \omega_1$

Set monochromator bandwidth = $1 \times 10^{-3}\ \omega_1$

Assume optimal bunching, $J^2 = 0.1$

Then radiator noise/signal ratio is

$$\left(\frac{P_n}{P_s}\right)_7 \approx \frac{h}{N_e J_h^2} \approx 1\times10^{-8} \text{ at 40 nm}$$

Upconvert to 0.1 nm to find final noise power after cascade

$$\left(\frac{P_n}{P_s}\right)_{0.1\ \mathrm{nm}} \approx 1\times10^{-8}\,(40/0.1)^2 \approx 2\times10^{-3} \text{ at 0.1 nm}$$

Summary

1. HHG XUV generation showing rapid advances in capability as a short wavelength seed source. May soon be competitive with FELs in nm wavelength range.
2. Timing of multiple lasers in large facility at femtosecond level appears feasible.
3. Analytic estimates indicate harmonic cascades from UV to hard x-ray may be possible, numerical confirmation underway.