Generating sub-100 fs X-ray pulses using the APS injection linac

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Outline

1. Motivation
2. Status of ultrafast X-ray sources and obstacles towards shorter pulse duration
3. Small angle Thomson scattering (SATS) as a solution, and its dynamics at high laser intensities
4. SATS at APS for 50 fs X-ray sources and applications
5. Summary and acknowledgement

Time scale in nature

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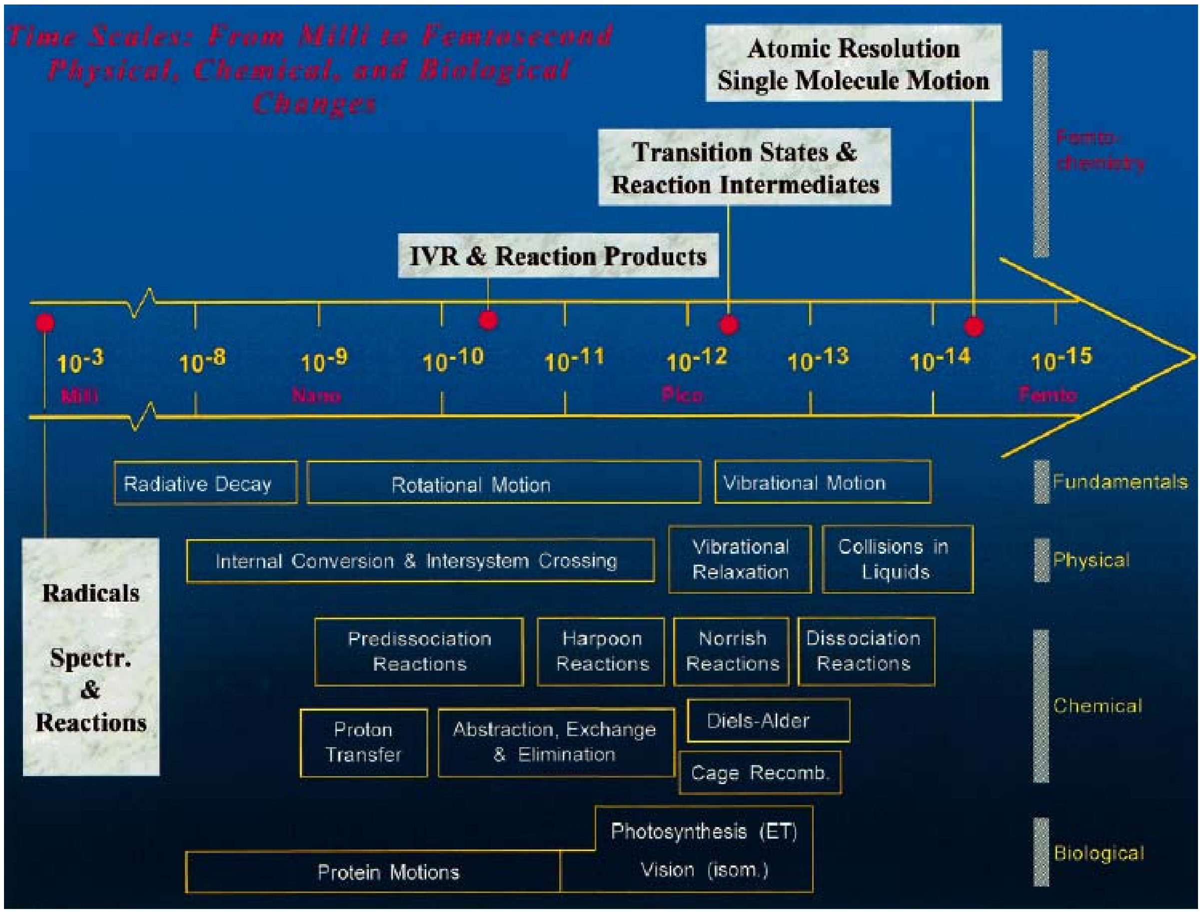
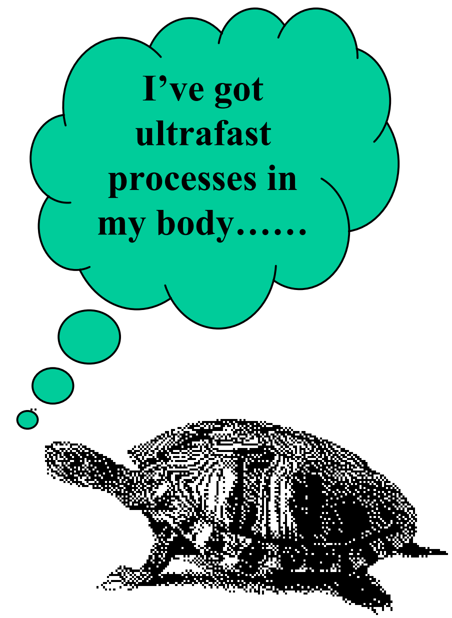
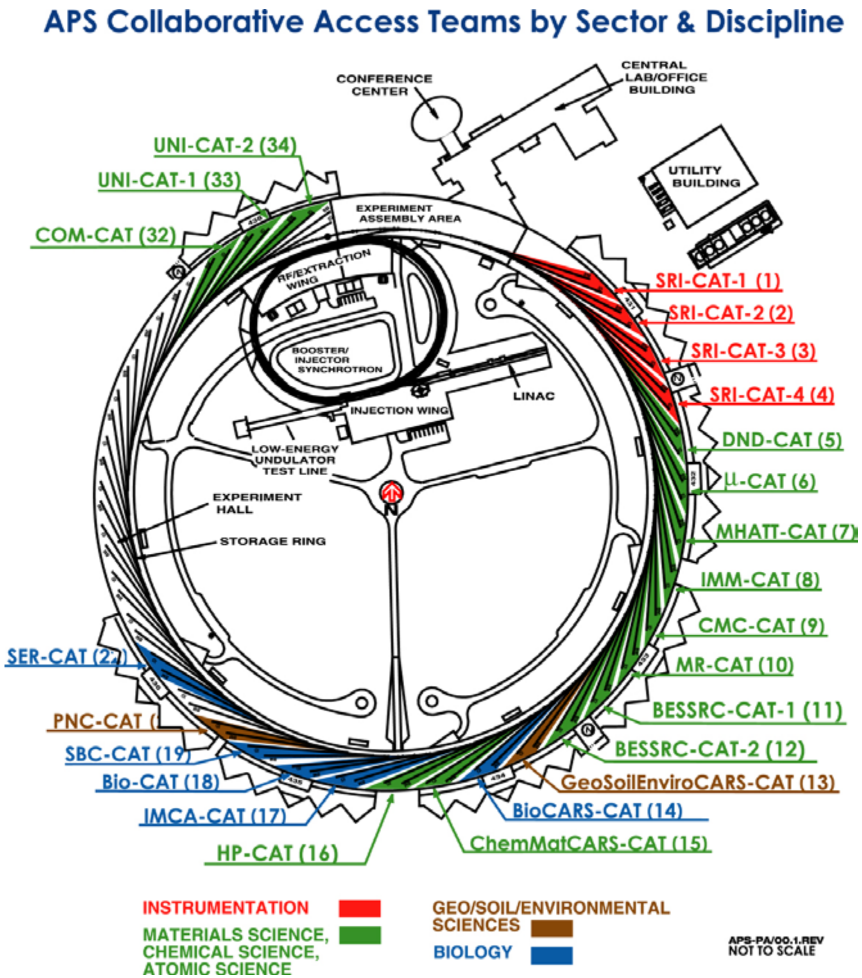
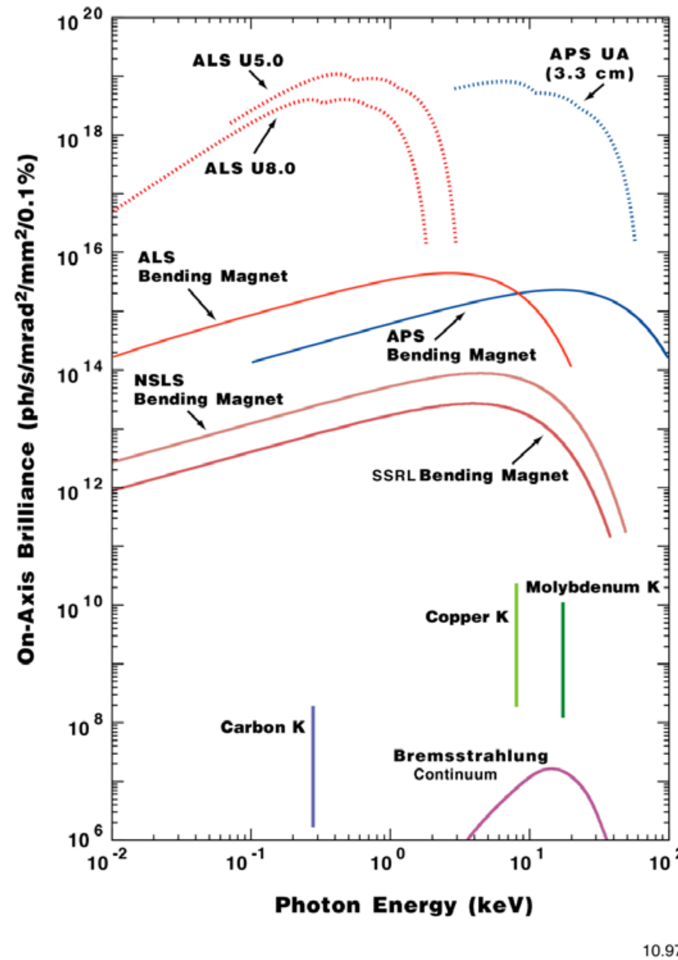




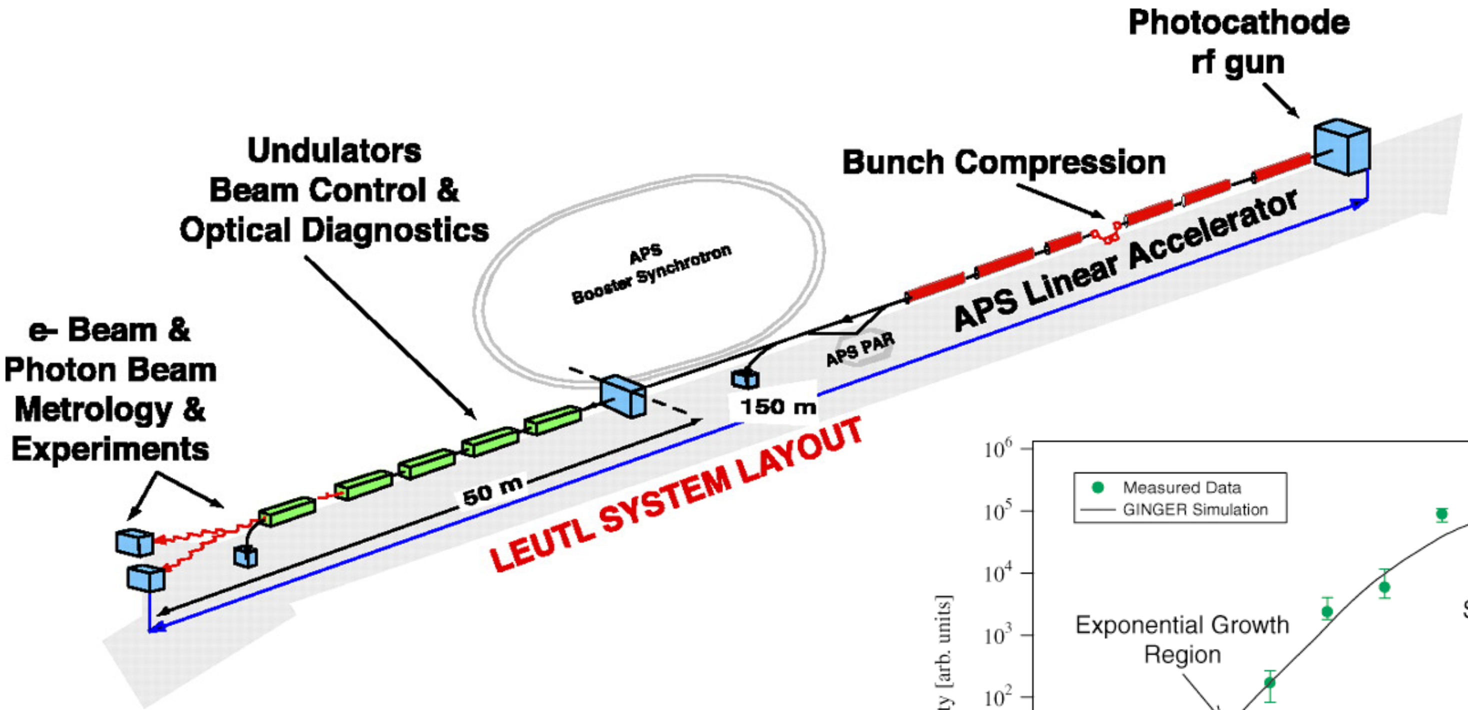
Ahmed H. Zewail, *J. Phys. Chem.* **A 104**, 5660 (2000)

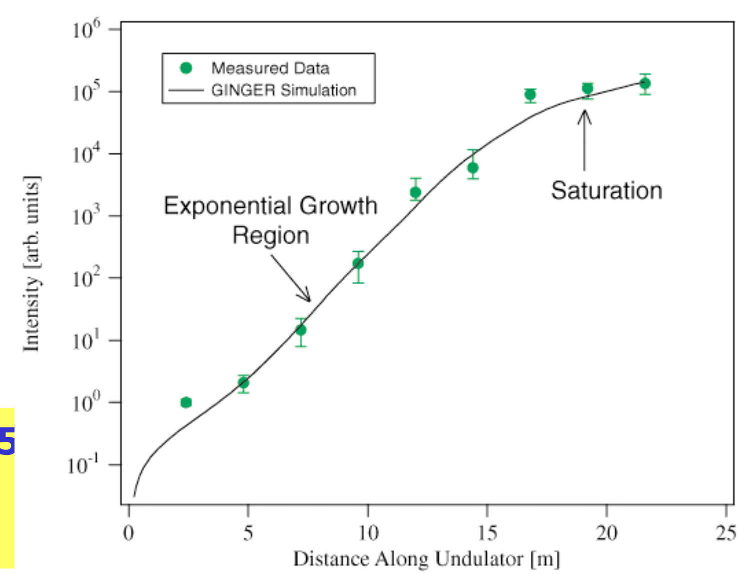
APS: an overview





Free electron lasers at APS



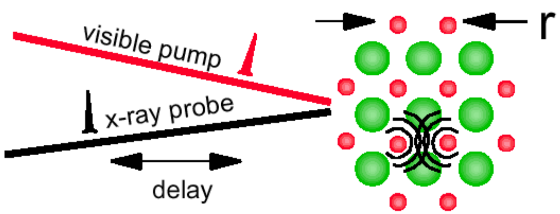


Saturated: 6 Hz, 0.5 ps, 50 μJ @ 265

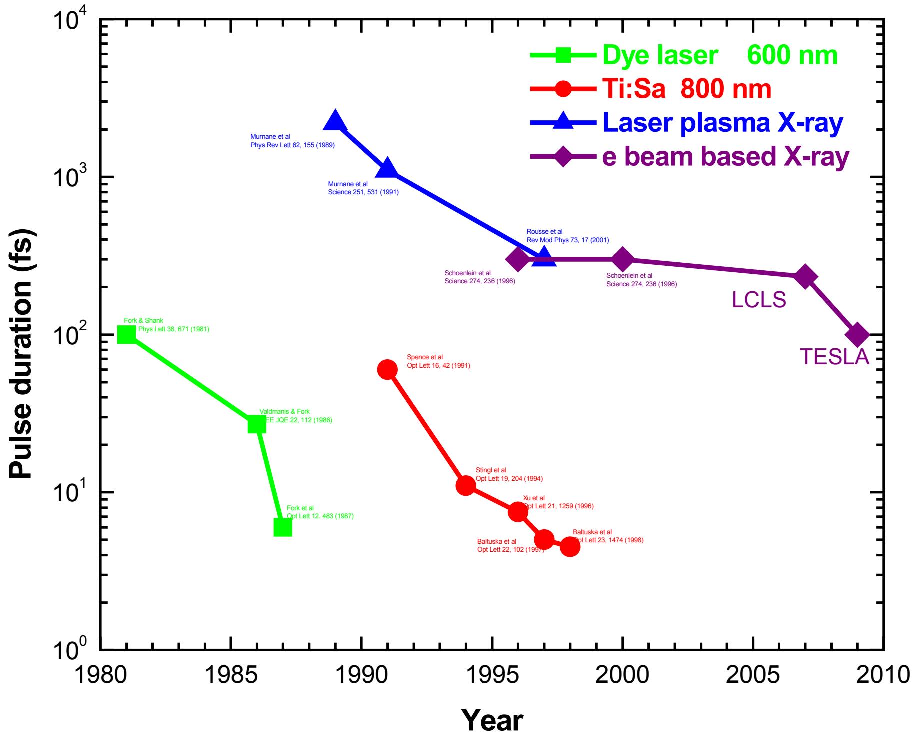
Goal: 30 Hz, 0.5 ps, 0.5 mJ, < 50 nm

Milton *et al*., *Science* **292**, 2037 (2001)

Introduction: to become faster



Schoenlein et al.



It is possible to shorten the pulse duration at the expense of photon flux/spectral brightness!!

Small angle Thomson scattering

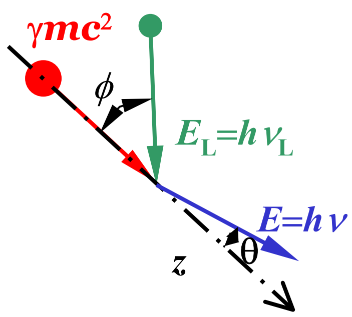
Energy relation

$$E \approx E_L \frac{2\gamma^2}{1+\gamma^2\theta^2}(1-\cos\phi)$$

Scattering cross-section

$$\frac{d\Sigma}{d\Omega} \approx 4r_e^2\gamma^2 \frac{1+(\gamma\theta)^4}{[1+(\gamma\theta)^2]^4}$$

A possible solution to the conflicting interest!!



Reduce interaction angle
→increased beam energy
→reduced slippage
→possible shorter pulse duration

Increased beam energy
→reduced X-ray divergence
→possible high spectra brightness

Why Small angle?

Minimum energy from the APS booster: 400 MeV
For 0.8 nm laser, 2 MeV @ 90^o and 4 MeV @ 180^o

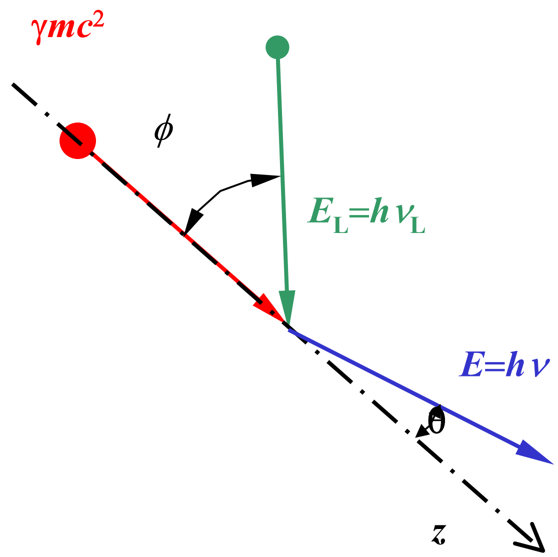
Minimum energy from the linac: 150 MeV
For 0.8 nm Laser, 0.3 MeV @ 90^o and 0.6 MeV @ 180^o

Energy relation

$$E \approx E_L \frac{2\gamma^2}{1+\gamma^2\theta^2}(1-\cos\phi)$$

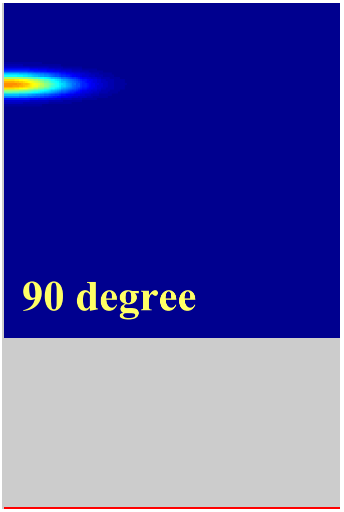
Scattering cross-section

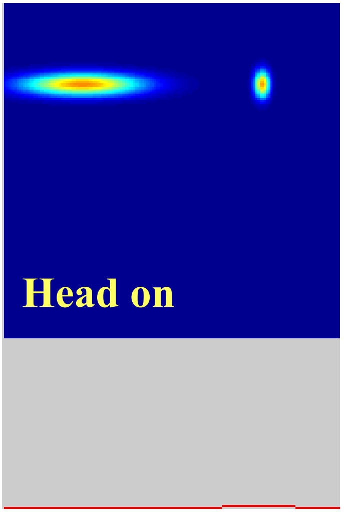
$$\frac{d\Sigma}{d\Omega} \approx 4r_e^2\gamma^2 \frac{1+(\gamma\theta)^4}{[1+(\gamma\theta)^2]^4}$$



For 0.8 nm laser and 8 keV X-ray
0.30 rad @ 150 MeV and 0.11 rad @ 400 MeV

Thomson scattering geometries





X-ray pulse duration

X-ray pulse duration estimate

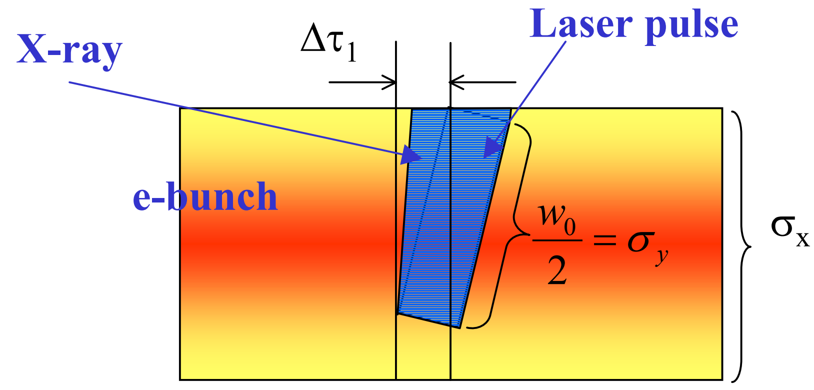
$$\Delta\tau_1 = (1-\cos\phi)\frac{w_0\cos\phi}{2c\sin\phi} - \frac{w_0\sin\phi}{2c} \approx -\frac{w_0}{4c}\phi$$

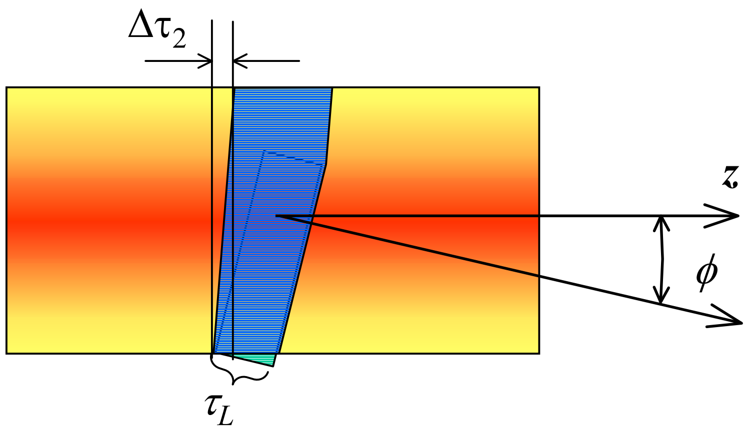
$$\Delta\tau_2 = (1-\cos\phi)\frac{\sigma_x}{c\sin\phi} \approx -\frac{\sigma_x}{2c}\phi$$

$$\tau = \left(\frac{\tau_L^2}{\cos^2\phi} + \Delta\tau_1^2 + \Delta\tau_2^2\right)^{1/2}$$

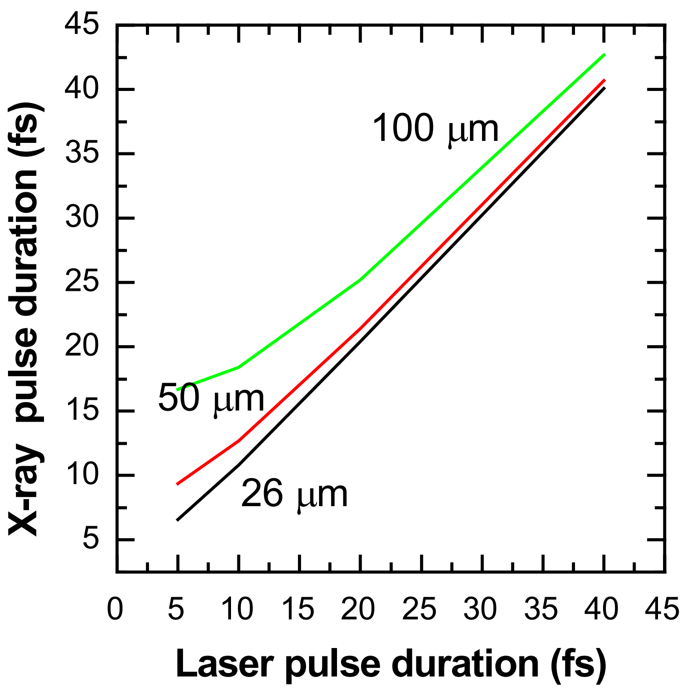
$$= \tau_L\left[1 + \left(1 + \frac{\sigma_x^2 + \sigma_y^2}{4\tau_L^2 c^2}\right)\phi^2\right]^{1/2}$$

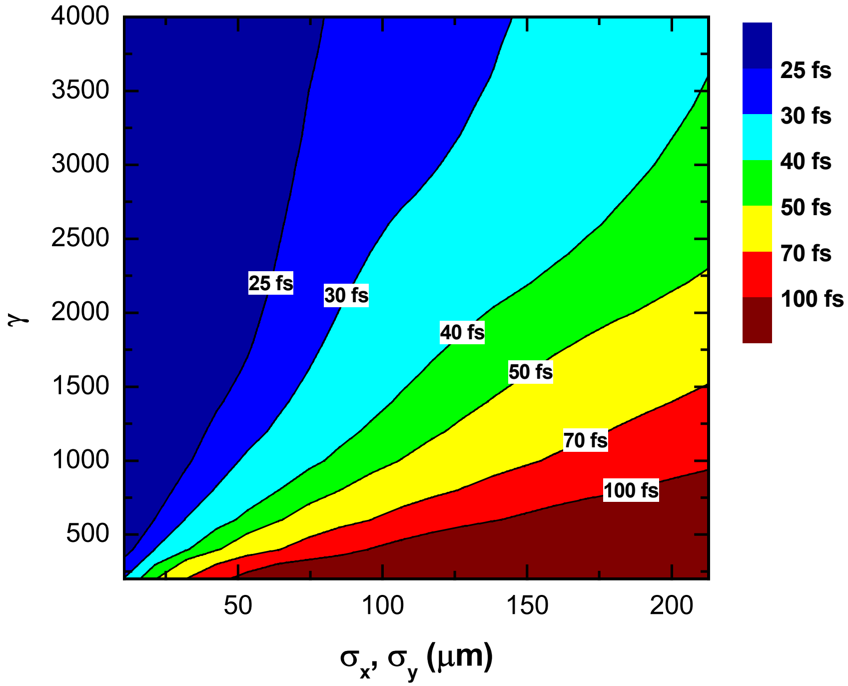
$$\tau \approx \tau_L$$





X-ray pulse duration





Photon energy	**8-keV**
Bunch energy	**650 MeV**
λ_L	800 nm
Φ	**60 mrad**

Scattering efficiency and bandwidth

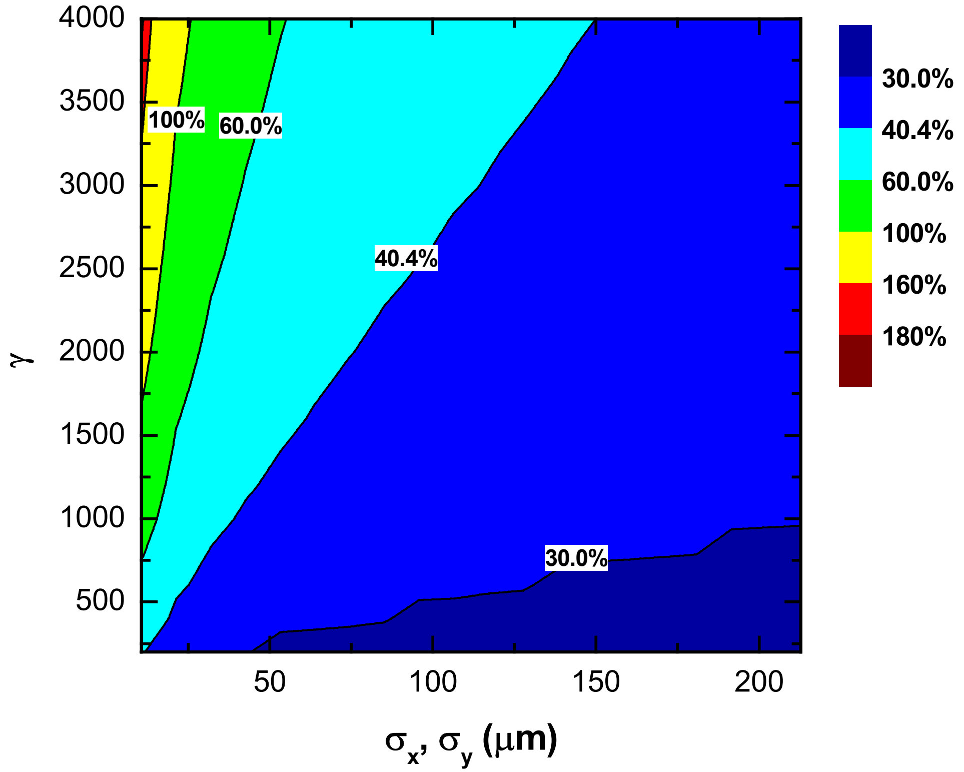
Total photon production

$$n \approx \frac{\Sigma_0}{4\pi}\frac{N_p N_e}{\sigma_y \sigma_z}\phi$$

For small enough ϕ, the angle-integrated bandwidth is

$$\left(\frac{\Delta E}{E}\right)_{\text{int}} \approx 2\frac{\sigma_\phi}{\phi} = \frac{\lambda_L}{2\pi\sigma_y\phi}$$

Full bandwidth



X-ray photon flux

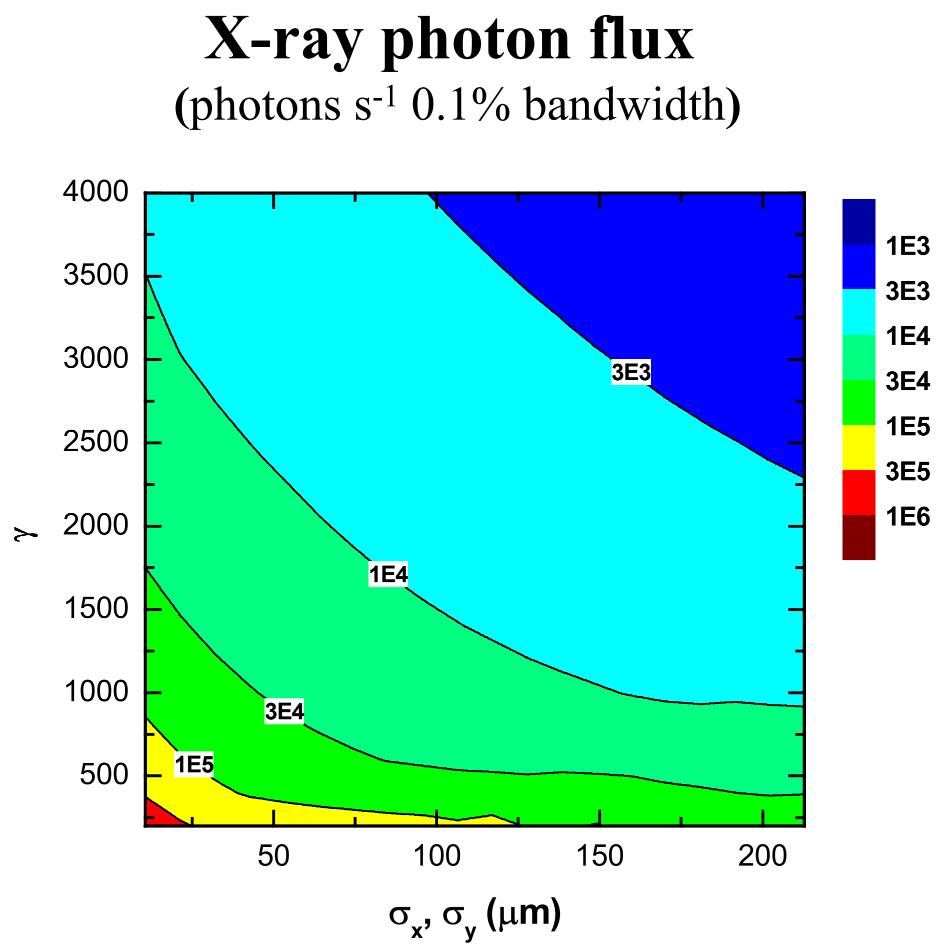
$$F \approx \frac{1}{2\pi}\frac{n}{\tau}\frac{\delta_{BW}}{(\frac{\Delta E}{E})_{\text{int}}}$$

$$\approx \frac{\Sigma_0}{4\pi}\frac{N_p N_e}{\sigma_z \tau_L}\frac{\delta_{BW}}{\lambda_L}\phi^2$$

$$\approx \frac{\Sigma_0}{4\pi}\frac{N_p N_e}{\sigma_z \tau_L}\frac{\delta_{BW}}{\lambda}\frac{1}{\gamma^2}$$

Where we used

$$\phi = \frac{1}{\gamma}\sqrt{\frac{E}{E_L}} = \frac{1}{\gamma}\sqrt{\frac{\lambda_L}{\lambda}}$$

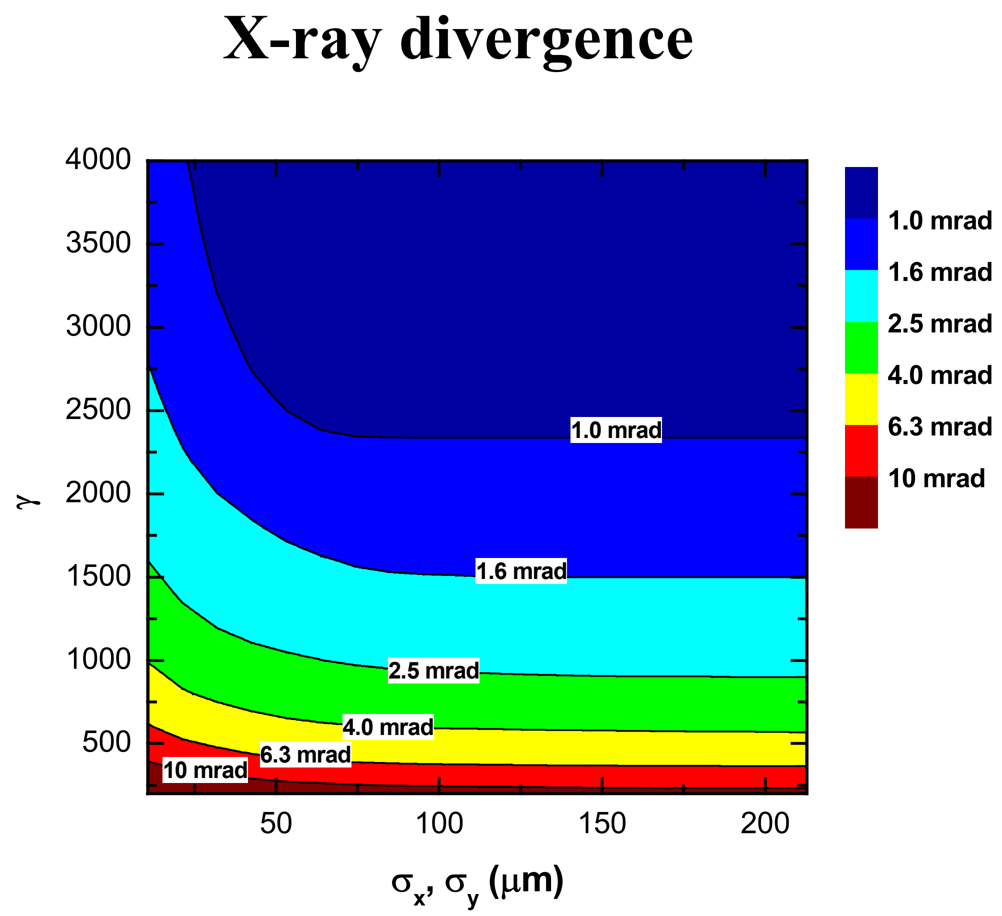


X-ray divergence

The divergence is the convolution of the Lorentz contraction effect and the divergence of the e-bunch:

$$\varphi_{x,y} \approx \left(\frac{1}{\gamma^2} + \sigma^2_{x',y'} \right)^{1/2}$$

$$\approx \frac{1}{\gamma}$$



X-ray spectral brightness

$$B = \frac{F}{(2\pi)^2 \varphi_x \varphi_y s_x s_y}$$

$$\approx \frac{\sqrt{2}\Sigma_0}{16\pi^3} \frac{N_p N_e}{\sigma_x \sigma_y \sigma_z \tau_L} \frac{\delta_{BW}}{\lambda}$$

Parameters

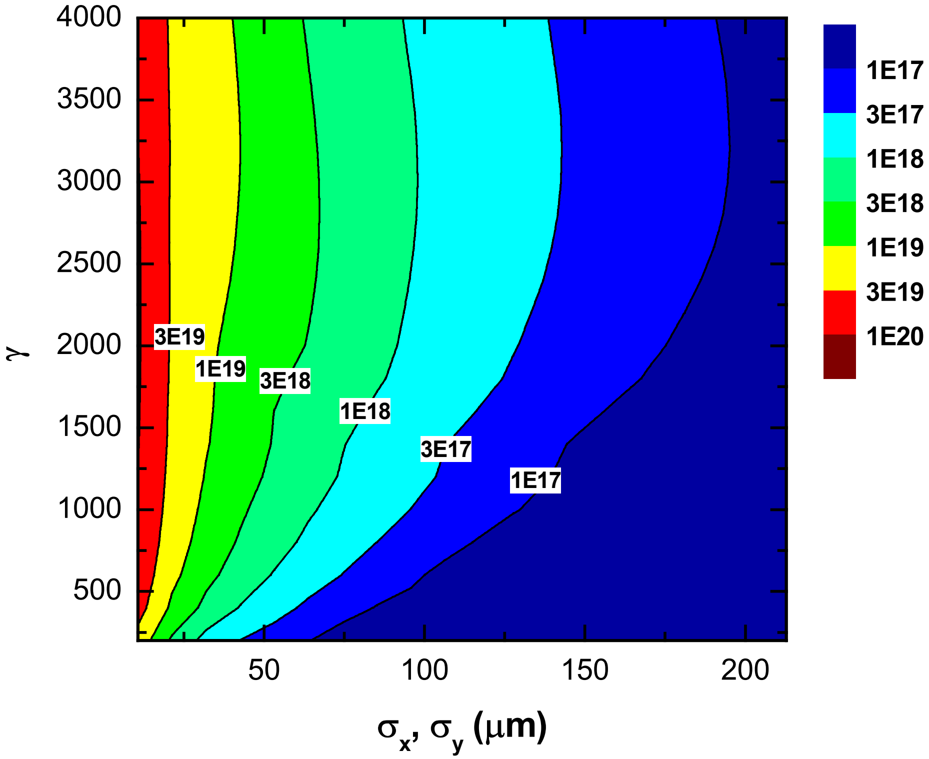
σ_z=0.212 ps
$\varepsilon_n=10^{-5}$ m rad
1 nC charge

τ_L=8.6 fs (FWHM 20)
λ_L=800 nm
2 J per pulse

E=8 keV

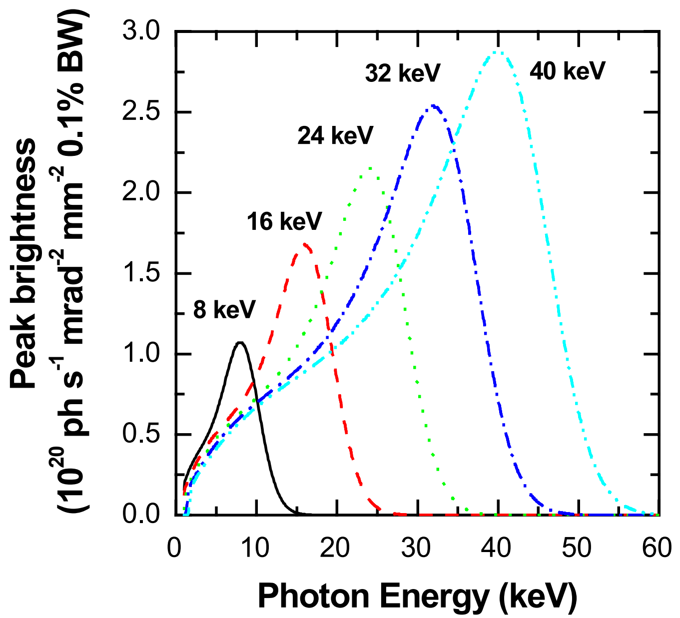
Peak spectral brightness

Photons s^{-1} mm^{-2} $mrad^{-2}$ per 0.1% BW

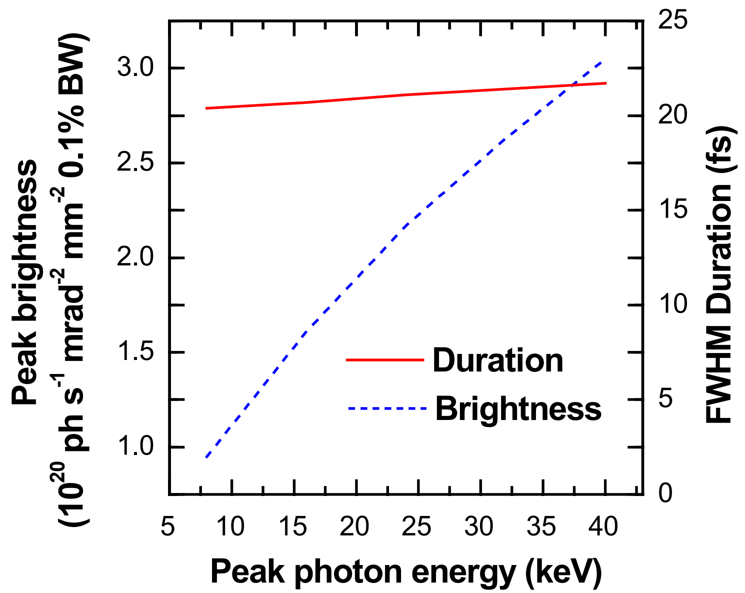


X-ray tunability

Sample spectra



Brightness and duration



Bunch Energy	**650 MeV**
Beta function	**1.5 cm**
Emittance	**10 μm**
Laser	**20-fs, 2-J @ 800 nm**

Comparison

	APS Linac [a]	ALS 90 TS [b]	ALS Slicing [c]	Laser plasma[d]
Wavelength (Å)	1.5-0.4	0.4	6	1-10
Rep rate (Hz)	6	100	10^5	10
Pulse length (fs)	**20**	300	~100	~300
Average flux [e]	5×10^4	10^5	10^7	10^9
Divergence (mrad)	3	10	0.6	4π srad
Peak brightness [f]	**$\sim10^{20}$**	$\sim10^{16}$	$\sim10^{19}$	$\sim10^{18}$

a. Predicted, with a 6-Hz, 20-fs, 2-J, 800-nm laser at 650 MeV beam energy
b. Schoenlein *et al*, *Science* **274**, 236 (1996), calculation
c. Schoenlein *et al*, *Science* **287**, 2237(2000), calculation
d. Rousse *et al*, *Rev Modern Phys* **73**, 17 (2001), experimental estimate
e. In photons s^{-1} per 0.1% BW
f. In photons s^{-1} mm^{-2} $mrad^{-2}$ per 0.1% BW

High intensity: dynamic simulation

Why?

1. The role of ponderomotive scattering
2. The contribution of high order harmonics

How?

1. Numerically solving the Lorentz equation, using the field by the angular spectrum representation method (Quesnel and Mora, PRE 58, 3719).
2. The radiation is calculasted using Lienard-Wiechert potentials [Jackson, Classical Electrodynamics, 2^{nd} ed. (Wiley, New York, 1975), chap. 14]

Test particle dynamic calculation

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Field formulas: angular spectrum representation

$$E_x = \frac{E_0}{4\epsilon^2}\left(I_1 + \frac{x^2 - y^2}{k_0 r^3} I_2 + \frac{y^2}{r^2} I_3 \right),$$

$$E_y = -\frac{E_0}{4\epsilon^2}\frac{xy}{k_0 r^3}(k_0 r I_3 - 2 I_2),$$

$$E_z = \frac{E_0}{4\epsilon^2}\frac{x}{r} I_4,$$

$$B_x = \frac{E_y}{c},$$

$$B_y = \frac{E_0}{4c\epsilon^2}\left(I_1 + \frac{y^2 - x^2}{k_0 r^3} I_2 + \frac{x^2}{r^2} I_3 \right),$$

$$B_z = \frac{E_0}{4c\epsilon^2}\frac{y}{r} I_4,$$

$$I_1 = \int_0^1 e^{-b^2/4\epsilon^2}(1 + \sqrt{1 - b^2})\sin(\phi_b) J_0(k_0 r b) b \, db$$

$$I_2 = \int_0^1 e^{-b^2/4\epsilon^2}\frac{\sin(\phi_b)}{\sqrt{1 - b^2}} J_1(k_0 r b) b^2 db,$$

$$I_3 = \int_0^1 e^{-b^2/4\epsilon^2}\frac{\sin(\phi_b)}{\sqrt{1 - b^2}} J_0(k_0 r b) b^3 db,$$

$$I_4 = \int_0^1 e^{-b^2/4\epsilon^2}\left(1 + \frac{1}{\sqrt{1 - b^2}} \right)\cos(\phi_b) J_1(k_0 r b) b^2 db$$

$$\phi_b = \omega_0 t - k_0 z\sqrt{1 - b^2} + \phi_0$$

$$r = \sqrt{x^2 + y^2}$$

$$\epsilon = 1/k_0 w_0$$

Test particle dynamic calculation

Energy spectrum calculation by Lienard-Wiechert potentials

$$\frac{d^2 I}{d\omega\, d\Omega} = \frac{e^2\omega^2}{4\pi^2 c} \left| \int_{-T/2}^{T/2} dt [\mathbf{n} \times (\mathbf{n} \times \boldsymbol{\beta})] \times \exp[i\omega(t - \mathbf{n}\cdot\mathbf{r}/c)] \right|^2$$

Ponderomotive scattering

The ponderomotive force

$$\frac{d\mathbf{p}}{dt} \approx -\frac{mc^2}{\gamma}\nabla a^2$$

Where a=10^{-9}$I^{1/2}\lambda_L$.

γ_0=1270
ϕ=0.062
λ=0.8 μm
w_0=10.5 μm
$\Delta\tau$=20 fs FWHM
E_L=2 J

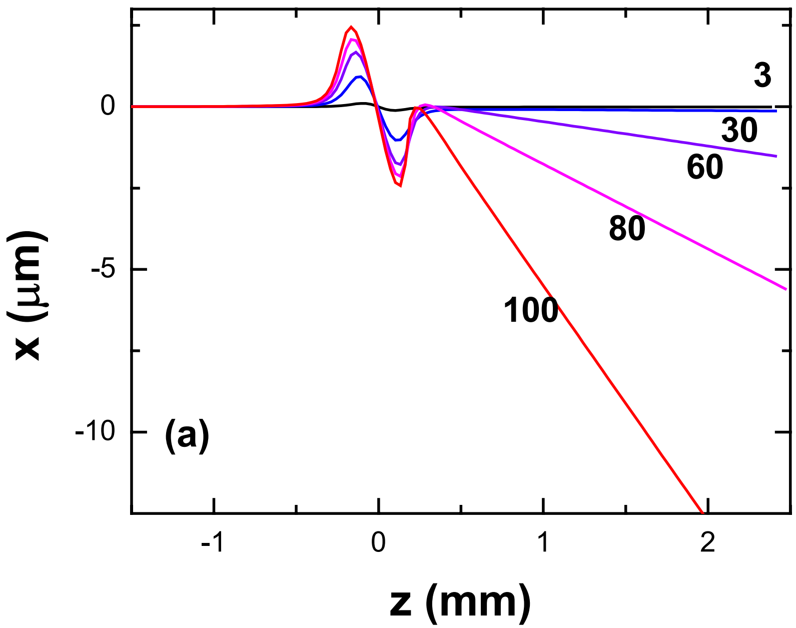
~10^{19} W cm^{-2}
a~3

$$d\phi = \frac{dp_\perp}{p} \approx -\left(\frac{a}{\gamma}\right)^2 \frac{1}{\phi}$$

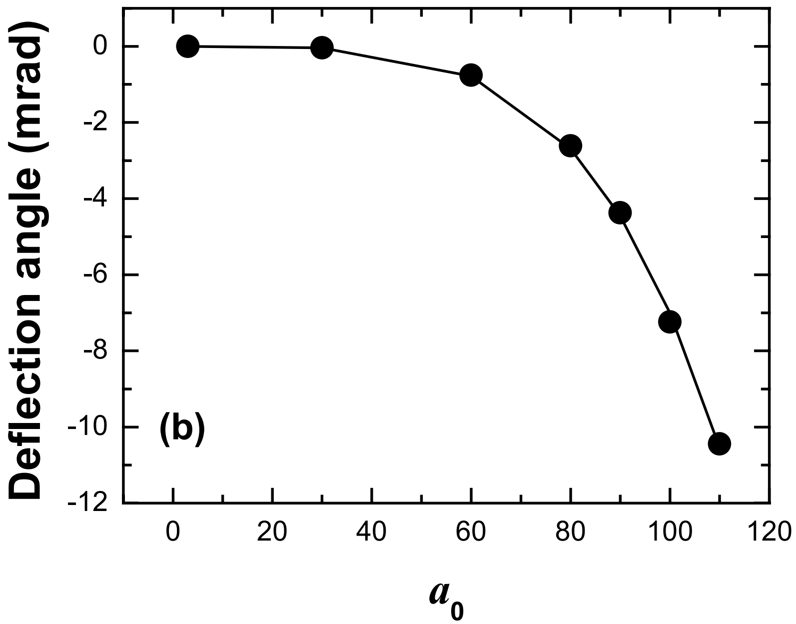
$$\mathbf{d\phi \approx -10^{-5} a^2}$$

High energy: laser scattering

Trajectory in x-z plane



Final scattering angle

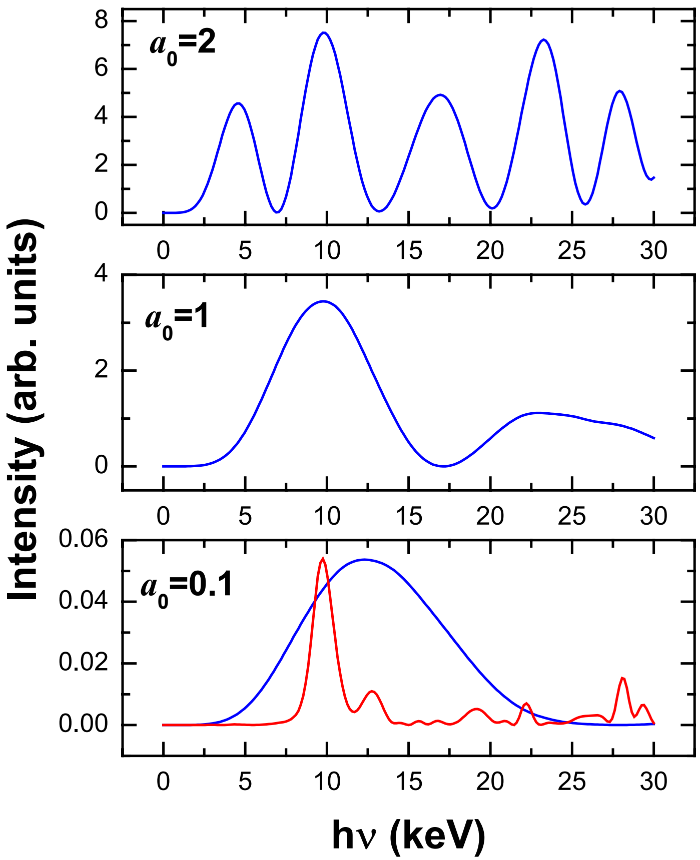


γ_0=1270
ϕ=0.062
λ=0.8 μm
w_0=10.5 μm
$\Delta\tau$=20 fs FWHM

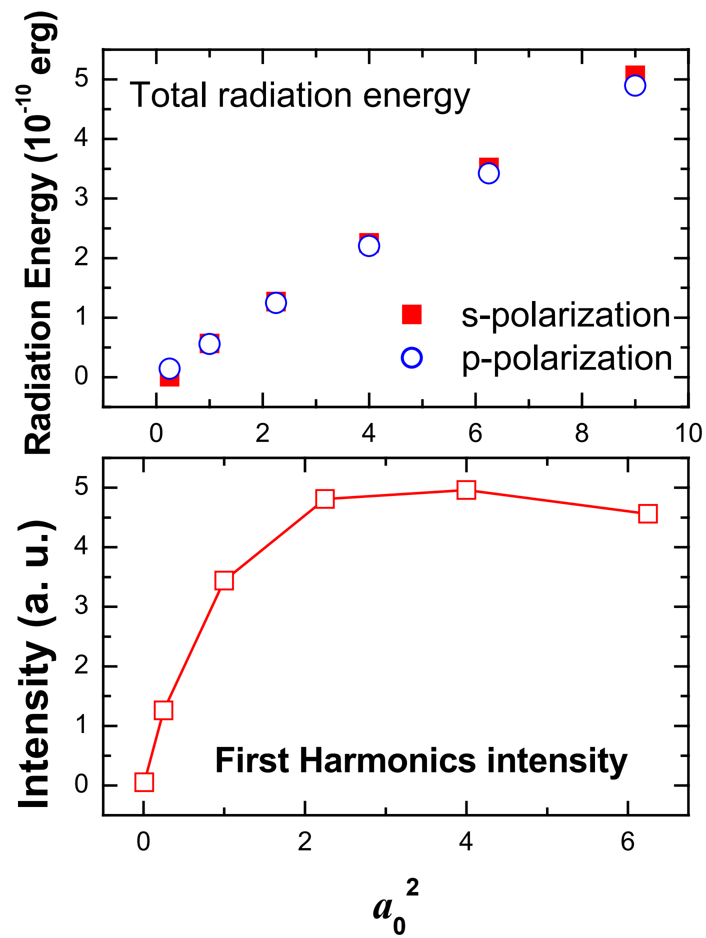
$$d\phi << -10^{-5} a^2$$

Harmonic generation and saturation

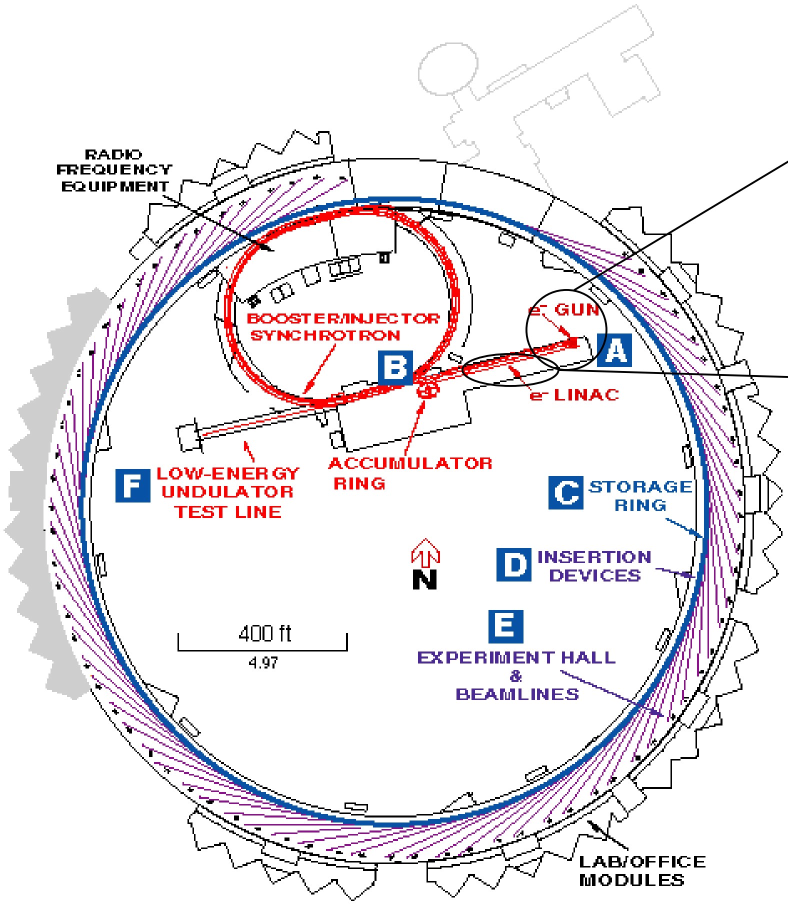
Spectra



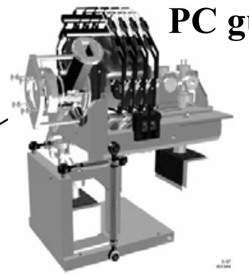
Intensity and energy



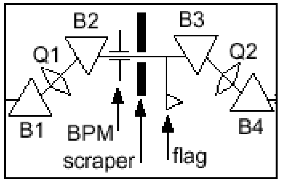
Case at APS: LINAC



PC gun

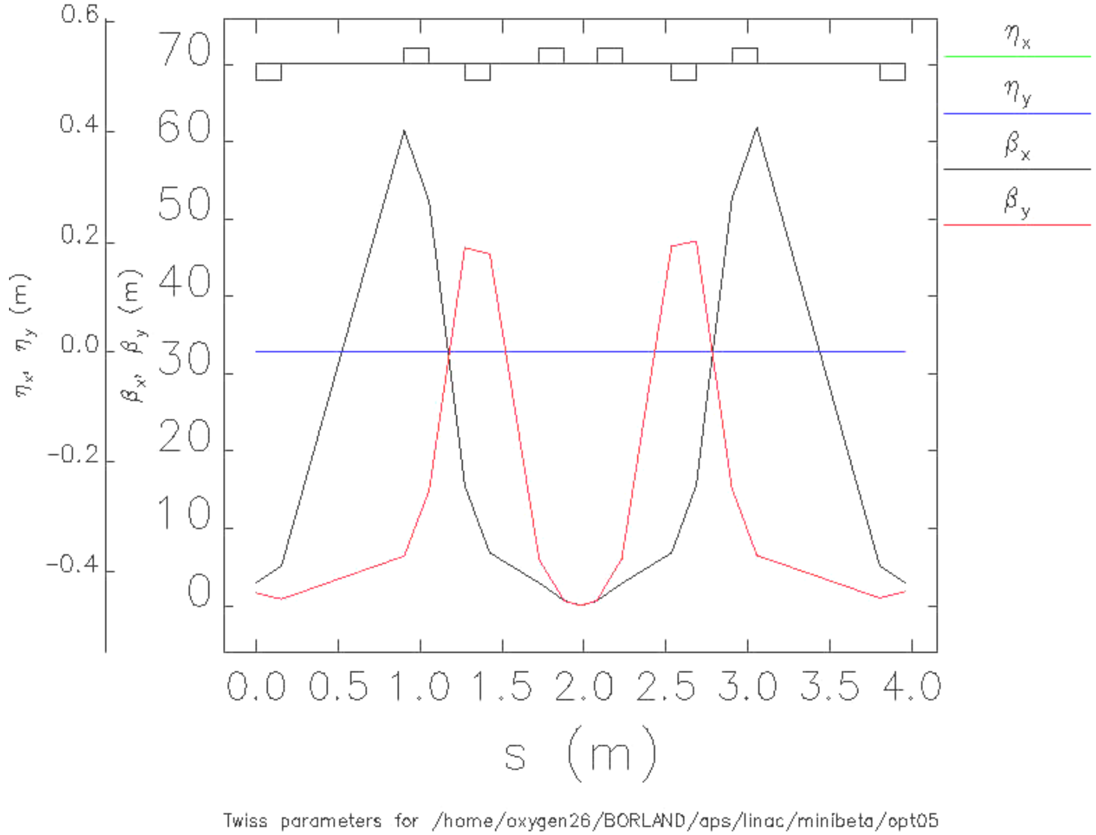


Bunch compressor



Performance (PC gun)	
Energy	200-700 MeV
Energy spread	0.1%
Charge per bunch	1 nC
Bunch length	0.2-3 ps
Normalized Emittance	3-10 μm
Rep Rate	6 Hz
Timing jitter	~1 ps

Case at APS: mini β function

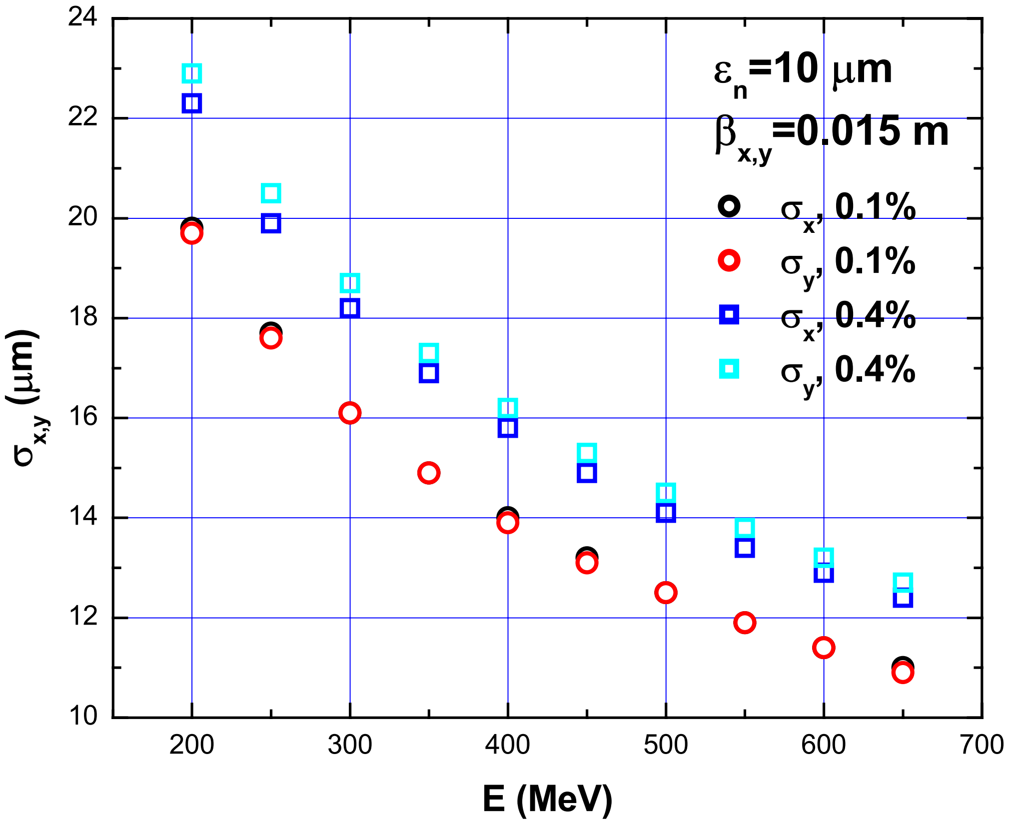


***E*=650 MeV**
$\beta_{x,y}$=0.015 m

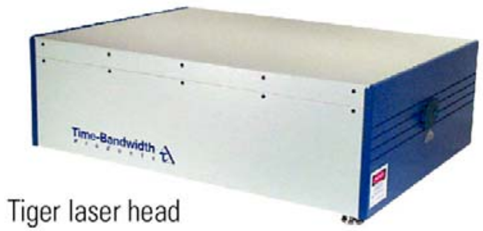
ε_n	**10 μm**	**3 μm**
$\sigma_{x,y}$	**11 μm**	**6 μm**
$\sigma_{x',y'}$	**0.7 mrad**	**0.4 mrad**

Case at APS: micro electron focus

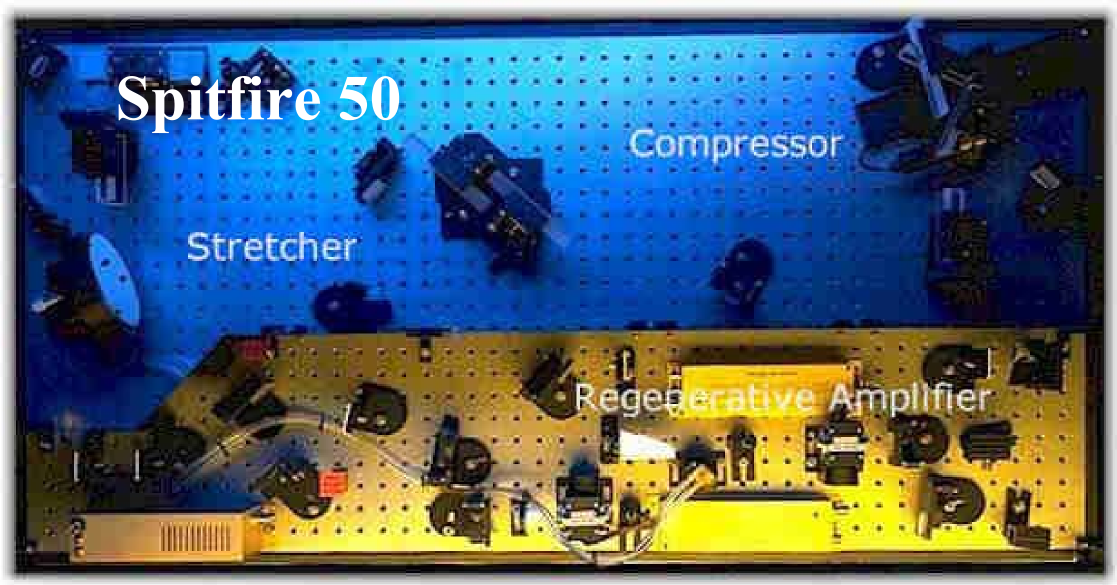
Electron bunch size at different energy spreads



Case at APS: laser



Tiger 200	
Bandwidth	**16 nm**
Pulse duration	**50 fs**
Rep Rate	**119 MHz**
Energy	**3 nJ/pulse**



System performance	
Pulse energy	**1.2 mJ**
Pulse duration	**<50 fs**
Timing jitter	**<1 ps**
Rep rate	**1 kHz**

Case at APS: performance

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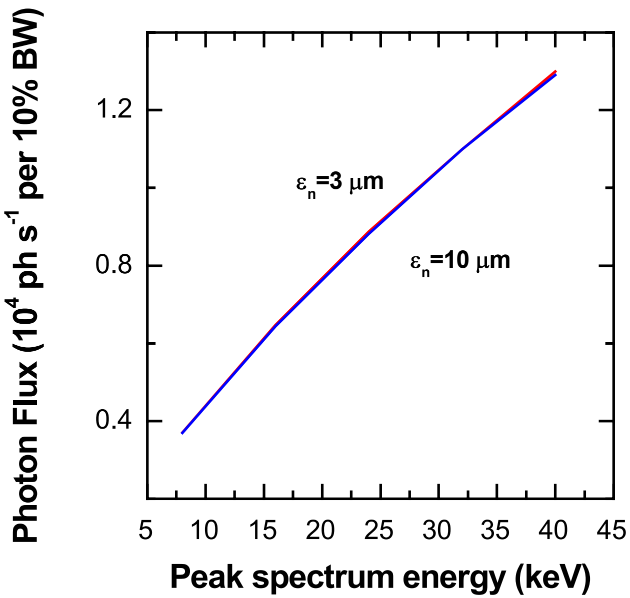
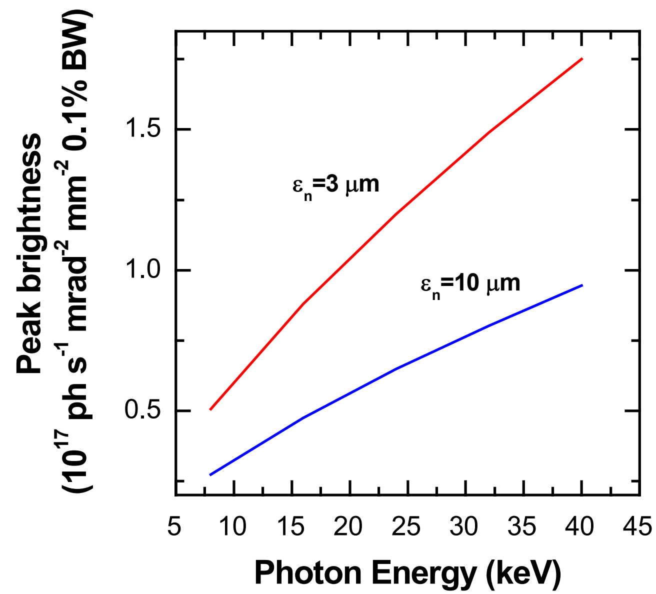
Photon flux



Spectral brightness

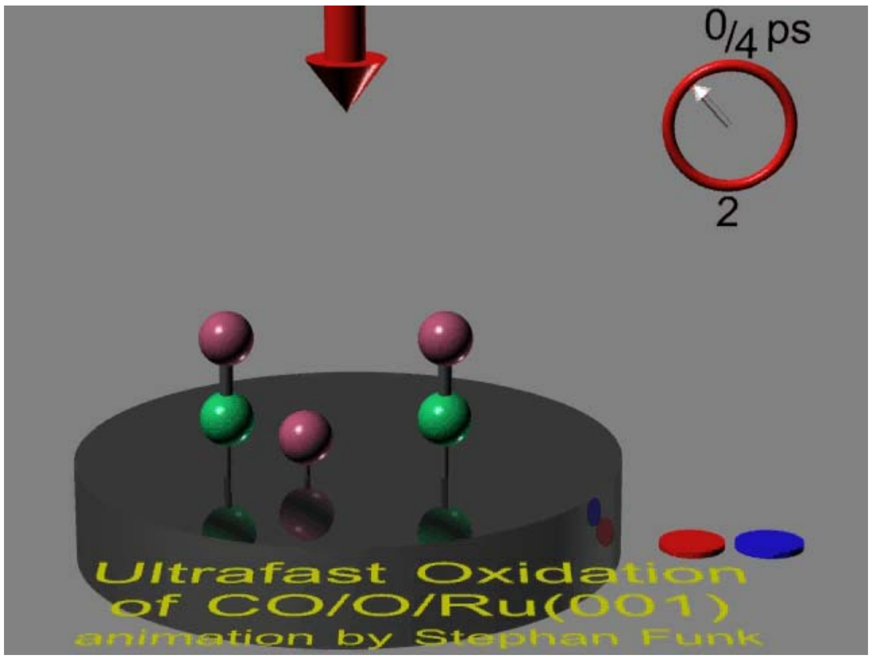


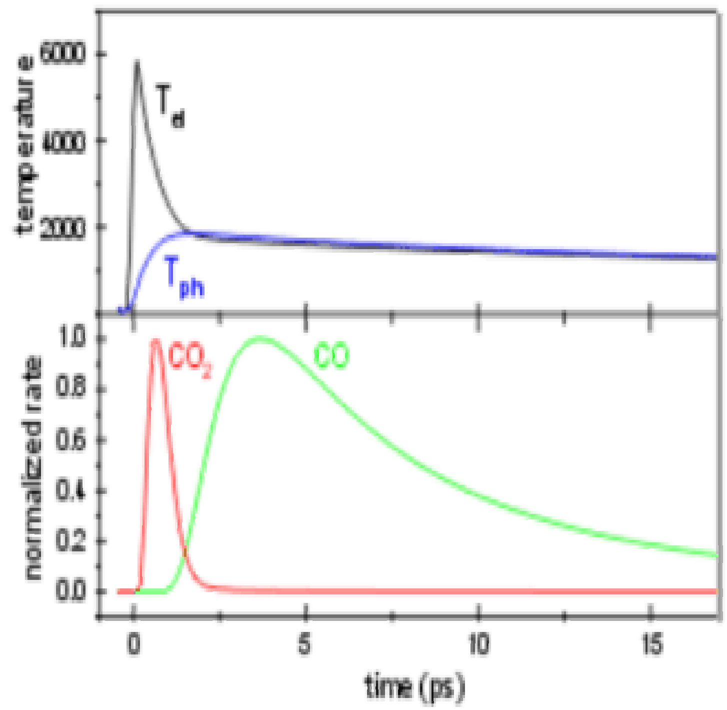
FWHM pulse duration: 50 fs

Application

Femtosecond dynamics of catalytic surfaces

$CO_{ads} + O_{ads}$ ---- on transition metal surface (Ru) ----> $CO_{2\ gas}$





Matin Wolf, Free university of Berlin, http://w3.Rz-Berlin.mpg.de
Science, 285, 1042 (1999).

Application

Dynamics at catalytic surfaces

Q

- What is the electron dynamics in the catalytic substrate
- What is the dynamics of the adsorbent regard to the catalytic?

A

- Small angle surface x-ray scattering (within a few atomic layers) to reveal the transient electron distribution due to the pump laser excitation
- EXAFS, NEXAS applied onto the few surface layers to reveal the bond distances between the surface metal and the adsorbent and the valence state of the catalytic material

Temporal resolution:	100 fs
X-ray source:	narrow and broadband
Laser:	50 mJ/cm^{-2}
Substrate:	Ru, Ag, Pt, Cu

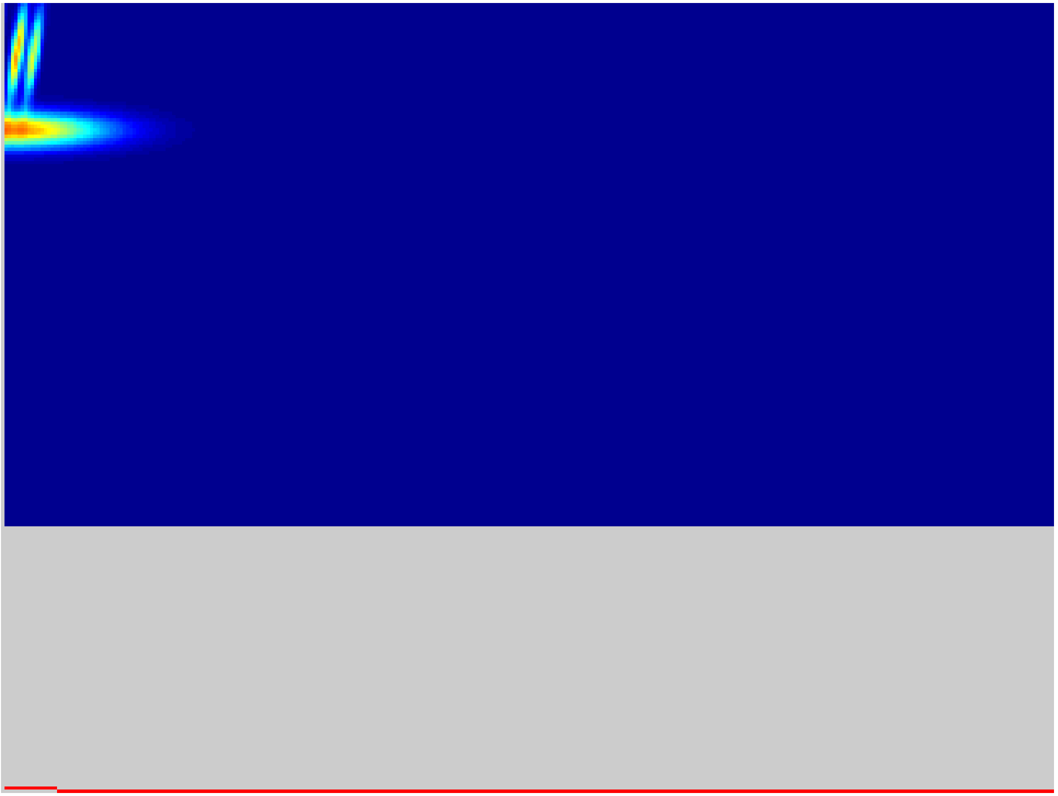
Summary

1. Small-angle Thomson scattering is a unique solution to the conflicting interest between high spectral brightness and short pulse duration for obtaining ultrashort X-ray pulse with high spectral brightness.

2. With the high quality electron bunches in combination with high power tabletop laser systems, broad band 10-20 fs X-ray pulses with brightness close to third generation synchrotron light source can be generated with minimum cost.

3. The high spectral brightness, short pulse duration and broad spectrum provide unique properties that no other sources can match for a variety of applications.

X-ray pulse shaping



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