Generation of intense attosecond x-ray pulse using Free Electron Lasers

Alexander Zholents

Center for Beam Physics, Lawrence Berkeley National Laboratory

Attosecond science conference, Santa Barbara, August 1-4, 2006

A. Zholents, UCSB, August 4, 2006

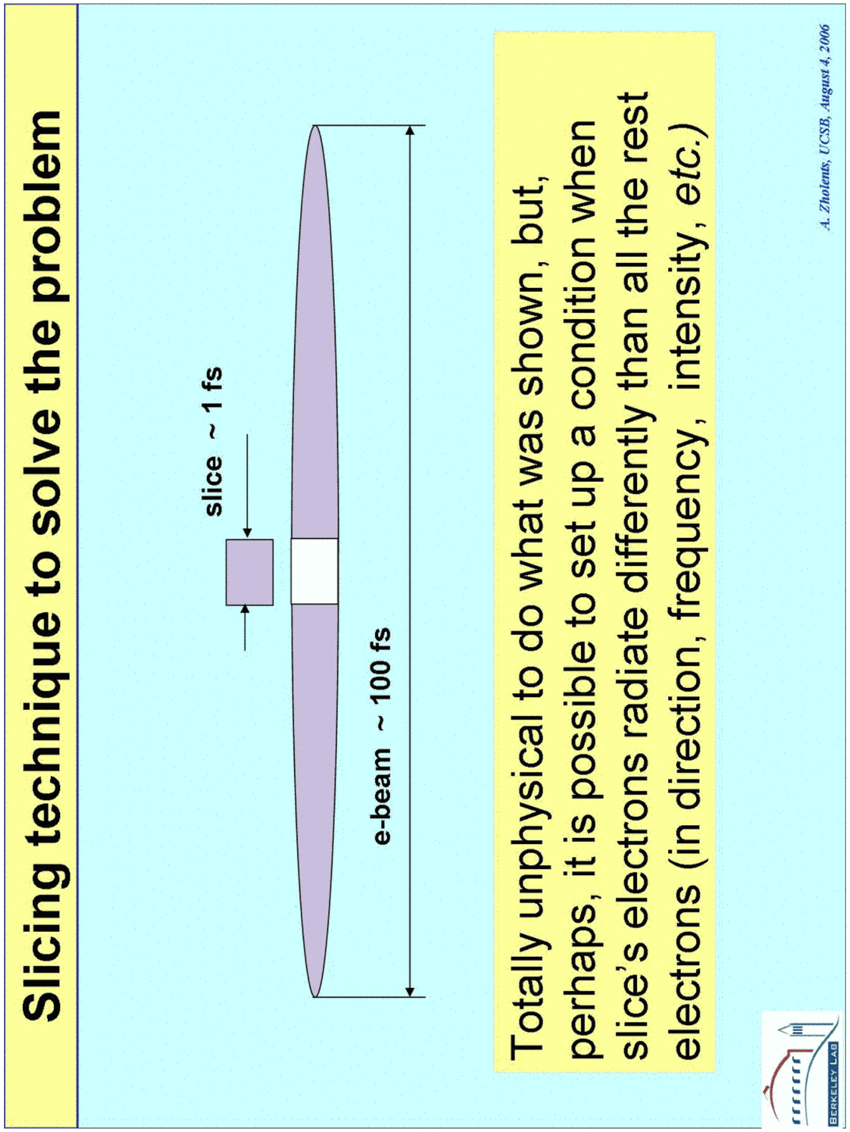
In this presentation we deal with unbounded "free" moving electrons

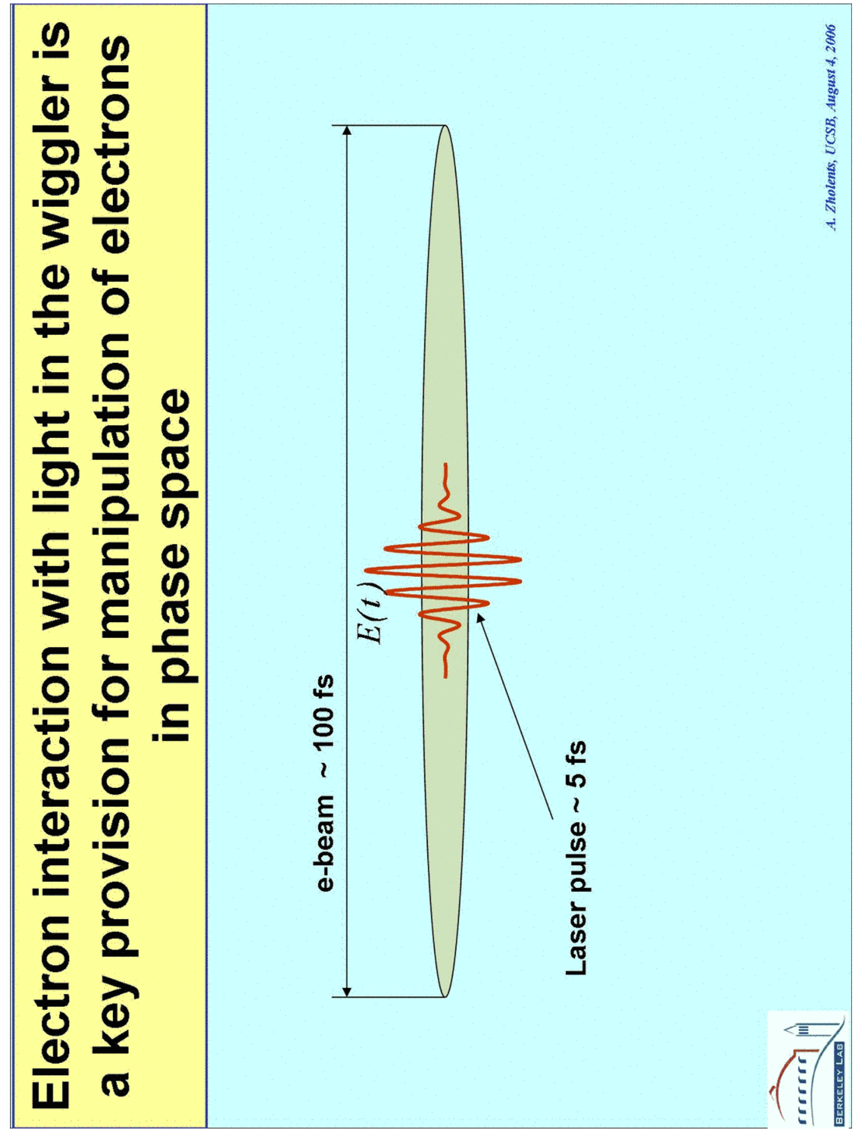
Problem:

a) electrons comes packed in bunches with a typical length > 100 fs in linacs (record is ~ 80 fs at SPPS, SLAC) and >10 ps in storage rings

b) length of the radiation pulse ≈ length of the electron bunch

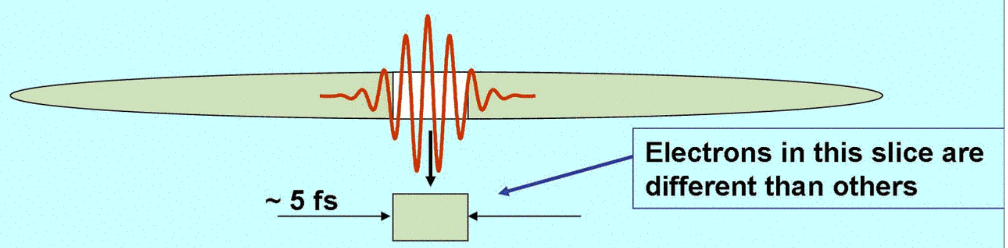
A. Zholents, UCSB, August 4, 2006


Slicing technique to solve the problem
slice ~ 1 fs
e-beam ~ 100 fs
Totally unphysical to do what was shown, but, perhaps, it is possible to set up a condition when slice's electrons radiate differently than all the rest electrons (in direction, frequency, intensity, etc.)
A. Zholents, UCSB, August 4, 2006
BERKELEY LAB


Electron interaction with light in the wiggler is a key provision for manipulation of electrons in phase space
e-beam ~ 100 fs
E(t)
Laser pulse ~ 5 fs
A. Zholents, UCSB, August 4, 2006
BERKELEY LAB

Electron interaction with light in the wiggler is a key provision for manipulation of electrons in phase space

Laser leaves a few fs long “mark” on the electron bunch by significantly changing the energy of some electrons

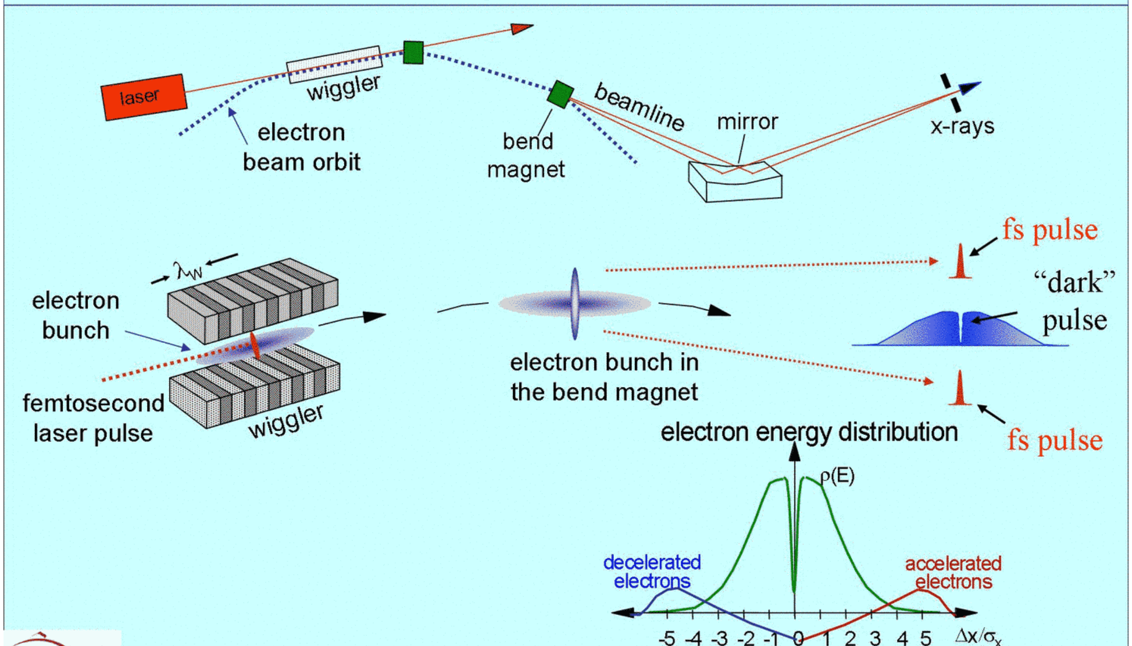


This idea has been used at ALS, LBNL (BESSY, Germany; SLS, Switzerland) for a generation of femtosecond x-ray pulses

R. W. Schoenlein, *et al*, Science, Mar 24, 2000
S. Khan, Part. Acc. Conf. 2005, TOAB007;

A. Zholents, UCSB, August 4, 2006

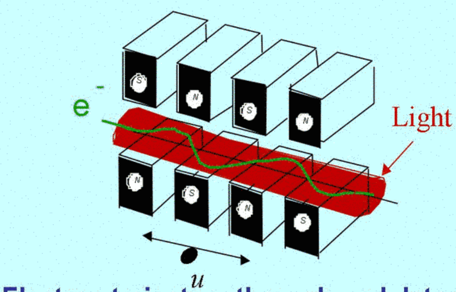
Femtosecond x-ray pulses from the storage ring: slicing technique [1]



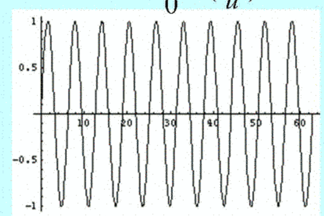
1) A. Zholents, M. Zoloterev, PRL 76 (1996), 912

A. Zholents, UCSB, August 4, 2006

Energy modulation of electrons in the undulator by the laser light

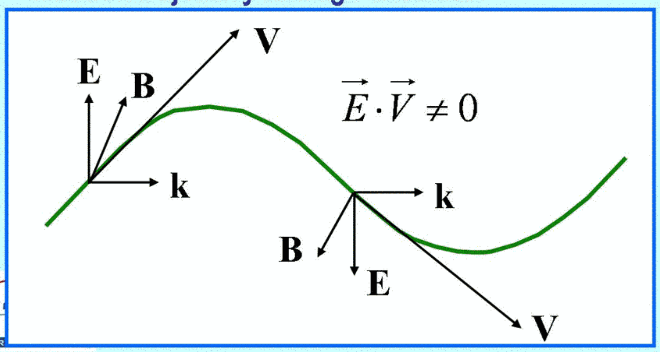


$B = B_0 \sin(k_u z)$



Magnetic field in the undulator

Electron trajectory through undulator



Undulator period   Laser wavelength

$$\lambda_u = 2\gamma^2 \lambda_L / (1 + K^2/2)$$

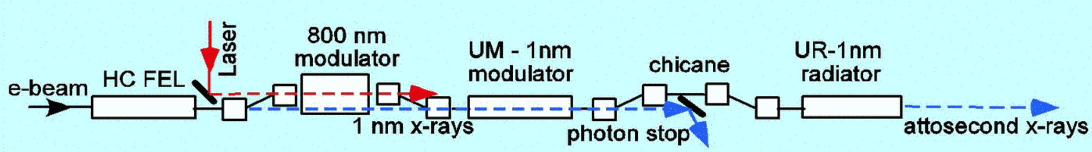
FEL resonance condition

While propagating one undulator period, the electron is delayed with respect to the light on one optical wavelength

A. Zholents, UCSB, August 4, 2006

Generation of attosecond pulses based on Harmonic Cascade FEL*

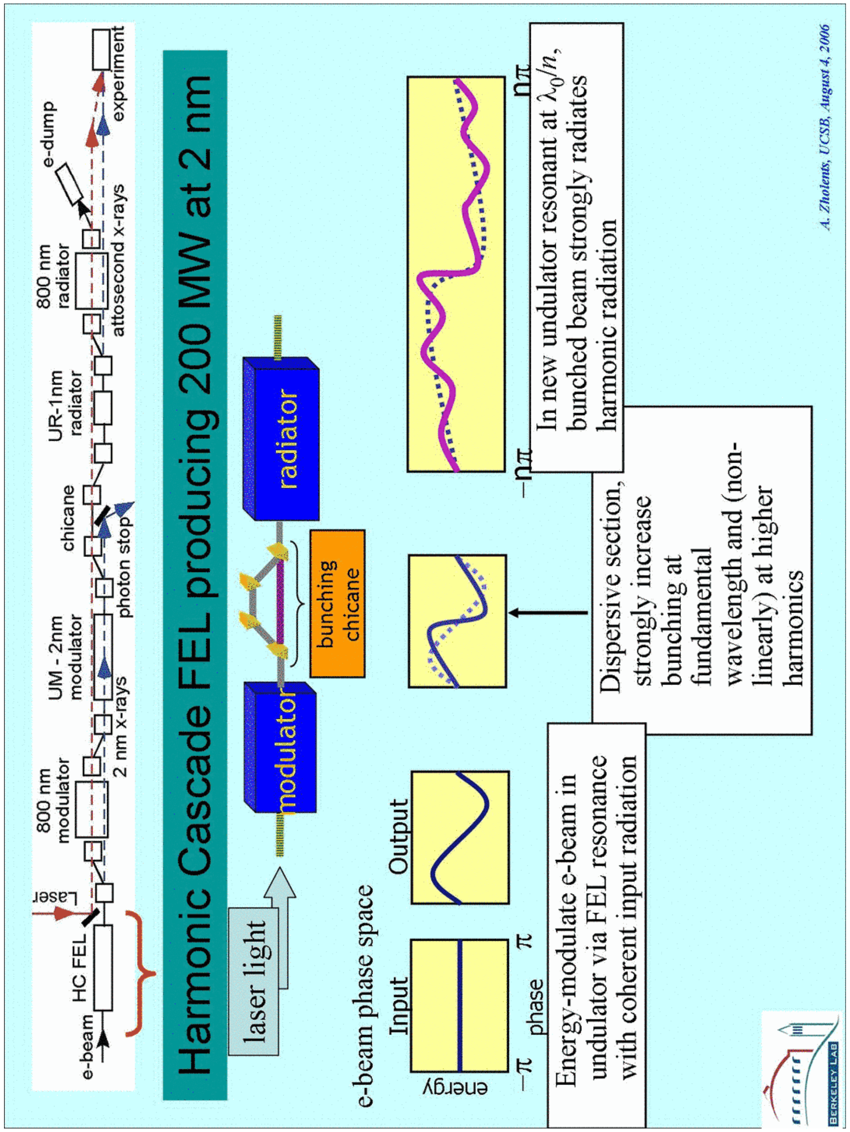
A schematic of the technique for attosecond generation …

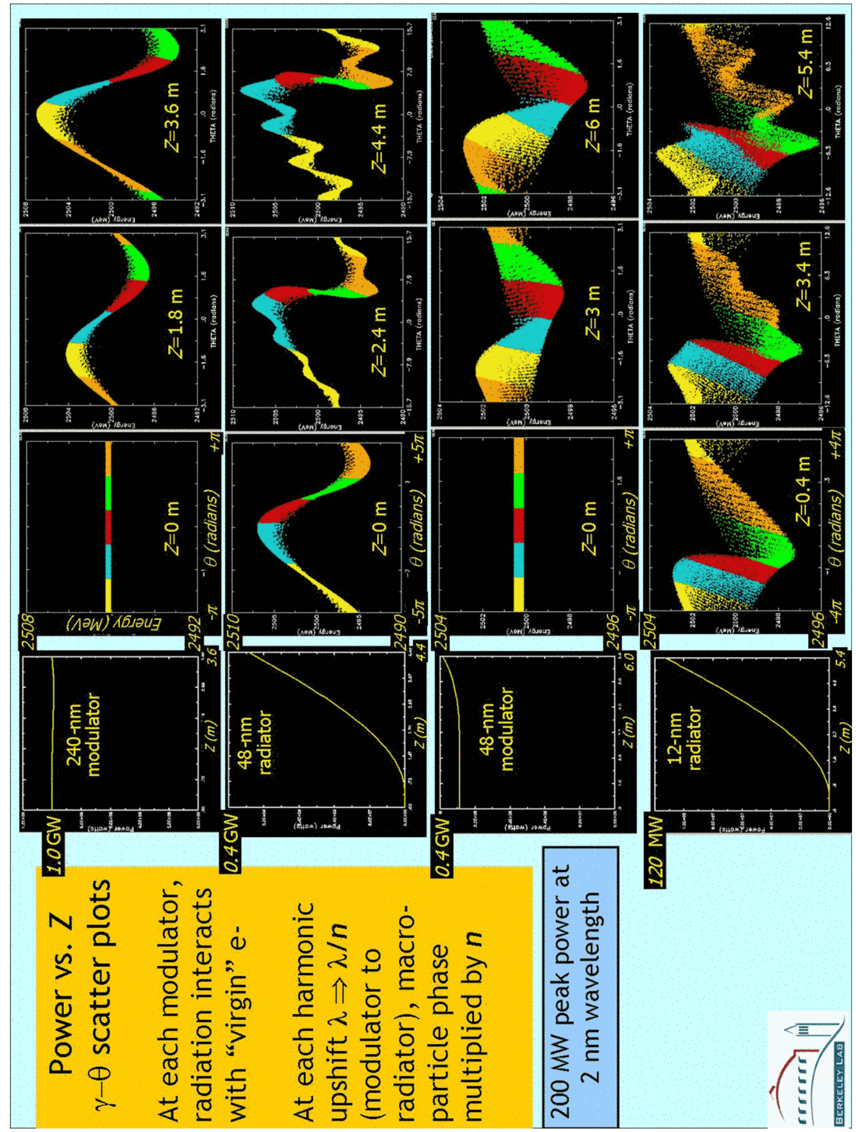


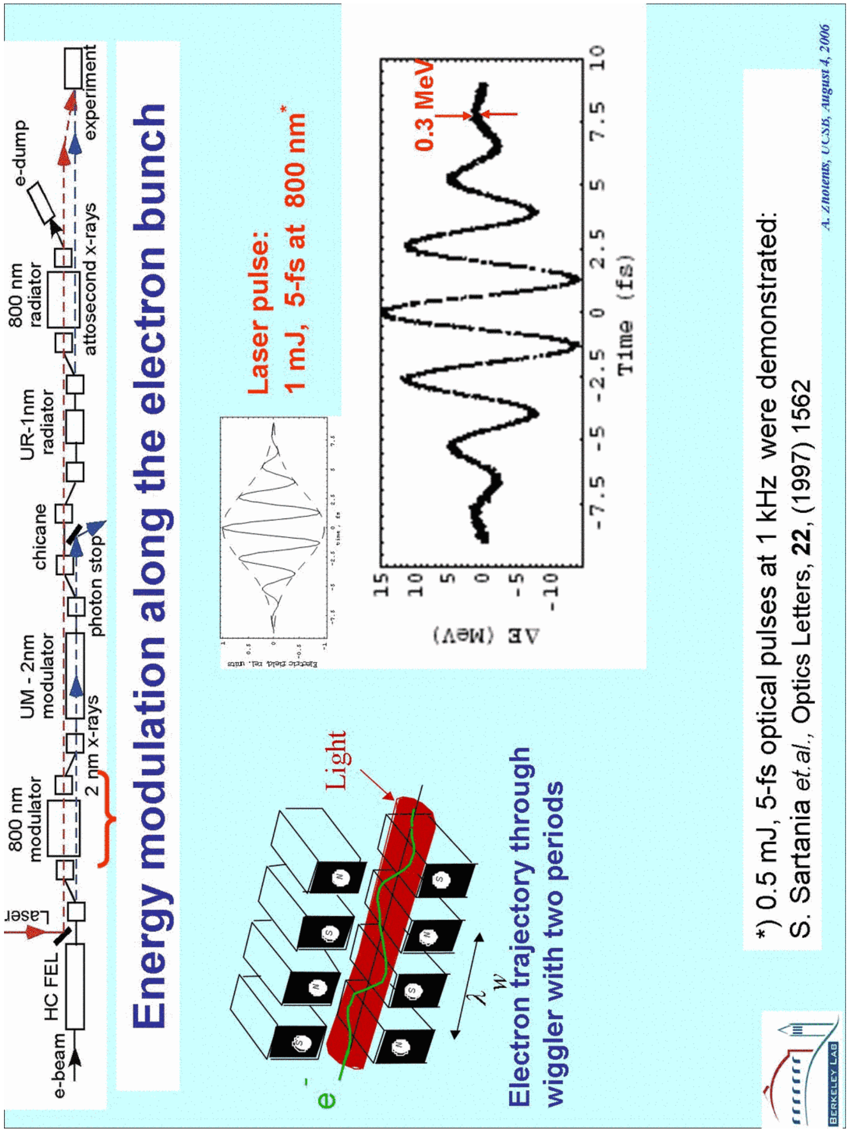
as add-on to FEL producing coherent radiation at 2-nm (in this example)

*) Zholents, Fawley, *Phys. Rev. Lett.*, 92,(2004)

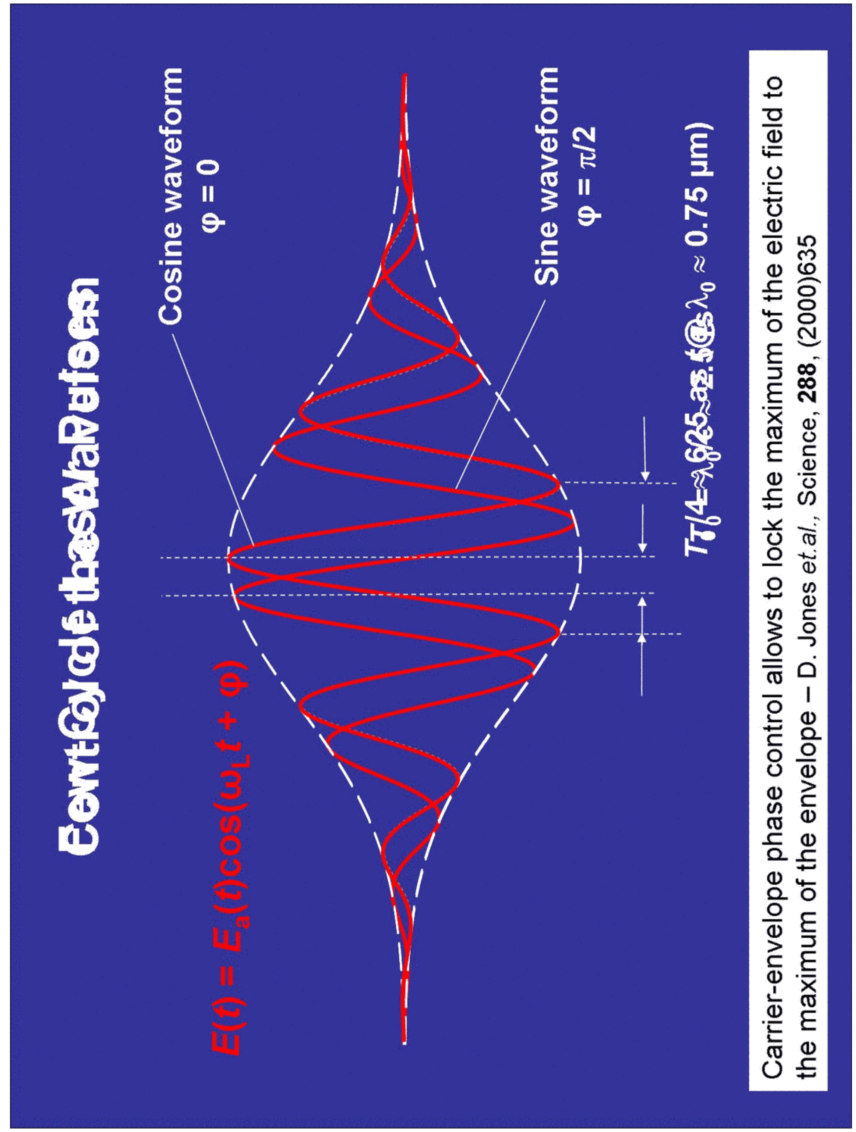
A. Zholents, UCSB, August 4, 2006


Harmonic Cascade FEL producing 200 MW at 2 nm
e-beam
HC FEL
Laser
800 nm modulator
2 nm x-rays
UM - 2nm modulator
photon stop
chicane
UR-1nm radiator
800 nm radiator
attosecond x-rays
e-dump
experiment
laser light
modulator
bunching chicane
radiator
e-beam phase space
Input
Output
energy
phase
−π
π
−nπ
nπ
Energy-modulate e-beam in undulator via FEL resonance with coherent input radiation
Dispersive section, strongly increase bunching at fundamental wavelength and (non-linearly) at higher harmonics
In new undulator resonant at λ_0/n, bunched beam strongly radiates harmonic radiation
A. Zholents, UCSB, August 4, 2006
BERKELEY LAB

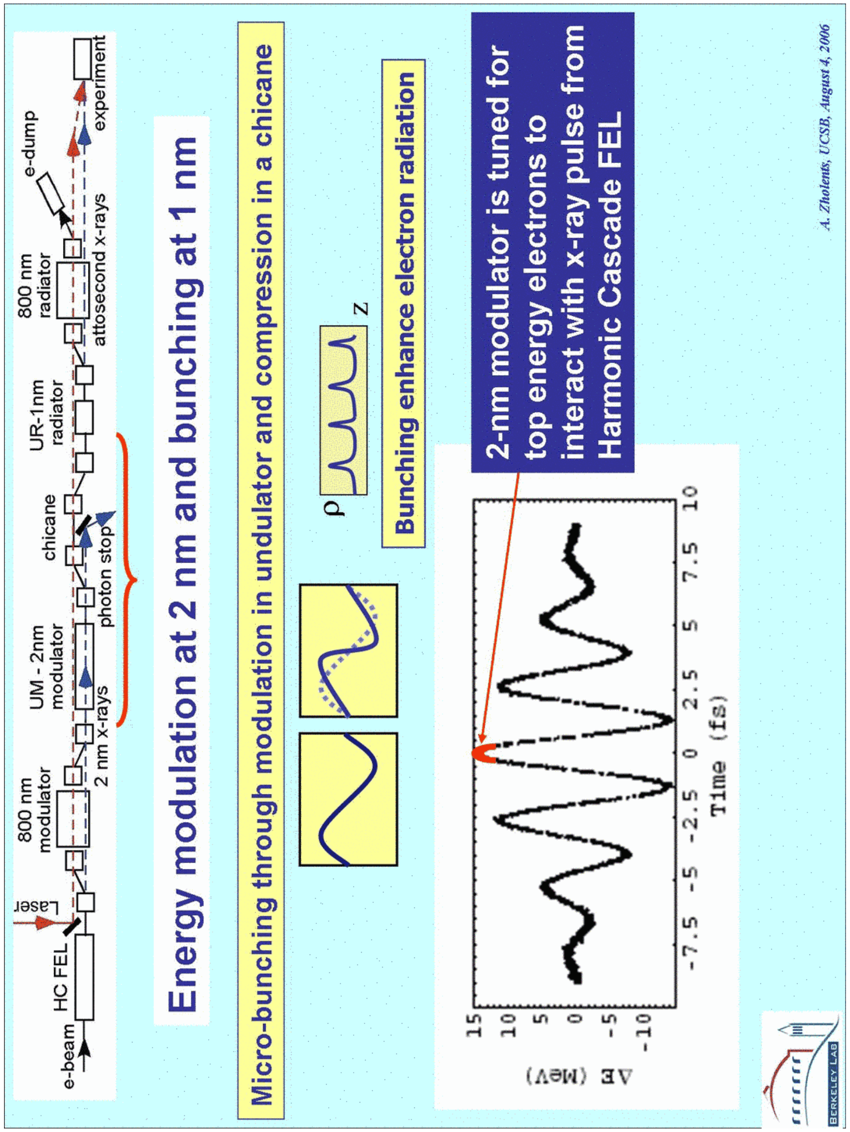

Power vs. Z
γ–θ scatter plots
At each modulator, radiation interacts with “virgin” e-
At each harmonic upshift λ ⇒ λ/n (modulator to radiator), macro-particle phase multiplied by n
200 MW peak power at 2 nm wavelength
1.0 GW
240-nm modulator
0.4 GW
48-nm radiator
0.4 GW
48-nm modulator
120 MW
12-nm radiator
Z (m)
Energy (MeV)
θ (radians)
Z=0 m
Z=1.8 m
Z=3.6 m
Z=0 m
Z=2.4 m
Z=4.4 m
Z=0 m
Z=3 m
Z=6 m
Z=0.4 m
Z=3.4 m
Z=5.4 m
BERKELEY LAB

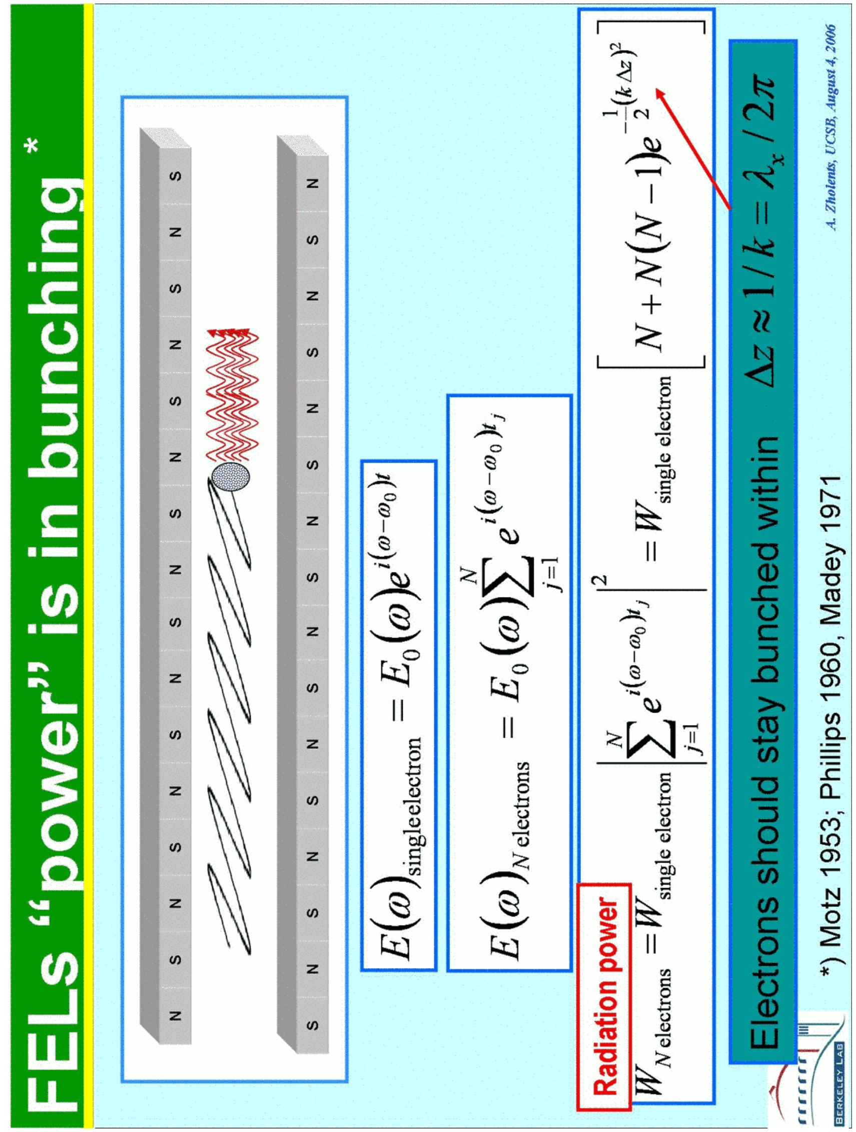


e-beam
HC FEL
Laser
800 nm modulator
2 nm x-rays
UM - 2nm modulator
photon stop
chicane
UR-1nm radiator
800 nm radiator
attosecond x-rays
e-dump
experiment
Energy modulation along the electron bunch
e
Light
λw
Electron trajectory through wiggler with two periods
Laser pulse:
1 mJ, 5-fs at 800 nm*
0.3 MeV
ΔE (MeV)
Time (fs)
*) 0.5 mJ, 5-fs optical pulses at 1 kHz were demonstrated:
S. Sartania et.al., Optics Letters, 22, (1997) 1562
A. Zholents, UCSB, August 4, 2006
BERKELEY LAB



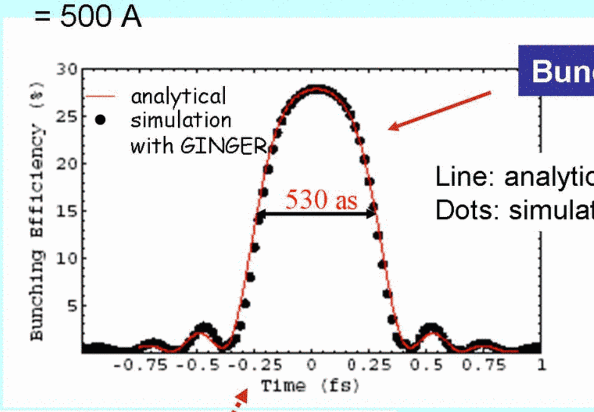
E(t) = Ea(t)cos(ωLt + φ)
Cosine waveform
φ = 0
Sine waveform
φ = π/2
≈ 0.75 μm)
Carrier-envelope phase control allows to lock the maximum of the electric field to the maximum of the envelope – D. Jones et.al., Science, 288, (2000)635


e-beam
HC FEL
Laser
800 nm modulator
2 nm x-rays
UM - 2nm modulator
chicane
photon stop
UR-1nm radiator
800 nm radiator
attosecond x-rays
e-dump
experiment
Energy modulation at 2 nm and bunching at 1 nm
Micro-bunching through modulation in undulator and compression in a chicane
ρ
z
Bunching enhance electron radiation
2-nm modulator is tuned for top energy electrons to interact with x-ray pulse from Harmonic Cascade FEL
ΔE (MeV)
Time (fs)
A. Zholents, UCSB, August 4, 2006
BERKELEY LAB

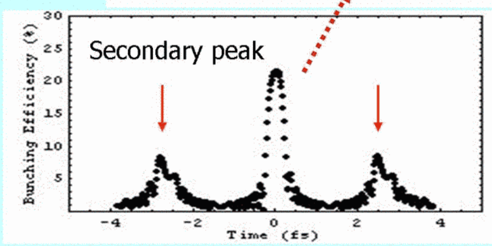

FELs “power” is in bunching *
$E(\omega)_{\text{single electron}} = E_0(\omega)e^{i(\omega-\omega_0)t}$
$E(\omega)_{N\,\text{electrons}} = E_0(\omega)\sum_{j=1}^{N} e^{i(\omega-\omega_0)t_j}$
Radiation power
$W_{N\,\text{electrons}} = W_{\text{single electron}} \left| \sum_{j=1}^{N} e^{i(\omega-\omega_0)t_j} \right|^2 = W_{\text{single electron}} \left[N + N(N-1)e^{-\frac{1}{2}(k\Delta z)^2} \right]$
Electrons should stay bunched within $\Delta z \approx 1/k = \lambda_x / 2\pi$
*) Motz 1953; Phillips 1960, Madey 1971
A. Zholents, UCSB, August 4, 2006
BERKELEY LAB

Electron beam parameters:
beam energy = 3 GeV
emittance = 2 mm-mrad
energy spread = 0.3 MeV
peak current = 500 A

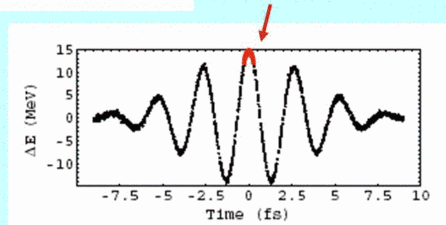
Bunching efficiency



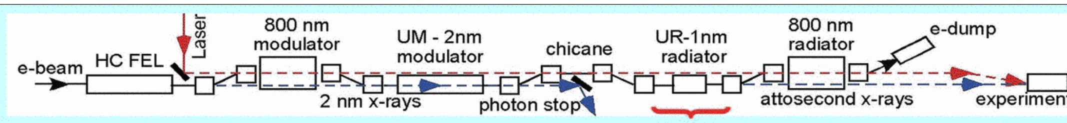
Line: analytical estimations
Dots: simulation with GINGER



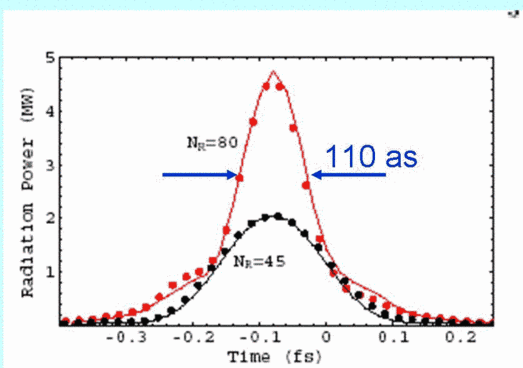
Only for this part of the beam



A. Zholents, UCSB, August 4, 2006

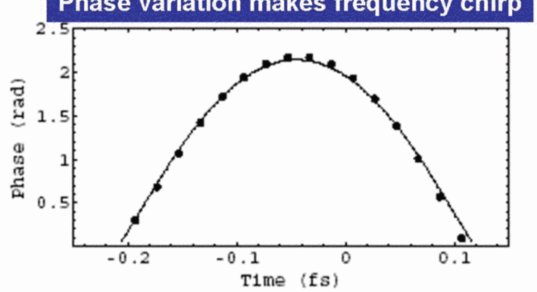


Bunched electrons radiate in the 1 nm undulator radiator



Pulse duration is shorter than width of the pulse on the "bunching" plot due to a destructive interference of the radiation from the "head" and the "tail".

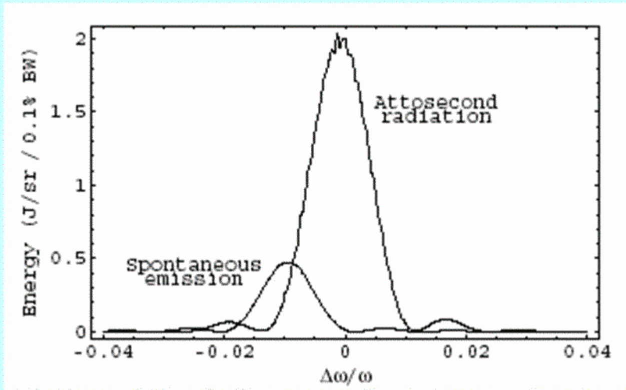
Phase variation makes frequency chirp



Phase modulation in the radiation field appears as a result of the time variation in the magnitude of the energy modulation of the "attosecond" electrons. Further compression to ~80 as FWHM might be possible!

A. Zholents, UCSB, August 4, 2006

Radiation spectra

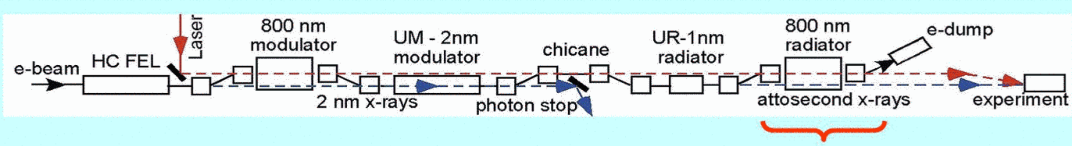


- Coherent radiation of the “attosecond” electrons dominates over the spontaneous emission from the entire bunch electrons (GINGER output).
- Spectral peak of the spontaneous emission is shifted into the red. A double grating monochromator with pathlength compensation can be used *).

Contrast = (energy in asec x-ray spike) / (energy in the rest of x-ray pulse) >> 1

*) P. Villoresi, Applied Optics, vol.38, p.6040 (1999).

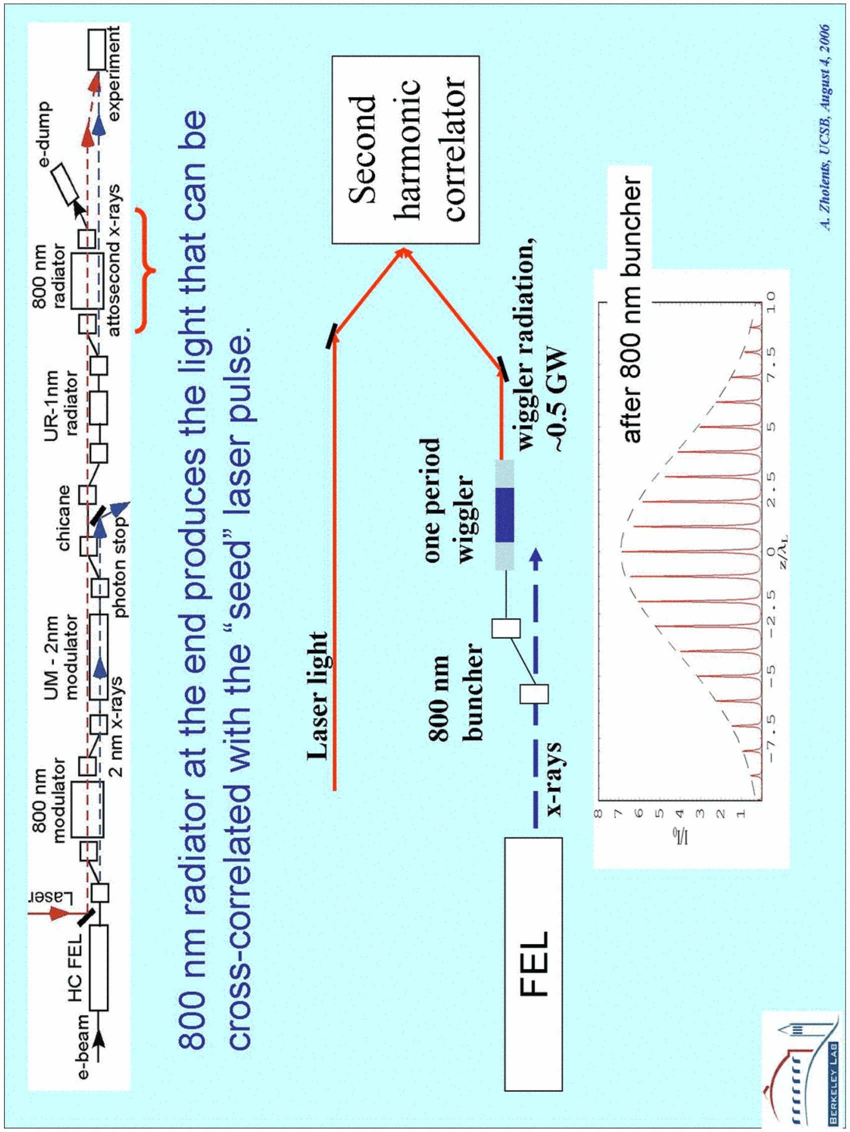
A. Zholents, UCSB, August 4, 2006

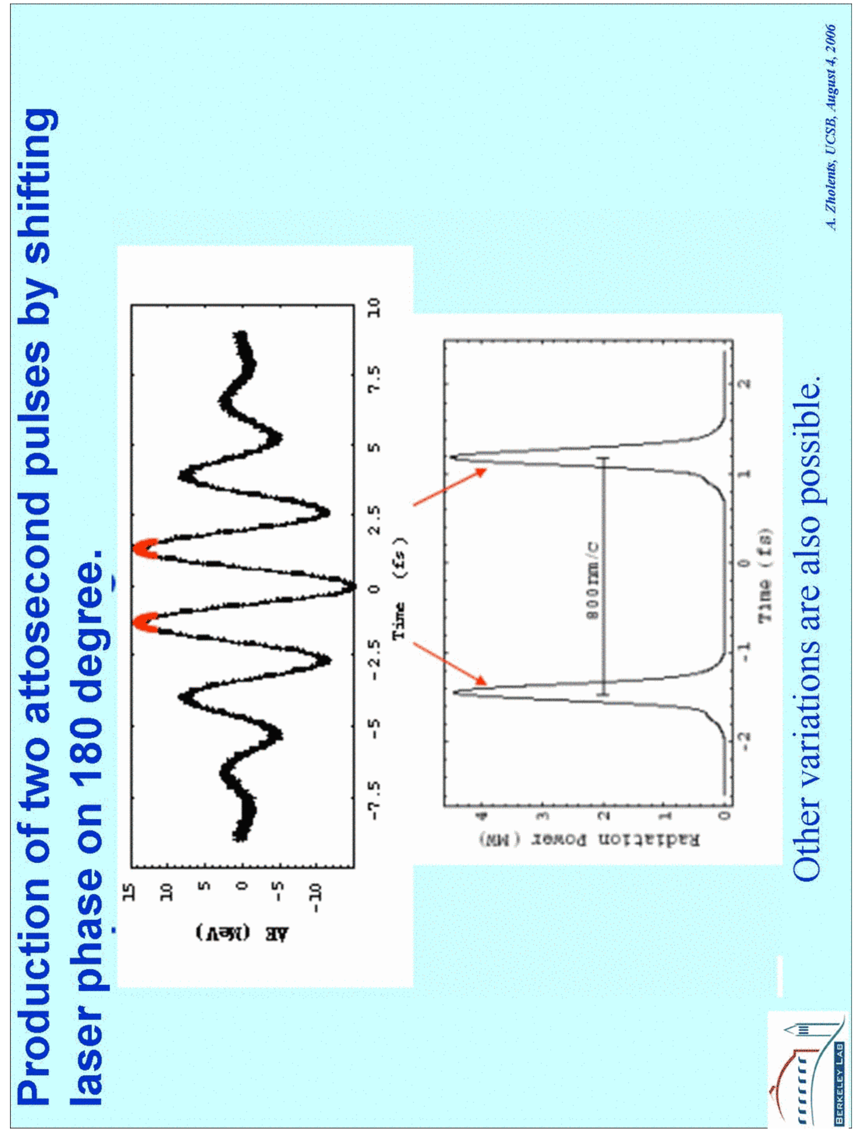


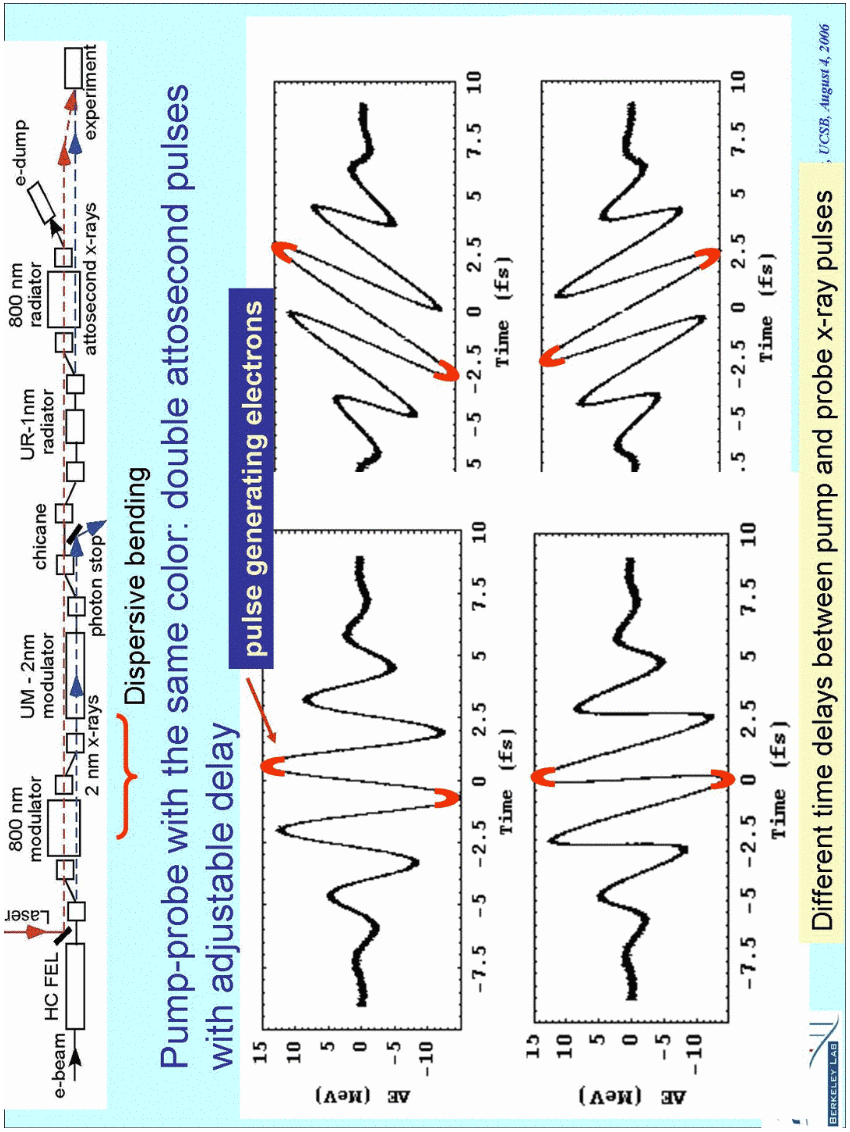
Synchronization

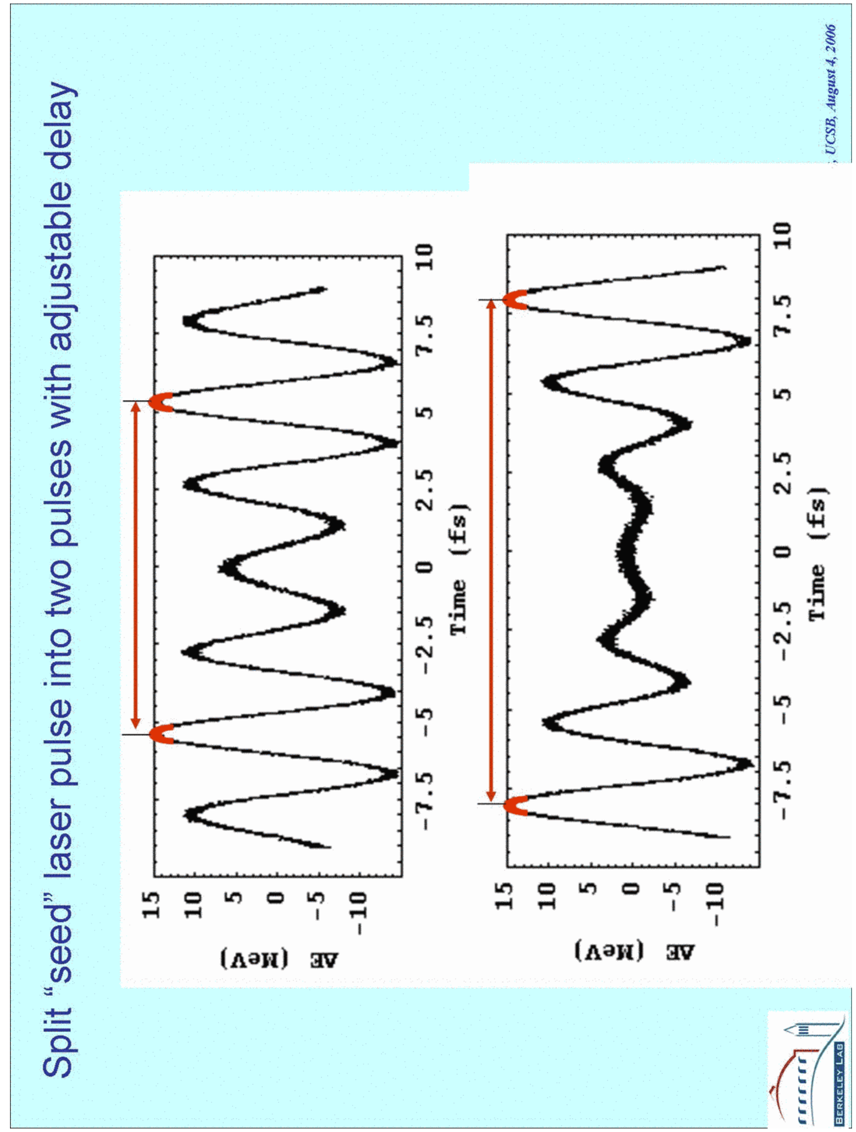
- In principle optical pump pulse and attosecond x-ray probe pulse are absolutely synchronized since both pulses are originated by the same source.

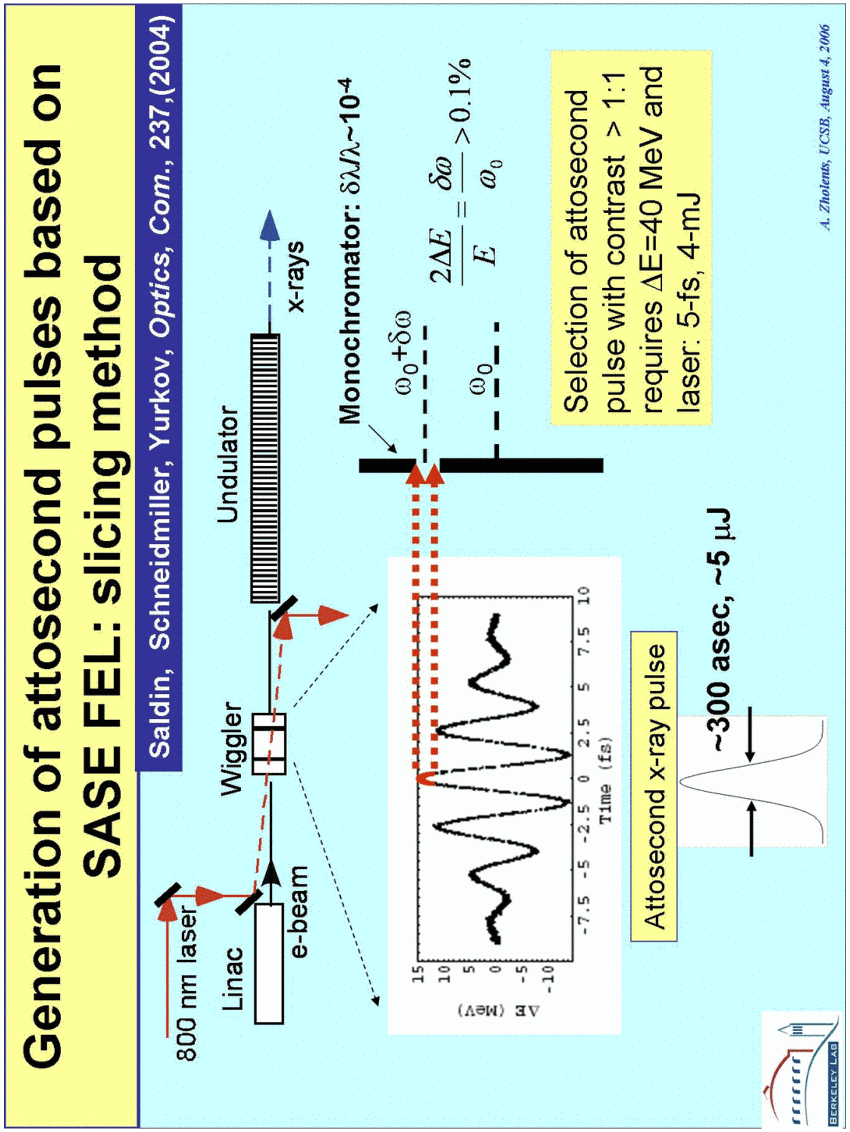
A. Zholents, UCSB, August 4, 2006

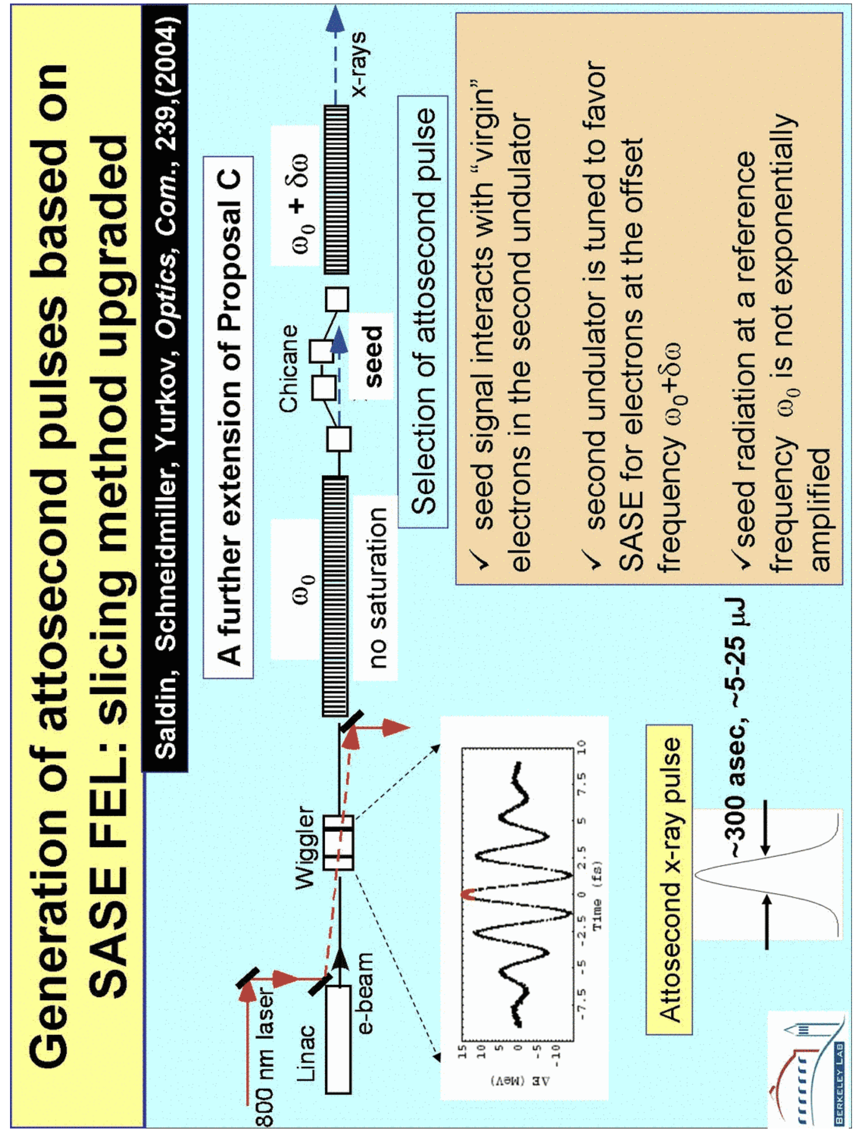

e-beam
HC FEL
Laser
800 nm modulator
2 nm x-rays
UM - 2nm modulator
photon stop
chicane
UR-1nm radiator
800 nm radiator
attosecond x-rays
e-dump
experiment
800 nm radiator at the end produces the light that can be cross-correlated with the “seed” laser pulse.
Second harmonic correlator
Laser light
800 nm buncher
one period wiggler
wiggler radiation, ~0.5 GW
x-rays
FEL
after 800 nm buncher
A. Zholents, UCSB, August 4, 2006


Production of two attosecond pulses by shifting laser phase on 180 degree.
ΔE (MeV)
Time (fs)
800nm/c
Radiation Power (MW)
Other variations are also possible.
A. Zholents, UCSB, August 4, 2006


Pump-probe with the same color: double attosecond pulses with adjustable delay
e-beam
HC FEL
Laser
800 nm modulator
2 nm x-rays
UM - 2nm modulator
photon stop
chicane
UR-1nm radiator
800 nm radiator
attosecond x-rays
e-dump
experiment
Dispersive bending
pulse generating electrons
ΔE (MeV)
Time (fs)
Different time delays between pump and probe x-ray pulses
UCSB, August 4, 2006
BERKELEY LAB

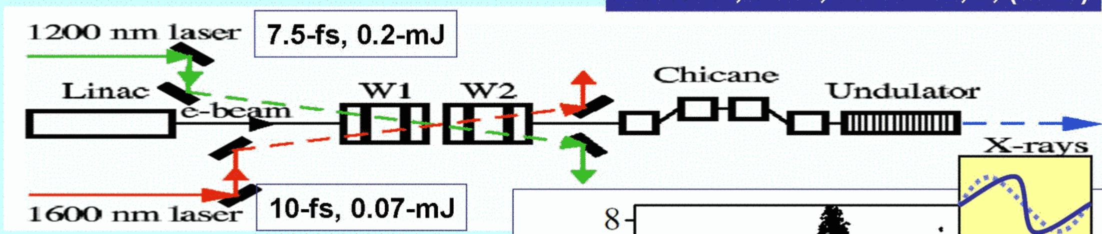

Split “seed” laser pulse into two pulses with adjustable delay
ΔE (MeV)
Time (fs)
UCSB, August 4, 2006
BERKELEY LAB

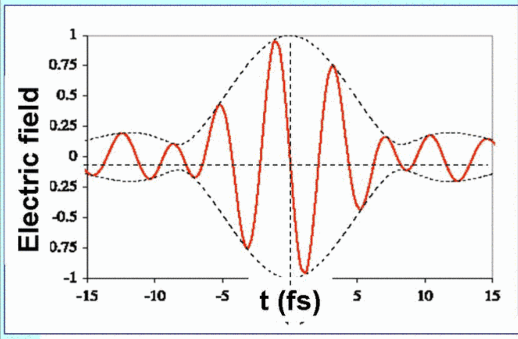

Generation of attosecond pulses based on SASE FEL: slicing method
Saldin, Schneidmiller, Yurkov, Optics, Com., 237,(2004)
800 nm laser
Linac
e-beam
Wiggler
Undulator
x-rays
Monochromator: $\delta\lambda/\lambda \sim 10^{-4}$
$\omega_0+\delta\omega$
ω_0
$\frac{2\Delta E}{E} = \frac{\delta\omega}{\omega_0} > 0.1\%$
Selection of attosecond pulse with contrast > 1:1 requires ΔE=40 MeV and laser: 5-fs, 4-mJ
ΔE (MeV)
Time (fs)
Attosecond x-ray pulse
~300 asec, ~5 μJ
A. Zholents, UCSB, August 4, 2006


Generation of attosecond pulses based on SASE FEL: slicing method upgraded
Saldin, Schneidmiller, Yurkov, Optics, Com., 239,(2004)
A further extension of Proposal C
ω_0
$\omega_0 + \delta\omega$
Chicane
seed
no saturation
x-rays
Selection of attosecond pulse
✓ seed signal interacts with "virgin" electrons in the second undulator
✓ second undulator is tuned to favor SASE for electrons at the offset frequency $\omega_0+\delta\omega$
✓ seed radiation at a reference frequency ω_0 is not exponentially amplified
800 nm laser
Linac
e-beam
Wiggler
ΔE (MeV)
Time (fs)
Attosecond x-ray pulse
~300 asec, ~5-25 μJ

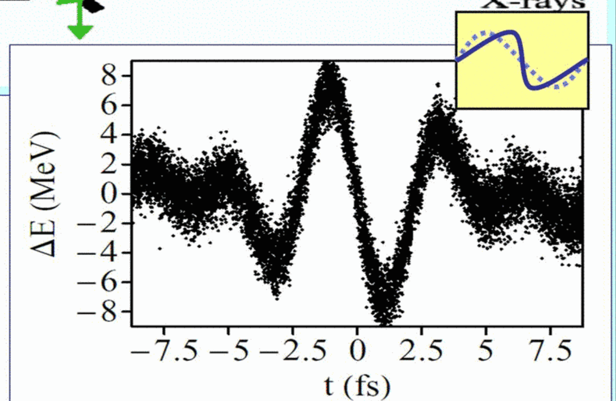
Attosecond pulses based on SASE FEL: current enhancement method

Zholents, Penn, PRST-AB, 8, (2005)





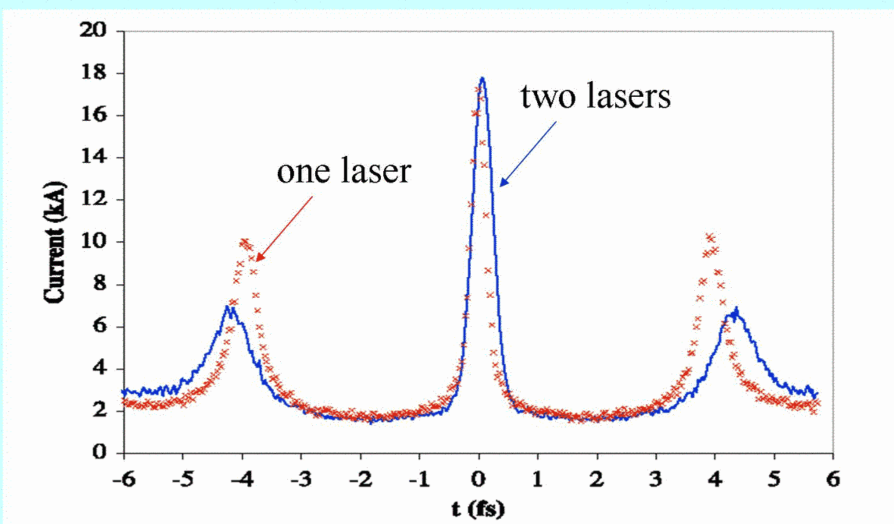
Combined field of two lasers: effective increase of the bandwidth



Energy modulation of electrons produced in interaction with two lasers

A. Zholents, UCSB, August 4, 2006

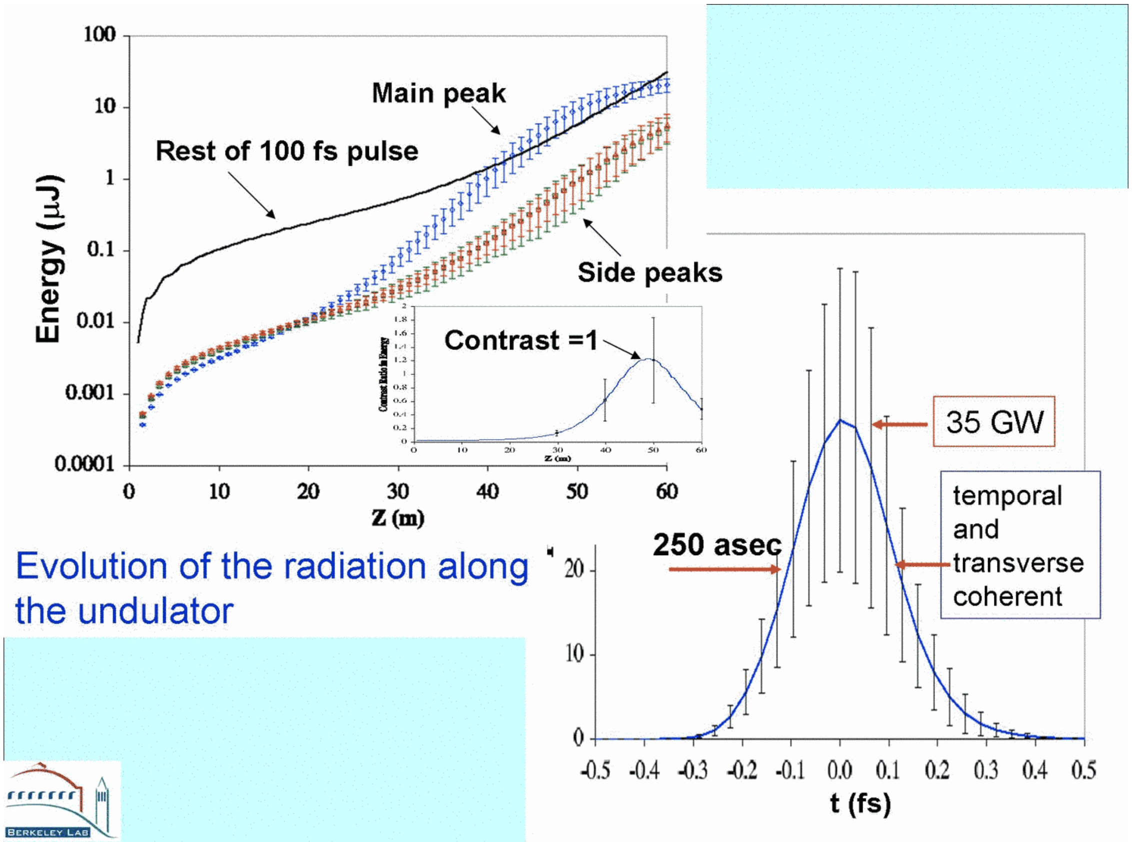
Current enhancement method cont'd



Peak current after chicane

Note: saturation length ~ (peak current)$^{-1/3}$

A. Zholents, UCSB, August 4, 2006



Comparison of four techniques for generation of attosecond x-ray pulses

Proposal	1	2	3	4
FEL type	HC	SASE	SASE	SASE
Numerical example shown for a wavelength	1 nm	0.15 nm	0.15 nm	0.15 nm
Absolute synchronization to external optical laser	Yes	Yes	Yes	Yes
Needs optical laser development	No	Yes	Yes	Yes
Needs monochromator	No	Yes	No	No
FWHM pulse duration, asec	100 -150	300	300	250
Peak power	10 MW	10 GW	10-100 GW	40 GW
Contrast of attosecond pulse	>>1	~1	~1	~1

A. Zholents, UCSB, August 4, 2006

Summary

1) Production of the attosecond x-ray pulses uses:
   - transversely and temporally coherent x-ray light
   - intense few-cycle optical pulse with carrier-envelope phase control

2) Shorter than 100 attosecond pulses might be possible.

3) There is an absolute synchronization between optical pump and x-ray probe pulses.

4) A proposed scheme for a production of attosecond x-ray pulses can be added to FEL facility at a relatively modest cost compared to the cost of a primary facility.

BERKELEY LAB

A. Zholents, UCSB, August 4, 2006

Acknowledgement

Many ideas discussed in this talk were developed together with Bill Fawley and Gregg Penn

Bill Fawley

Gregg Penn

BERKELEY LAB

A. Zholents, UCSB, August 4, 2006

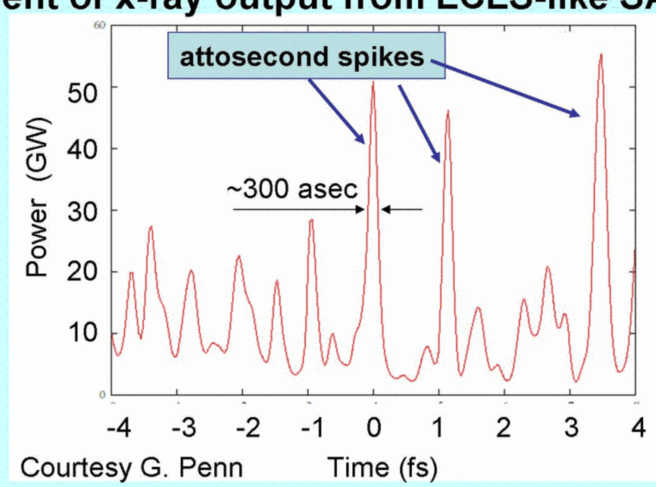
Thank you for your attention

A. Zholents, UCSB, August 4, 2006

Non laser based technique

Saldin, Schneidmiller, Yurkov, *Optics, Com.*,212,(2002)

A fragment of x-ray output from LCLS-like SASE FEL



300 asec -> 600 light cycles

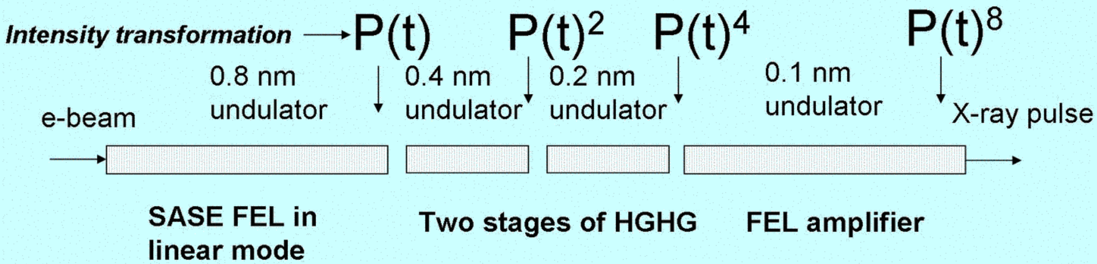
The idea is to select a dominant spike by means of nonlinear transformation, such as:

$$[Power]^n$$

ust 4, 2006

Non laser based technique cont'd

Realization:
through a combination of SASE and High Gain Harmonic Generation (HGHG) FEL techniques



Contrast = (energy in asec x-ray spike) / (energy in the rest of x-ray pulse)

Selection rule

1-10% of shots have contrast ≥ 1

Right shots can be identified from pulse energy which is >2x of the average energy taken over many pulses

A. Zholents, UCSB, August 4, 2006

Shortcomings of "Non laser technique"

- only 1 -10 % of total number of shots have contrast ≥ 1
- attosecond spike can appear anywhere along the x-ray pulse (because it comes out of amplified noise)
  - hard to use -- impossible to synchronize to external signal (laser)
  - only "single color" pump-probe experiments are possible
    - i.e. split and combine x-rays (with controlled delay between parts)

… were overcome in subsequent proposals

A. Zholents, UCSB, August 4, 2006