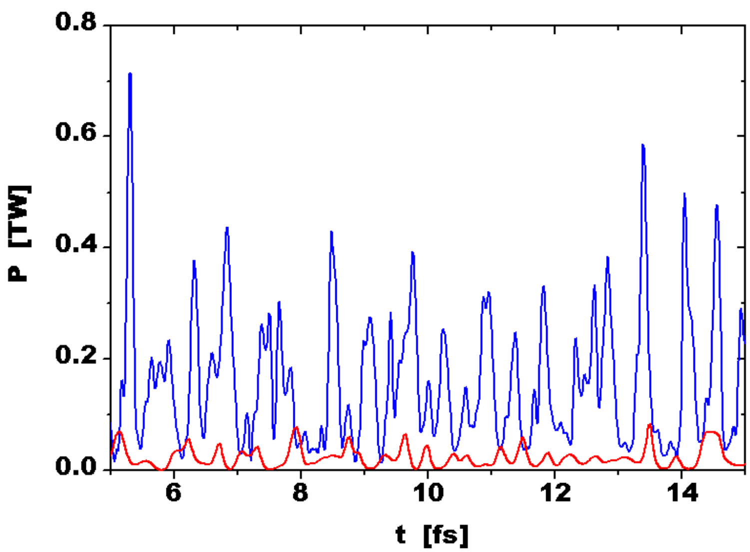
FLS2006 , Hamburg, May 17, 2006

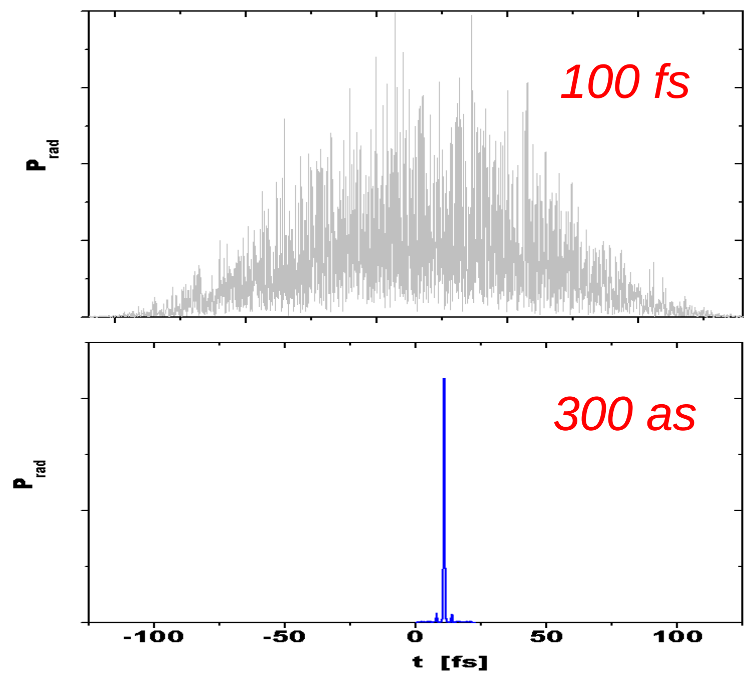
Schemes for generation of attosecond pulses in X-ray FELs

E.L. Saldin, E.A. Schneidmiller, M.V. Yurkov

The potential for the development of XFEL beyond stdandard (SASE) mode of operation:



High-power (TW level) X-ray pulses



Ultrashort X-ray pulses

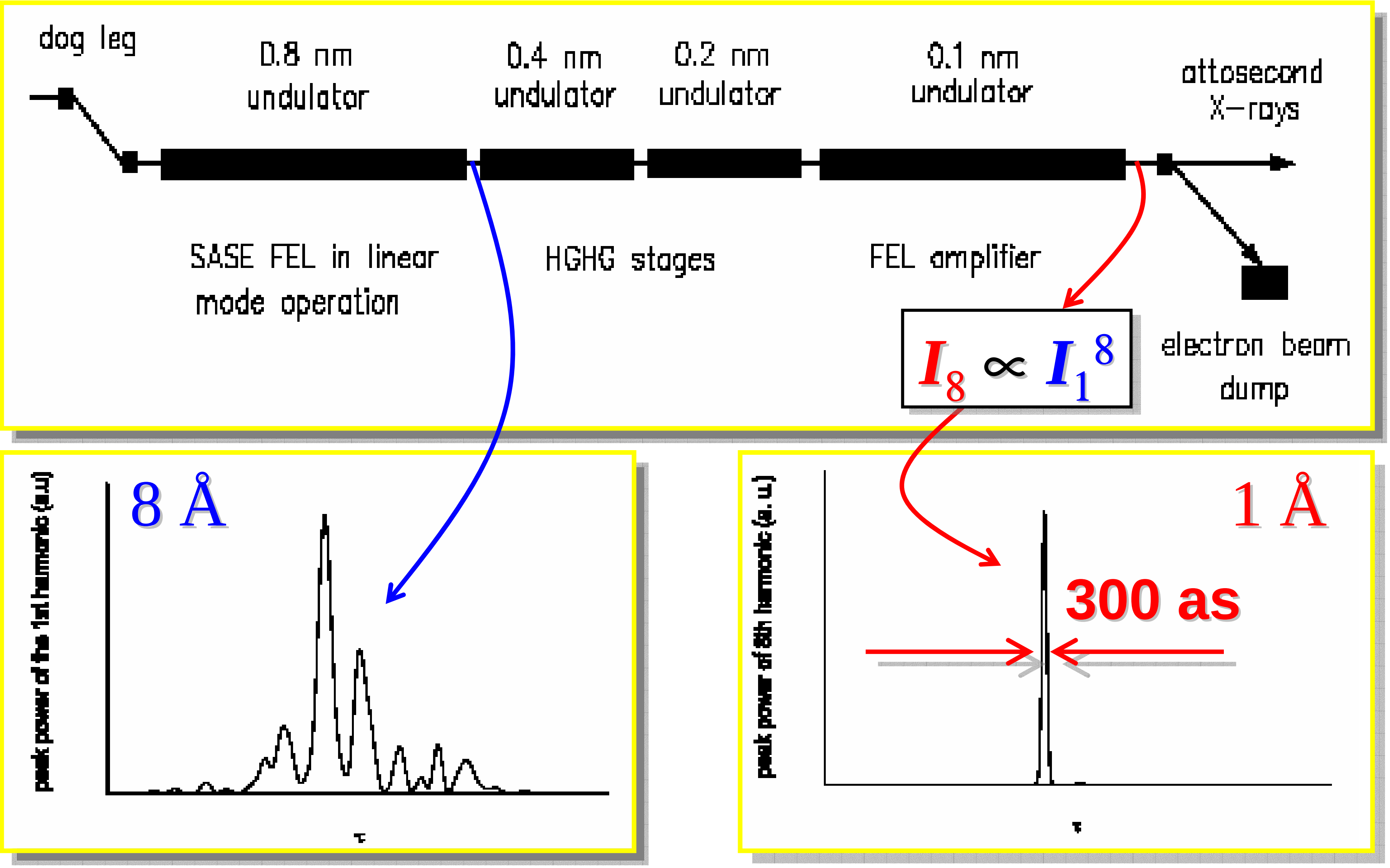
Schemes for attocesond XFEL

	A Ref. [1]	Ref. [2]	B Ref. [3]	C Ref. [4]	D Ref. [5]	E Ref. [6]	F Ref. [7]
FEL type	SASE	HC	SASE	SASE	SASE	SASE	SASE
Wavelength, nm	0.1	1	0.15	0.15	0.15	0.15	0.15
Synchronization to optical laser	No	Yes	Yes	Yes	No	Yes	Yes
Pulse duration, as	200-300	100-150	200-300	200-300	380-570	200-300	200
Peak power, GW	10	0.01	10	100	5-8	100	100

1. SSY, Opt. Comm., 212(2002)377
2. A. Zholents, W. Fawley PRL 92(2004)224801.
3. SSY, Opt. Comm., 237(2004)153
4. SSY, Opt. Comm., 239(2004)161
5. P. Emma et al., Proc. FEL 2004 Conf., p.333
6. A. Zholents and G. Penn, Phys. Rev. ST AB 8(2005)050704
7. SSY, Phys. Rev. ST AB 9(2006)050702

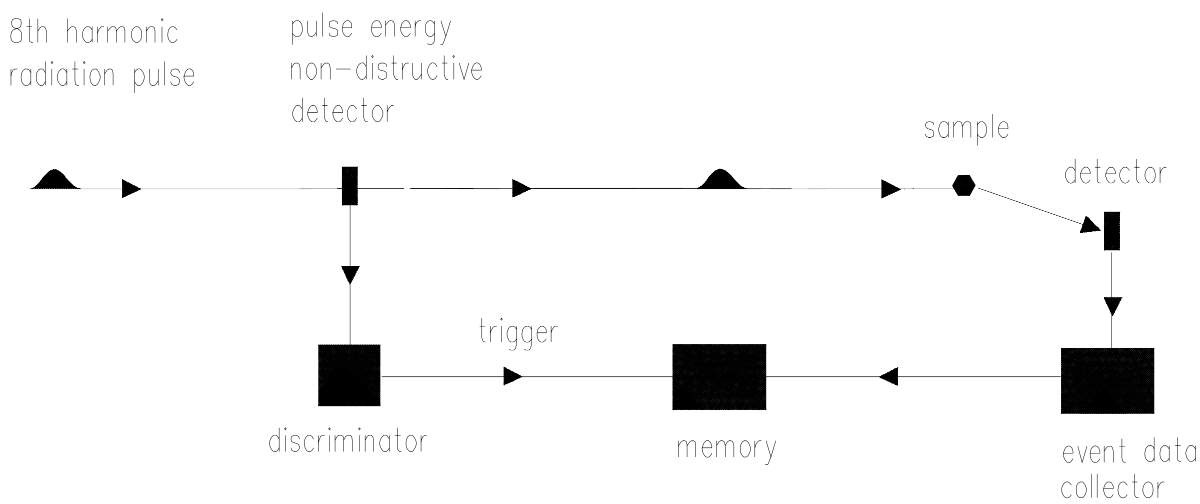
Statistical Single-Spike Selection

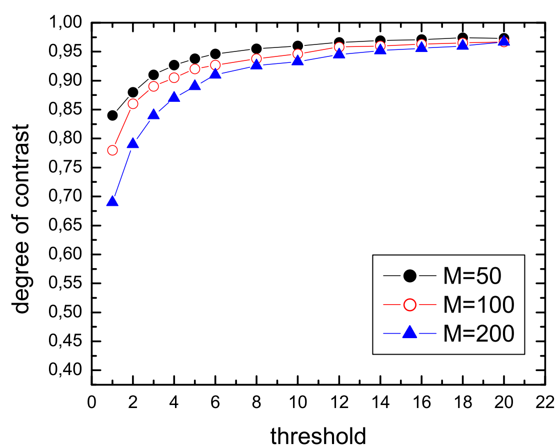
Un-seeded single-bunch **HGHG** (8 → 4 → 2 → 1 Å)

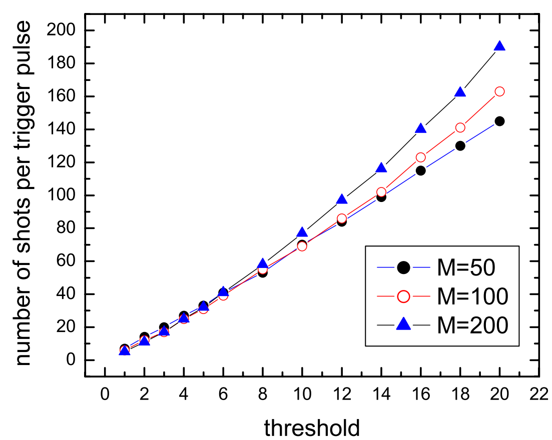


SSY, *Opt. Comm.*, 212(2002)377

Selection of attosecond pulses

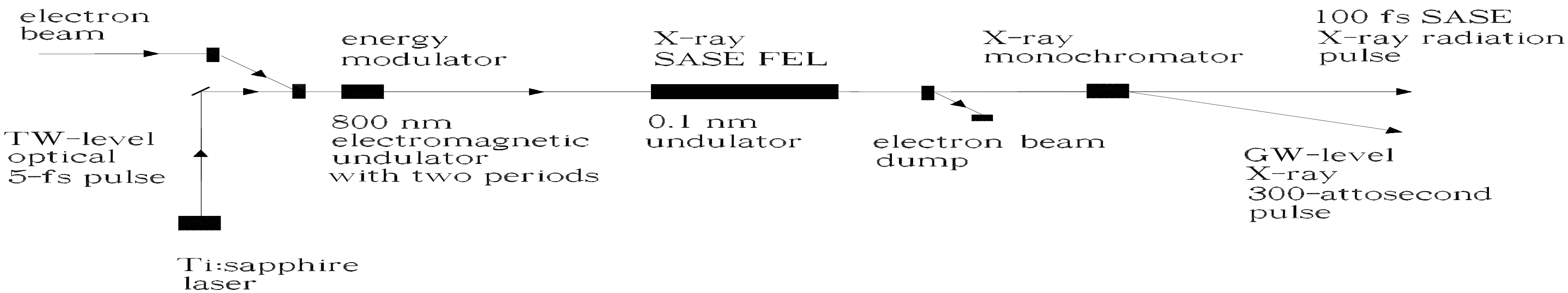


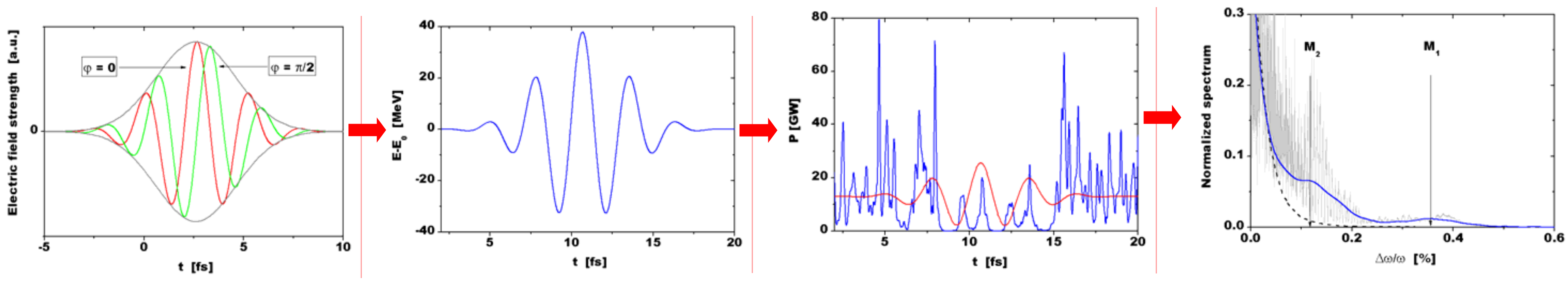




SSY, *Opt. Comm.*, 212(2002)377

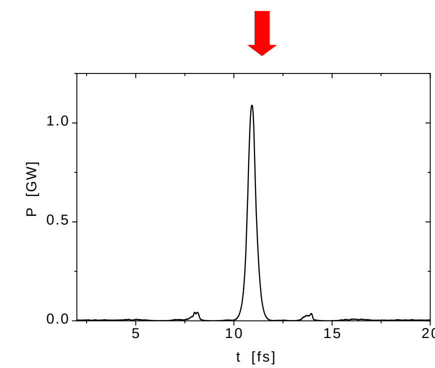
Generation of attosecond pulses in XFEL
/ „parasitic mode of operation“ /





Slicing of electron bunch with fs-laser

SASE process

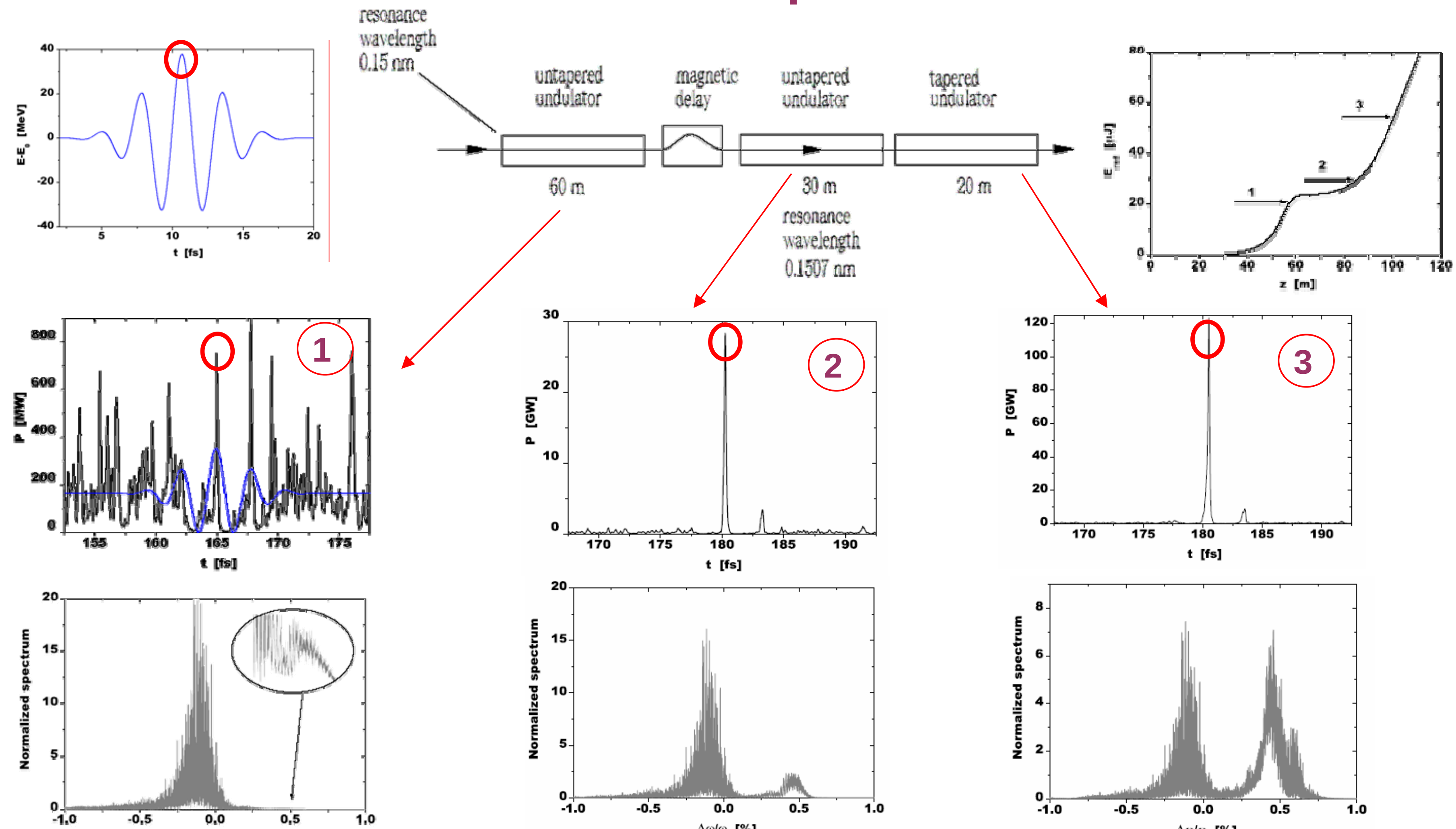


The laser-driven sinusoidal energy chirp produces a correlated frequency chirp of the resonant radiation $\delta\omega/\omega \simeq 2\delta\gamma/\gamma$. After the undulator, the radiation is passed through a crystal monochromator which reflects a narrow bandwidth. Since the radiation frequency is correlated to the longitudinal position within the beam, a short temporal radiation pulse is transmitted through the monochromator.

SSY, *Opt. Comm.*, 237(2004)153

Monochromator selects attosecond X-ray pulses

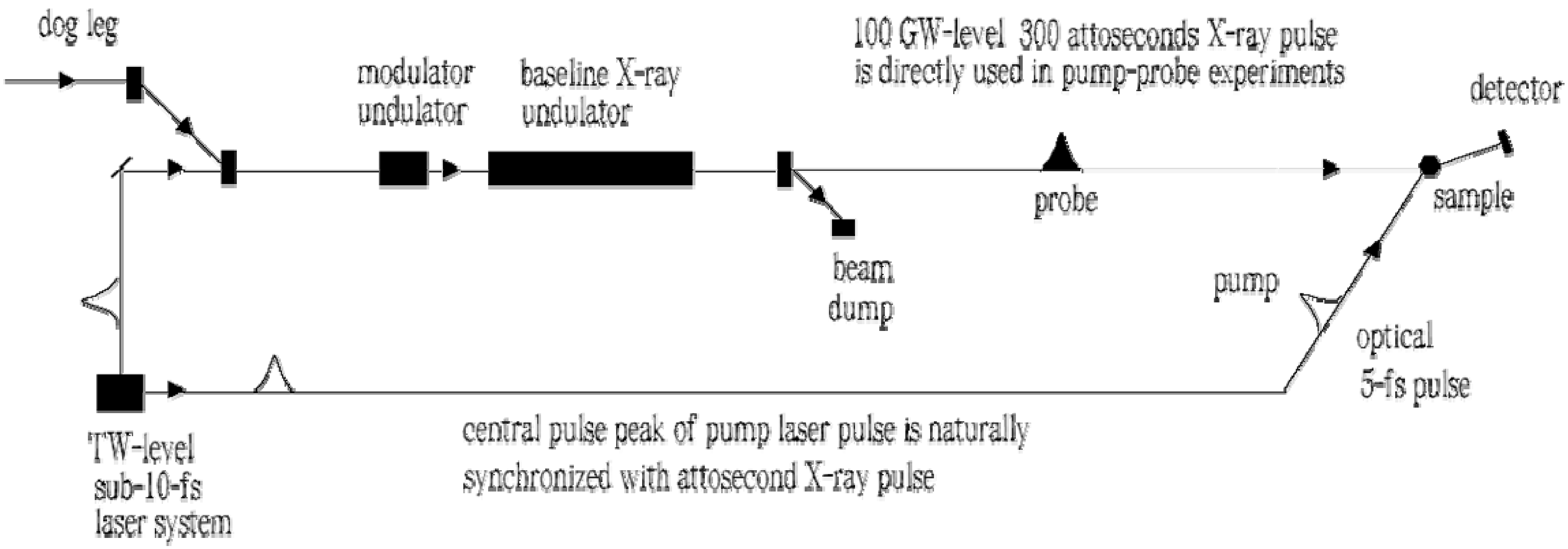
Generation of attosecond pulses in XFEL
/ 100 GW option /



- *The laser-driven sinusoidal energy chirp produces a correlated frequency chirp of the resonant radiation $\delta\omega/\omega \simeq 2\delta\gamma/\gamma$.*
- *After the first undulator the electron beam is guided through a magnetic delay which we use to position the X-ray spike with the largest frequency offset at the "fresh" part of the electron bunch.*
- *The second undulator is resonant with the offset frequency, and only a single (300 as duration) spike grows rapidly.*

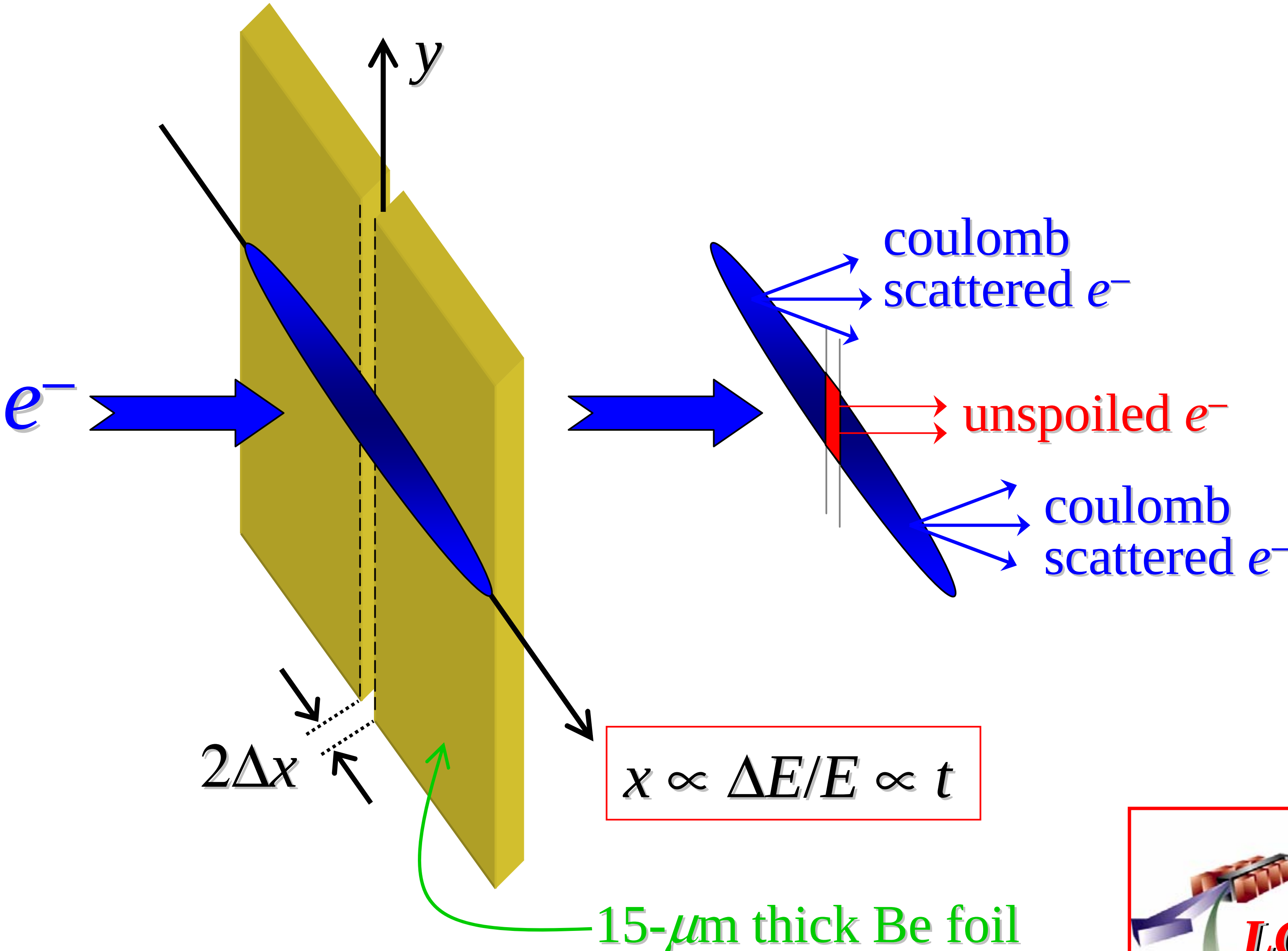
SSY, *Opt. Comm.*, 239(2004)161

Pump-probe experiments with attosecond SASE FEL



- *We suggest to combine attosecond X-ray pulses with fs optical pulses generated in the seed Ti:sapphire laser system for pump-probe experiments.*
- *Attosecond X-ray pulse is naturally synchronized with its fs optical pulse, and time jitter is cancelled.*
- *An advantage of the proposed scheme is the possibility to remove all X-ray optical elements between the X-ray source and a sample and thus to directly use the probe attosecond X-ray pulse.*
- *Usual optical elements are used for seed laser beam splitting and tunable delay. It should be possible to achieve a timing accuracy close to duration of the half period of the seed laser pulse (1 fs).*

Slotted foil method



P. Emma et al., Proc. FEL 2004 Conf., p.333

Slotted foil method

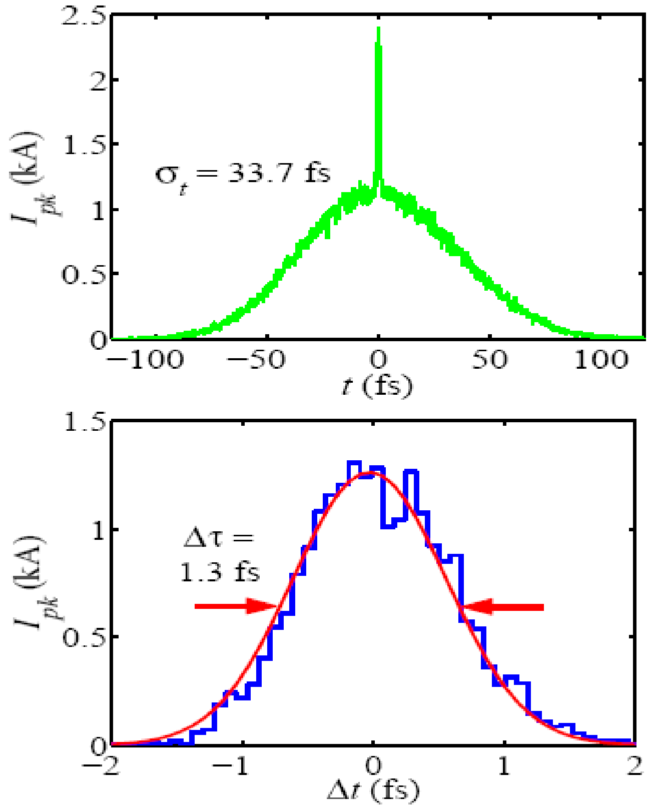


Figure 5: Current profile after BC2 (top) with spike created by e^- passing through the slit, and unspoiled e^- only (bottom) after BC2 with 1.3-fs FWHM and 1.3 kA.

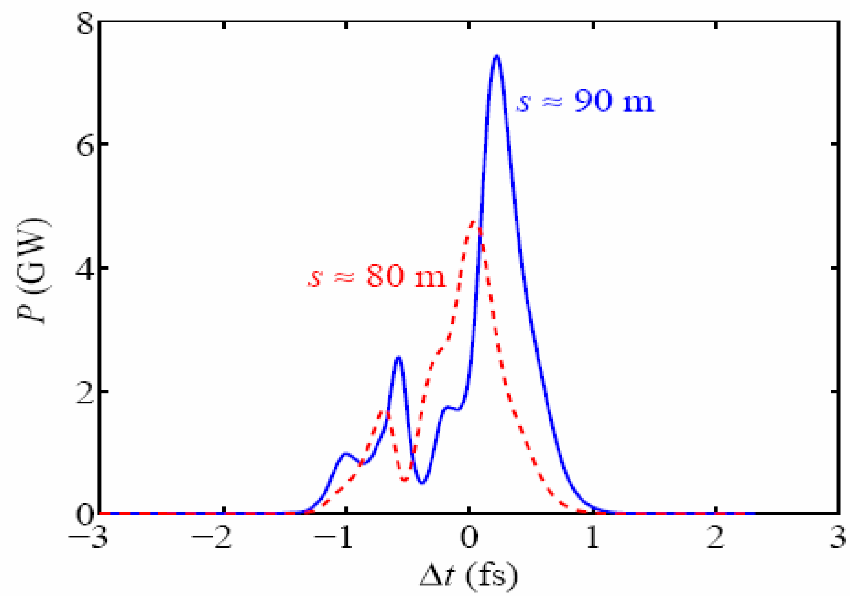
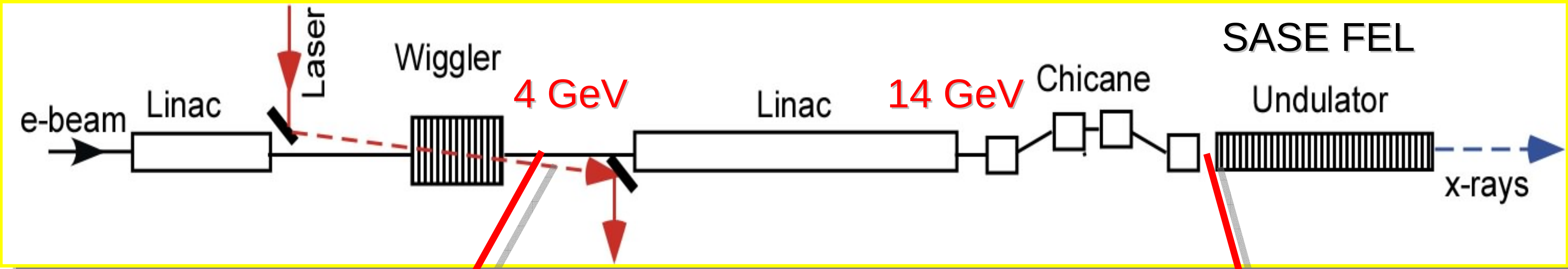
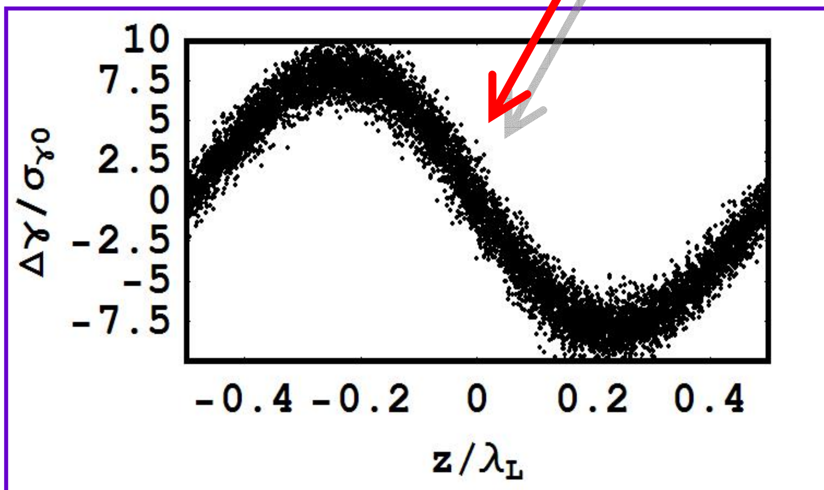


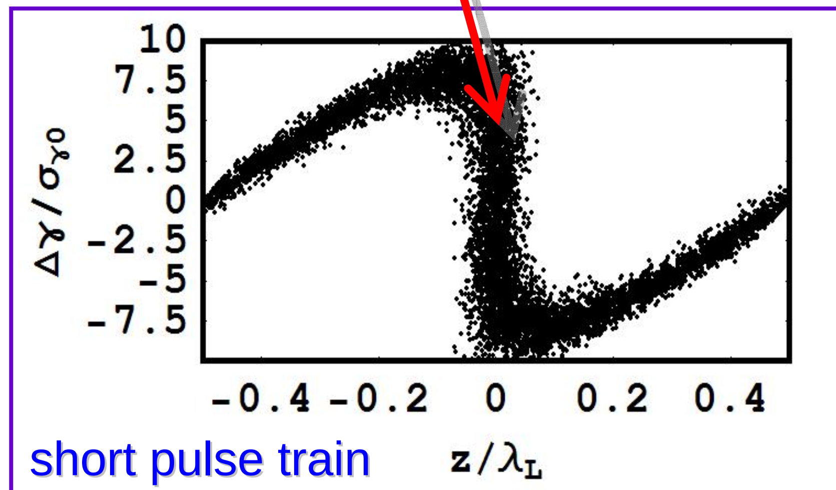
Figure 6: X-ray power profile at $s \approx 80$ m (red-dash) and $s \approx 90$ m (blue-solid) along the undulator, with 570-as (80 m) and 380-as (90 m) FWHM spike duration at 5-7 GW.

P. Emma et al., Proc. FEL 2004 Conf., p.333



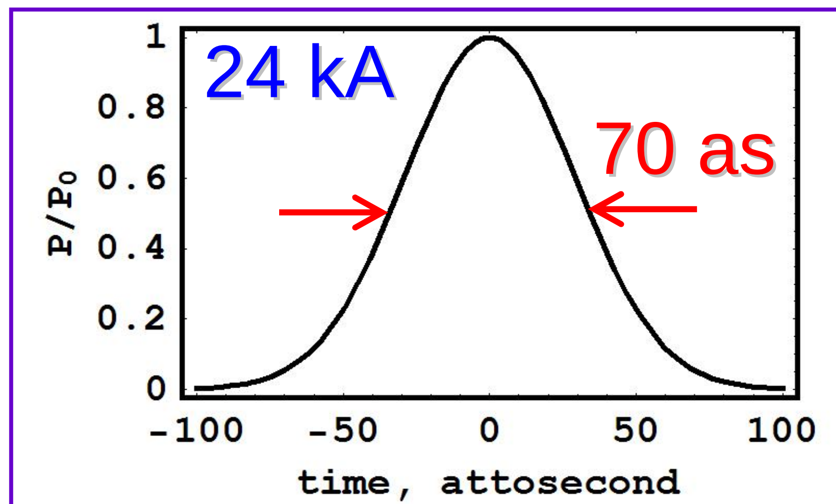


800-nm modulation (few GW)



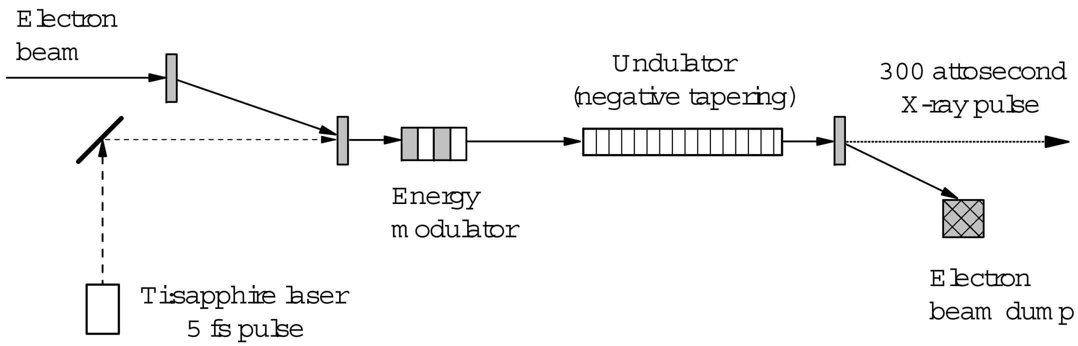
Allows synchronization between laser pulse and x-ray pulse

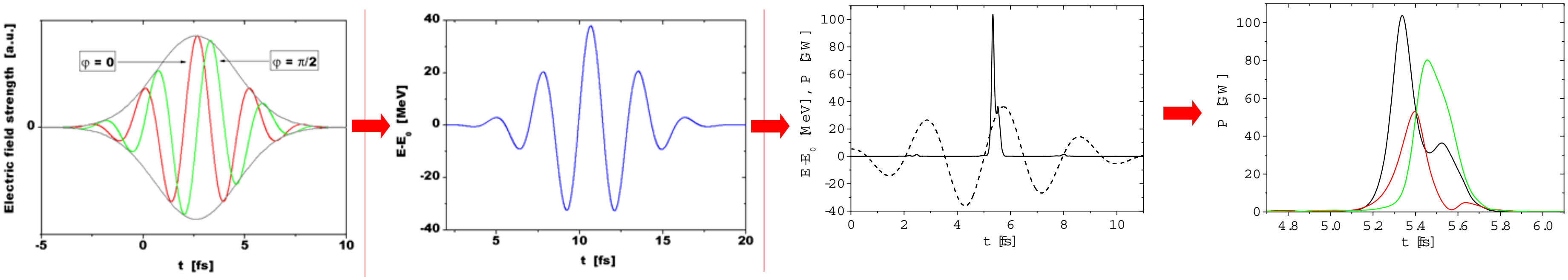
***E*-SASE** (applied to *LCLS*)



A. Zholents and G. Penn, Phys. Rev. ST AB 8(2005)050704

Generation of attosecond pulses in XFEL driven by energy-chirped electron beam





Slicing of electron bunch with fs-laser

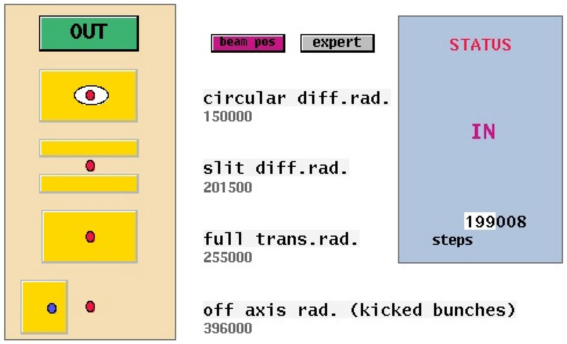
SASE process

Strong energy modulation within a short slice of an electron bunch is produced by few-cycle optical laser pulse in a short undulator, placed in front of the main undulator. Gain degradation within this slice is compensated by an appropriate undulator taper while the rest of the bunch suffers from this taper and does not lase. Three-dimensional simulations predict that short (200 attoseconds) high-power (up to 100 GW) pulses can be produced in Angstroem wavelength range with a high degree of contrast.

SSY, *Phys. Rev. ST AB 9(2006)050702*

The end

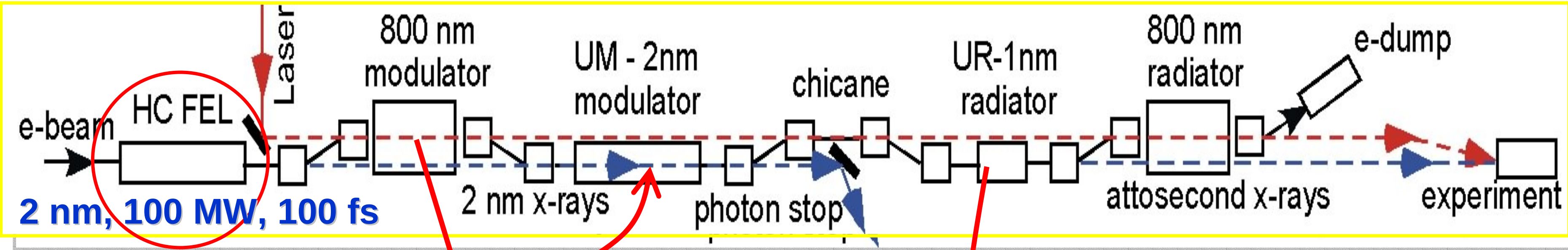
Effect of aperture limitations on SASE:
Coherent diffraction radiator, 4mm slit, position at 14ACC7

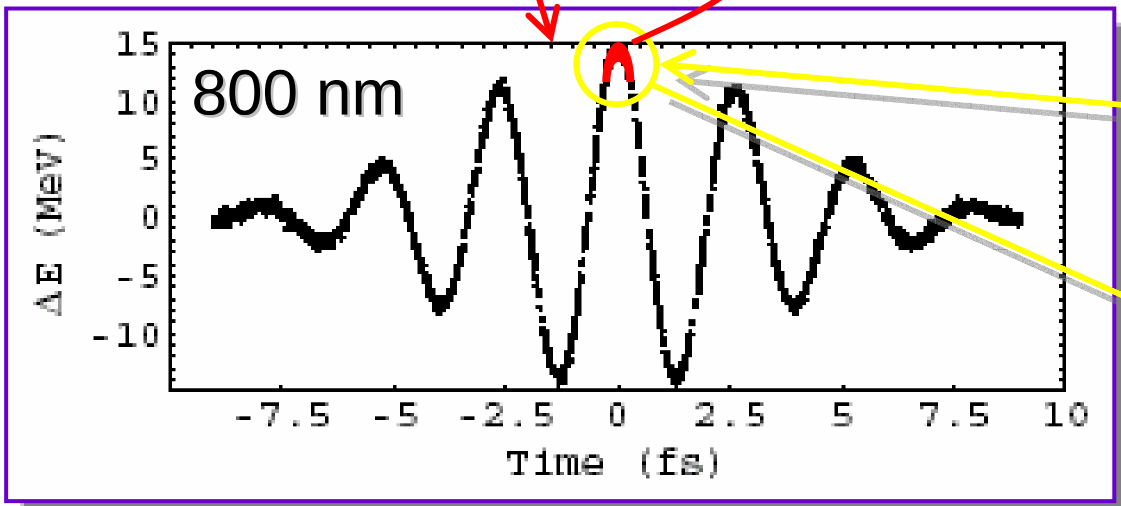


09.02.2006 08:55

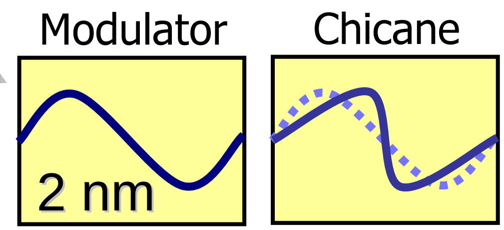
Three images below demonstrate an effect on SASE of diffraction radiator 14ACC7.
8:41 diffraction radiator inserted
8:53 diffraction radiator removed
CDR does not affect transmission, but reduction of SASE occurs. Fine positioning of slit done by Delsim did not result in recovering SASE level.

Note that during night shift CDR 14ACC7 was in. All attempts to improve SASE above 9 uJ failed. After discussion of their problems we decided to move out CDR 14ACC7. Within 10 minutes we tuned SASE to 11 uJ level.





Mod. tuned so only high energy e^- interact with 2-nm HC FEL radiation



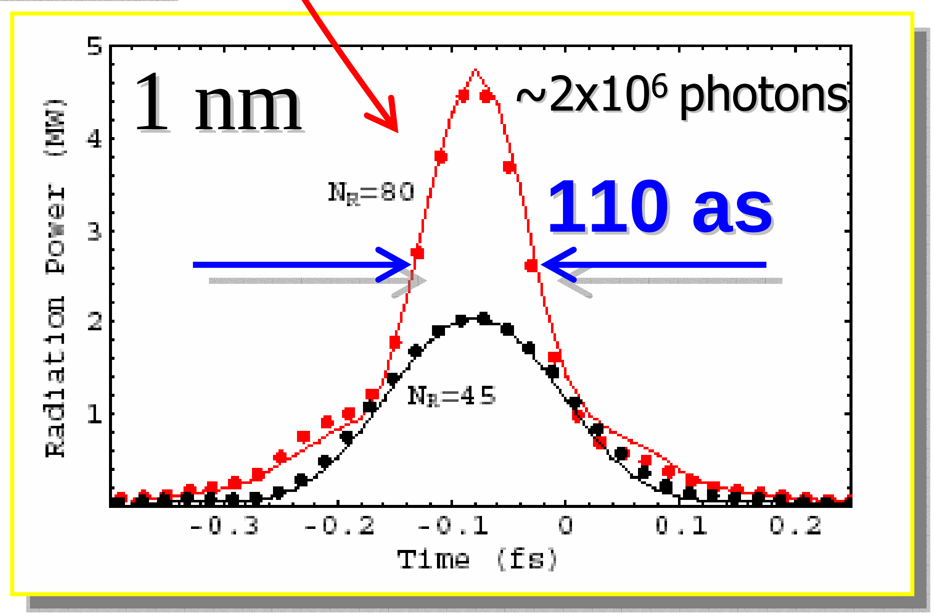
LUX electron beam parameters:

e^- energy	= 3 GeV
emittance	= 2 mm-mrad
energy spread	= 0.3 MeV
peak current	= 500 A

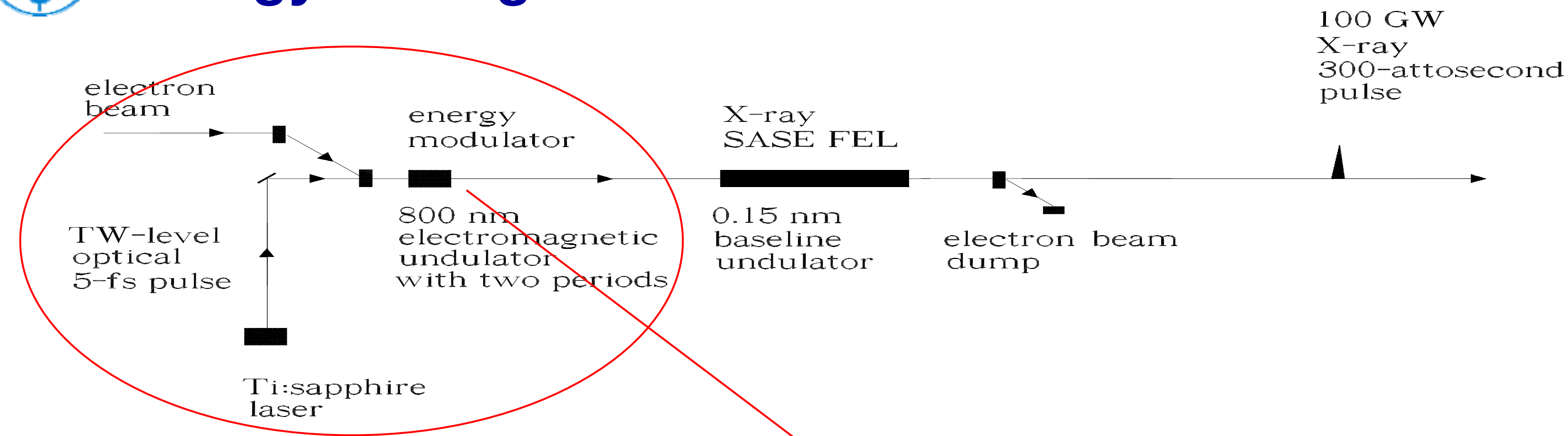
Generation of Attosecond Pulses…

A. Zholents, W. Fawley

PRL **92**, 224801 (2004).

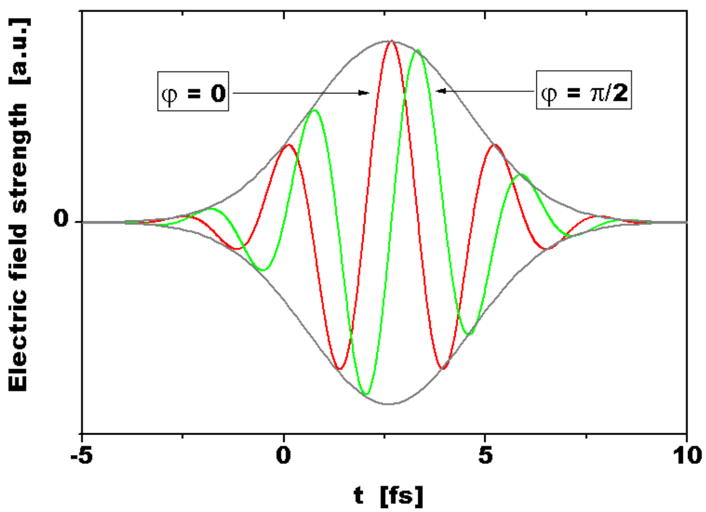


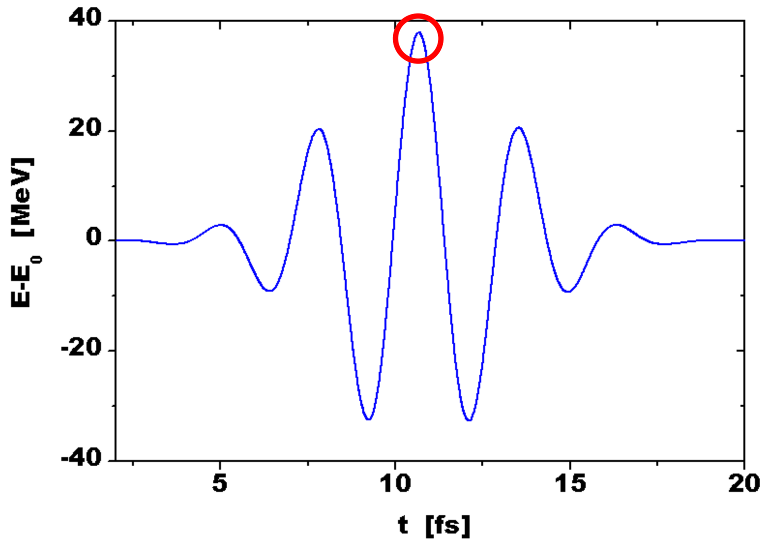
Energy slicing of the electron beam at sub-10fs scale



Laser: Ti:sapphire (800 nm)
flash energy 2-4 mJ
pulse duration 5 fs

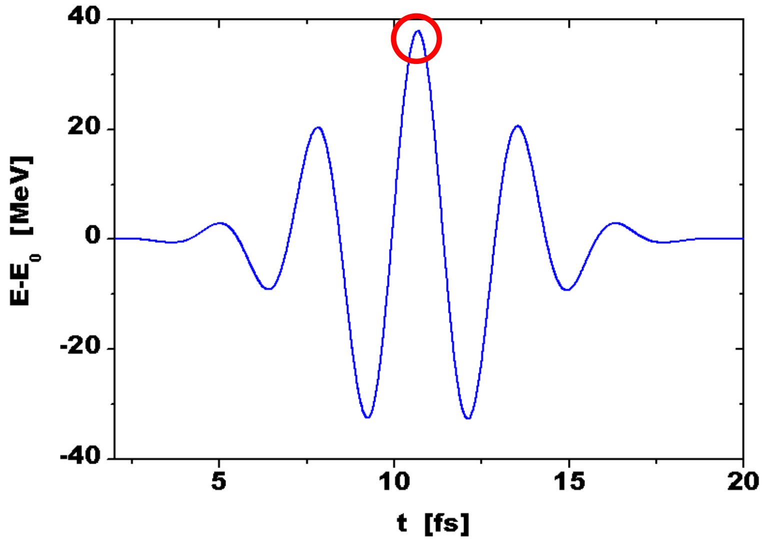
Undulator: period 50 cm
number of periods:2
peak magnetic field 1.6 T

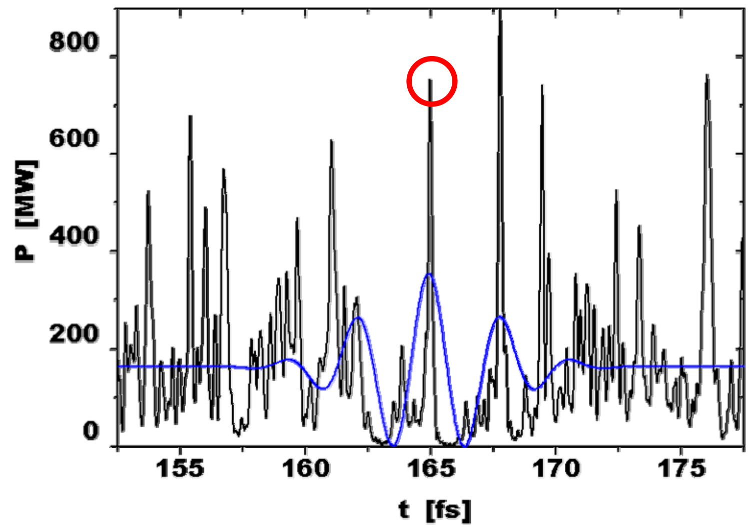




Slice energy modulation up to 40 MeV

Principle of as pulses production in X-ray SASE FEL





- The laser-driven sinusoidal energy chirp produces frequency chirp of the resonant radiation $\delta\omega/\omega$ ' $2\delta\gamma/\gamma$ correlated to the position along the bunch.
- Sensitivity of the SASE FEL process to the energy chirp along the bunch leads to effective isolation of radiative slices of the bunch.
- Selection of as pulses can be performed by:
  - a crystal monochromator which reflects a narrow bandwidth ("parasitic" mode of operation);
  - undulator tuned to offset frequency (dedicated 100 GW mode of operation).
- Since the radiation frequency is correlated to the longitudinal position within the beam, a short temporal radiation pulse is extracted.