Next Generation Light Sources

Roger Falcone

Physics Department, UC Berkeley
and
Director, Advanced Light Source, LBNL

Observations on soft x-ray FELs and optical lasers

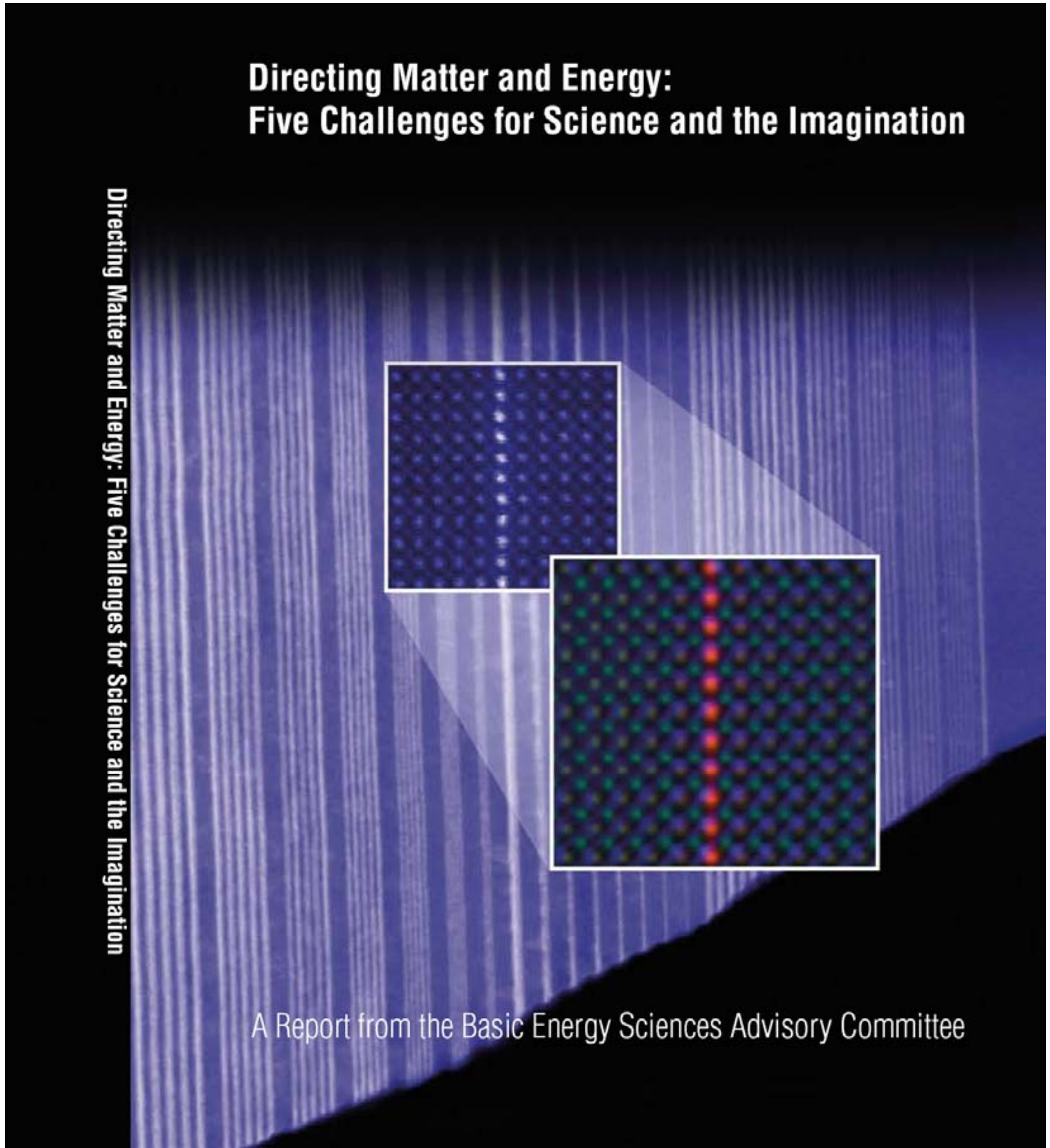
- International workshops and reports have made a strong case for compelling science that requires next-generation, soft x-ray sources

- Various international groups have modeled and converged on relatively similar designs for high-rep-rate, soft x-ray FELs

- Optical lasers and high harmonics will soon be available with sufficient power to seed high-rep-rate, coherent, soft x-ray FELs

- Optical lasers with high harmonic generation alone will not soon rival the average coherent power of soft x-ray FELs

- Optical lasers may become available to drive electron accelerators for soft x-ray sources

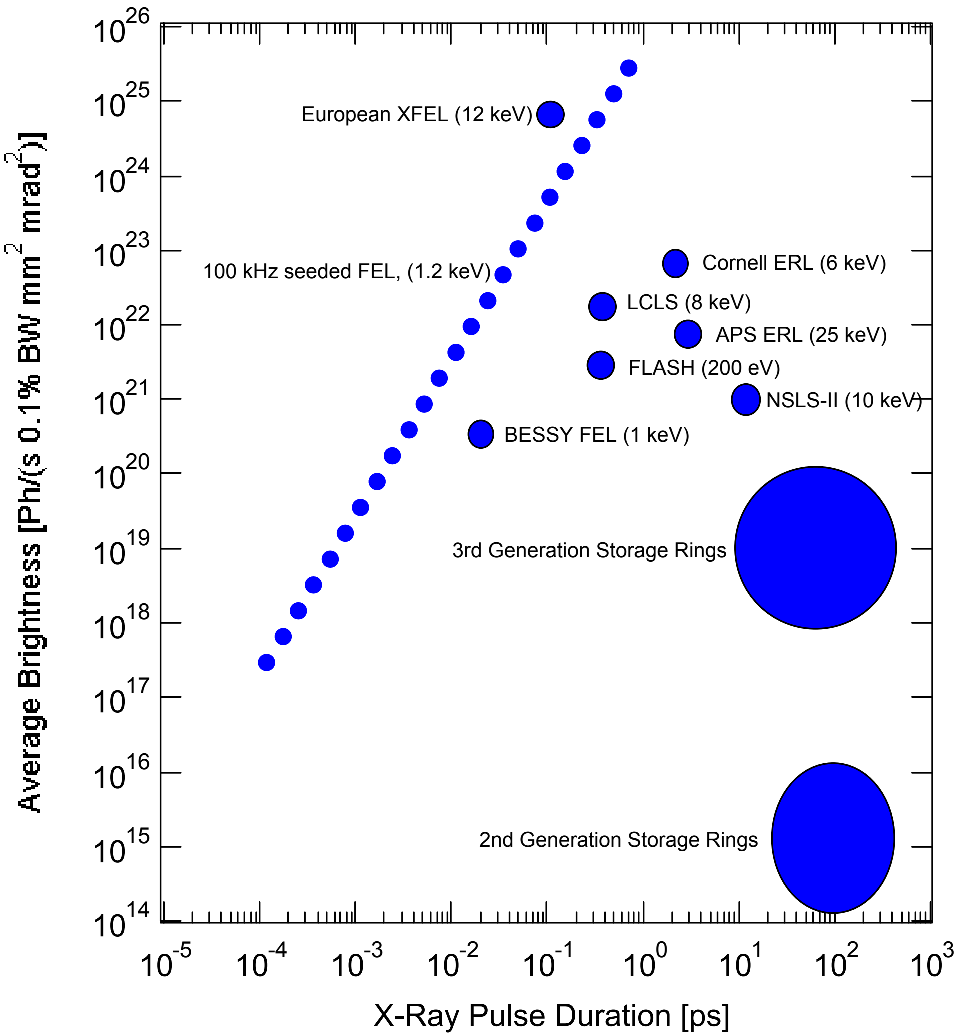

Directing Matter and Energy:
Five Challenges for Science and the Imagination
Directing Matter and Energy: Five Challenges for Science and the Imagination
A Report from the Basic Energy Sciences Advisory Committee

Five Grand Challenges for Science and the Imagination

- ***How do we control materials and processes at the level of electrons?***
- ***How do we design and perfect atom-and energy-efficient synthesis of new forms of matter with tailored properties?***
- ***How do remarkable properties of matter emerge from complex correlations of atomic and electronic constituents and how can we control these properties?***
- ***Can we master energy and information on the nanoscale to create new technologies with capabilities rivaling those of living systems?***
- ***How do we characterize and control matter away—especially very far away—from equilibrium?***

Next Generation of Instruments

What machines could have the broad impact of synchrotrons?



- **Higher time resolution**
- **Improved imaging methods**
- **Improved and new kinds of detectors**

Average brightness versus pulse duration for storage ring, ERL, and FEL sources. Values are shown for optimized brightness at the photon energies indicated, based on available data.

Workshop "Science for a New Class of Soft X-ray Light Sources"

October 8-10, 2007
http://hpcrd.lbl.gov/sxls/home.html

Consider the outstanding and challenging scientific questions that might require new soft x-ray light sources

Develop a scientific basis for the requirements and specifications of such facilities

Workshop “Science for a New Class of Soft X-ray Light Sources”

Focused on 5 areas:

1. Atomic, Molecular and Optical Physics
2. Chemical Physics
3. Correlated Materials
4. Magnetization and Spin Dynamics
5. Nanoscience and Coherence

Plenary talks:

Atomic and Molecular Physics: *Joachim Ullrich and Paul Corkum*

Magnetization and Spin Dynamics: *Joachim Stohr and Wolfgang Eberhardt*

Chemical Physics: *Steve Leone and Majed Chergui*

Nanoscience and Coherence: *Paul Alivisatos and Henry Chapman*

Complex Material Dynamics: *Z. X. Shen and Andrea Cavalleri*

Atomic, Molecular and Optical Physics

and

Chemical Physics Breakouts

- attosecond electron dynamics
- probe and control of electron correlation
- evolution of excited state dynamics in the gas phase
- extreme non-Born-Oppenheimer chemistry
- non-adiabatic control schemes
- 2d x-ray correlation spectroscopy

Workshop “Science for a New Class of Soft X-ray Light Sources”

- Soft x-rays are required for study of electron bonding and electron dynamics
  – complementary to hard x-rays, which reveal atomic positions
  – structure, bonding, and dynamics determine function

- Ultrafast timescales are used in nature to direct energy and information flow
  – beat the timescales for dissipation into unwanted modes:
    e.g., vision, photosynthesis -- we need efficient photovoltaics
  – allow multimode excitation to dissipate energy and minimize damage:
    e.g., DNA, damage -- we need materials that work in extreme conditions
  - speed is, and competing rates and quantum pathways are,
  critical to efficiency, and ultimately the optimization of function

- Coherent radiation implies longitudinal and transverse coherence
  – uniform transverse phase for high spatial resolution imaging
  – narrow-bandwidth radiation for high energy resolution spectroscopy

- Directing matter and energy flow will utilize coherent radiation (IR to x-ray) for both imaging of function and control

X-ray facilities for the future

WHAT ARE THE IMPORTANT PERFORMANCE GOALS?

Ultrafast Time resolution and Synchronization
required for all **dynamics studies**
(on sub-femtosecond to picosecond time scales)

Pulses from ps, to fs, to <fs duration
Synchronization with pump laser < pulse duration

High Average Flux and Brightness
required for **inelastic x-ray scattering**
X-ray emission spectroscopy
lensless imaging

>>10^{15} ph/s/0.1% BW
>> 3rd generation synchrotrons
- spectral brightness (meV resolution)
- spatial and temporal coherence (imaging)

High Repetition Rate
required for **inelastic x-ray scattering**
lensless imaging
time-resolved spectroscopy

10-100 kHz, MHz ?
limited flux/pulse on sample
- nonlinear effects, damage
- signal averaging

Tunability, Polarization Control, and Stability
required for all **spectroscopy research**

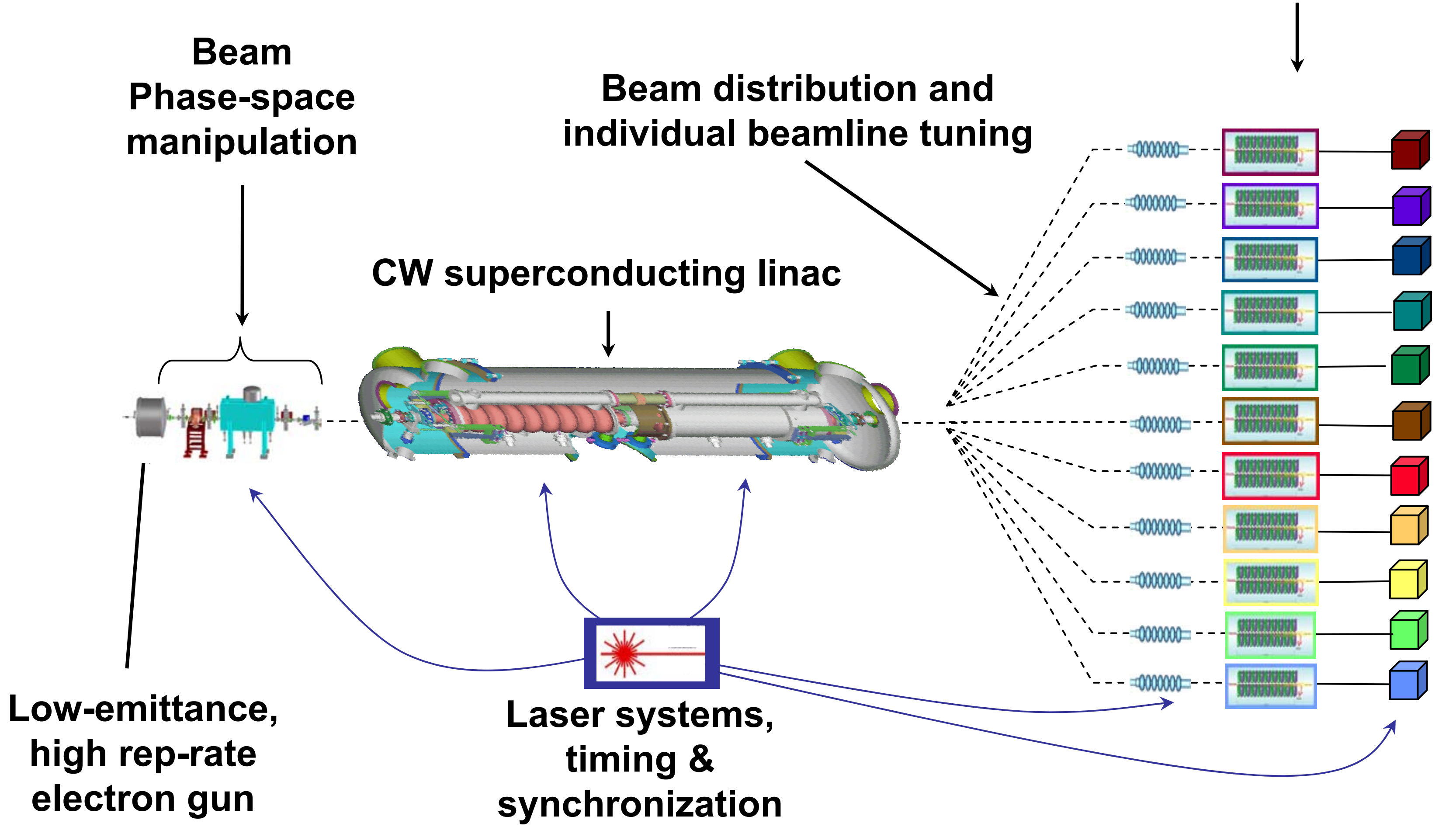
stability - small signal, large background

- **There are trade-offs in achieving optimized parameters**
- **We need to design systems optimized for particular experimental applications**
- **A facility with many independent and individually configured sources would provide sharp tools for a variety of applications**

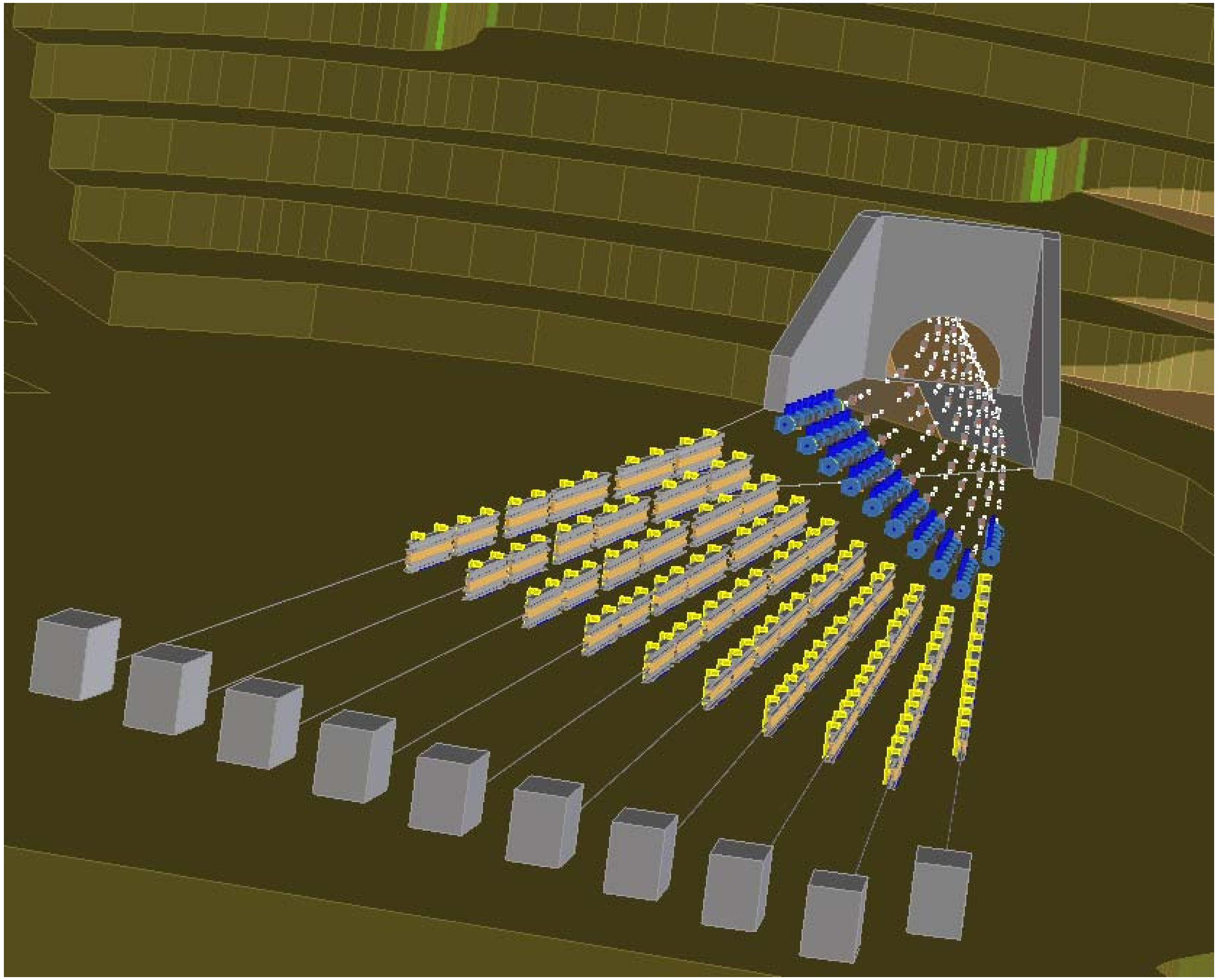
LBNL vision for a future light source facility

A HIGH REP-RATE, SEEDED, VUV — SOFT X-RAY FEL ARRAY

- Array of configurable FELs
- Independent control of wavelength, pulse duration, polarization
- Each FEL configured for experiment: seeded, attosecond, ESASE, etc



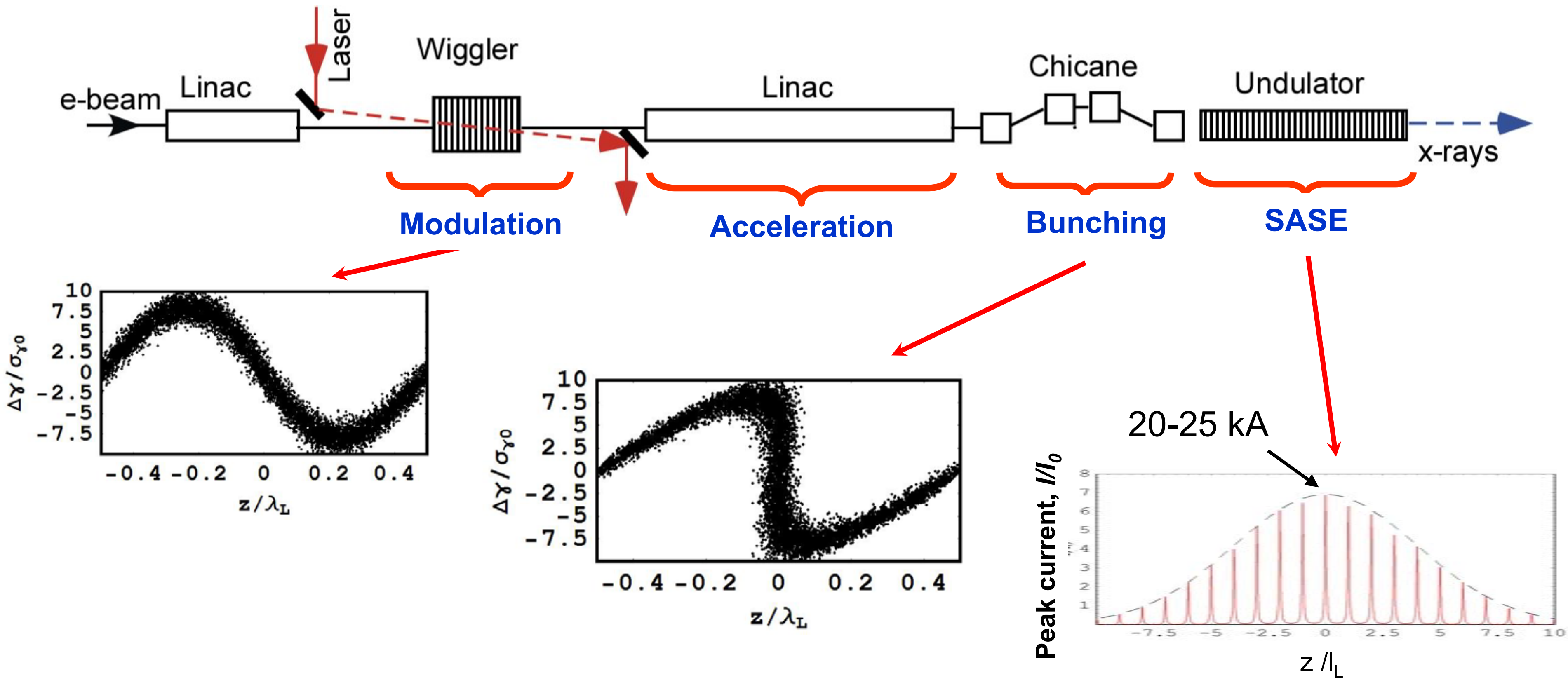
Spreader Region at Tunnel Exit



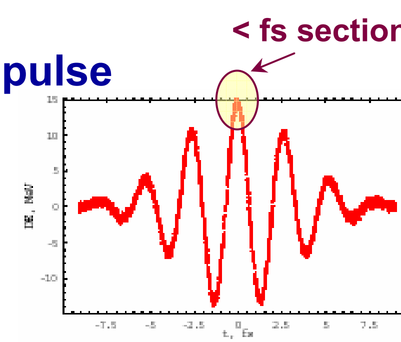
Electron beam is multiplexed to drive ~ 10 separate FEL beamlines

Optical manipulations techniques (1)

ESASE



- **Precise synchronization of the x-ray output with the modulating laser**
- **Variable output pulse train duration by adjusting the modulating laser pulse**
- **Increased peak current**
- **Shorter x-ray undulator length to achieve saturation**
- **Capability to produce a solitary ~100-attosecond duration x-ray pulse**
- **Other techniques can be used to produce controlled x-ray pulses**



A. Zholents, Phys. Rev. ST Accel. Beams 8, 040701 (2005)

Optical manipulations techniques (2)

HHG LASER SEED

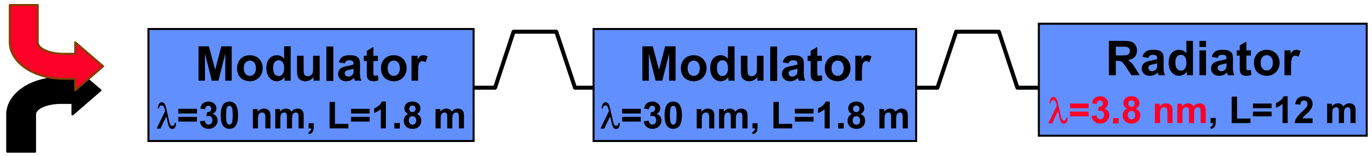
Example with seed at 30 nm, radiating in the water window

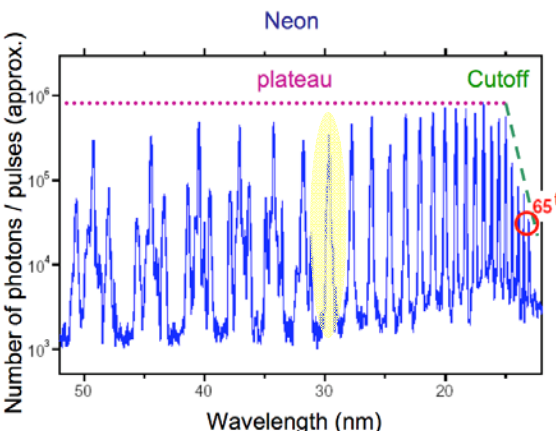
First stage amplifies low-power seed with "optical klystron"

- More initial bunching than could be practically achieved with a single modulator
- Output at 3.8 nm (8^{th} harmonic)

100 kW
λ=30 nm

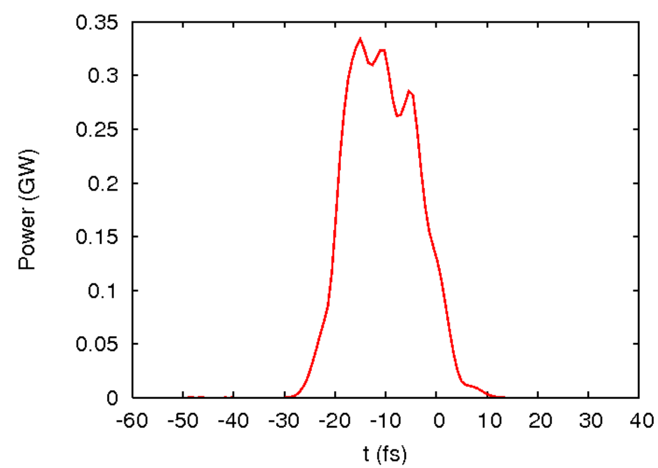
1 GeV beam
500 A
1.2 micron emittance
75 keV energy spread





Lambert et al., FEL04

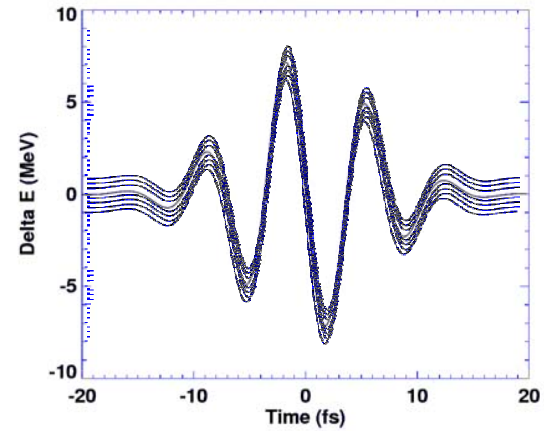
300 MW output at 3.8 nm (8^{th} harmonic) from a 25 fs FWHM seed



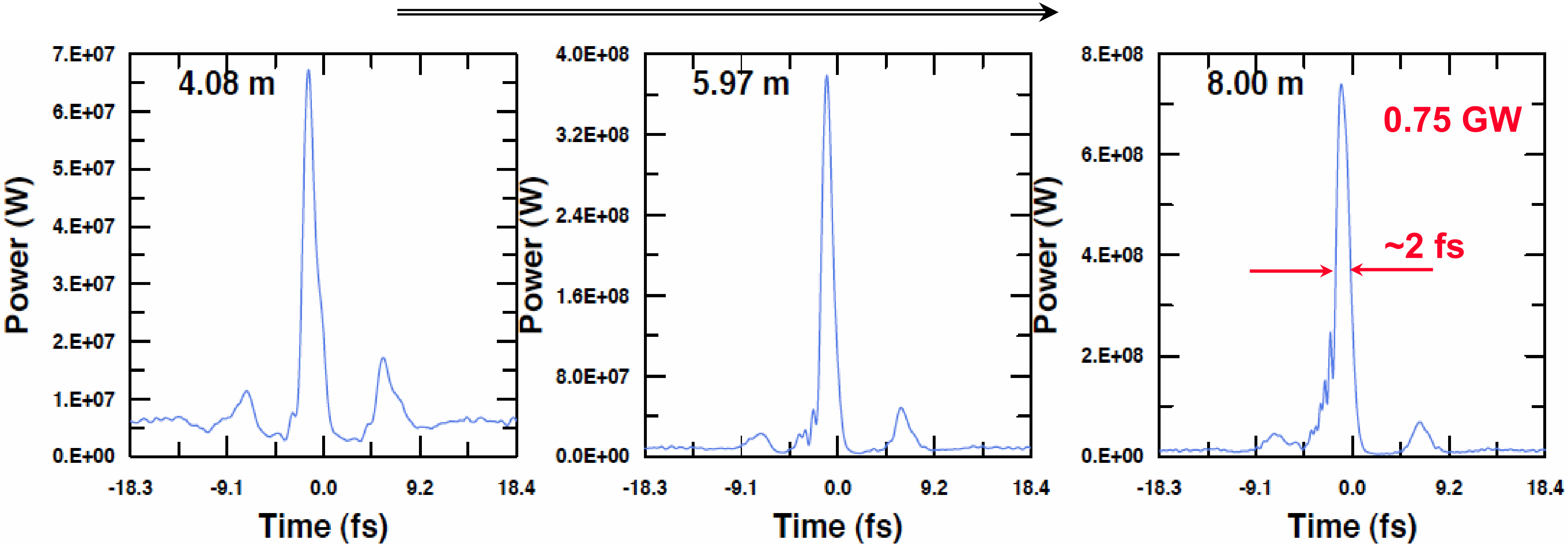
Optical manipulations techniques (3)

ULTRAFAST SASE PULSES IN VUV-SXR

- Again, a few-cycle optical pulse modulates electron beam
  - Modulating laser is possibly 1 - 2 μm wavelength
  - This time there is no compression following the modulation
  - Take advantage of the energy chirp in the bunch
  - Tapered FEL keeps the small section of appropriately chirped beam in resonance



Evolution of an 8 nm wavelength pulse along undulator



E.L. Saldin, E.A. Schneidmiller, and M.V. Yurkov, PRSTAB 9, 050702 (2006)

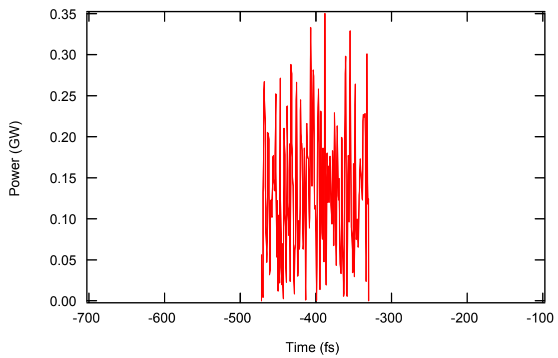
Seeded FEL

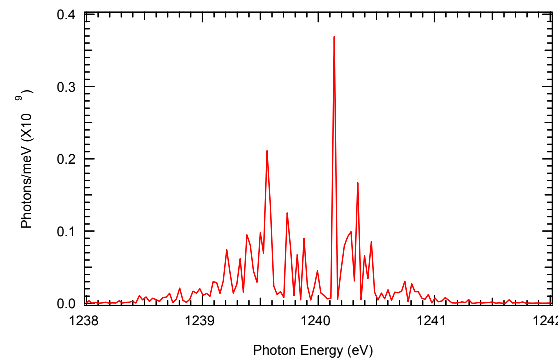
ENHANCED CAPABILITIES FOR CONTROL OF X-RAY PULSE

Pulse profile

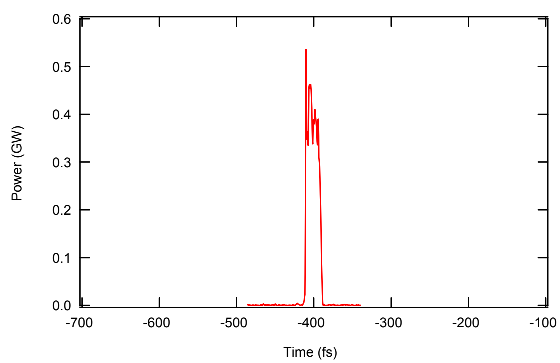
Spectrum

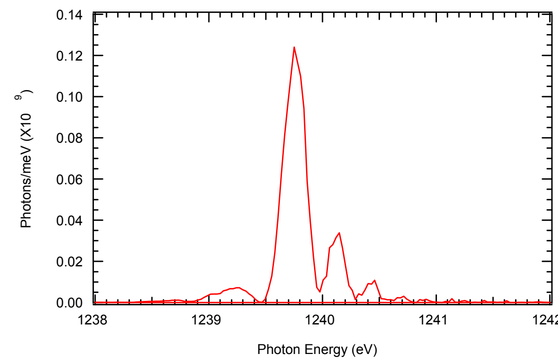
SASE



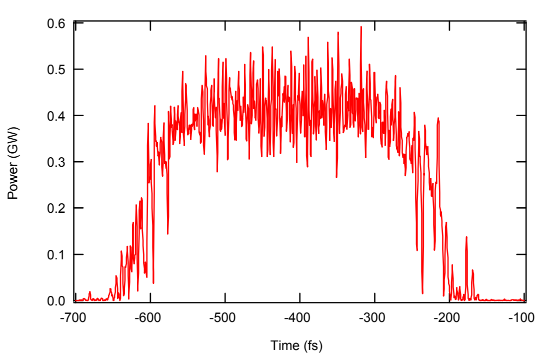


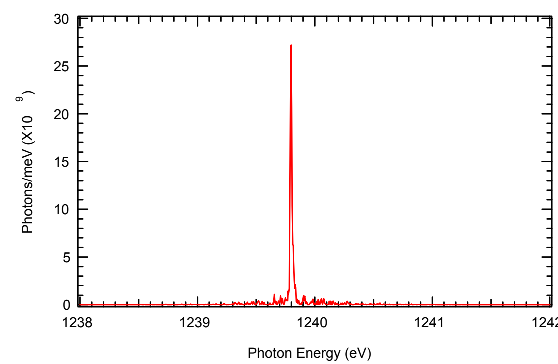
25 fs seed





500 fs seed





Electron beam is 1.5 GeV, energy spread 100 keV, 250 A current, 0.25 micron emittance; laser seed is 100 kW at 32 nm; undulator period 1 cm

Performance goals

FELs WITH THREE MODES OF OPERATION

	Short-pulse beamlines	High-resolution beamlines	Sub-femtosecond beamlines
Wavelength range (nm)	~200 Š 1	~200 Š 1	~40 Š 1
Photon energy (eV)	6 Š 1240	6 Š 1240	30 Š 1240
Repetition rate (kHz)	100	100	1-100
Peak power (GW)	1	1	0.1 Š 0.3
Photons/pulse (@1 nm)	5×10^{11} (in 100 fs)	2.5×10^{12} (in 500 fs)	1.5×10^{8} (in 100 as)
Timing stability (fs)	10	10	TBD
Pulse length (fs)	1 Š 100	100 Š 1000	0.1 - 1
Harmonics	² few%	² few%	² few%
Polarization	Variable, linear/circular	Variable, linear/circular	Variable, linear/circular

Observations on soft x-ray FELs and optical lasers

- Optical lasers and their high harmonics will soon be available with sufficient power to seed high-rep-rate, coherent, soft x-ray FELs

(note: R&D towards seeding of the LCLS at SLAC

is underway in collaboration with LBNL

and this could enable femtosecond pulses for single-molecule, lensless imaging)

Workshop “High Average Power Lasers and High Harmonics”

December 12, 2007
http://www-als.lbl.gov/sac/apsi/index.html

Discuss future possibilities for high average power lasers that could:

- drive high-peak and average power high-order harmonic sources
- seed FELs
- enable laser-based accelerators

Workshop “High Average Power Lasers and High Harmonics”

Introduction of issues

- Howard Padmore

Powerful lasers and harmonic short wavelength sources

- Margaret Murnane, Ferenc Krausz, Franz Kaertner, Steve Leone, Simon Hooker

Lasers, accelerators, and short wavelength sources

- Wim Leemans, Bob Byer

High average power lasers relevant to soft x-ray light sources

- Chris Barty, Bill White, Henry Kapteyn

Summary of integrated photon flux needed in condensed matter physics experiments

- angle resolved photoemission: volume datasets
  - 1e17 ph (20 – 100 eV)
- microscopy
  - 1e13 (280 – 1200 eV)
- spectro microscopy
  - 1e15 (280 – 1200 eV)
- time resolved microscopy
  - 1e16 ph (280 – 1200 eV)
- time resolved spectroscopy
  - 1e10 ph (280 – 1200 eV)

From H. Padmore

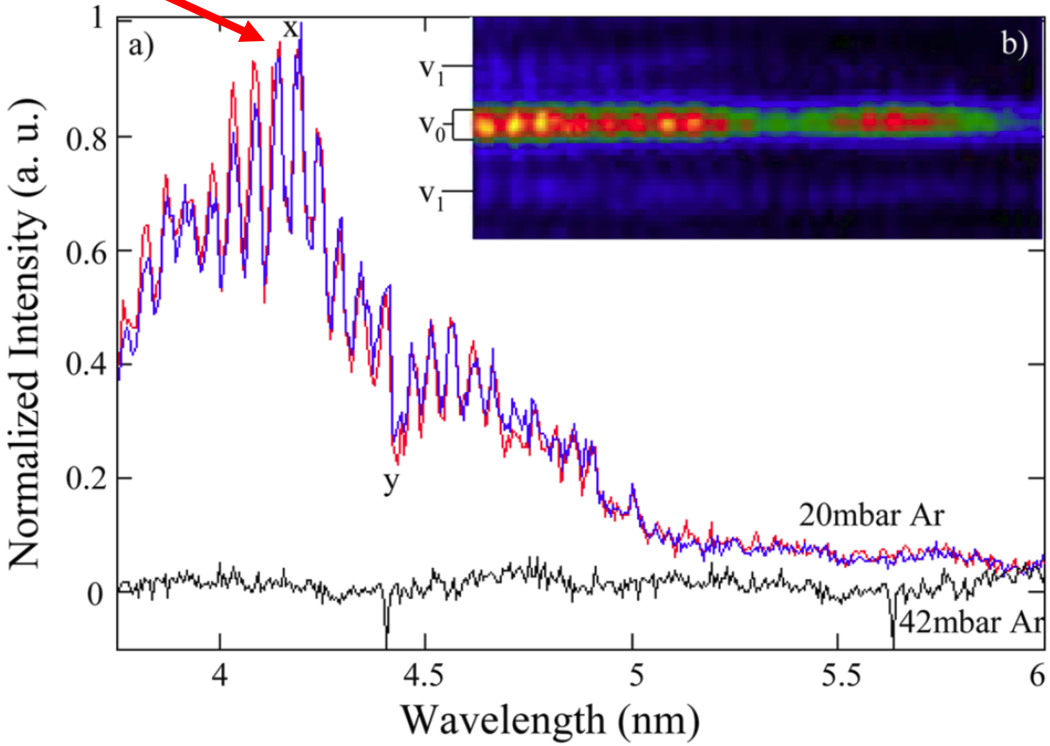
Quasi-phase matching at 300 eV in Ar

PRL 99, 143901 (2007) PHYSICAL REVIEW LETTERS week ending 5 OCTOBER 2007

Bright Quasi-Phase-Matched Soft-X-Ray Harmonic Radiation from Argon Ions

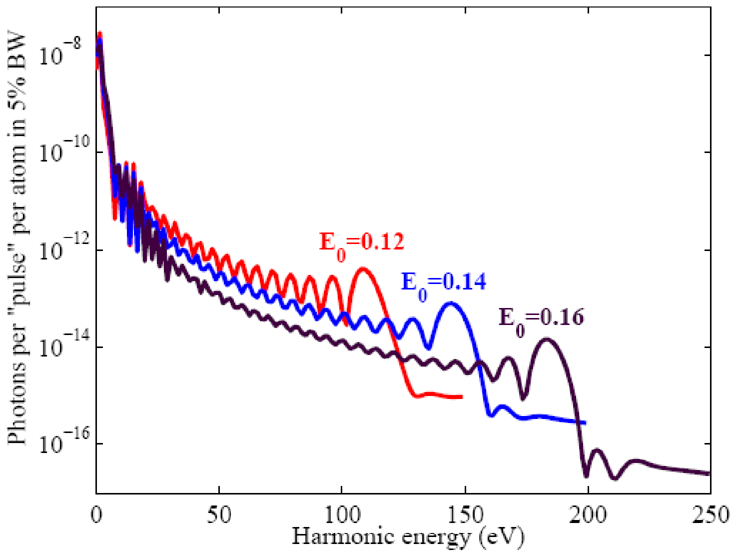
M. Zepf,[1,*] B. Dromey,[1] M. Landreman,[2] P. Foster,[3] and S. M. Hooker[2]

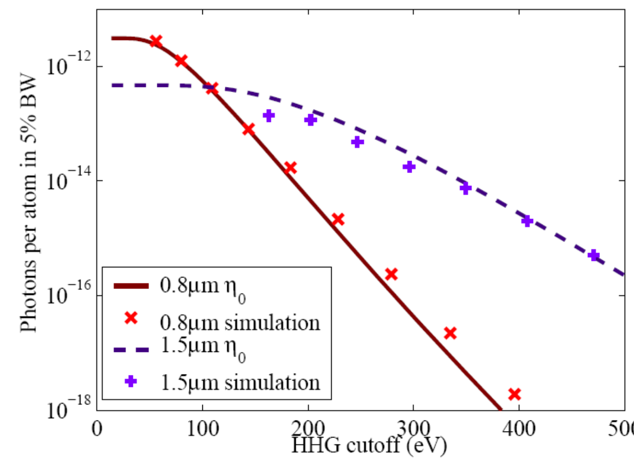
~1e9 ph/shot/harmonic @ 300 eV

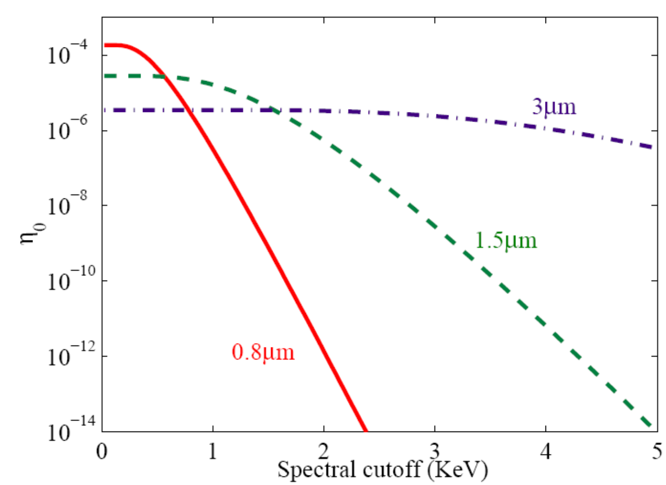


- 5 mJ / pulse, 800 nm, 40 fsec
- focused to ~ 1e15W/cm^2 into 1 cm length Ar filled capillary

Optimized HHG at longer drive wavelengths







Scaling of keV HHG photon yield with drive wavelength

Ariel Gordon and Franz X. Kärtner

18 April 2005 / Vol. 13, No. 8 / OPTICS EXPRESS 2947

High Power OPCPA in few micron regime

April 15, 2006 / Vol. 31, No. 8 / OPTICS LETTERS 1103

Parametric amplification of few-cycle carrier-envelope phase-stable pulses at 2.1 μm

T. Fuji, N. Ishii, C. Y. Teisset, X. Gu, Th. Metzger, and A. Baltuška
Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Strasse 1, D-85748 Garching, Germany

N. Forget and D. Kaplan
Fastlite, Bâtiment 403, Ecole Polytechnique, 91128 Palaiseau, France

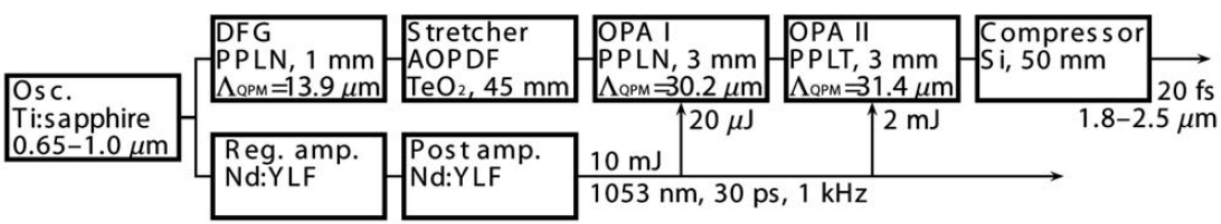
A. Galvanauskas
Department of Electrical Engineering and Computer Science, College of Engineering, University of Michigan, 1301 Beal Avenue, Ann Arbor, Michigan 48109-2122

F. Krausz*
Ludwig-Maximilians-Universität München, Am Coulombwall 1, D-85748 Garching, Germany

Received December 9, 2005; accepted December 23, 2005; posted January 27, 2006 (Doc. ID 66564)

We demonstrate an optical parametric chirped-pulse amplifier producing infrared 20 fs (3-optical-cycle) pulses with a stable carrier-envelope phase. The amplifier is seeded with self-phase-stabilized pulses obtained by optical rectification of the output of an ultrabroadband Ti:sapphire oscillator. Energies of ~80 μJ with a well-suppressed background of parametric superfluorescence and up to 400 μJ with a superfluorescence background are obtained from a two-stage parametric amplifier based on periodically poled $LiNbO_3$ and $LiTaO_3$ crystals. The parametric amplifier is pumped by an optically synchronized 1 kHz, 30 ps, 1053 nm Nd:YLF amplifier seeded by the same Ti:sapphire oscillator.

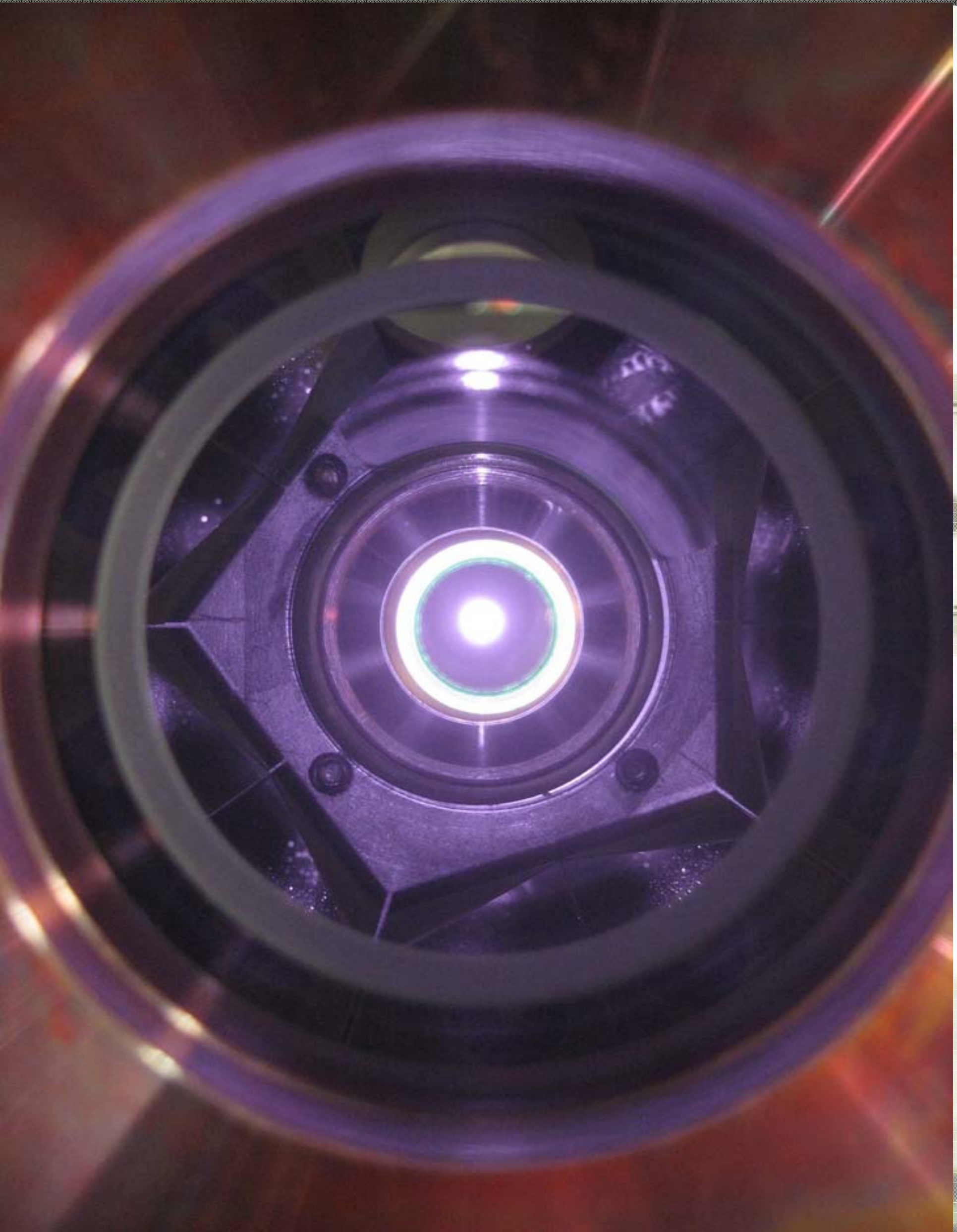
envelope phase (CEP).[2] While existing drive lasers operate near 0.8 μm, in the gain region of the Ti:sapphire, operating at longer, infrared wavelengths would be advantageous because the ponderomotive energy scales with λ^2. Therefore, the intensity of driving laser pulses needed to attain higher-order harmonic generation at a given x-ray photon energy can be substantially lower in comparison with the 0.8 μm case.[3–5] The use of IR drive pulses should extend the cutoff energy of x-ray photons and yield even shorter attosecond x-ray pulses. From the standpoint of laser technology, the longer duration of the IR optical period reduces the number of cycles for a given pulse envelope and, therefore, relaxes the requirement for amplifier gain bandwidth.



- up to 400 μJ, 20 fsec at 2.1 μm

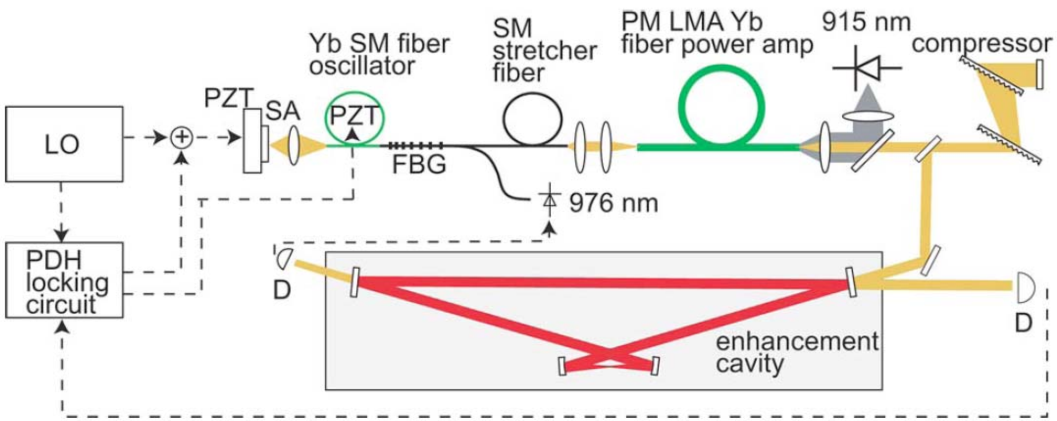
- oscillator stretched to 30 psec for overlap with 30 psec Nd:YLF pump…..power scalable

disc-based laser amplifier



- efficient heat removal
- one dimensional heat flow perpendicular to optical axis
- homogeneous temperature and stress profile
- excellent beam quality
- scalable (2 dimensional)
- extreme pump power densities (0.8 MW/cm^3)
- well developed technic
- 5 kW out of one disk (cw)

High rep rate + peak power:
power enhancement cavity + fiber laser



- 0.1 μJ/pulse at 136 MHz
- power enhancement factor 230
- 14 micron cavity focus

Cavity-enhanced similariton Yb-fiber laser frequency comb: 3×10^{14} W/cm^2 peak intensity at 136 MHz

I. Hartl,[1,3,*] T. R. Schibli,[2,4] A. Marcinkevicius,[1] D. C. Yost,[2] D. D. Hudson,[2] M. E. Fermann,[1] and Jun Ye[2]

[1]*IMRA America, Inc., 1044 Woodridge Avenue, Ann Arbor, Michigan 48105, USA*
[2]*JILA, National Institute of Standards and Technology and University of Colorado and Department of Physics, University of Colorado, Boulder, Colorado 80309–0440, USA*

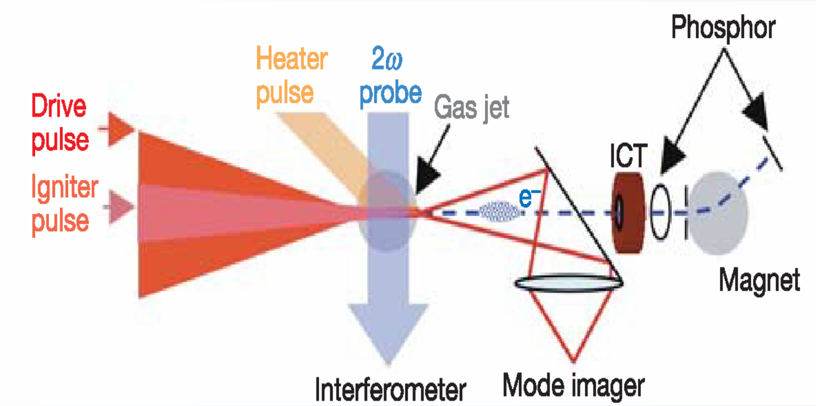
2870 OPTICS LETTERS / Vol. 32, No. 19 / October 1, 2007

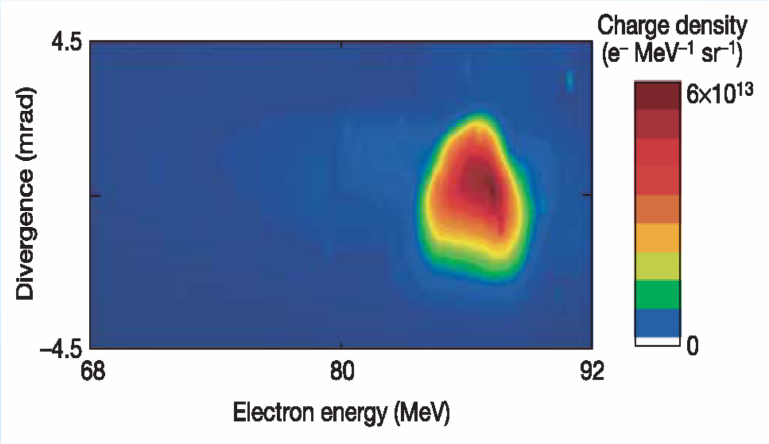
- this is at 1050 nm using Yb doped fiber
- could have been 1540 nm using Er…..
- power high enough for efficient harmonic generation
- 70 fsec optical pulses
- scaling above 1e15W/cm^2 possible

Observations on soft x-ray FELs and optical lasers

- Optical lasers may become available to drive electron accelerators for soft x-ray sources

Low energy spread beams at 100 MeV using plasma channel guiding

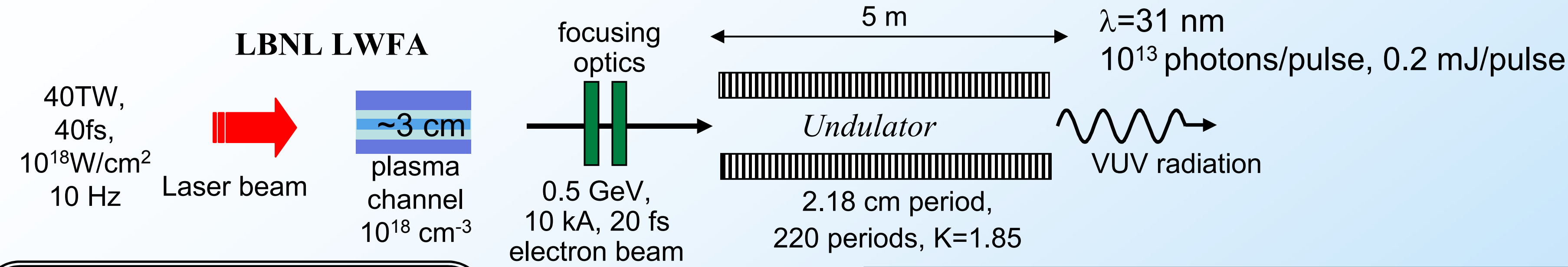




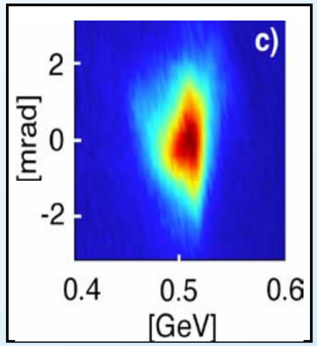
- Mono-energetic electron beams
  - Dephasing physics
  - Simulations
- Channel guiding
  - Laser produced channels -- advantages and limitations
  - Dark current free structures
  - Need lower density channels ->capillary discharges

C. G. R. Geddes,et al, "*High-quality electron beams from a laser wakefield accelerator using plasma-channel guiding*", Nature,**431**, p538, 2004

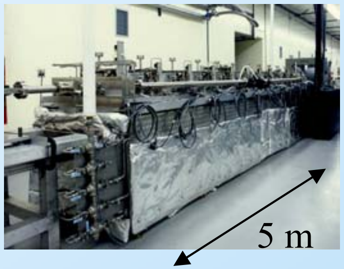
LWFA-driven coherent VUV source

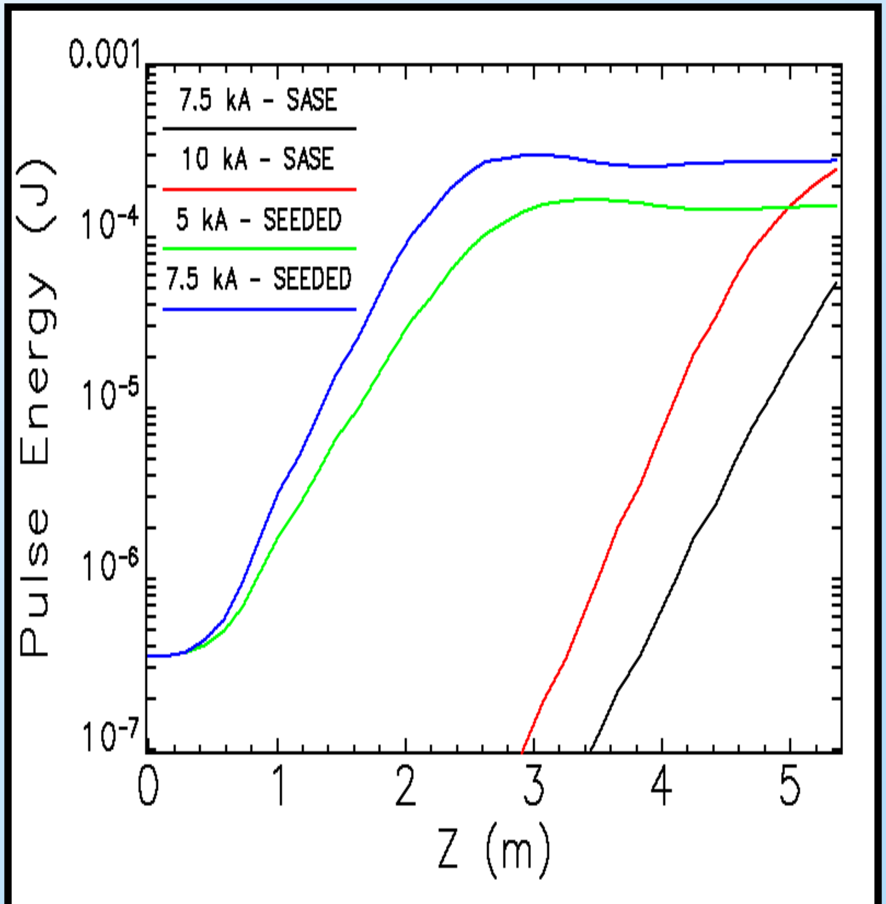


LWFA Electron Beam:	
Beam Energy	0.5 GeV
Peak current	10 kA
Charge	0.2 nC
Bunch duration, FWHM	20 fs
Energy spread (slice)	0.25 %
Norm. Emittance	1 mm-mrad



Undulator Parameters:	
Undulator type	planar
Undulator period	2.18 cm
Number of periods	220
Peak Field	1.02 T
Undulator parameter, K	1.85
Beta function (0.5 GeV)	3.6 m





Collaboration with MPQ, Germany

Conclusions

- Grand Challenge science requires a new generation of soft x-ray sources
- … but the science of thousands of users at existing 3rd generation synchrotrons also requires new investments in beamlines and instruments
- prototype designs exist for high-average-power, soft x-ray FELs, with flexible output parameters and multiple beamlines; R&D is needed
- optical lasers and high harmonics will soon be available with sufficient power to seed high-rep-rate, coherent, soft x-ray FELs; R&D is needed
- … but laser sources will not rival the peak or average coherent soft x-ray power from FELs, which have mA currents, GeV energies, and watts of coherent soft x-rays
- optical lasers and novel acceleration schemes may become available to effectively drive electron accelerators for light source applications