The Seeded X-ray FEL Concept: The Ultimate Source

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NSF Panel on Light Source Facilities
Lawrence Livermore National Laboratory
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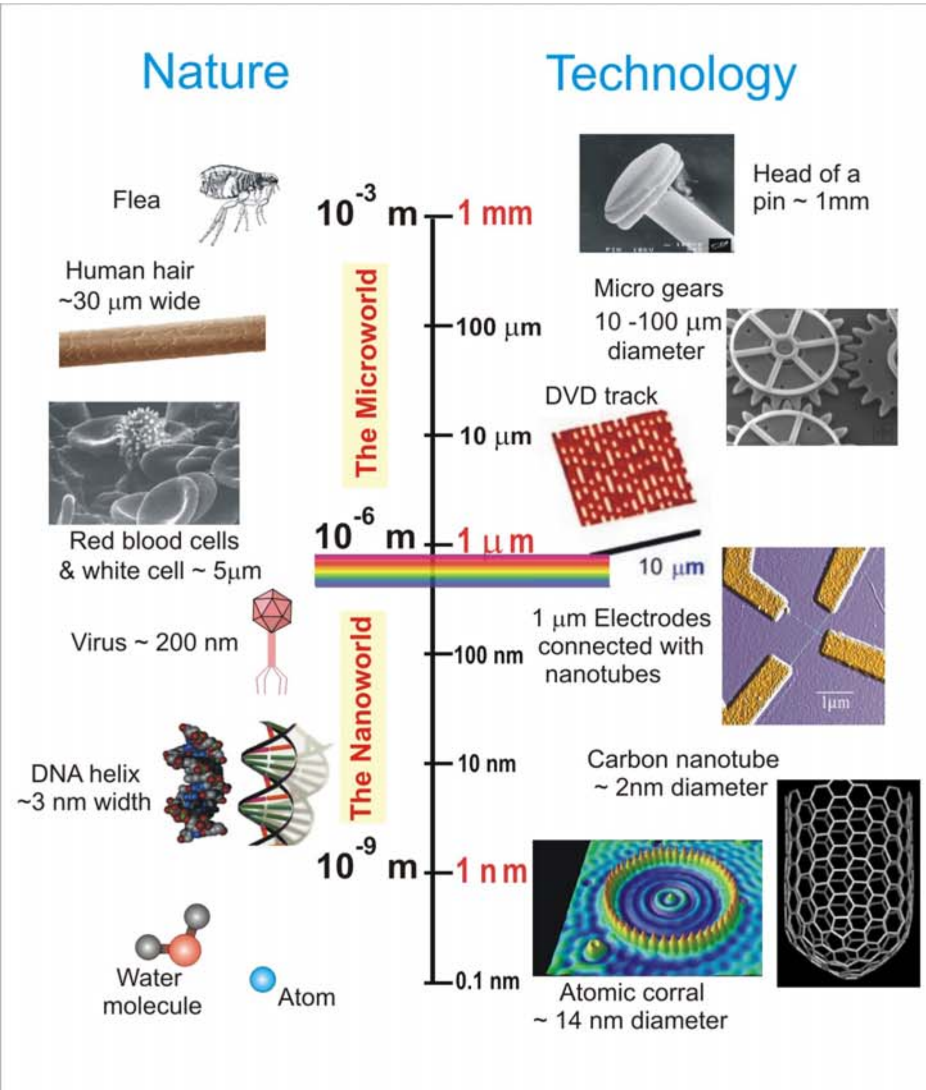
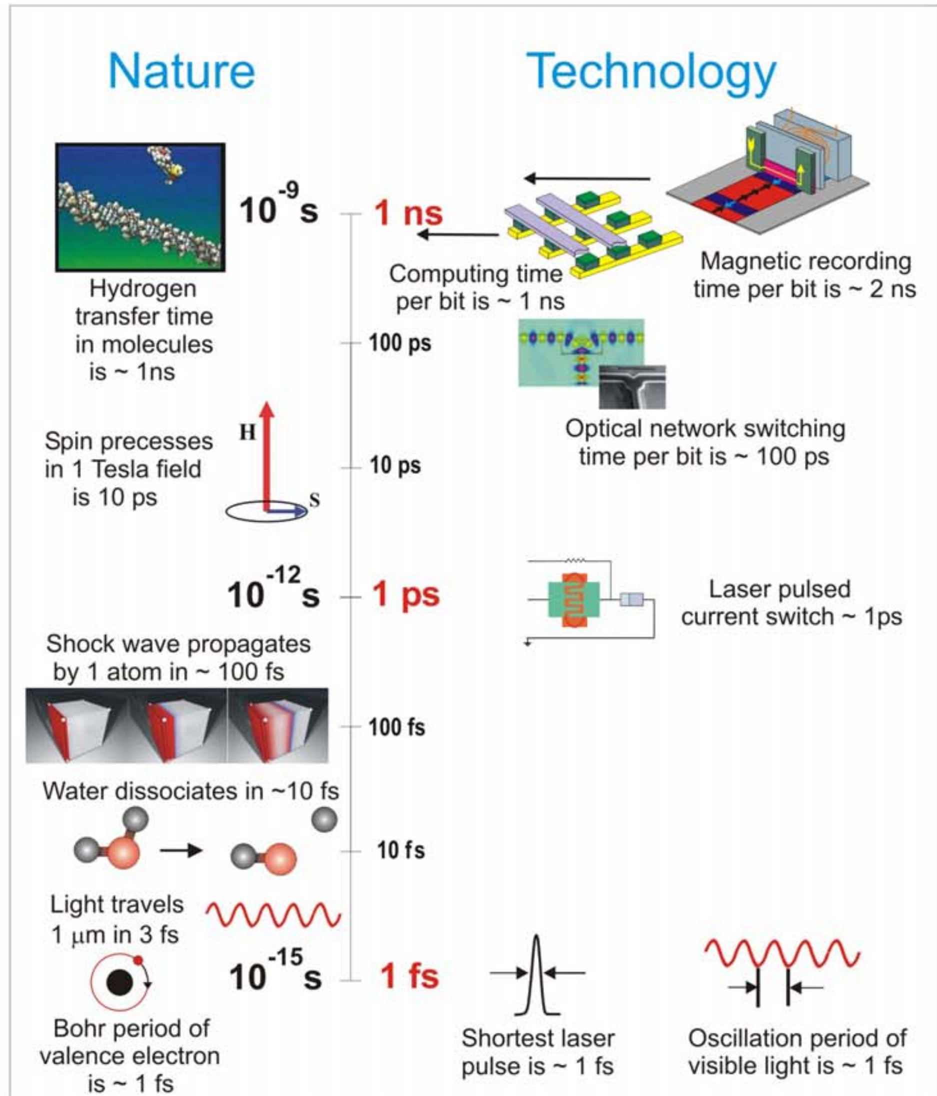
Future Light Sources

Challenge: Probe of all spatial and temporal scales and resolutions relevant to condensed matter

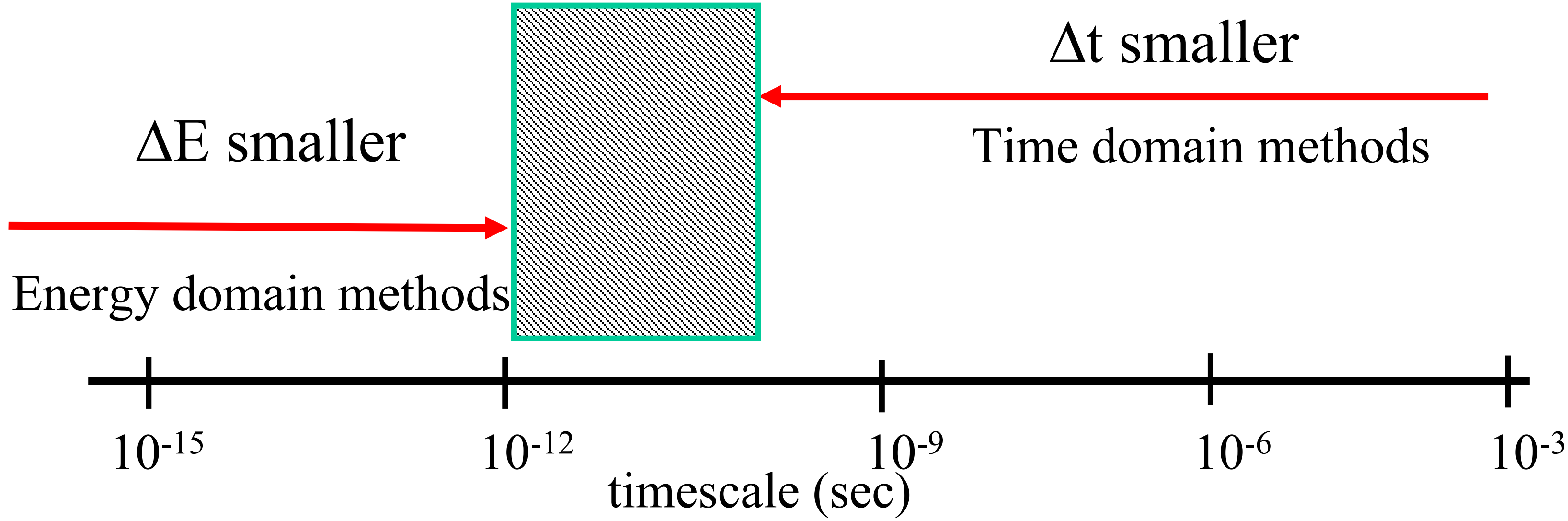
Spatial Scales



Temporal Scales



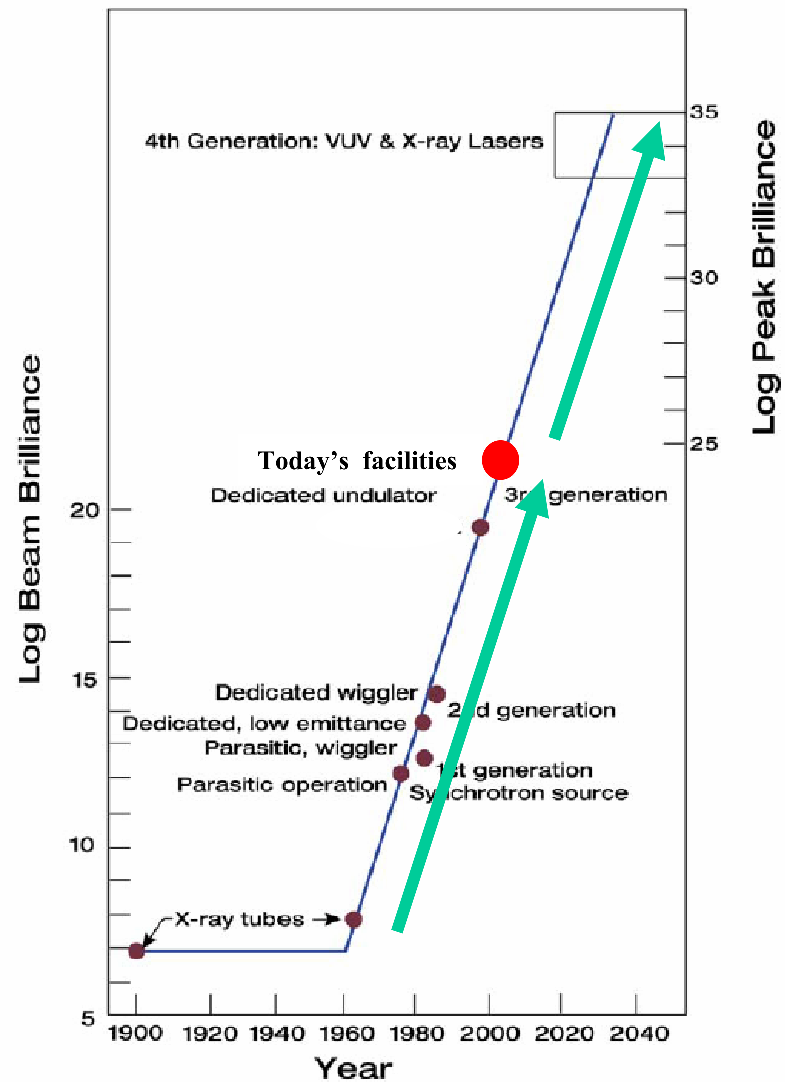
Temporal Structure of Condensed Matter



- Gap exists at 3rd gen sources in a critical region and flux is weak
- Seeded FELs close this critical gap with high power transform-limited pulses
- The beam has full longitudinal coherence and high stability
- Full longitudinal coherence would enable powerful new coherent dynamics methods
- This is a unique aspect of the seeded FELs such as we propose at the University of Wisconsin

X-ray Science Driven by Beam Brilliance

- X-ray sources have made extraordinary scientific contributions over 100 years
- Over a dozen Nobel Prizes
- The structure of virtually every material is determined by x-rays
- Medical Imaging and the CAT scan
- About three thousand protein structures per year
- Source brilliance increasing at 2x Moore's Law



Tutorial on Peak Brilliance

Peak Brilliance = # photons/ 6D phase space volume

= # photons/$\Delta x\ \Delta\theta_x\ \Delta y\ \Delta\theta_y\ \Delta t\ \Delta E$

- Conventional phase space units: $mm^2\ mrad^2\ sec\ 0.1\%\ bw$
- Fundamental phase space units: 1 quantum mode defined by

$$\Delta x\ \Delta\theta_x = \Delta y\ \Delta\theta_y = \lambda/4\pi; \quad \Delta t\ \Delta E = \hbar/2$$

- Conversion factor: $2.3 \times 10^{24}/\ \lambda^3\ (\mathring{A})$

Example—5×10^{10} 12 keV photons (0.1 mJ) in a coherent pulse,

then the peak brilliance is 1.2×10^{35}

Brilliance = Peak Brilliance x duty factor $\sim 10^{28}$

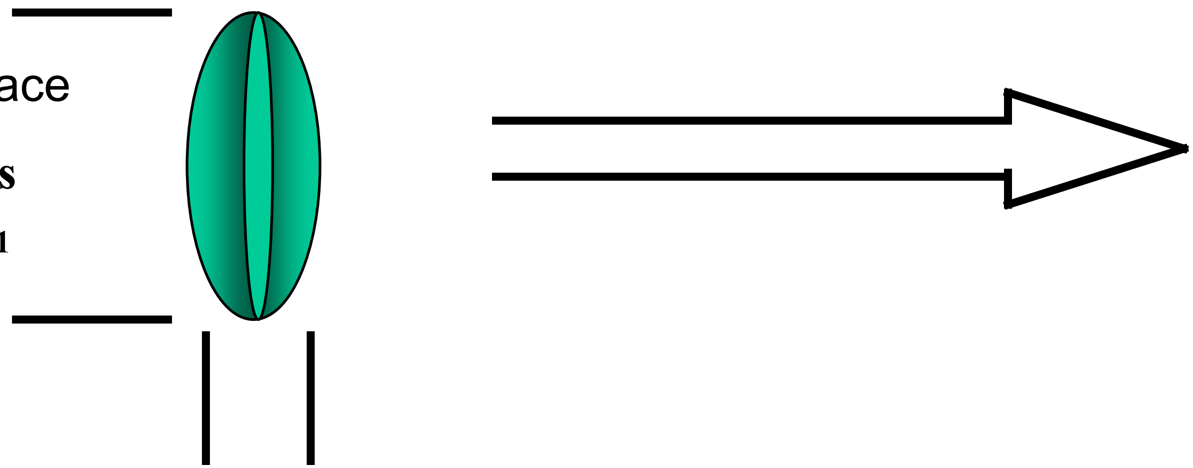
An Ideal XUV Source

- **Satisfies the Uncertainty Principle in all dimensions**

Transverse phase space

Δx , $\Delta y \sim 50$ microns

Δk_x , $\Delta k_y \sim 10^{-4}$ nm^{-1}



$\Delta x \;\; \Delta k_x = ½$

$\Delta y \;\; \Delta k_y = ½$

Longitudinal phase space

$\Delta t \sim 1$fs – 1ps $\quad \Delta\omega \sim 2$eV – 2meV

$\Delta\omega \;\; \Delta t = ½$

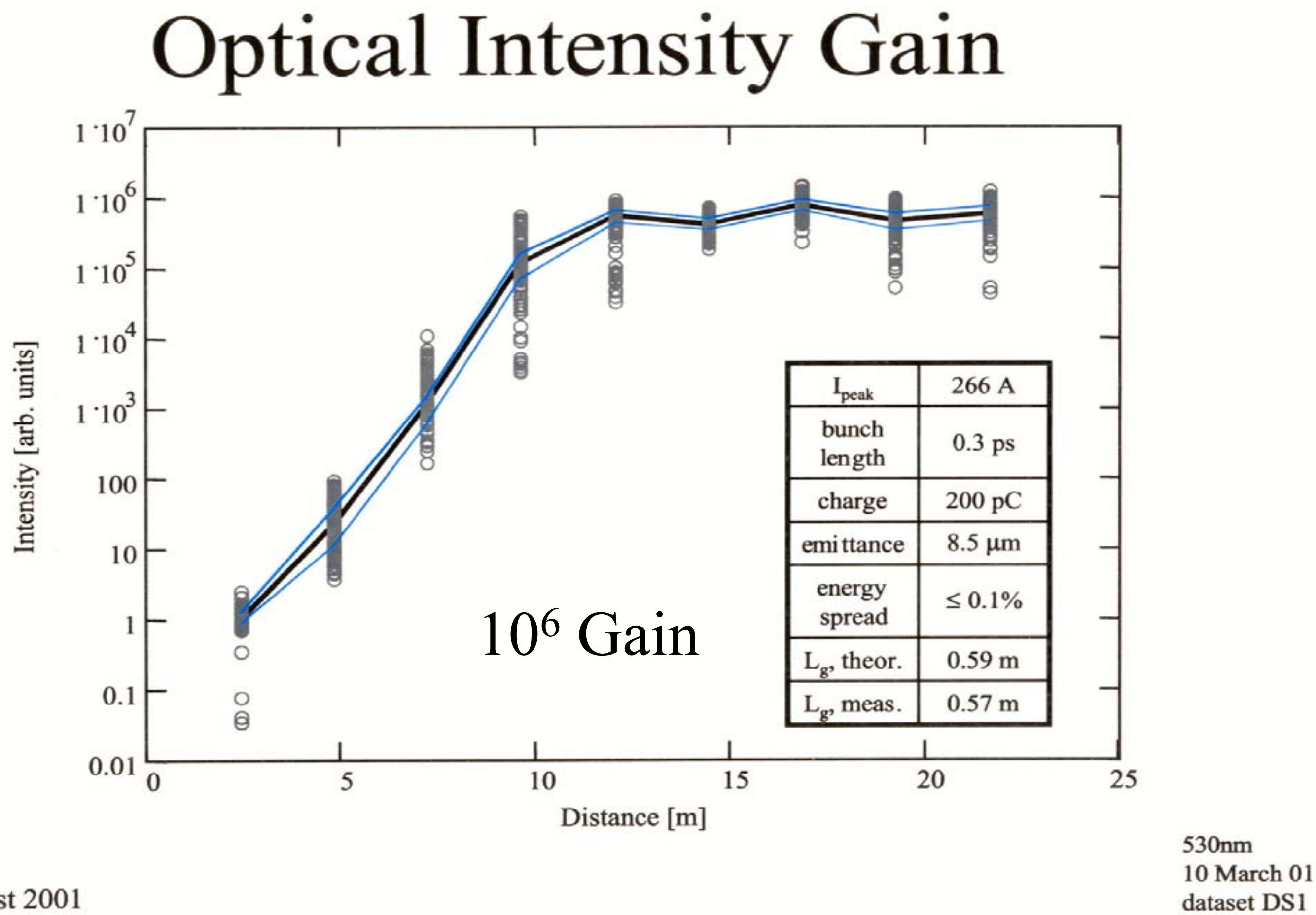
A 0.1 mJ pulse contains 5.0×10^{11} 1.2 keV photons

→ Peak brilliance = 1.2×10^{32}

3rd Gen: 10^{22}

FEL Undulator System at the Advanced Photon Source

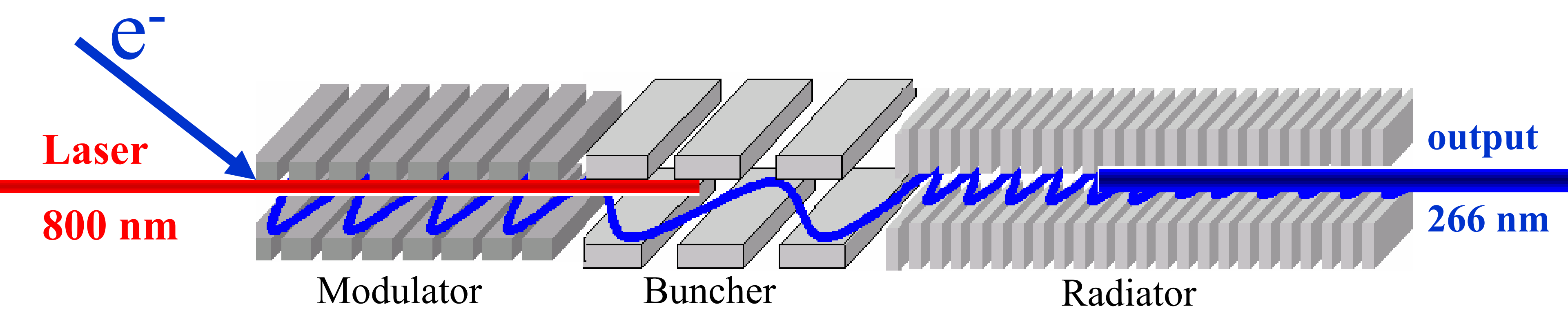
APS Demonstration of SASE



I_{peak}	266 A
bunch length	0.3 ps
charge	200 pC
emittance	8.5 µm
energy spread	≤ 0.1%
L_g, theor.	0.59 m
L_g, meas.	0.57 m

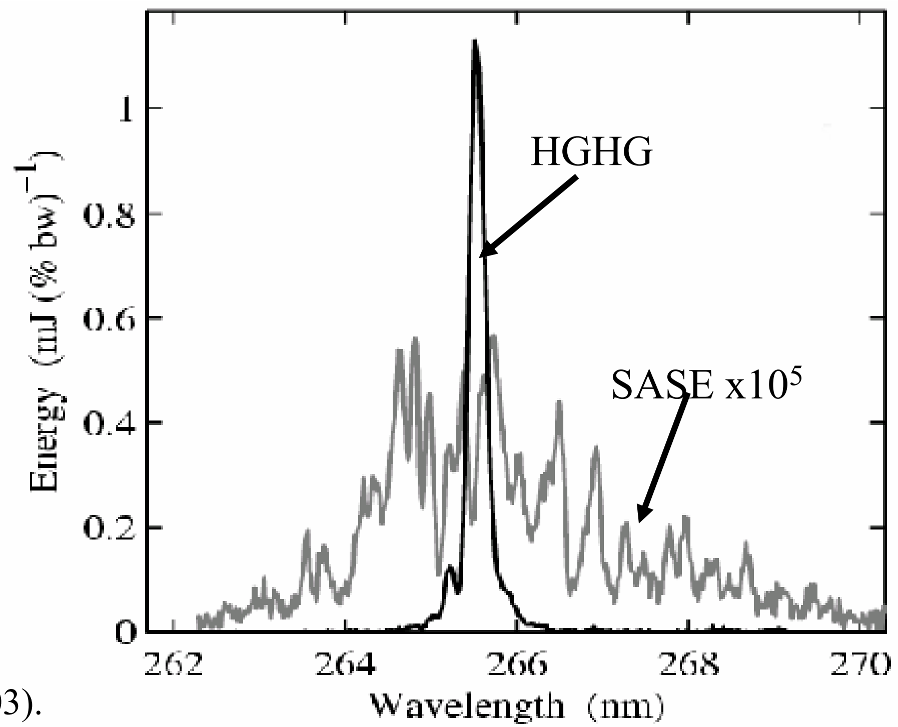
Milton S.V., et al, "Observation of Self-Amplified Spontaneous Emission and Exponential Growth at 530 nm," *Phys. Rev. Lett.* **85**, 988-991 (2000)

Brookhaven Laser Seeding Demonstration



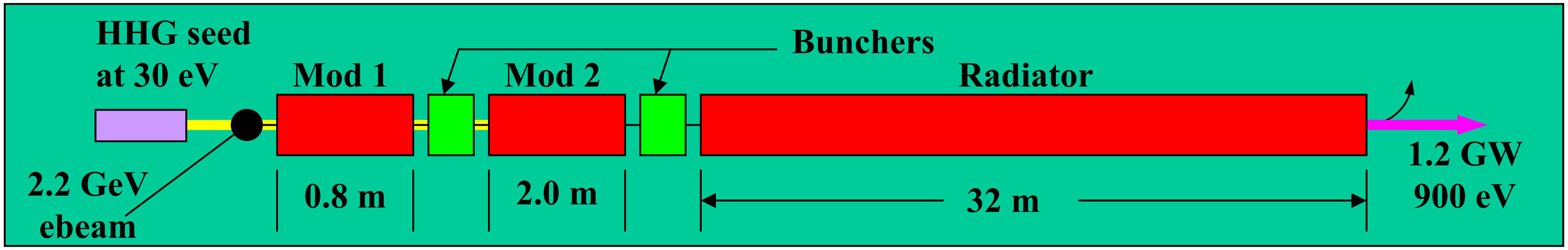
High Gain Harmonic Generation (HGHG)

- Suppressed SASE noise
- Amplified coherent signal
- Narrowed bandwidth
- Shifted wavelength



L.H. Yu et al., Phys. Rev. Lett. **91**, 74801 (2003).

Seeded FEL for 300-900 eV



30eV 60eV 300eV ------18m detuned----- 300eV out

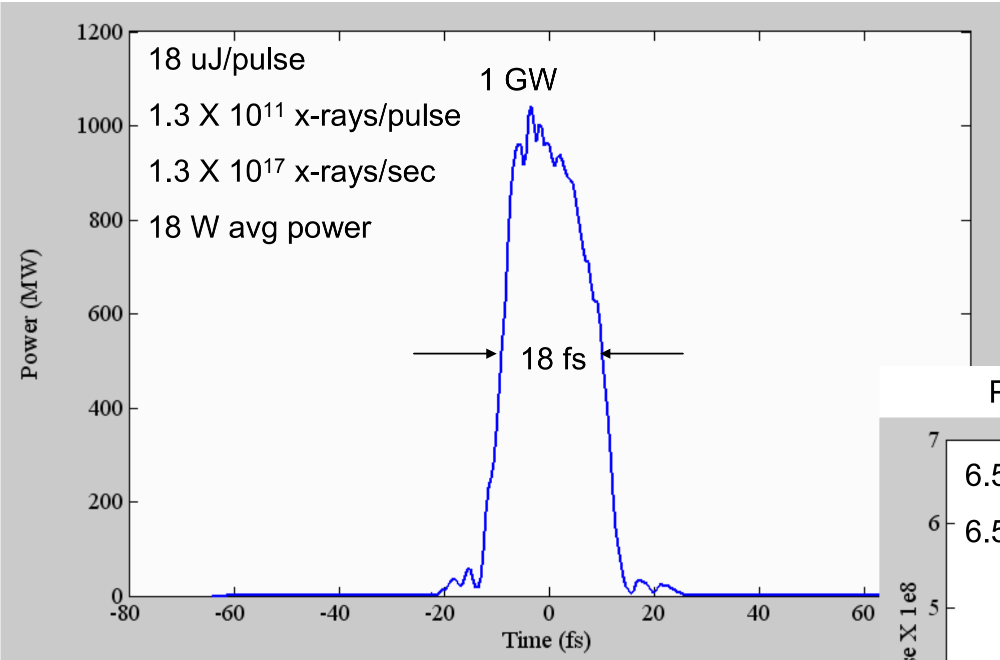
30eV 60eV 300eV ------24m 900eV----------- 900eV out

1. Electron bunches with 0.2nc, and seed pulses of 300nJ and 30fs.
2. The final radiator undulator is made of identical short sections allowing initial sections to be implemented as a third modulator.
3. Can adjust tuning to efficiently cover entire photon energy range and different operating modes
4. Can retune for different electron beam performance. Not locked to one set of parameters.

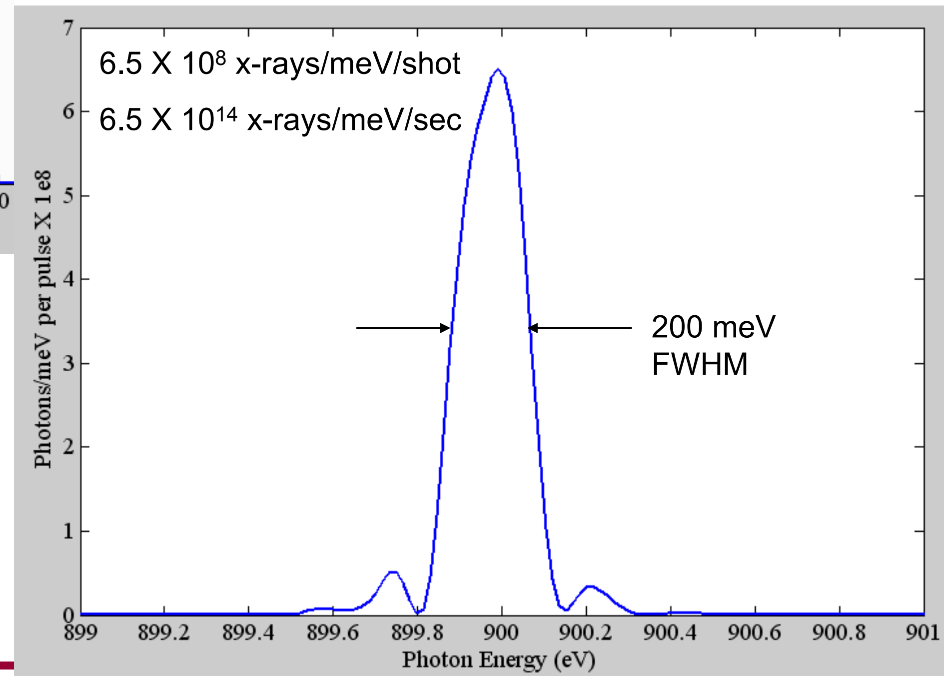
FEL calculations by Bill Graves, MIT Principal Research Scientist

900 eV Output

Pulse shape at end of undulator (before any optics).



Pulse spectrum at end of undulator (before any optics).

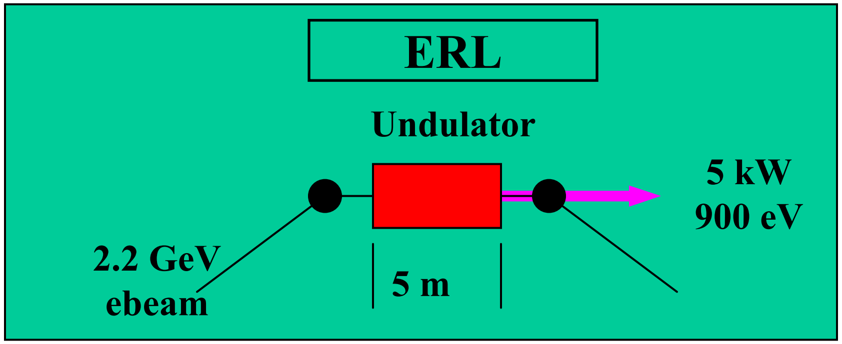


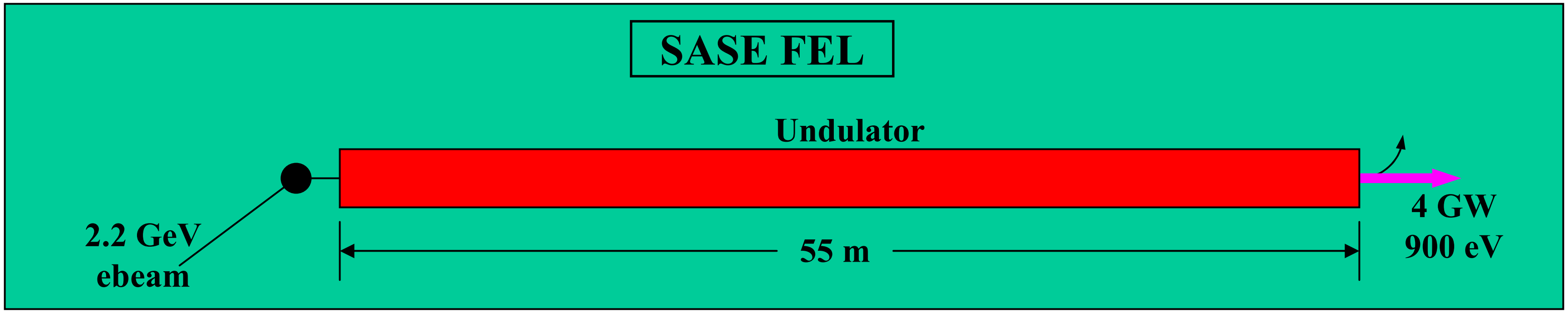
Generating High Peak Brilliance Radiation

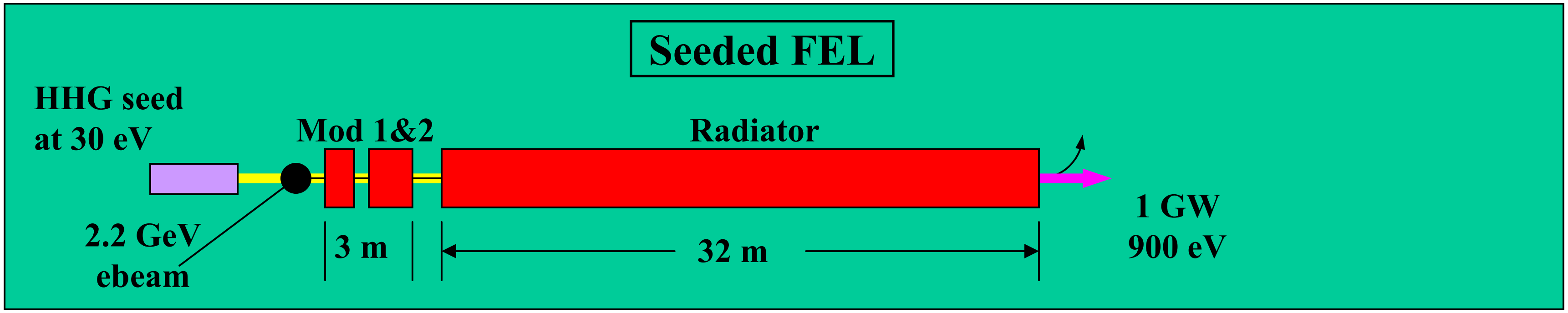
Key issues for next-generation accelerator-based light sources

- **Preserve low e-beam emittance:** Next generation photon sources all aim to preserve the low-emittance quality of the best electron bunches that can be produced, rather than letting the electron emittance relax to a poorer equilibrium value as the beam circulates in a storage ring.
- **Exploit coherent emission:** The charge per electron bunch for Seeded FELs, SASE FELs and ERLs will be essentially the same—about $n=10^9$ electrons. If radiation is emitted coherently by the electron bunch then the emitted flux is ideally proportional to n^2. The Seeded FEL takes the biggest advantage of this enormous gain. The ERL process is completely incoherent synchrotron emission proportional to n.
- **Produce only the beam that will be utilized:** Virtually all experiments driving the science for next generation facilities require narrow bandwidth, or short pulses. Furthermore the peak power is already high, so there is a strong premium on producing only radiation of bandwidth and pulse length that is useful in order to minimize the burden on optics. Only the transform-limited pulse of the Seeded FEL achieves this photon economy.

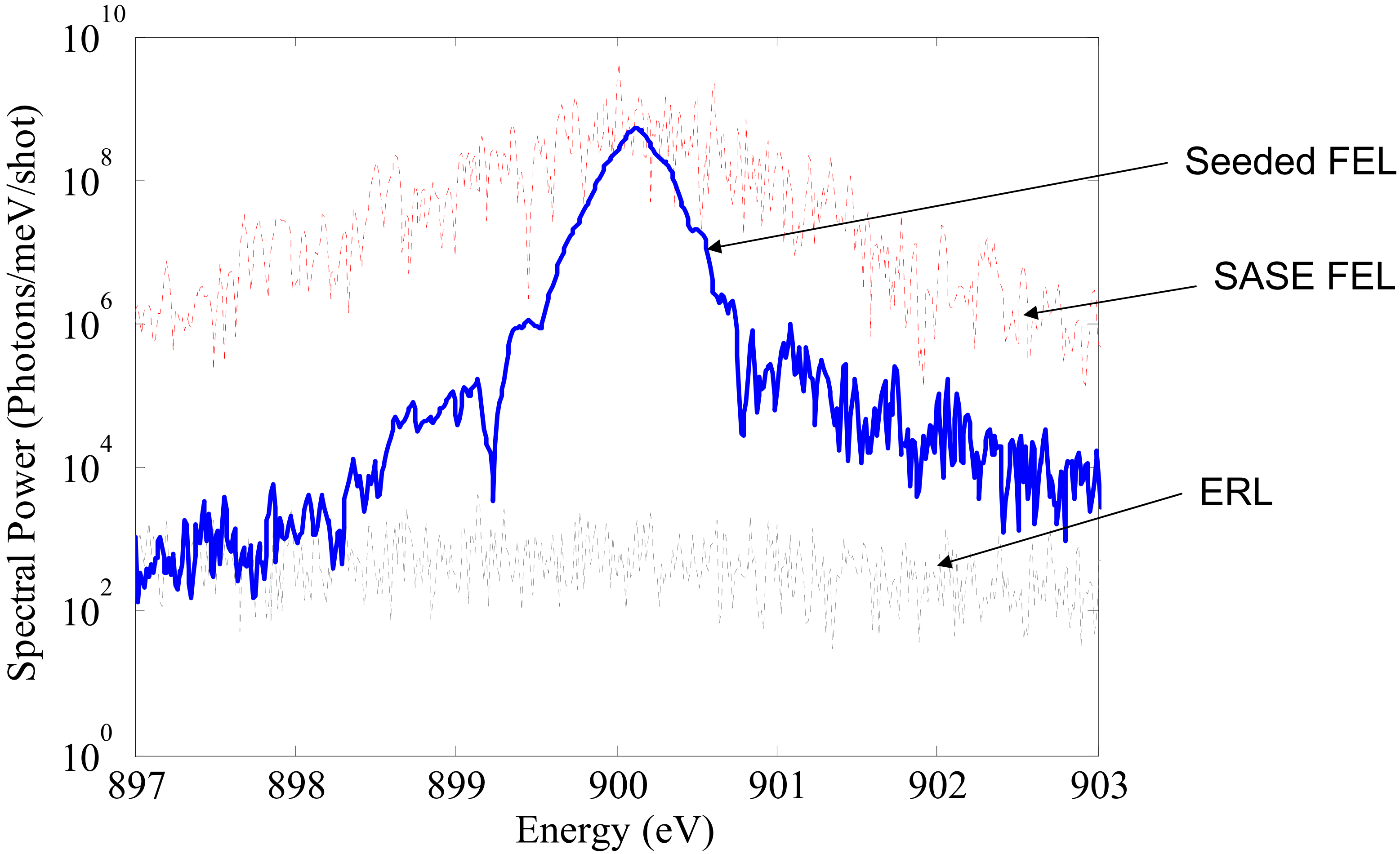
Comparing Sources of 900 eV Photons



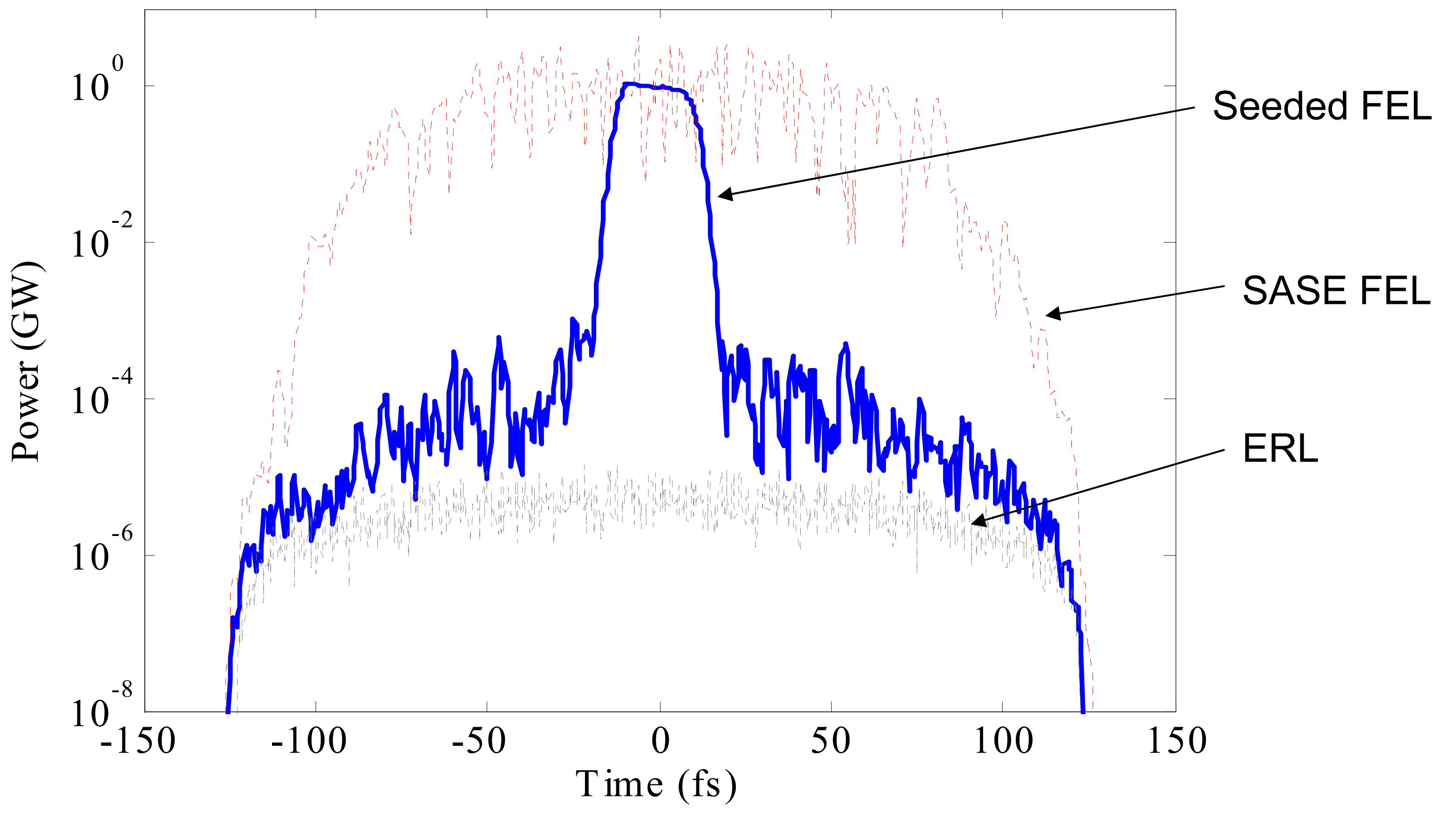




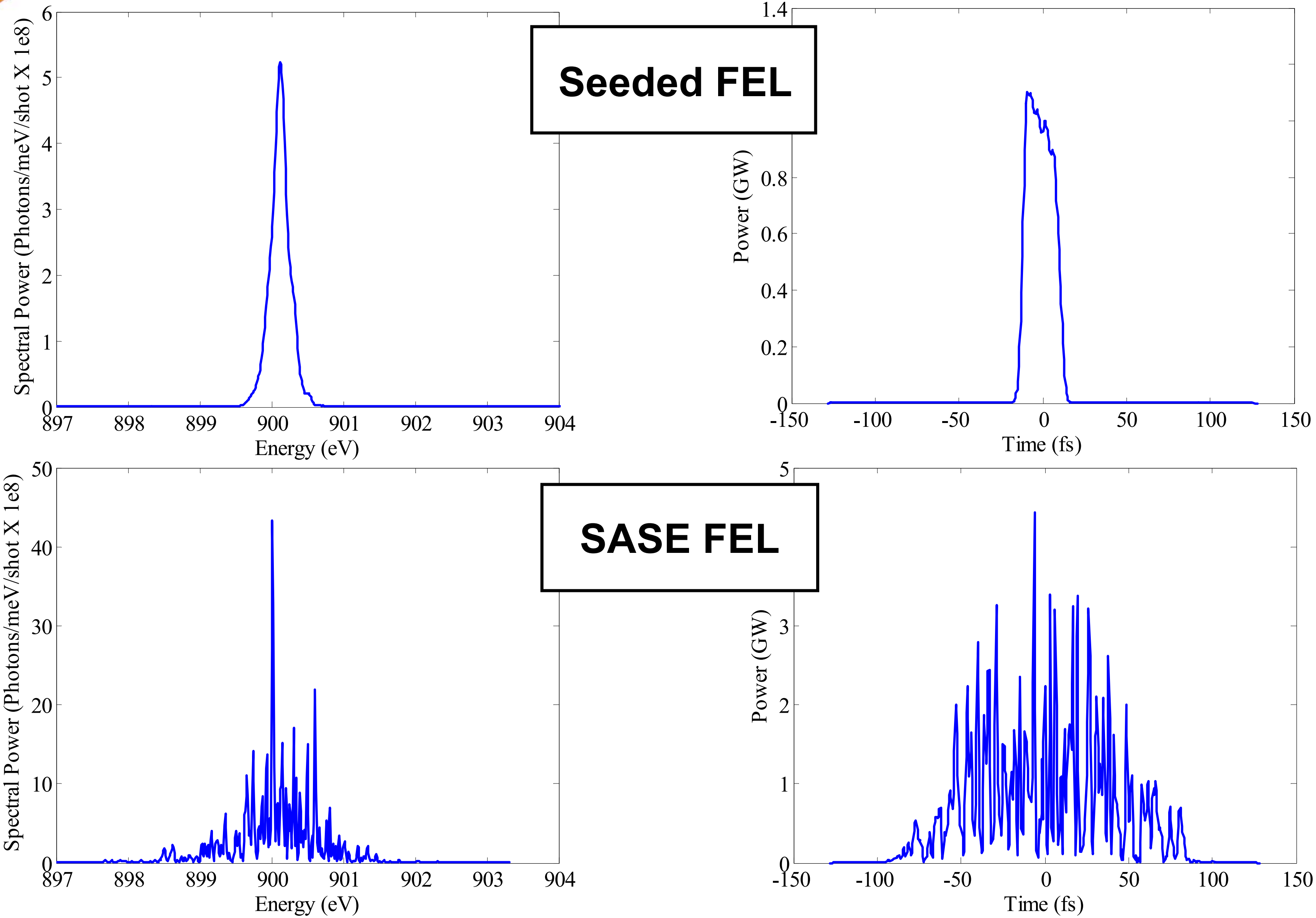
Photon Output: Frequency Domain



Photon Output: Time Domain



Comparing SASE and Seeded FELS



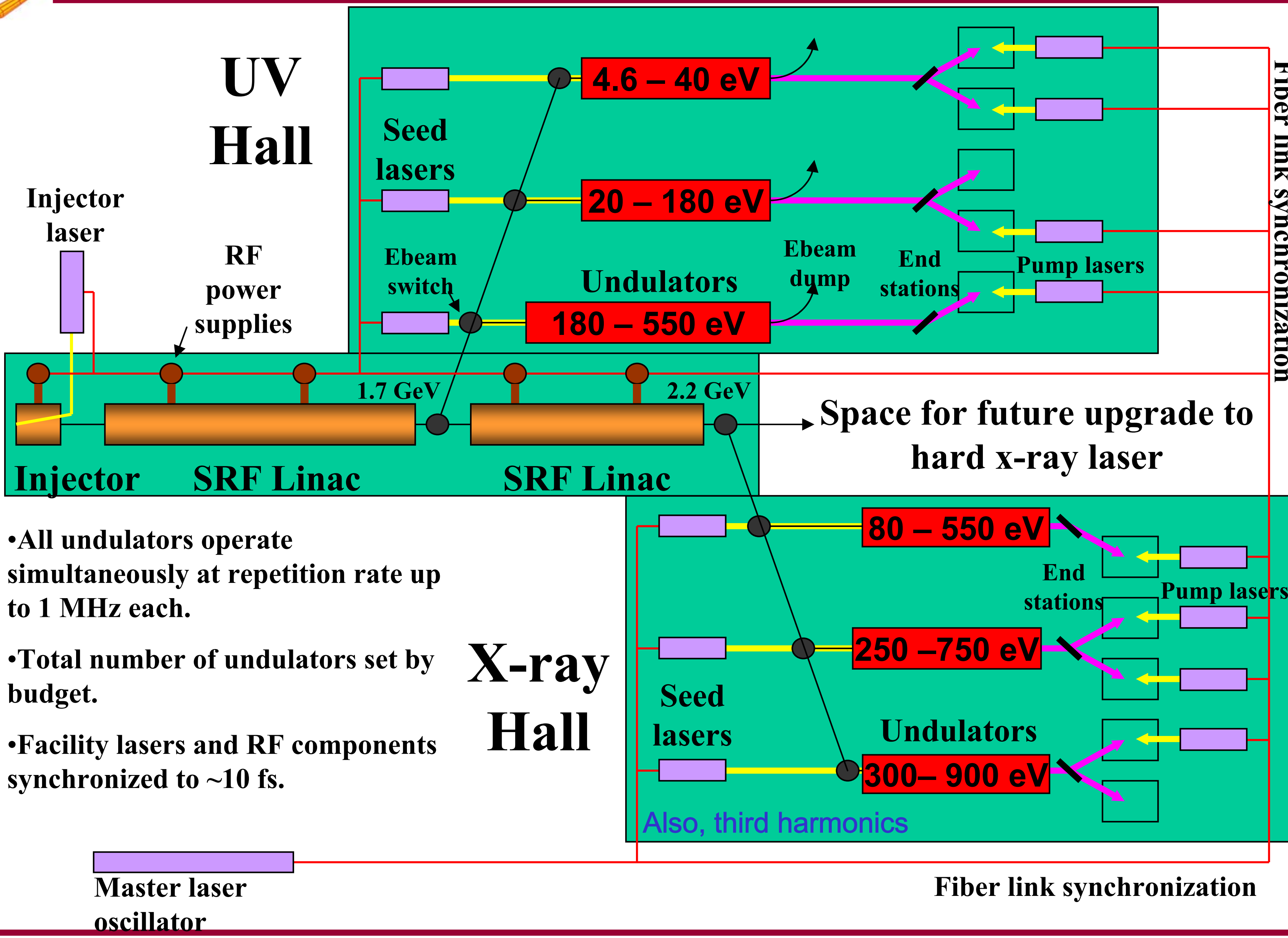
X-ray Sources Compared

Source Parameters	Seeded FEL*	SASE FEL*	ERL*	NSLS II†
Photon energy (eV)	900	900	900	900
Pulse output energy (mJ)	23	140	0.0009	0.003
Peak power (GW)	1.1	1.1	5.6e-6	1.1e-7
Photons per pulse	1.6e11	1.0e12	6.2e6	2.1e7
RMS x,y source size (mm)	24	29	9.3	85, 10
RMS x,y diffraction angle (mrad)	5	5	53.4	21, 12
M**2	1.07	1.2	4.6	8.5
RMS pulse length (fs)	7	39	55	11000
RMS bandwidth (meV)	140	596	3710	2500
Coherence time (fs)	15	3.5	0.6	0.8
Peak brightness (p/s/0.1%/ mm^2 mr^2)	4.5e31	0.8e31	4.5e23	8.8e22
Avg brightness (p/s/0.1%/ mm^2 mr^2)	1.8e24 1 mA	2.0e24 1 mA	1.5e19 100mA	8.0e20 500 mA

*Results of numerical simulations with code GINGER.

†From CD-0 design report

WiFEL Conceptual Design



- All undulators operate simultaneously at repetition rate up to 1 MHz each.
- Total number of undulators set by budget.
- Facility lasers and RF components synchronized to ~10 fs.

Symposium

Plans for the Wisconsin Free Electron Laser Facility: Preliminary Design Performance and Scientific Opportunities

Engineering Hall (Room 1610), UW-Madison Campus

October 11, 2007

8:00 – 8:30 ***Continental Breakfast*** (Engineering Lobby)

8:30 - 8:45 **Welcome**
Joe Bisognano, Synchrotron Radiation Center

Session Chair*: Joe Bisognano, Synchrotron Radiation Center*
8:45 - 9:30 **Free Electron Lasers: a European Perspective**
Wolfgang Eberhardt, BESSY G.m.b.H, Berlin, Germany
9:30 -10:00 **Introduction to the Wisconsin FEL Project**
David Moncton, MIT
10:00 -10:30 ***Break***

10:30 - 11:15 **Wisconsin FEL Performance Estimates**
Ken Jacobs, Synchrotron Radiation Center, UW-Madison
11:15 - 11:45 **Beamline Performance**
Ruben Reininger, Synchrotron Radiation Center, UW-Madison

12:00 – 13:00 ***Lunch*** (Engineering Lobby)

Session Chair*: Bertold Kraessig, Argonne National Laboratory*
13:00 – 13:30 **Atomic and Molecular Physics**
Ralf Wehlitz, Synchrotron Radiation Center
13:30 – 14:00 **Nanotechnology**
Franco Cerrina, UW-Madison
14:00 – 14:30 **Biological Sciences: Imaging**
Robert Austin, Princeton University
14:30 – 15:00 **Biological Sciences: Spectroscopy**
Steve Cramer, UC Davis
15:00 – 15:30 ***Break***

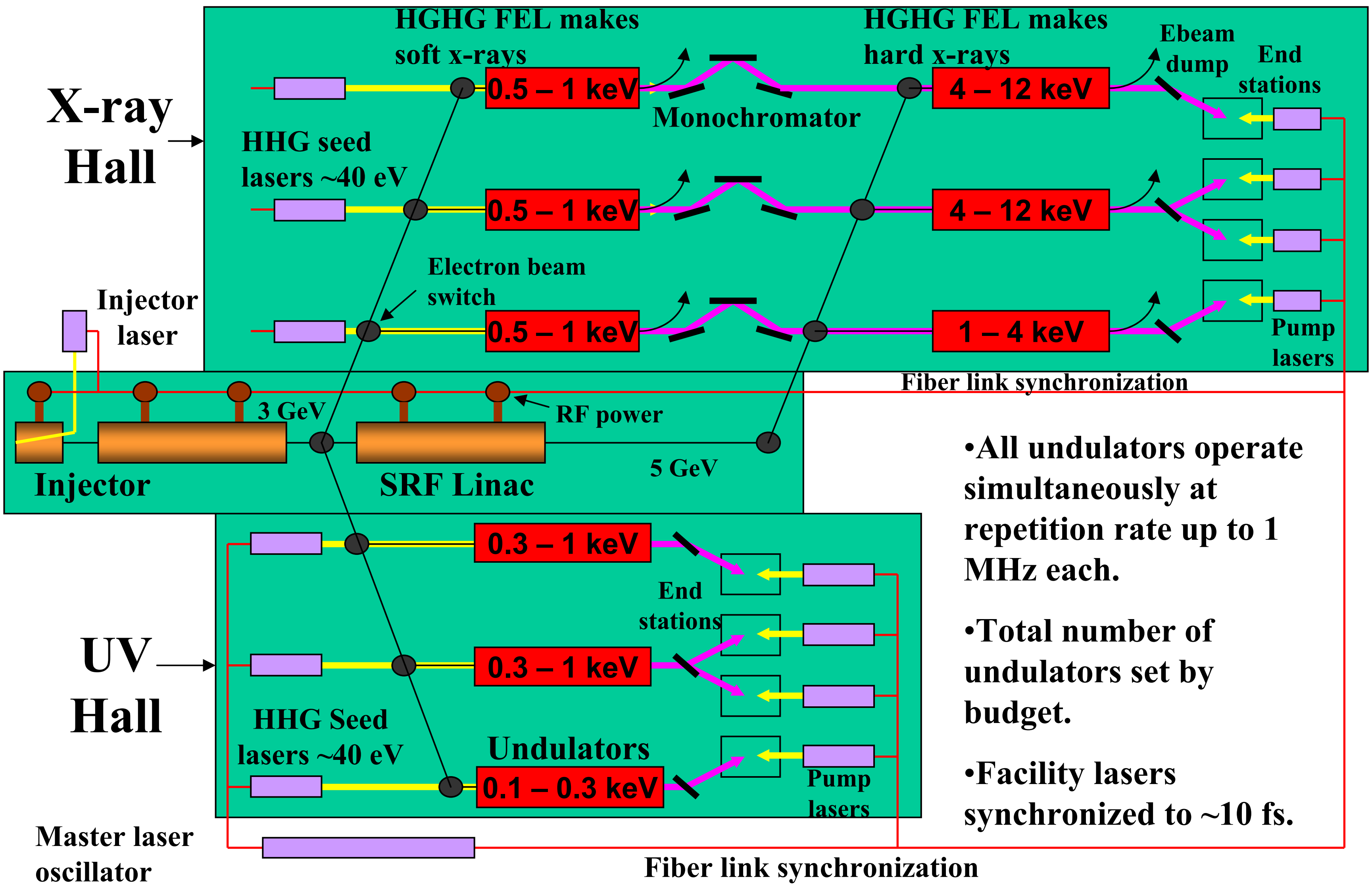
Session Chair*: Franz Himpsel, UW-Madison*
15:30 – 16:00 **Condensed Matter: Coherent Imaging**
Ian McNulty, Argonne National Laboratory
16:00 – 16:30 **Condensed Matter: Resonant Inelastic Scattering**
Peter Abbamonte, U of Illinois at Urbana-Champaign
16:30 – 17:00 **Condensed Matter: Photoemission Spectroscopy**
Tai-Chang Chiang, U of Illinois at Urbana-Champaign
17:00 – 17:30 **Femtochemistry**
Lin Chen, Argonne National Laboratory

Conclusions

- **The facility we envision will:**
  - Support tens of beamlines
  - Produce fully coherent light up to 900 eV
  - With ~0.1% of the power in the third harmonic
  - Tunable in energy and polarization
  - Enabling resolution to a meV or less
  - With pulses of 20 fs and ultimately less
  - With extremely high flux when needed
  - Which will also enable non-linear studies
  - With timing systems synchronized to 10fs
  - To enable two color pump-probe,
  - Maybe even two FEL colors

What could be better—besides hard x-rays?
—and that would be possible as an upgrade

A Seeded Hard X-ray FEL User Facility



- All undulators operate simultaneously at repetition rate up to 1 MHz each.
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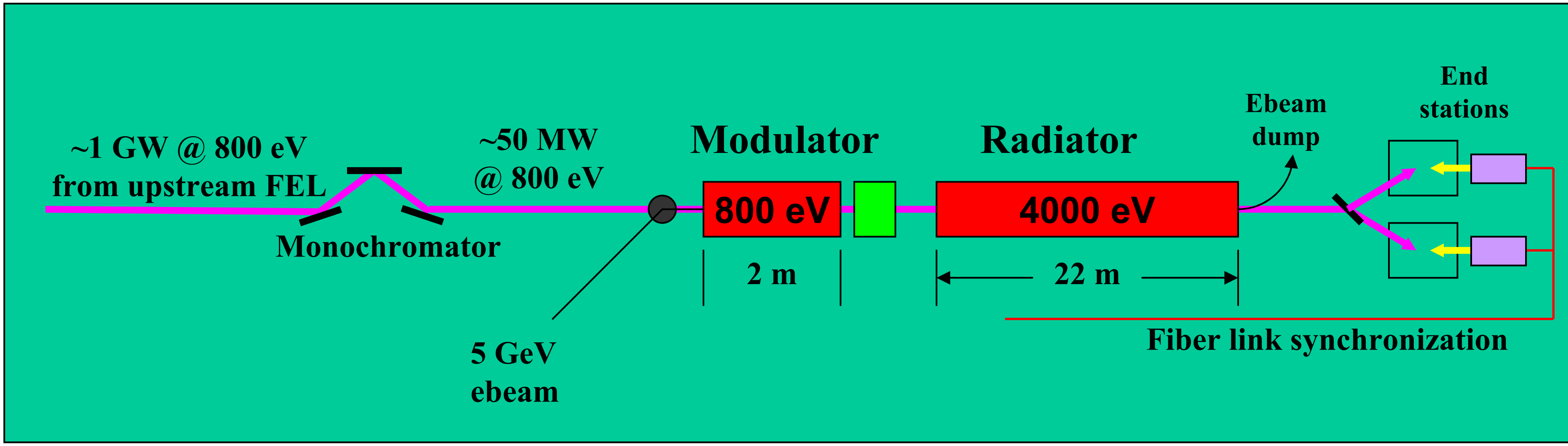
Harmonic Hard X-ray Generation

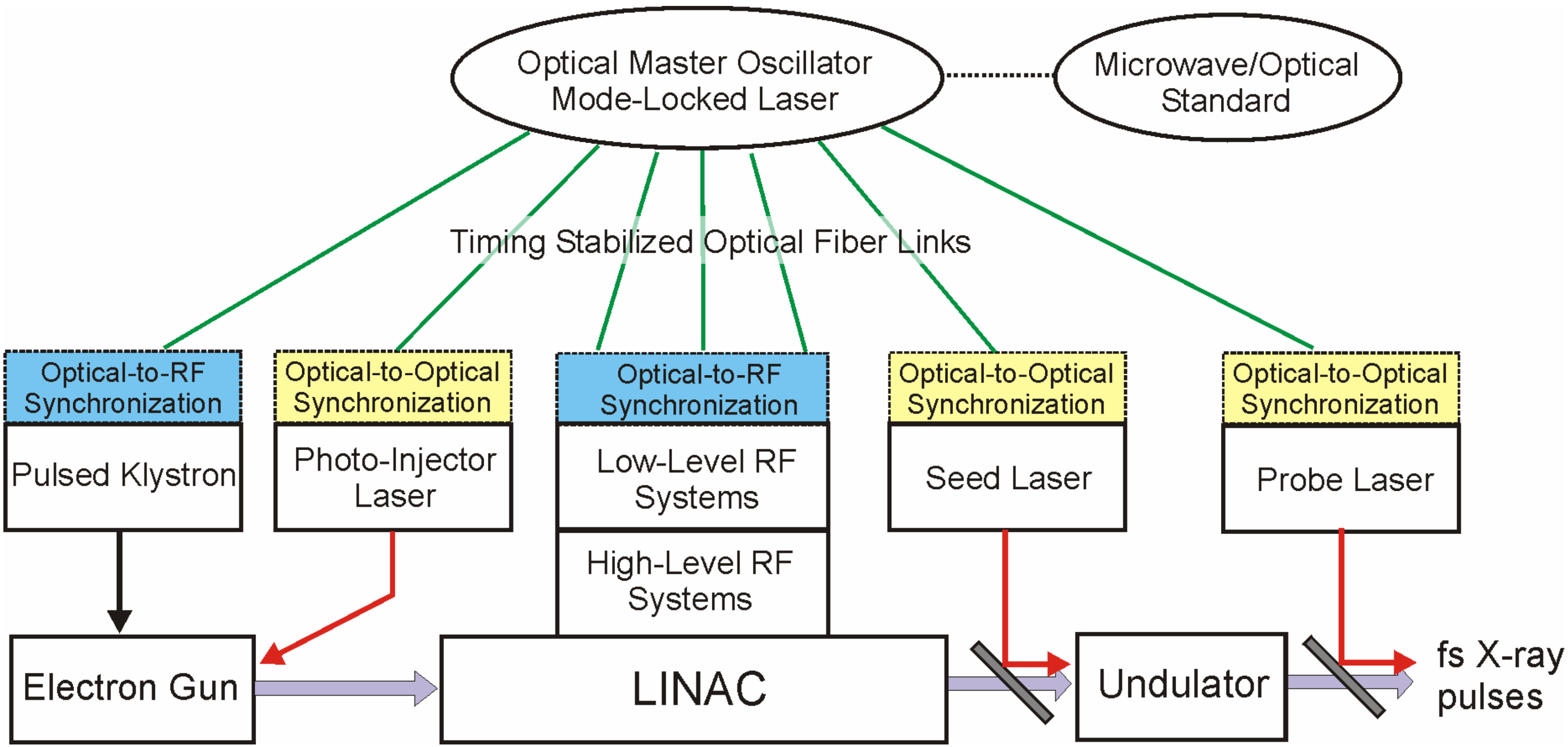


1. Output from soft x-ray FEL is monochromatized and used to seed final section.
2. Modulator undulator is tuned to 800 eV and fresh 5 GeV electron bunch is introduced.
3. Up to 5 GW peak power is produced at 4 keV fundamental of final radiator. Average power is 150 W, or 2e17 photons/sec.
4. Up to 100 MW coherent peak power is produced at 12 keV harmonic. Average power is 3 W, or 1e15 photons/sec.

Key Issues for NSF Role

- The advantages of NSF/University stewardship
  - NSF is responsive to the scientific community
    - FEL R&D was curtailed at BNL and ANL because it was not consistent with the DOE mission
    - US leadership in this area circa 2000 has now been lost to Europe
  - NSF/University stewardship can maximize the educational benefit
    - Broad interest in science and engineering user program opportunities
    - The underlying accelerator and laser technologies also offer many educational opportunities
  - Leverage the university intellectual breadth/depth in constructing the facility and in hosting the external user community
    - At the best universities, it is considerably greater than a national lab.
  - Leverage unique technology available at certain universities
    - Such as ultra-fast laser technology at MIT or Nanofab at UW
    - Some programs are at a higher level than comparable national lab programs.

Femtosecond Synchronization



Note: Laser systems development in the group of MIT professor Franz Kaertner is the world leading effort integrating laser and linac technology

J. Kim et al., FEL 2004.