Charge to the workshop

- Evaluate alternatives to canonical light sources that are becoming increasingly costly
- Examine the state of the technology for compact light sources (CLS) & expected progress in emerging technologies
- Identify advantages & disadvantages of CLS relative to third generation storage rings and FELs

Evaluate Compact Light Source

*Cost effectiveness, User access & availability, Reliability*

- We did not try to rank or directly compare approaches
What do we mean by a compact light source?

- Size: “University-scale” < few hundred m²
- Capital cost: < few tens of M$
- Operating cost: few M$/year
- Possibly modular or easily expanded

Advances in accelerator, laser, & nanotechnology offer opportunities to build high performance X-ray sources of the scale of a university laboratory
Overarching conclusions

- Compact light sources are **not a substitute** for large, synchrotrons & FELs that typically incorporate extensive user support facilities

- Scientific & technological vitality of X-ray science depends on access

- Compact light sources offer attractive, *complementary capabilities*
  - Small fraction of the cost & size of large national user facilities
  - Rapid turn around for high risk research, often unexpected breakthroughs
  - Rapid advance in source technologies
  - Impact on broad range of science & technology, even medicine
  - Personnel (i.e. students, scientists) with versatile capabilities
  - Potential for technological and commercial application
  - Take source to application

- On a 10 year plus timescale, they offer the potential for a new paradigm national user facility
R&D that would enhance performance potential of both compact & large sources

- IR laser systems delivering kW-class average power with femtosecond pulses at kHz repetition rates.
  - Application to ICS sources, plasma sources, & HHG sources, & seeding sources for conventional FELs

- Laser cavities for storage of 10 mJ, ps & fs pulses focused to μm beam sizes

- High-brightness, high-repetition-rate electron sources

- CW superconducting rf-linacs operating at 4 K, while not essential, would reduce capital and operating costs

*These items could be developed on a 5 year time scale assuming adequate funding*
Inverse Compton Scattering Sources (ICS)
Collision between a relativistic electron & a photon

In normal Compton scattering the $E_\gamma > E_e$

Inverse process has the Thomson cross-section when $\hbar \omega < \gamma$

Scattered photon satisfies the undulator equation with period $\lambda_L/2$ for head-on collisions

$$\lambda_x = \lambda_L \frac{1 + \gamma^2 \theta^2}{4 \gamma^2}$$

$\Rightarrow$ X-ray energy decreases by a factor of 2 at an angle of $1/\gamma$

Photon energy reach into hard gamma rays

*Challenge is matching laser & e-beam pulses in time & space*
### Present & near term planned performance: CW machines

<table>
<thead>
<tr>
<th>Machine</th>
<th>Range (keV)</th>
<th>Average Brightness</th>
<th>Peak Brightness</th>
<th>Flux (0.1% BW)</th>
<th>Pulse width (ps)</th>
<th>Rep Rat (MHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>JLAB</td>
<td>7-50</td>
<td>$10^8$</td>
<td>$10^12$</td>
<td>$10^9$</td>
<td>0.3</td>
<td>75</td>
</tr>
<tr>
<td></td>
<td>100-3k</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>KEK</td>
<td>0.1 - 50</td>
<td>$10^16$</td>
<td>CW</td>
<td>$10^13$</td>
<td>5</td>
<td>163</td>
</tr>
<tr>
<td>Lyncean</td>
<td>7-70</td>
<td>$10^12$</td>
<td>CW</td>
<td>$10^11$</td>
<td>100</td>
<td>65</td>
</tr>
<tr>
<td>MIT (proposed)</td>
<td>0.8 - 50</td>
<td>$10^15$</td>
<td>$10^19$</td>
<td>$10^12$</td>
<td>0.3</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>THOMX</td>
<td>50-90</td>
<td>$10^11$</td>
<td>CW</td>
<td>$10^11$</td>
<td>20</td>
<td>25</td>
</tr>
</tbody>
</table>

Coherent Compton scattering would increase brightness several orders of magnitude
### Present & near term planned performance: Timing mode pulsed machines

<table>
<thead>
<tr>
<th>Machine</th>
<th>Range (keV)</th>
<th>Peak Brightness</th>
<th>Photons/shot (0.1%)</th>
<th>Pulse width (ps)</th>
<th>Rep Rat (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BNL</td>
<td>1-30</td>
<td></td>
<td>$10^8$</td>
<td>4</td>
<td>10</td>
</tr>
<tr>
<td>LBNL-LPA</td>
<td>10-10k</td>
<td>$10^{22}$</td>
<td>$10^4$</td>
<td>.003</td>
<td>10</td>
</tr>
<tr>
<td>LLNL (planned)</td>
<td>600 400-5k</td>
<td>$10^{16}$ $10^{21}$</td>
<td>$10^6$</td>
<td>1</td>
<td>10 $&gt;&gt;100$</td>
</tr>
<tr>
<td>MIT (proposed)</td>
<td>0.8 - 50</td>
<td>$10^{23}$</td>
<td>$10^8$</td>
<td>0.5</td>
<td>10</td>
</tr>
</tbody>
</table>
High-Harmonic Generation (HHG) in gases
HHG driven by femtosecond lasers

- Low cost, stand-alone, table-top-scale, tunable EUV/XUV source
  - Full spatial and temporal coherence & ultrafast pulse duration

**Semi-classical picture:**

1. Atom is tunnel ionized by the laser’s intense EM field
2. Emitted electron accelerates in the laser field, gaining energy
3. Electron energy is released as harmonics of the fundamental laser when electron recombines with the ion

*Phase match the HHG process by equalizing laser and x-ray phase velocities*
Laser pulse energy required for HHG is < 5mJ
- Repetition rate can scale to 100’s of kHz or higher
Efficiency from laser to harmonics ~ $10^{-7} - 10^{-5}$
- $\approx \mu J$/harmonic/pulse
- Ultrafast (fs to as)
- High rep rate, pump-probe and coincidence imaging
- Broad band: from VUV to SXR

Current bright region of HHG (1 kHz, 10 - 5 nm)
Future bright region of HHG (50 kHz, 10 - 1 nm)
Plasma cavitation HHG
# High average power EUV/Soft X-ray facilities

<table>
<thead>
<tr>
<th>Status and outlook</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Present status</td>
<td>Ti:sapphire based pump lasers</td>
</tr>
<tr>
<td></td>
<td>~(\mu)W average power</td>
</tr>
<tr>
<td>2 year goal</td>
<td>Sub-100 W average power Yb/OPA systems at 1.5 (\mu \text{m}) and 3 (\mu \text{m})</td>
</tr>
<tr>
<td></td>
<td>&gt; 400 W 1(\mu \text{m}) Yb-doped femtosecond lasers</td>
</tr>
<tr>
<td></td>
<td>Recirculating cavities for HHG up to 100 eV</td>
</tr>
<tr>
<td>5 year goal</td>
<td>Sub-M$, 0.1-1 mW coherent soft x-ray sources</td>
</tr>
<tr>
<td></td>
<td>Fully coherent hard x-rays</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Investments required</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial R&amp;D (2 yr)</td>
<td>$2M - $4M (equipment plus labor)</td>
</tr>
<tr>
<td>Facility construction</td>
<td>Existing labs</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Operations Considerations</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Staffing levels required</td>
<td>1FTE</td>
</tr>
<tr>
<td>Annual operations cost</td>
<td>$0.5M</td>
</tr>
<tr>
<td>User access</td>
<td>2 teams at one time, access every other week</td>
</tr>
</tbody>
</table>
A PW HHG facility would deliver pulses in the XUV with parameters very similar to the FLASH FEL at DESY for a very modest investment.
## High peak power XUV facility:
Rep. rated PW laser HHG source – Costs & status

### Status and outlook

<table>
<thead>
<tr>
<th>Present status</th>
<th>TW class drivers demonstrated: ≤ 50 µJ per pulse @ 30 eV; 10 Hz focused intensity ~10^{13} W/cm²</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 year goal</td>
<td>Demonstrate 1 mJ @ 30 eV; single shot Perform R&amp;D on rep. rated 100 J amp</td>
</tr>
<tr>
<td>5 year goal</td>
<td>Construct PW-HHG facility with 2-4 beamlines</td>
</tr>
</tbody>
</table>

### Investments required

<table>
<thead>
<tr>
<th>Component</th>
<th>Cost Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial R&amp;D (2 yr)</td>
<td>$2M - $4M</td>
</tr>
<tr>
<td>Facility construction</td>
<td>$10M - $15M per facility</td>
</tr>
</tbody>
</table>

### Operations Considerations

<table>
<thead>
<tr>
<th>Consideration</th>
<th>Details</th>
</tr>
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<tbody>
<tr>
<td>Staffing levels required</td>
<td>6 – 10 FTEs</td>
</tr>
<tr>
<td>Annual operations cost</td>
<td>$2M</td>
</tr>
<tr>
<td>User access</td>
<td>~ 2-4 users at one time</td>
</tr>
<tr>
<td>Scheduled availability</td>
<td>~4 day/week</td>
</tr>
</tbody>
</table>
Laser-driven plasma sources

Schematic diagram of injection-seeded soft x-ray laser amplifier that produces a high brightness phase-coherent soft x-ray laser beam by seeding a dense laser-created plasma amplifier with high harmonic pulses.
Table-top soft x-ray lasers

🌟 Advantages:

→ **High pulse energy**: Highest pulse energy available from a coherent table-top source. (> $6 \times 10^{11}$ photons/pulse @ 100 eV in 13-33 nm region.
  - Extremely compact capillary discharge lasers already produce > $1 \times 10^{14}$ photons per pulse at 26.5 eV).

→ **High average flux.** (eg. 20 μW demonstrated at ~ 100 eV, with 1 mW potentially resulting from further development).
  - > 1 mW average power currently available at $\lambda = 46.9$ nm from capillary discharge lasers.

→ **Compact** (1-3 optical tables). Capillary discharge-pumped lasers are as small as desk-top size.

→ **Full Phase coherent for seeded SXRL** (plasma-based lasers are presently the only soft x-ray lasers with full temporal coherence)

→ **Short pulse** duration (1-5 ps). Potential for 50-100 fs with further development.

🌟 Limitations: Line-tunable, numerous lines accessible but not continuously tunable.
Brightness of table-top SXR lasers
Compact repetitive laser-pumped plasma Soft X-Ray Lasers

- Wavelength range coverage: 10 nm- 50 nm (present)- sub 10 nm (future)
- Average power: up to 20 μW (present), > 1 mW (future)
- Pulse energy: up to 10 μJ (present), > 0.1 mJ (future)
- Narrow spectral bandwidth: $\Delta \lambda / \lambda < 10^{-4}$
- Repetition rate: 1-10 Hz (present), > 100 Hz (future)
- Pulsewidth: 1-5 ps (present), < 100 fs (future)
- Size: 1-3 optical tables
- Coherence: full coherence (seeded mode), partial coherence (ASE mode)
- Facility cost: $2-4$ M
Discharge-pumped lasers produce coherent average power @ 46.9 nm similar to synchrotron beam line

Ne-like Ar Capillary discharge $\lambda=46.9$ nm laser

- Average power: > 1 mW
- Pulse energy: 0.01 mJ - 0.5 mJ
- Narrow spectral bandwidth: $\Delta\lambda/\lambda = 10^{-4}$
- Repetition rate: up to 10 Hz
- Pulselength $\sim 1$ ns
- Size: table-top to desk-top
- High spatial coherence
- Cost: $0.3$ - $0.4$ M. Can be easily installed in any lab
Sources based on plasma accelerators
(10 - 100 GeV/m)

PWFA schematic, indicating plasma oscillations set up by drive electron bunch expelling plasma electrons from the path of the drive bunch
Multi-spectral radiation from THz to γ’s.

Fully synchronized, ultra-short

Transition radiation from beam exiting plasma – MV/cm THz

Betatron radiation during acceleration – Multi keV

Thomson Scattering – Multi keV/MeV x-ray/gamma ray

Free Electron Laser-> XUV, X-ray
Linac cost is minimal ==> build multiple linacs & beam lines driven by single laser or multiple lasers

As laser cost decreases and performance increases: power each beam line with its own laser
Progress in plasma-accelerators for future light sources

- FEL and seeding technology R&D
- 1 Å FEL
- 1 nm FEL
- EUV seeded FEL 30 nm
- Technology mature for compact soft-x-ray user facility (10-100 Hz; high peak brightness)
- GeV LPA
- BELLA 10 GeV LPA
- FACET 25 GeV PWFA
- Ultra-high brightness LPA

Accelerator technology R&D
Small storage rings
Possible brightness and flux with current technology

**Ring characteristics:**
- 1.5 – 2.0 GeV
- 60 – 80 m circumference
- Several 5 T bend magnets
- 10 nm emittance
- 500 mA current
- ~ 40 bend magnet beamlines
  (maybe 1/2 on s/c magnets)

*Same as productive Superbend beamlines on ALS*
Pro’s and Con’s of small rings

**Pros:**
- High Flux, Moderate Brightness, Many Beamlines, Reasonable Cost per Beamline, High Stability, Option for (partial) circular polarization out of plane, If desired could provide round beams (with lower brightness)

**Cons:**
- Facility is smaller but not tabletop, Moderate total cost, Very limited potential for short pulses

**Future R+D**
- On axis injection for lower emittance lattices

**Other potential**
- Ring of this size but lower beam energy could be optimized as source for stable, broadband, coherent THz radiation
Small ring summary

🌟 Storage rings are
   ➡ Cost effective for large numbers of beamlines
   ➡ Providing large average flux and average brightness

🌟 New lattice designs & more compact magnets enable
   ➡ Reduced size (to 60-75 m circumference)
   ➡ Lower cost (to 50 M$)
   ➡ Facility that could offer 20-40 beamlines with same flux & same brightness as bend magnet beamlines at 3rd generation rings

*Very cost effective per beamline*
Thanks to all the participants

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