High Repetition Rate
Inverse Compton Scattering Source

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March 2, 2010
Future Light Sources Workshop
SLAC
1) **Overview** of the technology

2) Present **state of the technology** R&D and existing technology gaps

3) Likely **performance limitations** in terms of limiting brightness, limiting average power, and temporal properties (pulse duration, rep rate, coherence, spectral purity)

4) Nominal strawman design of a 500-eV source within a **5 year horizon**

5) Nominal strawman design of a 50-keV source within a **10 year horizon**

*Linac technology. R. Ruth will cover ring-based ICS technology in next talk.*
X-ray Science

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

Spatial Scales

Nature
- Flea
- Human hair ~30 μm wide
- Red blood cells & white cell ~5 μm
- Virus ~200 nm
- DNA helix ~3 nm width
- Water molecule
- Atom

Technology
- Head of a pin ~1 mm
- Micro gears 10-100 μm diameter
- DVD track
- 1 μm Electrodes connected with nanotubes
- Carbon nanotube ~2 nm diameter
- Atomic corral ~14 nm diameter

Temporal Scales

Nature
- Hydrogen transfer time in molecules is ~1 ns
- Spin precesses in 1 Tesla field is 10 ps
- Shock wave propagates by 1 atom in ~100 fs
- Water dissociates in ~10 fs
- Bohr period of valence electron is ~1 fs

Technology
- Computing time per bit is ~1 ns
- Optical network switching time per bit is ~100 ps
- Magnetic recording time per bit is ~2 ns
- Laser pulsed current switch ~1 ps
- Shortest laser pulse is ~1 fs
- Oscillation period of visible light is ~1 fs
ICS X-ray Science

CV-CT with 1µm resolution

Ultrafast x-ray diffraction

Correlated electrons

Protein Crystallography

Image-guided tumor radiation therapy

W.S. Graves    Future Light Sources Workshop 2010, Stanford, CA
ICS Beam Brilliance

3rd gen SR

ERL ICS
SRF ICS
Rigaku rotating anode

4th Generation: VUV & X-ray Lasers

Best "lab" source today
Who Wants a Compact Source?

**Academic**
Harvard, Purdue, Boston U., Niels Bohr Institute, London Center for Nanotechnology, Institute of Biophysics and Nanosystems – Austrian Academy of Sciences

**Medical**
Massachusetts General Hospital

**National Labs**
ORNL, National High Magnetic Field Lab, NIST

**Industrial**
Novartis, Wyeth, GE, Rigaku Americas Corp, Siemens

**Cultural**
Louvre Museum
Technology Challenges

1) Low emittance, high current CW gun
2) CW linac
3) Cryogenic systems
4) High power laser
# Approaches to Milliamp Electron Gun*

<table>
<thead>
<tr>
<th>Technology</th>
<th>Advantages</th>
<th>Disadvantages</th>
<th>Risk</th>
</tr>
</thead>
</table>
| **Superconducting RF at 4K**  
(NPS, Niowave, UW-Madison, MIT) | Reduced cryo cost  
Very high design gradient  
Modest RF power | Not yet demonstrated  
Moderate cryo cost/complexity  
No b-field at cathode  
Immature technology | High |
| **Superconducting RF at 2K**  
(FZD, DESY, BNL, Jlab) | Cavity designs mature  
High design gradient  
Modest RF power  
Demo’d performance | Design performance not yet reached  
Expensive & complex cryo  
No b-field at cathode | Moderate to High |
| **Room temp RF**  
(LBNL) | Moderate design gradient  
B-field at cathode OK  
No cryo cost | Not yet demonstrated  
Moderate gradient and exit energy  
Higher RF power | Moderate |
| **DC**  
(Jlab, Cornell, Daresbury) | Mature design  
Proven performance  
No RF effects on beam | Modest gradient and exit energy  
Ion back-bombardment  
Mature - further improvement difficult | Low |

*Laser plasma accelerator becoming viable at low average current*
## Approaches to CW Linac

<table>
<thead>
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<th>Technology</th>
<th>Advantages</th>
<th>Disadvantages</th>
<th>Risk</th>
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<tbody>
<tr>
<td>Superconducting RF at 2K</td>
<td>Cavity designs mature</td>
<td>Expensive, large, &amp; complex cryo</td>
<td>Moderate to low</td>
</tr>
<tr>
<td>(DESY, Jlab, Cornell, ACCEL, many others)</td>
<td>High pulsed gradient</td>
<td>High CW gradient not yet demo’d</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Demonstrated performance</td>
<td></td>
<td></td>
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<td></td>
<td>Small RF structures</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Superconducting RF at 4K</td>
<td>Reduced cryo cost and size</td>
<td>Larger RF structures</td>
<td>High to moderate</td>
</tr>
<tr>
<td>(JLab, ODU, ANL, LANL, MIT)</td>
<td>Moderate gradient</td>
<td>Immature technology</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Modest RF cost</td>
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</tbody>
</table>

Room temperature CW RF not feasible due to RF wall losses but OK at low rep rate.
Laser plasma accelerator becoming viable at low rep rate.
• 176 MHz RF frequency
• 10 – 20 MV/m cathode gradient
• 0.5 – 1 MeV exit beam energy
• Compatible with b-field at photocathode


Now funded by BES Accelerator and Detector R&D program

Courtesy of J. Corlett (LBNL)
Existing SRF Technology at 2K

1300 MHz SRF gun at FZ Dresden currently in operation.
Design cathode gradient is 25 MV/m. So far demonstrated 7 MV/m.

1300 MHz SRF gun with cold Pb cathode
J. Sekutowicz et al.
Demonstrated 46 MV/m cathode field.

SRF linac module at Daresbury. Uses 2 TESLA-type 1-m cavities.

Courtesy of J. Teichert (FZD)
Cryogenic Equipment

For a compact facility, the cryogenic system is the biggest and most expensive set of equipment.

Want 4K (or higher) temperature.

Gun and linac become larger.

Cost/size optimization quite different from major facility.
Next Generation SRF Injector at 4K

- 200 – 500 MHz RF frequency
- 45 MV/m cathode gradient at 105 mT peak B-field on wall
- 4 MeV exit energy
- 1 mA average current

4K operation to reduce cost and size of cryogenic system.

Under development at Naval Postgraduate School, Niowave Inc, and UW-Madison.
Next Generation CW SRF Linac at 4K

Spoke Resonators

+ Good mechanical rigidity
+ Lower RF-frequency for a given size (4K operation instead of 2K)
+ Compactness
+ Good Higher Order Mode (HOM) Control

− Moderate gradient (10-12 MV/m)
High Power Laser Challenges

- High power lasers, kW-class, pico and femtoseconds
- High-power enhancement cavities with MW stored power

See detailed talks on Thursday afternoon by T.Y. Fan (Lincoln Lab) and F.X. Kaertner (MIT)
Cryo-cooled Yb-doped Lasers

- Cryo-cooling allows efficient use of gain media (example Yb:YAG)
  - Yb:YAG has low quantum defect (~ 9%) and broad bandwidth (~1.5 nm)
  - 4-level laser at 100 K, saturation fluence of 2 J/cm² (3 level at 300 K, 9 J/cm²)
  - Spectral bandwidth of 1.5 nm: suitable for picosecond pulse amplification
- Improved thermo-optic properties at low temperature for power scaling
- Modest LN₂ usage – 1-kW laser needs ~0.1 liters/min
500-W-level CW Cryogenic Yb:YAG Oscillator

- Cryogenic Yb:YAG has enabled efficient, simple lasers with good beam quality
- 494-W cw power unpolarized
  - 71% optical-optical efficiency
  - M² ~ 1.4 at 455 W
- Performance limited by pump power
  Fan et al., JSTQE 13, 448 (2007)
Developments in Cryogenic Yb-doped Lasers

- Multi-kW average power in 15-ns pulses at 5-kHz PRF (Cryogenic Yb:YAG Development, formerly ATILL)
- ~10-ps pulses at 2-kHz pulse repetition frequency (PRF) with 100-W average power (DARPA HRS)
- 100 W in 10-ps pulses at 100-kHz PRF for photoinjectors (DOE STTR with Q-Peak)
- Multi-100-W, 1-ps pulses at 5-kHz PRF (Army)
- Power scaling of fs (<250 fs) pulsed lasers (HEL JTO)
- Tech transfer to multiple organizations
High-Power Enhancement Cavity

- Requirements: electron-beam access, high-intensity in interaction region, and low loss
- 1-MW intracavity power, 10 mJ, ~1-ps pulses circulating
- Cavity Finesse > 3000

Confocal cavity for high-intensity Bessel-Gauss beams – Cavity shown enables 1000 TW/cm²
ICS Parameter Optimization

• Electron emittance effects
• Laser and electron pulse length
• Laser and electron spot size
Electron Emittance Effects

Normalized emittance = 0.3 µm

Normalized emittance = 1.0 µm

Plane Perpendicular to Laser Polarization
**Electron Beam Parameters**

- \( \varepsilon_n = 0.30 \text{ mm-mrad (25 MeV)} \)
- Rms spot size = 2.9 \( \mu \text{m} \)
- \( Q = 0.1 \text{ nC} \)

**Laser Parameters**

- \( \lambda = 1 \mu \text{m} \)
- \( W = 10 \text{ mJ} \)
- Pulse duration = 0.5 ps

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**X-ray Flux vs Spot Size and Length**

![Graphs showing x-ray dose and average brightness/rep. rate vs rms laser spot size for different pulse durations.]
Intensity Profile of 12 keV X-rays with 0.1% bw

\[ \frac{\text{Intensity (keV/mrad}^2\text{)}}{\theta_y (\text{mrad})} \]

\[ \sim 10^{12} \text{ photons/sec @ 100 MHz in 0.1% BW for linac} \]

\[ \sim 2 \times 10^{14} \text{ photons/sec @ 500 MHz in 0.1% BW for ERL} \]
## X-ray Source Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Linac @ 1mA 5 year horizon</th>
<th>ERL @ 50 mA 10 year horizon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tunable monochromatic photon energy [keV]</td>
<td>3 – 12</td>
<td>3 – 12</td>
</tr>
<tr>
<td>Pulse length [ps]</td>
<td>0.3</td>
<td>0.5</td>
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<tr>
<td>Flux per shot [photons]</td>
<td>$1 \times 10^6$</td>
<td>$5 \times 10^7$</td>
</tr>
<tr>
<td>Repetition rate [Hz]</td>
<td>$10^8$</td>
<td>$5 \times 10^8$</td>
</tr>
<tr>
<td>Average flux [photons/sec]</td>
<td>$1 \times 10^{14}$</td>
<td>$2 \times 10^{16}$</td>
</tr>
<tr>
<td>FWHM bandwidth [%]</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>On-axis bandwidth [%]</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Source RMS divergence [mrad]</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Source RMS size [mm]</td>
<td>0.002</td>
<td>0.003</td>
</tr>
<tr>
<td>Peak brightness [photons/(sec mm$^2$ mrad$^2$ 0.1%bw)]</td>
<td>$2 \times 10^{19}$</td>
<td>$4 \times 10^{20}$</td>
</tr>
<tr>
<td>Average brightness [photons/(sec mm$^2$ mrad$^2$)]</td>
<td>$6 \times 10^{14}$</td>
<td>$1 \times 10^{17}$</td>
</tr>
</tbody>
</table>
## Electron & Laser Parameters

<table>
<thead>
<tr>
<th></th>
<th>Linac</th>
<th>ERL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Current [mA]</td>
<td>1</td>
<td>100</td>
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<tr>
<td>Bunch charge [pC]</td>
<td>10</td>
<td>100</td>
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<tr>
<td>Repetition rate [Hz]</td>
<td>$10^8$</td>
<td>$5 \times 10^8$</td>
</tr>
<tr>
<td>Energy [MeV]</td>
<td>10 - 50</td>
<td>10 - 50</td>
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<tr>
<td>Normalized emittance [mm-mrad]</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>FWHM bunch length [ps]</td>
<td>0.3</td>
<td>0.5</td>
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<tr>
<td>RMS energy spread [keV]</td>
<td>3</td>
<td>3</td>
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<tr>
<td>Laser power [kW]</td>
<td>1</td>
<td>5</td>
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<tr>
<td>Cavity frequency [MHz]</td>
<td>100</td>
<td>500</td>
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<tr>
<td>Cavity Q</td>
<td>1000</td>
<td>1000</td>
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<tr>
<td>Stored cavity power [MW]</td>
<td>1</td>
<td>5</td>
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<tr>
<td>Laser FWHM pulse length [ps]</td>
<td>0.5</td>
<td>0.5</td>
</tr>
</tbody>
</table>
Development Plans

5 Years

1 mA linac
100 MHz repetition rate
1 kW laser
1 MW laser coherent cavity

10 Years

50 mA ERL
500 MHz repetition rate
5 kW laser
5 MW laser coherent cavity
Coherent enhancement cavity with Q=1000 giving 5 MW cavity power

5 kW cryo-cooled Yb:YAG drive laser

Superconducting RF photoinjector

X-ray beamline 2

Inverse Compton scattering

X-ray beamline 3

X-ray beamline 4

Superconducting RF Linac

10 kW beam dump

Electron beam of 50 mA average current at 10-30 MeV

ERL-ICS Facility within 10 years
Summary

• Compact ICS x-ray sources provide scientific opportunities not otherwise available at universities, national labs, hospitals, and industry.

• Second only to 10 GeV FEL as source of ultrashort hard x-rays

• Performance depends on development of CW RF and laser technology: many efforts underway.

• Performance goals require short pulses and low emittance

• Equipment cost ~$10M for linac-based ICS