Nanoprobe Beamline for the Cornell ERL

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• Rational for a Nanofocus ERL beamline
• ERLspecs & Parameter Lists, 14 x-ray beamlines and their purposes, building floor plan
• Overview of delta undulator device and spectral curves
• Optical considerations and layout for Nanofocus beamline
• Issues yet to be resolved: should we have a secondary source defined or not?
• Can we make x-ray optics that can make a one nm spot size at 10 to 20 keV?
Nanofocus Opportunity

• New opportunity to use x-ray beams with the smallest possible beam size. Type of experiments we want to do is to collect information with minimal perturbation to the sample under study. So high average brightness is favored with low peak brightness so as not to disturb the sample too much.
• Potential to focus a hard x-ray beam to 1 nm beam size – but we currently don’t have optics that can reach this size scale.
• Need ultra-high brightness, high-rep rate source to have enough flux for x-ray fluorescence or EXAFs experiments, to make scanning images, etc.
• We won’t compete with electron probes, but could do very interesting work in buried layer structures, in diamond cells, nasty chemical cells, etc.
• Applications: Do experiments on a single atom (not possible now) or in clusters in a narrow line-width buried transistor structure, see single high-z atoms moving in-situ in a catalyst nanoparticle, etc.
• Will push x-ray physics to new levels of understanding.
• Routes to achieve this goal:
  • NSLSII is on this path with Laue lenses hoping to deliver 1E10 x-rays/sec into a 1 nm focus. Our scaling for ERL could provide 1 to 2 orders of magnitude of more flux in same spot size.
  • With an ERL, could have high-z fluorescent intensities of 1E6 x-rays/sec into a 2*pi detector for imaging, EXAFS, etc. This could provide some rapid, near real-time images of atoms moving.
Specifications for Cornell ERL$^1$

- Energy range: tunable, VUV to hard x-ray (30 eV to 100 keV)
- Spectral brightness$^2$: $10^{22}$ to $10^{23}$ x-rays/s/mr$^2$/mm$^2$/0.1%bw
- Highly Coherent Source$^2$: 60% at 10 keV in Hi-coherence mode
- Emittance: 8 pm (Hi-coherence mode) $\sim \lambda/4\pi$ @ 10 keV, 2 micron diameter electron beam (round) for best nanoprobe imaging
- Short pulse: $\sim$50 fsec
- Hi-flux: use 100 mA mode with 25m long undulators w/many short periods
- Number of ID beamlines: 14 in this layout

Notes:
1. not all parameters are obtained simultaneously
2. depends on the performance of the injector, $10^{23}$ is longer-term goal
## Basic ERL Parameters

<table>
<thead>
<tr>
<th>Modes</th>
<th>(A) Hi-flux</th>
<th>(B) Coherence</th>
<th>(C) Small Charge, Short Bunch, Hi-Rep Rate</th>
<th>(D) High Charge, Short Bunch, Lo-Rep Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy (GeV)</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Current (mA)</td>
<td>100</td>
<td>25</td>
<td>TBD(^1)</td>
<td>0.1</td>
</tr>
<tr>
<td>Bunch Charge (pC)</td>
<td>77</td>
<td>19</td>
<td>TBD(^1)</td>
<td>1000</td>
</tr>
<tr>
<td>Repetition Rate (MHz)</td>
<td>1300</td>
<td>1300</td>
<td>1300</td>
<td>0.1</td>
</tr>
<tr>
<td>Geom. Emittance, both Horiz. &amp; Vert. (pm)</td>
<td>30</td>
<td>8</td>
<td>TBD(^1)</td>
<td>500</td>
</tr>
<tr>
<td>RMS Bunch Length (fs)</td>
<td>2000</td>
<td>2000</td>
<td>&lt;100(^2)</td>
<td>&lt;100(^2)</td>
</tr>
<tr>
<td>Relative electron energy spread ((x10^{-3}))</td>
<td>0.2</td>
<td>0.2</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

\(^1\) To Be Determined by ongoing research. The appropriate compromise between bunch charge and current is limited by wake field effects yet to be evaluated. These, in turn, determine the emittance.

\(^2\) The higher energy spread in Mode C allows bunch compression prior to select beamlines, which then receive bunches for fast-pulse studies. Most beamlines precede the bunch compressors and receive native 2 ps bunches.

\(^3\) Mode D uses larger charge bunches, for more x-rays per pulse, at a sufficiently low rate that these bunches need not be energy recovered. Rather, they are dumped prior to reentry into the first linac.
ERL has ultra-high spectral brightness and is 60% coherent at 10 keV
Figure 1. Schematic ERL layout incorporating the existing Cornell Electron Storage Ring (CESR). Electrons are injected (1) and are accelerated to the right in a 2.8 GeV linac (2), loop through a turn-around arc (3), and accelerate to the left through an additional 2.2 GeV linac (4) to 5 GeV, past a non-recovered beamline option (5), through X-ray beamlines in the pink/red areas (6) and (8). Beams then pass clockwise around CESR (7) where bunches may be compressed to <100 fs and through more undulators (8) before being uncompressed, energy recovered in second passes through linacs (2) and (4), and finally terminate at a beam stop (10). The location of the cryo plant is shown in purple (9).
ERL Layout for X-ray Beamlines
# Tentative List of 14 ID Beam Lines

<table>
<thead>
<tr>
<th>Beam line</th>
<th>Application Notes</th>
<th>Operating Mode</th>
<th>ID Length (m)</th>
<th>ID Notes</th>
<th>Energy Range</th>
<th>BL Length (m)</th>
<th>Contact</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Coherent diffraction &amp; XPCS</td>
<td>Microscopy &amp; Dynamics at nm Scale</td>
<td>Hi-Coh</td>
<td>25</td>
<td>Undulator</td>
<td>5-25 keV</td>
<td>80</td>
</tr>
<tr>
<td>2</td>
<td>Nanoscope &amp; Nanoprobe</td>
<td>TXM &amp; STXM with high NA optics to nm</td>
<td>Hi-Coh</td>
<td>5</td>
<td>Undulator</td>
<td>5-25 keV</td>
<td>75</td>
</tr>
<tr>
<td>3</td>
<td>Soft X-ray I</td>
<td>microscope for biomaterials in water window, XMCD nano-magnetic imaging, ARPES</td>
<td>Hi-Coh</td>
<td>6</td>
<td>Apple II Undulator</td>
<td>100 eV to 5 keV</td>
<td>75</td>
</tr>
<tr>
<td>4</td>
<td>Nanoprobe</td>
<td>General Nanoprobe station (1nm beam size)</td>
<td>Hi-Coh</td>
<td>5</td>
<td>Undulator</td>
<td>1-10kev</td>
<td>80</td>
</tr>
<tr>
<td>5</td>
<td>Protein Crystallography I</td>
<td>High-Throughput, Microfocus</td>
<td>Hi-flux</td>
<td>5</td>
<td>Undulator</td>
<td>5-25 keV</td>
<td>40</td>
</tr>
<tr>
<td>6</td>
<td>Protein Cryst. II</td>
<td>Wide-range tunability</td>
<td>Hi-flux</td>
<td>5</td>
<td>Undulator</td>
<td>5-25 keV</td>
<td>40</td>
</tr>
<tr>
<td>7</td>
<td>Inelastic X-ray scattering</td>
<td>1mev resolution</td>
<td>Hi-flux</td>
<td>25</td>
<td>Undulator</td>
<td>5-25 keV</td>
<td>80</td>
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<tr>
<td>8</td>
<td>Femtosecond timing</td>
<td>Charge Density waves, etc.</td>
<td>Ultra-fast</td>
<td>5</td>
<td>Undulator</td>
<td>5-25 keV</td>
<td>60</td>
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<tr>
<td>9</td>
<td>Materials Science I</td>
<td>High pressure x-ray science</td>
<td>Hi-flux</td>
<td>5</td>
<td>Undulator</td>
<td>5-100 keV</td>
<td>75</td>
</tr>
<tr>
<td>10</td>
<td>Materials Science II</td>
<td>General materials science</td>
<td>Hi-flux</td>
<td>5</td>
<td>Undulator</td>
<td>5-25 keV</td>
<td>46</td>
</tr>
<tr>
<td>11</td>
<td>Resonant Scattering</td>
<td>X-ray Science</td>
<td>Hi-flux</td>
<td>5</td>
<td>Undulator</td>
<td>5-25 keV</td>
<td>80</td>
</tr>
<tr>
<td>12</td>
<td>SAX I / XPCS / grazing incidence</td>
<td>Mesoscopic science</td>
<td>Hi-flux</td>
<td>5</td>
<td>Undulator</td>
<td>5-25 keV</td>
<td>80</td>
</tr>
<tr>
<td>13</td>
<td>SAX II</td>
<td>Mesoscopic science</td>
<td>Hi-flux</td>
<td>5</td>
<td>Undulator</td>
<td>5-25 keV</td>
<td>80</td>
</tr>
<tr>
<td>14</td>
<td>Diagnostics</td>
<td>Beamsize and Position Measurements</td>
<td>All modes</td>
<td>5</td>
<td>Undulator</td>
<td>5-25 keV</td>
<td>40</td>
</tr>
</tbody>
</table>
“Delta” X-ray Undulator (A. Temnykh)

Prototype of small triangular blocks of NdFeB
Remnant field = 1.26 Tesla.
Center bore = 5 mm in diameter,
period = 24 mm

Prototype of small triangular blocks of NdFeB
Remnant field = 1.26 Tesla.
Center bore = 5 mm in diameter,
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from ERL Phase Ib proposal (2008)

Helical Mode, $B_{\text{max}} = 0.87$ T

Planar Mode, $B_{\text{max}} = 1.27$ T


In progress: 60 MeV tests at ATF Facility at BNL

FLS 2010 ICFA Beam Dynamics Workshop, SLAC, March 1-5, 2010 Slide 9 of 14
Nanofocus Optical Design

Note: Inner cone at 3% (6%) of outer cone diameter for 2 cm period undulator of 25 meter (5 meter) length on first harmonic
Nanofocus Optical Design

Last lens could be zone plate or Laue Lens. Laue Lens for 1 nm beam size on sample @ 10 to 20 keV has not yet been achieved. Opening of XBPM3 could be 100 microns.
From Ray Conley, NSLSII and APS groups, Data received 2/19/2010

Line Scan and Fluorescence Imaging by 2 Crossed MLLs (Yan)


2D focal size: ~ 21 nm x 39 nm.
Photon Energy: 19.5 keV
Efficiency: 17%
Smallest line focus: 16 nm
Photon Energy: 19.5 keV
Nano X-ray optics

Adaptive mirror optics

Silicon refractive optics
routine use: \(~100 \text{ nm focus}\)

Schroer et al., *APL* (2005) 87, 124101
From Christian Riekel
Design for a 1 micron resolution device (David Agyeman-Budu, Arthur Woll, Alexander Kazimirov, Don Bilderback- Cornell Univ.)

- **Constraints:**
  - 200 x 200 µm room at the top of optic
  - Maximum size of total device
  - 100 channels

- **Deliverables**
  - 1µm channel-wall arrangement at the top of the optic
  - Variations with respect to channel-wall widths
  - Deeply etched (100µm*)

We are investigating concepts to scale this down to nm resolution – new ideas always welcome!
Summary

We have a “concept” design for a hard x-ray nanoprobe on the proposed Cornell ERL facility.

The new opportunity will be to use ultra-small diameter x-ray beams down to the nm scale.