Toward an Energy Recovery Linac x-ray source at Cornell University

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• The ERL principle
• Limits of ERLs
• Studies for an x-ray ERL

• Ultra low emittance creation
• Gun prototyping
• Gun diagnostics
• Laser optimization

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Smaller dispersion $\rightarrow$ Smaller emittance

Dispersion:
- closed path for an off-energy particle

Path for design energy

Path for smaller energy
Beam Size in a Linear Accelerator

The beam properties are to a very large extend determined by the injector system:

1. The horizontal beam size can be made much smaller than in a ring

2. While the smallest beams that are possible in rings have almost been reached, a linear accelerator can take advantage of any future improvement in the electron source or injector system.

ESRF 6GeV@200mA → ERL 5GeV@100mA

Diffraction limited @ 8keV

courtesy Ivan Bazarov

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- Coherent x-ray diffraction imaging

- It would, in principle, allow atomic resolution imaging on non-crystalline materials.

- This type of experiments is completely limited by coherent flux.

Factor 100 more coherent flux for ERL for same x-rays, or provide coherence for harder x-rays
The bunch length can be made much smaller than in a ring.

While the shortest bunches possible in rings have almost been reached, a linear accelerator can take advantage of any future improvement in the source or injector system.
Pro and Con for an x-ray Linac

As compared to a ring, the beam properties are largely determined by the injector system:

1. The bunch length can be made much smaller than in a ring
2. Smaller emittances
3. Higher coherence fraction

Current of 100mA and energy of 5GeV leads to a beam power of 0.5GW !!!

The energy of the spent beam has to be recaptured for the new beam.
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X-ray analysis with highest resolution in space and time:

Challenges:
- Invented in 1965
- Needs superconducting RF, otherwise high Voltage CW cavities melt
- High Voltage SRF only had a boost end of ’90s due to the linear collider
### Nominal Parameters for 5GeV electron beam (Contain safety factors)

<table>
<thead>
<tr>
<th>Operation mode</th>
<th>High Flux</th>
<th>Coherence</th>
<th>Short pulse</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current (mA)</td>
<td>100</td>
<td>10</td>
<td>1</td>
</tr>
<tr>
<td>Charge/b (nC)</td>
<td>0.08</td>
<td>0.008</td>
<td>1.0</td>
</tr>
<tr>
<td>$\varepsilon_x / \varepsilon_y$ (nm)</td>
<td>0.1</td>
<td>0.015</td>
<td>1</td>
</tr>
<tr>
<td>Energy (GeV)</td>
<td>5.3</td>
<td>5.3</td>
<td>5.3</td>
</tr>
<tr>
<td>Rep. rate (GHz)</td>
<td>1.3</td>
<td>1.3</td>
<td>0.001</td>
</tr>
<tr>
<td>Av. flux ($\frac{\text{ph}}{0.1% \text{s}}$)</td>
<td>$9 \times 10^{15}$</td>
<td>$9 \times 10^{14}$</td>
<td>$9 \times 10^{12}$</td>
</tr>
<tr>
<td>Av. brilliance ($\frac{\text{ph}}{0.1% \text{s} \text{mm}^2 \text{mrad}^2}$)</td>
<td>$1.6 \times 10^{22}$</td>
<td>$3.0 \times 10^{22}$</td>
<td>$2.0 \times 10^{17}$</td>
</tr>
<tr>
<td>Bunch length (ps)</td>
<td>2</td>
<td>2</td>
<td>0.1</td>
</tr>
</tbody>
</table>
The ERL parameters are **dramatically** better than present 3\textsuperscript{rd} generation storage rings

The use of ERL microbeams, coherence, and ultra-fast timing will lead to new unique experiments that can be expected to transform the way future x-ray science experiments are conducted

Most critical parameters to achieve in an ERL are therefore, narrow beams, small emittances, short bunches, at large currents.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>APS ring</th>
<th>ERL*</th>
<th>Gain factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rms source size((\mu\text{m}))</td>
<td>239(h) x 15(v)</td>
<td>2(h) x 2(v)</td>
<td>1/900 in area</td>
</tr>
<tr>
<td>x-ray beamsize</td>
<td>100nm - 1(\mu\text{m})</td>
<td>1 nm</td>
<td>100 to 1000</td>
</tr>
<tr>
<td>Coherent flux</td>
<td>3 x 10\textsuperscript{11}</td>
<td>9 x 10\textsuperscript{14}</td>
<td>3,000</td>
</tr>
<tr>
<td>x-rays/s/0.1% bw</td>
<td>32 ps</td>
<td>0.1 ps</td>
<td>over 300</td>
</tr>
</tbody>
</table>
Flux and Brilliance

Average Flux (photons/sec/0.1%)

- ERL Hi-Flux: 25m 200mA
- ERL Hi-Coh: 25m 25mA
- ESRF 5m 200mA
- Sp8 25m 100mA
- CHESS 49p 300mA
- APS 2.4m 100mA
- LCLS SASE 0.07mA

Average Brilliance (ph/s/0.1%/bw/mm²/m²)

- ERL hi-coh: 25m 8pm 25mA
- LCLS 15pm 10mA
- ESRF 5m
- Sp8 25m
- APS 2.4m
- LCLS spont.
- CHESS 49p wiggler
- CHESS 24p wiggler

Photon Energy (keV)
Accelerator Physics @ CESR
Advantages of ERL@CESR

1. Operation of CESR and ERL test simultaneously.
2. Use all of the CESR tunnel.
3. Lots of space for undulators.
4. Space for future upgrades, like an FEL.
5. No basements of existing buildings to worry about.
6. Only one tunnel for two linacs.
7. Less competition, since other sights cannot offer upgrades.
8. Example character for other existing light sources.
Limits to an ERL

Limits to Energy:

Length of Linac and power for its cooling to 2K (supercond. RF)

Limits to Current:

Beam Break Up (BBU) instability (collective effects)
HOM heating (supercond. RF)

For small emittances in all 3 dimensions:

Coulomb expulsion of bunched particles (Space Charge, e-Source)
Radiation back reaction on a bunch (ISR and CSR)
Nonlinear beam dynamics
Ion accumulation in the beam potential
Stability against ground vibration (μm level)
Superconducting RF infrastructure

- RF measurement lab
- Shielded test pits, cryogenics
- Clean room
- Chemical handling
- Precision coordinate measurement
- Scanning electron microscope, Auger analysis
- Advanced \( \mu \)-Kelvin thermometry
Ongoing ERL prototyping

- Dump with quadrupole optic
- Main linac
- Buncher
- Injector
- Gun

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1) DC electron source
   - Gun development
   - HV power supply
   - Photocathode development
   - ERL injector lab
   - Laser system development

2) Superconducting RF
   - RF control
     (tests at CESR/JLAB)
   - HOM absorbers
   - Injector klystron
   - Input coupler (with MEPI)
   - Injector cavity / Cryomodule

3) Beam dynamics
   - Injector optimization with space charge
   - Beam break up instability (BBU)
   - Optics design / ion clearing

4) Accelerator design
   - Optics
   - Beam dynamics
   - Beam stability

5) X-ray beamline design
   - X-ray optics
   - Undulator design
Injector cryomodule Plans and Timeline

- **2005**: Order, review, design
- **2006**: Delivery, subsystems check, assembly
- **2007**: Cryomodule cooldown, refrigerator availability
- **2008**: Tuner availability, controls availability, full injector, test

Injector cryomodule
High loaded Q cavity control

- Run cavity at highest possible loaded Q for Energy recovery linac mode, i.e. without beam loading

- But: The higher the loaded Q, the smaller the cavity bandwidth!

Without feedback:

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Beam breakup instability (BBU) in one dimension (originally a major concern for current limit)

320 identical cavities → Current limited to 25mA

Randomized frequencies with rms of 10MHz → Current limited to 500mA

Polarized Cavities and x to y coupling → Current limited to 2000mA >> required 100mA

Now the current limited by a technical choice:
Cooling capacity of the HOM Dampers
HOM with BBU: Starting from Noise

V/c Stable: current below threshold

V/c Unstable: current above threshold

Cavity # in Linac

Cavity # in Linac
Isolation of modes

\[ \log(I_{th}[A]) \]

One cavity, tow higher order modes.
Randomization of frequencies

Average threshold current vs. Frequency spread

25mA to 500mA

x/y frequency separation

Frequency difference vs. Threshold current

500mA to 2000mA

Model of ERL@CESR

320 polarized cavities with fₓ-fᵧ=60MHz
spread=10MHz

1200-2800mA
Ion accumulation in the beam potential

Ion are quickly produced due to high beam density

<table>
<thead>
<tr>
<th>Ion</th>
<th>$\sigma_{col, \ 10\text{MeV}}$</th>
<th>$\sigma_{col, \ 5\text{GeV}}$</th>
<th>$\tau_{col, \ 5\text{GeV}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H_2$</td>
<td>$2.0 \cdot 10^{-23}\text{m}^2$</td>
<td>$3.1 \cdot 10^{-23}\text{m}^2$</td>
<td>$5.6\text{s}$</td>
</tr>
<tr>
<td>$CO$</td>
<td>$1.0 \cdot 10^{-22}\text{m}^2$</td>
<td>$1.9 \cdot 10^{-22}\text{m}^2$</td>
<td>$92.7\text{s}$</td>
</tr>
<tr>
<td>$CH_4$</td>
<td>$1.2 \cdot 10^{-22}\text{m}^2$</td>
<td>$2.0 \cdot 10^{-22}\text{m}^2$</td>
<td>$85.2\text{s}$</td>
</tr>
</tbody>
</table>

- Ion accumulate in the beam potential. Since the beam is very narrow, ions produce an extremely steep potential – they have to be eliminated.
- Conventional ion clearing techniques can most likely not be used:
  1) Long clearing gaps have transient RF effects in the ERL.
  2) Short clearing gaps have transient effects in injector and gun.
- DC fields of about $150\text{kV/m}$ have to be applied to appropriate places of the along the accelerator, without disturbing the electron beam.
CSR for 100fs bunch without spike

Horizontal emittance with coherent synchrotron radiation

\[ \varepsilon_x = 1.8 \cdot \varepsilon_x(0) \]

Result: After suitable nonlinear bunch length manipulation, the emittance growth can be controlled in all undulators.
Emittance growth along the X-ray ERL

Normalized, in mmmrad
due to incoherent synchrotron radiation
For 2ps bunches, CSR is close
to 10 times smaller than ISR.

A mini-workshop on ultra low emittance light-sources in July addressed this issue.

Other analyzed sources of emittance growth:
- Coupler kick: 7% of $10^{-6}$m emittance
- 30% of $10^{-7}$m emittance
Aspects of x-ray ERL that are of general relevance for future accelerators

- Bright electron beams, gun developments for ILC and beyond.
- Component and technology development
- Space charge dominated beams
- Coherent Synchrotron Radiation
- Bunch compression

First quantitative CSR/bunch length measurements (A.Sievers et al. at Cornell)
- Ongoing measurement developments
R&D toward an X-ray ERL

- Full average current injector with the specified emittance and bunch length
- Emittance preservation during acceleration and beam transport:
  - Nonlinear optics (code validation at CEBAF), coherent synchrotron radiation (JLAB, TTF), space charge
- Delivery of short duration (ca. 100 fs, and less in simulations), high charge bunches (TTF)
- Dependence of emittance on bunch charge
- Stable RF control of injector cryomodule at high beam power
- Stable RF control of main linac cavities at high external Q, high current, and no net beam loading (JLAB to 10mA)
- Understanding of how high the main linac external Q can be pushed (JLAB)
- Study of microphonic control using piezo tuners (JLAB, SNS, NSCL, TTF)
- Recirculating beam stability as a function of beam current with real HOMs, and benchmarking the Cornell BBU code (JLAB)
- Feedback stabilization of beam orbit at the level necessary to utilize a high brightness ERL
- Photocathode operational lifetime supporting effective ERL operation
- Performance of high power RF couplers for injector cryomodule
- Demonstration of non-intercepting beam size and bunch length diagnostics with high average current at injector energy and at high energy (TTF)
- HOM extraction and damping per design in injector and main linac (code validation from Prototype)
- Performance of HOM load materials to very high frequency
- Performance of full power beam dump
- Detailed comparison of modeled and measured injector performance
- Study of halo generation and control in a high average current accelerator at low energy and with energy recovery (JLAB)
- Study of beam losses and their reduction in recirculation of high average current with energy recovery (JLAB, NAA)
- Precision path length measurement and stabilization (Prototype, JLAB)
1. Emittance preservation during acceleration and beam transport
2. Recirculating beam stability (JLAB)
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ERL injector needs

- An ultimate ERL X-ray source \(\rightarrow\) diffraction limited emittance, high average current similar to that of storage rings

- 5 GeV machine producing hard X-rays \(\rightarrow\) 0.1 mm-mrad normalized rms emittance from the source at moderate charge per bunch (e.g. 80 pC)

- ERL becomes compelling (spectral brightness) if 0.1 mm-mrad can be achieved from the source starting from \(\sim\) 8 pC / bunch (10 mA average current); ultimately one would like to have such emittance at \(\times10\) current

- We have 3 more years to demonstrate a source capable of up to 100 mA average current with 0.1-1 mm-mrad transverse emittance
Max current         100 mA
Energy range        5 – 15 MeV
Installed RF power  0.5 MW + 75 kW HV PS
Emittance goal      0.1 – 1 mm-mrad
Typical bunch length 2-3 ps rms (shortest 0.2 ps)
Photocathode gun technology choice

**DC gun**

- Designed for 750 kV max voltage
- Excellent vacuum is essential for good lifetime of NEA cathodes
- 400 C air-bake to reduce (H) outgassing
- Load-lock system for cathode transport
- 20,000 l/s NEG pumping capacity + 400 l/s ion pump combination should bring the vacuum down to lower $10^{-12}$ Torr range
- The gun is already built
**DC/SFR/NCRF: emit. compensation works**

- **NCRF**
  - $E_{\text{cath}} = 120 \text{ MV/m}$
  - $\tau_{\text{laser}} = 2.7 \text{ ps rms}$
  - $\sigma_{\text{laser}} = 0.5 \text{ mm rms}$
  - $\tau_{\text{laser}} \rightarrow z = 0.08 \text{ mm}$
  - $2 \times 18 \text{ MV/m}$

- **SRF**
  - $E_{\text{cath}} = 43 \text{ MV/m}$
  - $\tau_{\text{laser}} = 5.8 \text{ ps rms}$
  - $\sigma_{\text{laser}} = 0.85 \text{ mm rms}$
  - $\tau_{\text{laser}} \rightarrow z = 0.12 \text{ mm}$
  - $2 \times 6 \text{ MV/m}$

- **DC**
  - $E_{\text{cath}} = 8 \text{ MV/m}$
  - $\tau_{\text{laser}} = 13 \text{ ps rms}$
  - $\sigma_{\text{laser}} = 2 \text{ mm rms}$
  - $\tau_{\text{laser}} \rightarrow z = 0.12 \text{ mm}$
  - $2 \times 1 \text{ MV/m}$

- $E_{\text{cath}} / E_{\text{s.charge}} = E_{\text{cath}} / E_{\text{s.charge}} = E_{\text{cath}} / E_{\text{s.charge}}$

- *same simulated emittance*
Low thermal emittance photocathode

(1) photon excites electron to a higher-energy state;
(2) electron-phonon scattering (~0.05 eV lost per collision);
(3) escape with kinetic energy in excess to $E_{\text{vac}}$

In GaAs the escape depth is sufficiently long so that photo-excited electrons are thermalized to the bottom of the conduction band before they escape – low thermal emittance allows larger illuminated laser spot (reduces space charge forces)

Response time $\sim (10^{-4} \text{ cm})/(10^7 \text{ cm/s}) = 10$ ps (wavelength dependant)
Simulated performance for the injector

Final emittance is dominated by the photocathode

\[ \varepsilon_n [\text{mm-mrad}] \approx (0.73 + 0.15/\sigma_z [\text{mm}]^{2.3}) \times q [\text{nC}] \]

good approx. in 0.1-1 nC / bunch range
Laser requirements

Optional depression in the middle

Steep fronts

Time shaping
Transverse shaping

> 20 W average
“green” power

\( f_R = 1.3 \text{ GHz} \)

\( E_{\text{pulse}} \approx 15 \text{ nJ} \)

Gun entrance window

“Flat-top”

Pulse width: 10 ps – 40 ps

+/− 1% rms energy

< 0.2 ps time jitter

Seed

Amplifier

Rep-rate control

SHG

Time and space shaping

\( \lambda = 1060 \text{ nm} \)

~ 100 mW

Linear polarization

\( ~ 100 \text{ W} \)
Laser work

• close collaboration with the Department of Applied Physics at Cornell University

• (Mostly) all fiber solution

• Seed R&D harmonically mode-locked fiber laser – passive HML seed operational at 1.3 GHz, work underway on actively harmonically mode-locked Yb-doped fiber version

• Longitudinal shaping: two options are being evaluated experimentally – self-phase modulation + dispersion in fiber and “stacking” of pulses with birefringent plates

• First pulse laser system meeting single pulse requirements (downsized rep. rate) will be ready in 2-3 months
Stages of commissioning of the injector

- photogun lab setup for initial beam test

- Initial power supply from the vendor for 300 kV
- 100 mA DC beam tests: a) cathode (GaAs, GaAsP, K₂CsSb) lifetime / ion backbombardment; b) thermal emittance characterization vs. wavelength
Planned sequence of activities

*Photogun lab*

- Pulsed laser ready in 3 month → measurements on space charge dominated beam (gun + solenoid)
- TM110 cavity & ps laser / RF synchronization → temporal response of photoemission for different cathodes

Trade-off between low thermal emittance / photoemission response time is not obvious, literature data for GaAs are not precise enough
Planned sequence of activities

Photogun lab

• 750 kV power supply to arrive late this year; repeat measurements with s.c. dominated bunches
• Gun transported to its final location by 2008

L0 area

• Piece-wise installation of components & beam characterization: gun, straight ahead dump section, solenoids, buncher, cryomodule, merger
Space charge dominated beam all the way

\[ R = \frac{I}{I_0 \beta \gamma} \frac{\sigma_x^3}{(\sigma_x + \sigma_y) \varepsilon_{n,x}^2} \]

space charge dominated if \( R >> 1 \)

Beam in optimized injector is space charge dominated even at > 10 MeV; interceptive diagnostics essential
Diagnostics being developed

- slit & TM110 for slice emittance measurements
- flying wire
- CSR spectrum measurements for bunch profile autocorrelation

*Under consideration:*
- small period high harmonic PPM undulator; μs RF kicker line; …
Summary

• Cornell has a long an **successful history** of accelerator physics, has the **facilities** and scientific **groups** to build a large scale accelerator based on SRF technology.

• The planned x-ray **ERL is an extension** to the existing CESR ring

• Significant ERL R&D is done with a **prototyping facility**, other issues have to be studied in **collaboration with other facilities**.

• **Numerous activities** are underway both short range (injector) and long range (x-ray source ERL)

• Wrap up for the injector phase is in **2008**, proposal for the full scale machine is planned for **2007**

• Sufficient overlap exists with BNL activities – e.g. source development, low energy high brightness beam diagnostics, ID design, simulation tools, etc. – **plenty of room for collaboration**