Energy Recovery Linac Development at Brookhaven National Laboratory

Presented at
Workshop to Explore Physics Opportunities with Intense, Polarized Electron Beams up to 300 MeV
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RHIC:
Discovery of a “perfect” liquid of strongly interacting quarks and gluons.
Deep mystery:
“missing” proton spin
What is an Energy Recovery Linac?

1. In a linear accelerator (or LINAC), beam is injected into a series of radio frequency (RF) cavities which accelerate the beam using the cavities’ electric field. The accelerated beam is used and dumped at full energy.

2. In a superconducting RF (SRF) linac, the cavities are superconducting, enabling CW operation at a good accelerating voltage.

3. In a multi-pass linac, the accelerated beam may be returned to the linac in phase, for further acceleration. This process may be repeated a few times, leading to cost savings (CEBAF is a good example).

4. In an Energy Recovery Linac (ERL), the high-energy beam, following its use, is returned to the linac in opposite RF phase to be decelerated back to about the injection energy. The beam is dumped at a low energy.

5. An analogy to this process is a hybrid car, which uses stored energy in a battery for acceleration, and returns some of this energy while braking.
What are the advantages of an ERL?

- **Relative to a linac:**
  - Higher beam current possible (RF power limit removed)
  - Reduced power bill (RF power recovered)
  - Reduced cost of RF amplifiers (smaller RF power amplifiers)
  - Reduced beam power and energy in beam dump (less shielding / activation issues)

- **Relative to a storage ring:**
  - Better beam quality (emittance, polarization – maintain non-equilibrium state due to short dwell time)
  - Easier to upgrade (add linac section or recirculation passes)
  - Tolerate more “damage” to the beam from collisions with a beam or a target (the beam is dumped soon after)
eRHIC: polarized electron ERL colliding with RHIC beams

eRHIC: 5–30 GeV electron beam accelerated with Energy Recovery Linac (ERL) inside existing RHIC tunnel collides with existing 250 GeV pol. protons and 100 GeV HI RHIC beams

CeC accelerator:
- A low frequency SRF gun,
- buncher and a 136 MeV ERL.

CeC accelerator:
- Polarized gun,
- 10 MeV injector linac
- and 600-MeV single-pass ERL.

Main ERL:
- Two 2.45 GeV SRF linacs in combination with six passes.

Single pass allows for large collision disruption of electron bunch and high luminosity (L ~ \(10^{34}\) cm\(^{-2}\)s\(^{-1}\)) and full electron polarization transparency.

Not shown: Energy loss and energy spread compensation linacs, crab cavities for electrons and ions.

Coherent e-cooler

LINAC

eRHIC is designed to probe structures with extreme precision, at the scale of 10⁻¹⁵ meters, both protons and heavy ions to reveal their inner secrets.
Accelerator R&D at the Collider-Accelerator Department

- eRHIC machine design
  - Lattice design
  - Wake fields and losses
  - Kink instability
  - IP design
  - Crab crossing
  - Small gap magnets
- Multi-pass high average current ERL
  - ERL highly-damped accelerating cavities
  - SRF photocathode gun
  - R&D ERL for 300 mA average current
- High current (50 mA) polarized electron gun
- Coherent electron cooling of hadron beam
- Misc. items: ERL BBU, photocathode R&D

Innovative approach: Use an Energy Recovery Linac for the electron machine

Double QWR crab cavity

Funneling for the gun,

Diamond Amplified Photocathode, chromaticity suppression of BBU
Total HOM power to extract is 7.3 kW per cavity at eRHIC 3.5 nC, 50 mA, 6 passes up + 6 passes down energy (loss factor 3.5 V/pC).
The copper cavity prototype

Cavity was fabricated by AES.
Tuned to specs (98.5% field flatness).
Acceptance measurements are finished.
Detailed HOM studies done.
A two-stage high-pass filter rejects fundamental frequency, but allows propagation of HOMs toward an RF load.

- 1\textsuperscript{st} HOM is at 0.82 GHz.
ERL layout.
Straight section is 7m long
R&D ERL, target: 300 mA at 20 MeV

- Test the key components of the High Current SRF ERL
- Test the beam current stability criteria for CW beam currents
  - measure beam quality
  - measure halo
  - measure spurious radiations
SRF Photocathode RF gun

Cut-away view of the 704 MHz elliptical half-cell SRF gun. Photocathode injection is on the left, beam transport is on the right.

High-Current ERL R&D
Many components installed

SRF Photocathode RF gun

The 704 half-cell elliptical shape SRF gun has two Fundamental input Power Couplers (FPCs) allowing to deliver 1 MW of RF power to 0.5 A - 2 MeV electron beam.

- HOM damping is provided by an external beam-line ferrite load with ceramic break.
Fundamental Power Coupler

2X 500 kW RF couplers built for 703 MHz injector
- Conditioning couplers at BNL using 1 MW klystron done
RF components

1 MW CW klystron
92kV at 17A
380 gpm of water
Power supply for a 1 MW klystron
(as needed for 10 MeV at 100 mA)
ERL layout

- SC RF Gun
- SC 5 Cell cavity
- Beam dump
Emittance - at the end of the linac

Emittances as a function of path length from the cathode to the end of the linac.
### PARMELA simulation results in two operating regimes

<table>
<thead>
<tr>
<th>Parameter</th>
<th>High Current</th>
<th>High charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charge per bunch, nC</td>
<td>0.5</td>
<td>5</td>
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<tr>
<td>Numbers of passes</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Energy maximum/injection, MeV</td>
<td>20/2.5</td>
<td>20/3.0</td>
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<tr>
<td>Bunch rep-rate, MHz</td>
<td>700</td>
<td>9.383</td>
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<tr>
<td>Average current, mA</td>
<td>350</td>
<td>50</td>
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<tr>
<td>Injected/ejected beam power, MW</td>
<td>1.0</td>
<td>0.15</td>
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<tr>
<td>R.m.s. Normalized emittances ex/ey, mm*mrad</td>
<td>1.4/1.4</td>
<td>4.8/5.3</td>
</tr>
<tr>
<td>R.m.s. Energy spread, $\delta E/E$</td>
<td>$3.5 \times 10^{-3}$</td>
<td>$1 \times 10^{-2}$</td>
</tr>
<tr>
<td>R.m.s. Bunch length, ps</td>
<td>18</td>
<td>31</td>
</tr>
</tbody>
</table>
High QE Photocathode for RF gun

Deposition System

- Base pressure $1 \times 10^{-10}$ Torr
- System designed to eliminate cross contamination of sources
- Robust CsK2Sb photocathode, high QE (8%) and low thermal emittance (0.37 microns / mm-rms) at a wavelength of 543 nm.

BNL cathode tested at Jlab
Up to 20 mA measured
Photocathode laser

- Lumera 5 W, 355 nm, 10 ps, 9.38 MHz laser system
- Will be operated at 532nm, 355nm, and 266nm
- Climate controlled, 1°C/hour, Humidity +/- 2%/hour HEPA Filters
20 cathode funneling polarized electron gun “Gatling Gun”

A current of a few mA has been demonstrated by the Jefferson Laboratory group with good charge lifetimes. While this performance is expected to improve with additional research, can we multiply the number of cathodes to get a large increase in the charge-lifetime?

The “Gatling Gun” R&D program is set to examine this question in a 20-cathode funneling system. The key question is the “cross-talk” due to the common vacuum system in an otherwise independent cathodes.
20 cathode funneling polarized electron gun ("Gatling Gun")

- 2 to 20 Photo-cathodes arranged in a ring
- Fixed bend magnets
- 30° bend
- 16 cm bend radius
- Bunching cavity (112 MHz)
- 3rd harmonic cavity
- Ballistic compression
- Booster linac

Images of the Gatling gun and its components.
**Beam Combiner**

- Bending the beam by dipole
- Equalize the focusing by quadrupole

**Parameters:**

- $I(t) = I_{od} \cdot \cos(\omega t + \phi)$ where $I_{od} = 70.7\, \text{A}$
- $I(t) = I_{oq} \cdot \cos(2\omega t + \phi)$ where $I_{oq} = 1.54\, \text{A}$
- $B(0,0,0) = 25.04\, \text{G}$
- $\text{Freq} = 704\, \text{kHz}$
- $\text{Bending angle} = 29\, \text{degrees}$
Particle tracking with space charge.

On diagnostic:
- Divergence angle: $X'/Y'=23.6\text{mrad}/25.1\text{mrad}$
- Beam profile: $X/Y=15.0\text{mm}/15.2\text{mm}$
- $\varepsilon_{n,x}/\varepsilon_{n,y}=20.5\text{mm-mrad}/20.1\text{mm-mrad}$
Beam motion by 3-D Particle In Cell code
XHV vessels $10^{-12}$ Torr scale vacuum achieved

Left: Cathode preparation chamber; Right: Main gun vessel
20 cathode XHV stainless steel shroud assembly
Setup for single cathode tests

- TC and Heater
- Anode
- RGA
- Ion pump
- Right angle valve
- Bellows
- NEG pump 1
- Window
- NEG pump 2
- O₂ Leak valve
- Ion Pump
- Cs source
- Gauge
- Laserport

View from:
- left, back
- right, front
Summary

- R&D is currently carried out on the eRHIC collider design, including various elements of the ERL, some of which are:
  - The 50 mA polarized electron gun
  - A 300 mA 20 MeV R&D ERL
  - Highly-damped 704 MHz 5-cell ERL cavities
- This research is highly relevant to a high-current, high-polarization and high-brightness medium energy ERL.
Backup slides
Damping of dipole modes has been considered important to avoid beam breakup (BBU).

- We simulated a model with just two HOM couplers per side using CST MWS, showing excellent damping.
- Modes at 1.62 GHz have R/Q of ~0.1 Ohm.
- Recent work by Vladimir Litvinenko points to a method of avoiding BBU by using the chromaticity in the ERL. See presentation MOPB034 in this conference.
Magnets and stands
SRF test facilities in building 912

- Mezzanine clean room
- Large Vertical Test Facility
- ERL
- Small VTF
- ERL / VTF cryogenic system
- 800°C vacuum oven for cavity baking
SRF test facilities in building 912 (cont’d)

- VTF dewar top plate
- Vertical Test Facility
- VTF Dewar
- ERL / VTF cryogenic system
Deposition with *In Situ* Analysis

UHV system w/ Load Lock
Sb Line Source (evaporation)
Sb Sputtering
K and Cs Alvasources
SAES Getter Sources
Heat Cathode to 800C
Gas cooling
QE Measurement with 532 nm
Residual Gas Analyzer, Quartz FTM

In-Situ Diagnostics (during growth):
XRD for grain size and orientation in plane and reflection geometry
X-ray fluorescence for stoichiometry and contamination
Reflection high energy electron diffraction
Some CsK2Sb photocathode results

Robust CsK2Sb photocathode, high QE and low thermal emittance of 0.37 microns / mm-rms at a wavelength of 543 nm.

On-line thermal emittance measurement

Test of lifetime under various vacuum conditions

• Routine diamond amplifiers with high gain into vacuum
• Large current density generated
• Samples are extremely robust
• Detailed simulations by Tech-X
• Preparation for tests in SRF gun under way
• PRL, PRST-AB, JAP publications

5 nC/cm²
Xiangyun Chang, et al,
Electron Beam Emission from a Diamond-Amplifier Cathode
PRL 105, 164801 (2010)
Load-lock transport for diamond amplifiers and CsK2Sb
Various results from diamond amplifier R&D

Systematic study of hydrogenation in a diamond amplifier
Erdong Wang, et al
Phys. Rev. ST Accel. Beams
14, 061302 (2011)

D. A. Dimitrov, et al,
Multiscale three-dimensional simulations of charge gain and transport in diamond,
JOURNAL OF APPLIED PHYSICS
108, 073712 (2010)
Angle Resolved Photoemission Spectroscopy (ARPES)

Beamline U13 at the National Synchrotron Light Source
hemispherical electron spectrometer
(<10 meV resolution)
Capability to heat diamond to 400°C, cool to 77K