R&D Efforts for ERLs

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A Possible Apparatus for Electron Clashing-Beam Experiments (*).

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(ricevuto il 2 Febbraio 1965)
What are ERLs good for?

Storage Ring

- High repetition rates (1000 MHz)
- High current (100+ mA)
- Many user stations
- Fixed energy spread (10^{-3} relative)
- Bunch durations (20 ps)
- Emittance determined by the ring

Linac

- Low repetition rates (120 Hz, 1 MHz)
- Low average current (10^{-4} mA) (but very high peak current)
- Few user stations
- Excellent energy spread (10^{-4} relative)
- Drive XFEL-Os
- Short bunch durations (0.1 – 2 ps)
- Emittance determined by the source

Flexible optics
Flexible bunch structure
Worldwide efforts on ERLs

- Facilities existing or planned
  - Jlab FEL/ ERL
  - ERL @ Budker
  - Alice @ Daresbury
  - IHEP ERL test facility
  - ERL facility @ BNL
  - cERL @ KEK
  - bERLinPro
  - Mesa @ U of Mainz
  - LHeC ERL
  - Cornell ERL R&D program
E = 135 MeV
135 pC pulses @ 75 MHz

20 μJ/pulse in 250–700 nm UV-VIS
120 μJ/pulse in 1-10 μm IR
1 μJ/pulse in THz

The first high current ERL, 14 kW average power in IR

Ultra-fast (150 fs)
Ultra-bright
\(10^{23} \text{ ph/sec/mm}^2/\text{mrad}^2/0.1\%\text{BW}\)
UV harmonics exceed FLASH average brightness (\(10^{21}\) average, \(10^{27}\) peak ph/sec/mm²/mrad²/0.1%BW)

Courtesy of: George Neil
Goal
Simulate high-power ERL operation with an internal gas target controlling power deposition from beam loss and impedance/wake effects from both beam core and halo components through a 12.5 cm long small aperture (6, 4, or 2 mm diameter)

Area: 1 mm x 1 mm;
Best Gaussian: fit \( \sigma_x = 50 \, \mu m; \sigma_y = 52 \, \mu m \)

Designed and constructed by MIT-Bates R&E Center in collaboration with JLab FEL staff

Courtesy of: George Neil
**Linac** | **Normal conducting, independent cavities, CW**
---|---
Number of cavities | 16
Phase advance, rad | $\pi$
Frequency, MHz | 180.4
RF quality | 40000
Total RF power, MW | 1
Maximum energy gain, MeV | 12

**Courtesy of: Nikolay Vinokurov**
International ERL
Cryomodule on ALICE

• Collaboration formulated in early 2005
• Objective to design and fabricate new CW cryomodule and validate it with beam
• Dimensioned to fit on the ALICE ERL facility at Daresbury:
  – Same cryomodule footprint
  – Same cryo/RF interconnects
  – ‘Plug Compatible’ with existing cryomodule

Parameter | Target
--- | ---
Frequency (GHz) | 1.3
No. of cavities | 2
No. of Cells per Cavity | 7
$E_{acc}$ (MV/m) | $>20$
$Q_0$ | $>10^{10}$
$Q_{ext}$ | $4 \times 10^6 - 10^8$

Courtesy of: Alan Wheelhouse
Cryomodule Evaluation

- Initial conditioning performed:
  - Gradients reached:
    - LC1 – 10.8MV/m
    - LC2 – 12.5MV/m
- No FE radiation observed
- Microphonic issues discovered

Future Plans:
- Microphonics investigation
- Establish full gradient and $Q_0$
- Measure Lorentz force detuning at high gradient
- Performance measurements with piezo tuners
- Determine DLLRF control limitations wrt $Q_{ext}$
- Evaluate the effect of beam loading with DLLRF
- Characterise cavities in CW mode at high gradient

Courtesy of: Alan Wheelhouse
An ampere class 20 MeV superconducting ERL (R&D ERL) is under commissioning at BNL. This facility enables testing of concepts relevant for high-energy coherent electron cooling, electron-ion colliders, and high repetition rate Free Electron Lasers. The machine consists of an SRF photoemission injector, an SRF accelerating cryomodule, a recirculating loop, and a beam dump.
For the first beam test, a Cs3Sb cathode was fabricated and QE has been measured at 0.25% in the deposition chamber. During the cathode insertion into the gun and initial start of RF power, there were several instances of vacuum spiking to 1e-8 Torr range. These significantly reduced QE of the cathode to the level, where it became impossible to measure the photoemission current.

However, a dark current was observed on a YAG screen and measured by the Faraday cup (1.4 uA at a cathode field of 15 MV/m). Gun has been running with 40 msec pulses with 1 second interval during the dark current measurements. Measurements of the dark current energy agree with RF gun voltage calibration.

The low power beam testing will continue in September after some improvements are mad to the cathode deposition chamber and transport cart.

The ERL 1 MW beam dump is installed. Extraction line magnets vacuum components are installed as well. We plan to start the gun to beam dump test later this fall.

After the recirculation loop is complete, we will be able to demonstrate energy recovery with high charge per bunch and high beam current. These experiments are planned for 2015.

Dark current image taken at beam profile monitor during energy measurement at gun voltage settings 1.2 MV. Corrector current top 0.5 A, bottom 1 A. 7mm shift due to 0.5 A corrector change corresponds to beam energy of 1.2 MeV
### Design Parameters of cERL

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum beam energy</td>
<td>35 MeV (upgradable to 125 MeV)</td>
</tr>
<tr>
<td>Injector energy</td>
<td>5 MeV (10 MeV in future)</td>
</tr>
<tr>
<td>Beam current (initial goal)</td>
<td>10 mA</td>
</tr>
<tr>
<td>Beam current (long-term goal)</td>
<td>100 mA</td>
</tr>
<tr>
<td>Normalized emittance @ bunch charge</td>
<td>0.3 mm·mrad @7.7 pC</td>
</tr>
<tr>
<td></td>
<td>1 mm·mrad @ 77 pC</td>
</tr>
<tr>
<td>Bunch length (rms)</td>
<td>1 - 3 ps</td>
</tr>
<tr>
<td></td>
<td>~100 fs with BC*</td>
</tr>
<tr>
<td>Accelerating gradient (main linac)</td>
<td>15 MV/m</td>
</tr>
<tr>
<td>RF frequency</td>
<td>1.3 GHz</td>
</tr>
</tbody>
</table>

*BC : bunch compression

### Purpose of the Compact ERL

- To demonstrate the generation and recirculation of ultra-low emittance beams
- To demonstrate reliable operations of our ERL components (photocathode gun, SC cavities, ...)
- Initial goal: 1 mm·mrad @7.7 pC/bunch (10 mA)

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**Courtesy of: Norio Nakamura**
Beam was successfully transported to the beam dump in Feb. 6, 2014.

**Beam parameters**
- Peak current: $\sim 24 \mu A$
- Macropulse width: $1.2 \mu s$
- Repetition of bunches: 1.3 GHz
- Repetition frequency: 5 Hz
- Average beam current: $\sim 140 \text{ pA}$

**Beam energy**
- Injector: 2.9 MeV
- Recirculation loop: 19.9 MeV

**Acceleration parameters**
- Gun voltage: 390 kV
- Buncher: OFF
- Injector cavities: $E_{\text{acc}} = (3.3, 3.3, 3.1) \text{ MV/m}$
- Main-Linac cavities: $V_c = (8.57, 8.57) \text{ MV}$

**Courtesy of:** Norio Nakamura
bERLinPro = Berlin Energy Recovery Linac Project (project phase 2011-2019, fully funded)
100 mA / low emittance technology demonstrator (covering key aspects of large scale ERL)

beam dump
6.5 MeV, 100 mA = 650 kW

modified Cornell booster
3 x 2 cell srf cavities, 4.5 MeV

srf-gun
1.5-2 MeV, single solenoid, no buncher cavity

linac module
3 x 7 cell srf cavities, 44 MeV

test and diagnostic line
(5mA@10MeV dump, energy & slice diag.)

recirculation arc

max. beam energy 50 MeV
max. current 100 mA (77 pC/bunch)
normalized emittance 1 \( \mu \text{m} \) (0.5 \( \mu \text{m} \))
bunch length (straight) 2 ps or smaller (100 fs)
rep. rate 1.3 GHz
losses < 10\(^{-5}\)

• cw srf technology for high current injectors and linacs
• explore parameter space of ERLs
• first operation of srf gun 2011
• building ready 2016
• first electrons 2017
• first recirculation + recovery 2019

Courtesy of: Andreas Jankowiak
MESA – Parameters:
CW electron beam
External: 155 MeV, 150 µA (polarized)
ERL: 105 MeV, 1 mA (stage-2: 10 mA)

Courtesy of: Robert Heine
LR LHeC: Straight or Recirculating Linac; RCL with Energy Recovery Operation

Courtesy of: Oliver Bruening
Science case gathered in international workshops

- Design report
  - 530 pages between conceptual design and engineering design
  - Access at www.classe.cornell.edu/ERL/PDDR
Cornell ERL Parameter

- 5 GeV, 100 mA CW beam
  - 8 pm emittance, 2 ps bunch length
- Stable operation
  - Strong HOMs can cause beam breakup
  - ~200 W HOM power in beamline loads/cavity
- CW operation
  - \( Q(1.8 \text{ K}) = 2 \times 10^{10} @ 16.2 \text{ MV/m} \)
    - 10 W cryogenic loss from fundamental/cavity
    - ~4 MW wall power
• 5 GeV, **100 mA** CW beam
  – 8 pm emittance, 2 ps bunch length

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• CW operation
  – \( Q(1.8 \, \text{K}) = 2 \times 10^{10} @ 16.2 \, \text{MV/m} \)
    • 10 W cryogenic loss from fundamental/cavity
    • ~4 MW wall power
Goal: Maximize $I_{th} > 100$ mA (under constraints)

**Center cells**
- Geometries are (nominally) identical
- Responsible for general properties of HOM spectrum
  - Controls frequencies of HOM passbands and dispersion relations
  - Determines cell-to-cell coupling and how sensitive HOM spectrum is to variation in cell shape

**End cells**
- Asymmetric design helps prevent trapped modes
- Responsible for coupling HOMs to HOM absorber
  - Directly controls quality factors of HOMs

**Beam Pipe**
- Should be short to improve linac fill factor but long enough to avoid dissipating too much power from the fundamental mode

**HOM load**
- Absorber material properties determine specific mode losses.
- Also serves as bellows connecting cavities
Horizontal Test Cryostat: (@16MV/m, 1.8K):

Q0 = 3.5E10 without coupler
Q0 = 2.0E10 with couplers
Q0 = 6.0E10 with coupler and HOM absorbers
Beamline HOM absorbers strongly damp dipole HOMs to under $Q \sim 10^4$. 

HTC-2: No HOM Absorbers
HTC-3: With HOM Absorbers
• No charge-up of the HOM ceramics observed
• HOM heating was less than expected

<table>
<thead>
<tr>
<th>Current, bunch length</th>
<th>ΔT (beam pipe behind Abs.) coated/uncoated</th>
<th>ΔT (80K gas temp) coated/uncoated</th>
<th>ΔT (80K absorber temp) coated/uncoated</th>
<th>ΔT (5K flange next to cavity) coated</th>
<th>ΔT, beam pipe to cavity coated/uncoated</th>
</tr>
</thead>
<tbody>
<tr>
<td>25 mA, 3.0 ps</td>
<td>0.075/0.075</td>
<td>1.14/0.82</td>
<td>1.02/0.975</td>
<td>0.007</td>
<td>0.076/-.005</td>
</tr>
<tr>
<td>40 mA, 3.4 ps</td>
<td>0.2475/0.335</td>
<td>2.95/2.16</td>
<td>2.72/2.53</td>
<td>0.021</td>
<td>0.179/0.009</td>
</tr>
<tr>
<td>40 mA, 2.7 ps</td>
<td>0.2975/0.425</td>
<td>3.00/2.22</td>
<td>2.772/2.63</td>
<td>0.027</td>
<td>0.203/0.014</td>
</tr>
</tbody>
</table>
ERL Injector Prototype: Achievements to date (last high current run Sept’13):

- 75 mA average current @ 4 MeV
- 0.3 μm emittance @ 77 pC, 8 MeV
Using a Na$_2$KSB photocathode, ran over 8 hours at 65 mA (2000 C) with a 2.6 day 1/e cathode lifetime. Reached as high as 75 mA for a short time.
Beam brightness

- Beam brightness
- Normalized rms emittance (horizontal/vertical) 90% beam, E ~ 8 MeV, 2-3 ps
  - 0.23/0.14 mm-mrad
  - 0.51/0.29 mm-mrad
- Normalized rms core* emittance (horizontal/vertical) @ core fraction (%)
  - 0.14/0.09 mm-mrad @ 68%
  - 0.24/0.18 mm-mrad @ 61%
- 9 pm at 5 GeV, diffraction limited for 12 keV photons
- At 5 GeV this gives 20x the world’s highest brightness (Petra-III)

Total 64 cryomodules, each:

- six packages of 7-cell cavity/Coupler/tuner
- a SC magnets/BPMs package
- five regular HOMs/two taper HOMs

Linac A
344 m with 35 cryomodules

Linac B
285 m with 29 cryomodules
ERL Cavity test results

- **Qo**
- **Eacc [MV/m]**

1.8 K

**Cornell ERL specs.**

ERL Cavity test results

9/2/14 Ralf Eichhorn  |  Cornell University  |  Linac 2014 Conference
In HTC, we reached a Q of $6 \times 10^{10}$ at 1.8 K with a fully dressed cavity.

We measured sufficient HOM damping.

We built a photo-injector, currently achieving 75 mA.

We reached our emittance goals.

A full, 6 cavity cryomodule is under assembly and will be finished by the end of this year.

So, what might come next?
Ready to propose:
Cornell recirculation loop
ERL/ FFAG ring option
The Cornell ERL team

Thank You!