Overview of Energy Recovery Linacs

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Talk Outline:

- Historical Perspective
- Parameter Space
- Operational ERLs & Funded Projects
- Challenges
ERL Concept: conventional linac

- e-source
- RF structure
- μ-wave tube
- high voltage (hv) production
ERL Concept: conventional linac
ERL Concept: energy recovery linac

hv production

\( I_{b,\text{acc}} \)
\( V_c, V_g \)
\( I_{b,\text{dec}} \)

\( \mu \)-wave source

RF structure

“same-cell”

e- source
ERL Concept: energy recovery linac

- **e- source**
- **μ-wave source**
- **RF structure**
- **hv production**
- **× 2**
- **V_c, V_g**
- **I_b, dec**
- **I_b, acc**
- **“same-cell”**
ERL Concept: energy recovery linac

- extends linac operation to high average currents
- reduces beam dump energy
ERLs: Historical Perspective

1960:

1965: M. Tigner
Nuovo Cimento
37 (1965) 1228

1970:

1980:

1986: Stanford SCA
T. Smith et al.
NIM A 259 (1987) 1

1990:

1990: S-DALINAC
(Darmstadt)

1999: JLAB DEMO-FEL

2000:

2000: Cornell gets $ IR
Wiggler
Beam
Transport

2004: ERL-P

2004: BNL R&D ERL

2004: JLAB FEL Upgrade

2004: BINP FEL

2004: JLAB FEL
ERL Applications

- Light Sources
  - FELs (low and high gain)
  - Spontaneous emission
- Electron Cooling
- Electron-Ion Collider
FELs

\[ \varepsilon_{x,y} = \frac{\lambda}{4\pi} \quad \Delta E/E = \frac{1}{4N_p} \quad I_{\text{peak}} \]

Low Gain

- e.g. JLAB 40 MeV DEMO-FEL
- \( \varepsilon_n \leq 13 \) mm-mrad, \( \Delta E/E \leq 0.25\% \)
- \( I_{\text{peak}} = 60 \) A to lase at \( \geq 3 \) \( \mu \)m

High Gain

- e.g. 0.7 GeV 4GLS
- \( \varepsilon_n \leq 3 \) mm-mrad, \( \Delta E/E \leq 0.1\% \)
- \( I_{\text{peak}} = 1.5 \) kA to lase at 12 nm

- \( E \leq 100 \) MeV, \( I \sim 100 \) mA

- \( E \geq \) GeV, \( I \sim 1 \) mA
Spontaneous Emission ERL Light Source

Expectations:

- Emittance close to the diffraction limit (both planes)
- Brilliance \( \geq 10^{22} \) ph/s/0.1\%/mm\(^2\)/mr\(^2\)
- Energy spread \( \sim 10^{-4} \) (long undulators)
- Sub-ps pulses (at reduced rep. rate, \( \sim \)MHz)

\( E \sim 5 \) GeV, \( I \leq 100 \) mA, \( \epsilon_n \leq 0.6 \) mm-mrad
Electron Cooling

RHIC cooler

E = 55 MeV
I = 200 mA
$\varepsilon_n \leq 40 \text{ mm-mrad}$
q = 20 nC
$\Delta E/E \leq 3 \times 10^{-4}$
magnetized beam

Kewisch, et al. TPPE043
**Electron-Ion Collider**

Litvinenko, et al. TPPP043

Derbenev, et al. TPPP015

- E = 2-10 GeV
- I ~ 100s mA*
- $\varepsilon_n \sim 10s$ mm-mrad
- polarized beam from the gun

* injector’s current with circulator ring can be much smaller
Operational ERLs
Demonstrated

\[ I = 9.1 \text{ mA at } \varepsilon_n = 7 \text{ mm-mrad (0.15 nC)} \]

10 kW at 5.7 µm
1.1 MW e- recirculated

80-160 MeV

Working on
lasing in UV
new 100 mA injector

Benson, et al., FEL 2004, p. 229
JAERI FEL

Demonstrated

I = 5 mA (1 ms pulse)
0.5 nC × 10 MHz
lasing at ~22 µm

Working on

injector upgrade (5 → 10 → 20 → 40 mA)
long pulse operation (1 s)

Hajima, et al., FEL 2004, p. 301
Demonstrated $I = 20 \text{ mA}$ at 0.2 kW at 0.12-0.18 mm ($5 \text{ mA}$ nominal).

**Future Plans**

- 4 orbits ($\rightarrow 50 \text{ MeV}$)
- 150 mA

Vinokurov, et al., FEL 2004, p. 226
Ongoing ERL Work
Cornell ERL Prototype
Cornell ERL Prototype

- DC gun
- Cornell ERL Prototype
- $E = 5-15$ MeV beam power $\leq 0.5$ MW
- max current 0.1 A
- $q = 0.01-0.4$ nC
- $\varepsilon_n = 0.1-1$ mm-mrad

Liepe, et al. TPPT094, 090 Sinclair, et al. WPAE025
BNL R&D ERL

Cornell University

Brookhaven National Laboratory

R&D ERL

Jefferson Lab

4GLS Daresbury

Rudjer Boskovic Institute

Jaeri

Agreement for Research Assistance
BNL R&D ERL

SrF gun

Ben-Zvi, et al. RPPE009
Litvinenko, et al. RPPT032
Kayran, et al. RPPT022

$q \sim 20 \text{nC}$
$\varepsilon_n \sim 30 \text{ mm-mrad}$
$I_{\text{max}} = 0.2 \text{ A}$

$q \sim 1.3 \text{ nC}$
$\varepsilon_n \sim 1-3 \text{ mm-mrad}$
$I_{\text{max}} = 0.5 \text{ A}$
Daresbury ERL-P

8 MeV merge

350 kV DC

35 MeV

Poole TOAB005
Challenges

• High current & low emittance beam production
• Emittance control
• Beam/orbit stability
• SRF issues
• Instrumentation & diagnostics
Injector

- Three gun types DC/NCRF/SRF
- Cathode QE/longevity/$E_{\text{therm}}$
- Laser for optimal shape
- Emittance compensation

*Exploring: SE cathode amplifier* (Chang, et al. RPPE032)
Cathode Field $\leftrightarrow E_{\text{therm}}$

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

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

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

**Pulsed!**

$2 \times 18$ MV/m $\rightarrow 2 \times 6$ MV/m $\rightarrow 2 \times 1$ MV/m

Same simulated emittance

$E_{\text{cath}} / E_{\text{s.charge}}$ = $E_{\text{cath}} / E_{\text{s.charge}}$ = $E_{\text{cath}} / E_{\text{s.charge}}$
Evolving Into Optimal Injector Design

Parallel Multiobjective Evolutionary Algorithm
Evolving Into Optimal Injector Design

> 20 variables optimization

through

parallel evolutionary algorithms

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

Bazarov, et al. WPAP031

\( B \sim 10^{23} \text{s.u.} \)

FIG. 10: Transverse emittance vs. bunch length for various charges in the injector (nC).
Emittance Control

- All of the many issues of pulsed linacs
- For non-FEL LS, $I_{\text{peak}}$ can be $\sim 10$ A $\rightarrow$ little CSR
- Emittance growth due to SR is important for $E \geq 5$ GeV; well understood.
- Good experience from JLAB FEL on longitudinal phase space manipulations with lattice when energy spread becomes important
BBU: Measurements

Extensive BBU study at JLAB FEL

- Three different methods of the threshold
  - direct observation
  - BTF measurement of $Q_{\text{eff}} = Q / (1 - I/I_{\text{th}})$
  - growth rate of HOM power $\tau_{\text{eff}} = \tau / (1 - I/I_{\text{th}})$

- Good agreement between measurements (2.5 mA) and simulations (2.7 mA)

- Various BBU suppression techniques increase the threshold by up to $\times 100$ times: a) phase advance; b) coupling; c) passive/active Q-damping
BBU: Theory & Computation

- Several different codes (JLAB, Cornell, JAERI)
- Mature theory; excellent agreement with codes

\[ R/Q = 50 \, \Omega, \quad Q = 2 \times 10^4, \quad m_{12} = -10^{-6} \, m/(eV/c) \]

\[ t_x \times c = 24 \, m \]

\[ t_y \times c = 232 \, m \]

\[ t_x \times c = 2307 \, m \]

\[ f_x = 2.2 \, GHz, \quad f_y = 2.3 \, GHz \]

\[ \propto 1/\sqrt{Q} \]

\[ \propto 1/Q \]

Hoffstaetter, Bazarov, Song
Orbit Stability

- Sub-micron stability (rms) is required for ERL LS in both horizontal and vertical planes
- E.g. CEBAF demonstrates 20 µm rms (limited by BPM noise)
- $10^{-4}$ energy stability is needed
- demonstrated at CEBAF
SRF Challenges

• $Q_0 = 2 \times 10^{10}$ at 15-20 MV/m is desirable
• cavity/cryomodule design that minimizes microphonics
• $Q \leq 10^4$ for primary dipole and $Q \leq 10^3$ for (resonant) monopole HOMs is desired
• smart HOM power handling
• superior LL RF control
High Current SRF Cavities

Optimized cavity shape

CESR style ferrite absorbers

Calaga, et al, C-A/AP/#111

BNL

Cornell

GHe cooling

Ferrite at 80 K

Cavity assembly

Vacuum vessel

4" RF shielded gate valve

HOM ferrite assembly

Tuner location

2K main line

Space frame support structure

Outer magnetic shield

2K fill line

BNL Thermal shield line
Cornell Low Level RF Control System

- Successfully tested at JLAB FEL

**Demonstrated:**

+ $Q_L = 1.2 \times 10^8$ with $I = 5.5$ mA
+ Energy recovered beam
+ Field stability $10^{-4}$
+ Phase stability $0.02^\circ$
Summary

• Good progress on several fronts
• Much remains to be done
• R&D on ERLs to intensify in the next few years
• Proposals for large scale ERLs to follow after
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