Review of various approaches to address high currents in SRF electron linacs

Ilan Ben-Zvi
Collider-Accelerator Department
Brookhaven National Laboratory
Why a high average current?

- High power FELs (currently 10 mA at JLab’s FEL upgrade) – possibly as much as 1 ampere.
- ERL based light sources – 100 mA and above, lower for high brightness mode, higher for high flux mode.
- Electron-ion colliders – possibly as much as 0.5 ampere.
- High-energy electron cooling – possibly as much as 0.5 ampere.
High current, SRF and ERL

• To get a high average current with a reasonable gradient, CW operation is necessary, thus SRF is required.
• High average current also requires energy recovery to be practical.

Result:
• No high-power input couplers necessary.
• High $Q_{ext}$ operation is desirable to minimize RF power requirements.
What are the issues?

- Generating the electron beam: Gun and booster.
- Reducing the amount of HOM power generated by the SRF structure.
- Extracting the HOM power out of the cavity.
- Overcoming multi-pass beam breakup.
- Mechanical vibration stability at high $Q_{\text{ext}}$, low steady state Lorentz detuning, low microphonics.
- Phase / amplitude control at high $Q_{\text{ext}}$, high reactive beam power.
- Lowering surface resistivity and avoiding field emission.
- Very high gradient is NOT an issue (limited by refrigeration), 20 MV/m but low loss is satisfactory.
## Main linac parameter space

<table>
<thead>
<tr>
<th>parameter</th>
<th>min value</th>
<th>max value</th>
</tr>
</thead>
<tbody>
<tr>
<td>linac energy gain</td>
<td>20 MeV</td>
<td>5 GeV</td>
</tr>
<tr>
<td>average current</td>
<td>10 mA</td>
<td>1 A</td>
</tr>
<tr>
<td>bunch charge</td>
<td>10 pC</td>
<td>1.5 nC</td>
</tr>
<tr>
<td>bunch length</td>
<td>2 ps</td>
<td>100 ps</td>
</tr>
<tr>
<td>cavity frequency</td>
<td>700 MHz</td>
<td>1.5 GHz</td>
</tr>
<tr>
<td>cells per cavity</td>
<td>5</td>
<td>9</td>
</tr>
<tr>
<td>acc. gradient</td>
<td>12 MV/m</td>
<td>20 MV/m</td>
</tr>
<tr>
<td>unloaded $Q_0$</td>
<td>$8 \cdot 10^9$</td>
<td>$2 \cdot 10^{10}$</td>
</tr>
<tr>
<td>loaded $Q$</td>
<td>$2 \cdot 10^7$</td>
<td>$1 \cdot 10^8$?</td>
</tr>
<tr>
<td>HOM power per cavity</td>
<td>some 10 W</td>
<td>&gt;1 kW</td>
</tr>
<tr>
<td>HOM spectrum, 95% upper freq.</td>
<td>1 GHz</td>
<td>60 GHz</td>
</tr>
<tr>
<td>amplitude/phase stability</td>
<td>$10^{-3}$ / 0.1 deg</td>
<td>$10^{-4}$ / 0.02 deg</td>
</tr>
<tr>
<td>ave./peak RF power per cavity</td>
<td>0.5 kW/1 kW</td>
<td>25 kW / 50 kW</td>
</tr>
</tbody>
</table>

Courtesy: Matthias Liepe, Cornell. Invited Plenary talk at ERL 2005 Workshop
Approximate longitudinal loss-factor for a multi-cell cavity:

\[ k_l = \frac{\Gamma(.25) Z_0 c}{4\pi^{2.5}} \frac{1}{a} \sqrt{\frac{d}{\sigma}} \sqrt{N_c} \]

- \( a \) is the cavity iris radius,
- \( d \) is the cell length
- \( \sigma \) is the beam bunch length
- \( N_c \) is the number of cells

For a fixed bunch and cavity length and cell proportions, \( k_l \) is proportional to the frequency squared.

The HOM power is proportional to the loss factor, to the current and charge of the beam:

\[ P_{HOM} = k_l Iq \]

For high Iq machines, \( k_l \) must be minimized by going to a lower RF frequency and opening the cavity’s irises.
Choice of frequency

- HOM power goes down with frequency
- Beam breakup improves rapidly with frequency
- The lowest frequency linac structure JLAB can handle in existing chemical cleaning is ~700 MHz
- High power CW klystrons (for the photoinjector) exist only at 500, 700 and 1250 MHz.
- Superconductor BCS surface resistance goes down with frequency squared,
- Inexpensive and compact RF exists at 700 MHz or lower (UHF TV transmitters using IOT devices)
- These considerations led a few laboratories to develop new SRF ERL structures.

I. Ben-Zvi, SRF 2005
New, active high-current linac SRF structure developments

• BNL
  – Construction of 5-cell, 703.75 MHz cavity, SRF electron gun, and construction 0.5A, 20 MeV ERL (design 80 MeV).

• Cornell
  – Construction of a 2-cell, 1300 MHz injector cavities, DC electron gun, cold HOM damping of TESLA type cavities and design of 100 mA, 100 MeV ERL.

• JLab
  – Design (construction in 2007) of a 5-cell cavity, DC gun with SRF booster under construction, design of 100 mA, 120 MeV ERL.

• KEK
  – Development of radial damping scheme for TESLA type ERL cavity, design of a 100 mA, 200 MeV ERL.
Removing the HOM power from the cavity

- The high HOM power must be dumped out of the liquid helium environment.
- HOM couplers must be able to handle the large amount of average power.
- The beam pipe is a practical conduit for the HOM, it is there anyway.
- The HOM modes must be well coupled to the beam pipe (no trapped modes)
- The beam pipe should propagate well all HOMs
- TESLA HOM coupler is inadequate.

I. Ben-Zvi, SRF 2005
The BNL approach
Aimed at ~1 ampere

- Low frequency: 703.75 MHz
- Cavity manufactured by AES
- Large beam pipe: 24 cm diameter
- HOM loads: Cornell ferrites at room temp (made by Accel)
- Cold loads: an alternate for multi-cavity cryomodules

ERL 5-cell cavity design for high currents
R. Calaga, proceedings SRF’05

Design and Fabrication of the RHIC Electron-Cooling Experiment
High Beta Cavity and Cryomodule
D. Holmes, proceedings SRF’05

I. Ben-Zvi, SRF 2005
BNL 5-cell impedance spectrum

Red line - MAFIA
Blue points - measured

I. Ben-Zvi, SRF 2005
The Cornell approach
Aimed at \(~0.1\) ampere

1300 MHz.
7-cell, TESLA shape, 10.6 / 7.8 cm diameter beam pipes.
Use combination coaxial HOM dampers (8 per cavity) AND ferrite rings.
Ferrite rings at 80 K.
Cornell 7 cell impedance spectrum

Monopole

Dipole

Conceptual Layout of the Cavity String of the Cornell ERL Main Linac Cryomodule
M. Liepe, SRF’03

GHe cooling loop
ferrite tile at 80 K
Integrated bellows

~An order of magnitude Better damping than TDR TESLA.
The JLab approach
Aimed at ~1 ampere

Low frequency:
750 MHz.

Waveguide HOM loads, 6 per cavity, water cooled.

14 cm diameter irises.
JLab 5-cell impedance spectrum

Monopole

Dipole

I. Ben-Zvi, SRF 2005
The KEK approach

TESLA type cavity fitted with a radial HOM absorber

I. Ben-Zvi, SRF 2005
Radial dampers with integral fundamental choke filter

Higher-Order-Mode Damping of L-band Superconducting Cavity Using a Radial-line HOM Damper

K. Umemori, et. al., proceedings PAC’05

Can achieve significant damping Depending on distance

I. Ben-Zvi, SRF 2005
Beam breakup

I. Ben-Zvi, SRF 2005
BBU analysis

Definitive work:

\[
I_{th} = \frac{-2c^2}{e(R/Q)_m Q_m \omega_m T_{12} \sin(\omega_m t_r)}
\]

Hoffstaetter and Bazarov simulations show \( \sim 200 \) mA threshold for a 5 GeV ERL using TESLA TDR cavities.
The new 700-750 MHz cavities (BNL, JLab) should have a factor of 2 by virtue of its lower frequency and another large factor, \( \sim 100 \), thanks to enhanced HOM damping, i.e. smaller \( (R/Q)_m Q_m \)
Beam Breakup threshold

Electron cooler linac (4 cavities, 54 MeV)

I. Ben-Zvi, SRF 2005
Amplitude and phase control.
Also applies to low current linacs.

- Cornell's newly developed digital control system, connected to a high loaded Q cavity at the JLab IR-FEL.
- Excellent cw field stability.
- Piezo tuner effective in keeping the cavity on resonance and allowed reliable to ramp up to high gradients in less than 1 second.

Pushing the Limits:
RF Field Control at High Loaded Q
M. Liepe et. al., proc. PAC’05 and SRF’05

Amplitude and phase stability
With $Q_L = 1.2 \cdot 10^8$ and 5 mA

I. Ben-Zvi, SRF 2005
Residual resistance and the choice of frequency

\[
R_{BCS} = 2 \cdot 10^{-4} \frac{1}{T} \left( \frac{f \text{(GHz)}}{1.5} \right)^2 \exp \left( -\frac{17.67}{T} \right)
\]

Figure 2 – Residual resistance as low as 0.5 nΩ is actually measured on large area cavities, giving an intrinsic quality factor \( Q_0 \) exceeding \( 2 \times 10^{11} \).

Residual resistance <1 nΩ possible

I. Ben-Zvi, SRF 2005
Cavity mechanical stiffness

1.2 Hz/(MV/m)^2

Mechanical Resonances (D. Holmes - FEA)

Modes 1-5 (96 - 214 Hz)

I. Ben-Zvi, SRF 2005
DC gun

Achieved:
JLab 350 kV gun, GaAs cathode,
9.1 mA (122 pC/bunch at 74.85 MHz)
processed 435 kV for 350 kV operation.
Future:
JLab gun at 500 kV, 100 mA average
w/ 750 MHz SRF booster (AES)
New design, 500 to 750 kV, at Cornell,
100 mA average

Issues: Field emission, vacuum.

I. Ben-Zvi, SRF 2005
Booster (or injector)

Boosters are accelerating sections that are not energy recovered. Their purpose is to increase the injections energy to the ERL for beam quality and/or energy recovery reasons, usually used with the DC guns that have relatively low energy.

Overview of the Cornell ERL Injector Cryomodule
H. Padamsee et. al., Proceedings PAC’03
Dipole-mode-free and Kick-free 2-cell Cavity for the SC ERL Injector
V. Shemelin, et. al., Proceedings PAC’03

Cornell
1 MV at 100 mA per cavity

JLab/AES
7 MeV + harmonic correction at 100 mA

Design and Fabrication of an FEL Injector Cryomodule
John Rathke et. al., proceedings PAC’05

I. Ben-Zvi, SRF 2005
Superconducting RF gun under development.

703.75 MHz gun.
2x0.5 MW input couplers.
HOM damping thru beam tube.
Various cathode schemes, including encapsulated cathode behind diamond window – isolation cathode ↔ gun.

CW performance
0.5 ampere @ 2 MeV.

State-of-the-Art of Electron Guns and Injector Designs
A. Todd,
Invited Plenary Talk ERL’05

I. Ben-Zvi, SRF 2005
ERL test facilities

• Currents under discussion (>100 mA) are an order of magnitude or more beyond current state-of-the-art.

• A number of test facilities are under construction at this current level:
  – Cornell, 100 mA at 100 MeV, injector funded and under construction.
  – JLab gun test facility, under construction.
  – BNL ERL, 20 MeV at 0.5 ampere under construction.

• Proposals for other facilities (KEK 100 mA 200 MeV, possibly others)

I. Ben-Zvi, SRF 2005
Cornell ERL prototype

THE CORNELL ERL PROTOTYPE PROJECT
G.H. Hoffstaetter et. al., Proceedings PAC’03

I. Ben-Zvi, SRF 2005
BNL ERL Facility at building 912

- 2 MeV SC RF electron gun
- 20 MeV cavity cryomodule
- Photocathode preparation and insertion chamber
- 1 MW CW beam dump
I. Ben-Zvi, SRF 2005

20 MeV, 0.5 ampere ERL
Under construction

Extremely High Current, High-Brightness
Energy Recovery Linac
I. Ben-Zvi et. al., proceedings PAC’05

High Current Energy Recovery Linac at BNL
V.N. Litvinenko et. al., proceedings PAC’05

I. Ben-Zvi, SRF 2005
JLab 100 mA injector test-stand

The JLab High Power ERL Light Source
G. Neil, invited plenary talk at ERL’05

Proposed:
100 mA, 120 MeV,
For 100 kW FEL at 1 micron

100 mA dump
Energy spread diagnostic
Emittance diagnostic
750 MHz cryounit
Bunch longitudinal profiling
Bunch transverse profiling

500 kV DC gun

Proposed:
100 mA, 120 MeV,
For 100 kW FEL at 1 micron

I. Ben-Zvi, SRF 2005

The RHIC
BROOKHAVEN NATIONAL LABORATORY
KEK test facility (proposed)

A conceptual pre-injector design for the KEK-ERL test accelerator
T. Suwada, et. al., proceedings ERL’05

I. Ben-Zvi, SRF 2005
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