SRF Challenges for Energy Recovery Linacs

Andrew Burrill
Outline

• Why we need Energy Recovery Linacs
• Current state of ERL development
• SRF Challenges
  – The Cavity
  – HOM dampers
  – RF and control system
  – Cryomodule
• Closing thoughts
**ERL Overview**

**BERLinPro**=high current ERL test facility

### Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy</td>
<td>50 MeV</td>
</tr>
<tr>
<td>Average current</td>
<td>100 mA</td>
</tr>
<tr>
<td>Bunch charge</td>
<td>77 pC</td>
</tr>
<tr>
<td>Normalized emittance</td>
<td>&lt;1 mm·mrad</td>
</tr>
<tr>
<td>Resonance frequency</td>
<td>1.3 GHz</td>
</tr>
</tbody>
</table>

Demonstration of the feasibility to use ERL technology for future 4th generation multi-user light sources

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• **Injector:** No energy recovery
  – Beam loading primary consideration!
  – Beam is “soft”, danger of emittance dilution
  – If SRF cavity injector: NC cathode in an SRF environment
Main Linac
BNL, Cornell, Daresbury, HZB, JLab, KEK, ...

- Main LINAC: Energy recovery
  - Beam loading no longer critical
  - RF Stability and microphonics is key
  - Optimize RF power to cavity
  - HOM excitation and power extraction
  - Cryogenic Load is significant
Why do we need SRF ERLs?

“Big” Machines

Cornell 5 GeV

KEK 3 GeV

X-ray Light Sources

LHeC 60 GeV

Electron Ion colliders

3 GeV ERL First Stage

7 GeV Double Acc

XFEL-O Second Phase

eRHIC 5-30 GeV

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<table>
<thead>
<tr>
<th>Machine</th>
<th>Beam Parameters</th>
<th>Beam Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cornell</td>
<td>5 GeV @ 100 mA</td>
<td>500 MW</td>
</tr>
<tr>
<td>KEK</td>
<td>3 GeV @ 100 mA</td>
<td>300 MW</td>
</tr>
<tr>
<td>BNL</td>
<td>20 GeV @ 6 mA</td>
<td>120 MW</td>
</tr>
<tr>
<td>LHeC</td>
<td>60 GeV @ 6.4 mA</td>
<td>384 MW</td>
</tr>
</tbody>
</table>

**XFEL Main Linac 2.5-20 GeV** 650 kW Avg beam power

Without Energy Recovery these machines would be cost prohibitive to build and operate!
<table>
<thead>
<tr>
<th>Location</th>
<th>Purpose</th>
<th>Current</th>
<th>Energy</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>SINAP (China)</td>
<td>THz FEL</td>
<td>20 mA</td>
<td>20 MeV</td>
<td>Prototype</td>
</tr>
<tr>
<td>BNL (USA)</td>
<td>high current R&amp;D/eRHIC</td>
<td>50-300 mA</td>
<td>20 MeV</td>
<td>Commissioning</td>
</tr>
<tr>
<td>Daresbury (UK)</td>
<td>FEL (IR), THz, Demo</td>
<td>13 mA</td>
<td>27.5 MeV</td>
<td>Operational</td>
</tr>
<tr>
<td>PKU (China)</td>
<td>FEL</td>
<td>1 mA</td>
<td>30 MeV</td>
<td>Prototype</td>
</tr>
<tr>
<td>IHEP (China)</td>
<td>ERL &amp; FEL</td>
<td>10 mA</td>
<td>35 MeV</td>
<td>Design Phase</td>
</tr>
<tr>
<td>KEK (Japan)</td>
<td>cERL/ light source</td>
<td>10-100 mA</td>
<td>35 MeV/3 GeV</td>
<td>Commissioning</td>
</tr>
<tr>
<td>TRIUMP (Canada)</td>
<td>Photo-fission driver</td>
<td>10 mA</td>
<td>50 MeV</td>
<td>Construction</td>
</tr>
<tr>
<td>HZB (Germany)</td>
<td>R&amp;D for future light source</td>
<td>100 mA</td>
<td>50 MeV</td>
<td>Construction</td>
</tr>
<tr>
<td>Mainz (Germany)</td>
<td>Electron scattering experiments</td>
<td>1-10 mA</td>
<td>100 MeV</td>
<td>Design Phase</td>
</tr>
<tr>
<td>JLab (USA)</td>
<td>FEL (IR, UV) THz</td>
<td>10 mA</td>
<td>200 MeV</td>
<td>Operational</td>
</tr>
<tr>
<td>Cornell (USA)</td>
<td>X-ray light source</td>
<td>100 mA</td>
<td>5 GeV</td>
<td>Prototype</td>
</tr>
<tr>
<td>CERN (Switzerland)</td>
<td>LHeC (EIC)</td>
<td>6.4 mA</td>
<td>60 GeV</td>
<td>Design Phase</td>
</tr>
</tbody>
</table>
SRF Challenges - The Cavity

• Cavity design needs to be optimized for c.w. application
  – Optimum frequency 700 MHz to 1.5 GHz
    Optimization depends on many parameters!
• High Qo at operating gradient (15-20 MV/m)
  – Reduced cryogenic load
• Fill every bucket at 700-1500 MHz
  – charge/bunch ~100 pC
  – Good emittance ( < 1mm*mrad)
• Maximized R/Q * G for the fundamental
• Designed for low $E_{\text{peak}}/E_{\text{acc}}$
  – Field emission

Make the design as economical to operate as possible
The Cavity 2

- **HOM propagation**
  - Cavity cell shape, iris diameter and beampipe transition optimized
  - Cavity design and measurements must be compared for *all* cavities.
  - Large projects benefit from a fabrication tolerance study (Cornell) + comparison with fabrication data (JLab)

- **BBU threshold**
  - Design must allow for the theoretical threshold to be at least $X$ times greater than what is necessary

- **Optimize for minimum $df/dp$**
  - Pressure fluctuations at high power are more likely
  - Impact on RF system
  - Significant impact on operations
    - Users
    - Cathode lifetime
SRF Gun Challenges

- Physics Design
  - Beam dynamics like very high fields on the cathode
    - Results in high peak electric fields (\(E_p = 40-60\) MV/m)
      - Possible conflict with routine insertion and retraction of photocathode
    - Not a true \(\beta=1\) structure
- Design of choke structure for operation with normal conducting photocathode
- Fabrication is not in large quantity
  - Usually 1 or 2 cavities with <3.5 cells
  - Significant machining work, lots of parts from ingot material
- Gun module needs to be as short as possible
SRF Gun Challenges

Requirements

• 2.3 MeV 100 mA beam = 230 kW RF power
• Loaded Q ($10^4$-$10^7$)
• Multiple beam operating conditions
  – Bunched operation
  – High current mode
  – High charge mode

• Superconducting magnet near the cavity
• Normal conducting cathode in SRF cavity

Associated Challenge

• Dual High power RF power couplers (115 kW each)
• Coupler Penetration into beampipe
• Power dissipation in coupler region – gasket heating
• Variable coupling, LLRF control, cavity stability
• Magnetic Shielding
• Quench recovery
• Thermal isolation
• Multipacting
• Contamination
SRF Gun Testing challenges

- Difficulties in testing the gun with a cathode stalk in the vertical tests
- Processing the cavity
- HPR in tight spaces
- Cathode contamination
Booster (Injector) Module

- Designed to accelerate low energy beam from gun to the main linac

Low energy beam
Cavity alignment is critical to low emittance
Strongly coupled cavity $Q_{ext} \times 10^4 - 10^7$
Coupler perturbation an issue
HOM power not the same as a Linac Cavity

Cornell Injector
- 0.5 – 5 MeV beam
- 100 mA – 33 mA
- 100 kW/ cavity
SRF Challenge - Cavity preparation

- Provide a reproducible and robust way to prepare cavities
  - High Q₀, minimal Q slope

- Important considerations
  - Chemical processing recipe
    - BCP, CBP, Flash BCP, EP
    - Heat treatment 600°C - 800°C with or without additional processing
    - HF rinses
    - High Pressure rinsing (4 hours – 12 hours)
  - Parts cleaning
  - Assembly techniques
  - Slow pump-down

  The Good: Many ways to reach the goal
  The not so good: highly variable from lab to lab
<table>
<thead>
<tr>
<th></th>
<th>ERL7-1 (HTC)</th>
<th>ERL7-2</th>
<th>ERL7-3</th>
<th>ERL7-4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bulk BCP</td>
<td>140um (witness sample)</td>
<td>135±10 um (cavity equator)</td>
<td>138±5 um (cavity equator)</td>
<td>132±7 um (cavity equator)</td>
</tr>
<tr>
<td>Degassing</td>
<td>Jlab, 650C*10hrs</td>
<td>TM-furnace 650C*4days</td>
<td>TM-furnace 650C*4days</td>
<td>TM-furnace 650C*4days</td>
</tr>
<tr>
<td>Tuning</td>
<td>88%</td>
<td>94%</td>
<td>91%</td>
<td>92%</td>
</tr>
<tr>
<td>Final BCP</td>
<td>10 um</td>
<td>10 um</td>
<td>10 um</td>
<td>10 um</td>
</tr>
<tr>
<td>120C bake</td>
<td>On insert</td>
<td>TM-furnace</td>
<td>On insert</td>
<td>TM-furnace</td>
</tr>
<tr>
<td>HF rinse</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>VT 1st (1.8K)</td>
<td>17MV/m, 1.6e10 (No T-map)</td>
<td>17MV/m, 1.53e10 w/ T-map</td>
<td>Limited by FE w/ T-map</td>
<td>17.4MV/m, 2.4e10 w/ T-map</td>
</tr>
<tr>
<td></td>
<td>HTC1, HTC2 (high rad)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Re-process</td>
<td>-BCP(10um)</td>
<td></td>
<td>Re-process to cure FE</td>
<td></td>
</tr>
<tr>
<td></td>
<td>-120C bake (in clean room, old set-up)</td>
<td></td>
<td>-BCP(10um)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>-HF rinse</td>
<td></td>
<td>-120C bake (TM-furnace)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>-HF rinse</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>HTC3, 16.2MV/m, 6.0e10 @1.8K</td>
<td></td>
</tr>
<tr>
<td>VT 2nd (1.8K)</td>
<td></td>
<td></td>
<td>17MV/m, 2.8e10 No T-map (PC down)</td>
<td></td>
</tr>
</tbody>
</table>

Data courtesy of Ralf Eichhorn
Cornell Linac Cavity

Cornell Vertical Test 1.8 K

Performance administratively limited
HTC performance $6 \times 10^{10}$

Bulk BCP
650 °C bake* 4 days
Light BCP
HF Rinse*

Qo

Eacc [MV/m]

1.3 GHz 7 cell

10 W Power

Data courtesy of Ralf Eichhorn

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Vertical Test at 2.07 K in the Helium Vessel

Bulk BCP
600 °C bake* 10 hours
30 μm EP

12 GeV Spec
1.5 GHz, 7 cell

29 Watt Limit

1,00E+11

1,00E+10

1,00E+09

0 5 10 15 20 25 30 35

Eacc (MV/m)

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7 cell ERL cavity, 77 pC, 100 mA

\[ P_{\text{HOM}} = k_{\text{HOM}} \cdot q_{\text{bunch}} \cdot I_{\text{beam}} \]

ERL Linac

\[ P_{\text{HOM}} = 12 \frac{V}{pC} \cdot 77pC \cdot 0.2A = 200 \text{ W} \]

HOM damper must be independent of 2K system

HOM damper must not reduce the cavity performance

**Table:**

<table>
<thead>
<tr>
<th>ERL</th>
<th>Beam Current [mA]</th>
<th>Average HOM power per cavity [W]</th>
<th>Required monopole Q</th>
<th>Required dipole Q</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cornell</td>
<td>100</td>
<td>200</td>
<td>(5 \times 10^3)</td>
<td>(1 \times 10^4)</td>
</tr>
<tr>
<td>KEK-c</td>
<td>100</td>
<td>185</td>
<td>(1 \times 10^6)</td>
<td>(1 \times 10^4)</td>
</tr>
<tr>
<td>BERLinPro</td>
<td>100</td>
<td>150</td>
<td>(1 \times 10^4)</td>
<td>(1 \times 10^4)</td>
</tr>
<tr>
<td>eRHIC</td>
<td>300</td>
<td>7,500</td>
<td>(1 \times 10^4)</td>
<td>(4 \times 10^4)</td>
</tr>
</tbody>
</table>

**Equation:**

\[ P_{\text{HOM-eRHIC}} = 3.5 \text{ V/pC} \times 3500 \text{pC} \times 0.05 \text{mA} \times 12 \text{ passes} \]
HOM Waveguide Absorbers

Key Advantages
- Require less length in the CM vs beamline absorber
- Move load material further from the cavity

Disadvantages
- Multiple loads required
- HV welding
- CM design

JLab 750/1500 MHz design

WG HOM load
Based on PEP-II

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Key Advantages
• Fewer loads required than WG style
• Less complicated CM design

Disadvantages
• Reduces real estate gradient
• Proximity of load to cavity
• Charging of material
• Cooldown rate control
HOM Couplers

Key Advantages
• Cleanroom compatible
• Highest real estate gradient

Disadvantages
• Thermal management critical
• Narrow notch filter makes it possible to couple out fundamental during upset condition
ERL linac cavities ideally see a zero net beam loading. $Q_L > 1 \times 10^8$ are possible.

- This requires very low microphonics
- $\sigma_A/A < 1 \times 10^{-4}$
- $\sigma_\phi < 0.02$

Measured Phase stability of 0.02 deg at $Q_L = 2 \times 10^8$ (3 Hz bandwidth)
Fast ramp to high field < 0.5 sec

Reduce $Q_L$, reduce capital & operating costs!
Cornell 5 kW Solid State RF Amp

- Many advantages: compact, modular design, good maintainability....
- Competitive cost (<15$/W) for low power CW applications
- High overall system efficiency
- Good linearity
- Stable operation after initial problems with overheating of transistors (resolved); occasional trips likely due to overdriving the amp

<table>
<thead>
<tr>
<th>Operation Frequency</th>
<th>1300MHz +/- 5MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gain</td>
<td>67 dB</td>
</tr>
<tr>
<td>Power RF Efficiency</td>
<td>40% at 5kW Output</td>
</tr>
</tbody>
</table>

Gain Plot of the Amplifier

Initial Test
With New Cable and New Power Module

Gain Plot of the Amplifier

- Initial Test
- With New Cable and New Power Module

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• Minimized microphonics susceptibility
  – Cavity design can only do so much. Must be rigid and not have any low frequency modes which may be excited.

• Finite element analysis of the systems
  – Cavity + He return + He Supply + tuner + ....
  – Look at entire cavity string motion
  – Understand accelerator environment
  – Understand the testing environment

Separate the cryomodule from the environment

K. Davis MOPB031 LINAC 2012 – JLab C100 experience
The '30 Hz' noise originates from the mechanical vibration of the 2 K pump.

The '16 Hz' microphonics noise was found to shift toward higher frequencies when the LHe level varies from top to bottom of the tube connecting the ballast tank to the cavity helium vessel. When its frequency reaches 30 Hz, there is a strong resonant excitation with a magnitude increase by more than a factor of five.

This microphonics spectrum line is associated with an acoustical resonance in this line.

The frequency detuning due to microphonics is comparable to the cavity bandwidth. A three stub tuner has been added to get better control of cavity in the further test. Also, a special feedback utilizing the piezo tuner is under development.
SRF Challenges - Cryomodule

• Cavity performance degradation is often noted once the cavities are installed in the cryomodule.
  – Low field Q degradation
    • Inadequate magnetic shielding
    • Use of magnetized components near the cavity
    • RF losses in components
  – Gradient limitations
    • Heating
    • Field emission
    • Helium vessel exhaust riser size

• Better than 1 mm*mrad emittance requires precise cavity alignment
  – Cavity to cavity in a module
  – Between modules
  – Relative to beamline components

• Proper heat intercepts to limit 2K load
For ERL prototype, it is necessary to have 15 MV in the cavity, due to beam-dynamics constraints in the beam combiner.

However, 11.5 MV/m was observed to be the threshold in CW mode, due to the AlMg₃ seal located between the NbTi and stainless steel flanges on the beam pipe (on FPC side).

Quasi-CW operation mode: Test showed that the cavity can safely (thermal stability) run at 18 MV/m with a 6.25% duty factor.
Issue of Injector module

- Three 2-cell cavity with double input couplers with five HOM couplers
  Acc. voltage of 5MV (cERL)
  10MV (ERL)
  (Eacc of 15MV/m)
- Input coupler power
  10kW (5 MV×10mA for cERL)
  170kW (10MV×100mA in ERL)
- Development of a HOM coupler
Performance of the module

- Eacc of >15MV/m in V.test.
- The module achieved 8MV/m in cw mode.
- Degradation of Q in the module test.
- Excessive heating of RF feedthroughs of HOM coupler causes an additional loss, since each feedthrough is anchored to 2K.

Heating of HOM of #3 cavity

![Graph showing heating of HOM of #3 cavity with labeled HOM feedthrough and HOM top.](image)

- Rather low Q is due to SUS seal flanges of each ports.
- Module power test

![Graph showing module power test with labeled cavity-1, cavity-2, and cavity-3.](image)
Cavity performance does not always get worse in the cryomodule!
By controlling the cooldown rate the $R_{surf}$ can be reduced significantly.
Performance Improvements 2

Cornell Linac Cavity HTC

Horizontal Test Cryostat: (@16MV/m, 1.8K)

HTC-I: $Q_0 = 3.5 \times 10^{10}$ without coupler

HTC-II: $Q_0 = 2.0 \times 10^{10}$ (reached with coupler)

HTC-III: $Q_0 = 6.0 \times 10^{10}$ (with coupler and HOM absorbers, after cavity reprocessing from HTC-II)

Data courtesy of Ralf Eichhorn
Conclusions

• A number of exciting projects underway
  – Huge opportunity for collaboration and knowledge transfer!

• Many technical challenges are being overcome
  – This is what needs to be documented!!

• 100 mA operation looks very promising
  – 75 mA from Cornell DC gun and Injector (ERL 2013)

• Methods to obtain and maintain $Q_0 > 3 \times 10^{10}$ and $E_{acc} \geq 16$ MV/m for a 1.3 GHz cavity
  – 10 W per cavity at 1.8K in the Linac!

• $Q_L > 1 \times 10^8$ for Linac operations
  – 5 kW solid state amplifier to drive Linac cavities
Acknowledgements


• Thank you for sharing what worked, and more importantly what didn’t work!
The End.