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
BERLlinPro=high current ERL test facility

Main Linac
1\textsuperscript{st} turn 6 MeV $\rightarrow$ 50 MeV
2\textsuperscript{nd} turn 50 MeV $\rightarrow$ 6 MeV

Booster (Injector)
2.3 MeV $\rightarrow$ 6 MeV

SRF Gun
2.3 MeV

Merger

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

X-ray Light Sources

KEK 3 GeV

3 GeV ERL First Stage

XFEL-O Second Phase

7 GeV Double Acc.
Why do we need SRF ERLs?

“Big” Machines

- Cornell 5 GeV
- KEK 3 GeV
- XFEL-O Second Phase
- 7 GeV Double Acc.
- LHeC 60 GeV
- eRHIC 5-30 GeV

X-ray Light Sources

- 3 GeV ERL First Stage
## Big Machine Beam Power

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<tr>
<th>Machine</th>
<th>Beam Parameters</th>
<th>Beam Power</th>
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**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!*
## ERLs around the world

<table>
<thead>
<tr>
<th>Location</th>
<th>Purpose</th>
<th>Current</th>
<th>Energy</th>
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<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>
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<td>ERL &amp; FEL</td>
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<td>KEK (Japan)</td>
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<tr>
<td>TRIUMP (Canada)</td>
<td>Photo-fission driver</td>
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<td>Construction</td>
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<td>HZB (Germany)</td>
<td>R&amp;D for future light source</td>
<td>100 mA</td>
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• 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 $E_{peak}/E_{acc}$
  – 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
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
SRF Gun Testing challenges

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Booster (Injector) Module

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

Cornell Injector
0.5 – 5 to 15 MeV beam
100 mA – 33 mA
100 kW/ cavity

23.Sep.2013   Andrew Burrill - HZB
Booster (Injector) Module

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

**Cornell Injector**

- 0.5 – 5 to 15 MeV beam
- 100 mA – 33 mA
- 100 kW/ cavity

**KEK**

- 0.5 – 5 MeV
- 10 mA
- 25 kW/cavity

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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

KEK

0.5 – 5 MeV
10 mA
25 kW/cavity

Cornell Injector
0.5 – 5 to 15 MeV beam
100 mA – 33 mA
100 kW/cavity

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• Provide a reproducible and robust way to prepare cavities
  – High Qo, 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
# SRF Cavity Prep - Cornell Linac Cavity

<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><strong>Bulk BCP</strong></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><strong>Degassing</strong></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><strong>tuning</strong></td>
<td>88%</td>
<td>94%</td>
<td>91%</td>
<td>92%</td>
</tr>
<tr>
<td><strong>Final BCP</strong></td>
<td>10 um</td>
<td>10 um</td>
<td>10 um</td>
<td>10 um</td>
</tr>
<tr>
<td><strong>120C bake</strong></td>
<td>On insert</td>
<td>TM-furnace</td>
<td>On insert</td>
<td>TM-furnace</td>
</tr>
<tr>
<td><strong>HF rinse</strong></td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td><strong>VT 1st (1.8K)</strong></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><strong>HTC1, HTC2 (high rad)</strong></td>
<td>HTC1, HTC2 (high rad)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Re-process</strong></td>
<td>-BCP(10um)</td>
<td>-BCP(10um)</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>-120C bake(TM-furnace)</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>-HF rinse</td>
<td></td>
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<td></td>
</tr>
<tr>
<td></td>
<td><strong>HTC3, 16.2MV/m, 6.0e10 @1.8K</strong></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td><strong>VT 2nd (1.8K)</strong></td>
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| VT 2nd (1.8K)    |                              |                         |                         |                         |

- Data courtesy of Ralf Eichhorn

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Cornell Linac Cavity

Cornell Vertical Test 1.8 K

Qo

Eacc [MV/m]

1.3 GHz 7 cell

10 W Power

ERL7-4
ERL7-3
ERL7-2
ERL7-1

Data courtesy of Ralf Eichhorn

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Cornell Linac Cavity

Cornell Vertical Test 1.8 K

Qo

Eacc [MV/m]

1,00E+11
1,00E+10
1,00E+09

0 5 10 15 20 25 30

1.3 GHz 7 cell

Data courtesy of Ralf Eichhorn

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

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

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

1.3 GHz 7 cell

Data courtesy of Ralf Eichhorn
Vertical Test at 2.07 K in the Helium Vessel

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

29 Watt Limit

12 GeV Spec

1.5 GHz, 7 cell

23.Sep.2013 Andrew Burrill - HZB
**SRF Challenges - Higher Order Modes**

7 cell ERL cavity, 77 pC, 100 mA

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

**ERL Linac**

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

HOM damper must be independent of 2K system

HOM damper must not reduce the cavity performance

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

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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
HOM Beamline Absorbers

BNL ECX Cavity

Cornell

KEK

Ti Cylinder with integral cooling

Thermal Shrink Fit

Flange to Cavity

Flange to Cavity

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HOM Beamline Absorbers

BNL ECX Cavity

XFEL

HOM ferrite damper with comb shield

Flange to Cavity

Ti Cylinder with integral cooling

Thermal Shrink Fit

Flange to Cavity

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HOM Beamline Absorbers

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

BNL ECX Cavity

XFEL

HOM ferrite damper with comb shield

Flange to Cavity

Thermal Shrink Fit

Ti Cylinder with integral cooling

Cornell

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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

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

Cryogenic Plant Capacity

More critical for booster

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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 AlMg$_3$ 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

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Vertical test results

Rather low Q is due to SUS seal flanges of each ports.

Module power test
Cavity performance does not always get worse in the cryomodule! By controlling the cooldown rate the $R_{surf}$ can be reduced significantly.
Performance Improvement in Cryomodule

SRF 2009 – World Record Tesla 9 cell Q - HZB

Cavity performance does not always get worse in the cryomodule!
By controlling the cooldown rate the $R_{surf}$ can be reduced significantly.

Influence of thermal cycling on $R_{surf}$

TUIOA01 Influence of Cooldown on Cavity Quality Factor - Kugeler
TUIOA02 – High Qo Research, The Dynamics of Flux Trapping in SC Niobium - Vogt

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Performance Improvements 2

Cornell Linac Cavity HTC

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

HTC-I: Q0 = 3.5E10 without coupler

HTC-II: Q0 = 2.1E10 (reached with coupler)

HTC-III: Q0 = 6.1E10 (with coupler and HOM absorbers, after cavity reprocessing from HTC-II)

Data courtesy of Ralf Eichhorn

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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.