PROGRESS ON SUPERCONDUCTING RF FOR THE CORNELL ENERGY-RECOVERY-LINAC

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Cornell is developing the technology for an Energy Recover Linac (ERL) based x-ray light source.

- An ERL injector prototype has been developed, fabricated, and is currently under commissioning.
- Design work on the main linac cryomodule has started.
Outline

• Superconducting RF for the ERL injector
  – Challenges and solutions

• Superconducting RF for the ERL main linac
  – Challenges and solutions

• Summary and outlook
Superconducting RF for the ERL Injector
The High Current Cornell ERL Injector

**Superconducting RF for the ERL Injector**

- Photocathode
- DC gun
- Buncher
- Cryomodule
- Experimental beam lines
- Deflector
- Beam dump

**Design Parameters**

<table>
<thead>
<tr>
<th>Nominal bunch charge</th>
<th>77 pC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bunch repetition rate</td>
<td>1.3 GHz</td>
</tr>
<tr>
<td>Beam power</td>
<td>up to 550 kW</td>
</tr>
<tr>
<td>Nominal gun voltage</td>
<td>500 kV</td>
</tr>
<tr>
<td>SC linac beam energy gain</td>
<td>5 to 15 MeV</td>
</tr>
<tr>
<td>Beam current</td>
<td>100 mA at 5 MeV, 33 mA at 15 MeV</td>
</tr>
<tr>
<td>Bunch length</td>
<td>0.6 mm (rms)</td>
</tr>
<tr>
<td>Transverse emittance</td>
<td>&lt; 1 mm-mrad</td>
</tr>
</tbody>
</table>

**Achieved so far**

- Nominal bunch charge: 77 pC
- Bunch repetition rate: 50 MHz and 1.3 GHz
- Beam power: 125 kW
- Nominal gun voltage: 350 kV
- SC linac beam energy gain: 5 to 15 MeV
- Beam current: 25 mA
- Bunch length: 0.6 mm (rms)
- Transverse emittance: < 1 mm-mrad

**World record for CW injector current!**

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ERL Injector: Technical Components

- Superconducting RF for the ERL Injector
- DC Gun
- SRF Injector Cryomodule
- 135 kW cw Klystrons (e2v)
- Beam Diagnostics
- Cold Box
- Gun Laser

Matthias Liepe, PAC 2011, New York, NY
The Cornell ERL Cryomodule

- **1.3 GHz RF cavity**
- **HOM beamline absorber at 80K between cavities**
- **Twin Input Coupler**
- **HGRP system with 3 sections**

**Parameters:**

- **Number of 2-cell cavities:** 5
- **Acceleration per cavity:** 1 – 3 MeV
- **Accelerating gradient:** 4.3 – 13.0 MV/m
- **R/Q (linac definition):** 222 Ohm
- **Q_{ext}:** 4.6×10^4 – 4.1×10^5
- **Total 2K / 5K / 80K loads:** 30W / 60W / 700W
- **Number of HOM loads:** 6
- **HOM power per cavity:** 40 W
- **Couplers per cavity:** 2
- **RF power per cavity:** 120 kW
- **Amplitude/phase stability:** 10^{-4} / 0.1° (rms)
- **ICM length:** 5 m
ERL Injector Module Assembly at Cornell

Beamline in clean room

Gate valve internal to cryomodule

Cleanroom assembly fixturing

Vacuum vessel interface flange

Cold mass assembly

1100 aluminum 80K shield

5K manifold

2K 2-phase pipe

Magnetic shield II

80K shield

Beam entrance gate valve

80K shield

1100 aluminum 80K shield

Instrumentation ports

RF coupler ports
ERL Injector SRF: Key Challenges

1. Limit emittance growth of the very low emittance beam in the injector module (essential for ERL x-ray performance)

2. Support high beam current operation up to 100 mA with short (2 ps) bunches

3. Transfer up to 100 kW of CW RF power per cavity to the beam

4. Provide excellent RF field / energy stability
Avoid transverse kick fields:

- Symmetrized beam line in injector module
  - Excellent cavity alignment (±0.5mm required, ±0.2mm achieved)
Fixed High Precision Cavity Support and Alignment

- High precision supports on cavities, HOM loads, and HGRP for “self” alignment of beam line
- Only very rough initial alignment is needed when beamline is assembled in clean room
- **Cavity string is aligned to ±0.2 mm after cooldown!**

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High Current Operation and HOMs

- HOM damping and HOM spectra measurements confirm excellent damping with **typical Qs of a few 1000**
- Total HOM power measurement gives longitudinal loss factor in good agreement with ABCI simulations
- Successfully operated injector SRF module with **beam currents of 25 mA**
  - $\Delta T$ of HOM absorbers small (<0.5K). **Module should easily handle operation at >100 mA.**

See paper TUP063
SRF Cavities and High RF Input Power

- SRF cavities meet gradient spec and have transferred >25 kW cw each to the beam
- Individual input couplers processed up to 25 kW cw
- Prototypes tested up to 60 kW cw, 80 kW pulsed
Excellent field stability achieved: \( \sigma_A/A < 2 \times 10^{-5} \) (in loop measurements)

\( \sigma_P < 0.01 \text{ deg} \)
Superconducting RF for the ERL Main Linac
Cornell ERL Main Linac

- 5 GeV total, 384 cavities
- 13 MV per cavity (~16 MV/m)
- 64 identical cryomodules, each with 6 cavities and a single quadrupole magnet
- Two continuous linac sections:

<table>
<thead>
<tr>
<th>Cavities per cryomodule</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cryomodules per linac</td>
<td>35 / 29</td>
</tr>
<tr>
<td># linacs</td>
<td>2</td>
</tr>
<tr>
<td># cavities</td>
<td>384</td>
</tr>
<tr>
<td># cryomodules</td>
<td>64</td>
</tr>
<tr>
<td>Cryomodule length [m]</td>
<td>9.82</td>
</tr>
<tr>
<td>Linac length [m]</td>
<td>344 / 285</td>
</tr>
<tr>
<td>Total active length [m]</td>
<td>~310</td>
</tr>
<tr>
<td>Module Filling factor</td>
<td>0.49</td>
</tr>
<tr>
<td>Final energy [GeV]</td>
<td>5.0</td>
</tr>
<tr>
<td>Gradient [MV/m]</td>
<td>16</td>
</tr>
</tbody>
</table>

= 0.25m Cold-warm transition

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Cornell ERL Main Linac Cryomodule

- Number of 7-cell cavities: 6
- Acceleration gradient: 16.2 MV/m
- R/Q (linac definition): 774 Ohm
- Qext: $6.5 \times 10^7$
- Total 2K / 5K / 80K loads: 76W / 70W / 1500W

- Number of HOM loads: 7
- HOM power per cavity: 200 W
- Couplers per cavity: 1
- RF power per cavity: 5 kW
- Amplitude/phase stability: $10^{-4}$ / 0.05° (rms)
- Module length: 9.8 m

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Main Linac SRF: Key Challenges

1. Support efficient CW cavity operation with high dynamic cryogenic loads
2. Support high beam current ERL operation up to 2x100 mA with short (2 ps) bunches
3. Efficiently operate the SRF cavities at a high loaded quality factor $Q_L \geq 6.5 \times 10^7$ while still achieving excellent RF field stability.
Main Linac Cryomodule Design

- Fixed, high precision supports for the cavities and the HOM loads
- One thermal shield at ~40K
- Cryogenic manifolds sized for high dynamic heat loads
- Three layers of magnetic shielding
Magnetic Shielding at Residual Resistance

B < 3 mG -> contribution to $R_{res} < 1 \text{n}\Omega$
ERL Main Linac Cavity: RF Design (I)

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Superconducting RF for the ERL Main Linac

Coupler kick compensation

Cell shape optimization for high R/Q of fundamental mode and strong HOM damping

Dipole mode damping calculated up to 10 GHz with realistic RF absorbers
ERL Main Linac Cavity: RF Design (II)

- Relaxed cavity shape tolerances:
  - increase the HOM frequ. spread
  - increase the risk of trapped HOMs
- Solution:
  - use several classes of cavities, which are small, controlled variations of the baseline 7-cell cavity design
  - yields threshold current >4 times above design value

See paper TUP064
ERL Main Linac Cavity: Mechanical Design and Prototyping

- Cavity was optimized for low microphonics
- Stiffening rings between the cells
  - reduce sensitivity of the fundamental mode frequency to changes in the LHe bath pressure (main source of cavity microphonics)
- Prototype cavities under fabrication
  - will be tested without and with beam in test/prototype cryomodules.

Sensitivity to pressure changes

Precision of cell shape (±0.2 mm)
Two reliable RF absorbing materials meeting all specifications have been identified:

- graphite loaded SiC,
- carbon-nanotube loaded ceramics
ERL Main Linac: Other Components

- Simplified 5 kW CW input coupler
- Superconducting magnet package
- Cold tuner (slow and fast piezo driven)
Demonstrated highly efficient operation of a full 9-cell cavity at very high loaded quality factors up to $2 \cdot 10^8$ (Test of Cornell’s LLRF system at HoBiCaT at HZB)

- Exceptional field stability: $\sigma_A/A < 1 \cdot 10^{-4}$, $\sigma_\phi \sim 0.01^\circ$
- Fast RF field ramp up in 0.5 s to high fields with piezo tuner
Active Microphonics Compensation

Piezo feedback on cavity frequency (ERL injector cavity):

⇒ Reduced rms microphonics by up to 70%!
⇒ Important for ERL main linac, where $Q_L > 5 \cdot 10^7$ and $P_{RF} \propto \Delta f$!
Summary and outlook
• ERL injector cryomodule:
  – Designed, constructed, and successfully tested
  – Cryogenics, cavity alignment, cavity voltage, input couplers, LLRF field control, and HOM damping all meet or exceed specs
  – 25 mA cw beam accelerated to 5 MeV; should easily support 100 mA operation
Summary and Outlook

- ERL main linac cryomodule:
  - Module design well underway
  - Cavity design optimized for high currents and efficient cavity operation; cavity fabrication has started
  - Plan:
    - One cavity test module: starting 2012, including beam test
    - Full prototype main linac module in ~4 years
End

Thanks for your attention!