Design and Construction Experiences for the Cornell ERL Injector and Main Linac Cryomodules

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The Cornell Energy Recovery Linac Project

- Cornell is pursuing funding for a Energy Recover Linac (ERL) based x-ray light source.
- A project design and description report is completed.
- An ERL injector prototype has been developed, fabricated, and is currently under commissioning.
- Design work on the main linac cryomodule has started.
Outline

- What is needed from an ERL cryomodule?
- Cornell ERL cryomodules: An overview
  - Design philosophy
  - The injector cryomodule
  - The main linac cryomodule
- Cavity support and alignment
- Magnetic shielding for high $Q_0$
- Cryogenics and thermal shield
- Mechanical design and microphonics
- Other design changes compared to FLASH/XFEL modules
- Summary and outlook

- Not discussed: Beamline design and performance
What is needed from and ERL Cryomodule?

- Provide good cavity alignment (<0.5 mm)
- Provide excellent magnetic shielding for high $Q_0$
- Minimize cavity vibration and coupling of external sources to cavities to support efficient cavity operation with high loaded $Q_L$ (no effective beam loading in main linac)
- Intercept significant heat loads from cw operation with high (100 mA) beam current (dynamic cavity load; HOM power; high RF input power in injector)
- High reliability
- Minimize cost (construction and operational)
Cornell ERL cryomodules: An overview

The injector cryomodule
The main linac cryomodule
Design Philosophy

• Use the same cryomodule concept in the injector and the main linac.
  – Reduces risk
• Rely on well established and tested performance of the TTF III technology to reduce risk, cost and minimize development time.
  – Many improvements
  – Cavities supported by large diameter Helium-gas return pipe (HGRP)
  – All cryogenic piping inside of cryomodule
  – Some changes needed for ERL specific needs
• Further simplify and reduce cost.
The Cornell ERL Injector

Nominal bunch charge: 77 pC
Bunch repetition rate: 1.3 GHz
Beam power: up to 550 kW
Nominal gun voltage: 500 kV
SC linac beam energy gain: 5 to 15 MeV
Beam current:
- 100 mA at 5 MeV
- 33 mA at 15 MeV
Bunch length: 0.6 mm (rms)
Transverse emittance: < 1 mm-mrad

Achieved so far:
- 77 pC
- 50 MHz and 1.3 GHz
- 125 kW
- 350 kV
- 5 to 15 MeV
- 25 mA

World record for CW injector current!
ERL Injector: Technical Components (I)

Cornell ERL cryomodules: An overview

- SRF Injector Cryomodule
- 135 kW cw Klystrons (e2v)
- DC Gun
- 120 W @2k Pumping Skid
- Cold Box
- Gun Laser
ERL Injector: Technical Components (II)

SF6 tank

DC gun

Diagnostics section
- emittance measurement systems
- deflecting cavity
- view-screens
- BPMs, BLMs, Faraday-cups, …

100 mA, 5 MeV SRF module
5 x 2-cell 1.3 GHz cavities
The Cornell ERL Cryomodule

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

**Specifications**:

- **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
- **Qext**: $4.6 \times 10^4 – 4.1 \times 10^5$
- **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**: $10^{-3} / 0.1^\circ$ (rms)
- **ICM length**: 5 m
ERL Injector Module Assembly at Cornell

Beamline in clean room

Cleanroom assembly fixturing

Gate valve internal to cryomodule

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

1100 aluminum
80K shield

Instrumentation ports

RF coupler ports

Cornell ERL cryomodules: An overview
ERL Injector Module Assembly at Cornell

Insight from the Assembly:
- Assembly revealed no significant problems
- Fast, easy assembly (once we had all parts)
- Fixed cavity alignment concept works well
- Full 3D modeling (including assembly drawings) extremely helpful
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>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cavities per cryomodule</td>
<td>6</td>
</tr>
<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>
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<tr>
<td>Linac length [m]</td>
<td>344 / 285</td>
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<tr>
<td>Total active length [m]</td>
<td>~310</td>
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<tr>
<td>Module Filling factor</td>
<td>0.49</td>
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<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
Cornell ERL Main Linac Cryomodule

- Number of 7-cell cavities: 6
- Acceleration gradient: 16.2 MV/m
- R/Q (linac definition): 774 Ohm
- Qext: 6.5×10^7
- 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
Cavity support and alignment
High precision supports (with keys, pins) on cavities, HOM loads, and HGRP for “self” alignment of beam line components.

Only very rough initial alignment is needed when beamline is assembled in clean room.

No final alignment needed (excellent warm alignment was verified at injector beamline).
ERL Injector Cavity Support (II)

- String is raised and the precision mounting surfaces on the string and the HGRP are brought together with alignment keys and pins being engaged.
- “Self” alignment proved to be quick and easy for the injector beam line (<1 hour)
Shift of cold mass (from Wire Position Monitor):

- Expected: $\Delta x = 0.38 \text{ mm}$
  $\Delta y = 0.94 \text{ mm}$
- Observed: $\Delta x = 0.58 \text{ mm}$
  $\Delta y = 0.81 \text{ mm}$

Cavity string is aligned to ±0.2 mm after cooldown!

- Cavity support and alignment concept works very well!
ERL Main Linac Cavity Support

- Titanium HGRP in two sections (connected by bellow) with 4 support posts per module acts as main support of beam line components
  - Simplifies design (fewer bellows, transitions to stainless steel)
  - Fewer bellows -> rigid design (good for low microphonics)
  - Smaller thermal contraction -> simplifies design
  - Sections (and cavities) can be re-aligned at 2K if needed

- Beamline is aligned via high precision mounting surfaces on HGRP as in injector module
• Simple, fixed high precision supports for the cavities and the HOM loads (bolted to HGRP) as in ERL injector module

• ERL main linac uses simple, low power, fixed input couplers
  – Easy to include flexibility for transverse deflection
  – Cavities can shift longitudinal relative to vacuum vessel by up to 1 to 2 cm
Magnetic shielding for high $Q_0$
Magnetic Shields

- Excellent magnetic shielding essential for high $Q_0$ in cw operation ($B < $ few mG at cavities)
- Use three layers of magnetic shielding
- ERL injector module:
  - Magnetic shield on outside of 80 K shield (Stainless steel vacuum vessel)
  - Two, spaced layers of magnetic shields on outside of cavity LHe tank
- ERL main linac module:
  - Carbon steel vacuum vessel
  - Inside of vacuum vessel lined with magnetic shield
  - Magnetic shields on outside of cavity LHe tank
Residual Magnetic Field Measurement at the Injector Test Module (at Room Temperature)

Axial magnetic field on axis, $B_z$

$B < 3 \text{ mG}$
Cryogenics and thermal shield
1.8K, 5K, 40 – 80 K Systems

**ERL Injector**
- Support post alignment
- Rails
- Support post alignment
- 80K return
- 80K supply
- 5K return
- 2K – 2 phase line
- HOM support
- Vacuum vessel
- He Gas Return Pipe
- 5K supply
- 80K supply
- 80K return
- Warm-up/Cool-down tube
- Wire position monitor
- HOM load
- Mumetal Shields
- Cryoperm

**ERL Main Linac**
- Support post
- Vacuum vessel
- HGRP
- Beam axis
- 40K shield

- **1.8 K** (HGRP, 2-phase, warm-up/cool down, 2K forward)
- **5 K** (forward and return)
- **40 – 80 K** (3 pipes)
Thermal Shields

- One thermal shield at ~40K (grade 1100 aluminum) with extruded supply pipe
- No 5K shield (not economical with high 1.8 K loads in cw cavity operation)

**With a 5K Shield:**
- 80K radiation load to a 5K shield = 0.656 [W] per module
- 64 module 5K shield load = 42 [W]
- 5K shield have linac wall-plug = 8.3 [kW]

**Without a 5K Shield:**
- 80K radiation load to 1.8K = 1.14 [W] per module
- 64 modules have 1.8K radiation load = 73 [W]
- 1.8K radiation linac wall-plug = 52.4 [kW]

**Conclusion:**
A 5K shield would provide linac wall-plug saving = 52.4 - 8.3 [kW] = 44.1 [kW]

**5K shield savings wall-plug [W]**

| electricity cost [$/kW/hr] | $0.20 |
| Linac avg duty cycle | 0.85 |
| Linac [$/yr] | $65,673.72 |
| # modules | 64 |
| Module [$/yr] | $1,026.15 |
| Estimate 5K shield material & labor per module [$] | $30,000.00 |
| Utility payback [yrs] | 29.2 |
1.8 K System in the Main Linac

- High 1.8K load (~80W) for cw cavity operation
  - Individual 2-phase line in each module with JT valve
  - Connection from 2-phase line to HGRP in middle of module to symmetrize gas flow and minimize gas velocity (stratified flow!)
  - Diameter of 2-phase line and connection to LHe vessel increased to >10 cm to keep gas velocity below 1 m/s and heat flux < 1 W/cm²

Matthias Liepe, TTC Meeting, February 28-March 3 2011, Milano, Italy
5 K and 40 – 80 K System

• Large diameter (~3”) supply lines along entire linac
  – 3 line layout gives ~uniform pressure drop (and thus flow) though large number (~100) of local heat exchangers, connected to supply lines in parallel

• Small diameter distribution pipe supply gas to local heat exchangers where needed (copper stripes used to intercepts smaller head loads)
5 K and 40 – 80 K System in the Injector Module

- 5K distribution to heat exchanger
- 5K supply
- 80K distribution to heat exchanger
- 80K supply

Cryogenics and thermal shield
Mechanical design and microphonics
Number of Support Posts

- HGRP needs to be straight to give good alignment of beamline
- 4 support posts gives factor of 2-3 smaller deformations of HGRP and stiffer structure with higher mechanical resonances
- Two ~ 5 m long HGRP sections per module give minimal deflection of HGRP from weight of beamline (<0.07 mm)
- Maximum relative shift at support post flanges on vacuum vessel: 0.05 mm
Mechanical Coupling Characterization
Measurements with a Modal Shaker

Shaker on module support

![Graph showing vibration frequency vs. response amplitude for different cavities.]

Shaker on module top (HGRP support)

![Graph showing vibration frequency vs. response amplitude for different cavities.]
Mechanical Coupling Characterization
Measurements with a Modal Shaker

<table>
<thead>
<tr>
<th>Excitation Point</th>
<th>Excitation Force</th>
<th>Detectable With Cavity Accelerometer</th>
<th>Detectable On Cavity RF Frequency (&gt;0.1Hz modul.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coupler Waveguide</td>
<td>110 N (25 lbs)</td>
<td>No</td>
<td>No</td>
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<tr>
<td>Coupler</td>
<td>110 N (25 lbs)</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Cryomodule Saw-Horse Support</td>
<td>110 N (25 lbs)</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Helium Gas Return Pipe Support</td>
<td>110 N (25 lbs)</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Beam Line</td>
<td>10 N (2 lbs)</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Helium Supply/Return</td>
<td>110 N (25 lbs)</td>
<td>No</td>
<td>No</td>
</tr>
</tbody>
</table>

- Ground vibrations and other mechanical vibrations do **not** strongly couple to the SRF cavities
- Main contribution to cavity microphonics comes from fast fluctuations in the He-pressure and the cryogenic system
Microphonics driven by the Cryogenic System in the ERL Injector Module: How things can go wrong...

- Significant changes over time
- Step impulses at second scale repeat rate!

After setting up flow through warm up – cool down pipe
Microphonics driven by the Cryogenic System in the ERL Injector Module: How things can go wrong...

Source of “bursts”:
Thermo-acoustic oscillations in Warm Up – Cool Down plumbing

Closed end (valve) creates dead end with trapped gas
Other design changes compared to FLASH/XFEL modules
Other changes compared to a TTF cryomodule: Gate Valves

Gatevalves at module ends are inside of module with actuator outside of module
Access Ports in the Vacuum Vessel

- Access ports in the vacuum vessel allow the tuner stepper motor, piezos, cables... to be accessible for repair without removing the cold mass.
Cold-Mass Rail System

- Rails mounted on the inside of the vacuum vessel and rollers on the composite support posts are used to insert the cold mass into the vacuum vessel.
Cold mass rolled into vacuum vessel (ERL Injector)
Summary and outlook
• ERL injector cryomodule:
  – Designed, constructed, and 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

• ERL main linac cryomodule:
  – Design underway: fixed, high precision cavity support; 3 layers of magnetic shielding; optimized for low cavity microphonics; cryogenic manifolds for high loads
  – Cavity fabrication has started
  – Goal: Full module ready for test in ~3 to 4 years
End

Thanks for your attention!