Considerations for the Cornell ERL Linac

Matthias Liepe, Georg Hoffstaetter
Cornell University
ERL Cryomodule Challenges

Operate high voltage SRF cavities CW
  Very reliable operation essential
  Avoiding excessive cryogenic loads
  Minimize RF drive power

Accelerate a high beam current
  Avoiding beam instability and excessive HOM losses
  Dispose high HOM power safely

Preserve beam emittance
  Small wake fields
  Good cavity alignment
  Small transverse kick fields
  Beam especially vulnerable in the low energy injector

Operation with very large loaded Q
  Control for very small resonance width
  Minimization of microphonics
ERL vs. ILC Linac vs. Rings

**ERL vs ILC**

Average HOM power $\propto q_{\text{bunch}} \times I$
- factor 100

Peak HOM power in resonant excitation $\propto I^2$
- factor $4 \cdot 10^6$

2K dynamic cavity load $\propto E^2 \cdot \text{duty factor}$
- factor 50

Cavity bandwidth $\propto 1/Q_{\text{ext}}$
- factor 0.05

**ERL vs. Rings**

Average HOM power $\propto q_{\text{bunch}} \times I$
- factor 0.05 (but at 300K)

Peak HOM power in resonant excitation $\propto I^2$
- factor 1

2K dynamic cavity load $\propto E^2 \cdot \text{duty factor}$
- factor 10

Cavity bandwidth $\propto f/Q_{\text{ext}}$
- factor 0.01
Some ERL linac parameters

- Single-Pass Linac Max Energy: 5 GeV
- total linac length: 711 m
- Geometric fill factor: 44%
- Injection Energy: 15 MeV
- Single-Pass Average Current: 100 mA
- Bunch Charge: 77 pC
- Bunch Length in Linac: 2 RMS ps
- Single-Pass Bunch Rep. Rate: 1.3 GHz
- Total number of cavities: 390
- Cavity frequency: 1.3 GHz
- Active Cavity Length: ≈ 0.8 m
- Number of Cells: 7
- Average Accelerating gradient: 16 MV/m
- Max. Accelerating gradient: 20 MV/m
- E_peak/E_acc: <2.4
- B_peak/E_acc: shape
- Average Unloaded Quality (Q_0): 2\times10^{10}
- Min Unloaded Quality (Q_0): 1\times10^{10}
- External Quality (Q_ext): 6.5\times10^{7}
- Full Bandwidth (f_0/Q_L): 20 Hz
- Impedance per cavity (circ. Def.): 400
- Lorentz-Force Det. Constant: 1
- Expected peak Detuning: <20 Hz
- Cavity Loss Factor (V/pC): 11
- Cavity offset tolerance: 1 mm
- Cavity angle tolerance: 1 mrad
- Average HOM Power: 170 W
- Max. HOM power per load (design): 200 W
- Operating temperature: 1.8K
- Average 1.8K Static Heat Load/Cavity: 0.5 W
- Average 1.8K Dyn. Heat Load/Cavity: 10 W
- Max. 1.8K Load in some Cavities: 32 W
- Total 5 K static load: 2.3 kW
- Total 5 K dynamic load: 3.4 kW
- Total 80 K static load: 5 kW
- Total 80K dynamic load: 70 kW
- Ave RF Power/Cavity: 2 kW
- Peak RF Power/Cavity: 5 kW
- Number of Cavities/RF Unit: 1
- Bunch to bunch energy fluct.: 2\times10^{-4}
- Field Ampl. Stab. uncorrelated. (rms): 5\times10^{-4}
- Field Ampl. Stab. correlated. (rms): <1\times10^{-4}
- Field phase stab. uncorrelated (rms): 0.15 deg
- Field phase stab. correlated (rms): 0.02 deg
- Coupling range (Q_ext): 2\times10^{7} - 2\times10^{8}
- Number of Cavities per Module: 5
- Number of BPMs per module: 1
- Number of gate valves per module: 2
- Number of quads per module: 1
- Number of kickers per module: 1
- Number of modules: 78
- Length per module: 9.1 m
Cryomodule components: (1) Cavity

- Support Posts
- Piezo Tuners
- Cold Part of RF Power Coupler
- Cold He Gas Return Pipe
- 2K Liquid Supply Line
Cryomodule components: (2) Coupler

- Support Posts
- Piezo Tuners
- Motorized Frequency Tuner
- Cold He Gas Return Pipe
- 2K Liquid Supply Line
Cryomodule components: (4) HOM absorbers

- Support Posts
- Cold He Gas Return Pipe
- Piezo Tuners
- Cold Part of RF Power Coupler
- Motorized Frequency Tuner
- 2K Liquid Supply Line
Cryomodule components: (5) Quadrupoles
Cavities

Parameters:

1) Challenge of low dynamic loss leads to
   a) Optimized cavity shape
   b) large $Q_0 = 2 \times 10^{10} /$ operating temperature $= 1.8K$

2) Challenge of low total cost and high operational stability leads to
   a) Operating voltage $= 16$MV/m

3) Challenge of high current leads to
   a) Number of cells $= 7$
   b) Beam pipe diameter to HOM absorber $= 53 / 39$mm

4) Challenge of low emittance growth leads to
   a) Summarizing input coupler region by a stub to limit coupler kick
   b) Cavity alignment tolerance $= 1$mm (needs more detailed study)
1.3 GHz center-cell:

- Cells optimized for fixed side wall angle (≤ 82 deg) and electric peak field (E/E_{acc} ≤ 2.2), maximizing Rs.

Comparison of 1-Cell Geometries

**R/Q*G**

- **Single cell**
  - Iris radius [cm]
  - Loss factor [V/pC]
  - Cooling power [kW]

**7-cell cavity**

**Total cooling power (fund. mode + HOM at 80K)**
- 16 MV/m, 2*100 mA
Optimal temperature

1 nΩ residual resistance
(Corresponds to $Q_0 = 3 \times 10^{11}$ at low T)

7 nΩ residual resistance
(Corresponds to $Q_0 = 4 \times 10^{10}$ at low T)

AC power per active meter [arb. units]

Temperature [K]

$\Rightarrow 1.8$K. Note: Lower T is unproven and might cause instability in the cryo-system.
Total SRF construction cost (Linac, tunnel, cryo)

Field gradient [MV/m]

Cost [arb. Units]

165
160
155
150
145
140
135
10
15
20
25

Cavity Q₀

Field gradient [MV/m]

σ₀

10¹¹
10¹⁰
10⁹
0
5
10
15
20
25

Additionally, the operational stability improves with lower voltage!

⇒ Average operation at 16 MV/m
Operation spec: 16 MV/m

But to have sufficient safety margin we design the Cryomodule for:

- max. supported gradient by cryo module: 20 MV/m at $Q = 1 \cdot 10^{10}$
- RF power installed for 20 MV/m, 20 Hz peak detuning = 5kW / cavity
- Min. (guaranteed) cavity performance in linac: 16 MV/m at $Q = 2 \cdot 10^{10}$
- Average cavity performance in linac: 18 MV/m at $Q = 2 \cdot 10^{10}$ with ±2 MV/m spread to allow loosing 4 cryomodules.
- 5GeV requires 390 seven-cell cavities!
- ⇒ Can use BCP cavities (Q-lope starts at ≈ 20 MV/m)

- This provides more than 10% safety margin
Trapped dipole HOMs in 9 cell cavities

Figure 5: Trapped dipole mode (comp. Figure 4) no. 40 ($f = 3.084$ GHz MAFIA; 3.078 GHz meas.), mode no. 87 ($f = 4.323$ GHz MAFIA; 4.314 GHz meas.) and mode no. 95 ($f = 4.426$ GHz MAFIA; 4.421 GHz meas.).
Trapped dipole HOMs in 9 cell cavities

\[(R/Q)Q_f \quad [\Omega MHz]\]

Mode #
Dimensions are optimized to reduce $Q^*(R/Q)$ of worst HOM until as many HOMs as possible are about equal.

Example: End cell shape has significant impact

Limitations of these optimizations:
- **HOMs couple through large beam tubes:**
  - Some modes will have high $R/Q$
  - Difficult to simulate. Actual $R/Q$ strongly impacted by fluctuation in cavity shapes
- **Still to be analyzed:** Coupling of main input coupler to HOMs.
7 cell design philosophy

- **Design approach:**
  - Optimize center and iris radius cell for power loss (started).
  - Optimize end cells for HOM damping
  - Optimize mechanical layout for low microphonics in final design
  - Input coupler region design (coupling, kicks, …)

- **Still needs significant work for Cornell ERL!**

- **Polarized cavities have been analyzed to suppress BBU but have been ruled out for now**
Reliability study for 7 cell cavities

- Collaborative development (Daresbury, Cornell, LBNL) for an advanced high-$Q_0$ cavity and cryomodule system for ERLs ($I=100$ mA)
- Housed in a modified Stanford/Rossendorf cryomodule
- Beam test on ERL-P in 2008 / possibly at Cornell with 100mA?
Microphonics and the optimal Q

- Cavity and cryostat design for low microphonics
- Active frequency control (fast frequency tuner)
- Lacking detailed knowledge, we work with 20Hz peak detuning.

Higher Q $\rightarrow$ less power needed
Detuning $\rightarrow$ more power needed especially for larger Q
Measured microphonics levels

<table>
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<tr>
<th>Machine</th>
<th>$\sigma$ [Hz]</th>
<th>$6\sigma$ [Hz]</th>
<th>Comments</th>
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<tr>
<td>CEBAF</td>
<td>2.5 (average)</td>
<td>15 (average)</td>
<td>significant fluctuation between cavities</td>
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<tr>
<td>ELBE</td>
<td>1 (average)</td>
<td>6 (average)</td>
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<tr>
<td>SNS</td>
<td>1 to 6</td>
<td>6 to 36</td>
<td>significant fluctuation between cavities</td>
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<tr>
<td>TJNAF FEL</td>
<td>0.6 to 1.3</td>
<td>3.6 to 7.8</td>
<td>center cavities more quiet</td>
</tr>
<tr>
<td>TTF</td>
<td>2 to 7 (pulsed)</td>
<td>12 to 42 (pulsed)</td>
<td>significant fluctuation between cavities</td>
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</tbody>
</table>

\[
Q_{L,\text{optimal}} = \frac{1}{2} \frac{f_0}{\Delta f}
\]

\[
P_{g,\text{minimal}} = \frac{V_{acc}^2}{2R/Q} \frac{\Delta f}{f_0}
\]

- Assume optimistic 10 Hz as typical detuning ($\leq$ 20 Hz peak).
- $\Rightarrow Q_L = 6.5 \cdot 10^7$

- This minimizes the typical (average) power need, not the maximum power that has to be available.
Mechanical frequencies

\[ R_{ring} = 0.65 \times \text{equator radius (Req)} \]

<table>
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<tr>
<th>ring</th>
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<th>freq / Hz</th>
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<td>8</td>
<td>549.51</td>
<td>394.77</td>
<td>456.85</td>
<td>319.34</td>
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</table>

Courtesy E. Zapatin
Low microphonics cavity design

- **Cavity design:**
  - Low sensitivity to He-pressure changes (of 0.1-1 mbar)
  - High mechanical vibration frequencies

- **Module design:**
  - High mechanical vibration frequencies
  - Decouple module from vibration sources
  - This vibration analysis has been done for the ERL injector, but not for the main linac yet.

[Graph showing frequency shift for different wall thicknesses.]

Caption: 1 bar pressure

*Courtesy E. Zaplatin*
Frequency tuners

- Fast frequency tuning (piezo tuner) essential for realistic microphonics and $Q_L > 3 \times 10^7$.

- Injector frequency tuner (modified INFN type) is a prototype for main linac tuner (Although $Q_L=10^4$, it is equipped with piezos for R&D).

- Future work:
  - Detailed studies of mechanical behavior (cavity + He-vessel + tuner)
  - Design modifications to lower cost
Couplers

- Peak power: 5 kW
  - Modified TTF coupler (3 kW average).
  - Modified injector coupler (reduced cooling, design modified for lower static loads)
  - Some modifications are similar to the changes needed for the 50kW ERL injector coupler.
Coupler Kicks

(1) Kick cancellation by symmetry

(2) Kick cancellation by a more symmetric coupler region
Higher order mode absorbers

- Cold beamline HOM absorbers between cavities
  - Adopted from the SRF ERL injector prototype (larger beam tubes for BBU):
  - End cells and tubes optimized for good HOM power extraction
  - All higher-order monopole, dipole and quadrupole modes propagate in beam tube
  - But: Higher current (200 vs 100mA) and longer cavities (7 vs 2 cells)
    ⇒ More power needs to be absorbed (170 vs 30W)
  - Resonant HOM excitation can result in a few 10W for a few cavities and the design therefore needs to work for > 200W.

- Future work:
  - Material studies
  - Improved and simplified design for higher power handling and reduced fabrication cost
• An optics for 10MeV to 5GeV and simultaneously 5GeV to 10 MeV can easily be found by letting the 5GeV beam drift through the first week quadrupoles.
• The decelerating optics is very close to the mirror image of the accelerating optics.
• The optics uses two quadrupoles after 10 cavities, each ...cm long and ... and ... apart.
Cryomodule needs

- **Cryomodule needs to**
  - Provide good cavity alignment (<1mm)
  - Minimize cavity vibration and coupling of external sources to cavities
  - Provide good magnetic shielding
  - Support cw cavity operation with high loads

- **Injector cryomodule serves also as main-linac module prototype**
  - Same cross section
  - All cryo-pipes designed for main linac loads
  - No Nitrogen cooling, but He gas for 80K
  - Piezo tuners provided as needed for much larger loaded Q
• **Differences to ILC**
  - No 5K shield for ERL because dynamic load >> static load
  - Narrow He-gas pipes to HOM loads
  - 3 magnetic shields (vs 1) for larger Q0
  - Ti - He return pipe to support cavities, no sliding support
  - Modified to easily exchange tuner motor
  - Piezo
  - Gate valve drives outside the module
  - Larger pipes for cw operation
  - Connect both ends of 2-phase line with He-return pipe to limit gas velocity.
Pipe sizes limit maximum heat load:

- Heat transfer in He-II (< 1 W/cm²)
- Vapor velocity in 2-phase lines
  (stratified flow ⇒ < 4 m/s)
- Pressure drop in pump lines

⇒ Careful module design essential!

⇒ Simulation has been done to specify pipe dimensions. There are used for the Cornell ERL injector prototype.
### Module length

**Most up to date Module:**
(Shortened for transportability, not the module for which optics and layout was designed)
- Five 7-cell cavities
- 6 HOM loads
- 1 quad
- 1 kicker (v. or h.)
- 1 BPM
- 2 gate valves

**Length = 9 m**

**Active length = 4 m**

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• Full main linac module design based on injector module design.

• Open issues:
  – Verification of HOM load operation
  – Verification of magnetic shielding for highest $Q_0$
  – Design optimization for low microphonics
  – Study best way to regulate cooling of HOM loads individually
  – Synchrotron radiation shielding of cavities
  – Beam collimation. Beam loss, radiation, and heating (especially for cavities at linac end)
Conclusion

- The parameters for the Cornell ERL main linac are challenging, but well motivated.
- High $Q_0 = 2 \times 10^{10}$ at 1.8K seems not unachievable, but needs verification.
- Amplitude and phase control for $Q_L = 10^8$ has been tested satisfactorily.
- Cavity shape has been optimized.
- HOM absorbers have been optimized but need cost reduction.
- Tuners are designed and will be tested.
- Low microphonics design needs modeling and model/reality checks will be done in the Cornell ERL injector.

⇒ Lots of work remains to be done!
   Cornell is looking for preconstruction funding to verify the feasibility of the x-ray ERL cryomodule.