Experience with the Cornell ERL Injector SRF Cryomodule during High Beam Current Operation

Matthias Liepe
Assistant Professor of Physics
Cornell University
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.
ERL Injector: Technical Components

- SRF Injector Cryomodule
- 135 kW cw Klystrons (e2v)
- DC Gun
- Beam Diagnostics
- Cold Box
- Gun Laser

Matthias Liepe, ERL 2011
### The High Current Cornell ERL Injector

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

#### 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</td>
</tr>
<tr>
<td></td>
<td>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: 425 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!*

Matthias Liepe, ERL 2011
Outline

• SRF Cryomodule for the ERL injector
  – Beamline components, module design and assembly

• Operational Highlights: Pushing the Envelope
  – SRF cavity and coupler performance
  – High current operation

• Summary and outlook
SRF Cryomodule for the ERL injector

Beamline components, module design and assembly
The Cornell ERL Cryomodule

1.3 GHz RF cavity

- 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
- $Q_{\text{ext}}$: $4.6 \times 10^4 – 4.1 \times 10^5$
- 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: $10^{-4} / 0.1^\circ$ (rms)
- ICM length: 5 m

HGRP system with 3 sections
Frequency tuner
HOM beamline absorber at 80K between cavities
Twin Input Coupler

Matthias Liepe, ERL 2011
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
**Beam Line Components (I)**

### SRF cavities:
- Designed, fabricated, and tested at Cornell
- All cavities met 15 MV/m spec in vert. test (BCP only)

### RF input couplers:
- Design by Cornell for high cw power > 50 kW
- 2 prototypes tested up to 60 kW cw, 80 kW pulsed
**HOM absorbers:**

- Design by Cornell for strong, broadband HOM damping (1.5 GHz -> 100 GHz)
- >200 W power handling

**Frequency tuners:**

- Modification of the DESY/INFN blade tuner
- Added piezos for microphonics compensation (R&D)
ERL Injector Module Innovations (I)

- Tuner stepper replaceable while string is in cryomodule
- Rail system for cold mass insertion into Vacuum Vessel
- Gatevalve inside of module with outside drive

SRF Cryomodule for the ERL injector
ERL Injector Module Innovations (II)

- Precision fixed cavity support surfaces between the beamline components and the HGRP ⇒ easy “self” alignment
- Cavity-subunits can be fine-aligned while cavities are at 2K (if required)
ERL Injector Module Assembly at Cornell

Cold mass rolled into vacuum vessel

Cold mass insertion rail
Roller bearings on composite post supports
Top of 80K shield
Vacuum vessel interior wall

Vacuum vessel
Coupler and instrumentation ports
Cryogen supply and return plumbing
Support post transitions and alignment screws
Operational Highlights: Pushing the Envelope

SRF cavity and coupler performance
High current operation
Emittance Preservation and Cavity Alignment

- 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
  - Rigid, stable support
  - Shift of beamline during cool-down as predicted

- **Cavity string is aligned to ±0.2 mm after cool-down!**

Operational Highlights
Beam Emittance

• At low bunch charge (at 5 MeV):
  – Normalized emittance is close to thermal limit at cathode for given laser size: \( \varepsilon_N = 0.2 \) to \( 0.4 \) mm mrad

• At higher bunch charge (10 MeV, 77 pC):
  – \( \varepsilon_N = 0.8 \) mm-mrad for 100% beam (core emittance = 0.3 mm-mrad)
  – Increasing the gun voltage to 500 kV is expected to reduce this number further
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
• Measurements of cavity dynamic 1.8K head loads shows intrinsic Q’s of $5 \cdot 10^9$ to $1 \cdot 10^{10}$

• Expected: $Q \sim 1.5 \cdot 10^{10}$

• Source of increased RF losses?
Cavity “$Q_0$” vs. External $Q_{\text{ext}}$

- Measured impact of input coupler coupling on $Q_0$
  
  -> found losses increase with coupling

- Note: Operate at very low $Q_{\text{ext}}$ (high beam current)
  
  -> large RF power/field in input coupler

From This Plot:

$Q_0 > 1 \times 10^{10}$ for large $Q_{\text{ext}}$
RF Losses at Input Coupler Flange

- Exposed stainless steel near knife edge of input coupler Conflat flanges responsible for increased RF losses at strong couplings (confirmed by simulations)
- New zero gap/impedance flange design developed for ERL main linac cavity can be used to eliminate this extra loss
Excellent field stability achieved: \( \sigma_A/A < 2 \cdot 10^{-5} \)

(phase: \( \sigma_P < 0.01 \text{ deg} \))
Highlight: Active Microphonics Control

Piezo Feedback on Tuning Angle/Cavity Frequency:

⇒ Reduces rms microphonics by up to 70%!
⇒ Important for ERL main linac, where $Q_L > 5 \cdot 10^7$ and $P_{RF} \propto \Delta f$!
HOMs and High Current Operation

• Beamline HOM absorber between cavities very effective

• HOM damping and HOM spectra measurements confirm excellent damping with typical Qs of a few 1000
Successfully operated injector SRF module with beam currents of 25 mA:

- No increase in 1.8K dynamic load observed
- $\Delta T$ of HOM absorbers small (<0.5K). Module should easily handle operation at >100 mA.
- HOM absorbers allow for calorimetric measurement of the total HOM power excited by the beam
- Heaters on the HOM loads used for calibration
- Total HOM power measurement at ~20 mA gives longitudinal loss factor in good agreement with ABCI simulations (~20 V/pC at $\sigma_b=1$ mm)
8 HOM antennas per load:
- Used as BPMs
- Allow studying HOM spectrum
• Changed bunch charge (and thus beam current), but kept bunch length and repetition rate constant
• Total HOM power: $P \propto I Q_b$ as expected
• Changed bunch repetition rate
• Total HOM power: $P \propto IQ_b$ as expected
• Spectrum and total loss factor in good agreement with ABCI simulation results for given bunch length
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
The End

Thanks for you attention!