The Cornell High-Current ERL Injector

Matthias Liepe
Cornell University
S. Belomestnykh
E. Chojnacki
B. Clasby
Z. Conway
R. Ehrlich
D. Heath
J. Kaufman
G. Hoffstaetter
M. Liepe
V. Medjidzade
D. Meidlinger
H. Padamsee
S. Posen
P. Quigley
J. Sears
V. Shemelin
E. Smith
V. Veshcherevich

…and the rest of the Cornell ERL Team
A 100 mA SRF Injector for the Cornell ERL X-ray Light Source

Cornell ERL:
5 GeV, 100 mA X-ray light source
• Introduction
  – The ERL Injector Prototype at Cornell
  – Highlights from Initial Beam Studies: Where we are, what worked and what needs more work …

• The ERL Injector Cryomodule
  – Injector Module Design and Innovations
  – Beamline Components and Module Assembly
  – Results from the first test period
    • Cool down, Alignment, Static Loads
    • RF System Commissioning
    • SRF Performance
    • LLRF Field Control
    • Cavity Microphonics and Frequency Control
    • HOM damping and absorber tile charging up
  – Cryomodule re-work for the second test period

• Outlook
Introduction: The ERL Injector Prototype at Cornell

Highlights from Initial Beam Studies: Where we are, what worked and what needs more work...
100 mA ERL Injector

- Nominal bunch charge: 77 pC
- Bunch repetition rate: 1300 MHz
- Max. beam current: 100 mA at 5 MeV, 33 mA at 15 MeV
- SC linac beam energy gain: 5 to 15 MeV
- Beam power: 550 kW
- Nominal gun voltage: 500 kV
- Bunch length: 0.6 mm rms
- Transverse emittance: < 2mm-mrad
ERL Injector Schedule

- **2001**: ERL prototype proposal submitted
- **2005**: NSF funds the injector part of the proposal
- **September 2006**: 1st beam from the DC gun
- **September 2007**: Beam line and cryomodule fabrication and assembly starts
- **March 2008**: Cryomodule assembly is finished
- **April 2008**: Module installation in ERL injector prototype and cool down
- **June 2008**: First RF
- **July 2008**: First beam test period starts
- **August 2009**: End of first test period; rework of DC gun and SRF cryomodule starts
100 mA ERL Injector

DC Gun

SRF Cryomodule

Diagnostics beam line
100 mA ERL Injector: Technical Components

SRF Injector Cryomodule

135 kW cw Klystrons (e2v)

DC Gun

120 W @2k Pumping Skid

Cold Box

Gun Laser
Beam Instrumentation to characterize 6D Phase Space

- **Emittance measurement**
- **Time domain (<0.1ps)**
- ‘Flying wire’ ~MW beam transverse profile

**BPMs, Timing & Control System**

**THz interferometer for bunch profile characterization**

0.5 pC

$\Delta\theta$

$\Delta x$
**Highlights: DC Gun & Laser**

- **DC photogun** operational for over 3 years
- Strong points: quick photocathode removal & activation, excellent vacuum (good lifetime)
- Major issues:
  - *Field emission & ceramic puncture* (425 → 250 kV)
  - Stability of HV at lower beam current (few mA)
- **Laser system**: individual pulse characteristics demonstrated at ×26 lower rep. rate
- Issues:
  - Thermal handling difficulties when trying to extend avg. power to 20W green (>50 W IR)
  - Laser stability
Highlights: High current status

- **20 mA** DC current demonstrated from the gun (limited by gas backstream from the dump)

- 5 MeV beam running so far reached ~**8 mA** as limited by beam stability (radiation losses)
**Highlights: Beam Emittance**

- **At low bunch charge (at 5 MeV):**
  - Normalized *emittance* in both planes is close to thermal limit at cathode for given laser size: 0.2 to 0.4 mm mrad

- **At higher bunch charge (space charge dominated):**
  - First studies show emittance impacted by low gun HV; optimization underway
• First injector beam run period has ended
• Improvements for next run period (2010):
  – Installation of new HV gun ceramics with bulk conductivity
  – Improved laser stability and power handling
  – Improved gun HV stability (control loop optimization)
  – Injector cryomodule re-work (focus on SRF cavities and HOM load absorber tiles)
The ERL Injector Cryomodule
Injector Module Design and Innovations
• Beam requirements (100 mA cw, 500 kW power transfer to beam, very low emittance) are extremely challenging!
• Started by adopting well-established platform of TTF technology to reduce risk and minimize development time
  – Cavities supported by large diameter Helium-gas return pipe (HGRP)
• Significant modifications for ERL specific needs:
  – Necessary modifications
    • Much higher beam current beam (100 mA, non-pulsed) ⇒ HOMs…
    • Much higher (100 kW per cavity) *average* power transferred to the beam
    • Much higher cryogenic loads
  – Innovations
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
- $Q_{ext}$: $4.6 \times 10^4 – 4.1 \times 10^5$
- Total 2K / 5K / 80K loads: 30W / 60W / 700W

- Number of HOM loads: 6
- Couplers per cavity: 2
- RF power per cavity: 120 kW
- Amplitude/phase stability: $10^{-3} / 0.1^\circ$ (rms)
- ICM length: 5 m

HOM absorber at 80K between cavities

Frequency tuner

HGRP system with 3 sections

15 feet

Twin Input Coupler

ERL Injector Cryomodule

Superconducting RF Workshop 2009, September 21–25, 2009
Berlin, Germany
ERL Injector Cryomodule Design

Necessary changes compared to a TTF cryomodule:

- Increased diameter of 2K He pipes for high dynamic CW cavity loads
- Direct gas cooling of chosen 5K and 80K intercept points
- No 5K shield, only a 5K cooling manifold
- HOM absorbers between cavities
- New end-cap and feed-cap concept with reduced length
ERL Injector Innovations (I)

• Tuner stepper replaceable while string is in cryomodule
• Rail system for cold mass insertion into Vacuum Vessel
• In-situ bake of “warm” coupler sections
• Gatevalve inside of module with outside drive
ERL Injector 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)
Module Assembly

Beam Line Components

String assembly

Cold mass assembly
**Beam Line Components (I)**

**SRF cavities:**
- Designed, fabricated, prepared and tested at Cornell
- Only BCP, no 800C
- All cavities met 15 MV/m spec in vert. test

**RF input couplers:**
- Design by Cornell for high cw power > 50 kW
- 2 prototypes tested up to 60 kW cw, 80 kW pulsed
- 10 production couplers supplied by industry

---

*ERL Injector 2-Cell Cavity Vertical Tests*

- cavity 1 @ 2K
- cavity 2 @ 1.8K
- cavity 3 @ 1.8K
- Inj Operating Point

---

**Cold couplers**
- Beamline antenna
- Cavity flange
- Interface to warm coupler

**Warm couplers**
- Waveguide transition window
- Vacuum vessel flange
- Interface to cold coupler
**Beam Line Components (II)**

**HOM absorbers:**
- Design by Cornell for strong, broadband HOM damping
- 6 production loads fab’ed by industry

**Frequency tuners:**
- Modification of the INFN blade tuner
- Added piezos for microphonics compensation (R&D)
- 6 units fabricated by industry
**Beamline String Assembly**

Attach cold couplers to beamline string

- Cold coupler
- Cavity
- He vessel pump port
- Beamline HOM load

Cleanroom assembly fixturing

- Gate valve internal to cryomodule
- Vacuum vessel interface flange
Cold Mass Assembly at Cornell University (I)

Beamline string rolling under HGRPs
- Superinsulated HGRPs
- 2K 2-phase pipe
- Beamline string on assembly fixture extracted from clean room

Instrumentation
- 80K manifold
- Coax RF instrumentation
- 80K circuits to HOM loads and RF couplers
- Cold couplers with protective caps
- Temperature sensor wiring

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
Cold mass rolled into vacuum vessel

- Cold mass
- Insertion rails
- Vacuum vessel
- RF coupler and instrumentation ports
- Cryogen supply and return plumbing
- Support post transitions and alignment screws
- Vacuum vessel interior wall
- Top of 80K shield
- Roller bearings on composite post supports

Cold Mass Assembly at Cornell University (II)
Cold Mass Assembly at Cornell University (III)

Insight from the Assembly:

- First assembly revealed no significant design problems
- Fast, easy assembly (once we had all parts)
- Fixed cavity alignment concept works well
- Full 3D modeling (including assembly drawings) extremely helpful
Injector Module installed in the ERL Prototype

Refrigeration transfer lines

Waveguide feeds from klystron

Beam exit
Cool-down, Cavity Alignment and Static Heat Loads
• Injector cryomodule cooldown to 4.2K in 2.5 days to minimize thermal stresses (<10 K/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 \( \pm 0.2 \text{ mm} \) after cooldown!
Cryogenics and Static Heat Leak

- Pump skids provide heat removal capacity of \( \sim 128 \text{W} \) at 2 K or \( 21 \text{W} \) of dynamic heat load per cavity → above the measured chimney limit of \( \leq 15.3 \text{W} \) at 2 K.
  - Chimney limit estimate at 2.0 K: 14.6W or 1.1W/cm\(^2\).
  - Switched ICM operation from 1.8K to 2K because of low intrinsic Q cavity factors.

- Static heat leak at 1.8 K is about \( 13 \pm 4 \text{W} \) (measured from LHe boil-off rate with closed JT valve; heaters on the 1.8K system used for calibration).
- Expected: \( \sim 10 \text{W} \)
- Dominating part of this static heat load comes from thermal conduction from "4.5K intercepts" in the input couplers, support posts and HOM loads to the 1.8K system.
- "4.5K system" of the cryomodule is currently at an elevated temperature of about 6 K (non-ideal heat exchange in the refrigerator system) ⇒ increases total 1.8K static load from \( \sim 5 \text{W} \) to \( \sim 10 \text{W} \).
• After cool-down, *frequency spread between cavities was < 20 kHz!*

• All 5 cavities easily powered to minimum gradient of 5MV/m within minutes
RF System Conditioning
• 7-cavity K3415LS tube manufactured by e2v
• Delivers up to 120 kW of CW RF power (160 kWCW saturated)
• 6 tubes were installed, tested again at Cornell, and are performing well
• Efficiencies exceed 50% at 120 kW output power
• All twin input couplers have been processed in pulsed mode up to 50 kW under full reflection
  • 25 to 75 hours of processing (RF on time).
• DC voltage can be applied to center conductors (the original intent was to provide bias voltage for suppressing multipacting).
• This proved to be very useful tool for beam diagnostics.
SRF Cavity Performance in the ERL Injector Cryomodule
SRF Cavity Performance

• Initial cavity performance looked good (Q \approx 1 \cdot 10^{10} \text{ at } 1.8K)
• But: more detailed measurements later showed low intrinsic quality factors \( Q_0 \) for all 5 cavities (Q \approx 4 \text{ to } 5 \cdot 10^9 \text{ at } 2K)
• Q degradation over time?
• Maximum total voltage of the module is limited to 14 MV by cryogenics (~12 MV/m), close to maximum specification of 15 MV.
• Some cavity processing was done to reduce field emission at higher field gradients
• Pulsed gradients: 16 to 24 MV/m (BCP treated cavities; no high temperature bake)
Intrinsic $Q$ vs. $E_{acc}$ at 2K

- Field emission at higher $E_{acc}$
- Voltage limit due to the chimney heat flux transfer, not quench
- Cavities on either end of the module show lowest $Q$
Intrinsic quality factor $Q$ vs. $E_{\text{acc}}$ for all cavities together

- Q Degradation over time?

- Slightly improved $Q_0$ by warm-up /cool down?

Cavity 2 before and after warm up to room temp.

August 2008
April 2009
Possible reasons:

- Losses in the beam tube and coupler regions (cavity flanges are thermally anchored to a "4.5K" cooling circuit, which was actually at 6K (inefficient heat exchanger in cold box) $\Rightarrow$ increased BSC resistance in beam tube sections ($R_{\text{BCS}} \propto \exp(T)$)
- Cryo-pumping of residual gases: degradation over time, end cavities have lower Q factors.
- Ferrite dust contamination. Was observed during test module test (broken ferrite tile), but recent disassembly of injector cryomodule showed that all tiles are intact.
- Dust from outside of the cryomodule
- Hydrogen Q-disease: unlikely (no indication during vertical tests, no Q-reduction after keeping module at 80 K for hours).
- Cavity processing (temp during BCP,...)?

Vertical cavity tests of these cavities during the next weeks will tell...
LLRF Field Control
LLRF Field Control

- LLRF electronics for the ERL injector is a new, improved generation of LLRF system previously developed for CESR
  - Faster hardware for lower loop latency (<1\(\mu\)s)
  - Increased ADC resolution (16 bits)
- Performs well with excellent field stability
- LLRF electronics also used to measure
  - Beam current amplitude and phase stability (using BPM signals)
  - Beam phase calibration (via measuring beam induced fields)
  - Soon: beam position in module via HOM probe signals on the HOM loads between cavities

Cavity voltage induced by 0.1 mA beam current vs. cavity detuning
ICM cavity#3 voltage polar plot
Excellent field stability achieved: amplitude: $\sigma_A/A < 2 \cdot 10^{-5}$

phase: $\sigma_p < 0.01$ deg
• Main source of field perturbation is a strong ripple on the klystron HV
• Ripple has relative amplitudes of several percent and frequencies ranging from 360 Hz to may kHz.
Cavity (De)tuning
SRF Cavity Frequency Tuner

- Modification of the INFN blade tuner
- Tuning range:
  - 500 kHz stepper
  - 500 Hz piezo
- Added piezos for microphonics compensation (R&D for ERL main linac)
Initial Cavity Tuning to Resonance after Cool-Down

- Tuned 100,000 steps (300 KHz)
- LLRF system can easily detect fields with cavity detuned by >500 bandwidths!
Microphonics in the Injector Module

- Significant changes over time
- Step impulses related to cryo-system?
Integrated Microphonics Spectrum

- Significant differences between cavities
- $\sigma_f = 3$ to $8 \text{ Hz}$

Measured during “step-impulse free time”

RMS Frequency Deviation Contribution Below $f_{\text{ vib}}$ (Hz)

Vibration frequency [Hz]

Superconducting RF Workshop 2009, September 21–25, 2009
Berlin, Germany
Microphonics Histogram

- Graph shows histogram of 30 Million samples over a period of 1 hour
- $\Delta f_{\text{max}} < 5^{*}\sigma_f$
- No extreme outliers

Measured during “step-impulse free time”
Mechanical Coupling Characterization Measurements with a Modal Shaker

**Shaker on module support**

- **Vibration frequ. [Hz]**
  - Cavity 1
  - Cavity 2
  - Cavity 3
  - Cavity 4

**Shaker on module top (HGRP support)**

- **Vibration frequ. [Hz]**
  - Cavity 3
  - Cavity 4
### 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>
</tr>
<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**
Active Compensation of Lorentz-Force Detuning

- Piezo-electric actuators implemented in the cavity frequency tuners
- Used feedback loop for active compensation
- Works very reliably
Active Compensation of Microphonics?

• Microphonics feedback challenging because of complex transfer function piezo $\rightarrow \Delta f$ with mechanical resonances

This work has just started...

So far: reached stable control with 20 Hz bandwidth
HOM Damping and Absorber Tile Charging
HOM Studies

- HOM absorbers allow for calorimetric measurement of the total HOM power excited by the beam.
- Heaters on the HOM loads used for calibration
- Maximum beam current so far 8 mA → only a few 100 mW of HOM power per cavity → undetectable
- At higher bunch charges and currents, we expect several 10W of HOM power per load!
- 8 HOM antennas per load:
  - Working on prototype electronics to use HOM load antennas as BPMs (will use beam induced signal at 2.6 GHz)
  - Study HOM spectrum.
• Preliminary network analyzer measurements of HOM damping in the ERL injector module confirm strong suppression of monopole and dipole HOMs (typical Q’s of a few 1000)
RF Coupler Kick as a BPM

- Orbit can be estimated by measuring transverse *kicks by the RF fields in the input coupler regions.*
- The RF field is exited by a forward power of up to 1 kW *with strongly detuned cavities.*
- By measuring magnitude and direction of the kick to the beam, the beam position in the coupler region can be determined.
250 keV Beam Trajectory determined by RF Coupler Kicks

Very low energy (250 keV) beam

remnant field?
Remnant Fields

- Beam studies with and w/o RF indicated that there are remnant fields inside the ICM
- Initial speculation: Residual magnetic fields
  - Warmed up cryomodule and opened access ports
  - Found only few very small regions (washers...) with fields of up to about 0.5 Gauss and a general mostly longitudinal background field of 0.05 Gauss
  - Demagnetized them anyway...
  - Cool-down: field was gone...
  ... but problem reappeared a few days later...
Remnant Fields

• **Low resistivity of HOM absorber tiles**: will hold charge for seconds to days!
  – Worst offender: **Ceramic 137Zr10**, followed by ferrite Co2Z and TT2

• Small beam loss charged up absorber tiles -> kV **electric** fields at beam position!

*See poster THPPO035 for details!*
Cryomodule Re-work for the Second Test Period (start early 2010)
Module Disassembly

- Injector module was disassembled during the last 3 weeks to
  - Re-process SRF cavities $\Rightarrow$ improve $Q_0$
  - Fix absorber charging problem

3 weeks later

“module in boxes”

Superconducting RF Workshop 2009, September 21–25, 2009
Berlin, Germany
RF Absorber Tile Work

• Currently exploring several potential solutions for absorber charging problem:
  – Remove all tiles facing beam
  – Thin gold coating (~3 nm)
    • Study charging in E-beam welder
  – Remove worst material(s)
  – New materials

• In addition: study ways to further reduce stresses on tiles during cool-down to 80K
Promising new RF Absorbers: Carbon nano-tubes (CNT) in alumina ceramic

- Strong, broadband RF absorption
- Sufficient DC conductivity (for >0.5% CNT concentration)

See poster THPPO036 for details!
Summary and Outlook
Summary and Outlook

• First phase of commissioning and testing of the Cornell SRF ERL injector prototype cryomodule was very successful: cryogenics, cavity alignment, cavity voltage, input couplers, LLRF field control, and HOM damping all meet specs.

• Current cryomodule re-work will address the two issues found:
  – Lower than expected intrinsic $Q_0$
  – Charging of absorber tiles by beam loss

• Beam tests will continue early 2010
  ➔ 100 mA in reach
80K Shield  
Top Support Cylinder  
Composite Post Support  
Gas Return Pipe  
RF Coupler  

Gate Valve  
2-phase Pipe  
7-cell cavity  
Beamline HOM Load  
Quadrupole & Steering Coils

80K Radiation to 1.8K

\[ \varepsilon = 2.14 \times 10^{-2} \text{ gives } 50 \text{ mW/m}^2 \text{ from 80K to 1.8K} \]
The End