Superconducting RF in the Cornell University Energy Recovery Linac

- Challenges and Solutions -

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Superconducting RF in the Cornell University Energy Recovery Linac

- ERL Light Source: Why?

- The Cornell ERL: An Overview
  - Prototype
  - 5 GeV SR Source

- SC RF in the Cornell ERL Injector
  - Challenges and Solutions

- SC RF in the Cornell ERL Main Linac
  - Challenges and Solutions

- Outlook and Summary
Today's Workhorse Light Sources: Storage Rings

• **1st generation**
  parasitic SR on high energy physics storage rings

• **2nd generation**
  dedicated bending magnet sources, designed for high flux SR

• **3rd generation**
  dedicated undulator sources optimized for brilliance, using high current, low emittance

Some rings use superconducting RF

Storage ring light sources give:

• Repetition rate

• Stability

• High flux, brilliance – average/peak
1952: 1st accurate measurement of synchrotron radiation power by Dale Corson with the Cornell 300MeV synchrotron.
1953: 1st measurement of the synchrotron radiation spectrum by Paul Hartman with the Cornell 300MeV synchrotron.
Worlds 1st synchrotron radiation beam line (Cornell 230MeV synch.)
1961: 1st measurement of radiation polarization by Peter Joos with the Cornell 1.1GeV synchrotron.
1978: X-Ray facility CHESS is being build at CESR
2003: 1st Nobel prize with CESR data goes to R.MacKinnon

Protein structures in Protein Data Bank (Mostly from SR)
1. High average and high peak
   • Brilliance (photons/s/0.1% bw/mrad²/mm²)
   • Flux (photons/s/0.1% bw)

2. Coherence

3. Flexible pulse structure
   • Programmable pulse trains (interval, bunch size)
   • Adjustable pulse lengths down to the femtosecond regime

3. Small x-ray source size of desired shape, e.g. circular

4. Flexibility of source operation
   • No fill decay
   • Stability & robustness
   • Easily upgraded
### Important Beam Parameters: A Wish List

**Low emittance**
- Decreasing the electron beam emittance down to diffraction limit
  \[ \epsilon_x < \frac{\lambda}{4\pi} \sim 10^{-11} \text{ mrad} \left( \lambda \sim 1 \text{ Å} \right) \]

**Long undulator**

**Low energy spread**

**Short bunches**

**High spectral brilliance SR sources**
- \[ B \propto \frac{1}{\epsilon_x \epsilon_y \tau} \]

**High coherence fraction:**
- \[ p_c = \frac{\lambda^2}{(4\pi)^2 \epsilon_x \epsilon_y} \]

**High beam current**

**High flux**
- \[ F \propto I_{\text{beam}} \]
**How do we get these Beam Parameters?**

**Limits of Storage Rings**

- Electron beam emittance, bunch profile and energy spread in a storage ring is determined by equilibrium between radiation damping and two main diffusion processes:
  - quantum fluctuation of the SR and
  - the intrabeam scattering.

⇒ There is no (affordable) way to decrease the horizontal emittance in storage ring $\varepsilon_x < 10^{-10} \text{ m·rad}$ and energy spread $\sigma_E/E < 10^{-3}$.

- Beam lifetime limits bunch length to about 10 ps. Too long for many dynamic processes.
- Technology well developed. Theoretical limits are being approached.
- Time structure cannot be tailored to user needs.
- Fills are necessary, intensity is not constant.

⇒ Equilibrium dynamics determines almost all the parameters on our wish list!
How do we get these Beam Parameters?
The Alternative: Linacs

- Injectors can be built with very brilliant e- beams and linacs can accelerate with very low emittance growth (if we do it right).
  - Emittance & pulse length determined by injector.
  - Single pass non equilibrium device.
  - Easy upgrade path: Better e- source gives higher brilliance.
  - Due to adiabatic damping an emittance $\varepsilon \sim 10^{-11}$ m·rad and energy spread $\sigma_E/E \sim 10^{-4}$ is possible for energies $E > 5$ GeV.
  - Potential for ultra high brilliance.
- Complete flexibility of bunch timing.
- No fill decay, constant intensity.
- Electron bunches dumped after single pass.
The Alternative: Linacs
Small Beam Size, Coherence, Short Bunches

- 5 GeV storage ring
- ERL 5GeV@100mA

ESRF emittance (4nm x 0.01nm)
Diffraction limited @ 8keV
ERL emittance (0.015nm)

3rd SR
ERL
coherent

cohherent

16ps
100fs
2ps

Factor 100 more coherent flux for ERL for same x-rays, or provide coherence for harder x-rays
**Short pulses, high brilliance:**

- ERL
  - 0.015nm 0.01A
  - 0.15nm 0.1A
  - 1.5nm 0.1A
  - 4.7ps

- 3rd SR
  - APS upg
  - Sp8-25m
  - ESRF

- 2nd SR
  - CHESS 49p
  - 24p
  - ALS sect.6 undulator
  - ALS 5.3.1

\[ f_{\text{rep}} = \text{MHz} \ldots \text{GHz} \]

**High coherent fraction:**

- ERL 25m
  - 0.015nm 10mA

- ERL 25m
  - 0.15nm 100mA

- APS 4.8m
- ESRF U35
- APS 2.4m
- Sp8 5m
- 25m

Plots from Q. Shen

Matthias Liepe 12/12/2003
Linac Light Source: X-Rays Studies in New Regimes

- Smaller beams lead to better spatial resolution (currently sub mm)
  ERL: 100 to 1000 times smaller area

- Smaller emittance leads to high brilliance.
  ERL: 10 to 1000 more brilliance.

- Shorter bunches allows much higher time resolution.
  ERL: 100 times shorter bunches

3-D Studies of Structure

Insect Breathing
Field museum of Chicago & APS, Argonne National Lab.

3D Tomograph of Cells
G. Schneider, CBNI
Linac Light Sources: How to get high currents?

- High photon flux $\Rightarrow$ need high current
- But: With a simple linac you’d go broke!!
- Example: $5 \text{ GeV} \times 100 \text{ mA} = 500 \text{ MW}$

$\Rightarrow$ The energy of the spent beam has to be recaptured for the new beam.
Previous Energy Recovery Machines

Leonardo da Vinci (1452-1519)
Linac Light Sources: How to get high currents? The Energy-Recovery-Linac

Solution: Use energy recovery. First proposed by M. Tigner in 1965.

- Re-use energy of beam after SR generation.
- Recirculate beam and pass it through the linac a second time, but 180 deg. out of phase to decelerate beam.
- ⇒ “Energy Storage Ring” but not “Beam Storage Ring”.
ERLs: What is the trick?

1. Injection: fresh beam
2. Acceleration
3. SR generation with low emittance beam
4. Recirculate beam
5. Deceleration to re-use energy
6. Dump beam: low dump energy, less radioactivity
ERLs Worldwide (FEL-ERLs and SR-ERLs)

M. Tigner, 1965

SCA, Stanford, 1986

S-DALINAC, 1990
IR FEL Jlab, 1999
JAERI, 2002

Cornell ERL
LUX (LBL)
PERL (NSLS)
4 GLS (Daresbury)
KEK

...
ERL Linacs: Why Superconducting Cavities?

SRF linacs can deliver beams of superior quality:
  - Smaller emittance (lower impedance) ⇒ higher brilliance
  - Better RF control and stability ⇒ lower energy spread
  - CW operation at high gradient ⇒ flexibility in pulse train, lower impedance, cost saving

In addition, SRF gives
  - Higher power conversion efficiency
  - ERL option (very low wall losses) ⇒ high beam current, high flux
Neither an electron source, nor an injector system, nor an ERL has ever been built for the required large beam powers and small transverse and longitudinal emittances.  A prototype at Cornell should verify the functionality.
Cornell ERL: Phase 1, the Prototype

100 MeV, 100 mA

100 MeV Main linac

5 MeV Injector

100 mA Gun

Buncher

Dump

Bates bends

s.c. main linac

s.c. injector linac

30m
## Cornell ERL Prototype: SRF Parameter

<table>
<thead>
<tr>
<th>Parameter</th>
<th>ERL buncher cavity</th>
<th>ERL s.c. injector cavities</th>
<th>ERL s..c. main linac cavities</th>
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<tr>
<td>frequency [MHz]</td>
<td>1300</td>
<td>1300</td>
<td>1300</td>
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<tr>
<td>number of cavities</td>
<td>1</td>
<td>5</td>
<td>7</td>
</tr>
<tr>
<td>cells per cavity</td>
<td>1</td>
<td>2</td>
<td>7</td>
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<tr>
<td>R/Q [Ω] (circuit def.)</td>
<td>105</td>
<td>109</td>
<td>392</td>
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<td>$Q_0$</td>
<td>20,000</td>
<td>&gt; 5·10⁹</td>
<td>&gt; 10¹⁰</td>
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<tr>
<td>$Q_{\text{ext}}$</td>
<td>9,900</td>
<td>4.6·10⁴ (4.1·10⁵)</td>
<td>2.6·10⁷ for 25 Hz peak detuning</td>
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<tr>
<td>acc. voltage per cavity [MV]</td>
<td>0.12</td>
<td>1 (3)</td>
<td>≈ 16 (20 MV/m)</td>
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<tr>
<td>required klystron power per cavity [kW]</td>
<td>7</td>
<td>130</td>
<td>11</td>
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<tr>
<td>required relative amplitude stability (rms)</td>
<td>8·10⁻³</td>
<td>1·10⁻³</td>
<td>3·10⁻⁴</td>
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<tr>
<td>required phase stability (rms)</td>
<td>0.1°</td>
<td>0.1°</td>
<td>0.06°</td>
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</table>
Initial idea

Energy Recovery Linac in the Wilson Tunnel

Richard Talman

ABSTRACT
This is a brief discussion of two out of the many modifications that will be needed to retrofit the Wilson laboratory as an energy recovery linac (ERL). The two issues are: fitting the facility within the existing site boundaries; and designing the approximately isochronous yet adjustable arcs needed to transport ultrashort bunches.
Phase 2: Cornell ERL @ CESR

Injector RF

Main Linac RF

Total straights with R = 65m
~380m

140m

Matthew Liepe 12/12/2003
Cornell ERL @ CESR: Work in Progress
Main Linac Tunnel with Two Linacs
Cornell ERL Injector RF Challenges

• High RF power transfer to beam for acceleration of high current beam ⇒ input coupler challenge
  
  1 MeV per cavity * 0.1 A = 100 kW!

• Strong damping of HOMs essential for beam stability and to reduce monopole power.

• Emittance preservation ⇔ space charge, small transverse kick fields
Low Emittance Preservation in a Linac

Wakefields:
- longitudinal wakes generate energy spread
- transverse wakes generate time dependent kick fields ⇒ transverse emittance growth

Coupler kicks:
- Rotation asymmetry of input coupler and HOM coupler generates time dependent transverse kick fields on the cavity axis

Space Charge

Emittance growth
- DC gun produces low emittance beam ($Q_b = 77 \text{ pC}$).
- Fast acceleration in first cavity to reduce space charge effects.
- Short 2-cell cavities to reduce RF power per input coupler and to achieve strong HOM damping.
**Cornell ERL Injector: 2-Cell Cavity**

- Symmetric twin input coupler
- $f_{\text{acc}} = 1.3$ GHz
- Large 106 mm diameter tube to propagate all TM monopole HOMs and all dipole modes
- Reduced iris to maximize R/Q of accelerating mode

First copper model
He gas return pipe

2-phase 2 K He pipe

77 K shield

5 K shield

vacuum vessel

2-cell cavity

cavity interconnection with bellow and HOM ring absorber

beam
Cornell ERL Injector: 2-Cell Cavity with LHe Vessel

- 2-cell cavity inside LHe vessel
- Input coupler flange
- 2-phase He pipe
Cornell ERL Injector: Cavity with Support and Alignment Structure

- invar rod
- sliding support with alignment screws
- frequency tuner
- He-gas return pipe
- sliding support with alignment screws
• Sliding supports define transverse cavity positions.
• Longitudinal position is defined by invar rod.
• Cavity stays in place during cool-down to 2 K.
Cornell ERL Injector Cryomodule: Cavity with HOM Absorber
Cornell ERL Injector: 50 kW CW Input Coupler

62 mm diameter outer conductor $\Rightarrow$ MP free

Design studies under progress, high power cw test planned.
Symmetric Twin Input Coupler

Symmetric twin input coupler

- 50 % less power per coupler.
- Reduced emittance growth in the injector.

<table>
<thead>
<tr>
<th></th>
<th>( q ) [pC]</th>
<th>( V_{\text{acc}} ) [MV]</th>
<th>( \varepsilon_0 ) [( \mu \text{m} )]</th>
<th>( \sigma_z ) [mm]</th>
<th>( \sigma_x ) [mm]</th>
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<td>single input coupler</td>
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<td>1.0</td>
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<td>6 %</td>
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<td>77</td>
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<tr>
<td></td>
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<td>1.0</td>
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<td>1 %</td>
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<td>0.1</td>
<td>0.6</td>
<td>0.3</td>
<td>1 %</td>
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</table>
Cornell ERL Injector Cryomodule: HOM Damping

- Accelerating mode does not propagate in tubes.
- All TM monopole HOMs and all dipole modes propagate in tubes and are damped by ferrite ring absorber between cavities.
- Example: Lowers frequency dipole mode:

  symmetric ferrite ring ⇒ no kick
ERL Injector: HOM Monopoles (CLANS Model)

4.34 m

ferrite #1
ferrite #2
defrite #3
defrite #4
defrite #5
defrite #6

beam
ERL Injector: Damping of HOM Monopoles (CLANS Simulation)

\[ f \text{ [MHz]} \]

\[ Q_{\text{ferrite}} \]

- Accelerating mode
- Strongly damped HOMs
• Strong damping of HOMs essential for beam stability and to reduce monopole power.
• HOM power extraction at temperature with good cryo-efficiency.
• Emittance preservation ⇔ small transverse kick fields.
• RF field control and efficient cavity operation.
• Cavity module operation at high cw field gradient with large cryo-losses.
**HOM Damping Challenge 1: High Beam Currents and HOM Monopole Power**

In *average* the total HOM losses per cavity are given by the single bunch losses (7cell ERL cavity, 77 pC bunch charge, 2.6 GHz bunch repetition rate, $\sigma_b = 600 \ \mu m$):

$$P_{||} = k_{||} Q_{bunch} I_{beam} = 9.1 \text{V/pC} \cdot 77 \text{pC} \cdot 0.2 \ \text{A} = 140 \ \text{W}$$

But: If a monopole mode is excited on resonance, the loss for this mode can be much higher:

$$P = 2 \left( \frac{R}{Q} \right) Q I_{beam}^2$$

⇒ Example: To stay below 200 W ($I = 2 \times 100 \ \text{mA}$):
- achieve $(R/Q)Q < 2500 \ \Omega$,
- or avoid resonant excitation of the mode.

Need strong HOM damping!
HOM Damping Challenge 2: HOM Monopole Power at High Frequencies

600 µm bunch length in the linac

integrated power up to frequency f

HOM power up to about 100 GHz.
**HOM Damping Challenge 3: Avoid Beam Breakup (BBU)**

- In an ERL the feedback system formed between cavities and the beam is closed. ⇒ Instability can result at sufficient high currents.

\[ I_{BBU} \propto \frac{\omega}{(R/Q)Q} \]

Need \( I_{BBU} > 100 \) mA!

**Strong HOM damping!**
$BBU$ Limit for the Cornell $5$ GeV, $100$ mA ERL

$\Rightarrow (R/Q)Q/f < 2 \cdot 10^5 \, \Omega/cm^2/GHz$ required for BBU instability current $> 100$ mA (with safety-factor).
HOM Damping in the Cornell ERL Main Linac: RF Structure Candidates

7-cell cavities:

good for 100 mA

2x7-cell superstructure:

good for 10 mA

9-cell cavities:

good for 10 mA

2x5-cell superstructure:

good for 100 mA?
HOM Damping in the Cornell ERL Main Linac: 7-Cell Cavity

\[ f_{acc} = 1.3 \text{ GHz} \]

- small 78 mm beam tube
- 7-cell s.c. cavity, TESLA shaped center cells
- reduced iris to maximize R/Q of accelerating mode
- large 106 mm diameter tube to propagate all TM monopole HOMs and most dipole modes
**HOM Damping in the Cornell ERL Main Linac: Damping Concept**

- Enlarged beam tube on one side to propagate all TM monopole modes and most dipole modes.
- Ferrite broadband absorbers at 80 K between cavities to damp propagating modes at temperature with good cryo-efficiency.
- 6 HOM loop coupler per cavity to reduce power per coupler and to damp quadrupole modes reliable.
- Opposite HOM couplers to reduce transverse kicks.
RF losses in the absorber material can be calculated from the reflected and transmitted power as function of the RF frequency.
Measured Ferrite Absorber Losses

Absorption Peak of HEX Z shifts to high frequency at low temperature
And the same happens to HEX M3

The same happens to TT2-111R

Frequency / GHz

Absorbed Power / Incident Power

TT2-111R 300K
TT2-111R 110K
M3 300K
M3 114K
Z 300K
Z 114K
Example: Ferrite TT2-111R Absorber Properties at 300 K and 80 K

- Real part of permittivity $\Re\varepsilon / \varepsilon_0$
  - Frequency range: $10^9$ Hz

- Imaginary part of permittivity $\Im\varepsilon / \varepsilon_0$
  - Temperature: 297K, 100K

- Real part of permeability $\Re\mu / \mu_0$
  - Frequency range: $10^9$ Hz

- Imaginary part of permeability $\Im\mu / \mu_0$
  - Temperature: 297K, 100K

Magnetic Resonance
HOM Damping in the Cornell ERL Main Linac: CLANS Simulations

Monopole Modes
- Fundamental mode
- Monopole limit for first beam harmonics
- Monopole limit for second beam harmonics
- Monopole limit for third beam harmonics

Dipole Modes

R/Q* per cavity [Ω]

\( \text{frequency [MHz]} \)

1000 2000 3000 4000 5000 6000 7000 8000

10^2 10^3 10^4 10^5 10^6 10^7 10^8 10^9 10^10 10^11 10^12 10^13 10^14

R/Q*Q per cavity [Ω/cm²GHz]

\( \text{frequency [MHz]} \)

1000 1500 2000 2500 3000 3500

10^-2 10^-1 10^0 10^1 10^2 10^3 10^4 10^5

TT2-111R ferrite absorber at 80 K
HOM Damping in the Cornell ERL Main Linac: Bellow-Ferrite-Bellow Section

53 mm ferrites (TT2-111R)

bellow

TT2-111R ferrite absorber at 80 K

longitudinal loss factor \( k_{\parallel} = 1.4 \text{ V/pC} \)
HOM Damping in the Cornell ERL Main Linac: Bellow-Ferrite-Bellow Section

Trapped modes in bellows: HOM power goes into wall, not into cooled ferrite!
HOM Damping in the Cornell ERL Main Linac: Improved Bellow-Ferrite-Bellow Section

TT2-111R ferrite absorber at 80 K

longitudinal loss factor $k_\parallel = 1.2$ V/pC
HOM Damping in the Cornell ERL Main Linac: Improved Bellow-Ferrite-Bellow Section

TT2-111R ferrite absorber at 80 K

HOM power goes into cooled ferrite!
Ferrite Shielded Bellow

- LN cooling loop
- Ferrite tile
- Bellows
HOM Loop Coupler Studies:

Microwave Studio model:

- Copper model:

- Coupler model:
  - Superconducting pick-up antenna
  - Superconducting pick-up loop
  - Capacitor of the 1.3 GHz notch filter

- Output to room temp. load
- Capacitive coupling

- Matthias Liepe 12/12/2003
Main Linac Accelerating RF Field

- Flexibility and stability with small $\Delta E/E$

- Efficient high $Q_L$ operation with energy recovery:
  - efficient energy recovery and RF control of random beam loading
  - RF control in presents of microphonics and Lorentz-force detuning $\Rightarrow$ optimal loaded $Q$?
  - Minimum RF power required?
\[ \Rightarrow \text{Path length errors (phase errors) and non-zero recirculation time will result in beam loading with fluctuation!} \]
**Microphonics**

- **Microphonics**: modulation of resonance frequency by external mechanical disturbances
- thin wall thickness and small bandwidth of superconducting cavities
  ⇒ sensitive to microphonics

*Example: TTF 9-cell cavity in a horizontal test cryostat (cw operation)*

![Graph showing cavity detuning over time](image)

Cornell ERL:
Cavity bandwidth = 25 Hz!
⇒ Large field errors without field control!
7-cell main linac cavity at 20 MV/m:

- 25 Hz peak detuning ⇒ 3.9 MW wall plug power
- 10 Hz peak detuning ⇒ 1.6 MW wall plug power

**Example:** 310 cavities for 5 GeV, 50 % klystron efficiency

\[ V = \frac{\sqrt{4 \frac{R}{Q} Q_L P_g}}{\sqrt{1 + \left( \frac{f - f_0}{f_{Q,\text{opt}}} \right)^2}} \]

\[ Q_{\text{opt}} = \frac{3}{2 \Delta f} \]

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

**Peak microphonics detuning important!**
**Cornell ERL: Frequency Tuner**

- **DESY blade tuner**
  - Slow and fast frequency control!
  - at 300 K!

- **Cornell ERL: Frequency Tuner**
  - Piezo: +/- 1 kHz, 1 Hz resol.
  - Stepping motor: +/- 200 kHz
  - JLab upgrade tuner
Ultra-Fast Digital RF Field Control System for the Cornell ERL

- very low delay in the control loop (< 1 µs)
- Field Programmable Gate Array (FPGA) design combines the speed of an analog system and the flexibility of a digital system
- high computation power allows advanced control algorithms
- all boards have been designed in house
- generic design: digital boards can be used for a variety of control and data processing applications
Test with Copper Cavity

500 MHz CESR copper cavity:

Digital Boards:
Cryogenic Challenges

• High gradient cw operation: dynamic head load dominates:
  Example: 20 MV/m, $Q_0 = 10^{10} \Rightarrow 40 \text{ W/m}$

• Module design:
  - Heat transfer through LHe $\Rightarrow$ need large enough pipes
  - Mass transport of helium gas $\Rightarrow$ need large enough pipes
  - HOM losses $\Rightarrow$ need cooling of absorbers

• Cavity:
  - Cavity treatment for high $Q_0$
  - Optimal bath temperature?
Maximum Heat Flux in a 2 K LHe II Bath

$q_{\text{max}}$ for $L=x$ cm $[\text{W/cm}^2]$

max tolerable $T$ [K]

$L=1$ cm tube length
$L=5$ cm tube length
$L=20$ cm tube length
$L=1$ m tube length

$\Rightarrow$ need large enough LHe pipes
Cornell ERL Cryomodule Concept: TTF Module modified for CW Operation

- 5 K forward
- 77 K forward
- 77 K HOM
- 2 K 2-phase He pipe
- 8 K return
- 70 K shield
- s.c. cavity in LHe vessel
- 77 K return
- 5 K shield

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### C-ERL: Cryogenic Loads per Module with 10 7-cell Cavities (20 MV/m, 100 mA, $Q_0=10^{10}$)

#### 2 K static loads
- Supports: 0.5 W
- Instrum. cables: 0.21 W
- Input Couplers: 0.2 W
- HOM absorber: 0.6 W
- HOM Couplers: 6 W
- Total 2 K: 363.1 W
- 2 K efficiency (TESLA TDR): 588 W/W
- Total wall plug power: **213.5 kW**

#### 5 K static loads
- Radiation: 1.7 W
- Supports: 2 W
- Instrum. cables: 1.2 W
- Input Couplers: 1.3 W
- HOM absorber: 15 W
- HOM Couplers: 12 W
- Total 5 K: 201.1 W
- 5 to 8 K efficiency (TESLA TDR): 168 W/W
- Total wall plug power: **33.8 kW**

#### 77 K static loads
- Current leads: 13 W
- Radiation: 38.4 W
- Supports: 5 W
- Instrum. cables: 4.5 W
- Input Couplers: 65 W
- HOM absorber: 1335 W
- HOM Couplers: 60 W
- Total 77 K: 1742.3 W
- 77 K efficiency (TESLA TDR): 17 W/W
- Total wall plug power: **29.6 kW**

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**Example:** 5 GeV, 20 % cryo overhead

- $Q_0 = 1 \cdot 10^{10} \Rightarrow 10.3$ MW wall plug power
- $Q_0 = 2 \cdot 10^{10} \Rightarrow 6.7$ MW wall plug power
$R_{BCS}$ and LHe Bath Temperature

- $R_{BCS}$ decreases significantly if $T$ is lowered.
- Important: The residual resistance must be low to make use of this! $\Rightarrow$ Very good shielding of Earth’s magnetic field ($< \text{some mOe}$).
- Examples:
  - $T = 2.0 \text{ K} \Rightarrow Q = 2.6 \cdot 10^{10}$
  - $T = 1.8 \text{ K} \Rightarrow Q = 6.3 \cdot 10^{10}$
  - $T = 1.6 \text{ K} \Rightarrow Q = 1.9 \cdot 10^{11}$
- A dream?…
High $Q_0$: Let’s dream...

$Q_0 > 2 \times 10^{11} !!$

Record $Q$ value reached in single cell

⇒ 2 W/m losses at 1.6 K instead of 20 to 40 W/m losses at 2 K?
Outlook and Summary:
SRF @ Cornell ERL

• ERLs have the potential to produce photon beams with ultra high brilliance, coherence and ultra short pulses.

• Cornell is proposing to built an 100 MeV, 100 mA ERL prototype and we study a 5 GeV SR ERL light source.

• SRF is a key technology for these machines.

• Many challenges need our attention:

  *HOM damping, emittance preservation, RF field control, cw cavity operation at high fields, high power input couplers, ...*

• We have started to work in these areas and hope to start with the construction of the injector soon.

• Next year: first 2-cell cavity, first 50 kW input coupler, first HOM ferrite ring-absorber, injector module design.
Et facta est lux.
(And there was light.)