Review of various approaches to address high currents in SRF electron linacs

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Why a high average current?

- High power FELs (currently 10 mA at JLab's FEL upgrade) – possibly as much as 1 ampere.
- ERL based light sources – 100 mA and above, lower for high brightness mode, higher for high flux mode.
- Electron-ion colliders – possibly as much as 0.5 ampere
- High-energy electron cooling – possibly as much as 0.5 ampere.

High current, SRF and ERL

- To get a high average current with a reasonable gradient, CW operation is necessary, thus SRF is required.
- High average current also requires energy recovery to be practical.

Result:

- No high-power input couplers necessary.
- High Q_{ext} operation is desirable to minimize RF power requirements.

What are the issues?

- Generating the electron beam: Gun and booster.
- Reducing the amount of HOM power generated by the SRF structure.
- Extracting the HOM power out of the cavity.
- Overcoming multi-pass beam breakup.
- Mechanical vibration stability at high Q_{ext}, low steady state Lorentz detuning, low microphonics.
- Phase / amplitude control at high Q_{ext}, high reactive beam power.
- Lowering surface resistivity and avoiding field emission.
- Very high gradient is NOT an issue (limited by refrigeration), 20 MV/m but low loss is satisfactory.

Main linac parameter space

parameter	min value	max value
linac energy gain	20 MeV	5 GeV
average current	10 mA	1 A
bunch charge	10 pC	1.5 nC
bunch length	2 ps	100 ps
cavity frequency	700 MHz	1.5 GHz
cells per cavity	5	9
acc. gradient	12 MV/m	20 MV/m
unloaded Q_0	$8 \cdot 10^9$	$2 \cdot 10^{10}$
loaded Q	$2 \cdot 10^7$	$1 \cdot 10^8$?
HOM power per cavity	some 10 W	>1 kW
HOM spectrum, 95% upper freq.	1 GHz	60 GHz
amplitude/phase stability	10^{-3} / 0.1 deg	10^{-4} / 0.02 deg
ave./peak RF power per cavity	0.5 kW/1 kW	25 kW / 50 kW

Courtesy: Matthias Liepe, Cornell. Invited Plenary talk at ERL 2005 Workshop

Approximate loss factors

Approximate longitudinal loss-factor for a multi-cell cavity:

$$k_l = \frac{\Gamma(.25) Z_0 c}{4\pi^{2.5}} \frac{1}{a} \sqrt{\frac{d}{\sigma}} \sqrt{N_c}$$

a is the cavity iris radius,
d is the cell length
σ is the beam bunch length
$\mathbf{N_c}$ is the number of cells

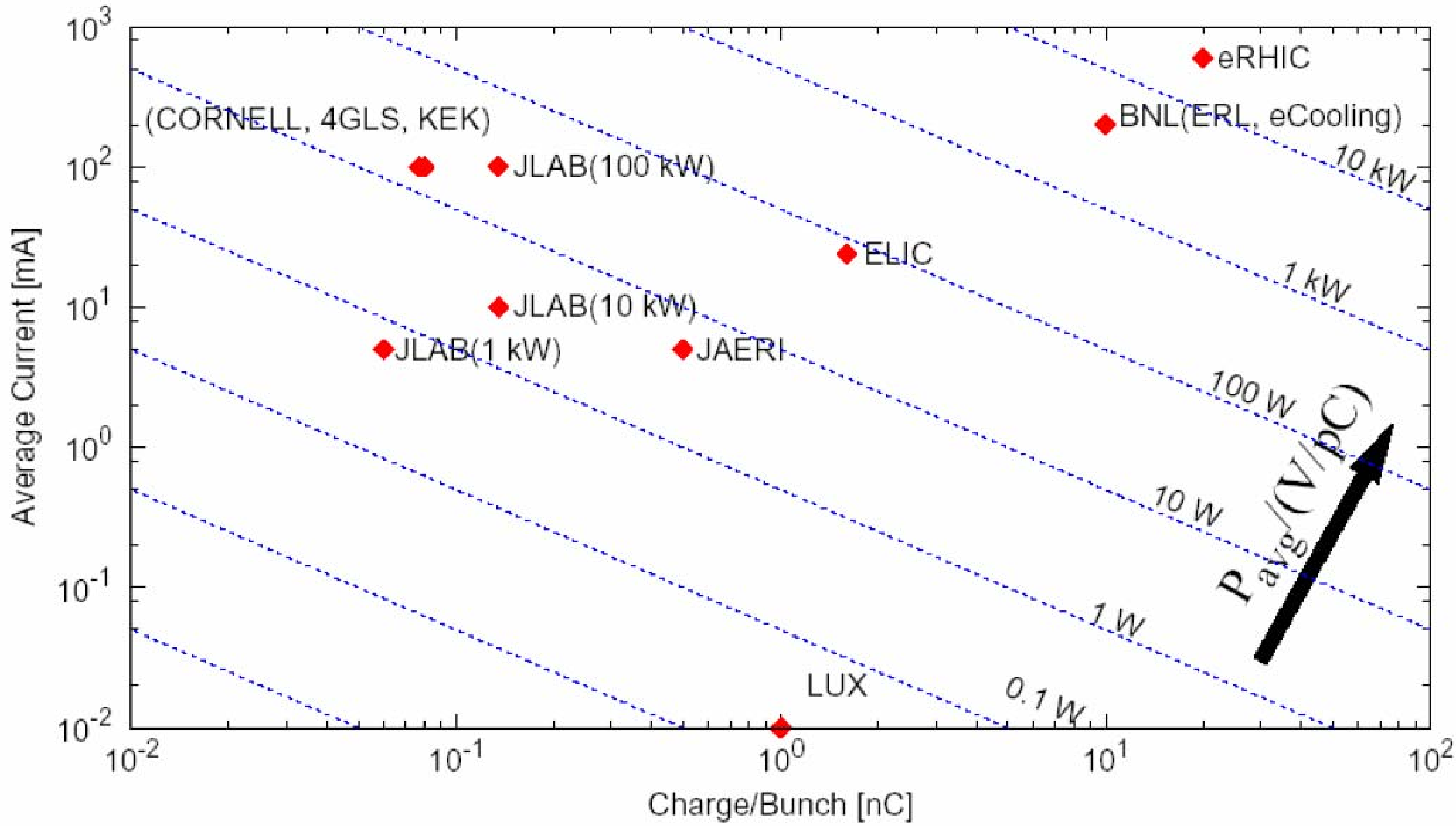
For a fixed bunch and cavity length and cell proportions, k_l is proportional to the frequency squared.

The HOM power is proportional to the loss factor, to the current and charge of the beam:

$$P_{HOM} = k_l I q$$

For high Iq machines, k_l must be minimized by going to a lower RF frequency and opening the cavity's irises.

Existing & Future ERLs



*** Avg. Power Normalized to 1 V/pC

Choice of frequency

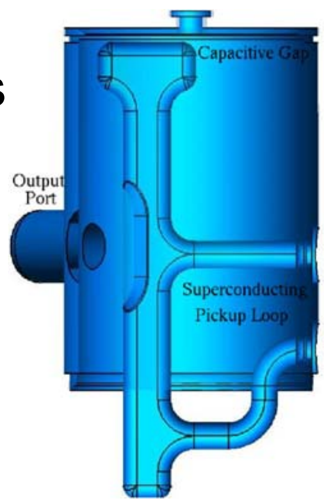
- HOM power goes down with frequency
- Beam breakup improves rapidly with frequency
- The lowest frequency linac structure JLAB can handle in existing chemical cleaning is ~700 MHz
- High power CW klystrons (for the photoinjector) exist only at 500, 700 and 1250 MHz.
- Superconductor BCS surface resistance goes down with frequency squared,
- Inexpensive and compact RF exists at 700 MHz or lower (UHF TV transmitters using IOT devices)
- These considerations led a few laboratories to develop new SRF ERL structures.

New, active high-current linac SRF structure developments

- BNL
  - Construction of 5-cell, 703.75 MHz cavity, SRF electron gun, and construction 0.5A, 20 MeV ERL (design 80 MeV).
- Cornell
  - Construction of a 2-cell, 1300 MHz injector cavities, DC electron gun, cold HOM damping of TESLA type cavities and design of 100 mA, 100 MeV ERL.
- JLab
  - Design (construction in 2007) of a 5-cell cavity, DC gun with SRF booster under construction, design of 100 mA, 120 MeV ERL.
- KEK
  - Development of radial damping scheme for TESLA type ERL cavity, design of a 100 mA, 200 MeV ERL.

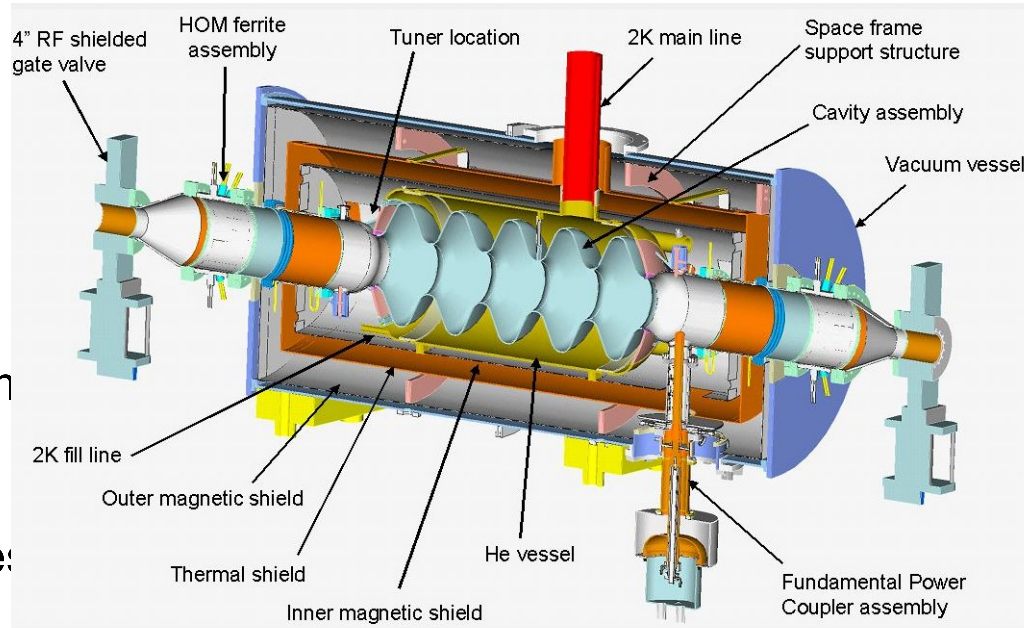
Removing the HOM power from the cavity

- The high HOM power must be dumped out of the liquid helium environment.
- HOM couplers must be able to handle the large amount of average power.
- The beam pipe is a practical conduit for the HOM, it is there anyway.
- The HOM modes must be well coupled to the beam pipe (no trapped modes)
- The beam pipe should propagate well all HOMs
- TESLA HOM coupler is inadequate.



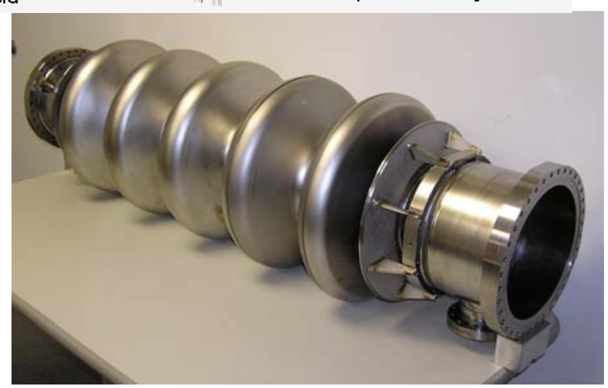
The BNL approach
Aimed at ~1 ampere

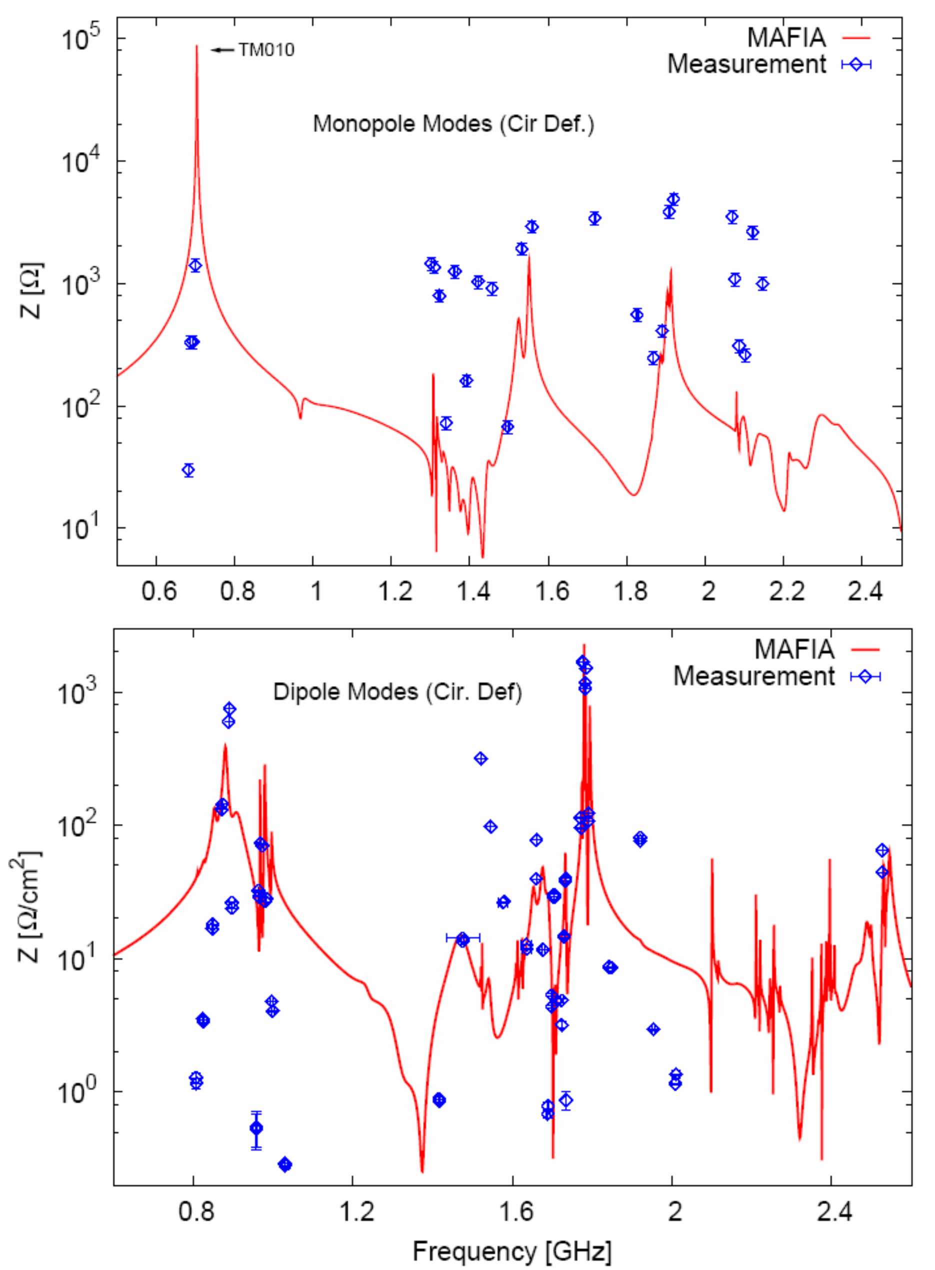
- Low frequency: 703.75 MHz
- Cavity manufactured by AES
- Large beam pipe: 24 cm diameter
- HOM loads: Cornell ferrites at room tem (made by Accel)
- Cold loads: an alternate for multi-cavity cryomodule



ERL 5-cell cavity design for high currents
R. Calaga, proceedings SRF'05

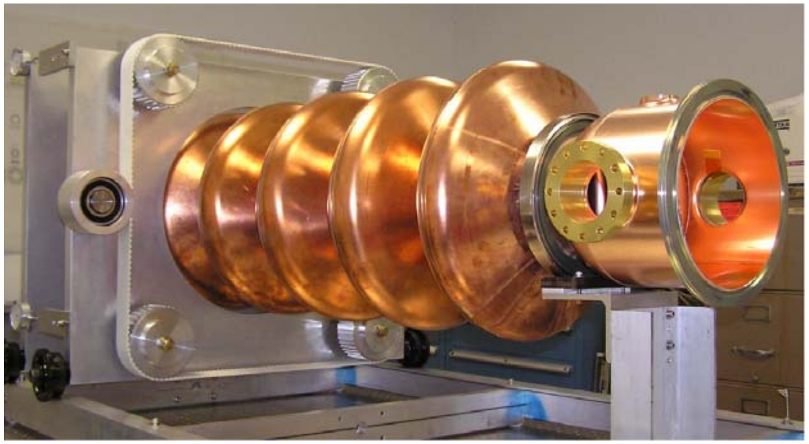
Design and Fabrication of the RHIC Electron-Cooling Experiment High Beta Cavity and Cryomodule
D. Holmes, proceedings SRF'05





BNL 5-cell impedance spectrum

Red line - MAFIA
Blue points - measured

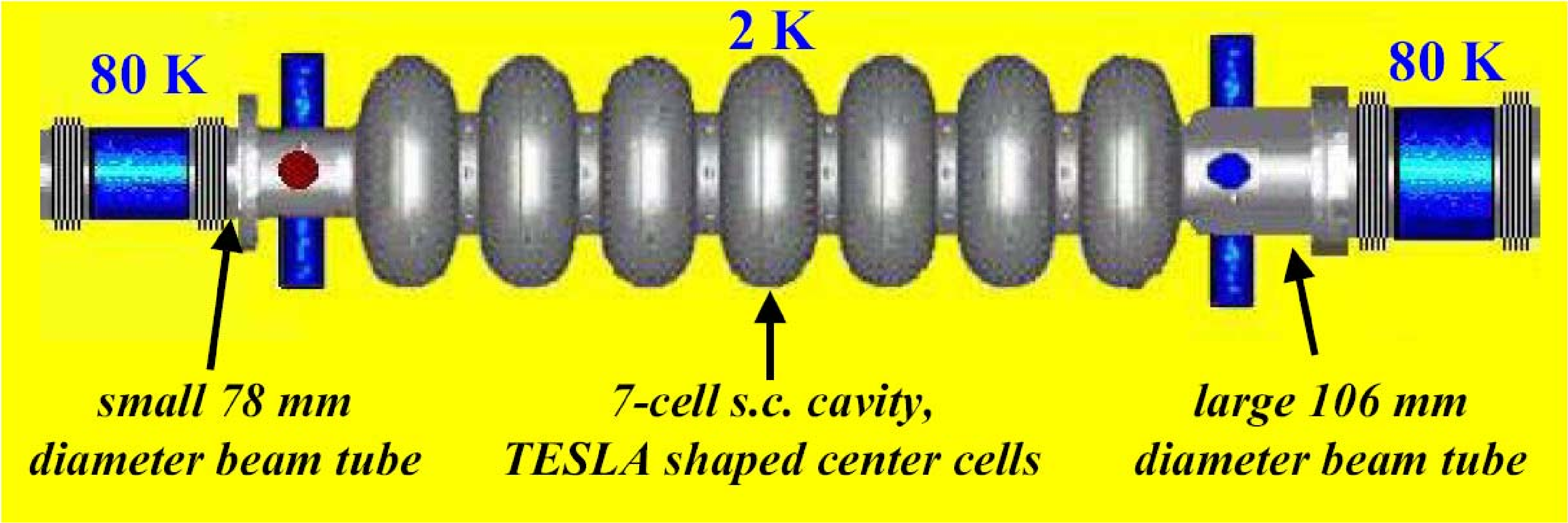


RHIC

I. Ben-Zvi, SRF 2005

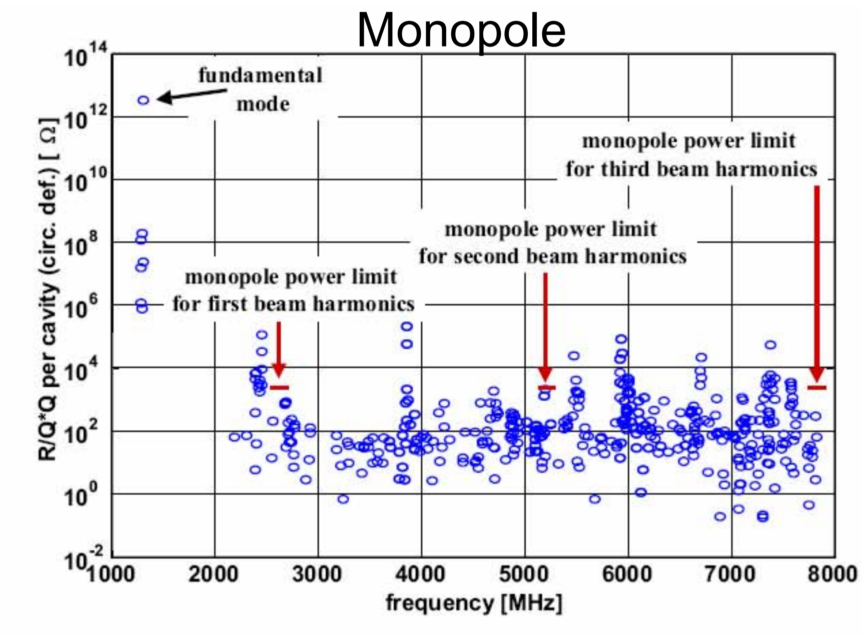
BROOKHAVEN NATIONAL LABORATORY

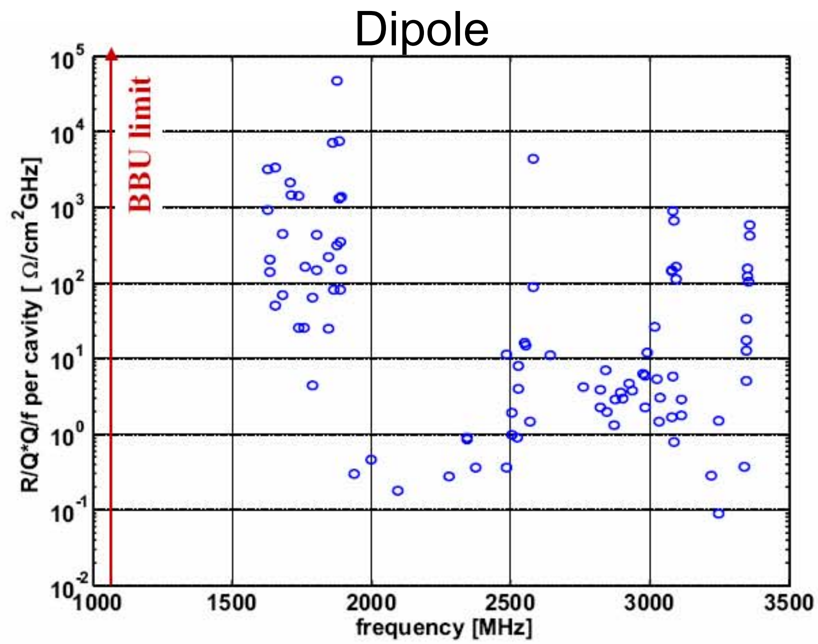
The Cornell approach
Aimed at ~0.1 ampere



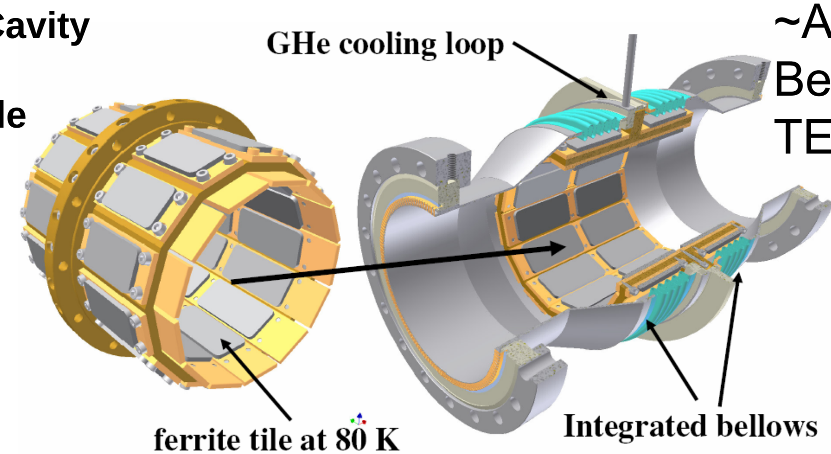
1300 MHz.
7-cell, TESLA shape, 10.6 / 7.8 cm diameter beam pipes.
Use combination coaxial HOM dampers (8 per cavity) AND ferrite rings.
Ferrite rings at 80 K.

Cornell 7 cell impedance spectrum





Conceptual Layout of the Cavity String of the Cornell ERL Main Linac Cryomodule
M. Liepe, SRF'03



~An order of magnitude Better damping than TDR TESLA.

RHIC

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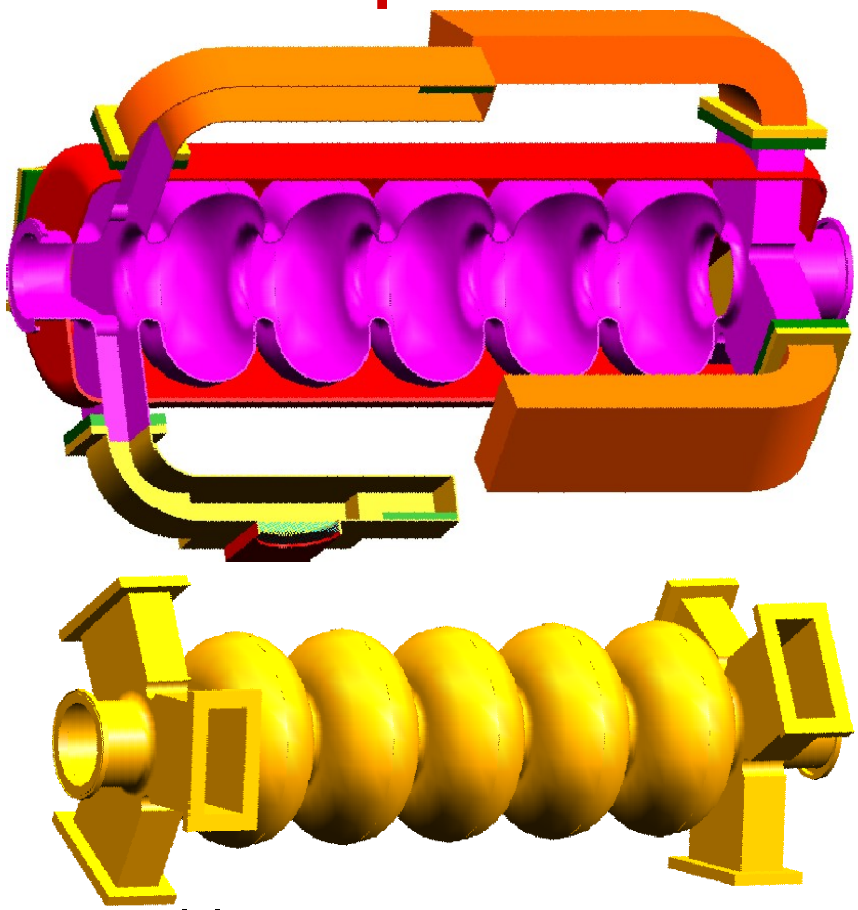
The JLab approach
Aimed at ~1 ampere

Low frequency:
750 MHz.

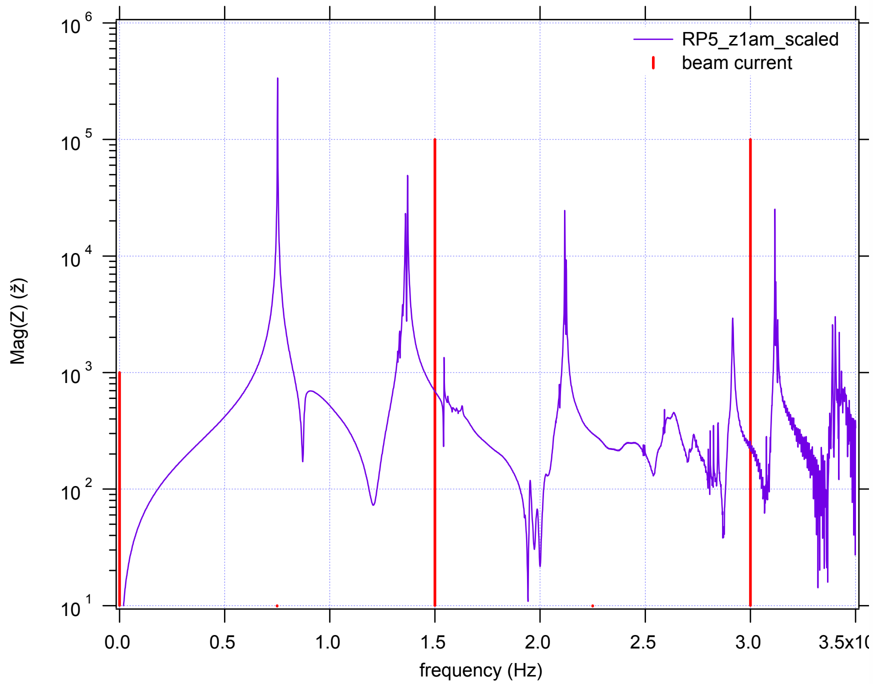
Waveguide HOM loads, 6 per cavity, water cooled.

14 cm diameter irises.

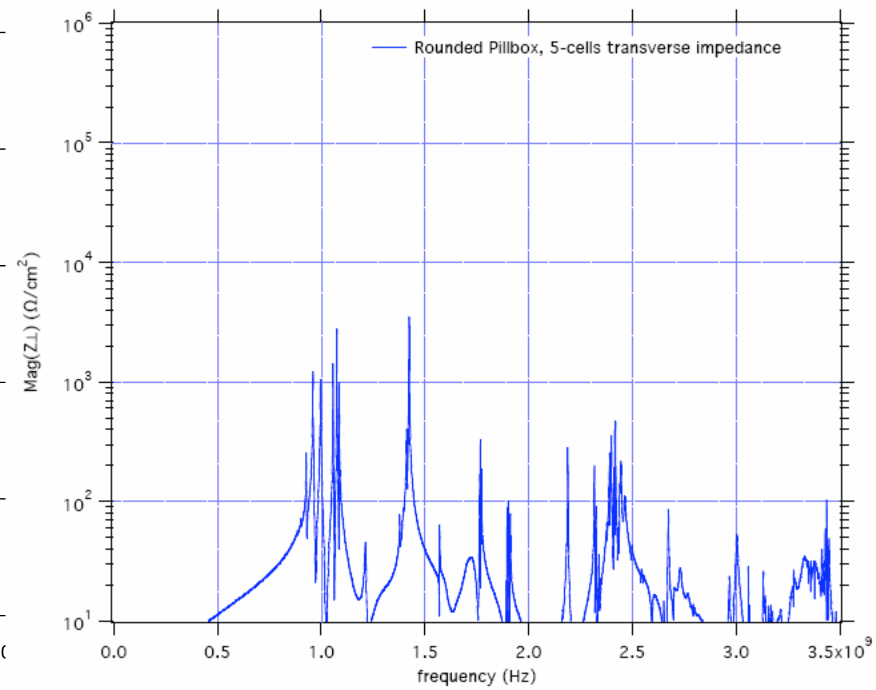


Concepts for the JLab Ampere-Class CW Cryomodule
R. Rimmer, et. al, Proceedings, PAC’05

JLab 5-cell impedance spectrum



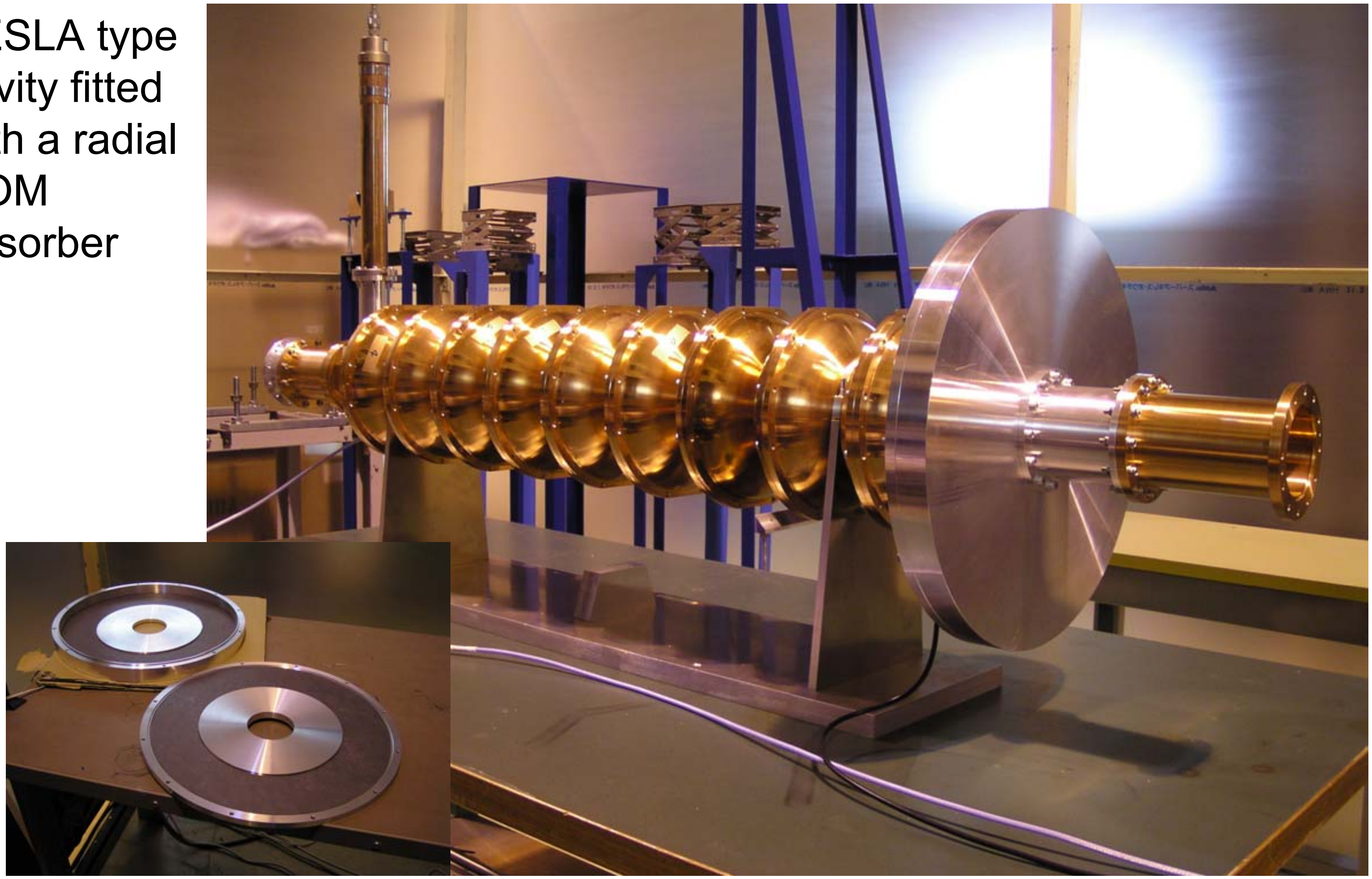
Monopole



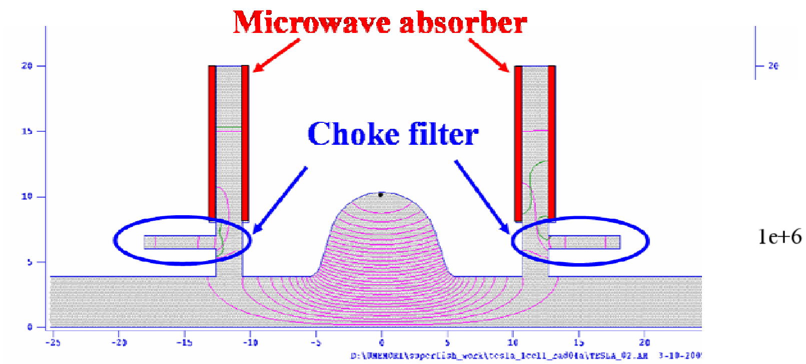
Dipole

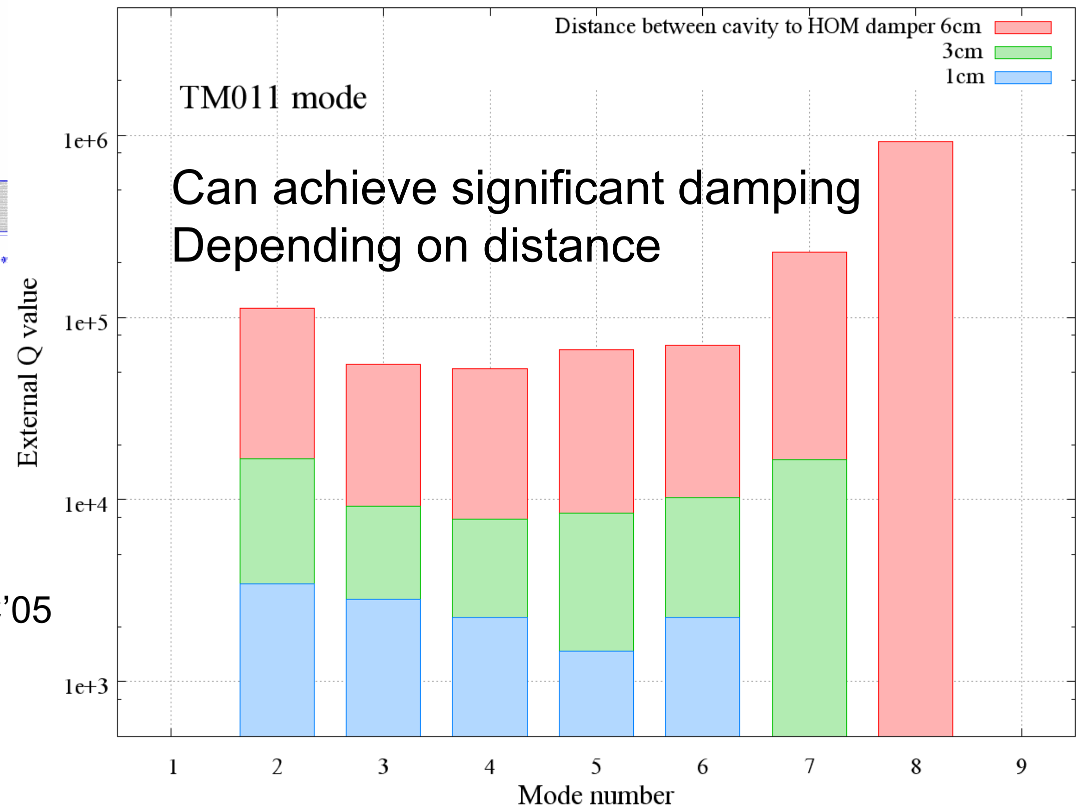
The KEK approach

TESLA type cavity fitted with a radial HOM absorber



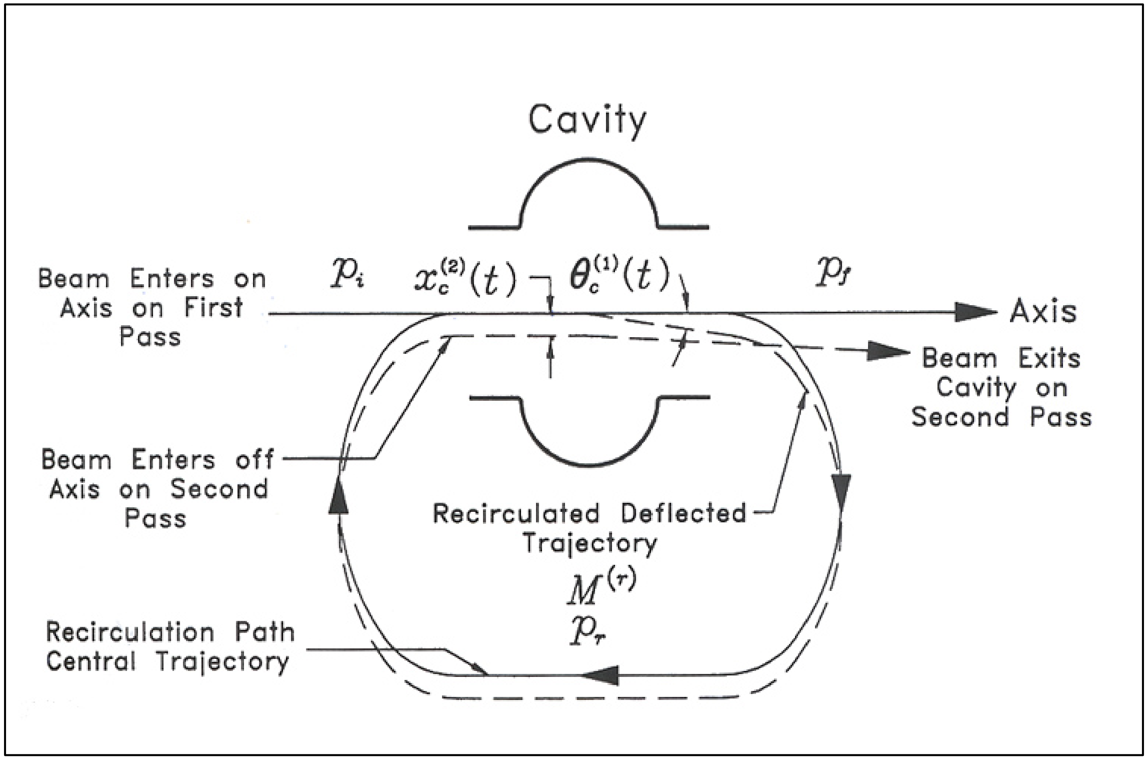
Radial dampers with integral fundamental choke filter





Higher-Order-Mode Damping of L-band Superconducting Cavity Using a Radial-line HOM Damper
K. Umemori, et. al., proceedings PAC'05

Beam breakup



BBU analysis

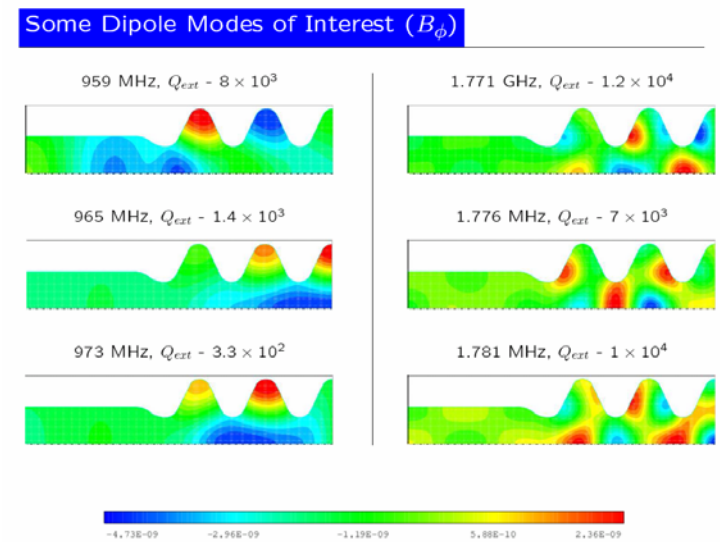
Definitive work:

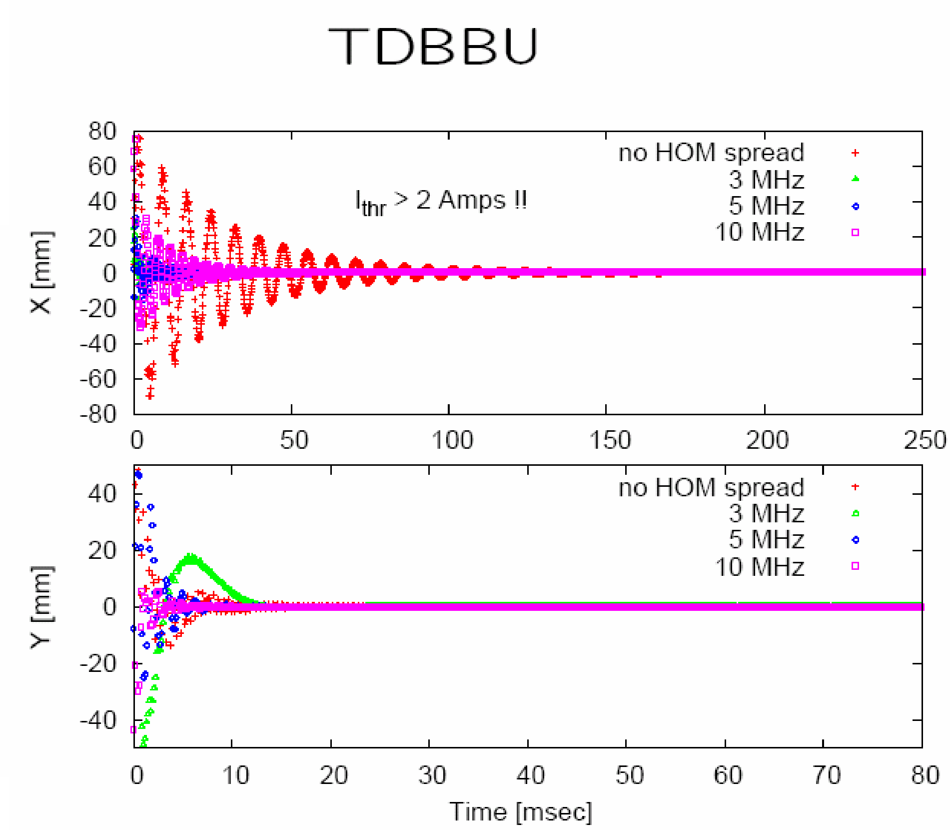
G.H. Hoffstaetter and I.V. Bazarov, “Beam-breakup instability theory for energy recovery linacs”, Phys. Rev. ST AB **7**, 054401 (2004).

$$I_{th} = \frac{-2c^2}{e\left(R/Q\right)_m Q_m \omega_m T_{12} \sin\left(\omega_m t_r\right)}$$

Hoffstaetter and Bazarov simulations show ~200 mA threshold for a 5 GeV ERL using TESLA TDR cavities.
The new 700-750 MHz cavities (BNL, JLab) should have a factor of 2 by virtue of its lower frequency and another large factor, ~100, thanks to enhanced HOM damping, i.e. smaller $(R/Q)_m Q_m$

Beam Breakup threshold





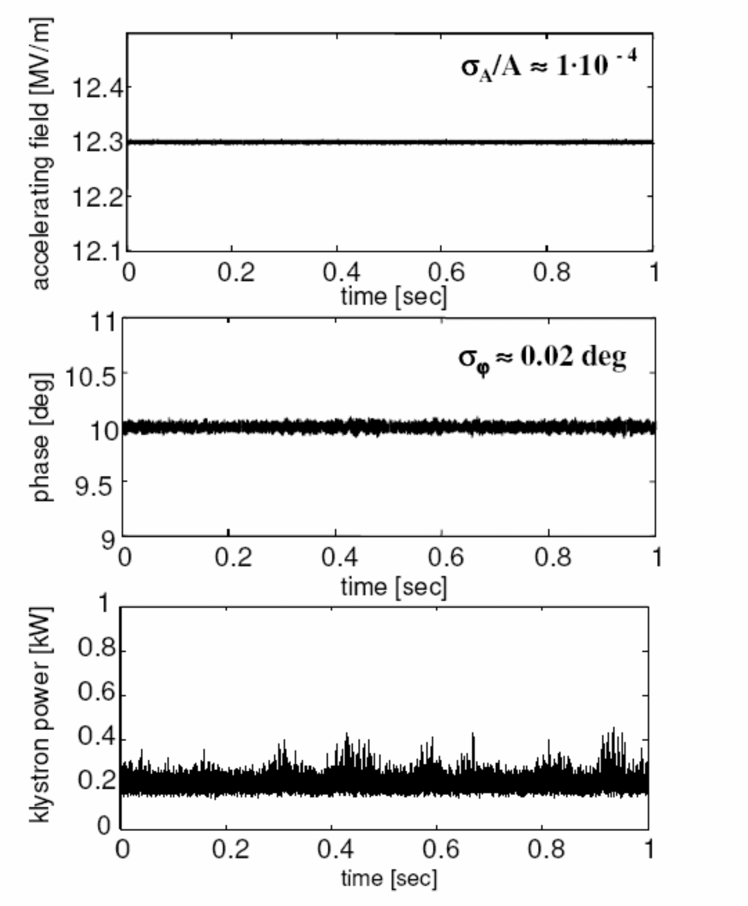
Electron cooler linac (4 cavities, 54 MeV)

Amplitude and phase control.

Also applies to low current linacs.

- Cornell's newly developed digital control system, connected to a high loaded Q cavity at the JLab IR-FEL.
- Excellent cw field stability.
- Piezo tuner effective in keeping the cavity on resonance and allowed reliable to ramp up to high gradients in less than 1 second.

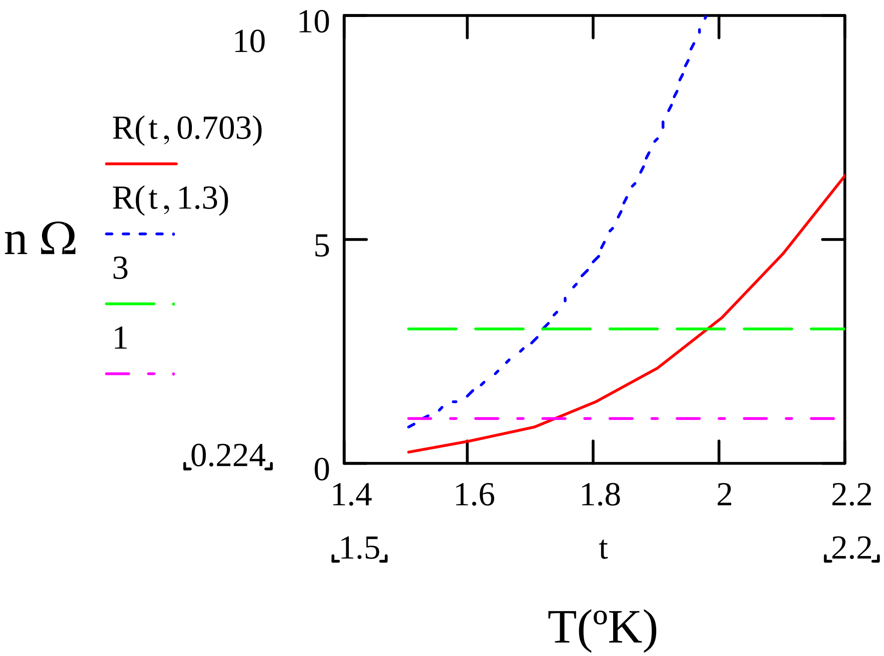
Pushing the Limits:
RF Field Control at High Loaded Q
M. Liepe et. al., proc. PAC’05 and SRF’05



Amplitude and phase stability
With $Q_L = 1.2\cdot10^8$ and 5 mA

Residual resistance and the choice of frequency

$$R_{BCS} = 2\cdot 10^{-4}\,\frac{1}{T}\left(\frac{f\,(GHz)}{1.5}\right)^2 \exp\left(-\frac{17.67}{T}\right)$$



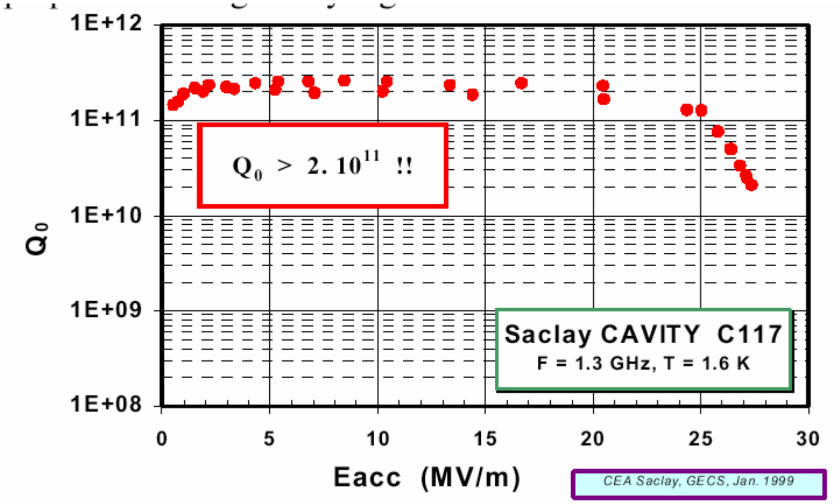


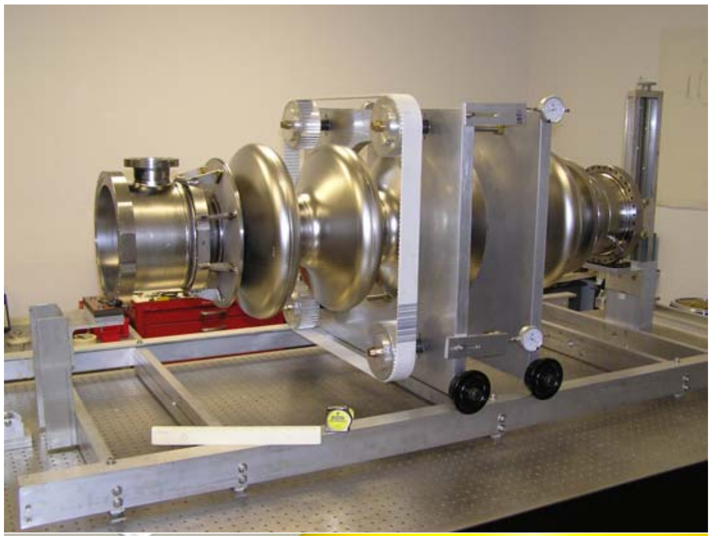
Figure 2 – Residual resistance as low as 0.5 nΩ is actually measured on large area cavities, giving an intrinsic quality factor Q_0 exceeding 2.10^{11}.

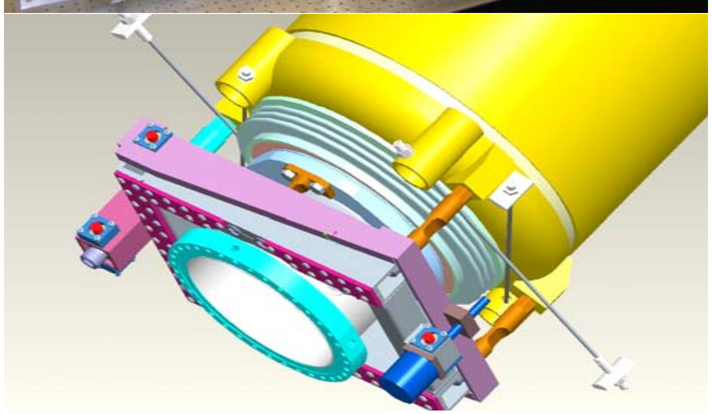
Residual resistance <1 nΩ possible

Cavity mechanical stiffness

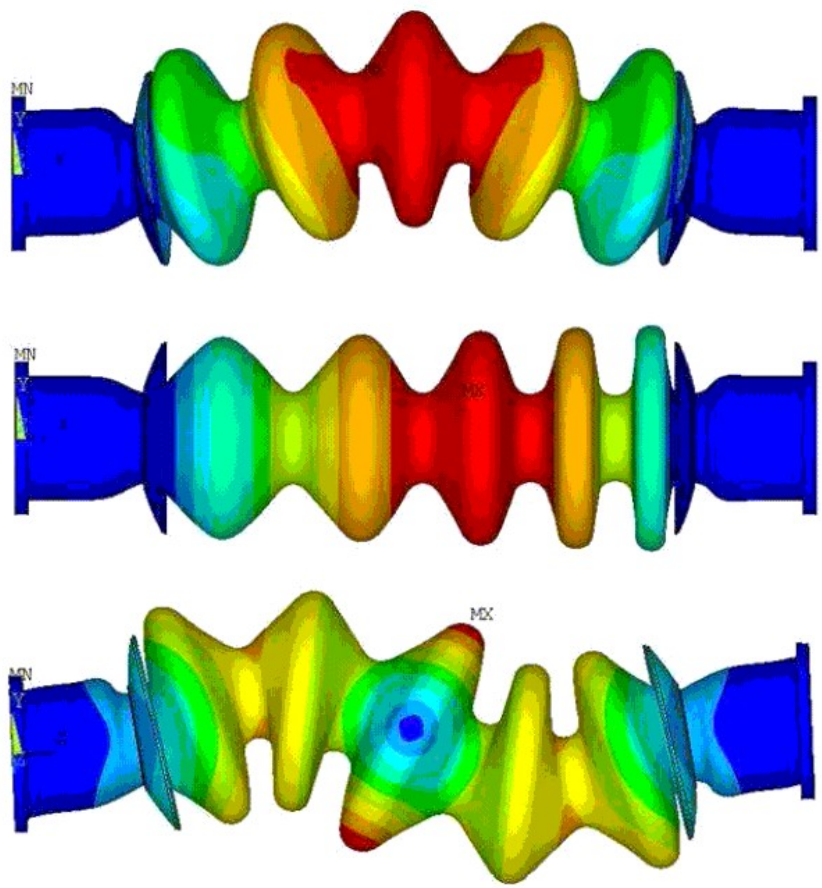
1.2 Hz/(MV/m)^2

Mechanical Resonances (D. Holmes - FEA)





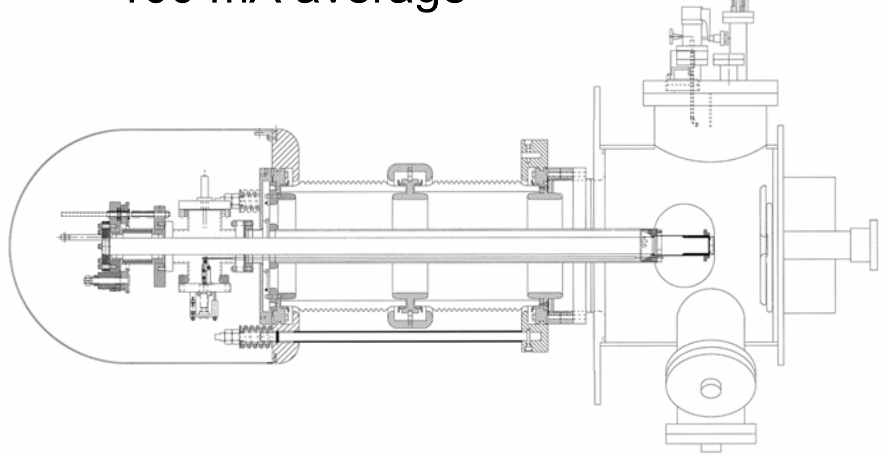
Modes 1-5 (96 - 214 Hz)

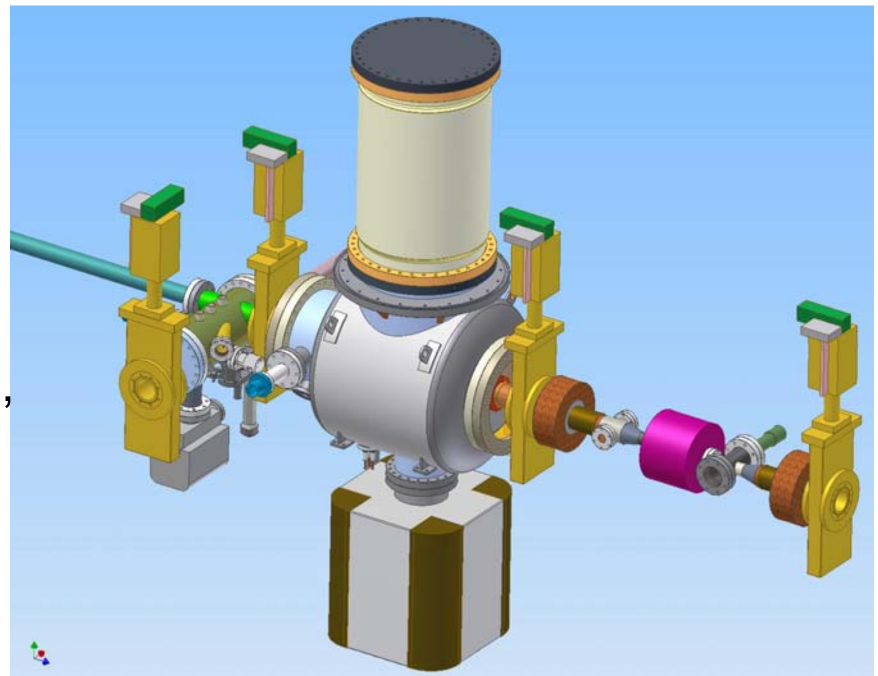


DC gun

Achieved:
JLab 350 kV gun, GaAs cathode,
9.1 mA (122 pC/bunch at 74.85 MHz)
processed 435 kV for 350 kV operation.
Future:

- JLab gun at 500 kV, 100 mA average w/ 750 MHz SRF booster (AES)
- New design, 500 to 750 kV, at Cornell, 100 mA average



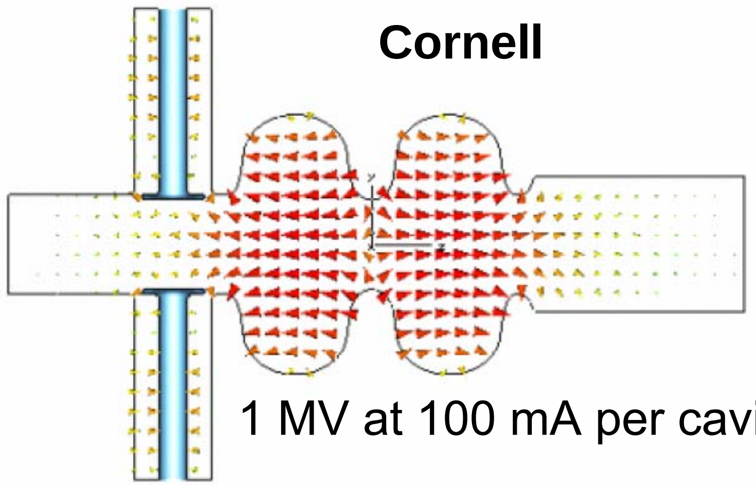


Issues: Field emission, vacuum.

Booster (or injector)

Boosters are accelerating sections that are not energy recovered. Their purpose is to increase the injections energy to the ERL for beam quality and / or energy recovery reasons, usually used with the DC guns that have relatively low energy.

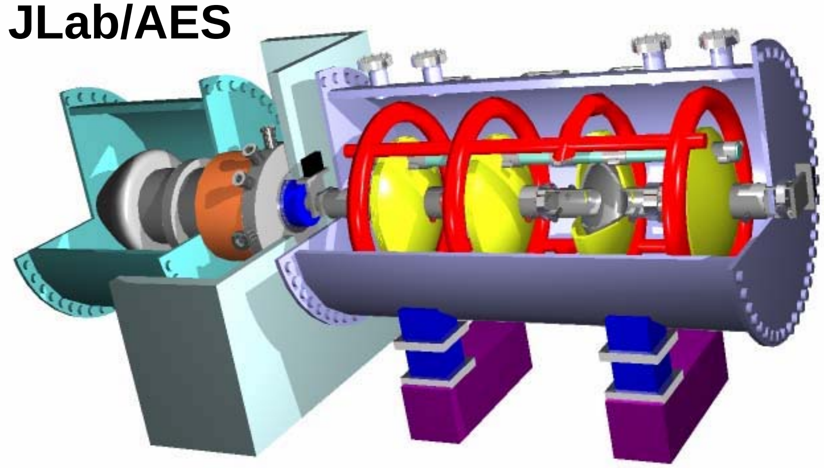
Cornell



1 MV at 100 mA per cavity

Overview of the Cornell ERL Injector Cryomodu
H. Padamsee et. al., Proceedings PAC'03
Dipole-mode-free and Kick-free 2-cell Cavity for the SC ERL Injector
V. Shemelin, et. al., Proceedings PAC'03

JLab/AES



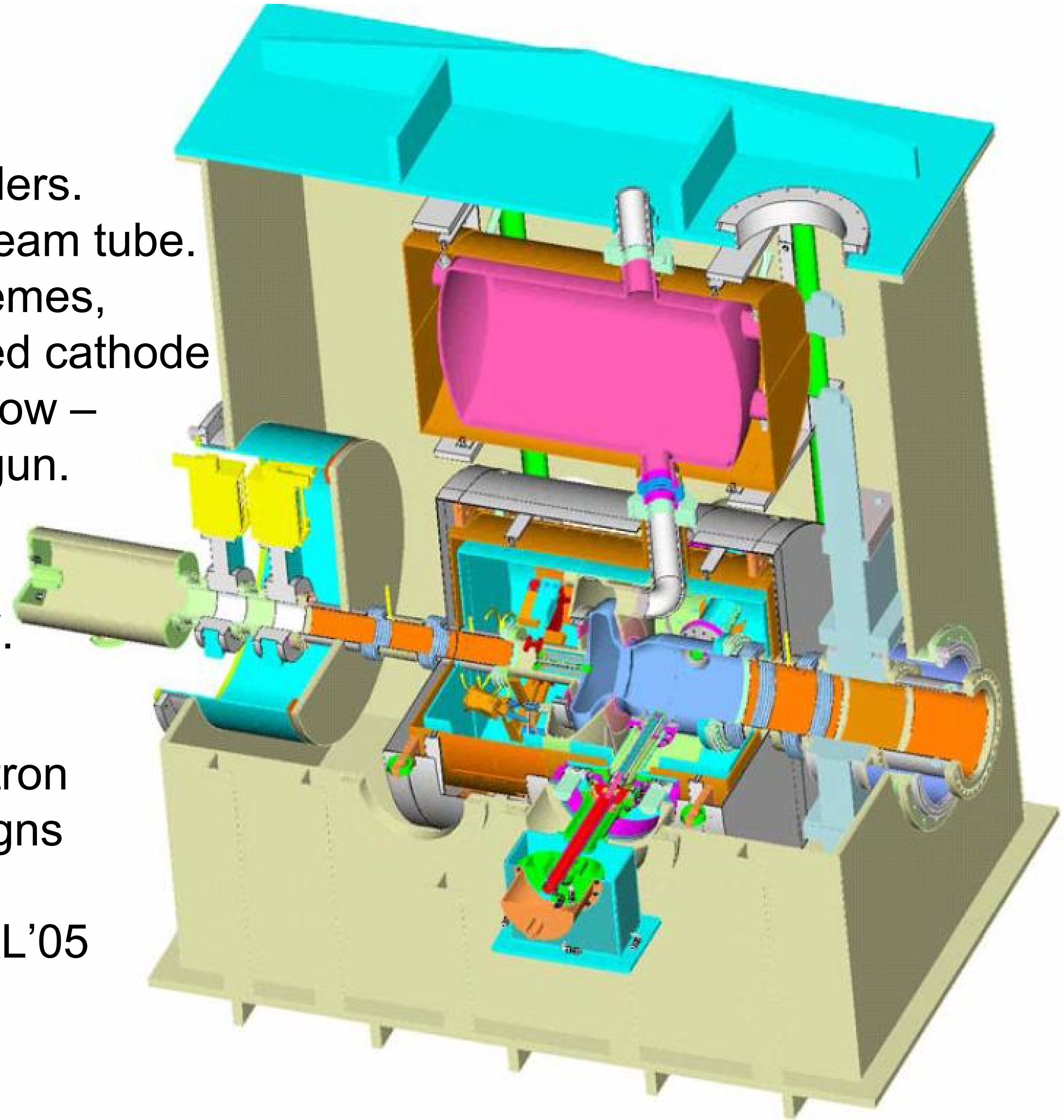
7 MeV + harmonic correction at 100 mA

Design and Fabrication of an FEL Injector Cryomodule
John Rathke et. al., proceedings PAC'05

Superconducting RF gun under development.

703.75 MHz gun.
2x0.5 MW input couplers.
HOM damping thru beam tube.
Various cathode schemes,
including encapsulated cathode
behind diamond window –
isolation cathode ↔ gun.

CW performance
0.5 ampere @ 2 MeV.

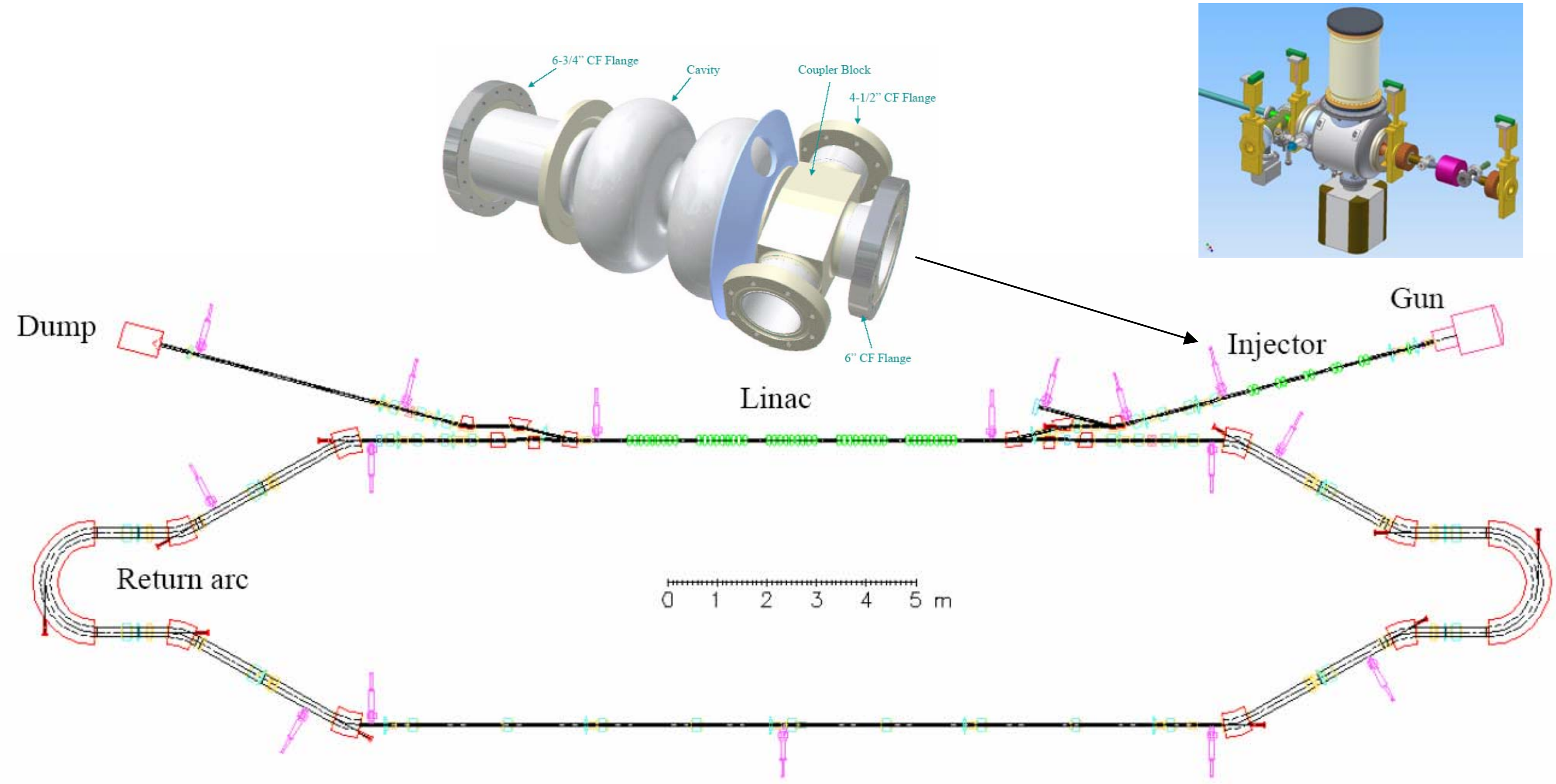


State-of-the-Art of Electron
Guns and Injector Designs
A. Todd,
Invited Plenary Talk ERL'05

ERL test facilities

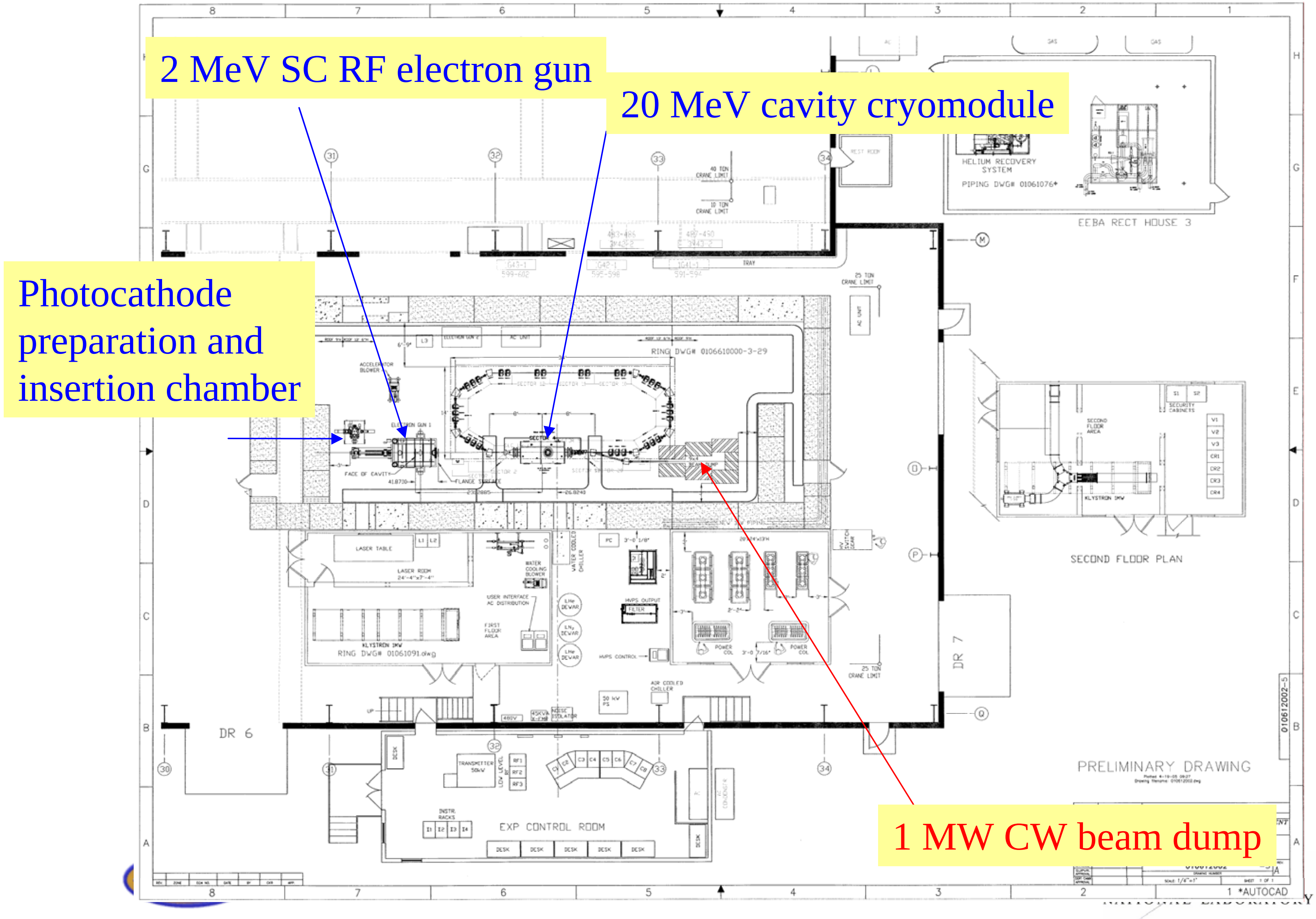
- Currents under discussion (>100 mA) are an order of magnitude or more beyond current state-of-the-art.
- A number of test facilities are under construction at this current level:
  – Cornell, 100 mA at 100 MeV, injector funded and under construction.
  – JLab gun test facility, under construction.
  – BNL ERL, 20 MeV at 0.5 ampere under construction.
- Proposals for other facilities (KEK 100 mA 200 MeV, possibly others)

Cornell ERL prototype



THE CORNELL ERL PROTOTYPE PROJECT
G.H. Hoffstaetter *et. al., Proceedings PAC'03*

BNL ERL Facility at building 912



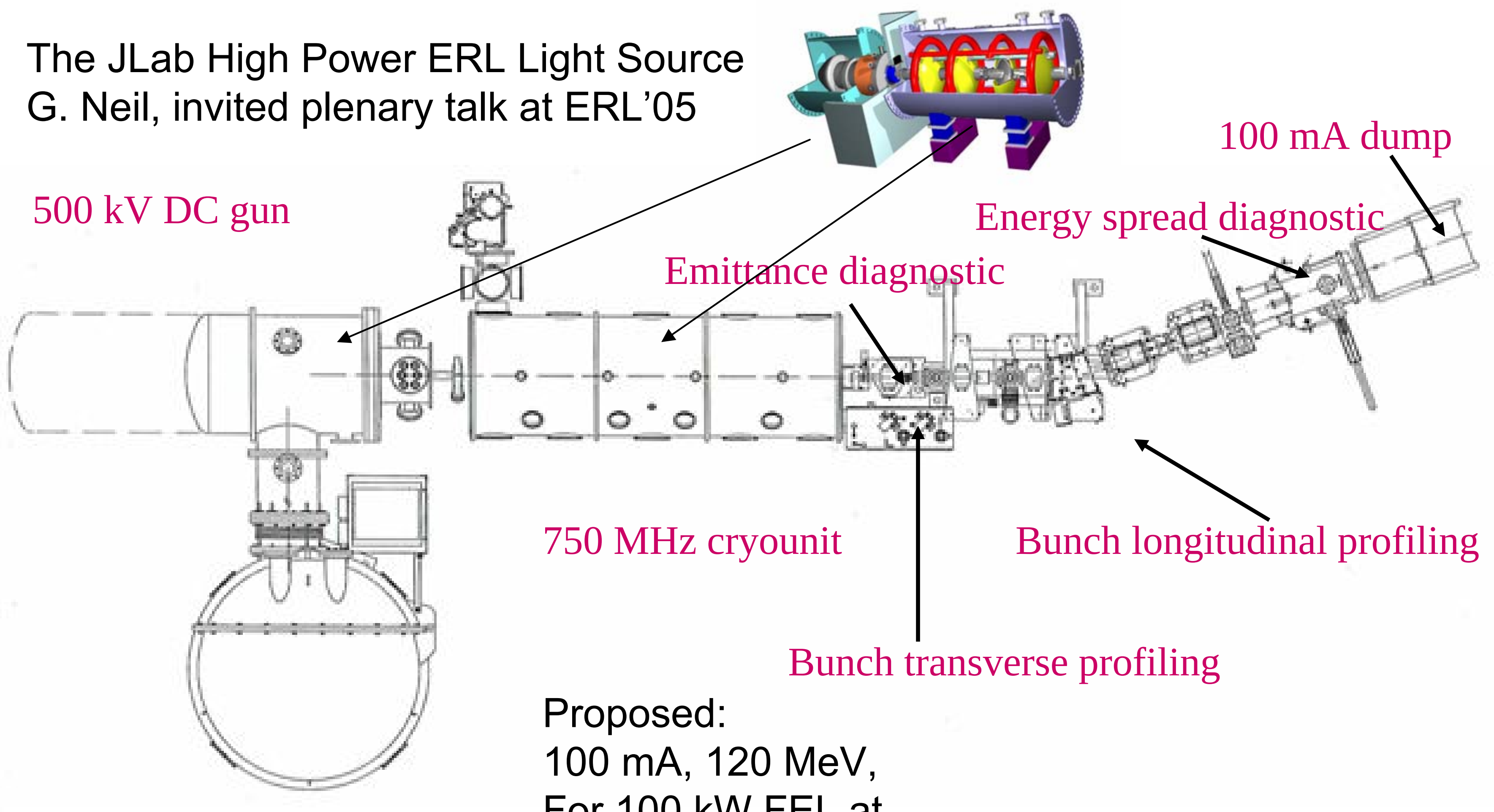
20 MeV, 0.5 ampere ERL
Under construction

Extremely High Current, High-Brightness Energy Recovery Linac
I. Ben-Zvi et. al., proceedings PAC'05

High Current Energy Recovery Linac at BNL
V.N. Litvinenko et. al., proceedings PAC'05

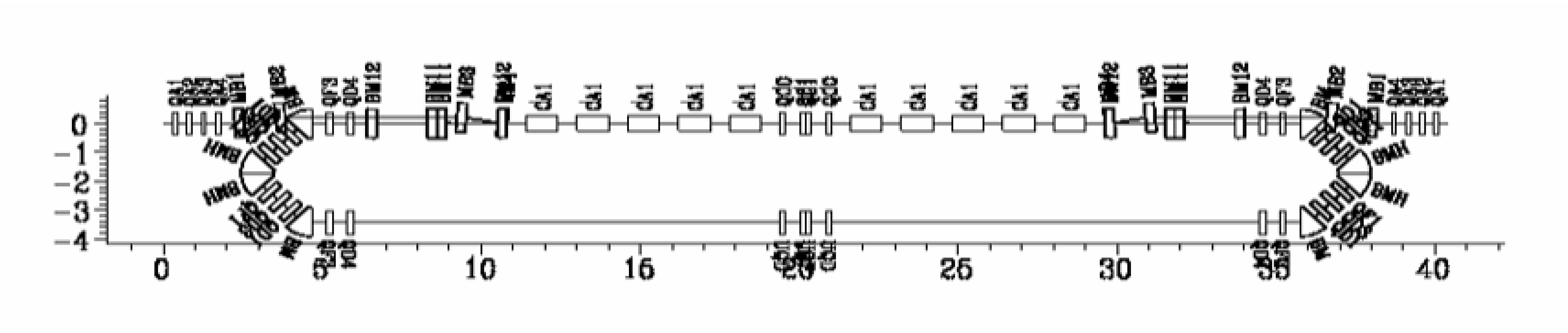
JLab 100 mA injector test-stand

The JLab High Power ERL Light Source
G. Neil, invited plenary talk at ERL'05



Proposed:
100 mA, 120 MeV,
For 100 kW FEL at
1 micron

KEK test facility (proposed)



Total length	112.78 m
Beam energy	200 MeV
Injection energy	5 MeV
Average current	100 mA
Bunch charge	77 pC
Injection bunch length	2 ps
Bunch length after compression	0.1 ps
Energy spread	3×10^{-4}
Normalized emittance	0.1 mm-mrad
Fundamental RF frequency	1.3 GHz
Types of injector	DC photo-cathode gun + 1-cell pre-buncher + 2-cell buncher cavity

A conceptual pre-injector design for the KEK-ERL test accelerator
T. Suwada, et. al., proceedings ERL'05

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  - AES: D. Holmes, A. Burger, M. Cole A. Favale, J. Rathke, T. Schultheiss, others
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  - DESY: J. Sekutowicz

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