

# SRF Challenges for Energy Recovery Linacs

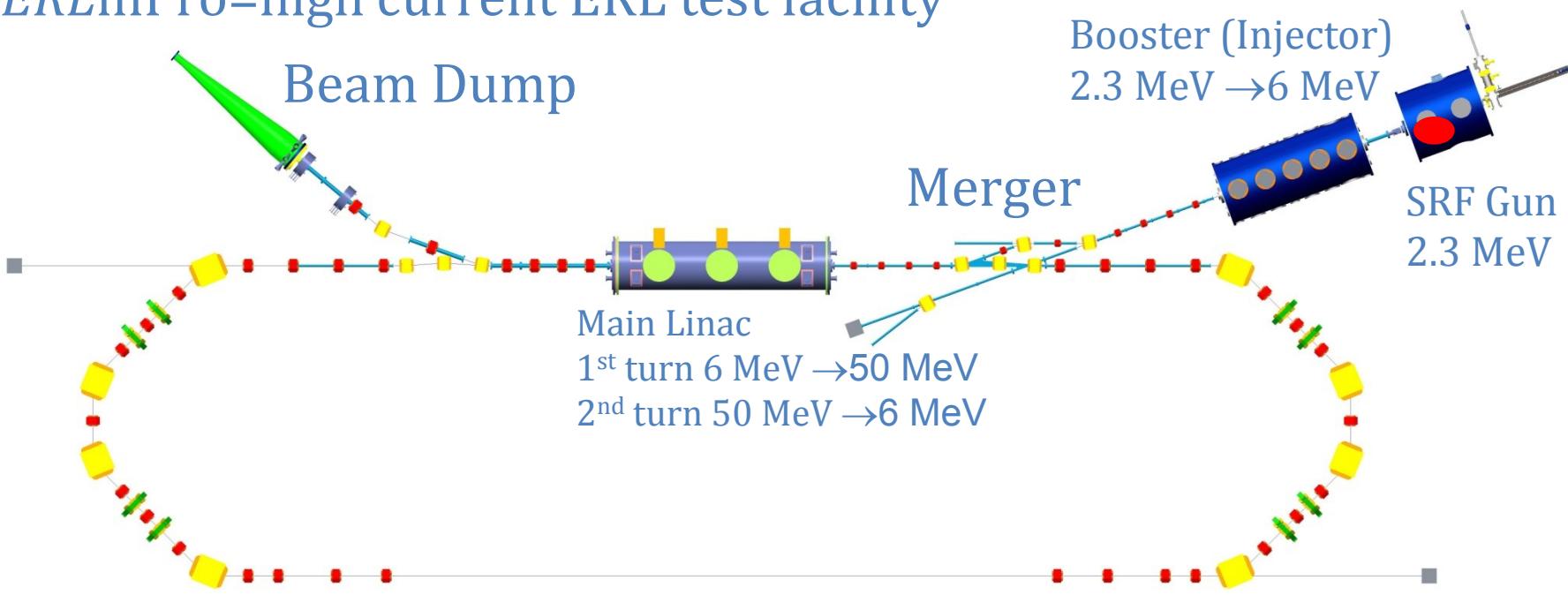
Andrew Burrill

# Outline

- Why we need Energy Recovery Linacs
- Current state of ERL development
- SRF Challenges
  - The Cavity
  - HOM dampers
  - RF and control system
  - Cryomodule
- Closing thoughts

# ERL Overview

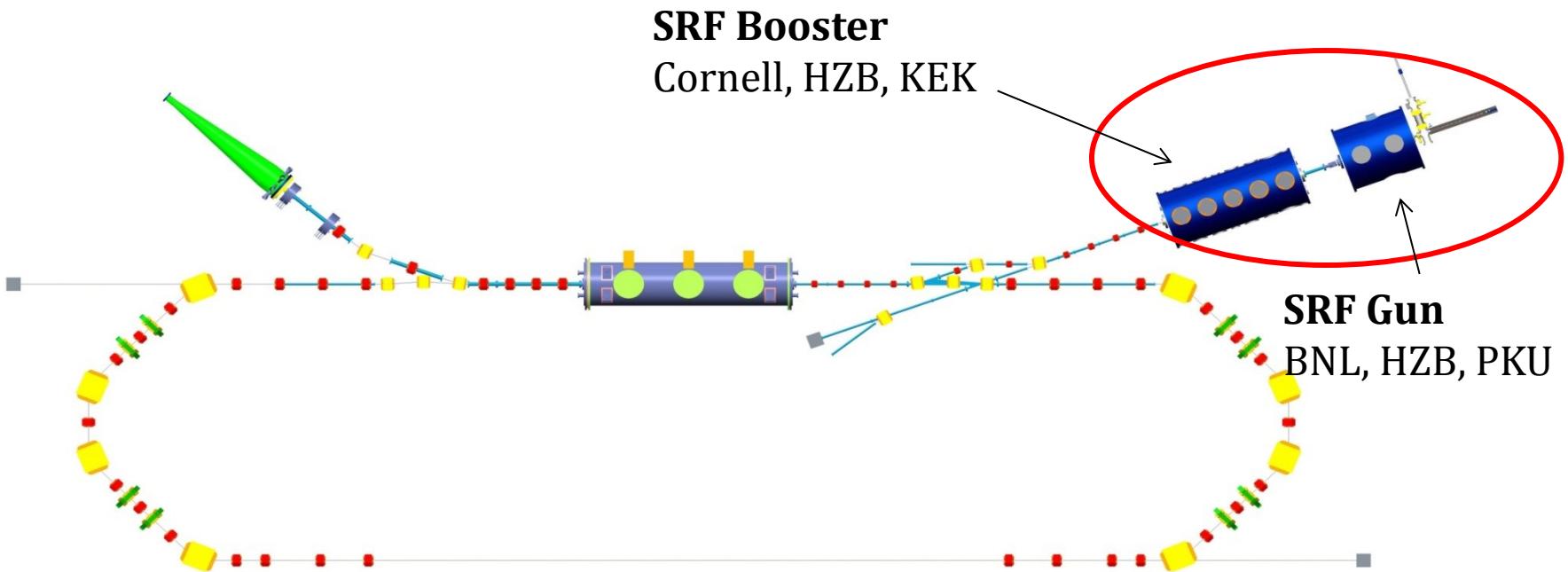
BERLinPro=high current ERL test facility



Beam energy	50 MeV
Average current	100 mA
Bunch charge	77 pC
Normalized emittance	<1 mm·mrad
Resonance frequency	1.3 GHz

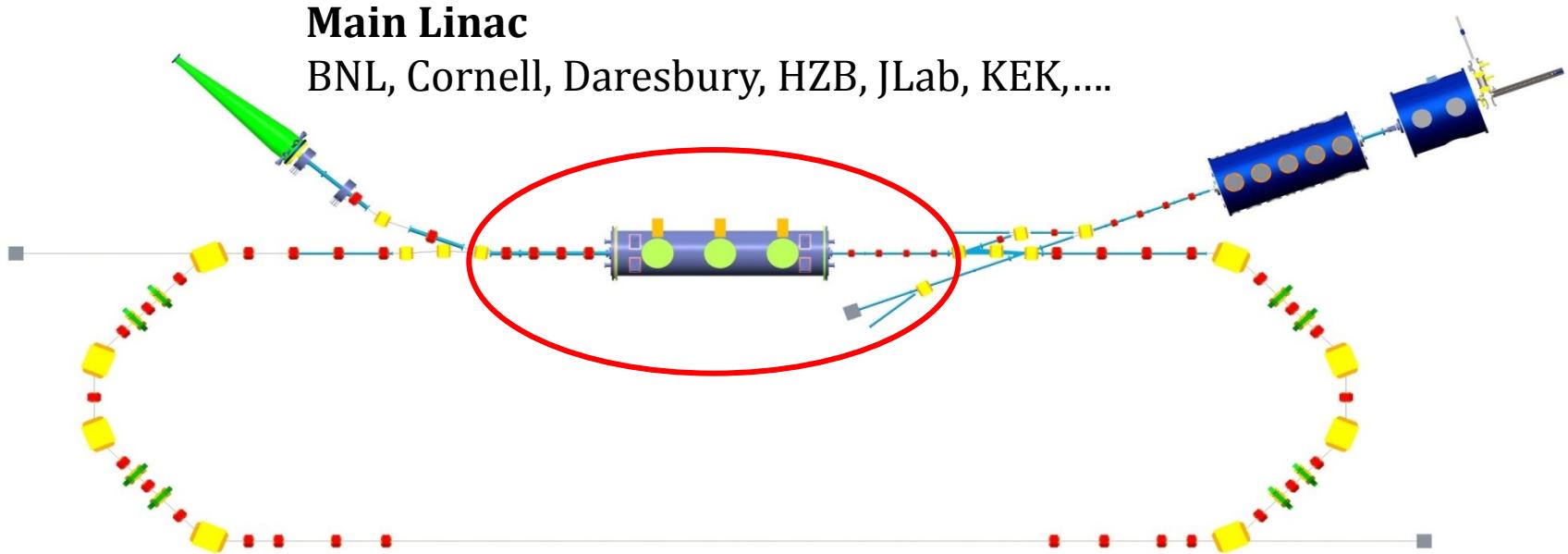
Demonstration of the feasibility to use ERL technology for future 4th generation multi-user light sources

# SRF in ERLs



- Injector: No energy recovery
  - Beam loading primary consideration!
  - Beam is “soft”, danger of emittance dilution
  - If SRF cavity injector: NC cathode in an SRF environment

# SRF in ERLs

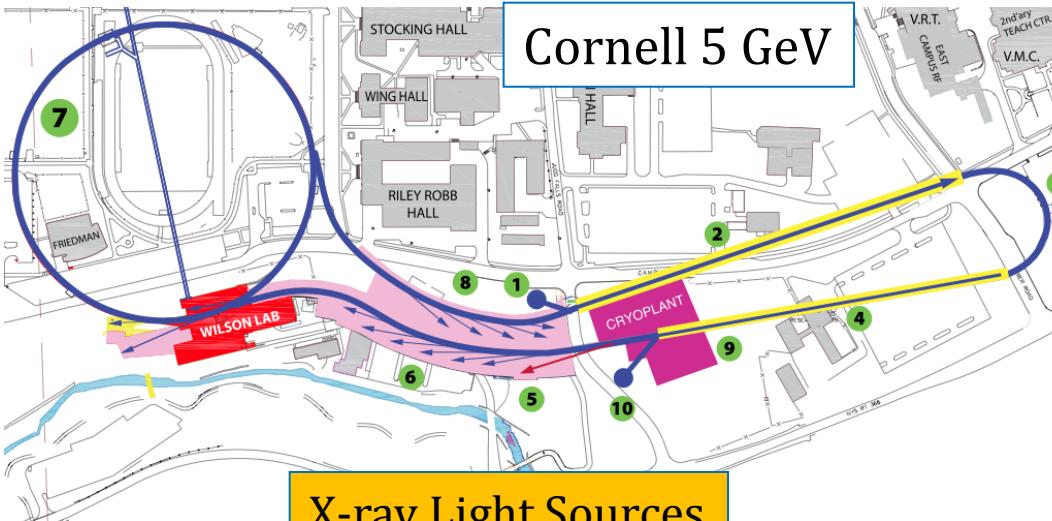


- Main LINAC: Energy recovery
  - Beam loading no longer critical
  - RF Stability and microphonics is key
  - Optimize RF power to cavity
  - HOM excitation and power extraction
  - Cryogenic Load is significant

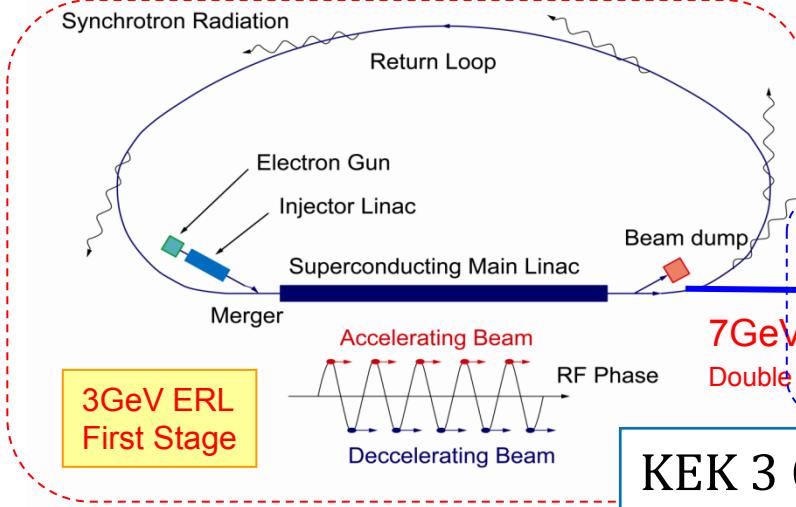
# Why do we need SRF ERLs?

## “Big” Machines

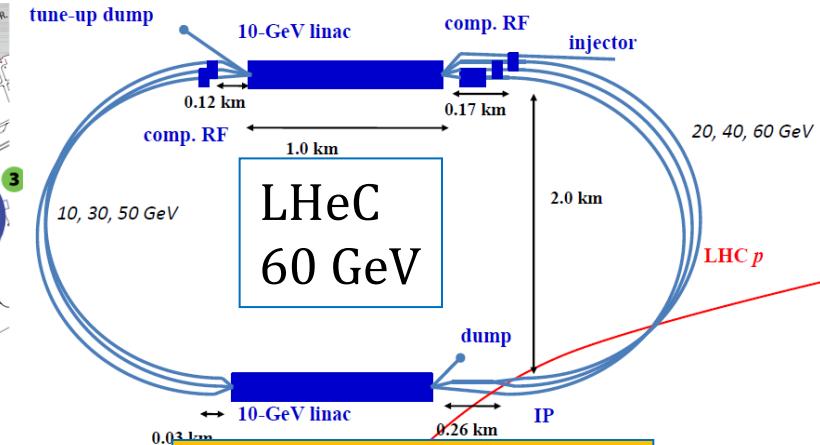
Cornell 5 GeV



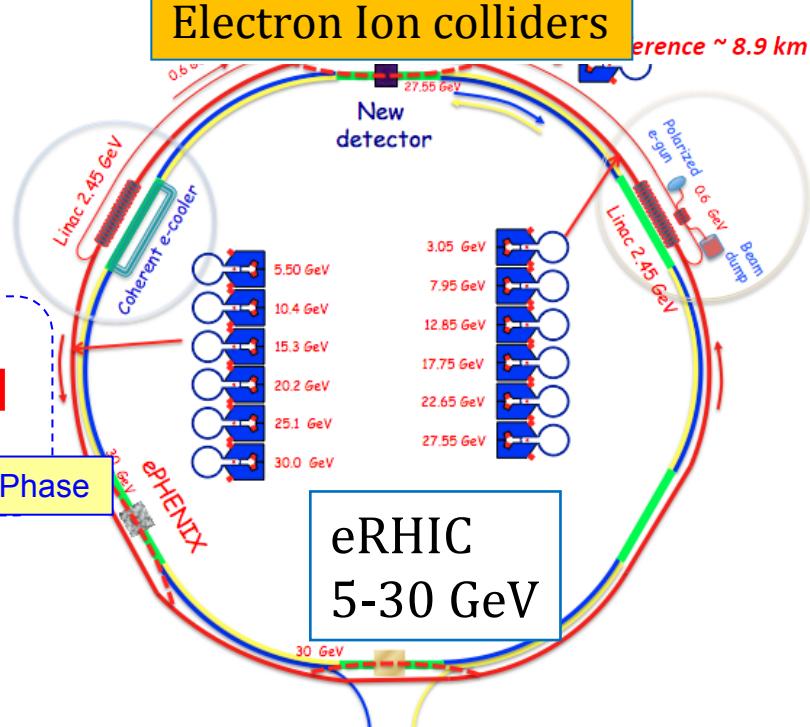
X-ray Light Sources



KEK 3 GeV



eRHIC  
5-30 GeV



# Big Machine Beam Power

<u>Machine</u>	<u>Beam Parameters</u>	<u>Beam Power</u>
Cornell	5 GeV @ 100 mA	500 MW
KEK	3 GeV @ 100 mA	300 MW
BNL	20 GeV @ 6 mA	120 MW
LHeC	60 GeV @ 6.4 mA	384 MW

XFEL Main Linac 2.5-20 GeV 650 kW Avg beam power

Without Energy Recovery these machines would be  
cost prohibitive to build and operate!

# ERLs around the world

Location	Purpose	Current	Energy	Status
SINAP (China)	THz FEL	20 mA	20 MeV	Prototype
BNL (USA)	high current R&D/eRHIC	50-300 mA	20 MeV	Commissioning
Daresbury (UK)	FEL (IR), THz, Demo	13 mA	27.5 MeV	Operational
PKU (China)	FEL	1 mA	30 MeV	Prototype
IHEP (China)	ERL & FEL	10 mA	35 MeV	Design Phase
KEK (Japan)	cERL/ light source	10-100 mA	35 MeV/3 GeV	Commissioning
TRIUMF (Canada)	Photo-fission driver	10 mA	50 MeV	Construction
HZB (Germany)	R&D for future light source	100 mA	50 MeV	Construction
Mainz (Germany)	Electron scattering experiments	1-10 mA	100 MeV	Design Phase
JLab (USA)	FEL (IR, UV) THz	10 mA	200 MeV	Operational
Cornell (USA)	X-ray light source	100 mA	5 GeV	Prototype
CERN (Switzerland)	LHeC (EIC)	6.4 mA	60 GeV	Design Phase



# SRF Challenges - The Cavity

- Cavity design needs to be optimized for c.w. application
  - Optimum frequency 700 MHz to 1.5 GHz  
Optimization depends on many parameters!
- High Q<sub>o</sub> at operating gradient (15-20 MV/m)
  - Reduced cryogenic load
- Fill every bucket at 700-1500 MHz
  - charge/bunch  $\sim$ 100 pC
  - Good emittance ( $< 1\text{mm}^*\text{mrad}$ )
- Maximized R/Q \* G for the fundamental
- Designed for low E<sub>peak</sub>/E<sub>acc</sub>
  - Field emission

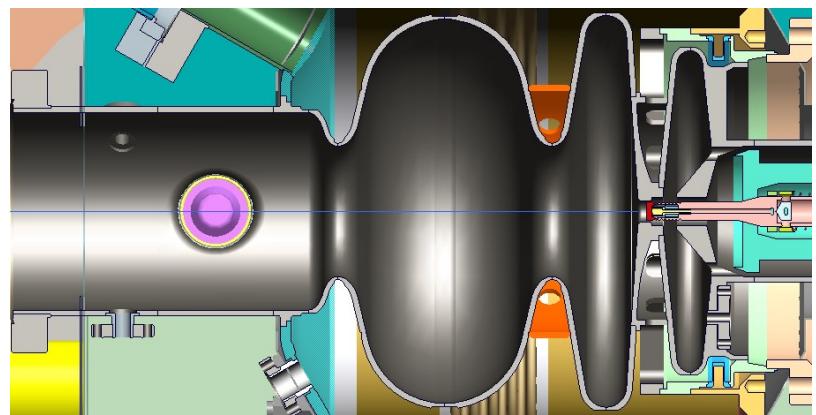
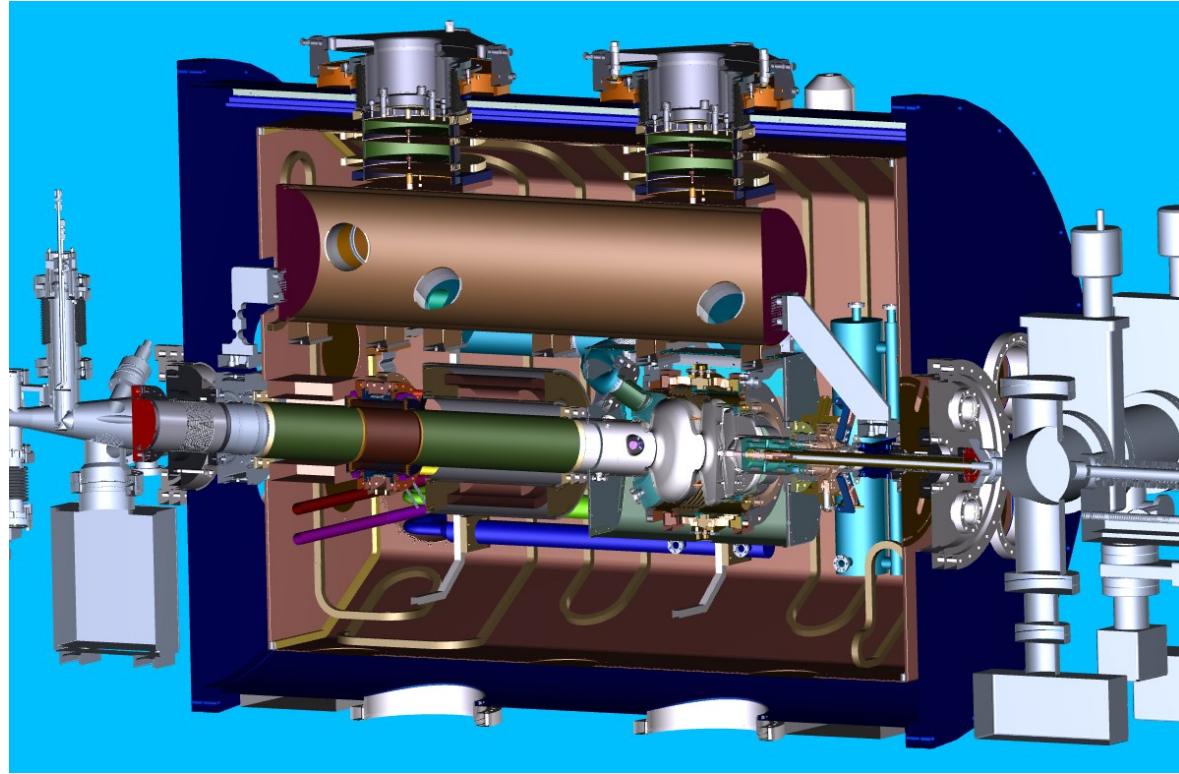
Make the design as economical to operate as possible

# The Cavity 2

- HOM propagation
  - Cavity cell shape, iris diameter and beampipe transition optimized
  - Cavity design and measurements must be compared for **all** cavities.
  - Large projects benefit from a fabrication tolerance study (Cornell)  
+ comparison with fabrication data (JLab)
- BBU threshold
  - Design must allow for the theoretical threshold to be at least X times greater than what is necessary
- Optimize for minimum df/dp
  - Pressure fluctuations at high power are more likely
  - Impact on RF system
  - Significant impact on operations
    - Users
    - Cathode lifetime

# SRF Gun Challenges

- Physics Design
  - Beam dynamics like very high fields on the cathode
    - Results in high peak electric fields ( $E_p = 40\text{-}60 \text{ MV/m}$ )
      - Possible conflict with routine insertion and retraction of photocathode
    - Not a true  $\beta=1$  structure
- Design of choke structure for operation with normal conducting photocathode
- Fabrication is not in large quantity
  - Usually 1 or 2 cavities with <3.5 cells
  - Significant machining work, lots of parts from ingot material
- Gun module needs to be as short as possible



# SRF Gun Challenges

## Requirements

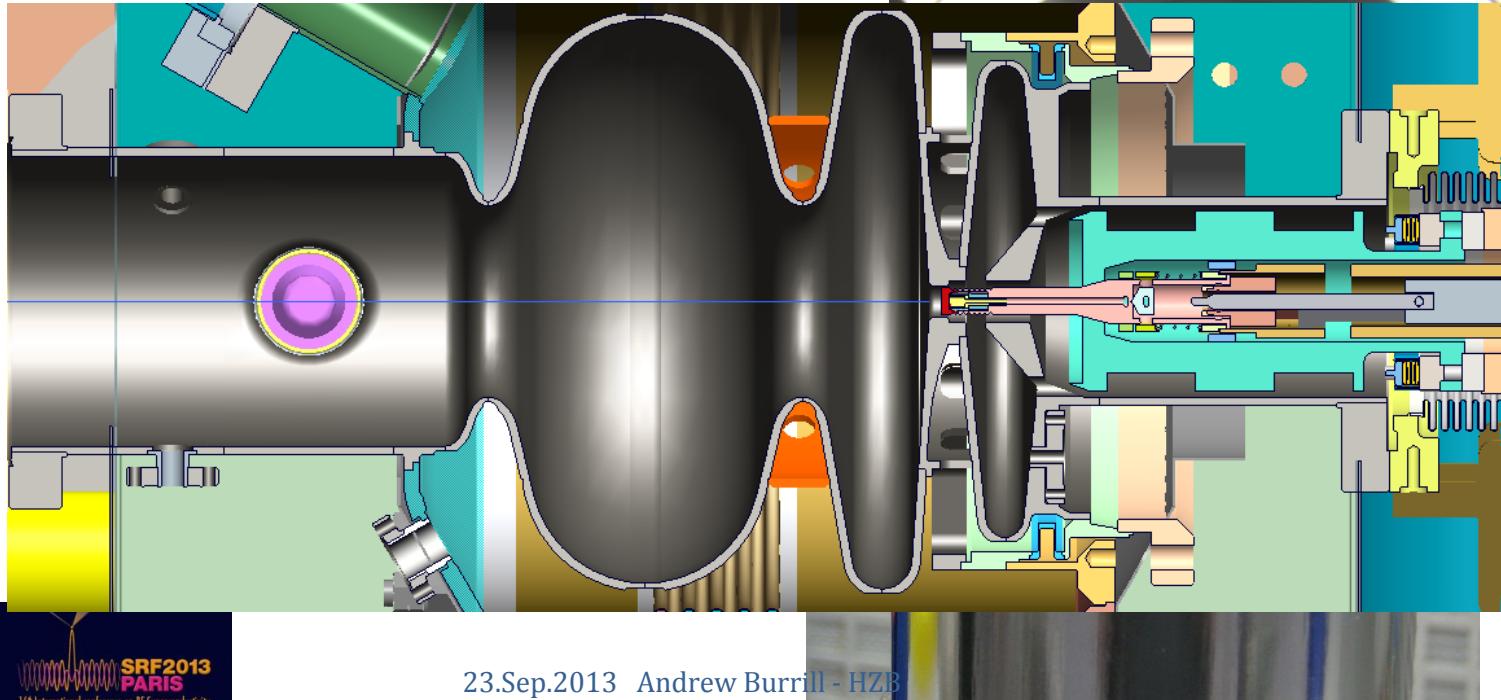
- 2.3 MeV 100 mA beam = 230 kW RF power
- Loaded Q ( $10^4$ - $10^7$ )
- Multiple beam operating conditions
  - Bunched operation
  - High current mode
  - High charge mode
- Superconducting magnet near the cavity
- Normal conducting cathode in SRF cavity

## Associated Challenge

- Dual High power RF power couplers (115 kW each)
- Coupler Penetration into beampipe
- Power dissipation in coupler region –gasket heating
- Variable coupling, LLRF control, cavity stability
- Magnetic Shielding
- Quench recovery
- Thermal isolation
- Multipacting
- Contamination

# SRF Gun Testing challenges

- Difficulties in testing the gun with a cathode stalk in the vertical tests
- Processing the cavity
- HPR in tight spaces
- Cathode contamination



# Booster (Injector) Module

- Designed to accelerate low energy beam from gun to the main linac

Low energy beam

Cavity alignment is critical to low emittance

Strongly coupled cavity  $Q_{ext} 10^4-10^7$

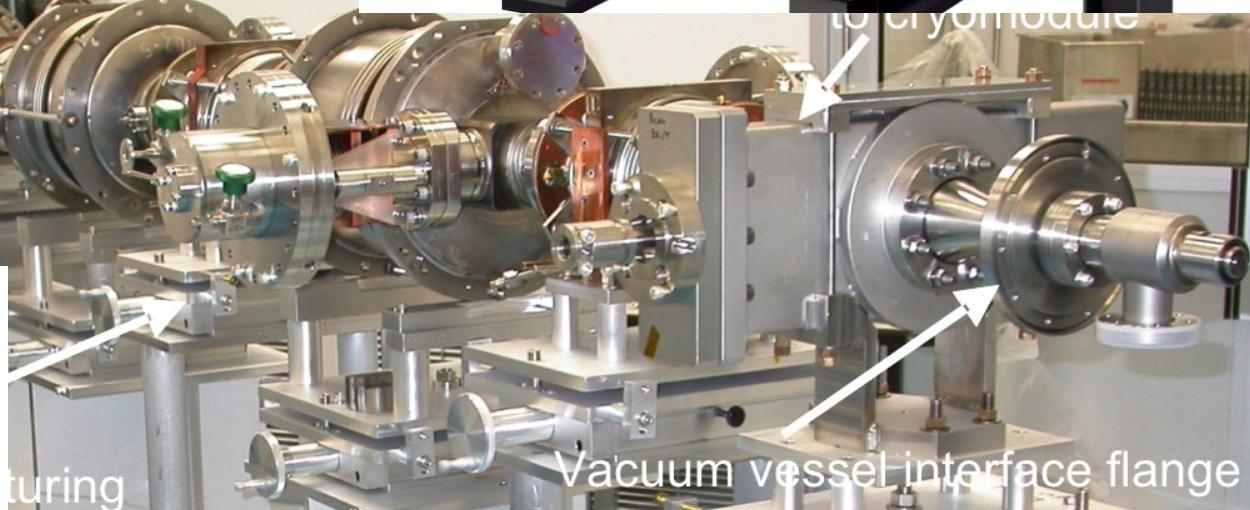
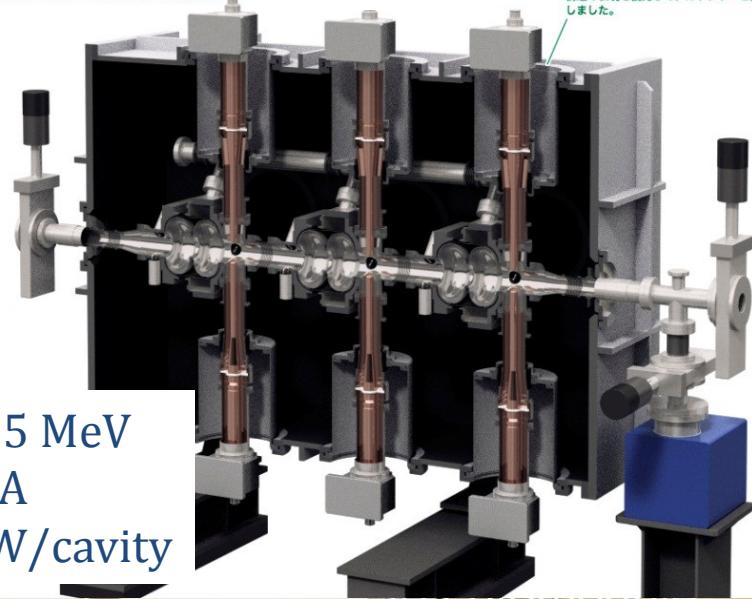
Coupler perturbation an issue

HOM power not the same as a Linac Cavity

PEARL動画・前段加速器 内部表現チェック 20130407 a  
電子銃の詳細表現に登場させる前段加速器の内部構造案です。

KEK

インプットカップラー取付け用のビットは、  
構造の表現を優先して、カップラーと同心に  
しました。



# SRF Challenge - Cavity preparation

- Provide a reproducible and robust way to prepare cavities
  - High Q<sub>0</sub>, minimal Q slope
- Important considerations
  - Chemical processing recipe
    - BCP, CBP, Flash BCP, EP
    - Heat treatment 600°C - 800°C with or without additional processing
    - HF rinses
    - High Pressure rinsing ( 4 hours – 12 hours)
  - Parts cleaning
  - Assembly techniques
  - Slow pump-down

The Good: Many ways to reach the goal

The not so good: highly variable from lab to lab

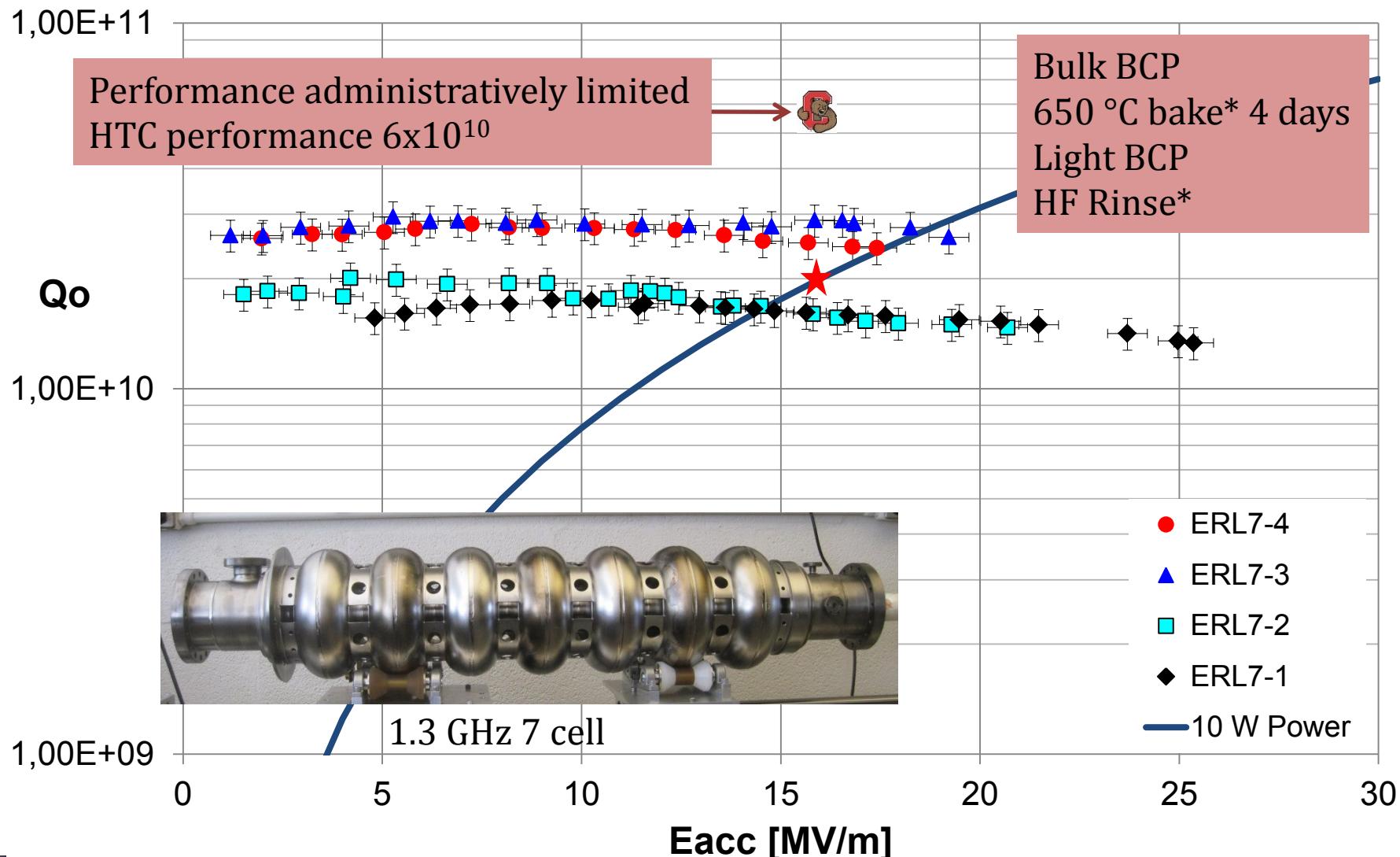


# SRF Cavity Prep -Cornell Linac Cavity

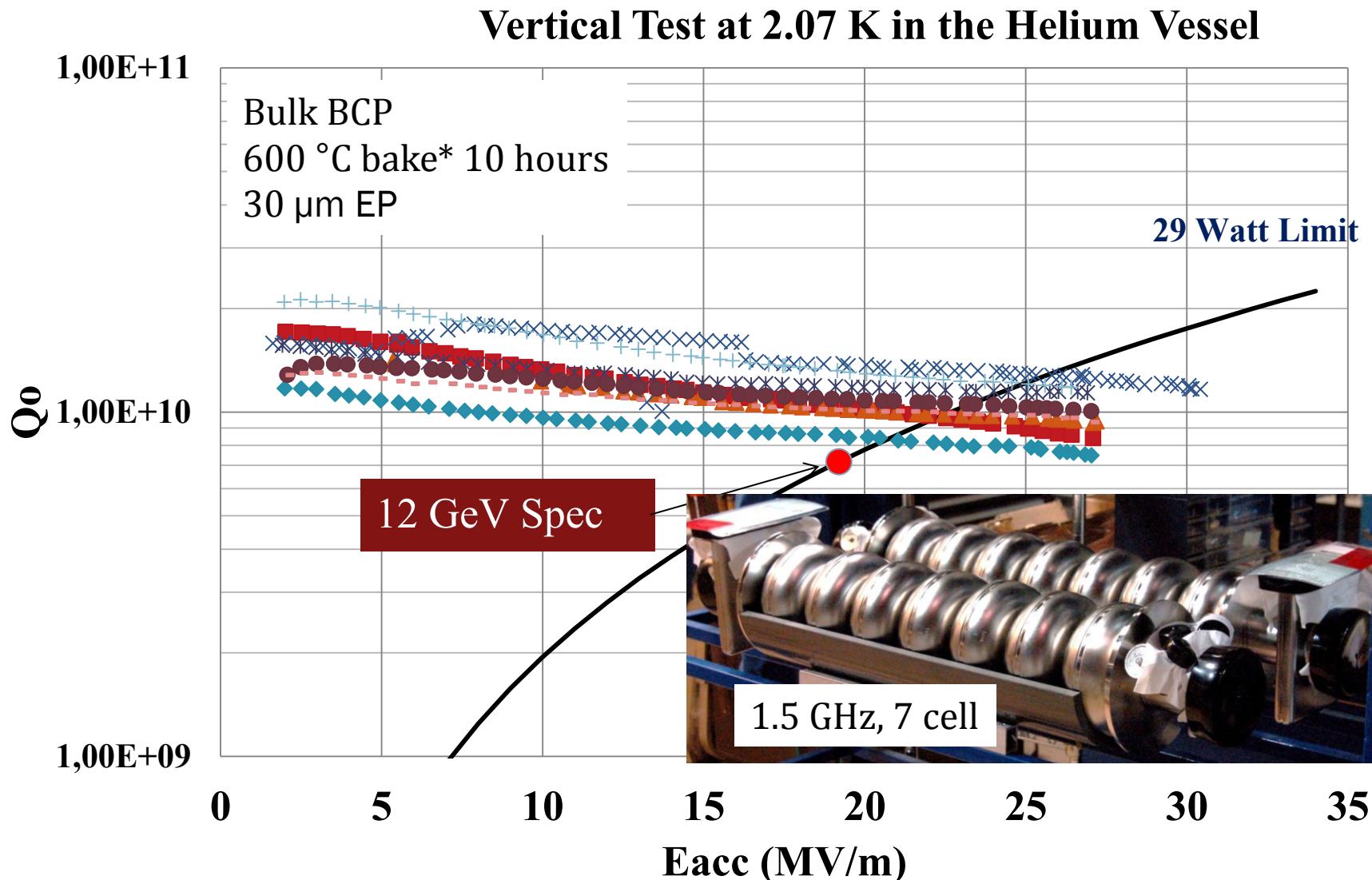
	<b>ERL7-1 (HTC)</b>	<b>ERL7-2</b>	<b>ERL7-3</b>	<b>ERL7-4</b>
Bulk BCP	140um (witness sample)	$135 \pm 10$ um (cavity equator)	$138 \pm 5$ um (cavity equator)	$132 \pm 7$ um (cavity equator)
Degassing	Jlab, 650C*10hrs	TM-furnace 650C*4days	TM-furnace 650C*4days	TM-furnace 650C*4days
tuning	88%	94%	91%	92%
Final BCP	10 um	10 um	10 um	10 um
120C bake	On insert	TM-furnace	On insert	TM-furnace
HF rinse	No	Yes	Yes	Yes
VT 1 <sup>st</sup> (1.8K)	17MV/m, 1.6e10 (No T-map)	17MV/m, 1.53e10 w/ T-map	Limited by FE w/ T-map	17.4MV/m, 2.4e10 w/ T-map
	HTC1, HTC2 (high rad)			
Re-process	-BCP(10um) -120C bake(in clean room, old set-up) -HF rinse		Re-process to cure FE -BCP(10um) -120C bake(TM- furnace) -HF rinse	
	<b>HTC3, 16.2MV/m, 6.0e10 @1.8K</b>			
VT 2 <sup>nd</sup> (1.8K)			17MV/m, 2.8e10 No T-map (PC down)	

# Cornell Linac Cavity

## Cornell Vertical Test 1.8 K



# SRF Cavity Prep -JLab 12 GeV upgrade



# SRF Challenges - Higher Order Modes

7 cell ERL cavity, 77 pC, 100 mA

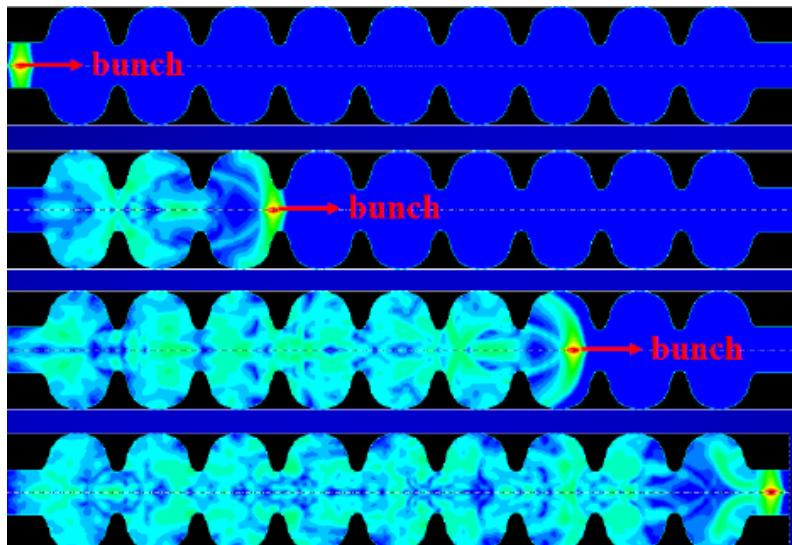
$$P_{HOM} = k_{HOM} \cdot q_{bunch} \cdot I_{beam}$$

ERL Linac

$$P_{HOM} = 12 \frac{V}{pC} \cdot 77pC \cdot 0.2A = \mathbf{200\,W}$$

HOM damper must be independent of 2K system

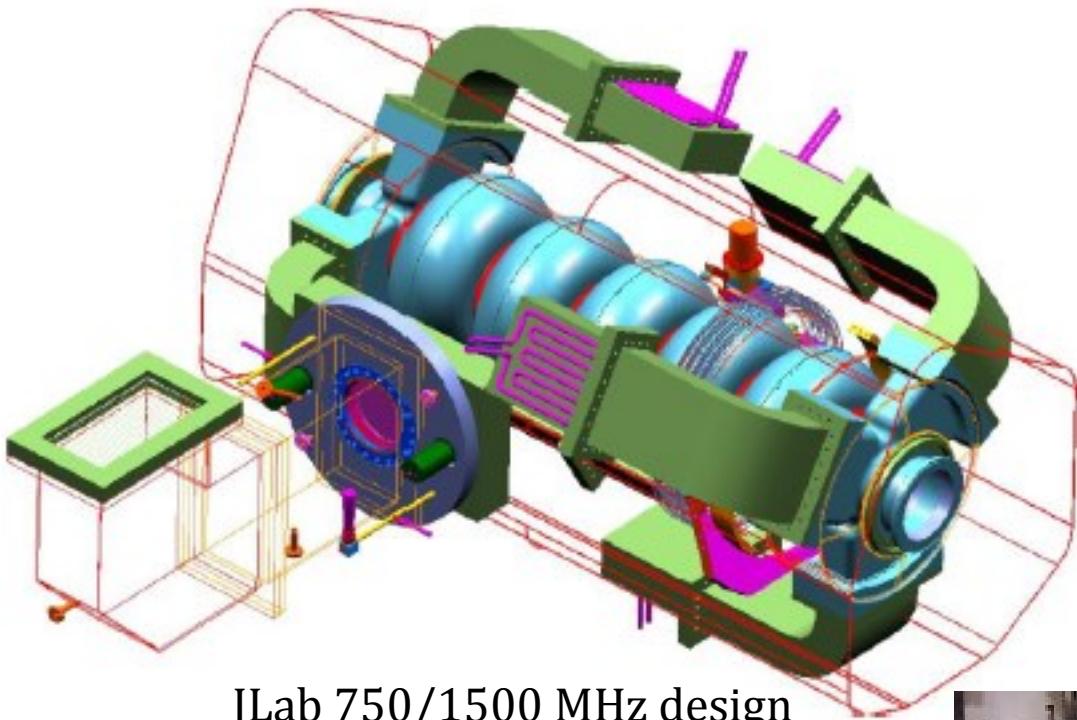
HOM damper must not reduce the cavity performance



ERL	Beam Current [mA]	Average HOM power per cavity [W]	Required monopole Q	Required dipole Q
Cornell	100	200	$5 \times 10^3$	$1 \times 10^4$
KEK-c	100	185	$1 \times 10^6$	$1 \times 10^4$
BERLinPro	100	150	$1 \times 10^4$	$1 \times 10^4$
eRHIC	300	7,500	$1 \times 10^4$	$4 \times 10^4$

$$P_{HOM-eRHIC} = 3.5 \text{ V/pC} * 3500 \text{ pC} * 0.05 \text{ mA} * 12 \text{ passes}$$

# HOM Waveguide Absorbers



JLab 750/1500 MHz design

## Key Advantages

- Require less length in the CM vs beamline absorber
- Move load material further from the cavity

## Disadvantages

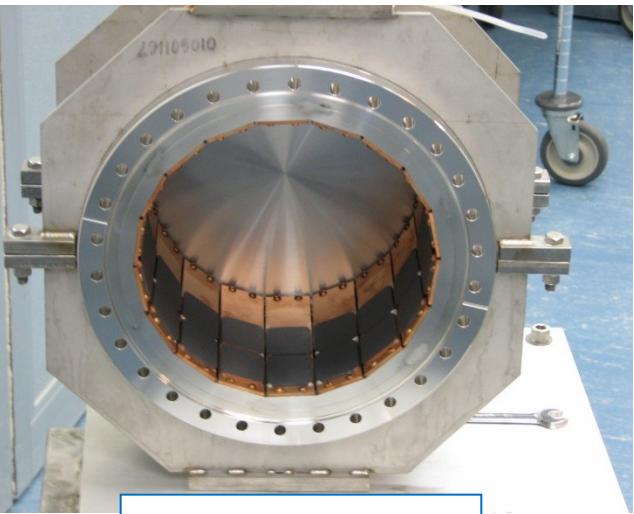
- Multiple loads required
- HV welding
- CM design



WG HOM load  
Based on PEP-II



# HOM Beamlime Absorbers



BNL ECX Cavity



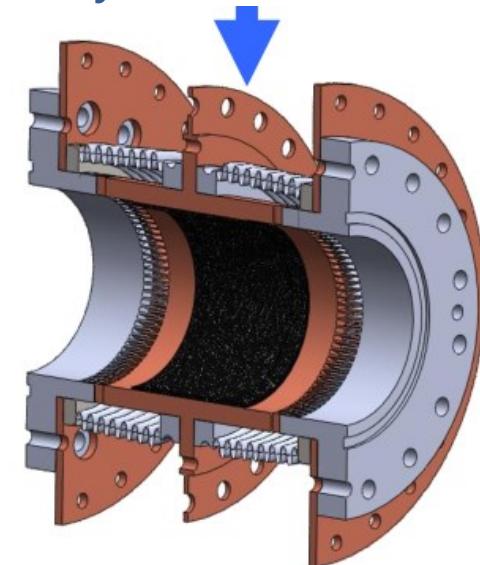
XFEL

## Key Advantages

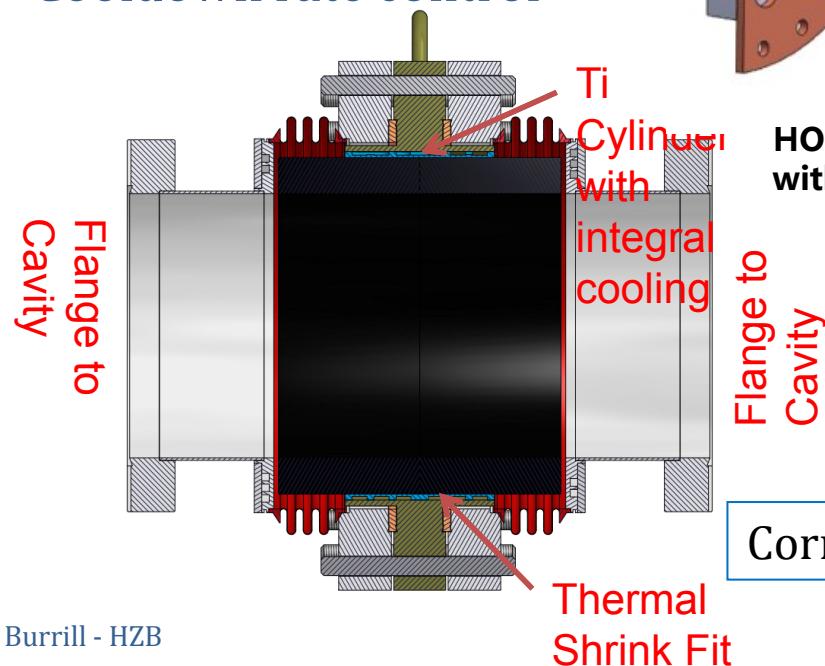
- Fewer loads required than WG style
- Less complicated CM design

## Disadvantages

- Reduces real estate gradient
- Proximity of load to cavity
- Charging of material
- Cooldown rate control



HOM ferrite damper  
with comb shield



Cornell

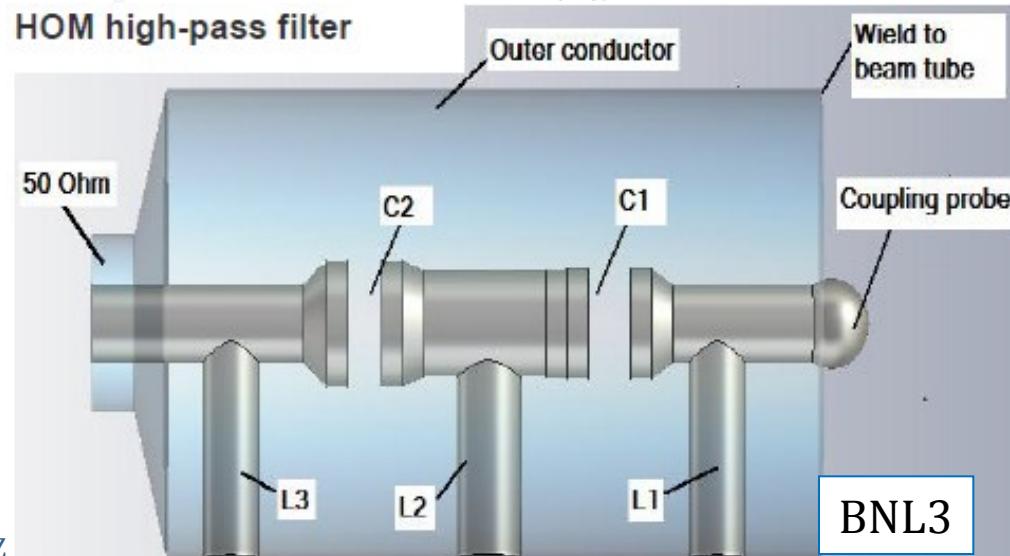
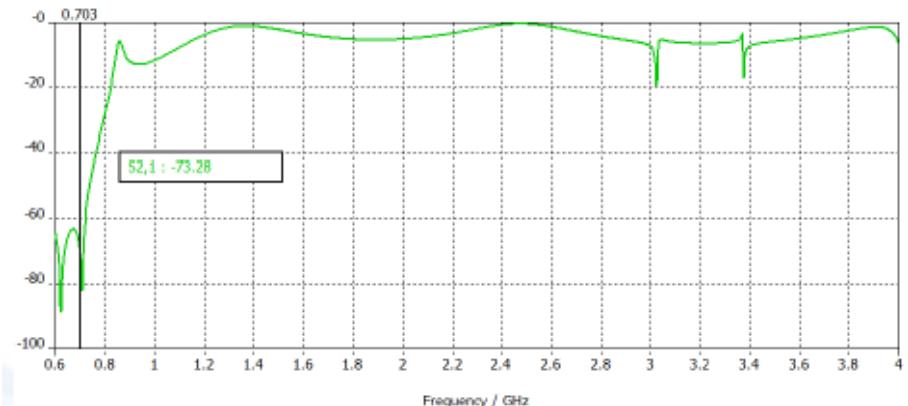
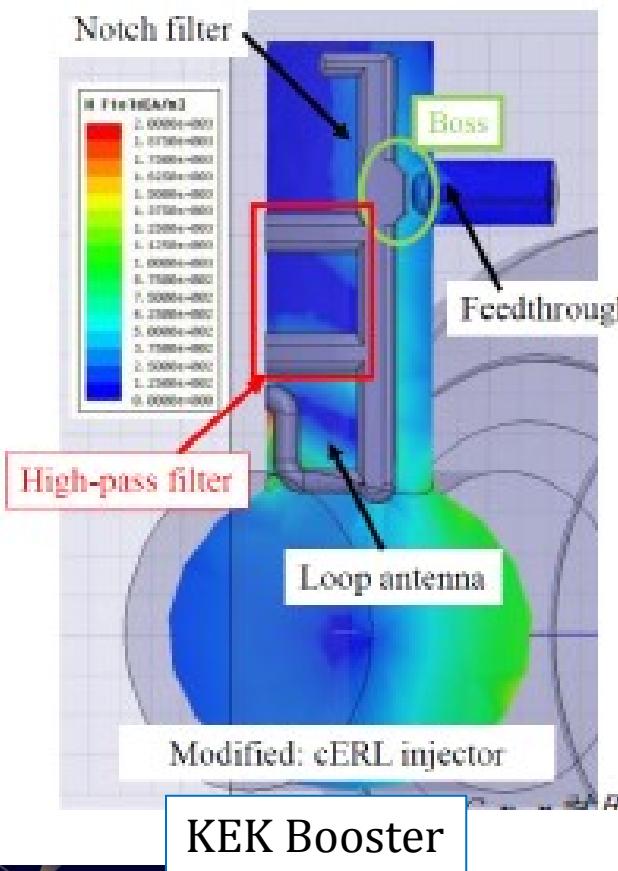
# HOM Couplers

## Key Advantages

- Cleanroom compatible
- Highest real estate gradient

## Disadvantages

- Thermal management critical
- Narrow notch filter makes it possible to couple out fundamental during upset condition



BNL3

# SRF Challenges - RF Stability

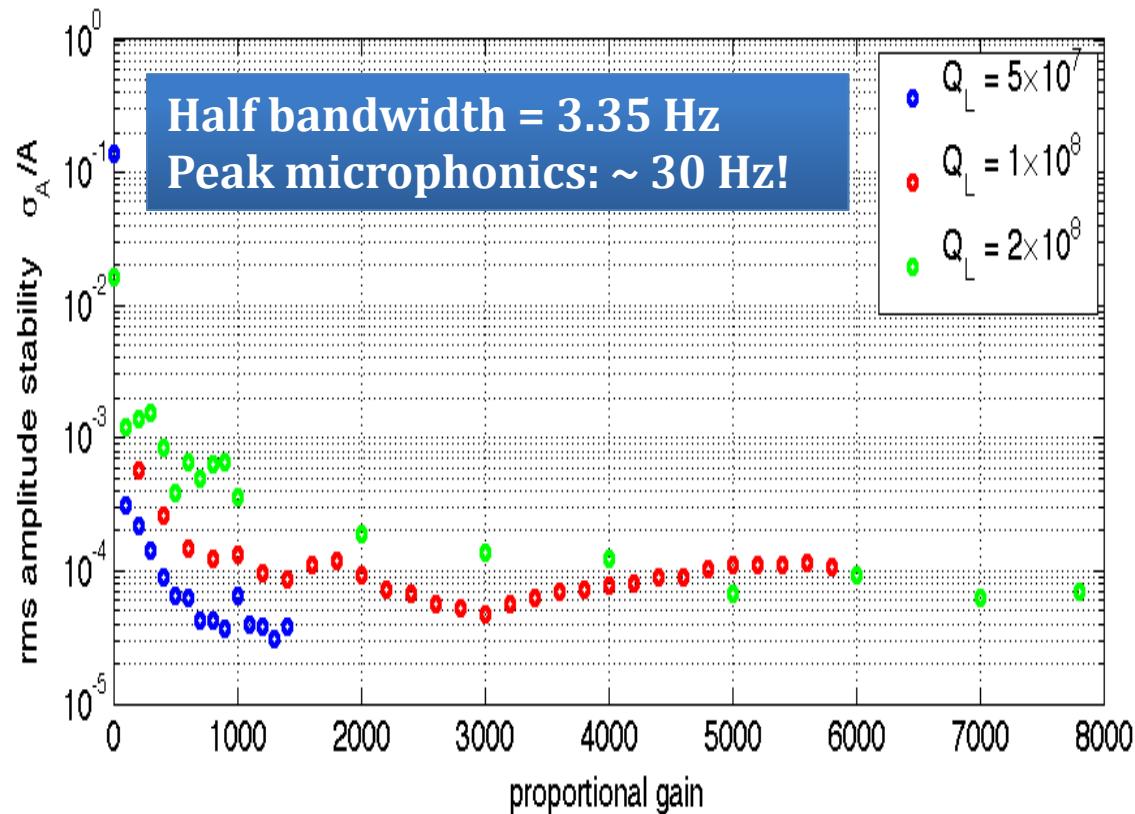
ERL linac cavities  
ideally see a zero net  
beam loading.

$Q_L > 1 \times 10^8$  are possible

- this requires very low microphonics
- $\sigma_A/A < 1 \times 10^{-4}$
- $\sigma_\phi < 0.02$

Measured Phase stability of 0.02 deg at  $Q_L = 2 \times 10^8$  (3 Hz bandwidth)  
Fast ramp to high field < 0.5 sec

LLRF measurement of Cornell system at HoBiCaT (HZB) on a 9 cell Tesla cavity



Reduce  $Q_L$ , reduce capital & operating costs!

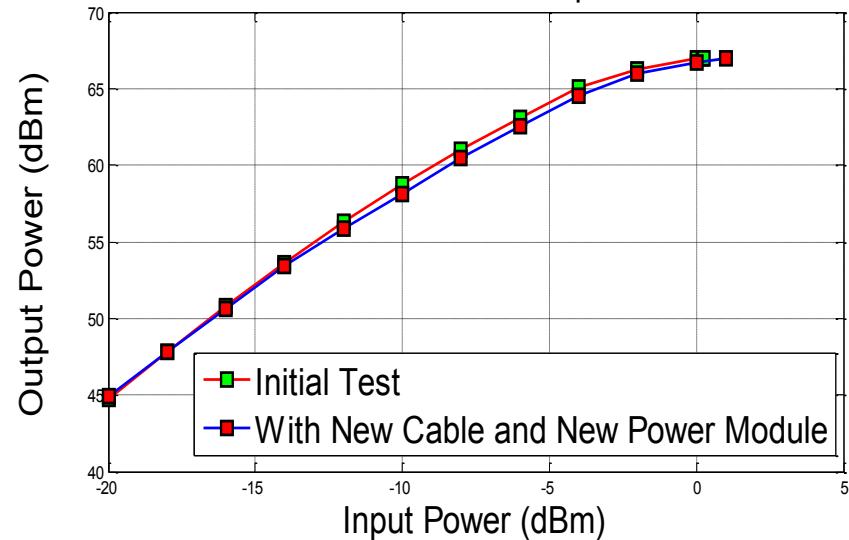
# Cornell 5 kW Solid State RF Amp

- Many advantages: compact, modular design, good maintainability....
- Competitive cost (<15\$/W) for low power CW applications
- High overall system efficiency
- Good linearity
- Stable operation after initial problems with overheating of transistors (resolved) ; occasional trips likely due to overdriving the amp

<b>Operation Frequency</b>	1300MHz +/- 5MHz
<b>Gain</b>	67 dB
<b>Power RF Efficiency</b>	40% at 5kW Output



Gain Plot of the Amplifier





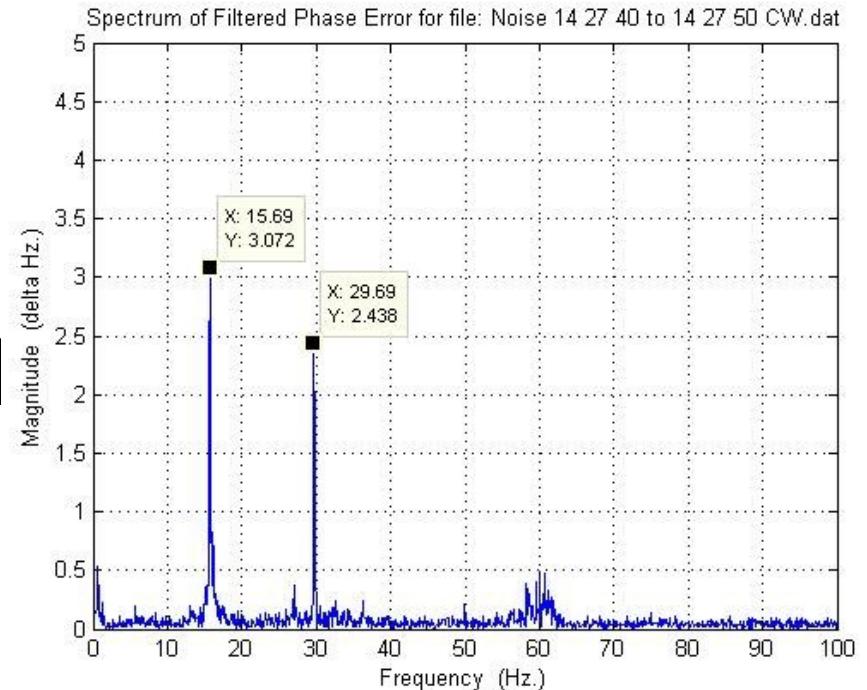
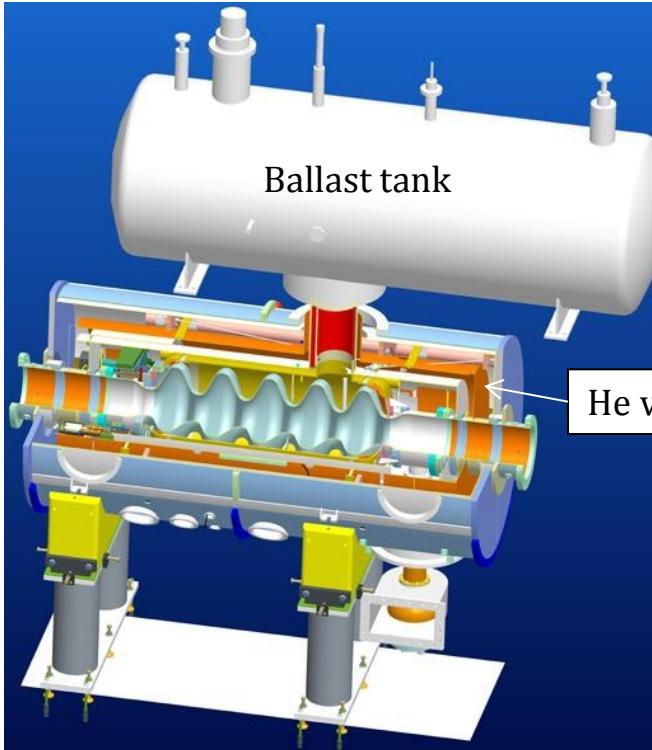
# SRF Challenges - Microphonics

- Minimized microphonics susceptibility
  - Cavity design can only do so much. Must be rigid and not have any low frequency modes which may be excited.
- Finite element analysis of the systems
  - Cavity + He return + He Supply + tuner + ....
  - Look at entire cavity string motion
  - Understand accelerator environment
  - Understand the testing environment

Separate the cryomodule from the environment

K. Davis MOPB031 LINAC 2012 – JLab C100 experience

# BNL 5-cell cavity: Microphonics



- The '30 Hz' noise originates from the mechanical vibration of the 2 K pump.
- The '16 Hz' microphonics noise was found to shift toward higher frequencies when the LHe level varies from top to bottom of the tube connecting the ballast tank to the cavity helium vessel. When its frequency reaches 30 Hz, there is a strong resonant excitation with a magnitude increase by more than a factor of five.
- This microphonics spectrum line is associated with an acoustical resonance in this line.
- The frequency detuning due to microphonics is comparable to the cavity bandwidth. A three stub tuner has been added to get better control of cavity in the further test. Also, a special feedback utilizing the piezo tuner is under development.

# SRF Challenges - Cryomodule

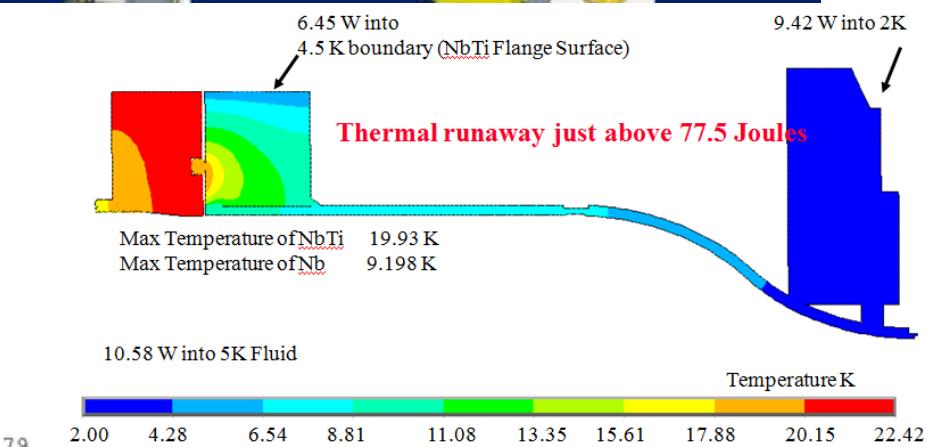
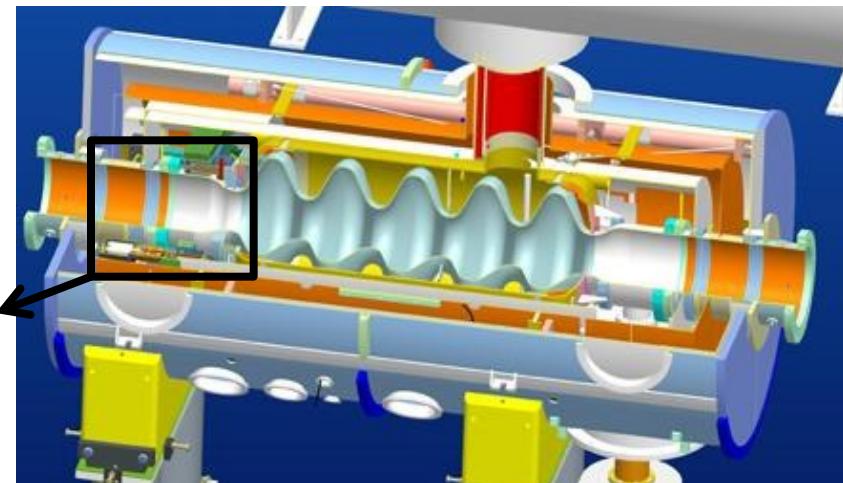
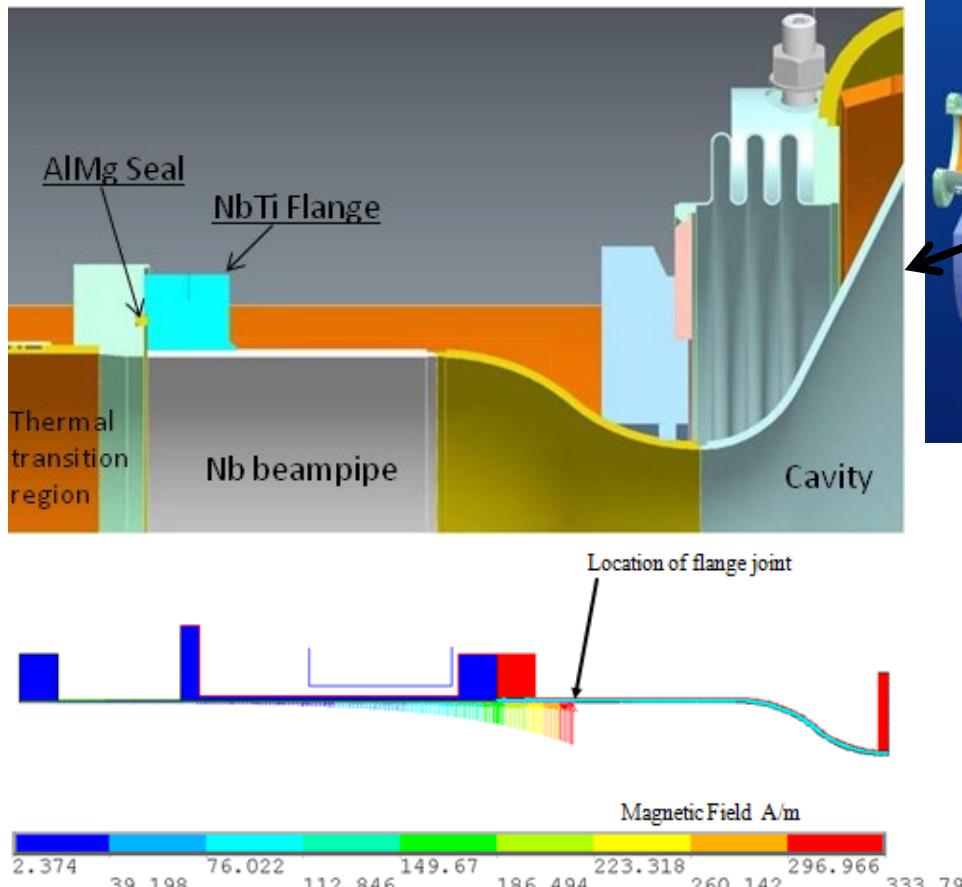
- Cavity performance degradation is often noted once the cavities are installed in the cryomodule.
  - Low field Q degradation
    - Inadequate magnetic shielding
    - Use of magnetized components near the cavity
    - RF losses in components
  - Gradient limitations
    - Heating
    - Field emission
    - Helium vessel exhaust riser size
- Better than  $1 \text{ mm}^* \text{mrad}$  emittance requires precise cavity alignment
  - Cavity to cavity in a module
  - Between modules
  - Relative to beamline components
- Proper heat intercepts to limit 2K load

Cryogenic Plant Capacity

More critical for booster

# BNL 5-cell cavity: cold test performance

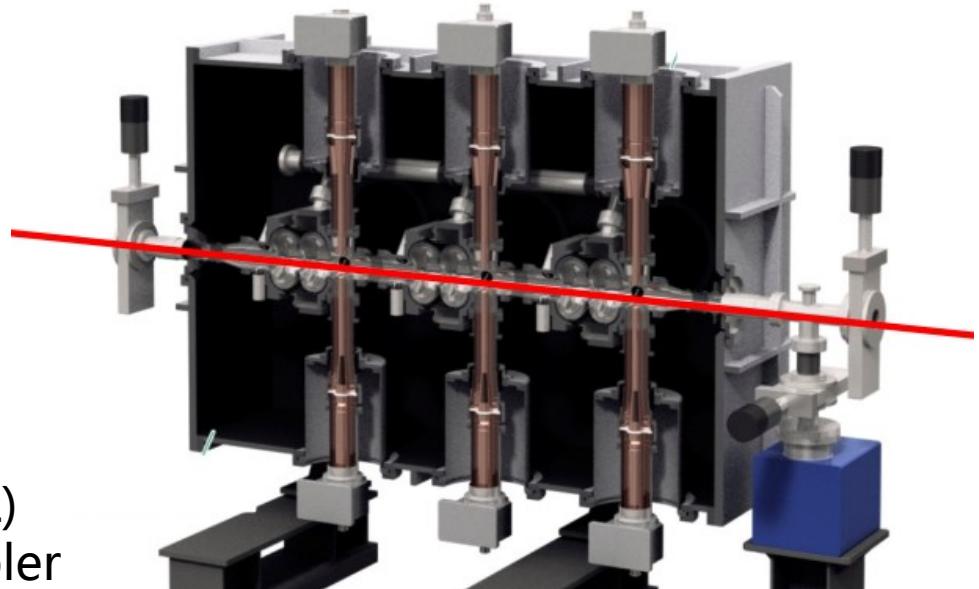
- For ERL prototype, it is necessary to have **15 MV** in the cavity, due to beam-dynamics constraints in the beam combiner.
- However, **11.5 MV/m** was observed to be the threshold in CW mode, due to the **AlMg<sub>3</sub>** seal located between the NbTi and stainless steel flanges on the beam pipe (on FPC side).
- Quasi-CW operation mode: Test showed that the cavity can safely (thermal stability) run at **18 MV/m** with a **6.25% duty factor**.



# KEK cERL Injector module

## Issue of Injector module

- Three 2-cell cavity  
with double input couplers  
with five HOM couplers  
Acc. voltage of 5MV (cERL)  
10MV (ERL)  
( Eacc of 15MV/m)
- input coupler power  
10kW ( 5 MV×10mA for cERL)  
170kW (10MV×100mA in ERL)
- development of a HOM coupler



2-cell cavity



Cavity assembly



Input couplers

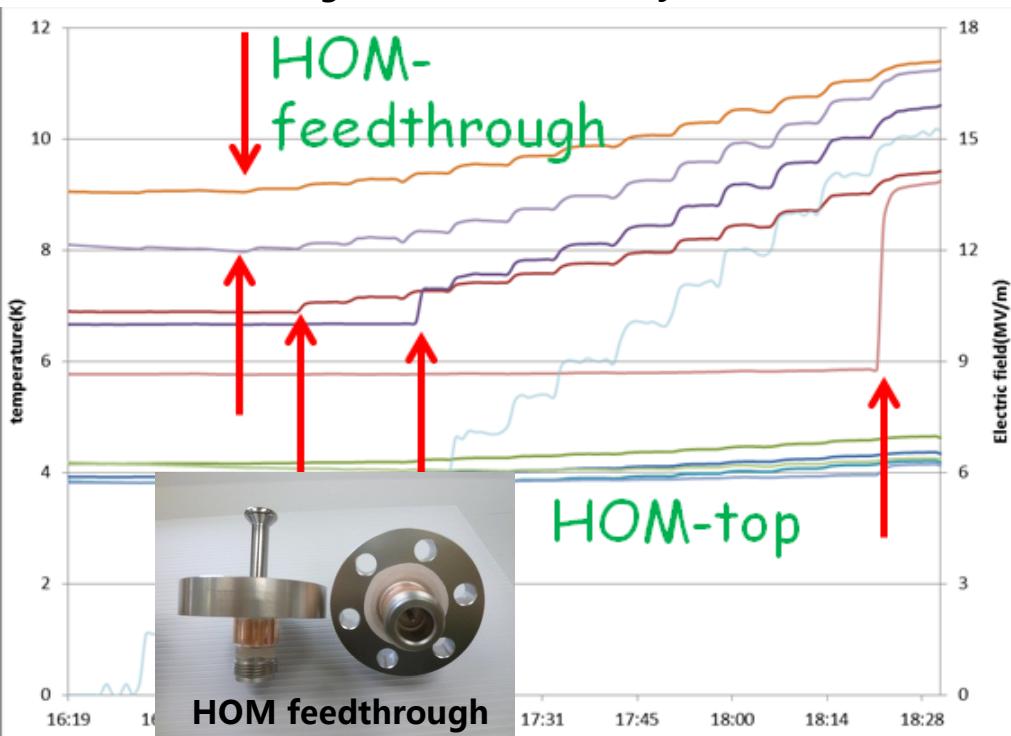
# KEK cERL performance

ERL2013  
T. Furuya

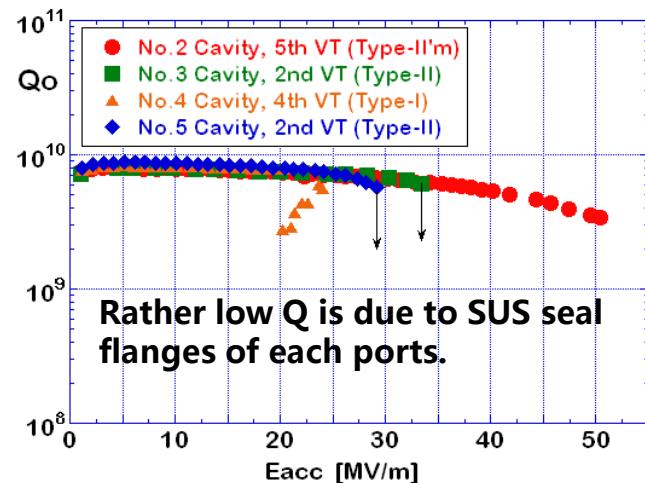
## Performance of the module

- Eacc of >15MV/m in V.test.
- The module achieved 8MV/m in cw mode.
- Degradation of Q in the module test.
- Excessive heating of RF feedthroughs of HOM coupler causes an additional loss, since each feedthrough is anchored to 2K.

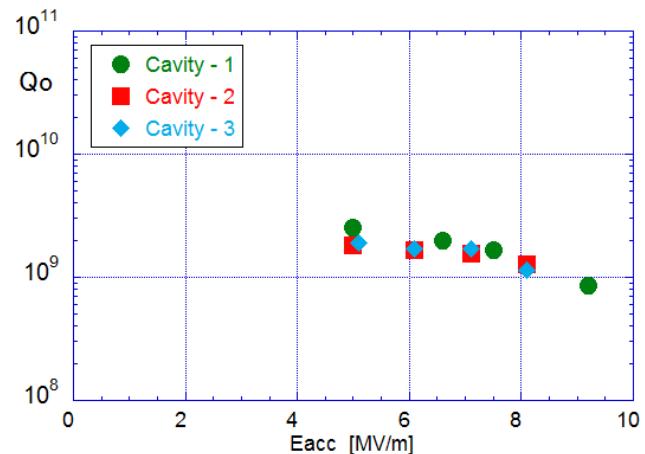
Heating of HOM of #3 cavity



Vertical test results

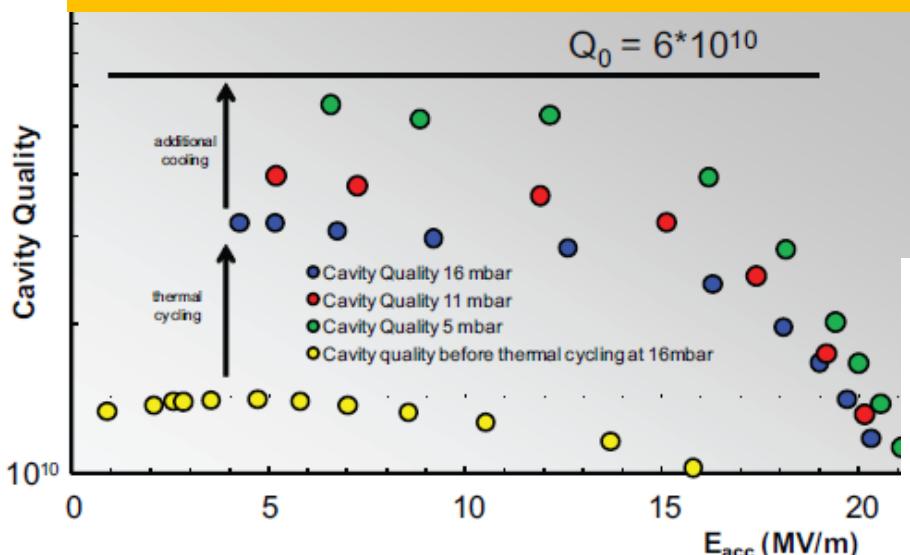


Module power test



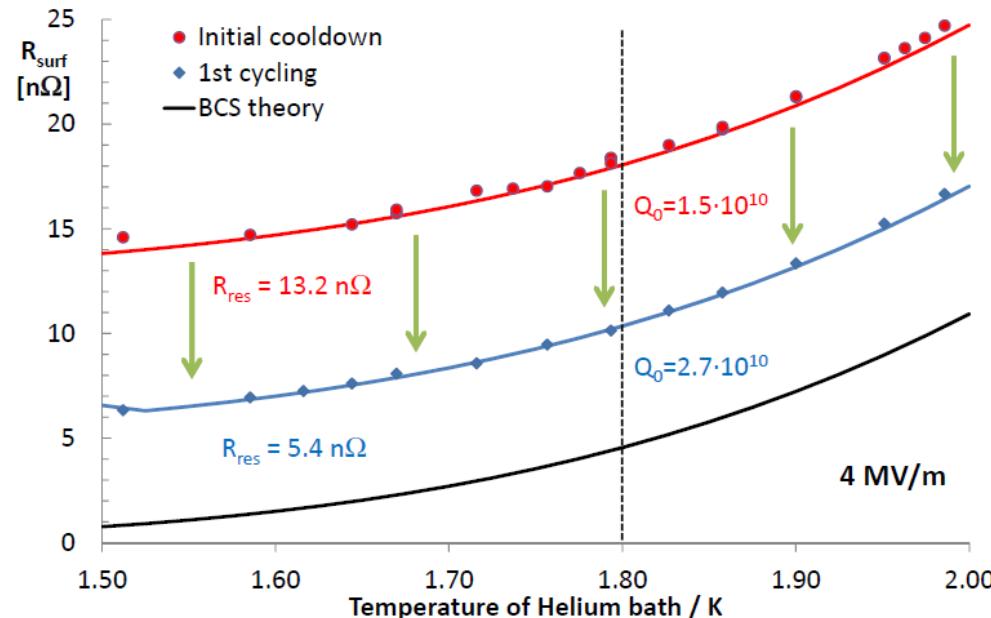
# Performance Improvement in Cryomodule

SRF 2009 – World Record Tesla 9 cell Q - HZB



Cavity performance does not always get worse in the cryomodule!  
By controlling the cooldown rate the  $R_{surf}$  can be reduced significantly

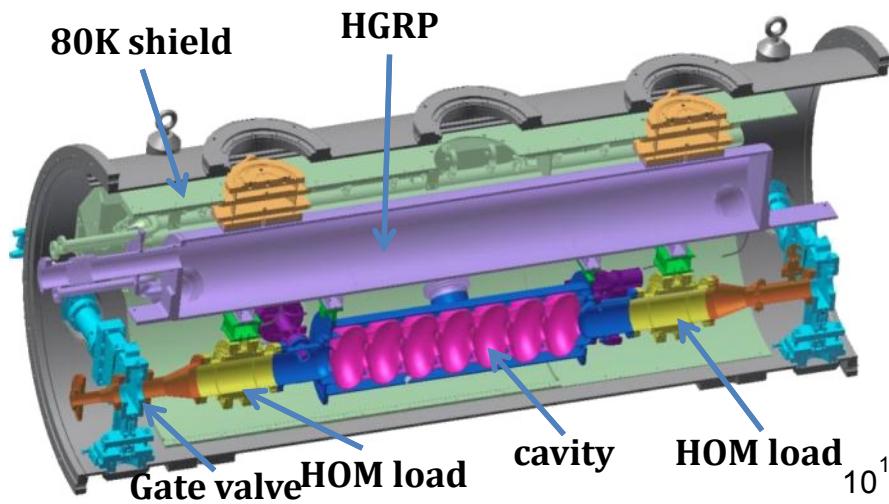
Influence of thermal cycling on  $R_{surf}$



TUIOA01 Influence of Cooldown on Cavity Quality Factor - Kugeler

TUIOA02 – High Qo Research, The Dynamics of Flux Trapping in SC Niobium - Vogt

# Performance Improvements 2



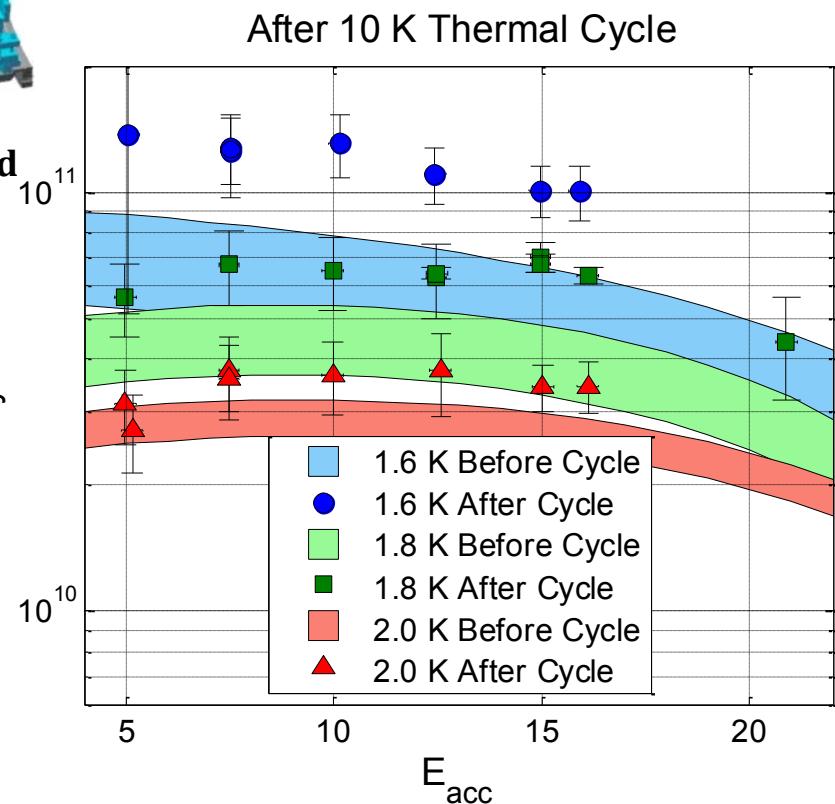
Horizontal Test Cryostat: (@16MV/m, 1.8K)

HTC-I:  $Q_0 = 3.5E10$  without coupler

HTC-II:  $Q_0 = 2.E10$  (reached with coupler)

HTC-III:  $Q_0 = 6.E10$  (with coupler and HOM absorbers, after cavity reprocessing from HTC-II)

Cornell Linac Cavity HTC



Data courtesy of Ralf Eichhorn

# Conclusions

- A number of exciting projects underway
  - Huge opportunity for collaboration and knowledge transfer!
- Many technical challenges are being overcome
  - This is what needs to be documented!!
- 100 mA operation looks very promising
  - 75 mA from Cornell DC gun and Injector (ERL 2013)
- Methods to obtain and maintain  $Q_0 > 3 \times 10^{10}$  and  $E_{acc} \geq 16 \text{ MV/m}$  for a 1.3 GHz cavity
  - 10 W per cavity at 1.8K in the Linac!
- $Q_L > 1 \times 10^8$  for Linac operations
  - 5 kW solid state amplifier to drive Linac cavities



# Acknowledgements

- A. Neumann, O. Kugeler, J. Knobloch, R. Eichhorn, S. Belomestnykh , H. Sakai, W. Xu, M. Liepe, E. Kako, S. Pattalwar, B. Dunham, T. Furuya, A. Nassiri
- Thank you for sharing what worked, and more importantly what didn't work!

# The End.