SRF2013 PARIS
16th International conference on RF Superconductivity

HZB Helmholtz Zentrum Berlin

SRF Challenges for Energy Recovery Linacs

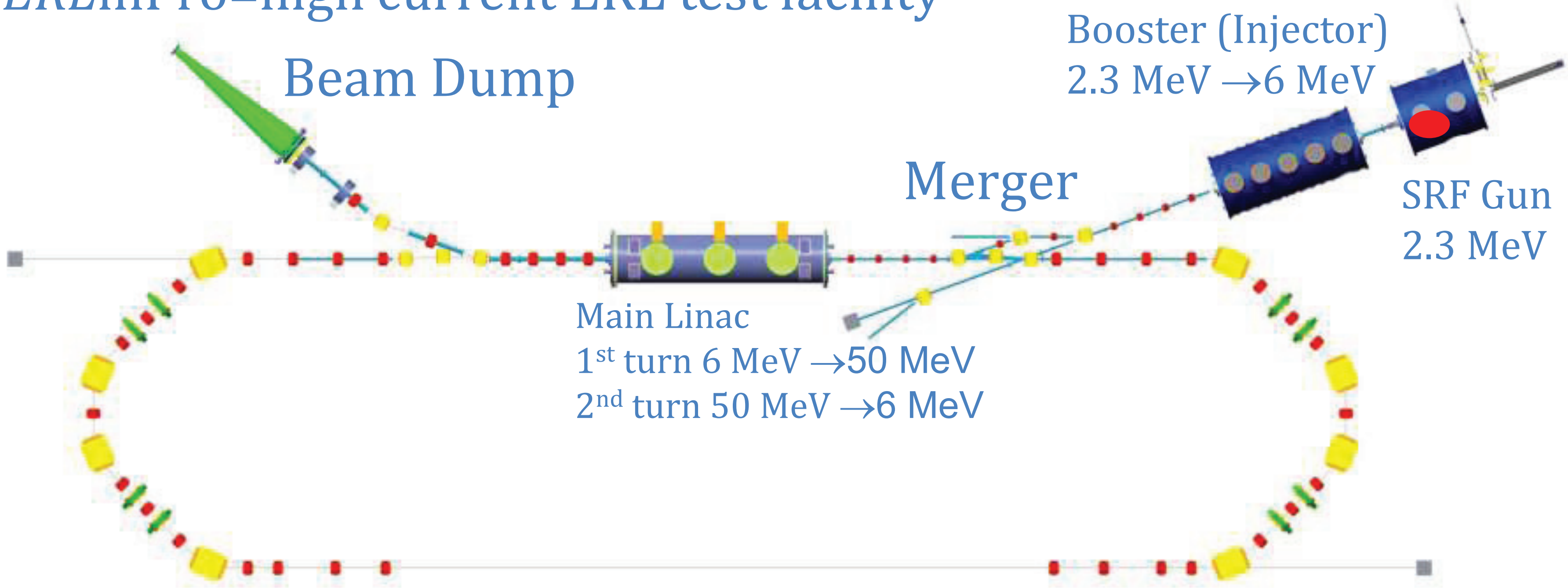
Andrew Burrill

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



ERL Overview

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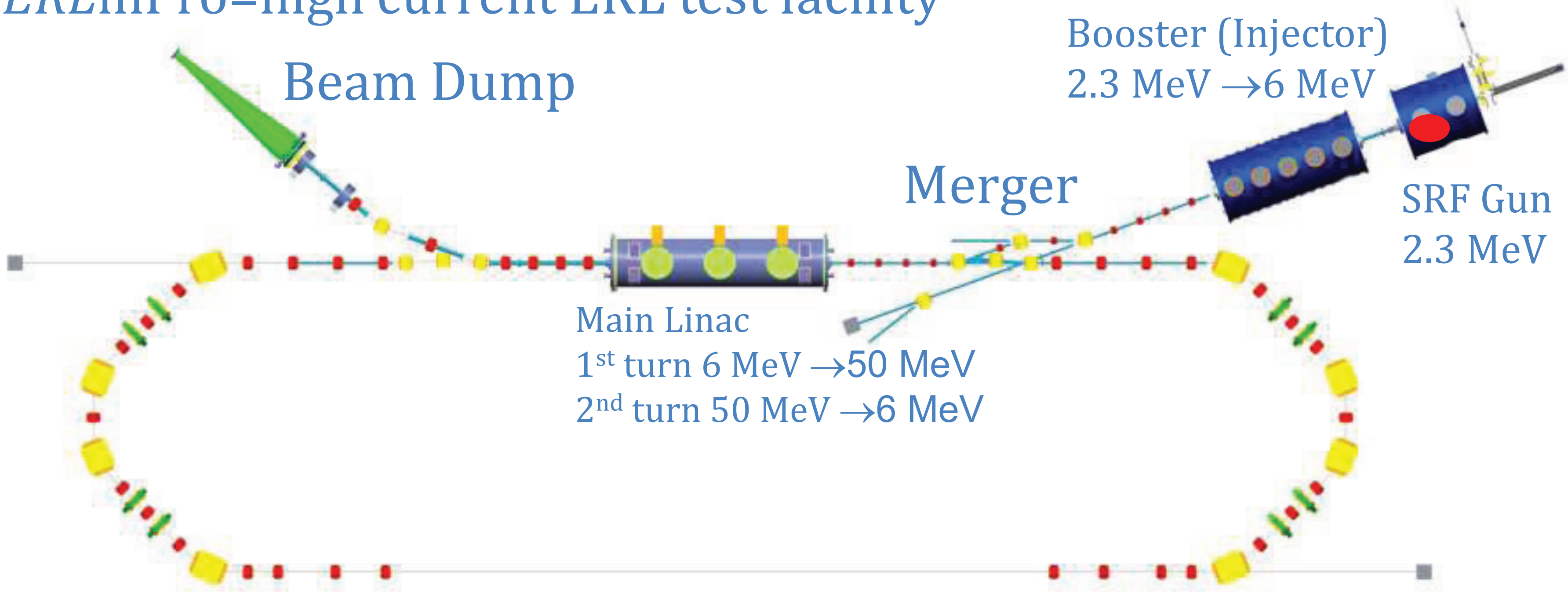
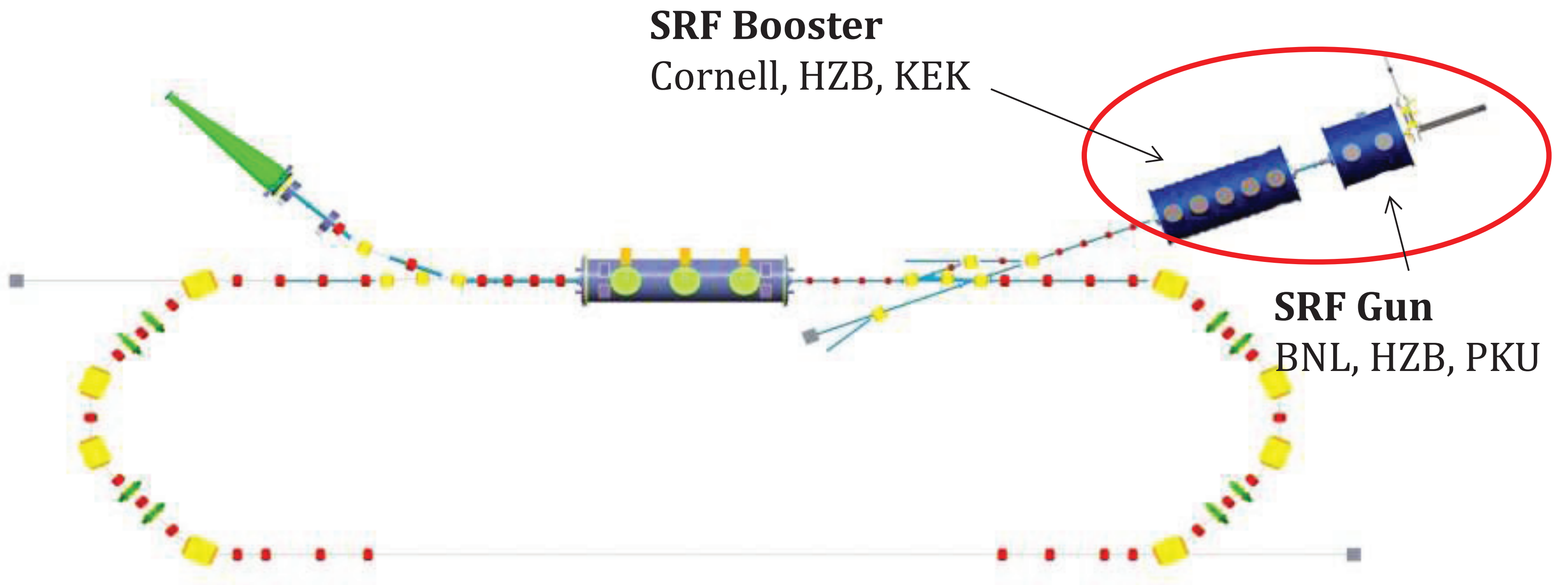


Beam energy	50 MeV
Average current	100 mA
Bunch charge	77 pC
Normalized emittance	<1 mm·mrad
Resonance frequency	1.3 GHz

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

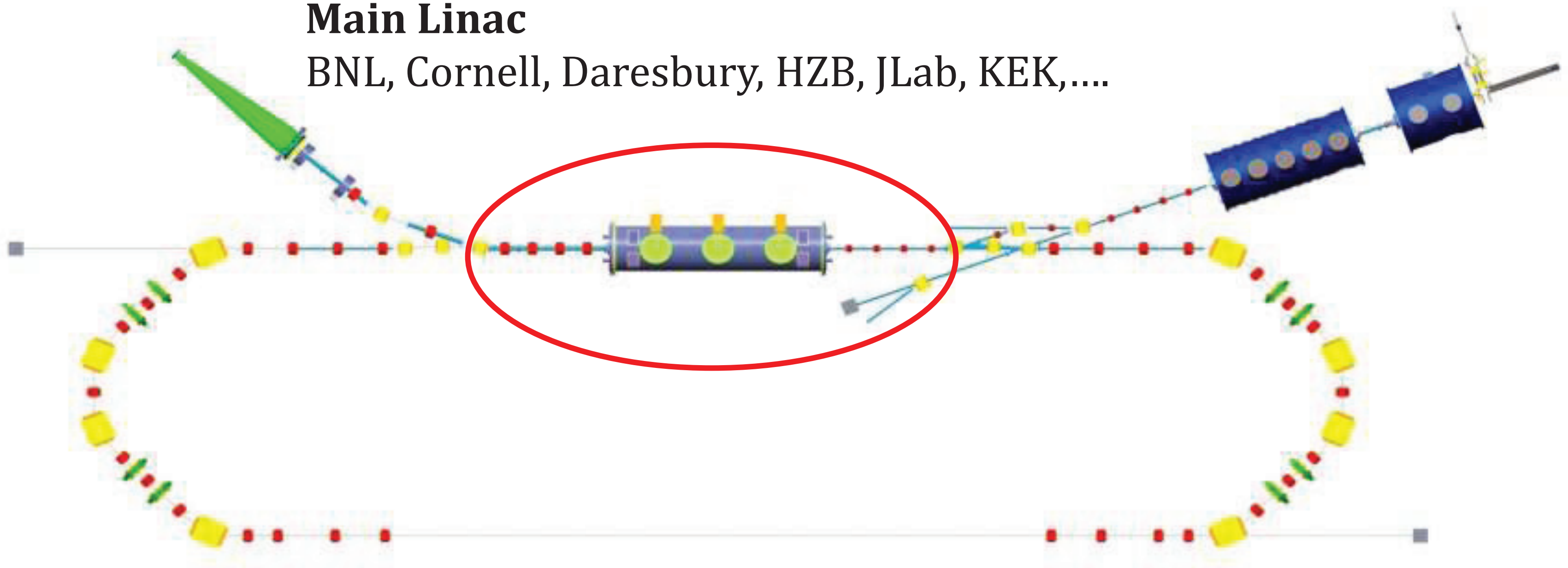
SRF in ERLs



- 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

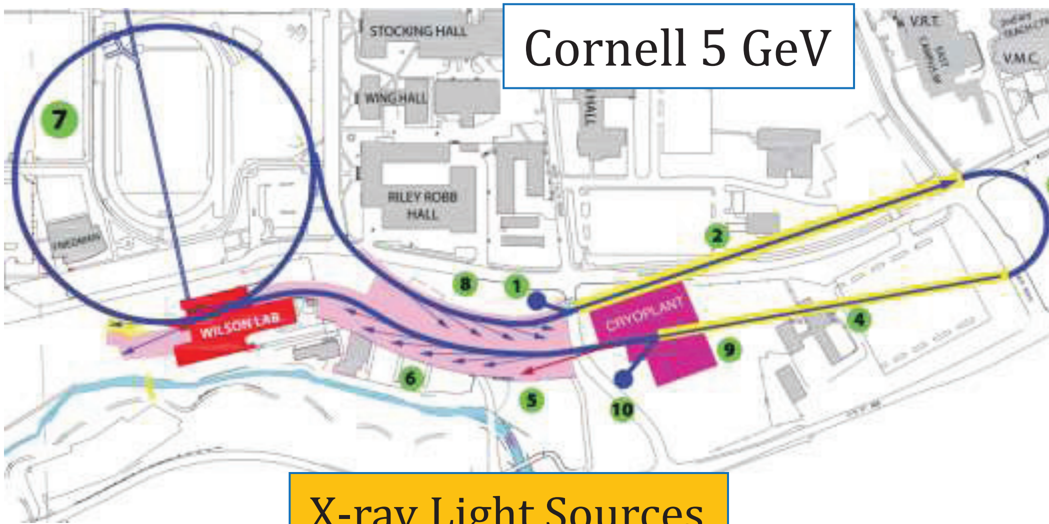
Main Linac
BNL, Cornell, Daresbury, HZB, JLab, KEK,….

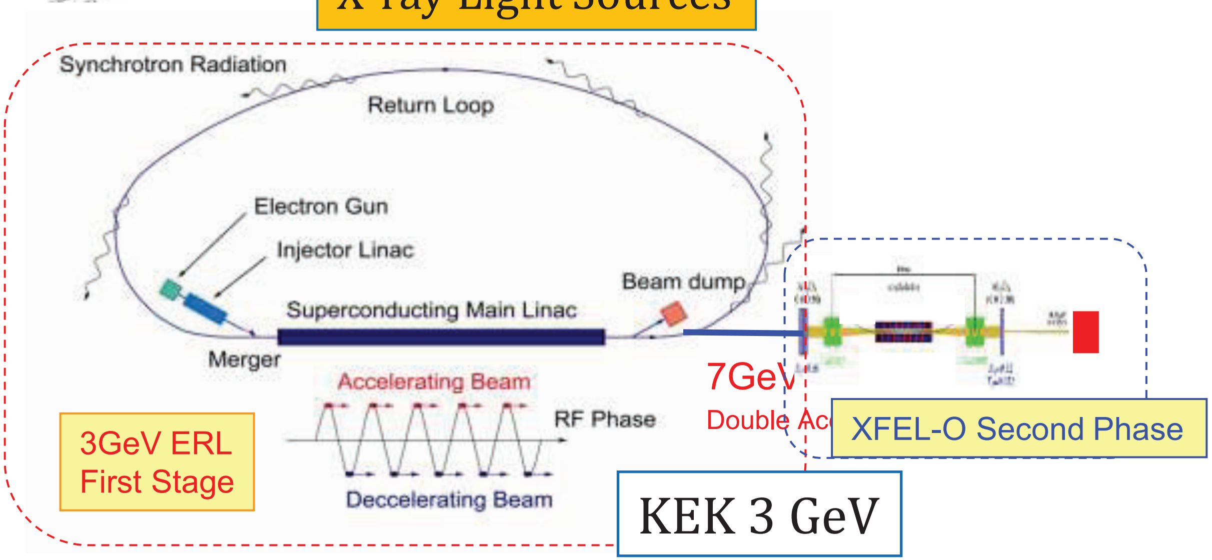


- Main LINAC: Energy recovery
  - Beam loading no longer critical
  - RF Stability and microphonics is key
  - Optimize RF power to cavity
  - HOM excitation and power extraction
  - Cryogenic Load is significant

Why do we need SRF ERLs?

"Big" Machines

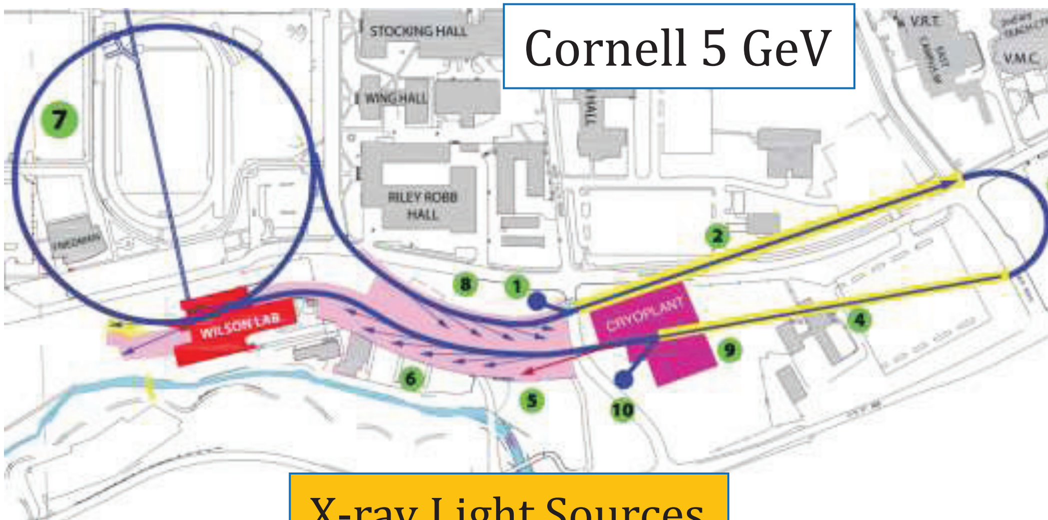




Why do we need SRF ERLs?

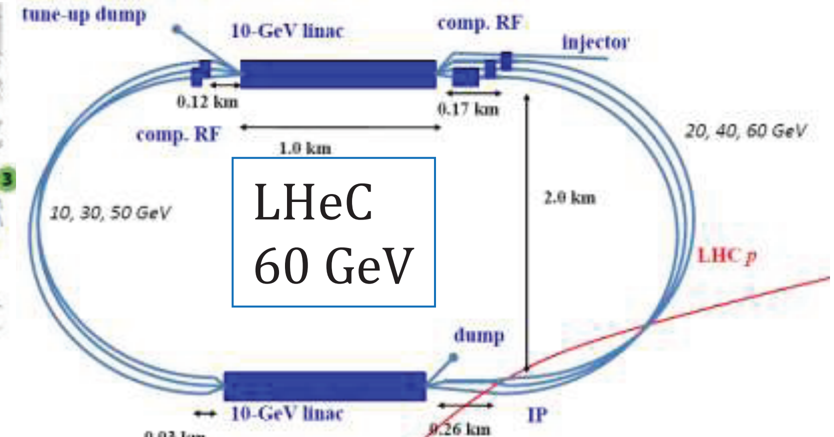
"Big" Machines

Cornell 5 GeV

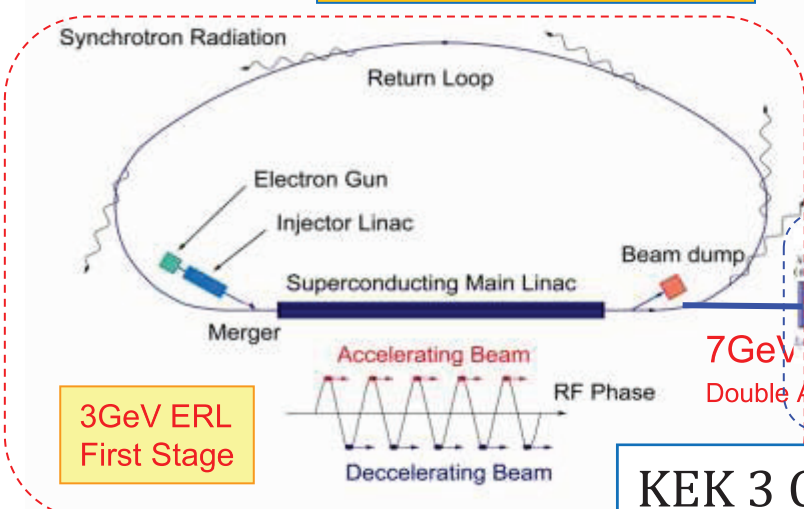


X-ray Light Sources

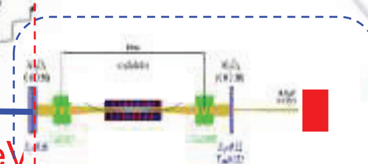
LHeC
60 GeV



Electron Ion colliders

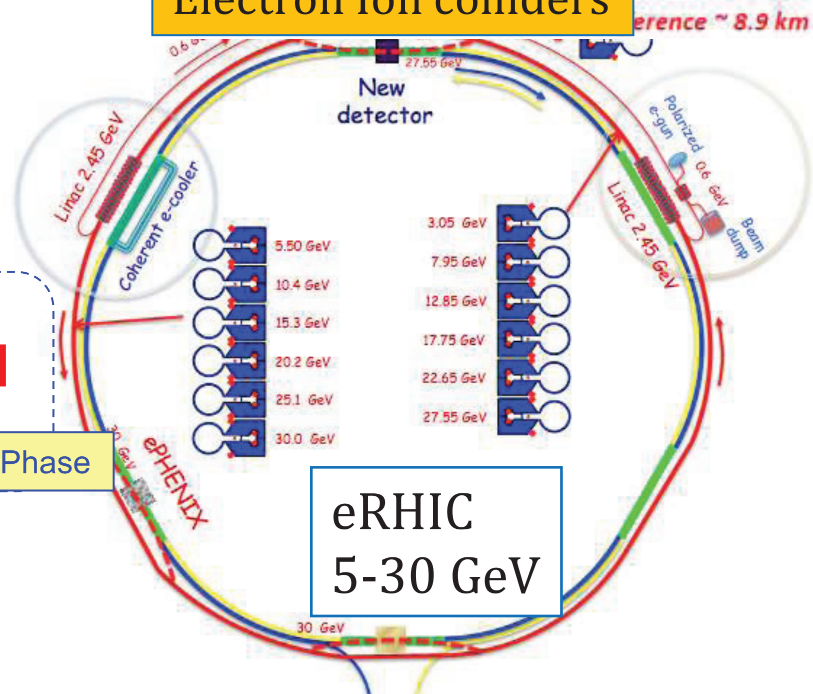


3GeV ERL
First Stage



XFEL-O Second Phase

KEK 3 GeV



eRHIC
5-30 GeV

Big Machine Beam Power

Machine	Beam Parameters	Beam Power
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

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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
TRIUMP (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

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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 Qo at operating gradient (15-20 MV/m)
  - Reduced cryogenic load
- Fill every bucket at 700-1500 MHz
  - charge/bunch ~100 pC
  - Good emittance (< 1mm*mrad)
- Maximized R/Q * G for the fundamental
- Designed for low E_{peak}/E_{acc}
  - Field emission

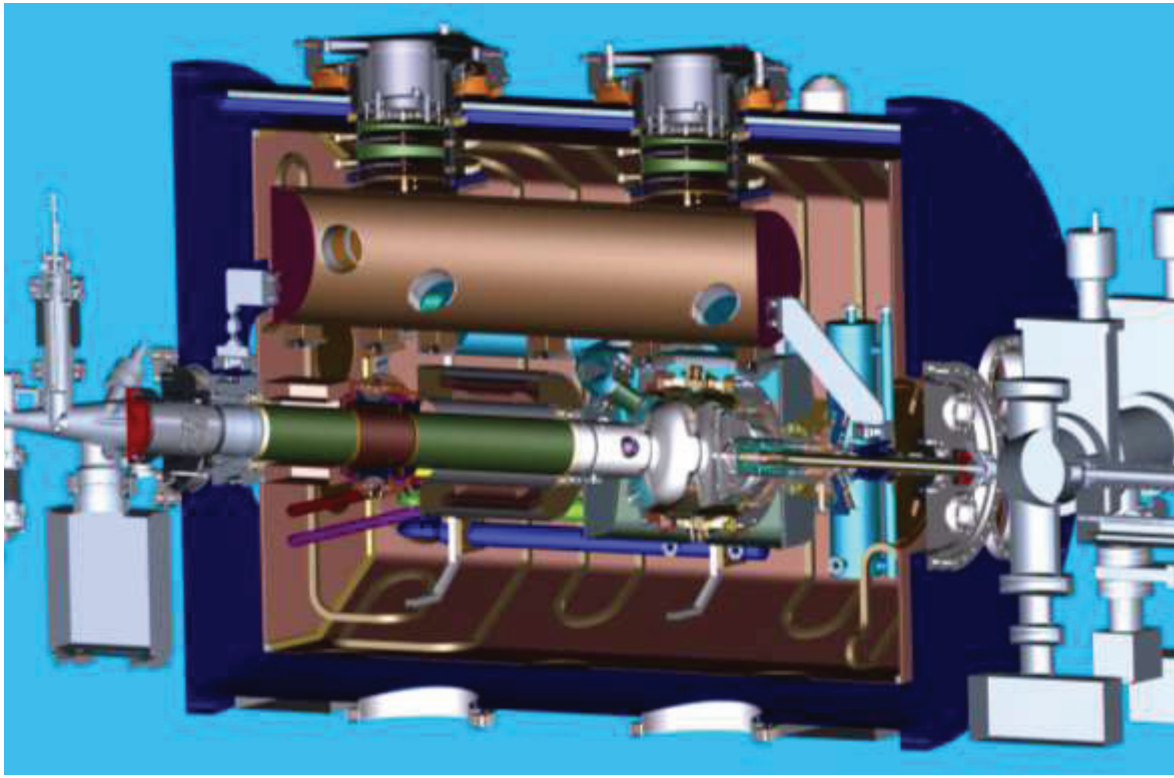
Make the design as economical to operate as possible

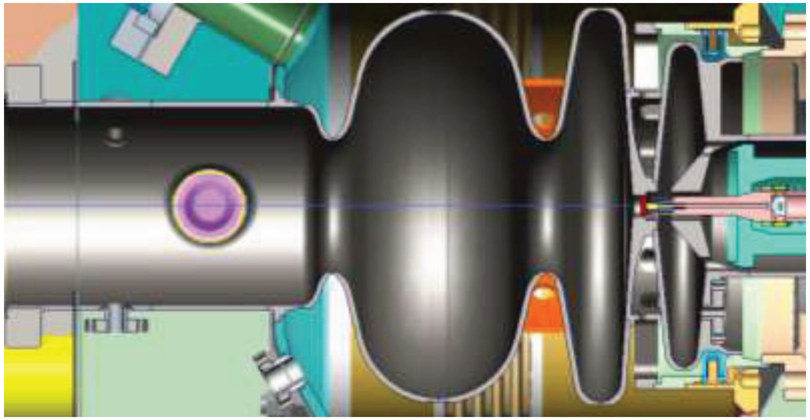
The Cavity 2

- 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 (Ep = 40-60 MV/m)
      - Possible conflict with routine insertion and retraction of photocathode
  - Not a true β=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

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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

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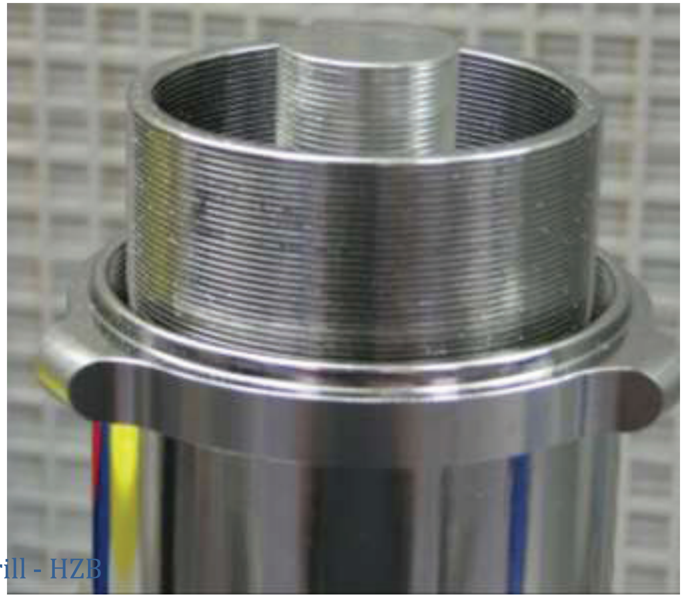

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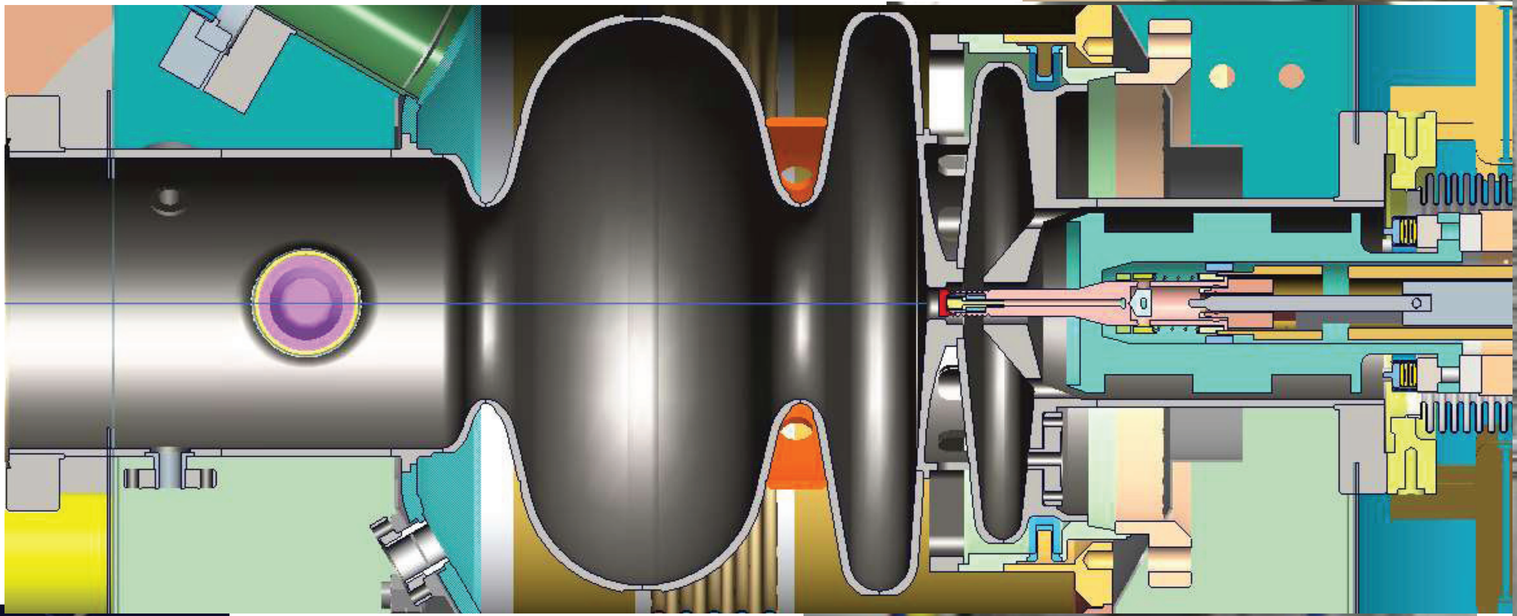
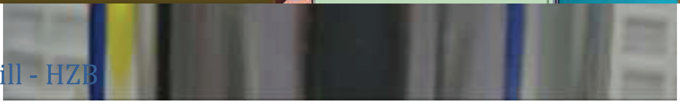
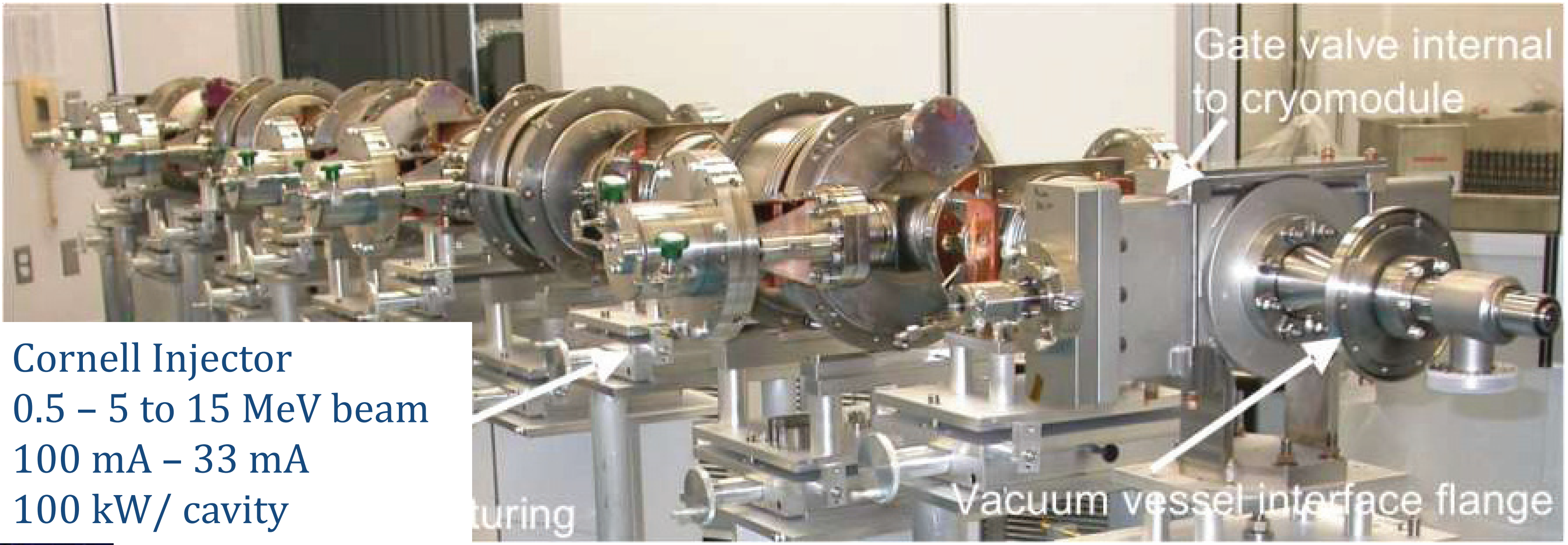




Booster (Injector) Module

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



Cornell Injector
0.5 – 5 to 15 MeV beam
100 mA – 33 mA
100 kW/ cavity

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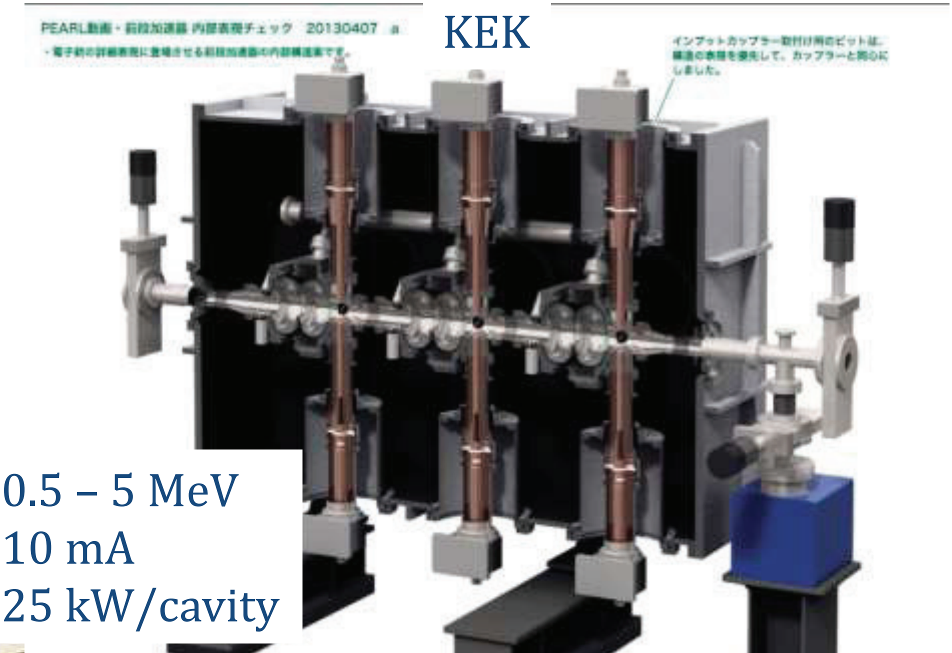
KEK



0.5 – 5 MeV
10 mA
25 kW/cavity

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Booster (Injector) Module

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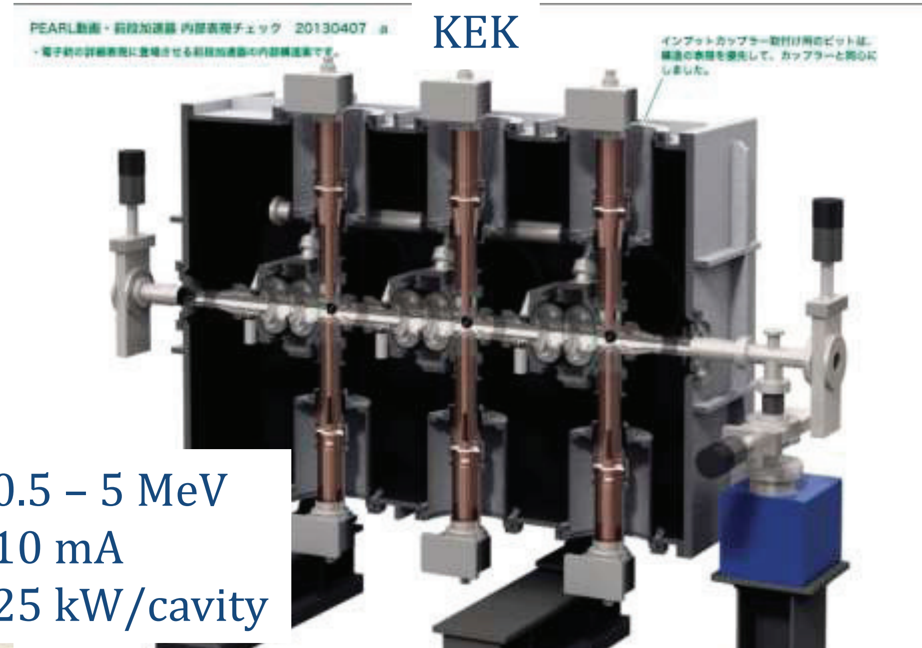
Low energy beam
Cavity alignment is critical to low emittance
Strongly coupled cavity Qext 10^4-10^7
Coupler perturbation an issue
HOM power not the same as a Linac Cavity

KEK



0.5 – 5 MeV
10 mA
25 kW/cavity

Cornell Injector
0.5 – 5 to 15 MeV beam
100 mA – 33 mA
100 kW/ cavity

SRF Challenge - Cavity preparation

- Provide a reproducible and robust way to prepare cavities
  - High Qo, minimal Q slope
- Important considerations
  - Chemical processing recipe
    - BCP, CBP, Flash BCP, EP
    - Heat treatment 600°C - 800°C with our 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

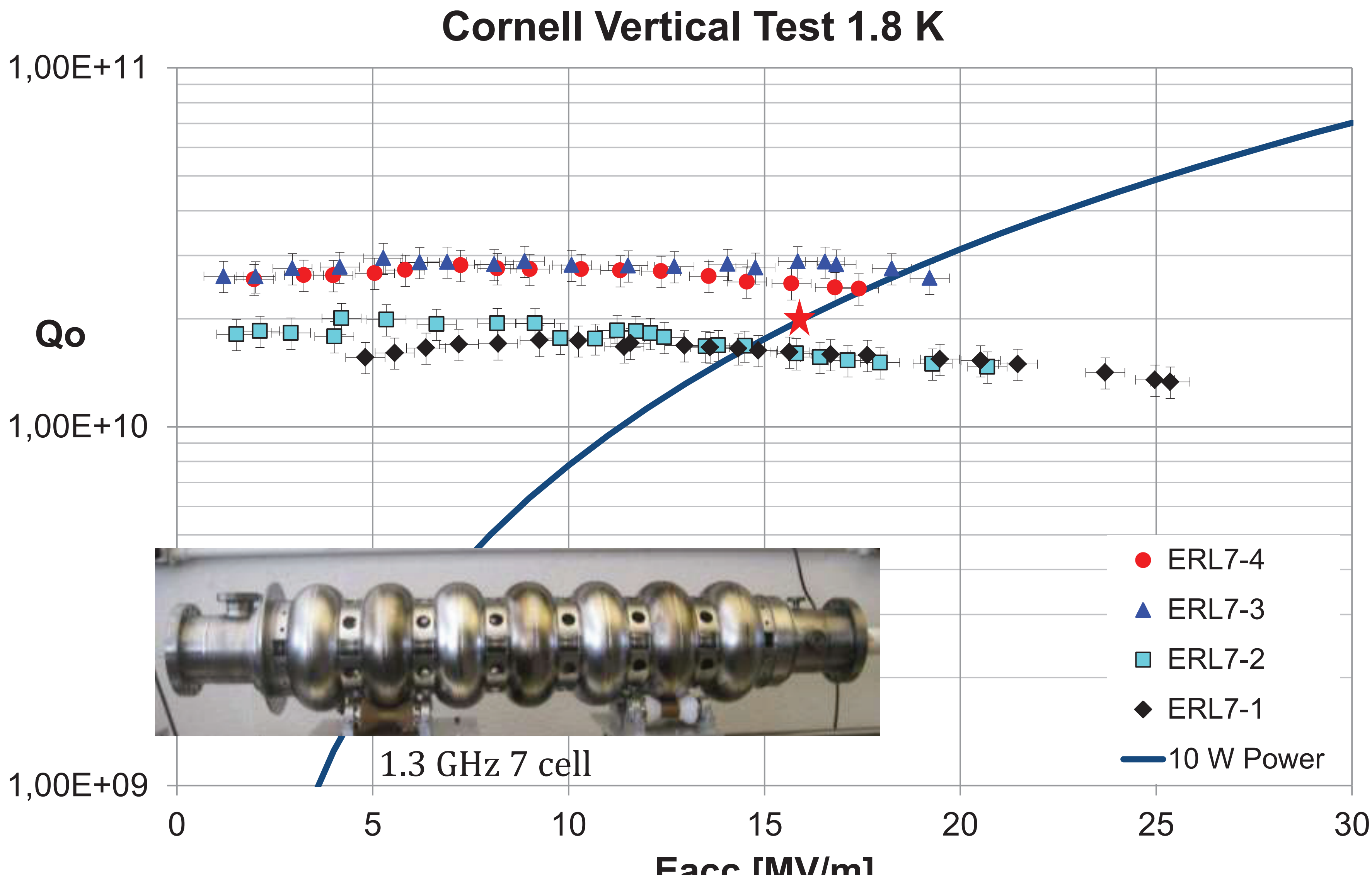
The not so good: highly variable from lab to lab

SRF Cavity Prep -Cornell Linac Cavity

	ERL7-1 (HTC)	ERL7-2	ERL7-3	ERL7-4
Bulk BCP	140um (witness sample)	135±10 um (cavity equator)	138±5 um (cavity equator)	132±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 1st (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	
	HTC3, 16.2MV/m, 6.0e10 @1.8K			
VT 2nd (1.8K)			17MV/m, 2.8e10 No T-map (PC down)	

Data courtesy of Ralf Eichhorn

Cornell Linac Cavity



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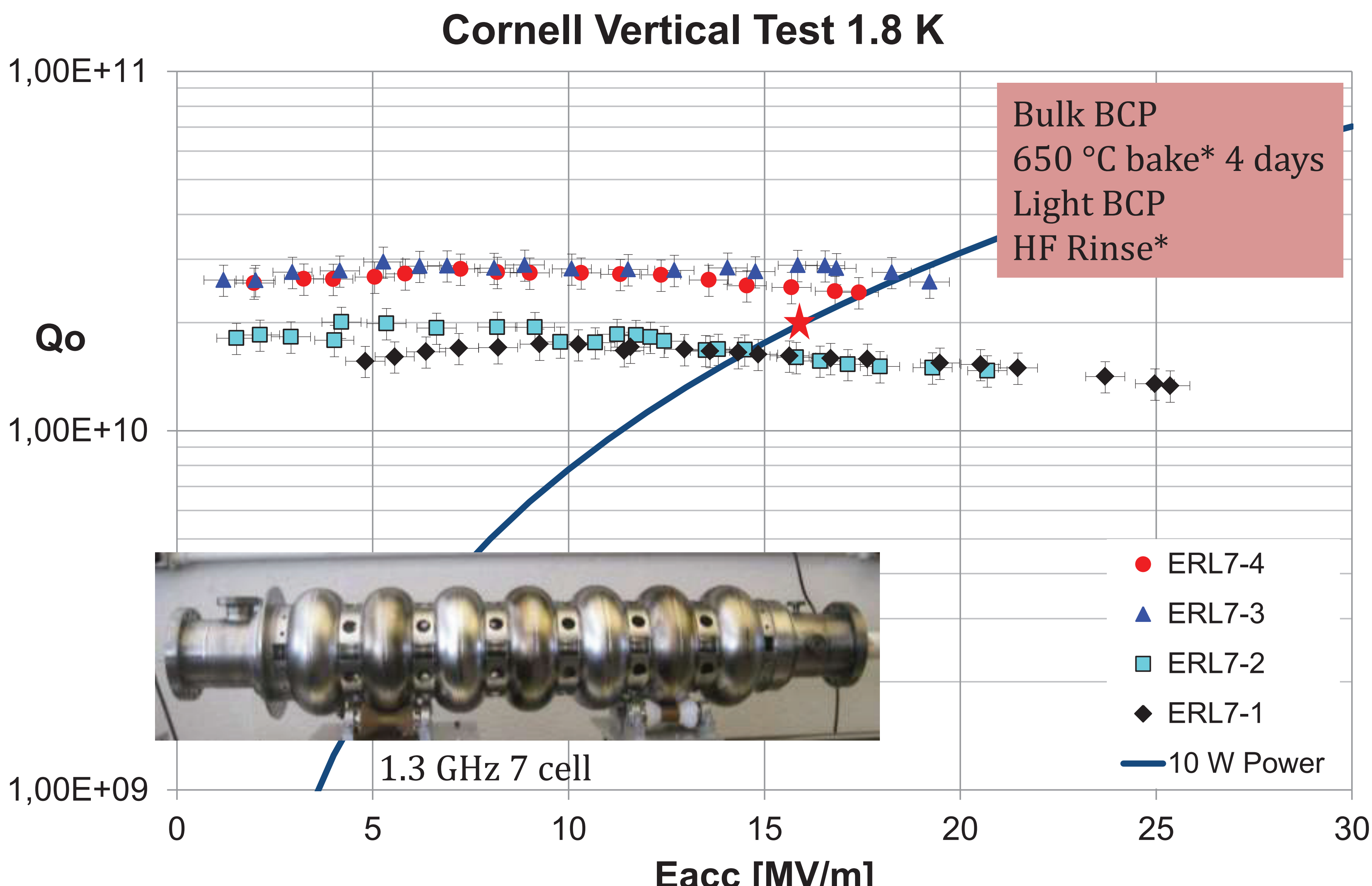

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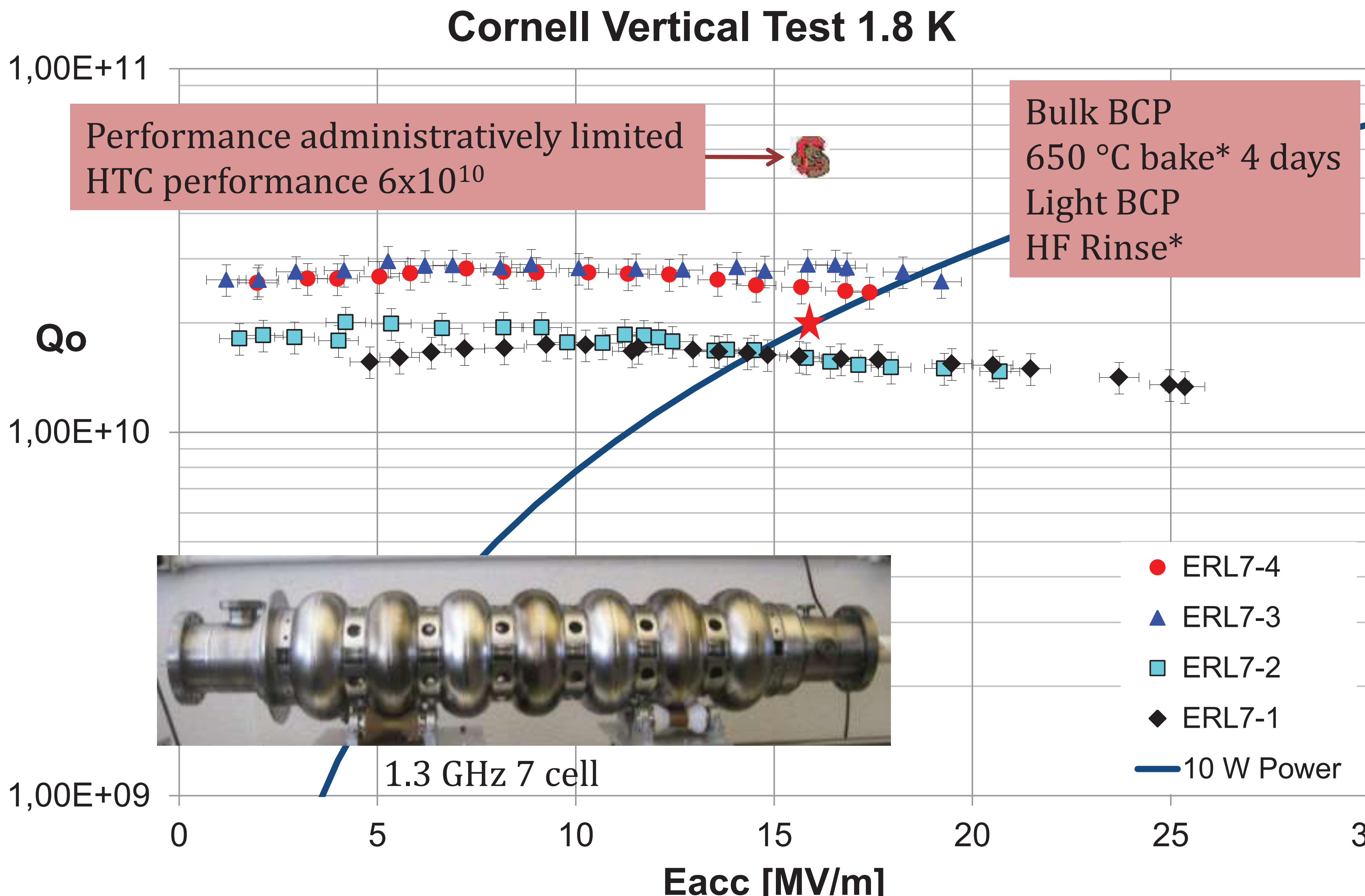
Cornell Linac Cavity



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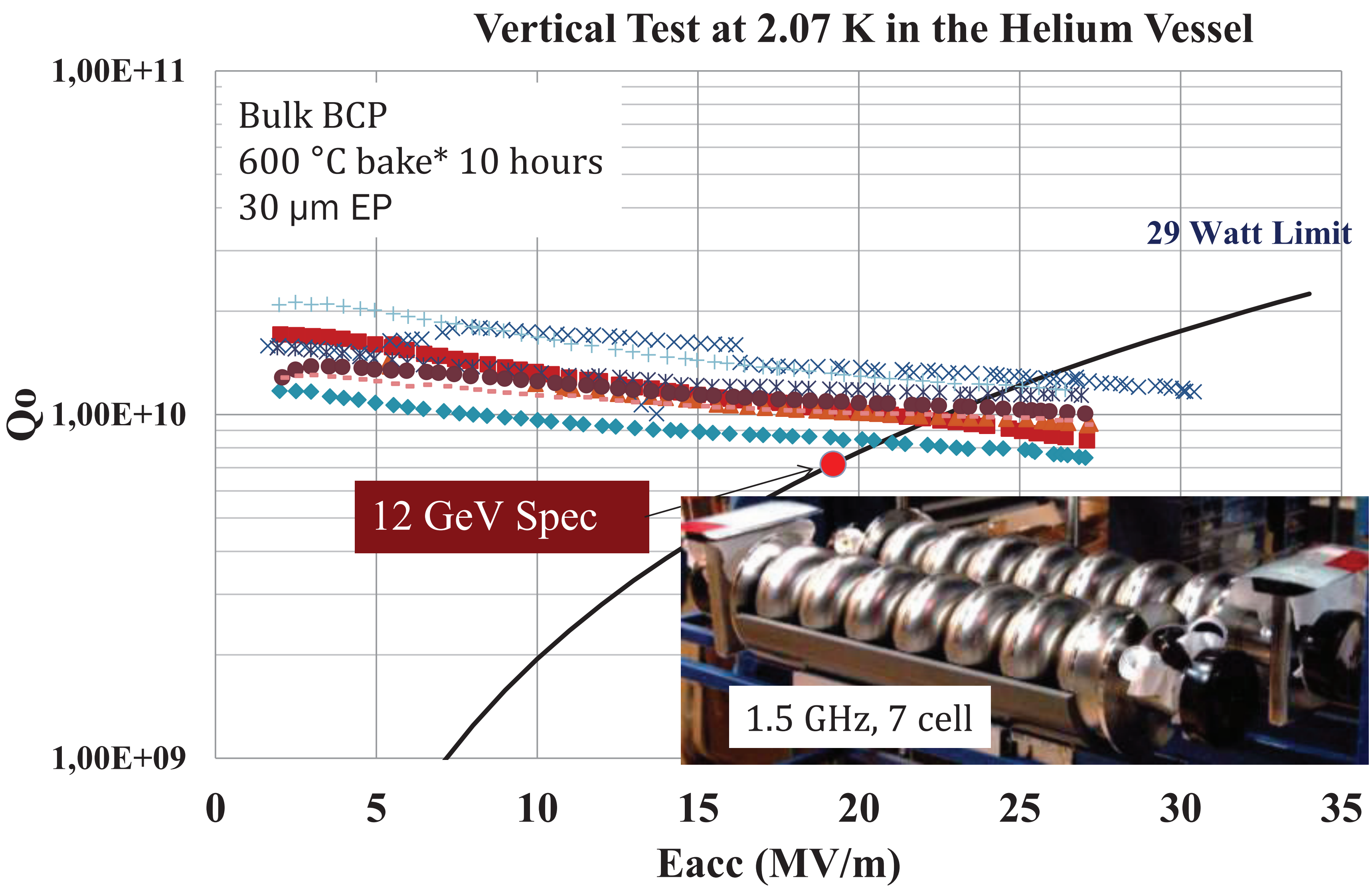
SRF Cavity Prep -JLab 12 GeV upgrade



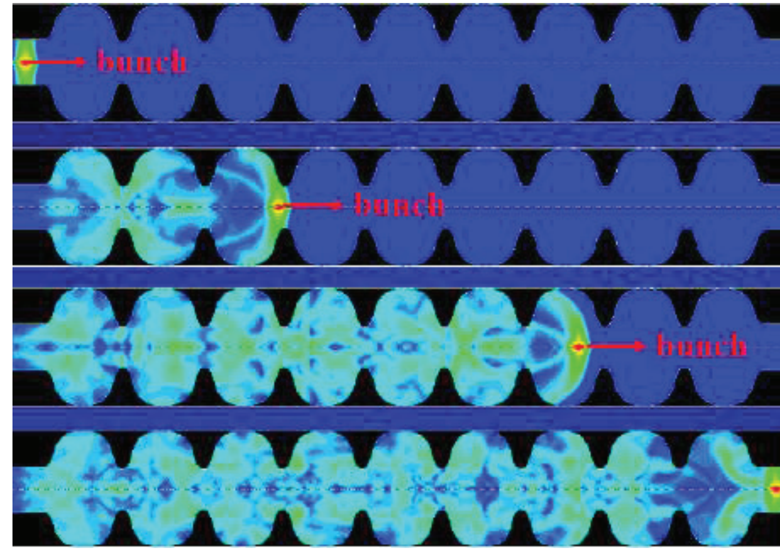
SRF Challenges - Higher Order Modes

7 cell ERL cavity, 77 pC, 100 mA

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

ERL Linac

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



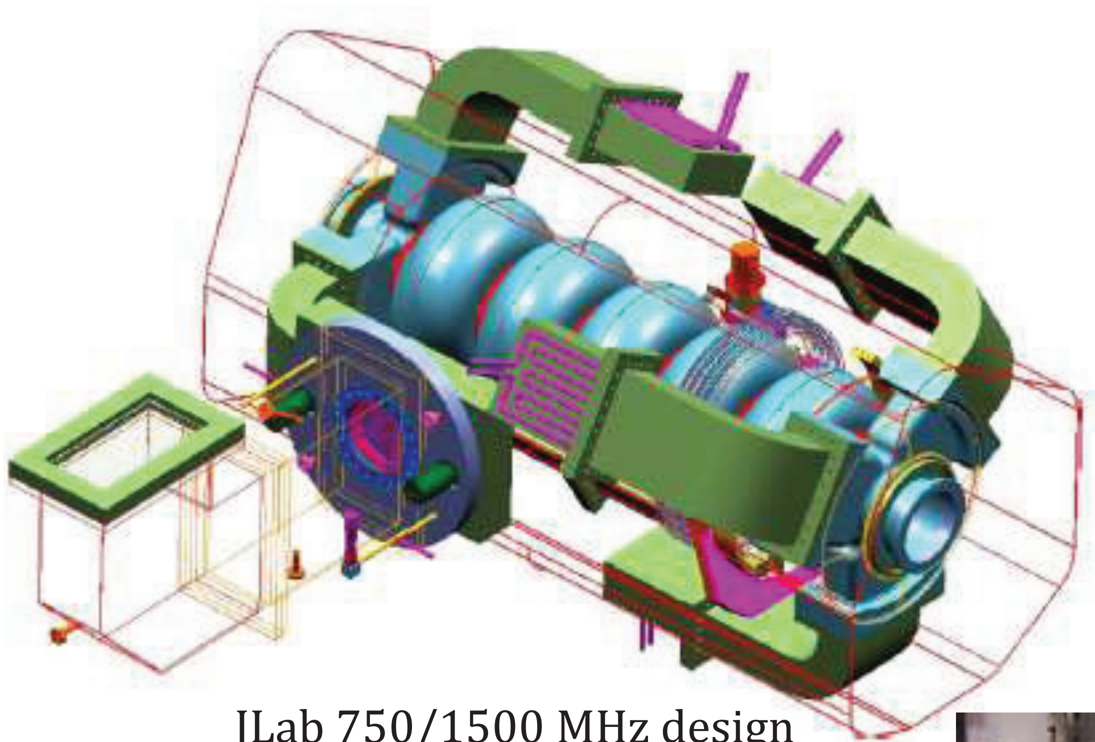
HOM damper must be independent of 2K system

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	5×10^3	1×10^4
KEK-c	100	185	1×10^6	1×10^4
BERLinPro	100	150	1×10^4	1×10^4
eRHIC	300	7,500	1×10^4	4×10^4

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

HOM Waveguide Absorbers



JLab 750/1500 MHz design

Key Advantages

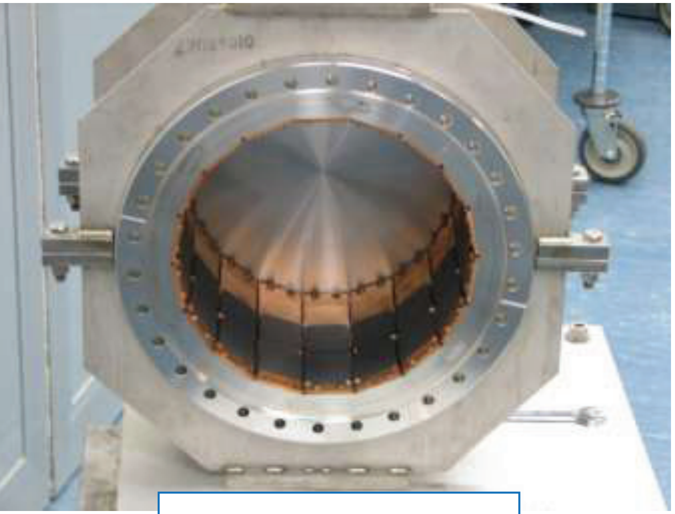
- Require less length in the CM vs beamline absorber
- Move load material further from the cavity

Disadvantages

- Multiple loads required
- HV welding
- CM design

WG HOM load
Based on PEP-II

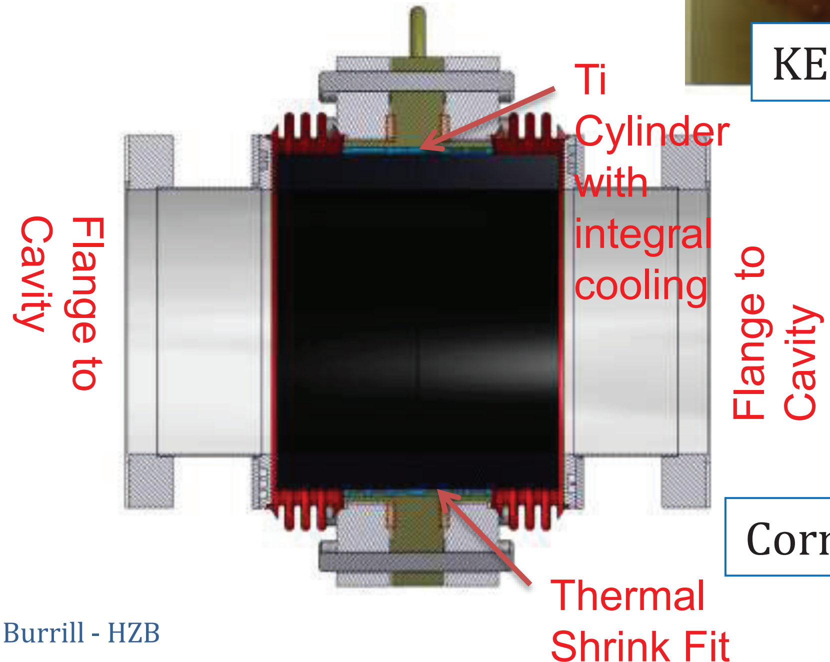
HOM Beamline Absorbers



BNL ECX Cavity

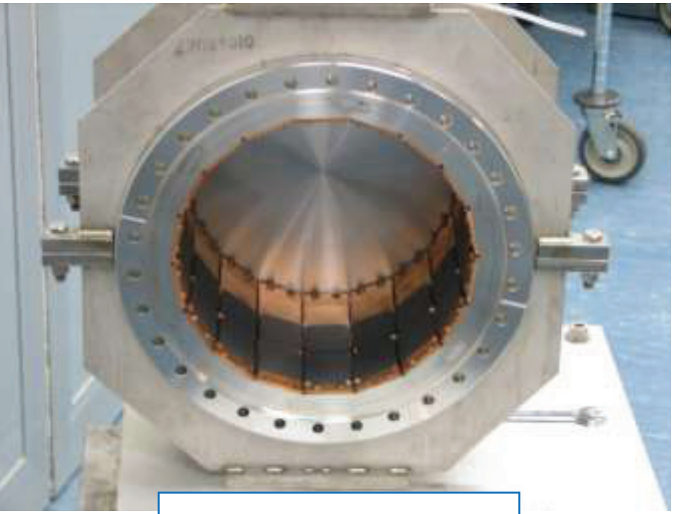
XFEL

KEK



Cornell

HOM Beamline Absorbers



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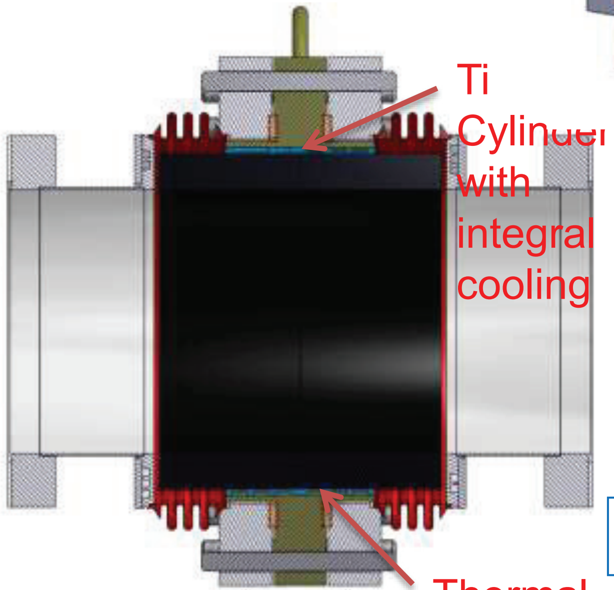

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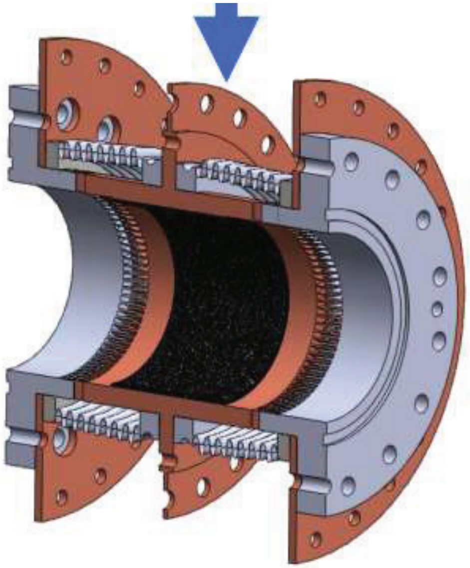
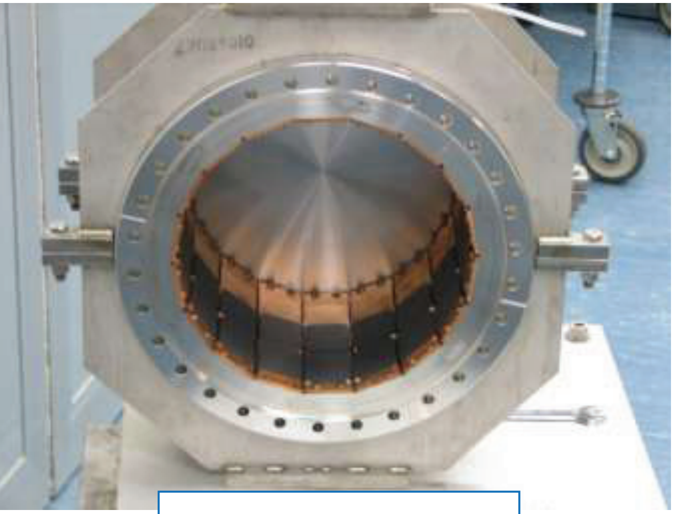


HOM ferrite damper with comb shield

HOM Beamline Absorbers



BNL ECX Cavity

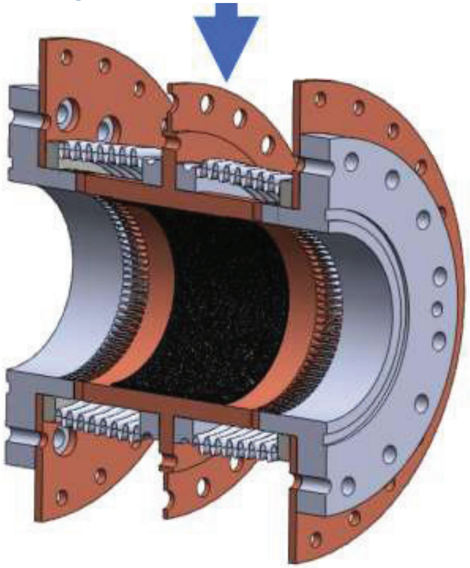
XFEL

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



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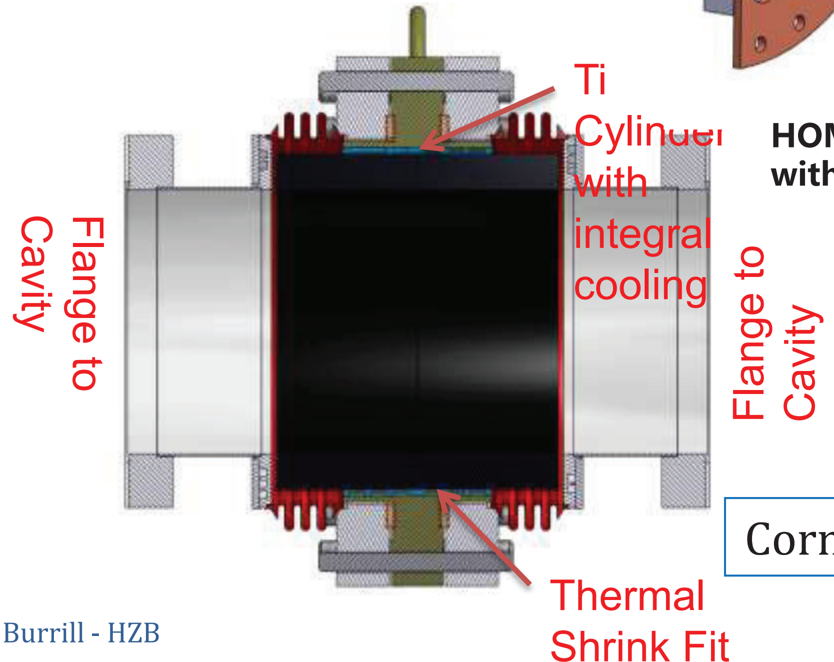


Cornell

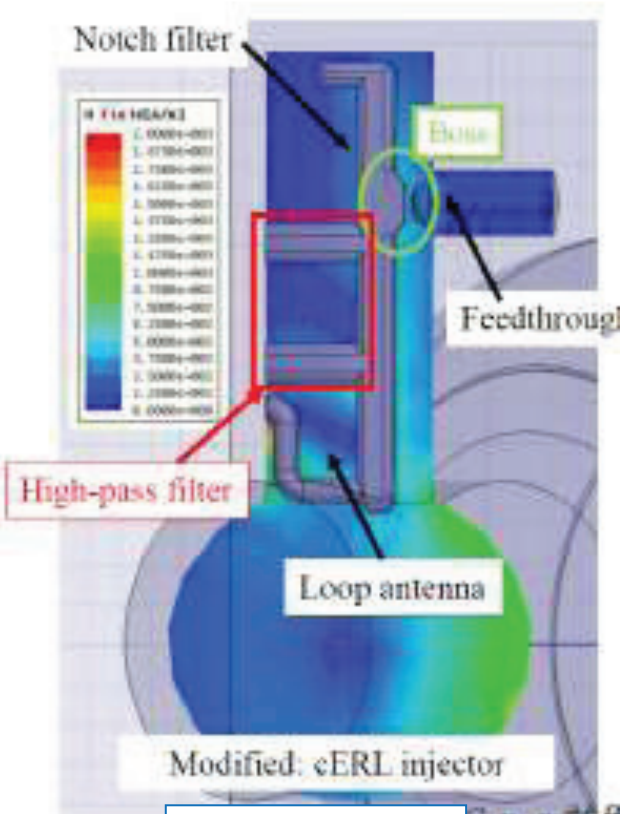
HOM Couplers

Key Advantages

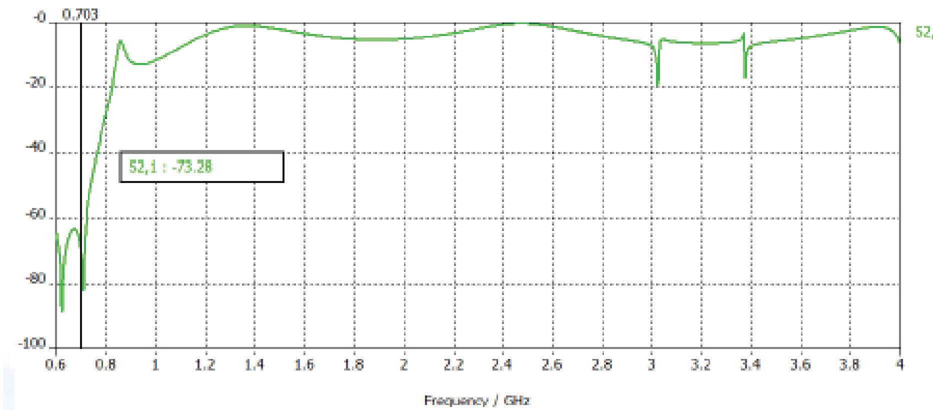
- Cleanroom compatible
- Highest real estate gradient

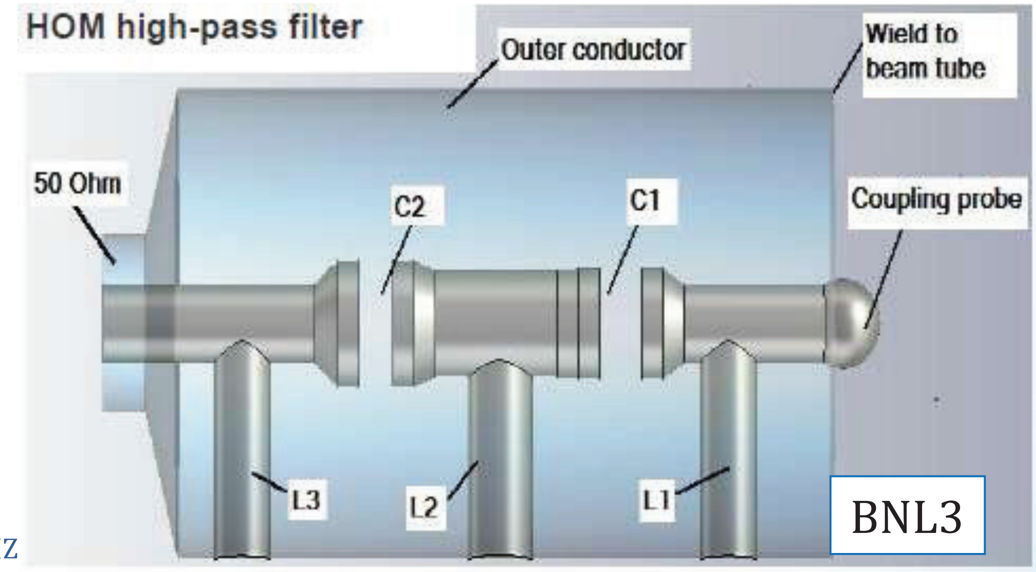
Disadvantages

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



KEK Booster





BNL3

SRF Challenges - RF Stability

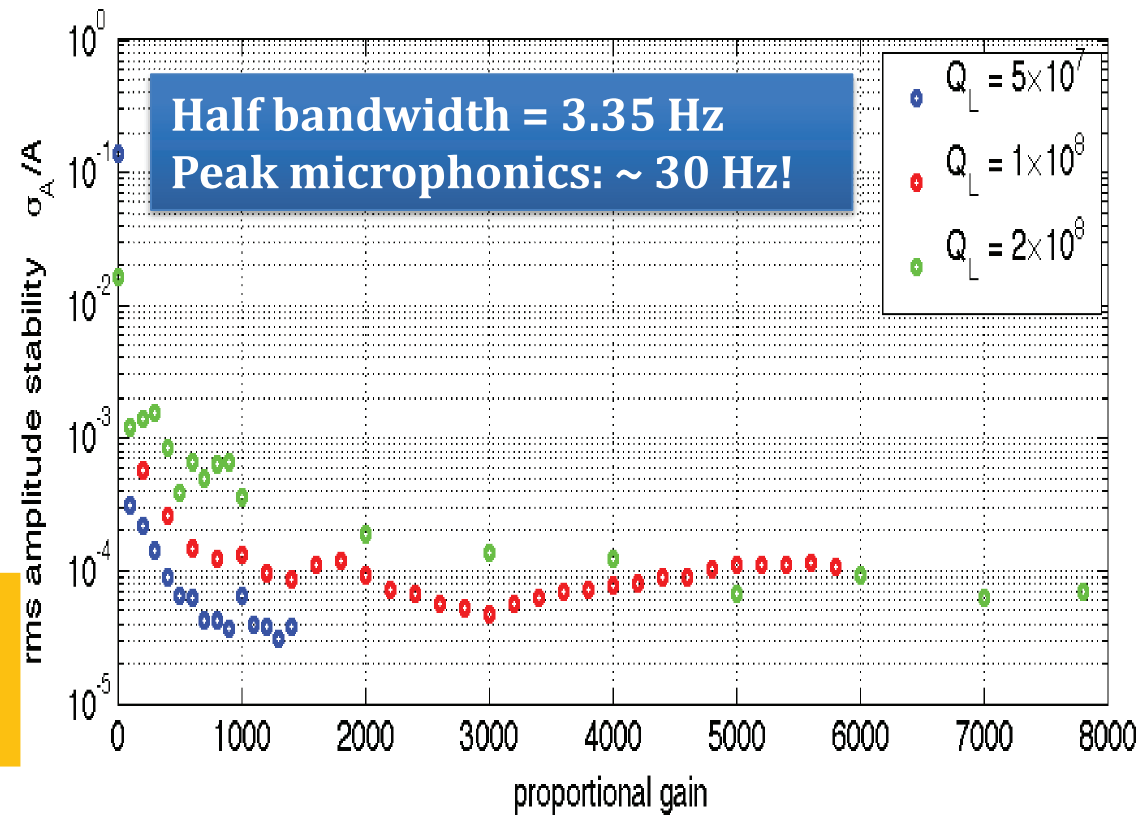
ERL linac cavities ideally see a zero net beam loading.

$Q_L > 1x10^8$ are possible

- this requires very low microphonics
- $\sigma_A/A < 1x10^{-4}$
- $\sigma_\phi < 0.02$

Measured Phase stability of 0.02 deg at Q_L $2x10^8$(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



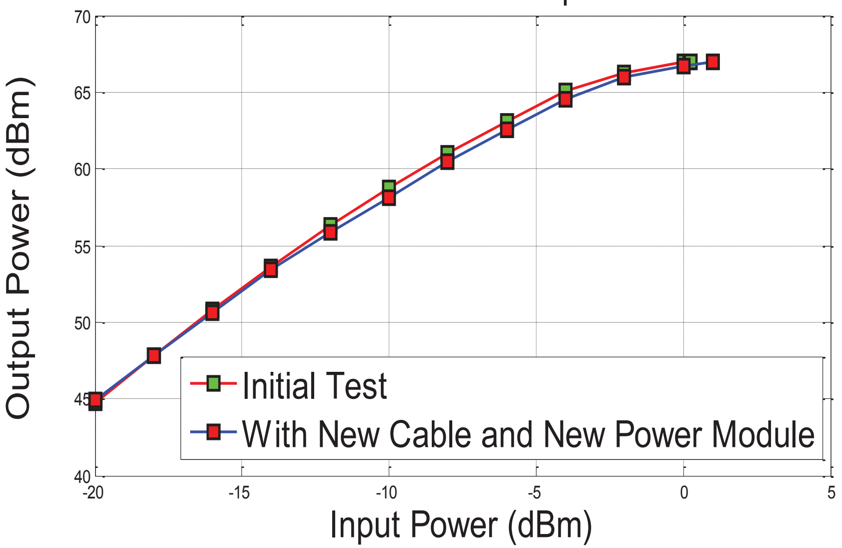
Reduce Q_L, reduce capital & operating costs!

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

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

Gain Plot of the Amplifier



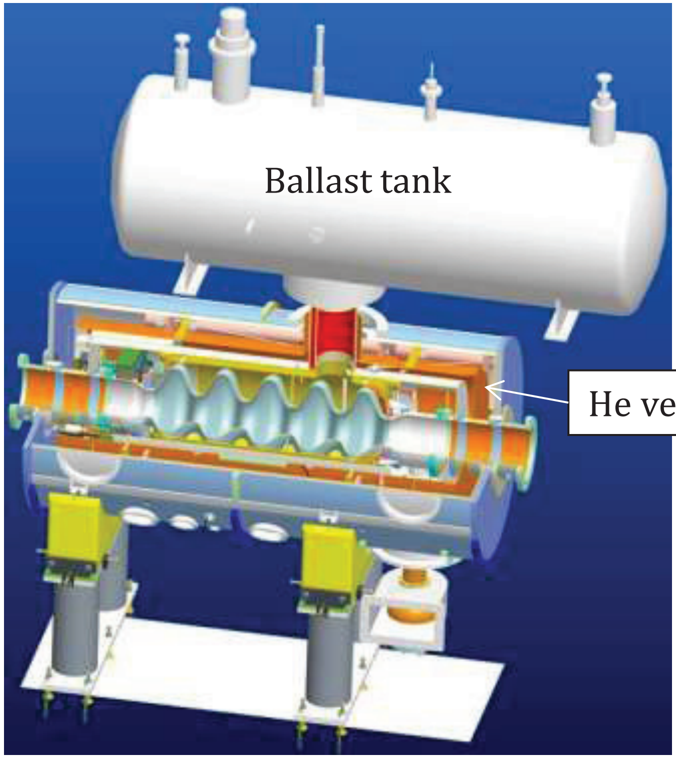
SRF Challenges - Microphonics

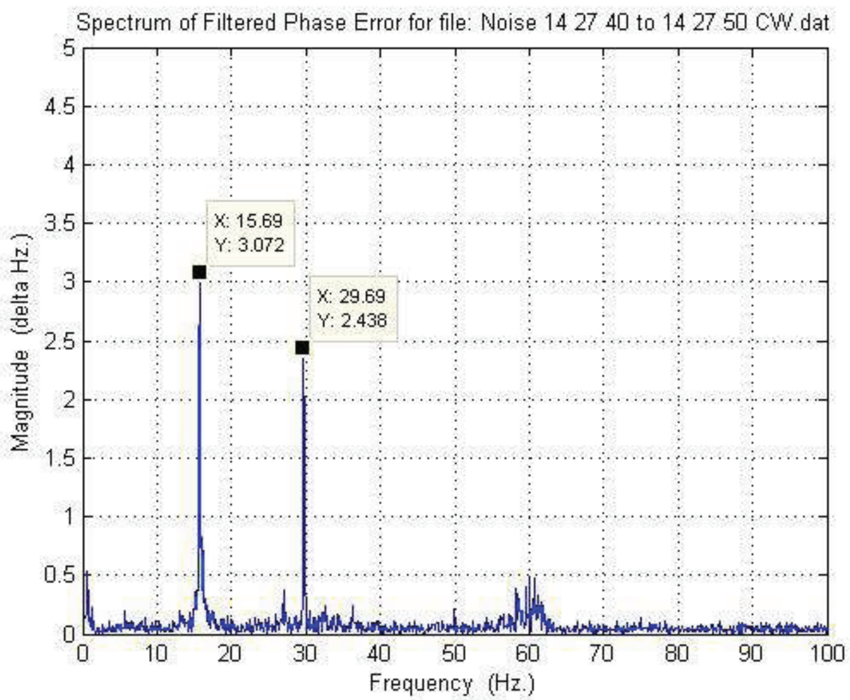
- Minimized microphonics susceptibility
  - Cavity design can only do so much. Must be rigid and not have any low frequency modes which may be excited.
- Finite element analysis of the systems
  - Cavity + He return + He Supply + tuner + ...
  - Look at entire cavity string motion
  - Understand accelerator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

Slide courtesy of Wencan Xu

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

Cryogenic Plant Capacity

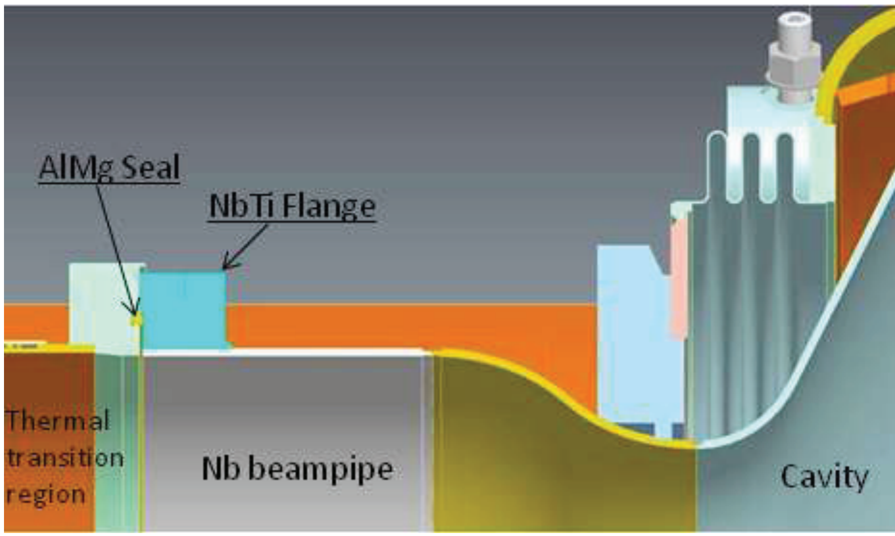
- Better than 1 mm*mrad emittance requires precise cavity alignment
  - Cavity to cavity in a module
  - Between modules
  - Relative to beamline components

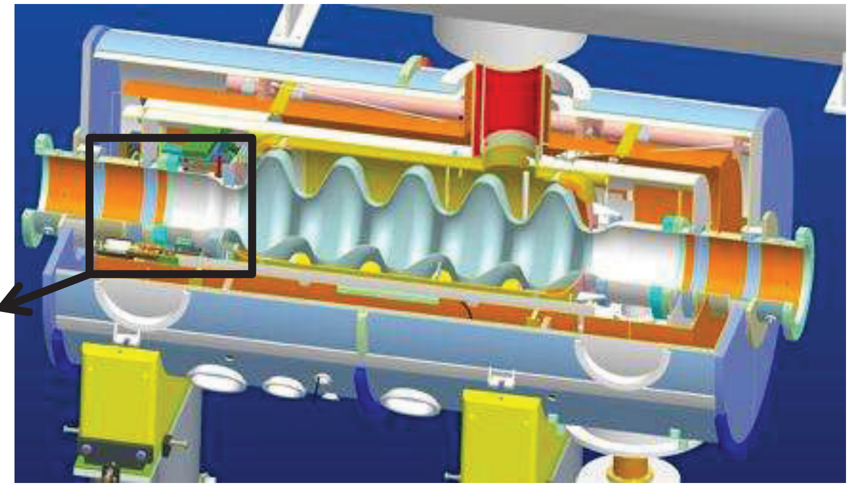
More critical for booster

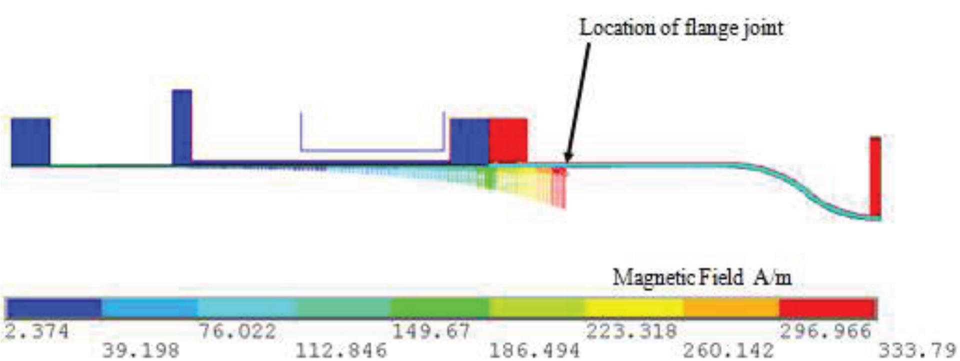
- Proper heat intercepts to limit 2K load

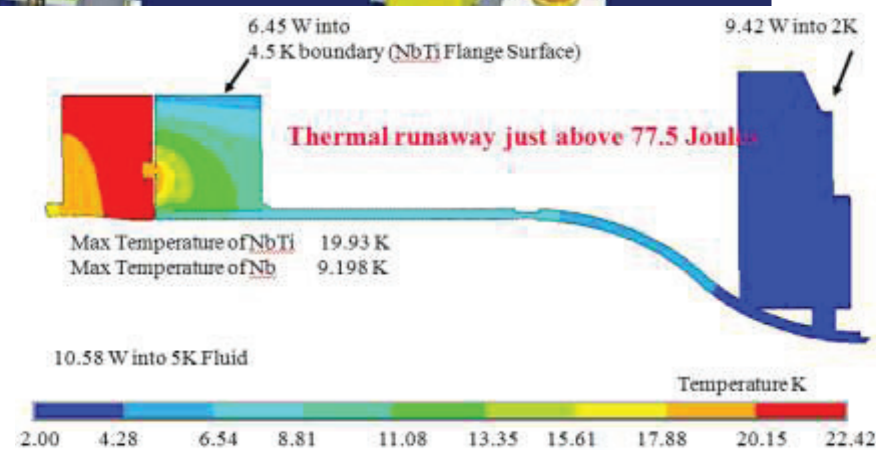
BNL 5-cell cavity: cold test performance

- 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 $AlMg_3$ 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.







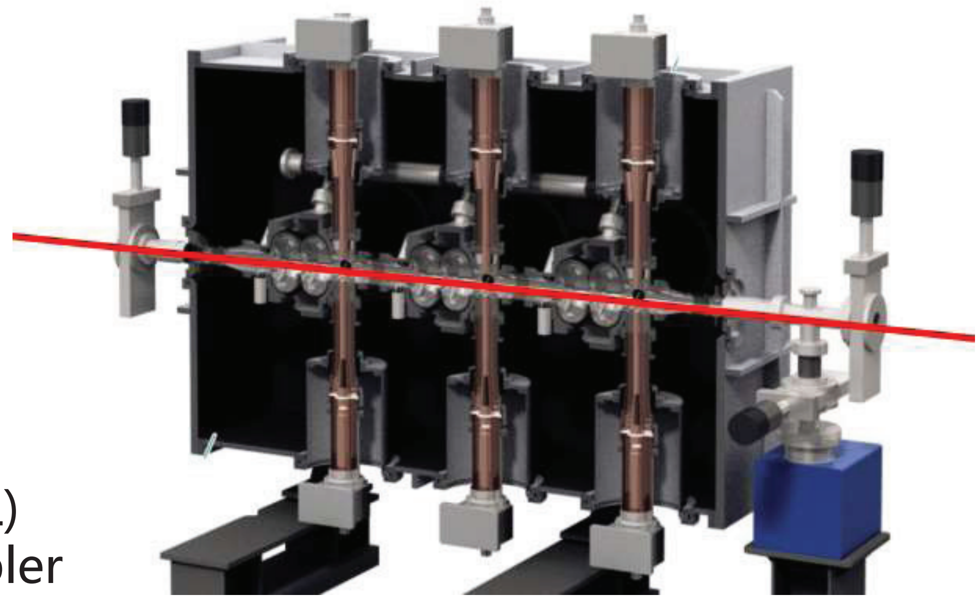


Slide courtesy of Wencan Xu

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

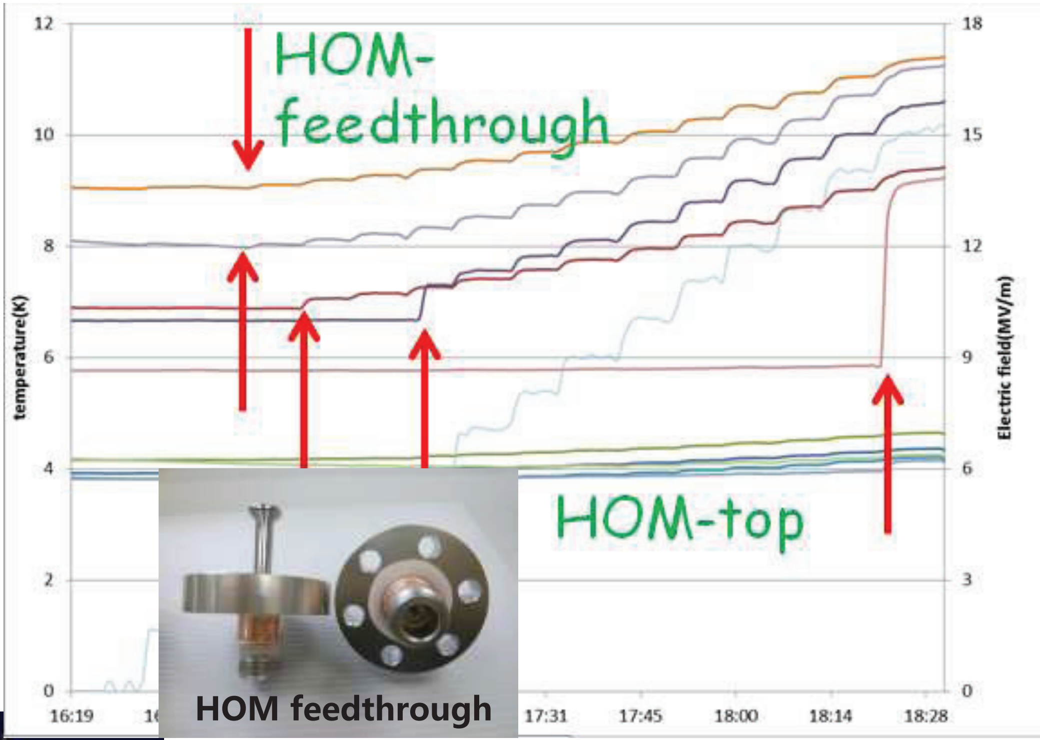
Input couplers

KEK cERL performance

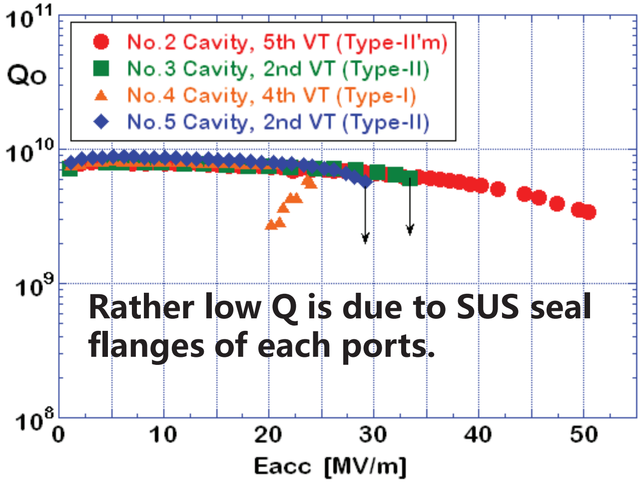
Performance of the module

- 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.

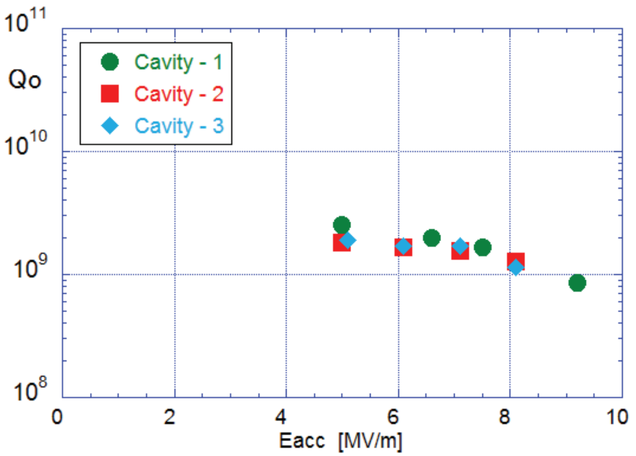
Heating of HOM of #3 cavity



Vertical test results

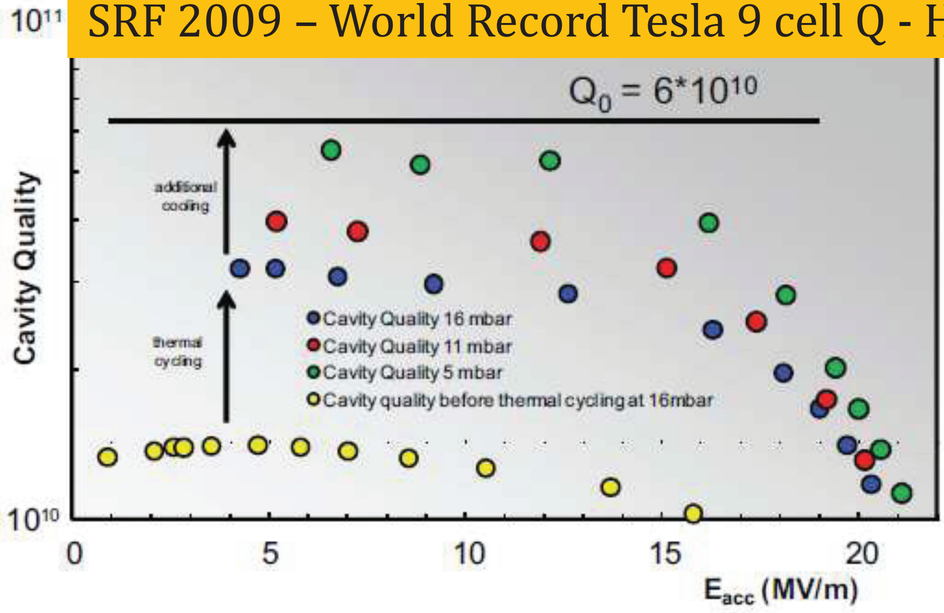


Module power test



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

Performance Improvement in Cryomodule

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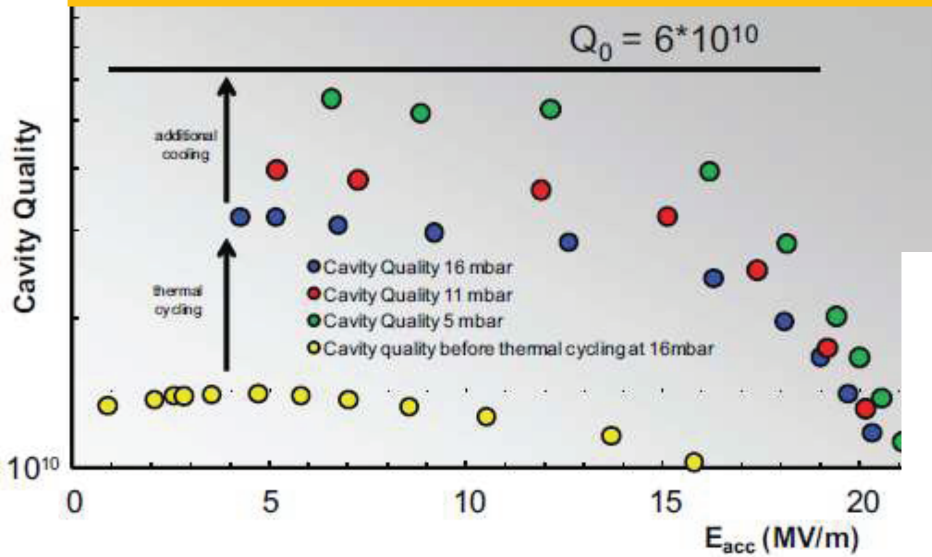

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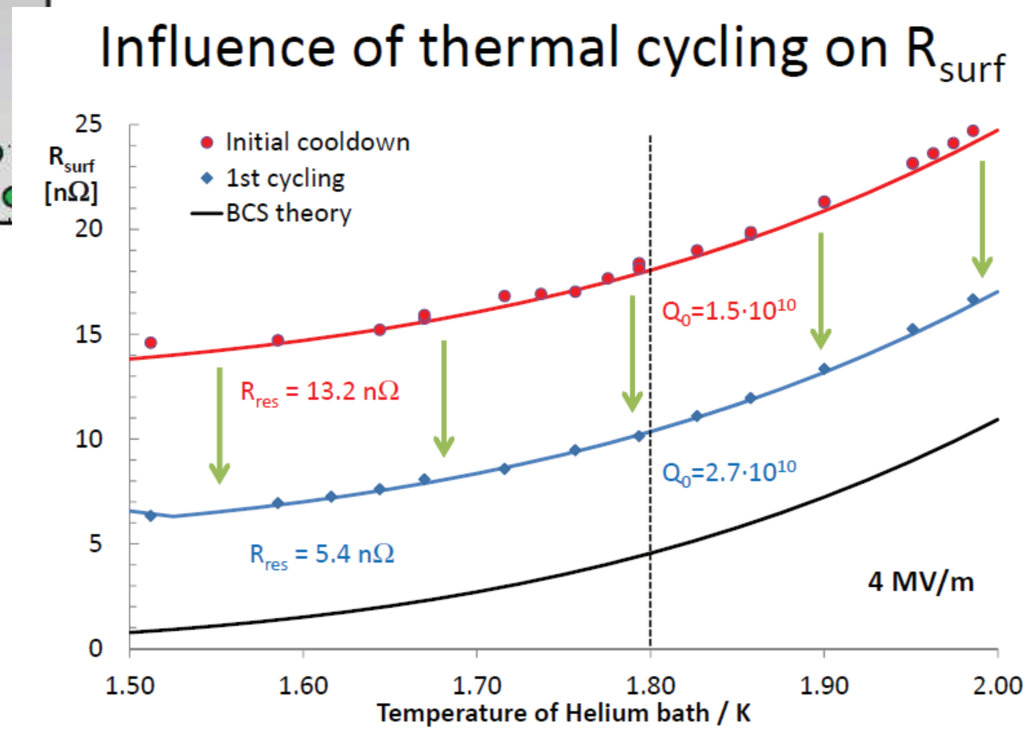
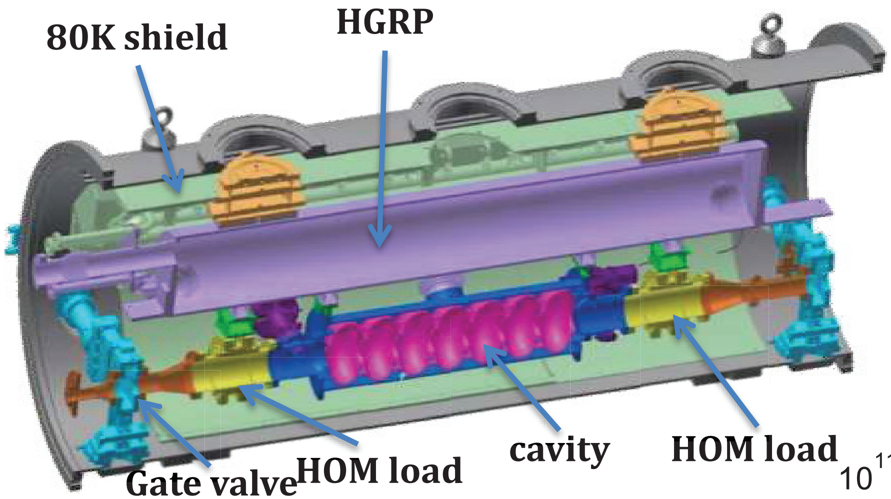
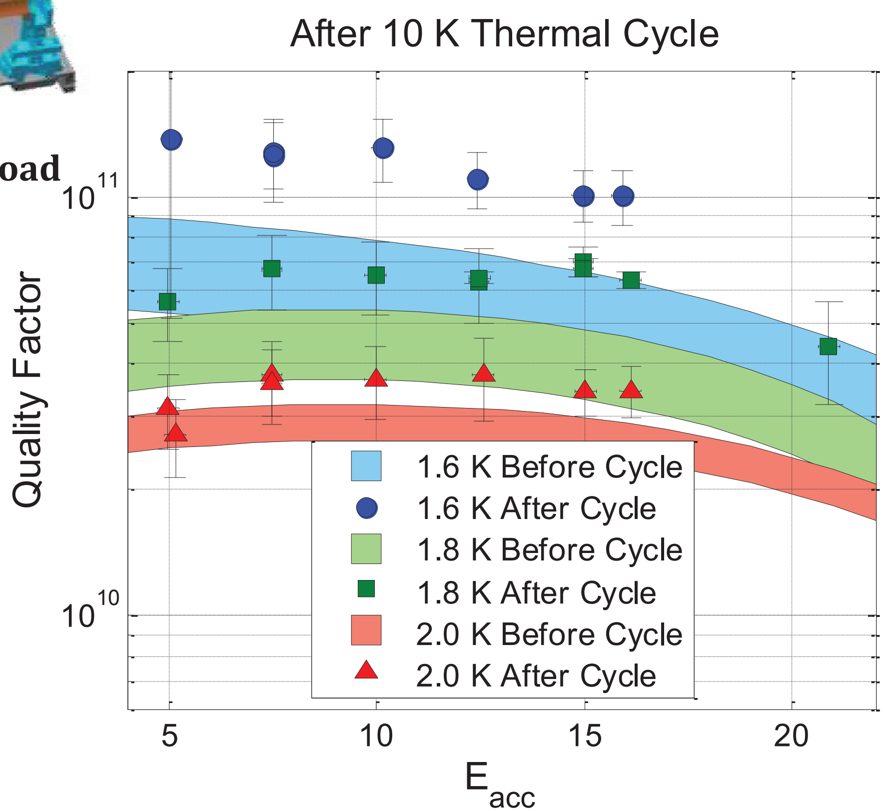


TUIOA01 Influence of Cooldown on Cavity Quality Factor - Kugeler
TUIOA02 – High Qo Research, The Dynamics of Flux Trapping in SC Niobium - Vogt

Performance Improvements 2



Cornell Linac Cavity HTC



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

HTC-I: Q0 = 3.5E10 without coupler

HTC-II: Q0 = 2.E10 (reached with coupler)

HTC-III: **Q0 = 6.E10** (with coupler and HOM absorbers, after cavity reprocessing from HTC-II)

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 Qo > $3x10^{10}$ and $E_{acc} \geq 16$ MV/m for a 1.3 GHz cavity
  - 10 W per cavity at 1.8K in the Linac!
- $Q_L > 1x10^8$ 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.