Recent Results on a Multi-Cell 802 MHz bulk Nb Cavity

FCC Week 2018

9-13 April 2018

Beurs van Berlage

Amsterdam

Frank Marhauser

Jefferson Lab

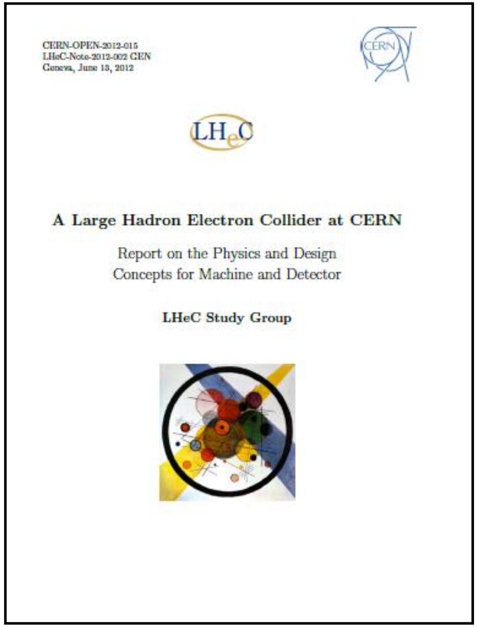
CERN

Outline

- JLab's role in SRF cavity development for CERN's FCC and LHeC
- Cavity design principle
- Relevant key performance parameters
- Cavity fabrication stages
- Vertical test results in dewar
- Summary

JLab’s Role in SRF Cavity Studies for CERN

- CERN and JLab had signed a general Memorandum of Understanding to cooperate in the development of SRF accelerator technologies specifically related to CERN’s FCC studies
- FCC includes a hadron-electron collider program envisioning a 60 GeV 3-pass race-track **ERL**
- ERL is similar to that conceived for the LHeC linac-ring collider proposal (CDR 2012) utilizing the LHC protons or ions for collision
  - LHeC provides strong, complementary physics case to LHC/HE-LHC physics program and would run concurrently
  - Would bridge gap until FCC would be on horizon


CERN-OPEN-2012-015
LHeC-Note-2012-002 GEN
Geneva, June 13, 2012

LHeC

A Large Hadron Electron Collider at CERN

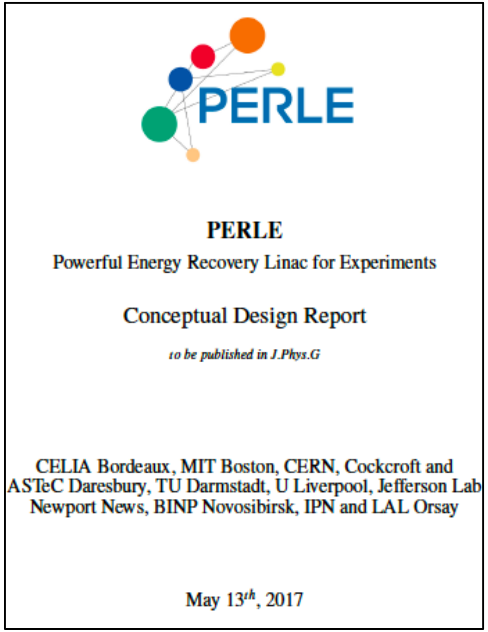
Report on the Physics and Design Concepts for Machine and Detector

LHeC Study Group

arXiv:1206.2913, 2012

JLab's Role in SRF Cavity Studies for CERN

- In any case, substantial R&D for the ERL including SRF cavity technology is required
  - Triggered CERN to prepare studies for a multi-pass ERL test facility with up to 1 GeV electron beam energy
  - However, this was not endorsed at CERN
- But: To showcase the ERL concept, this eventually led to the proposal for ***PERLE*** (Powerful ERL Linac Experiments) facility to be hosted by INP+LAL in Orsay/France
  - *PERLE* (~500 MeV) serves as a key demonstration machine for LHeC and FCC-he (CDR submitted May 2017)


PERLE

PERLE

Powerful Energy Recovery Linac for Experiments

Conceptual Design Report

to be published in J.Phys.G

CELIA Bordeaux, MIT Boston, CERN, Cockcroft and ASTeC Daresbury, TU Darmstadt, U Liverpool, Jefferson Lab Newport News, BINP Novosibirsk, IPN and LAL Orsay

May 13^{th}, 2017

arXiv:1705.08783, 2017

JLab's Role in SRF Cavity Studies for CERN

- Note: CERN requires SRF technology at 801.58 MHz for several other programs
  - 20th integer ref. to 25 ns bunch spacing, e.g. FCC-ee (ttbar) needs 802 MHz 5-cell cavities
  - Frequency is good choice concerning cost optimization rationales
- To initiate SRF cavity R&D, CERN and JLab had agreed on a Joint Work Statement to:

  1) Develop a conceptual design of a five-cell 802 MHz ERL-type cavity

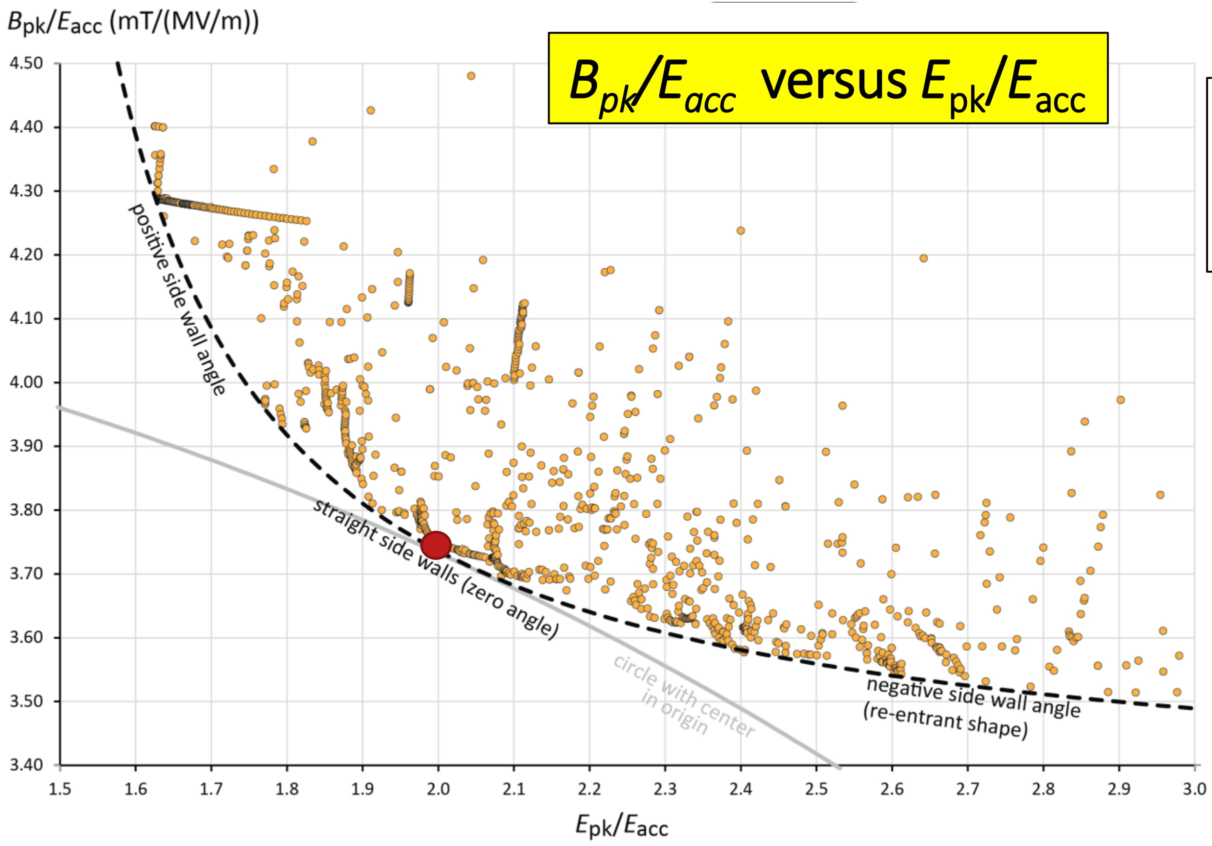
  2) Fabricate and test the cavity vertically at 2 K to validate the RF design
- Concerning task 1); one cannot optimize all cavity key parameters simultaneously

  → always a trade-off

  → geometry should relate to needs of the specific machine

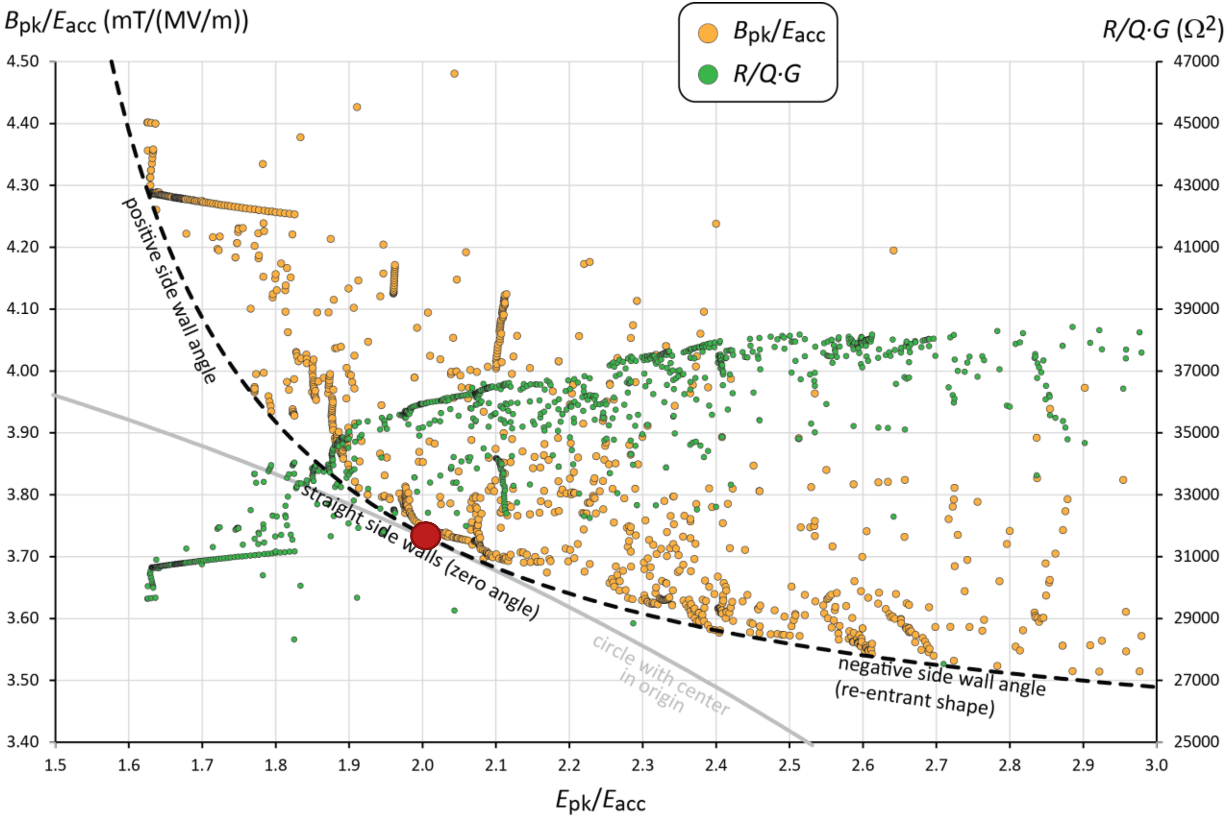
  → aim was to obtain a geometry that well balances all key parameters

Cavity Design Rationale - When is a Cavity Shape Optimized ?



> 1000 half-cells at 802 MHz,
iris ID fix for fair comparison
(example ID= 115 mm)

Cavity Design Rationale - When is a Cavity Shape Optimized ?



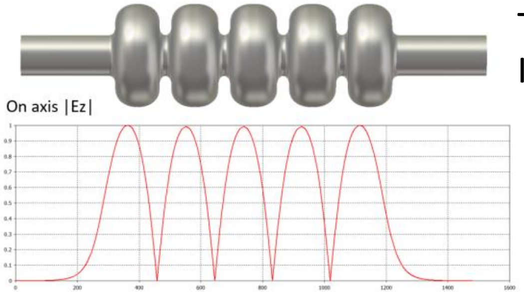
> 1000 half-cells at 802 MHz,
iris ID fix for fair comparison
(example ID= 115 mm)

Dynamic RF losses dissipated in Helium bath

$$P_{RF} = \frac{V_{acc}^2}{\boldsymbol{R/Q \cdot G}} \cdot R_s$$

Cavity Design Studies

JLab version

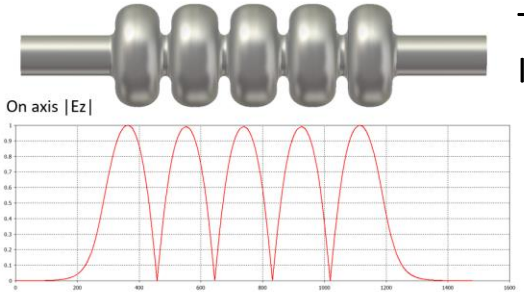


Tube ID = 130 mm
Iris ID = 130 mm

- Final design selected with:
  iris ID = 130 mm = beam tube ID
  - **Same design principle applied**
  - This ID yields better mechanical stability
  - Considers HOM-damping need (strong cell-to-cell coupling factor of 3.2%)

Cavity Design Studies

JLab version



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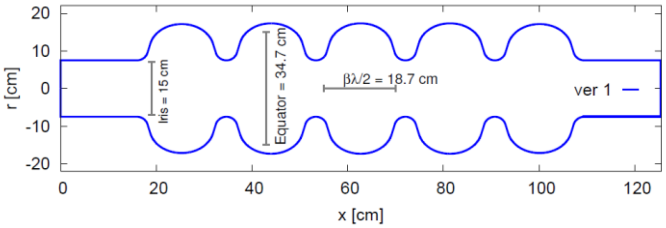
CERN version 1

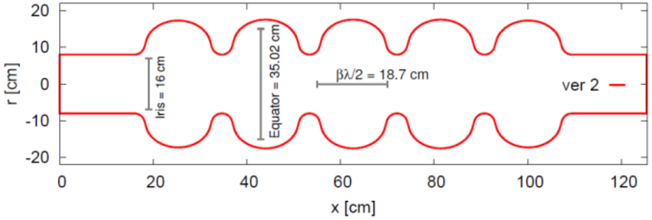
scaled from 704 MHz design
(E. Jensen et al. LINAC 2014)



Tube ID = 150 mm
Iris ID = 150 mm

CERN version 2

(R. Calaga, CERN-ACC-NOTE-2015)



Tube ID = 160 mm
Iris ID = 160 mm

Parameter Table for ERL Cavity Candidates

Parameter	Unit	Value	Value	Value
Cavity type		JLab	CERN Ver. 1*	CERN Ver. 2*
Frequency	MHz	801.58		
Number of cells		5		
L_{active}	mm	917.9	935	935
Long. loss factor (2 mm rms bunch length)	V/pC	2.742	2.894	2.626
$R/Q = V_{eff}^2/(\omega * W)$	Ω	523.9	430	393
G	Ω	274.6	276	283
$R/Q \cdot G$/cell		**28788**	**23736** -18%	**22244** -23 %
Eq. Diameter	mm	328.0	350.2	350.2
Iris Diameter	mm	**130**	**150**	**160**
Tube Diameter	mm	130	150	160
Eq./Iris ratio		2.52	2.19	2.19
Wall angle (mid-cell)	degree	0	14.0	12.5
E_{pk}/E_{acc} (mid-cell)		2.26	**2.26**	**2.40** +6 %
B_{pk}/E_{acc} (mid-cell)	mT/(MV/m)	4.20	**4.77** +14%	**4.92** +17 %
k_{cc}	%	**3.21**	4.47	5.75
cutoff TE_{11}	GHz	1.35	1.17	1.10
cutoff TM_{01}	GHz	1.77	1.53	1.43

* R. Calaga, CERN-ACC-NOTE-2015, 5/28/15

Cavity Fabrication Tools

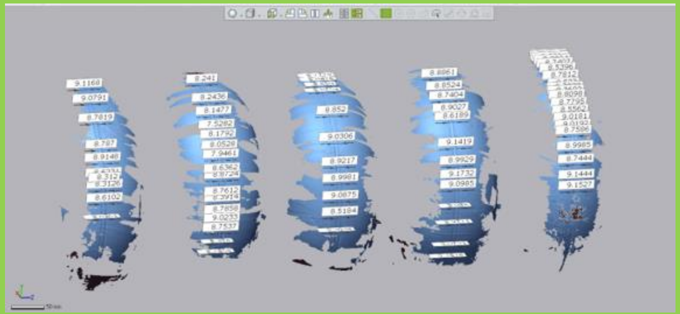
802 MHz half-cell deep-drawing and beam tube rolling dies

Half-cell during pre-trimming by wire electro-discharge machining and final milling for iris weld joint preparation

802 MHz RF measurement fixture for dumbbells and end-groups

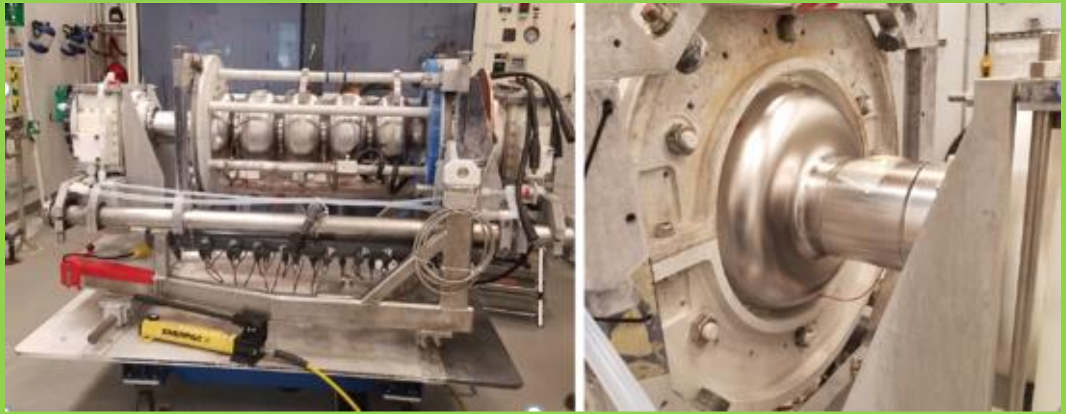
Cavity Fabrication Tools

Five-cell cavity at various equator weld stages of sub-assemblies



Assessment of weld-shrinkage with 3D laser scanner

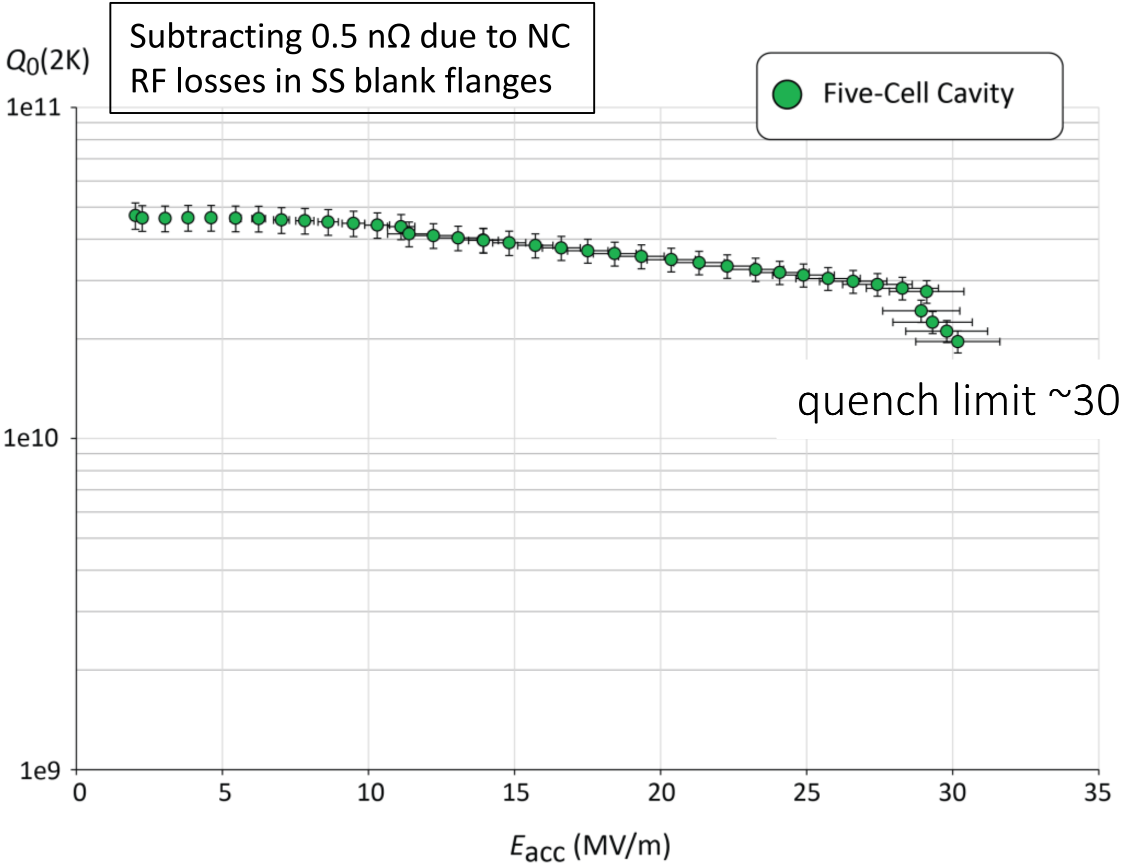
Cavity on the tuning bench

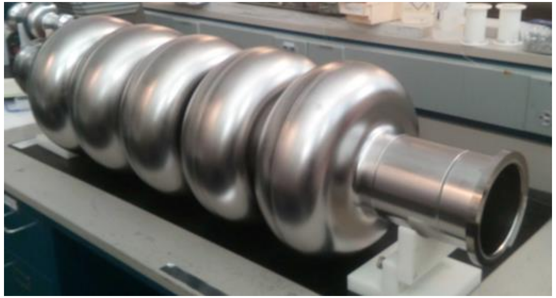


Five-cell in preparation for electropolishing (EP)

Final Vertical Test Result at 2K (Five-cell *CRN5*)

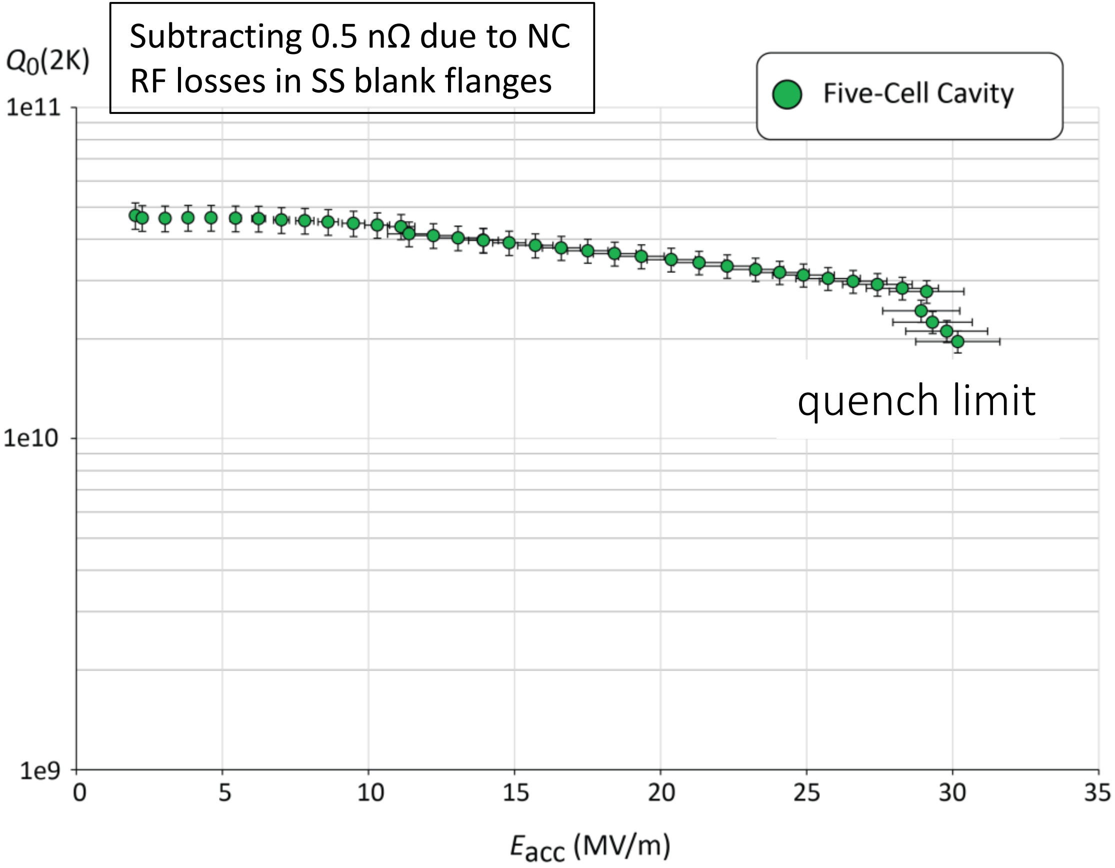
Final Vertical Test Result at 2K (Five-cell *CRN5*)

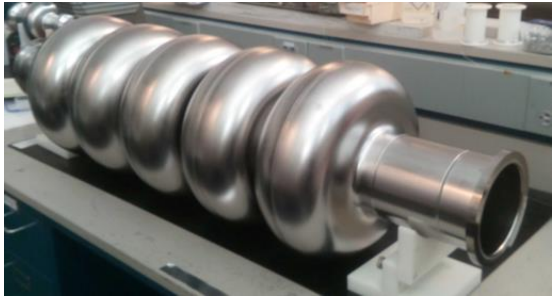




quench limit ~30 MV/m

Final Vertical Test Result at 2K (Five-cell *CRN5*)

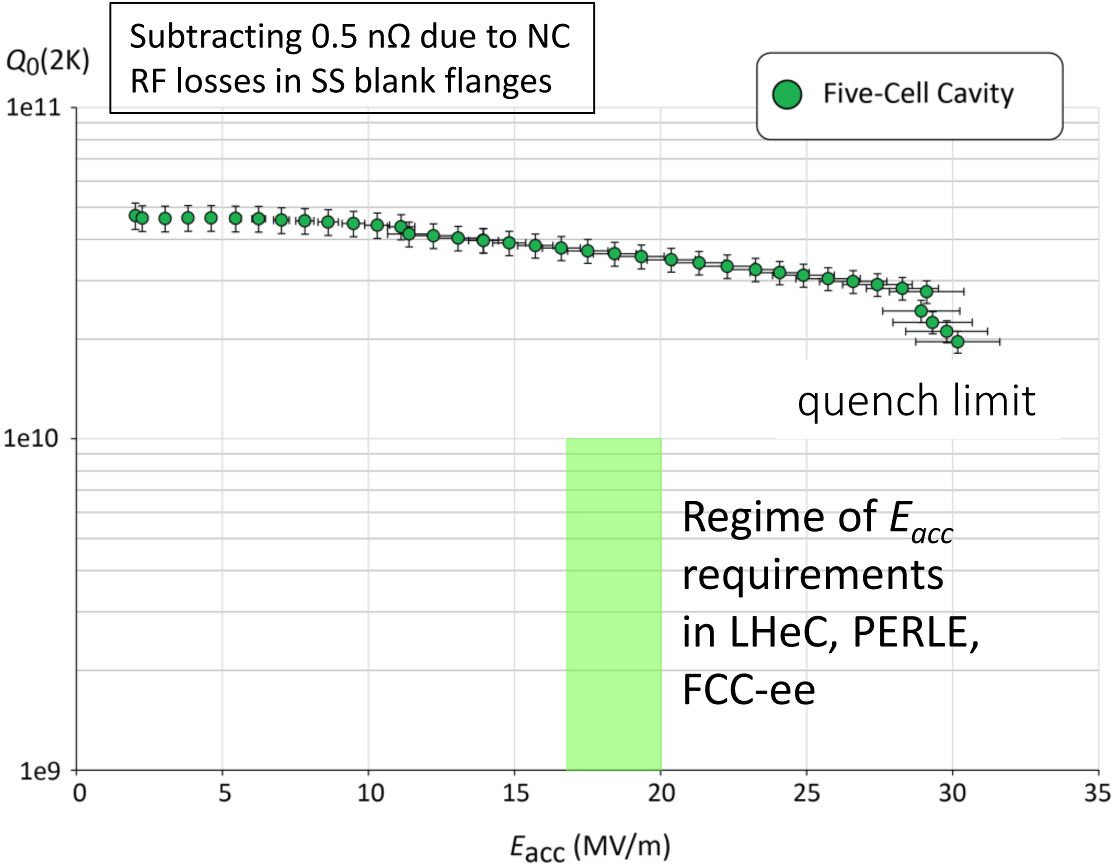


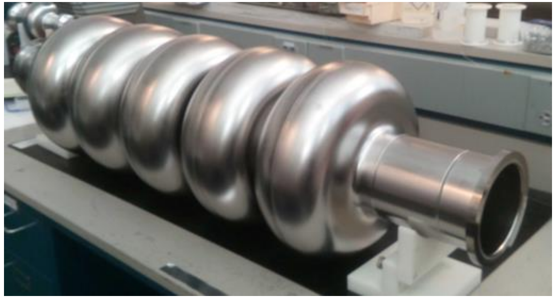


Record Q_0-values at 2K in this frequency regime

Q_0(2K) = 3e10 @ ~27 MV/m

Final Vertical Test Result at 2K (Five-cell *CRN5*)

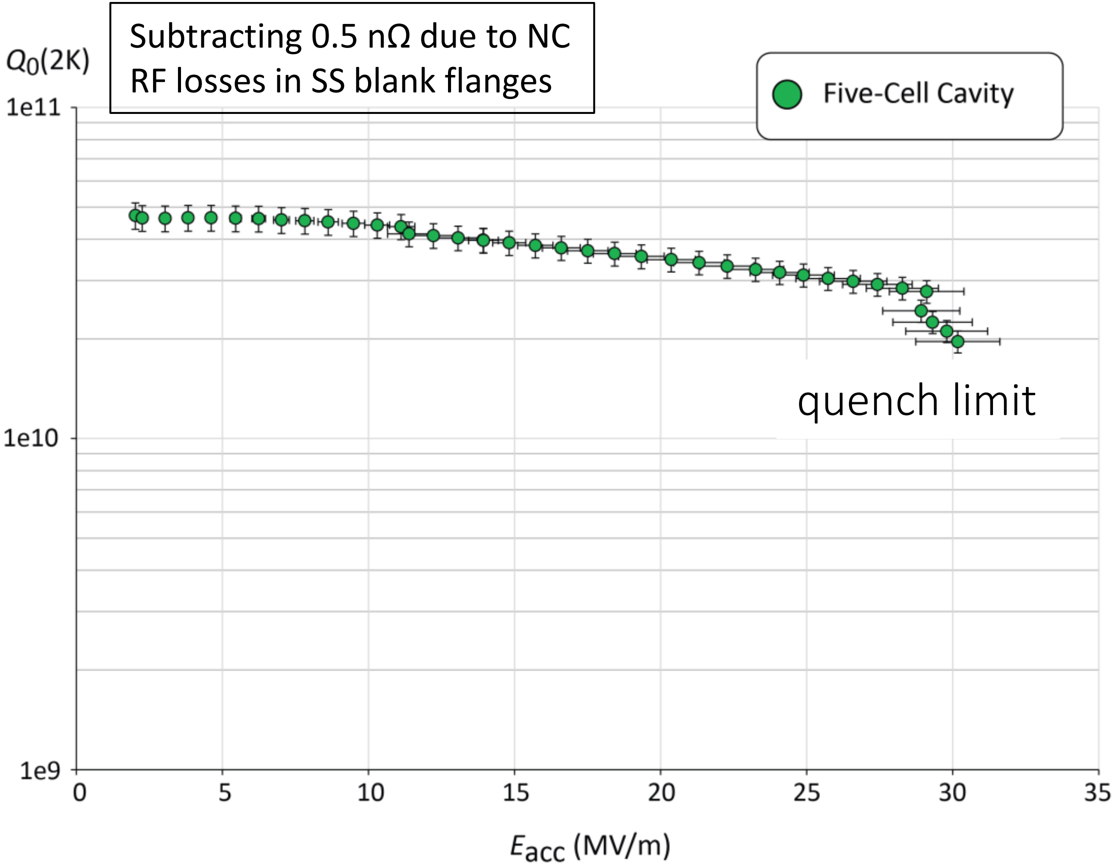


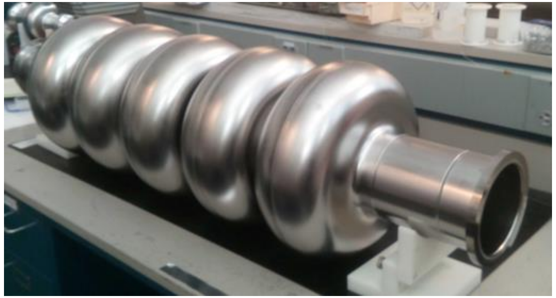


Cavity design has been adapted as baseline for PERLE

Prototype well exceeds conceived E_{acc} requirement with Q_0-values > 3e10 at 2K

Last Vertical Test Result at 2K (Five-cell *CRN5*)

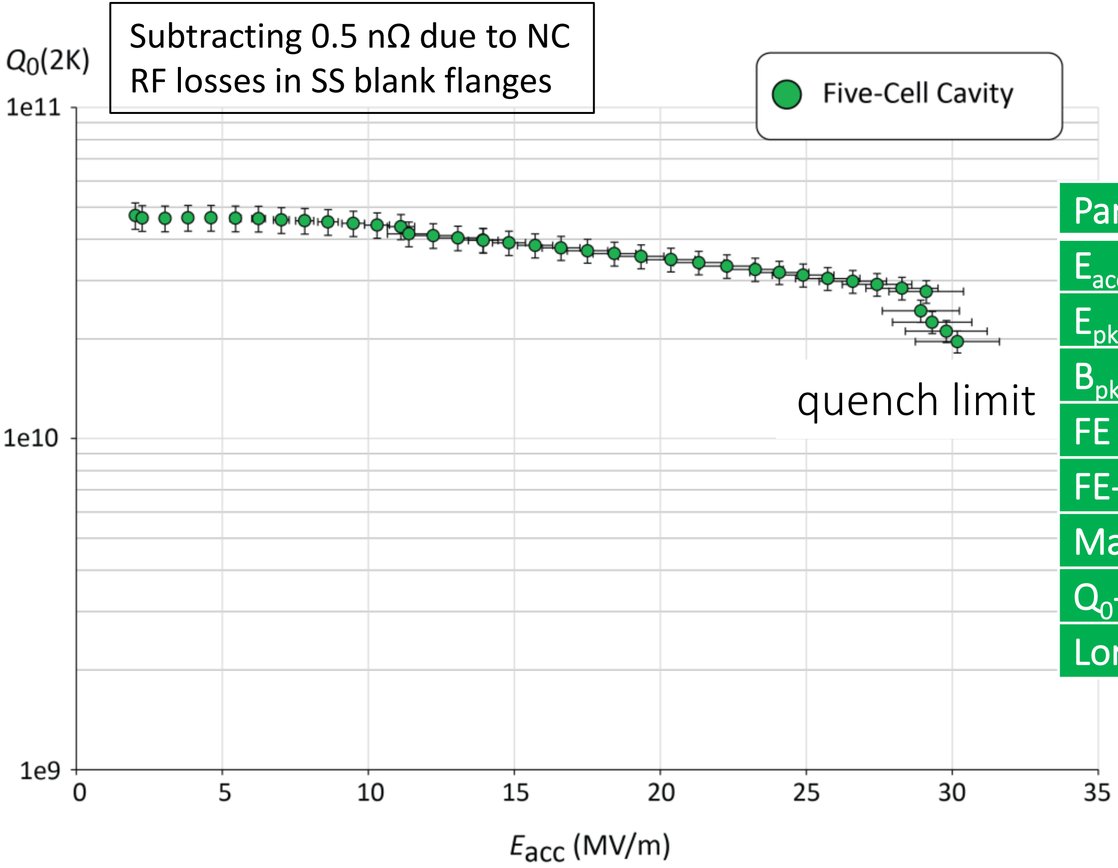




Main post-processing steps

	Unit	*CRN5*
Bulk BCP	µm	216
High-T heat treatment	°C, hrs.	800, 3
Final EP	µm	30
HPR cycles		4
Low-T bake-out	°C, hrs.	120, 12

Final Vertical Test Result at 2K (Five-cell *CRN5*)

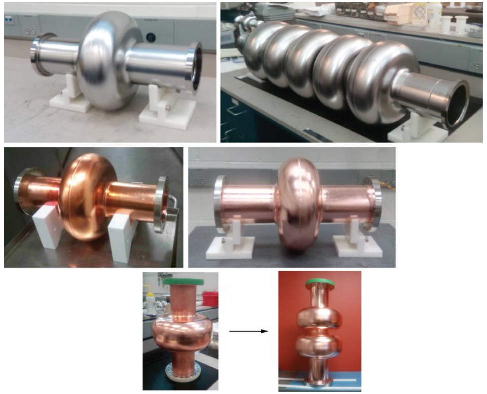


Tabulated Results

Parameter	Unit	*CRN5*
E_{acc} at quench	MV/m	30.1
E_{pk} at quench	MV/m	68.1
B_{pk} at quench	mT	126.3
FE onset field	MV/m	~25
FE-induced radiation (max.)	mR/hr.	0.06
Max. Q_0-value	/1e10	4.72
Q_0-value at 25 MV/m	/1e10	3.12
Lorentz Force Detuning	$Hz/(MV/m)^2$	-1.5

Summary

- JLab completed the design, fabrication and vertical test of a 5-cell ERL prototype cavity suitable for LHeC PERLE, FCC-he, and FCC-ee (ttbar)
  - Validation of RF design successful
  - Record Q_0-values achieved, ~30 MV/m quench field



- The fabrication efforts covered:
  1) Bulk Nb 5-cell cavity
  2) Bulk Nb 1-cell cavity
  3) Two OFHC Cu 1-cell cavities – for thin film coating R&D at CERN
  4) OFHC Cu cavity for R&D bench measurements at CERN allowing to add cells

- JLab looks forward to collaborate with CERN and also with PERLE member institutions beyond the completion of this project
  - Towards a production cavity incl. HOM couplers, input couplers, helium tank etc.

Many Thanks…

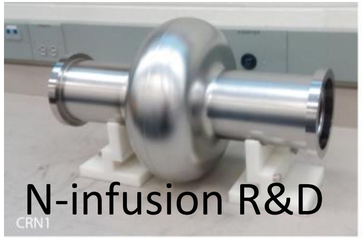
…particularly to the CERN colleagues
for the fruitful collaboration
and to all PERLE members!

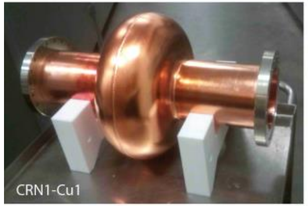
Questions ?

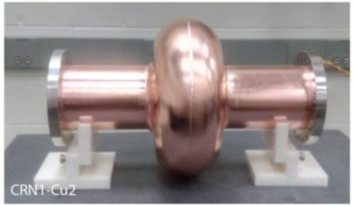
Supplemental Slides

Ensemble of Cavities Fabricated

All 802 MHz prototype cavities built

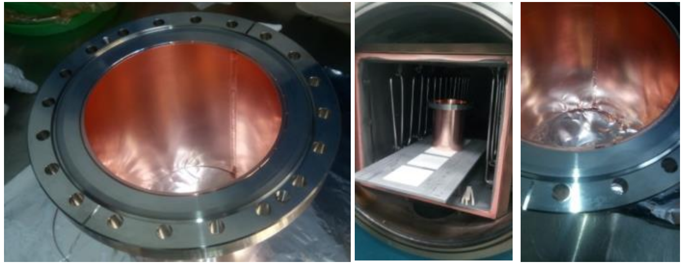






CRN1_2 - For bench measurements allowing to join multiple cells

Copper cavities required brazing of tubes to SS flanges



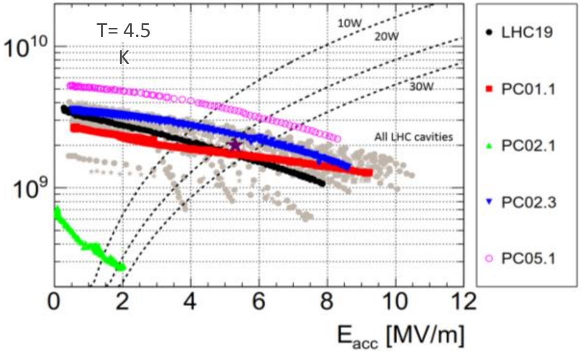
Nb/Cu Technology - 400 MHz LHC Nb/Cu

SRF R&D Overview
Monday R&D summary talk
by A.-M. Valente-Feliciano

G. Rosaz et al.

Progress: Spare cavities coated

Best RF performance achieved



CERN requires SRF Technology for Several Program

- Cavities at 801.58 MHz needed

CERN

Program	Frequency (MHz)
LHC, spare and more	401
LHC upgrade	200, **802**
HIE-ISOLDE	101
HL-LHC crab cavities	401
SPL (ESS)	704
LHeC, FCC-he, *PERLE*	**802**
FCC-ee, FCC-hh	401 & **802**

From Erk Jenson, LHeC workshop, 2015

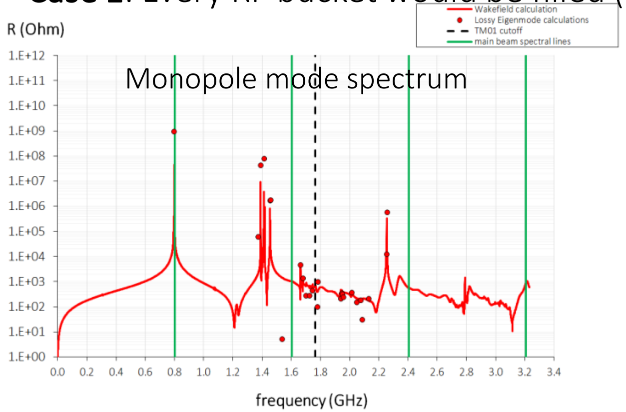
International (SRF)

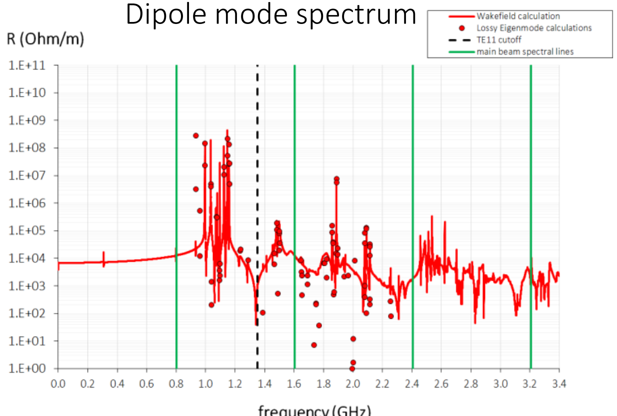
Program	Frequency (MHz)
JLab CEBAF & LERF	1497
ILC, X-FEL, LCLS-2, …	1300
JLab EIC	952.6
SNS	**805**
JLab HC	750
ESS	704
PIP-II	650
JAERI	500
eRHIC	394
CERN Linac4, ESS	352

Beam Spectra vs. HOM Frequencies

- Cavity design took into account avoiding main 802 MHz beam spectral lines

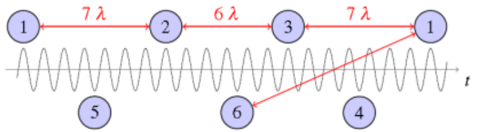
Case 1: Every RF bucket would be filled (no gap)



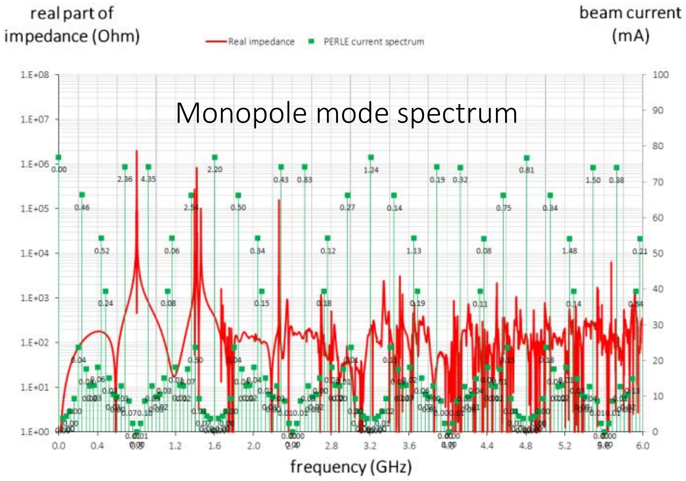


Case 2: PERLE baseline bunch spectrum for 801.58 cavities:
Bunch spacing 801.58MHz/20 = 40.079 MHz

PERLE Powerful energy recovery linac experiments



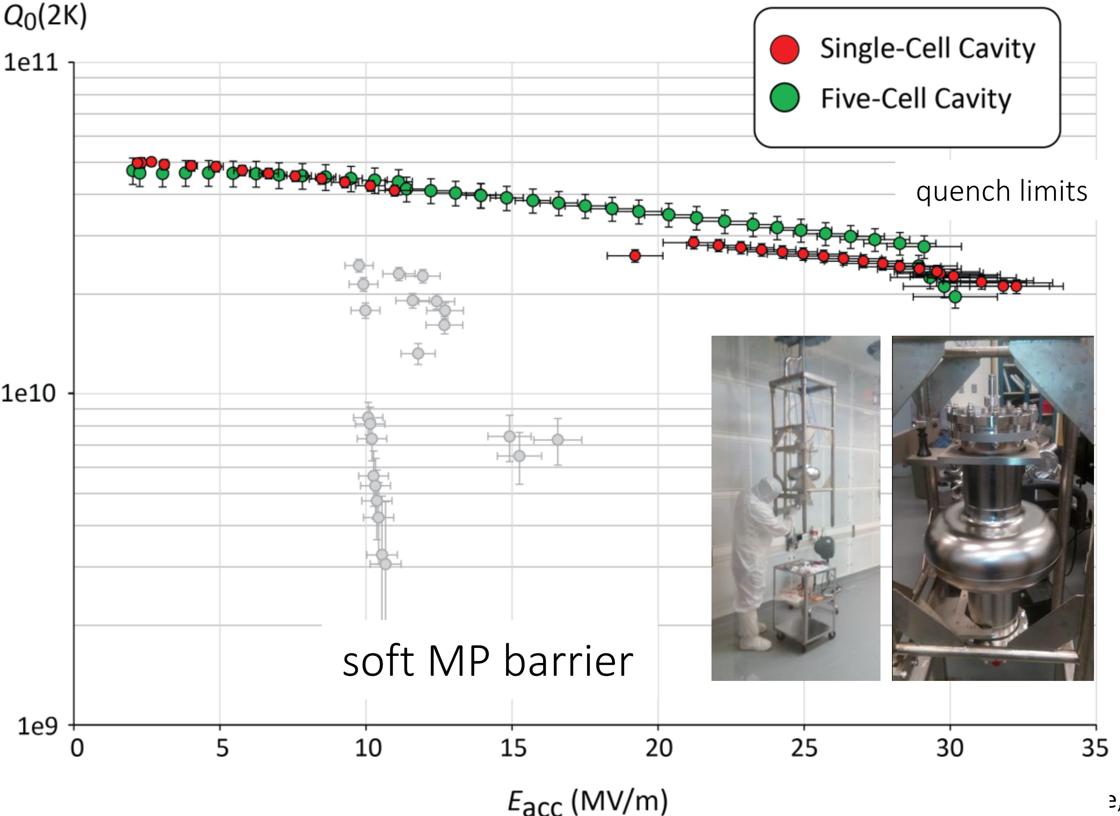
Bunch recombination pattern for PERLE. Bunches at different energies (the turn number is indicated) are separated by nearly constant bunch spacing.



Q_b = 320 pC

Latest Vertical Test Results at 2K

- A single-cell Nb cavity (*CRN1*) was built and tested
- MP activities observed at ~10 MV/m, but quickly processed, re-rinse & re-test planned



Main post-processing steps

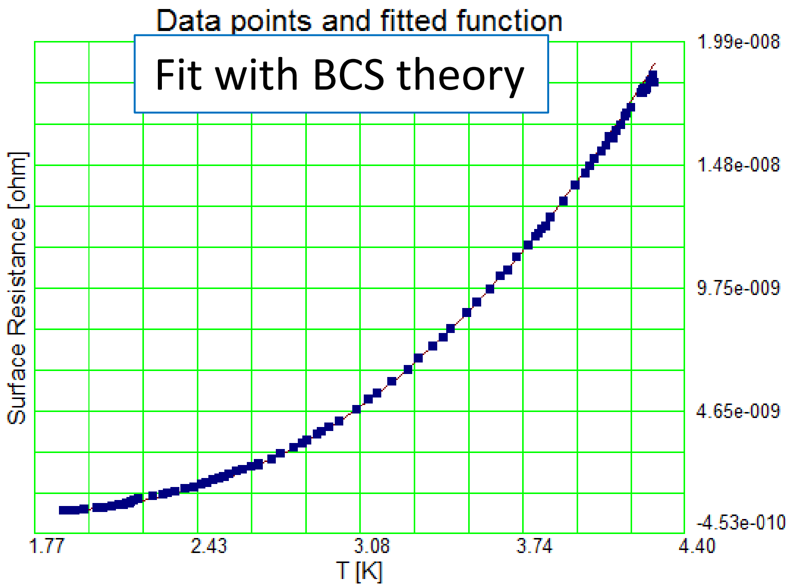
Post-Processing steps	Unit	*CRN1*	*CRN5*
Bulk BCP	µm	160	216
High-Temperature heat treatment	°C, hrs.	800, 3	800, 3
Final EP	µm	30	30
High Pressure Rinse (HPR) cycles		2	4
Low temperature bake-out	°C, hrs.	120, 12	120, 12

Summary of main results

RF results	Unit	*CRN1*	*CRN5*
E_{acc} at quench	MV/m	32.3	30.1
E_{pk} at quench	MV/m	61.3	68.1
B_{pk} at quench	mT	129.0	126.3
FE onset field	MV/m	~20	~25
FE-induced radiation (max.)	mR/hr.	2.3	0.06
Residual resistance	nΩ	3.19	n.m.
Max. Q_0-value	/1e10	4.97	4.72
Q_0-value at 25 MV/m	/1e10	2.62	3.12
Lorentz Force Detuning	$(MV/m)^2/Hz$	-7.1	-1.5

Residual Resistance

- Material used is OTIC Ningxia high-RRR (250) fine grain Nb
- Residual resistance has been assessed during tests for *CRN1*

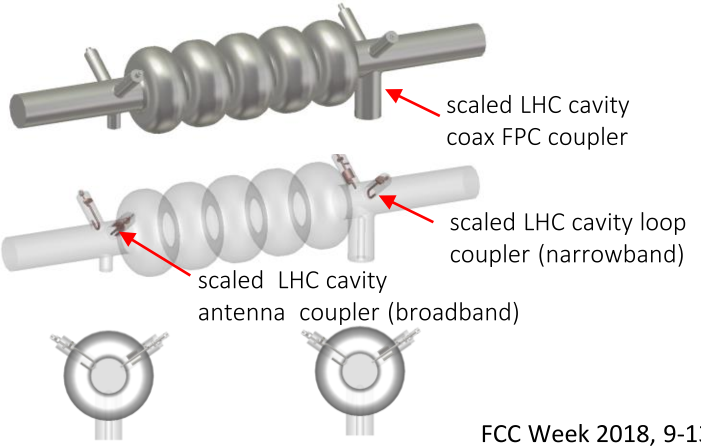


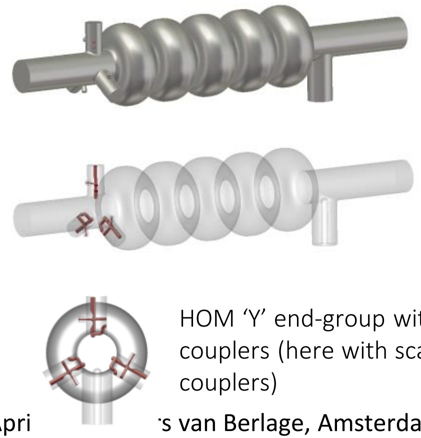
$R_{res} = 3.19 \pm 0.79\ n\Omega$

Note: This takes into account 2.49 nΩ due to NC RF losses in SS blank flanges for the single-cell cavity

HOM Damping Studies

- Preliminary HOM studies carried out incorporating LHC-type HOM couplers (and coaxial input coupler) scaled to adapt to new cavity shape at 802 MHz
  - Broadband damping efficiency was found to be not optimal since also narrowband loop couplers are employed as required for LHC cavities
- We considered using new coaxial HOM-couplers or scaled versions of existing designs (TESLA/JLab-type couplers) with up to 3 couplers combined in a single 'Y' end-group
  - Benefit of 'Y' end-group: Minimizes/eliminates dependency on transverse mode polarization

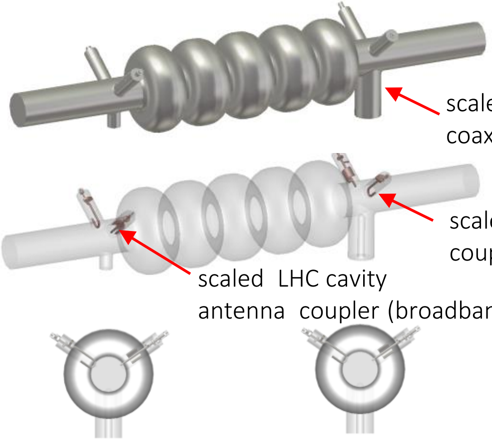




Jefferson Lab

HOM Damping Studies

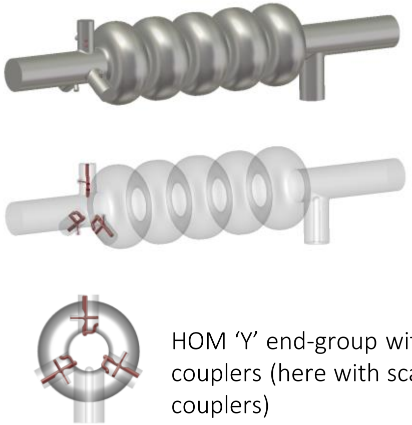
- Alternative: Broadband waveguide HOM couplers such as developed at JLab in the past for Ampere-class ERLs
  - Waveguide couplers could be ‘overkill’ for PERLE since 3-pass peak beam current is comparably small (< 100 mA)
  - Benefit: Waveguides do not require fundamental mode notch filter and are broadband by nature
  - Yet, trapped TE_{111} and TM_{110} dipole modes with high impedances might be better captured with coaxial couplers (cf. *Supercond. Sci. Technol. 30 (2017) 063002*)



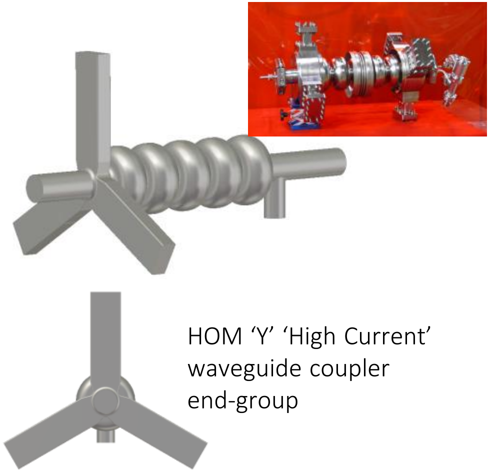
scaled LHC cavity coax FPC coupler

scaled LHC cavity loop coupler (narrowband)

scaled LHC cavity antenna coupler (broadband)



HOM ‘Y’ end-group with 3 coaxial couplers (here with scaled TESLA-type couplers)



HOM ‘Y’ ‘High Current’ waveguide coupler end-group