PERLE Cavity Design and Results and First Thoughts on HOM-Couplers

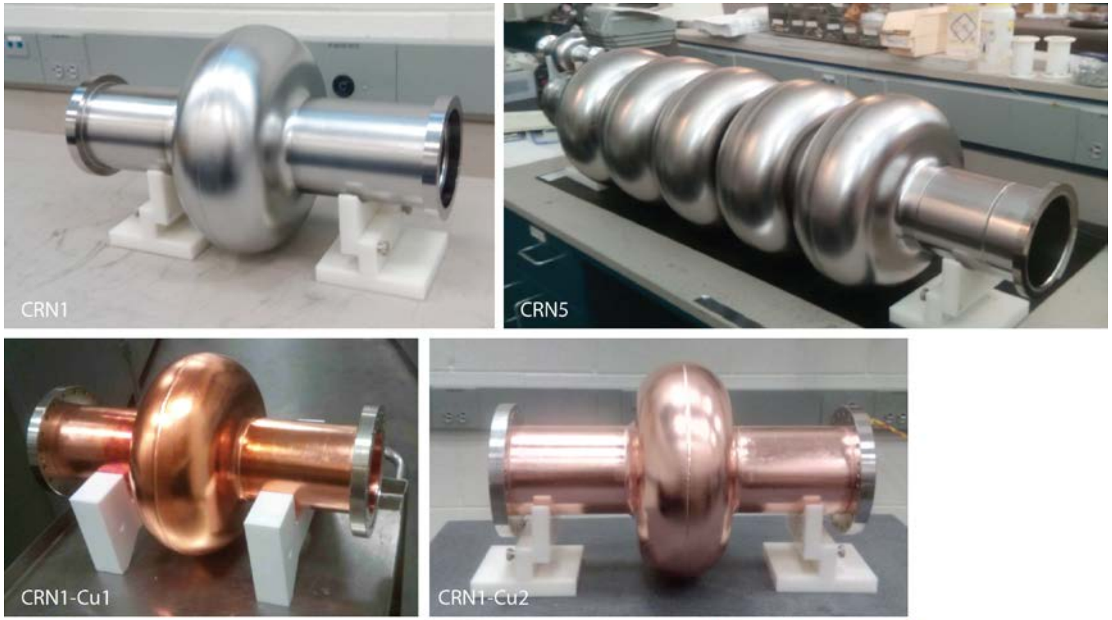
PERLE HOM Coupler Meeting

Oct 11th 2019, CERN

F. Marhauser

Monday, October 11, 2019

Ensemble of Cavities Fabricated at JLab



CRN1_2 - For bench measurements allowing to join multiple cells

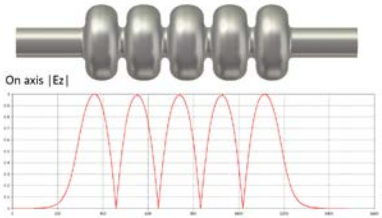
CERN-JLab Collaboration:

- Prototype fabrication and vertical dewar tests of Nb cavities completed beginning of 2018
- Results reported

FCC Week 2018
9-13 April 2018
Beurs van Berlage
Amsterdam

- No funds and activities since then at JLab

Parameter Table for ERL 5-Cell Cavity



“Well Balanced“ Design

Parameter	Unit	Value
Frequency	MHz	801.58
Number of cells		5
L_{active}	mm	917.9
Long. loss factor (2 mm rms bunch length)	V/pC	2.742
$R/Q = V_{eff}^2/(\omega * W)$	Ω	523.9
G	Ω	274.6
$R/Q \cdot G$/cell	Ω^2	28788
Eq. Diameter	mm	328.0
Iris Diameter	mm	130
Tube Diameter	mm	130
Eq./Iris ratio		2.52
Wall angle (mid-cell)	degree	0
E_{pk}/E_{acc} (mid-cell)		2.26
B_{pk}/E_{acc} (mid-cell)	mT/(MV/m)	4.20
k_{cc}	%	3.21
cutoff TE_{11}	GHz	1.35
cutoff TM_{01}	GHz	1.77

$R_{BCS} \sim f^2$ key deciding factor. Thermal instability limit (option to reach higher fields)

max. number determined by HOM requirements (trapped modes, HOM Q_{ext}, $\delta A_{cell} \sim N^2/k_{cc} * \delta f_{cell,error}$), real estate and ancillary components (power/HOM couplers, tuners, He vessels) ~1/N → capital costs

cell geometry → $R_s = Q_0/G$

Cryogenic RF losses in wall ~ $1/(R/Q \cdot G)$
→ capital/operational costs

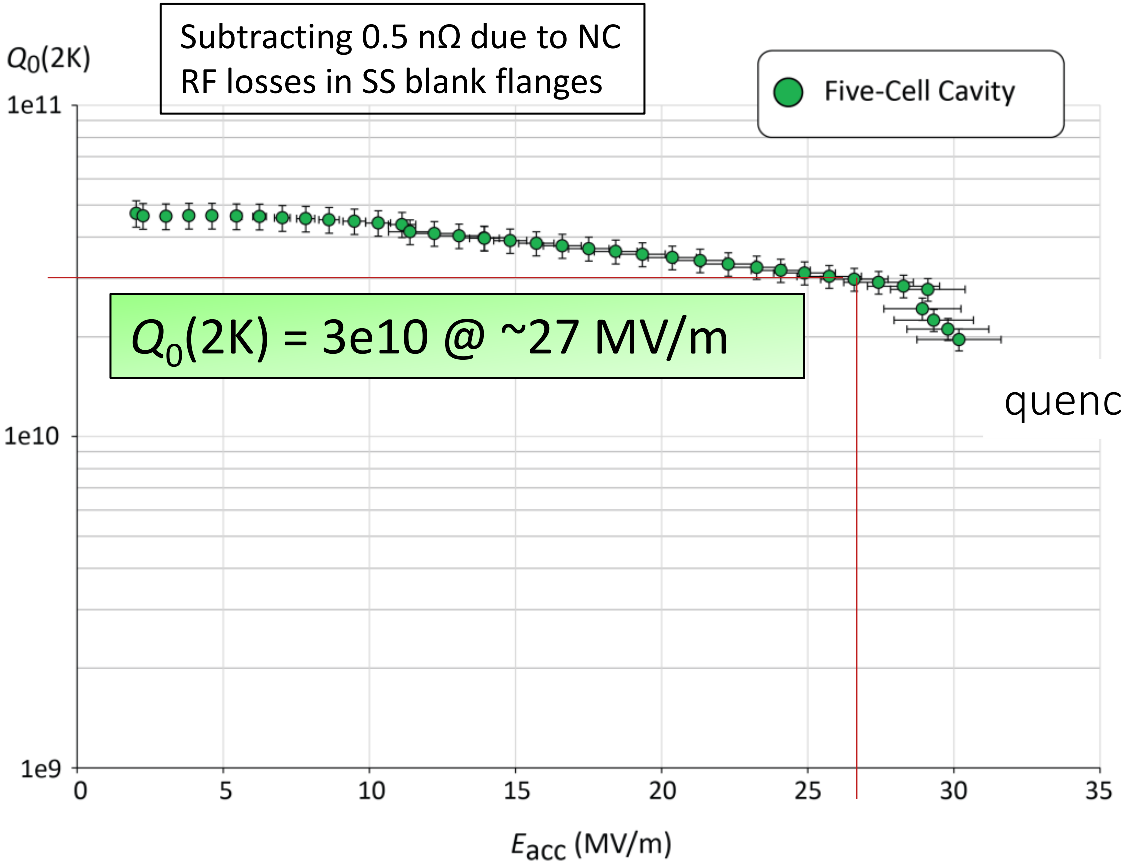
wakefields ($\kappa_{||} \sim 1/ID^3$, $\kappa_{\perp} \sim 1/ID^4$), confined HOMs

field emission/dark current

thermal breakdown

fundamental field flatness ($\delta A_{cell} \sim N^2/k_{cc} * \delta f_{cell,error}$)

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



Subtracting 0.5 nΩ due to NC RF losses in SS blank flanges

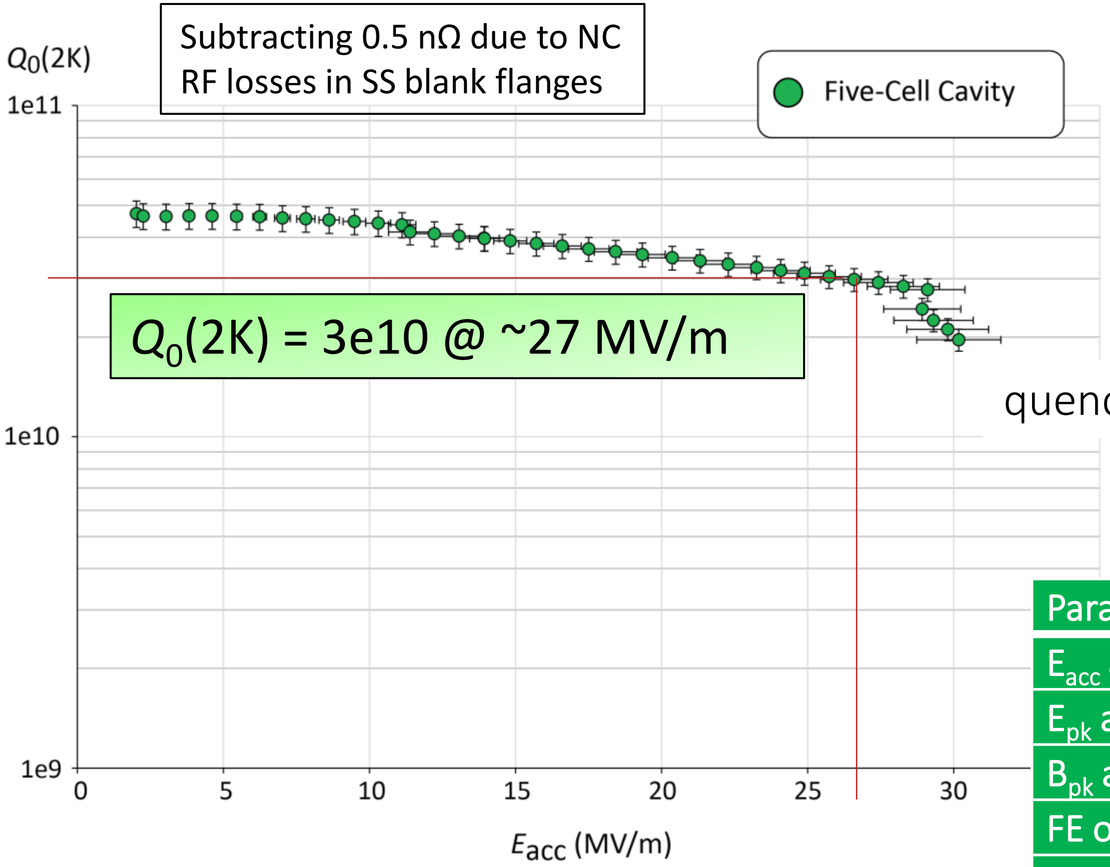
Q_0(2K) = 3e10 @ ~27 MV/m

quench limit ~30 MV/m

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*)



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

quench limit ~30 MV/m

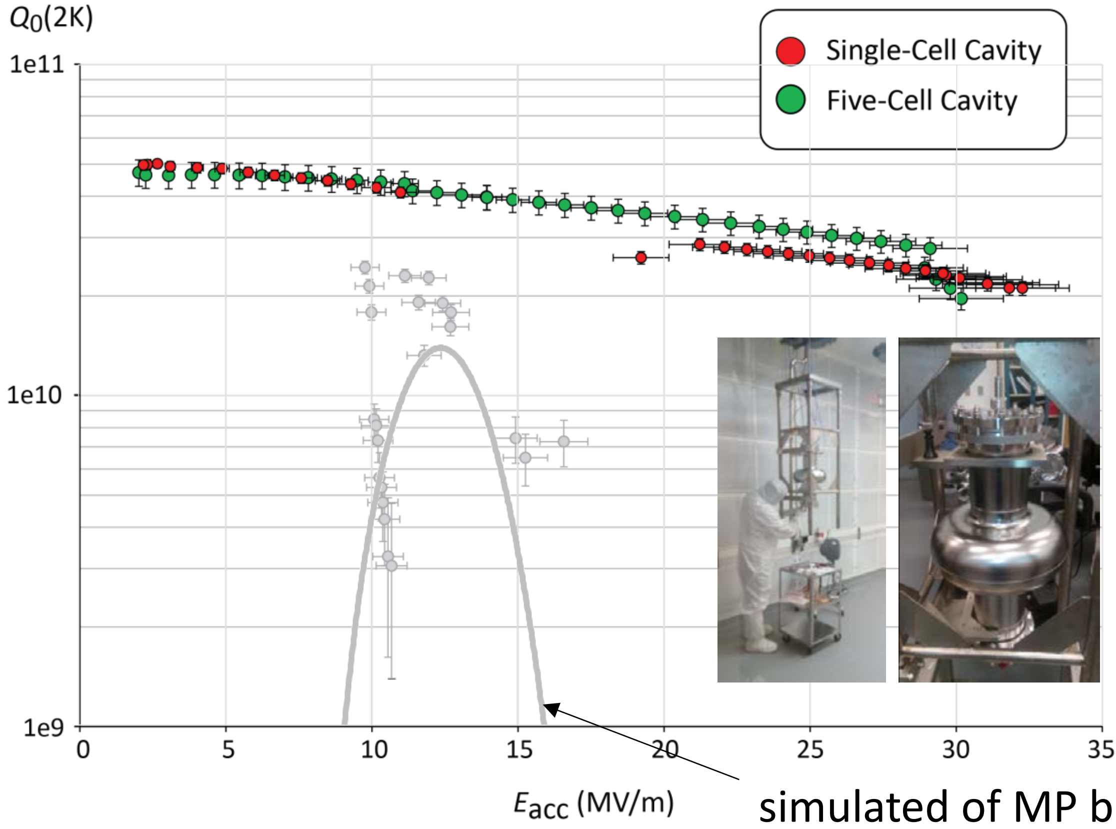
Tabulated Results

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

Jefferson Lab

Latest Vertical Test Results at 2K (1-cell *EIC1*)

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



simulated of MP barrier

Main post-processing steps

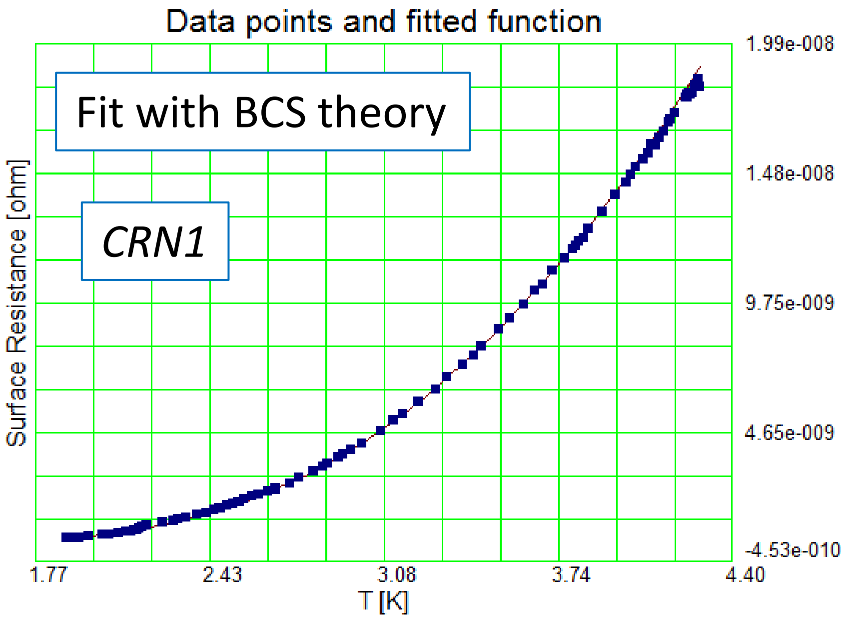
Post-Processing steps	Unit	*CRN1*	*CRN5*
Bulk BCP	µm	160	216
High-Temperature heat treatment	°C, hrs.	800, 3	800, 3
Final EP	µm	30	30
High Pressure Rinse (HPR) cycles		2	4
Low temperature bake-out	°C, hrs.	120, 12	120, 12

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	Hz/(MV/m)^2	-7.1	-1.5

Residual Resistance

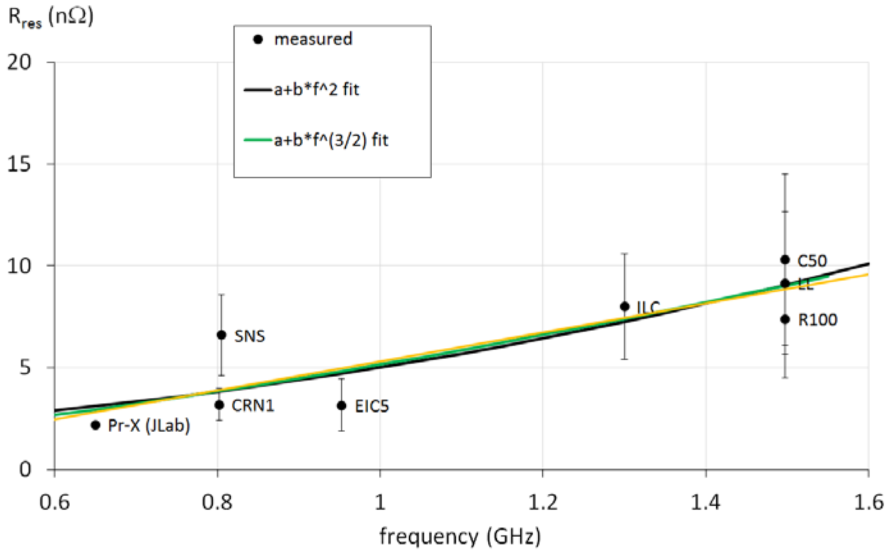
- Material used is OTIC Ningxia high-RRR (250) fine grain Nb
- Residual resistance has been assessed during tests for *CRN1*



$R_{res} = 3.19 \pm 0.79$ nΩ

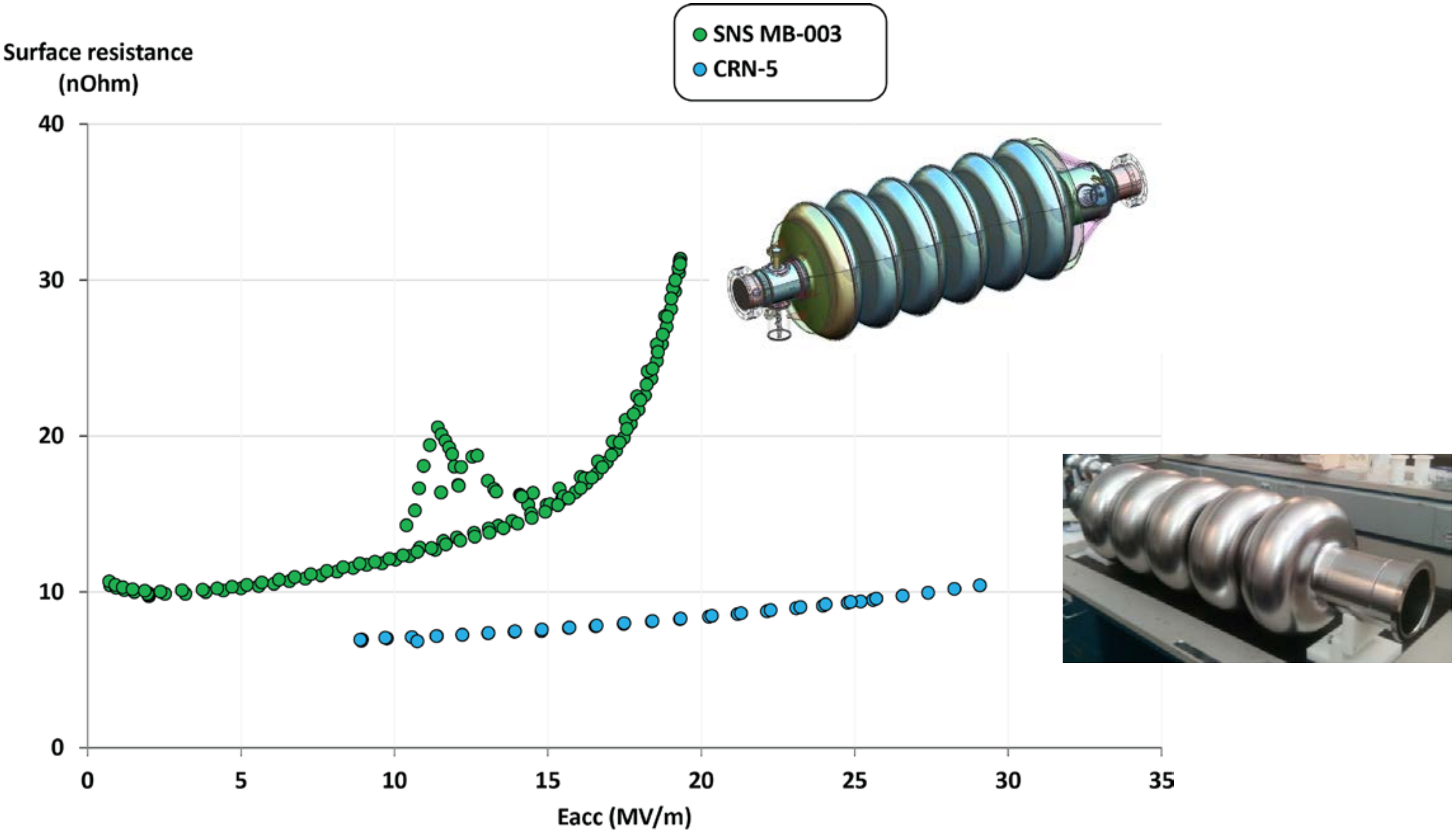
Note: This takes into account 2.49 nΩ due to NC RF losses in SS blank flanges for the single-cell cavity

- How does residual resistance scale with frequency ?



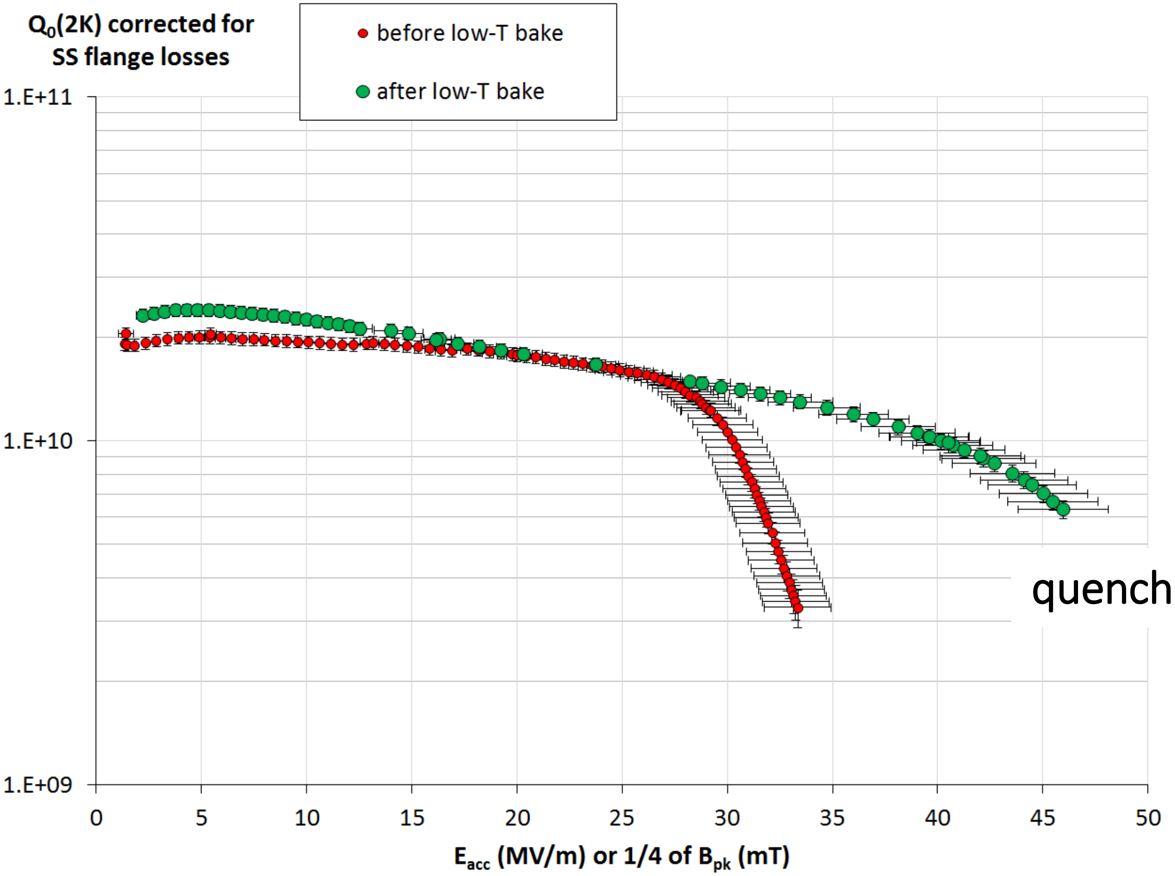
Surface Resistance

- Comparison of ~800 MHz cavities
- *CRN5* versus typical (but recent) medium-beta (MB) proton cavity built for SNS



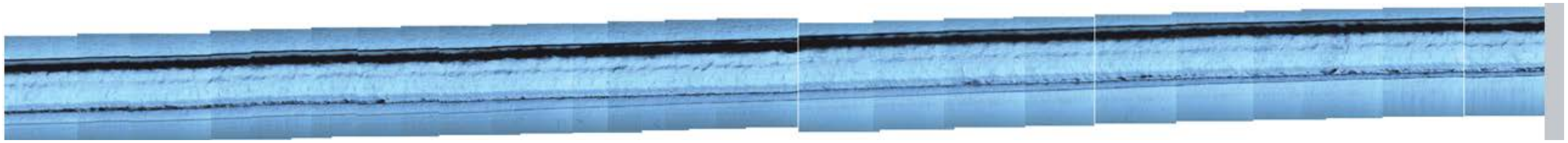
Weld Quality Matters

- RF test of **953 MHz** of 1-cell (*EIC1*) cavity



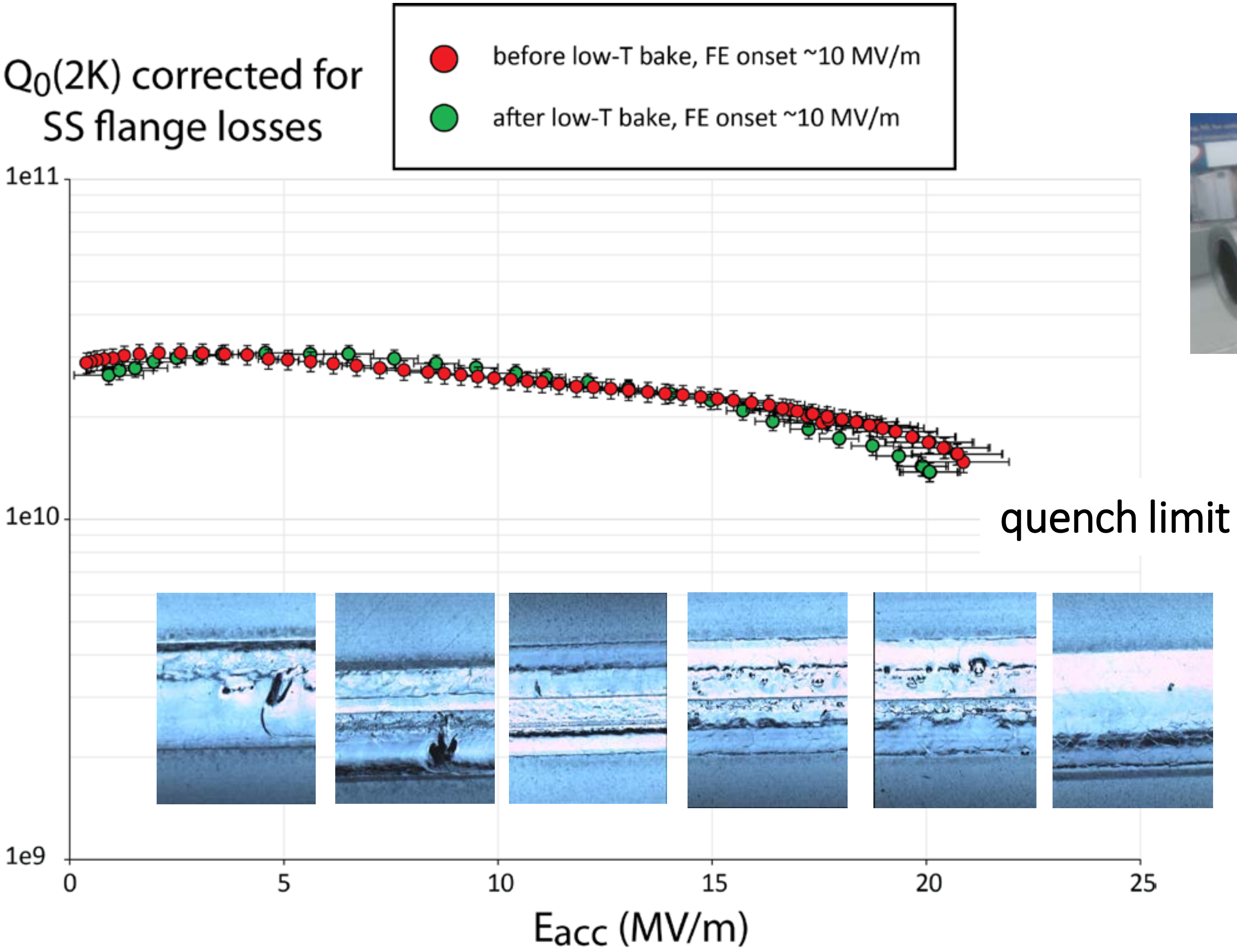
quench limit

EIC1



Weld Quality Matters

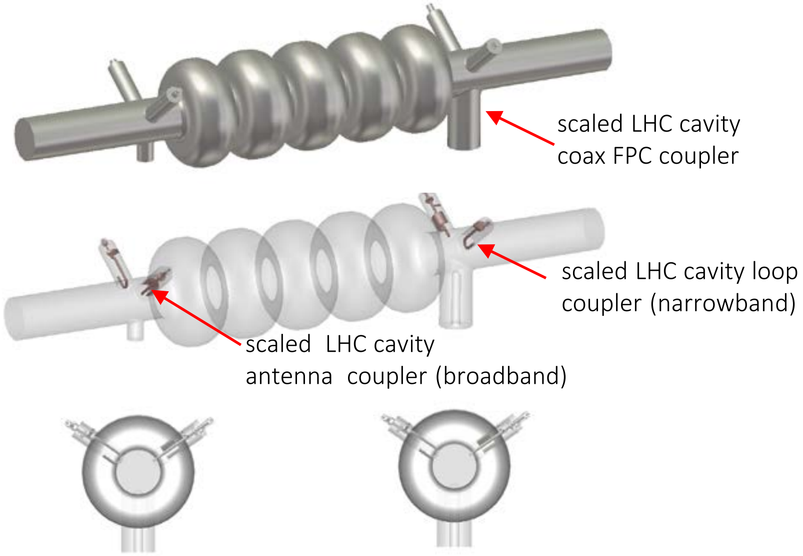
- RF test of **953 MHz** of 5-cell (*EIC5*) cavity

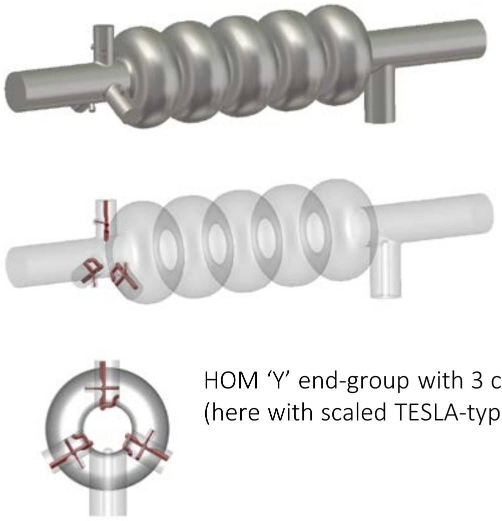


EIC5

HOM Damping Studies

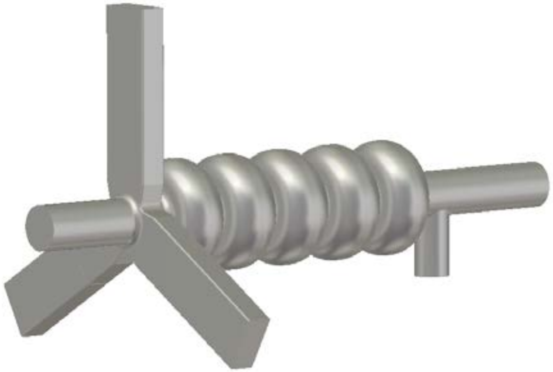
- Preliminary HOM studies carried out incorporating LHC-type HOM couplers (and coaxial input coupler) scaled to adapt to new cavity shape at 802 MHz
  - Broadband damping efficiency was found to be not optimal since also narrowband loop couplers are employed (as required for LHC cavities)
- Also considered 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
  - Monopole power deposition to each coupler quasi identical

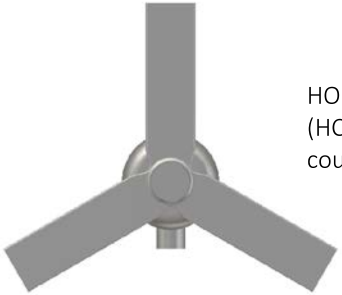



HOM ‘Y’ end-group with 3 coaxial couplers
(here with scaled TESLA-type couplers)

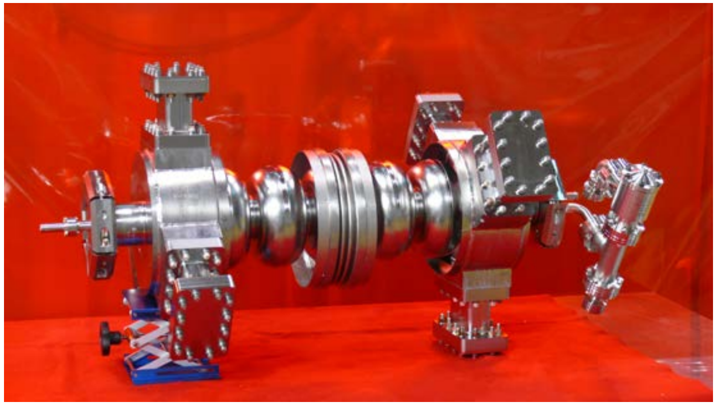
HOM Damping Studies

- 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 could be better captured with coaxial couplers (cf. *Supercond. Sci. Technol. 30 (2017) 063002*)





HOM ‘Y’ High Current (HC) waveguide coupler end-group

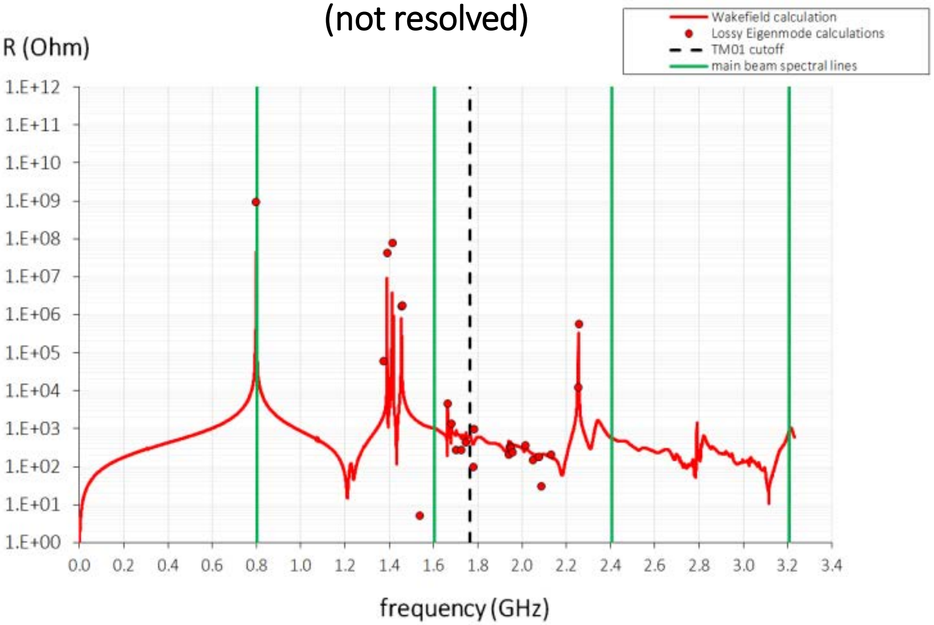


Beam Spectra vs. HOM Frequencies

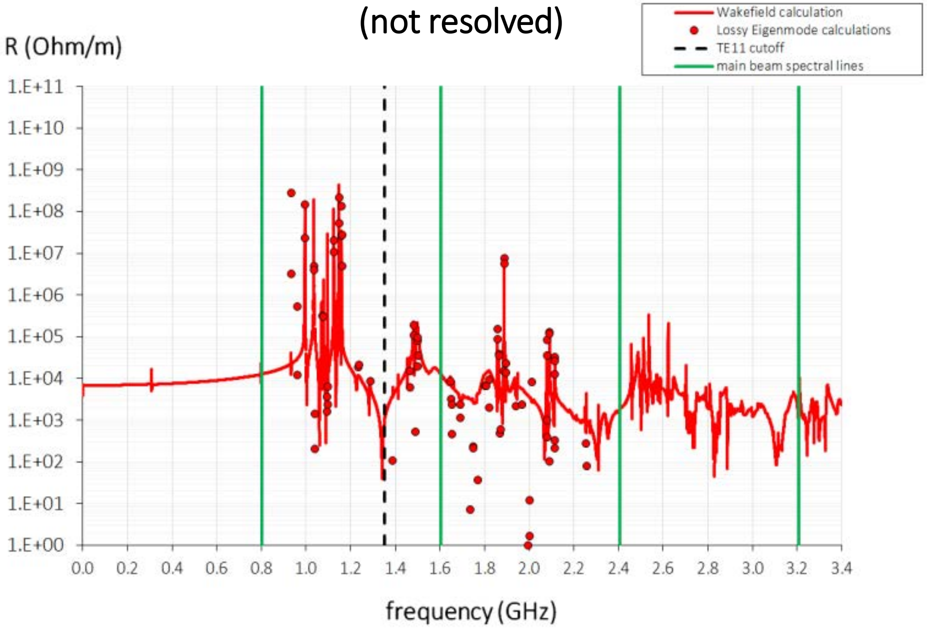
- Cavity design took into account avoiding main 802 MHz beam spectral lines

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

Monopole mode spectrum
(not resolved)



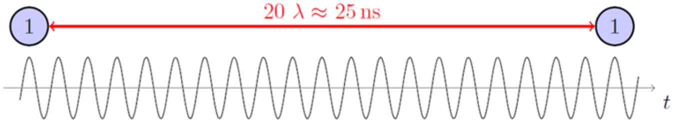
Dipole mode spectrum
(not resolved)

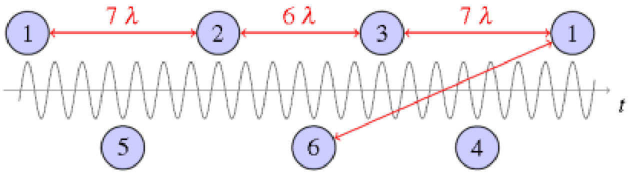


- **Cavity design also avoids HOMs hitting major beam current lines for PERLE recombination pattern (next slides)**

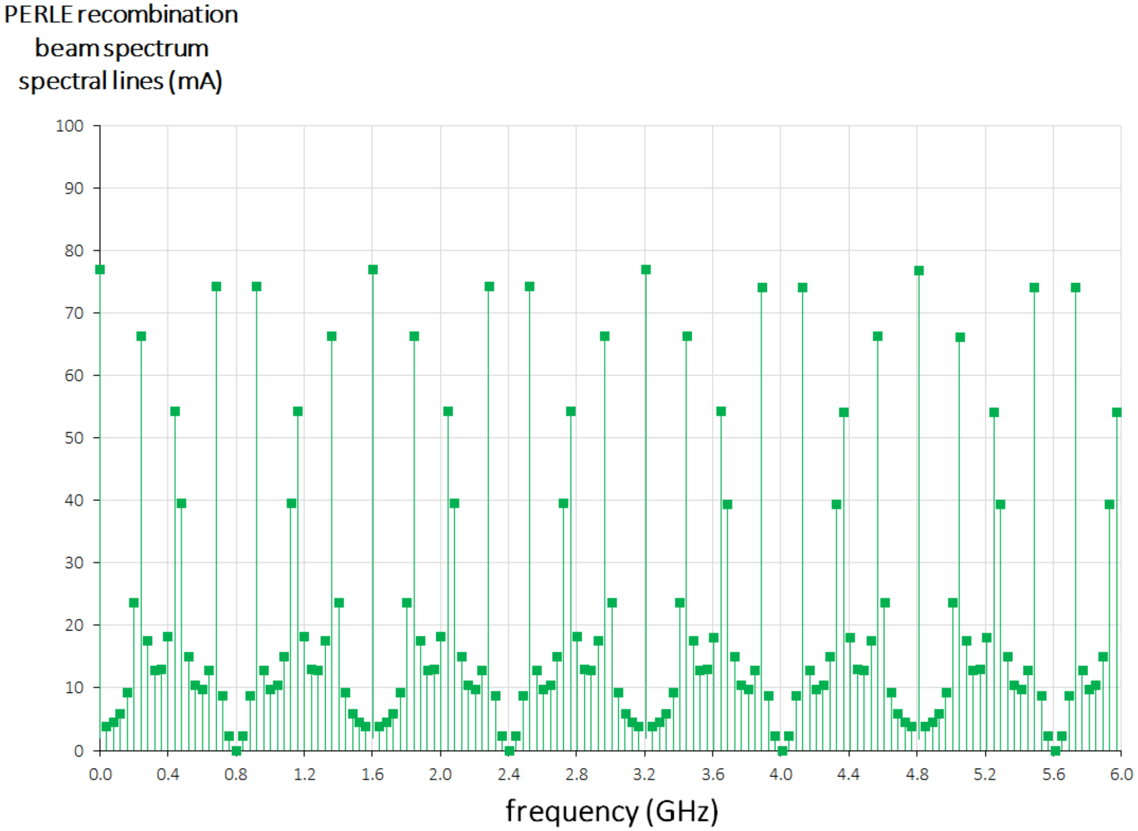
PERLE Beam Spectrum

Case 2: PERLE baseline bunch spectrum for 801.58 cavities:
Bucket spacing 801.58MHz/20 = 40.079 MHz, Q_b = 320 pC





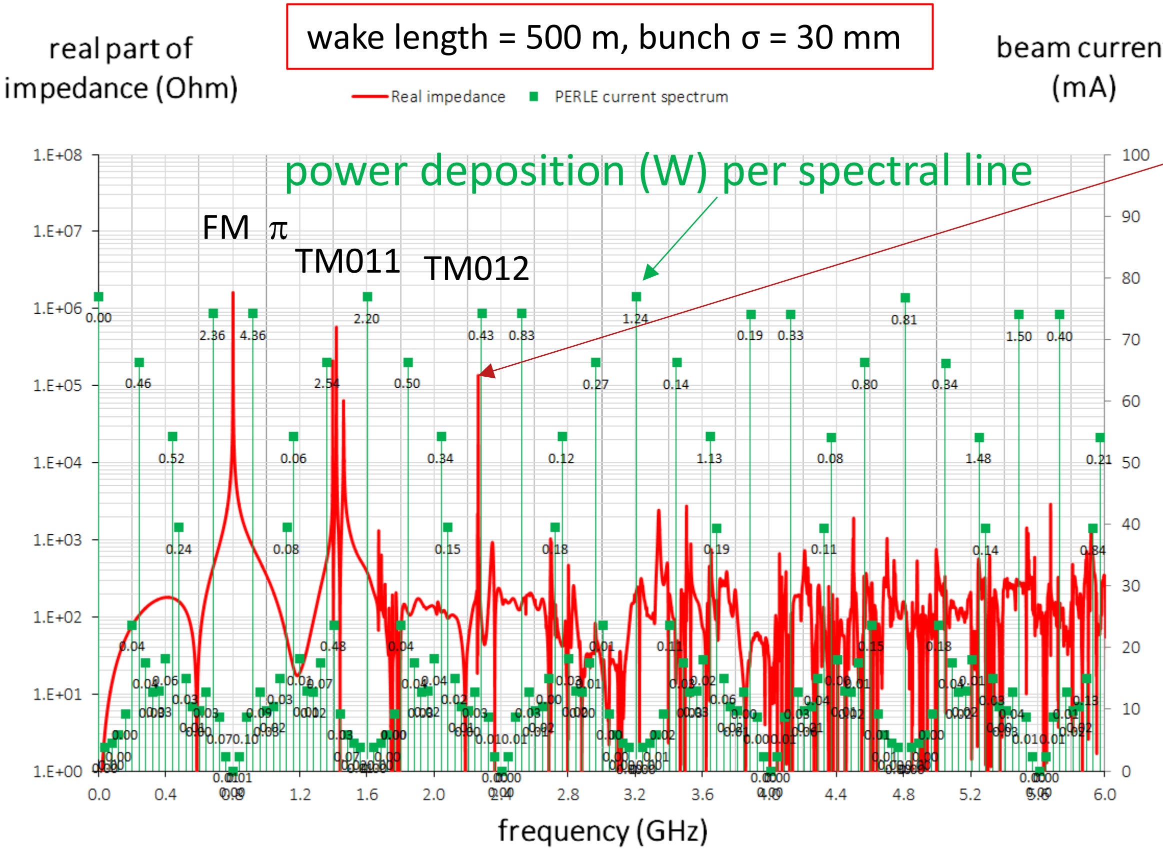
Bunch recombination pattern for PERLE. Bunches at different energies (the turn number is indicated) are separated by nearly constant bunch spacing.



F. Marhauser, PERLE HOM Coupler Meeting, 2019-10-11

HOM Power Example 1

Scaled DESY/TESLA-type couplers



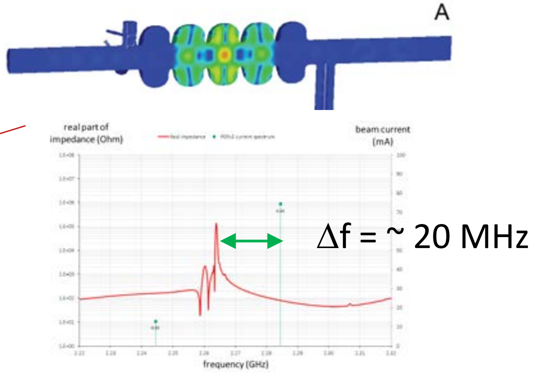
wake length = 500 m, bunch σ = 30 mm

power deposition (W) per spectral line

FM π

TM011

TM012

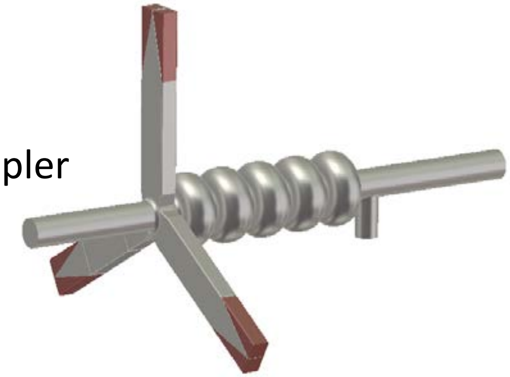


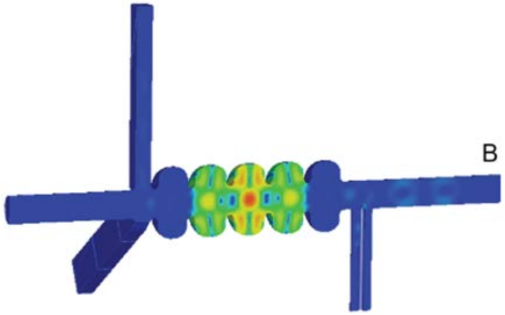
Δf = ~ 20 MHz

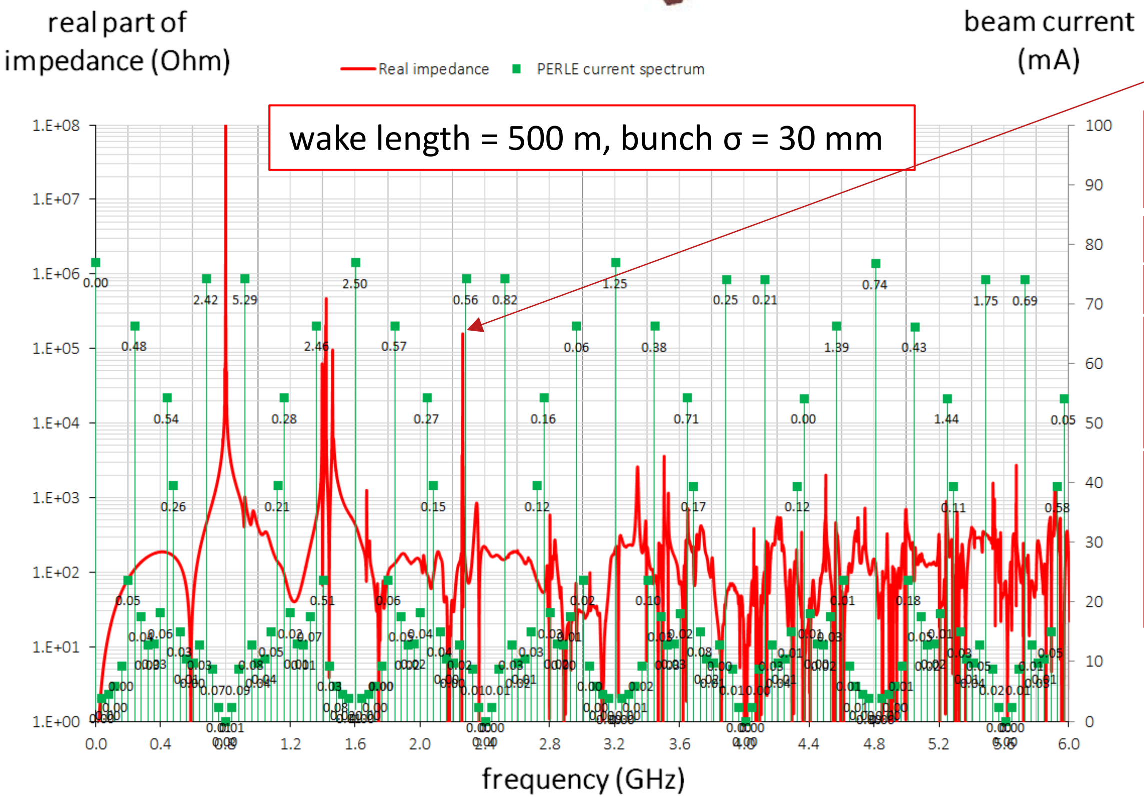
HOM power dissipation (monopoles)	W
Up to 6 GHz	28.6
Up to TM01 cutoff (1.765 GHz) (definitely trapped)	14.2
Up to TM01 cutoff (1.765 GHz) per coupler for symmetric Y-endgroup	4.73

HOM Power Example 2

Scaled HC-type coupler endgroup





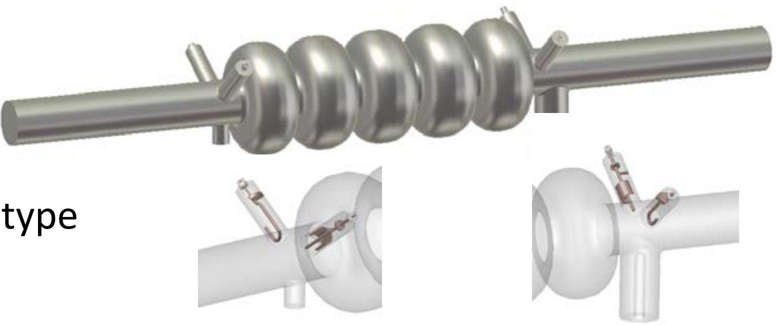


wake length = 500 m, bunch σ = 30 mm

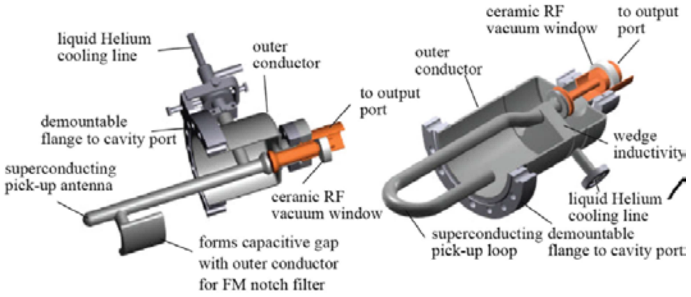
HOM power dissipation (monopoles)	W
Up to 6 GHz	30.5
Up to TM01 cutoff (1.765 GHz)	15.9
From TE10 (898.6 MHz) to TM01 cutoff (definitely trapped)	11.8
From TE10 (898.6 MHz) to TM01 cutoff per coupler for symmetric Y-endgroup	2.95

Similar values as before since well missing major HOM resonances

HOM Power Example 3

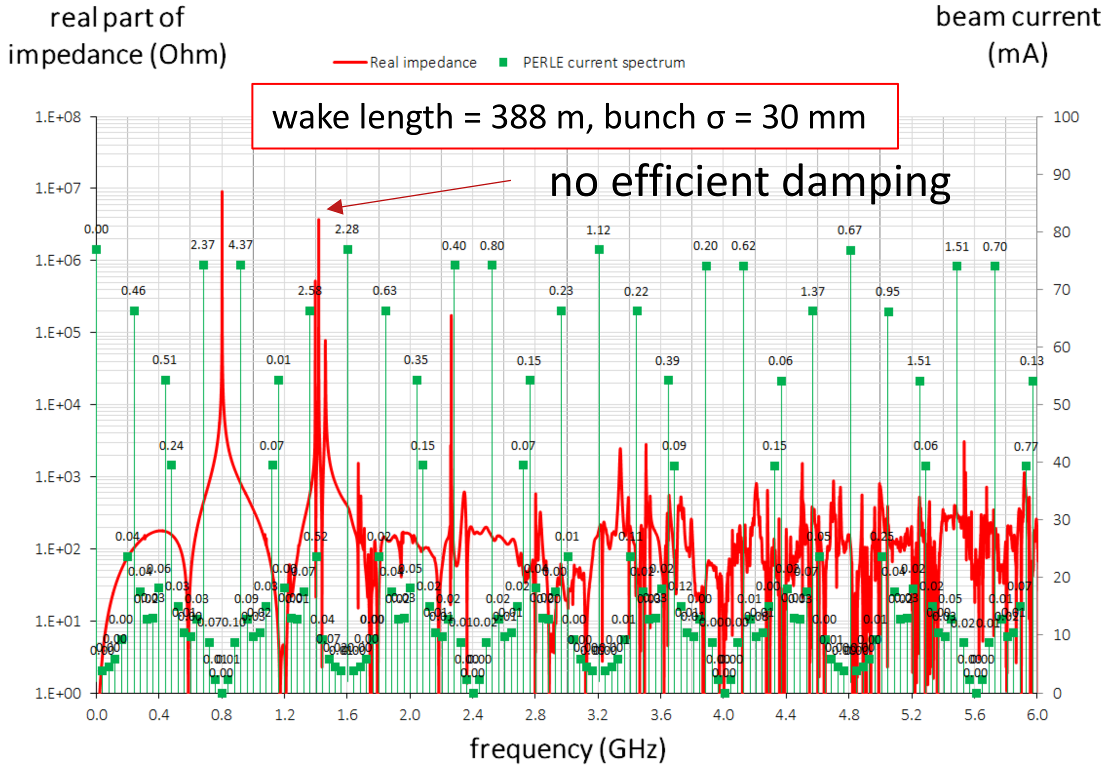


Scaled LHC-type couplers



LHC broadband antenna coupler

LEP-type LHC narrowband loop coupler for dipole modes



wake length = 388 m, bunch σ = 30 mm

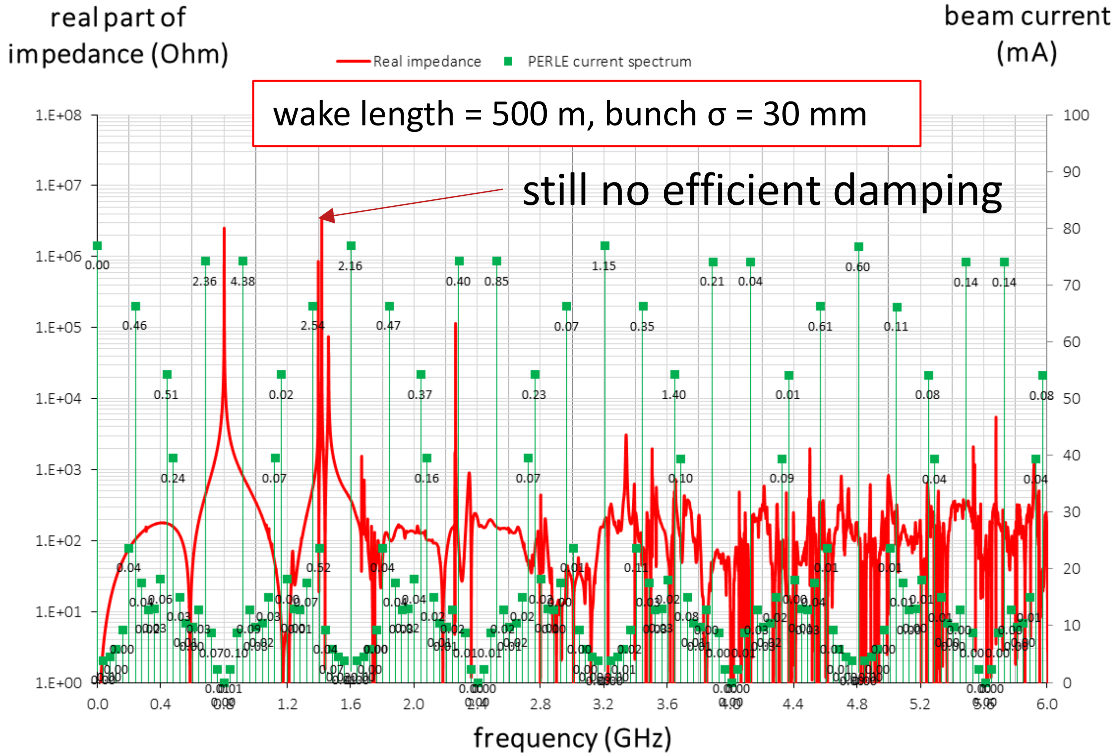
no efficient damping

HOM power dissipation (monopoles)	W
Up to 6 GHz	29.2
Up to TM01 cutoff (1.765 GHz) (definitely trapped)	14.3
Up to TM01 cutoff (1.765 GHz) per coupler for symmetric Y-endgroup	4.76

Similar values as before since well missing major HOM resonances

HOM Power Example 4

HOM-couplers relocated 50 mm closer to cell



wake length = 500 m, bunch σ = 30 mm

still no efficient damping

HOM power dissipation (monopoles)	W
Up to 6 GHz	23.0
Up to TM01 cutoff (1.765 GHz) (definitely trapped)	14.2
Up to TM01 cutoff (1.765 GHz) per coupler for symmetric Y-endgroup	4.71

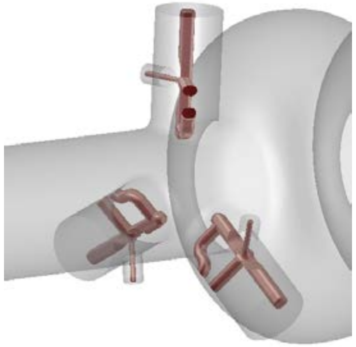
Similar values as before since well missing major HOM resonances

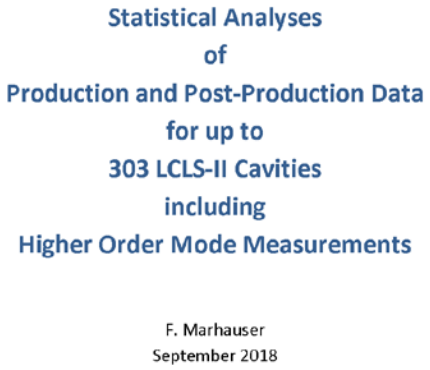
Summary

- Preliminary HOM studies performed for 5-cell cavity only using existing, scaled HOM coupler designs (already beyond funded collaboration goals)
- No specific design optimization was carried out for HOM couplers
- Cavity design well avoids HOMs hitting PERLE beam spectral lines for given recombination pattern
- Anticipated HOM monopole mode power deposition below first beam tube cutoff (covering high impedance, trapped HOMs) is principally the same for all HOM coupler configurations studies, and about 30 W (Q_b = 320 nC) up to 6 GHz
    - Power scaled with I_{inj}^2, so at Q_b = 2*320 NC we have 120 W up to 6 GHz
    - Thermal analyzes needed, i.e. active cooling of coupler needed or not ?
- PERLE project requires dedicated coupler design studies for given cavity
- HOM power beyond first cutoff depends on bunch σ, so far σ = 30 mm only
    - For nominal σ = 2 mm (!), 3D wakefield computations will consume much more CPU time → need to evaluate total power up to ~80 GHz
- Any new HOM coupler version should consider 3D multipacting analyzes
    - Just scaling from existing design can be dangerous due to potential MP (cf. SNS coupler)

Summary (cont'd)

- 'Y' endgroup proposed using 3-couplers (waveguide or coax) to symmetrize fields and better equalize damping for transversely polarized HOMs

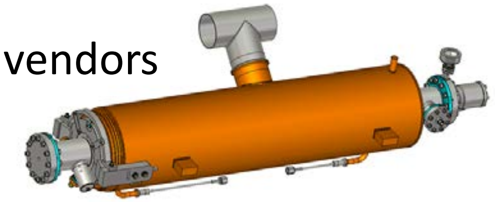


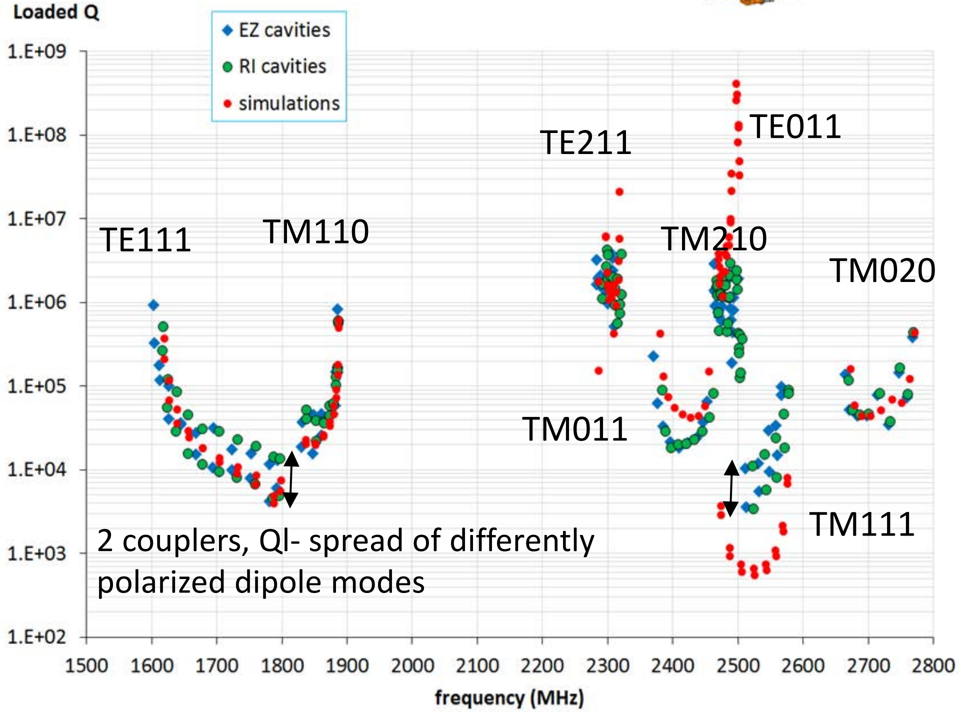


Statistical Analyses
of
Production and Post-Production Data
for up to
303 LCLS-II Cavities
including
Higher Order Mode Measurements

F. Marhauser
September 2018

TESLA cavities produced by vendors





2 couplers, Ql- spread of differently polarized dipole modes

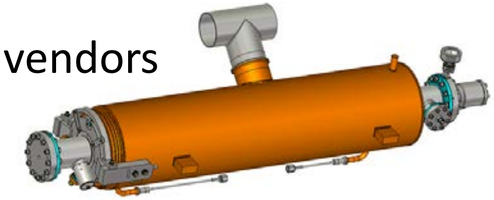
Average loaded Q of cavities up to TM020-like passband

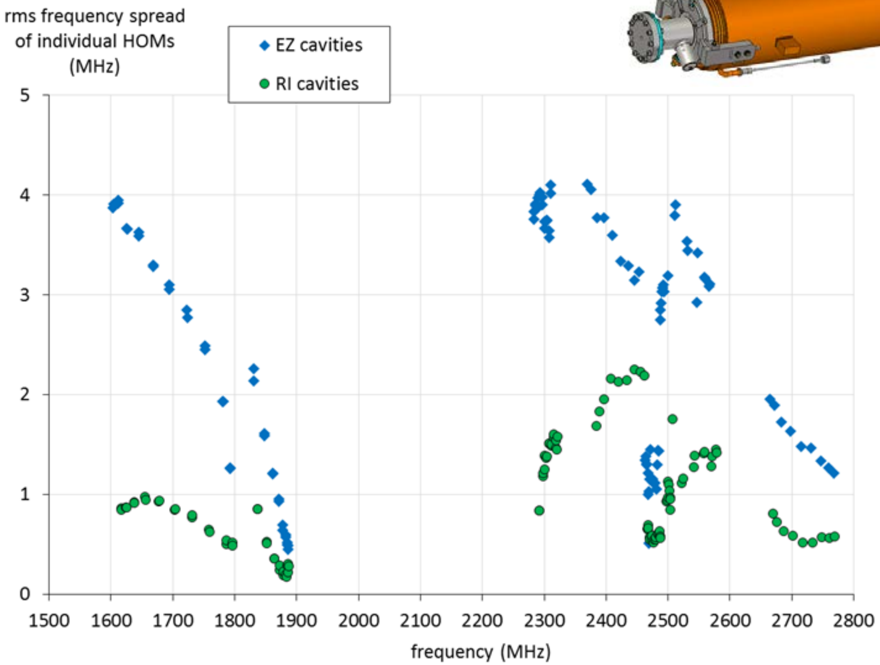
Summary (cont'd)

Comparably, larger cell-to-cell coupling in 802 MHz cavity design should reduce affect of fabrication tolerances on HOM-damping

$$\delta A_{cell} \sim N^2/k_{cc} * \delta f_{cell,error}$$

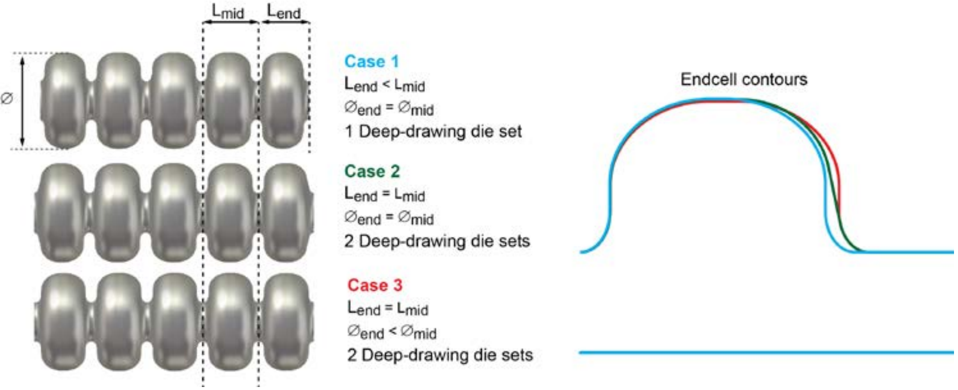
TESLA cavities produced by vendors





Standard deviation of frequency spread as evaluated for each individual HOM in EZ cavities (blue diamonds) and RI cavities (green dots).

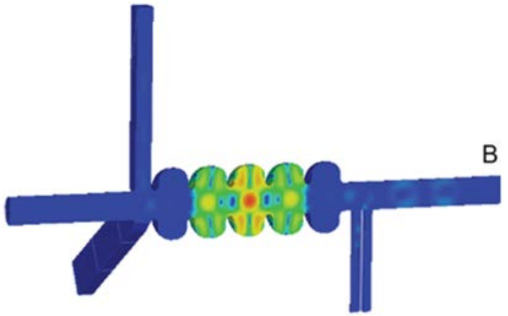
More HOM Studies

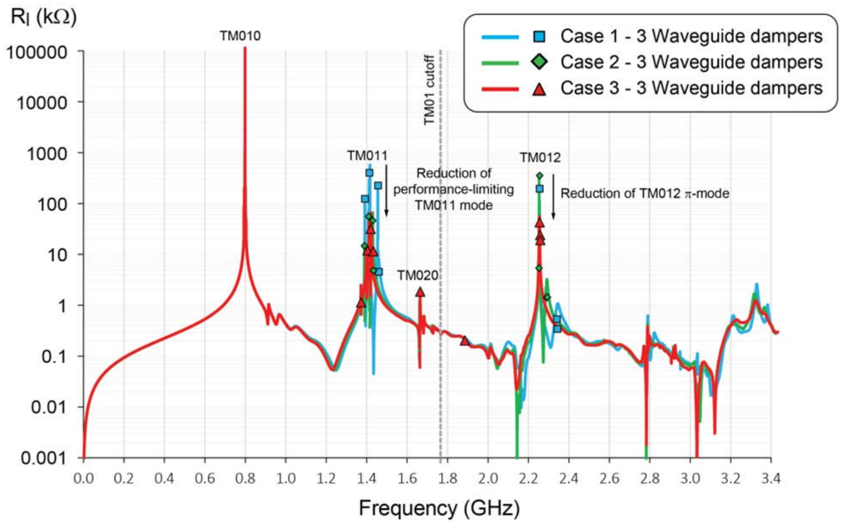


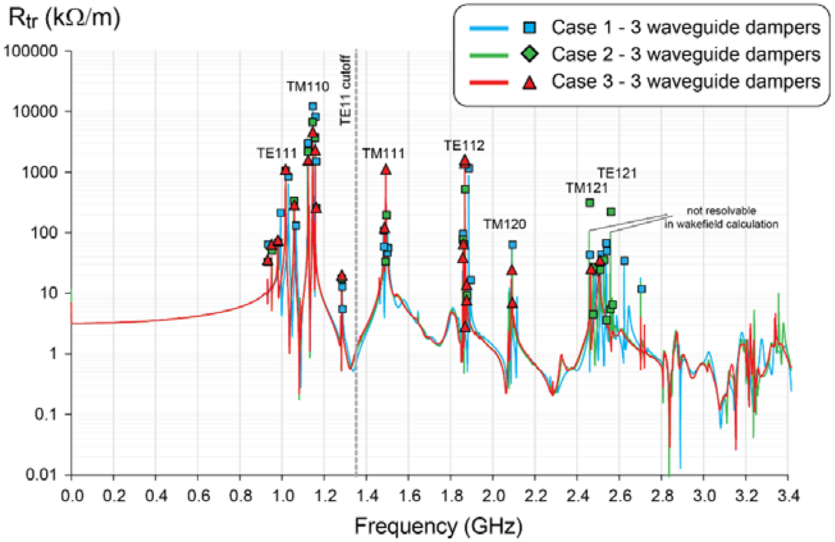
Case 1
$L_{end} < L_{mid}$
$\varnothing_{end} = \varnothing_{mid}$
1 Deep-drawing die set

Case 2
$L_{end} = L_{mid}$
$\varnothing_{end} = \varnothing_{mid}$
2 Deep-drawing die sets

Case 3
$L_{end} = L_{mid}$
$\varnothing_{end} < \varnothing_{mid}$
2 Deep-drawing die sets







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Supercond. Sci. Technol. **30** (2017) 063002 (38pp) https://doi.org/10.1088/1361-6668/aa6b8d

Topical Review

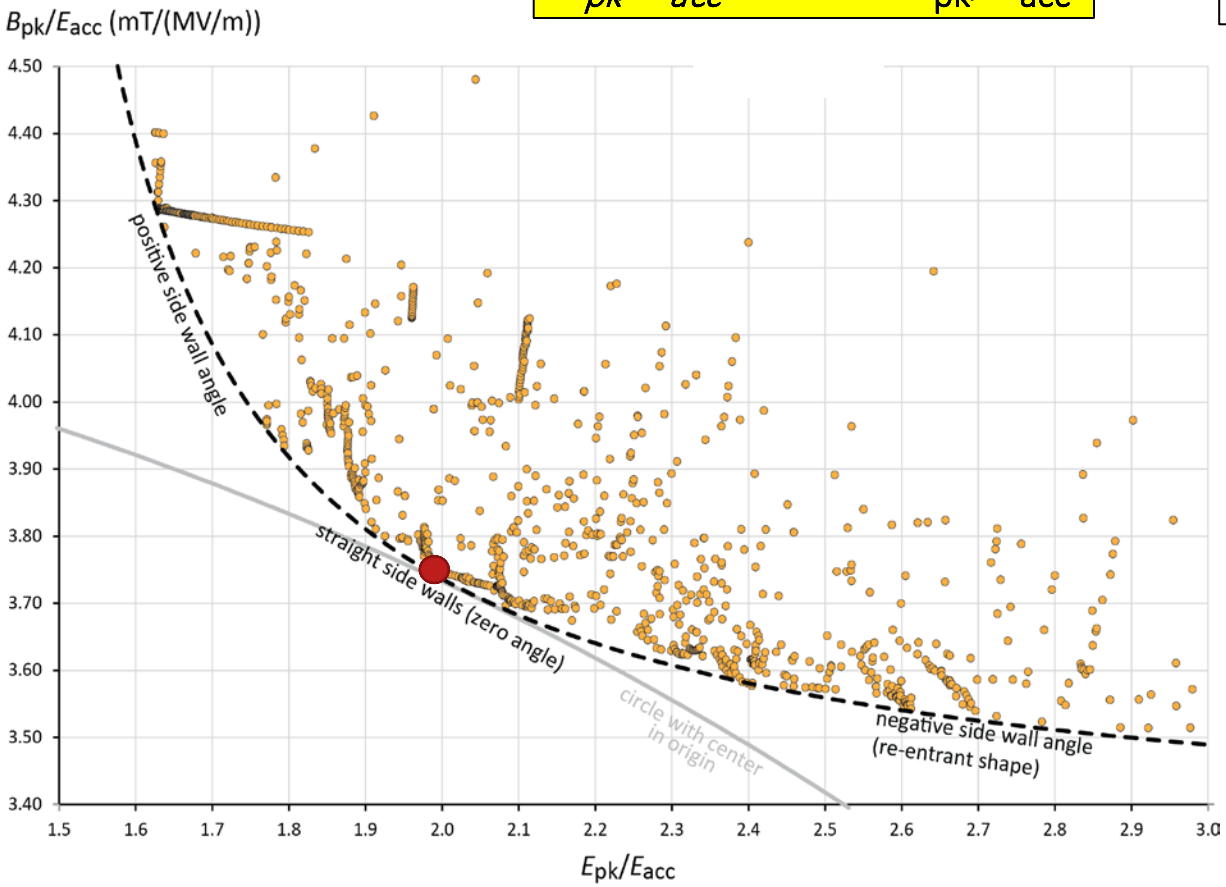
Next generation HOM-damping

Additional Slides

Cavity Design Rationale - When is a Cavity Shape Optimized ?

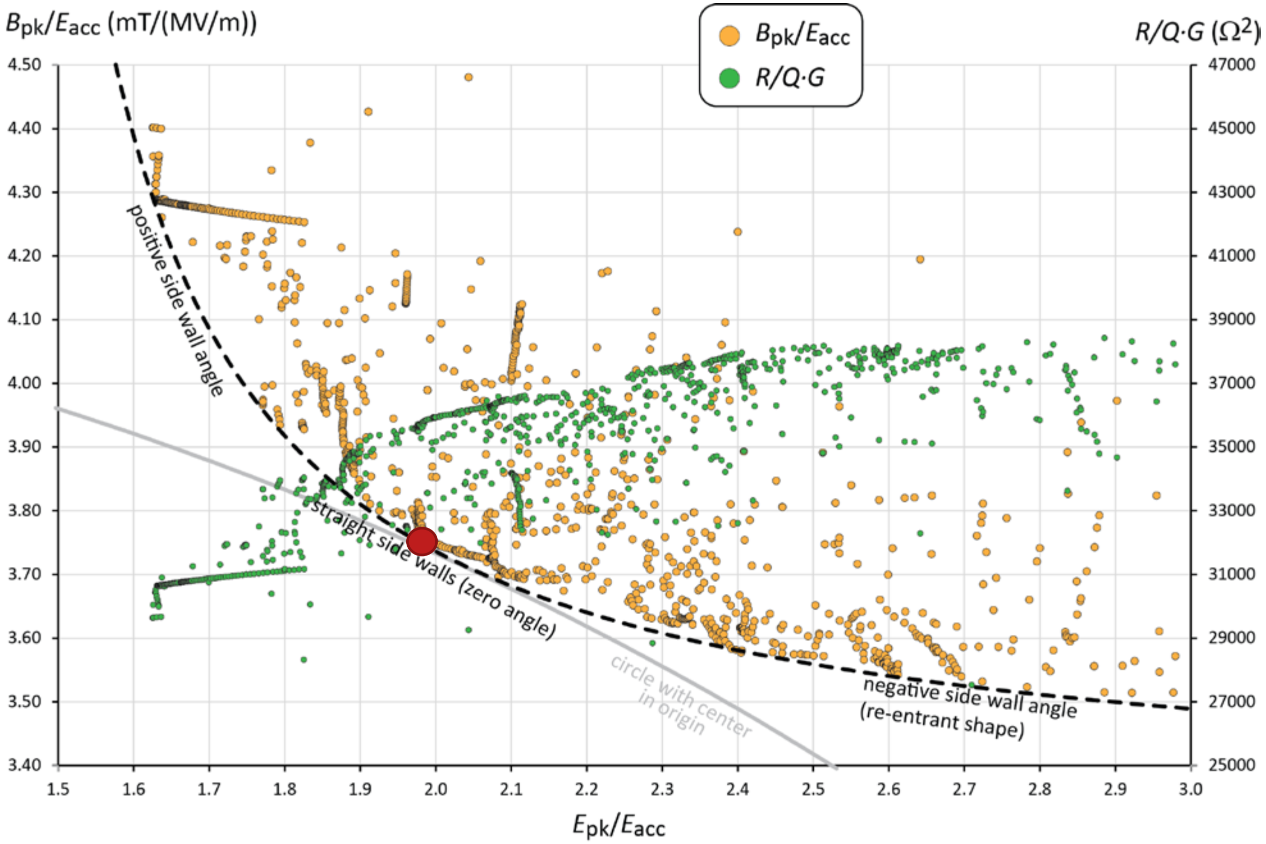
> 1000 half-cells at 802 MHz, **iris ID fix for fair comparison** (example ID= 115 mm)

B_{pk}/E_{acc} versus E_{pk}/E_{acc}



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)

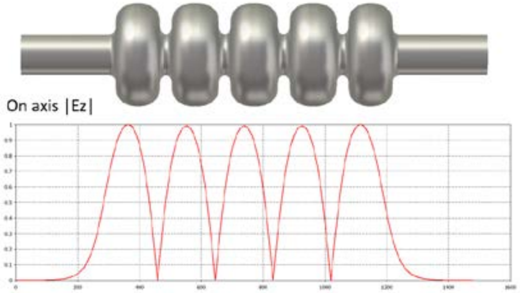


Dynamic RF losses dissipated in Helium bath

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

Cavity Design Studies

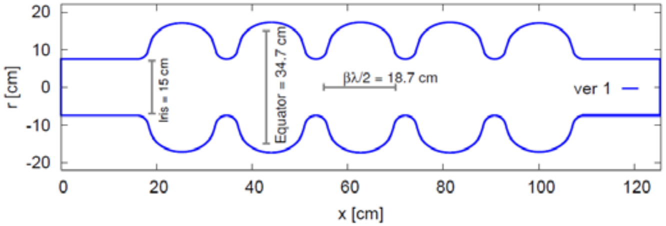
JLab version



- 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%)

CERN version 1

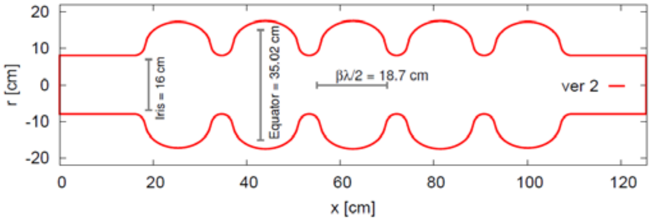
scaled from 704 MHz design
(E. Jensen et al. LINAC 2014)



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	Ω^2	**28788**	**23736**	**22244**
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**
B_{pk}/E_{acc} (mid-cell)	mT/(MV/m)	4.20	**4.77**	**4.92**
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

-18%

-23 %

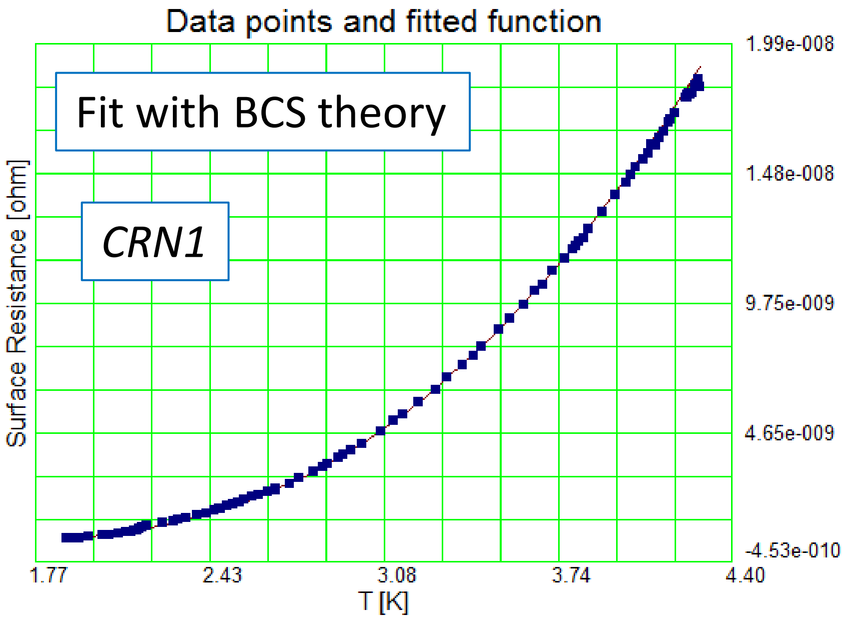
+14%

+6 %

+17 %

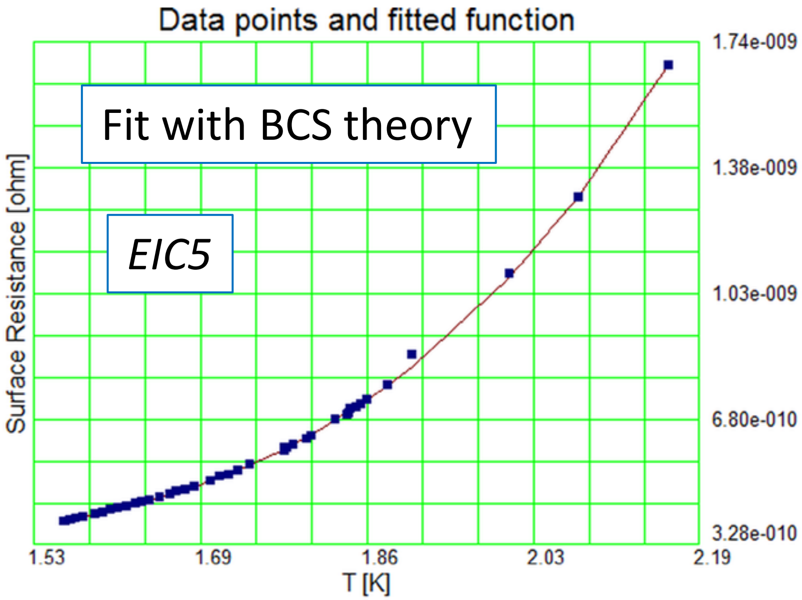
Residual Resistance

- Material used is OTIC Ningxia high-RRR (250) fine grain Nb
- Residual resistance has been assessed during tests for *CRN1 and EIC5*



$R_{res} = 3.19 \pm 0.79$ nΩ

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



$R_{res} = 3.16 \pm 1.28$ nΩ

Note: This takes into account 1.31 nΩ due to NC RF losses in SS blank flanges for the single-cell cavity