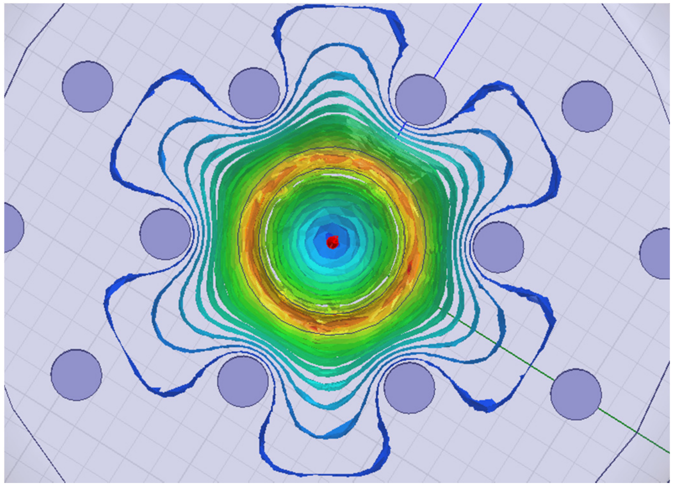
High gradient testing of the five-cell SRF module with a PBG* coupler cell



SRF2015 in Whistler, Sep 16, 2015

Sergey Arsenyev, R.Temkin, Massachusetts Institute of Technology
E.Simakov, T.Tajima, D.Shchegolkov, W.B.Haynes, Los Alamos National Lab
C.Boulware, A.Rogacki, T.Grimm, Niowave Inc.

Work was supported by the U.S. Department of Energy (DOE) Office of Science Early Career Research Program and a DOE SBIR grant.

* PBG = Photonic Band Gap

Outline

- Motivation
- How a Photonic Band Gap (PBG) structure works
- Design
- Fabrication & tuning
- First high gradient test and a low Q problem
- Improved RF joint
- Future plans

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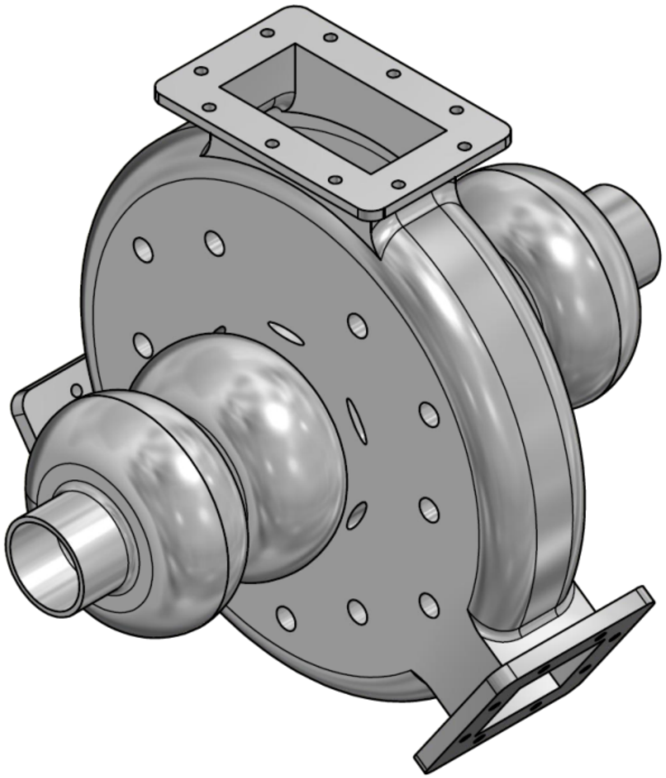
Motivation

- **Beam break-up** (BBU) limits max current.
- BBU is caused by parasitic **higher order modes** (HOMs).
- PBG accelerating module provides **HOM suppression**.
- The structure comes with a bonus of increased **real estate gradient.**
- The structure is proposed as a harmonic cavity for **eRHIC** at BNL.



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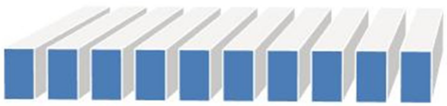
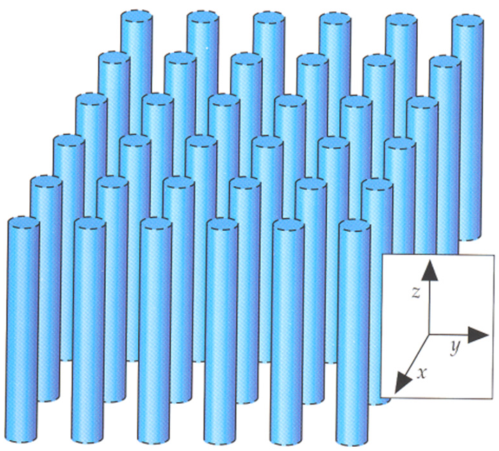
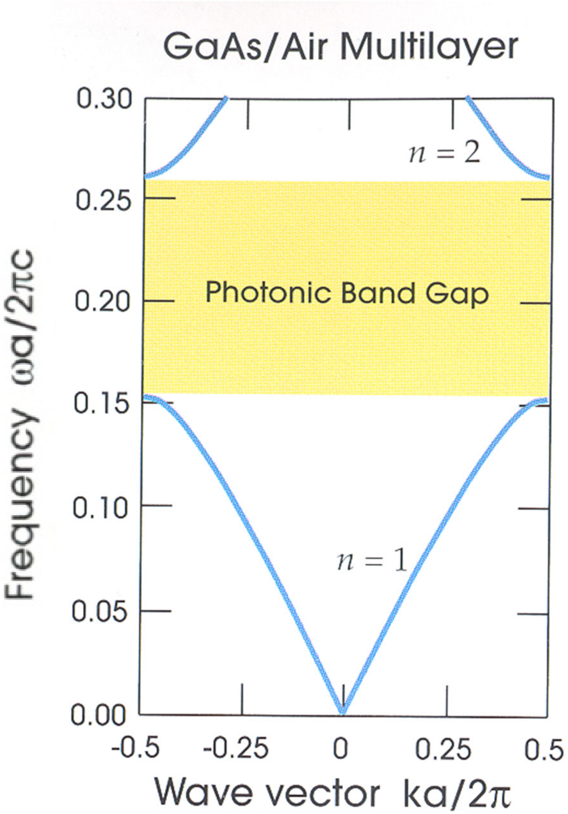
How PBG works



1D Bragg reflector

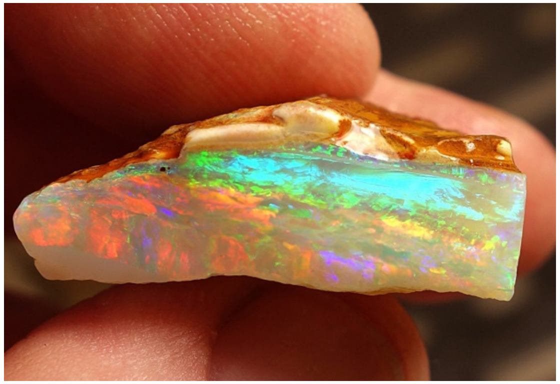


Photonic Band Gap lattice

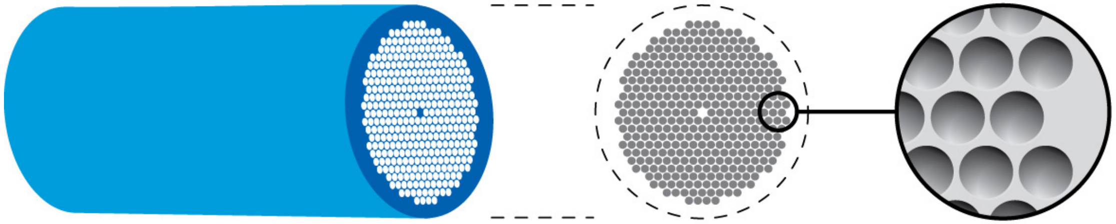


Dispersion diagram of a PBG structure

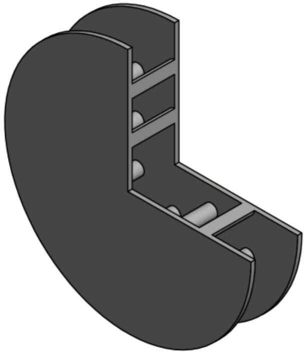
Examples of PBG structures

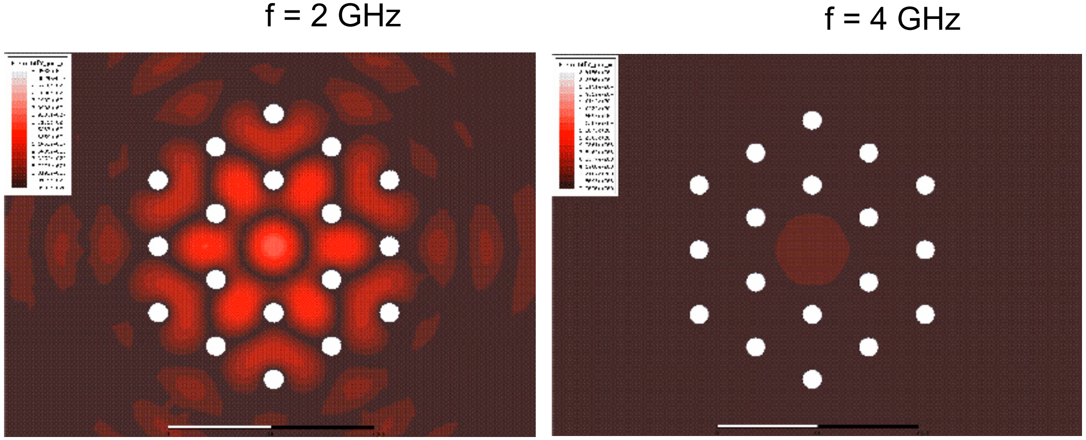


Opal is a natural photonic crystal



Photonic Crystal Fibers used in optics





RF cavity formed by 2 layers of photonic crystal

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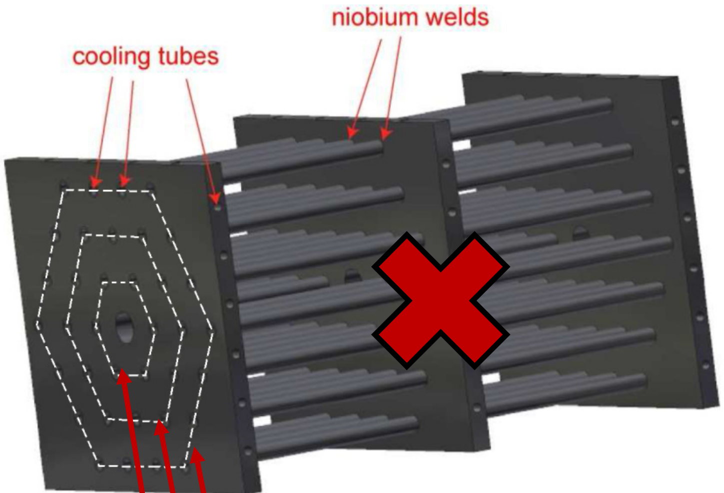
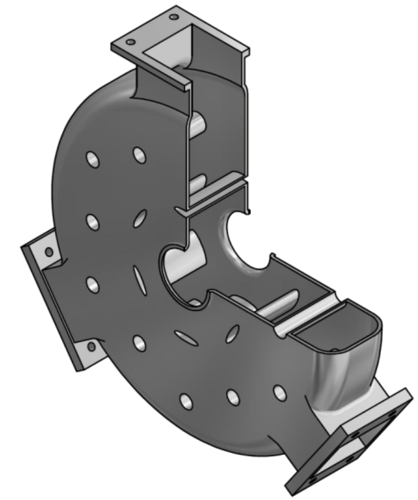
Evolution of the design



Layers or rods

Initial idea:
700 MHz open PBG structure with many layers of photonic crystal

Conventional "low-loss shape" cell

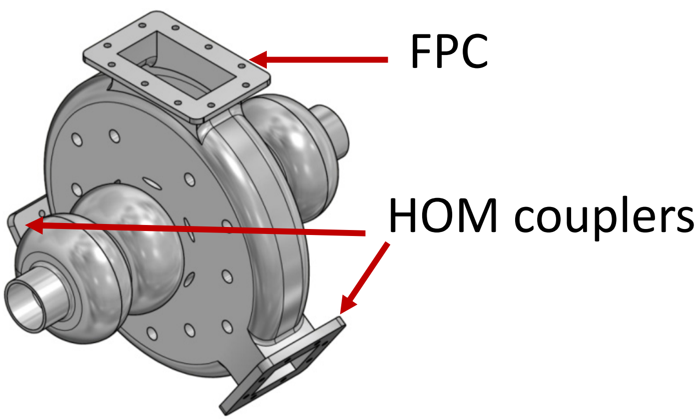


Photonic Band Gap cell

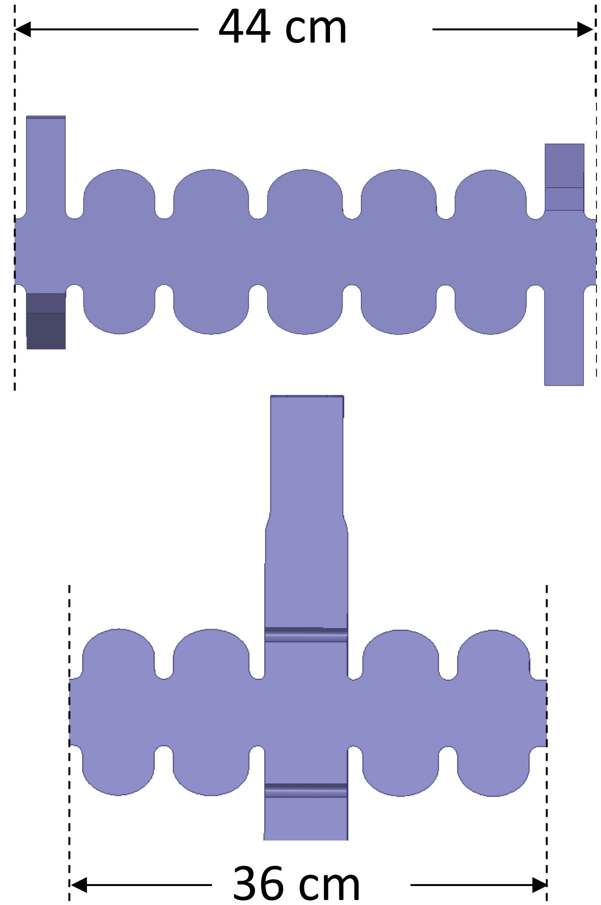
PBG becomes especially attractive for higher frequency linacs, when it is reasonably small.

Evolution of the design

JLab 750 MHz 5 cell module
(photo by R. Rimmer *et al*)

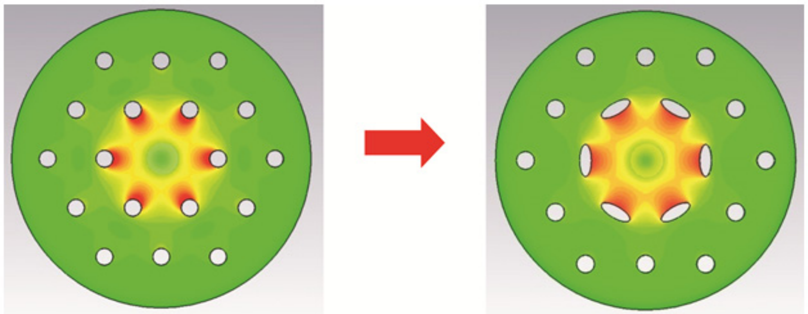


2.1 GHz PBG module

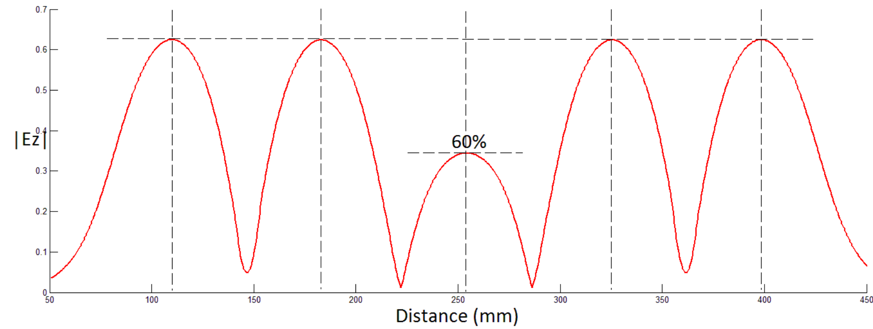


Shorter length means increased "real estate" gradient

Uneven gradient profile

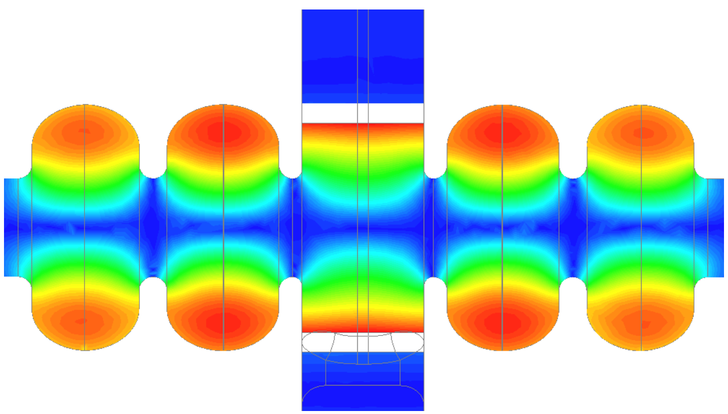


Shape of the PBG rods is optimized to minimize surface magnetic field



Gradient profile along central axis

Uneven gradient shape provides equal B_{peak} on the surface of every cell by sacrificing accelerating voltage.



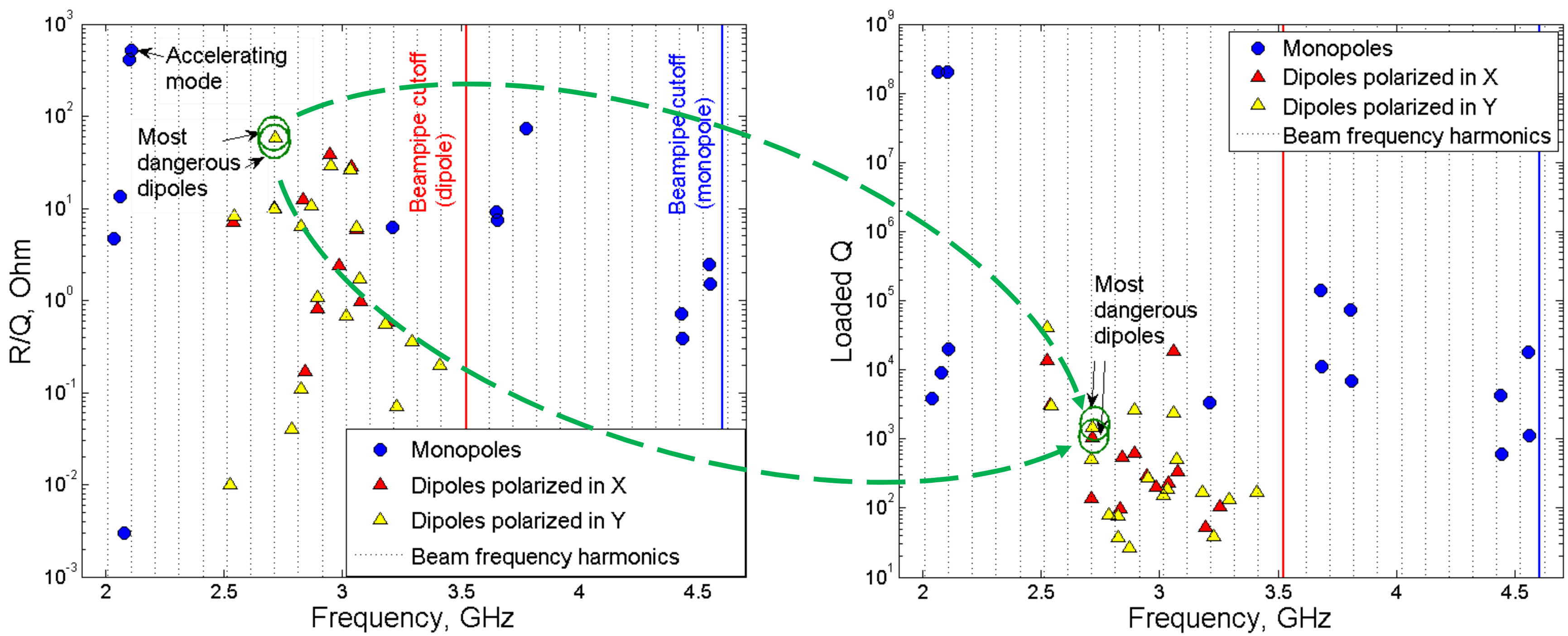
Magnetic field magnitude

Accelerating properties

	5 elliptical cells	PBG module	
Frequency	2.1 GHz	2.1 GHz	
Shunt impedance R/Q	525 Ω	515 Ω	-2%
Geometry constant G	276 Ω	265 Ω	-4%
Peak surface electric field ratio E_{peak}/E_{acc}	2.50	2.65	+6%
Peak surface electric field ratio B_{peak}/E_{acc}	4.27 $\frac{\text{mT}}{\text{MV}/m}$	4.48 $\frac{\text{mT}}{\text{MV}/m}$	+5%
Length of cavity + endgroups	44 cm	36 cm	-19%

The PBG design is very similar to 5 elliptical cells, but about 20% shorter

HOM damping: theory



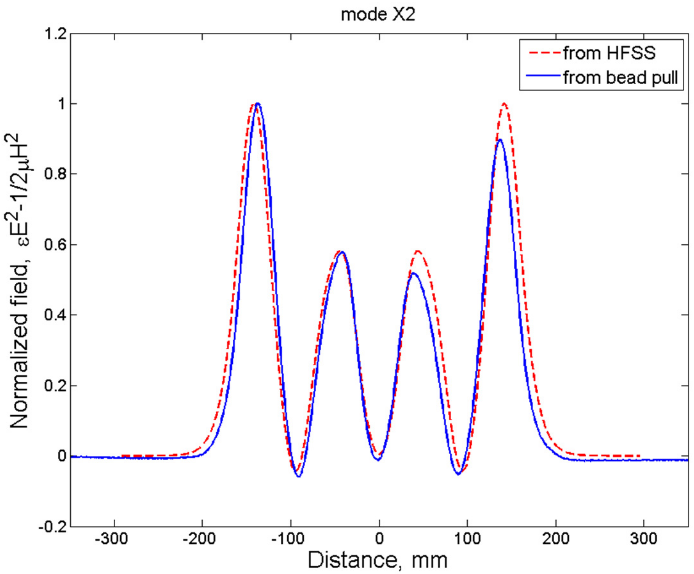
Simulated shunt impedances and loaded Q factors for monopole and dipole modes

Loaded Qs are in the range $10^2 - 10^4$, with most dangerous HOMs damped to Q in the order of $\mathbf{10^3}$.

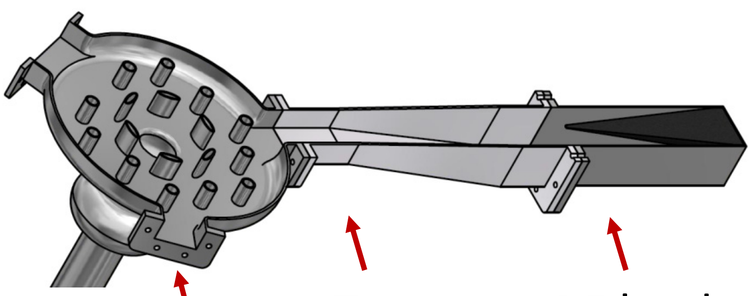
HOM damping: measurements

Dipole	HFSS f/ measured f, GHz	HFSS G/ measured G, Ohm	HFSS Q_{ext}/ measured Q_{ext}
X1	2.541 / 2.546	199 / 215	3.1×10^3 / 2.7×10^3
X2	2.715 / 2.705	232 / 220	1.0×10^3 / 9.4×10^2
X3	2.945-2.962 / 2.972	295 / 298	2.9×10^2 / 1.4×10^2
Y1	2.543 / 2.545	207 / 223	3.0×10^3 / 3.0×10^3
Y2	2.703 / 2.708	209 / 232	2.0×10^3 / 1.3×10^3
Y3	2.950-2.957 / 2.969	295 / 293	2.8×10^2 / 1.1×10^2

Comparison between simulation and experiment for some HOMs



Example of an HOM beadpull



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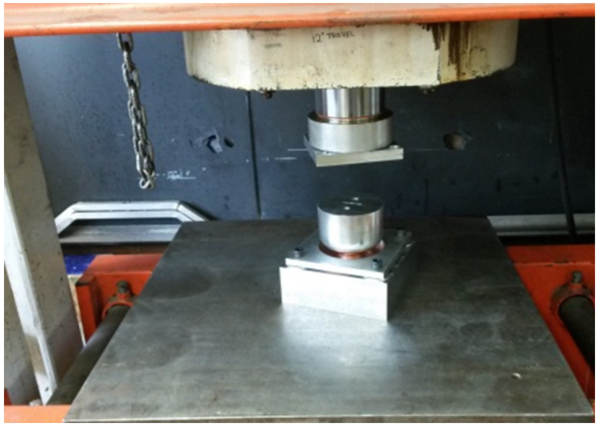
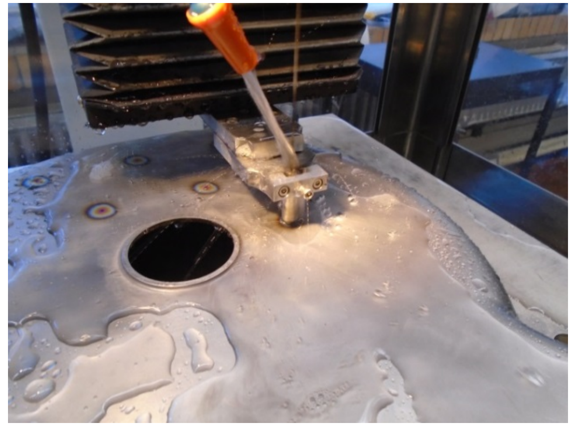
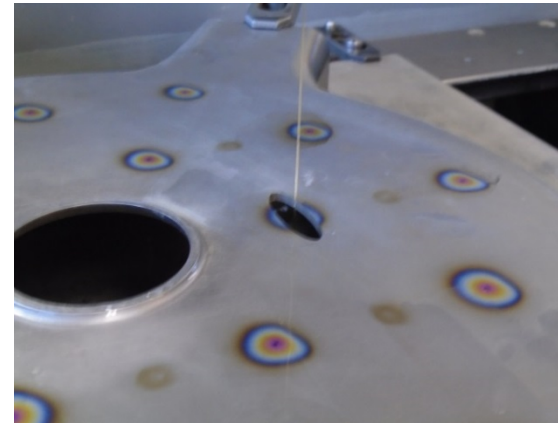
Cavity fabrication





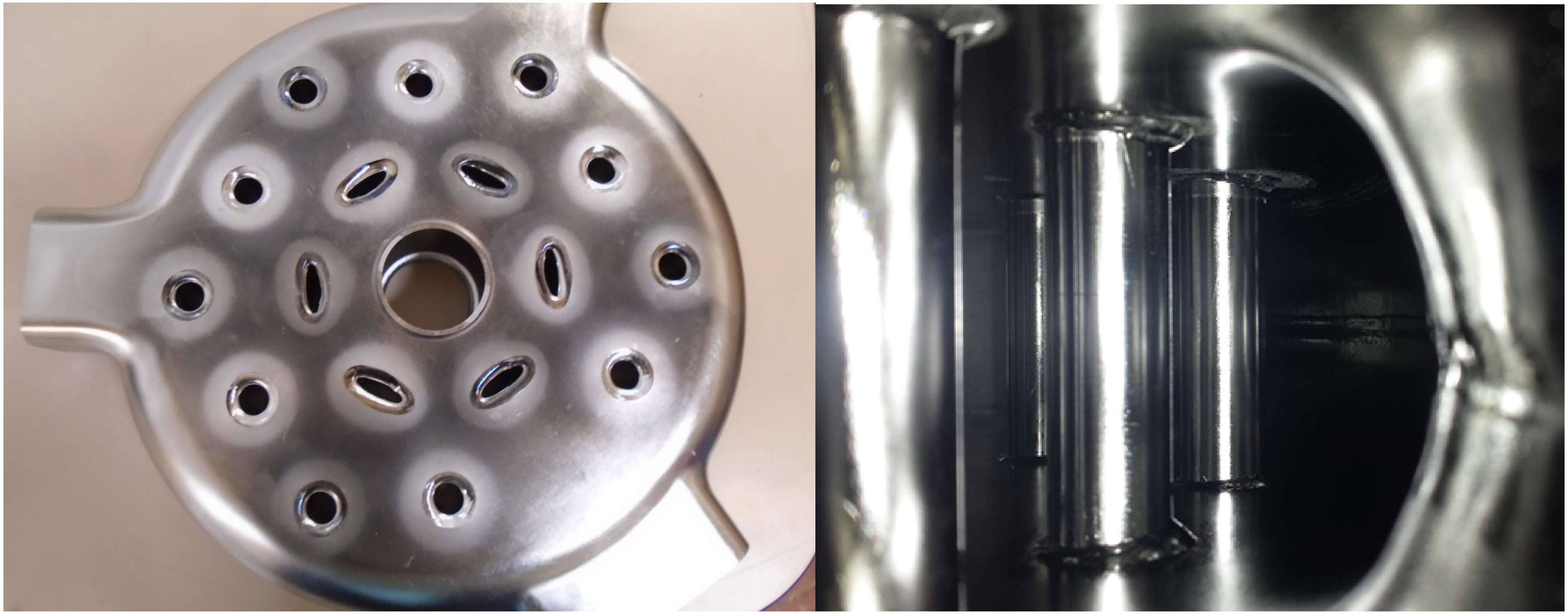


Forming press is used for making halves of each cell

Holes are made in the PBG cell to fit in the rods

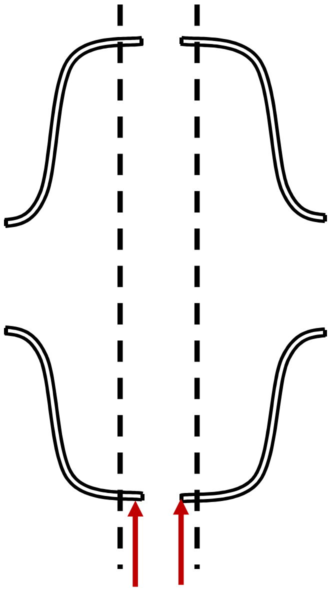
PBG rods are made separately and then fitted in the cell

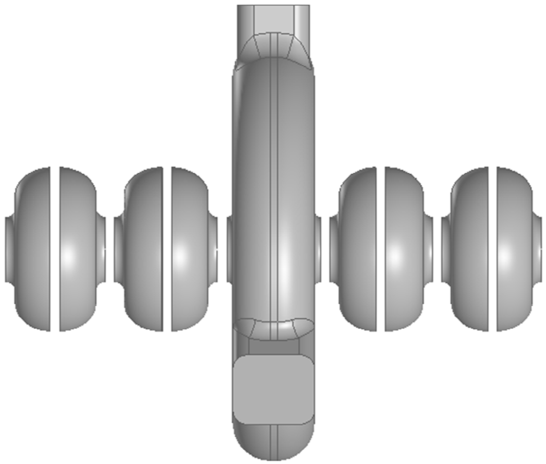
Cavity fabrication



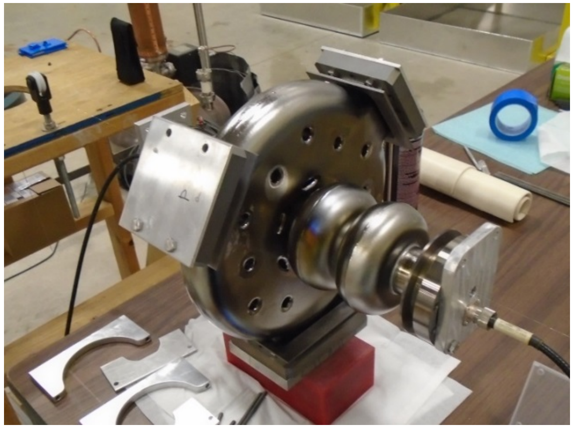
PBG rods electron-beam welded into the central cell.

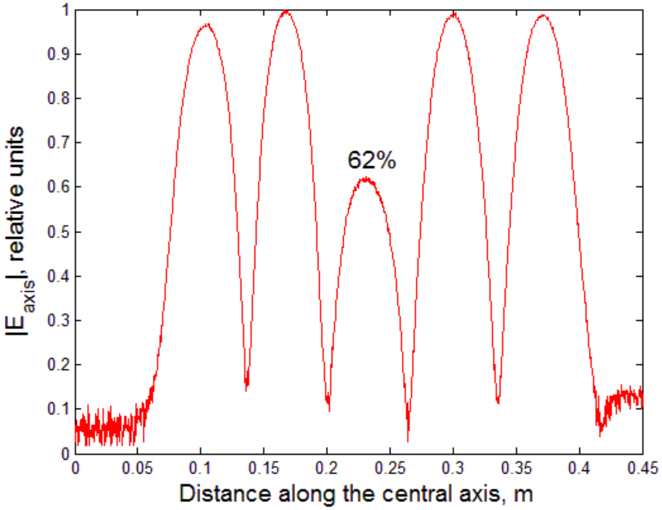
Cavity tuning





The 5 cells before welding





Gradient profile after tuning

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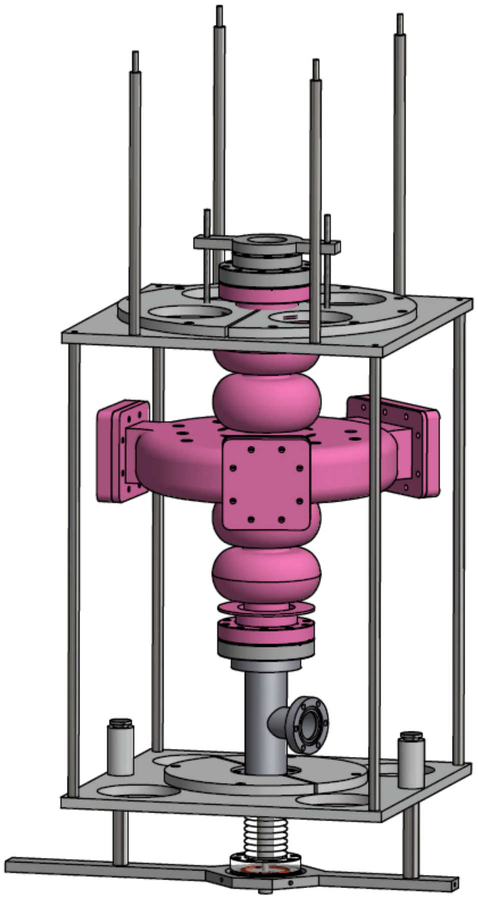
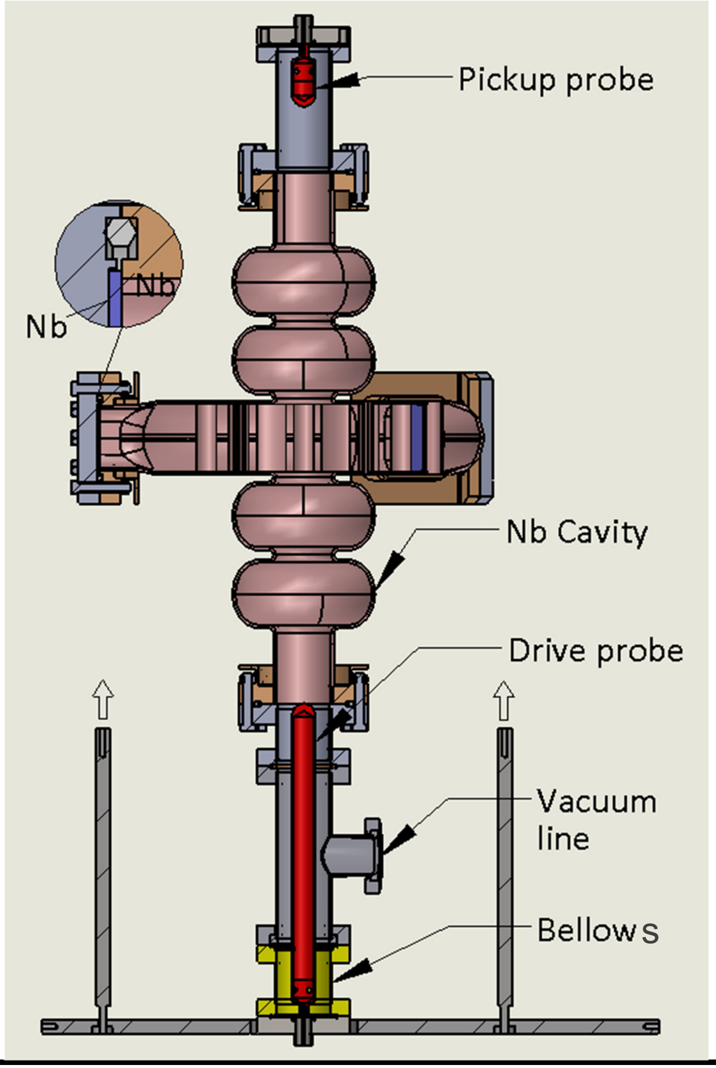
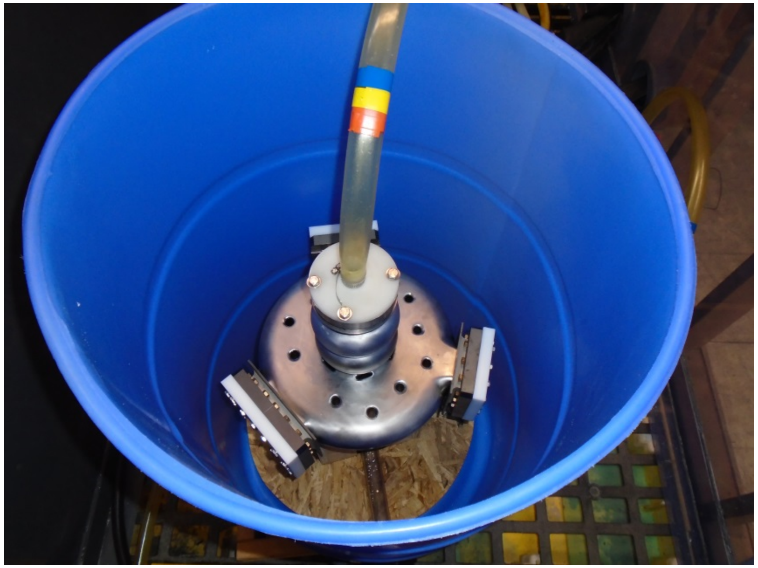
High gradient test assembly



Test stand assembly at LANL



Preparation

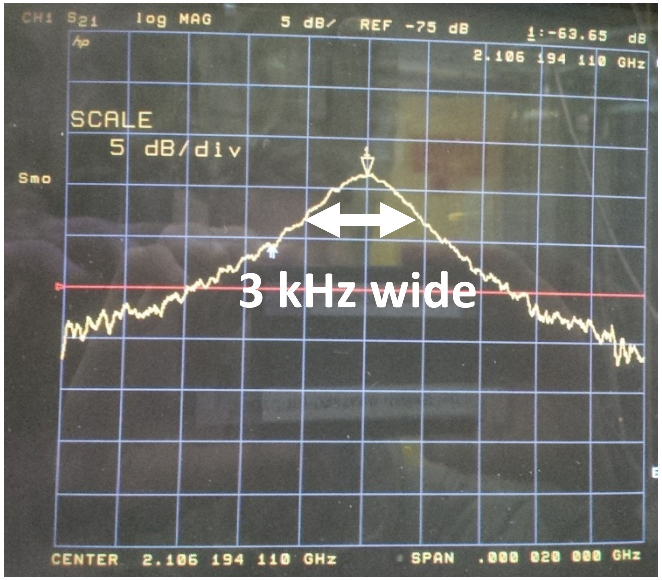


Cavity is BCP-etched at Niowave Inc.

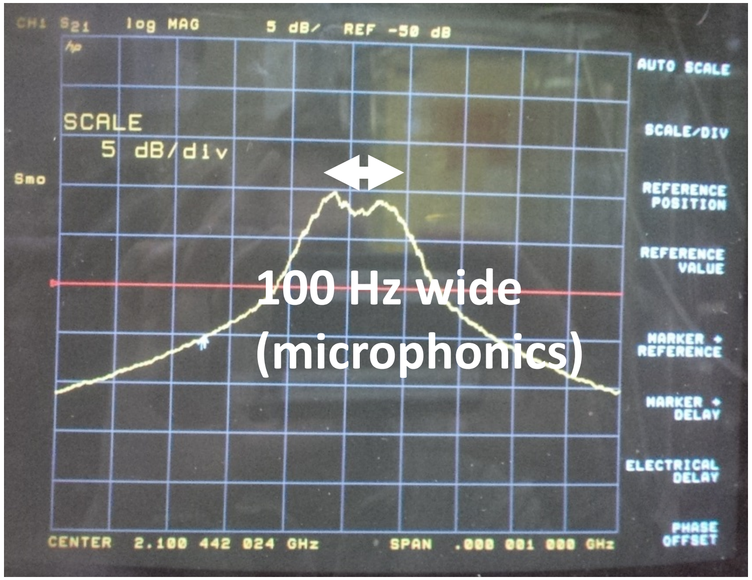
Class 100 clean room at LANL

- Cavity is etched using BCP to remove 150 μm from the inner surface
- The rest of the test assembly is cleaned with an ultrasonic machine and high pressure rinsed with ultra-pure water
- "Cold mass" is assembled in a class 100 clean room
- The assembly is baked at 120 C for 3 days

High gradient test results



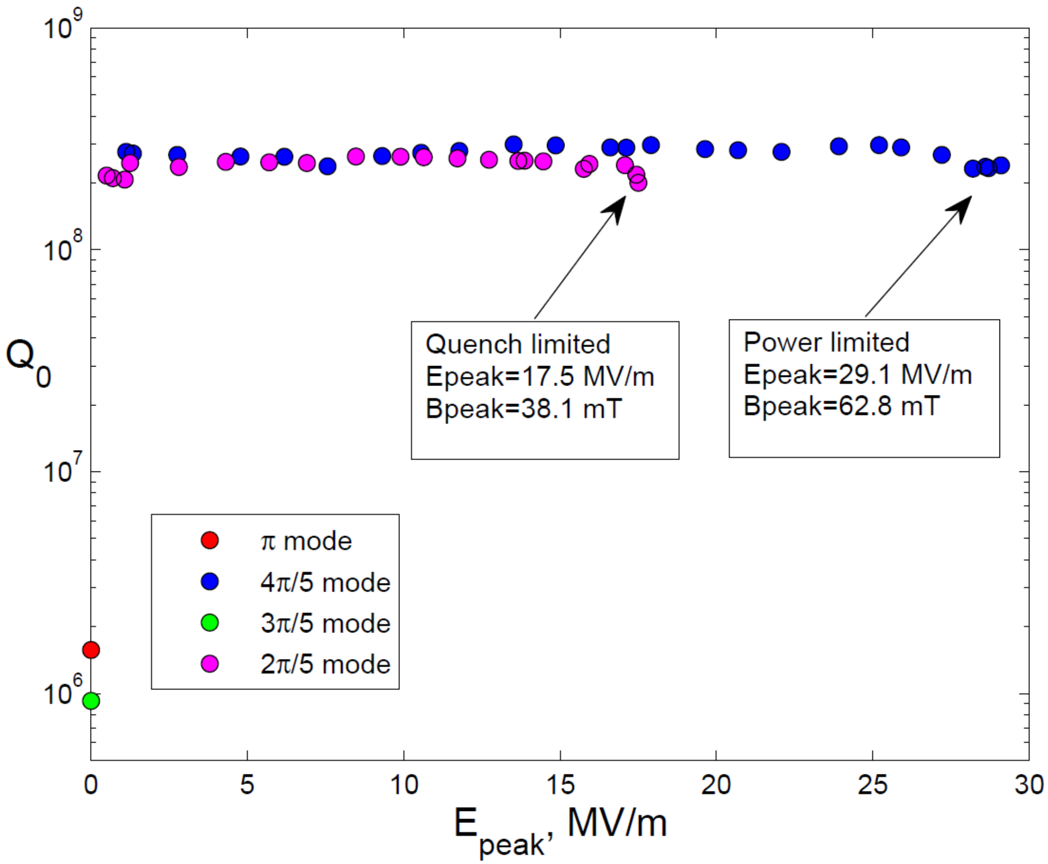
S21: accelerating π mode at 4.0K.



S21: $4\pi/5$mode at 4.0K.

- Different passband modes showed very different bandwidths
- The accelerating mode was strongly undercoupled
- Accelerating mode peak did not change with temperature drop from 4K to 2K
- Accelerating mode peak did not change when input power was increased

High gradient test results



Unloaded Q vs peak surface E field for 4 passband modes at 4K

Passband mode	Theoretical Q_0	Measured Q_0
$\pi/5$	2.0×10^8	Not measured
$2\pi/5$	2.4×10^8	2.2×10^8
$3\pi/5$	2.1×10^8	9.3×10^5
$4\pi/5$	2.3×10^8	2.7×10^8
π	2.2×10^8	1.6×10^6

Unloaded Q factor of 10^6 is very unusual for a superconducting cavity

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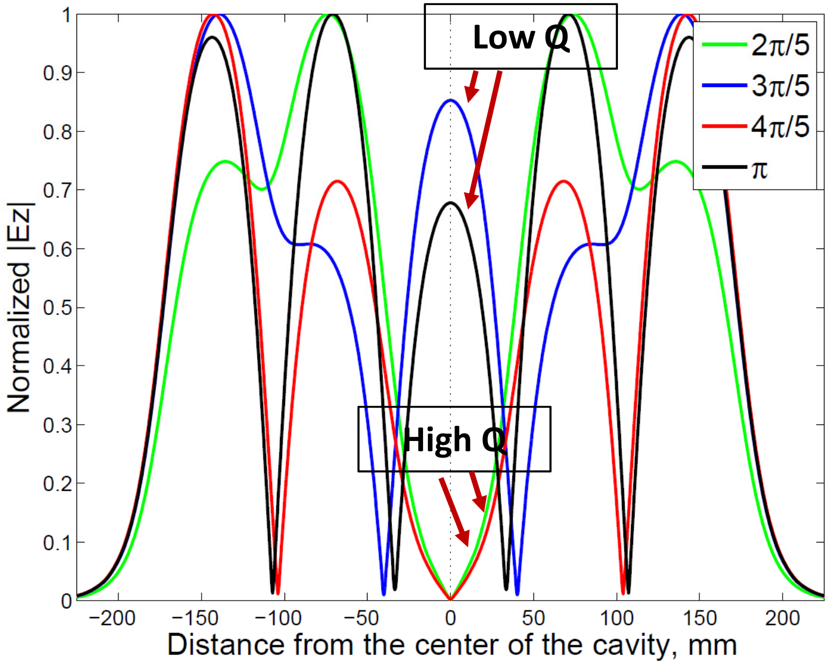
Finding the problem

Fact 1: Only the modes with high field in the PBG cell have low Q



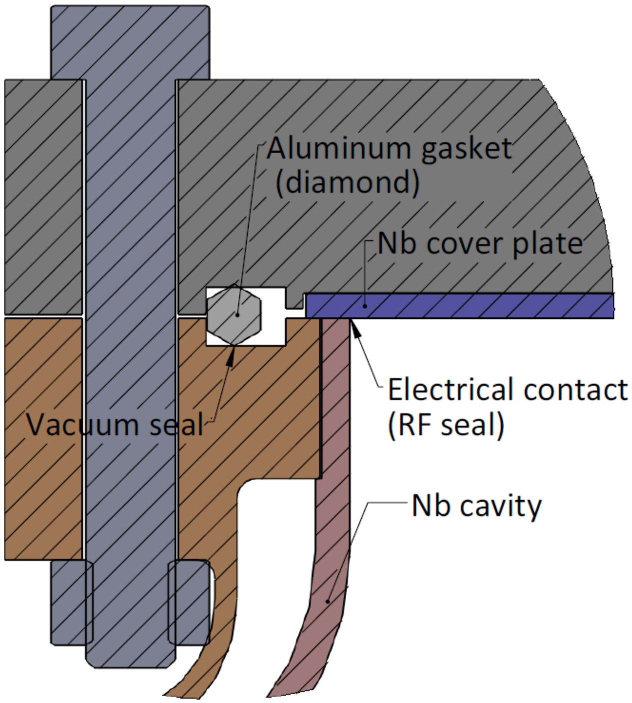
Gradients for the passband modes

Fact 2: No experiments with single PBG cells had the low Q problem

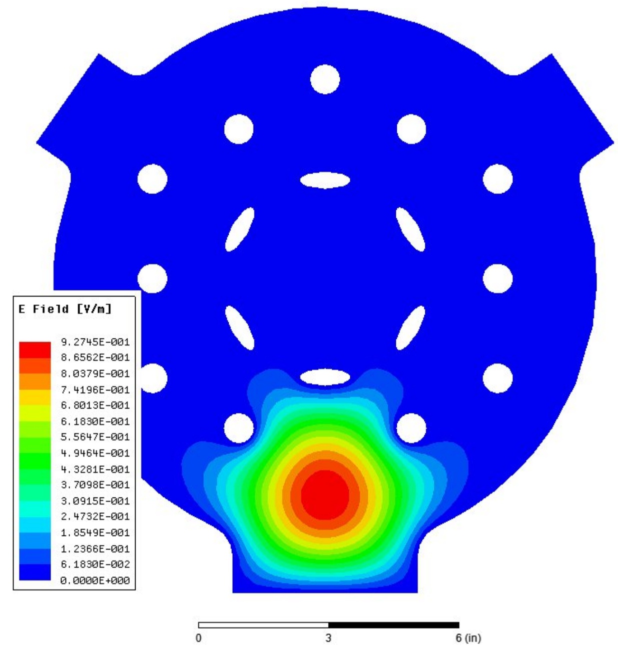
Single PBG cells did not have waveguide couplers

Problem in the waveguides?

Waveguide joint structure



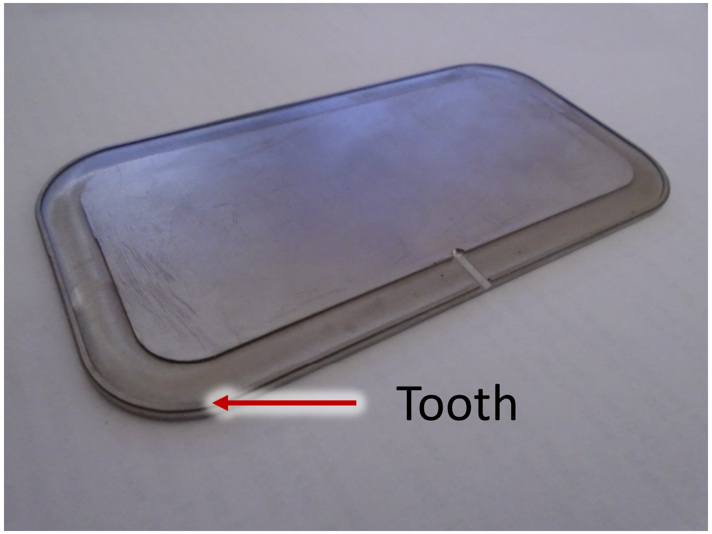
Vacuum and RF seals are provided by different gaskets.



"Trapped" waveguide mode

We used a different mode to test the quality of the joint

Modified RF joint



Modified Nb cover plate

	Trapped mode Q at room temperature
Theoretical value for zero joint loss	5710
Measured value for the old (poor) joint	140
Measured value for the new joint	5650

The source of the low Q was not in the cavity, but in a bad joint!

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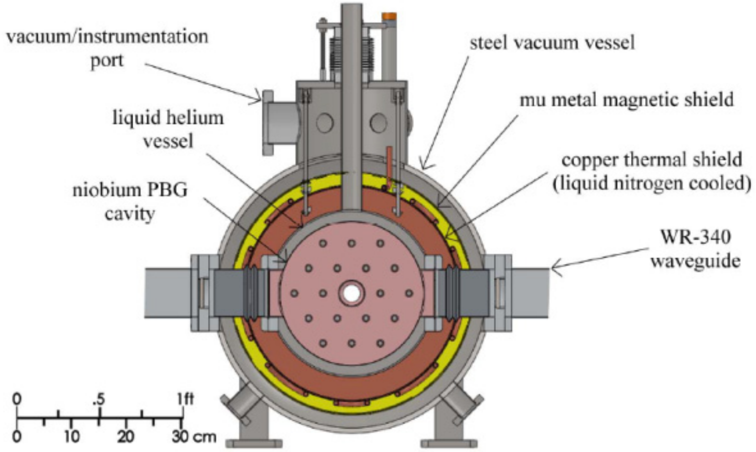
Future plans

1) Repeat the high gradient test with the improved waveguide joint (**October 2015**)
   - Demonstrate high Q factor at 4K and possibly at 2K.
   - Demonstrate high gradient in the accelerating mode.
   - Find out if multipacting is a significant issue.
   - Prove that maximum gradient is not limited by the PBG cell.

2) Develop a cryomodule design compatible with the proposed eRHIC ERL
   - Titanium He vessel
   - Tuner design
   - RF windows



Summary

- A PBG cavity can be used when strong HOM damping is required, especially for higher frequency linacs.
- The first PBG SRF cavity was successfully fabricated and tuned.
- First high gradient test was not successful due to a poor RF joint.
- New technique for testing joint quality was developed.
- Second high gradient test with an improved joint is planned in October 2015.