Superconducting photonic band gap structures for high-current applications

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Outline

- Background and motivation.
- PBG resonators for accelerators to date.
- 2.1 GHz SRF PBG cavities – design and testing.
- Conclusion and plans.

Background and motivation

Background: beam breakup in SRF accelerators

- Average current in multi-cell SRF cavities is limited by beam breakup (BBU) instabilities caused by higher order modes (HOM), which if not damped can have high quality factor Q.
- Since BBU threshold scales with frequency as $1/f^2$, present SRF cavities designed for high current operation use low frequency, necessitating high charge per electron bunch.
- Operating at high frequency and low bunch charge reduces the risks of brightness degradation in electron beam transport.
- High current and high frequency SRF cavities require loading the HOMs to reduce their Q_{ext} to lower than 100 and removing HOM power from the liquid helium environment.

Methods for BBU suppression

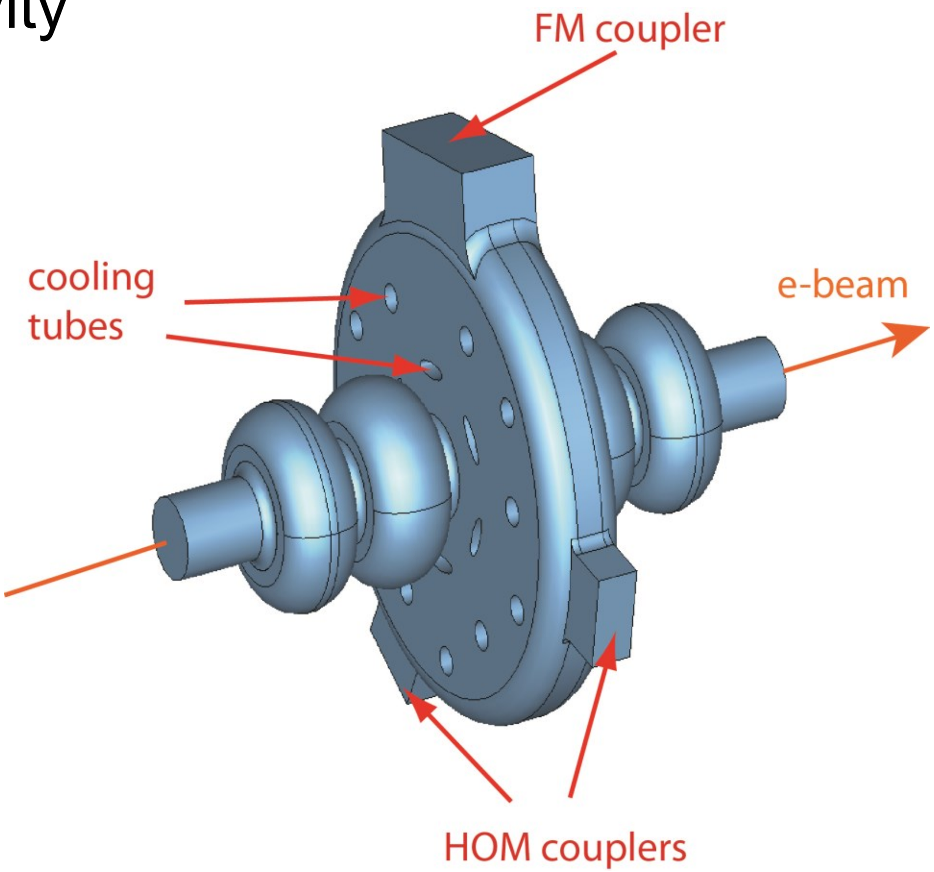
The primary approach to avoiding beam instabilities is to lower the external Q-factors for the HOMs.

Method	Problems
Ferrite HOM dampers (Q_{ext} ~ 100)	• Located in beam pipes outside of the cryostat. Greatly reduce real estate gradient. • Ferrite materials are brittle and contaminate SRF cavities if cracked.
HOM couplers (Q_{ext} ~ 1000)	• Located in beam pipes. Reduce real estate gradient. • Do not sufficiently damp HOMs.

PBG structures: what it means for Navy

PBG structures present us with a unique way to place HOM couplers in an accelerating cavity

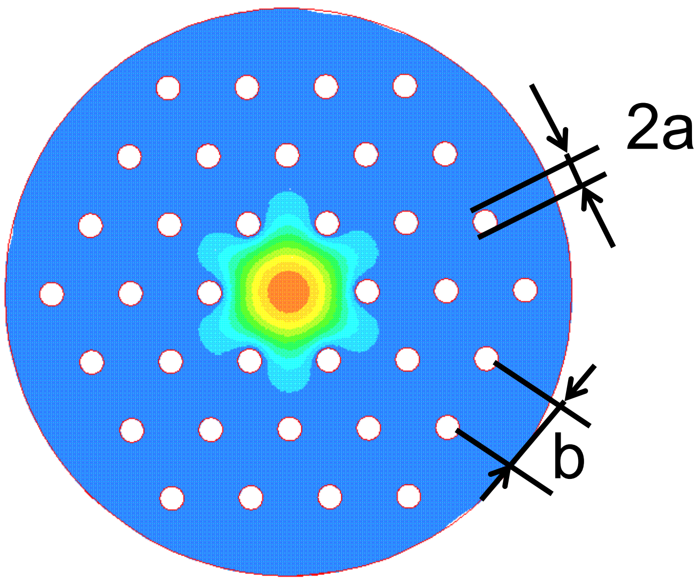
- Much lower external Q-factors for HOMs
- Higher real estate gradient
- **Possibility to scale SRF accelerators to higher frequency ⟹ more compact accelerators with reduced footprint, lower bunch charge (higher brightness).**



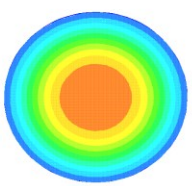
PBG resonators for accelerators to date

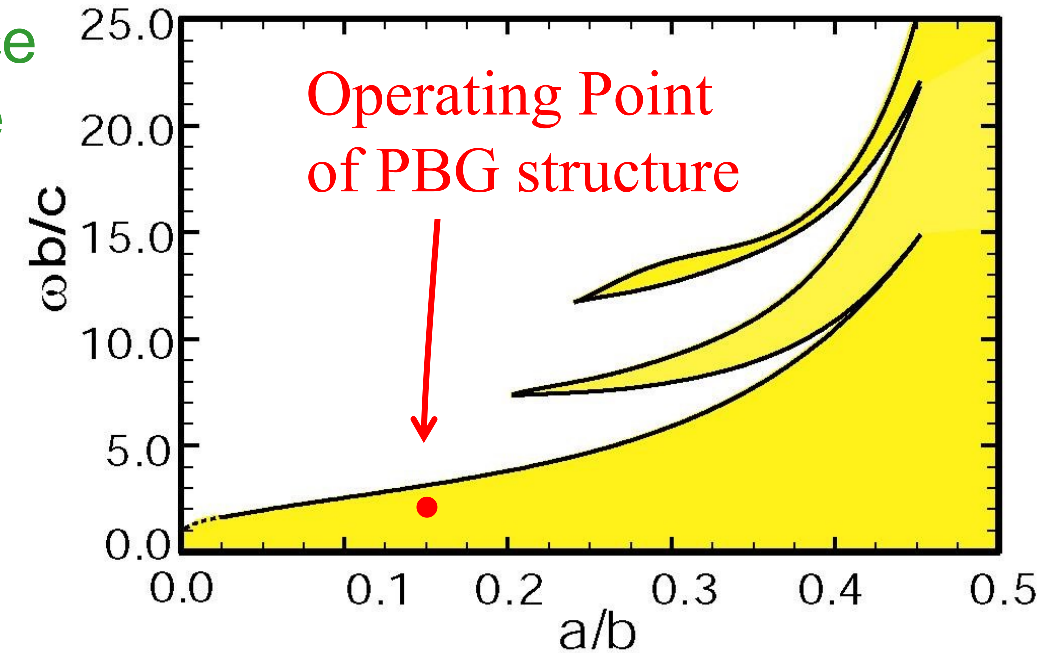
PBG resonators

PBG Cavity, triangular lattice
a/b=0.15, TM_{01} –like mode



Pillbox Cavity, TM_{01} mode

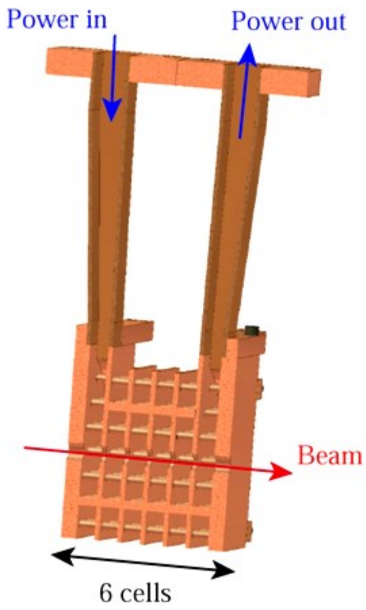


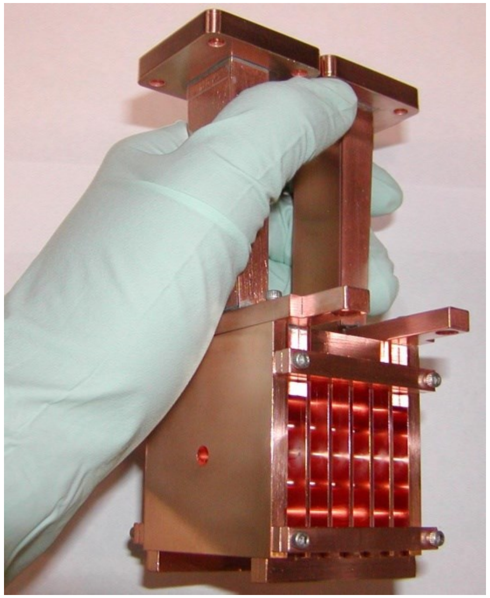


Single mode operation.
No higher order dipole modes.
This structure is employed for the MIT PBG accelerator

MIT PBG accelerator

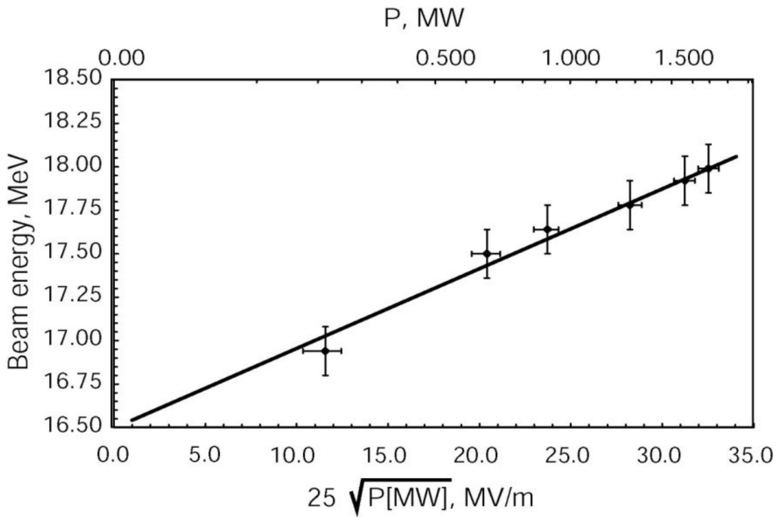
MIT PBG accelerator at 17 GHz – first experimental demonstration of acceleration in a PBG structure:





E.I. Smirnova *et al.*, Phys. Rev. Lett. **95(7),** 074801 (2005).

- A 6 cell TW PBG accelerator structure @17.137 GHz.
- Open structure, wakefields radiate freely into the vacuum chamber.



SRF PBG resonators

- The UCSD team fabricated several SRF PBG cavities at 11 GHz.
- Fabrication was done at CEBAF.
- The cavity was open and had 3 rows of PBG rods.
- The unloaded Q-factor was measured at 4.8K and was dominated by radiation losses.

D.R. Smith et al., AIP Conference Proceedings, 398, p. 518, (1997).

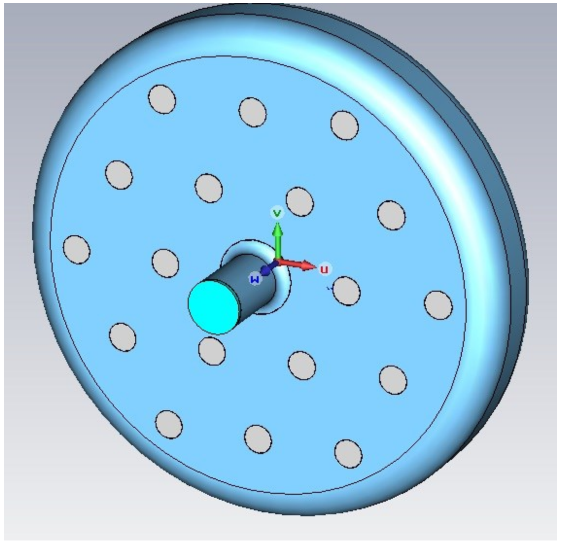
- The INFN-Napoli team fabricated SRF PBG cavities at 6 GHz and at 16 GHz.
- The cavities were fabricated from a bulk piece of Nb with no welds.
- The cavity was open and had 3 rows of PBG rods.
- The unloaded Q-factor was measured at 1.5 K and was dominated by radiation losses.

M. R. Masullo et al., Proceedings of EPAC 2006, p. MOPCH167, (2006).

2.1 GHz SRF PBG cavities – design and testing

SRF PBG resonator – basic design

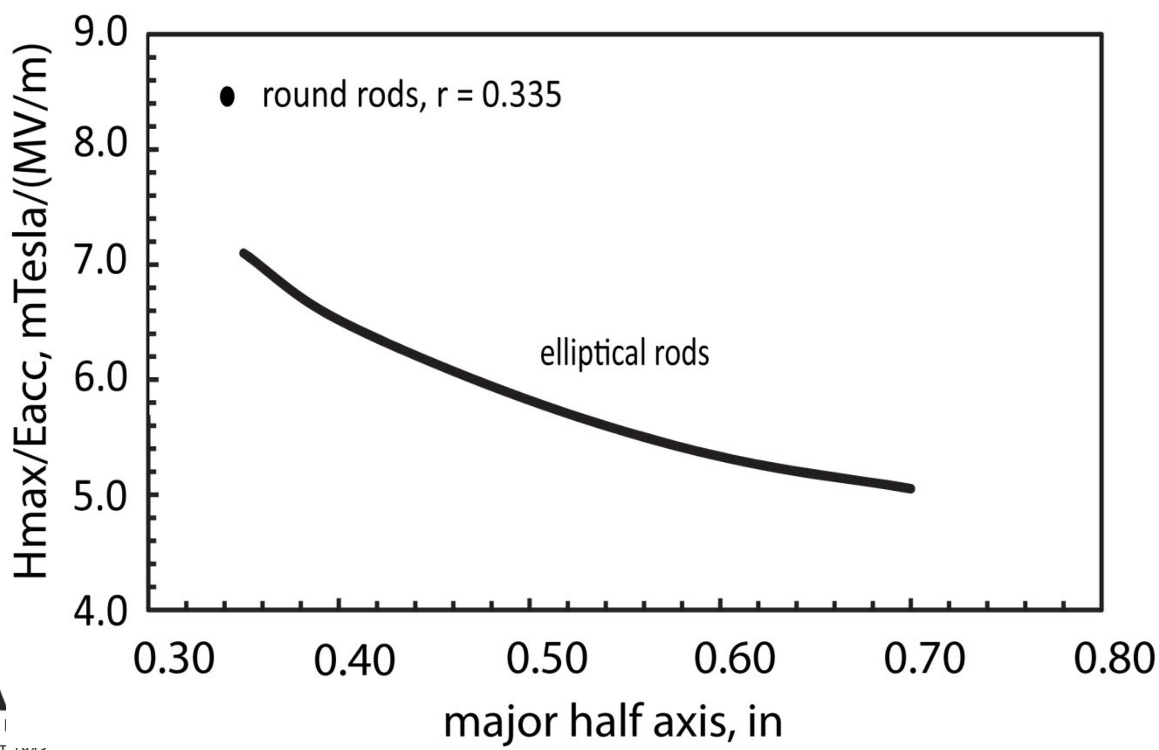
The SRF PBG resonator was designed at the frequency of 2.1 GHz.

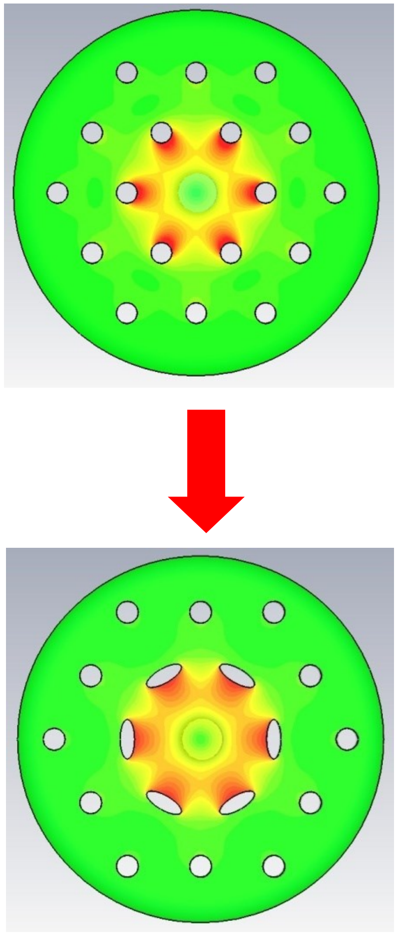


Spacing between the rods, p	56.56 mm
OD of the rods, d	17.04 mm = 0.3*p
ID of the equator, D0	300 mm
Length of the cell, L	60.73 mm (λ/2)
Beam pipe ID, Rb	1.25 inches = 31.75 mm
Radius of the beam pipe blend, rb	1 inch = 25.4 mm
Q_0 (4K)	$1.5*10^8$
Q_0 (2K)	$5.8*10^9$
R/Q	145.77 Ohm
E_{peak}/E_{acc}	2.22
B_{peak}/E_{acc}	8.55 mT/(MV/m)

Reduction of surface magnetic fields

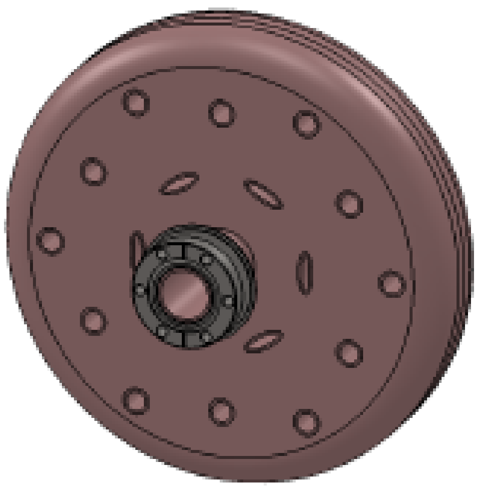
Changing the cross-section of the rods from round to elliptical decreases the curvature and reduces maximum surface magnetic fields up to 40 per cent.





Final design of PBG resonators with elliptical rods

PBG resonator was designed with 6 elliptical inner roads slightly shifted towards the center.



Spacing between the rods, p	56.57 mm
OD of the round rods, d	17.04 mm = 0.3*p
Major OD of the elliptical rod, a	27.94 mm =0.5*p
Minor OD of the elliptical rod, b	9.80 mm
ID of the equator, D0	300 mm
Length of the cell, L	71.43 mm (λ/2)
Q_0 (4K)	$1.8*10^8$
Q_0 (2K)	$6.2*10^9$
R/Q	150.7 Ohm
E_{peak}/E_{acc}	2.37
B_{peak}/E_{acc}	5.66 mT/(MV/m)

Fabrication of 2.1 SRF PBG resonators

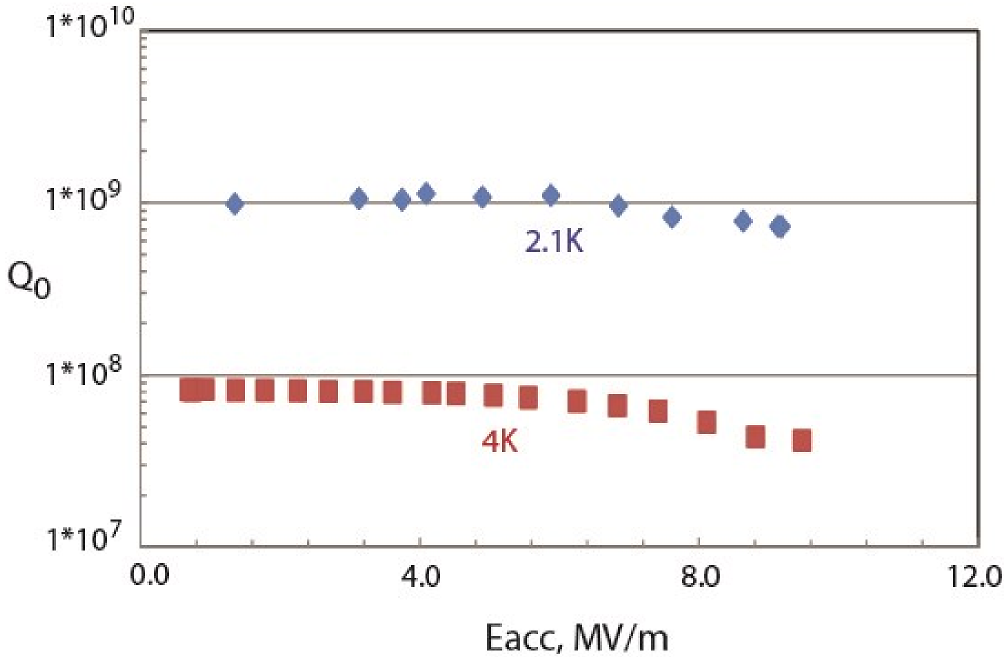
• The 2.1 GHz PBG cavity was fabricated at Niowave, Inc. from a combination of stamped sheet metal niobium with RRR>250 and machined ingot niobium components with RRR>220.

• After welding, a Buffered Chemical Polish etch was performed to prepare the RF surface for testing.

Test results – resonator 1, round rods

Resonator 1 was tested on March 27-30th, 2012. This cavity was opened up a few times in the clean room during preparation for the experiment. It also developed a super leak at 2 Kelvin.

Frequency	2.10669 GHz
Q_0 (4K)	$8.2*10^7$
Q_0 (2K)	$1.1*10^9$
Maximum E_{acc} (4K)	9.5 MV/m
Maximum E_{acc} (2K)	9.1 MV/m
B_{peak} (4K)	81 mT
B_{peak} (2K)	78 mT

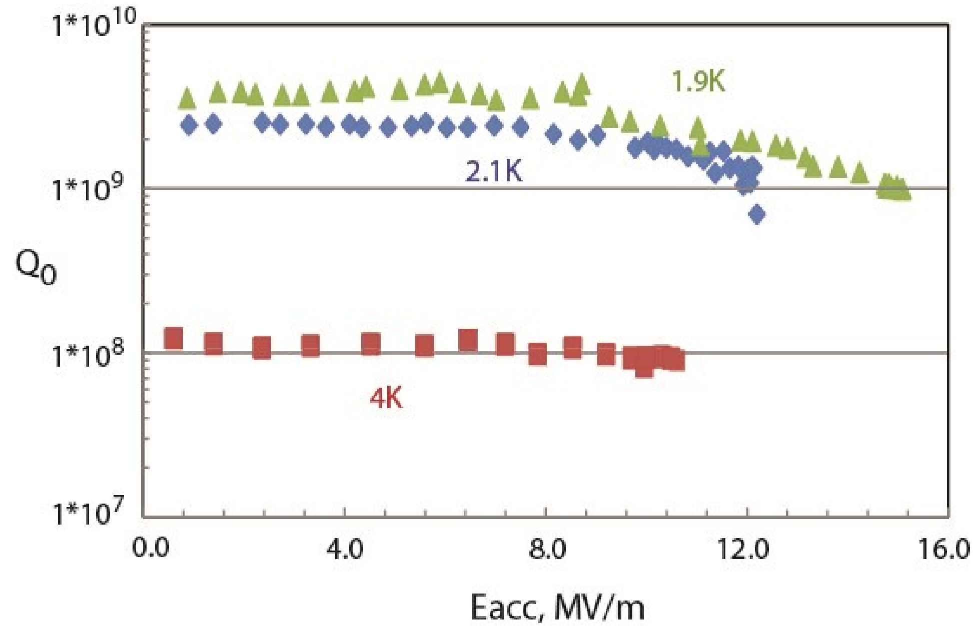


Test results – resonator 2, round rods

Resonator 2 was tested on April 23-27th, 2012. Measured characteristics were very close to theoretical predictions.

Frequency	2.09984 GHz
Q_0 (4K)	$1.2*10^8$
Q_0 (2K)	$3.9*10^9$
Maximum E_{acc} (4K)	10.6 MV/m
Maximum E_{acc} (2K)	15.0 MV/m
B_{peak} (4K)	91 mT
B_{peak} (2K)	129 mT

Maximum achieved gradient was 15 MV/m.



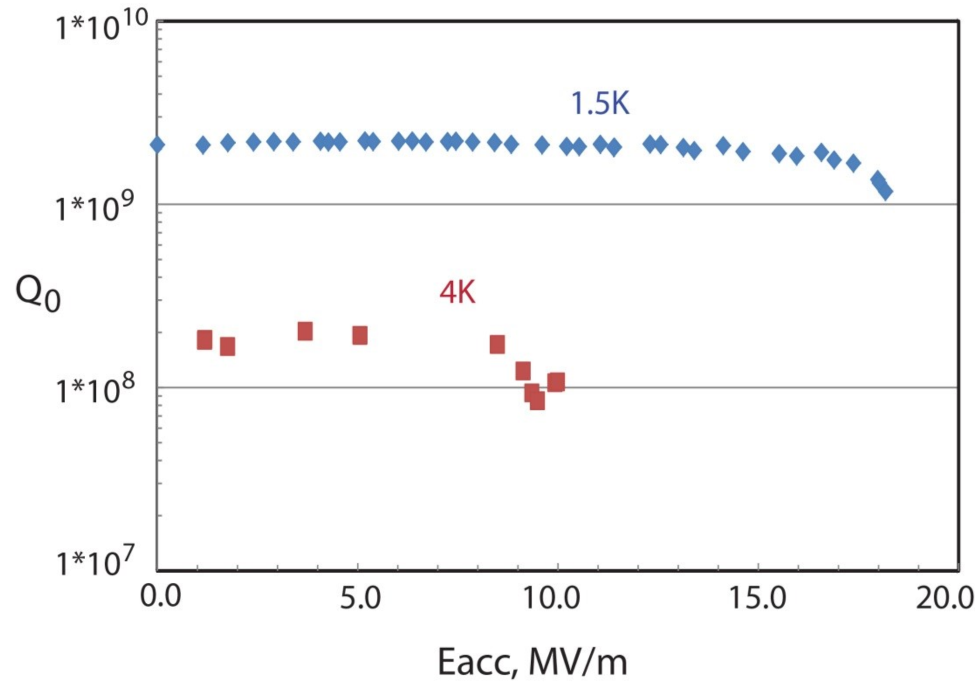
E.I. Simakov *et al.*, Phys. Rev. Lett. **109**, 164801 (2012).

Test results – resonator 3, elliptical rods

Resonator 3 was tested on July 15-18th, 2013. The cavity was undercoupled at 4K. Performance at 2K was excellent.

Frequency	2.11524 GHz
Q_0 (4K)	$1.6*10^8$
Q_0 (1.5 K)	$2.2*10^9$
Maximum E_{acc} (4K)	10.0 MV/m
Maximum E_{acc} (2K)	18.3 MV/m
B_{peak} (4K)	57 mT
B_{peak} (2K)	104 mT

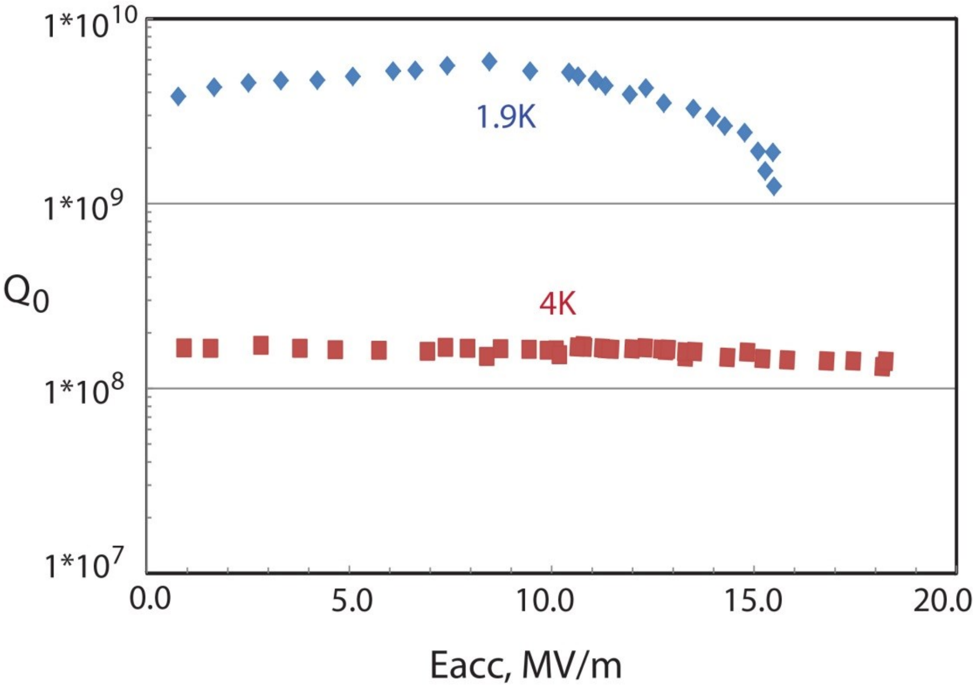
Maximum achieved gradient was 18.3 MV/m.



Test results – resonator 4, elliptical rods

Resonator 4 was tested on August 19-22th, 2013. Excellent performance at 4K. Frequency shifted 300 kHz up after the pump down. Possible mechanical issues?

Frequency	2.11292 GHz
Q_0 (4K)	$1.6*10^8$
Q_0 (2K)	$3.9*10^9$
Maximum E_{acc} (4K)	18.2 MV/m
Maximum E_{acc} (2K)	15.3 MV/m
B_{peak} (4K)	103 mT
B_{peak} (2K)	87 mT



Conclusion and plans

Conclusions

- We performed fabrication and testing of four SRF PBG resonators at 2.1 GHz and demonstrated their proof-of-principle operation at high gradients.
- Measured characteristics of the resonators were in good agreement with theoretical predictions.
- SRF PBG cavities with round rods were operated at 15 MV/m accelerating gradients.
- SRF PBG resonators with elliptical rods were operated at 18.3 MV/m accelerating gradient.
- The next step is experimental demonstration of an accelerator section with a PBG cell.