Photonic Band Gap Resonators and Accelerator Structures

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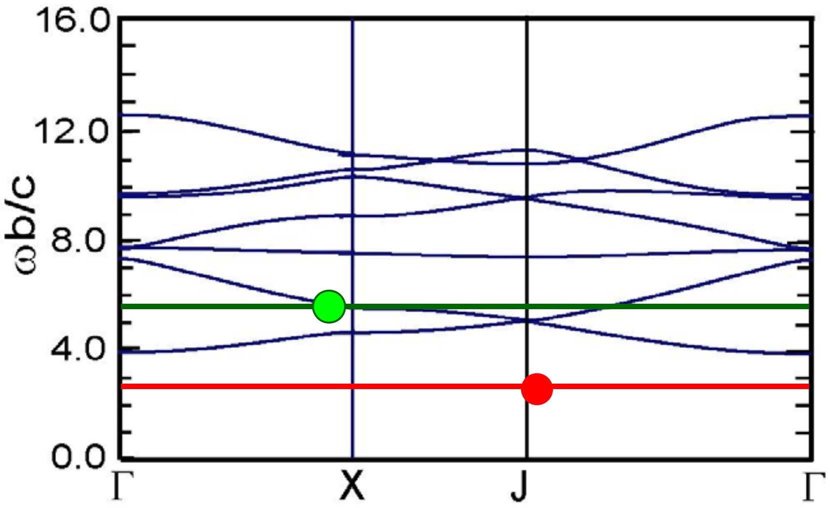
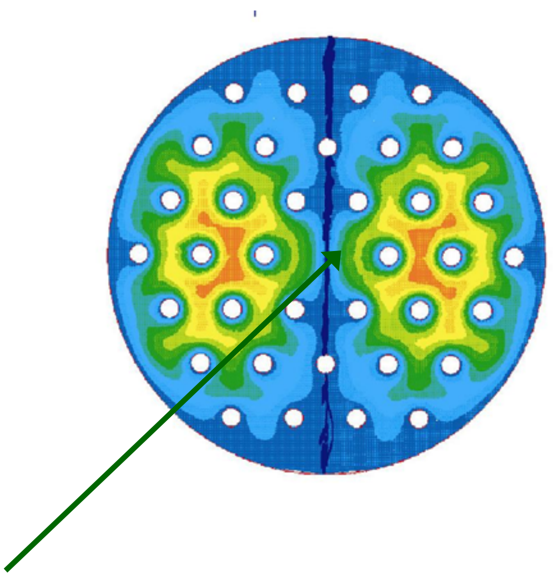
Outline of this lecture

- 2D Photonic band gap resonators: theory and first tests.
- MIT PBG accelerator.
- Wakefields in PBG resonators: beam tests.
- PBG resonators at high gradients.
- SRF PBG resonators.
- PBG resonators with elliptical rods.
- SRF cavities with PBG couplers.
- Exotic: PBG structures for laser acceleration.
- Totally exotic: channel-drop filter.

Mode confinement in a PBG resonator

A defect in a PBG structure may form a PBG resonator:

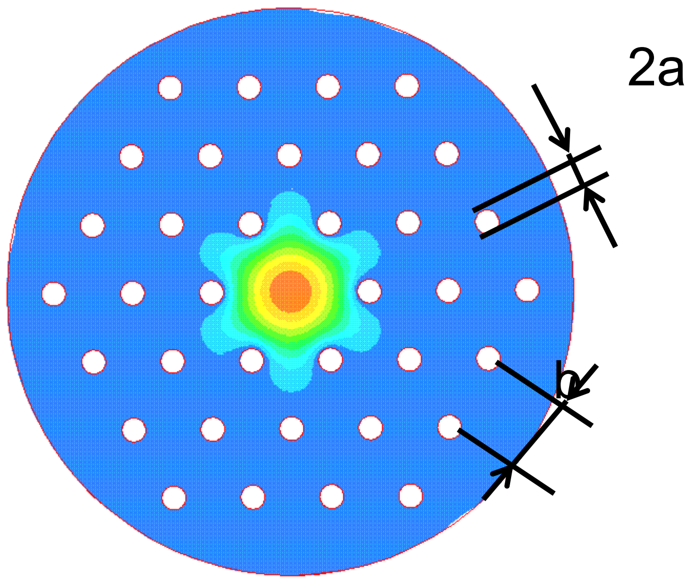




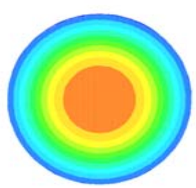
PBG cavity formed by a defect

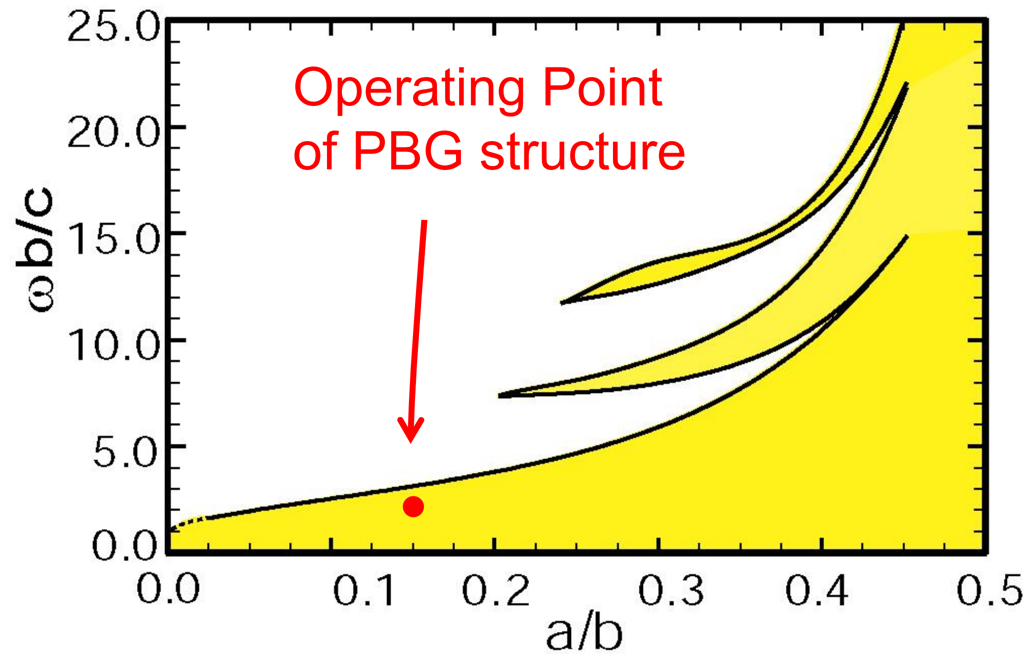
The TM_{01} mode in the PBG resonator

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



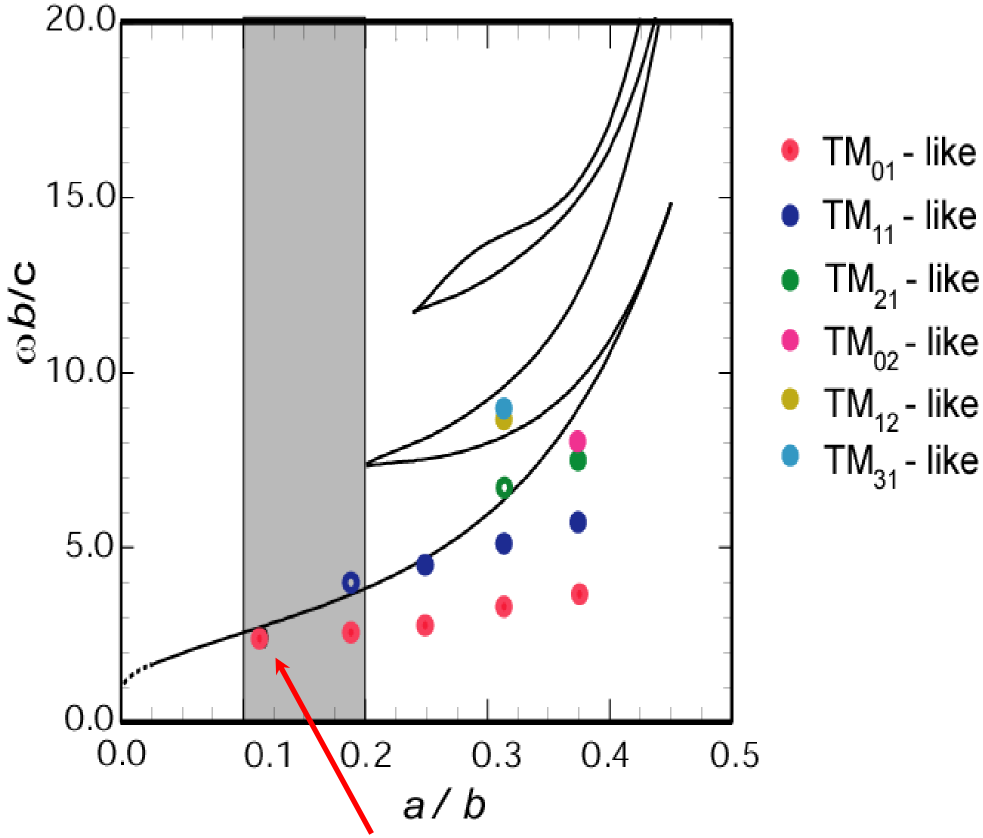
Pillbox Cavity, TM_{01} mode



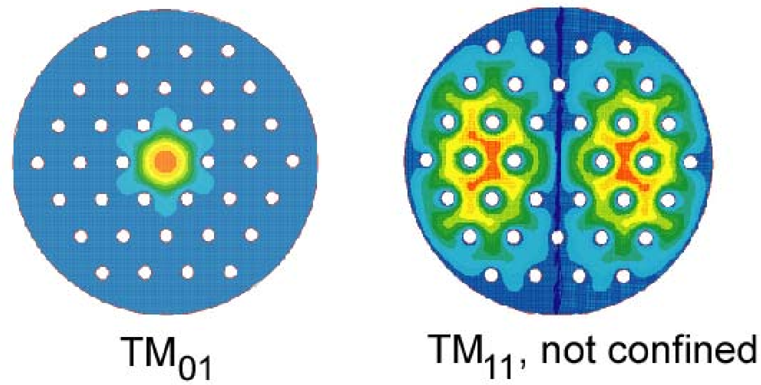


Single mode operation.
No higher order dipole modes.
This structure is employed for the MIT PBG accelerator

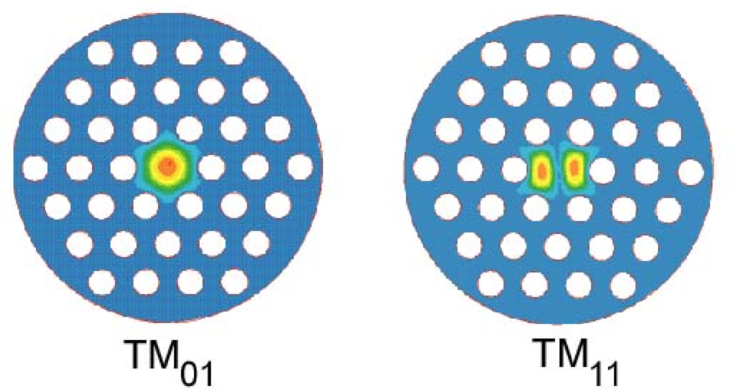
Higher order mode in a PBG resonator



Only a single mode confined for *0.1 ≤ a/b ≤ 0.2*



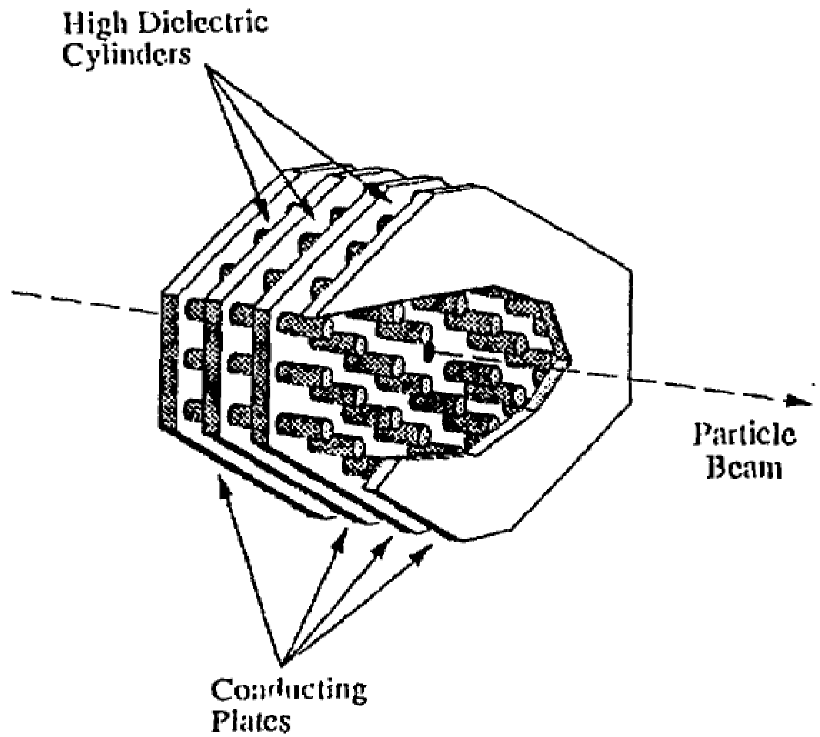
a/b = 0.15, one mode confined



a/b = 0.30, two modes confined

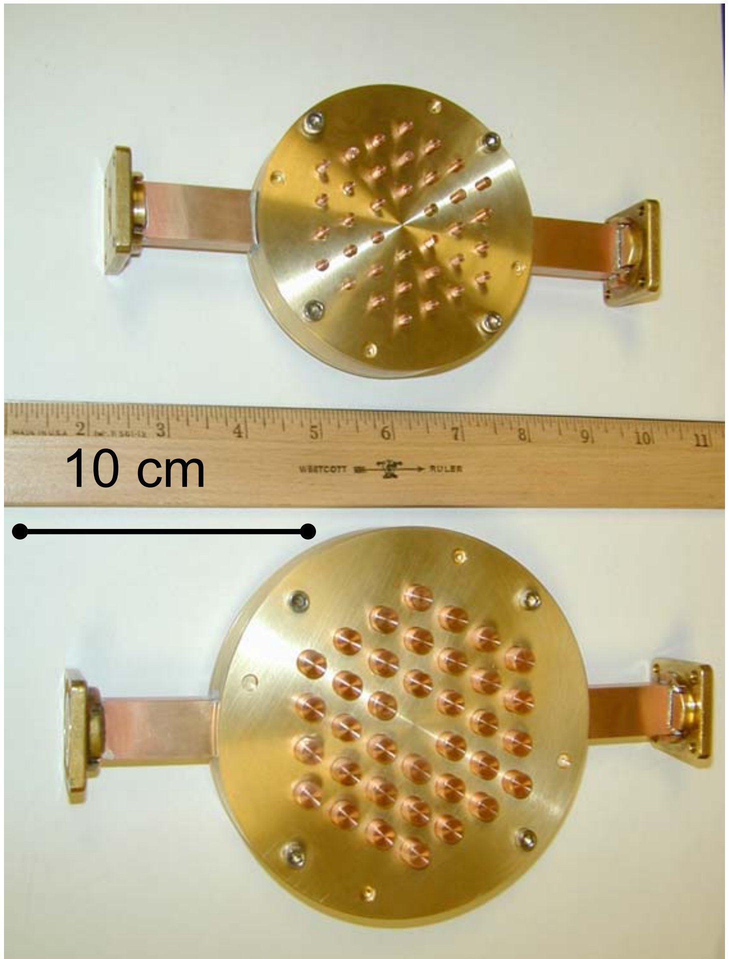
Very early PBG resonators: Smith and Kroll

- First proposal to apply the PBG structures for filtering wakefields in accelerators.
- Proposed dielectric PBG resonators, metal PBG resonators, and superconducting PBG resonators.
- Built a few cavities for cold testing.



N Kroll, D. Smith *et al.*, AIP Conf. Proceedings 279, 197 (1992).

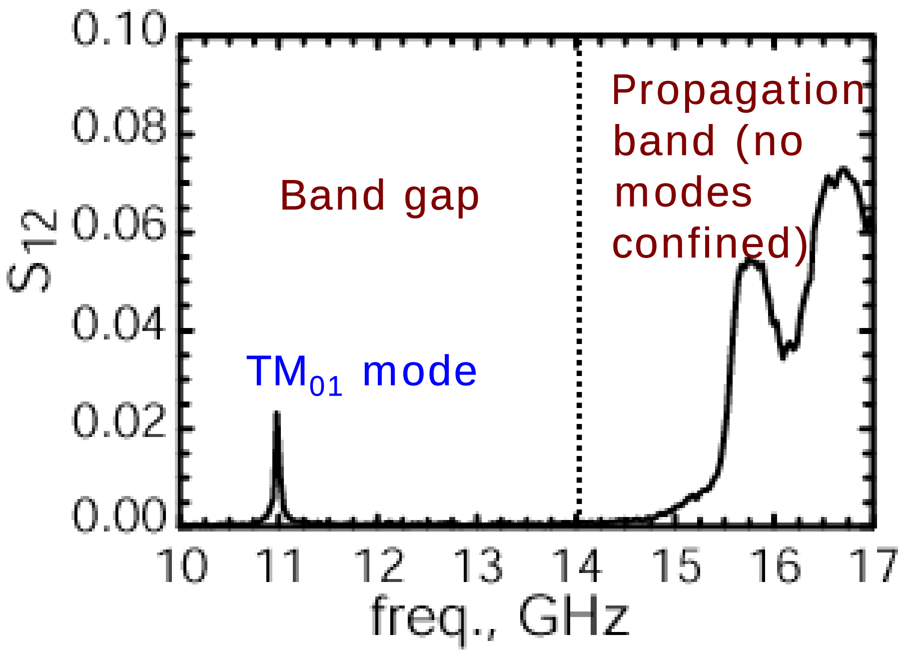
MIT's 11 GHz PBG resonators



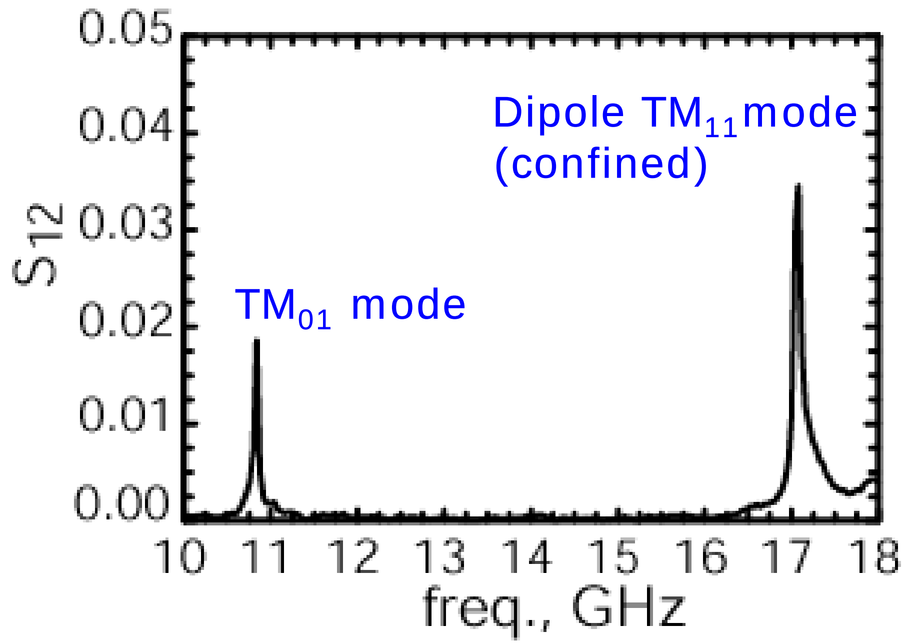
	Cavity 1	Cavity 2
Lattice spacing *b*	1.06 cm	1.35 cm
Rod radius *a*	0.16 cm	0.40 cm
a/b	0.15	0.30
Cavity radius	3.81 cm	4.83 cm
Freq. (TM_{01})	11.00 GHz	11.00 GHz
Freq. (TM_{11})	15.28 GHz	17.34 GHz
Axial length	0.787 cm	0.787 cm

E. Smirnova *et al.*, AIP Conf. Proceedings 647, 383 (2002).

MIT's 11 GHz resonators in cold test



a/b=0.15



a/b=0.30

No confined wakefield modes.
Good for accelerators

Confined TM_{11} mode
Bad for accelerators

2.7 GHz open-wall PBG resonator

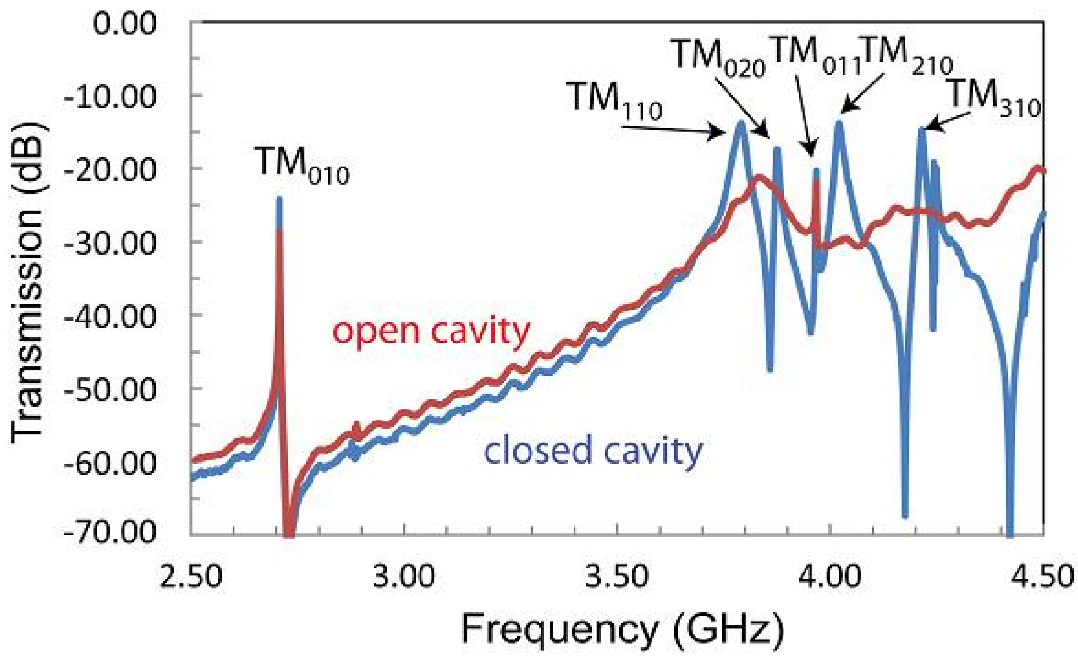
- The resonator built by Niowave as a test bed for future SRF PBG resonators.

Spacing between the rods, p	1.693 inches
Diameter of the rods, d	0.508 inches = 0.3*p
Outside diameter, D0	8.8 inches
Length of the cell, L	2.56 inches
Diameter of the beam pipe, Rb	0.5 inches
Radius of the beam pipe blend, rb	0.25 inches

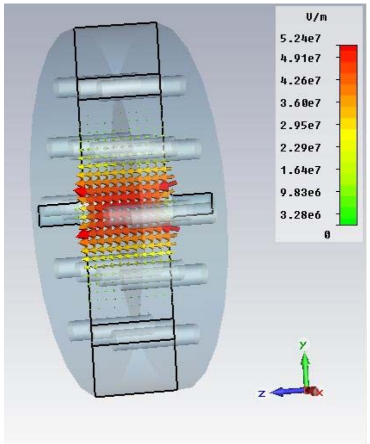
E. Simakov *et al.*, in Proceedings of the 2011 Particle Accelerator Conference, p. MOP042, (2011).

HOM test of the 2.7 GHz resonator

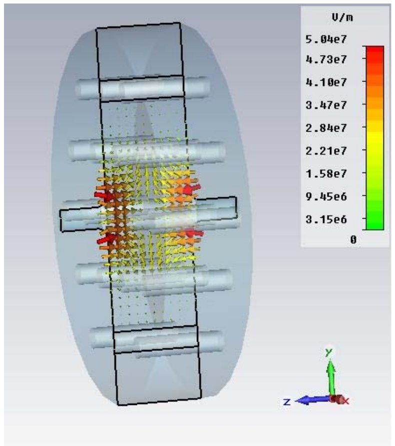
- HOMs were measured with two co-axial electrical probes inserted off-axis.
- It was confirmed that HOMs radiate out of the open structure, except for the TM_{011} mode.



TM_{010} mode, 2.708 GHz

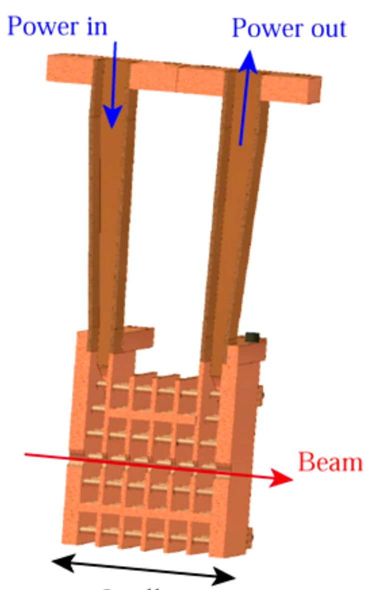


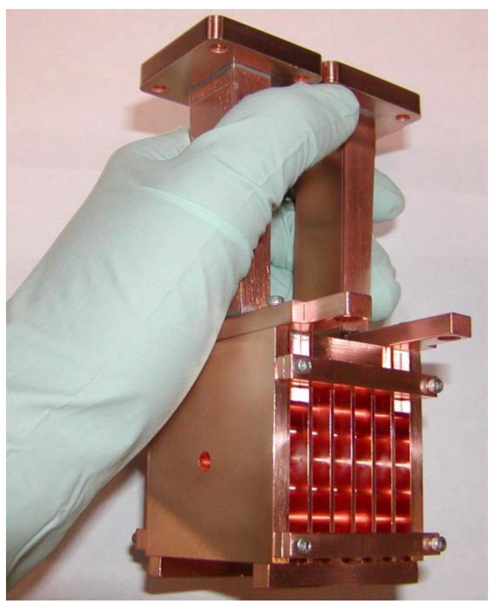
TM_{011} mode, 3.970 GHz



MIT PBG accelerator

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



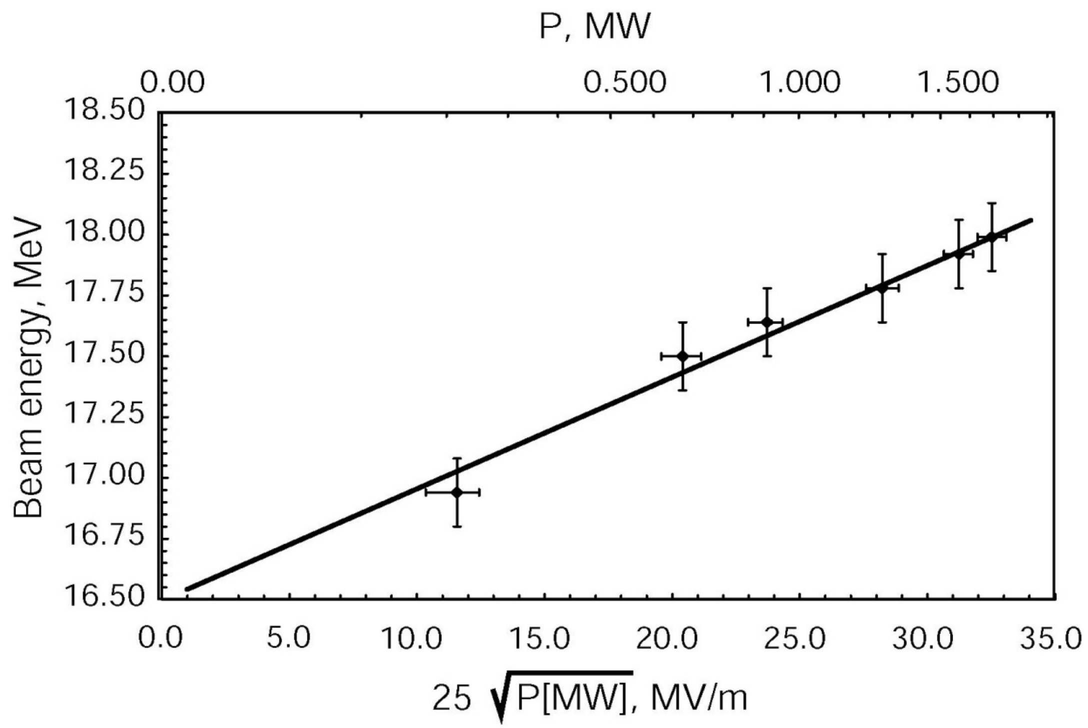


- A 6 cell TW PBG accelerator structure.
- Frequency: 17.137 GHz.
- Open structure, wakefields radiate freely into the vacuum chamber.

Rod radius	1.08 mm
Rod spacing	6.97 mm
Cavity radius	24.38 mm

First demonstration of a PBG accelerator

- Beam energy increased with power as $P^{1/2}$, as expected.
- First successful PBG accelerator demonstration.

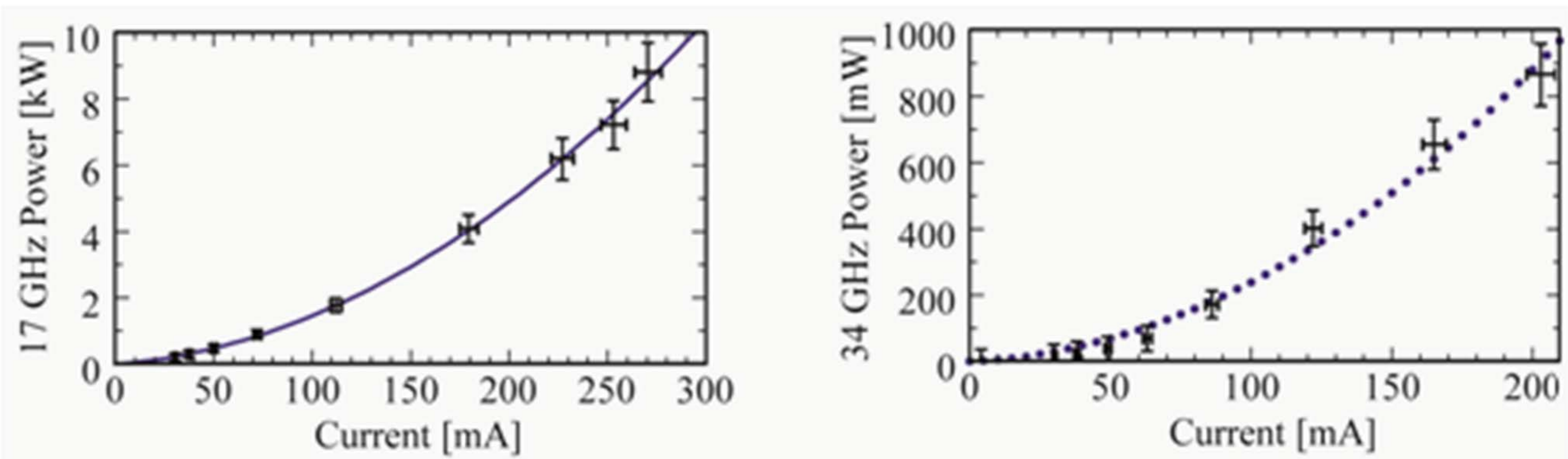


E.I. Smirnova *et al.*, Phys. Rev. Lett. **95(7),** 074801 (2005).

Wakefield test at MIT

The 17 GHz 6-cell PBG structure was excited by a train of 1 ps 18 MeV electron bunches. Radiation was observed at multiples of 17 GHz. Radiated power scaled quadratically with current.

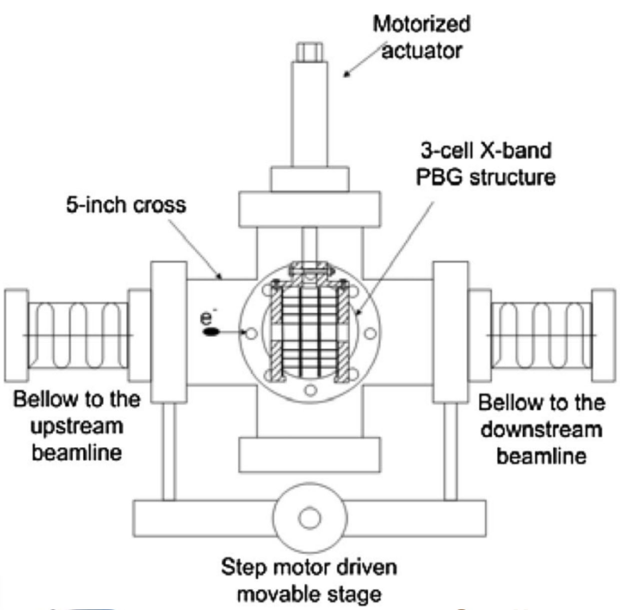
No coherent radiation into the dipole mode could be measured with MIT setup.

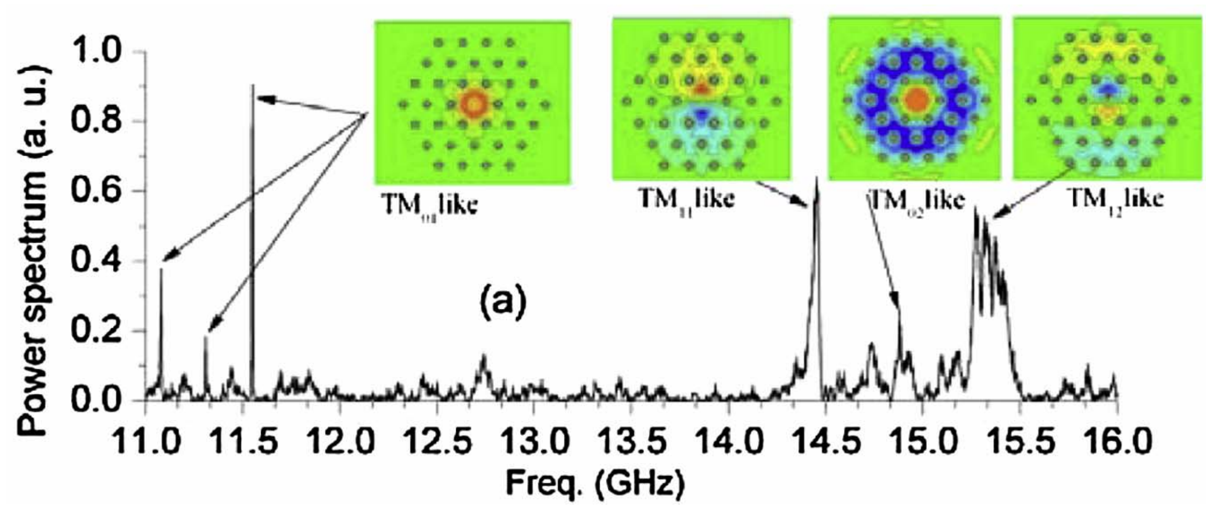


R.A. Marsh *et al.*, Nucl. Inst. And Meth. Phys. Res. A **618**, p. 16 (2010).

PBG wakefield tests at ANL

ANL team constructed a 3-cell SW PBG structure to operate at around 11.4 GHz. Wakefield excitation was experimentally studied. Position of the beam injection was precisely controlled. Major monopole (TM01- and TM02-like) and dipole (TM11- and TM12-like) modes were identified and characterized.



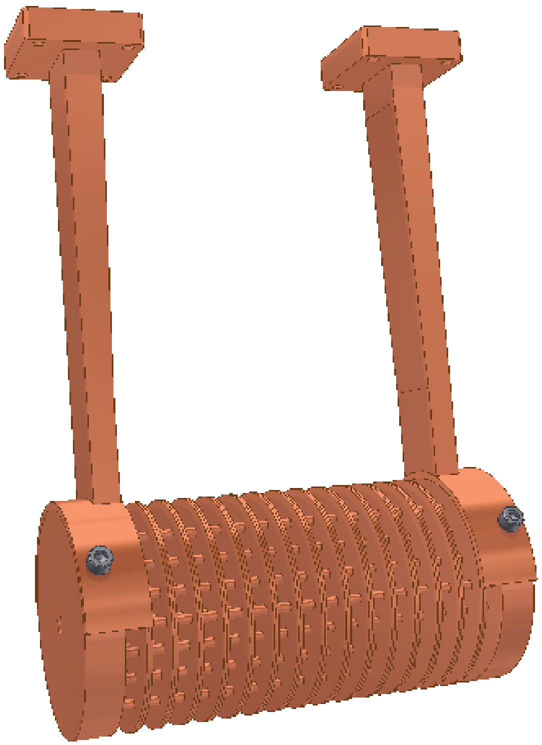


C. Jing *et al.*, Phys. Rev. STAB 12, 121302 (2009).

The 16 cell PBG structure for wakefield tests

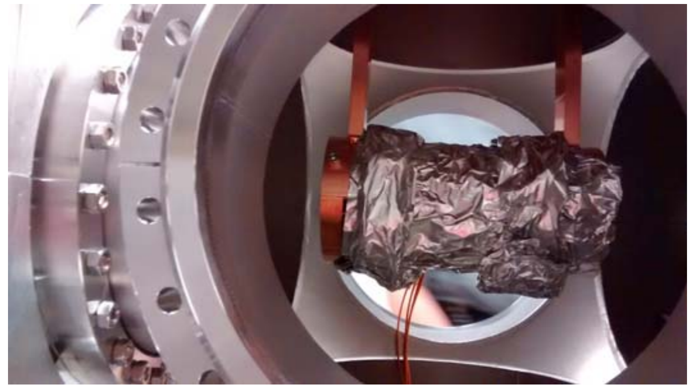
The 16-cell PBG structure for the wakefield testing was designed at the frequency 11.7 GHz (9 times the frequency of AWA). Very close scale of the MIT 17 GHz structure.

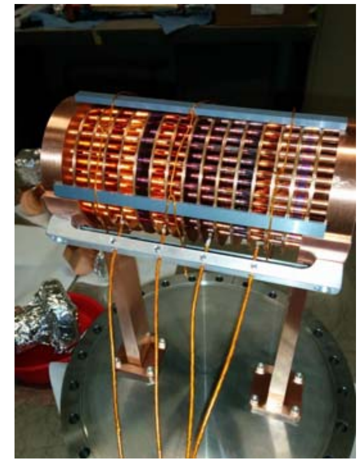
Frequency	11.700 GHz
Phase shift per cell	$2\pi/3$
Q_w	5000
r_s	72.5 MΩ /m
$[r_s/Q]$	14.5 kΩ /m
Group velocity	0.015c
Gradient	$15.4\sqrt{P[\mathrm{MW}]}$ MV/m



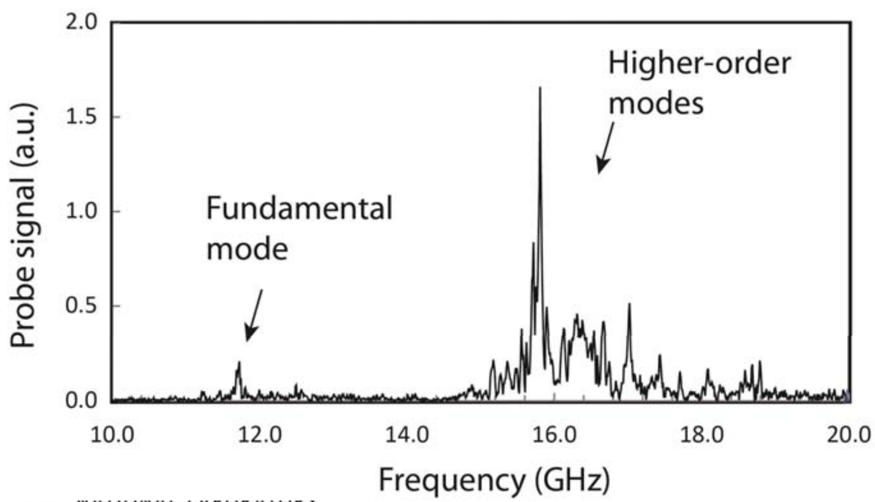
Data: higher order modes

HOMs were measured with 4 loop antenna probes installed at the periphery of the structure.

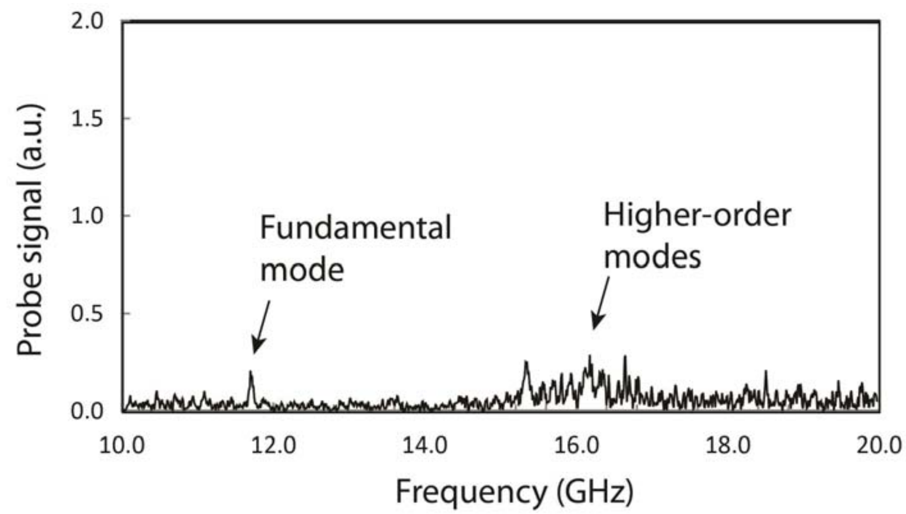




PBG structure wrapped in foil:

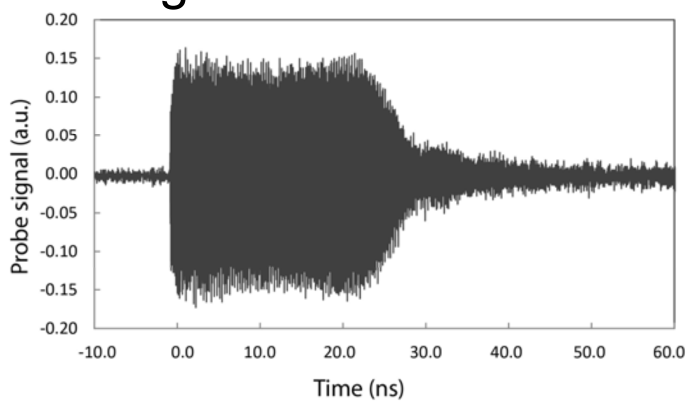


Open PBG structure with 6 SiC slabs:

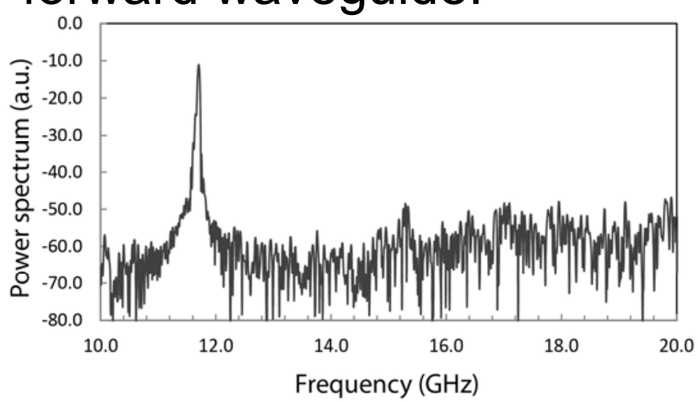


Data: fundamental mode

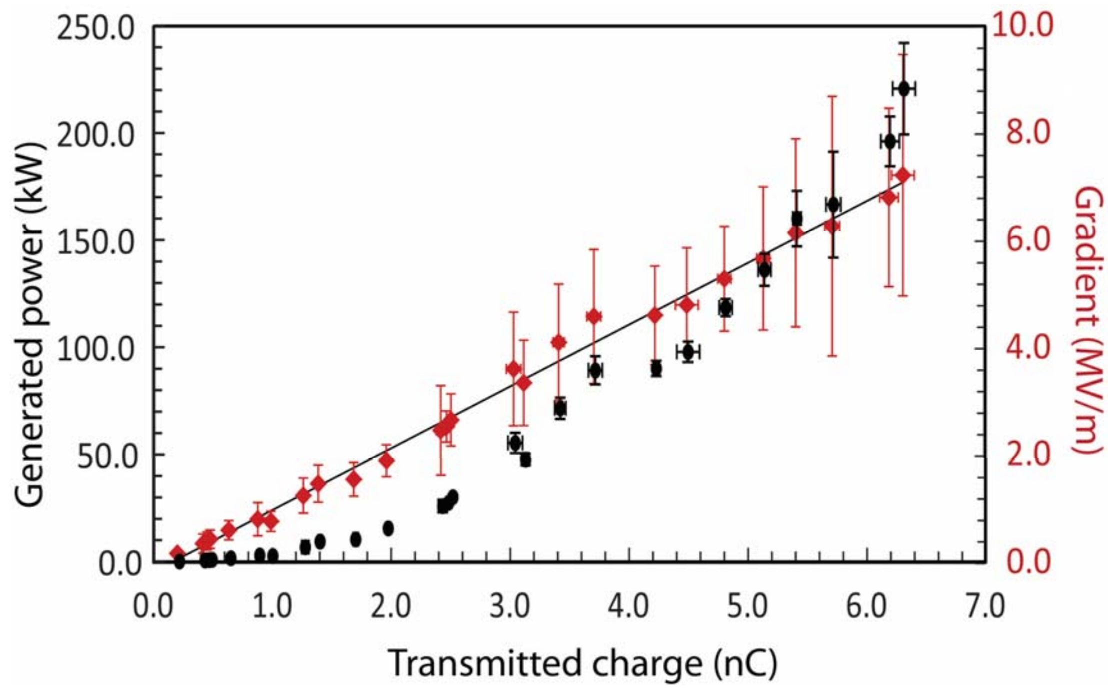
Signal in the forward waveguide:



Power spectrum in the forward waveguide:



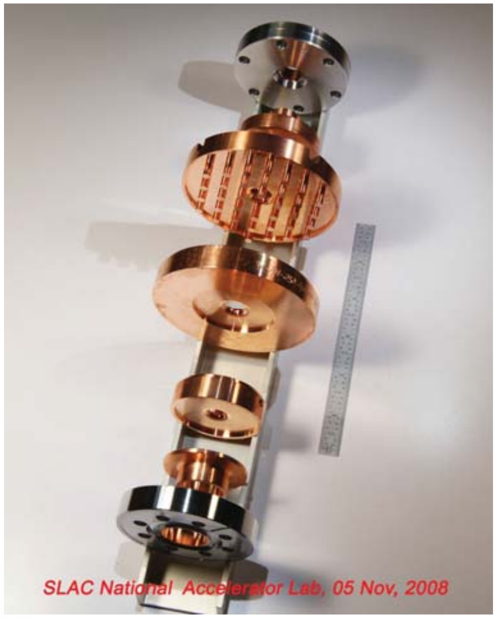
Measured power in the forward waveguide and computed accelerating gradient:

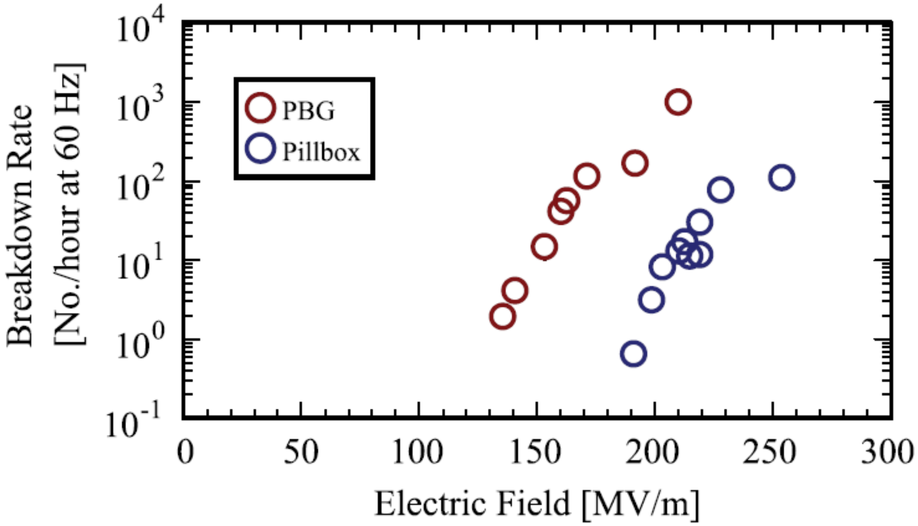


E.I. Simakov *et al.*, Phys. Rev. Lett. **116,** 064801 (2016).

MIT X-band PBG resonator with round rods for high gradient tests

- An X-band resonator with thicker round rods, r/p = 0.18.
- Round rods were slightly bigger than in the previous version with all round rods, a/p=0.18.
- Observed high breakdown probability raised questions.

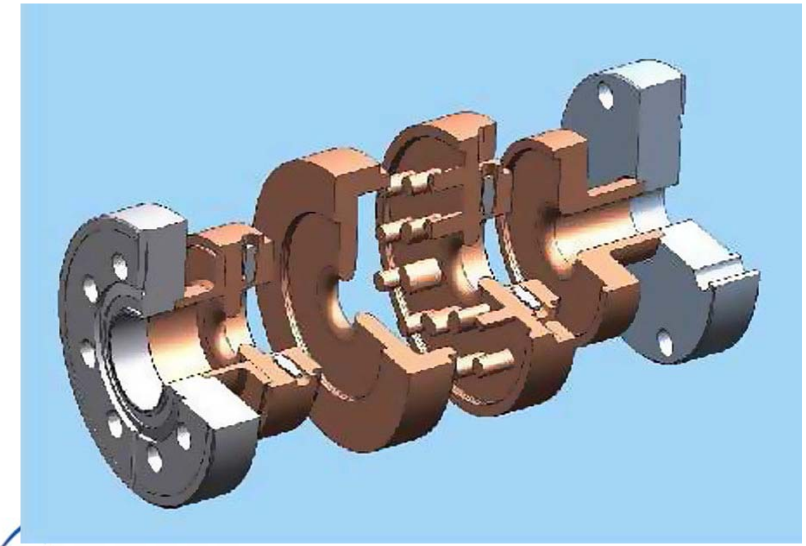


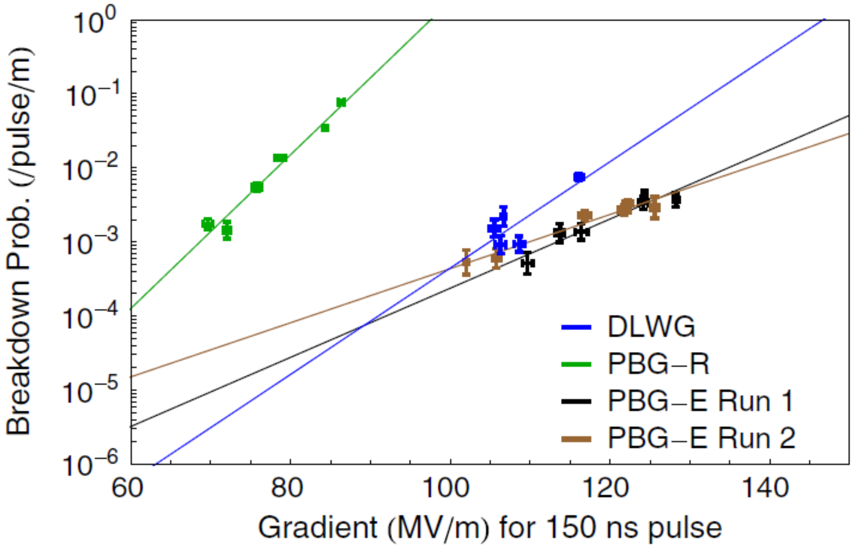


R.A. Marsh *et al.*, PR STAB **14,** 021301 (2011).

MIT X-band PBG resonator with elliptical rods for high gradient tests

- An X-band resonator with 6 elliptical inner rods.
- Measured breakdown probability was very similar to that in DLWG structure in spite of higher peak surface magnetic fields.
- Concluded that high breakdown probability in the structure with round rods was probably due to some damage.

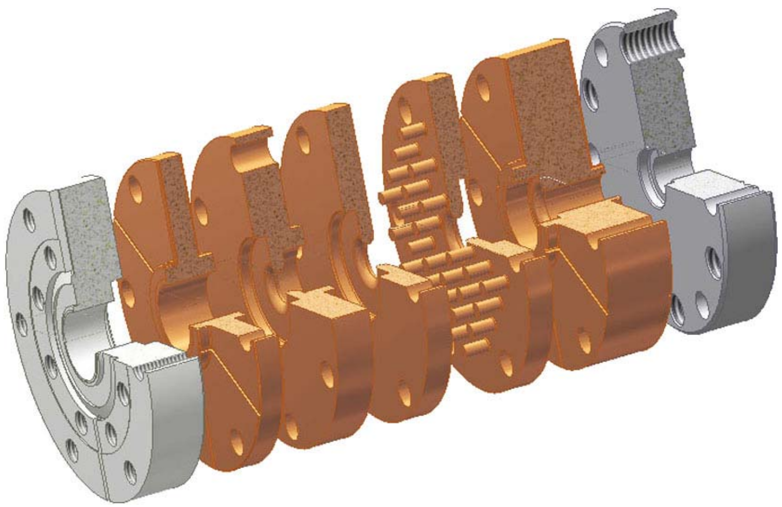


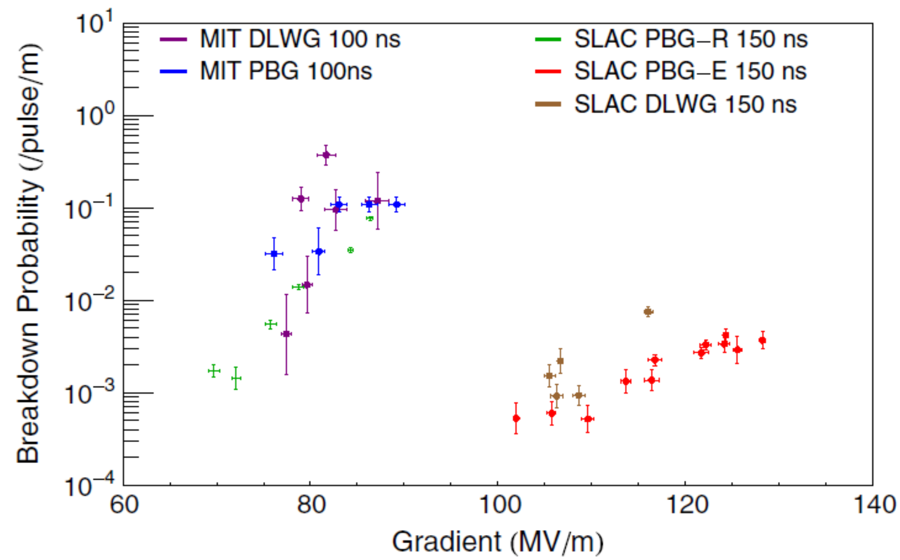


B.J. Munroe *et al.*, PR STAB **16,** 012005 (2013).

MIT K-band PBG resonator with round rods

- A K-band open resonator with thicker round rods, r/p = 0.18.
- Clamped structure, no brazing.
- Tested at the MIT 17.1 GHz high power test stand.
- A data point for breakdown's scaling with frequency

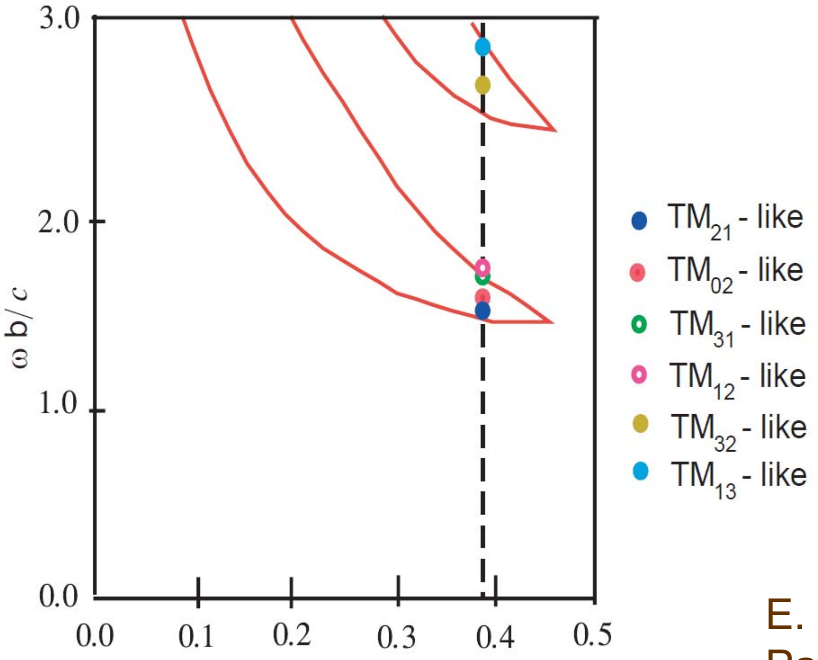


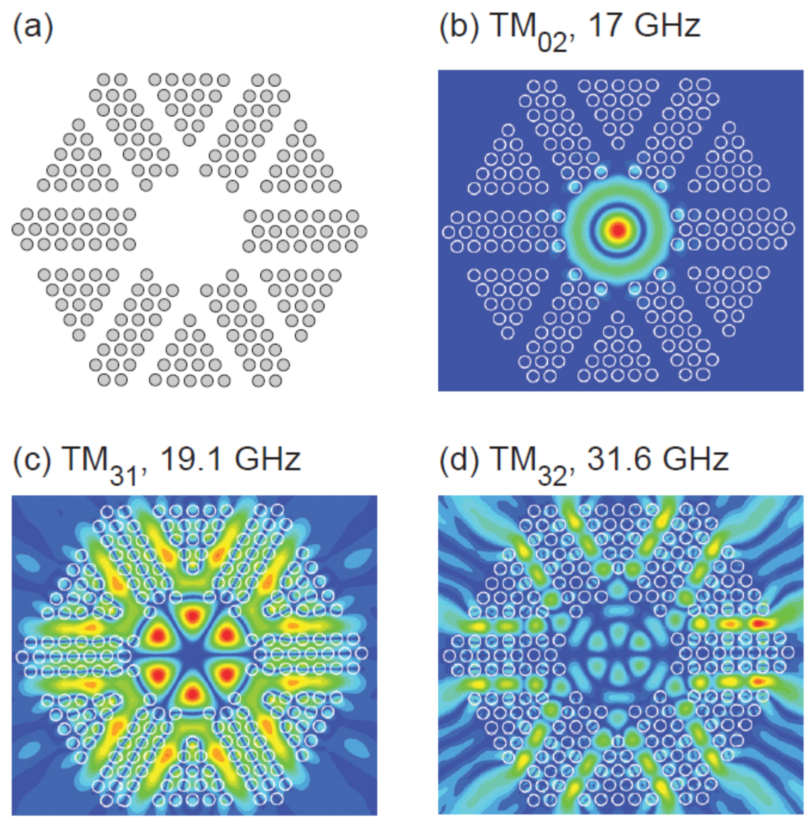


B.J. Munroe *et al.*, PR STAB **19,** 031301 (2016).

Second-mode PBG accelerator cavity

In the structure of dielectric rods it is possible to confine a higher-order TM_{02} mode without confining the lower-order or the higher-order wakefields.

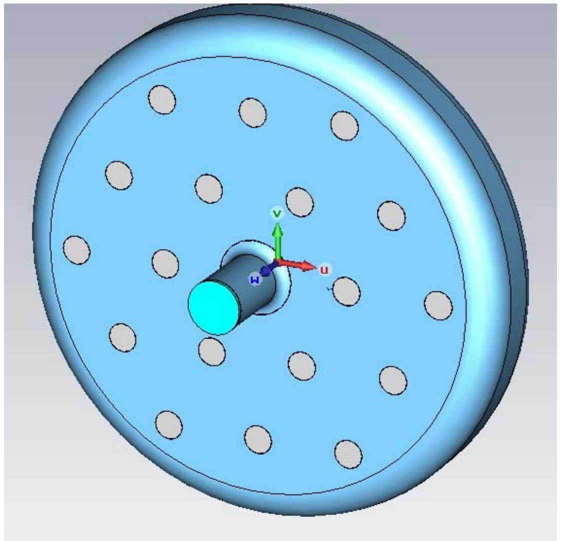




E. Smirnova *et al.* Proceedings of the 2003 Particle Accelerator Conference, p. 1255 (2003).
A. Cook *et al.*,

2.1 GHz SRF PBG resonator

2.1 GHz is 3 x 700 MHz, which is the operating frequency of the Navy FEL beamline.



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	71.43 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)

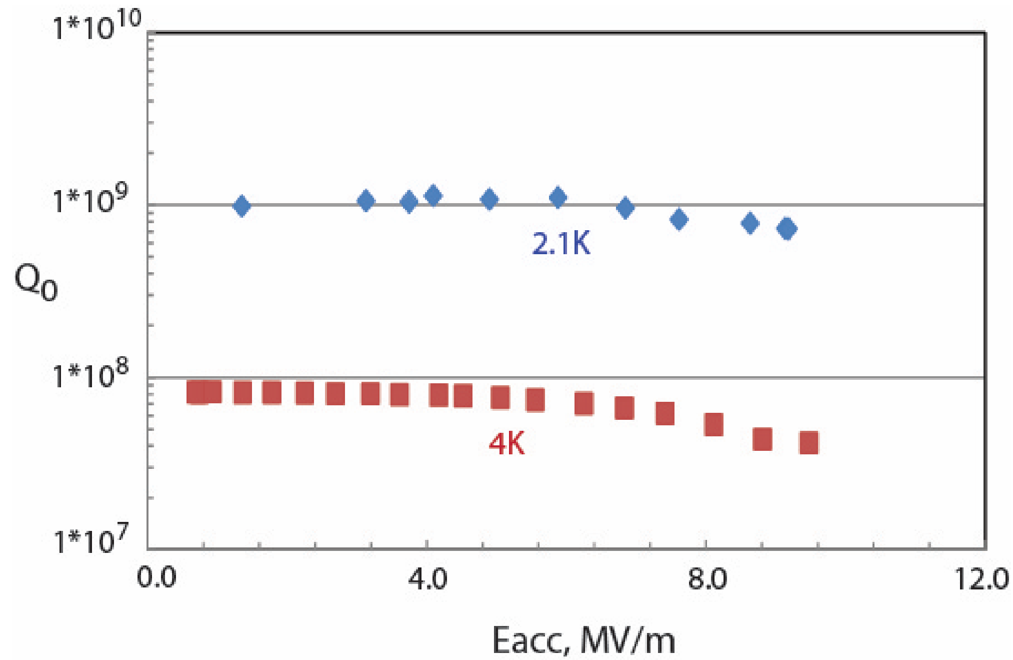
Fabrication of 2.1 SRF PBG resonators

- 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

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

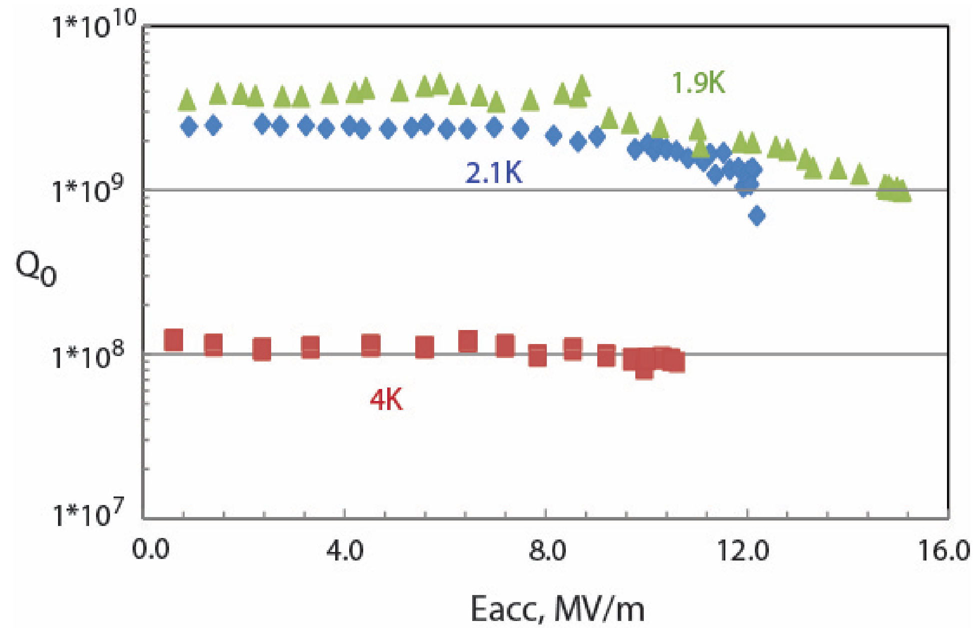


Test results – resonator 2

Resonator 1 was tested on April 23-27, 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

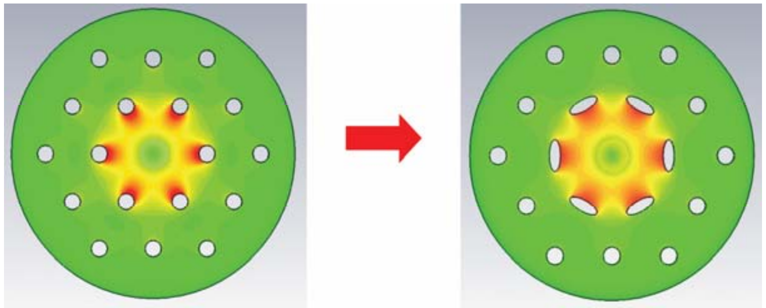
Maximum achieved gradient is 15 MV/m.

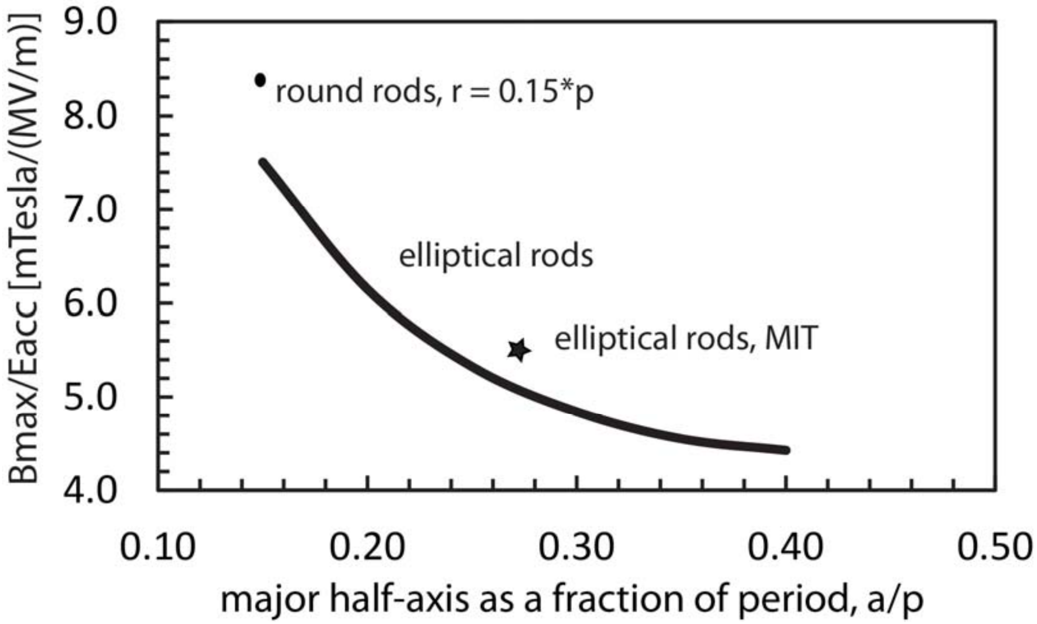


E.I. Simakov *et al.*, Phys. Rev. Lett. 109, 164801 (2012).

PBG accelerator with elliptical rods

- Changing the shape of the rods in a PBG structure to elliptical reduces surface magnetic fields and improves high gradient performance.
- Shape of the elliptical rods must be optimized.

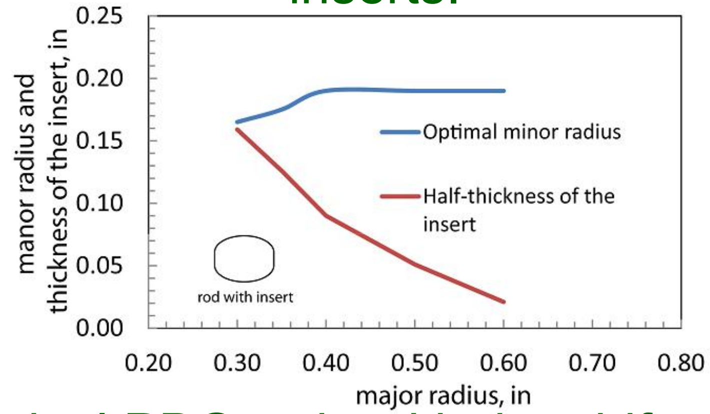




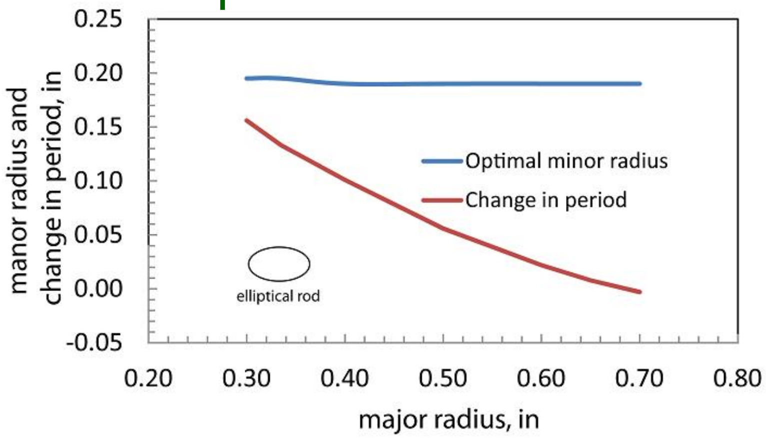
Adjusting the geometry to compensate for the frequency shift

The minor radii of elliptical rods were adjusted first to minimize peak fields. The dimensions of the structure were adjusted second to tune the cavity for the frequency of 2.1 GHz.

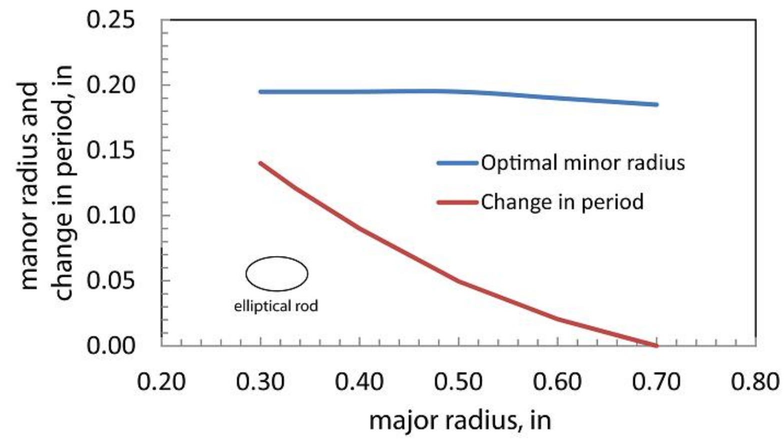
PBG rods with rectangular inserts.



Elliptical PBG rods with the reduced period of the structure.



Elliptical PBG rods with the shifted first row of rods.

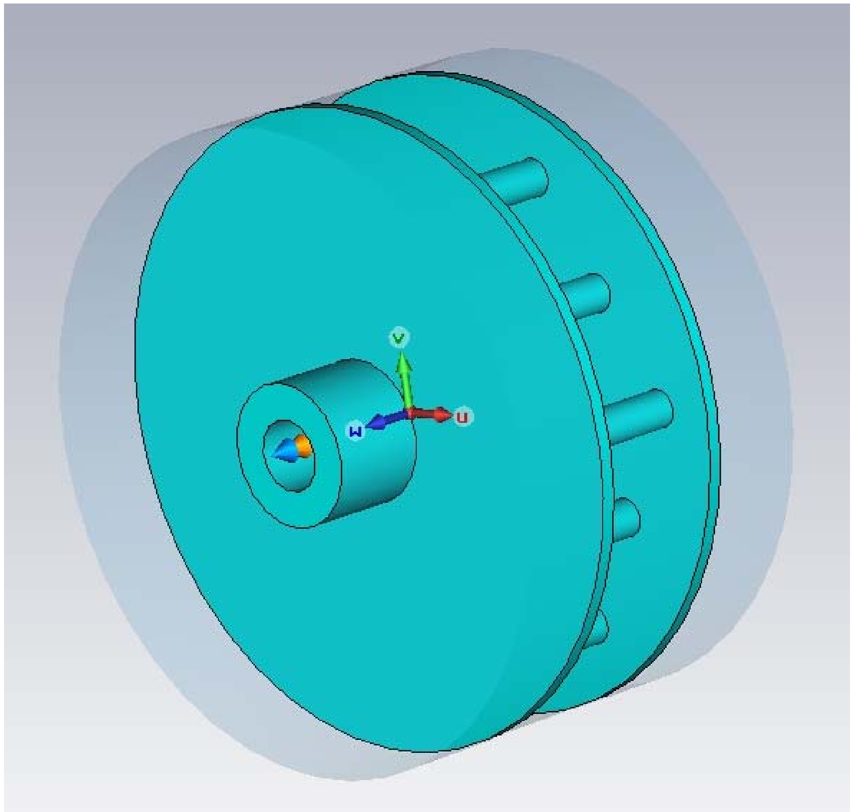


Characterization of the HOM spectrum

We modeled HOMs in a PBG geometry with opened side walls in two ways:

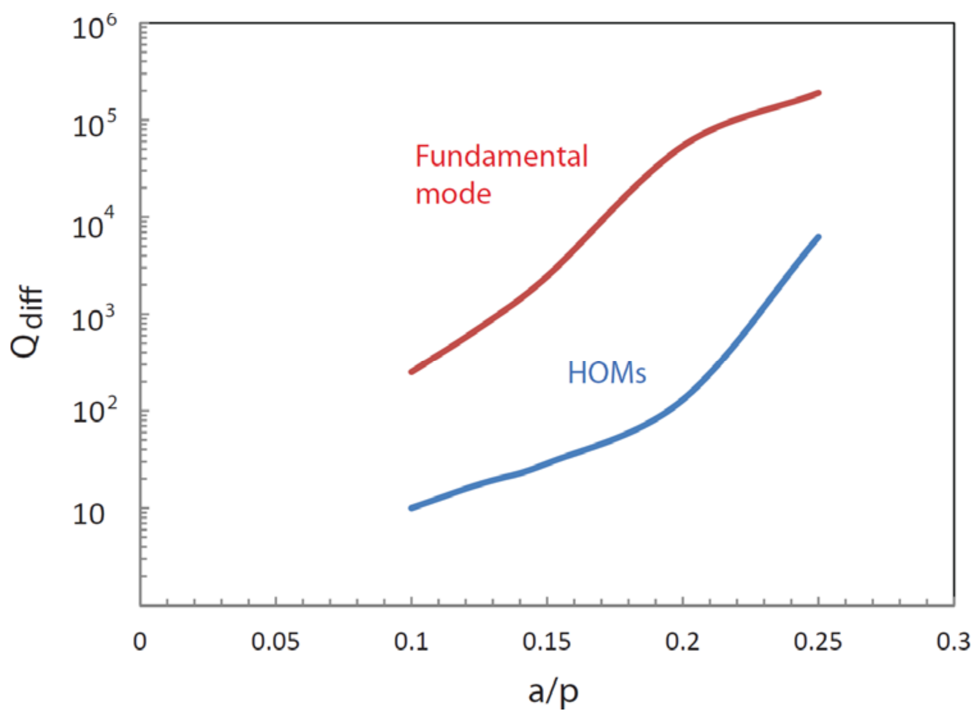
- We excited the cavity with an electron beam (Particle Studio) and looked at the decay of wakefields.
- We excited the cavity with a current pulse (Microwave Studio) and looked at the decay of stored microwave energy and computed Q-factors of decaying modes.

The second method runs faster and converges more easily.



Characterization of HOMs: proof-of-principle

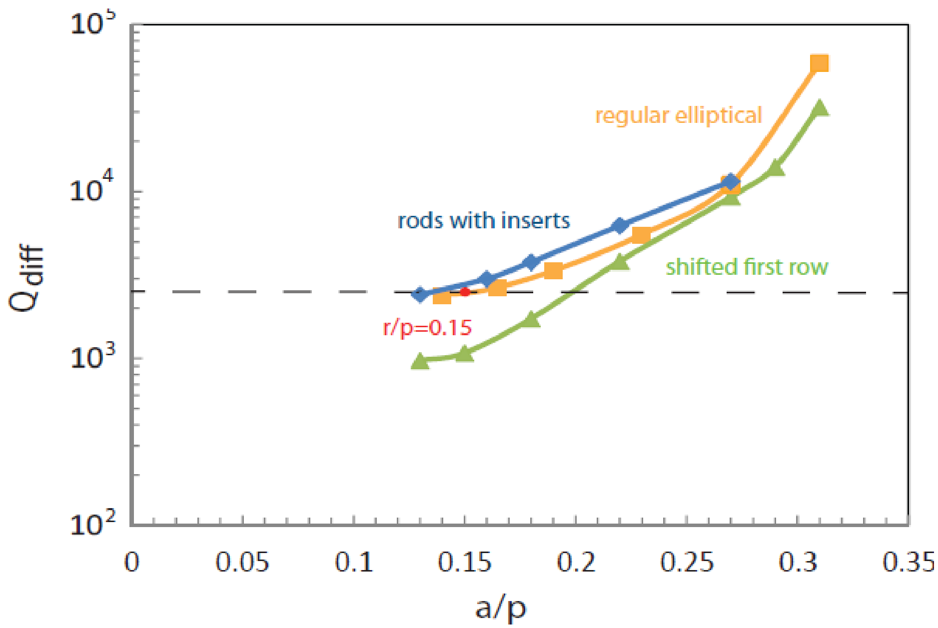
The graphs below illustrate the proof-of-principle application of the energy decay method for characterization of the confinement of the fundamental mode and HOMs in a PBG cavity with cylindrical rods.



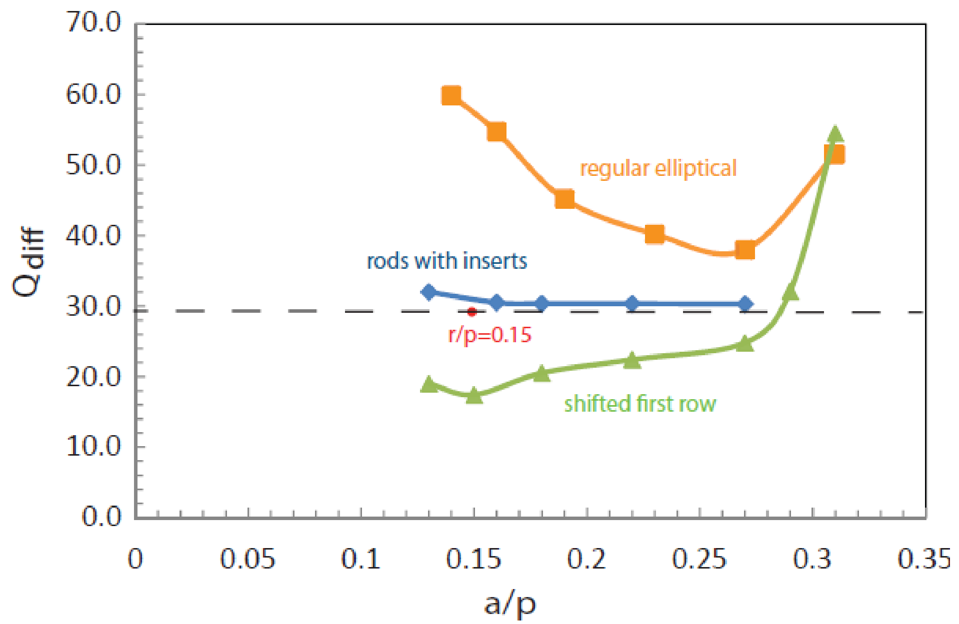
Mode decay in new geometries

The geometries with disturbed PBG structures filter out HOMs more effectively and at the same time confine the fundamental mode well.

Fundamental mode

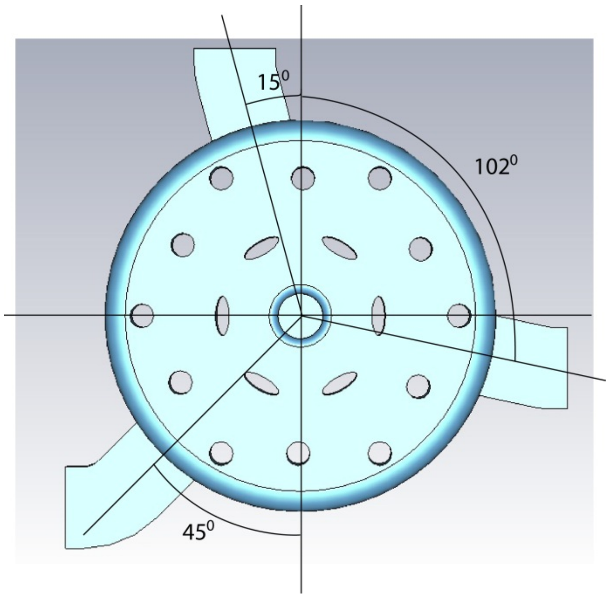


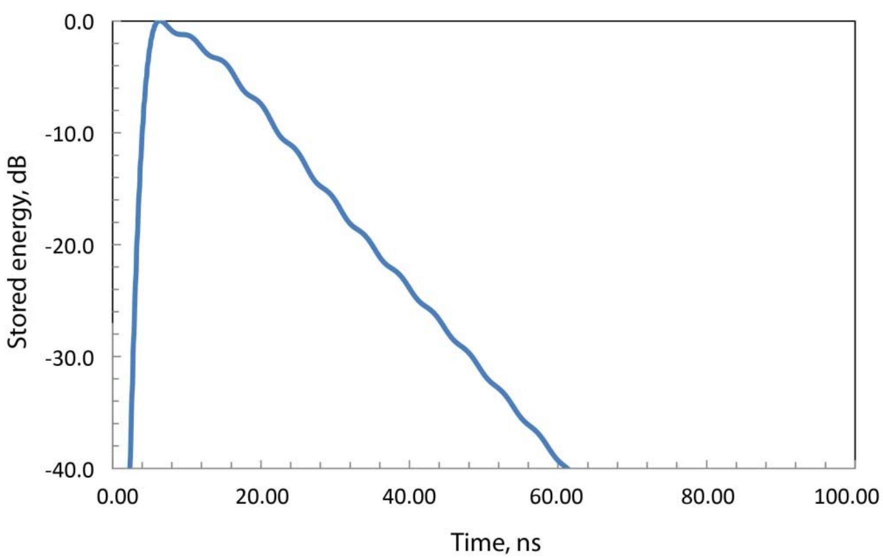
HOMs



HOM couplers

Once the open PBG structure is optimized for HOM suppression, we modeled HOM attenuation in geometries with different configurations of waveguide couplers. The position of the couplers were adjusted for optimal suppression of HOMs. In our best geometry, all major HOMs have Q-factors below 115.





Final design of PBG resonators with elliptical rods

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

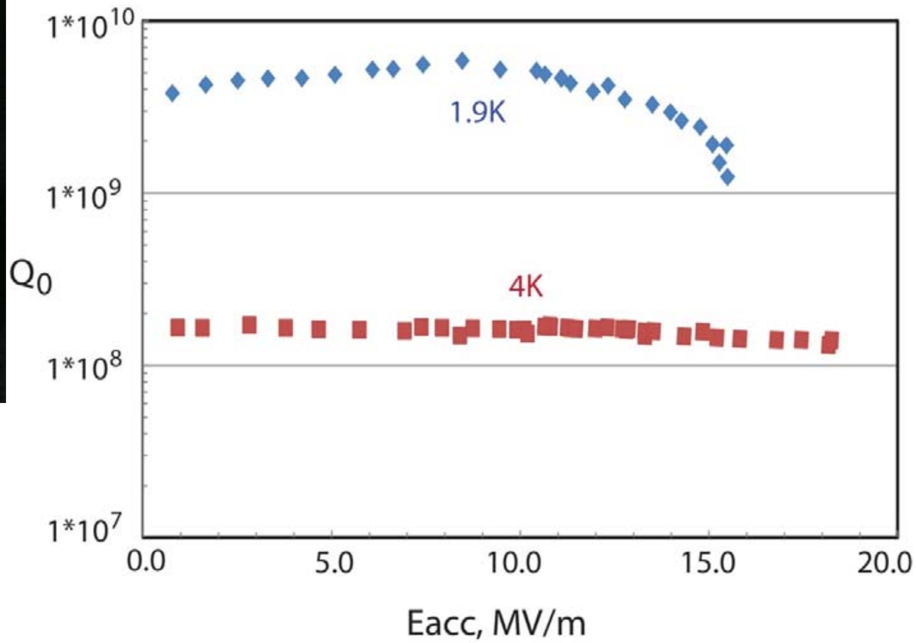
Spacing between the rods, p	56.57 mm
OD of the round rods, d	17.04 mm = 0.3*p
Major OD of the elliptical rod, a	27.94 mm =0.5*p
Minor OD of the elliptical rod, b	9.80 mm
ID of the equator, D0	300 mm
Length of the cell, L	71.43 mm (λ/2)
Q_0 (4K)	$1.8*10^8$
Q_0 (2K)	$6.2*10^9$
R/Q	150.7 Ohm
E_{peak}/E_{acc}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

2.1 GHz SRF PBG resonator with elliptical rods

In 2014 two 2.1 GHz SRF PBG resonators with elliptical rods were designed and tested for DOD JTO. They performed better than resonators with round rods.

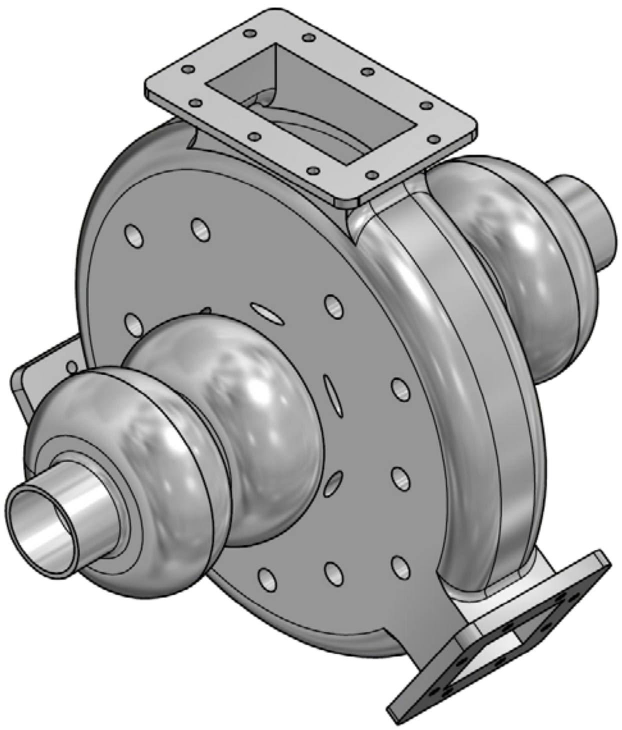
E.I. Simakov *et al.*, Appl. Phys. Lett. **104**, 242603 (2014).

Maximum achieved gradient is 18.3 MV/m.



2.1 GHz multi-cell SRF cavity with a PBG coupler cell

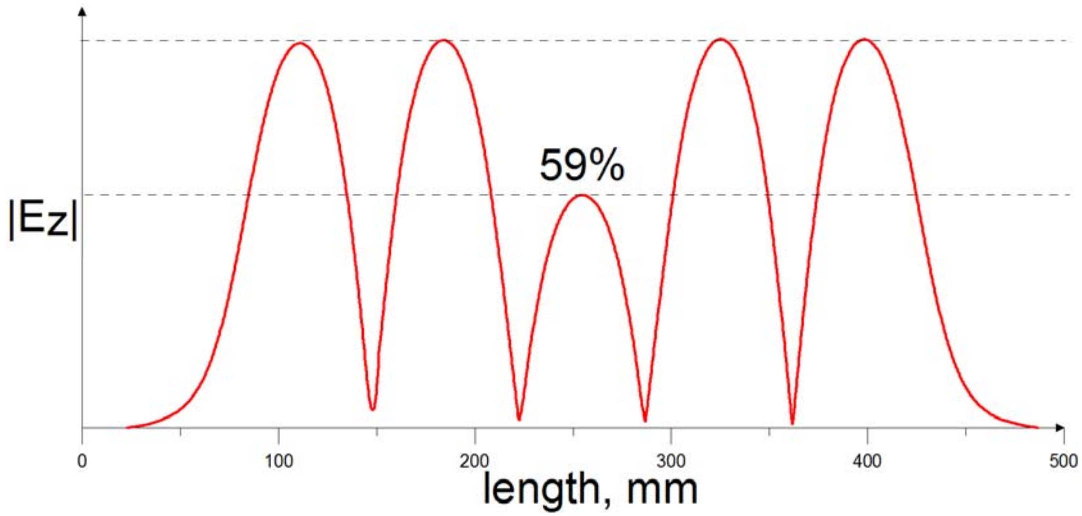
A 5-cell structure was designed with a PBG coupler cell in the middle.

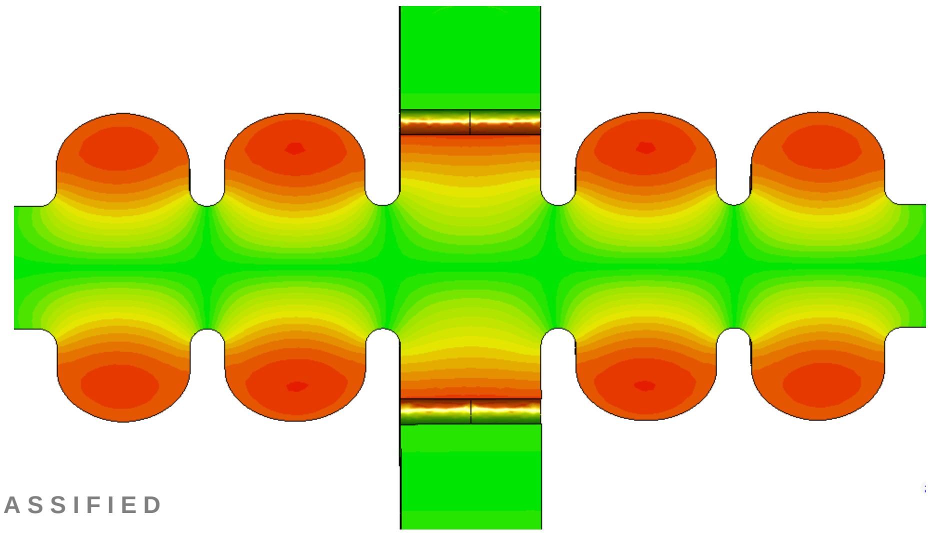


	Module with the PBG cell	Module with five elliptical cells
Length of the module	14.05 in (35.69 cm)	
OD of the elliptical cells	4.95 in (12.57 cm)	
OD of the PBG cell	12.32 in (31.3 cm)	-
Frequency	2.1 GHz	
r/Q	1440 Ohm/m	1468 Ohm/m
R/Q	515 Ohm	525 Ohm
G	265 Ohm	276 Ohm
E_{peak}/E_{acc}	2.65	2.5
B_{peak}/E_{acc}	4.48 mT/(MV/m)	4.27 mT/(MV/m)

Accelerating field profile in the section with PBG cell

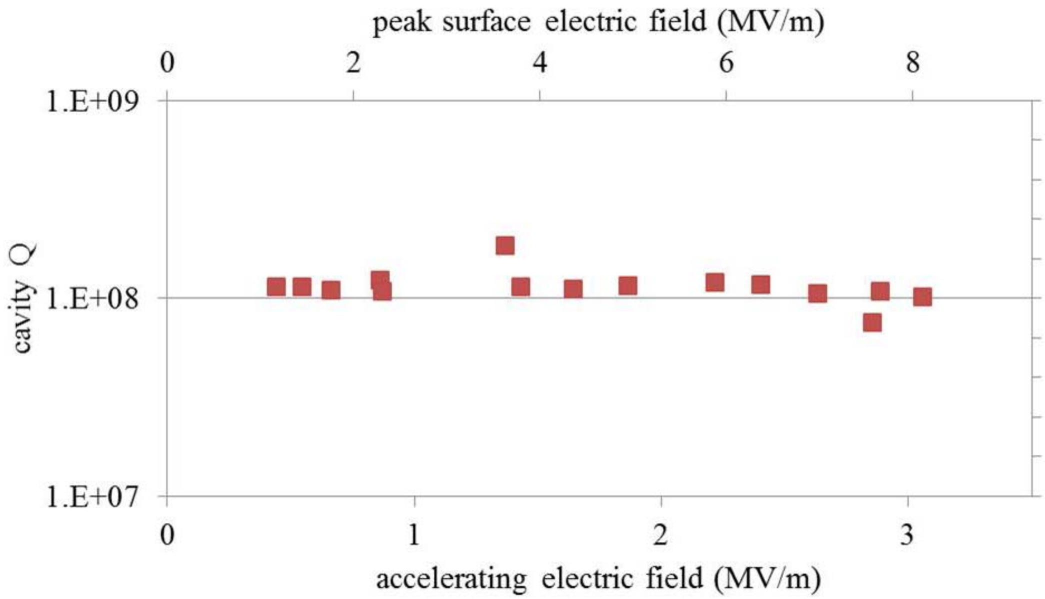
The peak magnetic field on the niobium surfaces in PBG cell can set the operational limits for the whole structure. Thus the cavity is tuned such that the peak magnetic fields are equal in all cells. This reduces the on-axis electric fields in the PBG cell.





Multi-cell SRF cavity: final SRF test

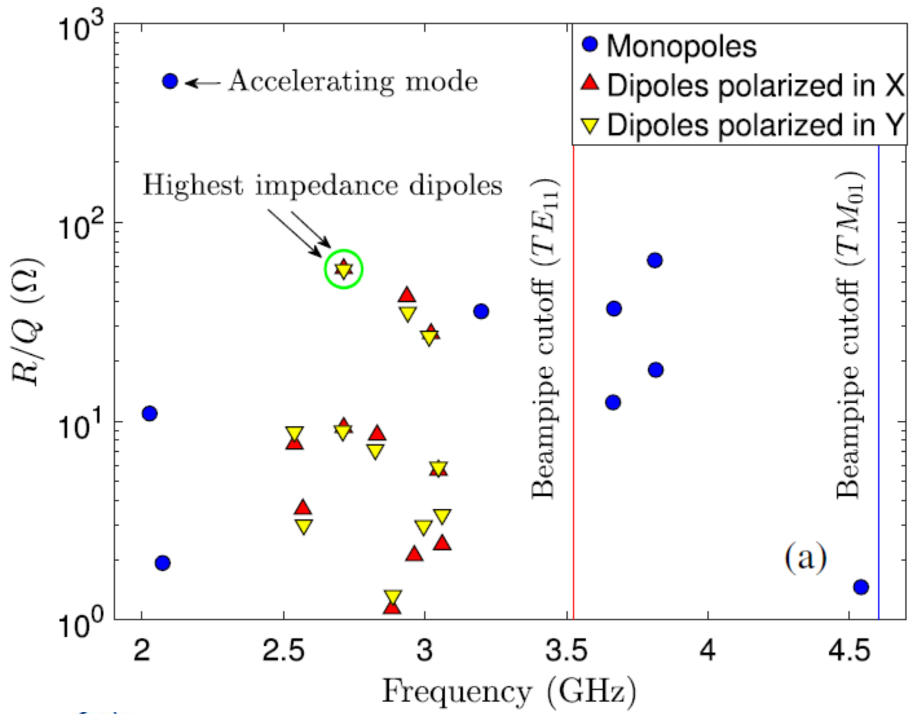
- First SRF test was conducted at LANL.
- The final SRF test was conducted at Niowave in December, 2015.
- High accelerating gradients (limited by available RF power) and high Qs were demonstrated.

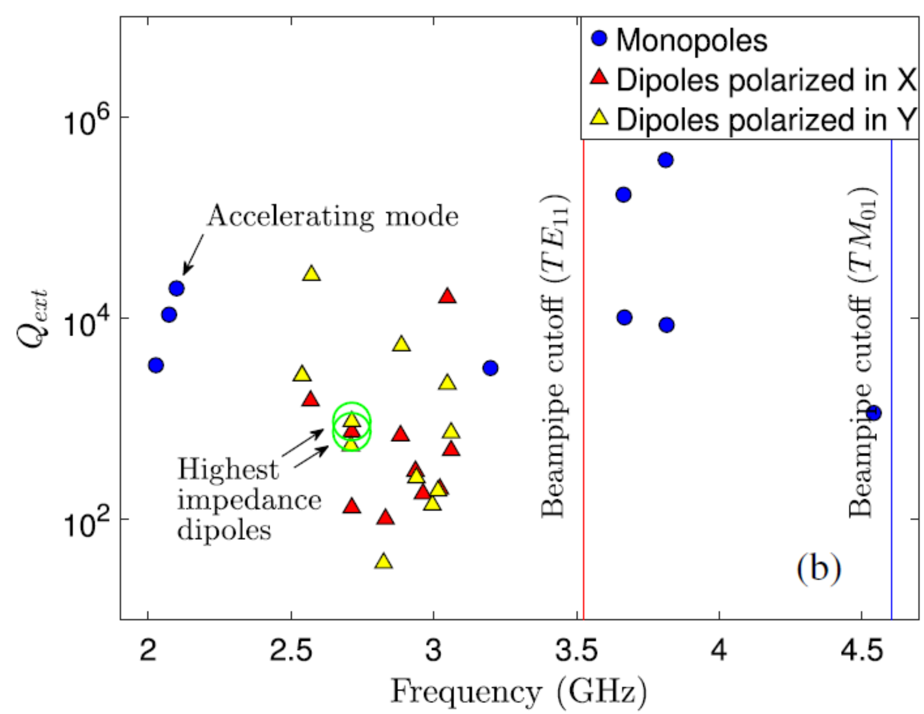


S.A. Arsenyev *et al.*, Appl. Phys. Lett. **108**, 222603 (2016).

Multi-cell SRF cavity: final wakefield measurements

- The five-cell cavity was designed with supreme wakefield suppression properties.
- HOM spectrum was studied in the cold test.

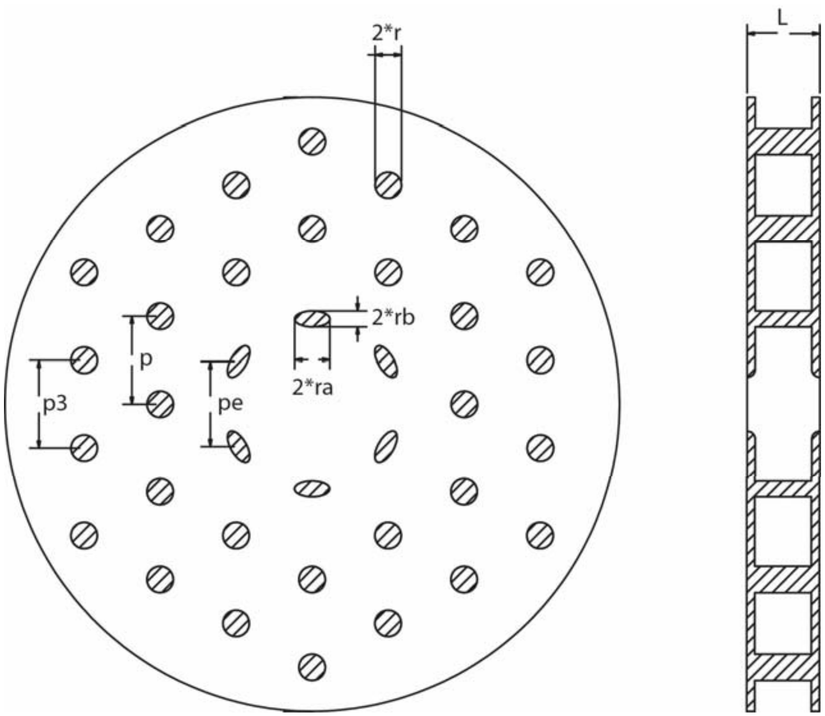




S.A. Arsenyev *et al.*, PR STAB **19**, 081301 (2016).

X-band PBG resonator with elliptical rods

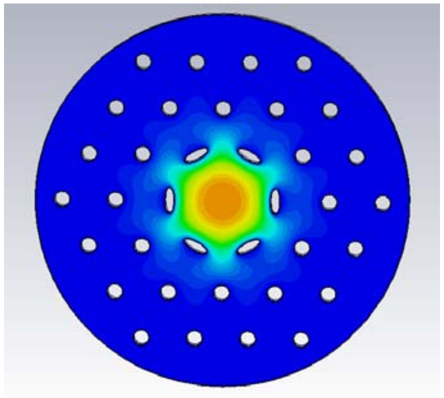
A schematic of the PBG resonator with 6 elliptical rods



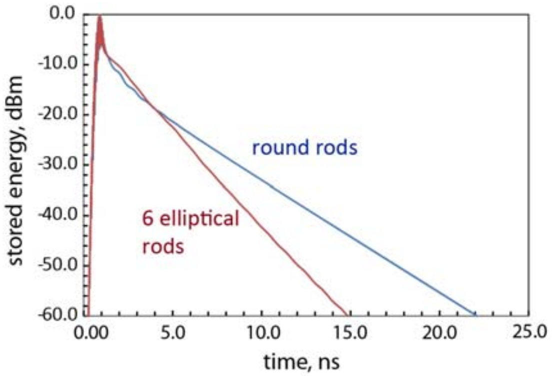
Frequency	11.700 GHz
Phase shift per cell	2π/3
Cell's length, L	8.54 mm
Period of round rods, p	10.33 mm
Radius of round rods, r	1.55 mm=0.15*p
Period of e-rods, pe	10.22 mm = 0.99*p
Period of the 3rd row of rods, p3	10.85 mm = 1.05*p
Major radius of e-rods, ra	2.58 mm = 0.25*p
Minor radius of e-rods, rb	0.93 mm = 0.09*p

Comparison to the PBG resonator with round rods

Field profile in a resonator with 6 elliptical rods



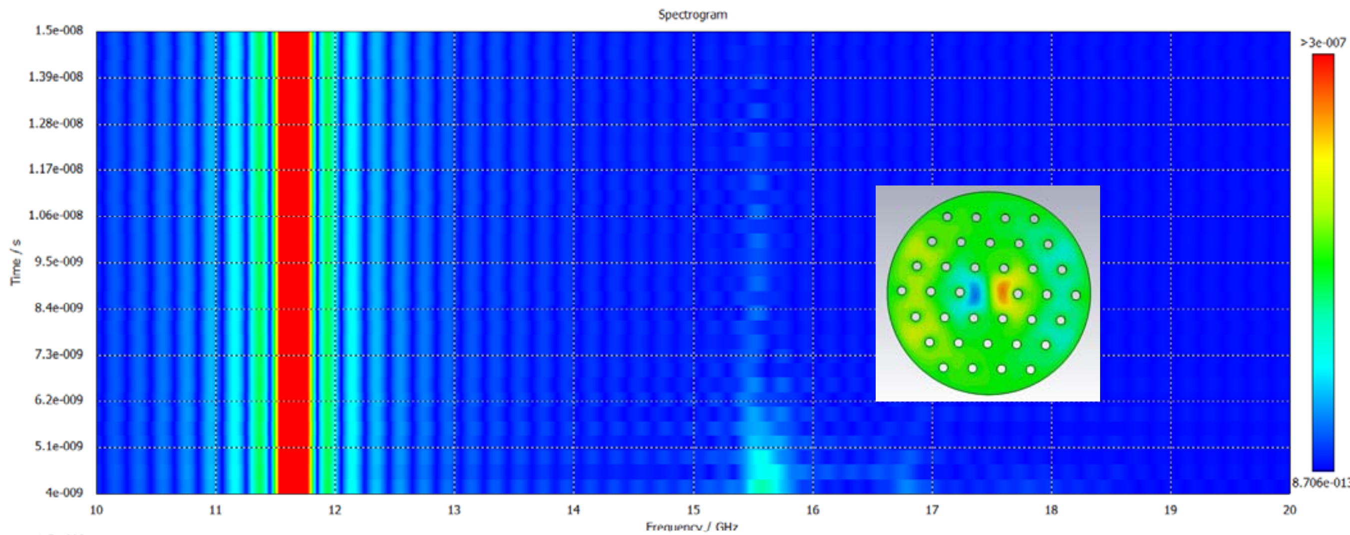
Decay of the energy stored in HOMs in the frequency range 14-18 GHz.



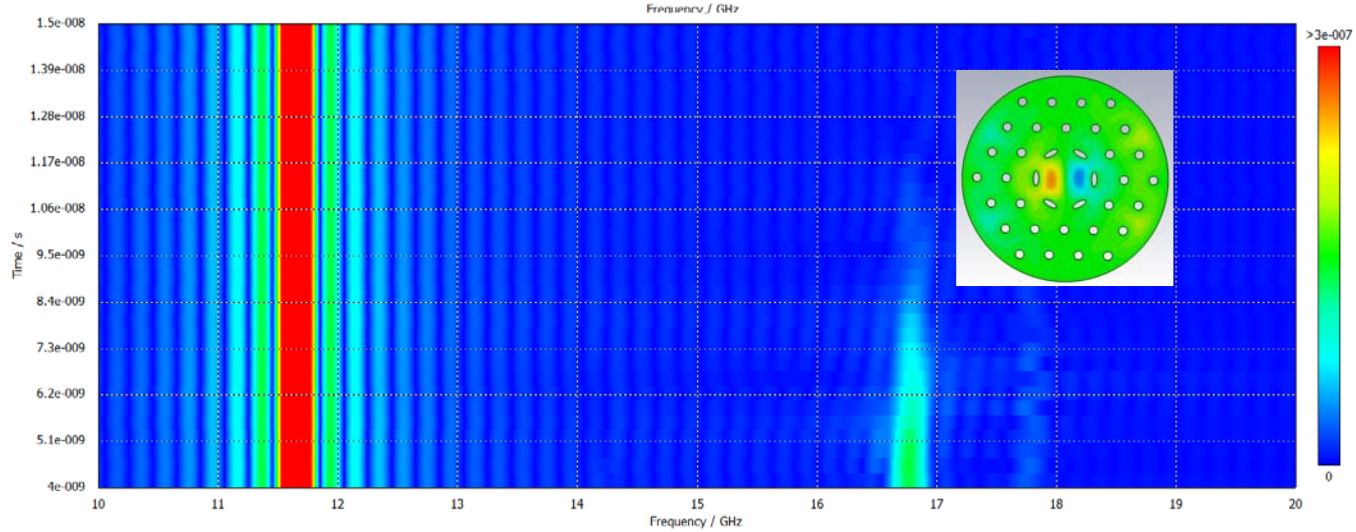
	Resonator with 6 elliptical rods	Resonator with round rods	MIT's resonator with elliptical rods
Q_w	5600	5000	5800
r_s	83.66 MΩ /m	69.75 MΩ /m	86.13 MΩ /m
$[r_s/Q]$	14.94 kΩ /m	13.8 kΩ /m	14.85 kΩ /m
B_{peak}/E_{acc}	5.3 mTesla/(MV/m)	8.4 mTesla/(MV/m)	5.6 mTesla/(MV/m)
E_{peak}/E_{acc}	1.98	2.13	2.07
Q_{diff} (HOMs)	130	212	431

Spectrogram of wakefields: round vs. optimized elliptical

The resonator with all round rods, a/p=0.15



The resonator with 6 elliptical rods and optimized spacing



Additive manufacturing of PBG cavities

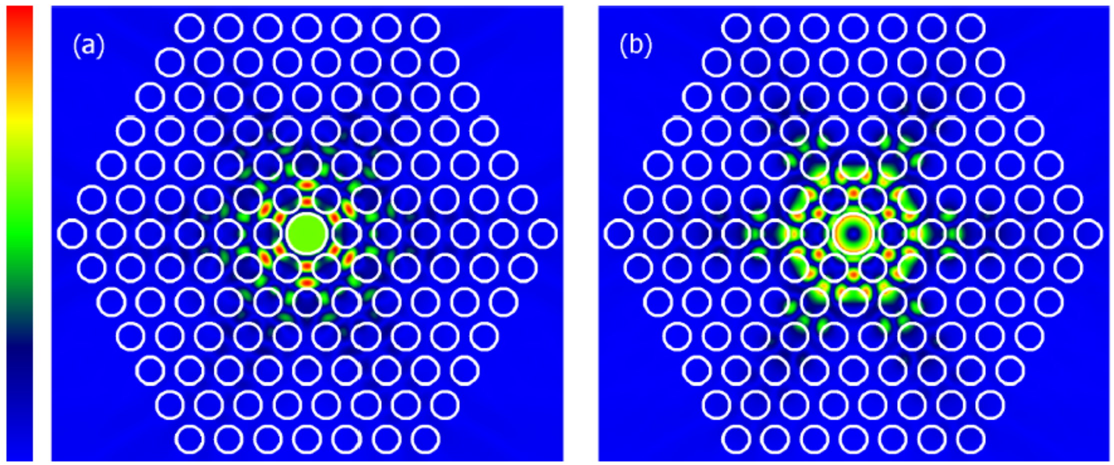
- At LANL we can print plastic models of SRF PBG cavities using the rapid prototyping method.

- Currently, we plan to use cheap plastic models to fine-tune the physical vapor deposition technique for Nb_3Ge coatings.

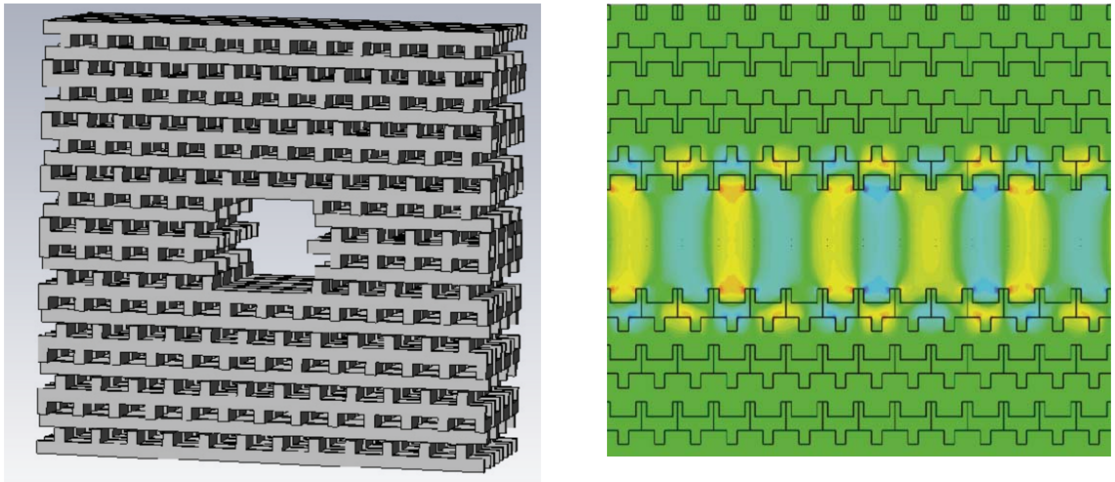
- At some point we may be able to produce niobium SRF PBG with additive manufacturing.

PBG structures for laser acceleration

Hollow fiber:

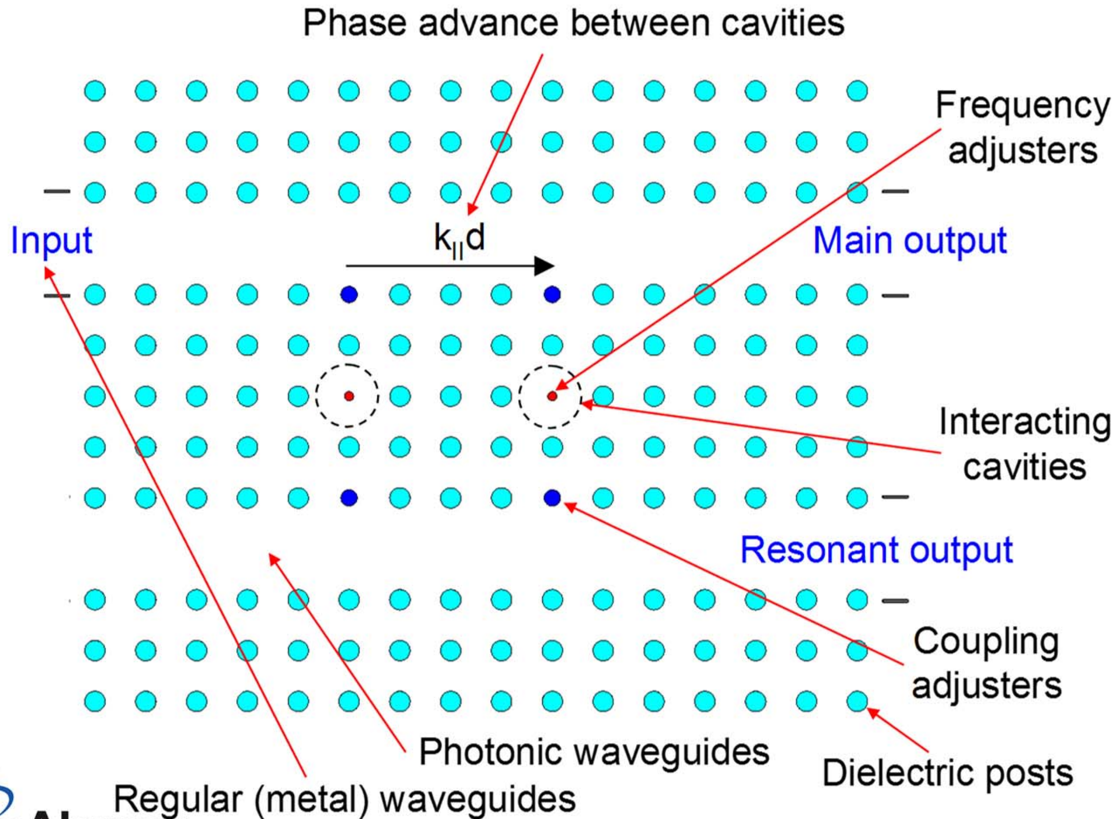


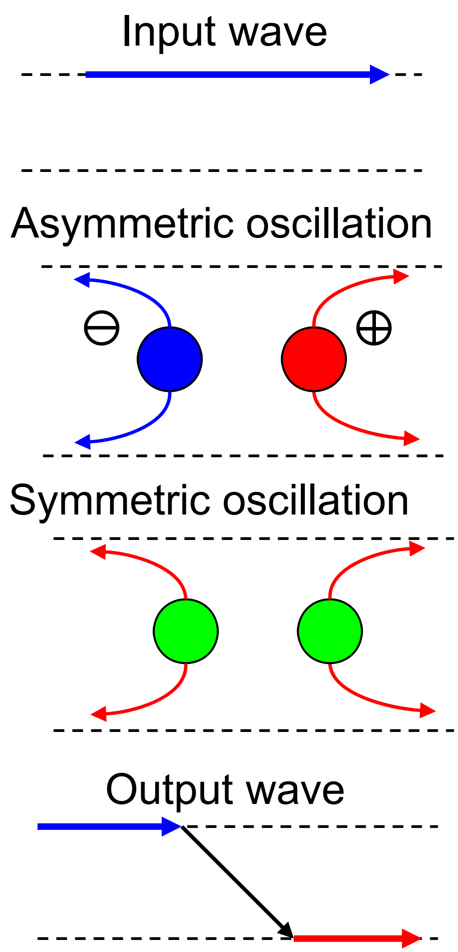
Woodpile structure:



Channel-drop filters

PBG **channel-drop filters** (CDFs) operate based on a constructive interference between resonances in two PBG cavities.

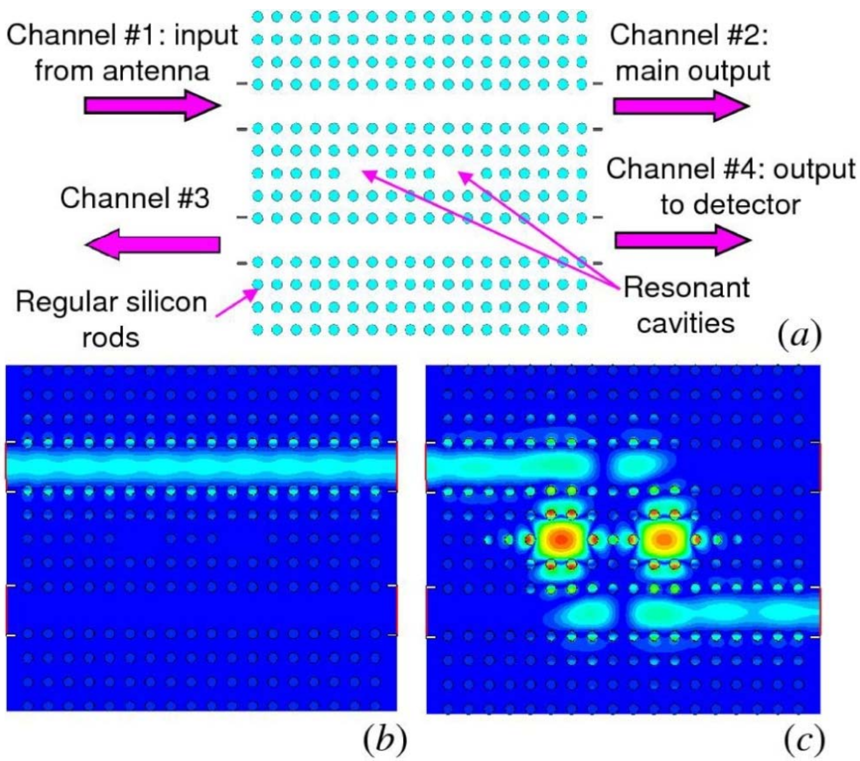


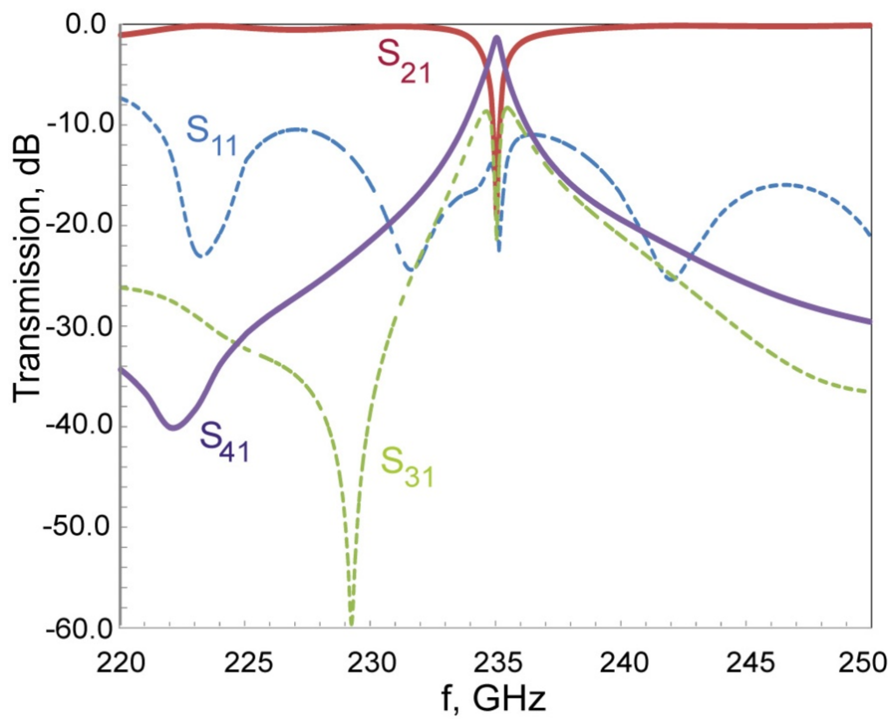


240 GHz channel drop filter

A 240 GHz PBG CDF was designed as a rectangular lattice of high resistivity silicon posts (ε = 11.7) sandwiched between two gold-plated wafers.

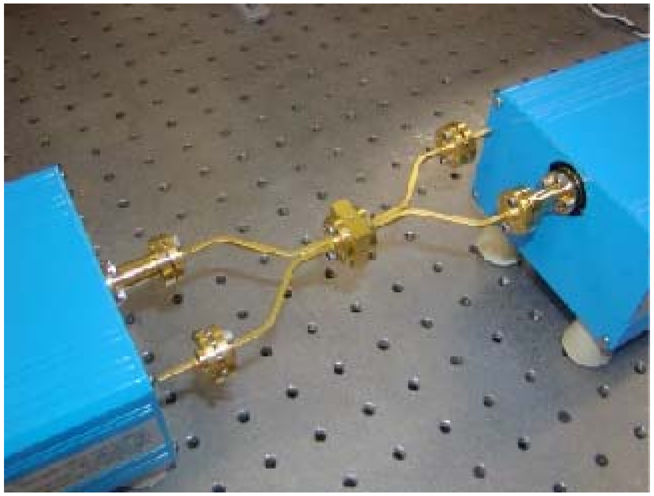
Diameters of the posts	0.188 mm
Spacing between the posts (horizontal/vertical)	0.376 mm / 0.447 mm
Height of the structure	0.432 mm

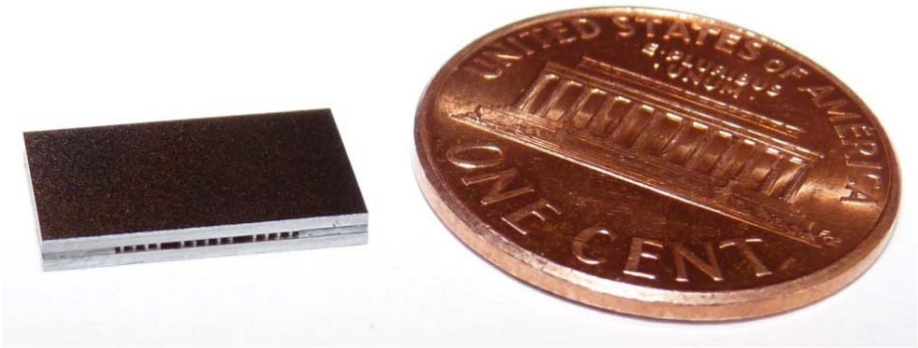


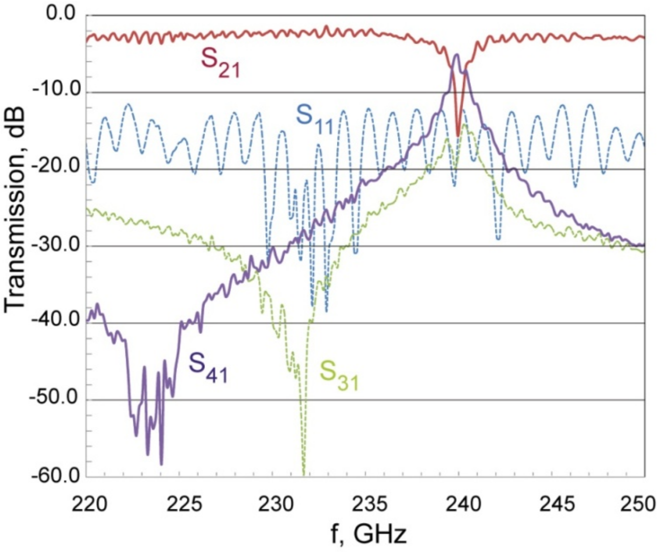


240 GHz channel drop filter: test results

Finished samples were installed inside of a containment structure with screw holes for connection to two pairs of WR03 waveguides. The waveguide ports were connected to WR03 Oleson Microwave millimeter-wave test heads. The transmission properties were measured.





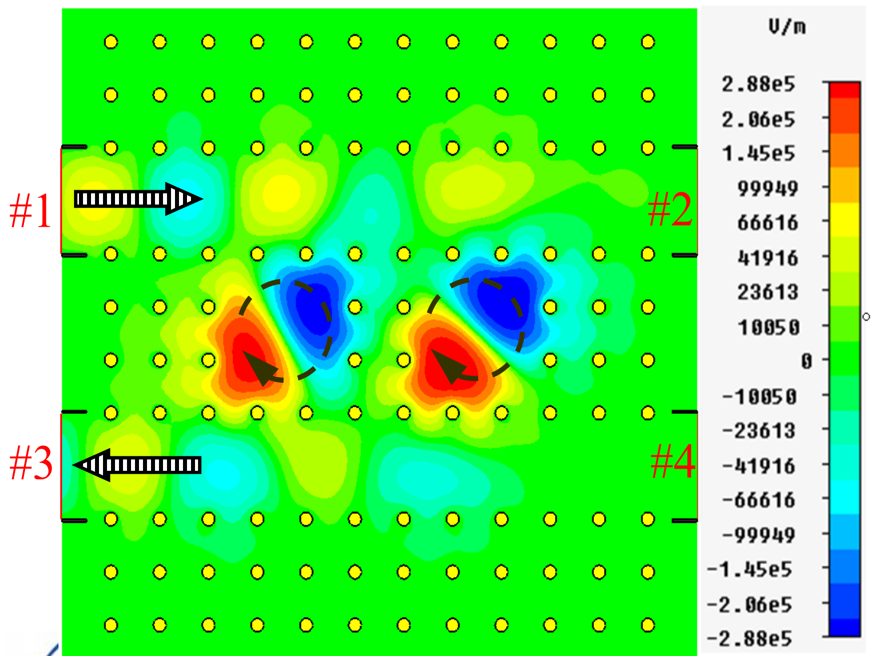


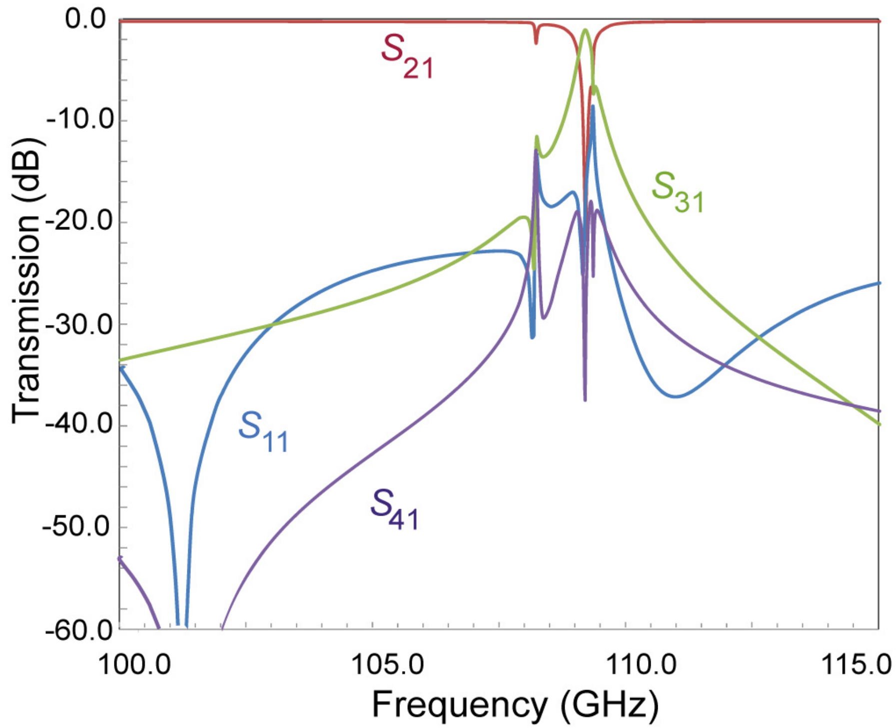
E.I. Simakov *et al.*, Rev. of Sci. Inst. **81,** 104701 (2010).

W-band copper channel-drop filter

A 110 GHz PBG CDF was designed to operate in a higher-order dipole mode to mitigate losses in copper. The filtered power went backward to channel #3.

Diameters of the posts	0.26 mm
Spacing between the posts	1.02 mm
Height of the structure	1.02 mm



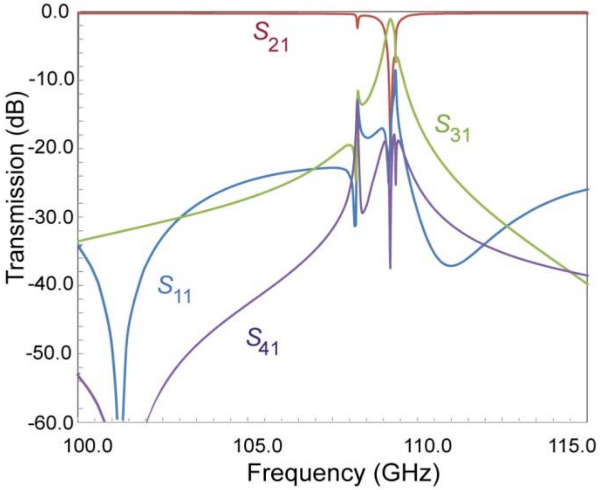


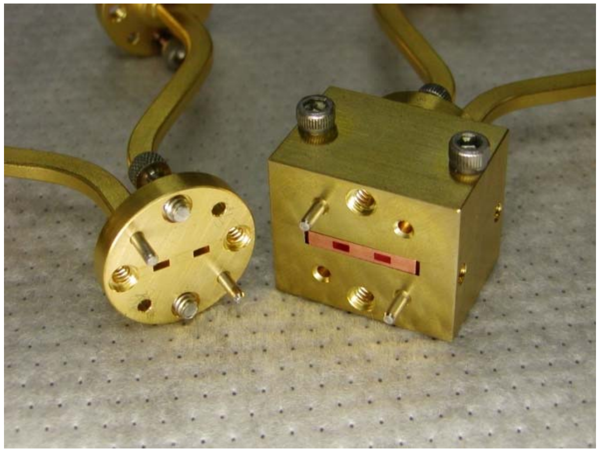
Copper channel-drop filter: test results

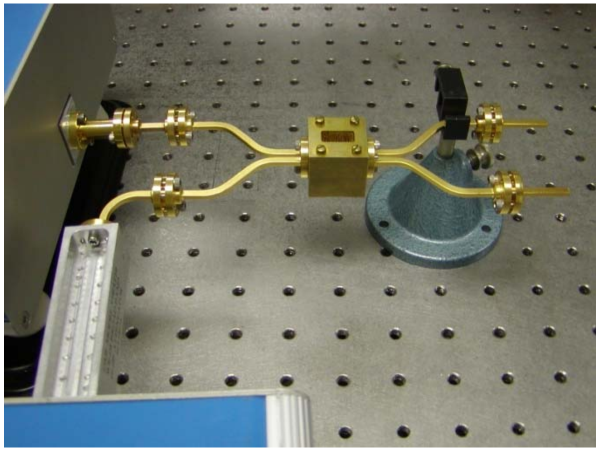
Finished samples were installed inside of a containment structure with screw holes for connection to two pairs of WR08 waveguides. The waveguide ports were connected to WR08 Oleson Microwave millimeter-wave test heads. The transmission properties were measured.

Measurements and simulations were found to be in good agreement.

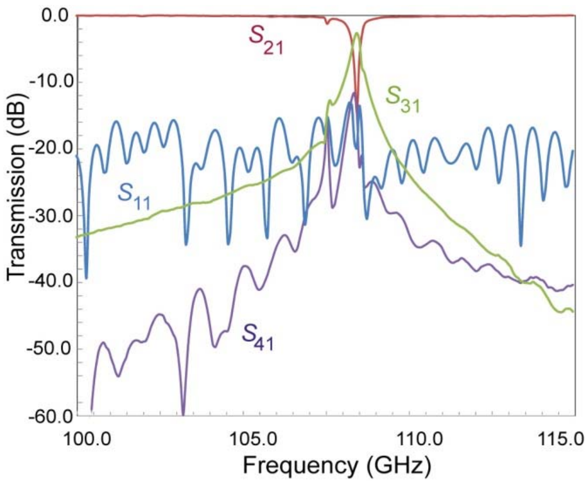
Simulations:





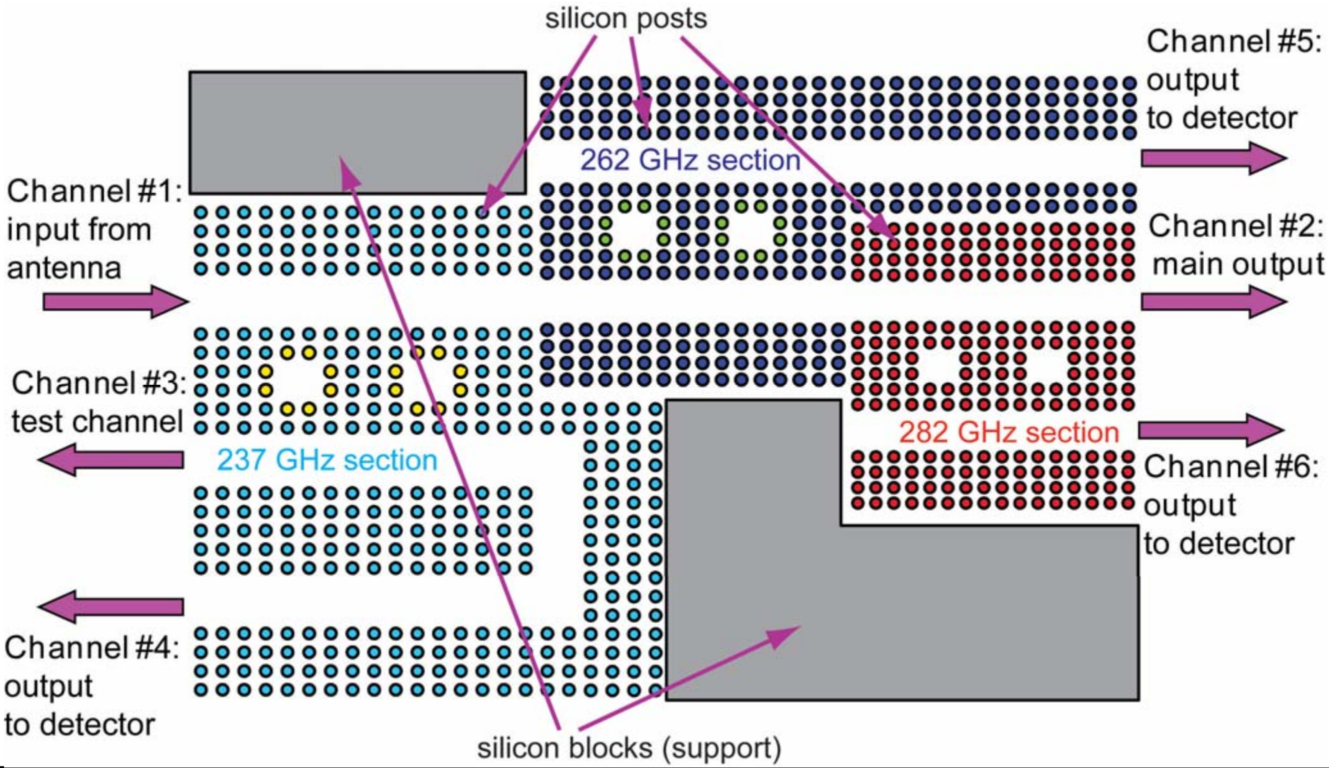


Measurements:



D.Y. Shchegolkov *et al.*, PIER **111,** 197 (2011).

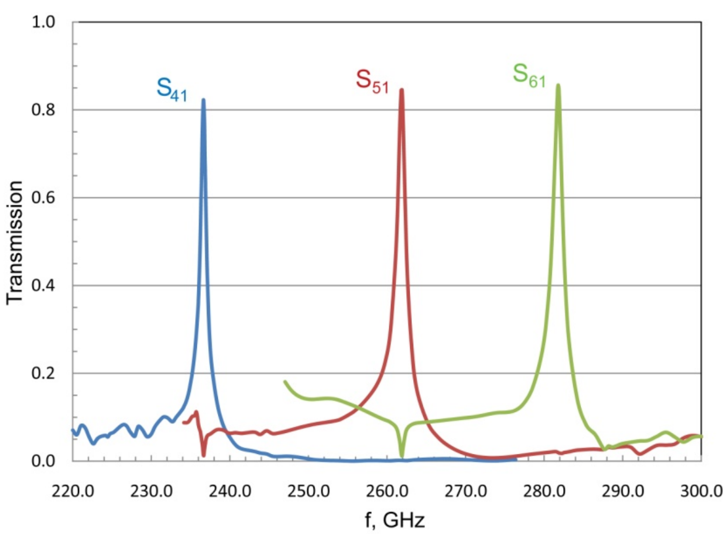
3-channel filter

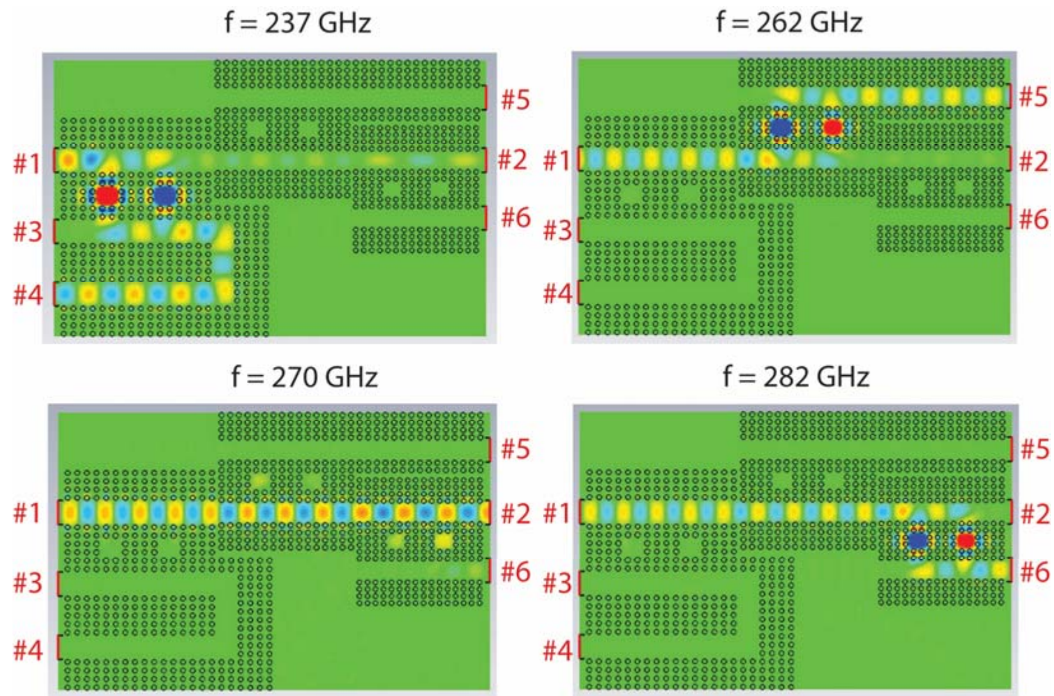


Diameters of the posts	0.170-0.197 mm
Horizontal spacing between the posts	0.297-0.357 mm
Vertical spacing between the posts	0.255-0.310 mm
Width of the PBG waveguide	0.864-1.080 mm
Height of the structure	0.432 mm

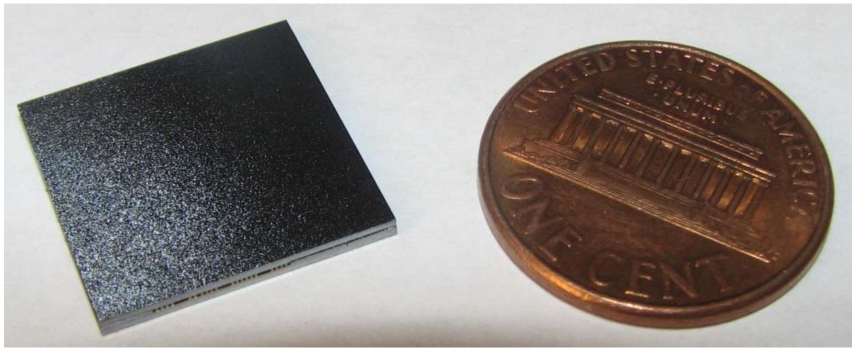
Transmission characteristics for the 3-channel filter

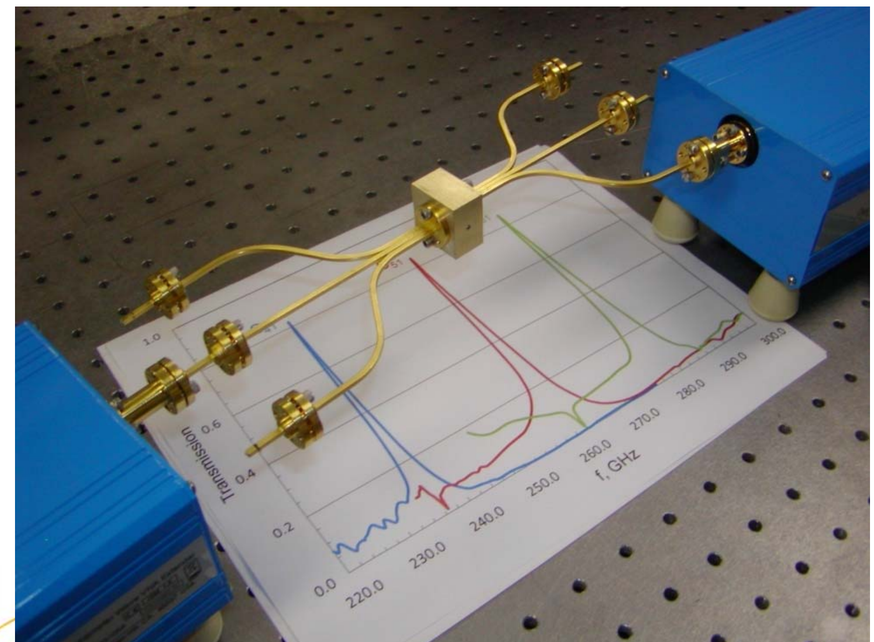
A three-channel device was designed with the channel frequencies near 240 GHz, 260 GHz, and 280 GHz. The diameters of the posts and the spacings varied in three different sections of the filter. Channel #1 was the drive channel. The resonant frequencies were filtered and could be sampled in output channels #4, #5, and #6.





Performance of the 3-channel sample





Measurements of the final device confirmed the validity of the design. However, we observed losses due to:

- the reduced overall height of the device;
- quality of fabrication.