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Title: Advanced accelerator and mm-wave structure research at LANL

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# Advanced accelerator and mm-wave structure research at LANL

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**June 23rd, 2016**

# Outline

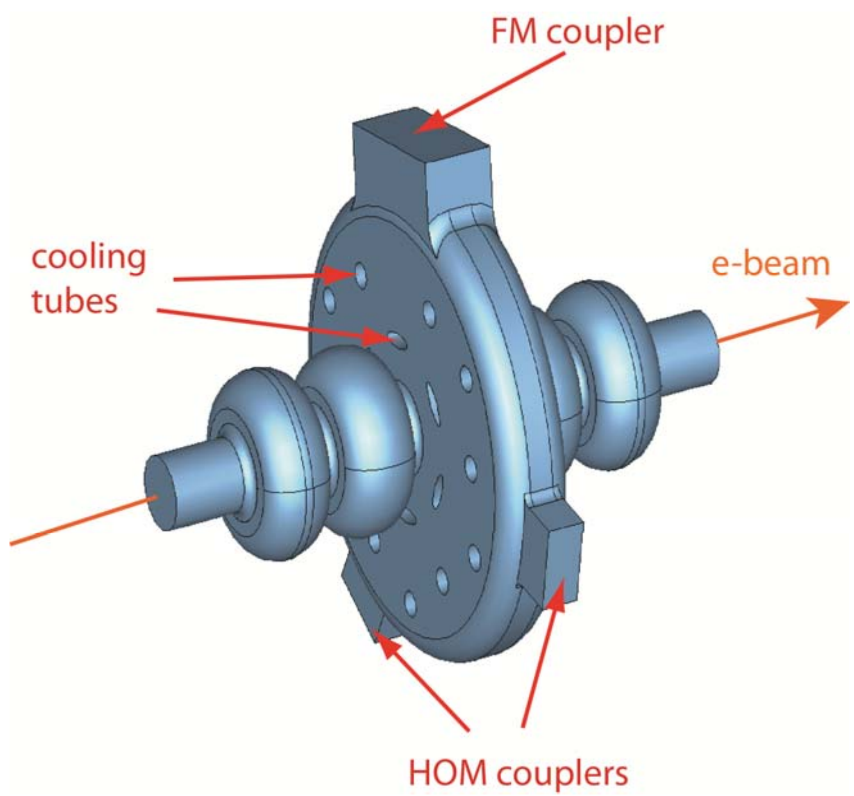
- **Motivation for PBG research**
- **PBG structures, MIT PBG accelerator.**
- **SRF PBG cavities at LANL:**
  - 2.1 GHz single-cell SRF PBG cavity
  - 2.1 GHz single-cell SRF PBG cavity with elliptical rods
  - 2.1 GHz multi-cell SRF PBG cavity – Sergey's thesis
- **X-band PBG cavities at LANL:**
  - 11.7 GHz structure – wakefield experiment
  - Optimized 11.7 GHz structure with elliptical rods
- **W-band PBG TWT at LANL.**
- **Other advanced accelerator projects:**
  - Beam shaping with an Emittance Exchanger
  - Diamond field emitter array cathodes
  - Additive manufacturing of novel accelerator structures

# Motivation for PBG research

# PBG couplers for superconducting accelerators

PBG structures present us with unique means to place FM and HOM couplers in an accelerating cavity

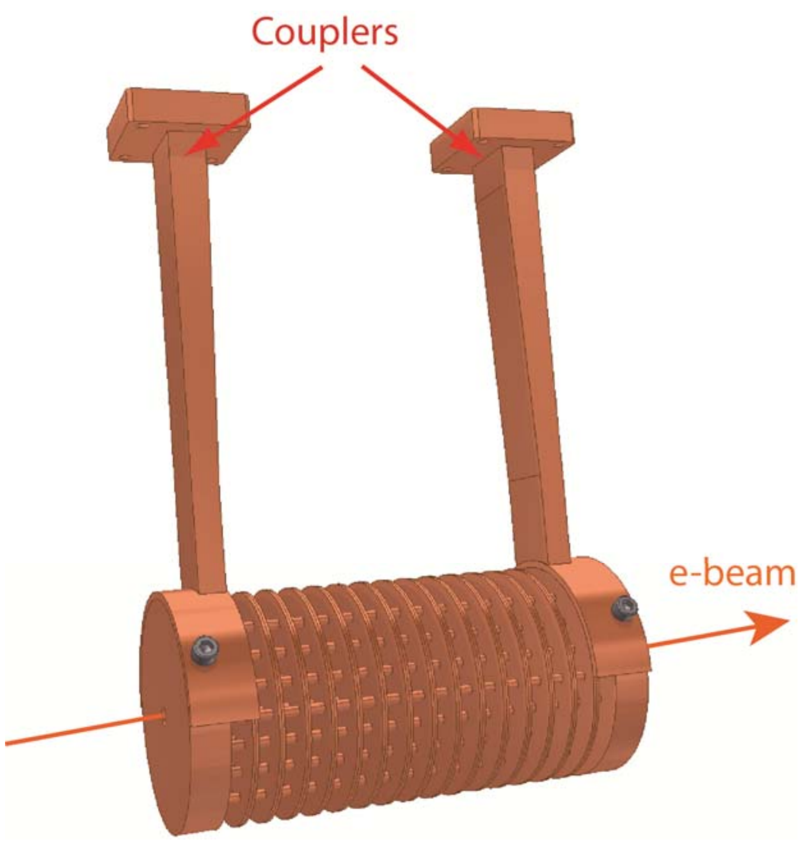
- Much lower external Q-factors for HOMs
- Higher real estate gradient
- Possibility to scale SRF accelerators to higher frequency. Examples – linearizing cavities.



## Open PBG structures for room-temperature accelerators

PBG structures present us with unique means to construct an open accelerating structure with freely radiating wakefields:

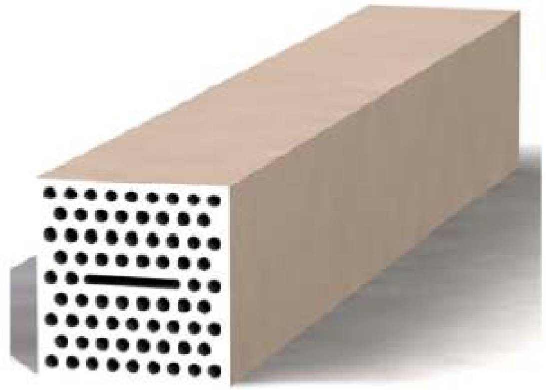
- Much lower external Q-factors for HOMs
- Possibility to scale NCRF accelerators to higher frequency $\Longrightarrow$ more compact accelerators, higher accelerating gradients, lower power requirements.



# PBG structures for W-band TWTs

**LANL is conducting research to demonstrate W-band synthetic aperture radar (SAR) with sub-millimeter resolution.**

- SAR is typically mounted on a moving platform such as an aircraft or spacecraft.
- Current (2010) airborne systems provide resolutions of about 10 cm.
- Laboratory experiments demonstrate that 1 cm resolution can be achieved with an ultra-wideband W-band system.
- W-band SAR requires a traveling-wave tube with1 kW average power, 10 GHz bandwidth.
- This cannot be accomplished by simply scaling conventional TWT architectures to W-band. **New concepts required.**

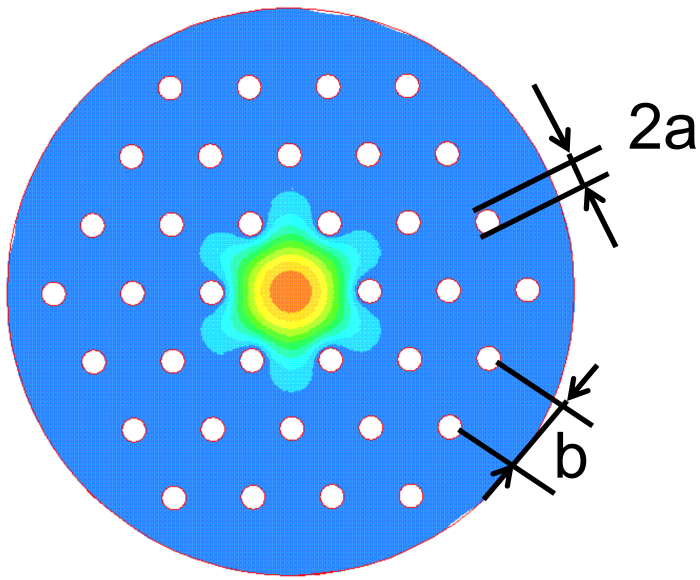


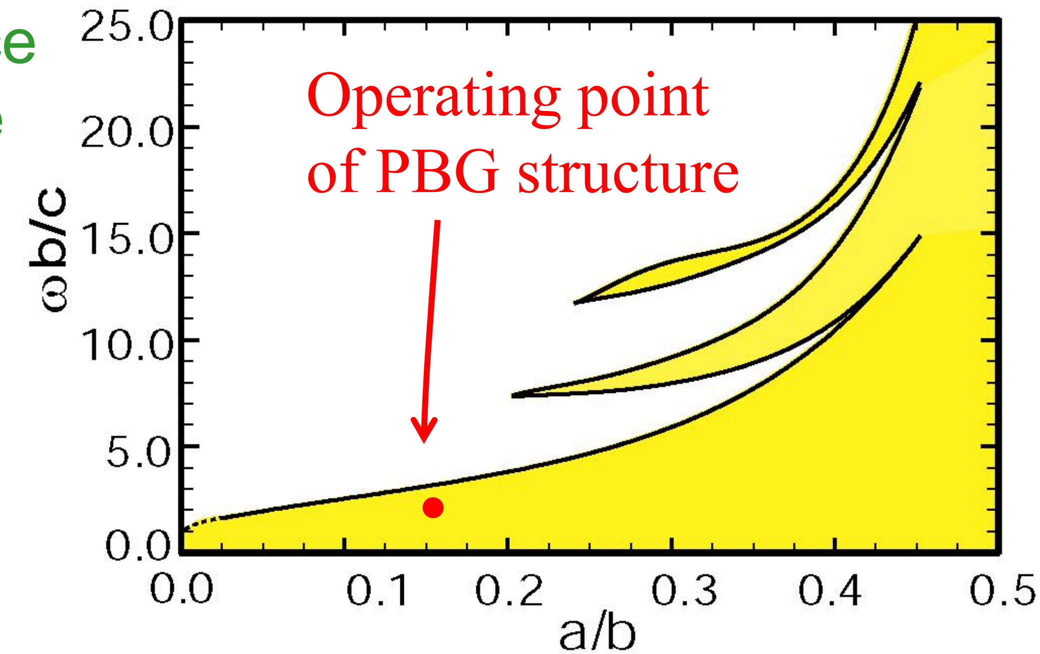
# PBG structures,

# MIT PBG accelerator

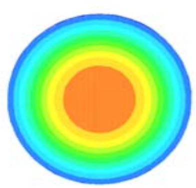
# PBG resonators

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




Pillbox Cavity, $TM_{01}$ mode



Single mode operation.

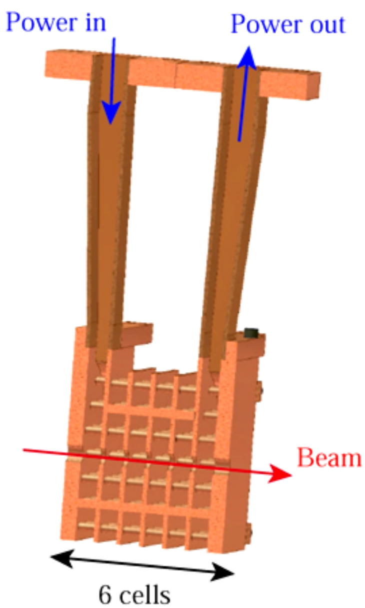
No higher order dipole modes.

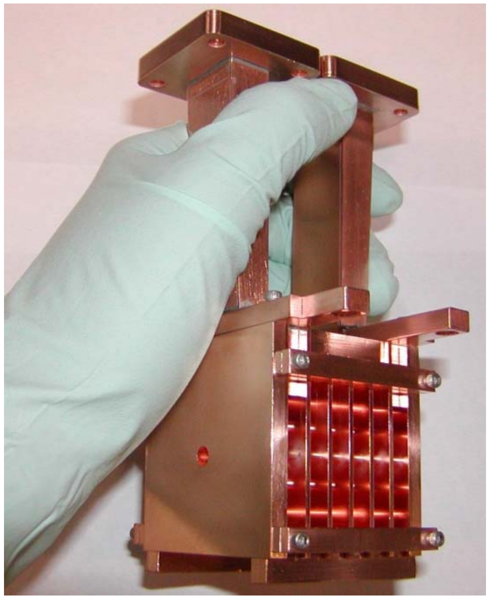
MIT PBG accelerator uses this structure.

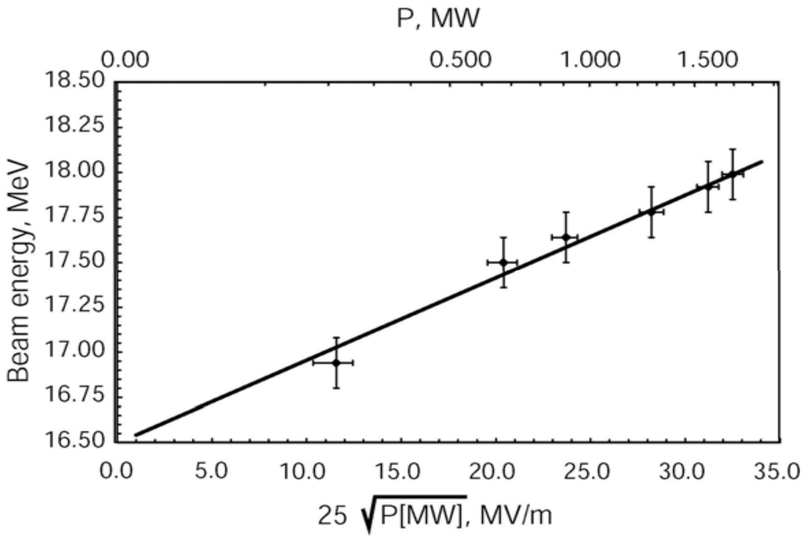
## MIT PBG accelerator

**17-GHz MIT PBG accelerator** – first and only experimental demonstration of acceleration in a PBG structure.

- Frequency: 17.137 GHz.
- Open structure, wakefields radiate freely into the vacuum chamber.



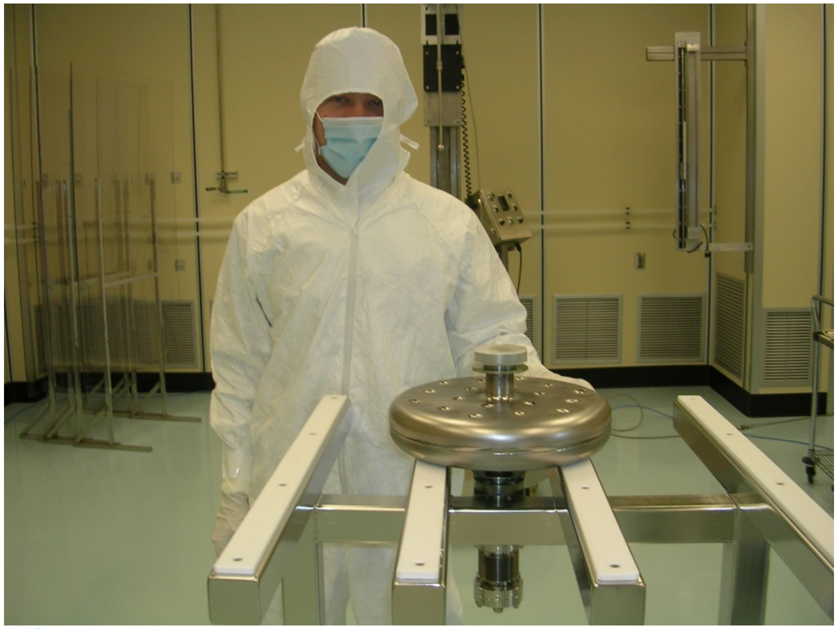


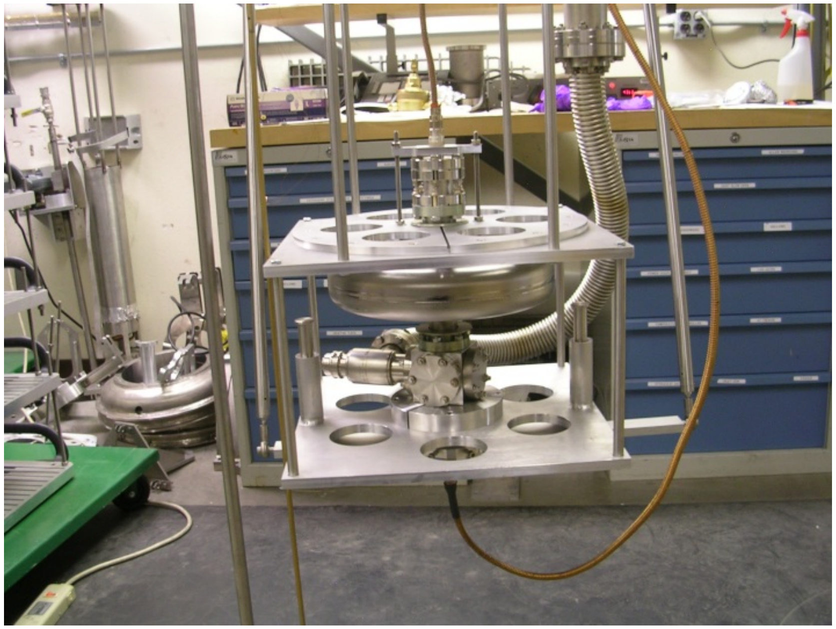

E.I. Smirnova *et al.*, Phys. Rev. Lett. **95(7),** 074801 (2005).

# SRF PBG cavities at LANL

## LANL's SRF facility

- LANL owns a class 100 cleanroom and the SRF testing facility with two vertical cryostats (34 inches and 17 inches).
- We collaborate with Niowave for fabrication and can do limited cleaning and baking procedures at LANL.



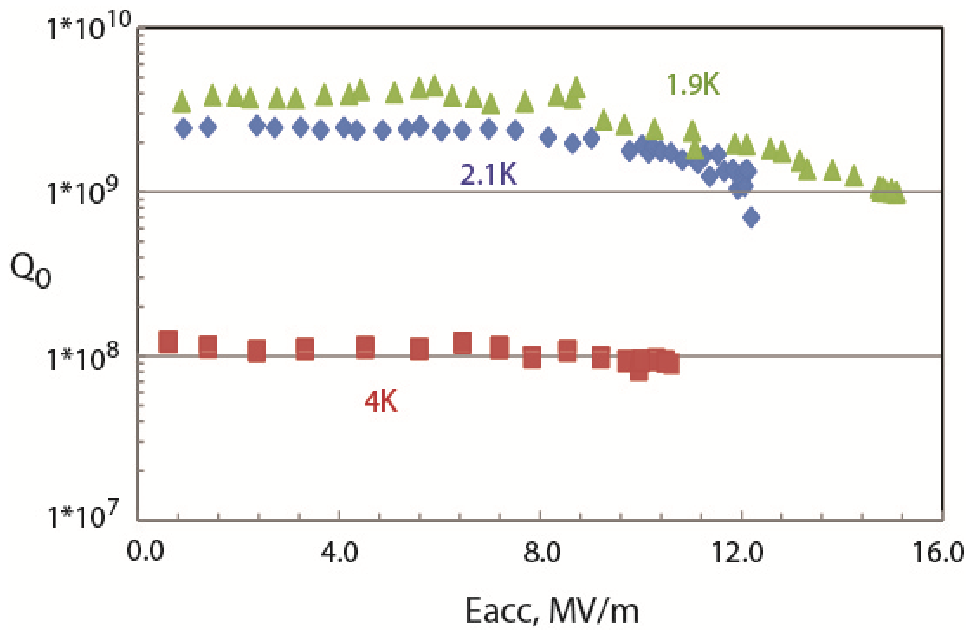


# 2.1 GHz SRF PBG resonator with round rods

Two 2.1 GHz SRF PBG resonators were designed and tested during the DOE Early Career project


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

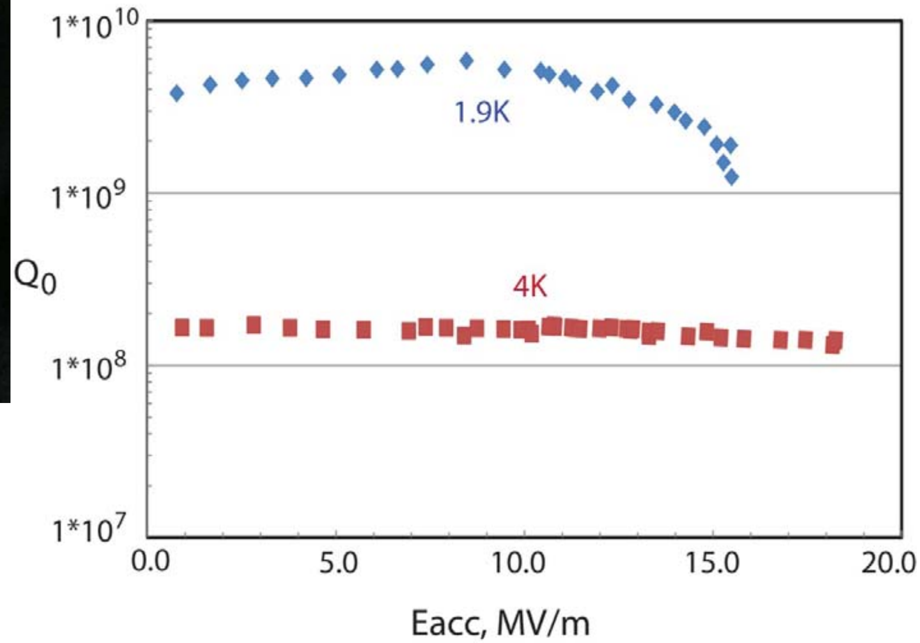
**Maximum achieved gradient is 15 MV/m.**



## 2.1 GHz SRF PBG resonator with elliptical rods

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.

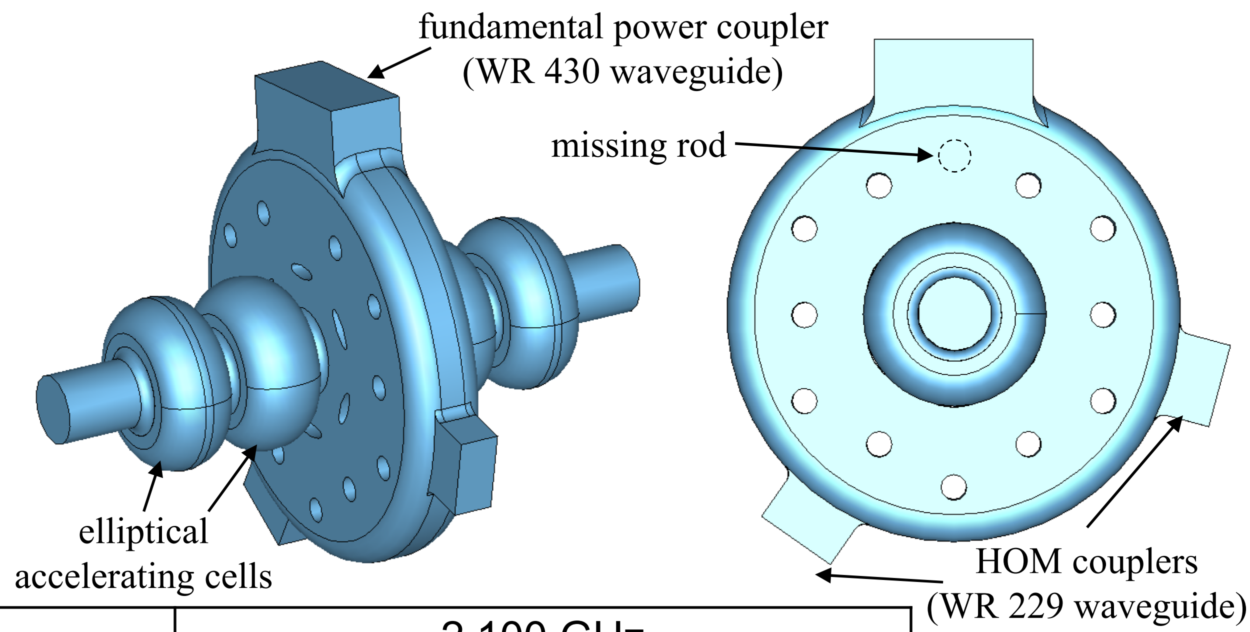

**Maximum achieved gradient is 18.3 MV/m.**




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

# SRF section with a PBG coupler cell

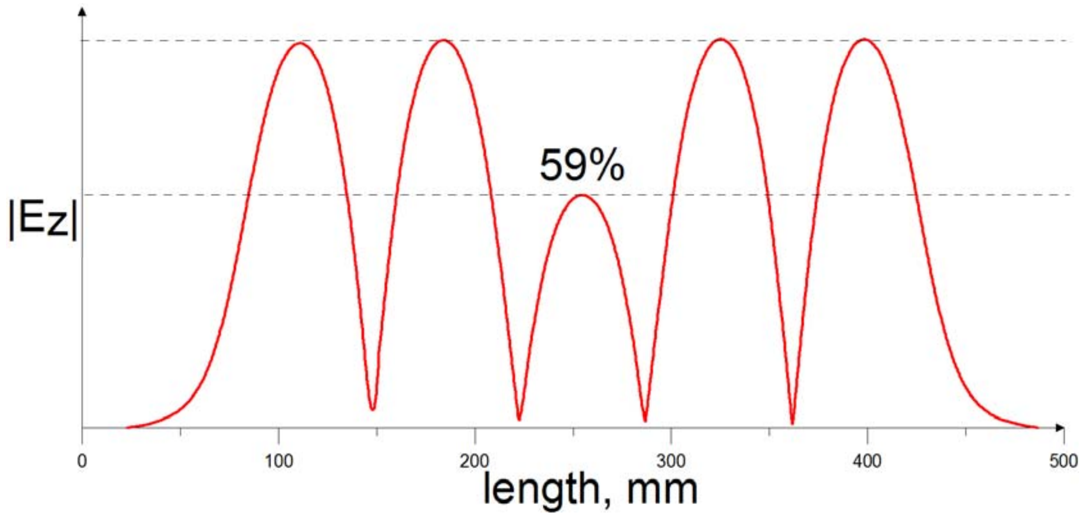
We designed an SRF accelerator section with four regular elliptical cells and one PBG cell in the middle. The WR-430 FM coupler and two WR-229 HOM couplers attach to the PBG cell.

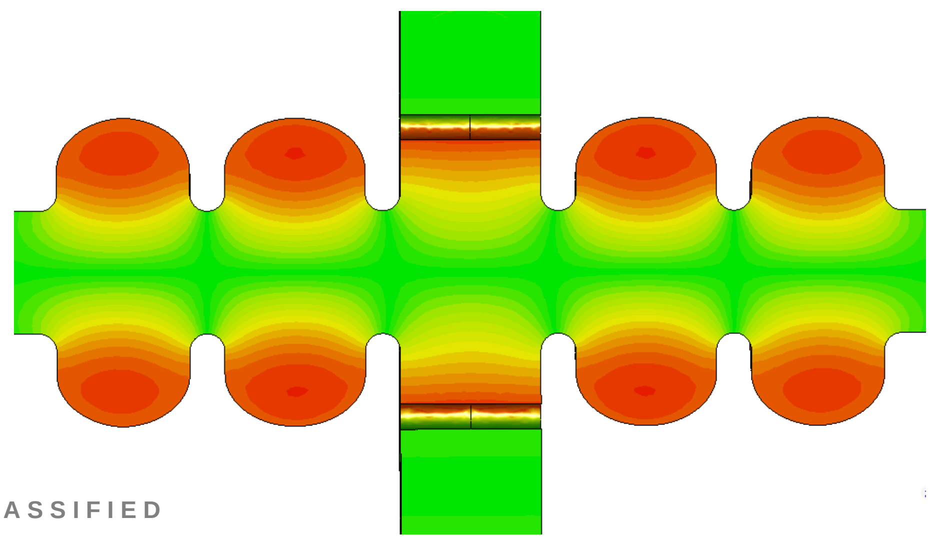



| | |
|---|---|
| Frequency | 2.100 GHz |
| Diameter of elliptical cells | 4.94 in (12.55 cm) |
| Diameter of the PBG cell | 12.37 in (31.42 cm) |
| Distance between the rods | 2.35 in (5.97 cm) |
| Radius of the rod | 0.35 in (0.89 cm) |
| Dimensions of the elliptical rod | 0.59 in x 0.21 in (1.51 cm x 0.52 cm) |

# Accelerating field profile in the section with PBG cell

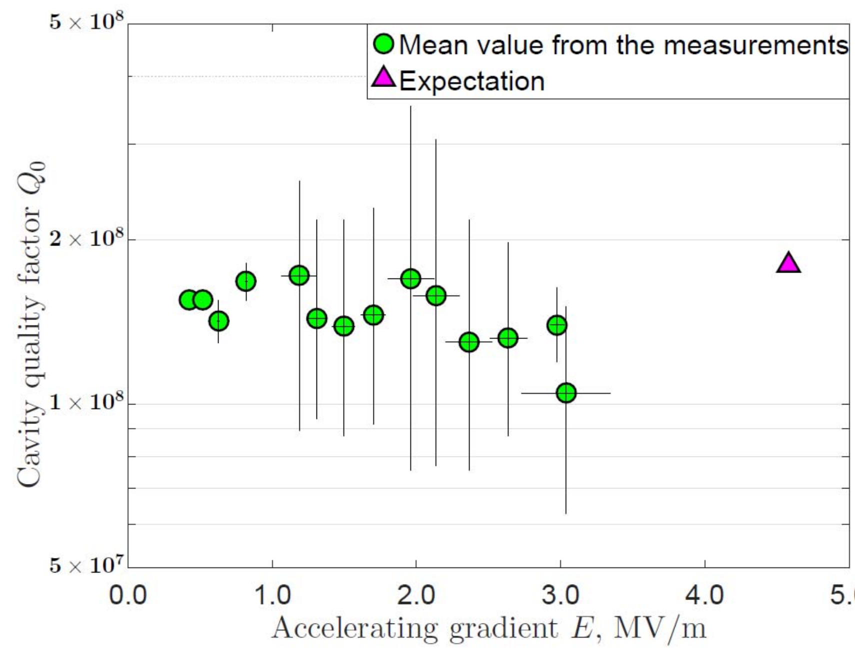
The peak magnetic field on the niobium surfaces in PBG cell can set the operational limits for the whole structure. Thus the cavity is tuned such that the peak magnetic fields are equal in all cells. This reduces the on-axis electric fields in the PBG cell.



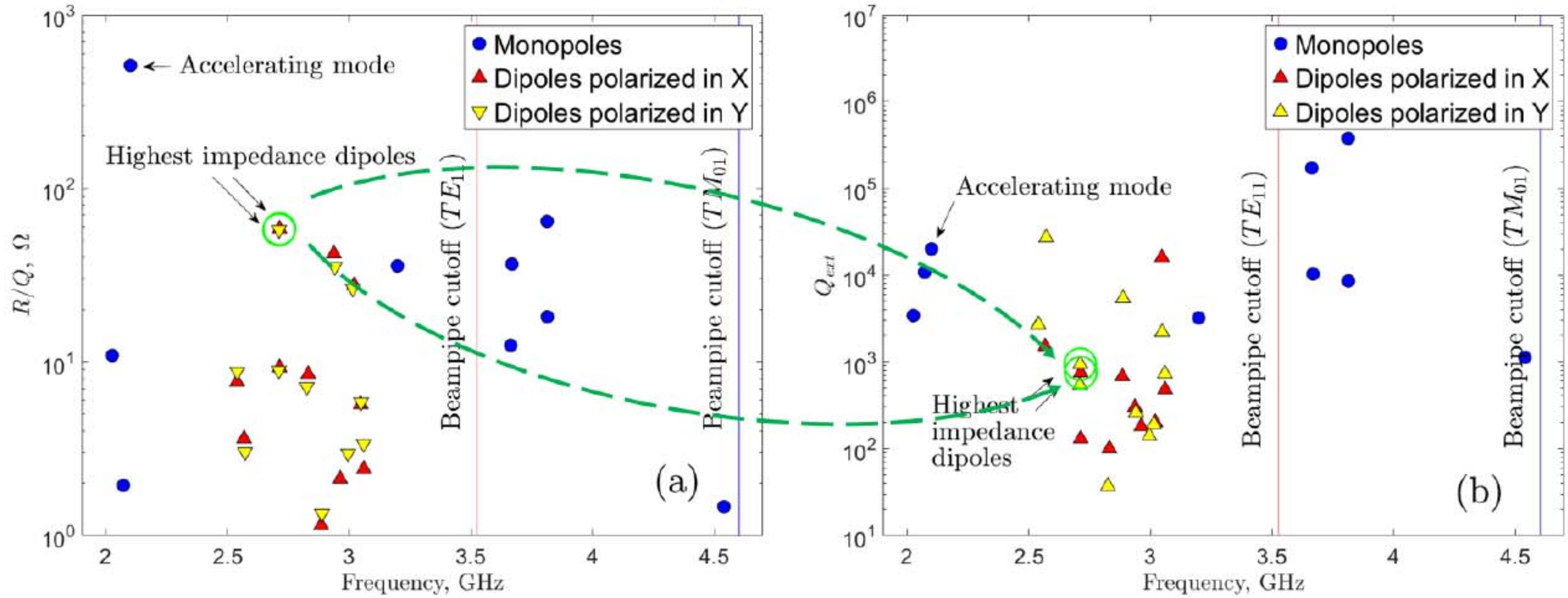
# SRF tests of the 5-cell cavity

- First SRF test was conducted at LANL in March, 2015.
- The accelerating mode had low Q due to the poor electrical contact at the coupling flange.
- The problem with low Q is now resolved. New successful SRF test was conducted at Niowave in December, 2015.

# Wakefield measurements in the 5-cell cavity

- Wakefields were studied in simulations and in a cold test.
- Most dangerous wakefields had external Q-factors below $10^3$.

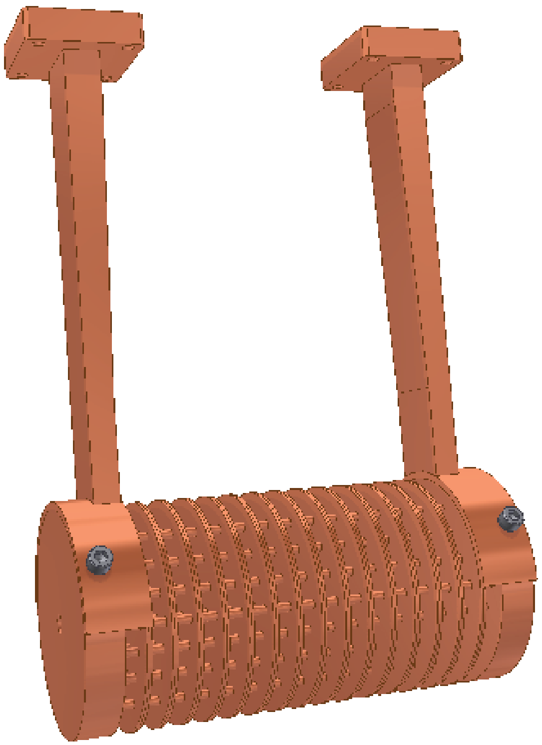


# X-band PBG cavities at LANL

# New 16-cell X-band PBG structure

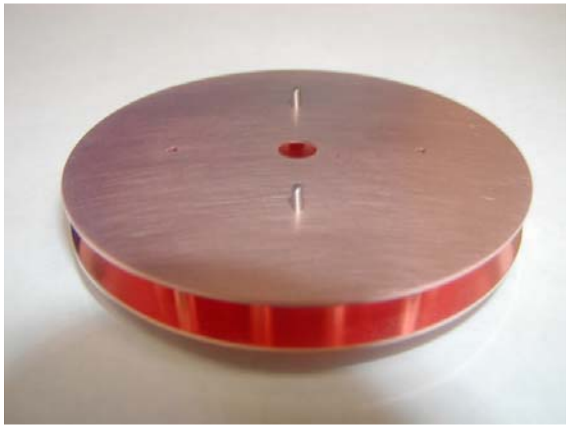
The 16-cell PBG structure for the wakefield testing was designed at the frequency 11.7 GHz (9 times the frequency of AWA ). Very close scale of the MIT 17 GHz structure.

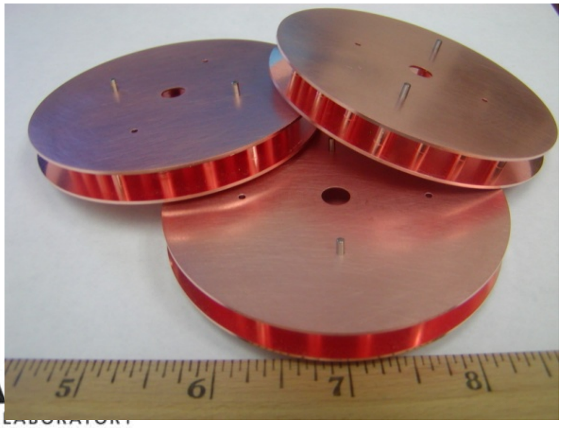
| | |
|---|---|
| Frequency | 11.700 GHz |
| Phase shift per cell | $2\pi/3$ |
| $Q_w$ | 5000 |
| $r_s$ | 72.5 MΩ /m |
| $[r_s/Q]$ | 14.5 kΩ /m |
| Group velocity | 0.015c |
| Gradient | $15.4\sqrt{P[\mathrm{MW}]}$ MV/m |

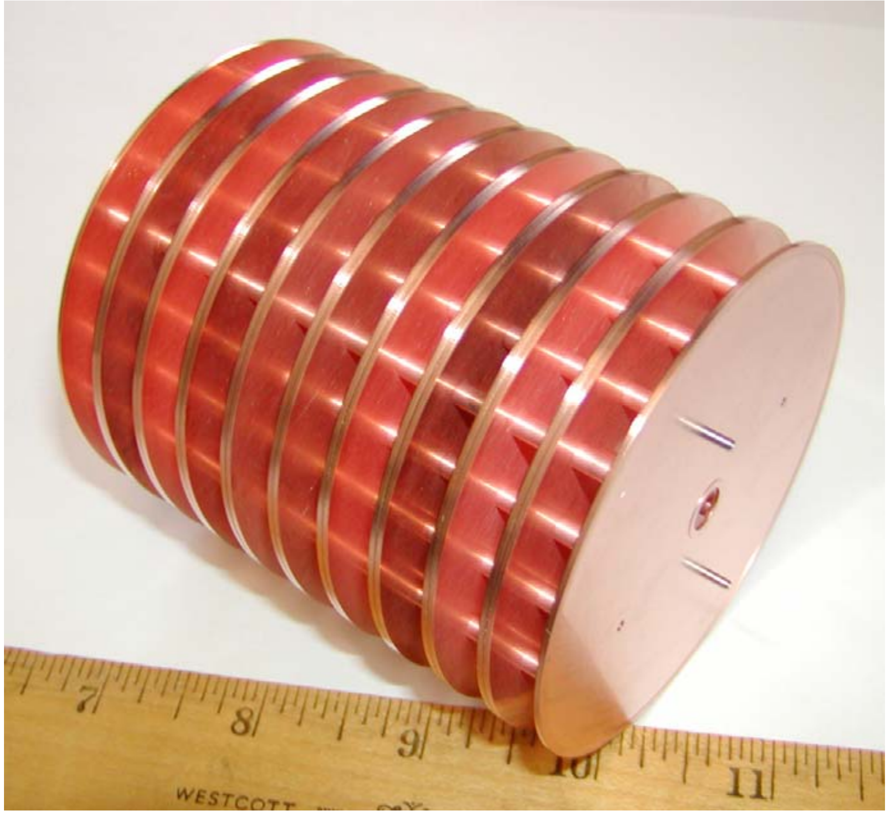


# 11.7 GHz TW cells

25 TW PBG cells, 4 end cells, and 2 coupling waveguides were fabricated by Custom Microwave, Inc.

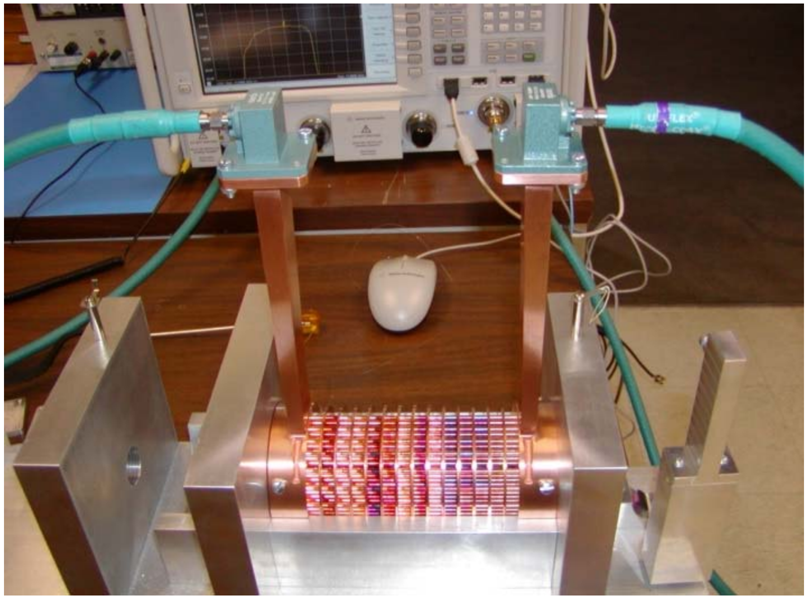


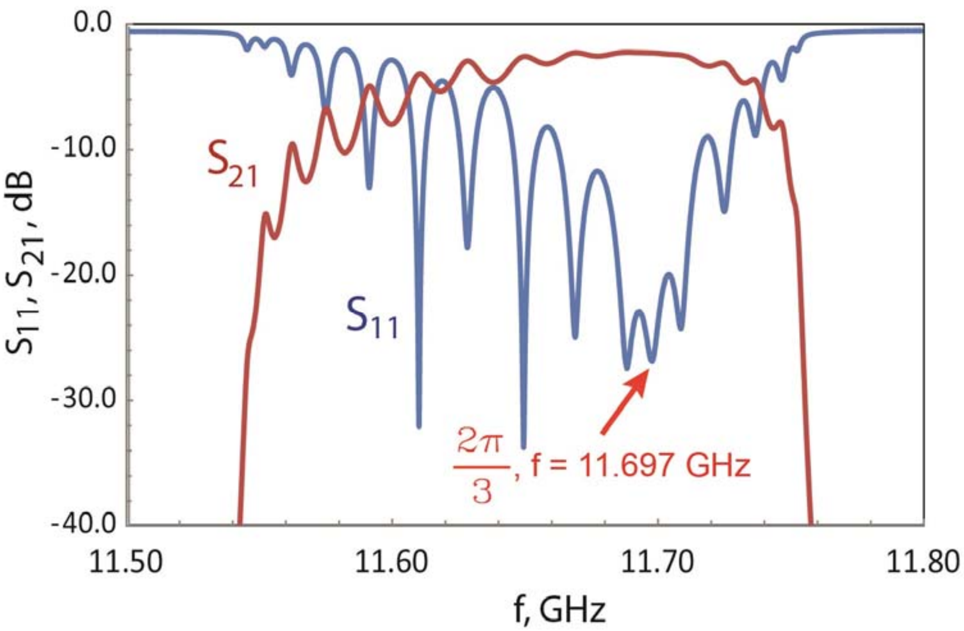


# 11.7 GHz 16-cell PBG accelerator

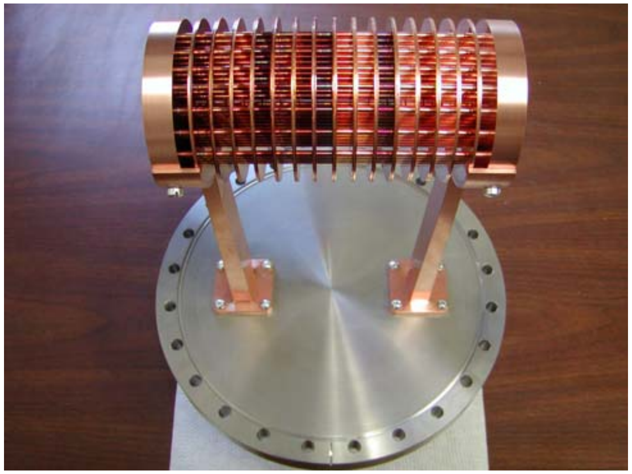
- The bonded structure underwent the final cold-test with a VNA.
- The *2π/3* mode is at 11.697 GHz in air.

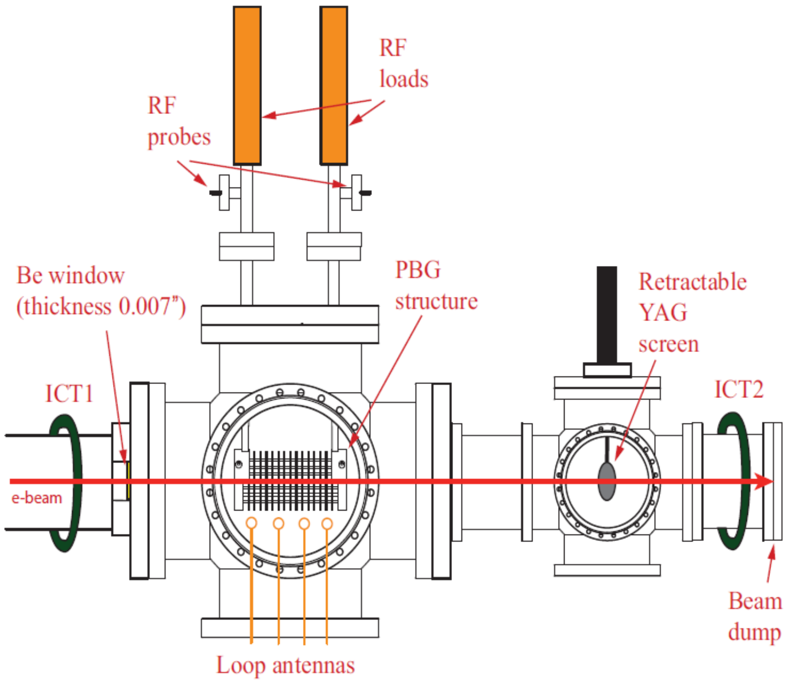


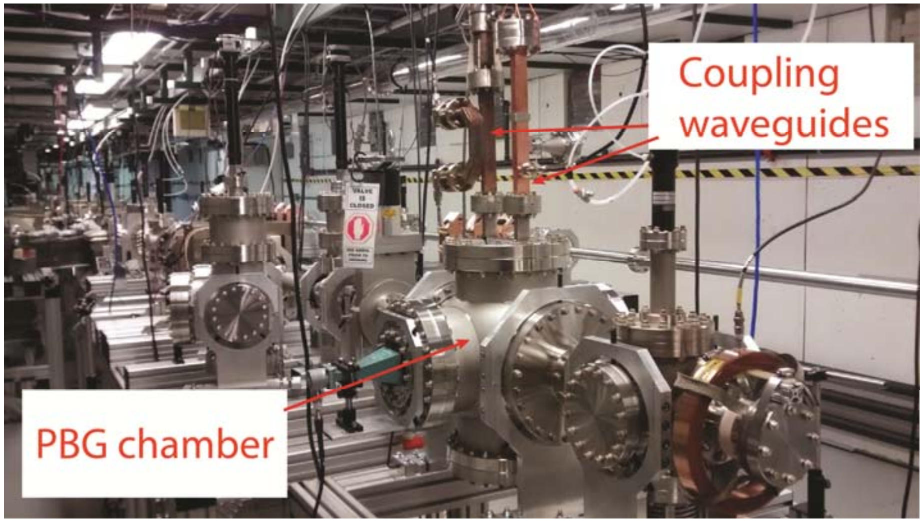


# Structure on the Argonne Wakefield Accelerator beamline

The structure was installed on a 10-inch flange at the end of the AWA 1.3 GHz beamline:

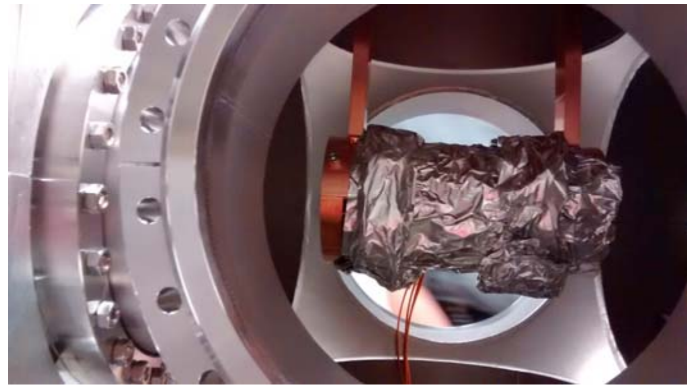


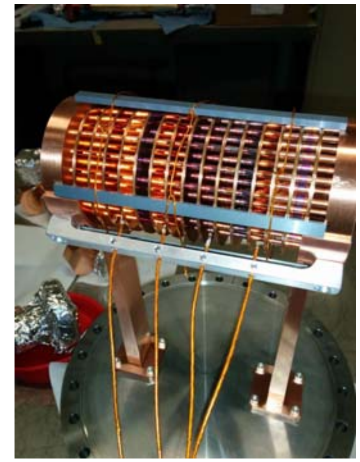


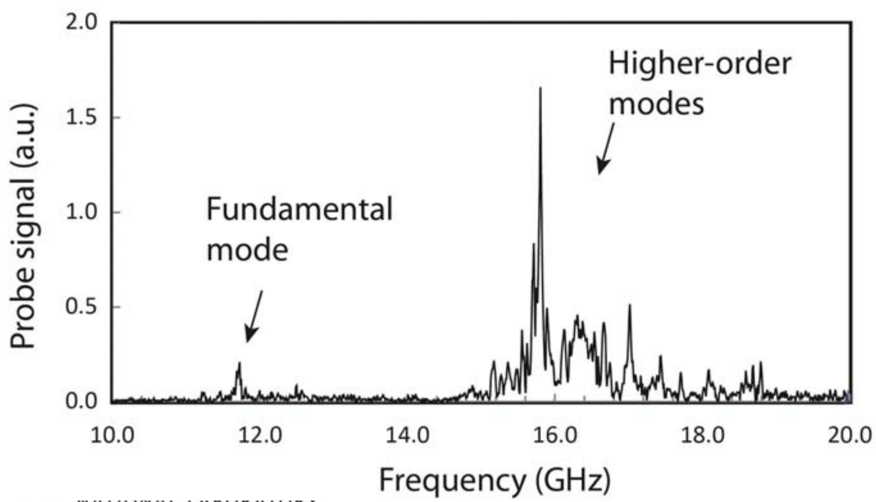
# Data: higher order modes

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

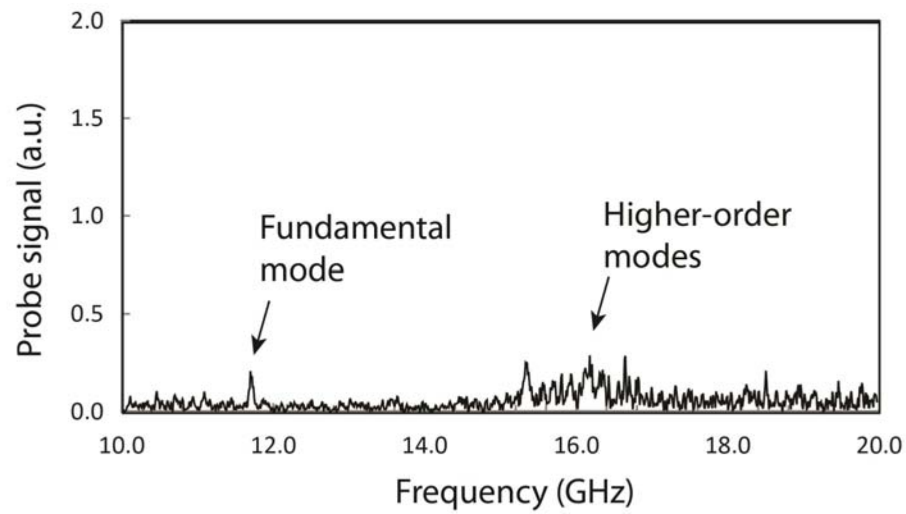




PBG structure wrapped in foil:

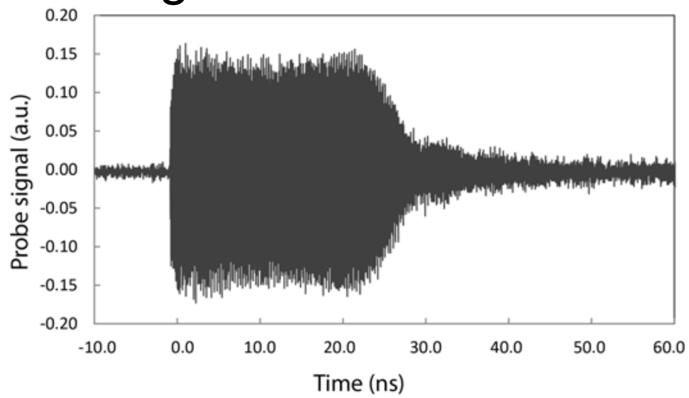



Open PBG structure with 6 SiC slabs:

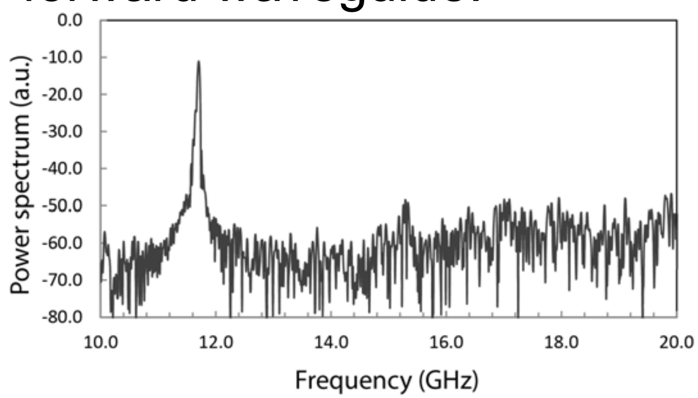


# Data: fundamental mode

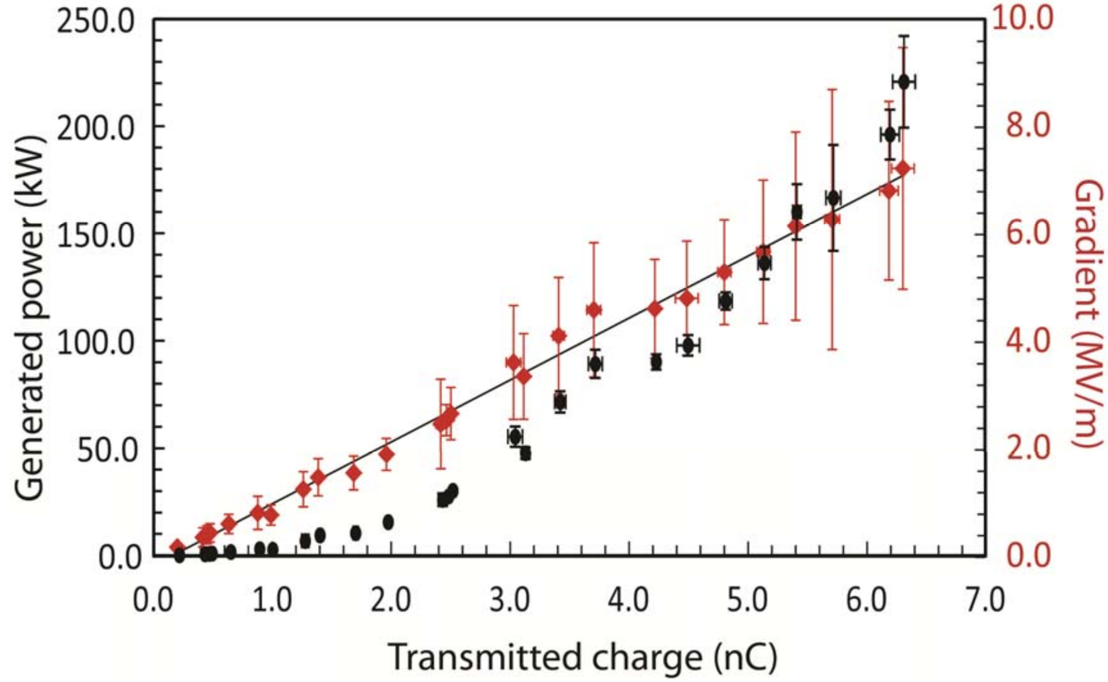
Signal in the forward waveguide:




Power spectrum in the forward waveguide:



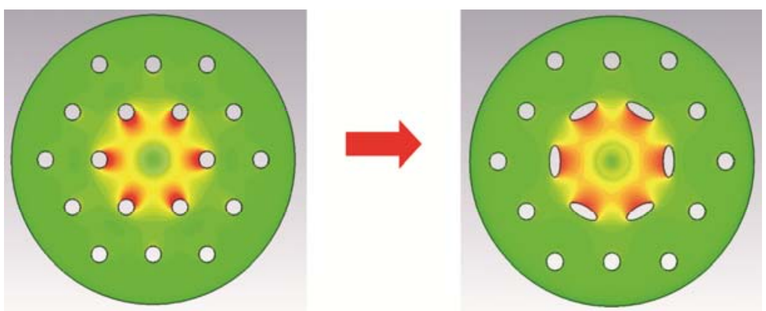

Measured power in the forward waveguide and computed accelerating gradient:

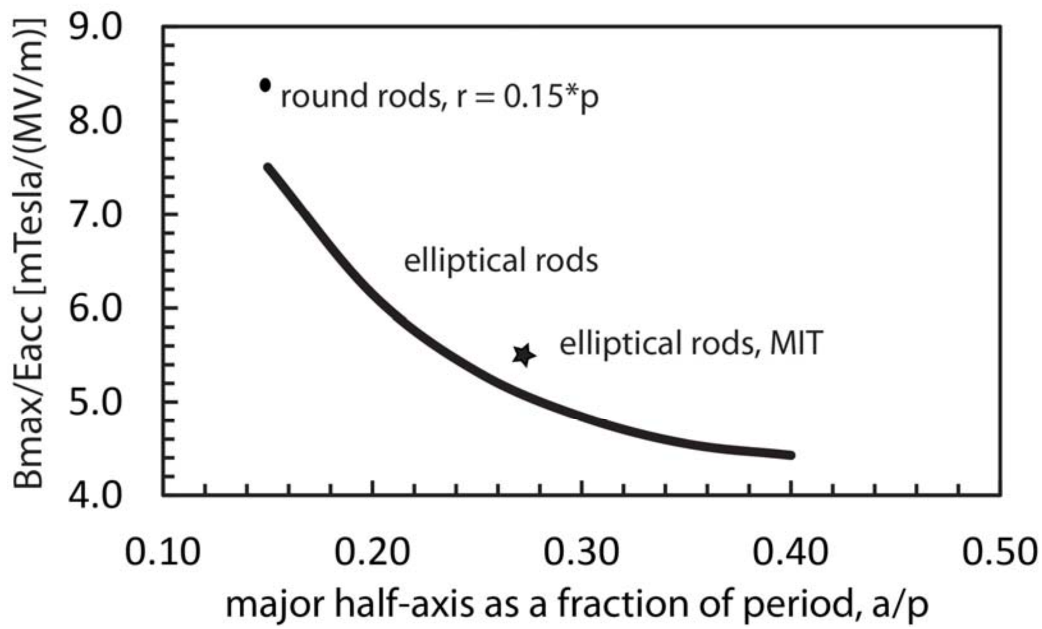



E.I. Simakov *et al.*, Phys. Rev. Lett. **116,** 064801 (2016).

# X-band PBG accelerator with elliptical rods

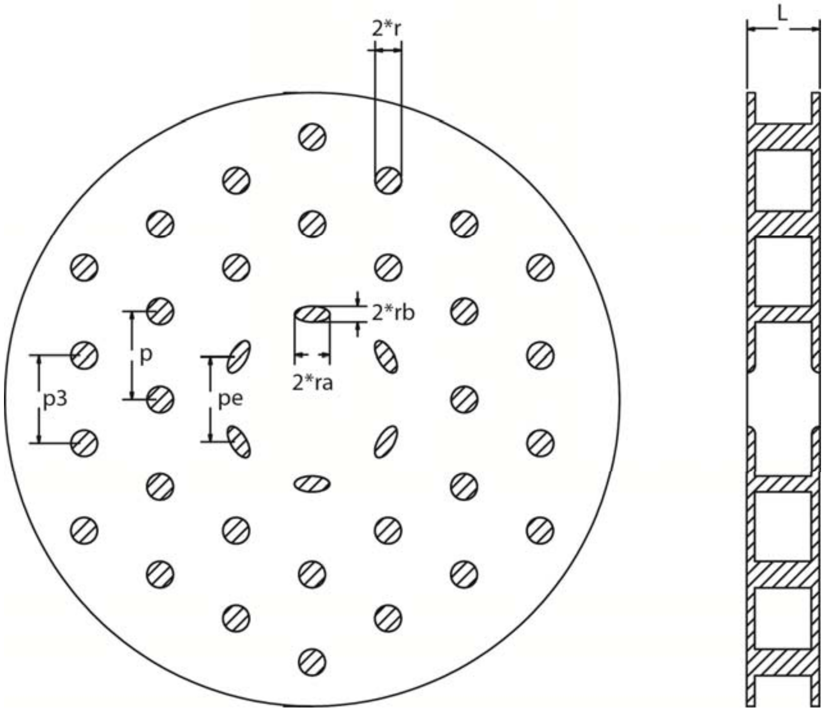
- Changing the shape of the rods in a PBG structure to elliptical reduces surface magnetic fields and improves high gradient performance.
- Shape of the elliptical rods must be optimized.





# X-band PBG resonator with elliptical rods

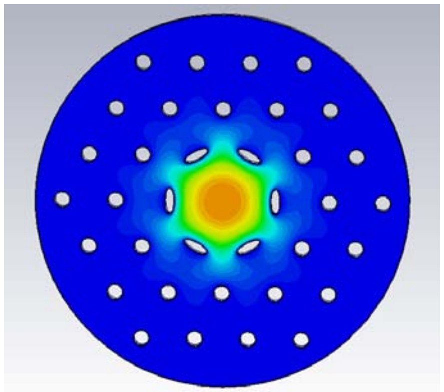
A schematic of the PBG resonator with 6 elliptical rods



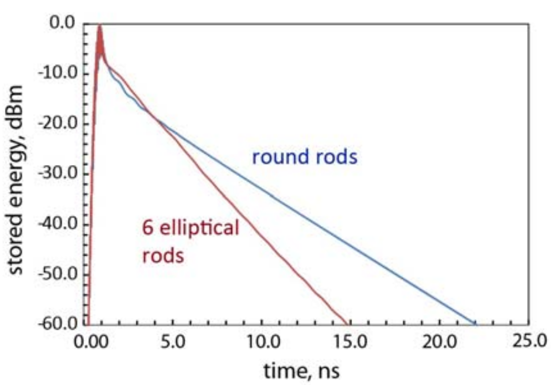

| | |
|---|---|
| Frequency | 11.700 GHz |
| Phase shift per cell | $2\pi/3$ |
| Cell's length, L | 8.55 mm |
| Period of round rods, p | 10.33 mm |
| Radius of round rods, r | 1.55 mm=0.15*p |
| Period of e-rods, pe | 10.22 mm = 0.99*p |
| Period of the 3rd row of rods, p3 | 10.85 mm = 1.05*p |
| Major 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



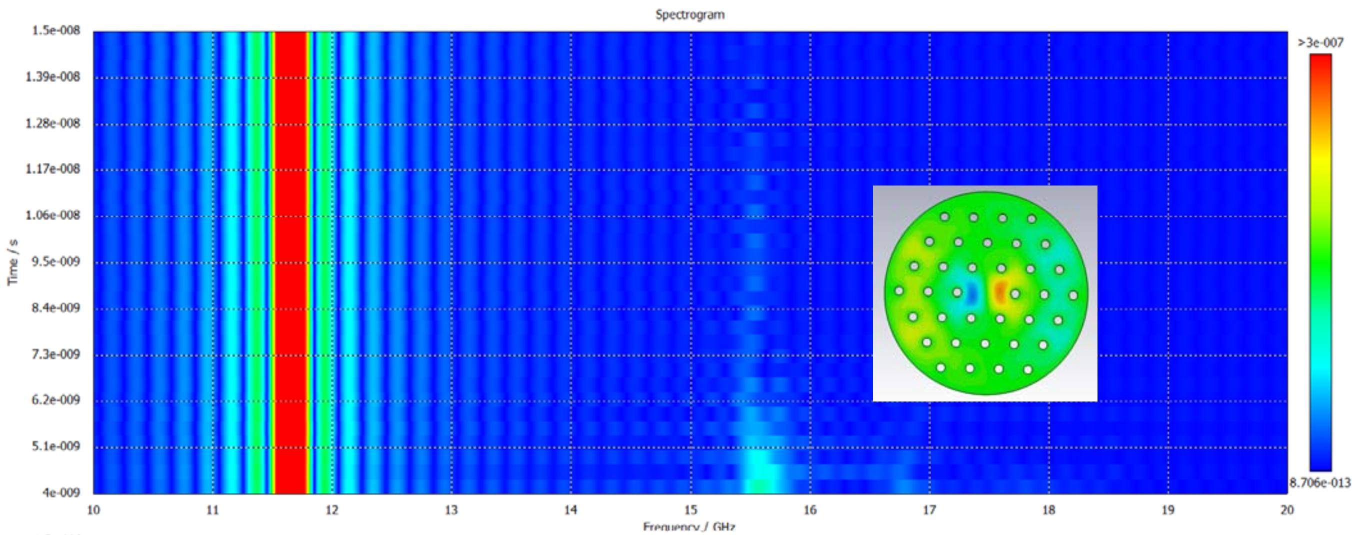
Decay of the energy stored in HOMs in the frequency range 14-18 GHz.



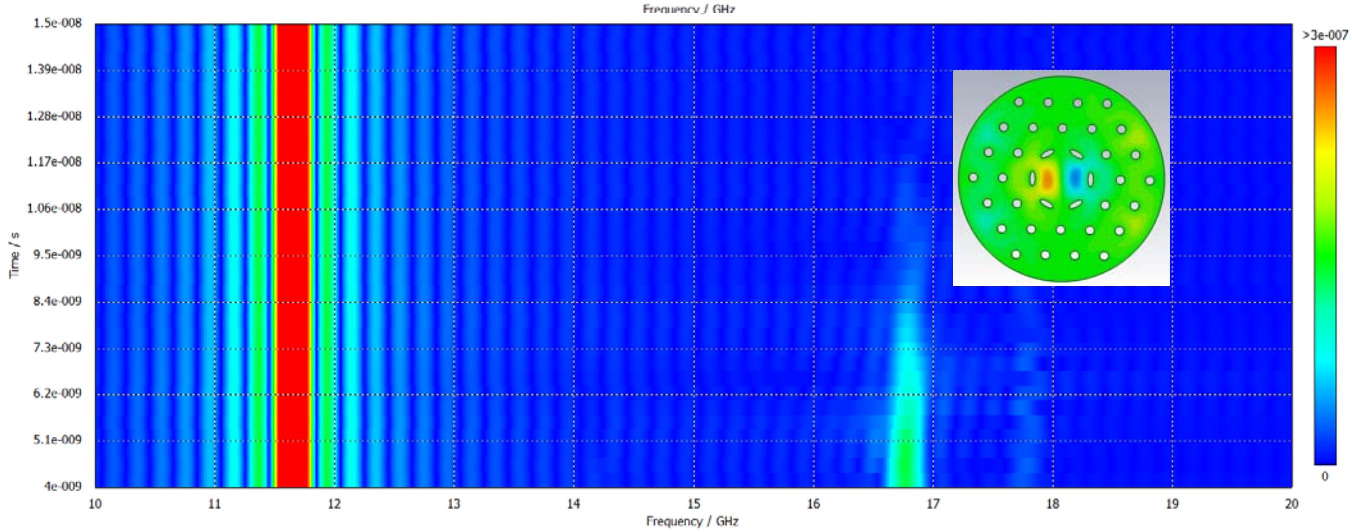

| | Resonator with 6 elliptical rods | Resonator with round rods | MIT's resonator with elliptical rods |
|---|---|---|---|
| $Q_w$ | 5600 | 5000 | 5800 |
| $r_s$ | 83.66 MΩ /m | 69.75 MΩ /m | 86.13 MΩ /m |
| $[r_s/Q]$ | 14.94 kΩ /m | 13.8 kΩ /m | 14.85 kΩ /m |
| $B_{peak}/E_{acc}$ | 5.3 mTesla/(MV/m)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

# Spectrogram of wakefields: round vs. optimized elliptical

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

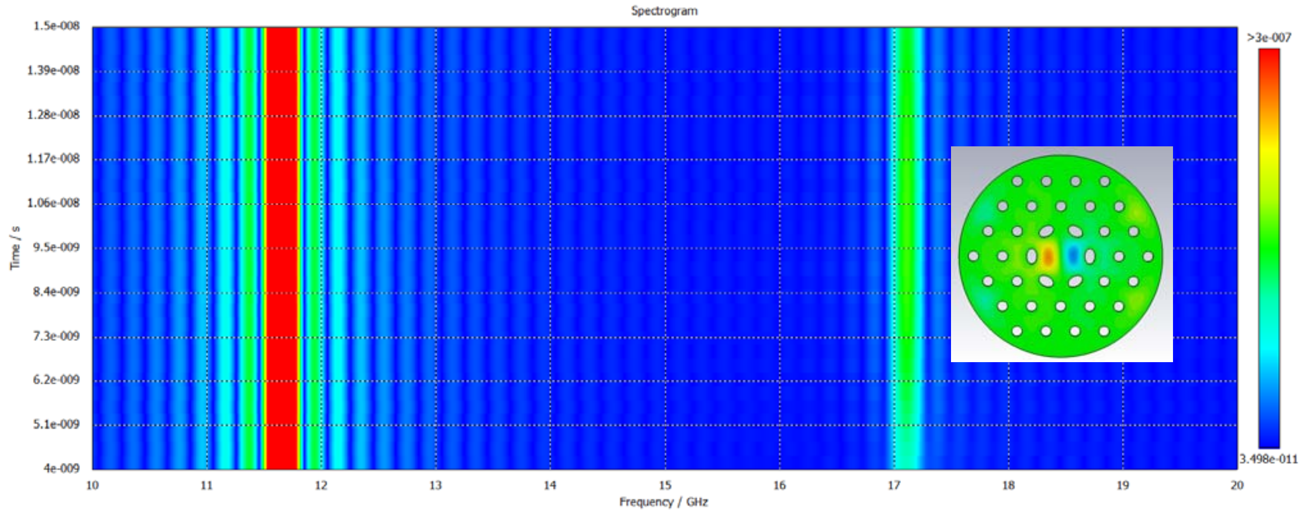



The resonator with 6 elliptical rods and optimized spacing

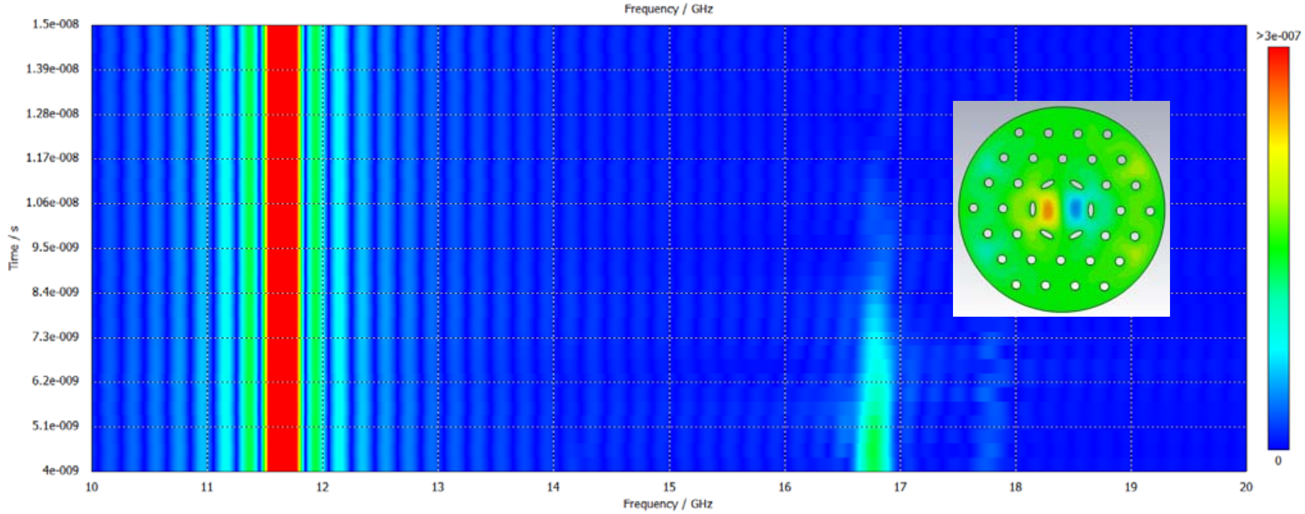


# Spectrogram of wakefields: MIT's vs. optimized elliptical

The resonator with 6 elliptical rods tested at MIT




The resonator with 6 elliptical rods and optimized spacing



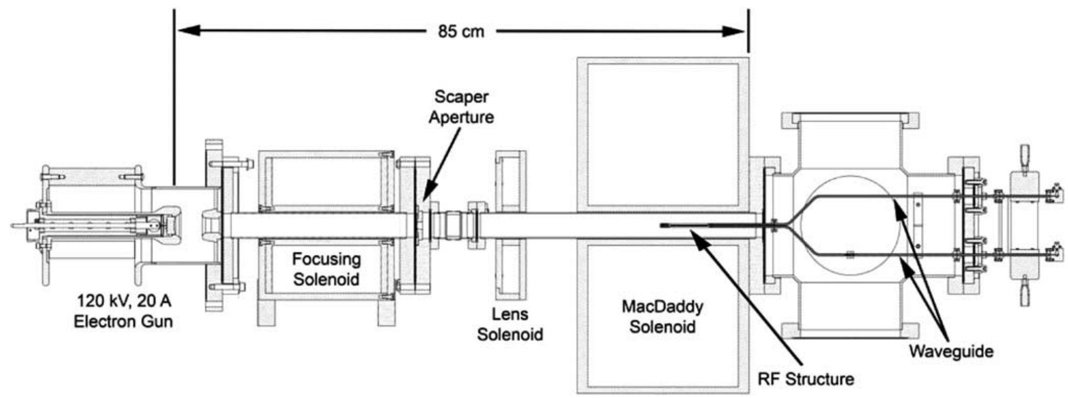
# Current and future work

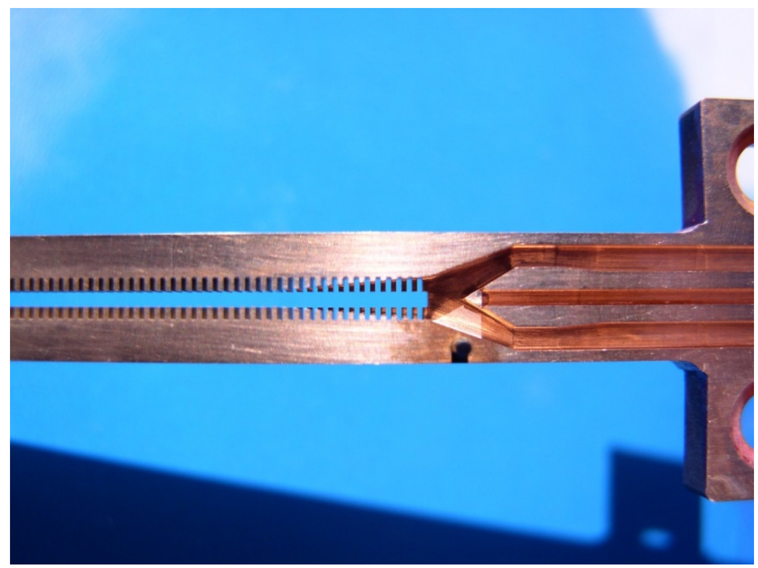
- The PBG resonator with elliptical rods was designed.
- Simulations of wakefields in 11.7 GHz PBG resonators are being conducted.
- More experiments at AWA are being discussed:
    - Reduction of noise.
    - Beam energy measurements.
- High gradient testing of the new PBG cells with elliptical rods at SLAC is planned:
    - Open structures are good for studying breakdown.

# W-band PBG TWT at LANL

# 94 GHz vane-loaded TWT at LANL

- **Ridged waveguide, wide bandwidth structure (2003-2006).**
- 7% bandwidth demonstrated in cold test.
- 120 kV, 2 A electron beam
- 22 dB of amplification demonstrated over a length of 5 cm.

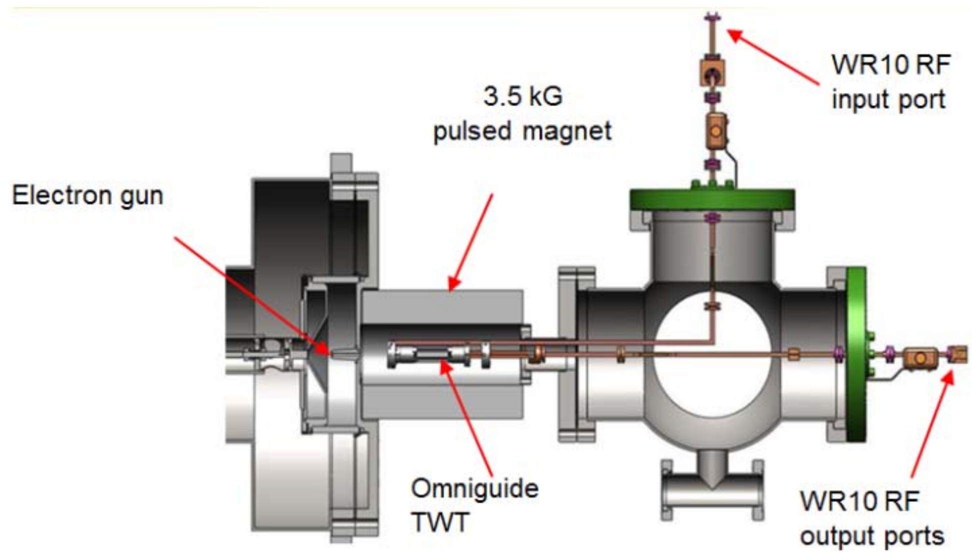


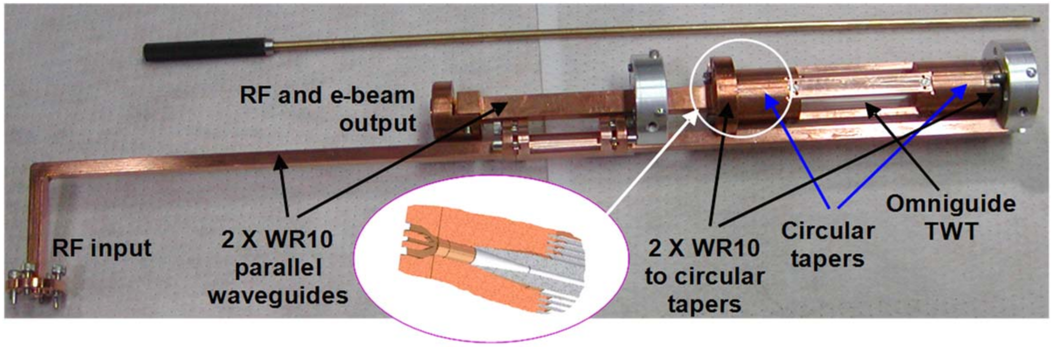



Bruce E. Carlsten, *et al.*, IEEE Trans. on Plasma Science, 34(5), 2393 (2006).

# Omniguide W-band TWT at LANL

- **Photonic band gap, dielectric, very wide bandwidth structure (2008-2011).**
- Larger than 10% bandwidth demonstrated.
- 120 kV, 2 A electron beam
- 2.5 dB/cm gain in a 5 cm tube was demonstrated.

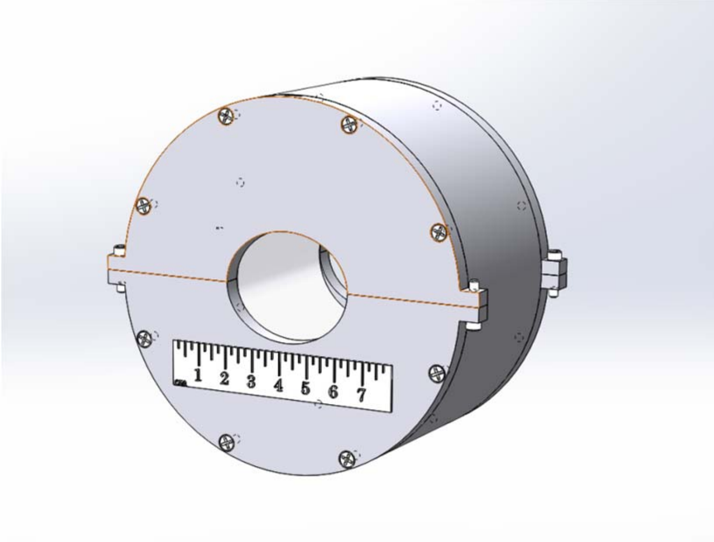


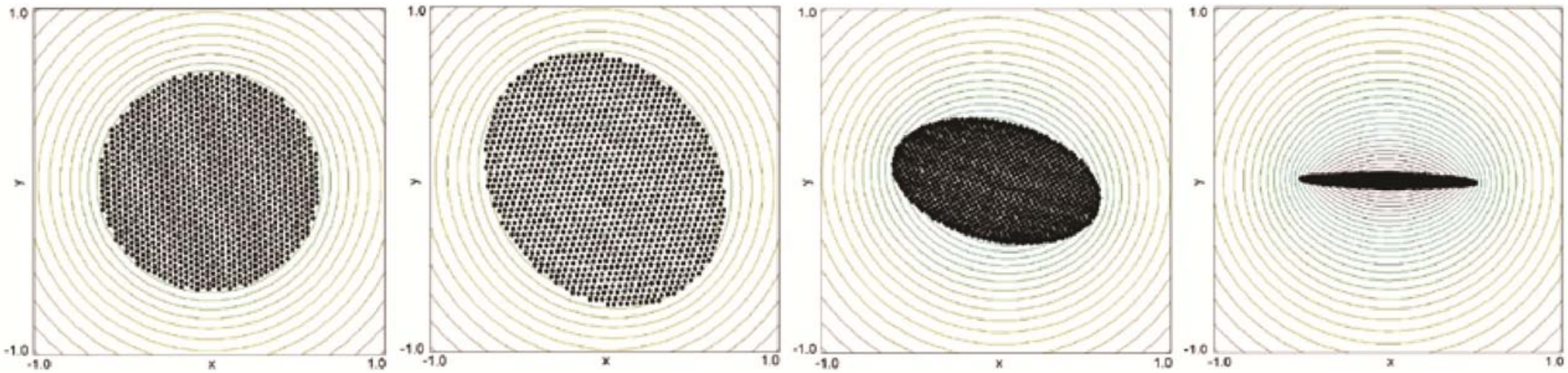




E.I. Smirnova, *et al.*, IEEE Trans. on Plasma Science, 36(3), 763 (2008).

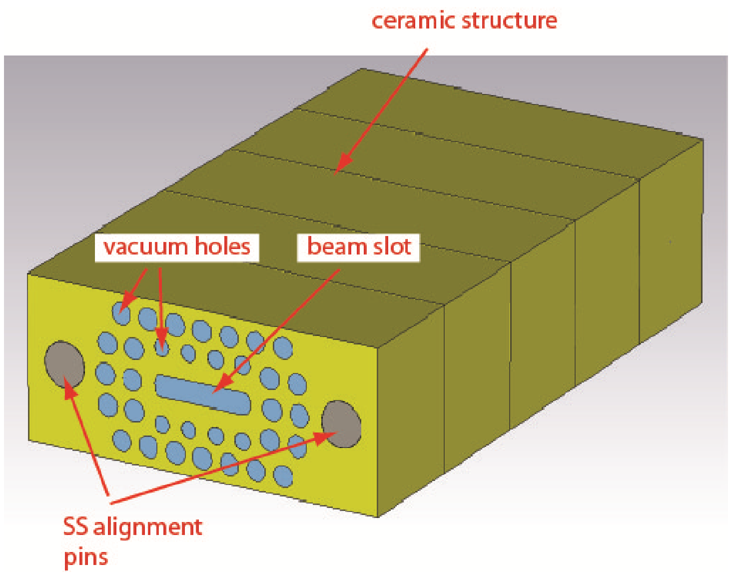
# Sheet beam

- By adjusting the elliptical aperture of the pole pieces we design the focusing ratio for the x and y planes and transform a high-perveance circular beam to a planar configuration.
- In future will be replaced by skew quadrupole flat-beam transport.

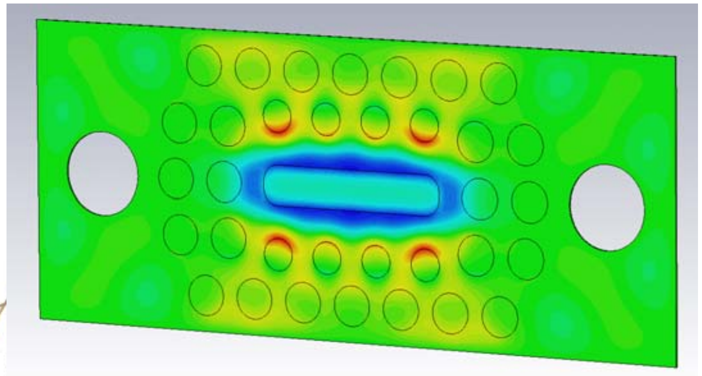


# Photonic band gap TWT design




$TM_{11}$-like mode

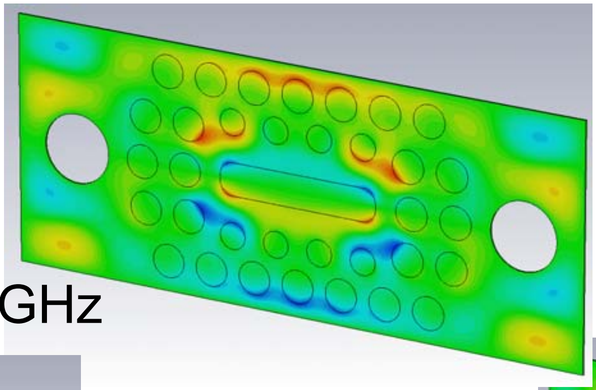


| | |
|---|---|
| Central frequency | 96 GHz |
| Beam slot | 0.5 mm x 2.5 mm |
| Dielectric | Ceramics, ε=20 |
| Diameters of large holes | 0.5 mm |
| Diameters of small holes | 0.4 mm |
| Spacing between the holes | 0.7 mm |
| Section's length | 3 mm |
| Structure's length | 10 cm |
| Interaction impedance | 0.018 Ω |
| Gain | 5.75 dB/cm |

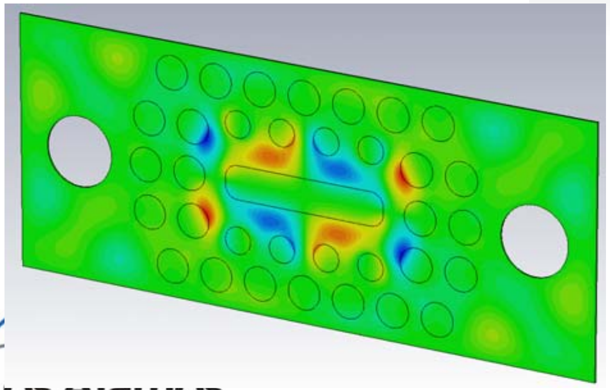
# Higher order modes

HOMs are not as strongly confined around the beam slot as $TM_{11}$-like mode. This presents opportunities to place HOM absorbers.

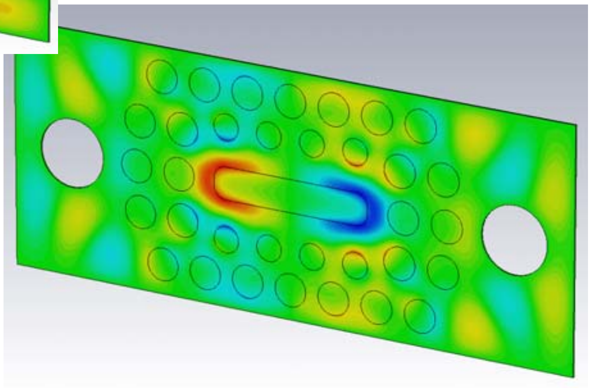
$TM_{21}$-like mode, 94.25 GHz



$TM_{22}$-like mode, 96.15 GHz



$TM_{12}$-like mode, 96.53 GHz



# Fabrication of ceramic PBG structures

We purchase low loss ε ≈ 20 ceramics from Euclid Techlabs ($Al_2O_3$-Ti mix).

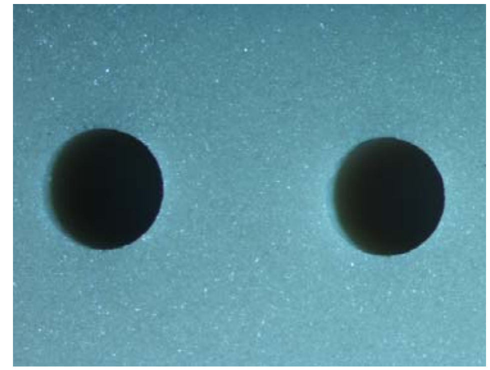
The holes are drilled with KERN Evo 5-Axis Micro-Milling Machine.

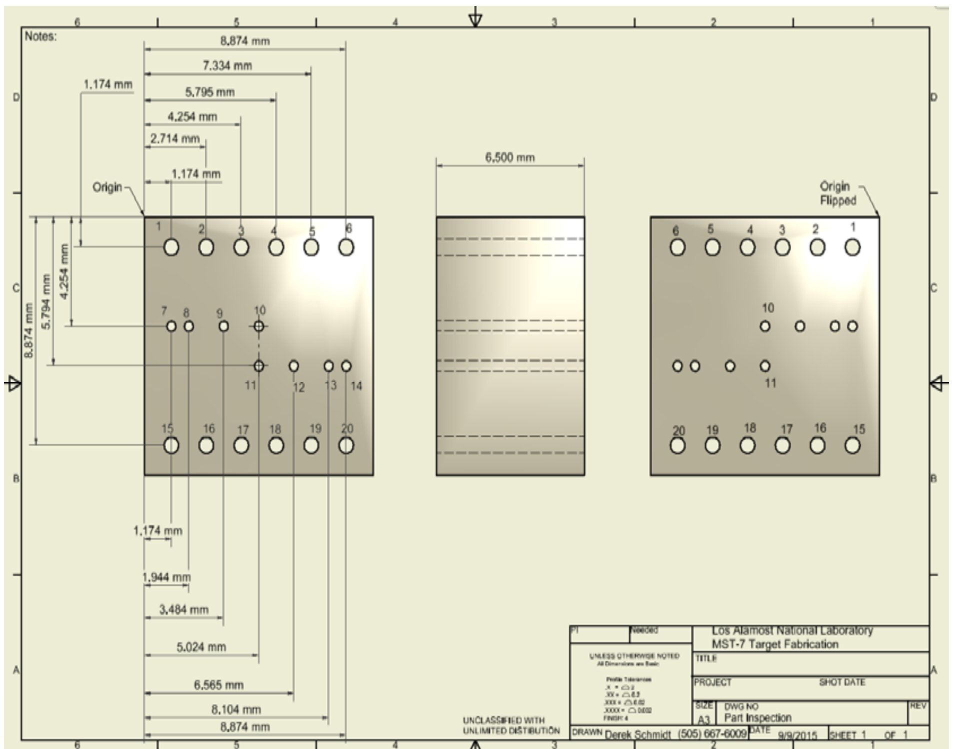
Intended for applications requiring the following features:

- Highest precision on the work piece (deviation of position Pa ±0.5 μm)
- Excellent surface quality Ra <-0.1 μm
- Resolution 0.1 μm (0.0000039")
- Positioning scatter PS±0.5 μm (0.0000196")
- Positioning tolerance P ±1.0 μm (0.0000393")
- Precision on the workpiece (3-axis) ±2.0μm(0.0000787")

# Fabrication and inspection

We fabricated several samples with holes with diameters from 400 to 700 μm. The holes were inspected with a microscope. Some findings:



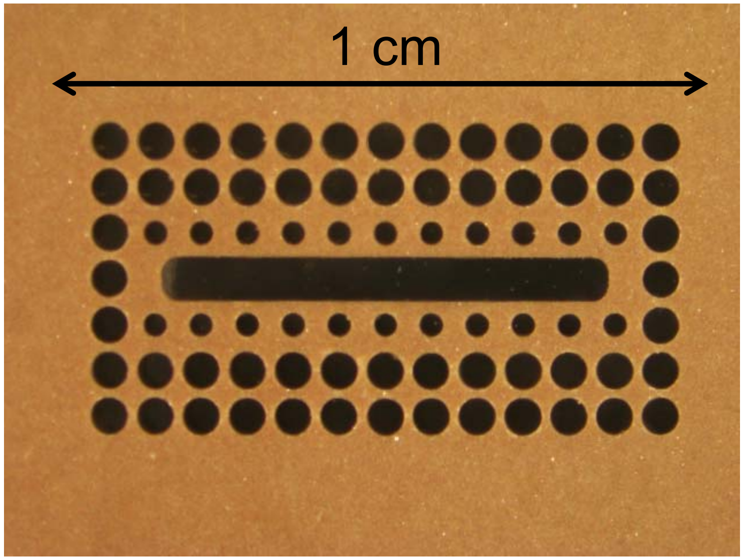


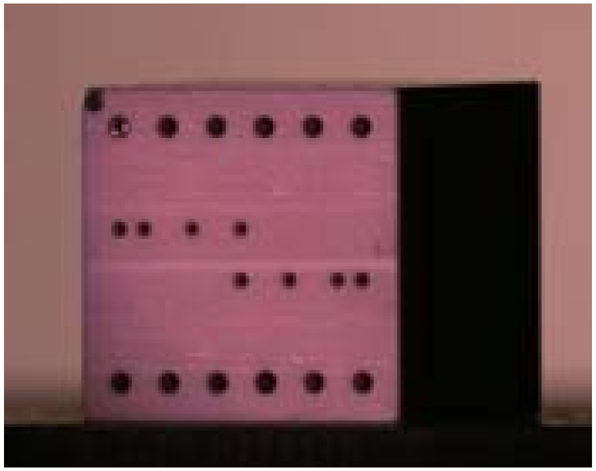

- There is some optimal drill rotation speed and feed to minimize taper and drill wonder.
- The maximum hole depth is about 3 mm.
- The ceramics with higher epsilon ($\varepsilon \approx 25$ ) was slightly easier to drill.

# Fabricated samples

The holes needed to be pre-drilled and then milled with a diamond-coated end mill for the best precision.

- With drilling only the positional accuracy is 25 microns, diameters are within 10 microns from the goal.
- With drilling and milling the positional accuracy is below 3 microns, diameters are within 8 microns.
- Beam slot: 2 microns width variance, parallelism 0.03 degrees.
- Stacking of different fabricated pieces can be done with 5 micron accuracy.



# Current and future work

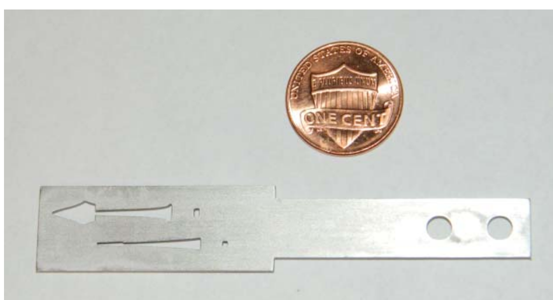
- FY16: finish structure's design.
- FY16: finish beamline's assembly.
- FY17: demonstration of the electron beam generation and transport.
- FY17: fabrication and cold-testing of the ceramic structure.
- **FY18: TWT demonstration.**

# Other advanced accelerator projects

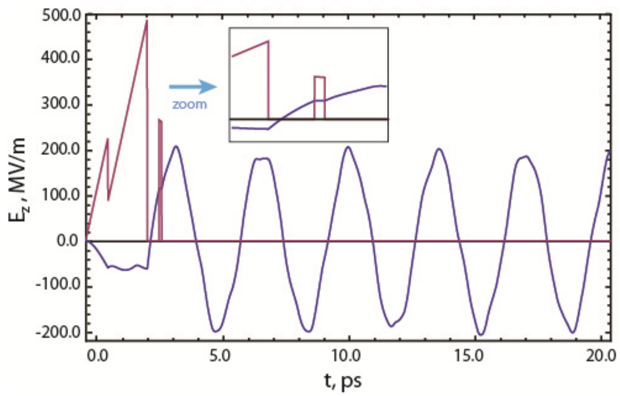
# Dielectric wakefield accelerator project

LANL LDRD funded a project to combine the two proven concepts of the Dielectric Wakefield Accelerator (DWA) and the Emittance Exchanger (EEX) to experimentally demonstrate a high-brightness DWA with an acceleration gradient above 100 MV/m and less than 0.1% induced energy spread in the accelerated beam.

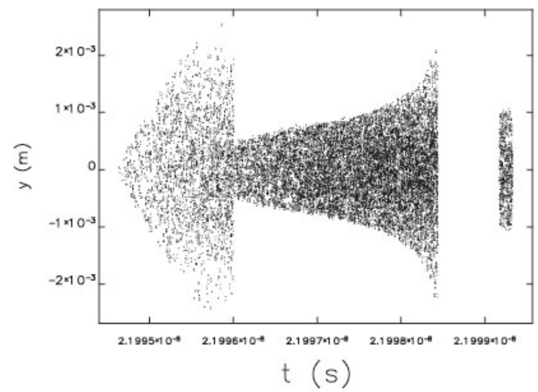
A mask producing shaped electron bunches.

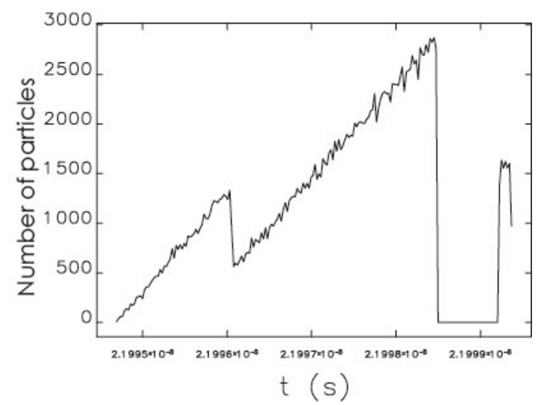



The high transformer ratio wakefield excited by the shaped electron bunches.




Distribution of electrons within shaped electron bunches.



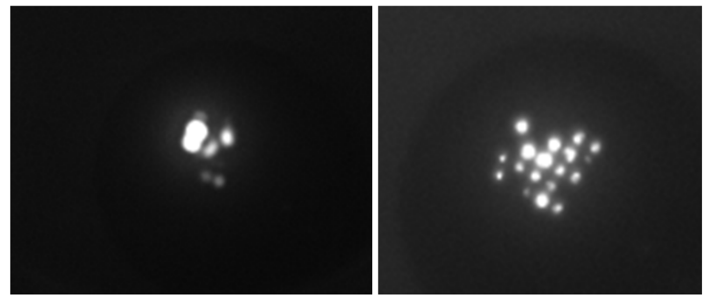



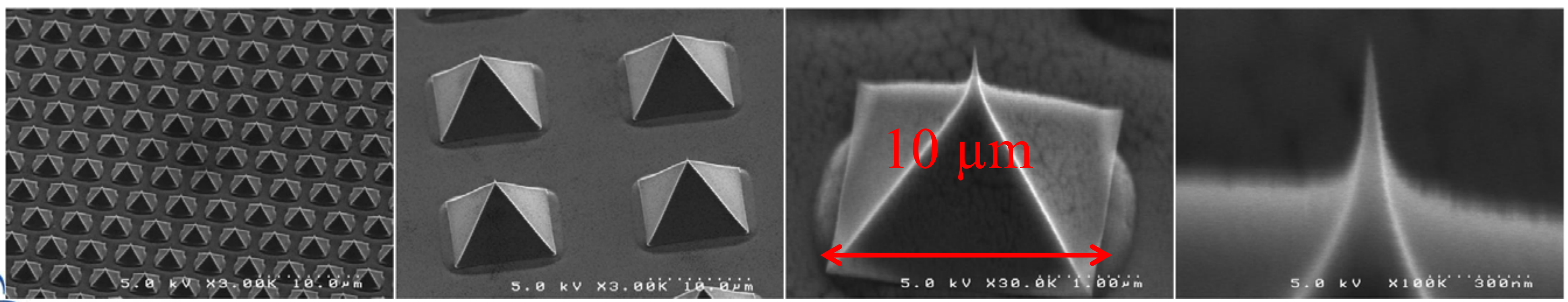
# Diamond Field Emitter Arrays Cathodes

- Exquisitely sharp  diamond pyramids.
- Current > 1 A/mm$^2$.
- Emittance < 1 mm*mrad.
- Photoemission never studied.

**Should produce more current with smaller emittance.**

LANL measured ~20 µA currents emitted by single diamond pyramids (applicability to dielectric laser accelerators).

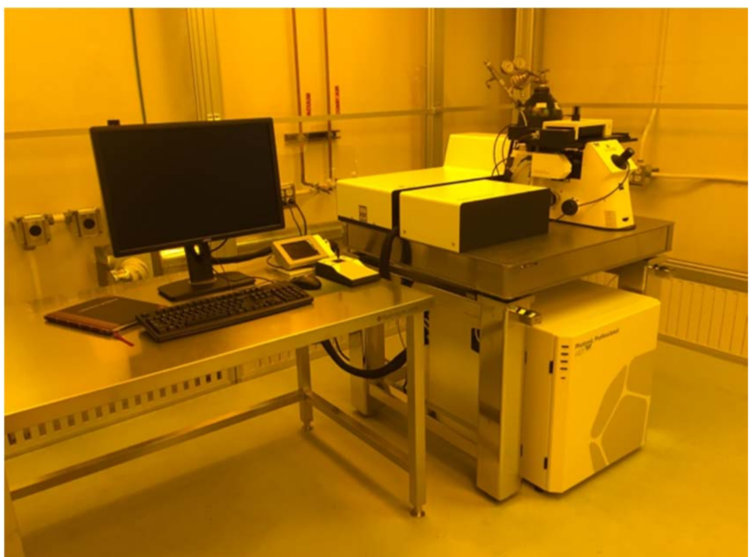


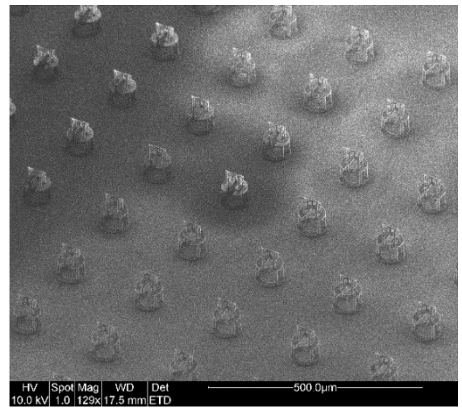


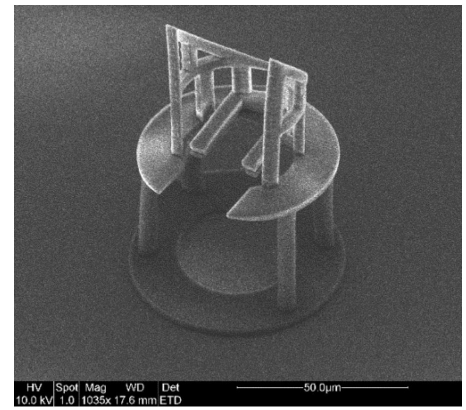
# Additive manufacturing of novel accelerator structures

## LANL acquired Nanoscribe Professional GT in 2015.

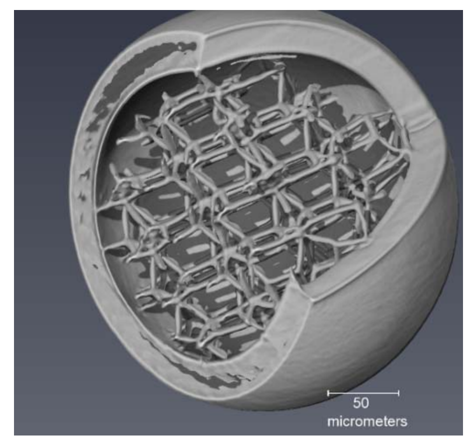
- 3D laser lithography system
- Resolutions down to 100 nm (highest resolution commercially available)
- Print areas as large as 100 x 100 mm
- 2-photon exposure of common positive-tone photoresists





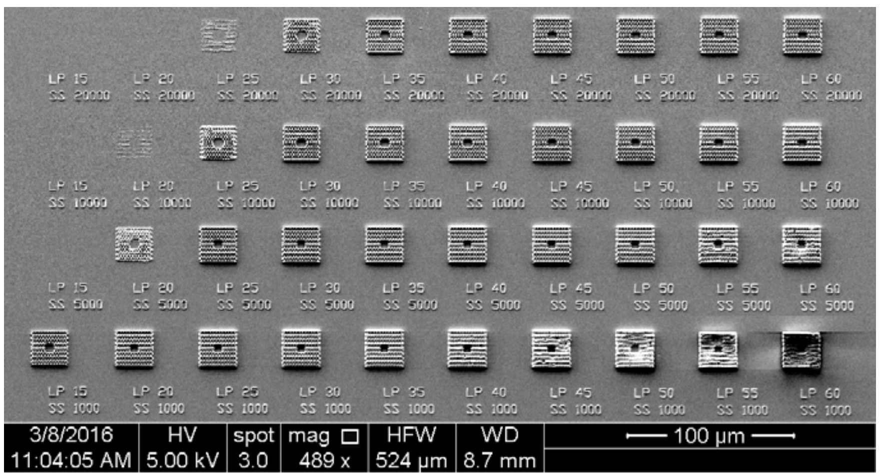



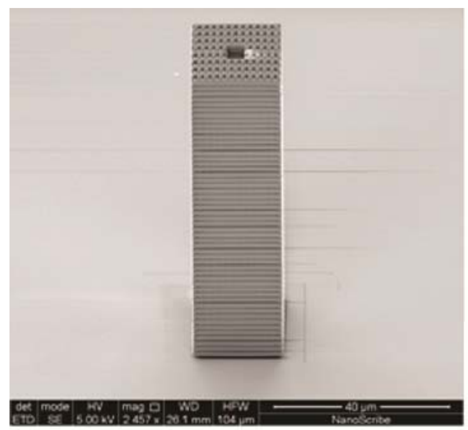

Print of a LANL designed, greatly scaled down, NIF Cepheus mirror physics package holder. Imaged with CT scan.



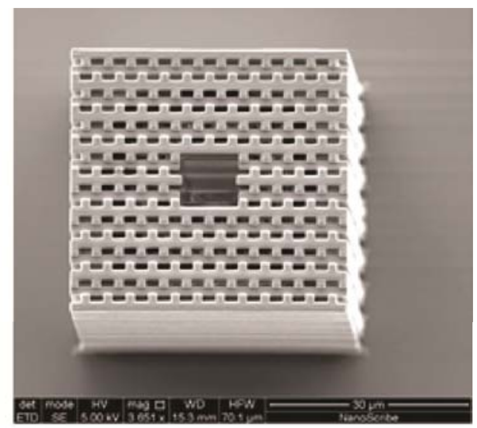
# Fabrication of the woodpile structures

- We can print woodpile structures with right dimensions with proprietary Nanoscribe resin (IP-Dip).
- Proprietary resins do not have right dielectric properties. Material science research is underway to design resins with dielectric properties of interest.




(a)




(b)