# Photonic Band Gap Structures

Sergey Antipov and Chunguang Jing

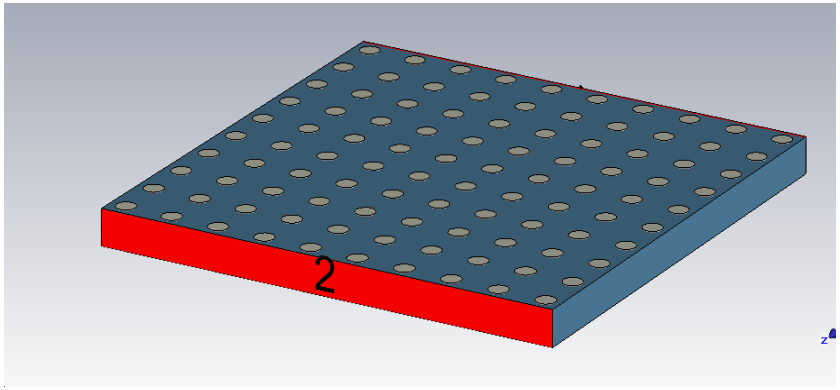
# outline

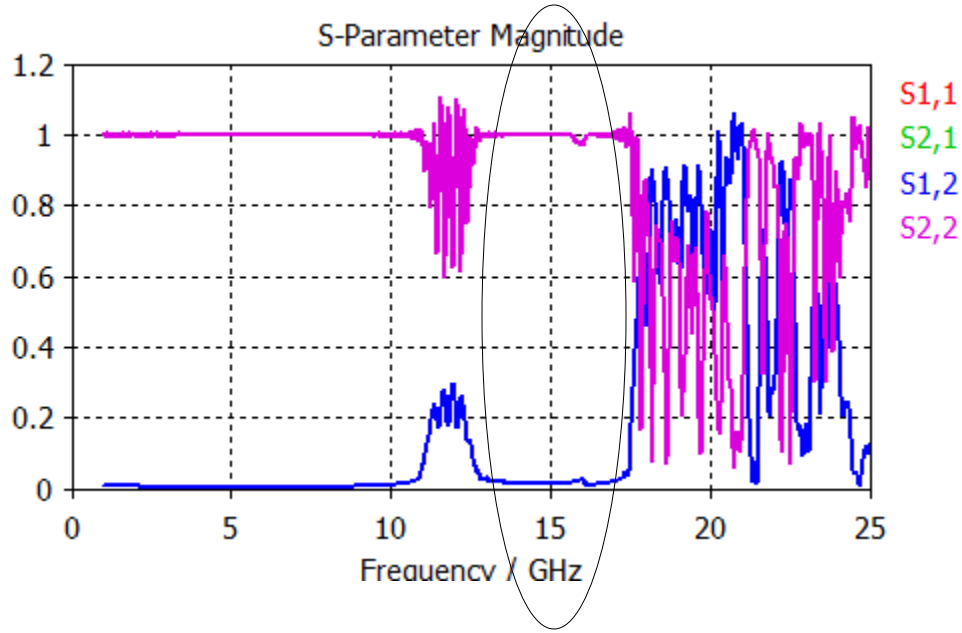
- We will review efforts by several groups:

MIT, SLAC, ANL, CU Boulder, TECH-X and others

- Band gap diagram will be simulated along with some applications: wavegude, splitter, directional coupler etc.
- Final project will contain a simulation of PBG standing wave accelerating structure

# Wave propagating through a periodic structure example



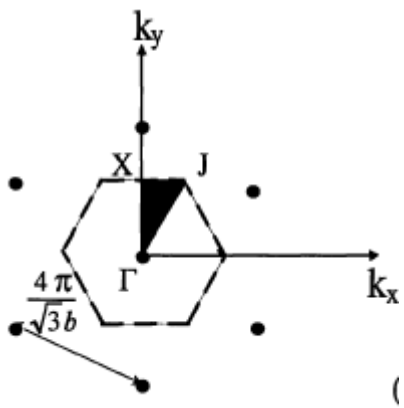



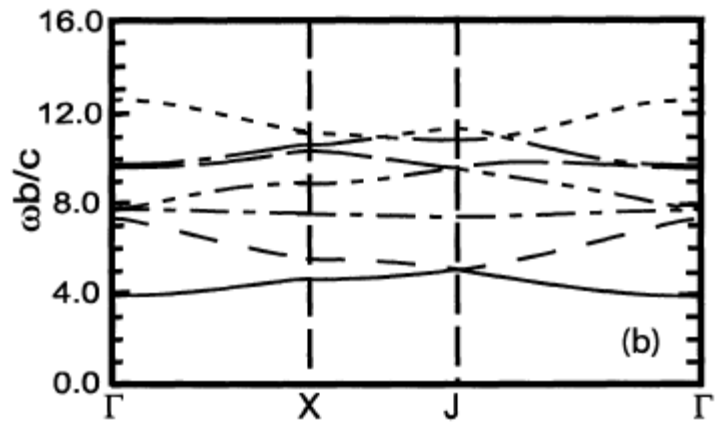

- Why? Band Gap. Recall Iris-loaded structure from Monday lecture.
- Solid state physics analogy

# PBG band gap

$$\triangle \overrightarrow{E} - \frac{\epsilon\mu}{c^2}\frac{\partial^2 \overrightarrow{E}}{\partial t^2} = 0$$

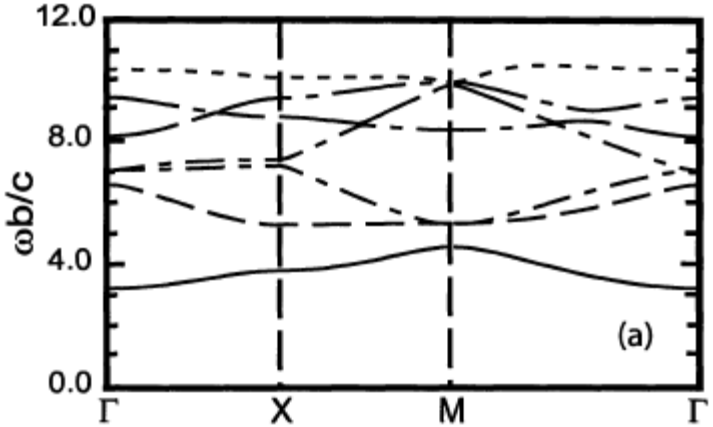
$$\boxed{\triangle_\perp E_{z\perp} = \left(k_z^2 - \epsilon\mu k_0^2\right) E_{z\perp}}$$

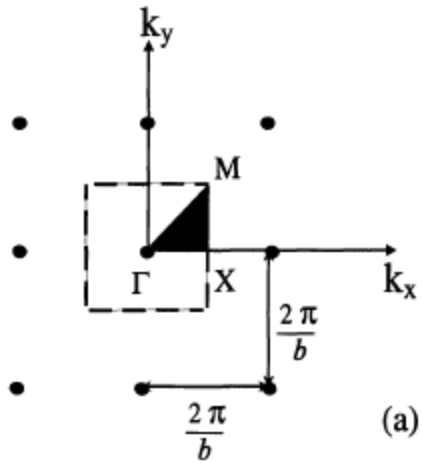



- Picture from E. Smirnova

# Band Gap Calculation Simulation




Perform parametric simulation in CST, using phase advance in two pairs of periodic boundary conditions

- Picture from E. Smirnova

# PBG parameter scanning

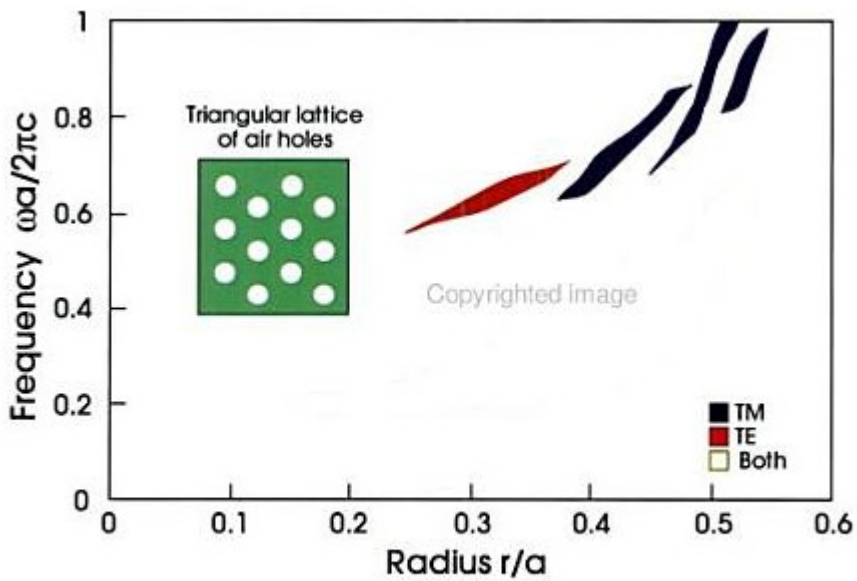
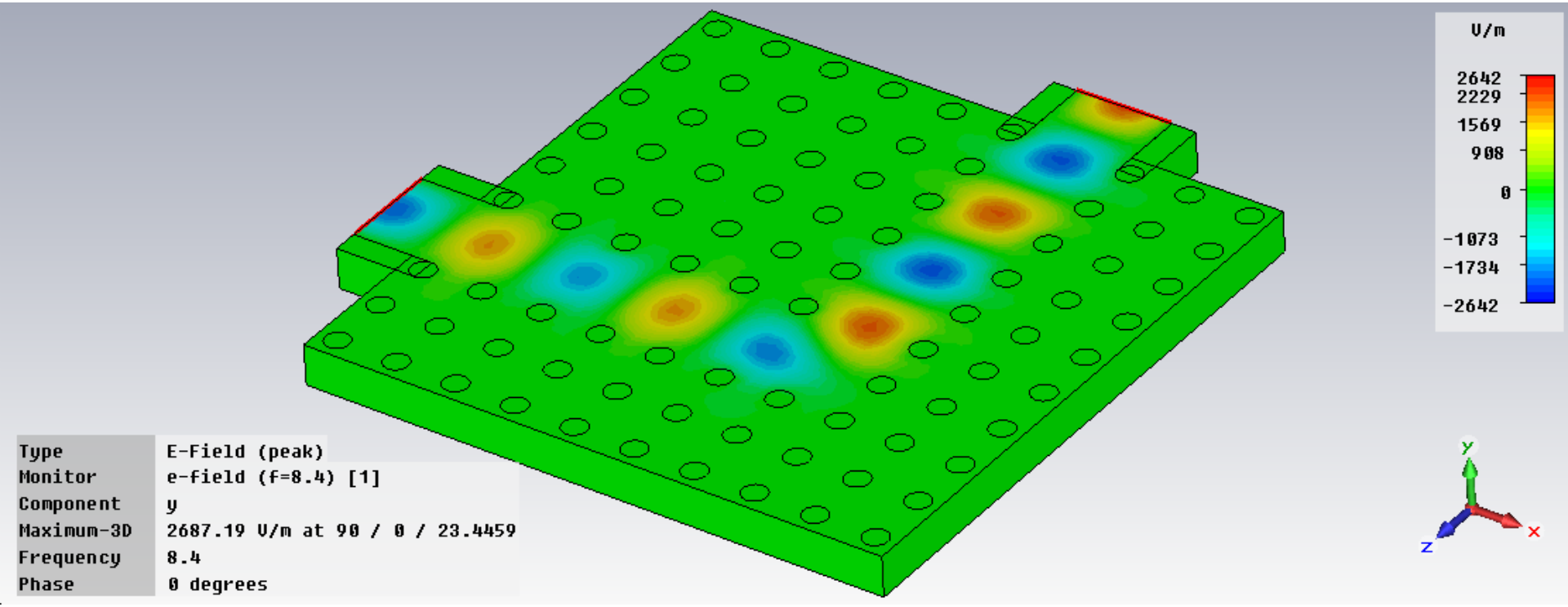



**Figure 6:** Gap map for a triangular lattice of air holes in dielectric ($\varepsilon = 11.4$).

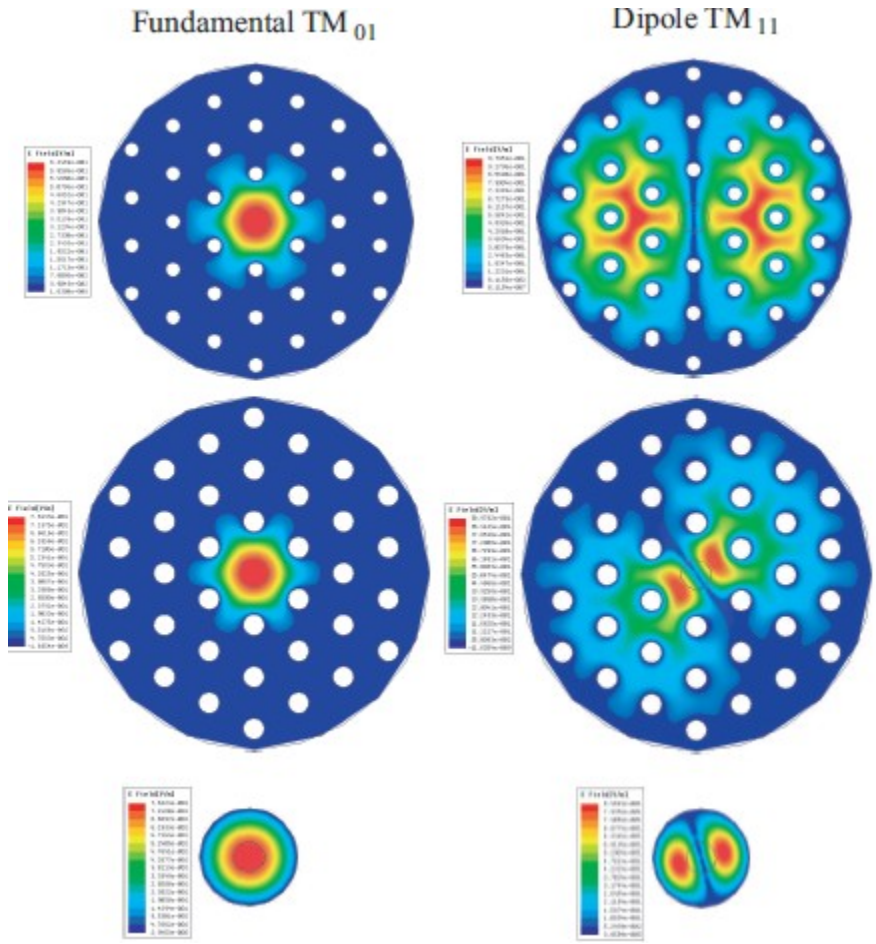
- Picture from Joannopolous book

# PBG resonators, waveguides etc…

- Simulate examples:

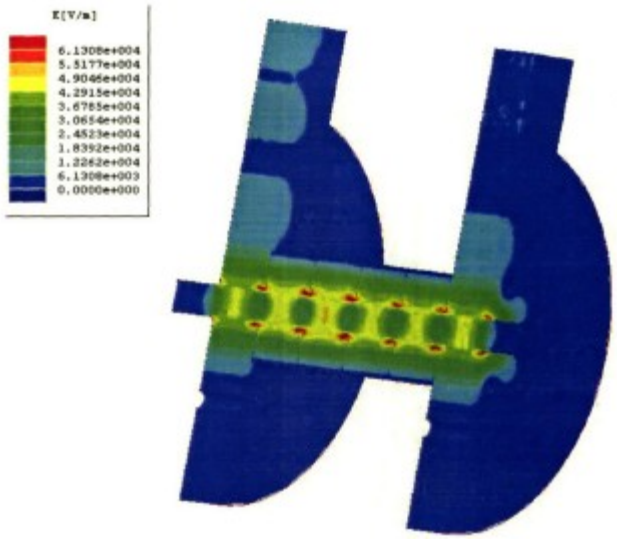


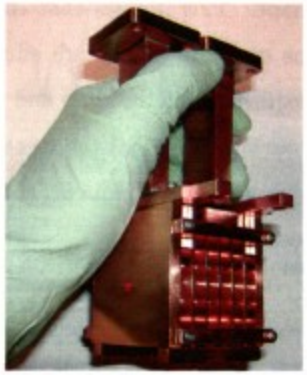
# PBG accelerating structures idea

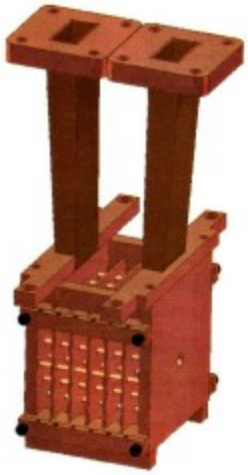



- Picture from R. Marsh

# PBG design (MIT)





| | |
|---|---|
| Rod radius (TW cell / coupler cell), $a$ | 1.04 mm/ 1.05 mm |
| Spacing between the rods, $b$ | 6.97 mm |
| $a/b$ | 0.155 |
| Cavity length, $L$ | 5.83 mm |
| Phase advance per cell | $2\pi/3$ |
| Iris radius, $d$ | 2.16 mm |
| Iris thickness, $t$ | 1.14 mm |
| Frequency ($TM_{01}$ mode) | 17.137 GHz |

- from E. Smirnova

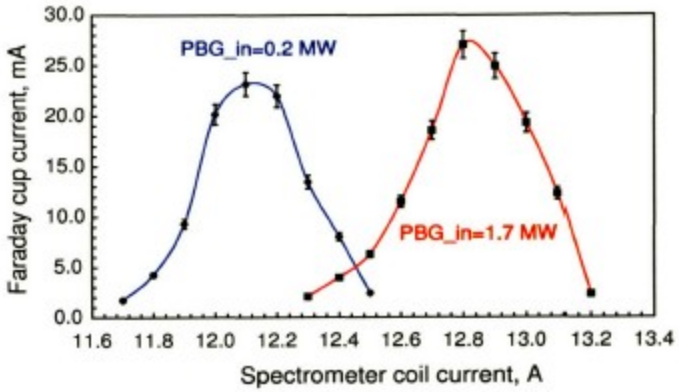
# PBG vs Iris loaded structure

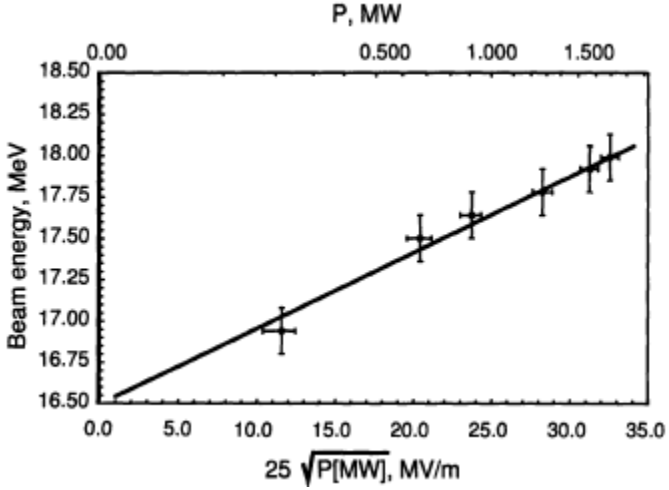
| | PBG disk-loaded structure | Disk-loaded cylindrical waveguide |
|---|---|---|
| Frequency | 17.137 GHz | 17.137 GHz |
| $Q_w$ | 4188 | 5618 |
| $r_s$ | 98 MΩ/m | 139 MΩ/m |
| $[r_s/Q_w]$ | 23.4 kΩ/m | 24.7 kΩ/m |
| Group velocity | $0.013c$ | $0.014c$ |
| Gradient | $25.2\sqrt{P\,[\mathrm{MW}]}$ MV/m | $25.1\sqrt{P\,[\mathrm{MW}]}$ MV/m |

- from E. Smirnova

# MIT PBG results

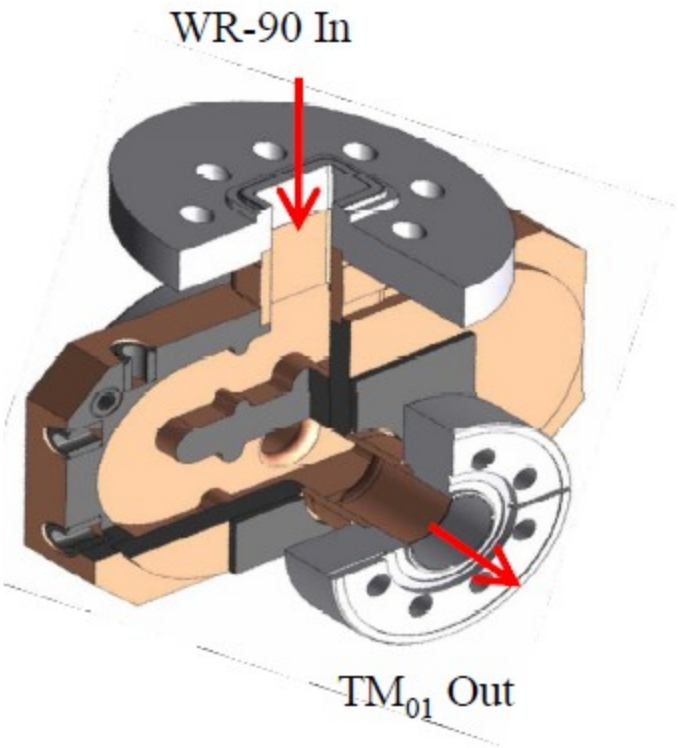
- Gradient 35 MV/m

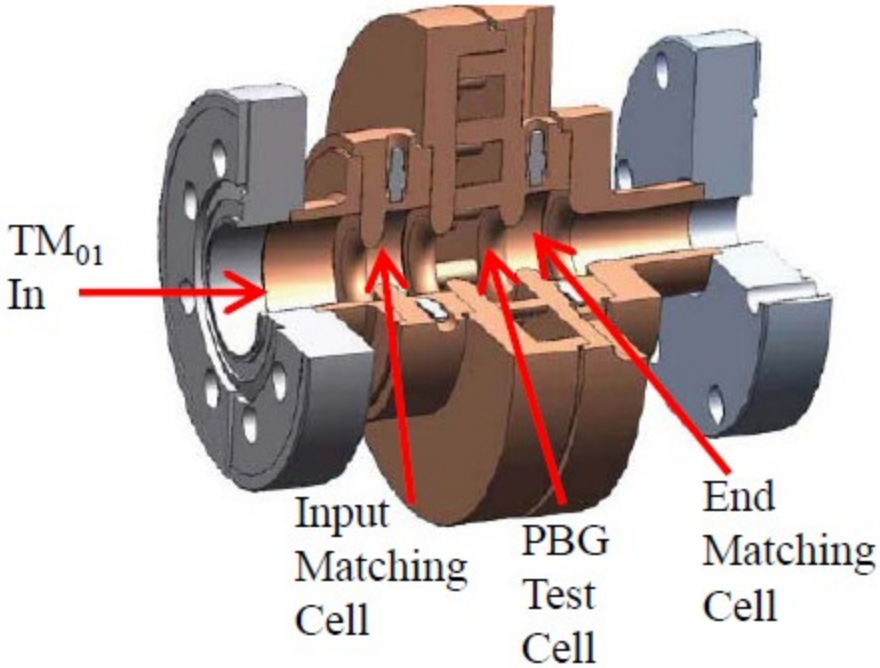


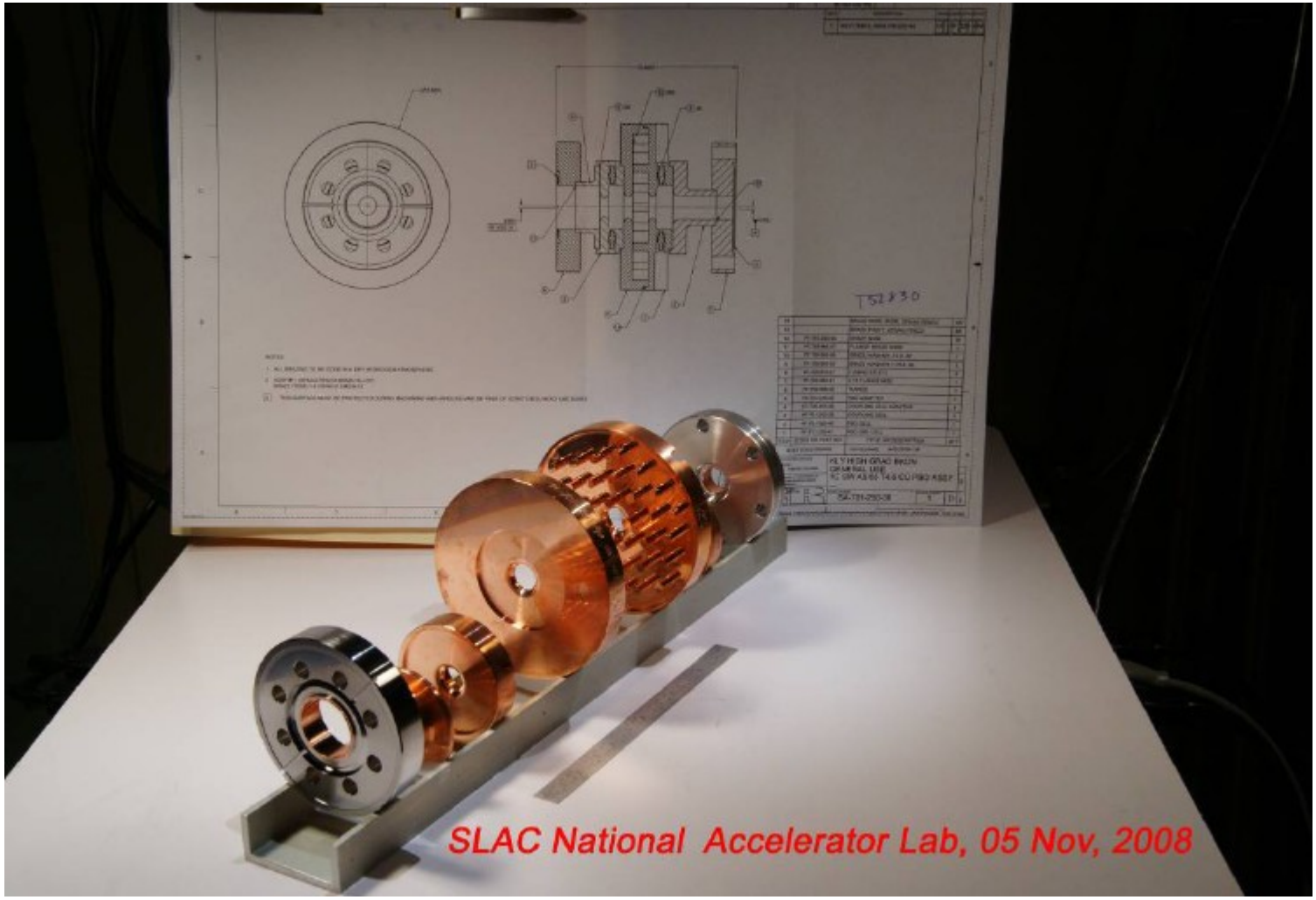

- from E. Smirnova

# MIT – SLAC PBG test



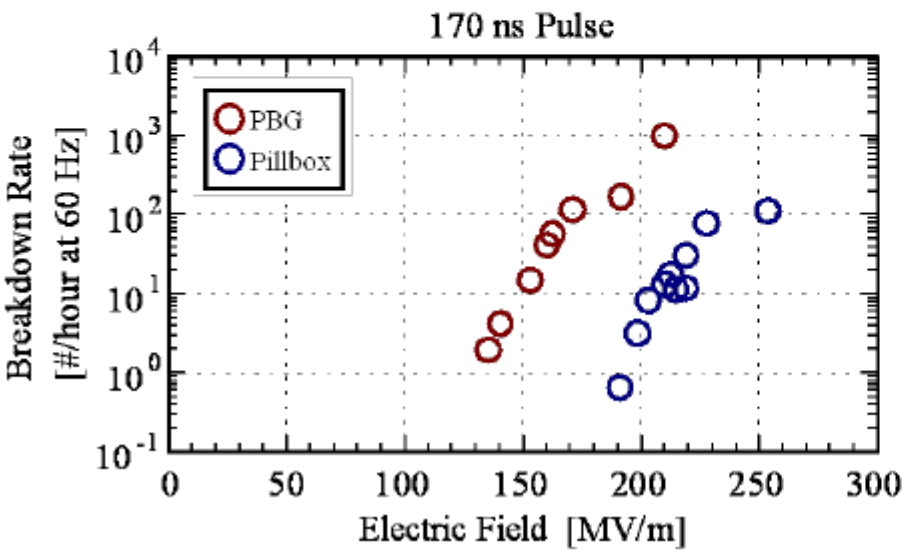



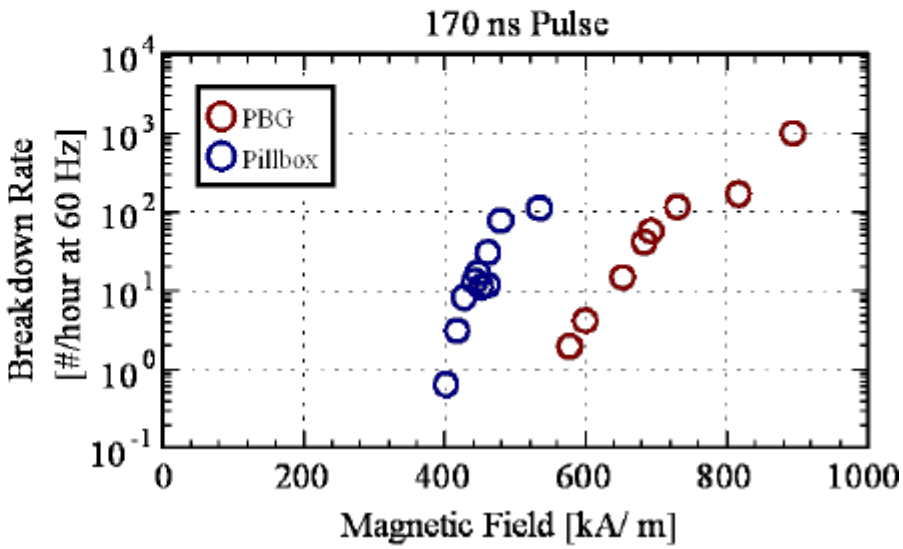

- Picture from R. Marsh


SLAC National Accelerator Lab, 05 Nov, 2008

# Pulse heating

- PBG has low E/H ratio due to high H-field on rods
  - Do see higher breakdown rates, but at high H regions, not high E regions

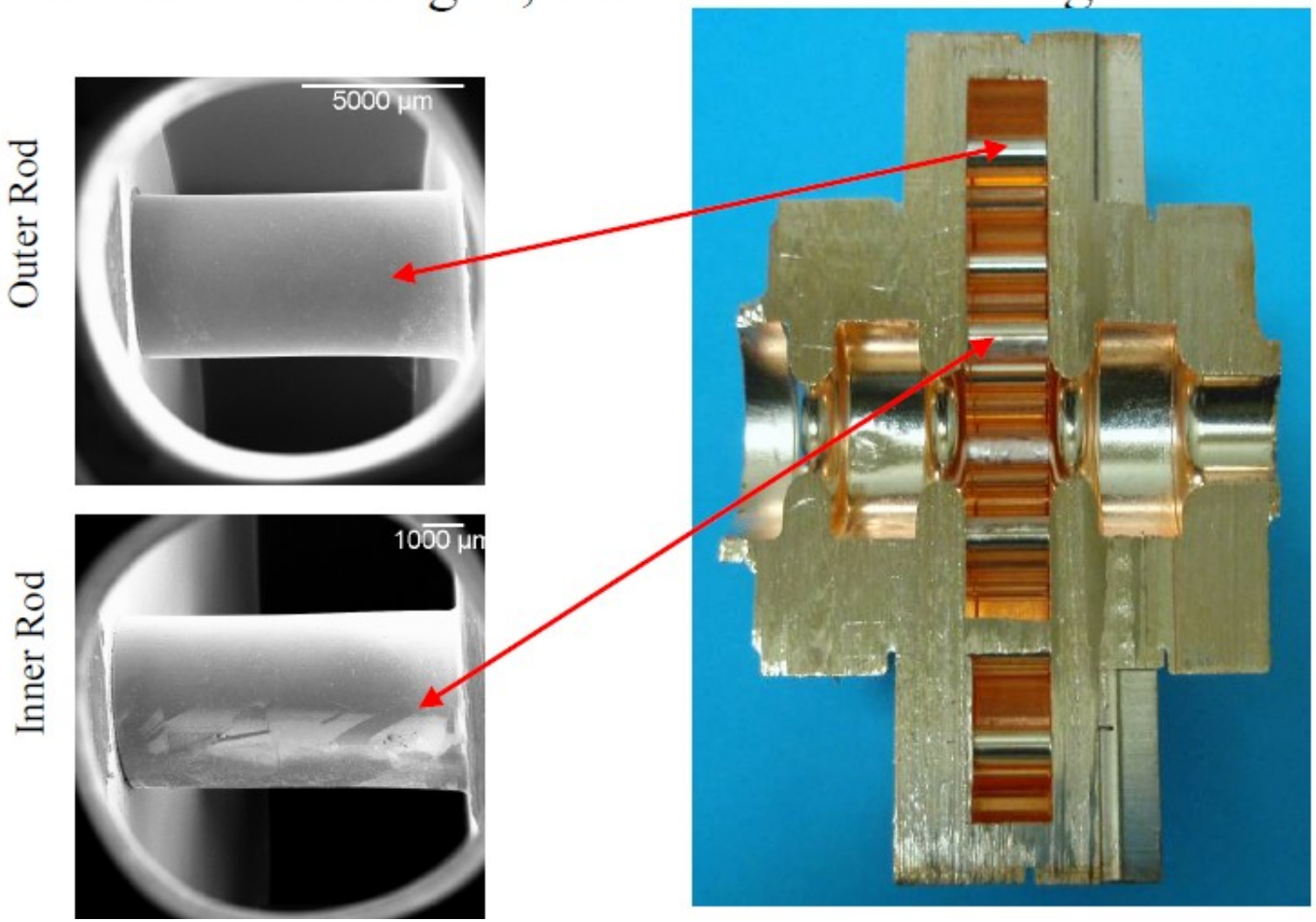



- Picture from R. Marsh, B. Munroe

# Analysis

- Inner Rods damaged, Outer Rods undamaged



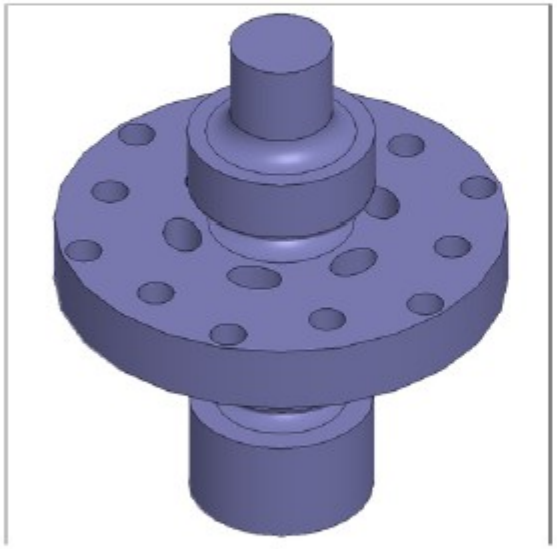

- Picture from R. Marsh, B. Munroe

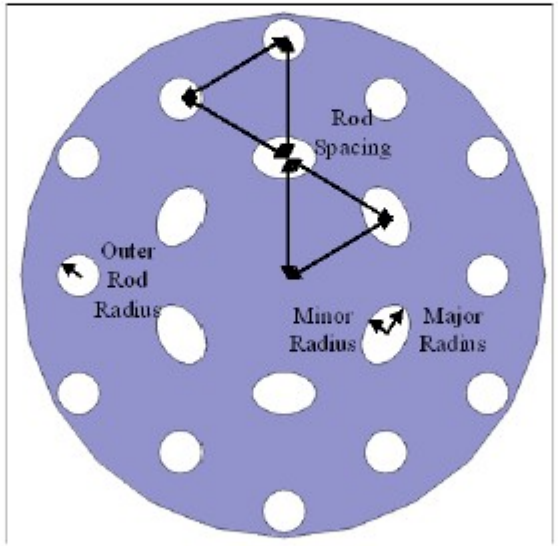
# Pulsed Heating Damage

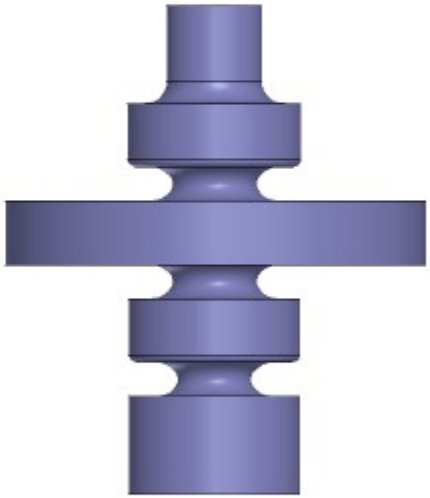
- For pillbox pulsed heating averages 60K per shot
- For PBG pulsed heating averages 120K per shot
- PBG additionally saw excursions to $\Delta T > 400K$ early in testing
  - These excursions may have caused immediate damage, degrading future performance
  - Pulsed heating must be limited in future experiments

# Improved Design at 11 GHz

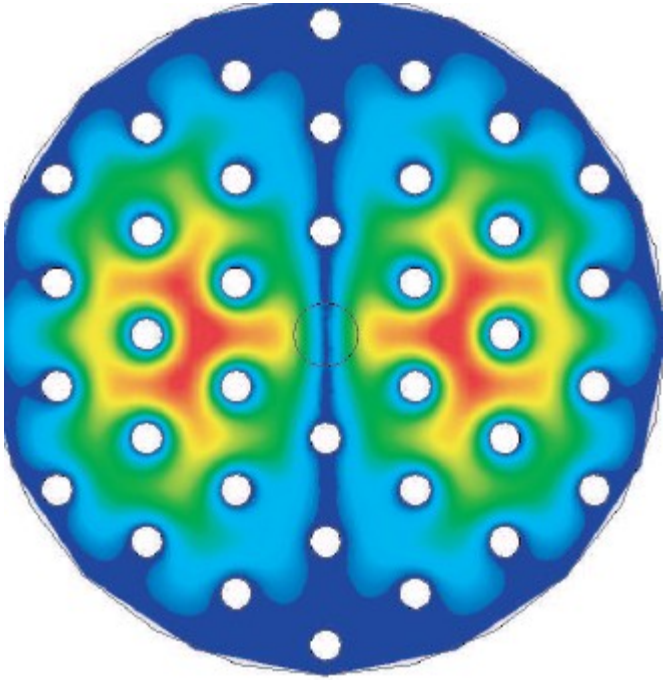
- Based on what we learned, we need to:
  - Reduce H on inner rods
  - Be more careful when processing the structure
- Elliptical inner rods reduce pulsed heating by 50%

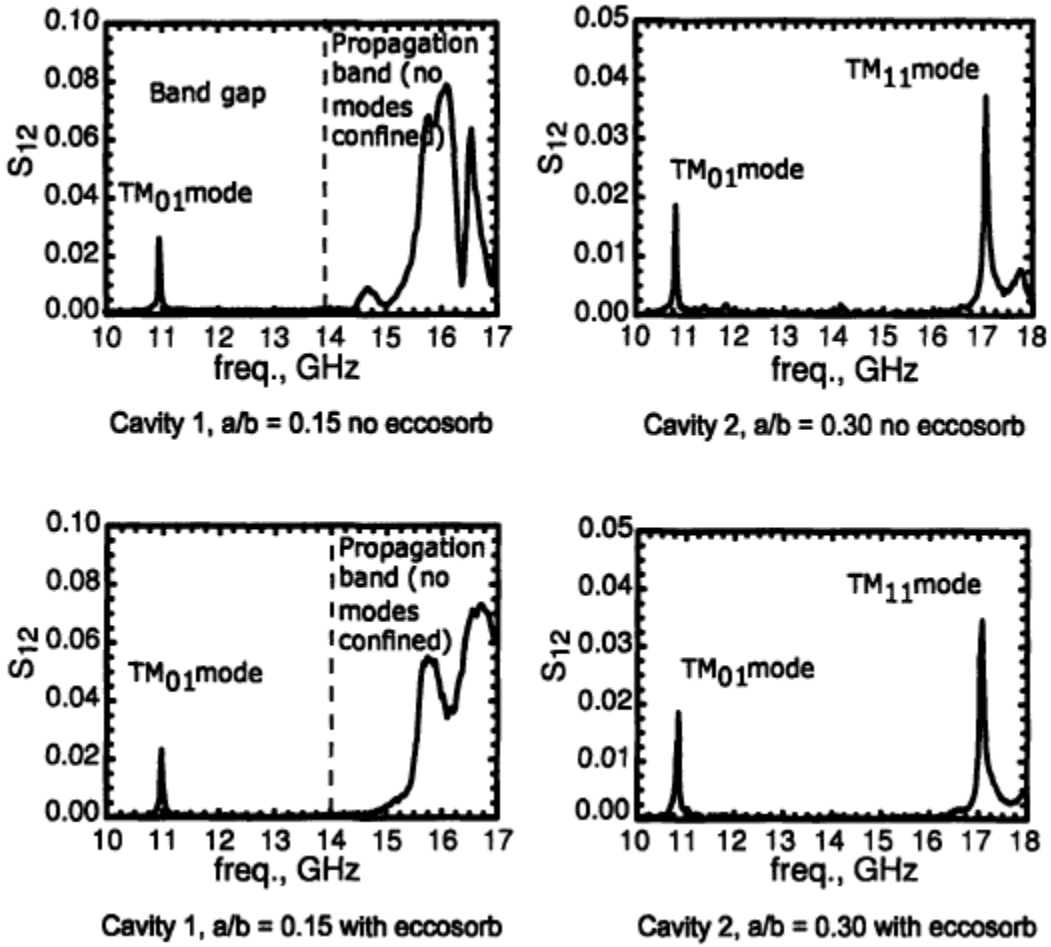




# HOM confinement

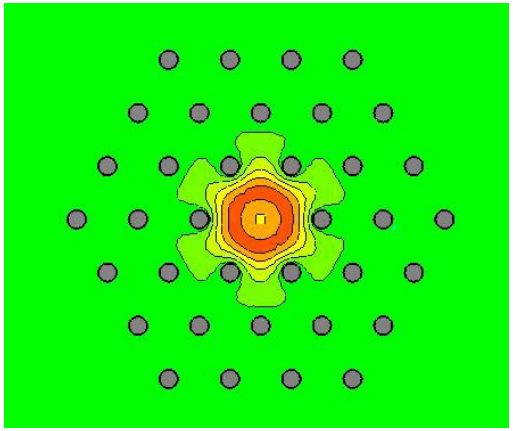


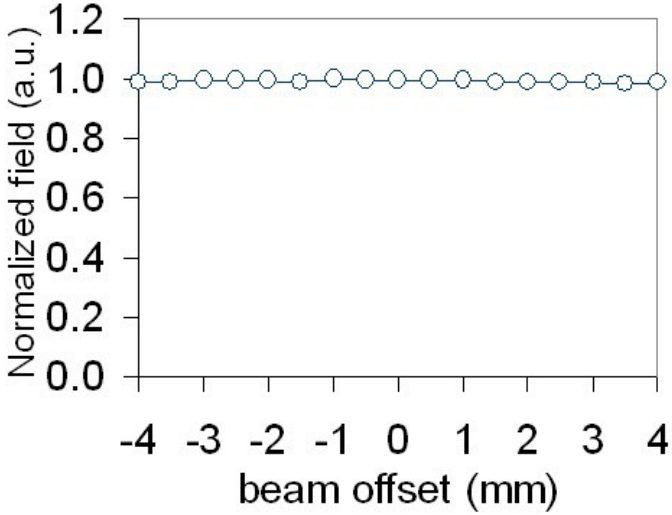



From E. Smirnova

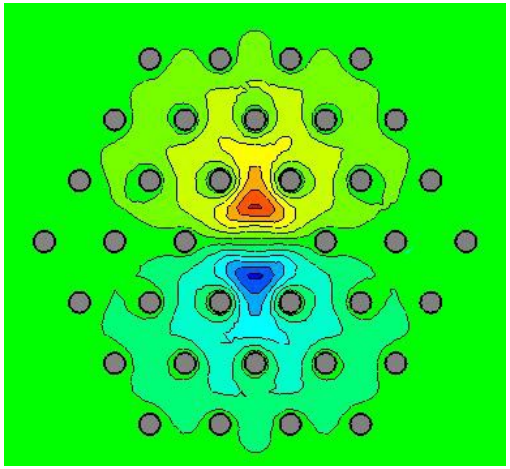
# HOM confinement (AWA)

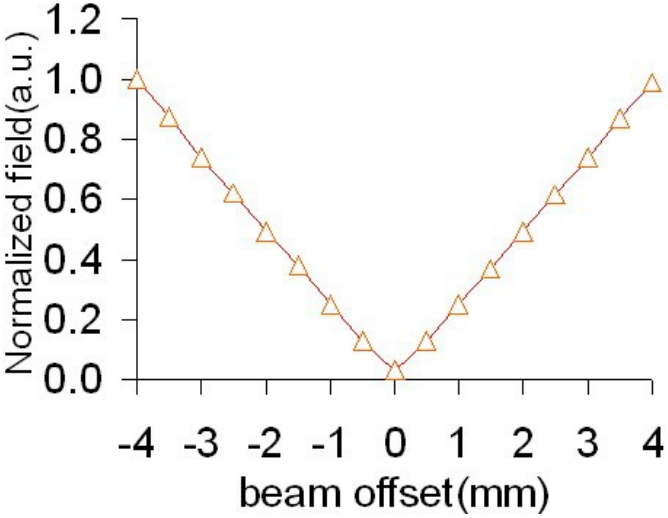
Accelerating Mode






Dipole Mode

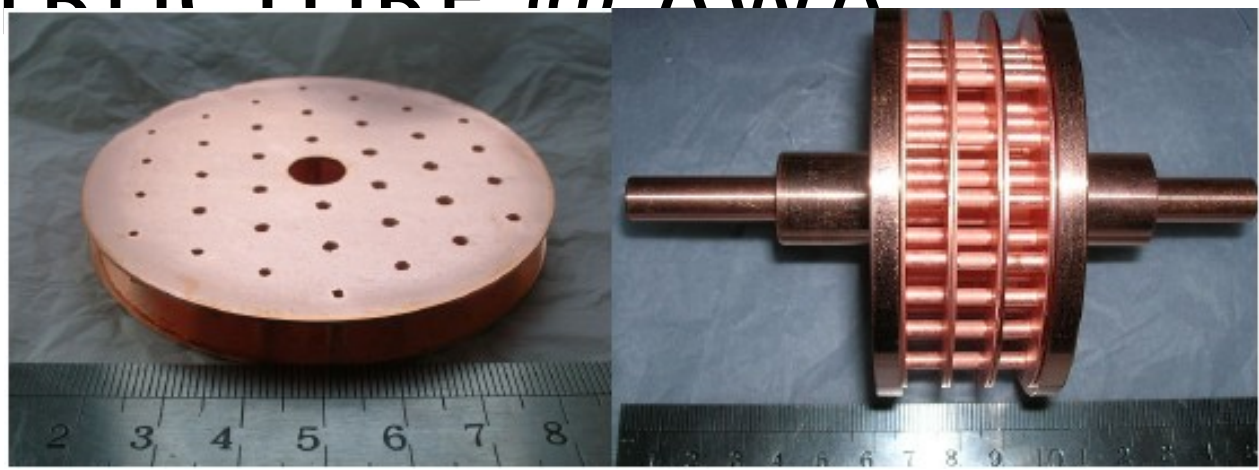


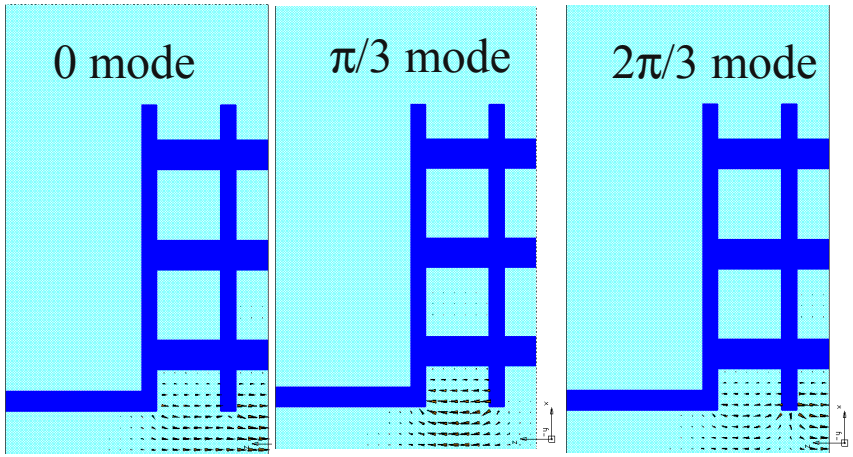



From C. Jing AWA experiments

# WAKEFIELD EXPERIEMENT OF THE PBG STRUCTURE @ AWA

We designed and fabricated a X-band PBG structure using electroforming technique at Tsinghua University, China.

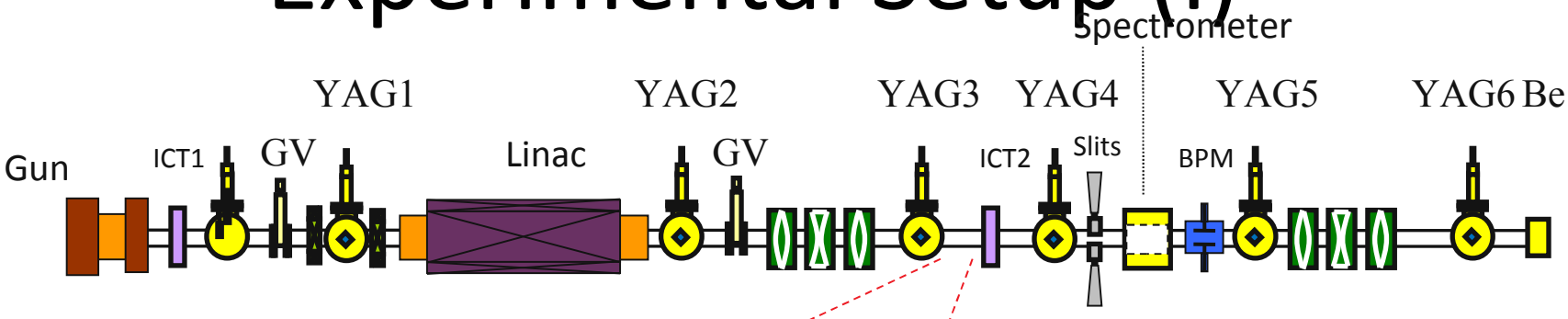


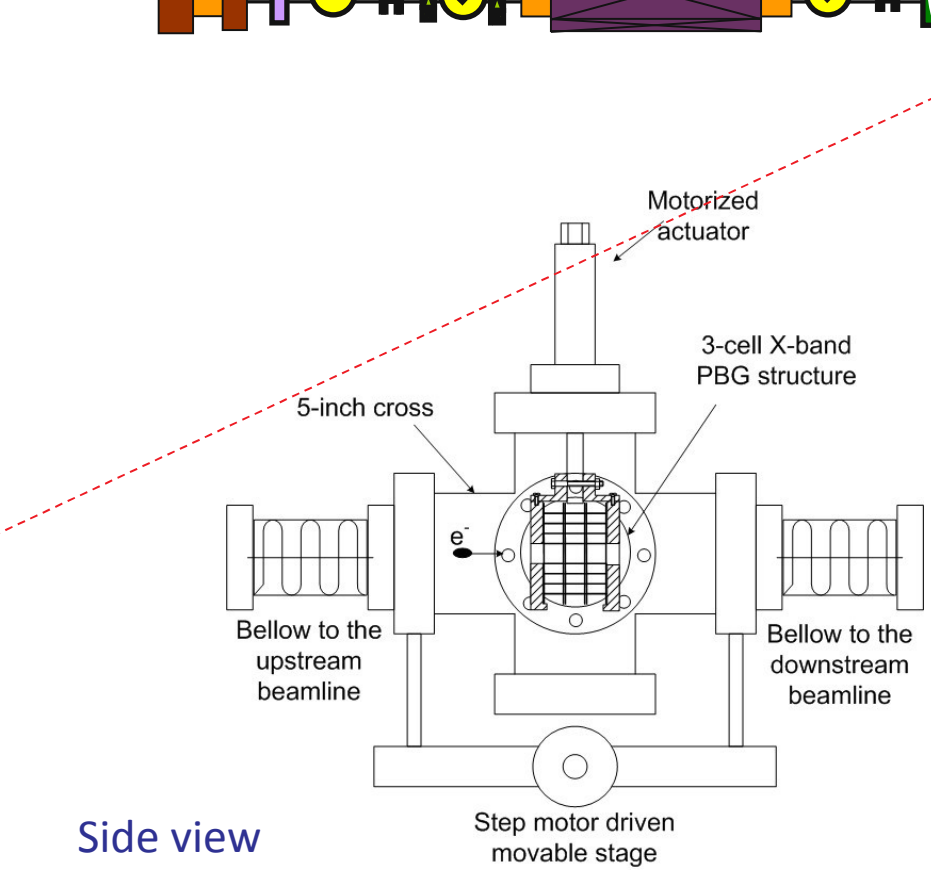



| $TM_{01}$ like Modes | Freq. (GHz) | R/Q (Ω) |
|---|---|---|
| 0 mode | 11.10 | 4.86 |
| π/3 | 11.31 | 148.5 |
| 2π/3 | 11.52 | 148.1 |

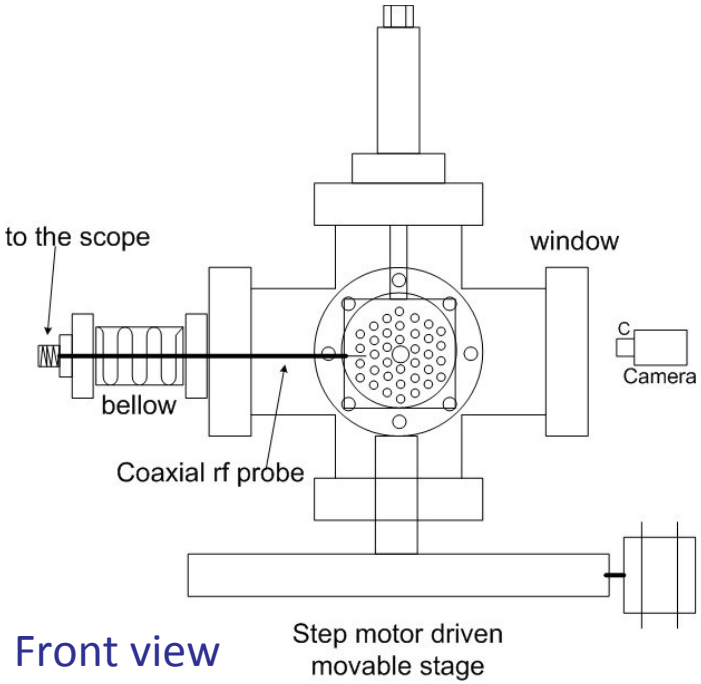
From C. Jing AWA experiments

# Experimental Setup (I)



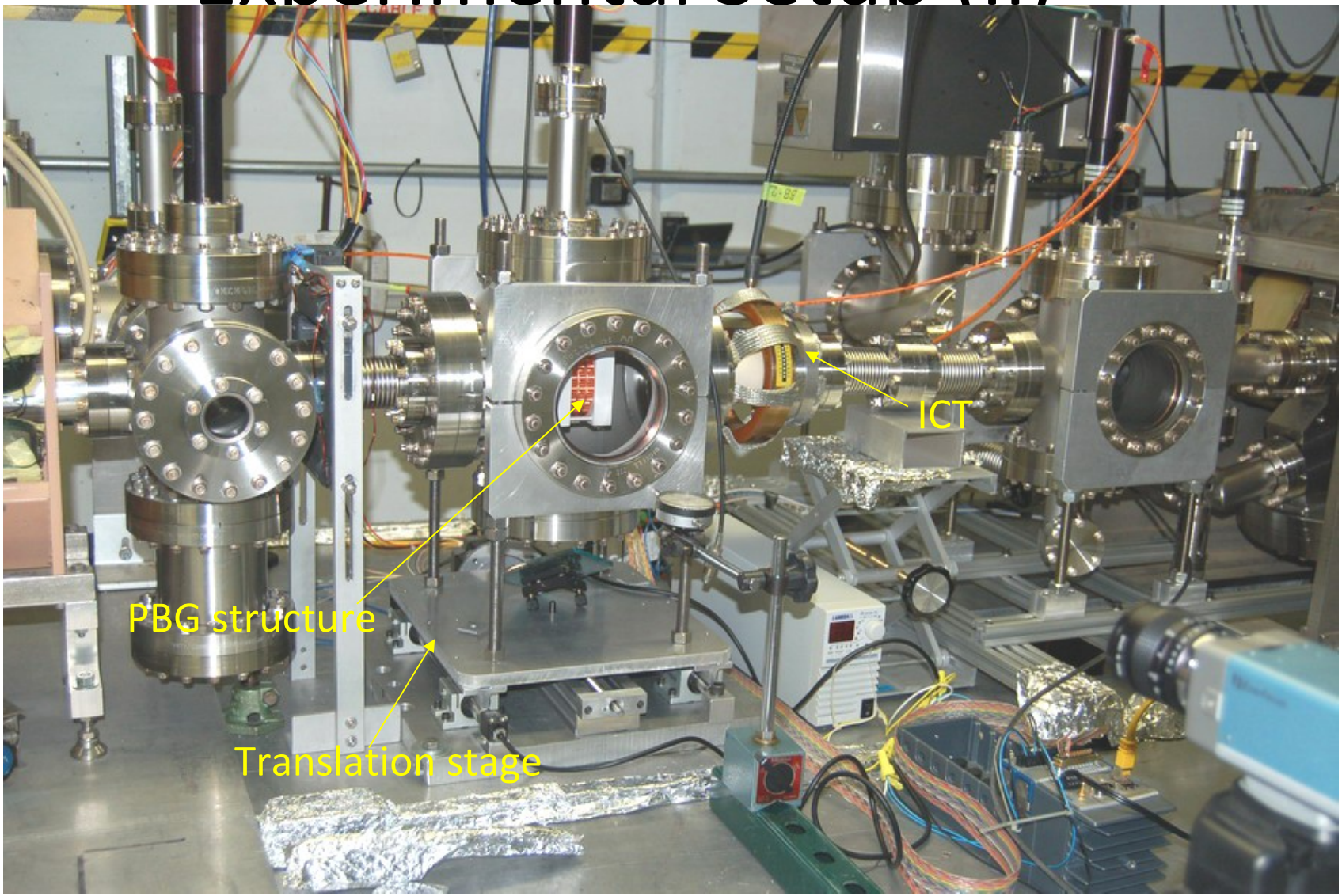

Side view




Front view

From C. Jing AWA experiments

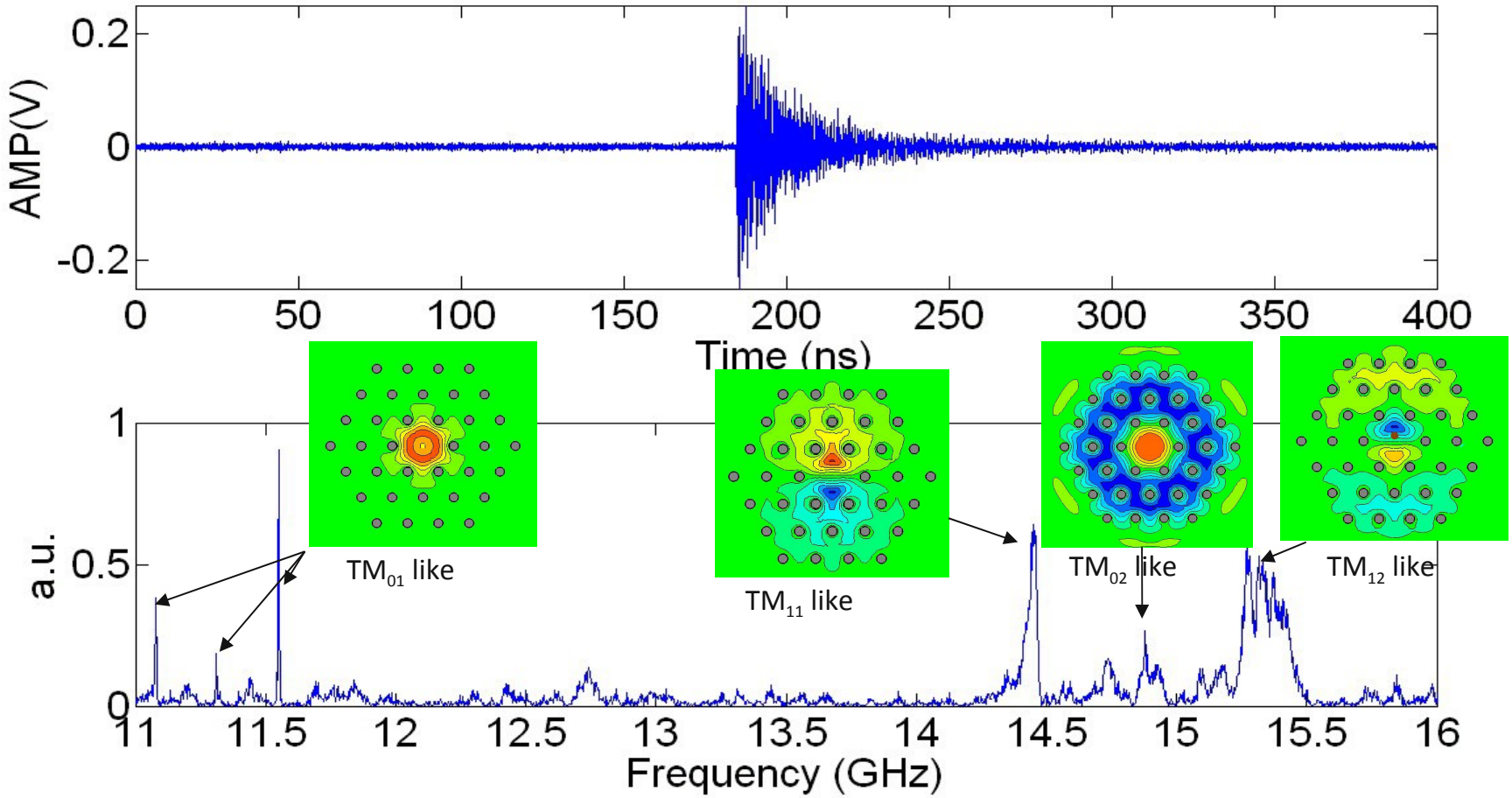
# Experimental Setup (II)




From C. Jing AWA experiments

# Experimental Results (I)----mode identification

Probe signal @ ~3.5mm of beam off-axis

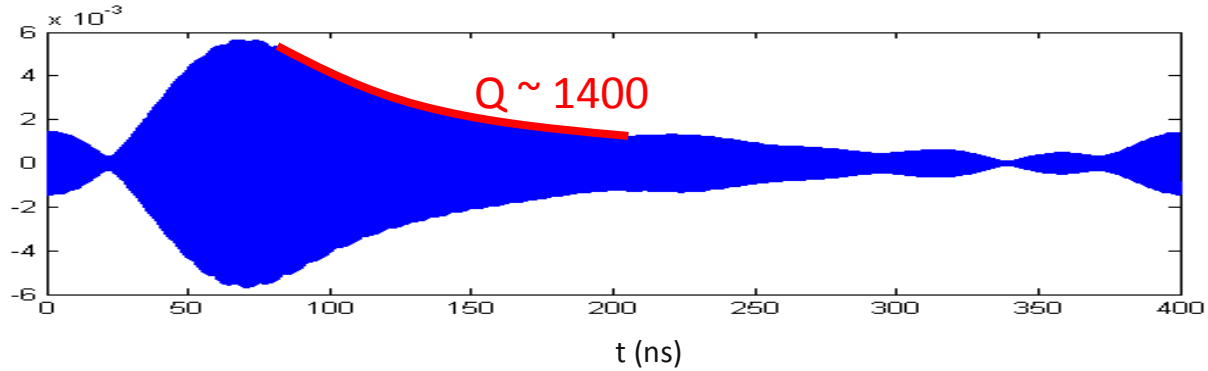



From C. Jing AWA experiments

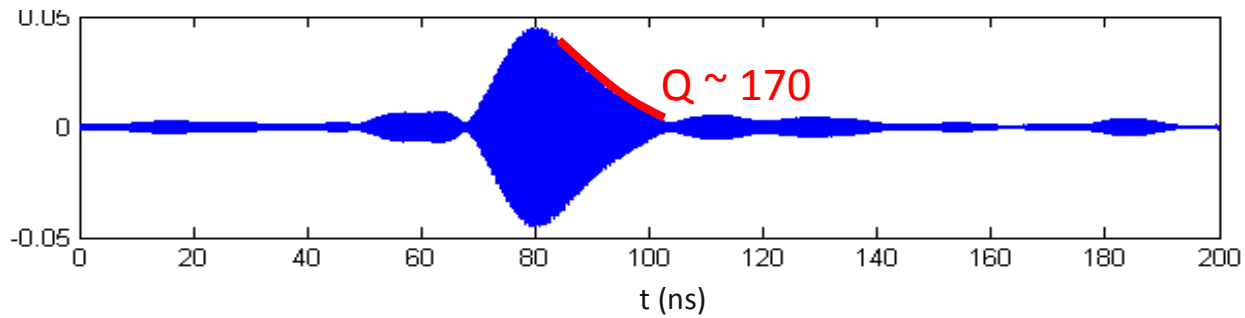
# Experimental Results (II)----Q estimation

Q estimation based on the filtered mode signal

Acceleration mode (11.55GHz)

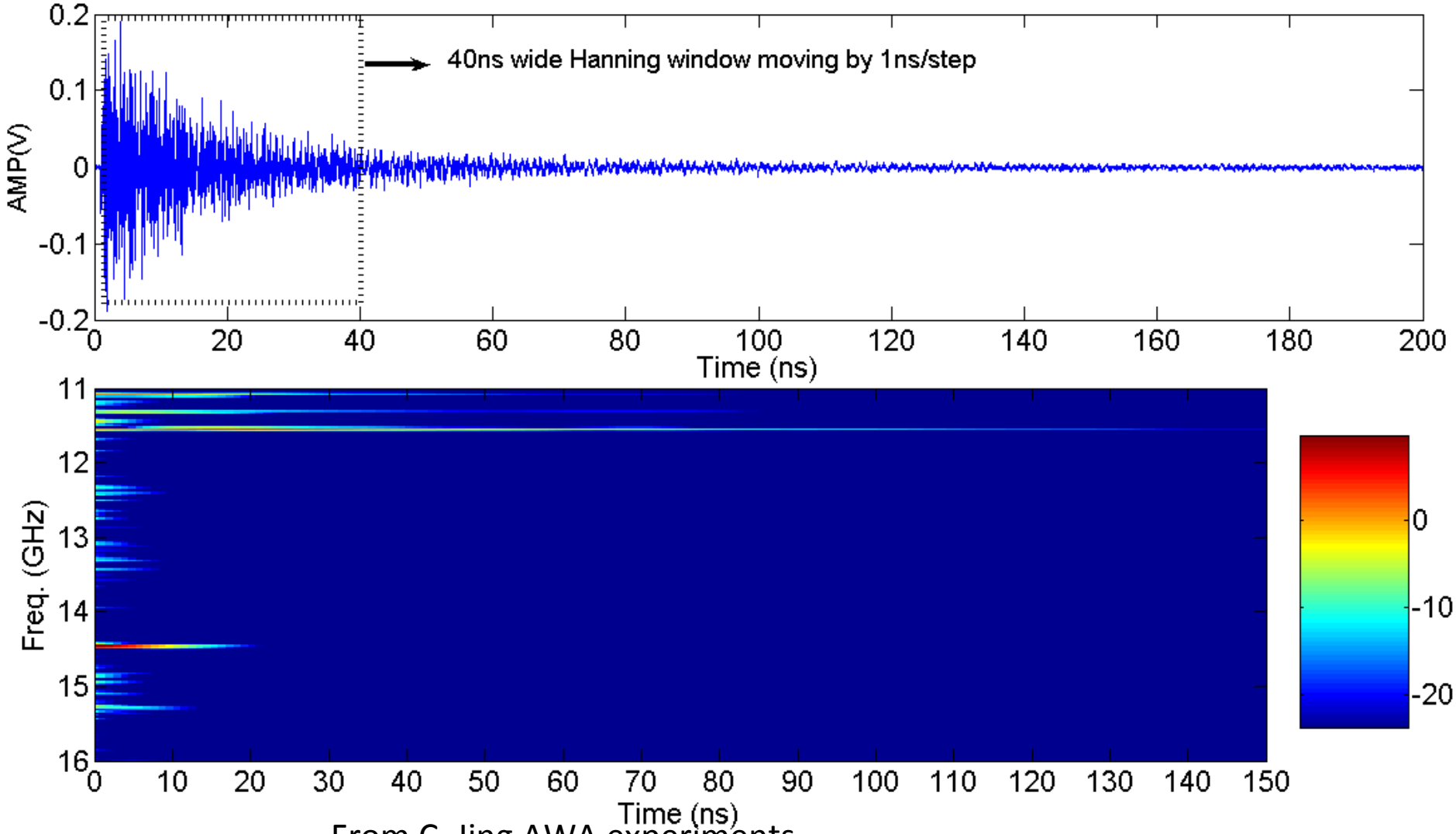



Dipole (14.46GHz)



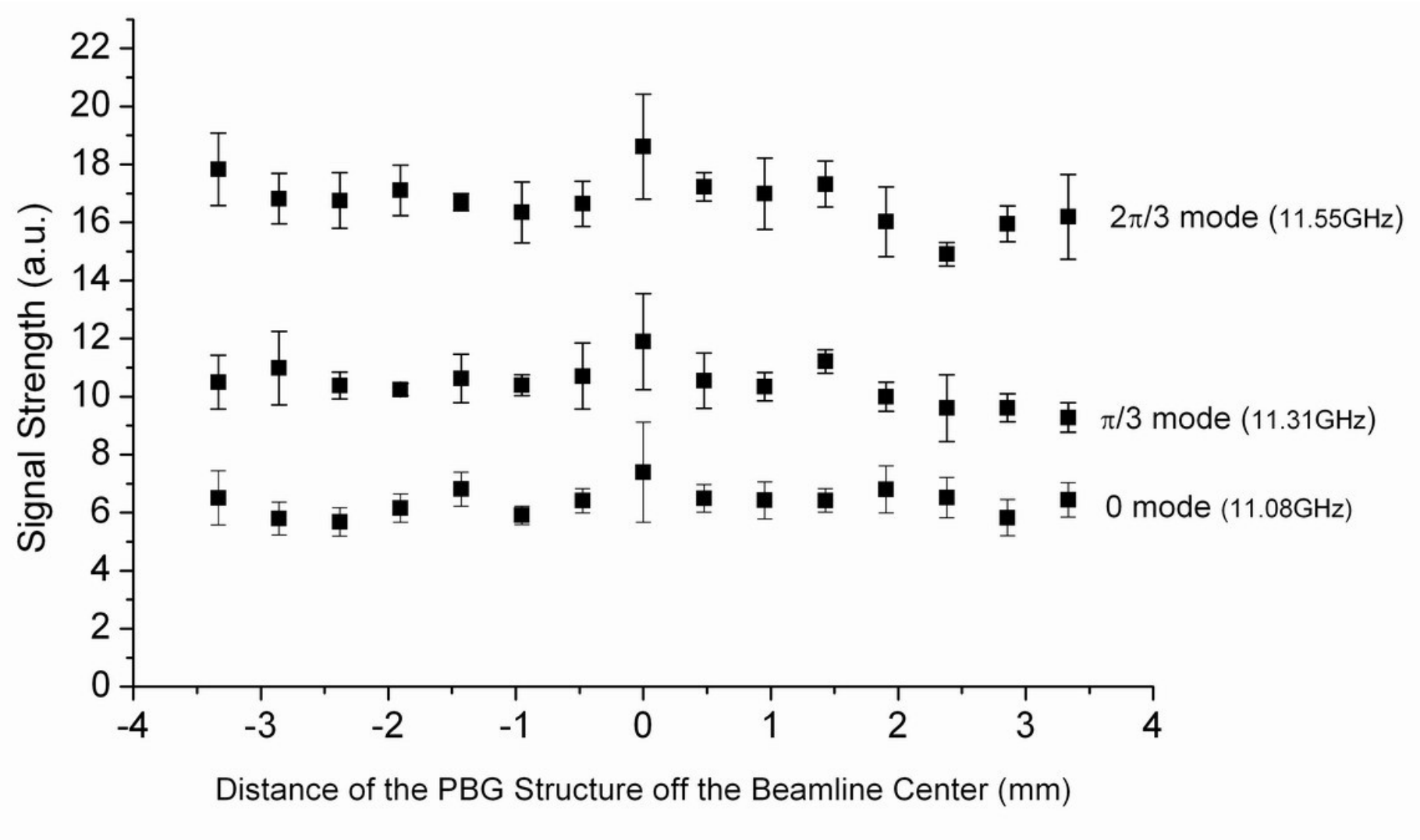

From C. Jing AWA experiments

# Experimental Results (III)----time-



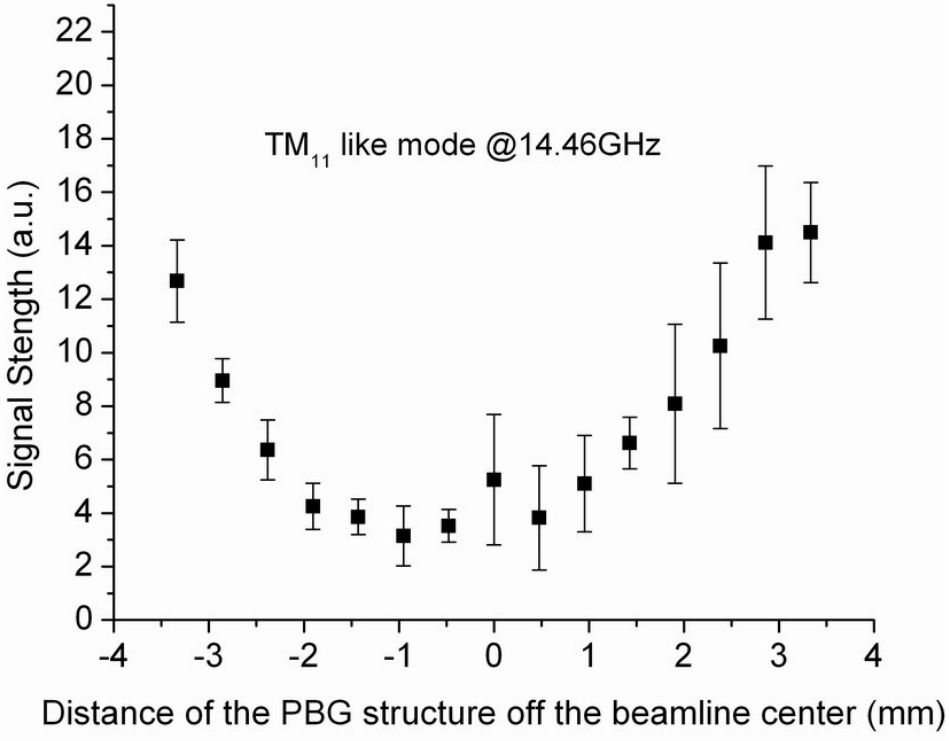

From C. Jing AWA experiments

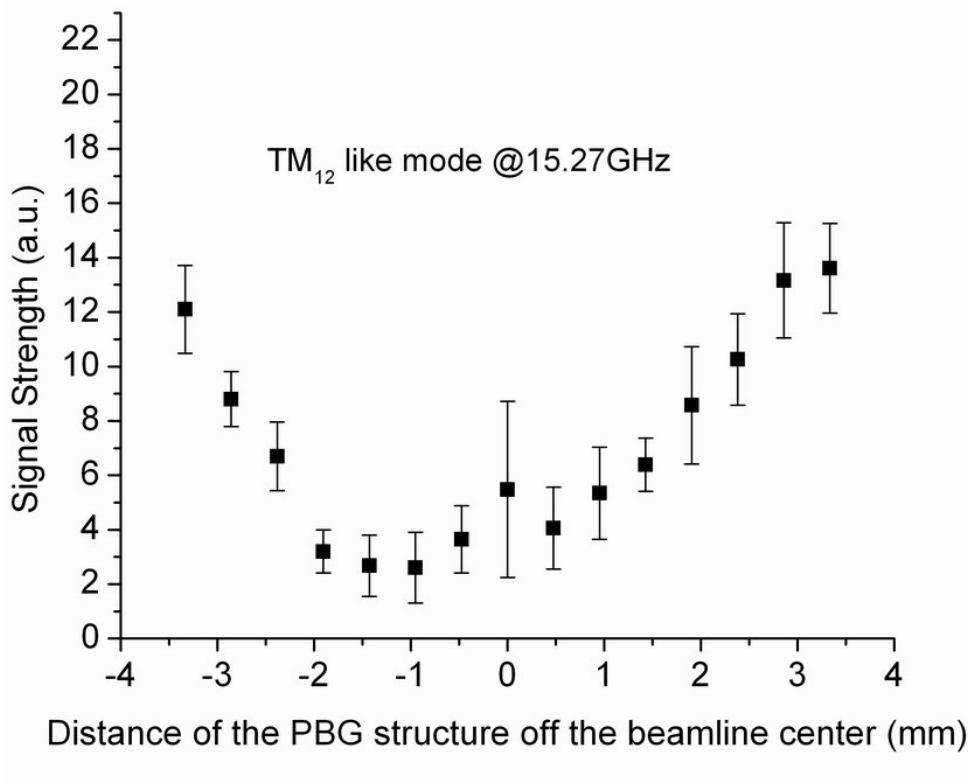
# Experimental Results (IV)----




From C. Jing AWA experiments

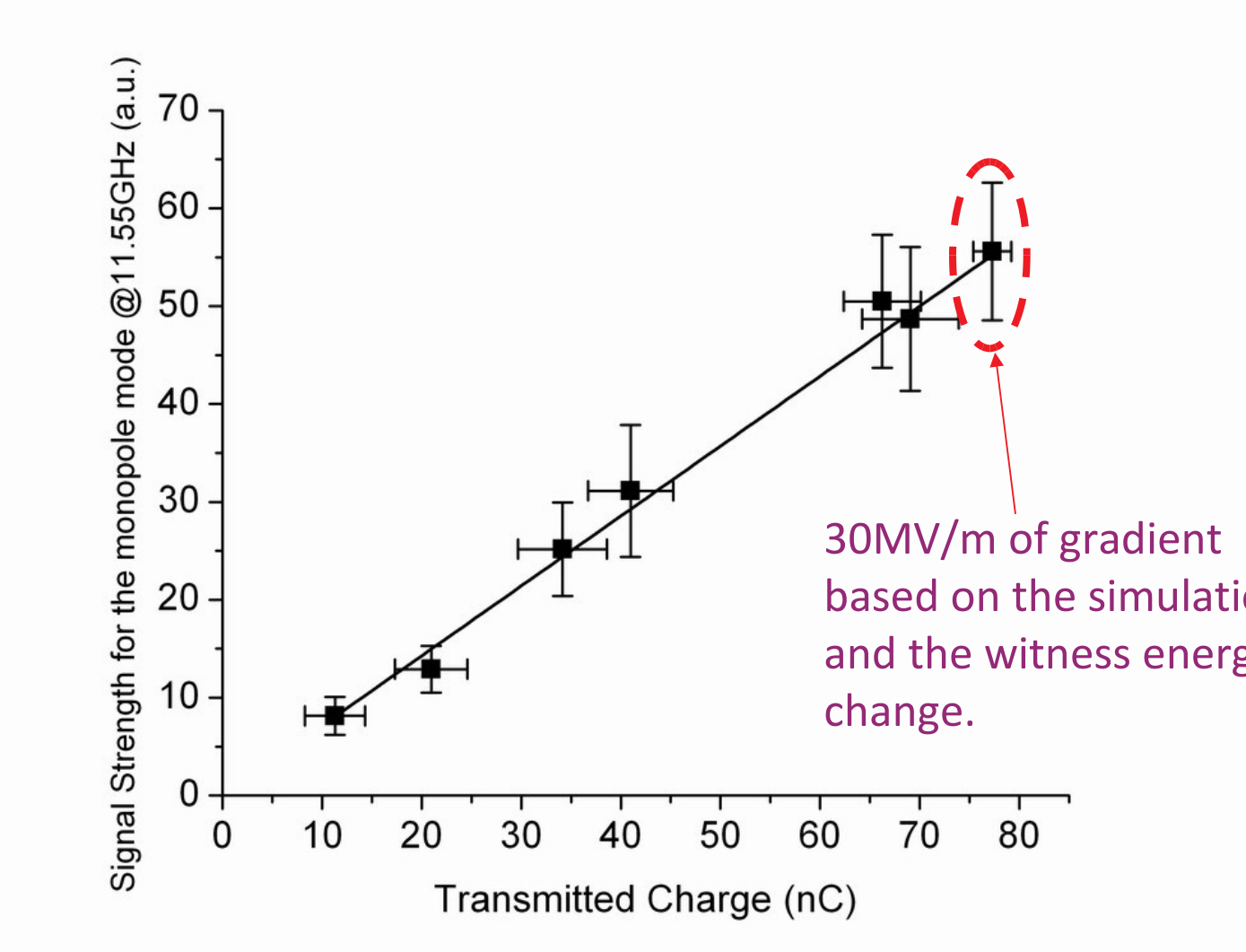
# Experimental Results (V)----dipole mode characterization



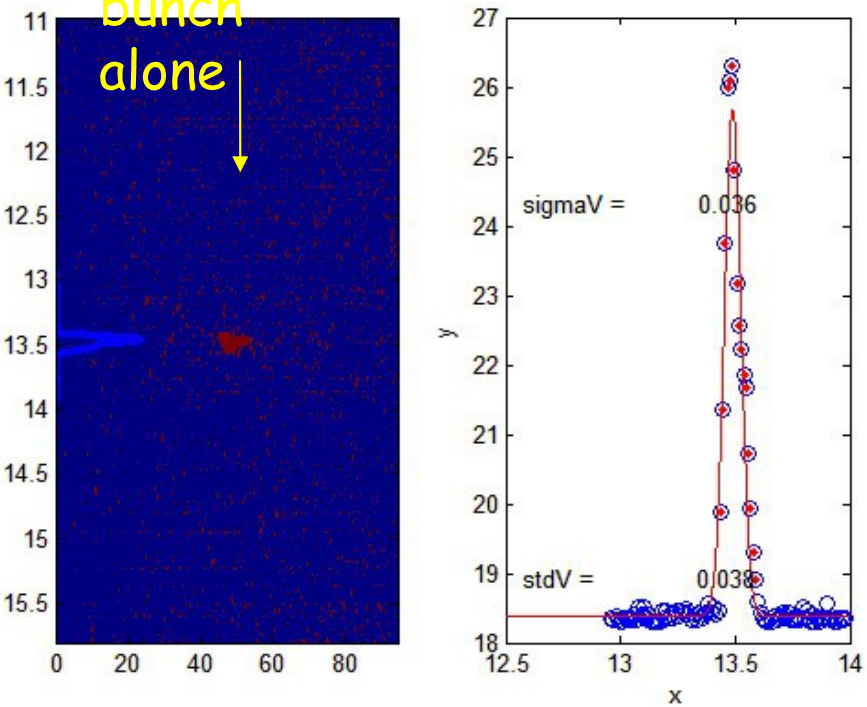

From C. Jing AWA experiments

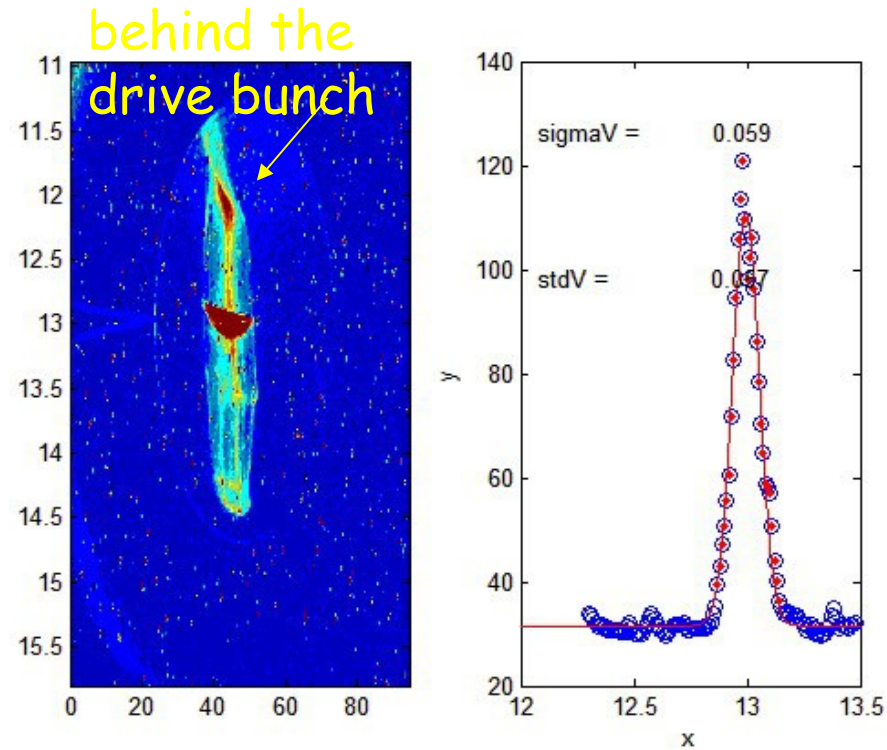
# Experimental Results (VI)----charge




From C. Jing AWA experiments

# Experimental Results (VII)----two-bunch collinear acceleration



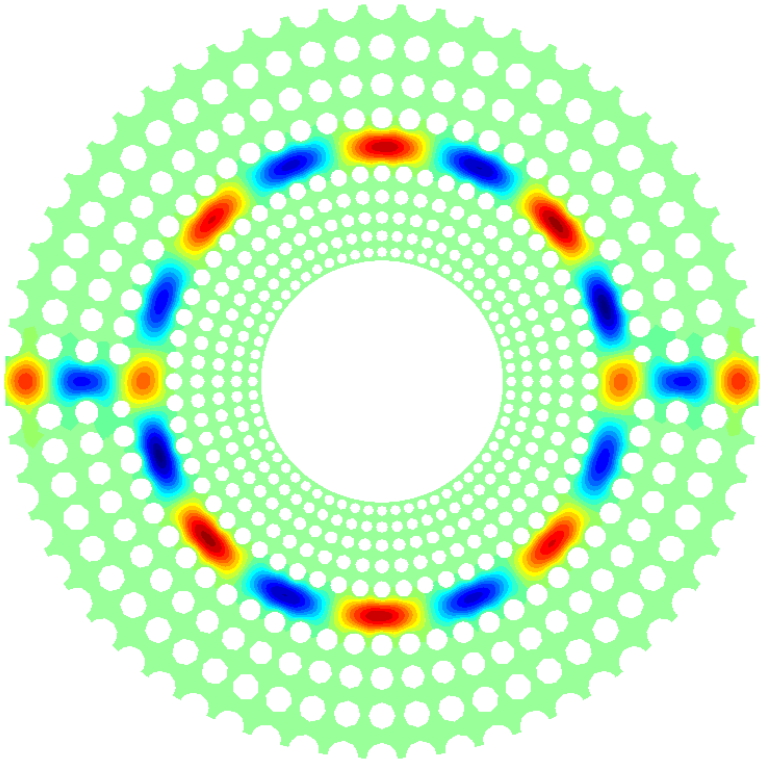




We observed 0.44MeV/m/nC Deceleration.

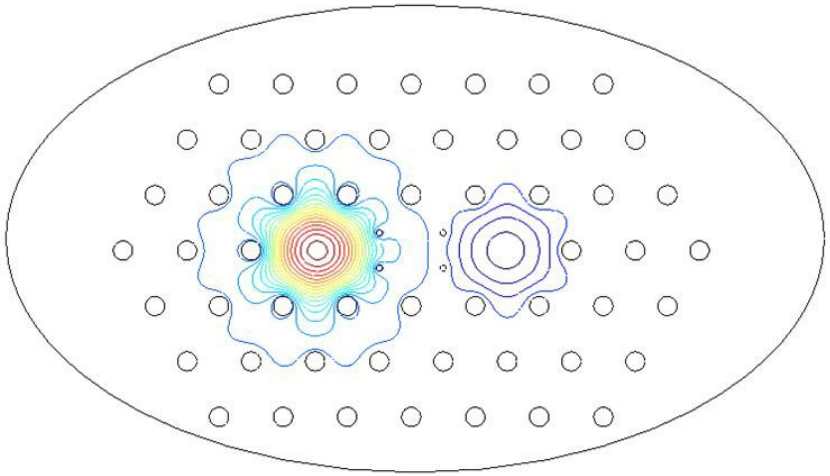
From C. Jing AWA experiments

# FURTHER EXPLORATION---exotic ideas

PBG Circulating waveguide

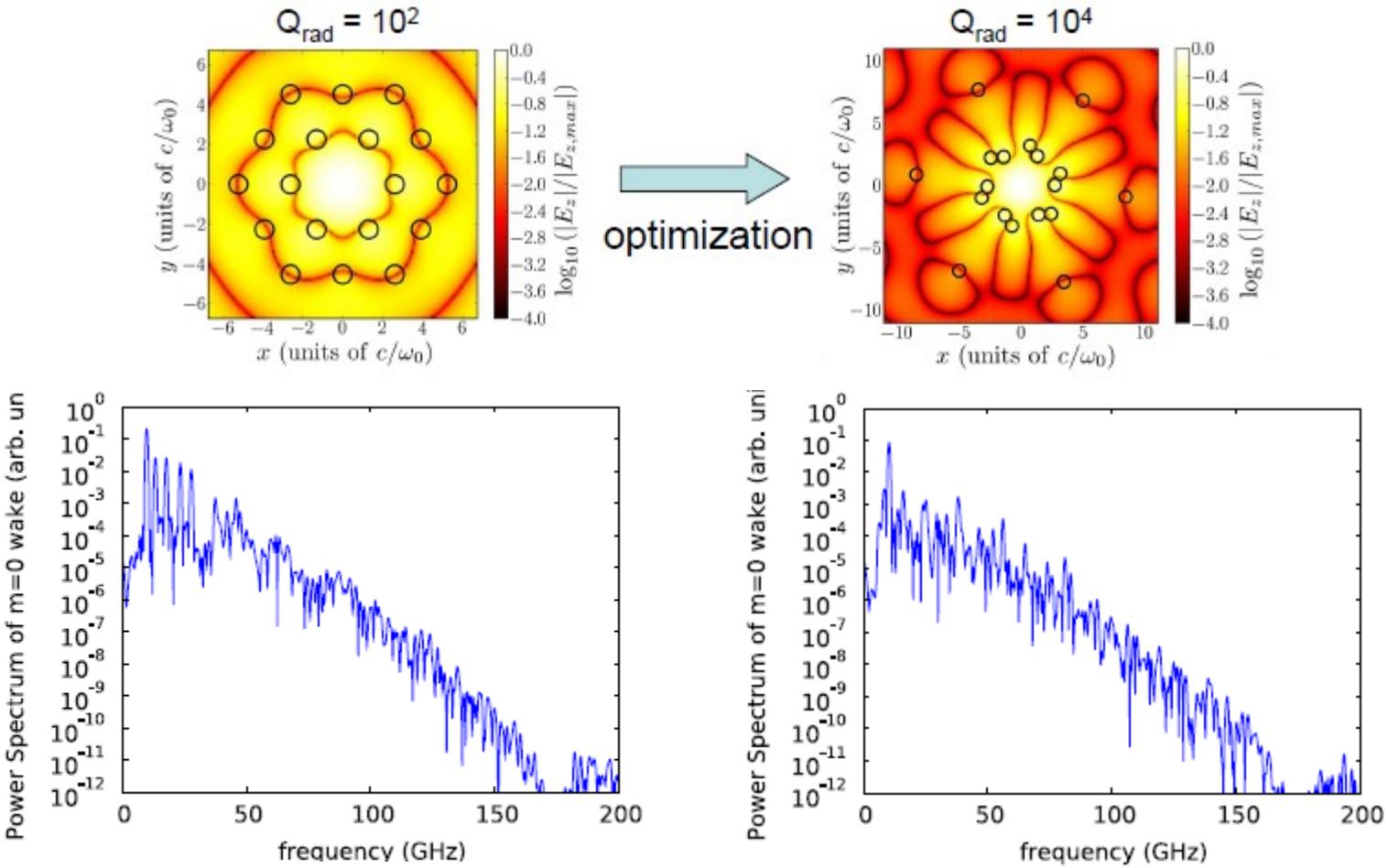


PBG Two channel accelertor



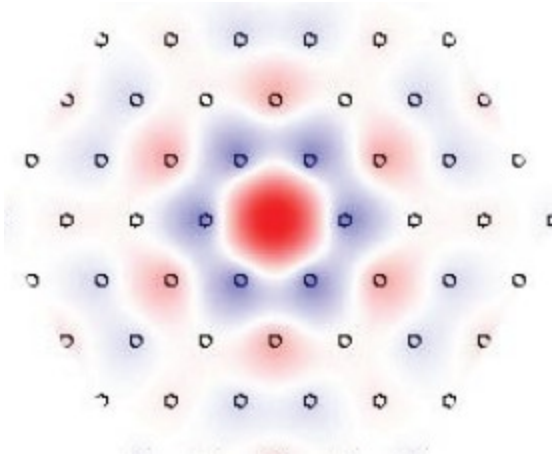
From C. Jing AWA experiments

# HOM confinement (CU Boulder)




- G. Werner, C. Bauer

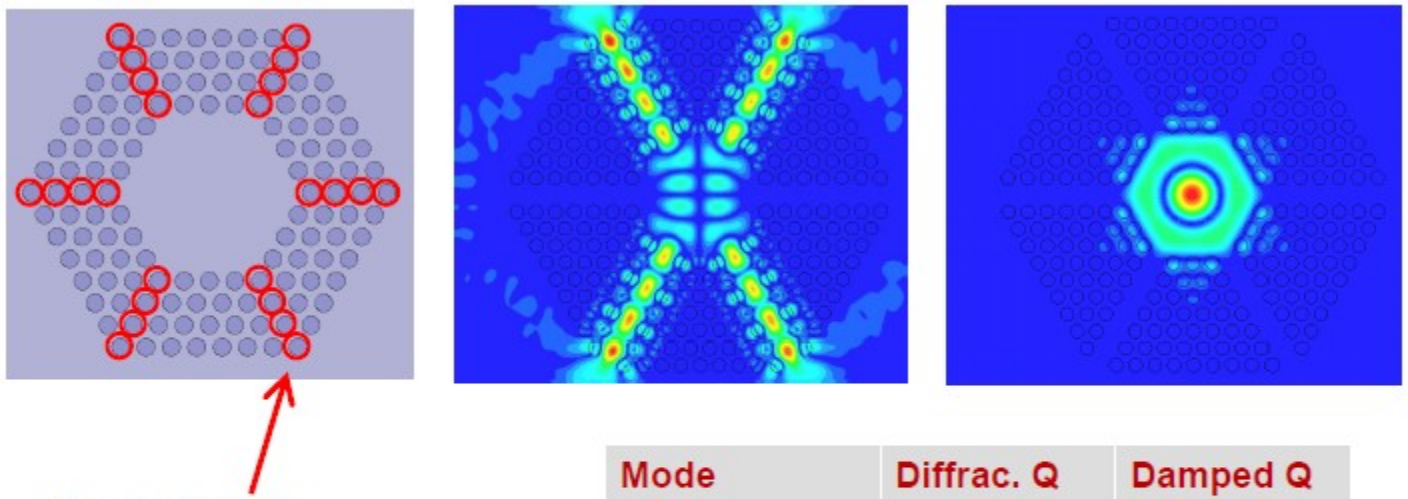
# Dielectric PBG Accelerators



| material | $f$ (GHz) | $T$ (K) | $R_s$ (mΩ) | $\tan\delta/10^{-5}$ | | $R$ (mm) | $a$ (mm) | $Q$ |
|---|---|---|---|---|---|---|---|---|
| Cu | 3 | 300 | 15 | | [19] | 38 | | $6.0 \times 10^4$ |
| Cu | 30 | 300 | 44 | | [2] | 3.8 | | $2.1 \times 10^4$ |
| Cu | 30 | 100 | 17 | | [2] | 3.8 | | $5.3 \times 10^4$ |
| Sapphire PC | 3 | 300 | | 2 | [13] | | 52 | $5 \times 10^5$ |
| Alumina PC | 3 | 300 | | 4–13 | [13] | | 52 | $7\text{–}20 \times 10^4$ |
| Sapphire PC | 22 | 300 | | 0.7–2 | [9] | | 7.1 | $5\text{–}15 \times 10^5$ |
| Sapphire PC | 22 | 100 | | 0.02–0.05 | [9] | | 7.1 | $2\text{–}5 \times 10^7$ |
| Sapphire PC | 72 | 300 | | 3 | [1] | | 2.2 | $3 \times 10^5$ |
| Sapphire PC | 72 | 100 | | 0.1 | [1] | | 2.2 | $1 \times 10^7$ |

- G. Werner, C. Bauer

# Multi mode PBG

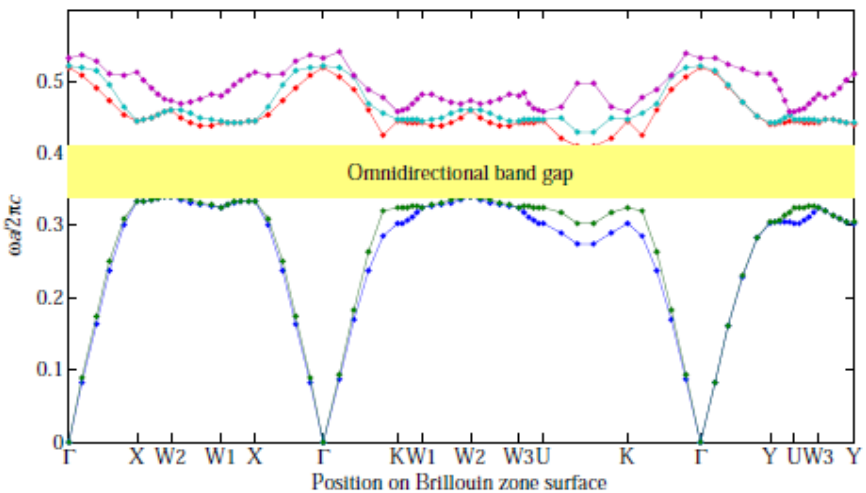


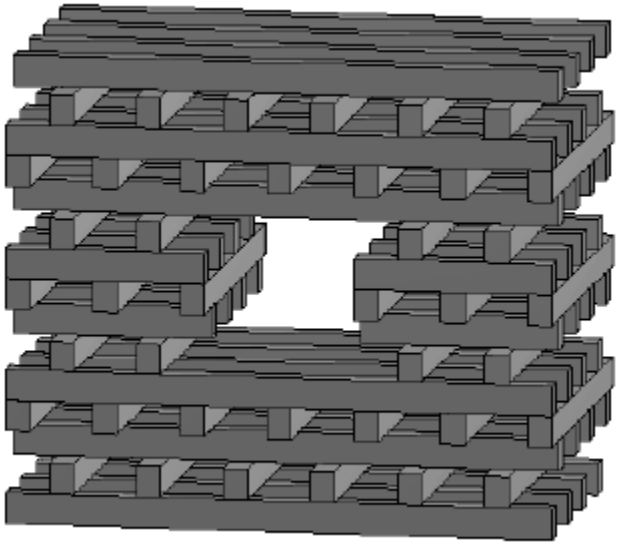
- Remove rods
- Radial defects function as waveguides
- Operating mode still well-confined (below cutoff)

| Mode | Diffrac. Q | Damped Q |
|---|---|---|
| $TM_{02}$ 17 GHz | 19,000 | **18,000** |
| 19 GHz | 3500 | 600 |
| 31 GHz | $3*10^6$ | 90 |
| 31.1 GHz | $3*10^6$ | 90 |

- A. Cook et al (MIT)

# Woodpile structure



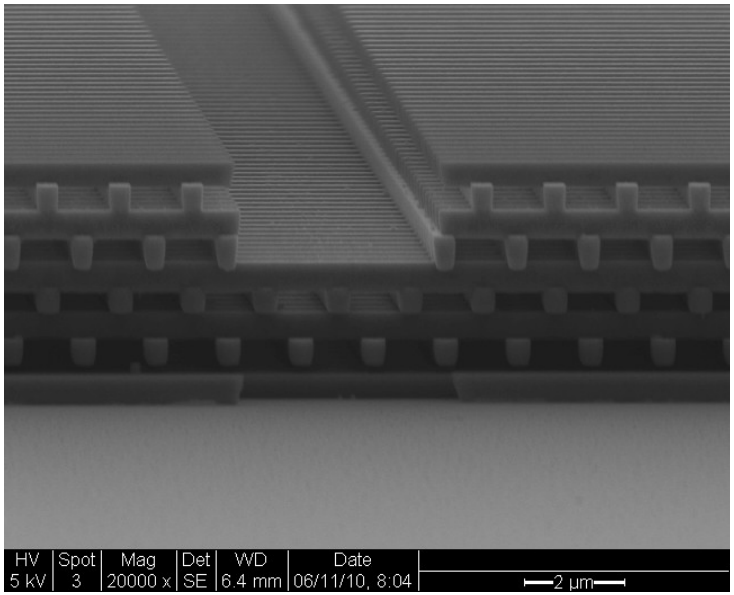



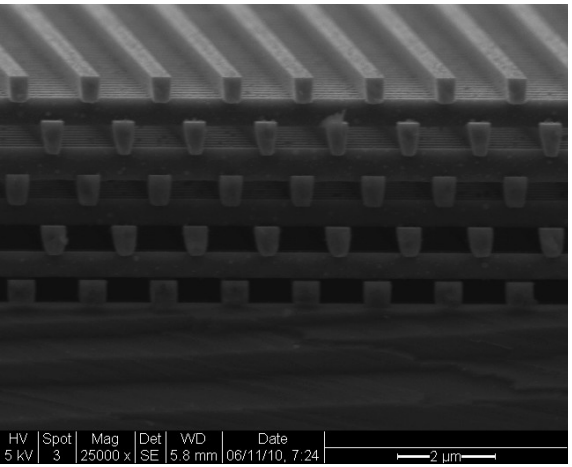
Laser-driven structure
(1500 – 2200 nm)

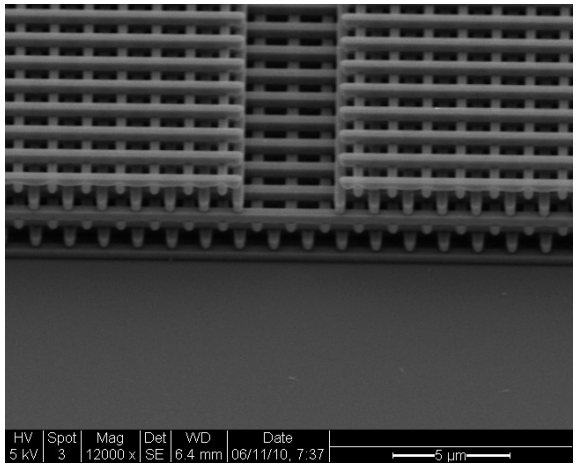
B. Covan

# Fabrication

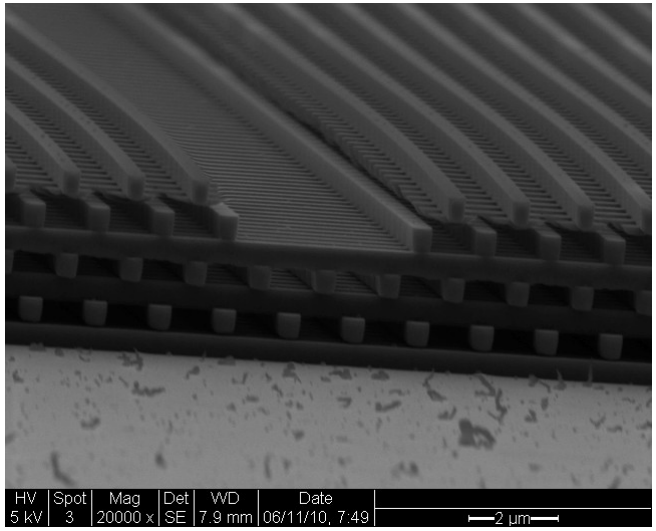
Wafer 4-13 (9 layers)

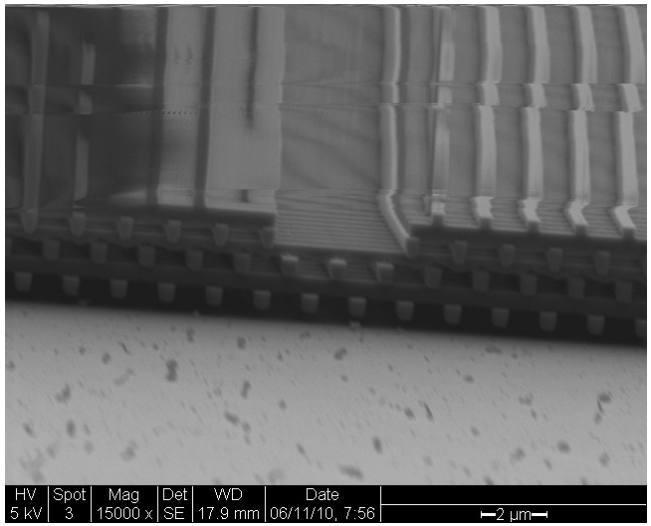


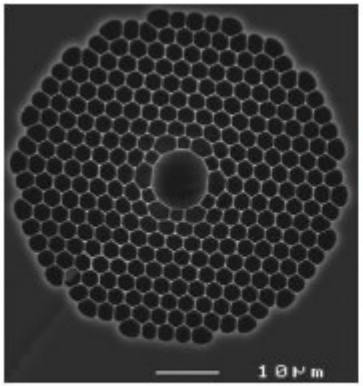




Wafer 4-15 (8 layers)

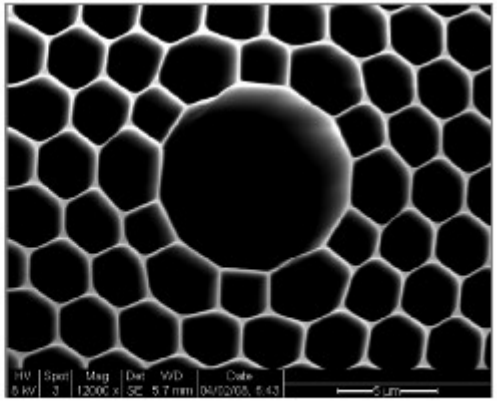



C. McGuinness



> 90%
air



Crystal Fibre HC-1060 Fiber

Defect ~ 9.5 microns, Lattice period ~ 2.75 microns

B. Noble (SLAC)

# summary

PBG has a built in HOM absorption mechanism

It has been shown to work

Scalable up to optical

Current challenges: Pulsed heating of he inner rods; manufacturing tolerances

Mode excitation for optical