Photonic Crystal Cavities with Reduced Wakefields

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Abstract

Long-range wake fields are significantly reduced in accelerator structures that are based on dielectric photonic crystal cavities, which can be designed to trap modes only within a narrow frequency range (the band gap of the photonic crystal). A 2D photonic crystal structure can be used to create a 3D accelerator cavity by using metal end-plates to confine the fields in the third dimension; however, even when the 2D photonic structure allows only a single mode (in 2D), the 3D structure may trap higher order modes (HOMs), such as guided modes in the dielectric rods, that increase wake fields. For a 3D cavity based on a triangular lattice of dielectric rods, the rod positions can be optimized (breaking the lattice symmetry) to reduce radiation leakage using a fixed number of rods; this optimization can reduce leakage by more than 2 orders of magnitude while reducing the wake fields in the structure.

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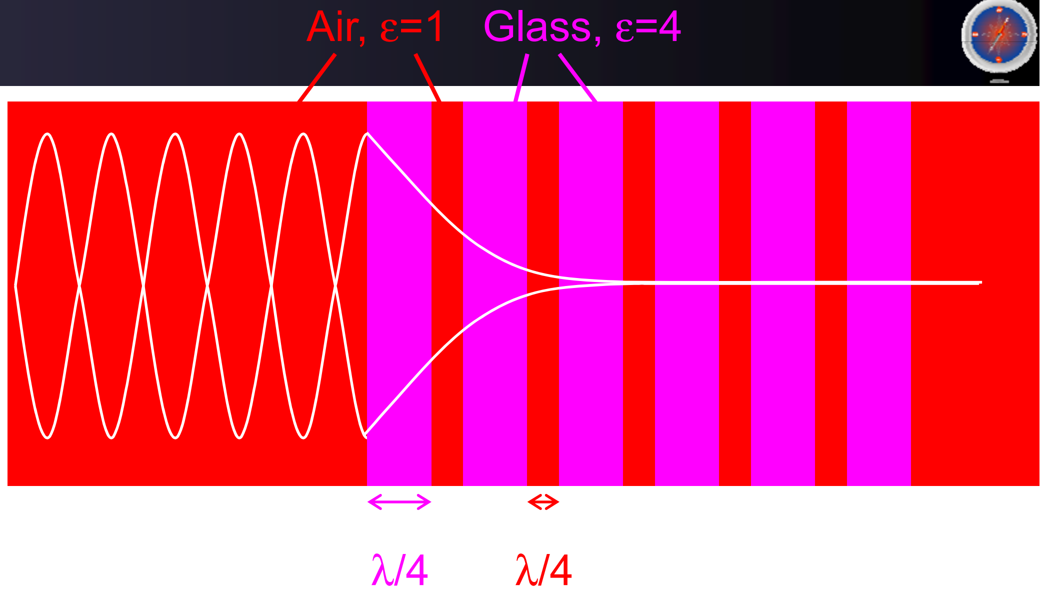
Outline

- Example: Finding better performing Photonic Crystal cavity from computation with optimization
- Frequency extraction
- Return to the PhC cavity: did we achieve reduced wake fields?

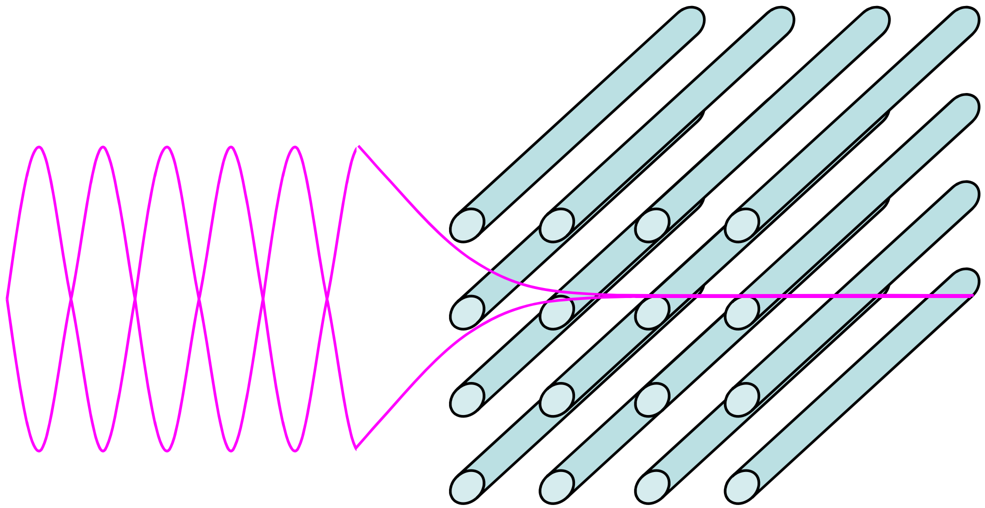
Photonic crystals have frequency-dependent reflectivity

- A 1D photonic crystal (alternating dielectric layers) is highly reflective to a normally incident wave of the right frequency, due to destructive interference.



Frequencies within the PBG cannot propagate within the PC, and decay exponentially

- 2D and 3D photonic crystals (like atomic crystals but with “dielectric atoms” and lattice spacings on the order of the wavelength of interest) can be tailored to reflect waves within a certain frequency bandgap, regardless of their angle of incidence or polarization.



Photonic Crystals can be used to create systems with many different properties

- **Photonic crystals can be low-loss mirrors for waveguide/cavity walls, especially at optical frequencies, where dielectric mirrors can withstand higher fields than metal mirrors**
- **Photonic crystals are frequency-selective mirrors for waveguide/cavity walls**
- **The dispersion relation for light in a PC can be interesting (e.g., the group velocity can be lowered significantly below the speed of light).**
- **Photonic crystals made from adjustable dielectrics (dielectrics that change with external electric/magnetic fields, temperature, pressure, etc.) will have tunable characteristics.**

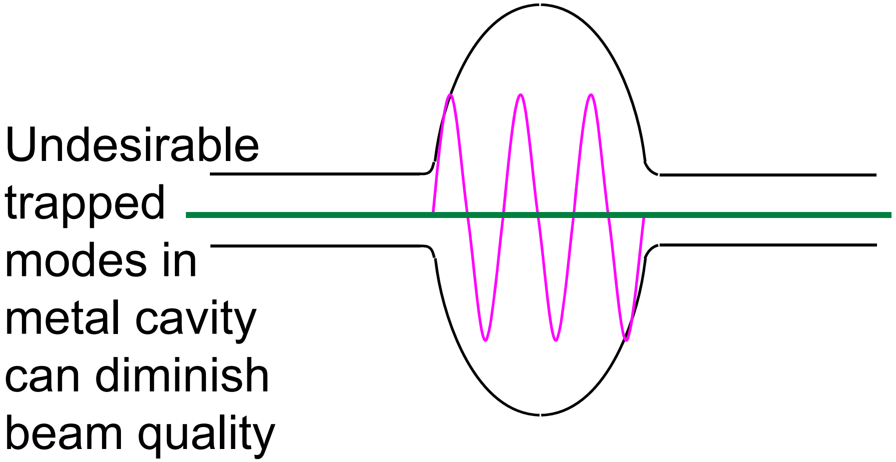
Although photonic crystals will likely be most wildly successful at optical frequencies, (nano)fabrication is difficult. On the other hand, properties of photonic crystals and PBG devices can be just as easily tested at RF frequencies; moreover, computer simulations of PBG properties can be validated at RF frequencies (and then applied to optical frequencies).

Photonic Crystals have many possible applications

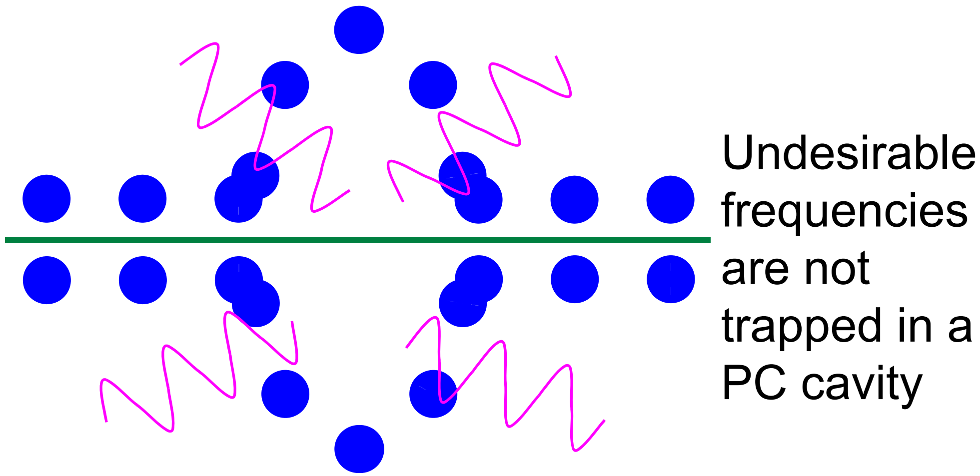
- **Waveguides/cavities free of higher-frequency modes (or wakefields) excited by the beam**
- **Waveguides/cavities to be operated in modes well above the fundamental: for example, a PC waveguide several centimeters wide might have a bandgap corresponding to a frequency with millimeter wavelength**
- **H□□igh-Q cavities at room temperature**
- **Tunable cavities and waveguides (with “controllable” dielectrics)**
- **Delay lines and energy storage devices (with low or zero group velocity)**

Frequency dependent photonic crystals have promise of cavities with reduced wake fields

A beam of charged particles excites high order modes in an accelerating cavity that, unless sufficiently damped, diminish the quality of following particle bunches.



If the cavity walls have a PhC at the cavity's resonant frequency, the cavity will have a high Q at that frequency, but frequencies not in the PBG will pass harmlessly out of the cavity.



Previous studies showed photonic crystal cavities were not practical

STUDY OF HYBRID PHOTONIC BAND GAP RESONATORS FOR PARTICLE ACCELERATORS

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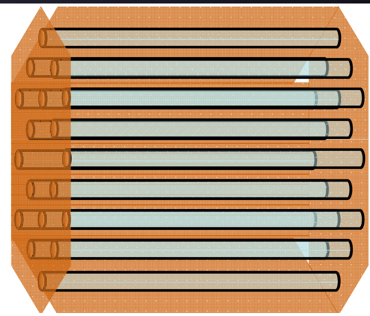

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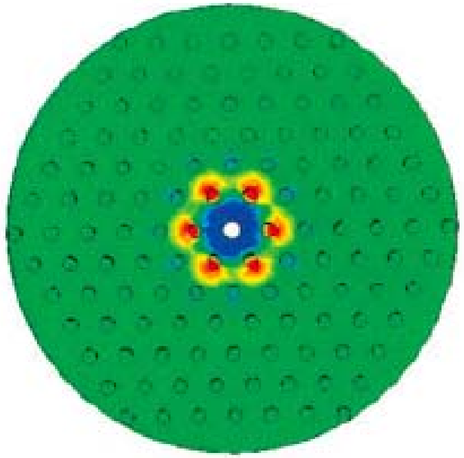
room temperature confirm the monomodal behavior, but the Q value is lower than expected (roughly 10^3). This is mainly due to



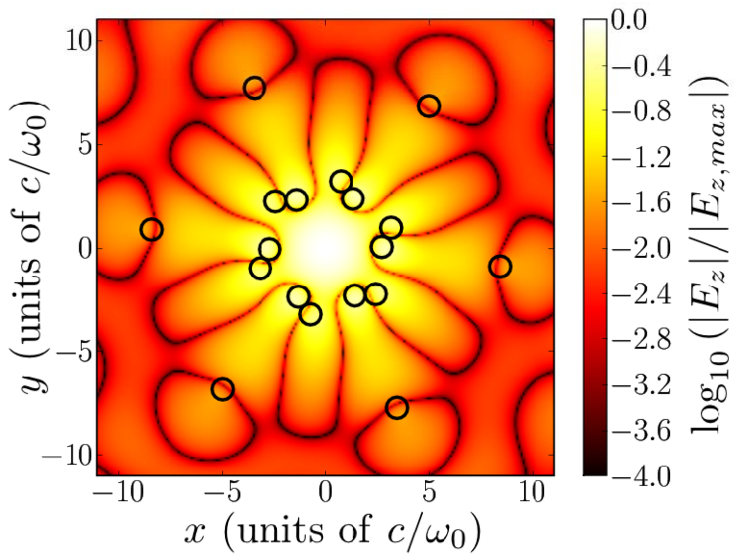
- 5 layers of (147) metal cylinders, yet Q ~ 10^3
- Cavity already larger by 5x (1D) than conventional
- Would need >8 layers for Q ~ 10^5

Computational serendipity led to trying to optimize

- Originally interested in basic physics: when does Mie scattering give way to coherent PhC behavior?
  - Vary randomness, fill fraction
- Computing various configurations with irregularly bound waveguides
- Some found to be better, so see if we can find the best through putting an optimization loop around the computation
- Result in PhcOptSymNoOverlapLabeled.mov

Optimizations found asymmetric systems with many fewer rods, yet larger Q

- C. A. Bauer, G. R. Werner, and J. R. Cary, "Optimization of a photonic crystal cavity," J. Appl. Phys. **4** (105), 053107 (2008); DOI:10.1063/1.2973669.
- **Q larger by 2 orders of magnitude for optimized 18 rods compared with best truncated crystal**
- **Q larger for optimized 18 rods by one order of magnitude compared with 147 rods in truncated crystal**
- **For 24 rods, we find vacuum Q of 10^5**



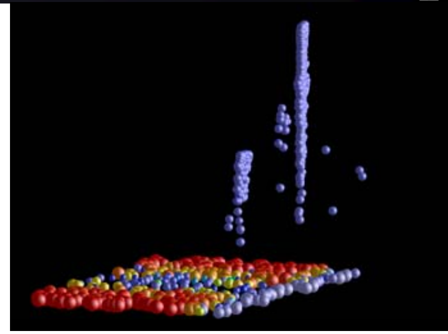
So how do we do computations in beams and plasmas?

Finite-difference, time-domain electromagnetics with Particle in Cell and the gather-scatter algorithm: FDTD EM-PIC

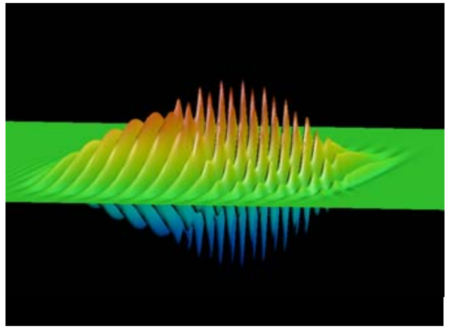
- FDTD electromagnetics
- Particles in fields (gather)
- Self-consistency
- Parallelism

Our implementations are in the VORPAL Computational Framework

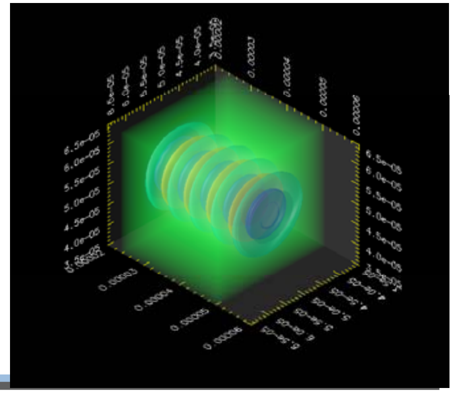
- Laser-plasma and laser-gas interactions (collab. with LBNL)
  - multiple invited talks at DPP, PAC
  - PRL's, Nature cover, …
- Electron cooling for RHIC (collab. with Brookhaven National Lab)
- Thruster modeling (DOD)
- Photonic Band Gap structures
- Recognized as one of the SciDAC codes
- Originally supported by NSF, but most of the subsequent development supported by HEP-TECH, NP, OFES, AFOSR



Particle beams



Colliding laser pulses



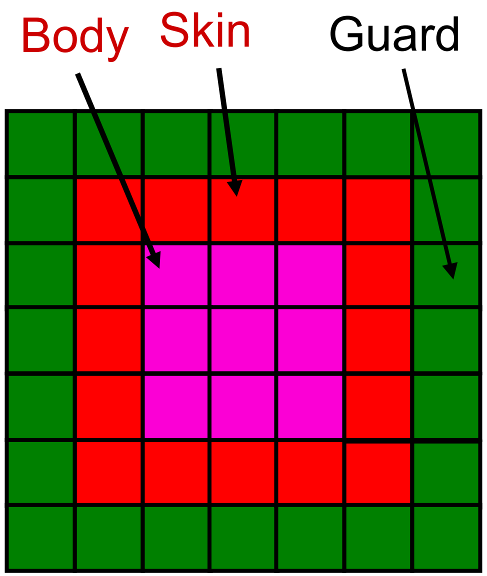
Wake fields

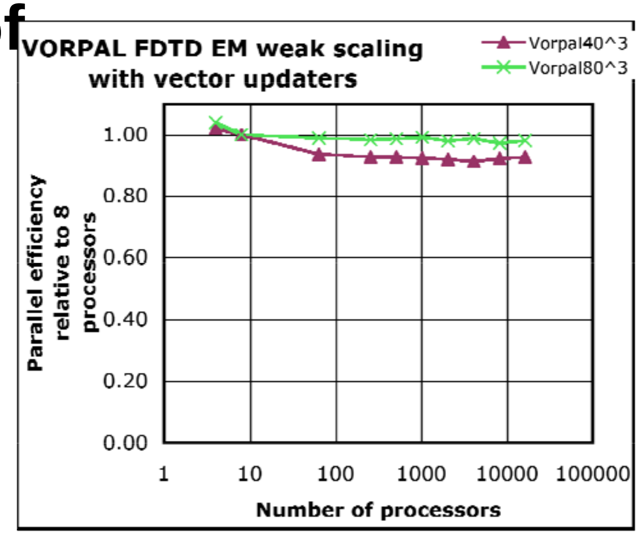
Finite-difference time-domain computations very efficient

- All communications through boundary
- Measure is scaling
  - Weak: region size per processor constant
  - Strong: total region remains of constant size

BG/L, 192x128^2 weak scaling

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

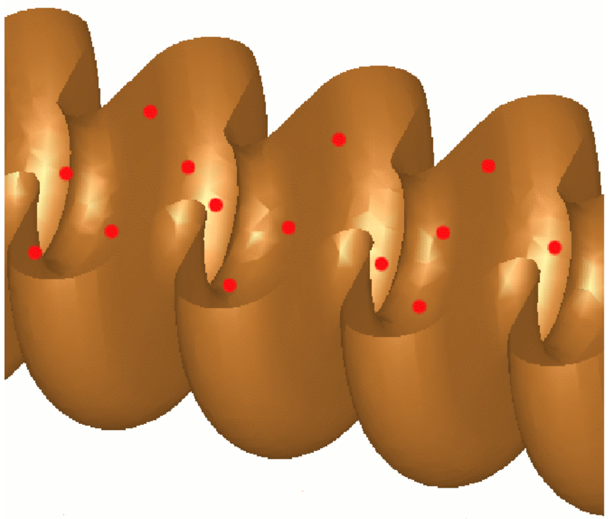




Lastest GPU speedup: 45x

Frequencies obtained from subspace diagonalization

- Modified Filtered Diagonalization Method (FDM) of quantum mechanics, NMR
- Beats Heisenberg!
- Ring up finite bandwidth, compute time series in subspace
- Diagonalize subspace
- Multiple simulations if near degeneracies



G. R. Werner and J. R. Cary, "Extracting Degenerate Modes and Frequencies from Time Domain Simulations," J. Comp. Phys. **227**, 5200-5214 (2008), http://dx.doi.org/10.1016/j.jcp.2008.01.040

Ringing up the cavity isolates modes of interest

- Driven harmonic oscillators
- Eigenmodes (small number present) give solution
- Harmonic oscillator response
- Gaussian hat selects range
- Density of states gives approximate number of modes in any range

$$\frac{\partial^2 s}{\partial t^2}(t)+Hs(t)=f(t)g$$

$$Hv_m = k_m^2 v_m$$

$$s=\sum \alpha_m v_m$$

$$\frac{\partial^2 \alpha_m}{\partial t^2}(t)+k_m^2\alpha(t)=\beta(t)g_m$$

$$\alpha_m(t)=\frac{ig_m}{2k_m}\tilde{\beta}(\kappa_m)e^{-ik_m t}+c.c.$$

$$\tilde{\beta}(k)=\frac{1}{\sqrt{2\pi\sigma_\omega}}\int_{-\infty}^{\omega} d\omega' \left\{ \exp\left[-\frac{(\omega'-\omega_1)^2}{2\sigma_\omega^2}\right]-\exp\left[-\frac{(\omega'-\omega_2)^2}{2\sigma_\omega^2}\right]\right\}$$

Small number of eigenvectors span solution space

- **Solution known for simulation ℓ of L**
- **Underlying coefficients not known**
- **Solution extracted for points (p of P) and times (t_n of N)**
- **Solution indexed by**
- **Solution matrix: rows of solution states**

$$s_\ell(t) = \sum_{m=1}^{M} c_{\ell,m}(t) v_m$$

$$c_{\ell,m}(t) = \bar{c}_{\ell,m} \cos(k_m t + \phi_m)$$

$$s_{\ell,p}(t_n) = \sum_{m=1}^{M} c_{\ell,m}(t_n) v_{m,p}$$

$$i = (\ell - 1)N + n$$

$$S_{i,p} \equiv s_{\ell,p}(t_n)$$

Can reduce to relative eigenvalue problem

- Application of operator known
- Define solution matrix with H applied
- Goal: find eigenvectors as linear combination of samples
- Matrix notation
- A contains left eigenvectors of R relative to S

$$r_\ell(t) = Hs_\ell(t) = \sum_{m=1}^{M} c_{\ell,m}(t) k_m^2 v_m$$

$$R_{i,p} \equiv r_{\ell,p}(t_n)$$

$$v_m = \sum_{i=1}^{LP} a_{m,i} r_i = \sum_{i=1}^{LP} a_{m,i} k_m^2 s_i$$

$$A(R - \lambda S) = 0$$

SVD techniques required for subspace degeneracy

- To ensure that eigenvalues can be obtained, want LN and P to exceed expected number of eigenvalues
- This implies that S and R have a number of zero eigenvalues = size of space - number of modes present
- Diagonalization of sample space shows zero eigenvalues
- Diagonalize in space on nonzero eigenvalues of W

$$A(RS^T - \lambda SS^T) = 0$$

$$A(RS^T - \lambda UWU^T) = 0$$

$$A'(U^T RS^T U - \lambda W) = 0$$

Matrix A gives amplitudes of eigenmodes in terms of snapshots - get eigenmodes by superposition!

Multiple simulations allow handling of near degeneracies

- Two modes
- If frequencies are nearly the same, the sample space contains only one linear combination of the eigenvectors - subspace not sampled

$$s_\ell(t) = \sum_{m=1}^{M} c_{\ell,m}(t) v_m$$

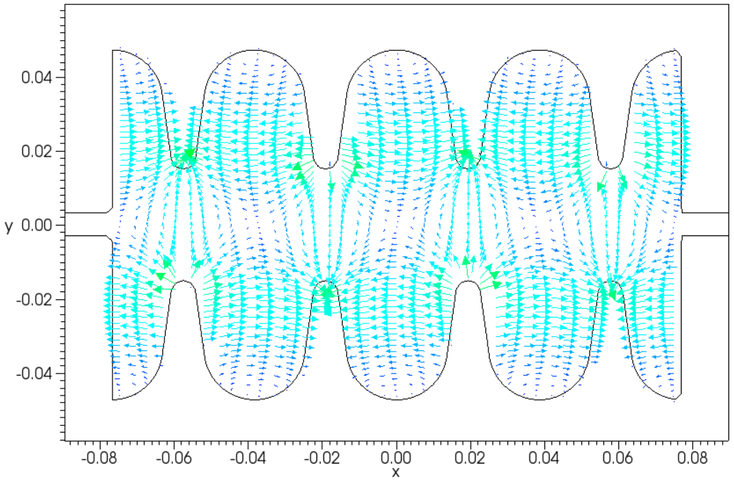
$$s_\ell(t) = \bar{c}_{\ell,1} \cos(k_1 t + \phi_1) v_1 + \bar{c}_{\ell,2} \cos(k_2 t + \phi_2) v_2$$

- Two simulations with different excitations give different linear combinations

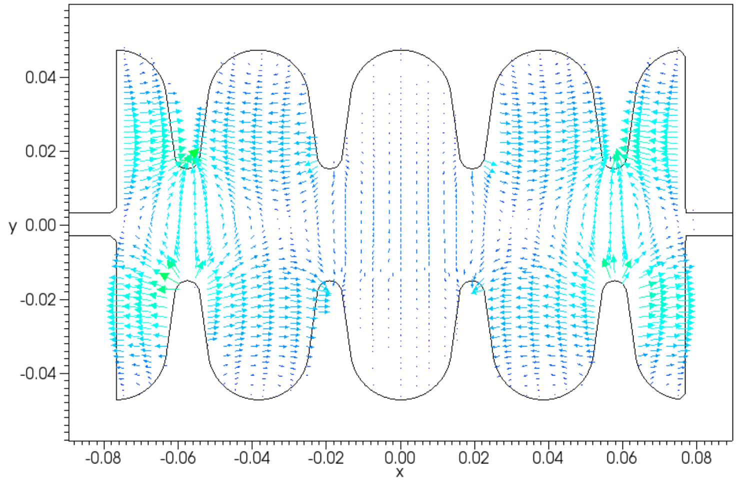
$$c_{\ell,m}(t) = \bar{c}_{\ell,m} \cos(k_m t + \phi_m)$$

Eigenmodes (E shown) reconstructed from the dump files

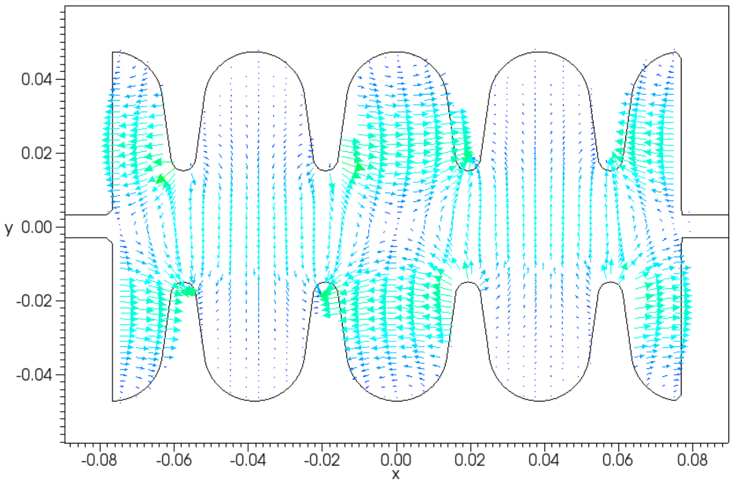
3902.810 MHz (π mode)



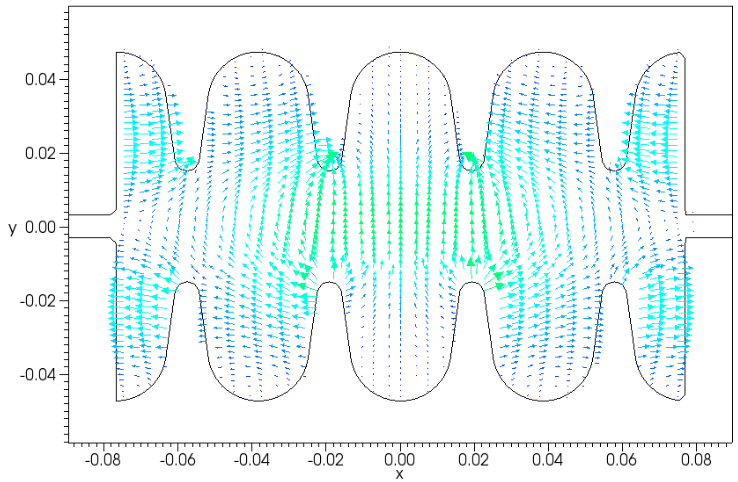
3910.404 MHz



3939.336 MHz

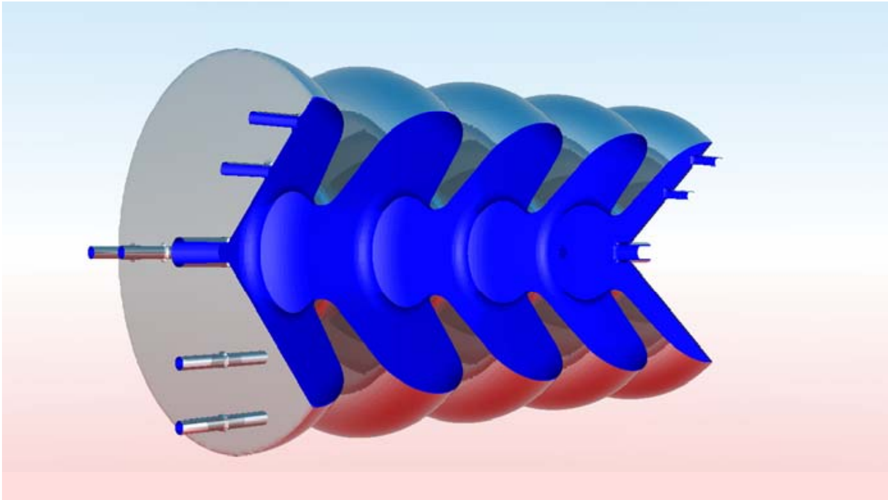


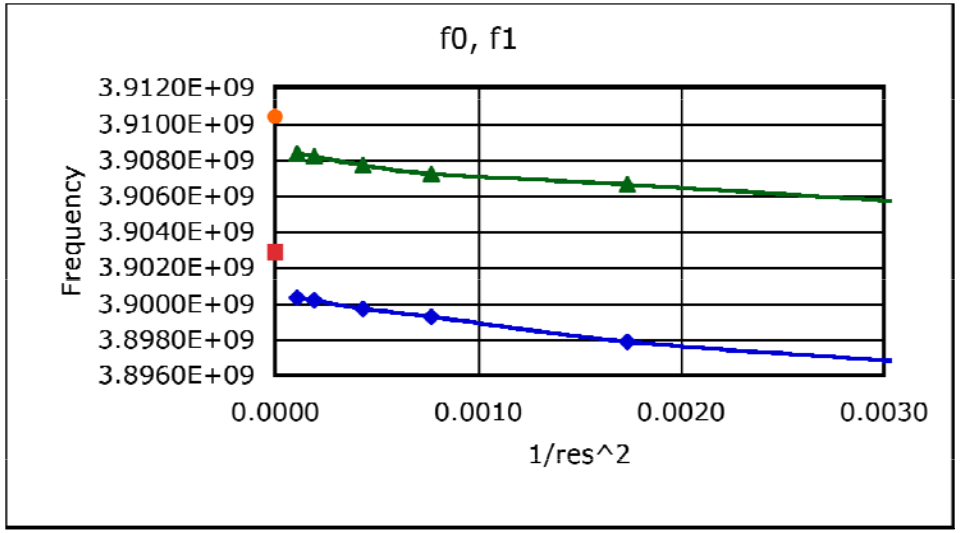
4001.342 MHz



Validation studies to determine correctness

- Previous computations gave frequencies low by 5 MHz out of 4 GHz.
- Ours (improved algorithm and parallelism) were low by 2 MHz, yet we had verified against exact solutions!
- Model no holes? One? All?
- Correct for dielectric of air





The validation study showed that we had the wrong model

- Reduce the equator radius by 0.001 inch to find sensitivity
- Get better agreement, shows reduction of 0.0012 in = 30 μm would fit
- Cordex measurements revealed that cavities indeed had equator radius smaller by about 25 μm

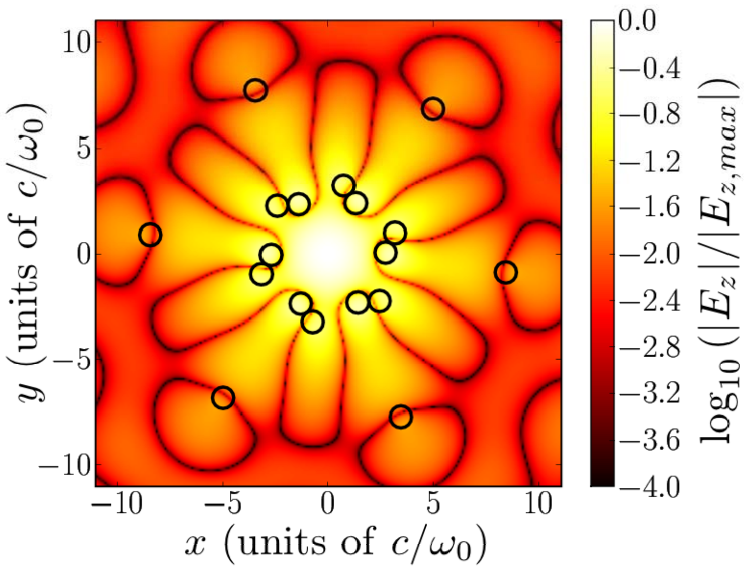
- To what extent can we determine the precise shape of objects by measuring their frequency spectra?

From the modes we can get the important parameters

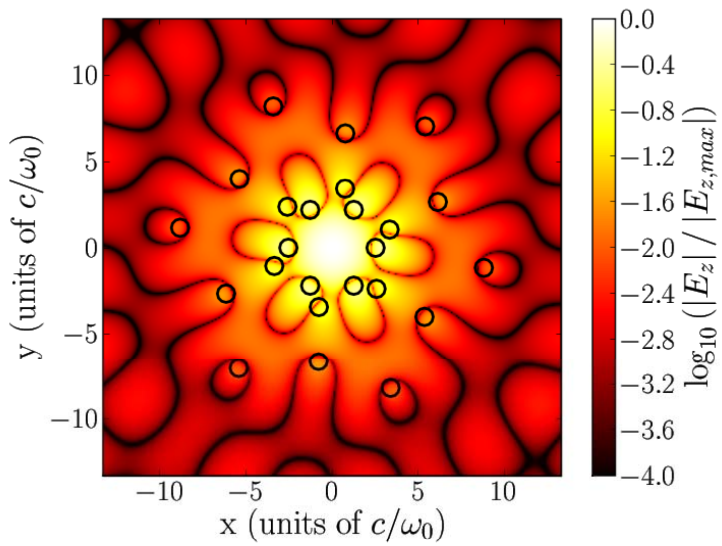
- Check for hot spots
- Optimize:
  - –Reduce |B| at max
  - –Maximize vacuum Q of desired mode
  - –Reduce multipactoring

VorpalCrabOascr08.mov shows critical results of the computations

With 6 more rods, get Q ~ 10^5



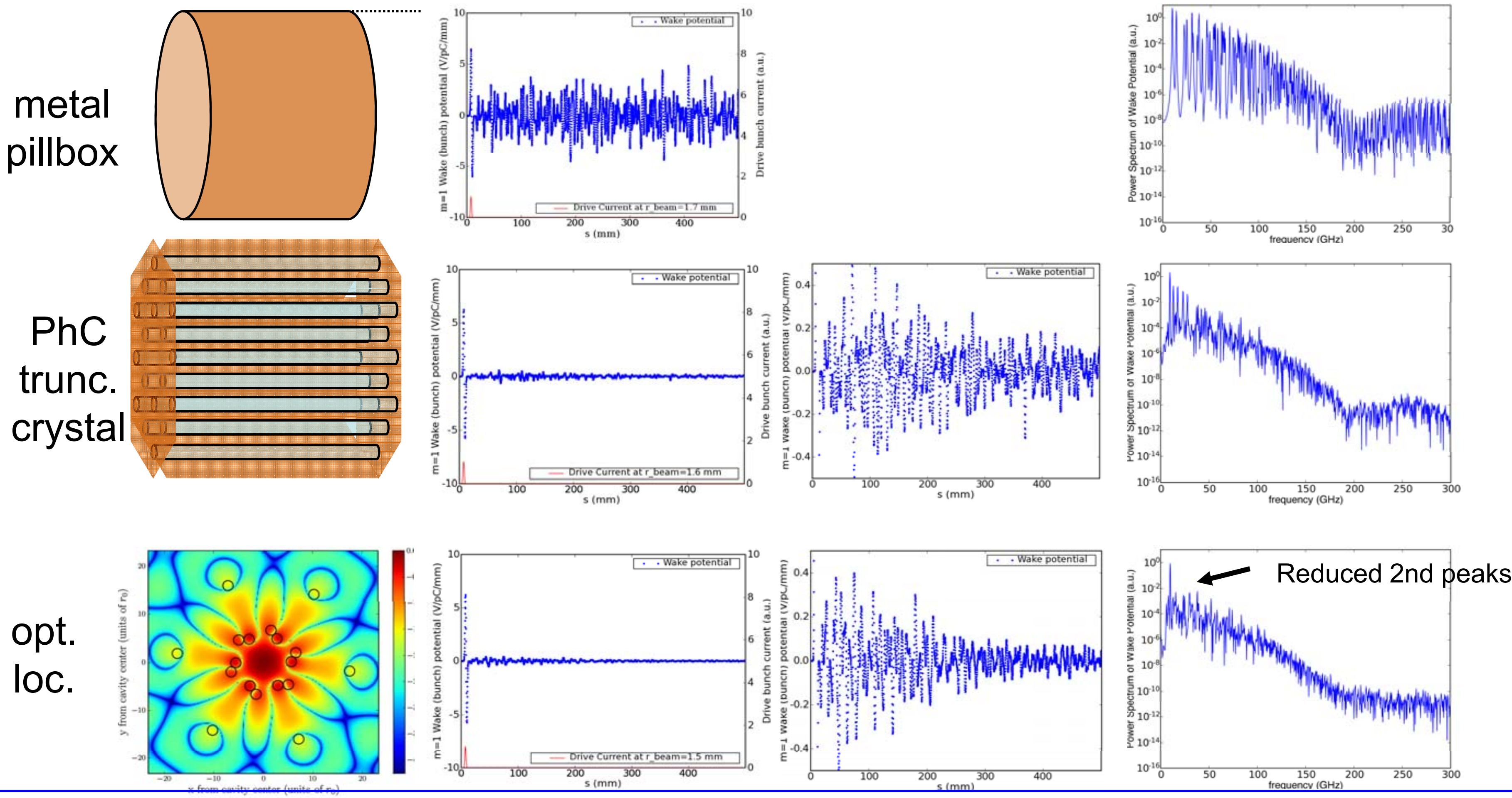
Q~11,000
(alumina)



Q~200,000
(sapphire)

BTW: wake fields in resulting cavity much smaller

Dipole in time | Dipole 20x mag | Accel mode Fourier

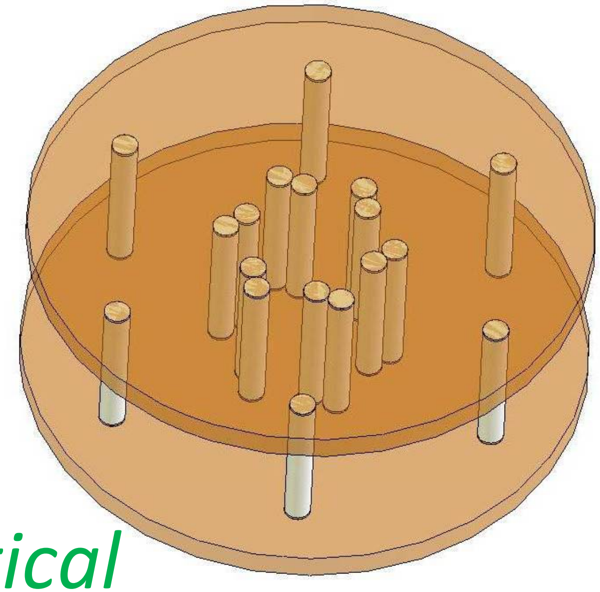


Wake potentials were calculated by VORPAL, a versatile physics simulation platform, for a beam at radius r=0.7mm.

Reality

PhC Cavity Fabrication by brazing

2-D Cavity:



- Conducting top/bottom plates
- Sapphire rods *(brazed at ends)*

Brazing at 800 ℃ : thermal stress critical

- Titanium brazing foil for sapphire/moly joinery
- Graphite breakaway jig for ± .002” rod placement
- Match expansion coefficients of

Rods (Sapphire) :	6.0×10^{-6}/°C
Jig (Graphite) :	5.8×10^{-6}/°C
Plates (Molybdenum) :	4.8×10^{-6}/°C

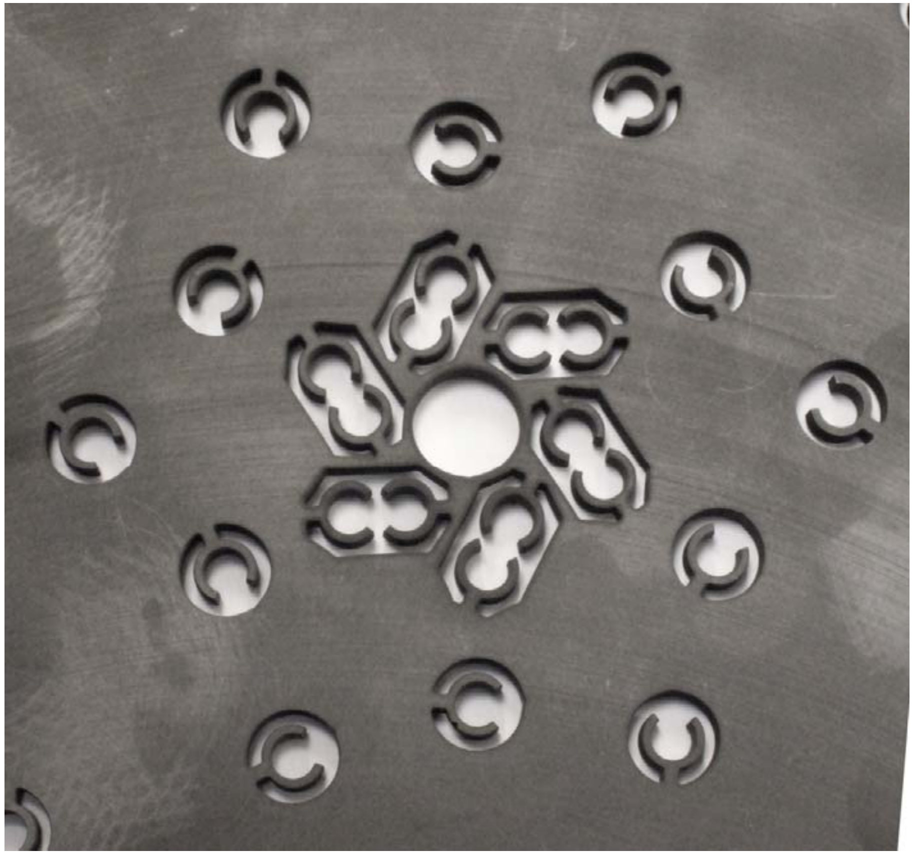
Breakaway jig used for fabrication

Sapphire rods:

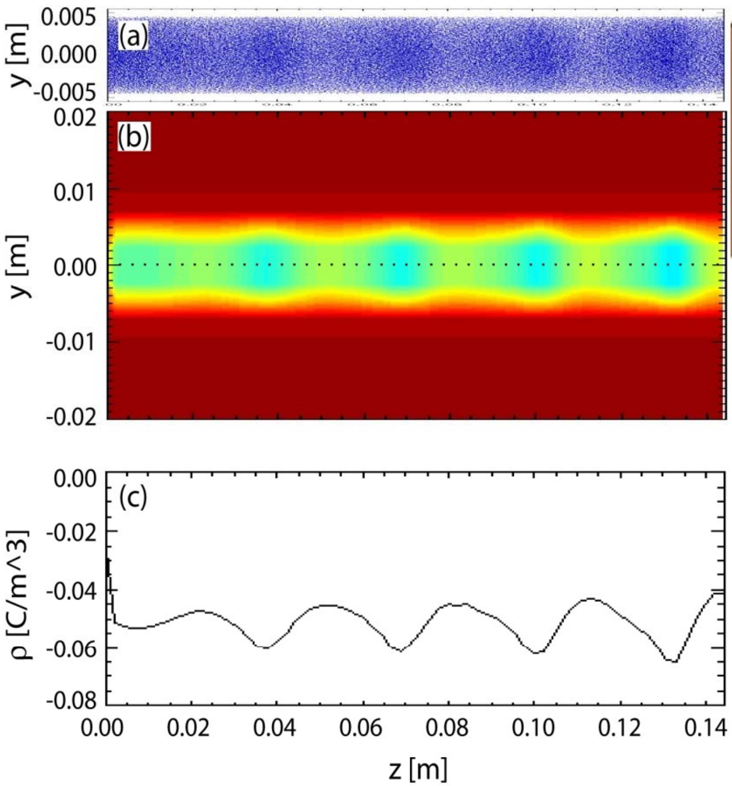
centerless ground to ± .001” diameter

Graphite Jig:

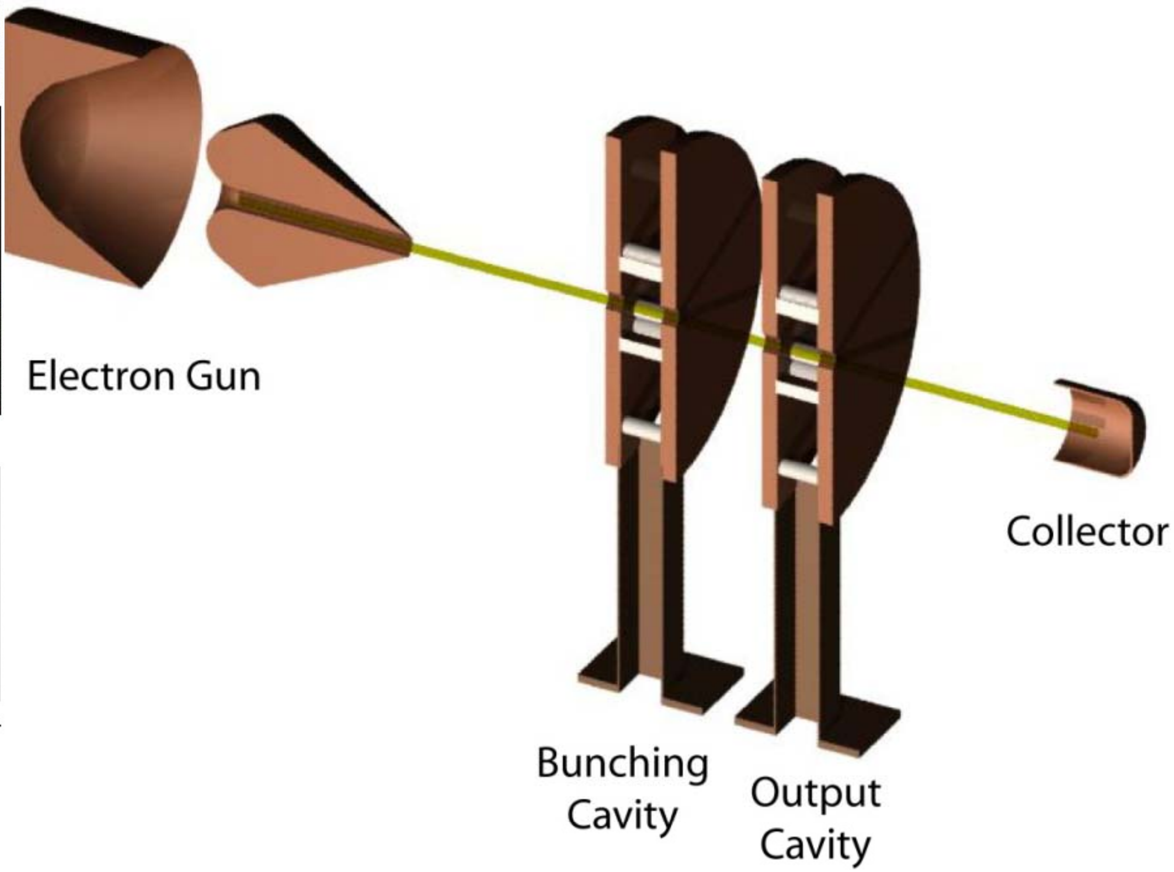
Carbonix 2160 pressed graphite cut with water jet



Ideas for the future: two-cavity Klystron



Preliminary beam-bunching simulation in VORPAL



Schematic of simplest PHC-based klystron

Conclusions

- New frequency extraction algorithm allows for
  - Effective use of massively parallel hardware
  - Gets multiple frequencies at once
  - To high accuracy, sufficient for optimization
- Optimization of dielectric, photonic crystal cavities finds new configurations
  - Many fewer rods
  - Much higher Q
- Fabrication now underway at the University of Colorado (under direction of Prof. Tobin Munsat)