DIELECTRIC AND HYBRID ACCELERATING STRUCTURES: COMPUTATIONAL NEEDS

- Why are we here?
- Some previous accomplishments
- The computational difficulties of dielectric structures
- Where we need to go
  - Algorithms
  - Optimizations

John R Cary
Prof. Physics, U. Colorado
CEO, Tech-X

Greg Werner (CU)
Carl Bauer (CU)
Ben Cowan (Tech-X)

New configurations have the goals: Stronger, Stabler, Smaller

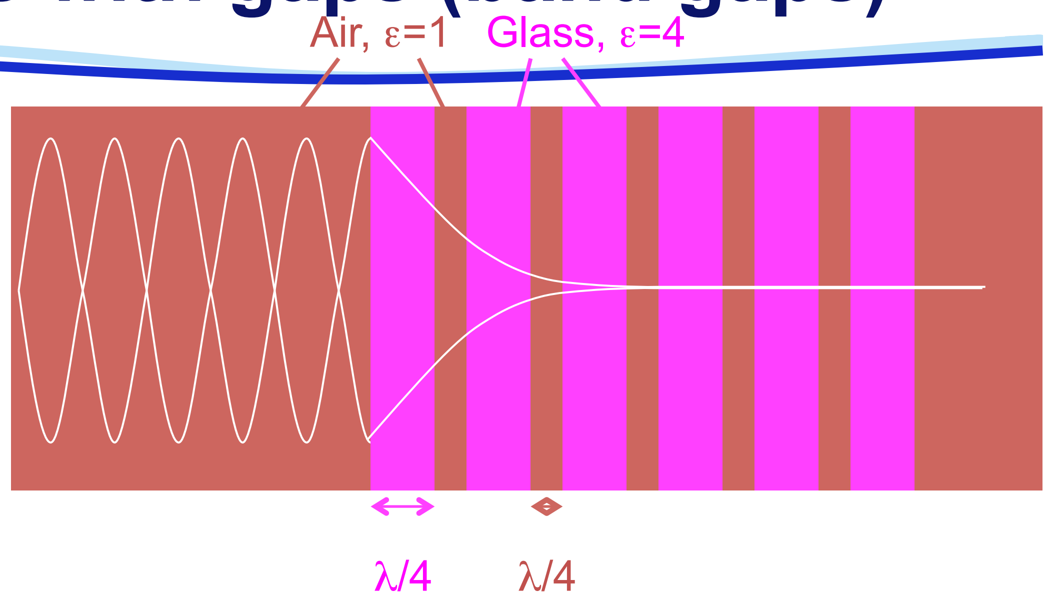
- **Stronger**: be able to have higher accelerating gradients before breakdown
- **Stabler**: have reduced generation of wake fields, which lead to instabilities
- **Smaller**: Reduce the size of systems to reduce cost, real estate

Dielectric accelerators may be Stronger

- Dielectric Laser Accelerators have the goal of making use of the high laser powers
- Optical (1): “The onset of breakdown, detected through light emission from the tube ends, is observed to occur when the peak electric field at the dielectric surface reaches 13.8±0.7 GV/m.”
- GHz (2): experimental evidence is lacking but accelerating gradients near 10 MV/m have been observed without breakdown; multipacting currently prevents studies at higher surface fields in the DLA geometry

1. M. Thompson, H. Badakov, A. Cook, J. Rosenzweig, R. Tikhoplav, G. Travish, I. Blumenfeld, M. Hogan, R. Ischebeck, N. Kirby, et al., Physical review letters 100, 214801 (2008), ISSN 1079-7114.
2. C.Jing,W.Gai,J.Power,R.Konecny,W.Liu,S.Gold,A.Kinkead,S.Tantawi,V.Dolgashev, and A. Kanareykin, Plasma Science, IEEE Transactions on 38, 1354 (2010)

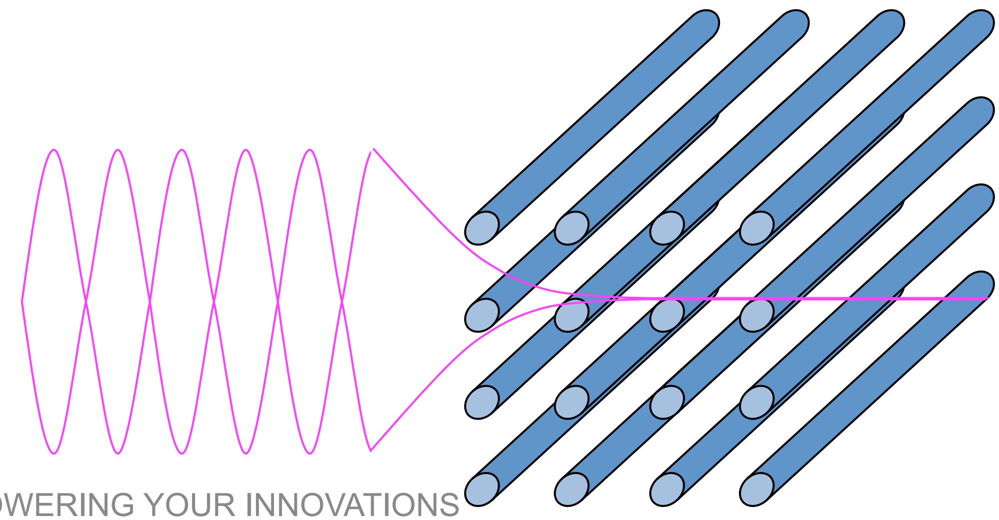
Basic Physics: Photonic crystals have propagation bands with gaps (band gaps)



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

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

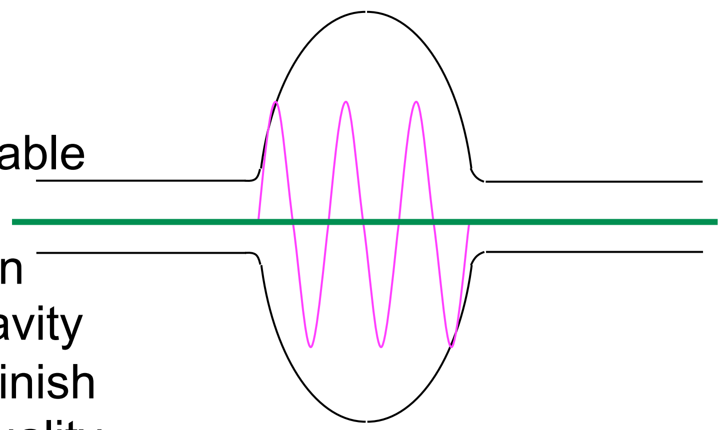
- **2D and 3D photonic crystals (like atomic crystals but with "dielectric atoms" and lattice spacings on the order of the wavelength of interest) can be tailored to reflect waves within a certain frequency bandgap, regardless of their angle of incidence or polarization.**



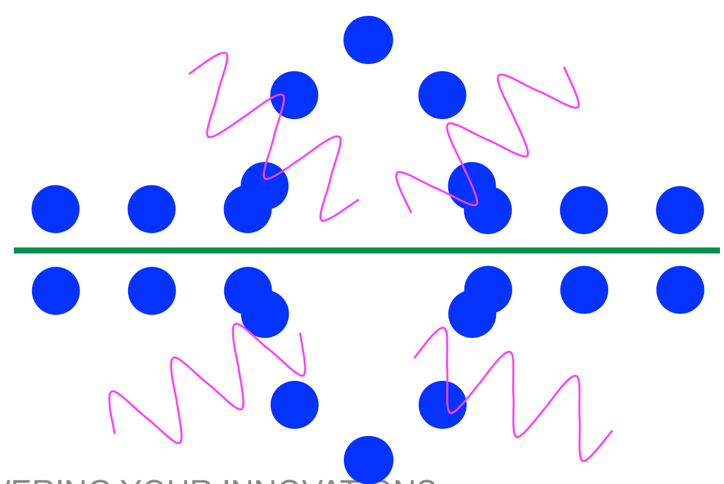
With reduced wake fields, dielectric structures may be <u>Stabler</u>

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

Undesirable trapped modes in metal cavity can diminish beam quality



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.



Undesirable frequencies are not trapped in a PC cavity

Dielectric systems may be Smaller

- If one gets breakdown at 10 GeV/m, then 100x shorter
- As seen at right, much narrower
- Smaller (µm sized) structures have been fabricated
  - Wood pile
  - Dielectric fibers

TUYB02 Proceedings of IPAC2012, New Orleans, Louisiana, USA

MANUFACTURE AND TESTING OF OPTICAL-SCALE ACCELERATOR STRUCTURES FROM SILICON AND SILICA*

R. J. England, E. R. Colby, R. Laouar, C. M. McGuinness, B. Montazeri, R. J. Noble, E. A. Peralta, K. Soong, J. Spencer, D. Walz, Z. Wu, SLAC, Menlo Park, CA 94025, USA
M. Qi, C. Lee, Y. Xuan, L. Fan, L. T. Varghese, Purdue Univ., West Lafayette, IN 47907, USA
R. L. Byer, C-M. Chang, K. J. Leedle, Stanford Univ., Stanford CA, USA
B. Cowan, Tech-X, Boulder CO, USA

(a) (b) (c)

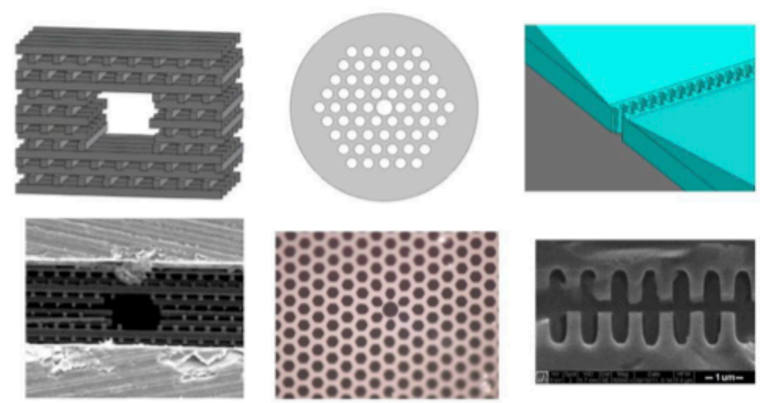


Figure 1: Three dielectric laser accelerator topologies: (a) a 3D silicon photonic crystal structure, (b) a hollow-core photonic bandgap fiber, and (c) a dual-grating structure, showing conceptual illustration (top) and recently fabricated structures (bottom).

Two directions of current photonic cavity research

RF

- Claddings
- 2D rod arrays
  - Metallic
  - Dielectric

Optical

- Dielectric fibers
- 3D structures like woodpiles
- Gratings

Have common goals

- Reduce wake fields (Stable)
- Improve coupling
- Increase breakdown voltage
- …

Just cavity optimization is many faceted

TABLE I: Figures of merit for the accelerating mode in periodic single cell cavities.
$a = 3.15\text{mm}$, $d = 1.67\text{mm}$, $\phi = 2\pi/3$. All simulations performed at $\Delta z/d = 8$.

	Pillbox	CLIC	Tri-4-Sapphire	Opt-18-Sapphire
v_g/c (%)	1.83	1.65	1.16	0.78
Q_{metal}	6,700	5,900	11,400	11,400
Q_{rad}	∞	∞	26,600	3,800
Q_{diel}	∞	∞	67,000	39,000
Q_{total}	6,700	5,900	7,100	2,700
r_{shunt} (MΩ/m)	106	82	70	18
k (V/pC/m)	298	260	187	125
$E_{\text{surf,metal,max}}/E_{\text{acc}}$	1.93	1.96	1.93	1.93
$cB_{\text{surf,metal,max}}/E_{\text{acc}}$	1.0	1.54	1.49	1.73
$E_{\text{surf,diel,max}}/E_{\text{acc}}$	—	—	0.54	0.64
$cB_{\text{surf,diel,max}}/E_{\text{acc}}$	—	—	1.26	1.79
$E_{\text{diel,max}}/E_{\text{acc}}$	—	—	0.60	0.79

Opt-18 not optimized for these 3D values!

There have been many successes of computational optimization

- Coupling (Cowan)
- Hybrid cavity optimization (Werner)

Coupling improvement found by Ben Cowan

- Demonstrated high-efficiency coupling to a photonic crystal accelerating waveguide — over 90% power efficiency into the forward direction
- Efficiency improved by adjustments of individual rods
- Geometry adjustments amenable to lithographic fabrication
- Structure designed by parameter scans with high-performance Vorpal simulations

Ability to compute cavity Q allows configuration optimization

STUDY OF HYBRID PHOTONIC BAND GAP RESONATORS FOR PARTICLE ACCELERATORS

M. R. Masullo,[1] A. Andreone,[2] E. Di Gennaro,[2] S. Albanese,[3] F. Francomacaro,[3] M. Panniello,[3] V. G. Vaccaro,[3] and G. Lamura[4]

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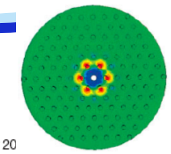
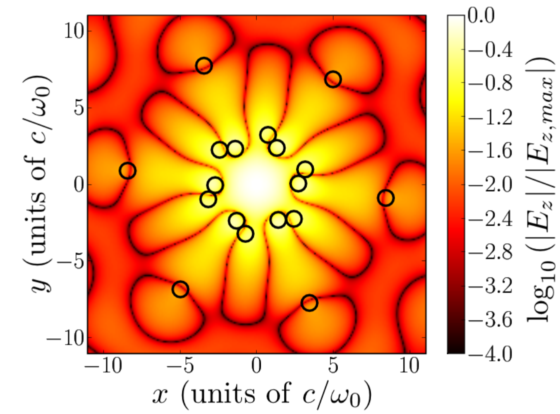
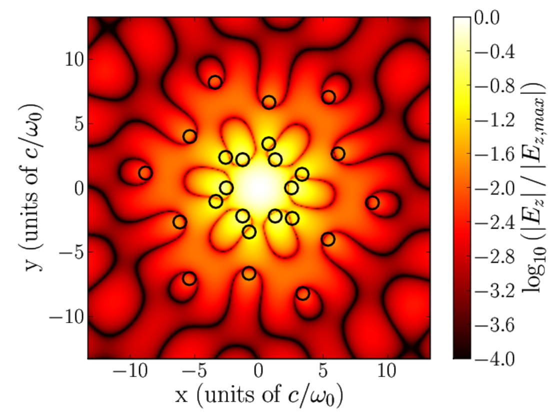
room temperature confirm the monomodal behavior, but the Q value is lower than expected (roughly 10^3). This is mainly due to



- 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 18-rod 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: 100x improvement in Q, 1/6 the number of rods, ¼ the volume!



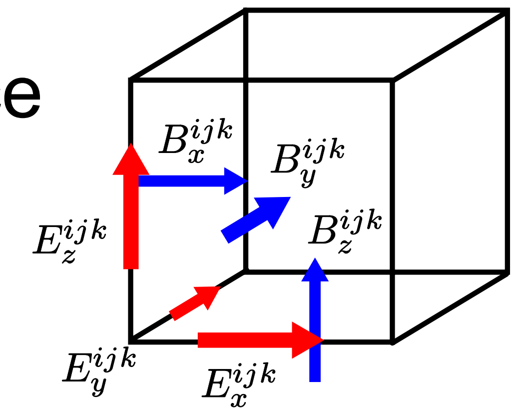


Dielectric Laser Acceleration and Hybrid Cavities are computationally difficult

- Many length scales
  - Beam width is 1/10 of
  - Waveguide radius is 1/10 of
  - Transverse decay is multiple layers
  - Outgoing waves
  - So resolve 100x implies 1000x
- Many time scales
  - Courant time for fraction of beam
  - Decay time of modes
  - Time of bunch train
  - Time of dielectric heating

New algorithm provides the speed of FDTD with the accuracy of FEM

- Maxwell discretized by finite difference



$$\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E}$$

$$\frac{\partial \mathbf{E}}{\partial t} = c^2[\nabla \times \mathbf{B} - \mu_0 \mathbf{j}]$$

$$B_{x,i,j,k}^{n+1/2} - B_{x,i,j,k}^{n-1/2} = \Delta t \left(\frac{E_{z,i,j,k}^{n} - E_{z,i,j+1,k}^{n}}{\Delta y} + \frac{E_{y,i,j,k+1}^{n} - E_{y,i,j,k}^{n}}{\Delta z} \right)$$

- Same for E
- Regularly structured data is desired
  - Best for access, esp on modern architectures
  - Works well (only?) with particles if rectilinear
- But then, conformal (curved) surfaces are represented by embedded boundaries

What is the embedded boundary algorithm for dielectric conformal surfaces?

J. Comput. Phys. **230**, 2060-2075 (2011)

A second-order 3D electromagnetic algorithm for curved interfaces between anisotropic dielectrics on a Yee mesh

Carl A. Bauer[a,*], Gregory R. Werner[a], John R. Cary[a,b]

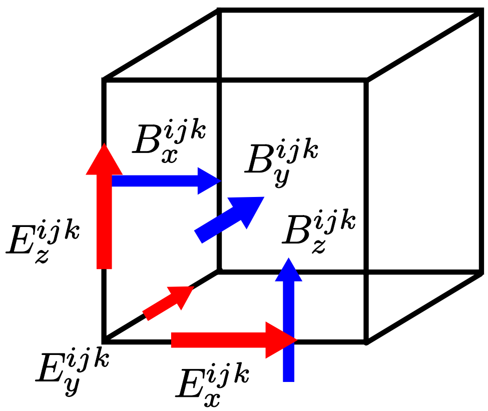
[a] *Department of Physics and the Center for Integrated Plasma Studies, University of Colorado, Boulder, Colorado 80309*

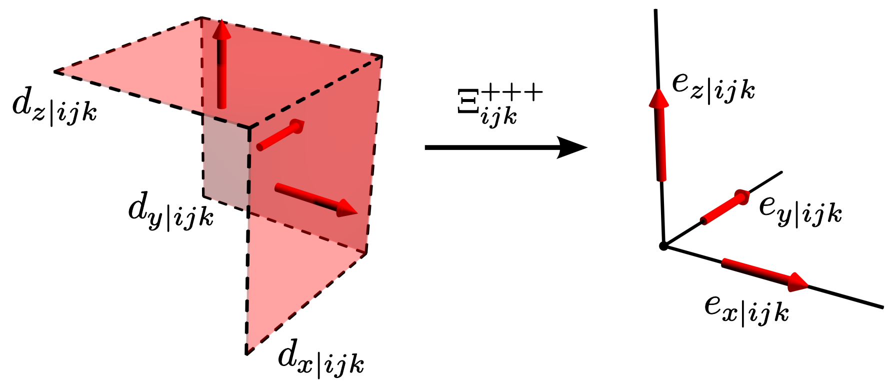
[b] *Tech-X Corporation, Boulder, Colorado 80303*

Abstract

A new frequency-domain electromagnetic algorithm is developed for simulating curved interfaces between anisotropic dielectrics embedded in a Yee mesh with second-order error in resonant frequencies. The algorithm is systematically derived using the finite integration formulation of Maxwell's equations on the Yee mesh. Second-order convergence of the error in resonant frequencies is achieved by guaranteeing first-order error on dielectric boundaries and second-order error in bulk (possibly anisotropic) regions. Convergence studies, conducted for an analytically solvable problem and for a photonic crystal of ellipsoids with anisotropic dielectric constant, both show second-order convergence in error; the convergence is sufficiently smooth such that Richardson extrapolation yields roughly third-order convergence.

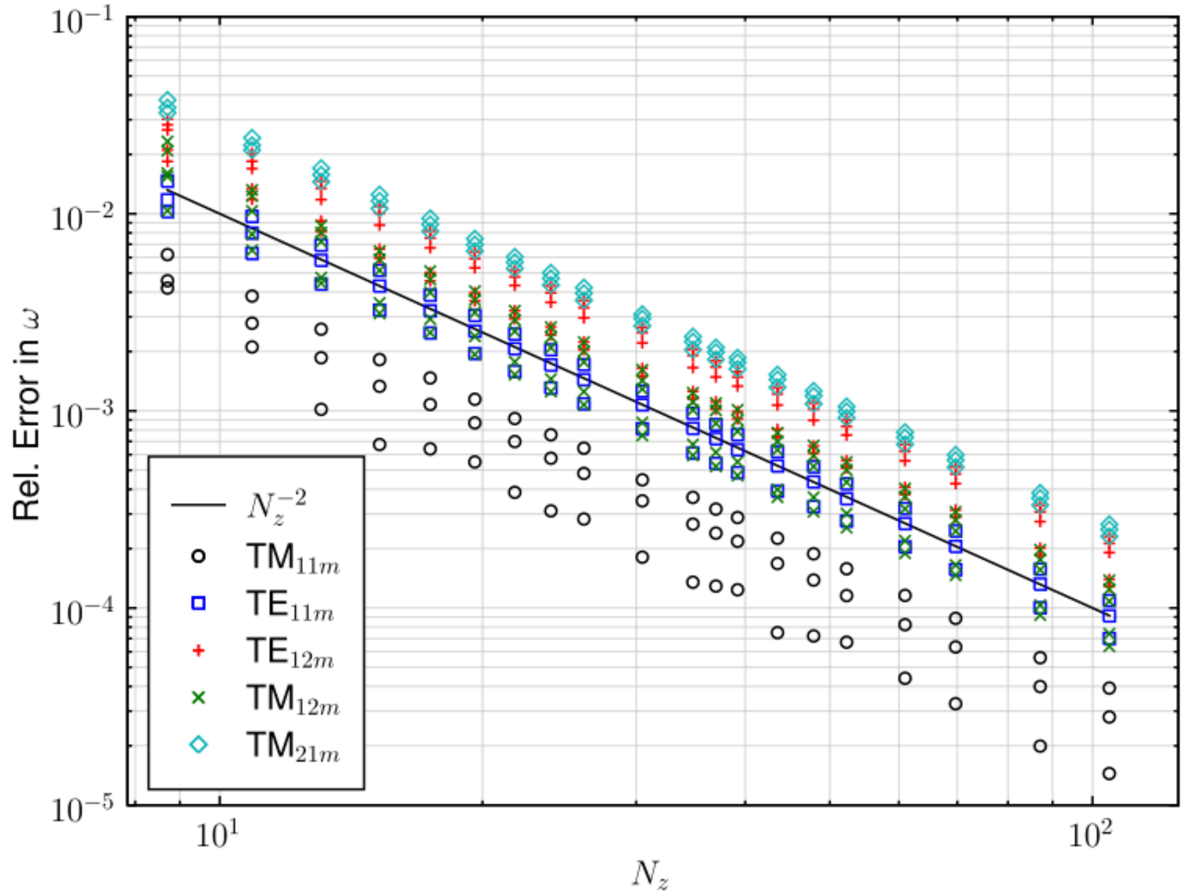
Basics of algorithm: find local, 1st-order accurate relation between E and D





- Assume local plane having different dielectrics on each side
- Assume normal D, tangential E continuous
- Find **D**(D_n, E_t), **E**(D_n, E_t)
- Invert first to find (D_n, E_t)
- Insert these into second

Result: Perfect 2nd-order convergence



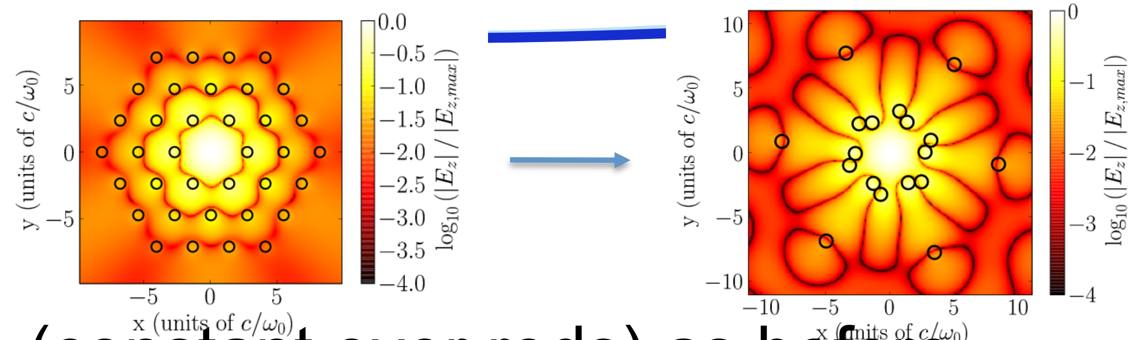
Dielectric sphere inside metal sphere

Multiple needs for algorithmic research

- Time-domain higher order (due to pulse nature)
- Dispersive media
- Accurate surface fields (multipacting, heating, breakdown)
- Optimal implementations with advanced instructions and on accelerators
  - AVX
  - GPU
  - MIC
- Do we continue to custom code each chip? (Or move to OpenCL or OpenACC?

Optimization: identify parameters, targets, opt algorithm, then do the work

Reduce hybrid cavity wakefields



- Parameters
  - Location and radius (constant over rods) as before
  - Elliptical rods: both major and minor radii (5 more parameters)
  - Varying rod permittivities (a discrete parameter)
- Targets: Reduce Q of troublesome modes
  - Identify modes
  - Rapidly calculate Q's
  - Loop
  - Check

Need campaigns for other areas

World of multiphysics only just now being defined

- Raiation deforms the dielectric structures
  - Electro-acoustics
- Radiation heats dielectrics
  - Electro-thermal

Conclusions

- Much computational progress in the complementary areas of RF and Optical dielectric structures
  - New, low-wakefield cavities
  - In coupling of laser radiation improved
- Improved algorithms found
  - 2^{nd}-3^{rd} order on regular arrays (good for accelerators)
  - Scalable
- More algorithmic work needed
  - Dispersive, time domain
  - Advanced accelerators, instructions
- Beam simulations (self-consistent) needed
- Optimization campaigns
- Multiphysics
  - Electro-acoustic
  - Electro-thermal