GALAXIE: **G*V*-per-meter *Acce*L*erator* *A*nd**
***X*-ray-source *I*ntegrated *E*xperiment**

A Dielectric Laser Accelerator-Based, GV/m All-Electromagnetic FEL

James Rosenzweig

UCLA Dept. of Physics and Astronomy

IPAC 2013, Shanghai, China

May 14, 2013

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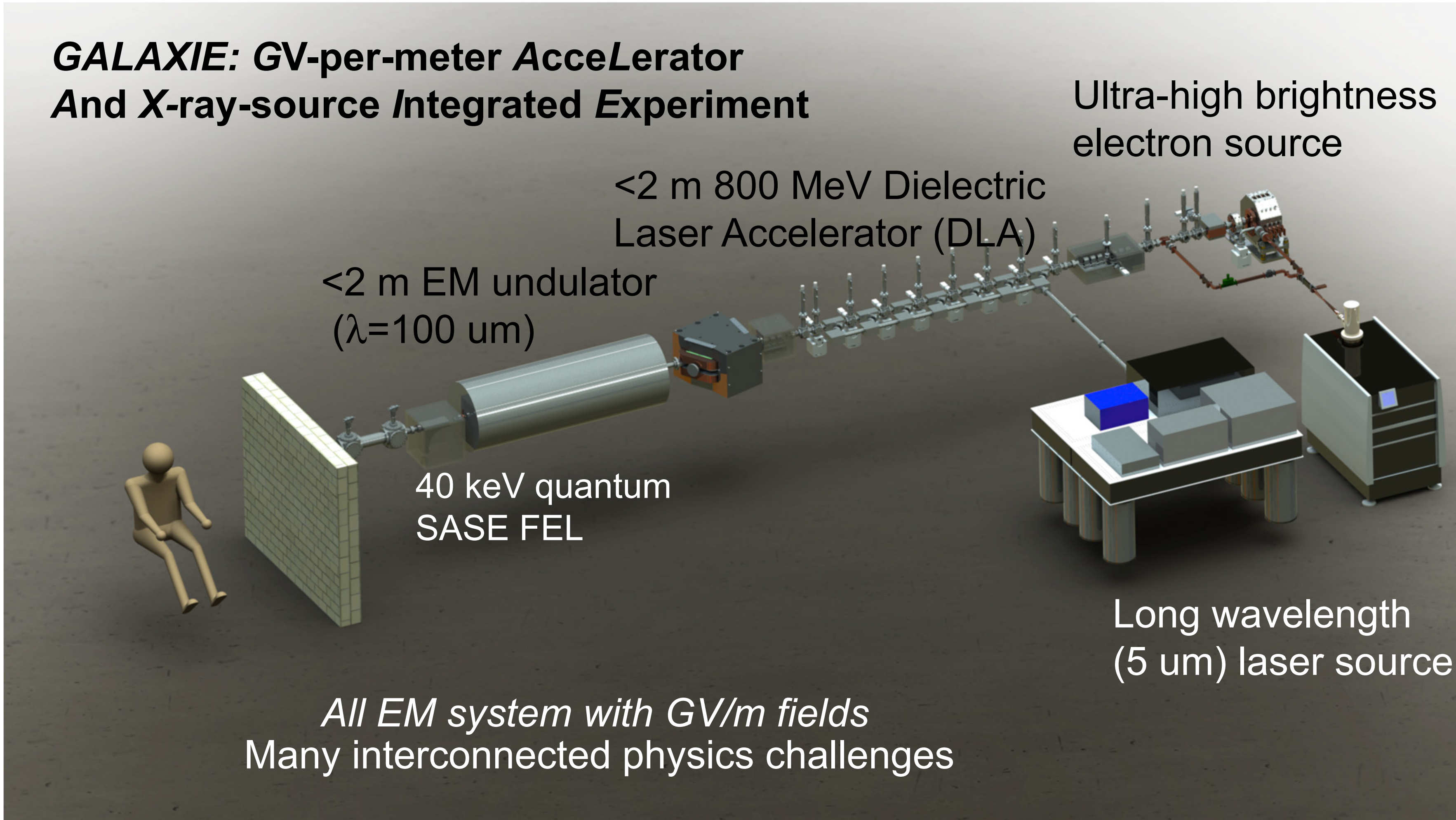
The GALAXIE Collaboration

- UCLA Dept. of Physics and Astronomy
  - Miao, Musumeci, Putterman, Rosenzweig
- Stanford Linear Accelerator Center
  - Tantawi, Yakimenko (late of BNL)
- Penn State University
  - Jovanovic
- RadiaBeam Technologies
  - Murokh, Boucher
- UCLA Electrical Engineering
  - Candler
- Brookhaven National Laboratory
  - Pogorelsky

Collaborations on micro-undulators/MEMS beam optics with Candler group (UCLA) and Arnold group (Florida); cathode physics with SRI

GALAXIE: An *Integrated* Table-top X-ray FEL



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GALAXIE: A 5th Generation Light Source

Physics & Applications of High Brightness Electon Beams: Towards a 5th Generation Light Source

ICFA sponsored workshop
San Juan, Puerto Rico,
March 25-28, 2013

5th Generation: Marriage of new high gradient accelerators and light sources; burgeoning field with intense activity. GALAXIE is a key example (of many), within ambitious DARPA program

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High brightness electrons beget high brightness photons

- FEL: 3-wave interaction instability
- Growth rate depends on e- beam *brightness* $B_e \equiv \frac{2I}{\varepsilon_n^2}$

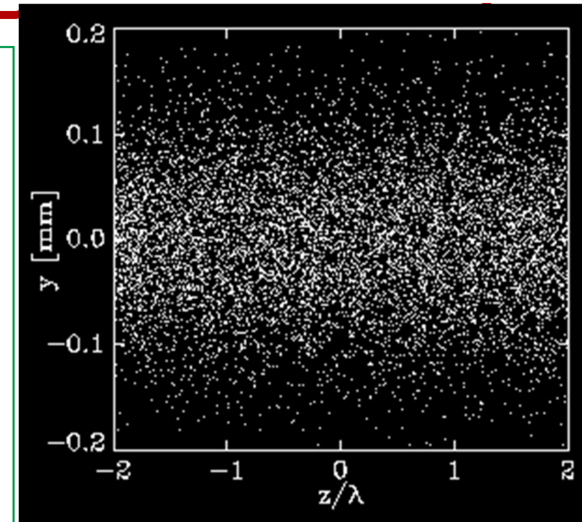
$$L_{g,1D} = \frac{\lambda_u}{4\pi\sqrt{3}\rho_{1D}} \qquad \rho_{1D} = \left[\frac{JJ(K_{rms})K_{rms}k_p}{4k_u}\right]^{2/3} \propto B_e^{1/3}$$

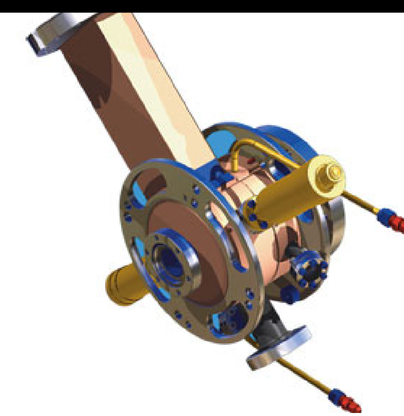
- High *I*, small ε: dense lasing medium

$$E_{rad} \propto \exp(z/L_g);\ L_g \propto B_e^{-1/3}$$

- +8 orders of magnitude photon brightness: fs, *coherent* X-rays
  - Revolution in imaging
- X-ray FEL needs high energy, very high quality electron beams
  - *Energy mitigated by short* λ_u
  - Compact FEL possible, w/new accelerator

$$\boxed{\lambda \approx \lambda_u / 2\gamma^2}$$





$$B_e = 2\times10^{14}\ \text{A/m}^2$$

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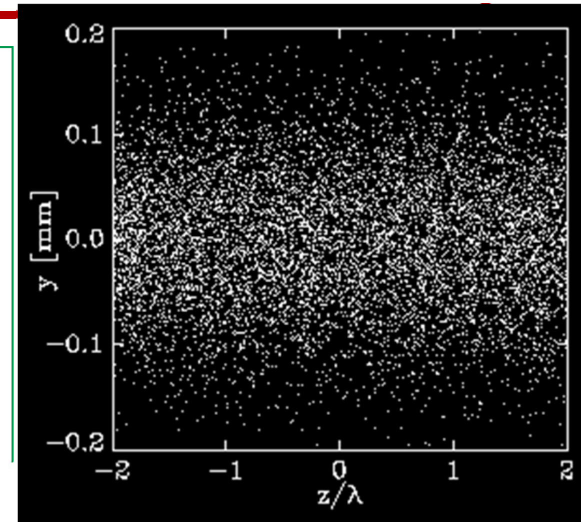

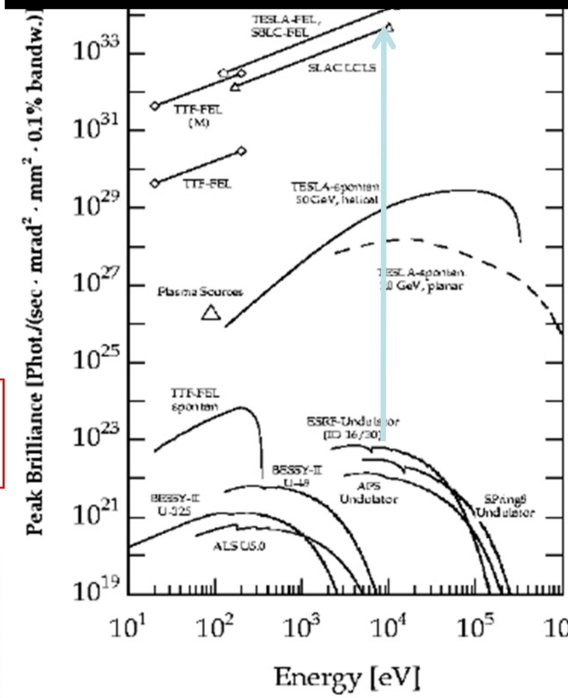

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Glance at GALAXIE parameters

GALAXIE nominal design parameter list.

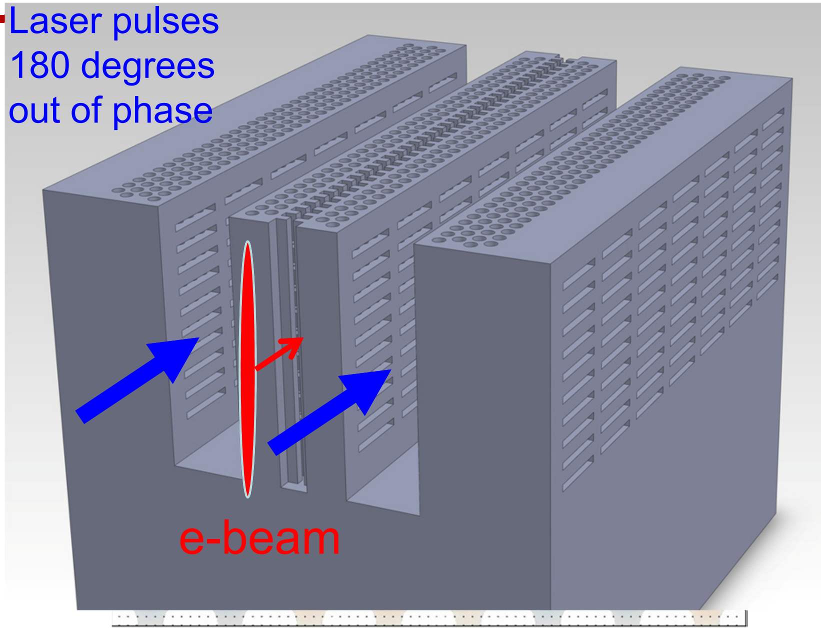
Parameter	Symbol	Value
Injection Energy	U_i	3-6 MeV
Normalized Emittances (split)	$\varepsilon_x, \varepsilon_y$	$2\times10^{-7}, 2\times10^{-9}$ m-rad
Normalized Emittances (round)	$\varepsilon_x = \varepsilon_y$	2×10^{-8} m-rad
Injection current (unbunched)	I_{ave}	1 A
Peak current (bunched)	I_p	300 A
Nominal acceleration field	E_{acc}	1 GV/m
Accelerating laser wavelength	λ	5 μm
FEL Operational Energy	U_f	720 MeV
FEL EM undulator wavelength	λ_u	100 μm
FEL undulator strength parameter	K	0.11
FEL Pierce parameter (3D)	ρ_{3D}	5×10^{-5}
FEL Gain Length	$L_{g,3D}$	9.3 cm
FEL Saturation Length	L_{sat}	1.8 m

Injector parameters set by FEL *and* accelerator

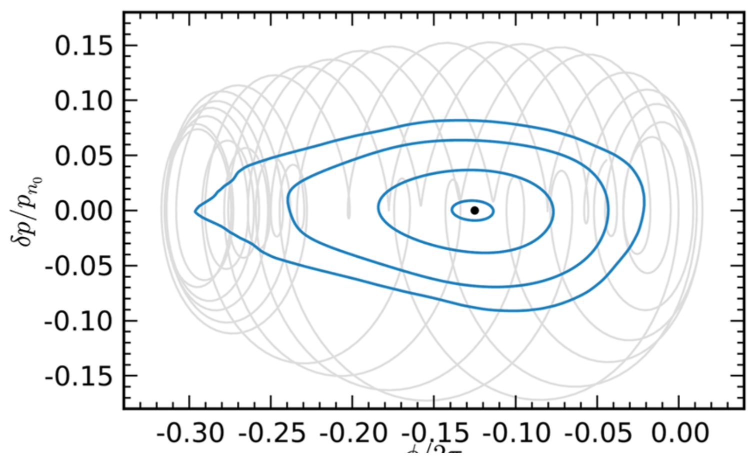
Choice of DLA wavelength

Why longer λ? Structure/dynamics

- Avoid aperture limitations
  - Vertical ε @ 1E-9 m-rad for 5 μm case; 3E-11 m @ 0.8 μm!
  - Strong 2nd order focusing still needed
- More stable longitudinal acceleration — enlarged "buckets" ~λ
  - Complex dynamics from focusing harmonic
  - Uses *adiabatic compression* in acceleration
- Mitigate structure (GV/m) breakdown
  - Small quantum energy
  - Optimize at ~ps pulse length
- Breakdown thresholds unknown (>GV/m)
  - *Material investigations performed*



Biharmonic ~2D structure



Longitudinal phase space

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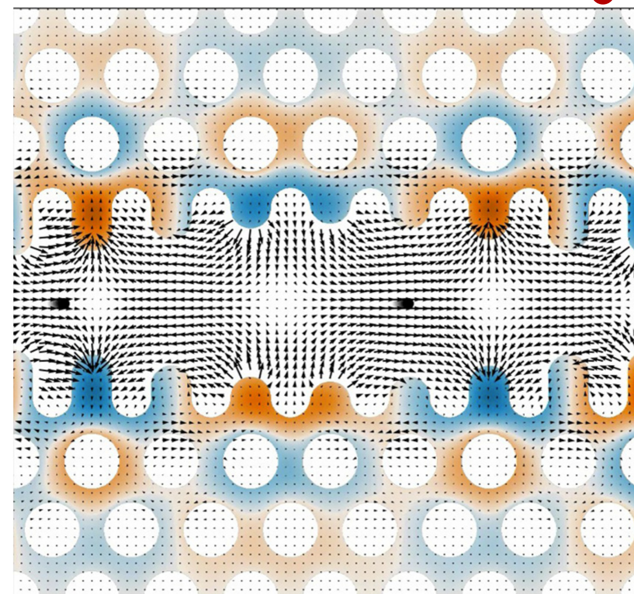

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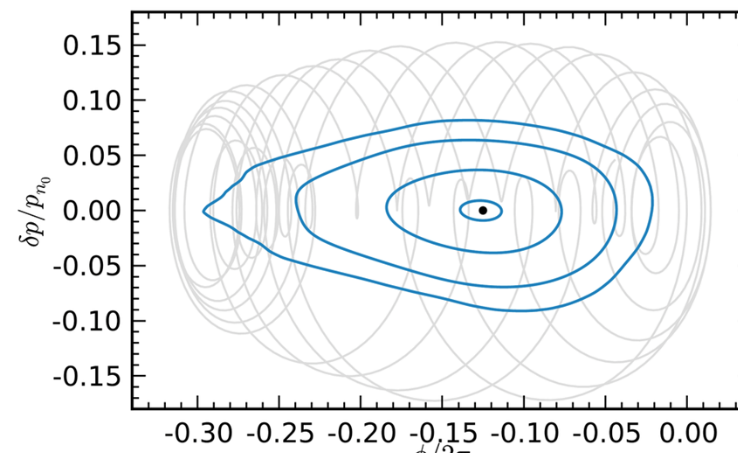

Longitudinal phase space

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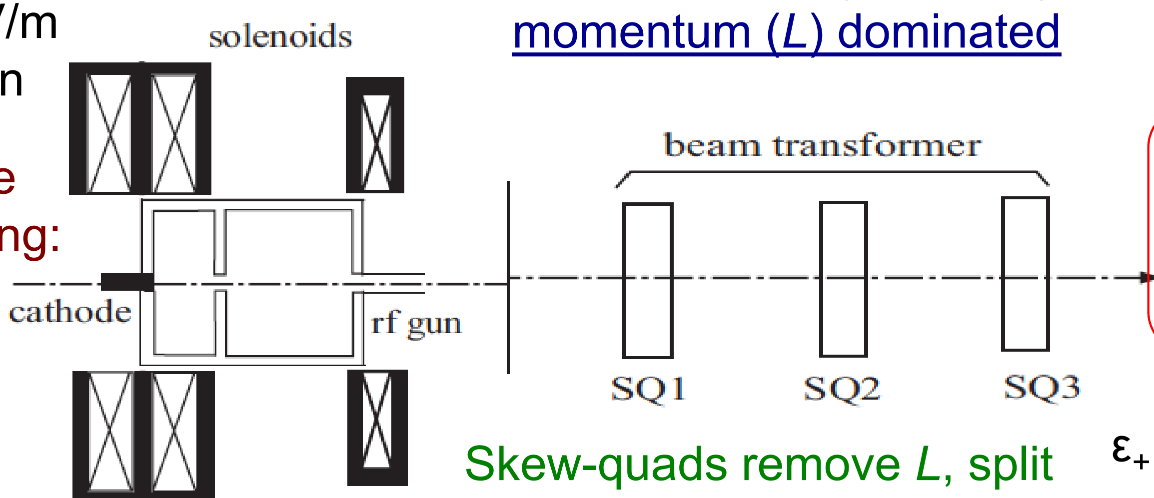
Ultra-high Brightness Electron Source

- DLA 3D stability requires injection >3 MeV
- Very high gradient (~150-200 MeV/m) S-band or X-band RF gun
  - Synergistic with standard FEL injectors
  - *No need to improve cathode "temperature"*; small spot possible!
- Magnetize cathode to obtain asymmetric emittances
  - skew quad splitter

150-200 MV/m
HB photogun

B_z at cathode gives coupling: – *L:* angular momentum



Beam post-RF gun is angular momentum (*L*) dominated

$$\begin{cases} \varepsilon_+ = \varepsilon + L \\ \varepsilon_- = \varepsilon - L \end{cases}$$

Skew-quads remove *L*, split emittances in *x* and *y*

$\varepsilon_+ \approx 10^{-7}$ m-rad

$\varepsilon_- \approx 10^{-9}$ m-rad

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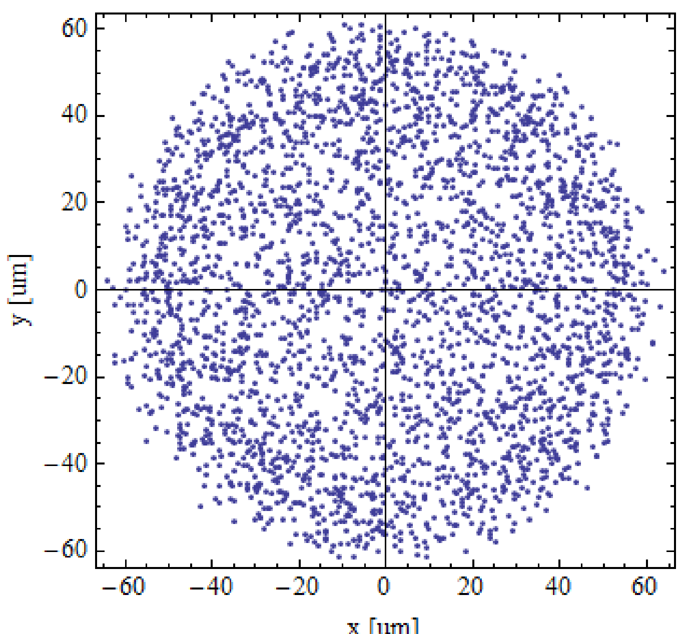
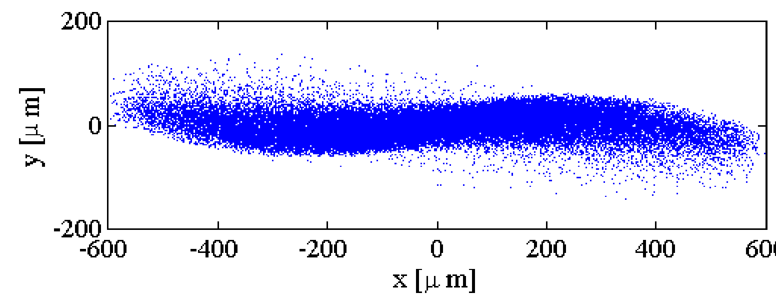
Source: simulated performance

- Dynamics include space-charge (Q=1 pC)
  - Emittance compensation w/angular momentum



Beam after photoinjector (w/o AM)

$\varepsilon_{xn}=\varepsilon_{yn}=2.8 \times 10^{-8}$ m-rad



Beam after splitter

Normalized Emittance

$\varepsilon_{n-},\varepsilon_{n+=}2.9\times10\text{-}9,\ 2.6\times10\text{-}7$ m-rad

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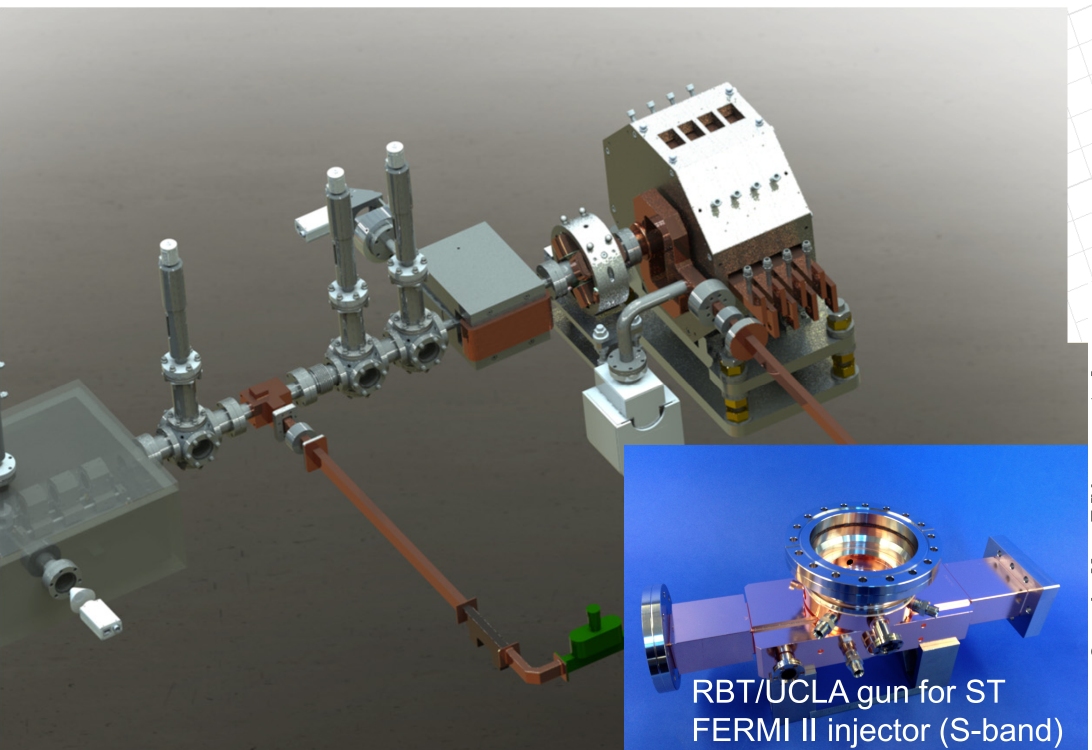
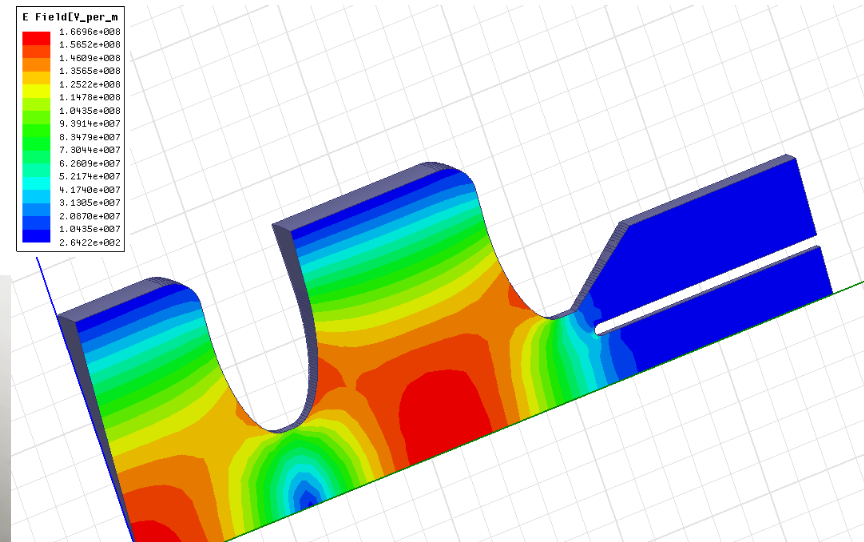
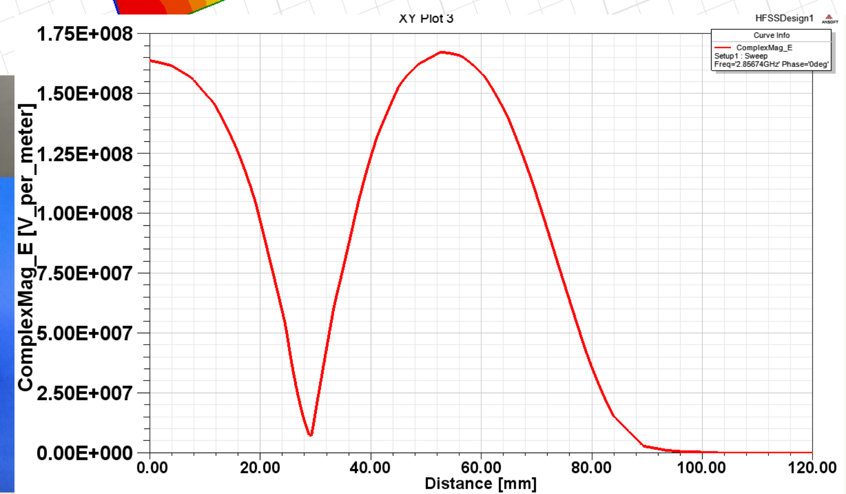
Injector RF design and engineering

- S-band "Super-Gun" permits 160 MV/m injection
- 7 MeV beam, ~3x current B_e
- "Disruptive" to FEL comm.
- Fabrication at RadiaBeam



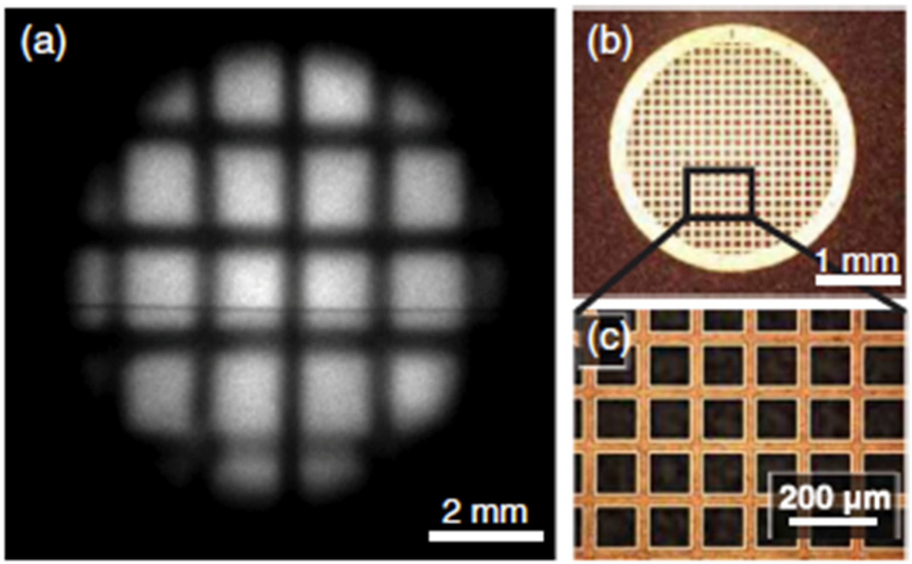
RBT/UCLA gun for ST FERMI II injector (S-band)

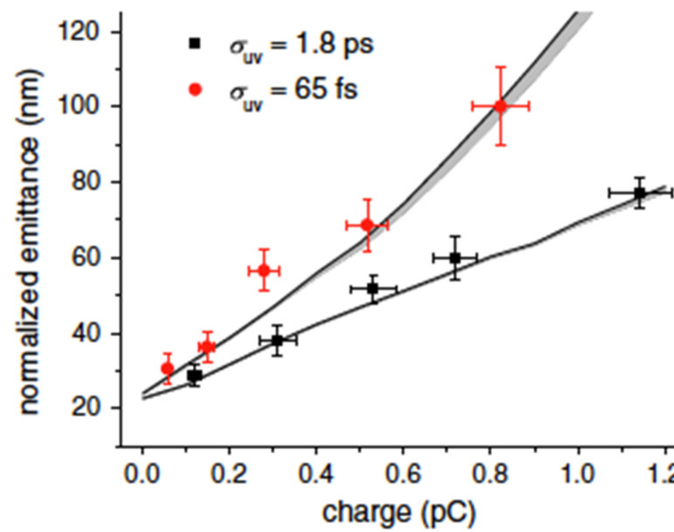




Creation and measurement of nm emittances

- New dark-field technique pioneered at UCLA Pegasus
  - Low gradient RF gun
- Uses TEM grid, edge distribution – 10 nm ε resolution





R.K. Li, et al., Phys. Rev. ST-Accel Beams 15 090702 (2012)

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GALAXIE GV/m DLA structure

- Myriad challenges:
  - Optimized field on dielectric (GV/m breakdown)
  - Novel wavelength (5 um)
  - Photonic confinement (no metals allowed)
  - Beat Earnshaw's theorem (y. 1842!), obtain simultaneous transverse & longitudinal focusing
  - Utilize a continuous coupling to yield long interaction between DLA and e-beam
  - *Fabrication.* Start with Si, aim for sapphire later...

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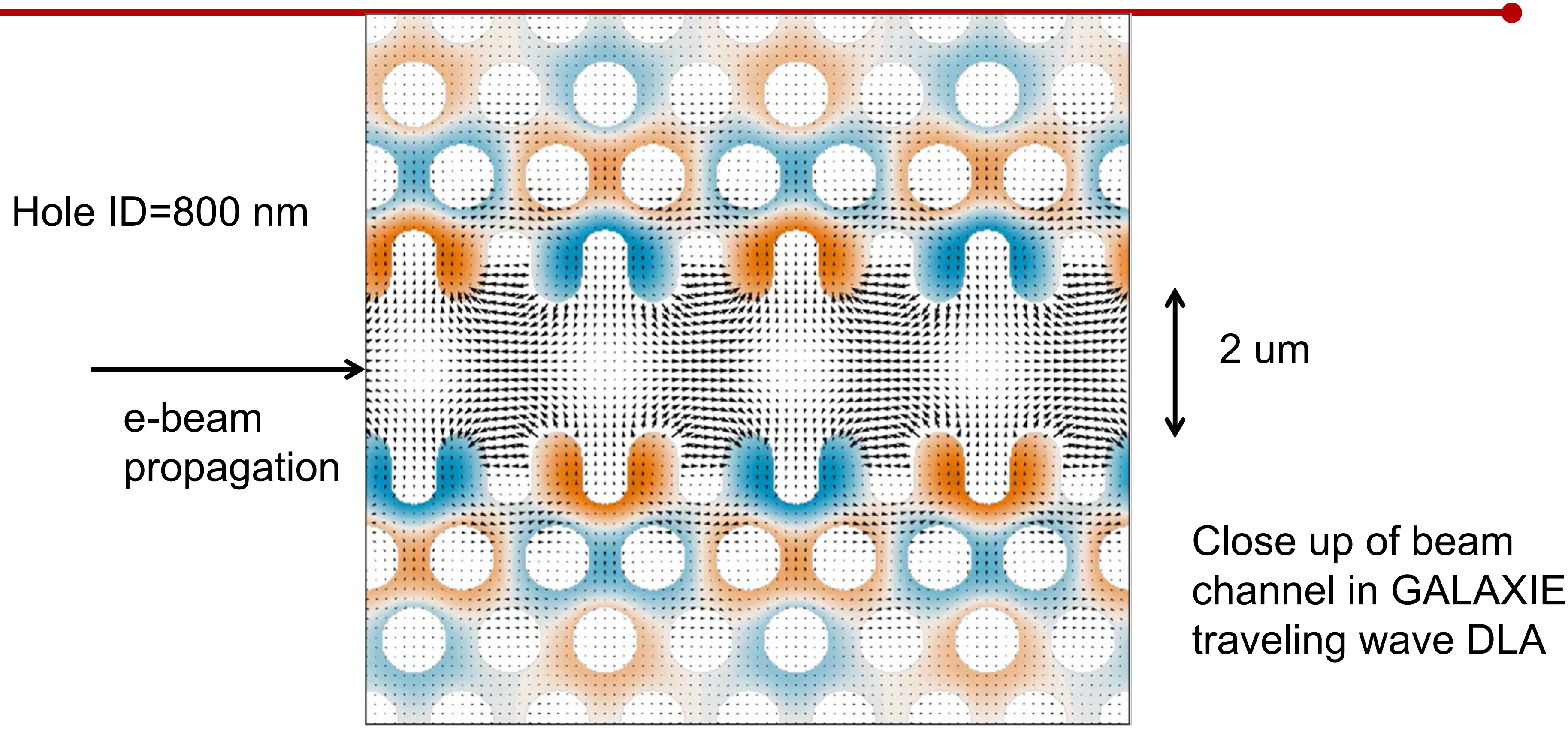
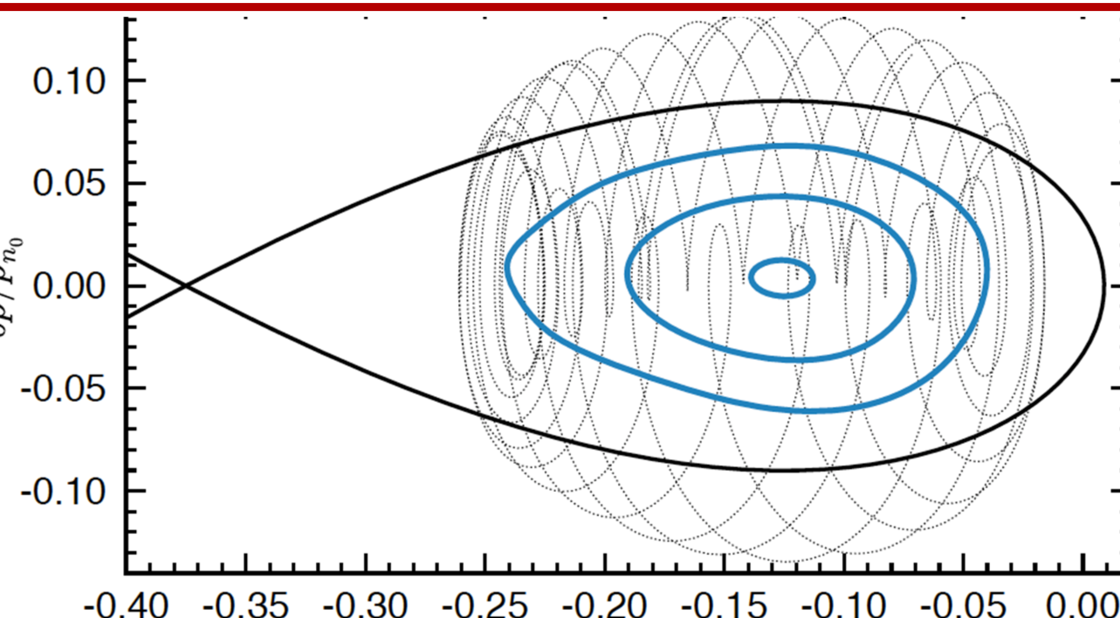
Optimized DLA structure design



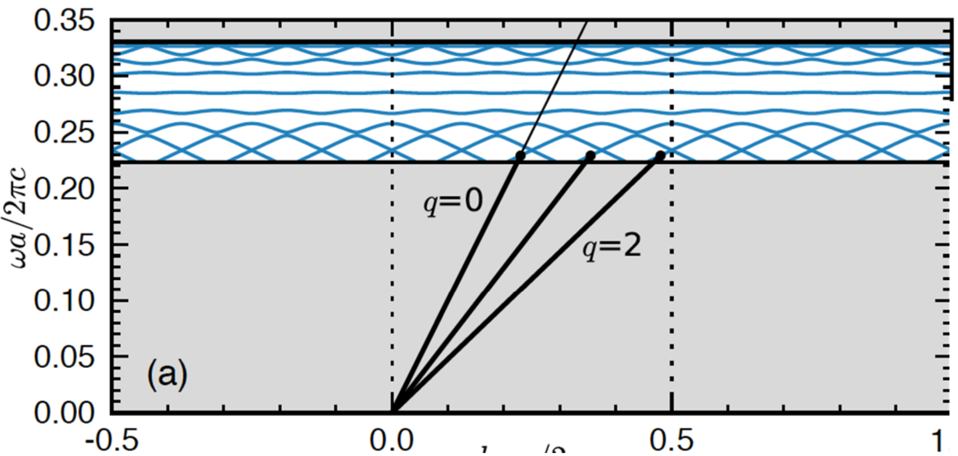
- *Single material* (Si, Al_2O_3) *photonic* structure
- Rich spatial harmonic spectrum
- Described in recent PRL
  - Naranjo, Valloni, Putterman, Rosenzweig, *PRL* 109, 164803 (2012)

Focusing and acceleration provided by nearby spatial harmonics

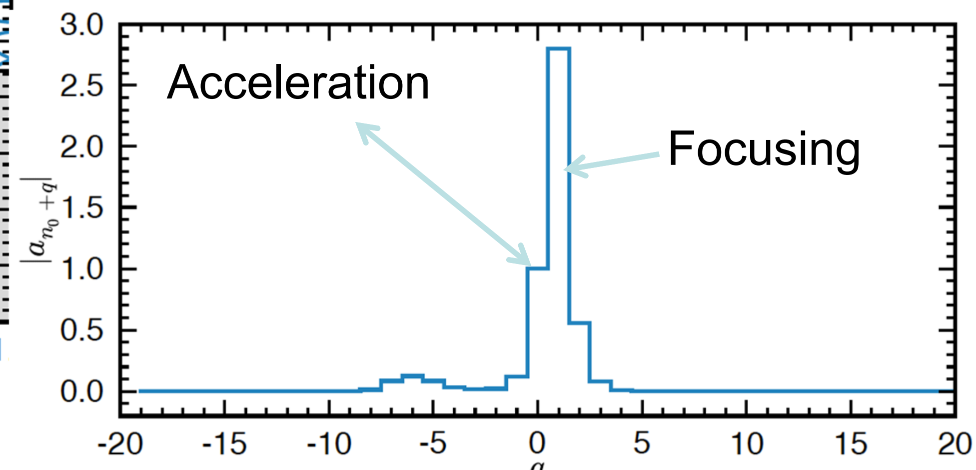
Focusing given by 2nd order interaction with non-synchronous fields



Longituindal phase space (Poincare and actual). Note bouncing due to harmonics

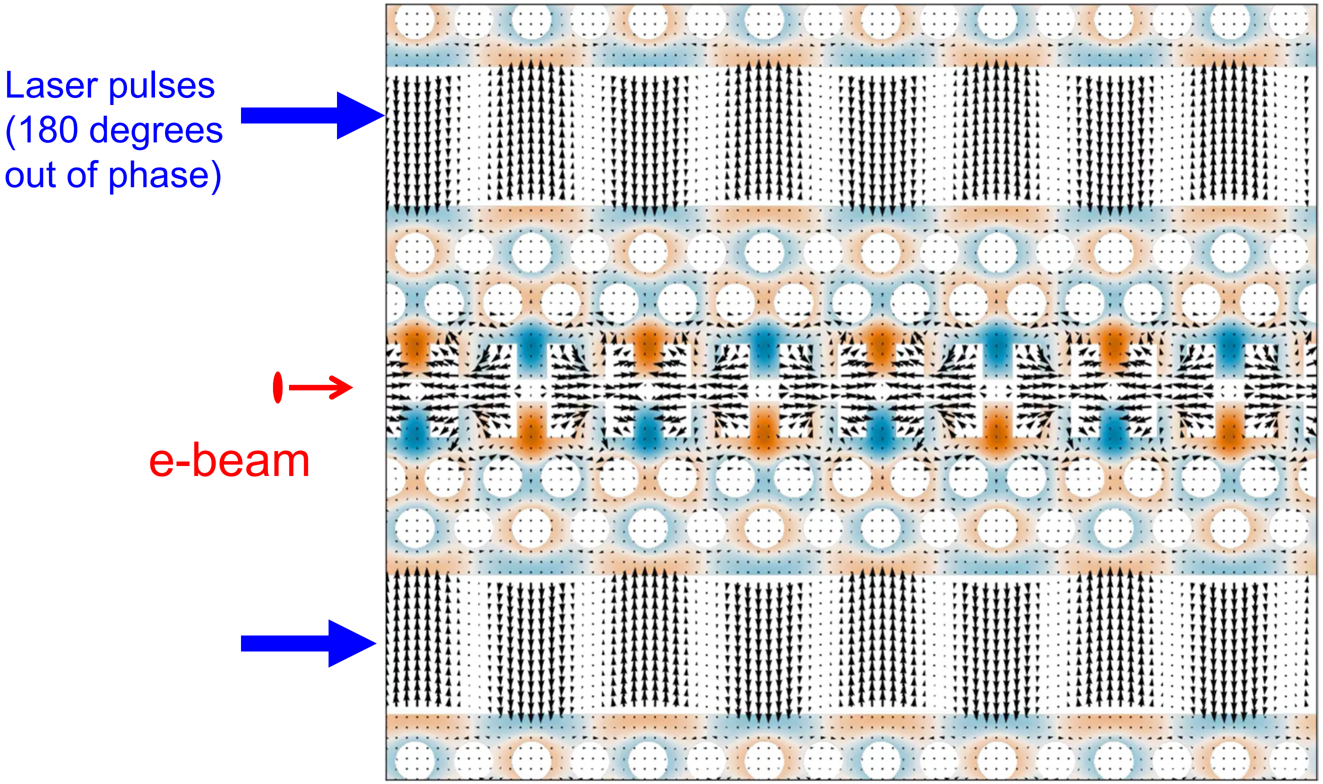


Brillouin diagram for GALAXIE structure



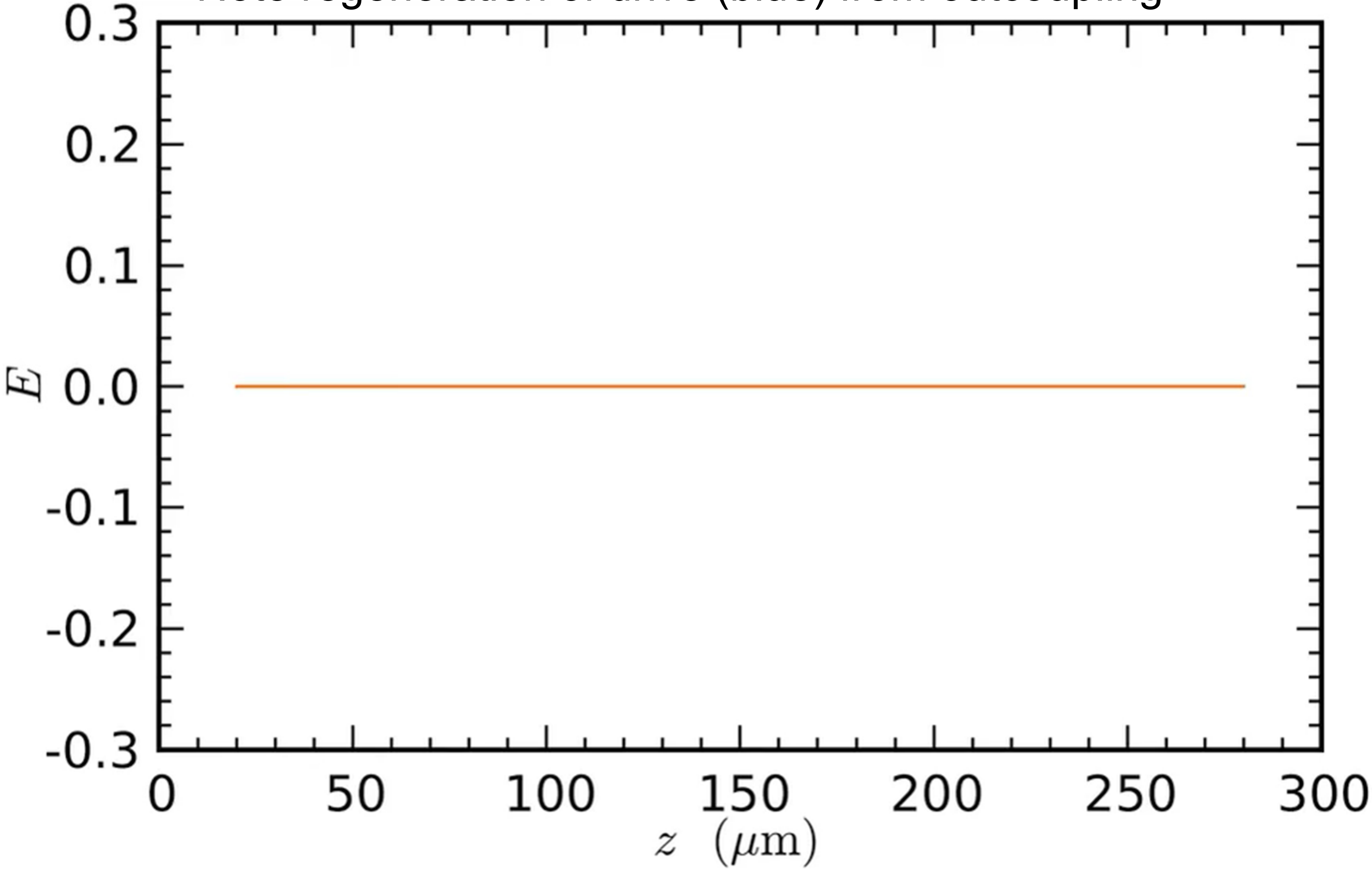
Laser-Structure Coupling

Dual laser drive structure, large reservoir of power recycles



“Rolling” coupling to give synchronism between beam and v_g

Note regeneration of drive (blue) from outcoupling



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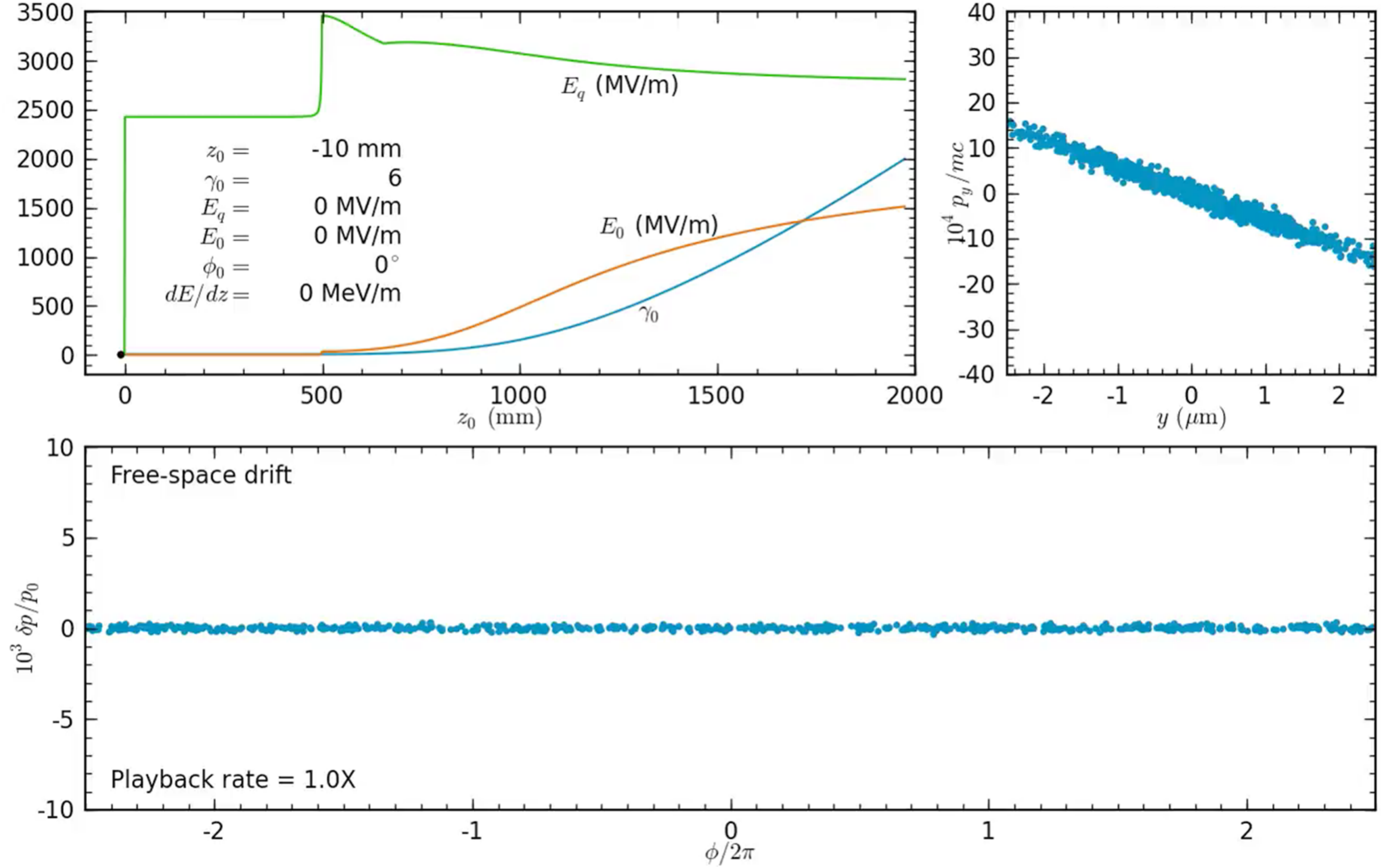
Beam dynamics: injection to final energy



Adiabatic: (1) focusing (2) capture (3) compression (x1000!)

Under preparation for PRSTAB

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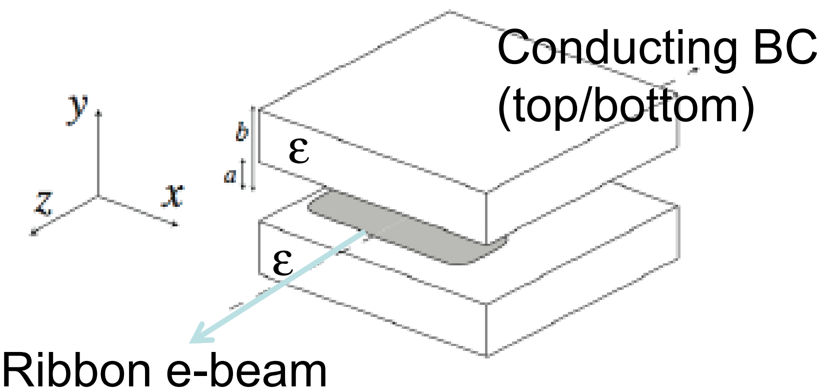
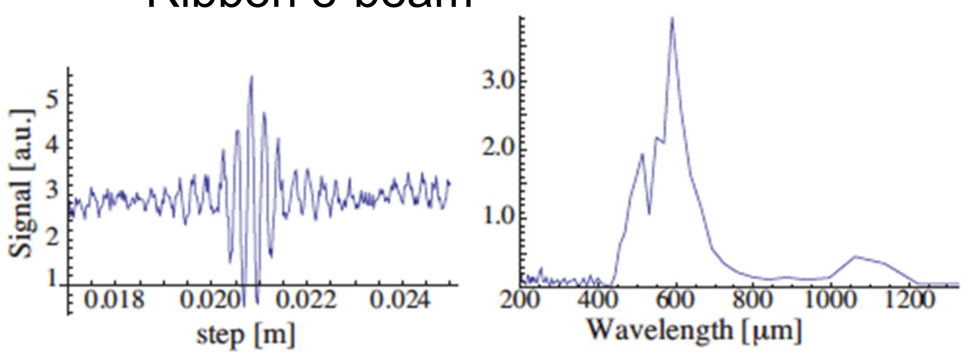
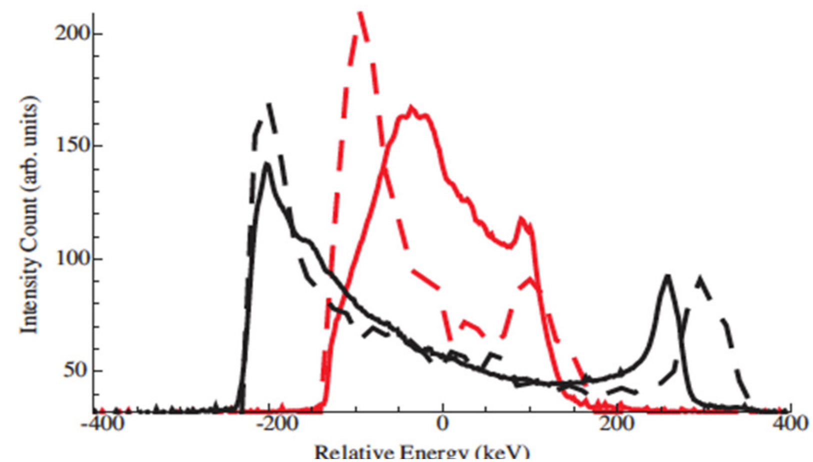
Collective effects beyond space-charge: wakefields

- 1st observation of *slab-symmetric* dielectric structure wakes
  - Key for DLAs: mitigates wakes, space-charge, beam loading
  - Coherent Cerenkov radiation benchmark on mode frequencies
  - Deceleration/acceleration observed (several 100 keV); STE simulated





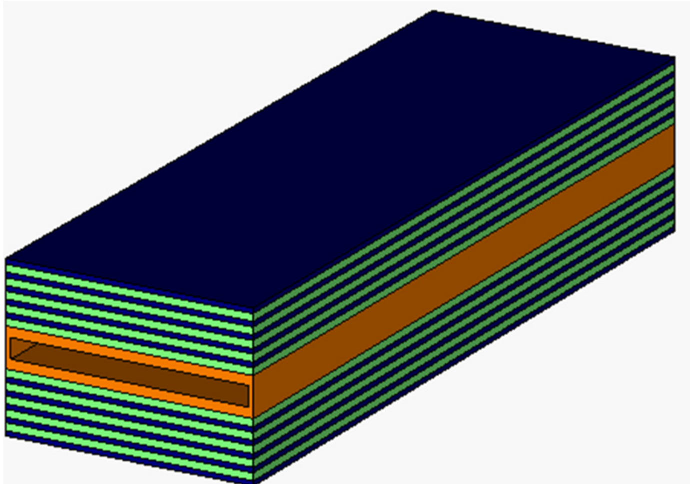
CCR signal and FFT



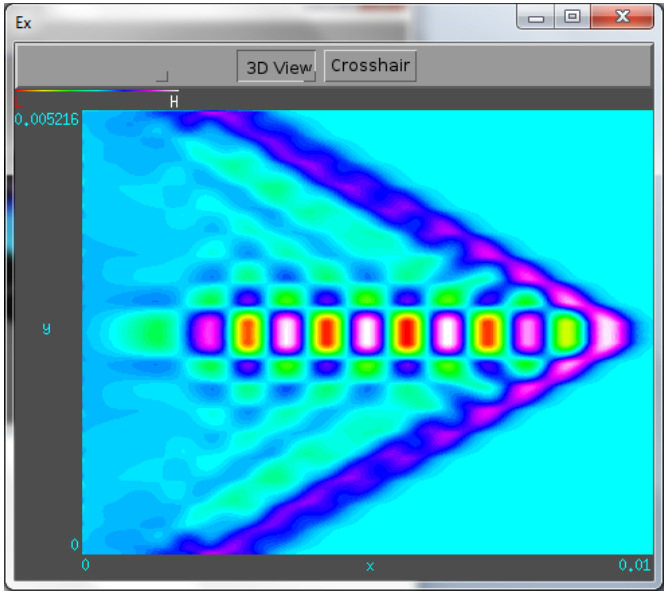
Observed (solid) and simulated (dashed) momentum spectra

G. Andonian, et al., *PRL*108, 244801 (2012)

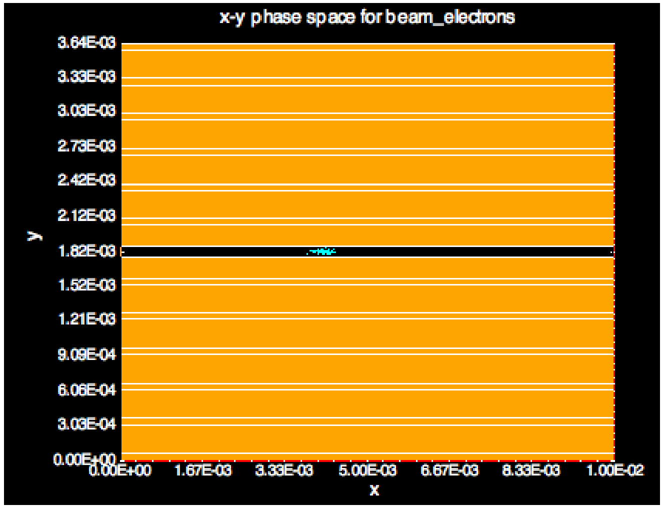
Photonic device wakes I: Bragg



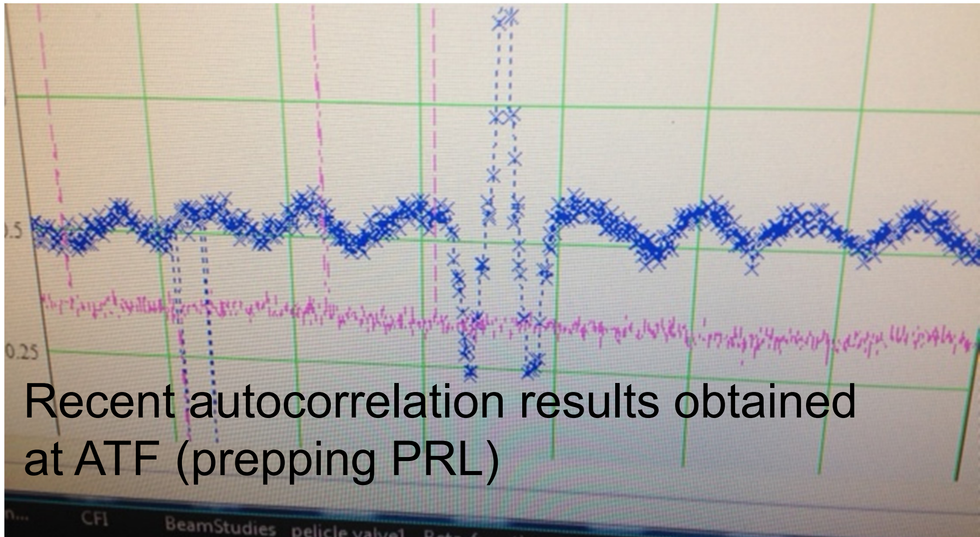
Bragg eliminates metal use in THz



VORPAL simulation



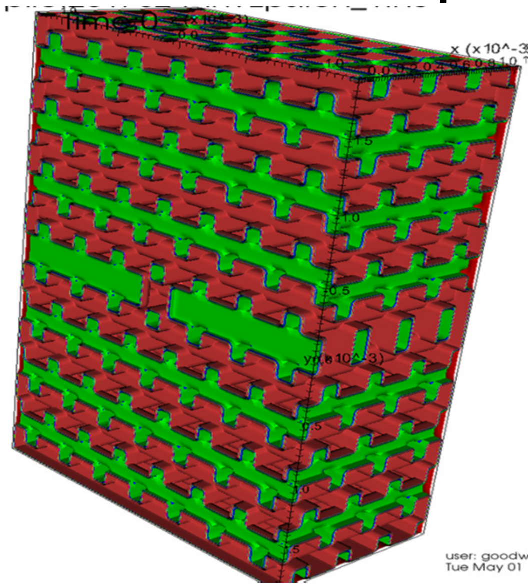
Simple 2D photonics (1st of its kind)
Quartz (also matching layer) + ZTA

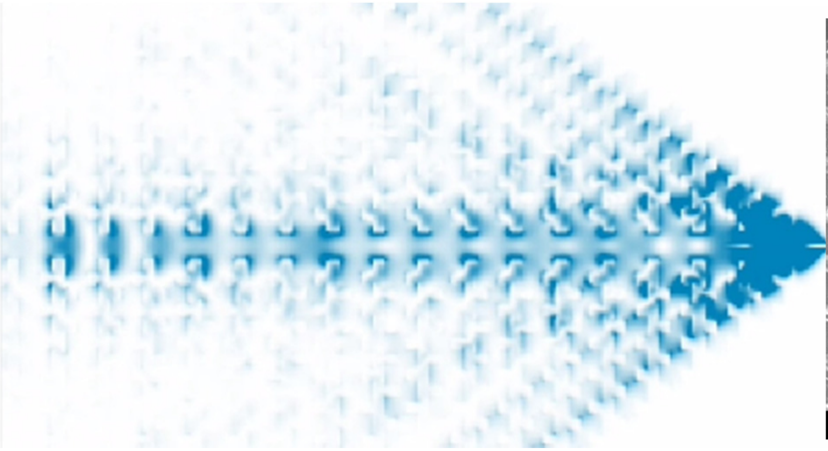


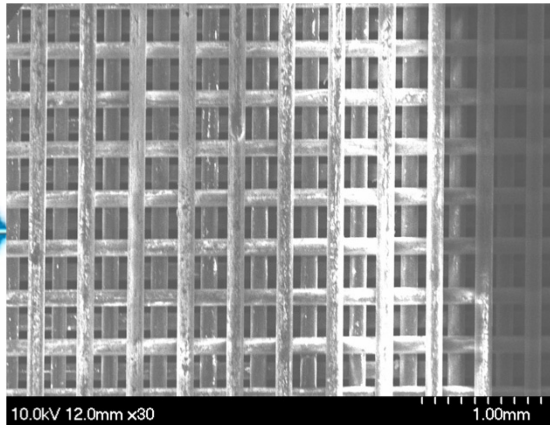
Recent autocorrelation results obtained at ATF (prepping PRL)

New studies at FACET and BNL ATF

- Very high field longitudinal wakes
  - >5 GV/m DWA before breakdown in THz
- New, photonic structures
  - Woodpile (canonical), scaled GALAXIE







Photonic structure (woodpile) wakes; as constructed (left)

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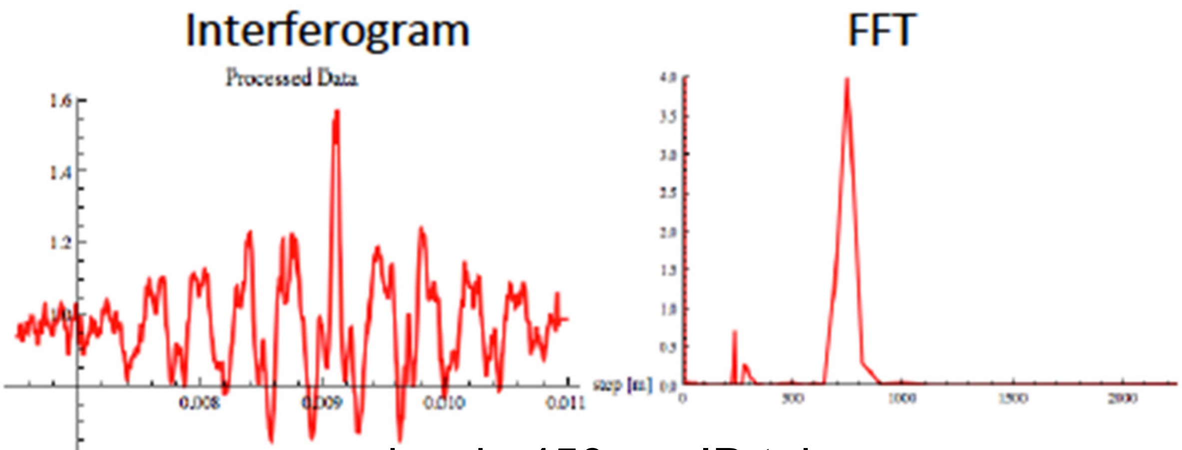
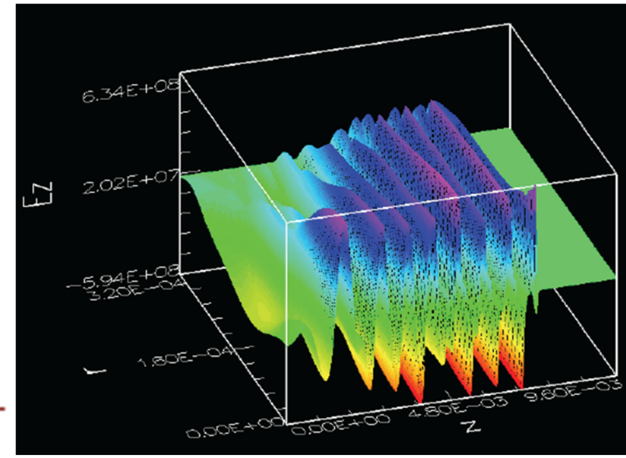
New FACET results

- GV wakes in tubes and slabs observed



wakes in 450 um ID tubes



OOPIC sims of tube wake

- 100 MW narrow band THz source!
- On to Bragg, woodpile…

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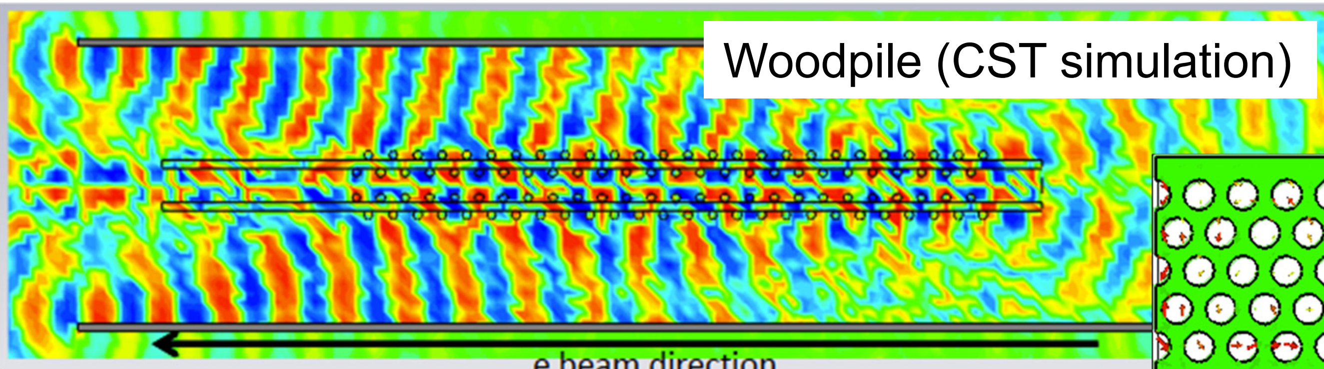
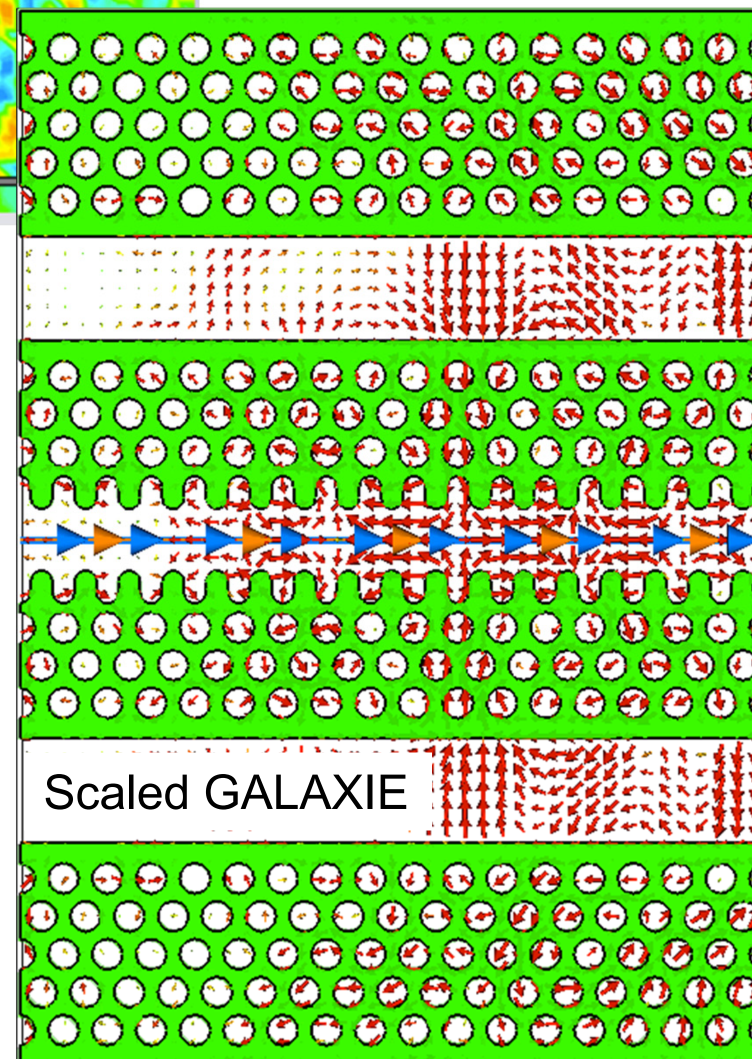
Next generation wakes: 3D photonics





- Woodpile fabricated
  - June 2013 test at ATF
- Scaled GALAXIE structure fabricate by *laser assisted etching* of sapphire

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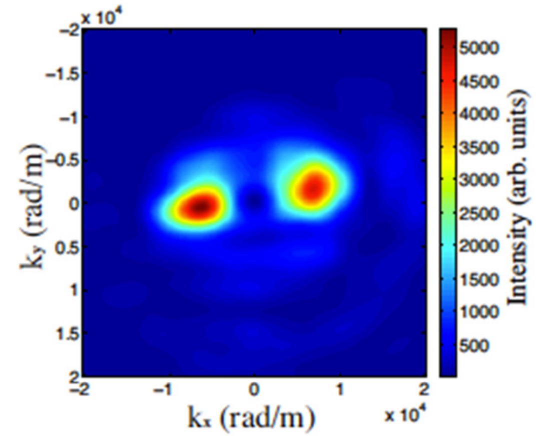
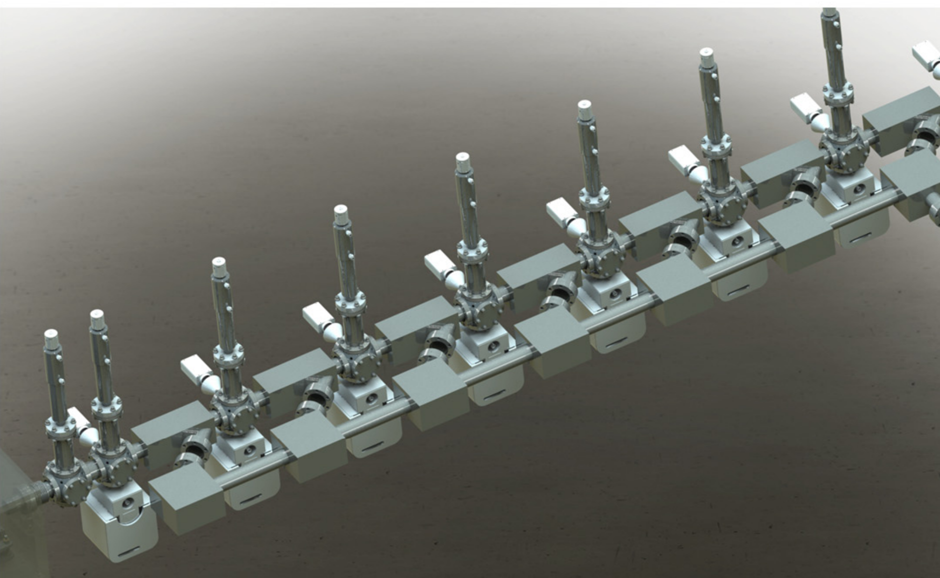
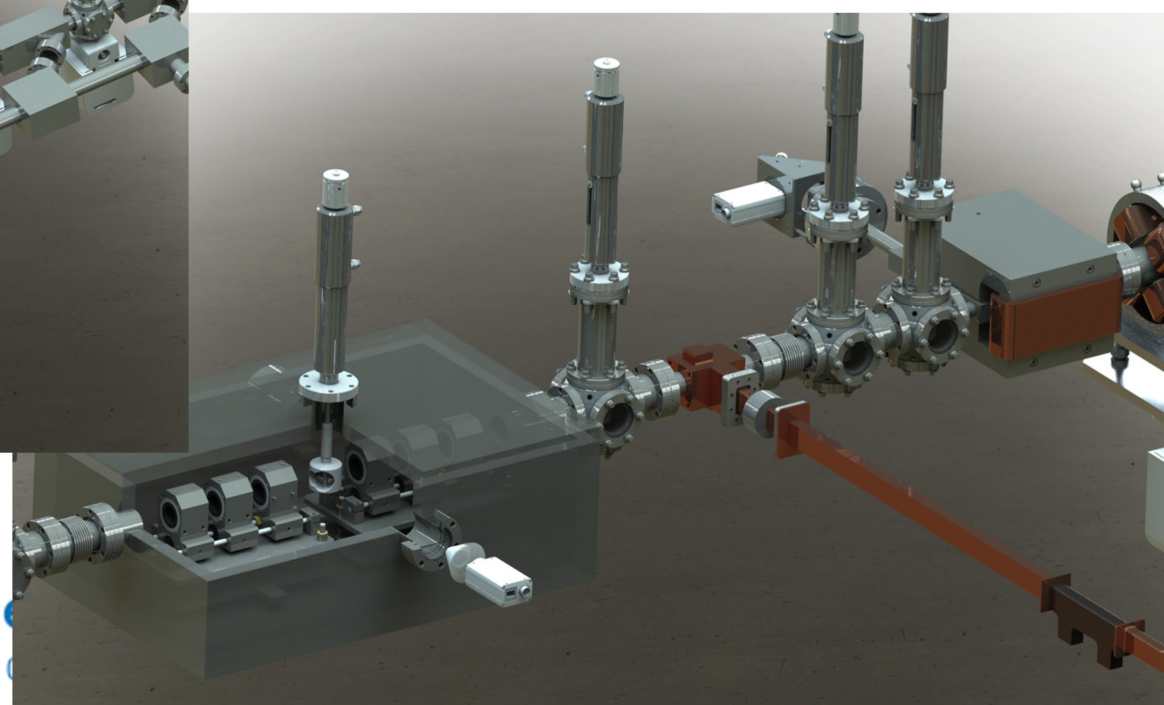
Integration studies (and their lessons)

- **Need um beam diagnostics**
  (coherent imaging, λ–scale)
- **Develop μ-beam optics**

  (Candler group)







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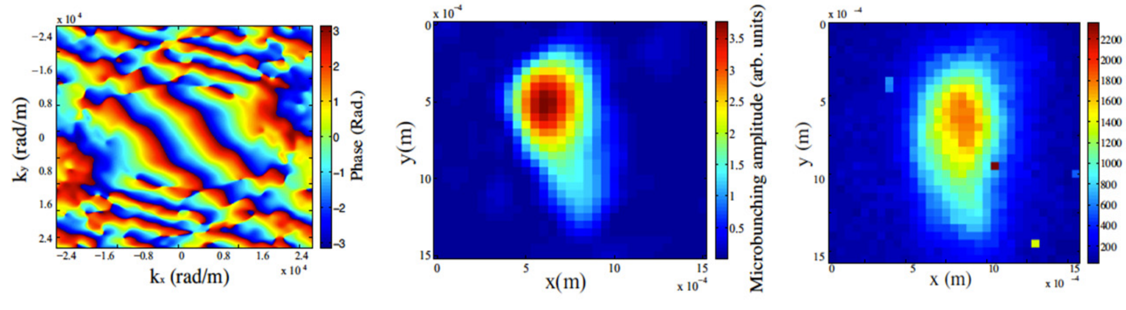
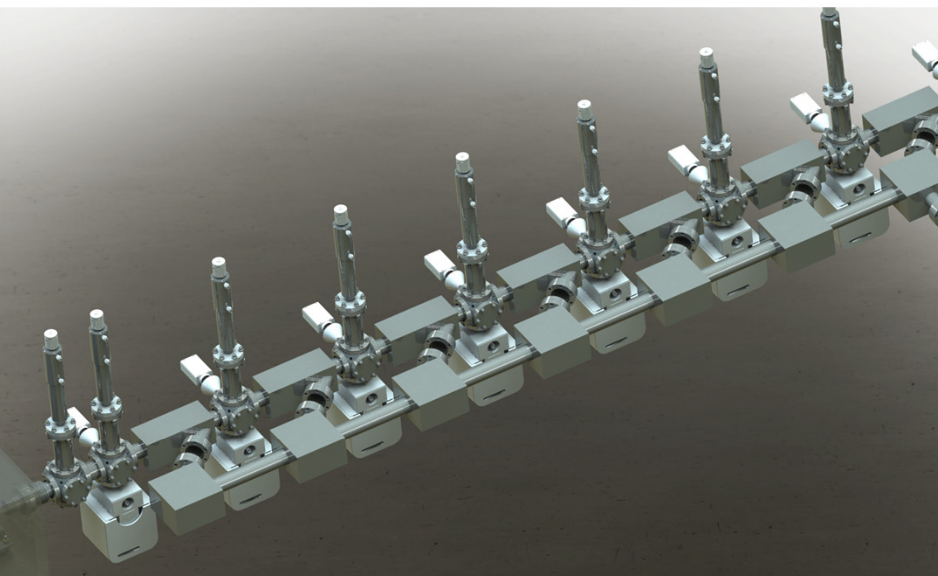
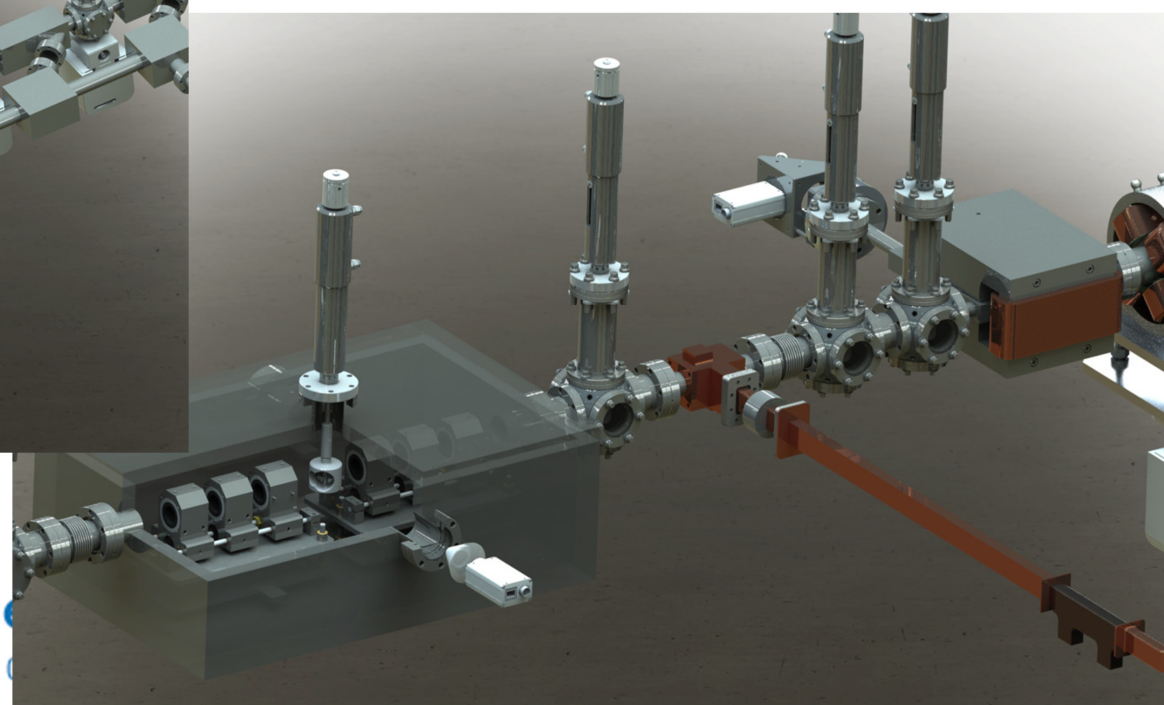


A. Marinelli et al., *Phys. Rev. Lett.* 110, 094802 (2013). UCLA expts. at SLAC

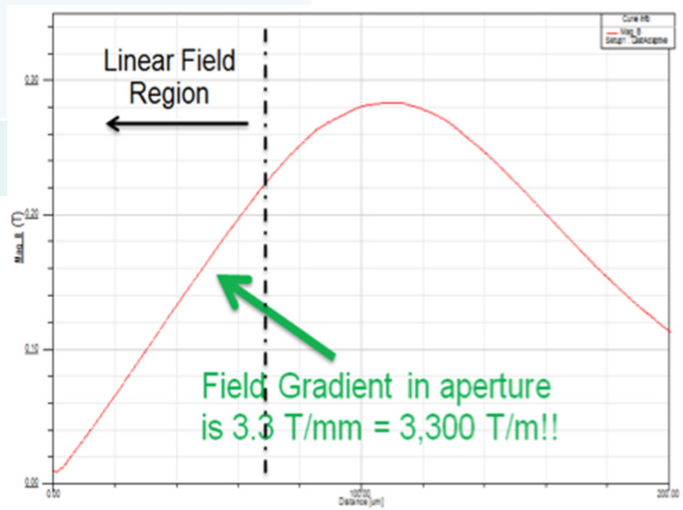


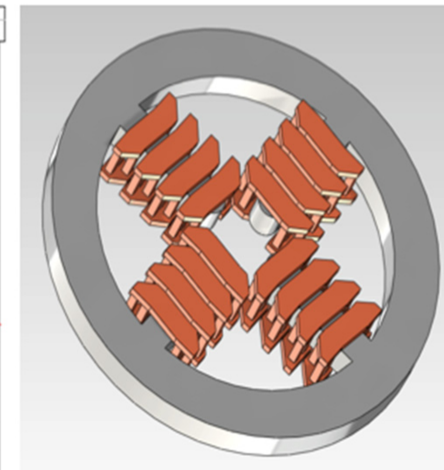


MEMS Quadrupole Focusing Magnets

Courtesy R. Candler (UCLA), B. Jacobsen (RBT)

Technology	μmachined Electromagnets
∇B	>3,000 T/m
Inner diameter	200 μm
Tuning	Electromagnet





Beam Parameters	
Energy	12 MeV
Charge	1 pC
Emittance	20 nm
Energy spread	0.05 %
Bunch length	200 fs (10 fs compressed)

Very compact, short focal quads!
Numerous applications (FEL, ICS, PWFA)

UCLA

At screen (simulation)

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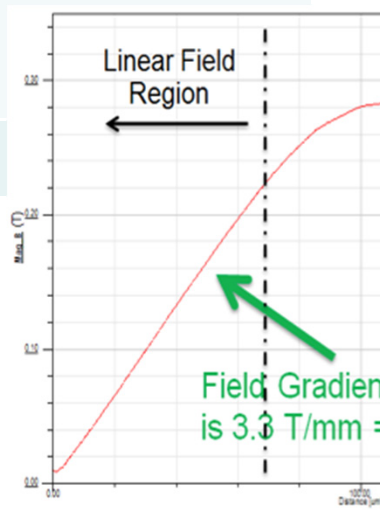
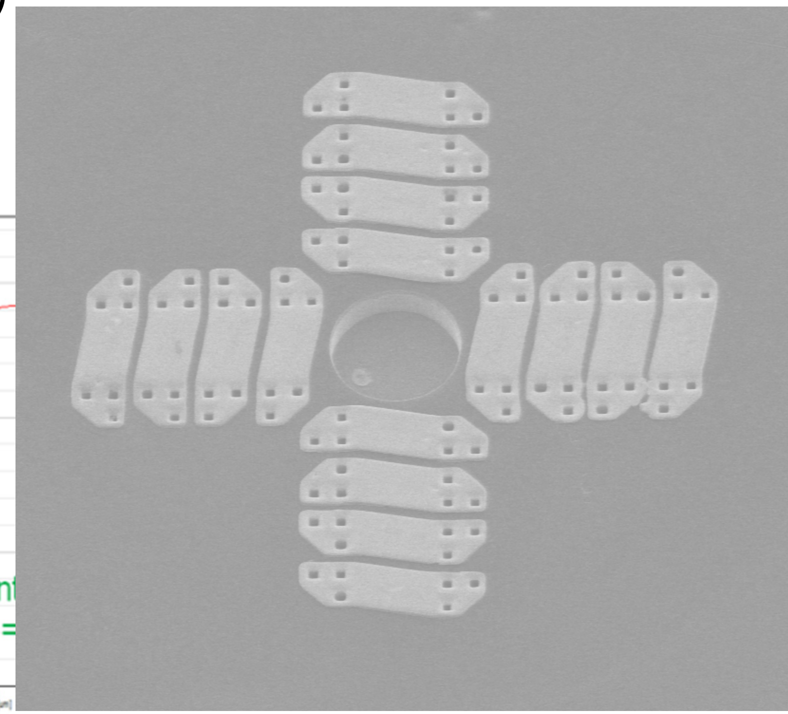
Inner diameter	200 μm
Tuning	Electromagnet





Beam Parameters	
Energy	12 MeV
Charge	1 pC
Emittance	20 nm
Energy spread	0.05 %
Bunch length	200 fs (10 fs compressed)

Very compact, short focal quads!
Numerous applications (FEL, ICS, PWFA)

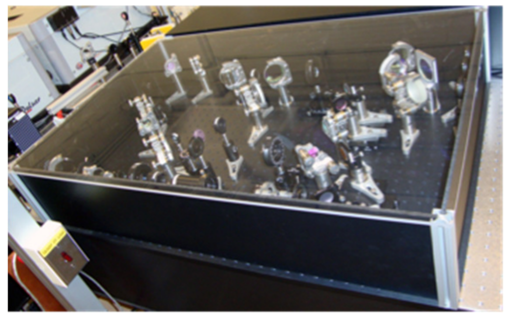
UCLA

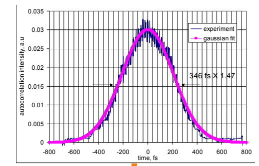
At screen (simulation)

Development of 5-μm laser at PSU

Poster WEPME063 (G. Xu, S. Wandel, I. Jovanovic)

Future: direct pumping by Tm/Ho/Cr-based high-energy short-pulse laser

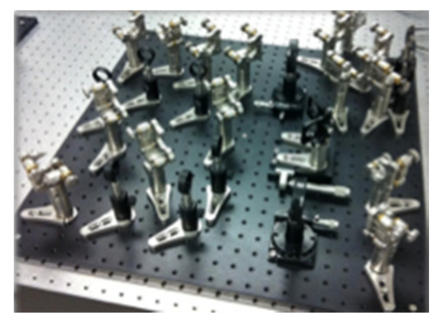




Ti:sapphire commercial pump laser → 15 mJ, 0.8 μm, 10 Hz → OPG/OPA 2 μm pump source → 2 mJ, 2 μm, 10 Hz → OPG/OPA 5 μm source → ~500 μJ, 5 μm, 10 Hz

BBO: 2 μm

ZGP: 5 μm



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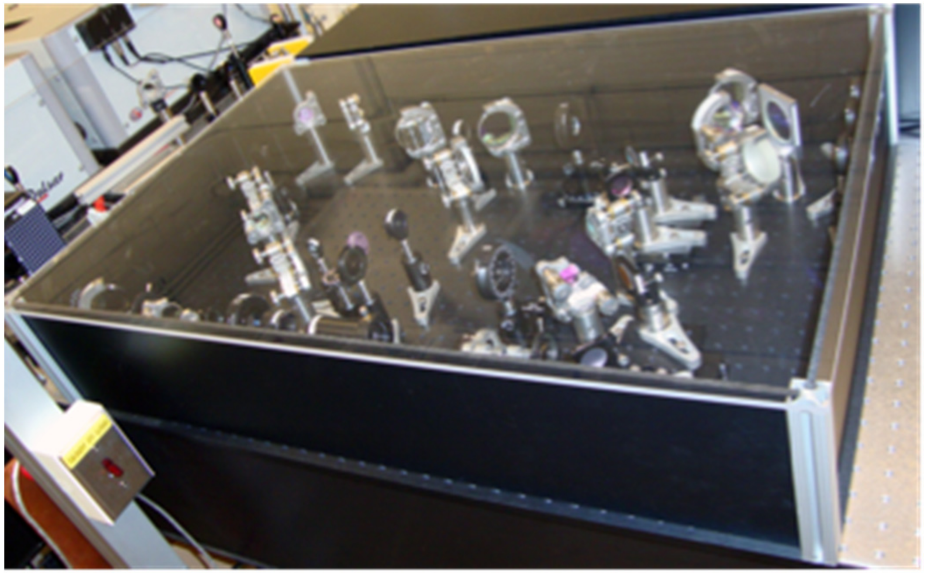
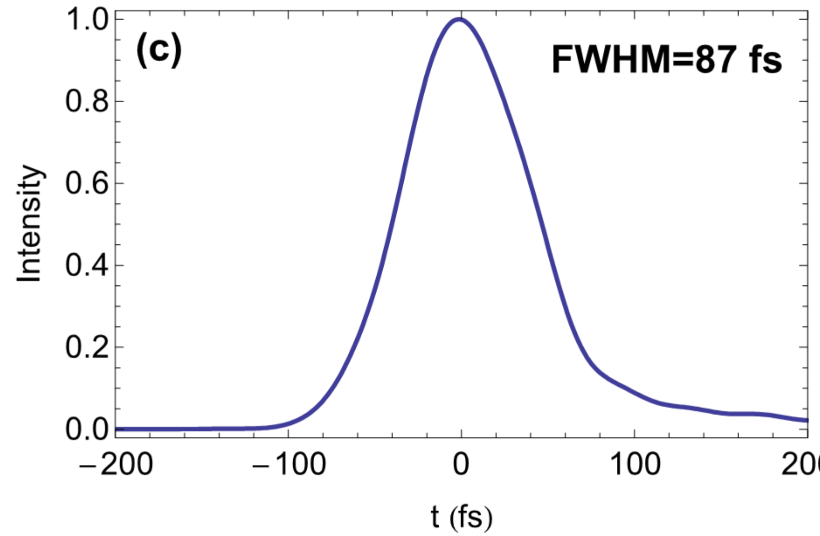
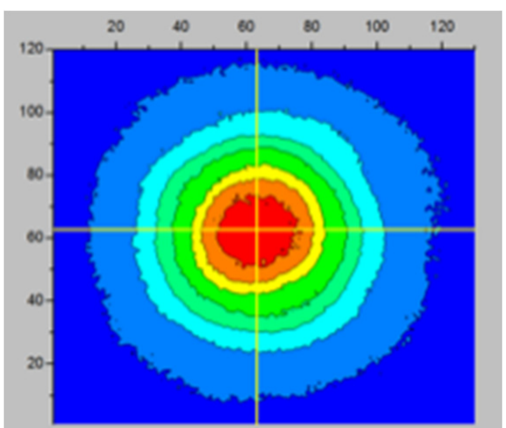
High-energy, compact 2-μm source produces high quality, <100 fs pulses

High-energy 2-μm OPA (2’x3’)







Large-aperture BBO crystal is used as OPA.

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2.2 mJ pulses now generated at 2 μm

OPA 1

0.8 μm pump: 795 μJ
1.3 μm signal: 58 μJ
(after energy losses on beam expander and dichroics)

1:7 beam expander

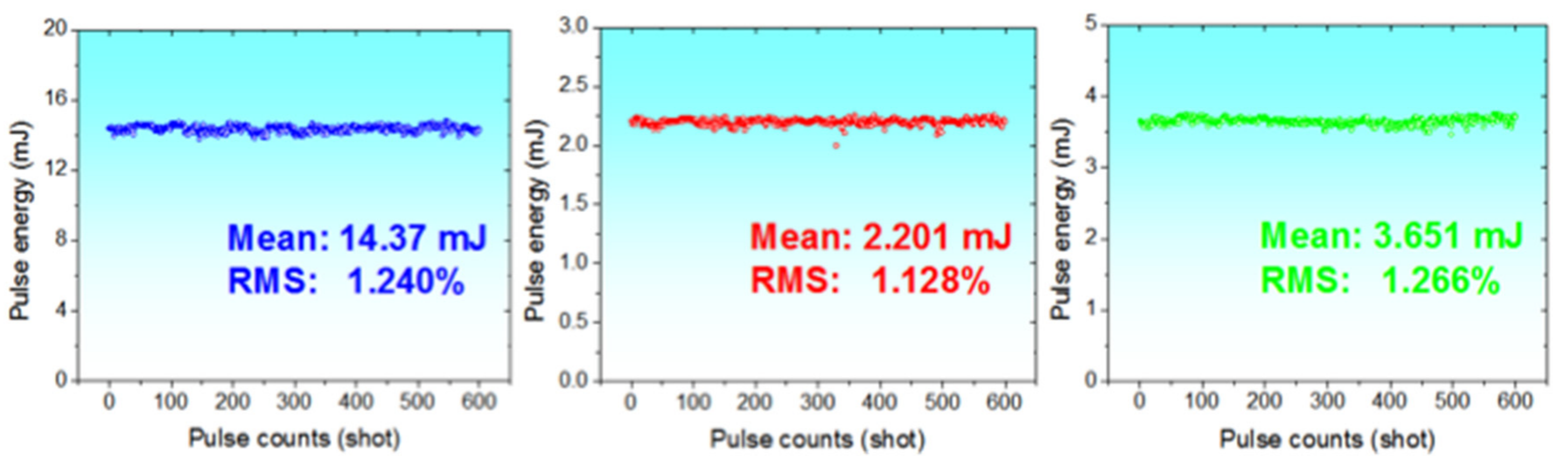
OPA 2

0.8 μm pump: 14.3 mJ
1.3 μm signal: 3.65 mJ
2 μm idler: 2.2 mJ
(after energy losses on beam expander and dichroics)

Pump pulses at 792 nm

Idler pulses at 2.05 μm

Signal pulses at 1.29 μm



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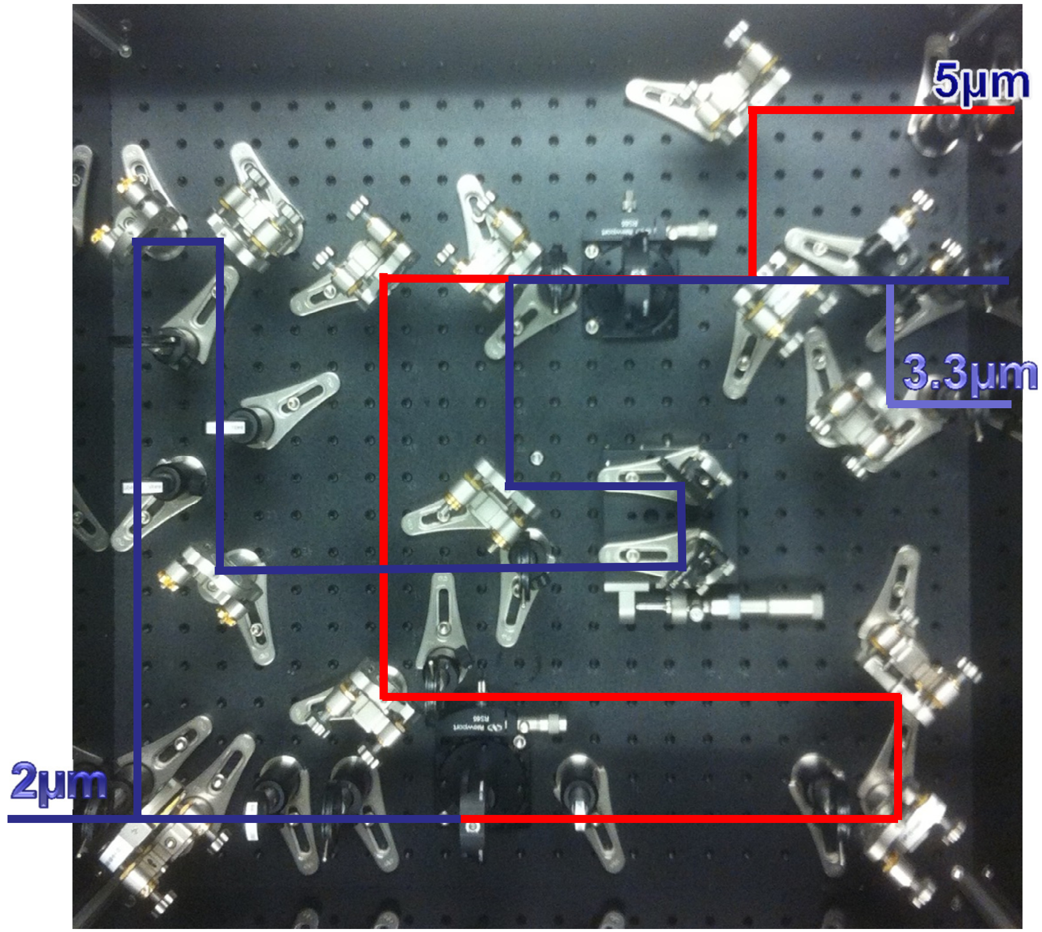
5-μm source layout

ZGP Type I Phase Matching
2.0 μm (o) →
3.3 μm (e) + 5.0 μm (e)

1-mm-thick ZGP with a cut angle of 56.1º is used in OPG and OPA



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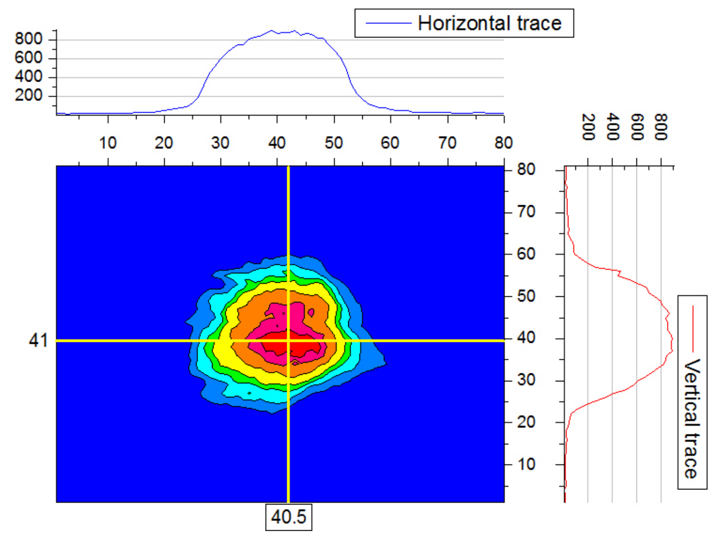
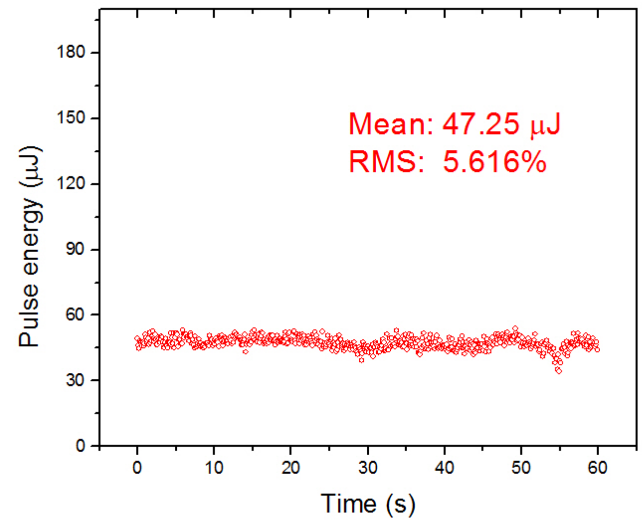
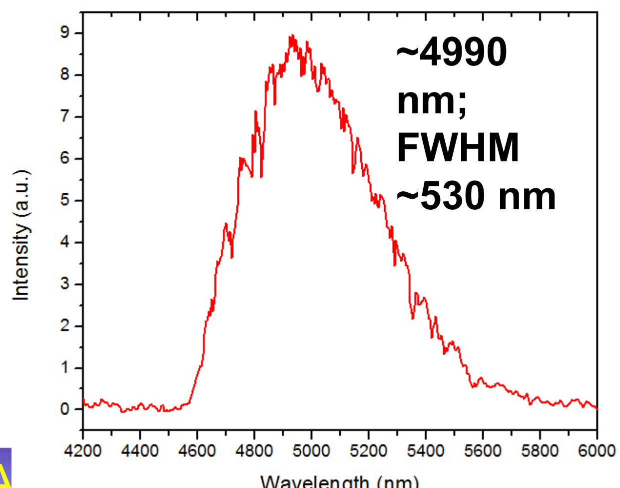
5-µm source performance to date







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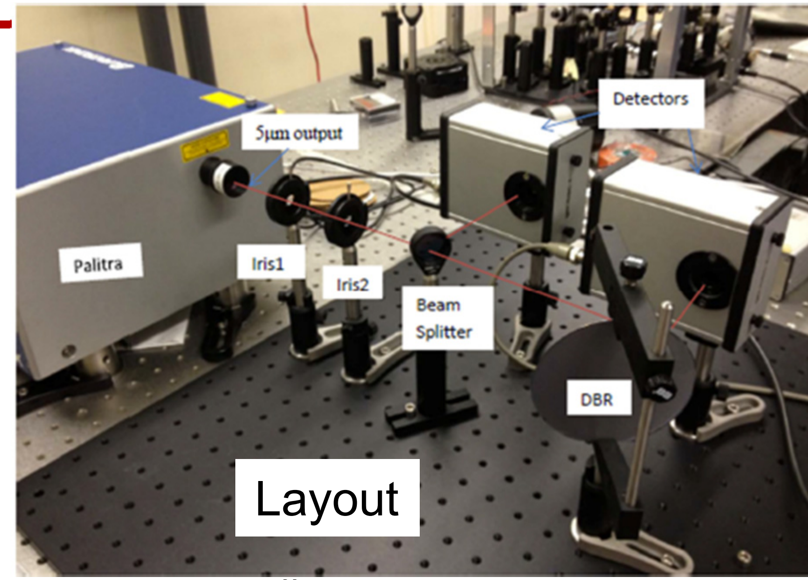
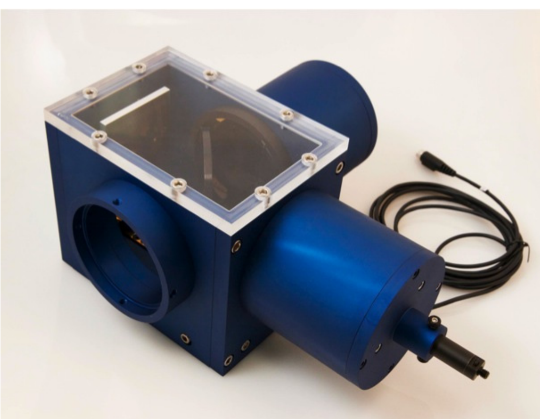
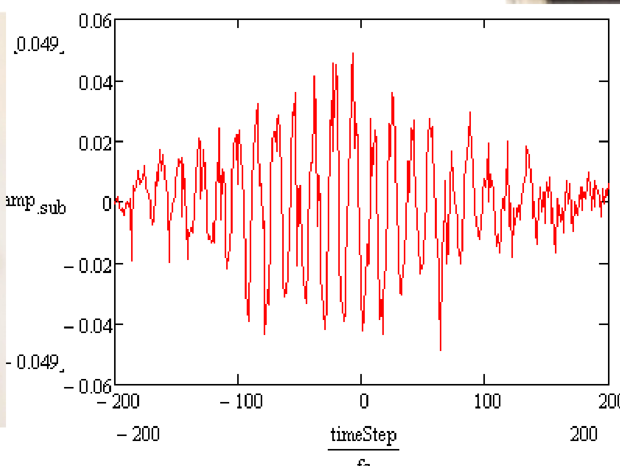
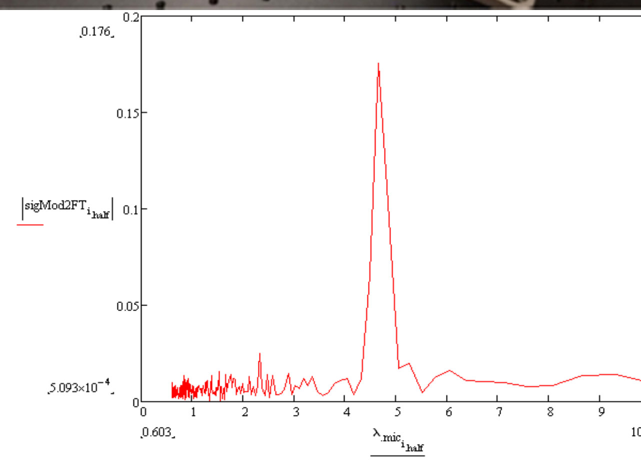
5 um testing of structures: INRWA

- Infrared Network Analyzer (IRNWA)
- Based on Palitra OPA (Quantronix).
- Up to 0.5 mJ at 5 um
- Test 5 um structures fabricated at UCLA









Autocorrelation of 5 um pulse from Palitra

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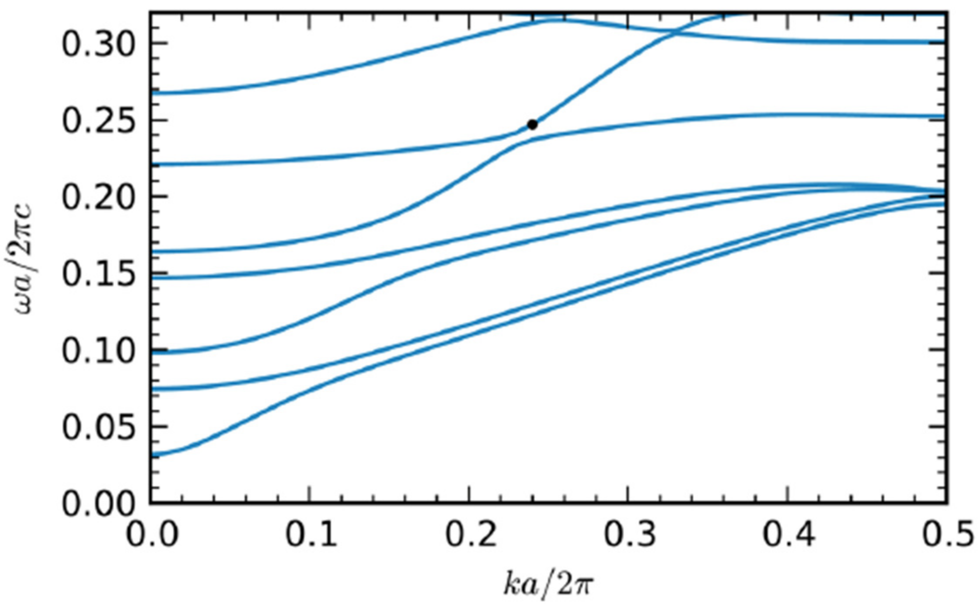
Upgrades in IRNWA perfomance

- Precision measurements with QCL and spectrum analyzer
- High power in sub-ps system: *breakdown*?



GALAXIE band diagram

Daylight solutions QCL (4/13)

Toptica wavelength meter

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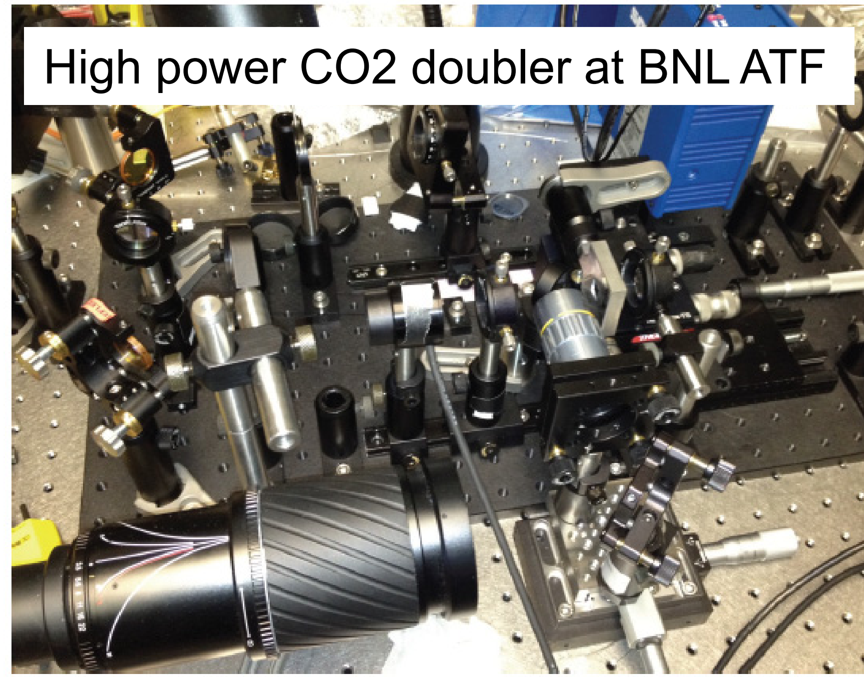
Material properties, breakdown at 5 μm

- Limited data on 5 μm light interactions
  - Index, loss tangent, *breakdown*
  - Long pulses more often studied.
    - Avalanche ionization dominant
- Study critical for:
  - Structure (accelerator)
  - Undulator (dielectric version)
  - Optical components
- Candidate material crystals
  - CaF2,MgF2,ZnSe,Ge,Si,Al_2O_3



- CO_2 regen output ~15 mJ, 3 ps (long)
- 5 μm conversion target efficiency 30%
- peak 5 μm intensity=15 J/cm^2

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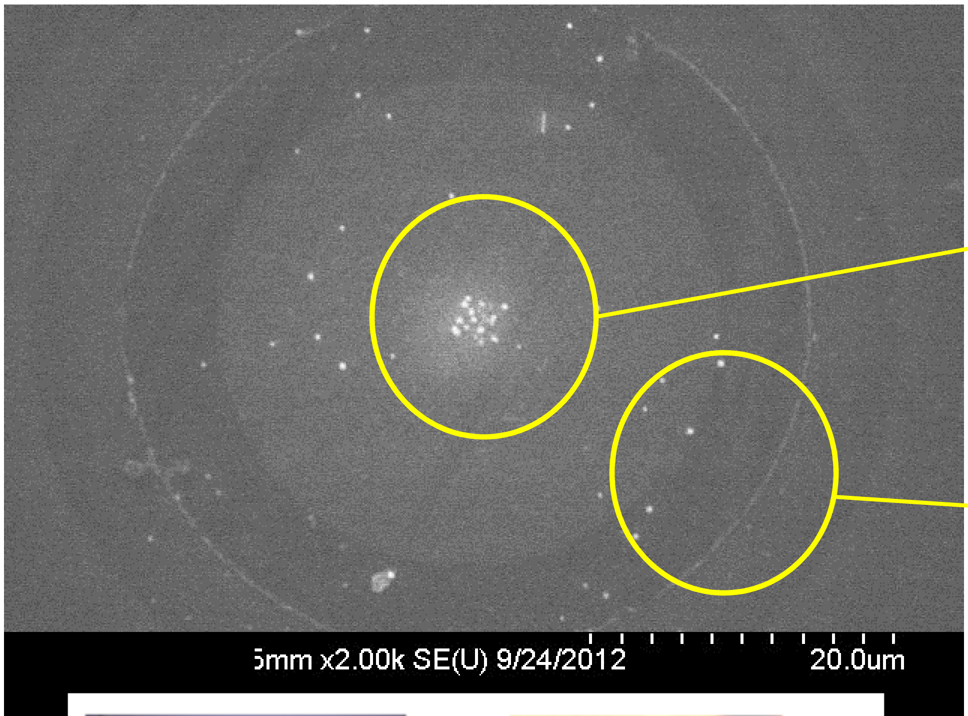
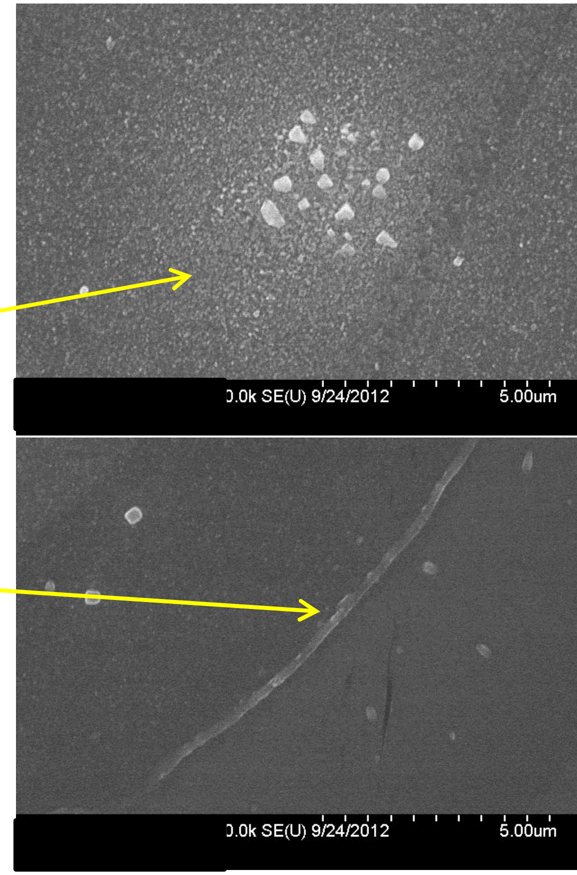
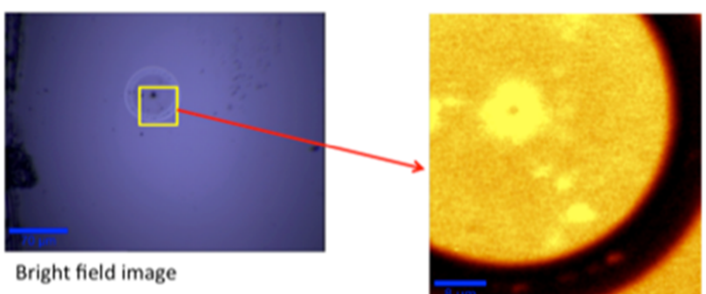
Breakdown in Si

- Peak field ~1.3 GV/m







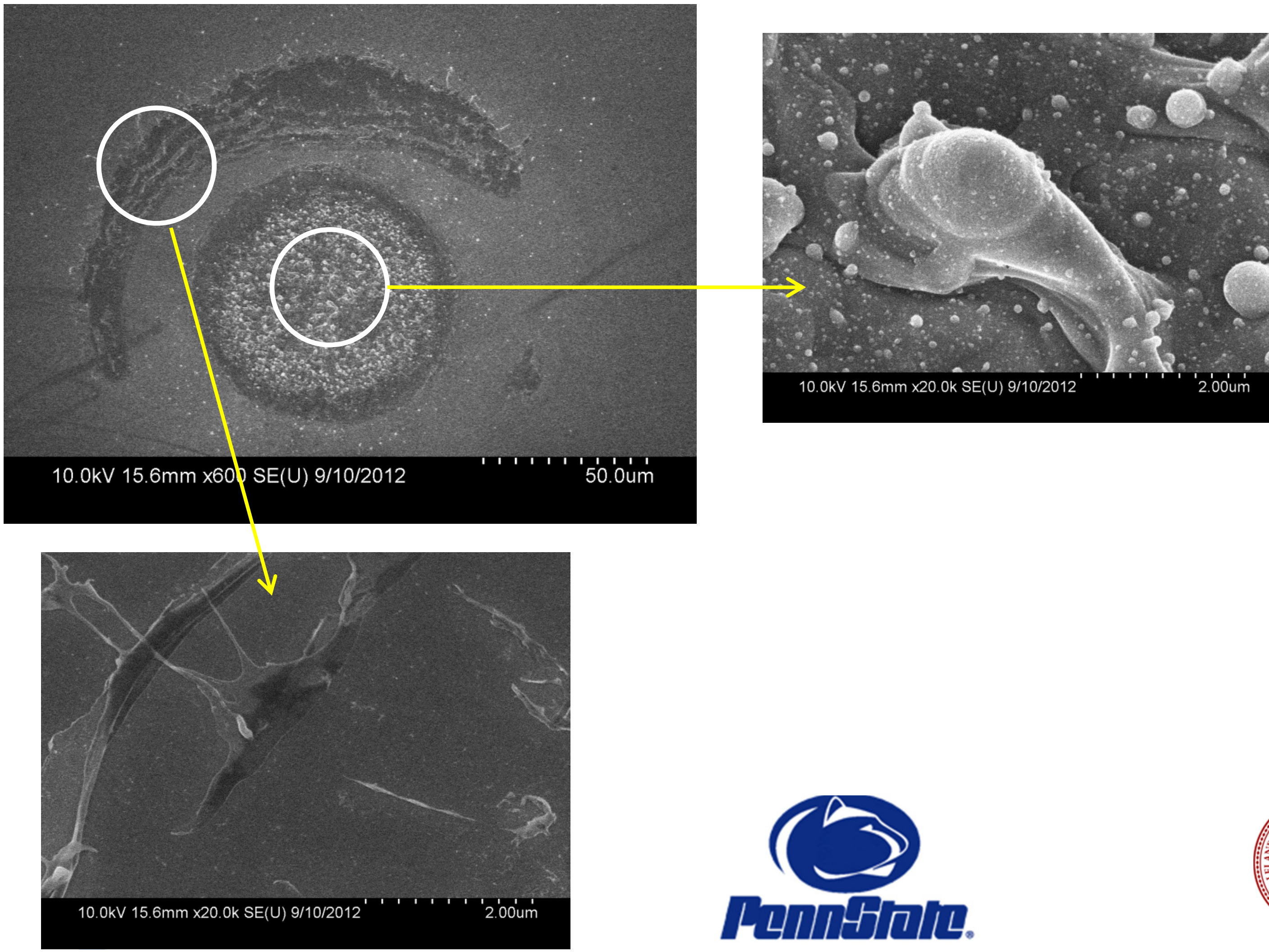
Bright field image

Raman microscopy of Si

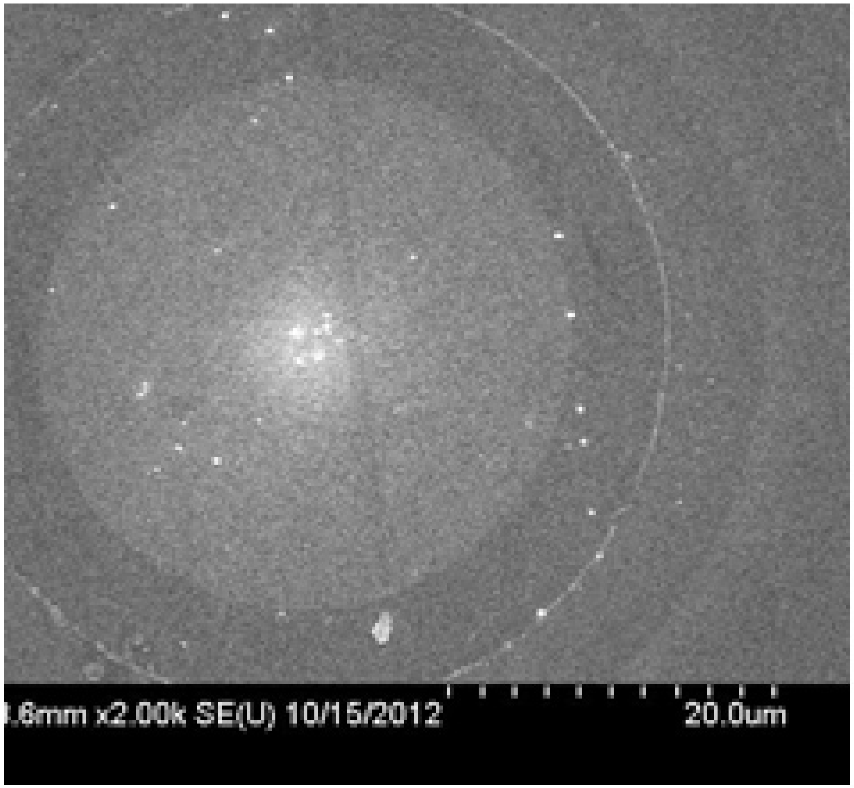
Raman intensity map using 521 cm^{-1} Si band

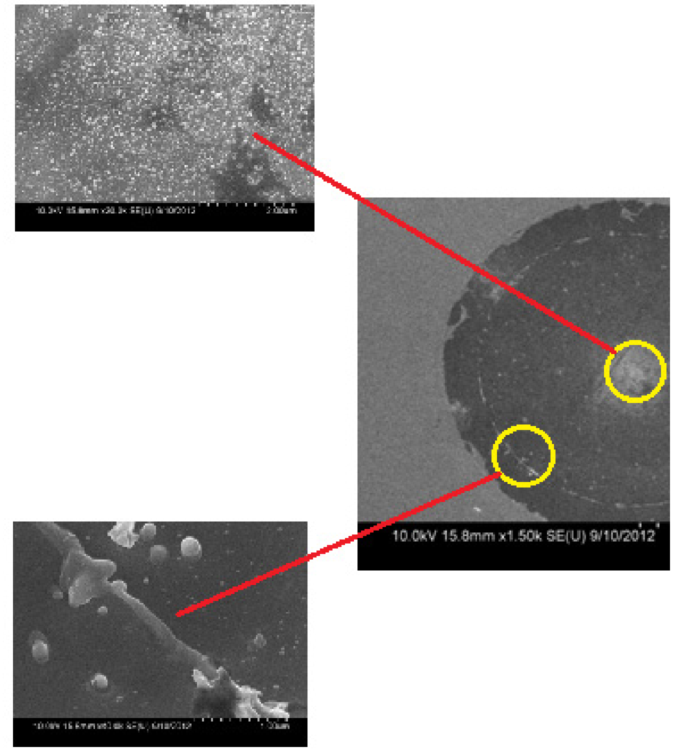
Breakdown in Ge

- Peak field similar to Si



Breakdown in Sapphire

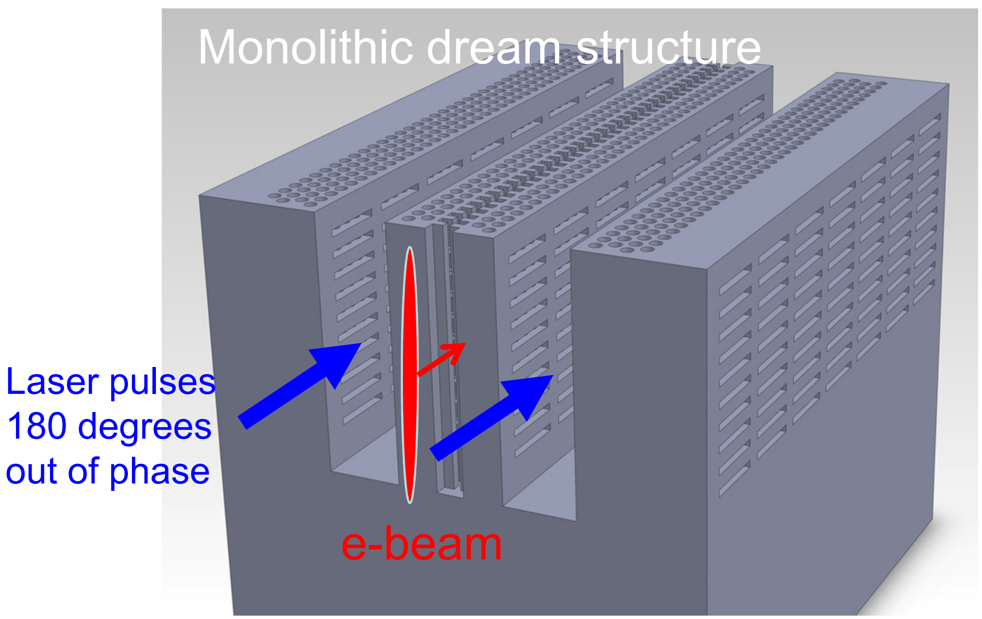




Breakdown > *4 GV/m fields*, as expected (higher band gap material)

Beautiful Structure: How to Fabricate?

- UCLA Nano Laboratory provides fabrication capabilities for monolithic/joined structures
- Exploit structure features for 2-etch fabrication
- First step: “single layer” structure
- Next step: “stacking” studies



Main challenges:
- High aspect ratio holes
- Precision accelerator features

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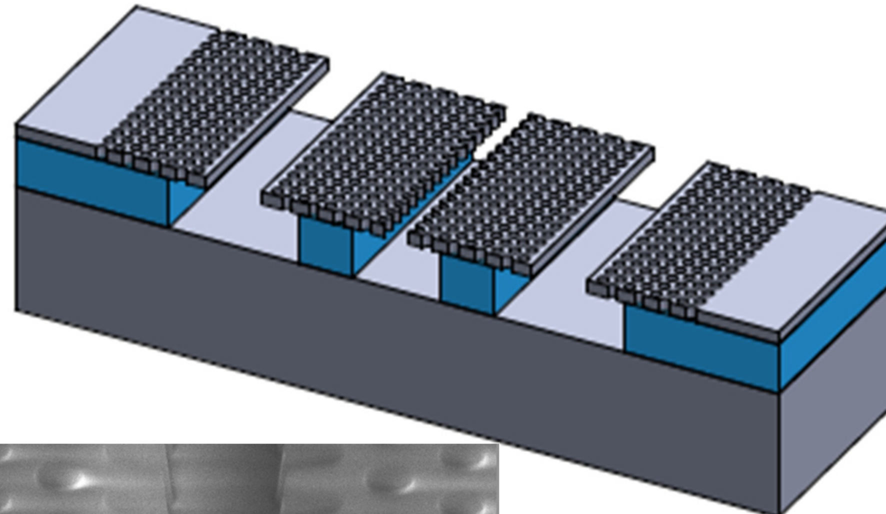
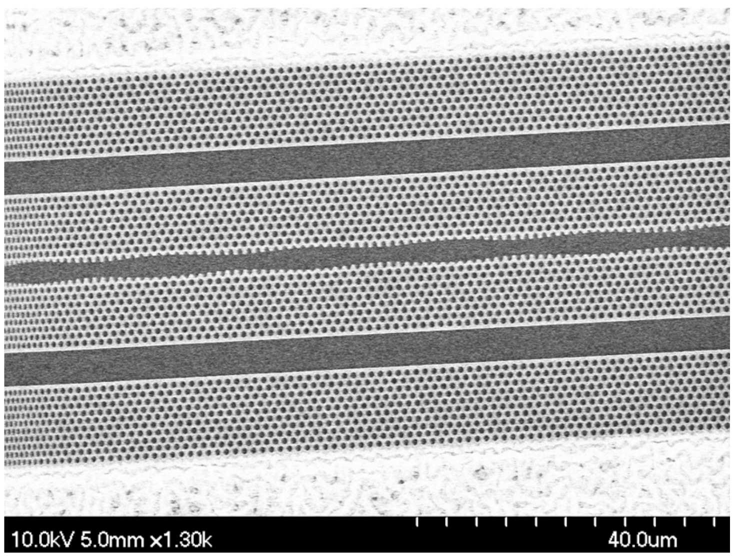
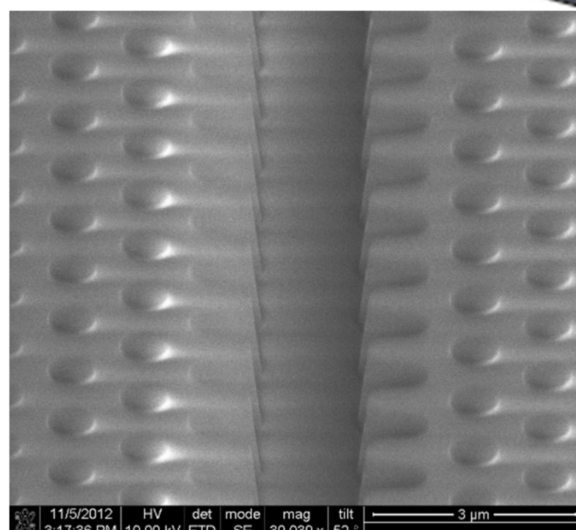
Single layer structure

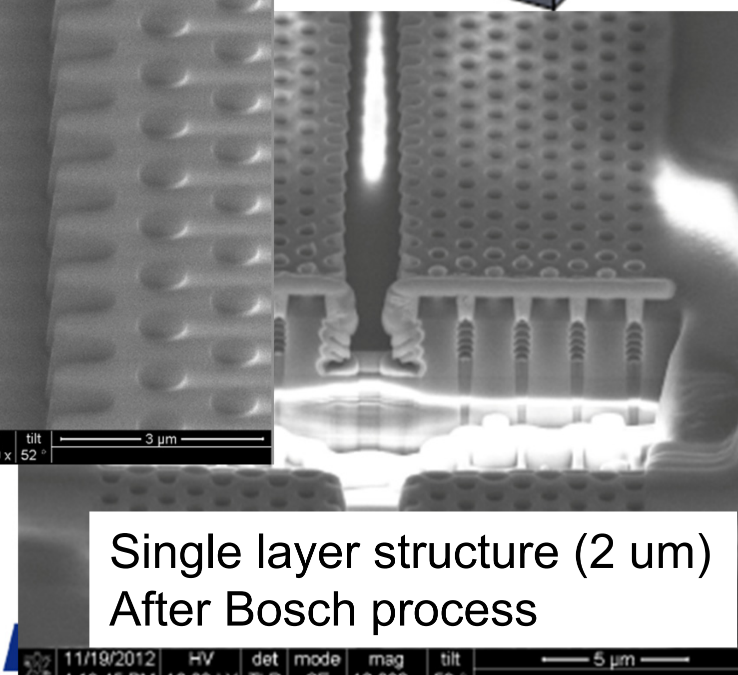
- First tests of fab and mode structure
- On SOI, DRIE etch with wet undercut





Mask for single layer structure





Single layer structure (2 um)
After Bosch process

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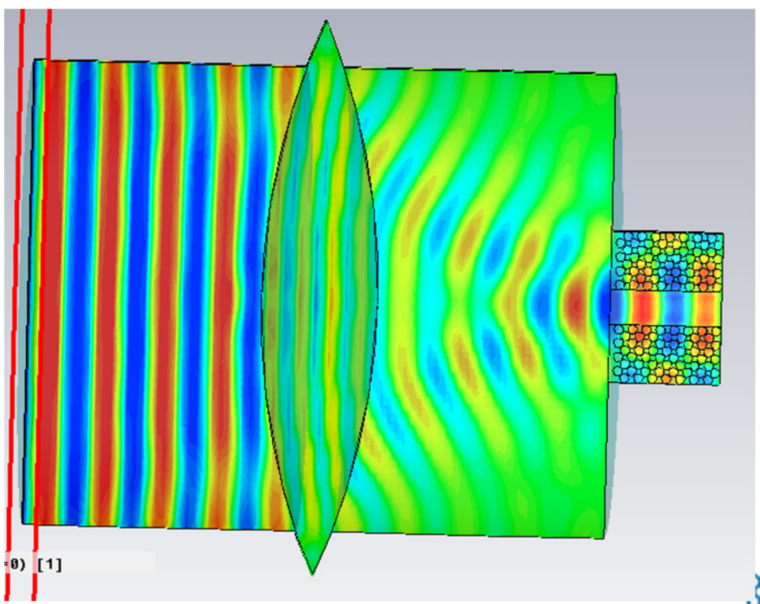
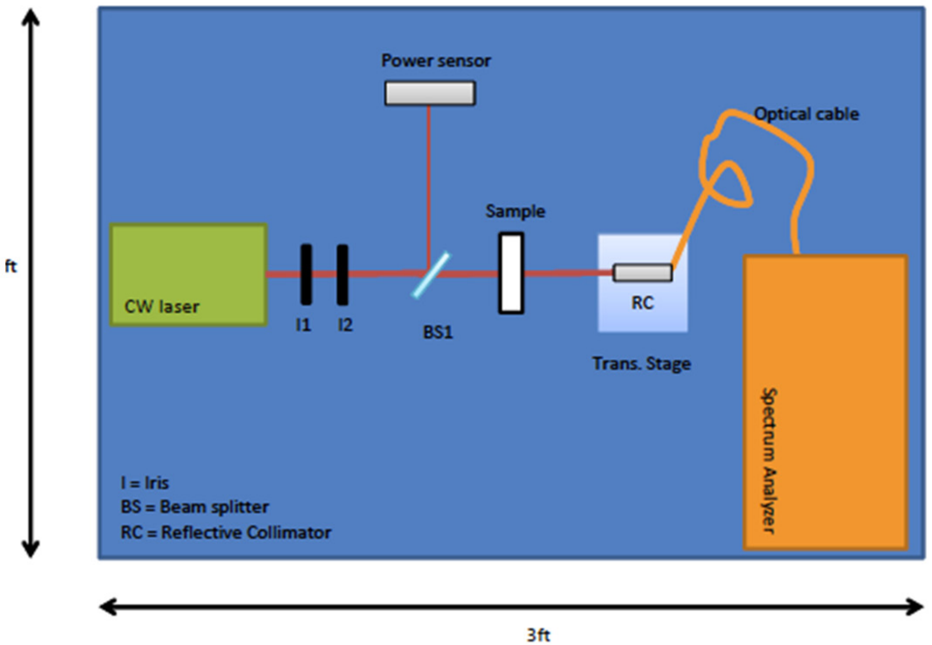
Single layer testing at IRNWA

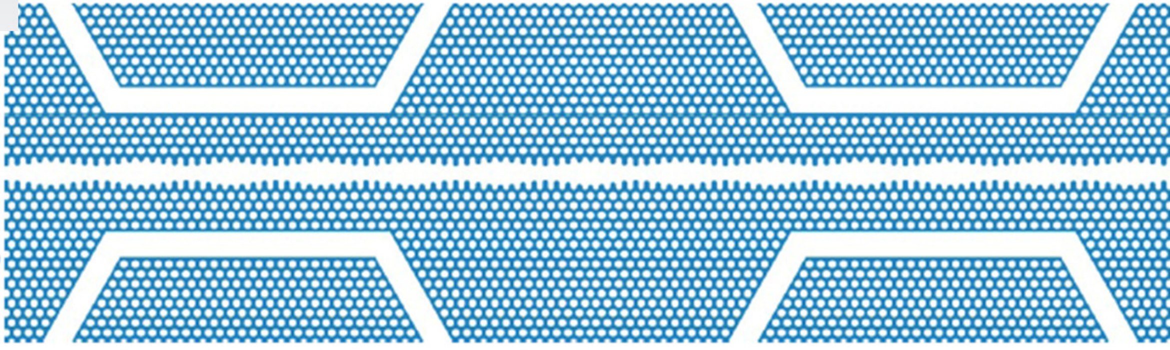
- Precision IRNWA for mode transmssion



Simulation of coupling (CST)



Single layer structure projection



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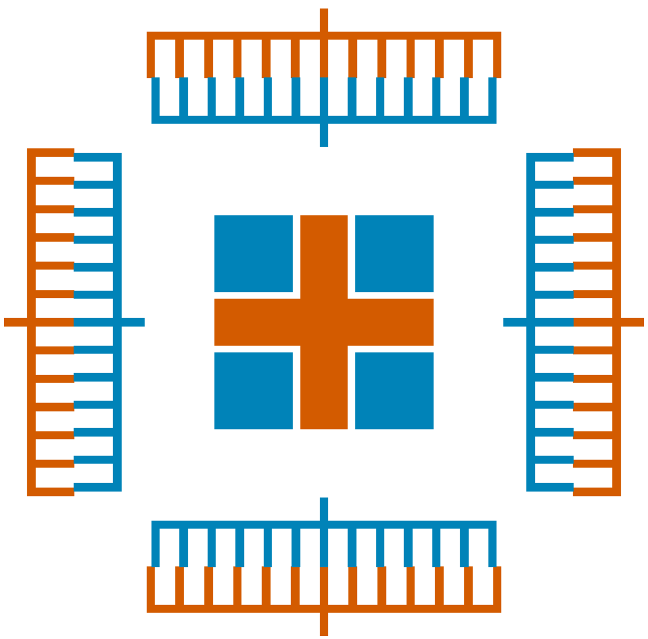
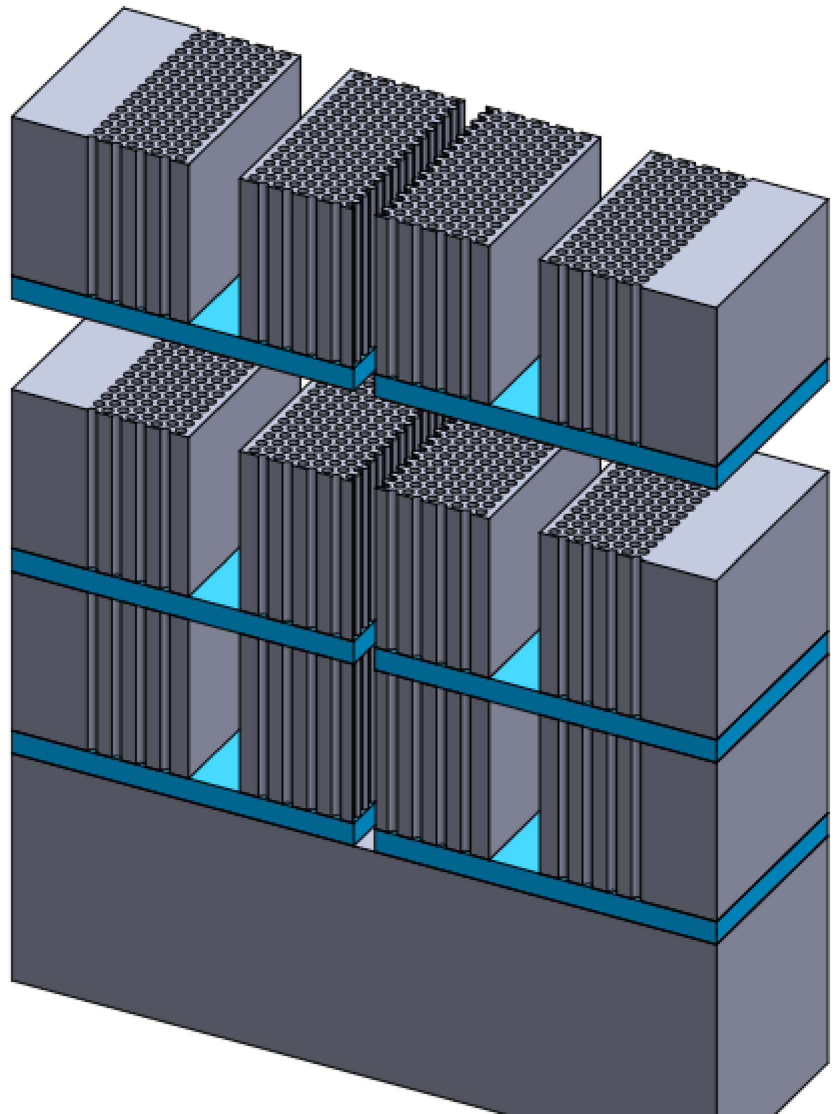
Stackable DLA structures

3-level alignable stack

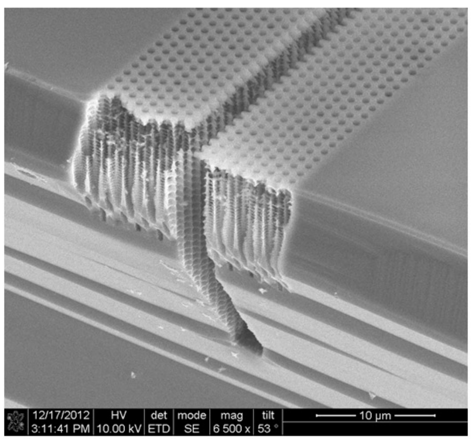
Not full photonic control in *x*



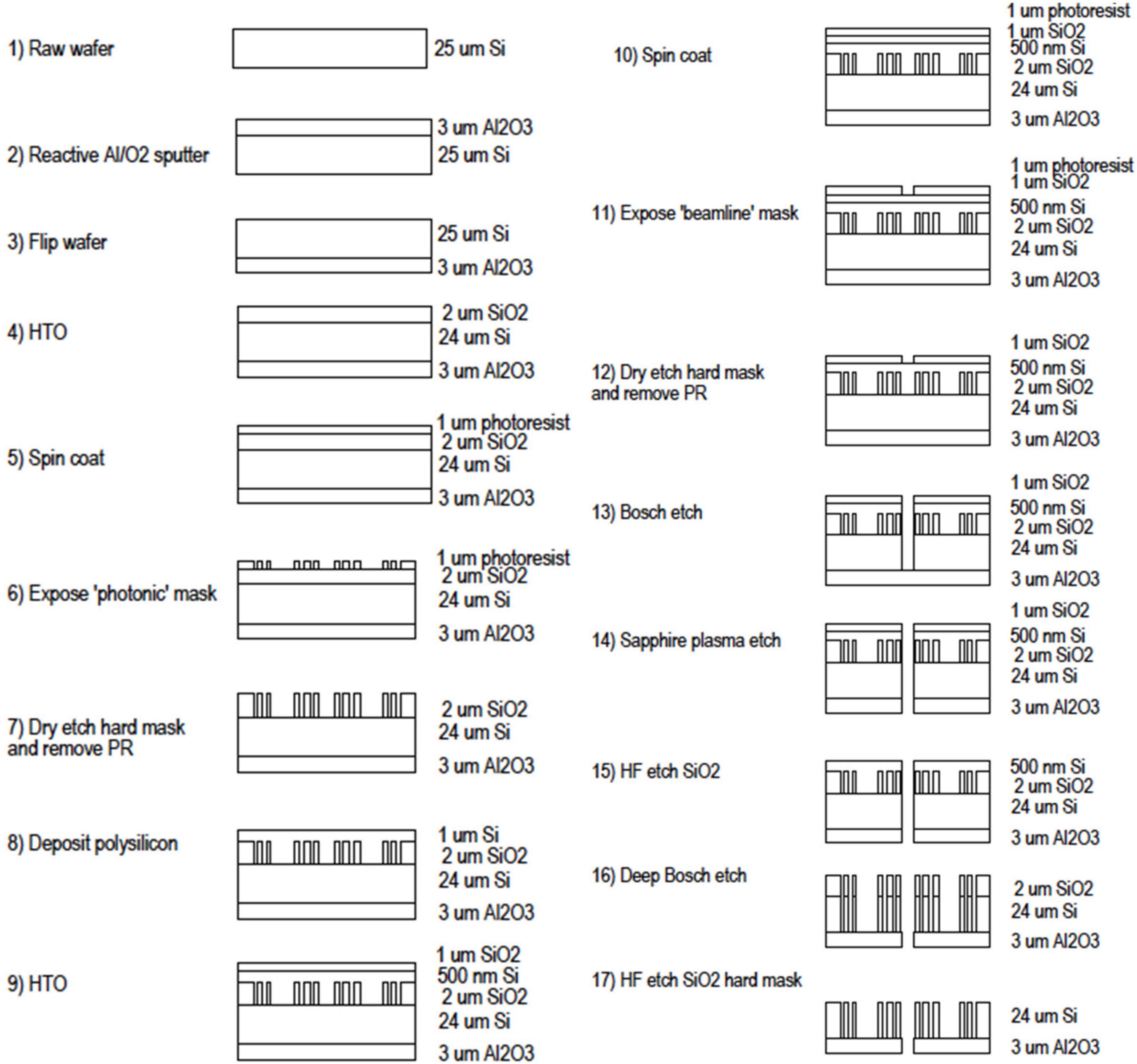
Closeup of alignment mark



Thick, stackable layer fabrication plan



Ist attempt at DRIE



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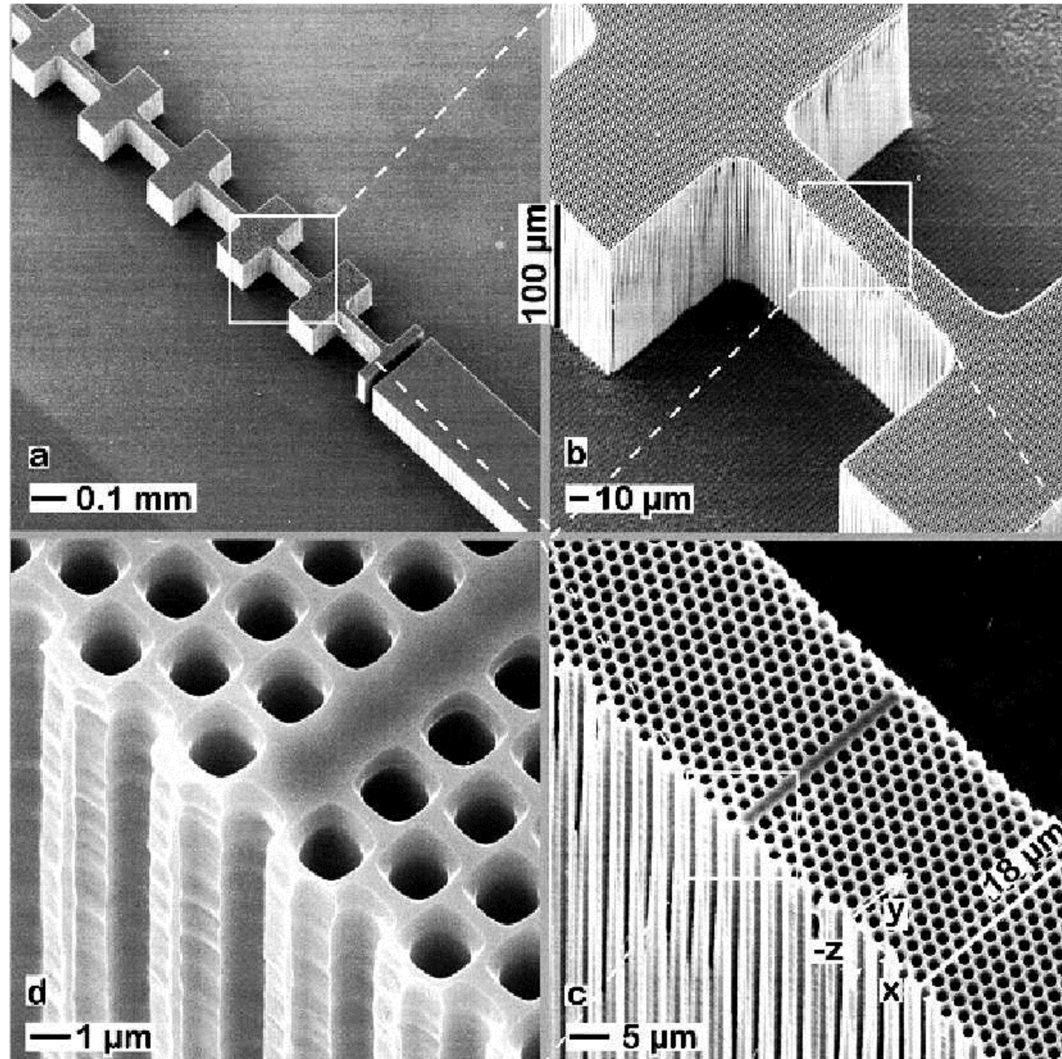
Returning to the monolithic dream…

- Macroporous Si may provide path
- Extremely high aspect ratios possible (400 demonstrated)
- Active development at UCLA

see, *e.g*. S. Ottow, *et al.*, J. Electrochem. Soc.**143** 385 (1996).



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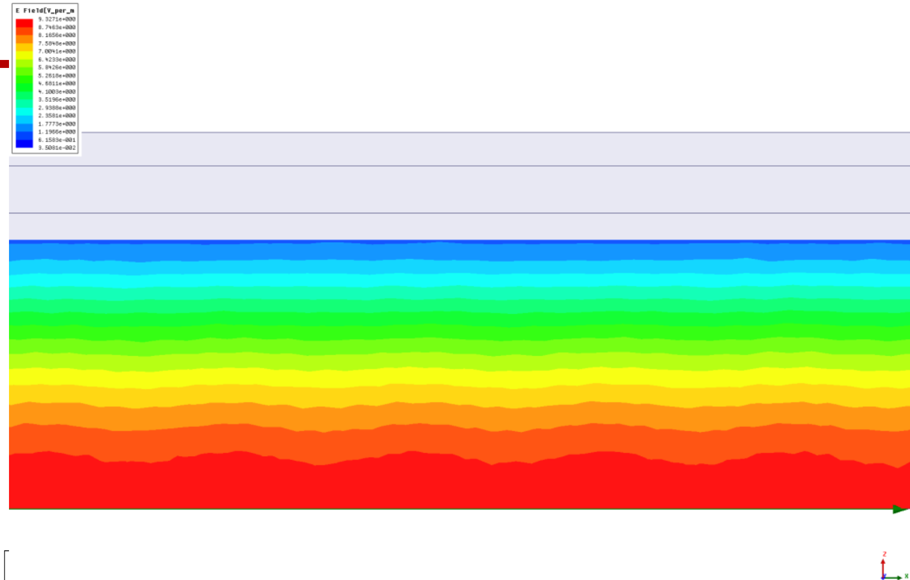
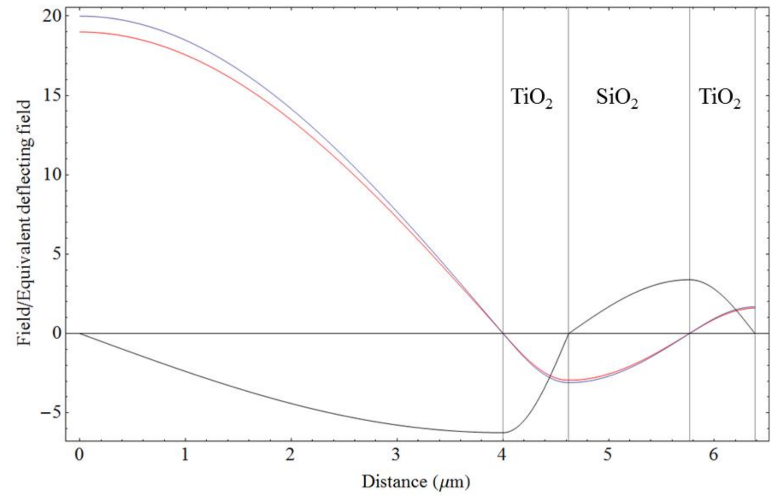
Electromagnetic Undulators: Approaches

All electromagnetic undulator for GALAXIE has two notable approaches:

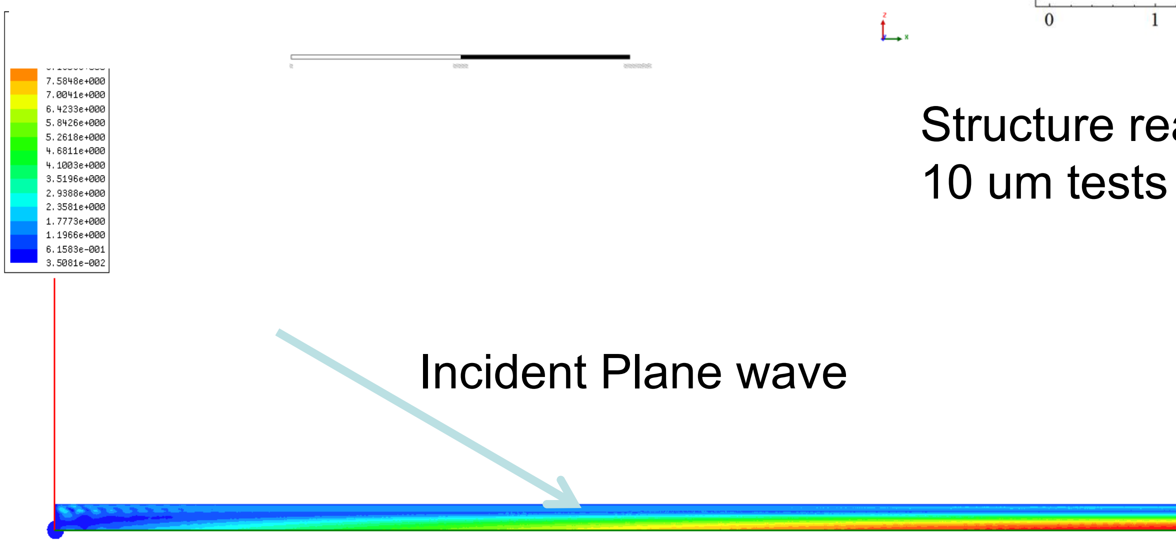
- An all-optical undulator
  - EM wave at 5 um co-propagates with e-beam; stretch undulator wavelength to 100 um.
  - E and B field foruces tend to cancel; the surface and bulk fields high compared to net equivalent deflecting field.
  - Aperture in this device ~1-2 times that of laser wavelength; extremely small, wakefield problems must be studied carefully.
  - GALAXIE has implementation a Bragg type structure
- THz structure with wave propagating opposed to e-beam.
  - With EM-wave propagating counter to beam, the undulator wavelength is ~1/2 free space wavelength. E and B forces *add.*
  - To realize undulator we *invented* a new type of an RF cavity structure that supports a SW with very high field at center, low field near walls

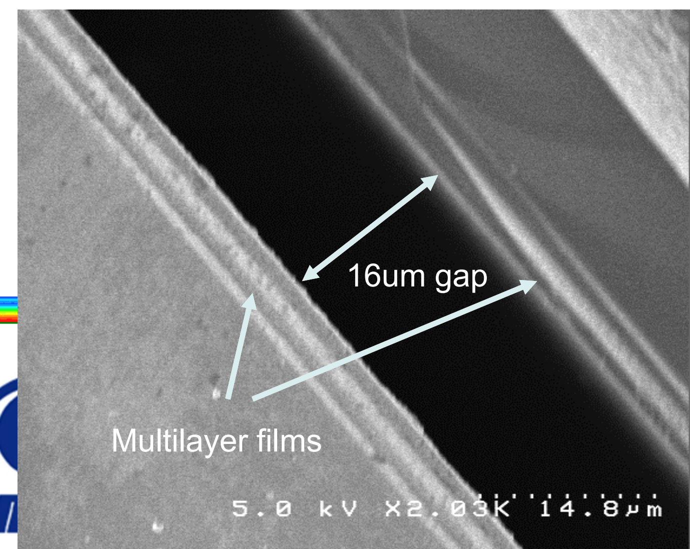
Bragg Undulator Field Profile





Structure realized, now undergoing testing
10 um tests at BNL ATF in late summer





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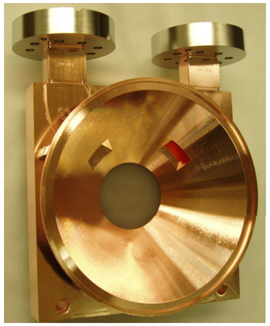
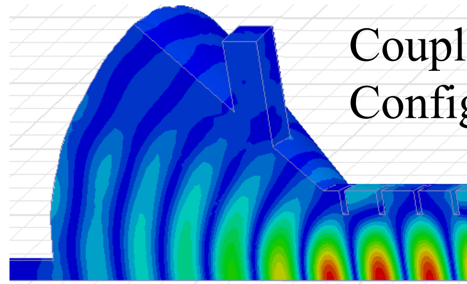
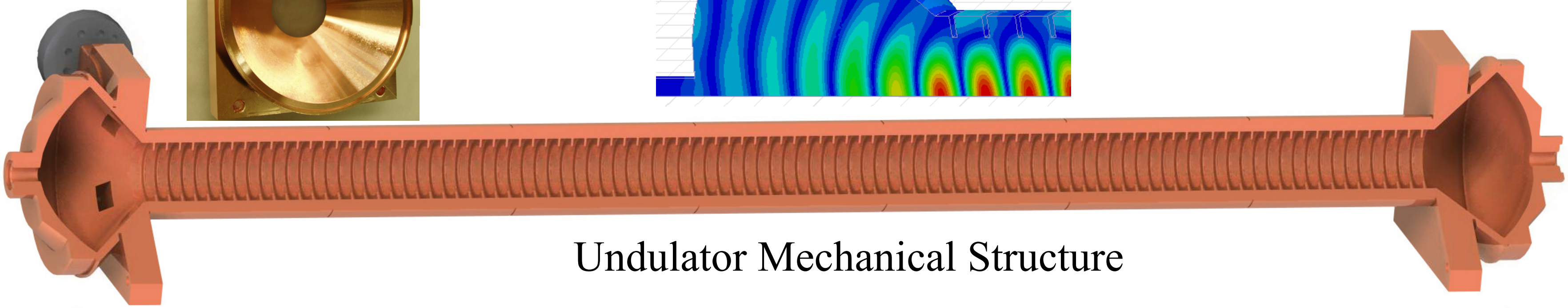
Scaled THz (microwave) Undulator Design

Two coupling ports 90^{o} apart to excite two polarizations independently

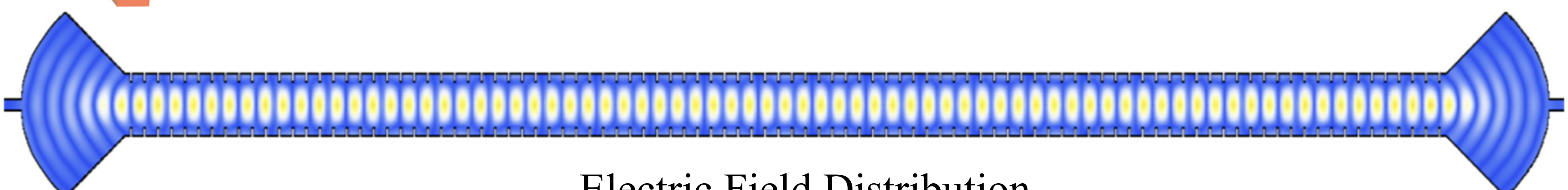




Coupler Field Configuration



Undulator Mechanical Structure



Electric Field Distribution

Corrugation Period=0.4254 λ
Inner Radius=0.75 λ
Outer radius= 1.01293 λ
Corrugation Thickness= $\lambda/16$
Number of periods =98

λ=2.624 cm
Undulator Wavelength=1.393 cm
Power required (linearly polarized, K=1): 49 MW
Q_0=94,000

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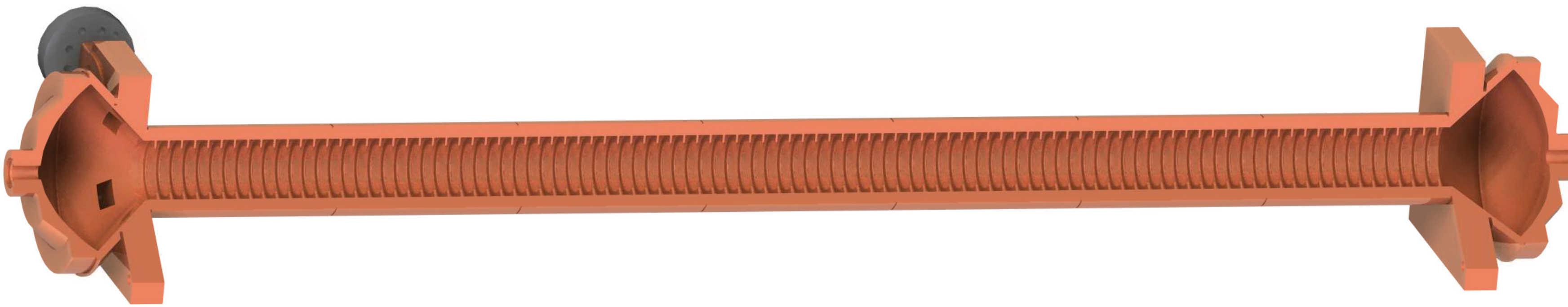
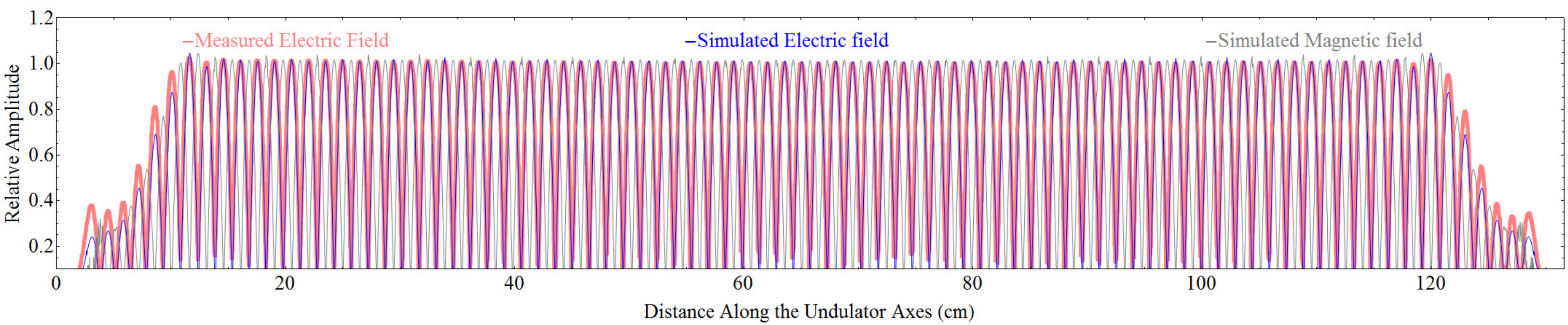
LELAND STANFORD JUNIOR UNIVERSITY · DIE LUFT DER FREIHEIT WEHT · 1891

Simulations and Cold Test Comparison





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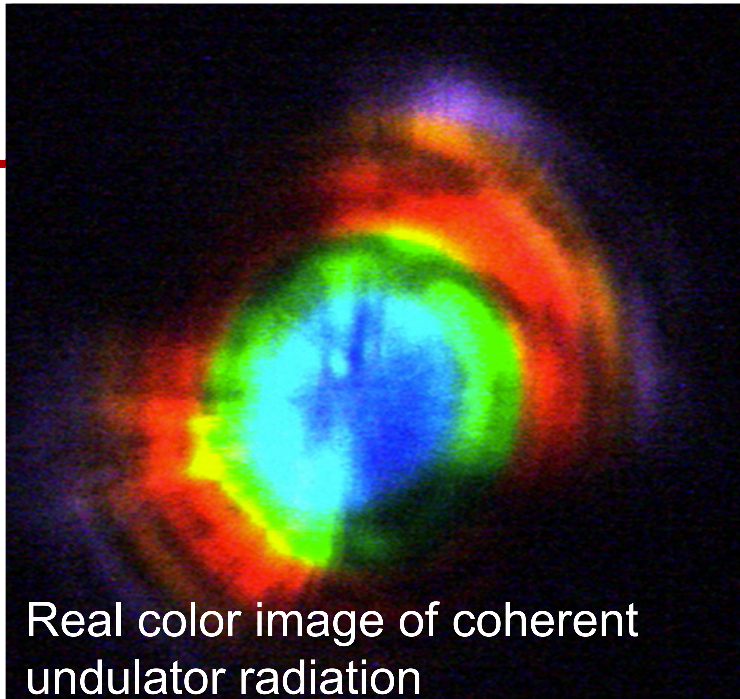
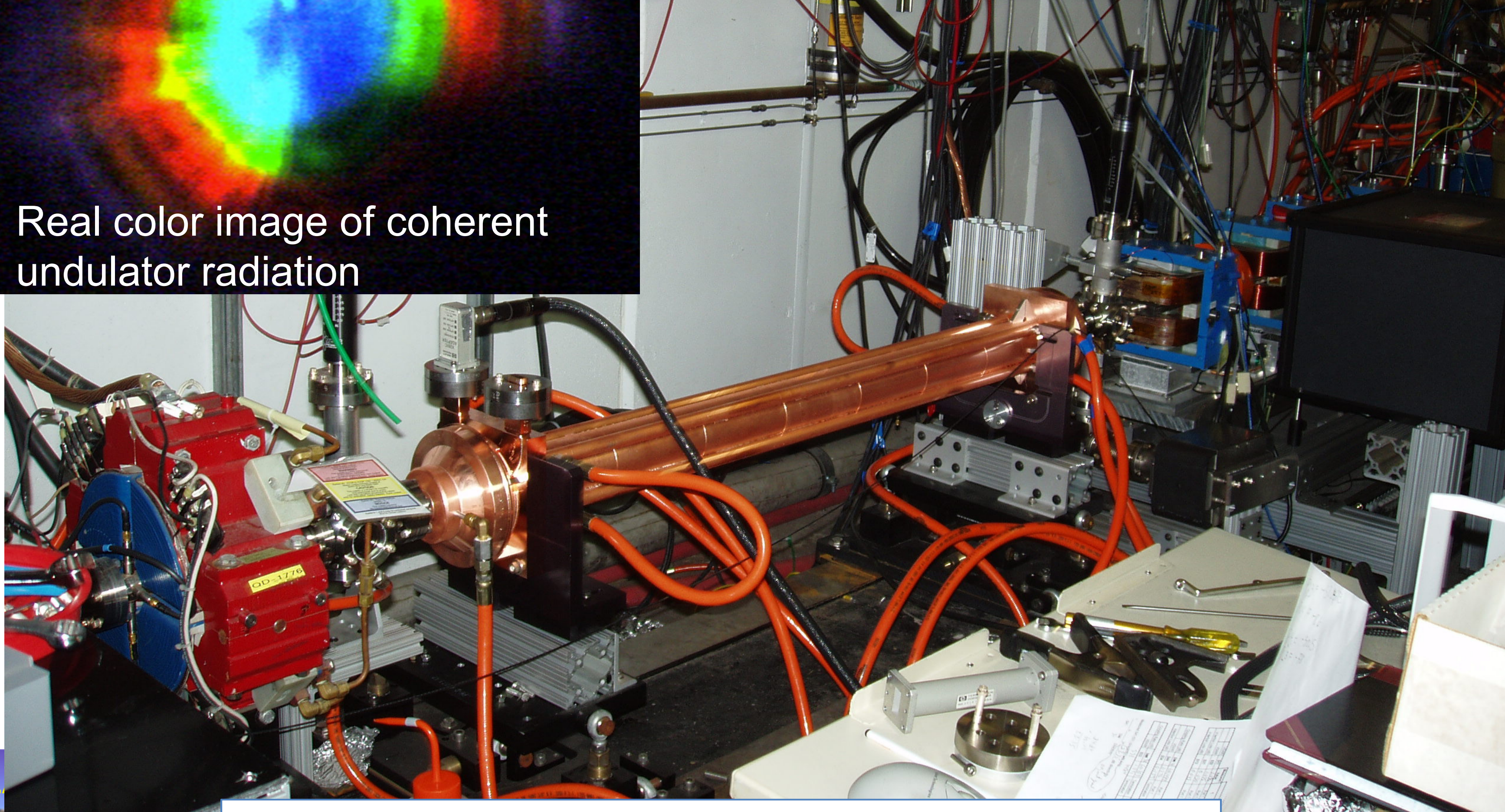
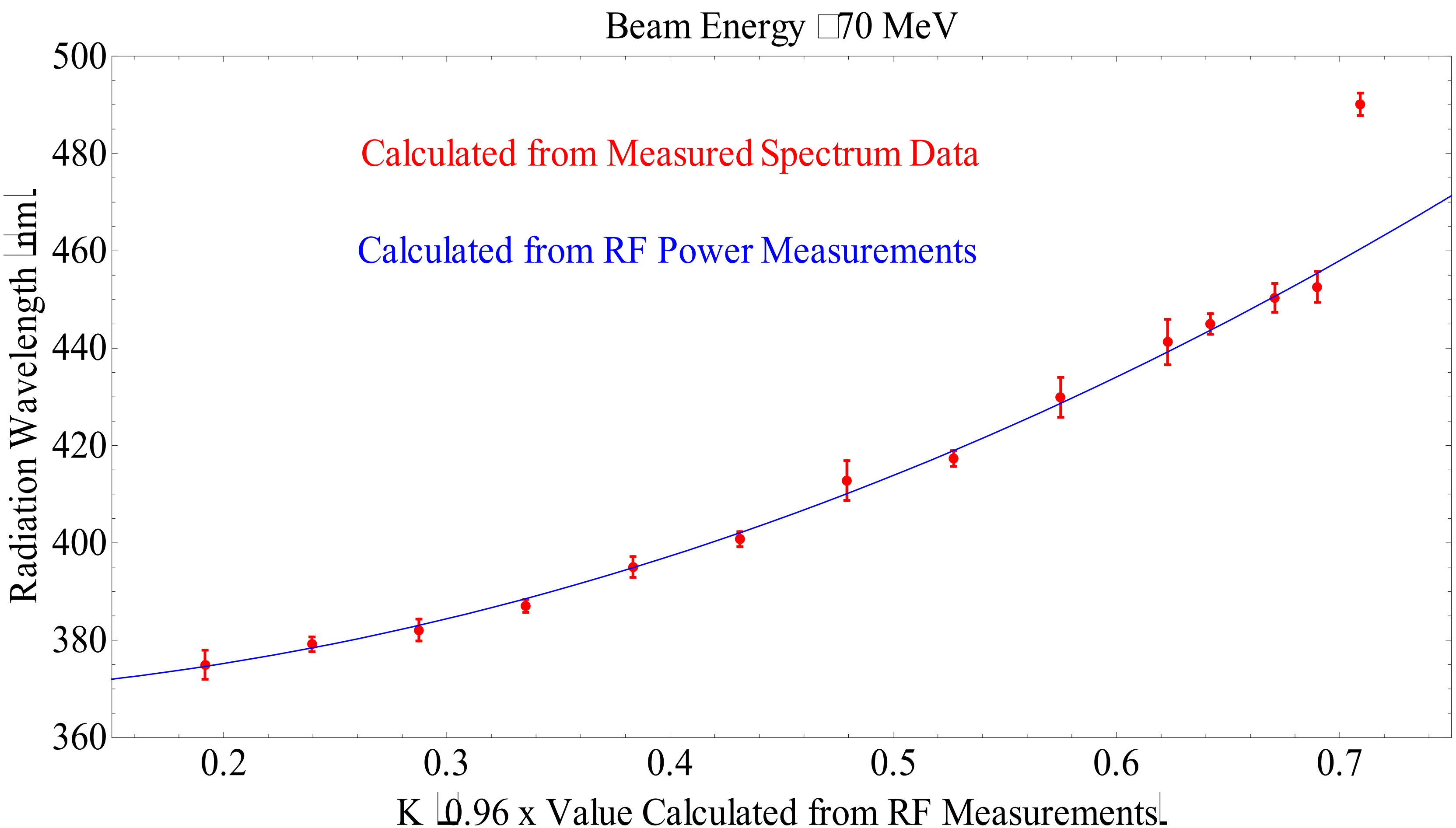


Real color image of coherent undulator radiation



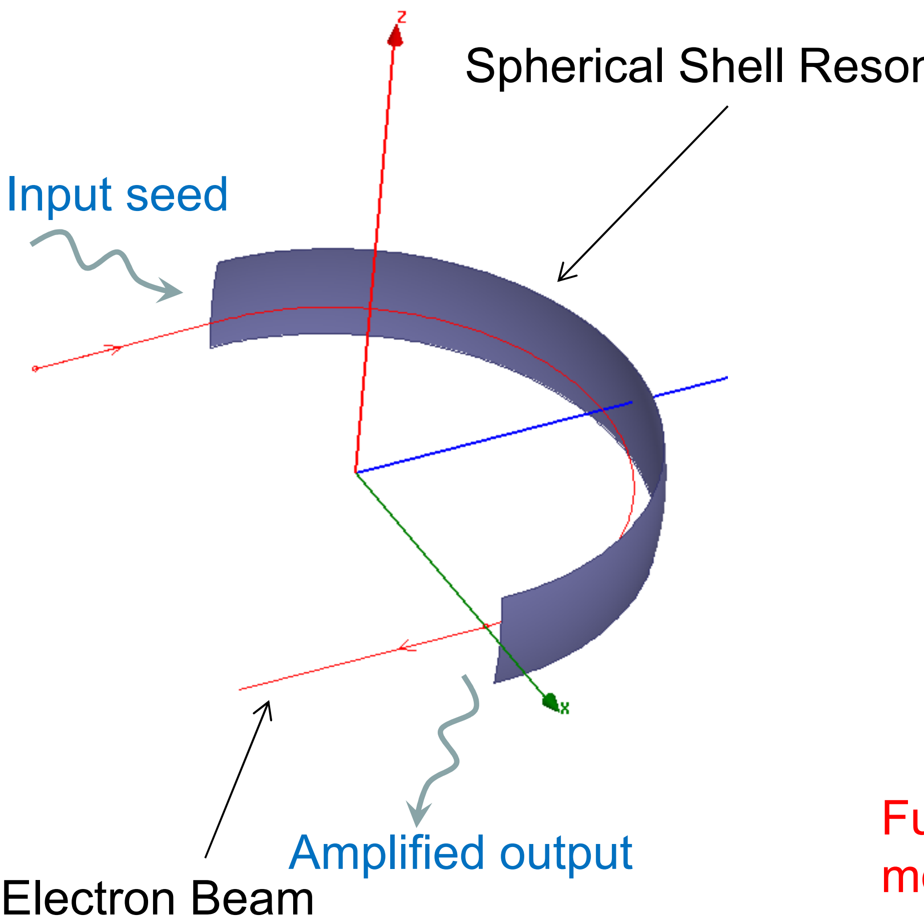
NLCTA installation/beam testing

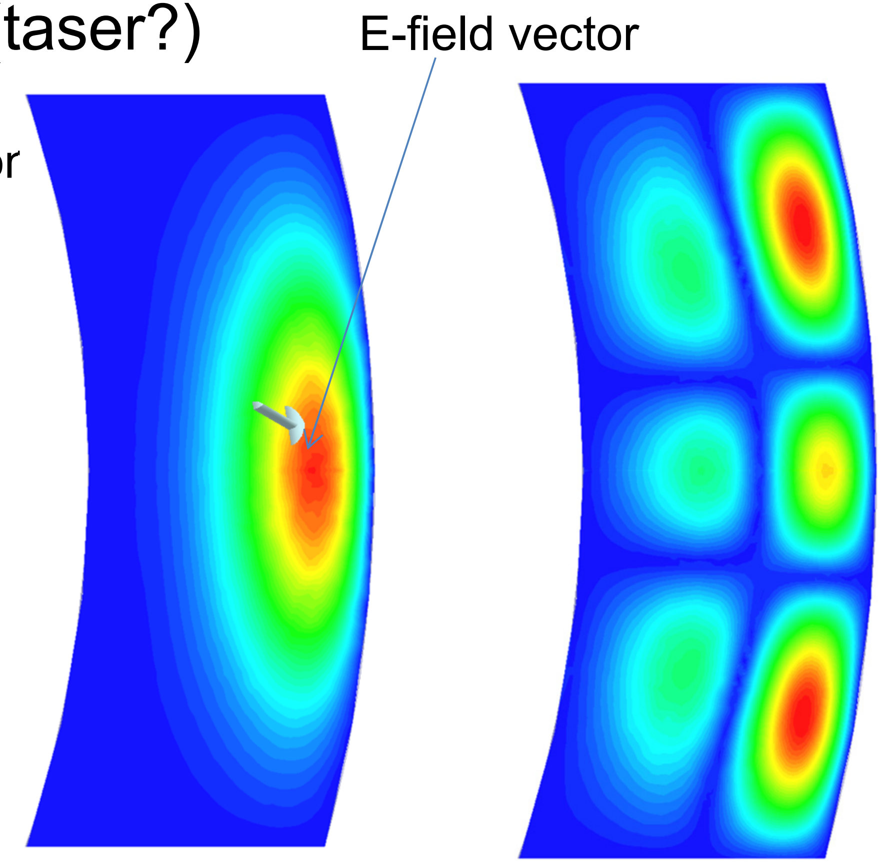
Measurement of the undulator *K*



THz undulator challenge: source

- Possible solution: THz maser (taser?)





Fundamental mode has high Q

Higher order modes have lower Q; $Q_{hom}/Q_{fundmental} \sim 2x10^{-2}$

S. Tantawi (SLAC)

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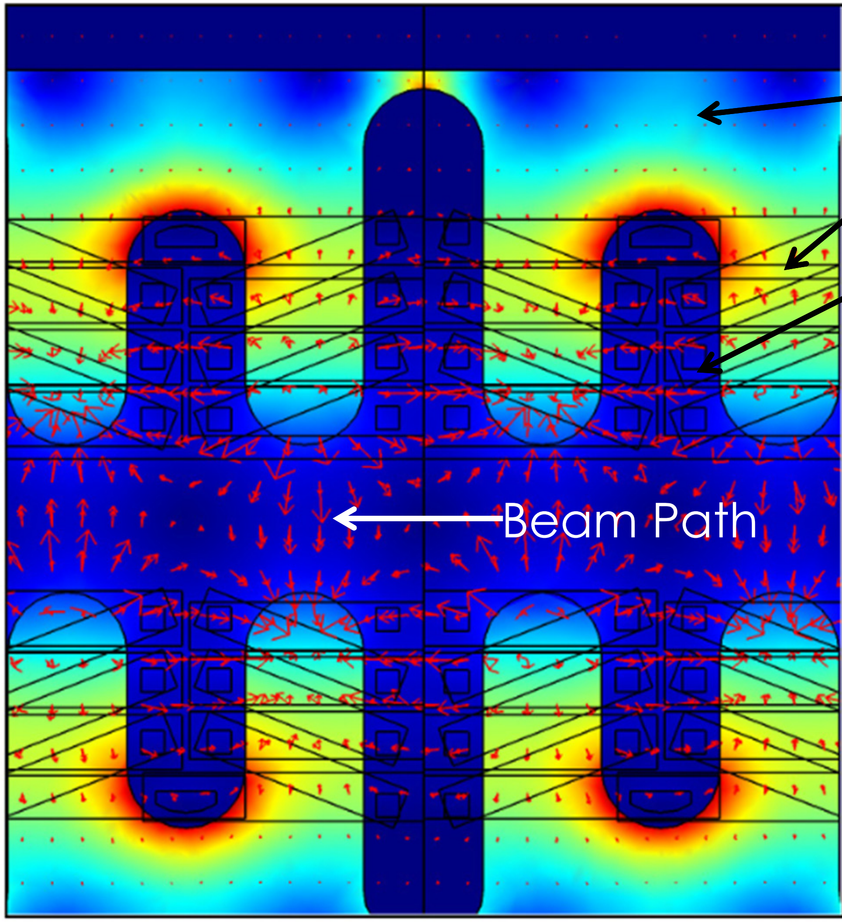
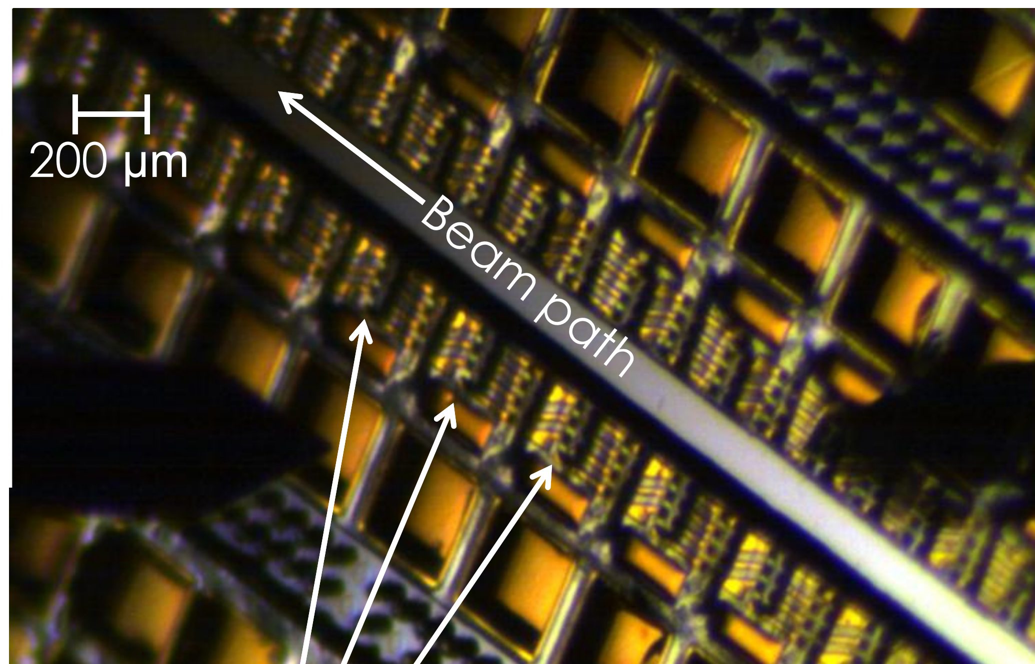
Alternative approach: MEMS Undulator



Candler group device

R. Candler group, UCLA EE

First test with visible light emission at Pegasus, next two months, then SLAC
One-m long water window FEL possible



Summary

- *Comprehensive approach to 5th generation light source*
- Sophisticated new design for DLA
- Advanced dynamics (transverse and longitudinal)
- Exploration of material breakdown limits
- Novel DLA fabrication approaches needed
- GV/m wakefield studies
- High power mid-IR laser development
- Next generation injector pursued
- New approaches to optics and beam measurement
- New class of undulators
- *Fascinating interconnected challenge set. Keep going!*