Novel Structures for High Gradient Acceleration with High Frequency Microwaves

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Outline

- **Introduction / Motivation**
- Millimeter Wave Sources
- Millimeter Wave Structures
- Wakefields / Photonic Bandgap Structures
- Dielectric Loaded Structures
- Other Ideas
- Conclusions

Motivation: Why High Frequency Microwaves?

High frequency microwaves provide a realistic opportunity to extend the energy reach of linear colliders to > TeV

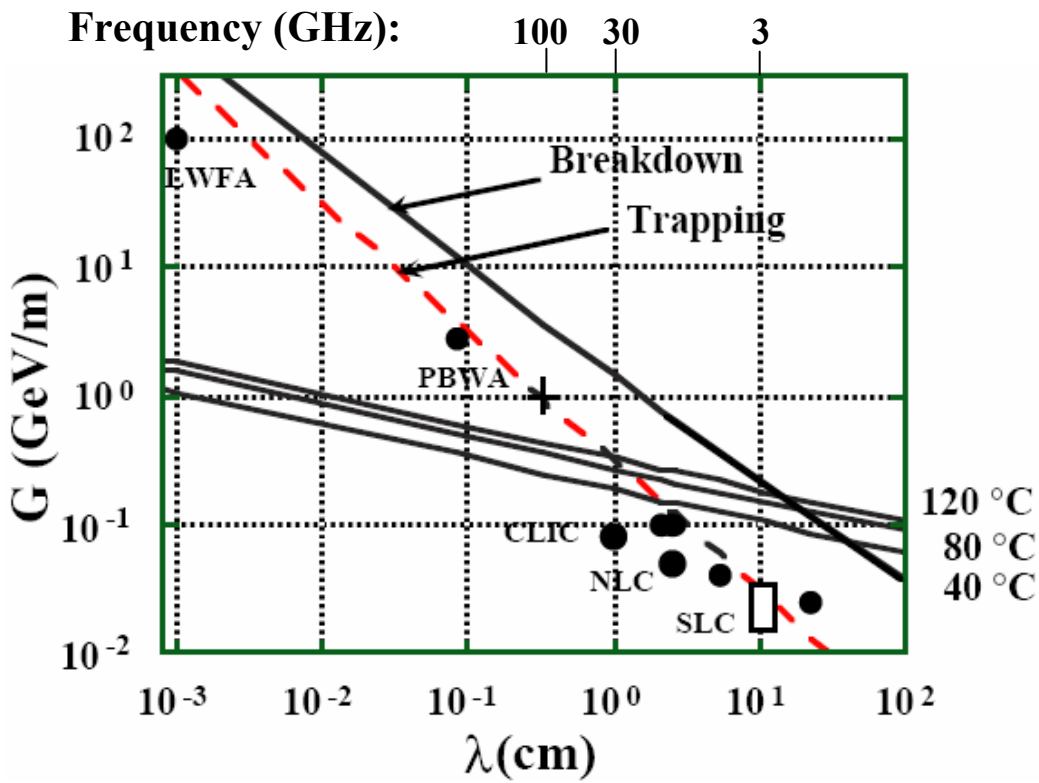
To accomplish this, we desire a gradient G > 150 MeV/m

- **High Luminosity requires high average power particle beams and high peak / average power sources to drive them.**

- **Advantages of High Frequency (up to 100 GHz) Microwaves:**
  - Higher gradient likely at higher frequency
    - Gradient limit due to dark current capture increases with ω.
    - What is the ultimate limit?
  - High peak and average power drive sources are available (or can be developed)
  - Reduced stored energy in accelerator

- **Issues of High Frequency Microwaves:**
  - Smaller structures hard to build
  - Wakefields increase with frequency as ω^3

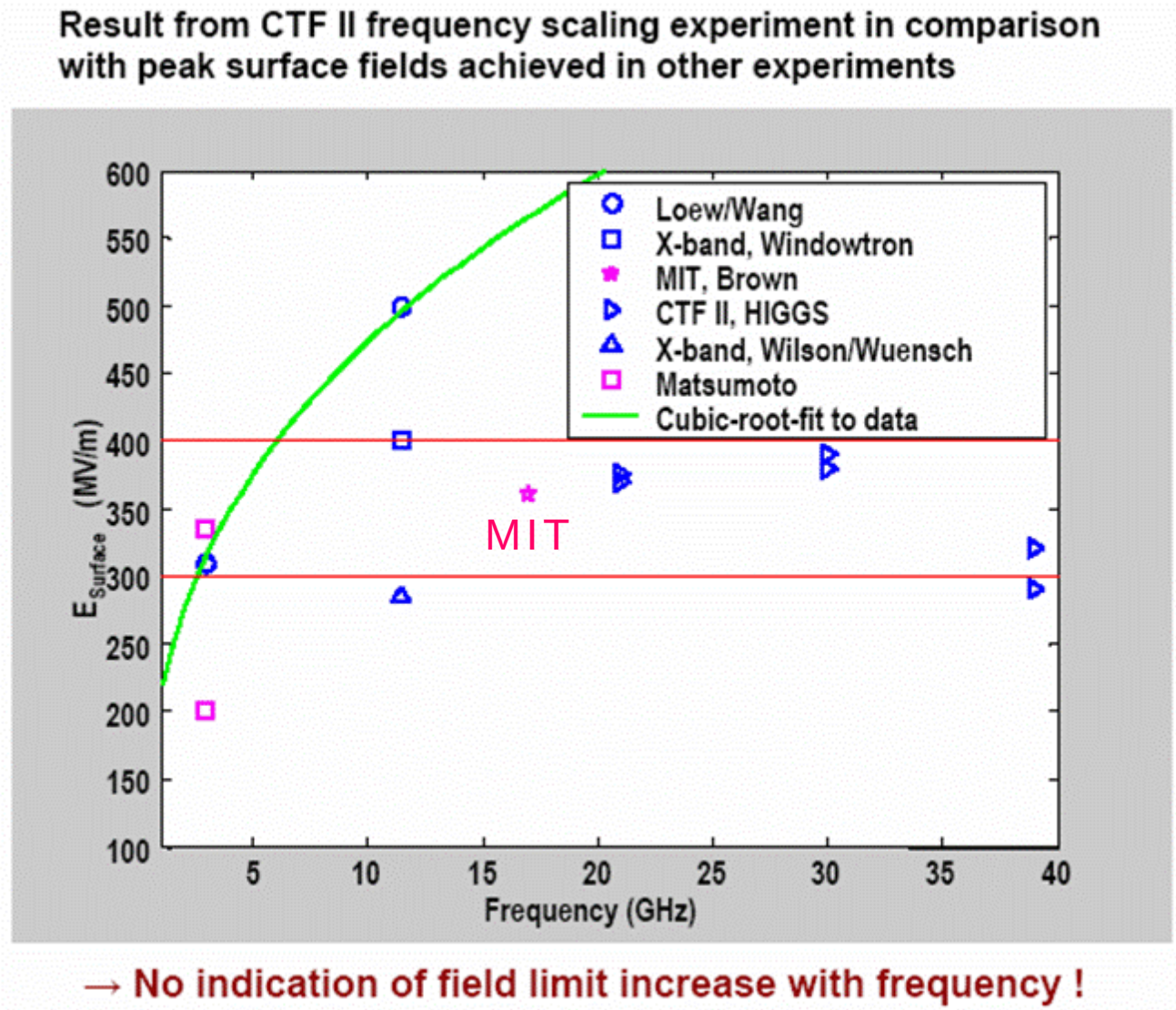
High Frequency Accelerators: 1990's View



From: D. Whittum, "Millimeter-Wave Accelerators," in Handbook of Accelerator Physics and Eng., Chao and Tigner, 1999

- This graph is based on mid to late-1990's data and ideas
- What have we learned?
  - Many new results especially from SLAC and CERN
  - Talks by S. Tantawi, W. Wuensch!
- Breakdown line is not correct
  - **Too optimistic!**

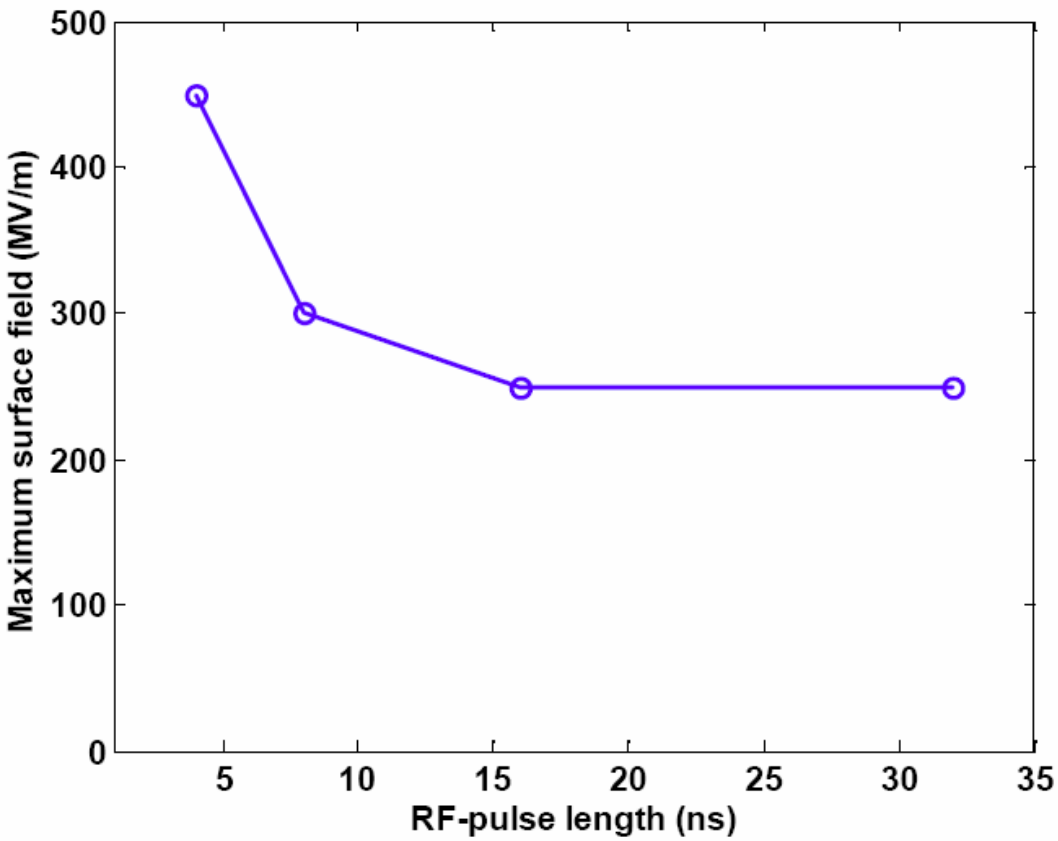
Breakdown vs. Frequency: Recent Data



- No apparent frequency scaling
- ~ 400 MeV/m is upper limit for surface field
- 200 MeV/m may be the limit for gradient in a TW linac

From: Braun, CERN, ILC 2006

CERN Breakdown vs. Pulse Length data



- Breakdown threshold does not improve until pulse lengths are very short
  - < 10 ns in CERN expts.

Data from Wuensch, PAC 2003

Surface Heating

- **Surface heating** leads to cyclic fatigue

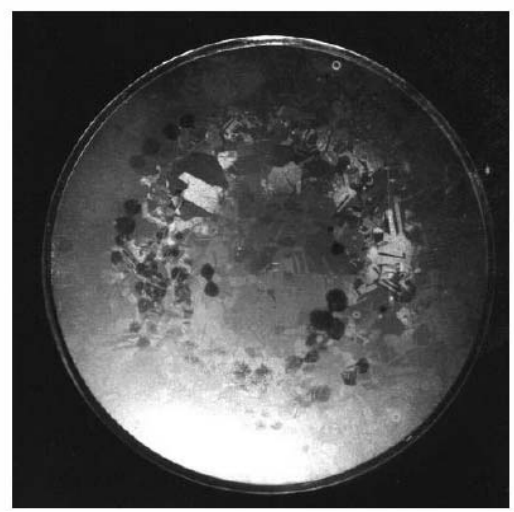
$$\Delta T = \frac{G^2\sqrt{\tau}}{Z_H^2}\frac{R_S}{\sqrt{\pi\rho CK}}$$

- Where G = gradient; τ = pulse length; $Z_H = G/H_{MAX} \approx 300\Omega$; ρ = density; C = specific heat; K = thermal conductivity
- R_S = surface resistance

$$R_S = \sqrt{\pi f \mu / \sigma} \sim f^{1/2}$$

- Note favorable scaling with pulse length
  - Assume scaling of pulse length with filling time, $t \sim \lambda^{3/2} \sim f^{-3/2}$
- Then: Gradient $G \sim f^{1/8}$

- Max value of $\Delta T < 100K$ for copper (Pritzkau and Siemann, PRSTAB, 2002)



Electron Capture and Trapping

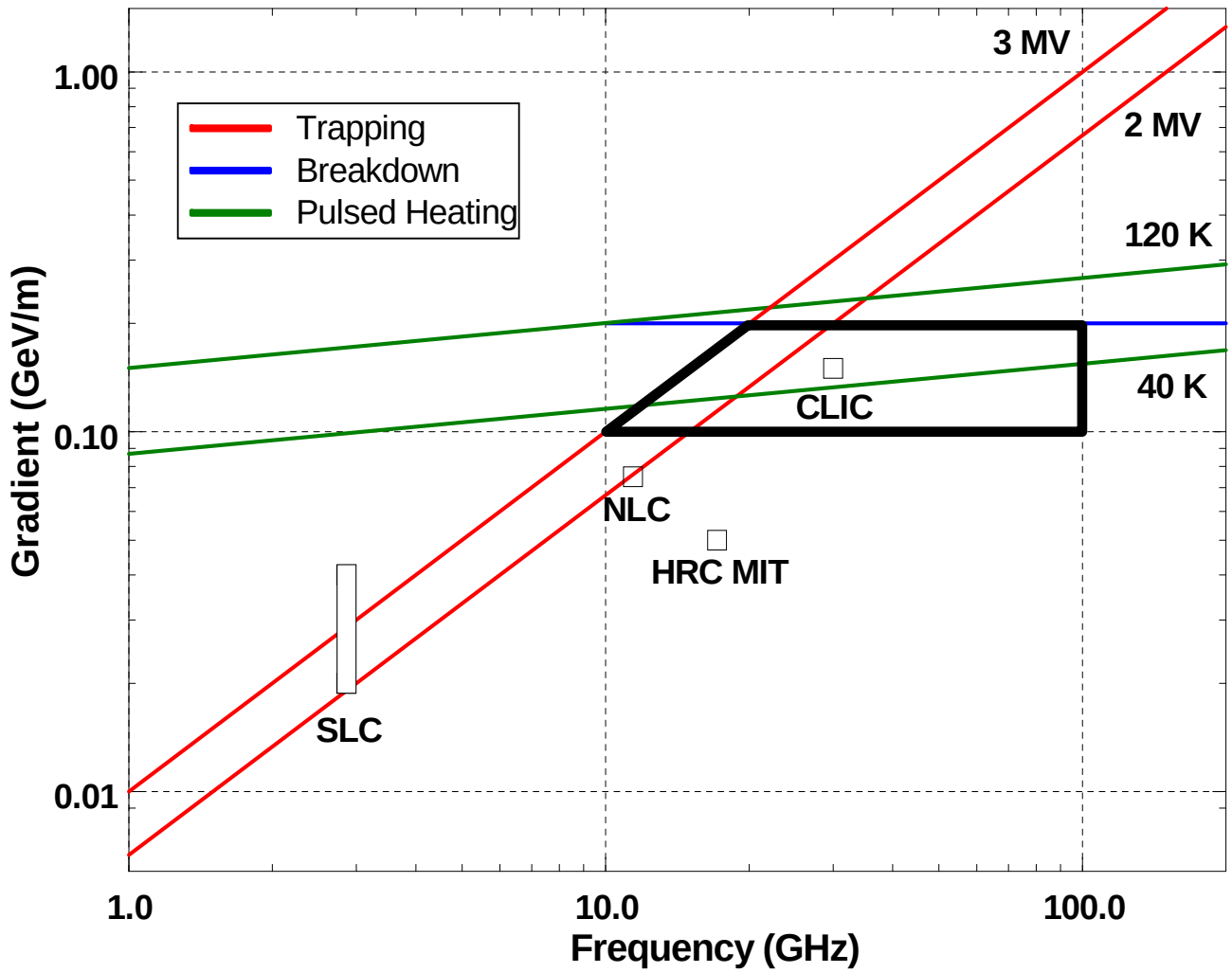
- **Trapping**: Electrons, initially at rest, can be accelerated and captured. Theory (Chodorow, 1955) gives a threshold:

$$\alpha \approx \frac{eG\lambda}{2\pi mc^2} = \frac{1}{2} \qquad \text{or} \qquad G\lambda \approx 1.6MV$$

- More realistic value may be: **Gλ ≈ 2 to 3 MV**

- Limit is too pessimistic at low frequency.

Approx. Limits of Accelerator Gradient

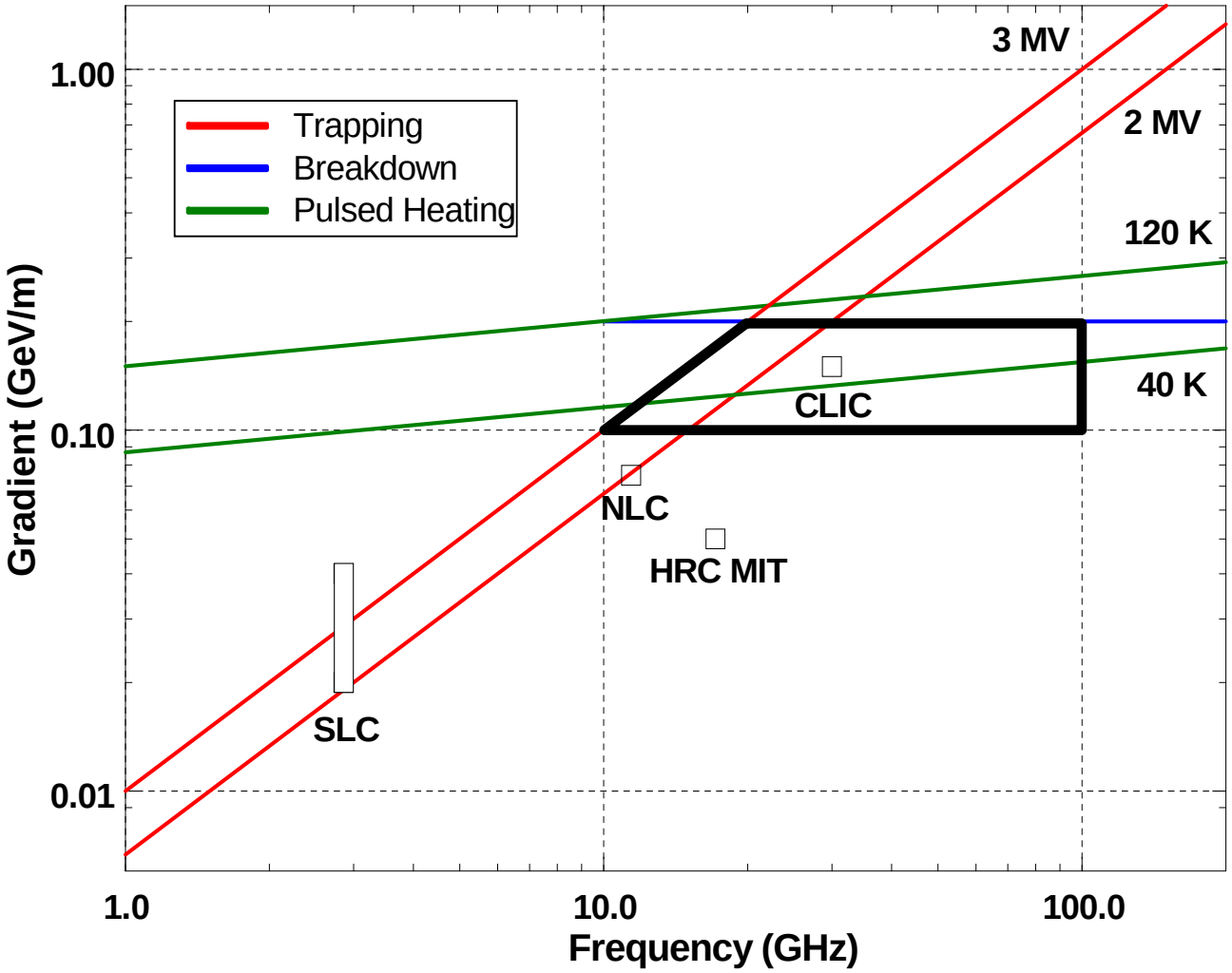


Assumptions:

- Pillbox structure of Cu
- Breakdown < 200 MV/m
- Source < 100 GHz
- Electron capture $G\lambda \sim 2$ to 3 MV ?
- Pulse length 360 ns at 11.4 GHz

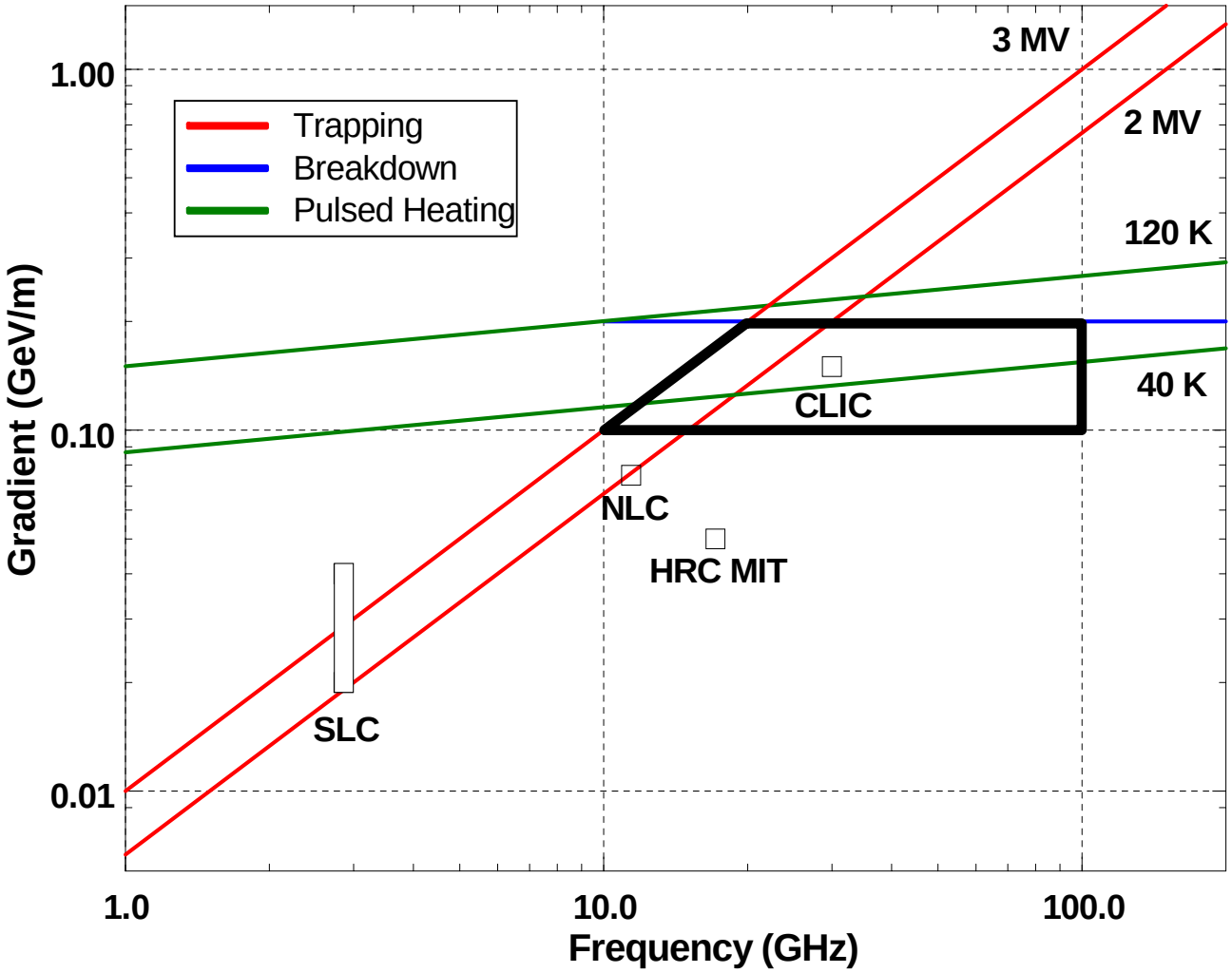
Limits are approximate!

Approx. Limits of Accelerator Gradient



How can we get outside of the box?

Approx. Limits of Accelerator Gradient



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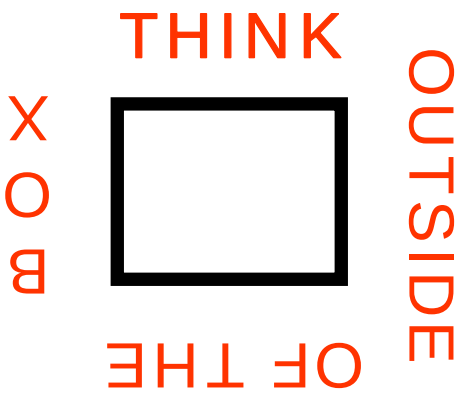
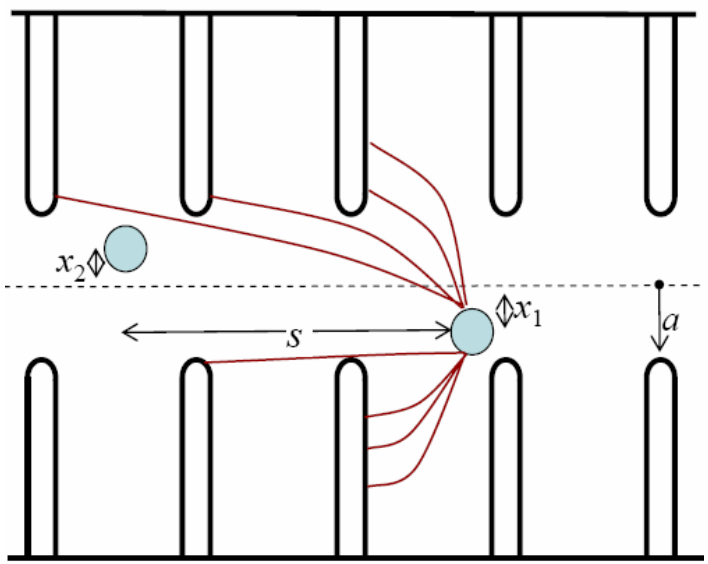


Another Issue: Wakefields



	effect	scaling	Counter measures
W_L	energy spread increase	ω^2	phasing Increase bunch length Limit bunch charge
W_T	emittance growth	ω^3	Tight alignment Strong focusing Decrease bunch length BNS damping Tight orbit control Emittance bumps Feedback Limit bunch charge

- Transverse Wakefields scale as ω^3

From: Braun, CERN, ILC 2006

Research Goals – High Frequency Microwaves

- Evolutionary Advances
  - Optimize conventional structures for minimum surface fields (Z_H)
  - Damped detuned structures for wakefield suppression
  - Use better materials than Cu at high stress locations (ΔT)
- Revolutionary Advances: Novel Structures
  - Photonic Bandgap Structures: wakefield suppression
  - Quasi-optical structures: short pulses (τ)
  - Dielectric loaded structures
  - High Order Mode Structures: reduced surface fields (Z_H)
- Revolutionary Advances: Novel Configurations
  - Two beam accelerator: CLIC at 30 GHz
  - Inverse Cerenkov or Smith-Purcell accelerators

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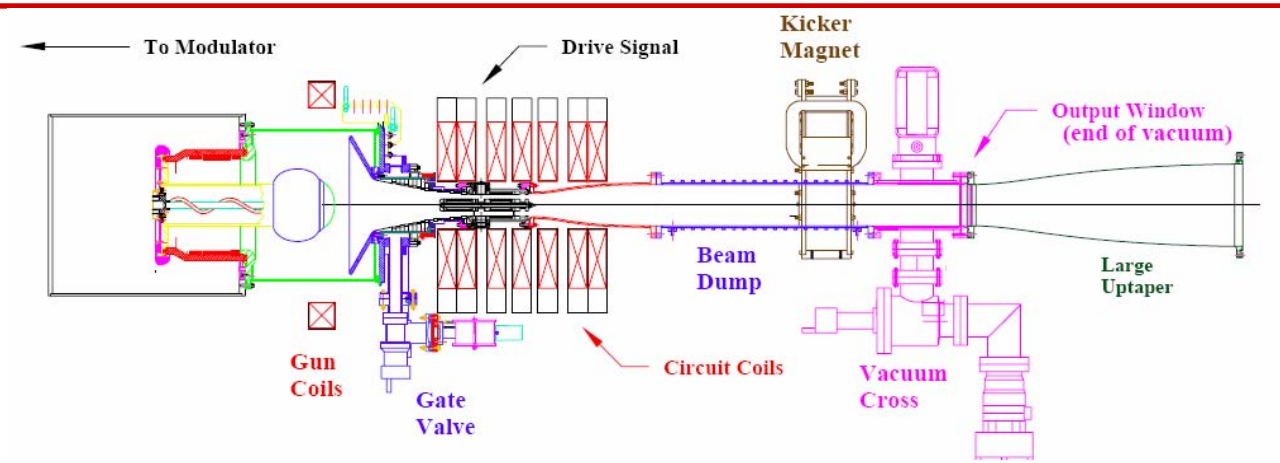
MMW Sources: 17 GHz Haimson Klystron

- **High Efficiency Relativistic Klystron** using a High Current Linear Accelerator TW Buncher Output Circuit
  - 17.14 GHz
  - 6 cavities

Collector	**89.9**	**A**
Gun Volts	**545**	**kV**
P. RF Out	**25.5**	**MW**
Efficiency	**51.9**	**%**
P. Drive	**1.8**	**W**
Gain	**71.5**	**dB**

Haimson Research Corp.

MMW Sources: Univ MD Gyroklystron



Parameter	Circular Tubes				Coaxial Tubes	
Harmonic	1	1	2	3	1	2
Freq. (GHz)	9.875	9.87	19.76	29.7	8.6	17.14
Power (MW)	24	27	32	1.8	75	28
Efficiency (%)	30	32	29	2	32	13
Gain (dB)	33	36	27	14	30	25
Voltage (kV)	425	425	457	435	460	425
Current (A)	190	195	244	212	510	550

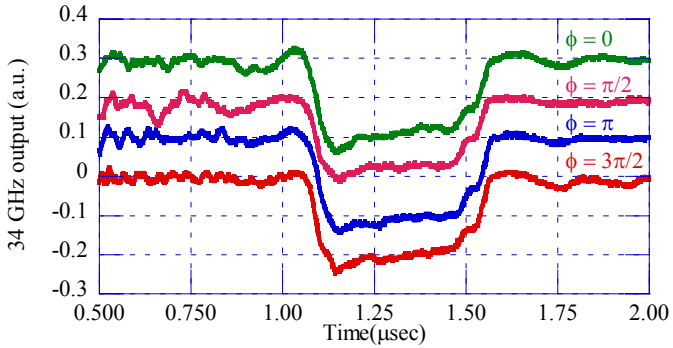
Source: W. Lawson, Univ. MD

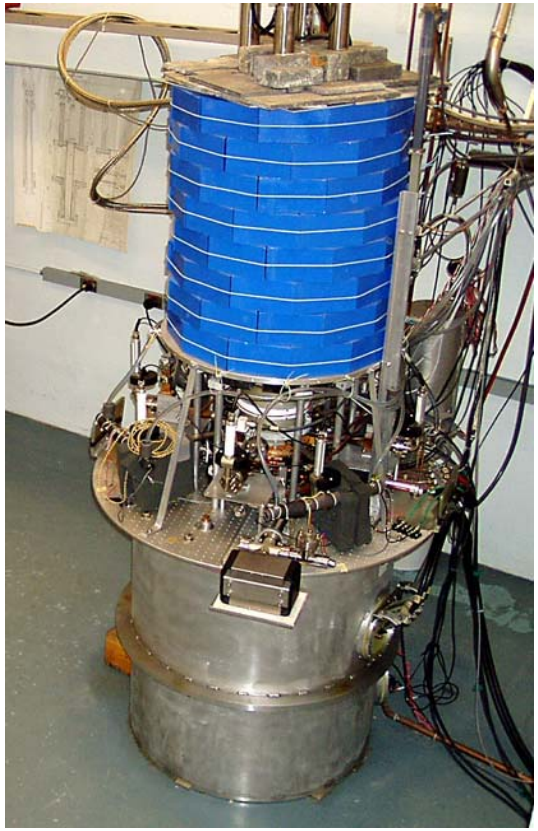
MMW Sources: 34 GHz Magnicon at Yale/Omega-P

34 GHz magnicon (J.L. Hirshfield, *this meeting)*

Single frequency amplifier suitable for accelerator driver has been demonstrated.

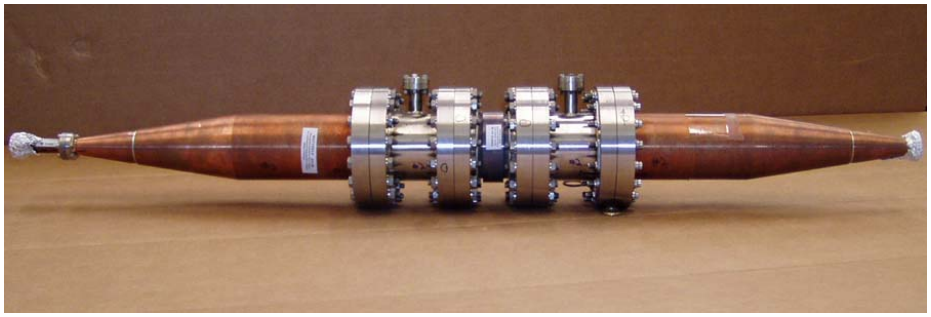
beam power 95 MW (475 kV, 200 A)
drive frequency 11.4 GHz (magnicon is tripler)
RF power 26 MW, 450 ns; in 4 WR-28 outputs





High-power Ka-band components

mode converters, windows, pulse compressors, power combiner, transmission lines, and couplers to MM-wave test structures are already developed and built.



63-mm Ø window assembly (1 of 4)

Source: J. Hirshfield

MMW Sources: Calabazas Creek Res. 91 GHz GK

- 91 GHz Gyroklystron amplifier built by CCR.
  - Power level of 10 MW
  - Efficiency > 40%
  - Gain of 55 dB
  - Frequency doubling option chosen

- Status: Completely built, waiting for testing at SLAC.

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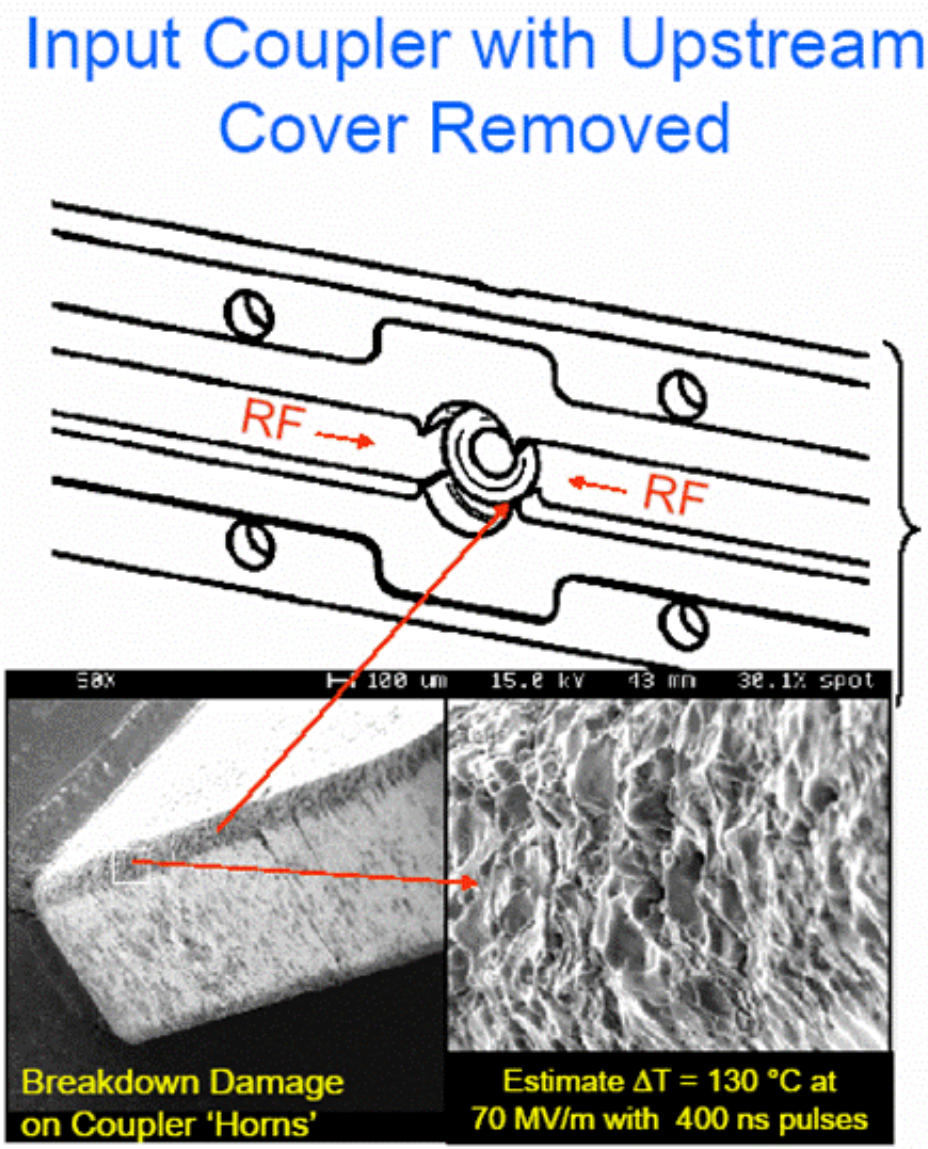
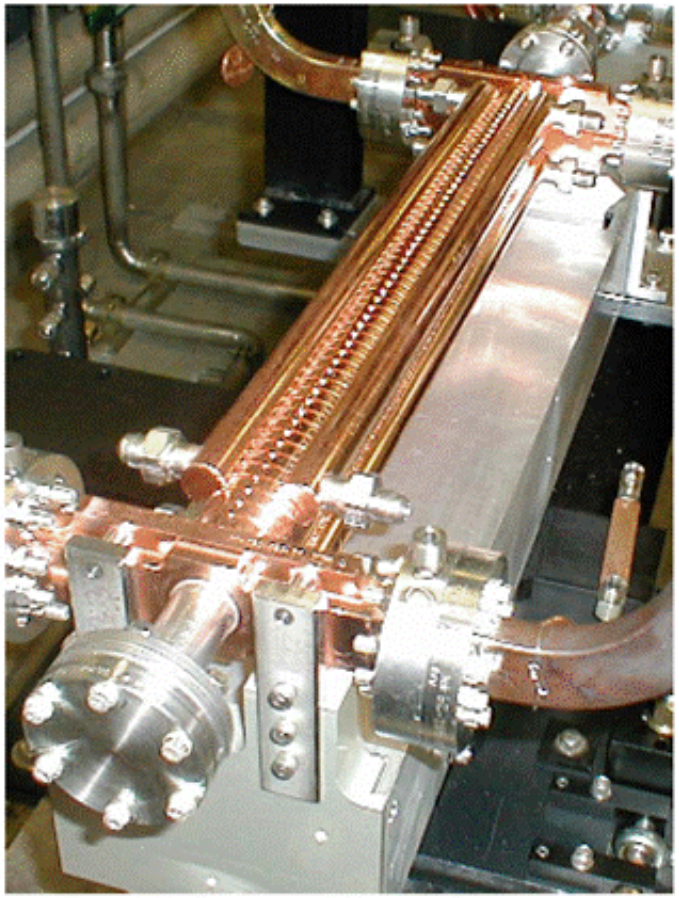
Erosion at Input Coupler (SLAC)

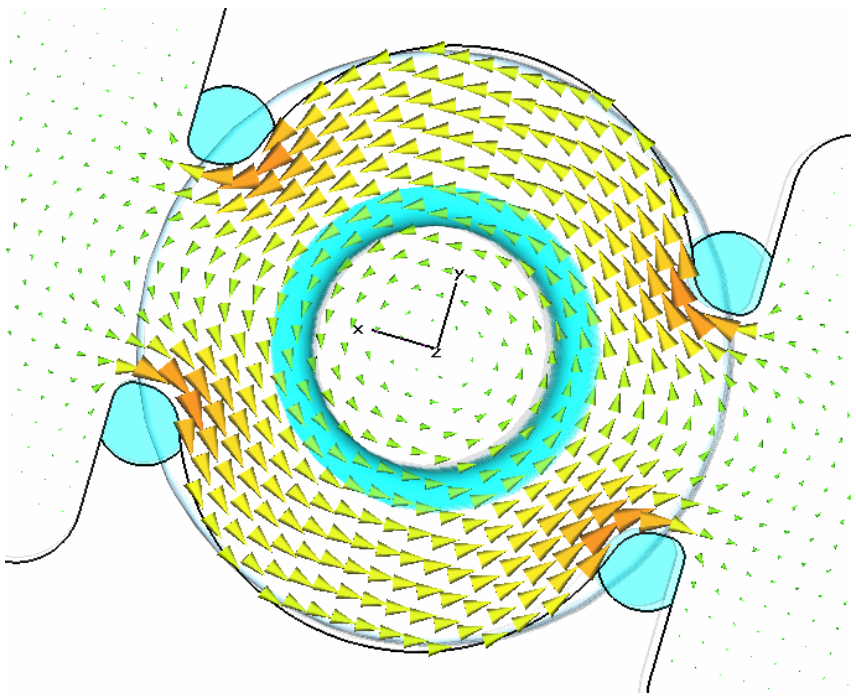




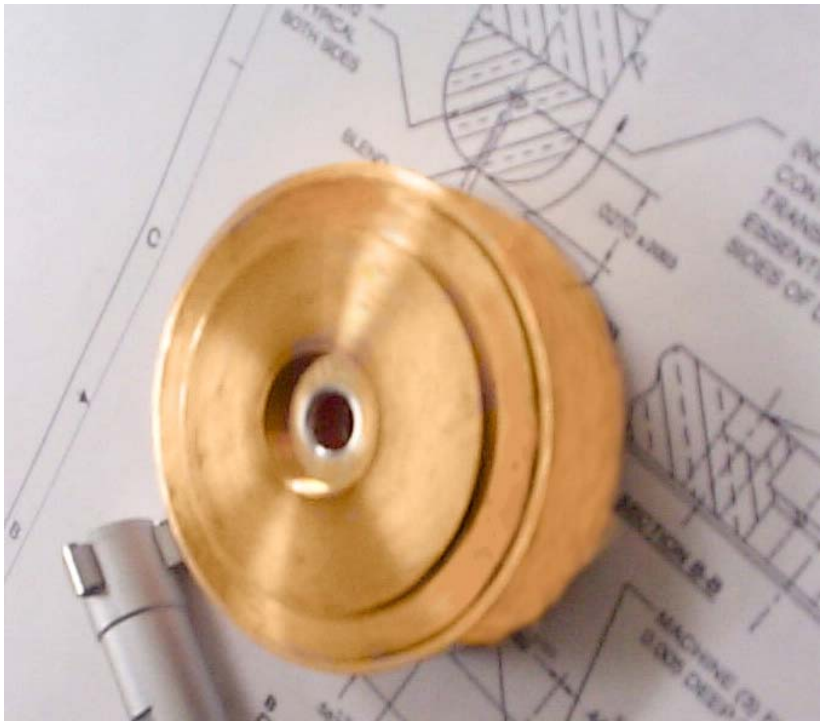
T53VG3 Structure
(53 cm Long, 3% c Initial Group Velocity)

Source: C. Adolphsen, 2005

Improved 17 GHz Structure Using Molybdenum Inserts (HRC)



Racetrack Coupler with Optimized Profile Brazed Insert Lips for High Gradient Linac (Haimson Res.)

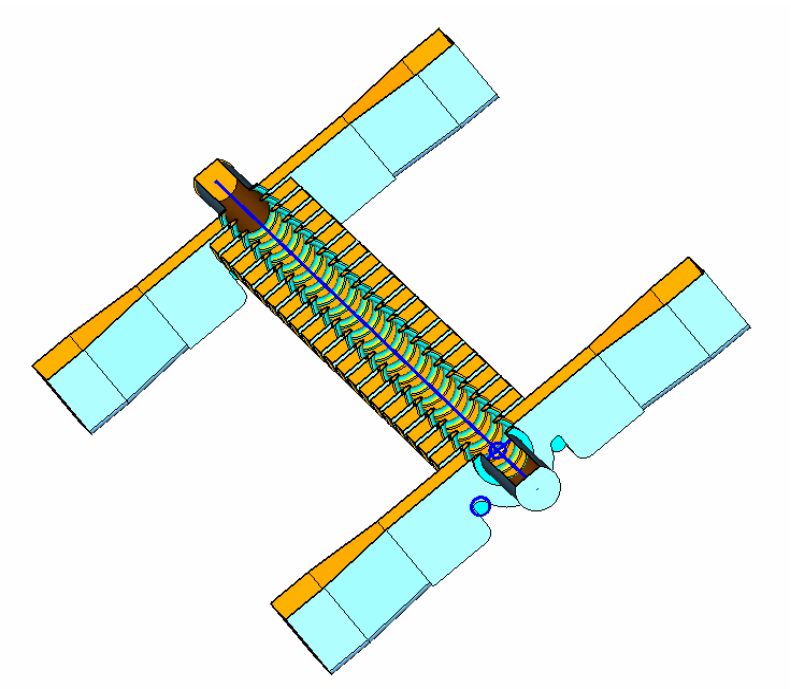


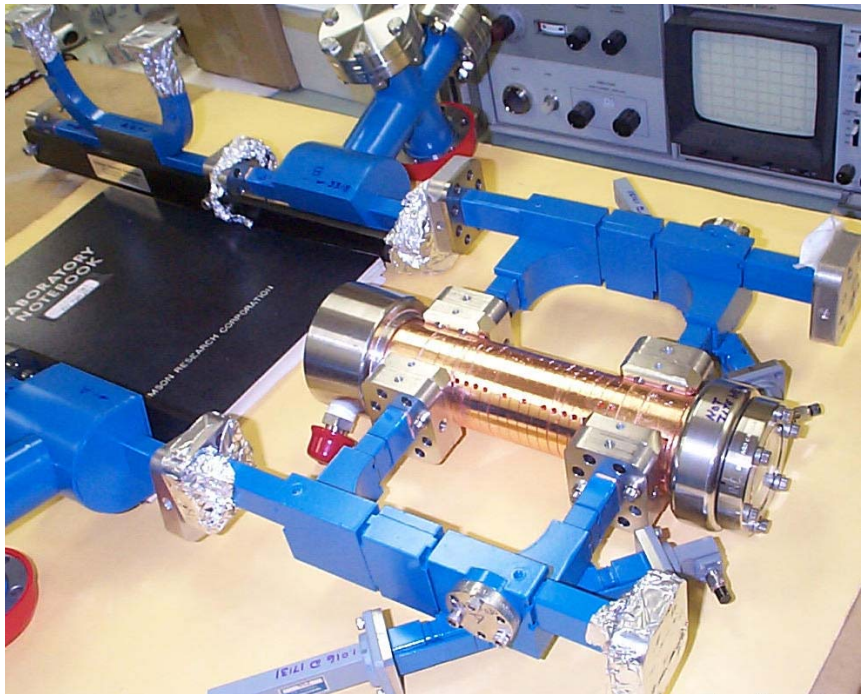
Brazed Molybdenum/Copper Disc 17 GHz Linac Test Cavities (Haimson Res.)

- Similar research being conducted at CERN, SLAC, Omega-P, etc.

Source: J. Haimson

Gradient Hardened 22 Cell 17 GHz Linac Test Structure





- Test structure ready for testing at 17 GHz source, such as U MD 17 GHz Gyroklystron or MIT/HRC 17 GHz Klystron

Source: J. Haimson

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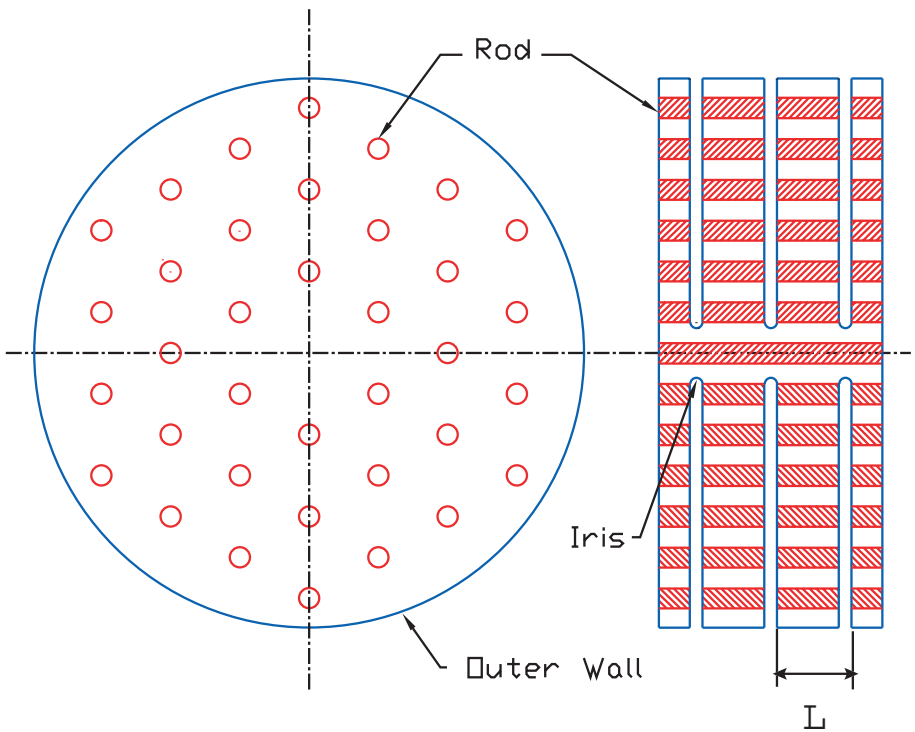
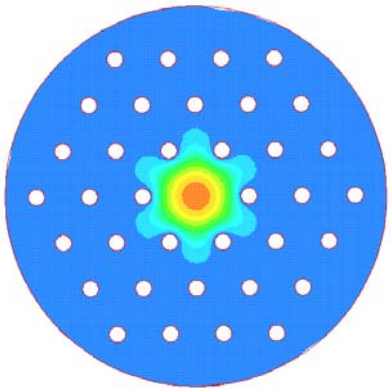
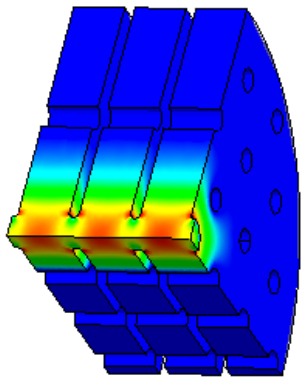
Motivation for Photonic Structure Research

- Wakefields increase with frequency as ω^3
- PBG (Photonic Bandgap) structure is effective for damping wakefields



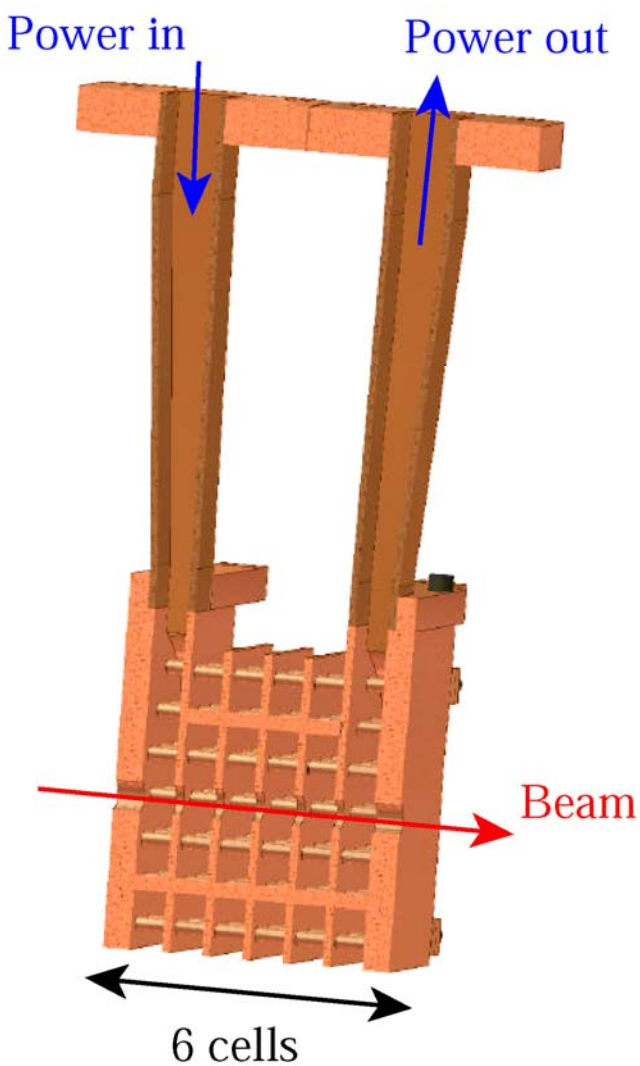


TM_{01}-like Mode of PBG Structure



3D View Of Fields

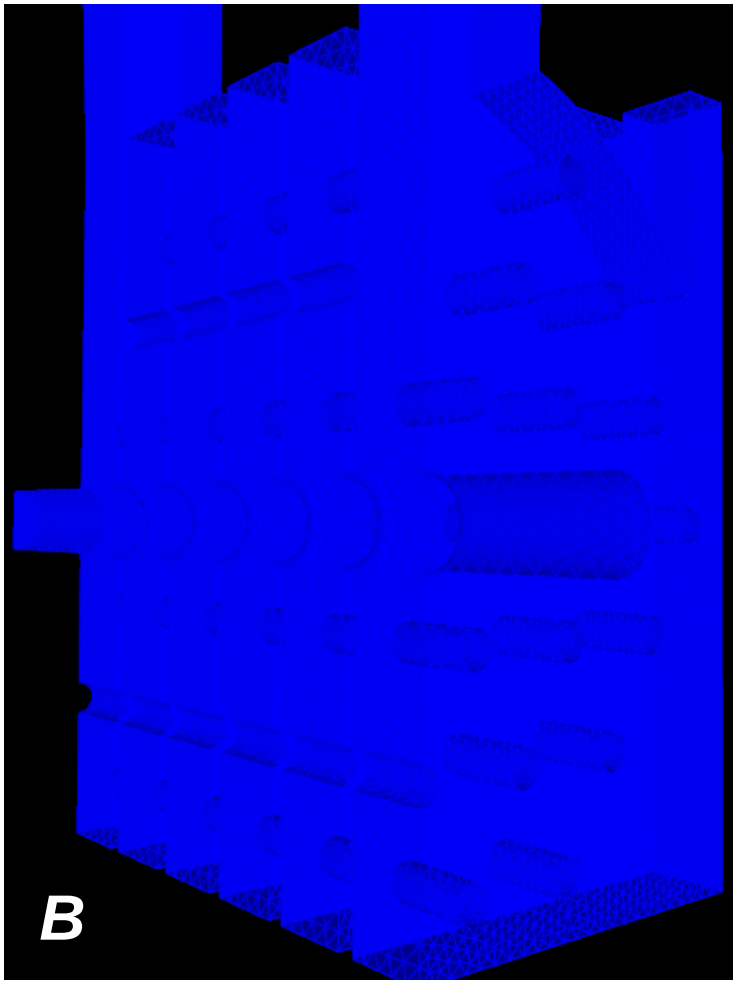
Accelerator with PBG cells



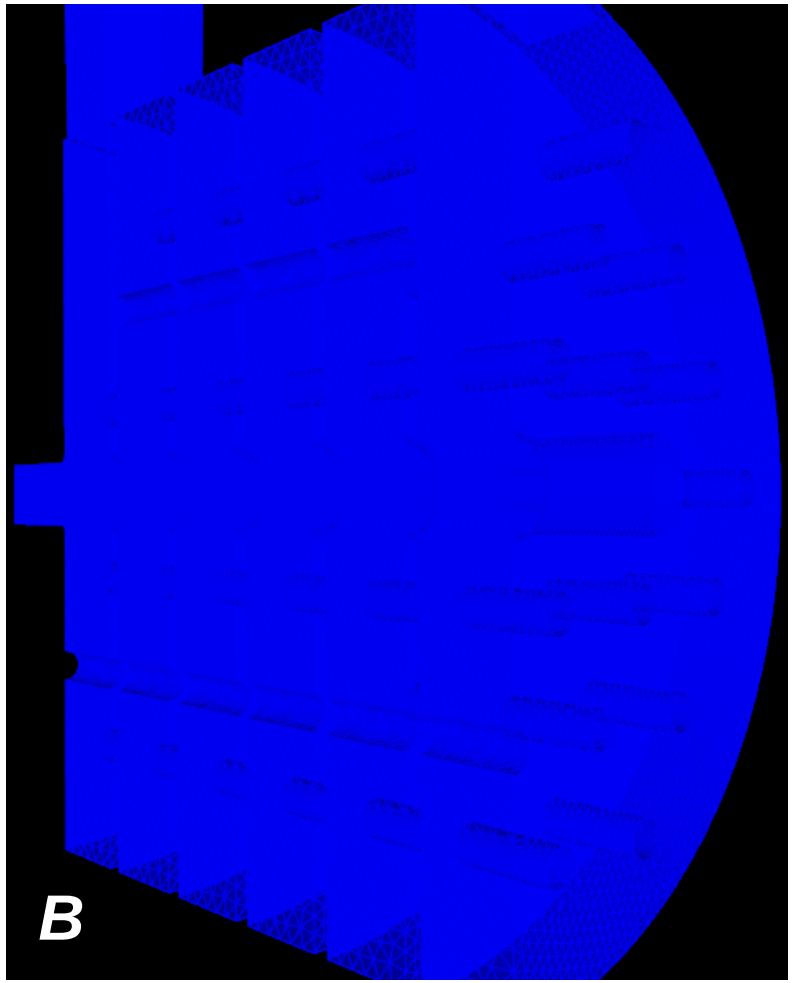
Frequency	**17.140 GHz**
Phase shift per cell	**$2\pi/3$**
Q_w	**4188**
r_s	**98 MΩ /m**
$[r_s/Q_w]$	**23.4 kΩ /m**
Group velocity	**0.013c**
Gradient	**$25.2\sqrt{P}$[MW] MV/m**
Rod radius, *a*	**1.08 mm**
Lattice vector, *b*	**6.97 mm**
Iris radius	**2.16 mm**

MIT PBG Structure – T3P (SLAC, STAR Inc)

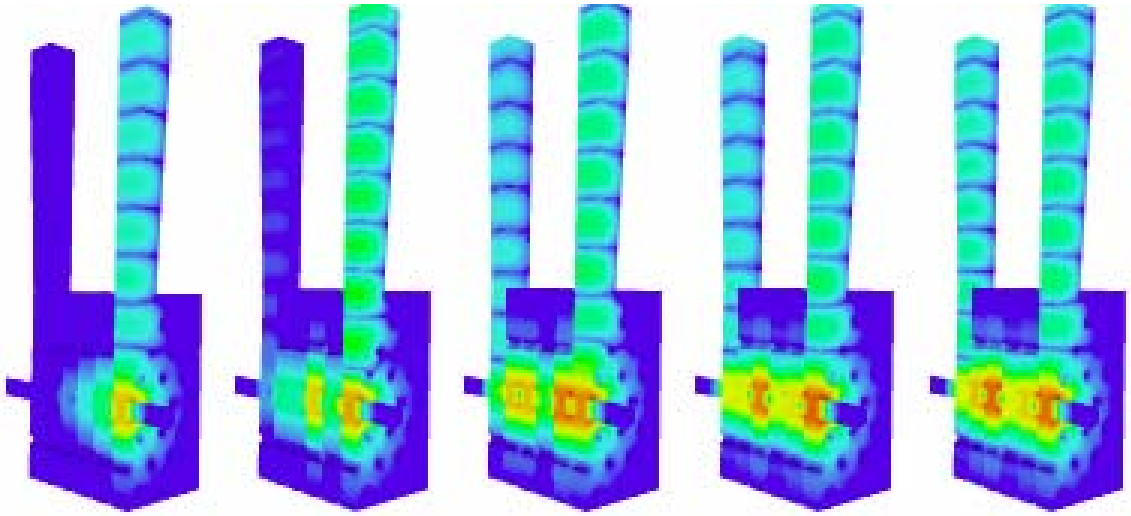
Input drive pulse to study transient heating of rods



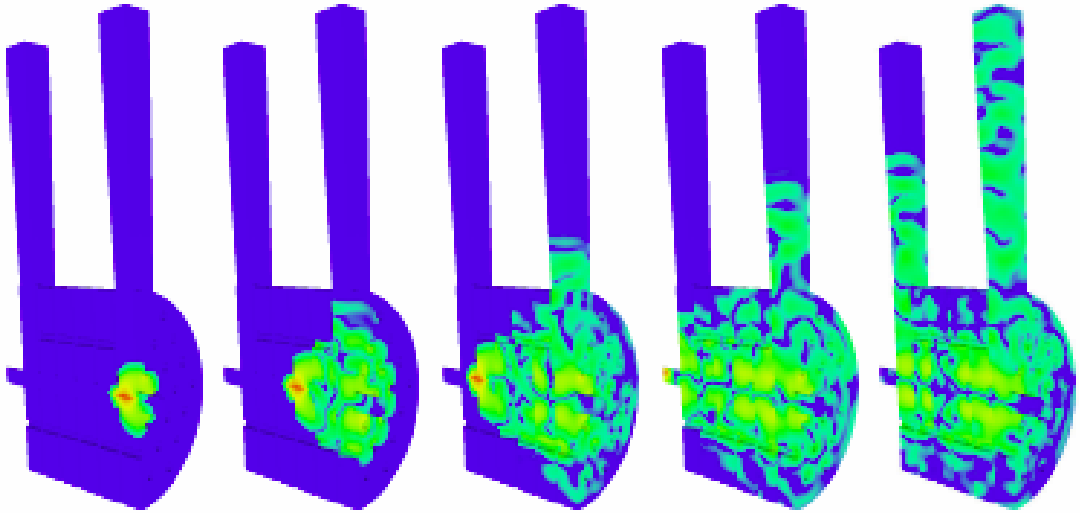
Off-axis transit beam to model dipole wakefields



PBG Fields calculated by DeFord and Ko



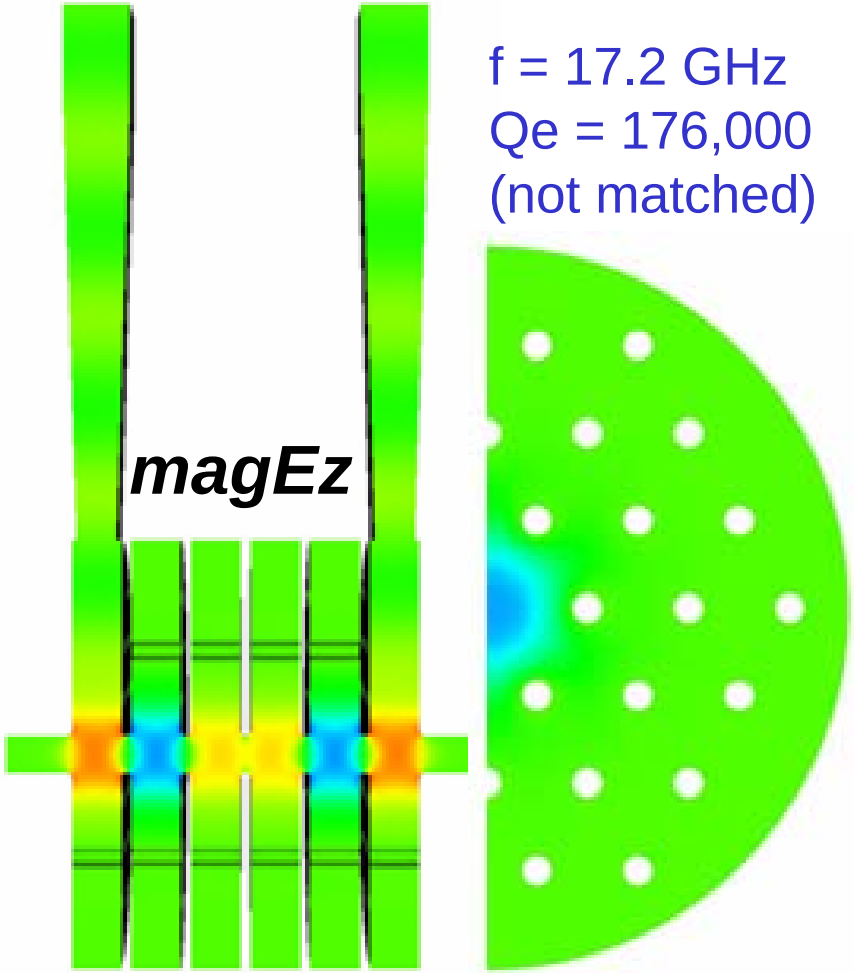
Snapshots of E field magnitude due to a drive pulse, as generated by T3P



Snapshots of magnetic field magnitude due to a beam bunch as generated by T3P

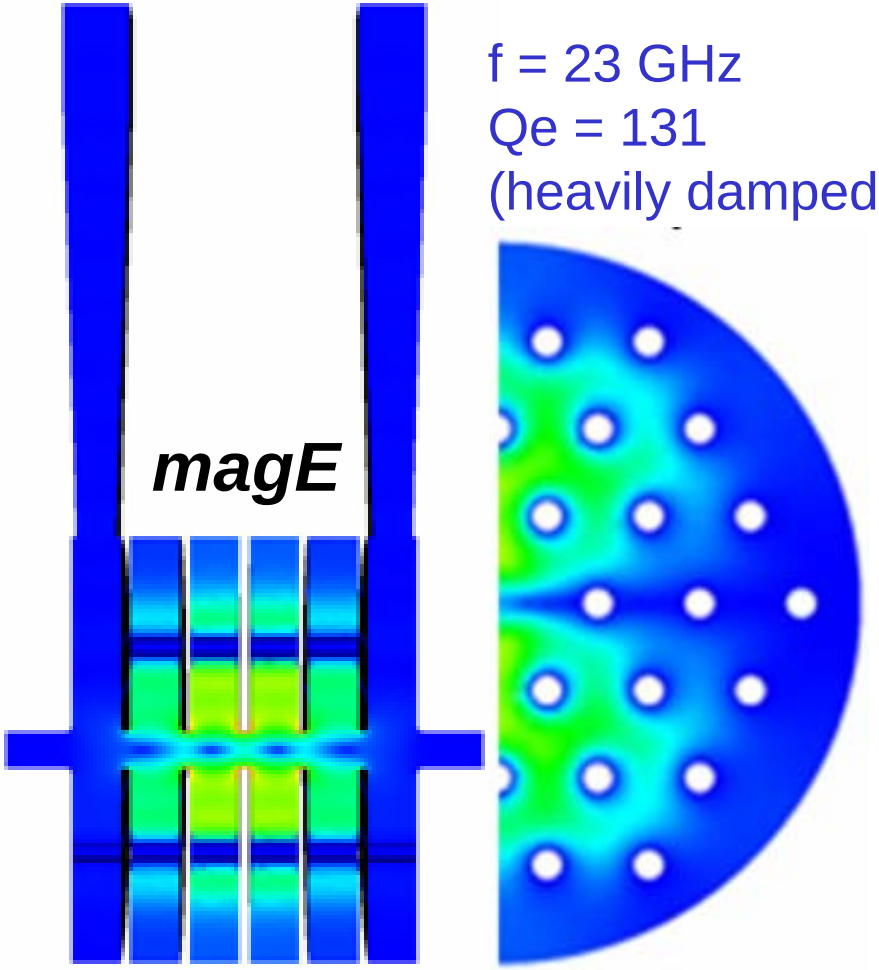
MIT PBG – Omega3P (SLAC, STAR Inc)

Accelerating mode coupled to input/output waveguides



f = 17.2 GHz
Qe = 176,000
(not matched)

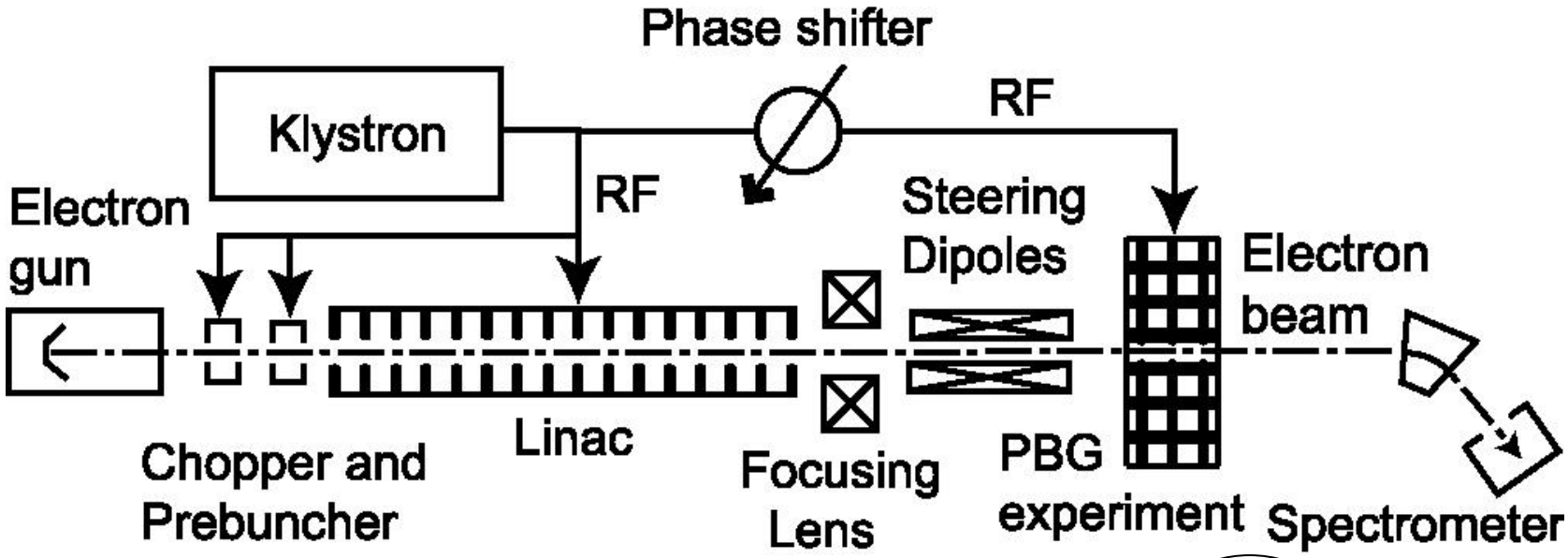
Damped dipole mode due to open BC @ outer wall

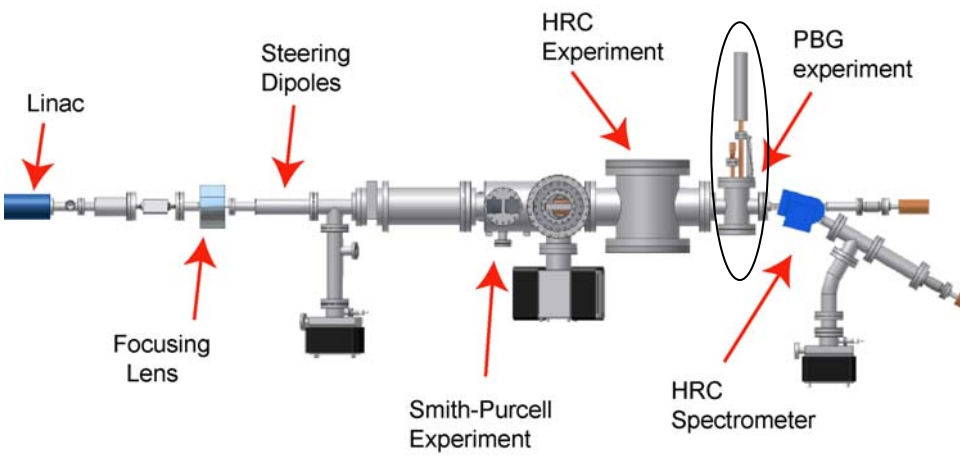


f = 23 GHz
Qe = 131
(heavily damped)

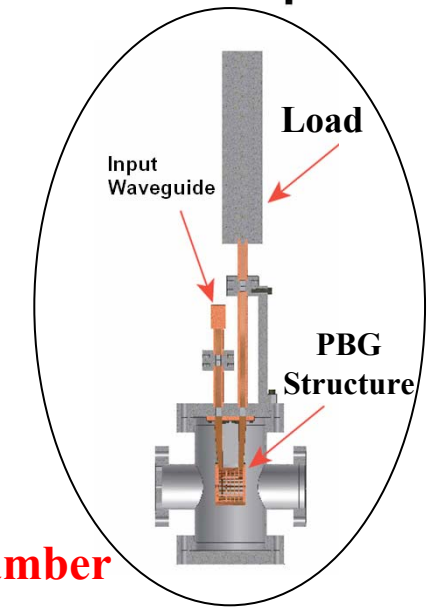
Source: Kwok Ko, SLAC

Experimental Schematic



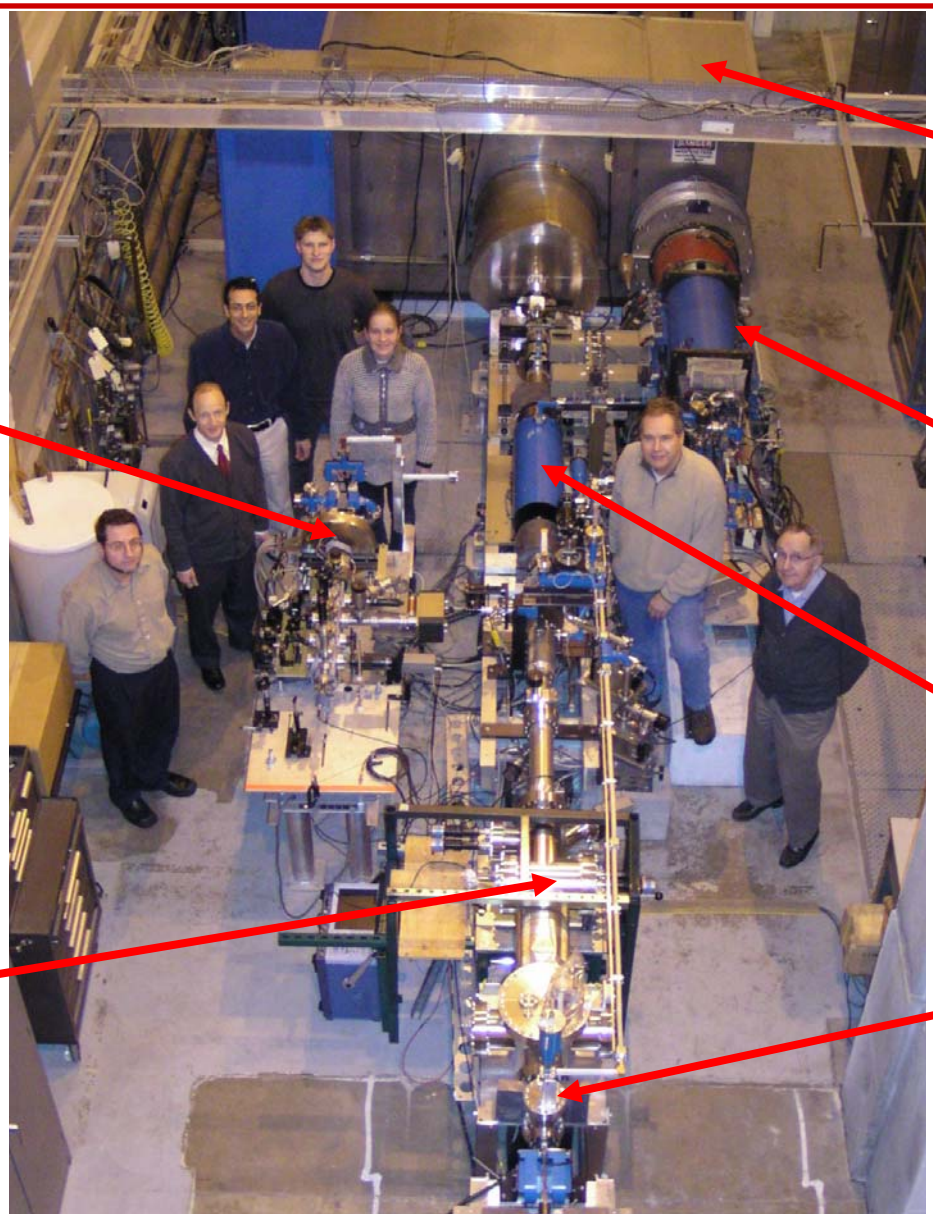


Beam Line



Test Chamber

17 GHz Accelerator Lab and User Facility at MIT



RF Break-down / RF Gun Test Stand

THz Smith-Purcell Expt.

Modulator
700 kV, 780A
1 μs flattop

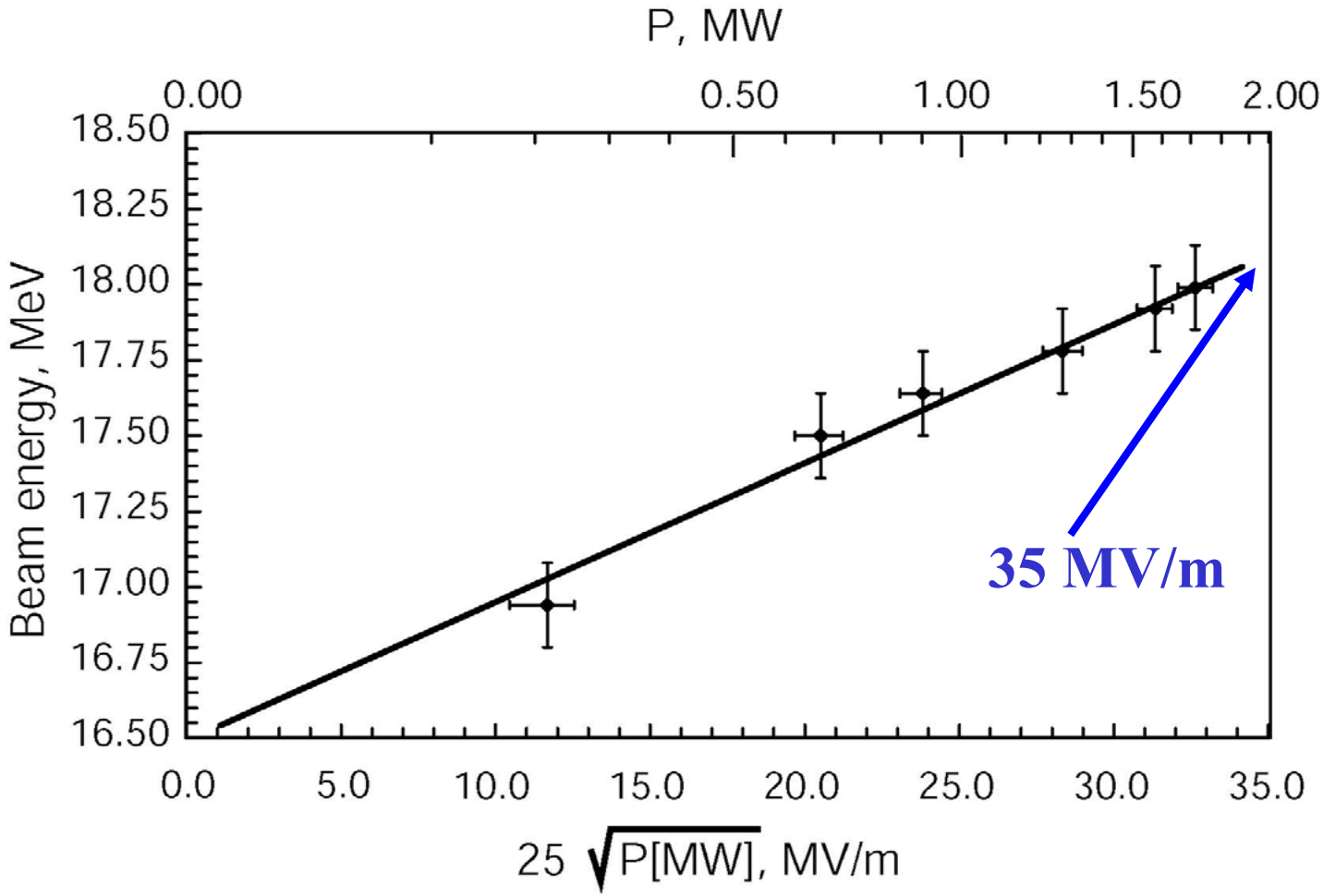
Klystron 25 MW
@ 17.14 GHz

25 MeV Linac
0.5 m, 94 cells

Novel High Gradient Structure / Photonic Bandgap Test Stand

Accelerator demonstration

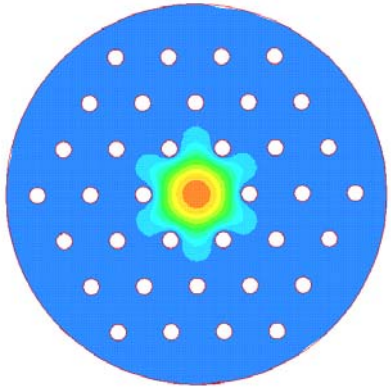
- Beam energy increased with power as $P^{1/2}$, as expected.
- First successful PBG accelerator demonstration.
- Next step: Wakefield measurements



E. I. Smirnova et al., Physical Review Letters (2005).

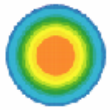
PBG and DDS vs. Pillbox Resonator

PBG Resonator



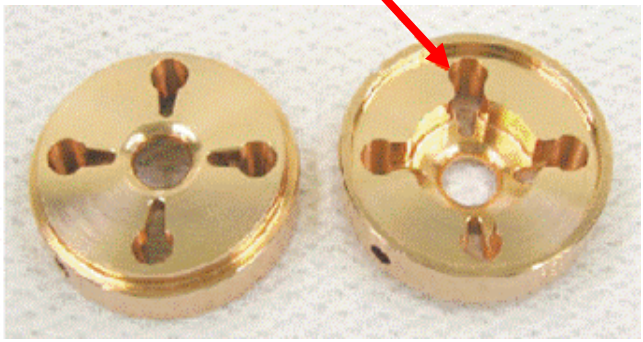
TM_{01}-mode

Pillbox Resonator



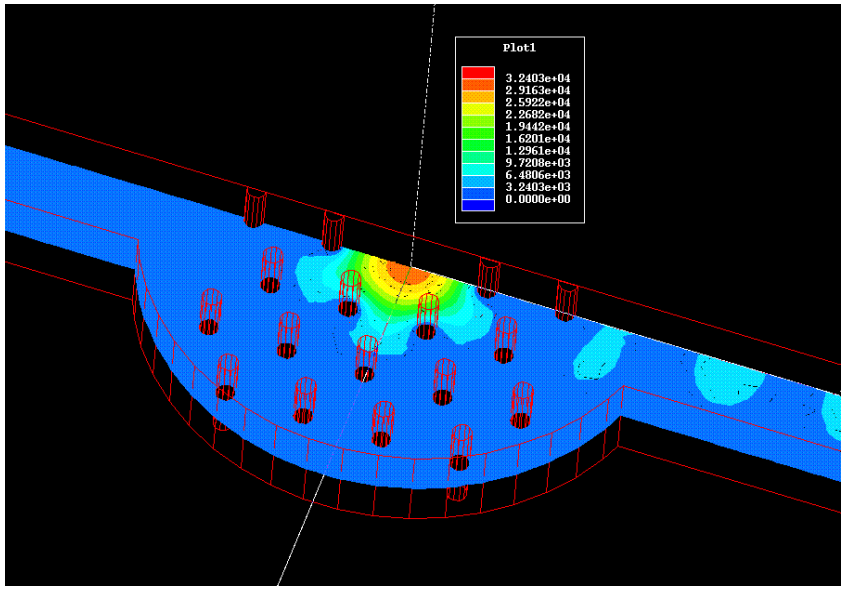
Damped Detuned Structure

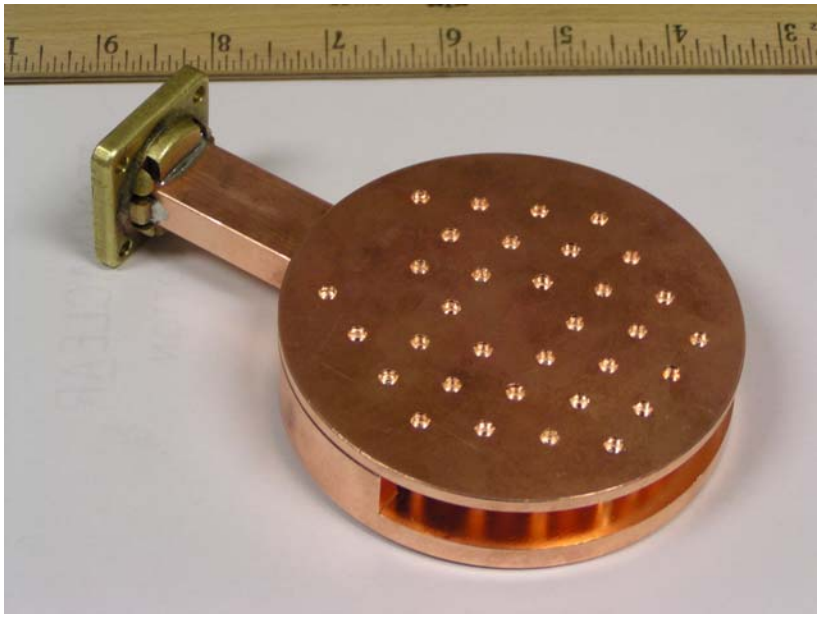
Slots for damping



- Both PBG and Damped Detuned (DDS) structures have higher ratio of surface field to gradient than a pillbox structure.

PBG Structure Coupling: No small aperture





•HFSS simulation of rf coupling into PBG cavity

•Brazed single cell PBG structure

- Coupling into PBG structure avoids small aperture
- Avoids melting or breakdown at aperture
- Useful for testing breakdown on central rods

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  - **Dielectric Loaded Accelerator Structures**
  - **Dielectric Loaded Wakefield Accelerators**
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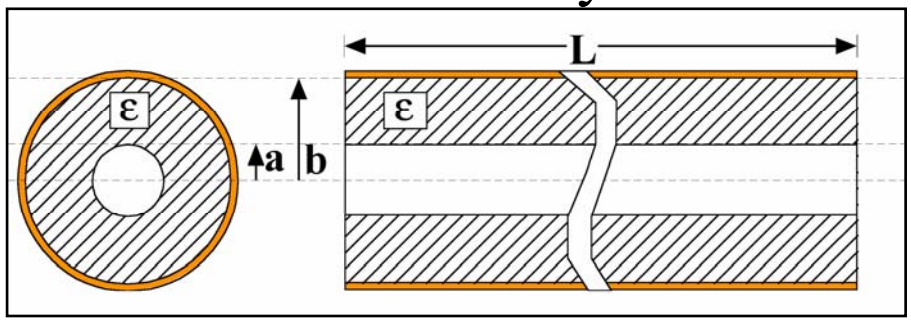
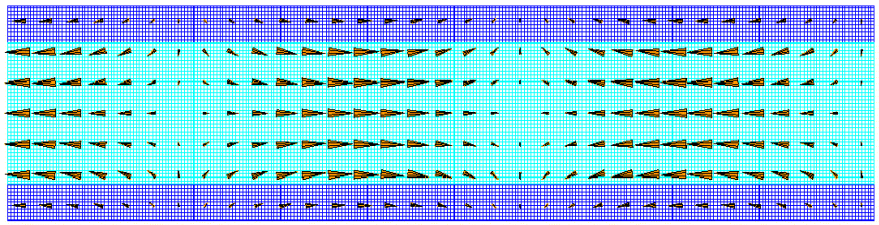
Dielectric Loaded Accelerating Structures

→ANL, NRL, SLAC Collaboration
→Externally RF driven
→Program Goals
  →DLA Structure Development
  →DLA High Power RF Testing

Geometry



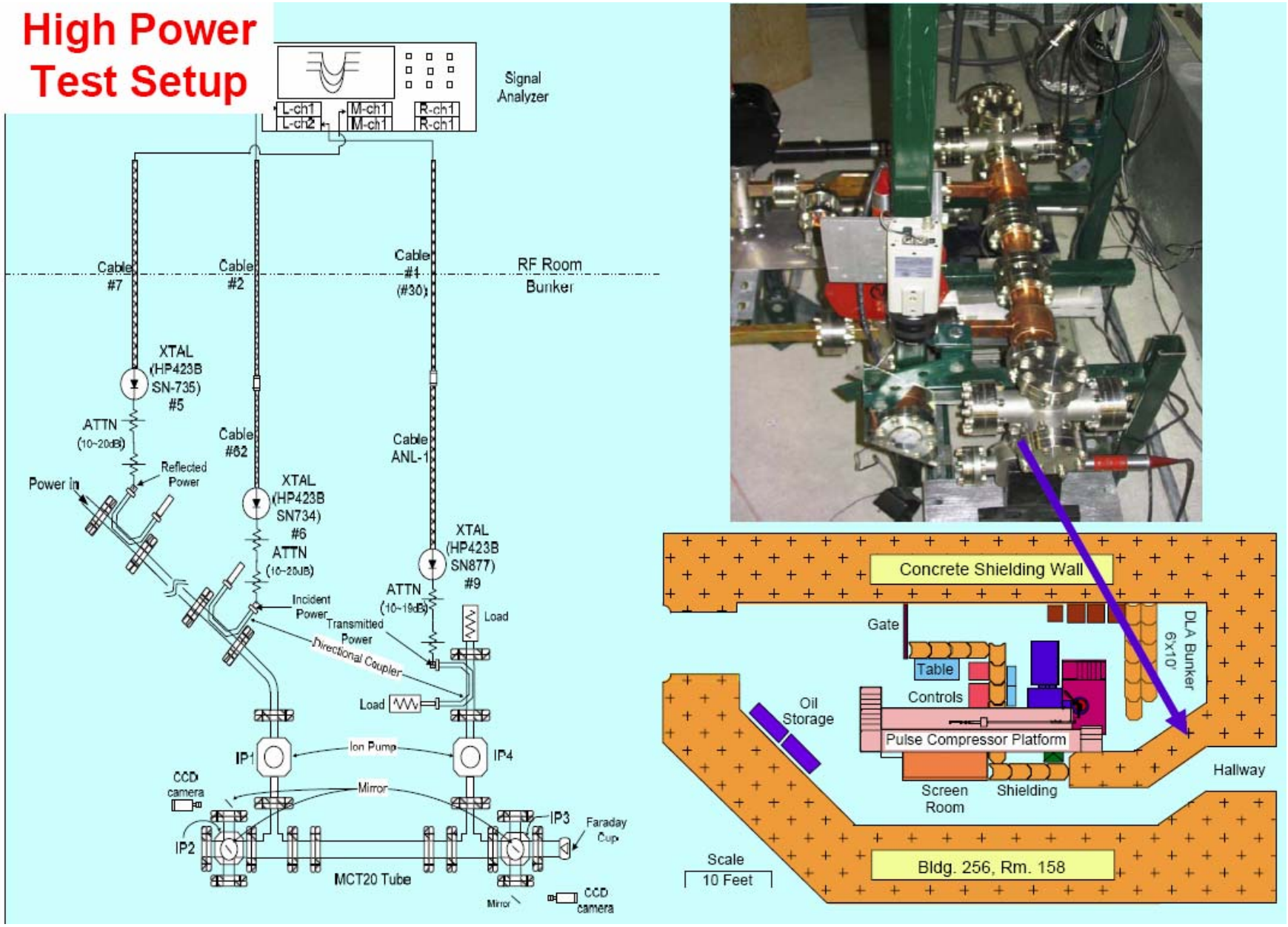
Electric Field Vectors (TM_{01})



Advantages of DLA

- Simple geometry
- No field enhancements on irises
- High gradient potential
- Comparable shunt impedance
- Easy to damp HOM

Test Setup at Naval Research Lab



High Power Testing at the NRL Magnicon Facility

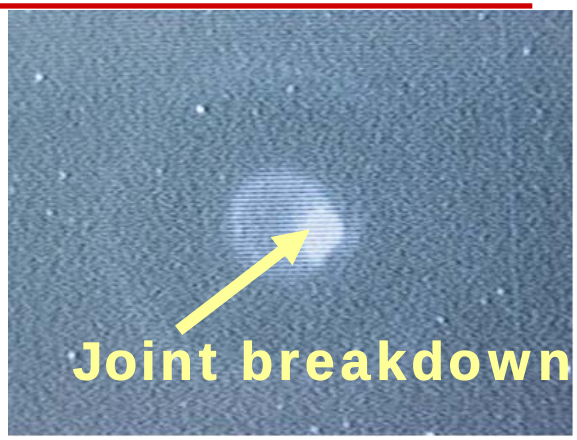
→Experimental

→No breakdown in the bulk dielectric

→Demonstrated ~ 8 MV/m gradient in alumina DLA structure without rf breakdown or dark current, but with unexpectedly strong multipactor RF loading.

→Theoretical

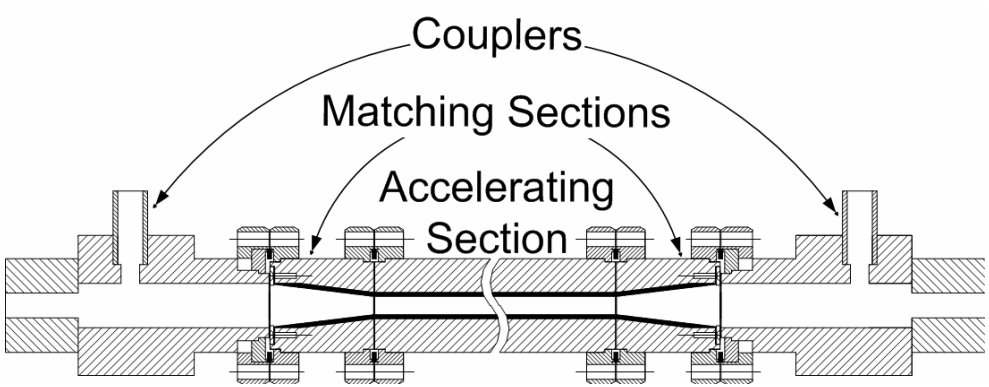
→Developed new multipactoring theory, work still ongoing

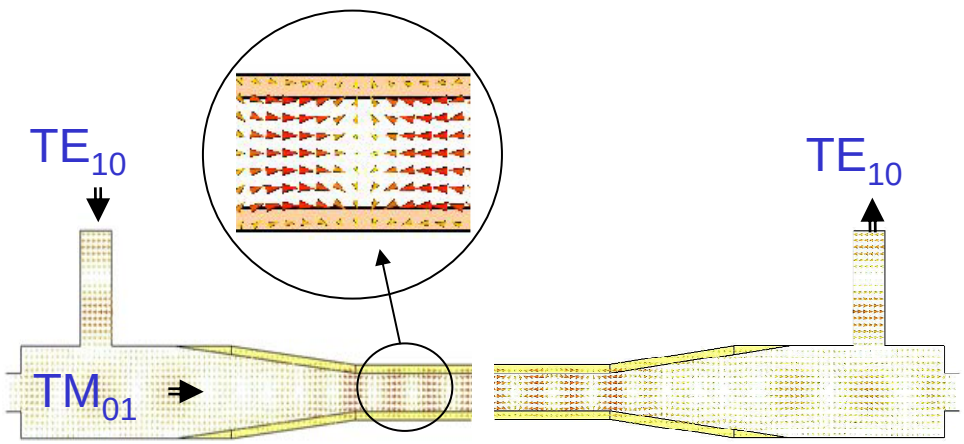


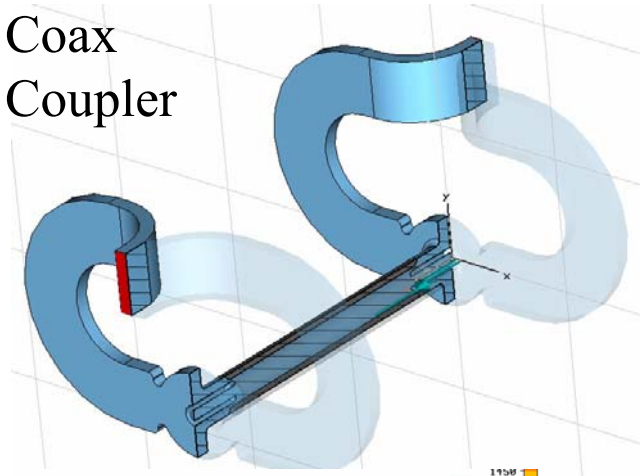
Design and EM Simulations of DLA Structures

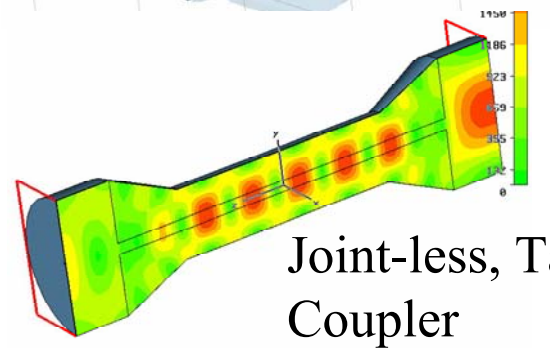
3rd Generation Structure

→eliminated coupler breakdown









New Structures

→joint-less (avoid joint breakdown)

→small I.D. (high gradient, reduce multipactor)

Dielectric Loaded Accelerating Structures

→DLA Progress to Date

- →Four generations of couplers and structures tested.
- →Four different dielectric materials tested (Alumina, Fused Quartz, MCT, TiN-coated Alumina)
- →No Breakdown of the bulk dielectric observed (up to 8 MV/m)
- →Multipactoring and joint breakdown discovered
- →Gained fundamental understanding of the issues: developed new multipactoring theory, designed new structures and couplers

→DLA Future Program

- →High Power Testing: (i) Joint-less DLA Structures (avoid joint breakdown); (ii) Small I.D. DLA Structures (high-gradient, reduced multipactor); (iii) Double-Layer Dielectric DLA Structures (lower power attenuation)
- →Multipactor Modeling (make more realistic, effect of TiN, make 3D)

The Argonne Wakefield Accelerator Facility (AWA)

High Power Electron Beam (~ GW) Technologies

Operating a unique facility to study high current electron beam generation and propagation for efficient beam driven schemes.

Advanced Accelerating Structures

Current effort has lead to comprehensive knowledge on construction and testing of dielectric based accelerating structures.

Fundamental beam physics and advanced diagnostics

High brightness beam generation and propagation, and development of novel beam diagnostics.

Brief history:

The AWA Facility successfully demonstrated collinear wakefield acceleration and two-beam-acceleration in dielectric loaded structures. The initial accelerating gradients were limited to modest values (< 15 MV/m) due to the quality of the drive electron beam. The upgraded drive gun has led to increasingly higher gradients, recently reaching **86 MV/m**.

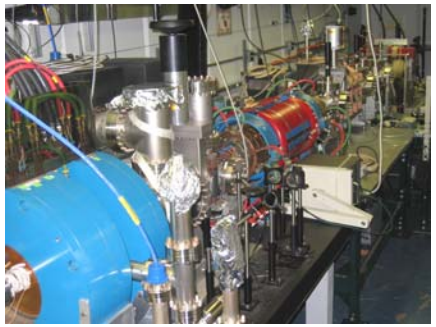
AWA Electron Beam

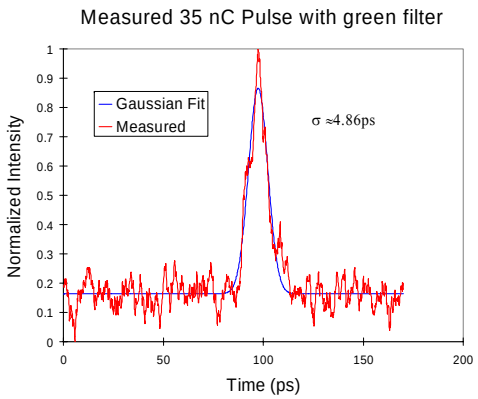
Drive Gun

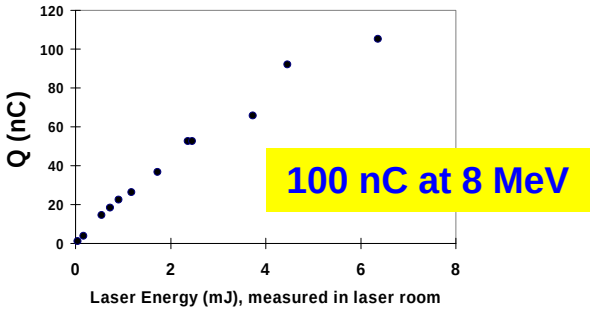
- 1 ½ cell, L-band (1.3 GHz)
- 12 MW yielding 80 MV/m on cathode
- **8 MeV electron bunches with 1 -100 nC**
- bunch length < 13 ps FWHM (with 35 nC)
- Emittance < 300 mm mrad (with 35 nC)
- Base pressure: 4×10^{-10} Torr
- Mg photocathode (Cs_2Te cathode under development)

Linac Structure

- **Boosts energy to 14 MeV**
- Large irises to minimize wakefields





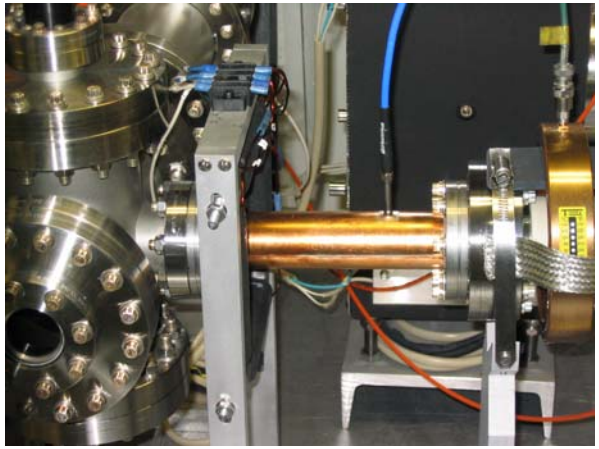


High Gradient Wakefield in Dielectric Loaded Structures

- High gradient wakefields are excited by high charge electron bunches traversing short standing-wave dielectric-loaded structures.
- A field probe is used to monitor the electric field inside the structure, and verify that breakdown does not occur.
- MAFIA is used to simulate the wakefield gradient generated by the traversing charge.

Parts and accessories

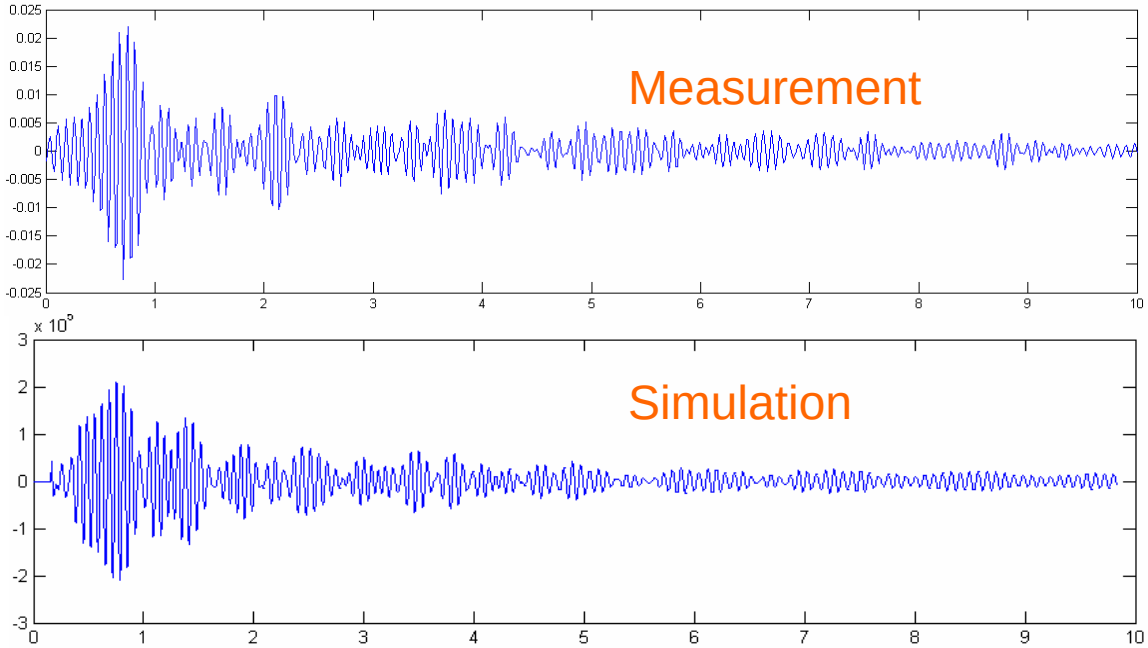
Structure Parameters	Structure1	Structure2
Material	Cordierite	Cordierite
Inner diameter	10 mm	5 mm
Outer diameter	15 mm	15 mm
Dielectric Const	4.76	4.76
Length	23 mm	28 mm
Freq. of monopole modes	~14 GHz	~10 GHz
Wakefield gradient (per nC)	0.5 MV/m	1 MV/m

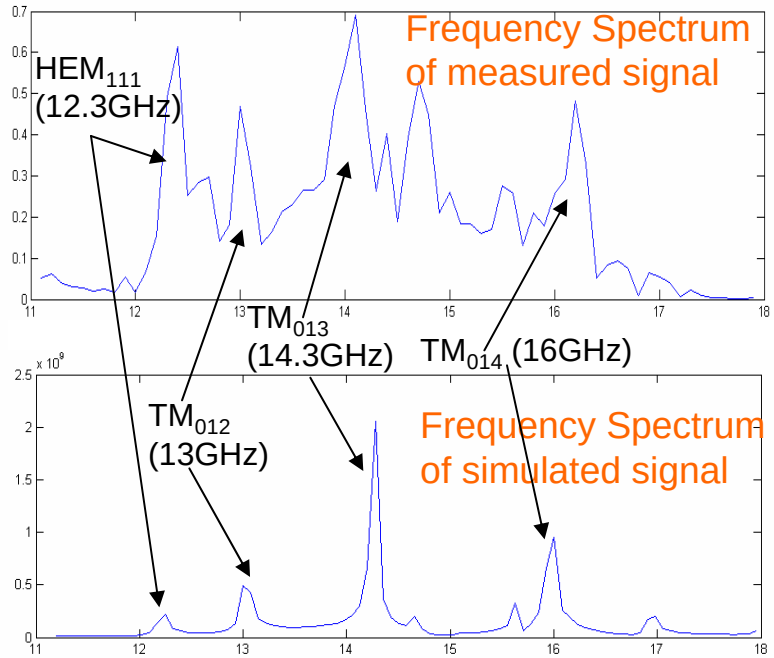


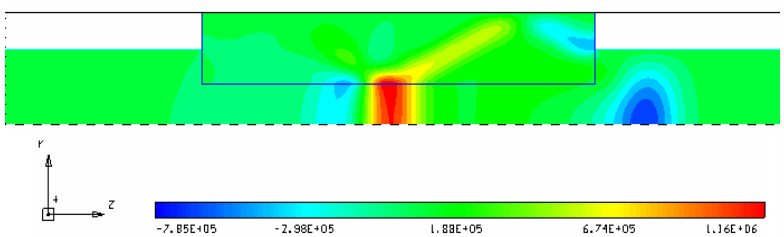
Final assembly in beamline

Wakefield Measurements and Simulation

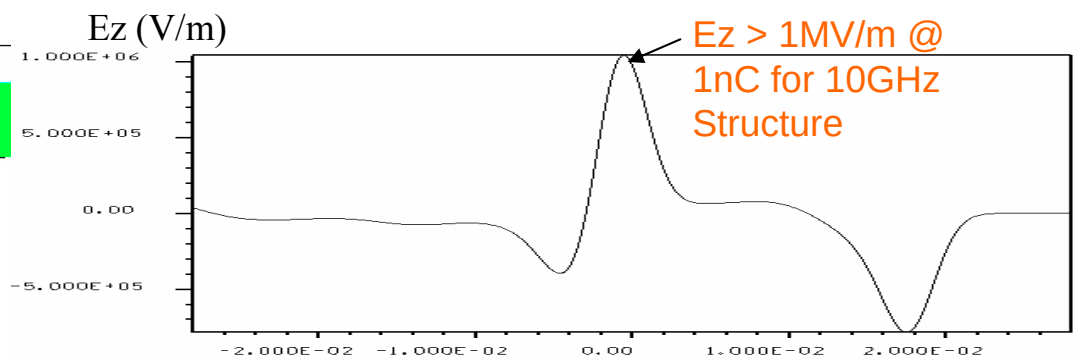
Measurement and simulation of 14GHz DLA Structure @ 86nC passing charge







E-field pattern

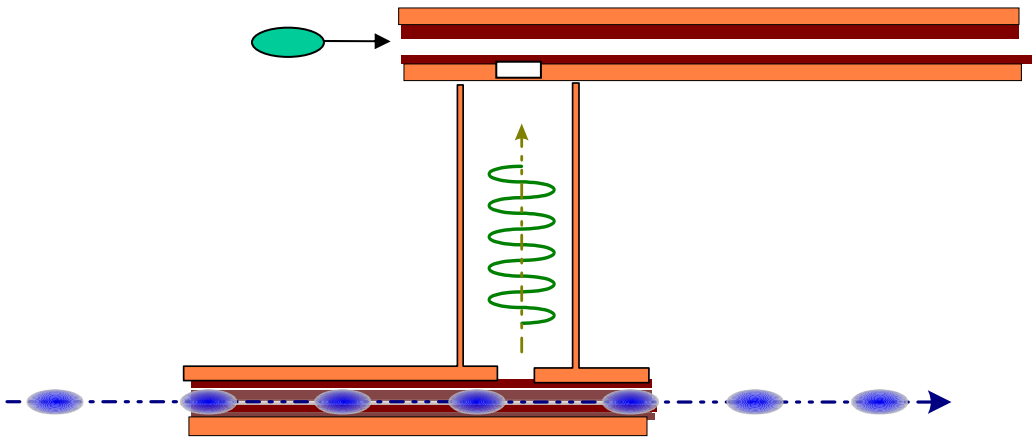


Present Status and Future Plans

- The maximum bunch charge passed through these recently tested structures has been 86 nC.
- According to MAFIA simulations, this corresponds to accelerating gradients of about 43 MV/m in the 14 GHz structure and 86 MV/m in the 10 GHz structure.
- The field probe that monitors the electric field in the structures has not shown any signs of electric breakdown.
- In the near future, a new structure with smaller inner diameter, will allow excitation of accelerating fields in excess of 100 MV/m.
- Presently the AWA Facility is being upgraded.

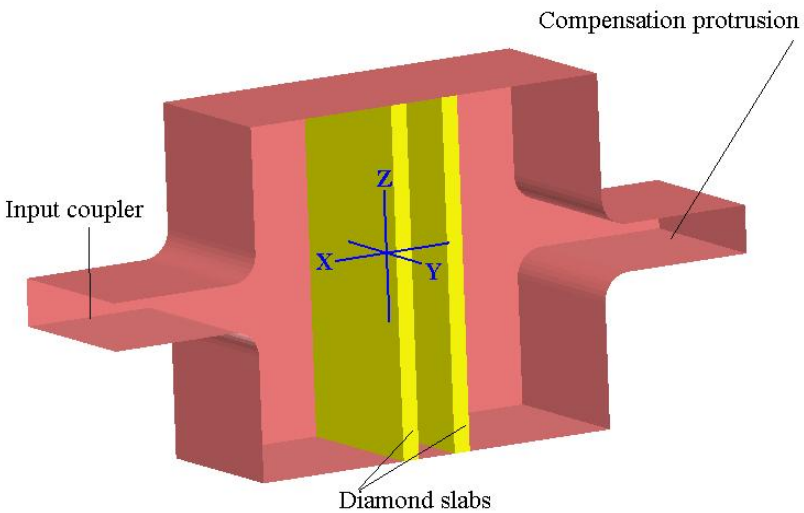
An Example of Two-Beam Accelerator (Future Goal)

- Drive beam: 64 bunches of 50 nC, each separated by one RF period, generating a 50 ns long RF pulse.
- Stage I (28 cm long): 2a=11 mm, 2b=22 mm, ε = 4.6, 45 MV/m deceleration field, generating 500 MW (flat top).
- Stage II (85 cm long): 2a= 6mm, 2b= 11 mm, ε = 20, 112 MV/m acceleration field, yielding a total acceleration of 95 MeV.



Proposed DLA using diamond (Omega-P & Yale)

Rectangular dielectric-loaded structures with peak RF fields on dielectrics are now under study (C.Wang, *this meeting).* Diamond has an advertised DC breakdown strength of 2 GV/m, but RF breakdown limits must be measured. Test cell cavity is being designed for this purpose, using RF power from the Yale/Omega-P Ka-band magnicon.



cutaway view of test cavity

<u>parameters of cavity</u>

<u>frequency</u>: 34.3 GHz;

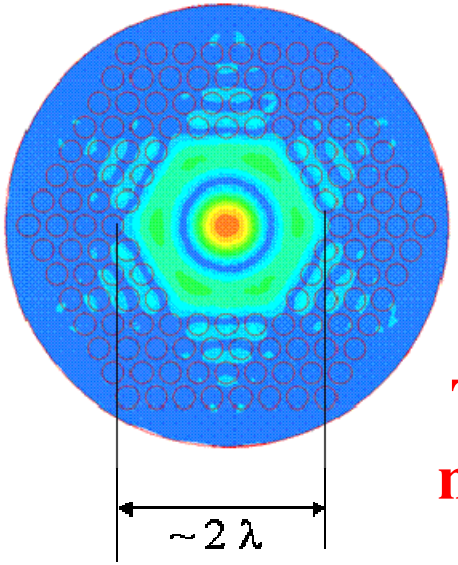
<u>diamond</u>: ε = 5.7, tanδ = 3×10^{-5},
two slabs, $26.2\times12.0\times1.3$ mm^3;

<u>max field on diamond</u> = 900 MV/m,
for RF input power of 10 MW
at a pulse width of ~100 ns,
unless breakdown prevents.

Tests planned for hydrogenated and de-hydrogenated diamond.

Novel Structure Research

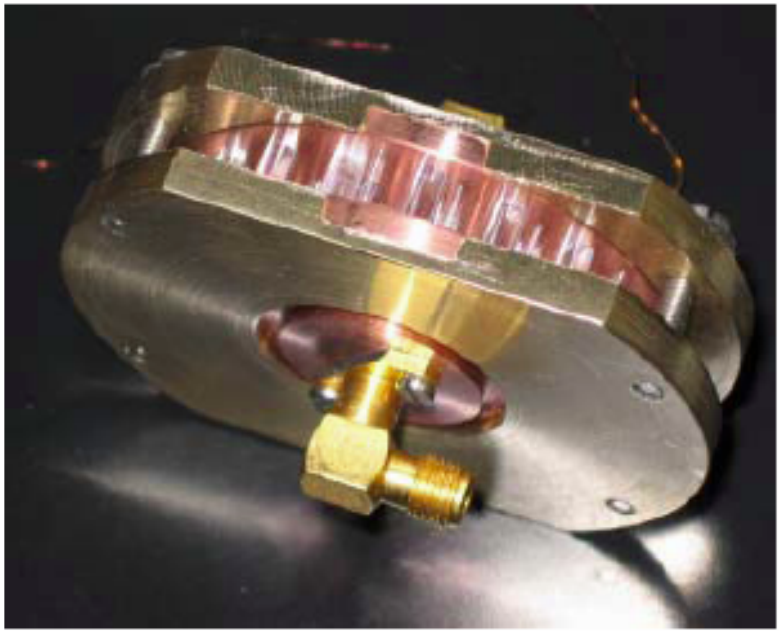
- Dielectric Photonic Bandgap Structures
  - High order mode accelerator
  - Shapiro et al., PAC03



TM_{02}–like mode

- A hybrid metallic-dielectric PBG test cavity: sapphire cylinders between two Copper plates.

- Built and tested by research groups in Napoli, Italy
Ref.: Andreone et al., EPAC 2004.

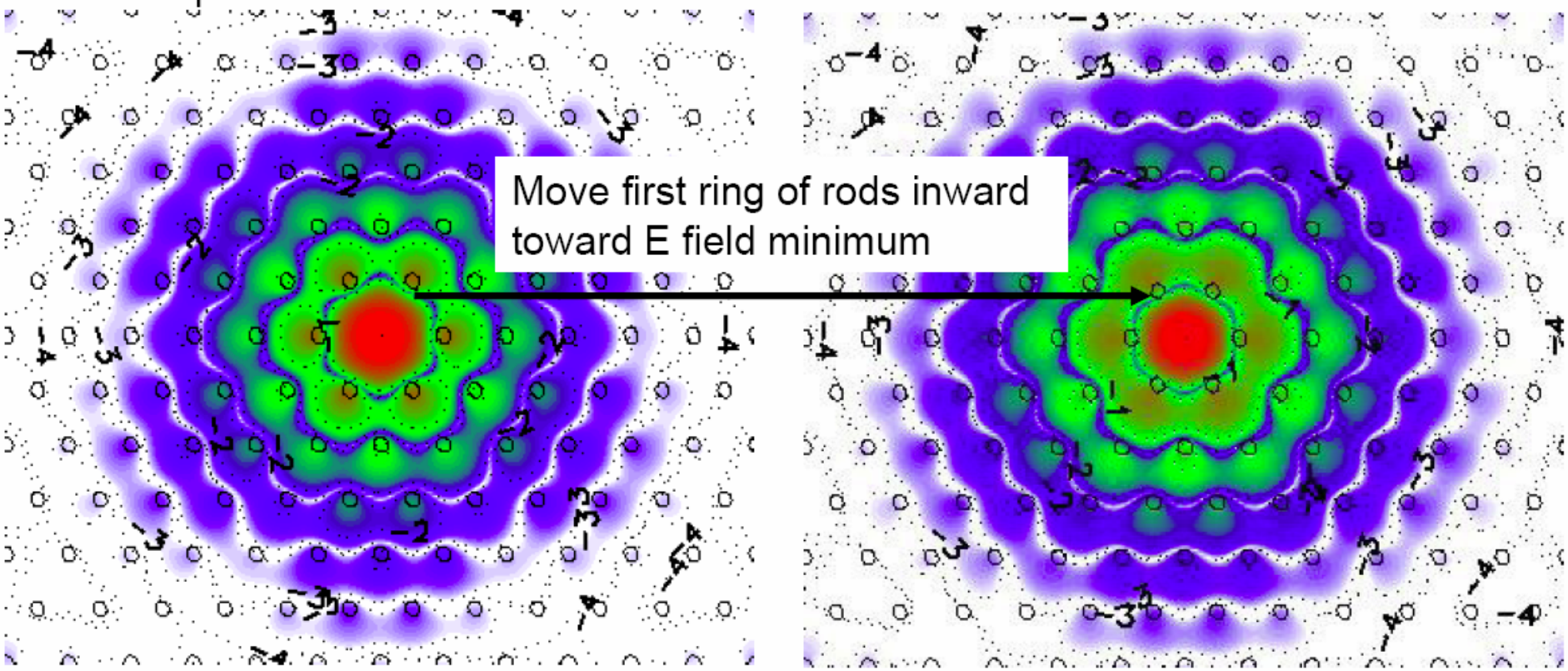


How Can PCs Increase Gradients?

G. Werner,
J. Cary, U CO

Novel field configurations that reduce maximum surface fields, especially with dielectric PCs, but also with metal PCs.

Example: with dielectric PC



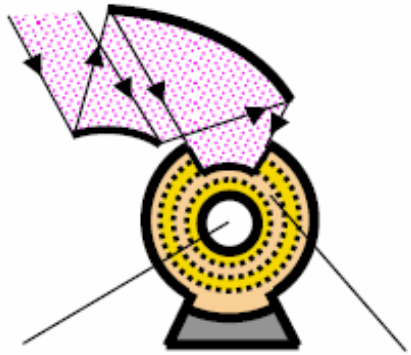
Example: with dielectric or metal PC

Remove first ring of rods entirely! The selective reflection of PCs makes working in high order modes easier.

Other Ideas

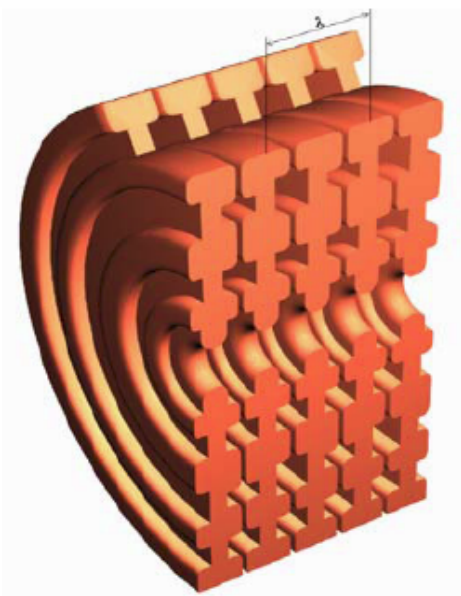
- Space available for your new idea here!

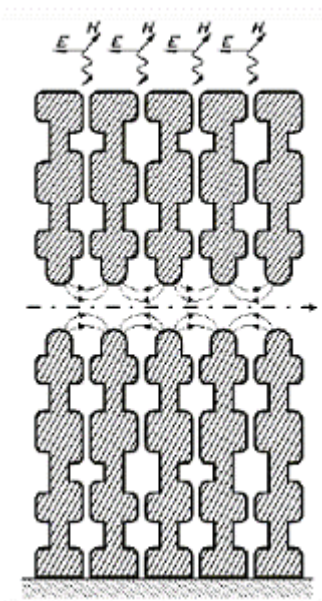
Quasi-optical Structures



Channel for microwave energy storage and particle acceleration

Radial Bragg reflector





- High-intensity power flow controlled by oversized, high selectivity, quasi-optical components.
- Structure may be attractive for maximizing the accelerating gradient while avoiding RF breakdown and surface fatigue from pulsed RF heating

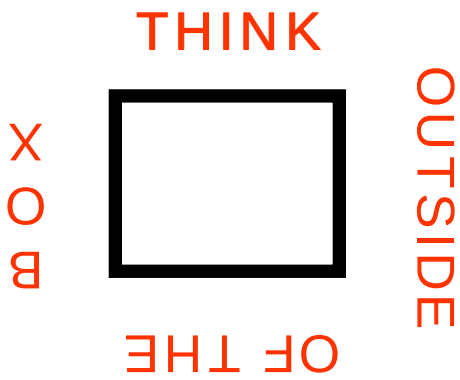
Ref.: Petelin, Hirshfield, et al. High Power RF Workshop, 2006

Outline

- Introduction / Motivation
- Millimeter Wave Sources
- Millimeter Wave Structures
- Wakefields / Photonic Bandgap Structures
- Dielectric Loaded Structures
- New Ideas: Quasi-optics
- **Conclusions**

Conclusions

- **High Frequency Microwave technology is a practical path toward a multi-TeV, high luminosity linear collider in the next 30 years.**
- **Research has demonstrated major advances in:**
  - High Frequency Microwave Sources
  - Studies of breakdown and pulsed heating at 11 through 30 GHz
- **Research is needed to:**
  - Reduce peak surface fields
  - Reduce wakefields.
- **Need a New Graph!**



- **High Frequency microwave accelerators are very promising to provide reliable structures for accelerator operation in the 100 to 200 MV/m range**

Acknowledgments

THANKS TO:

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