Advanced Materials for High Gradient Dielectric Based Accelerator

Euclid Techlabs and Accelerator R&D, HEP, ANL

A.Kanareykin

Euclid TechLabs LLC, Rockville, MD

This work is supported by
the DOE, High Energy Physics

Euclid Techlabs

Euclid TechLabs LLC, founded in 1999 (as Euclid Concepts LLC) is a company specializing in the development of advanced dielectric materials for particle accelerator and other microwave applications. Additional areas of expertise include theoretical electromagnetics; dielectric structure based accelerator development; superconducting accelerating structure design; "smart" materials technology and applications; and reconfigurable computing.

Euclid and the Argonne Wakefield Accelerator group at ANL have a long history of successful collaboration in engineering development and experimental demonstration of high gradient acceleration using a number of different dielectric structures and electron beam configurations.

Collaborations with ANL, FNAL, Yale/Omega-P, UCLA.

Dielectric Based Accelerator:

High Gradient (>100 MV/m)

High Efficiency (high shunt impedance, low losses)

and

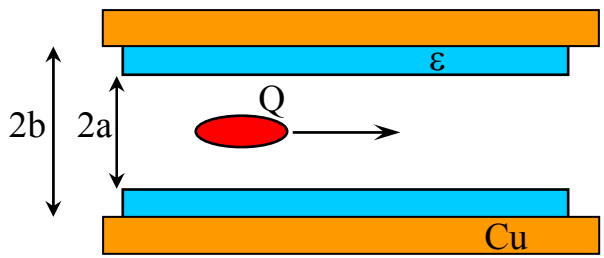
- Coupling (field enhancement) for externally powered (rf) structures
- High Transformer Ratio (energy transfer) for Wakefields
- Multipacting/Breakdown suppression
- Tuning

Outline

- Diamond Based DLA Structure
- Coaxial Coupling Section for the DLA Structure
- Transformer Ratio Experiment
- BST Ferroelectric Development/Tunable DLA
- Multilayer Dielectric Based Accelerator
- Active Media Development

This work is supported by the DOE SBIR program, High Energy Physics

Dielectric Materials for the HG Dielectric-Based Accelerator



material	ε	tanδ, X-band	Δε/ε, 4 V/μm
BST+MgO	350-500	5×10^{-3}	1.30

material	ε	tanδ, X-band	thermo-conductivity
diamond	5.7	1×10^{-4}	2500W/m/^{0}K

material	ε	tanδ, X-band	thermo-conductivity
quartz	3.8	1×10^{-4}	1.4 W/m/^{0}K

Low loss microwave ceramic

Materials	ε (f = 9,4 GHz)	tan δ (f = 9.4 GHz)
Cordierite	4.5±0.2	$\leq 2\times10^{-4}$
Forsterite	6.3±0.3	$\leq 2\times10^{-4}$
Alumina	9.8±0.3	$\leq 1\times10^{-4}$
D-10	9.7±0.2	$\leq 1.5\times10^{-4}$
D-13	13.0±0.5	$\leq 2\times10^{-4}$
D-14	14.0±0.5	$\leq 0.6\times10^{-4}$
D-16	16.0±0.5	$\leq 2\times10^{-4}$
MCT-18	18.0±3%	$\leq 1\times10^{-4}$
MCT-20	20.0±5%	$\leq 1.5\times10^{-4}$
V-20	20.0±5%	$\leq 3\times10^{-4}$
V-37	37.0±5%	$\leq 3\times10^{-4}$

CVD DIAMOND-BASED ACCELERATOR

*

PROJECT IN COLLABORATION

WITH ANL/AWA

* Rough Octohedral Diamond Crystal USGS, http://chemistry.about.com/cs/geochemistry/a/aa071601a.htm

DIAMOND CHEMICAL VAPOR DEPOSITION (CVD)

CVD DIAMOND PROPERTIES:

- RF BREAKDOWN THRESHOLD OF ~ 2 GV/m

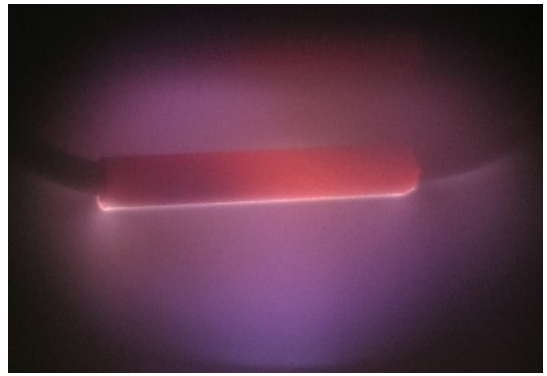
- HIGHEST THERMAL CONDUCTIVITY (2.5×10^3 W /m $\times^0$K)

- MULTIPACTING CAN BE SUPPRESSED

- We measured the loss tangent and permittivity of the sample at 19.25 GHz. The dielectric constant 5.69±0.02 (5.7 nominal for diamond) and LOSS TANGENT is of $(22\pm4)*10^{-5}$ at 19.25 GHz.

...and CVD DEPOSITION NOW CAN BE USED TO FORM CYLINDRICAL WAVEGUIDES

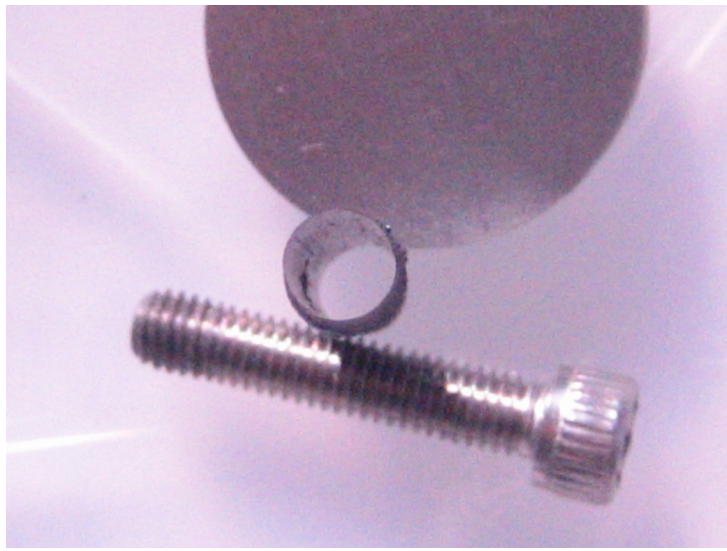
PLASMA SUPPORTED CVD-DIAMOND CYLINDRICAL WAVEGUIDE FABRICATION



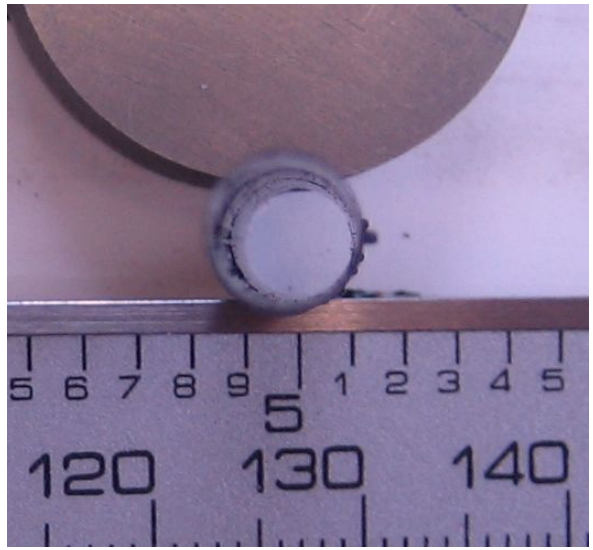
Photographs of the 5 mm ID alumina substrate in the PECVD reactor *.

*Developed for Euclid Techlabs by Coating Technology Solutions, Inc. Somerville, MA

CVD – DIAMOND 30-34 GHz



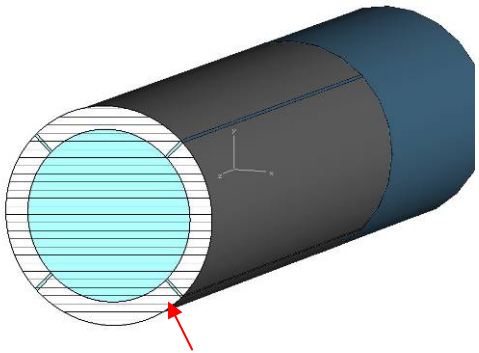
CVD-diamond Ka-band 5 mm ID cylindrical waveguide*



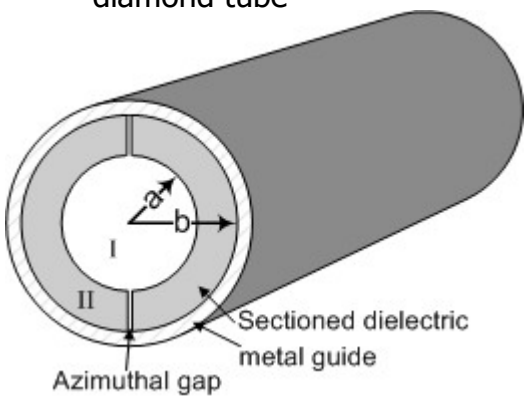
Scaling of the CVD Diamond Ka-band 5 mm ID structure.

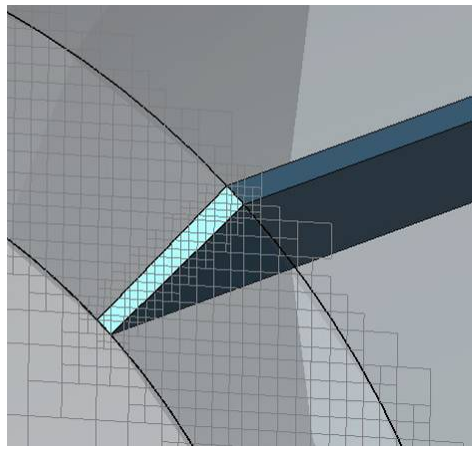
*Developed for Euclid Techlabs by Coating Technology Solutions, Inc. Somerville, MA

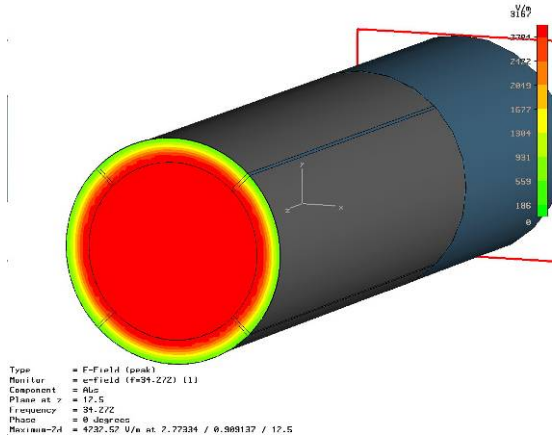
Segmented Diamond Tube

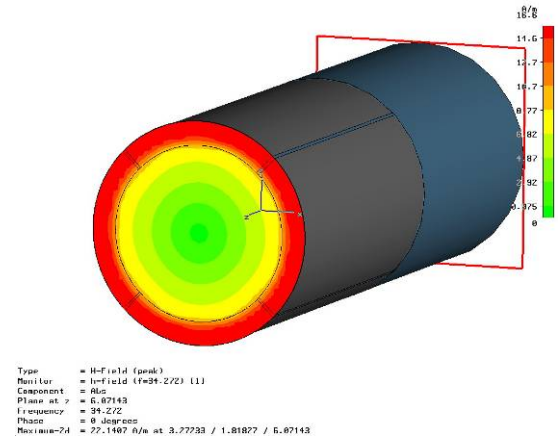


Segmented diamond tube

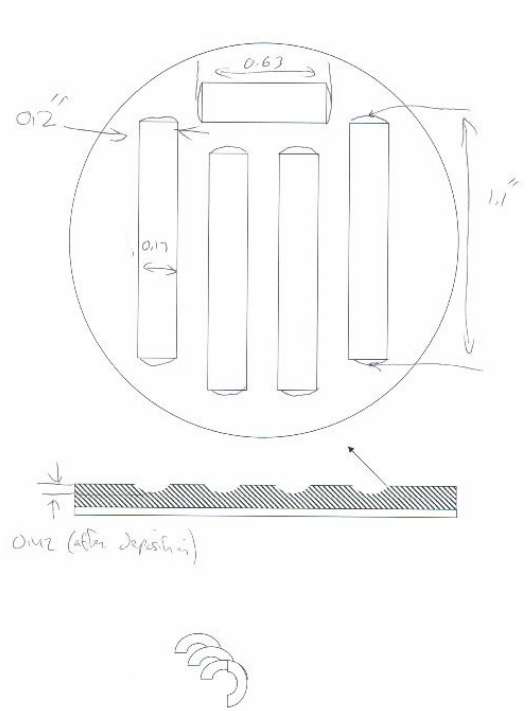


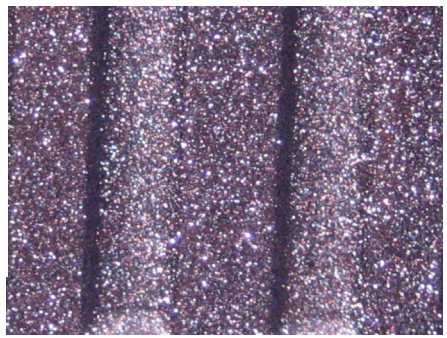


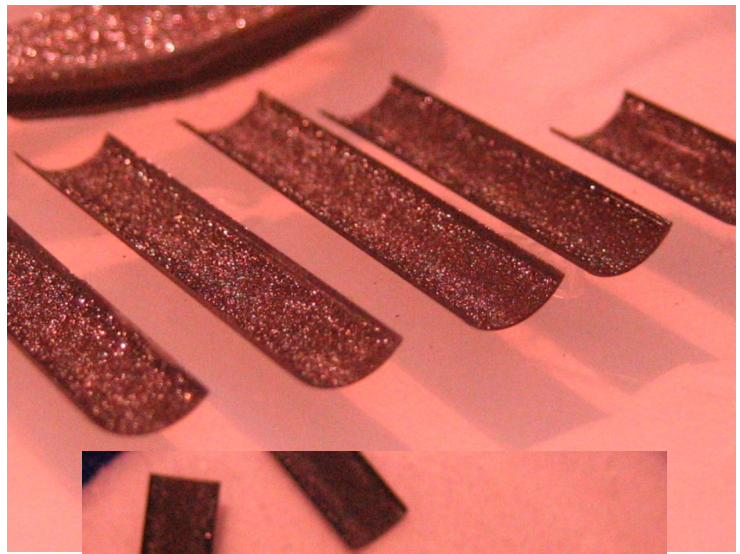


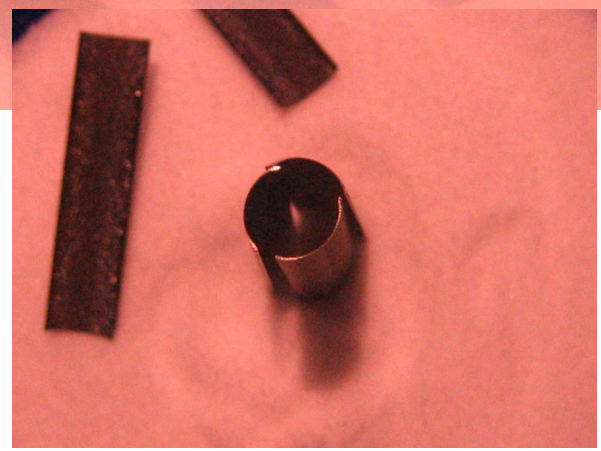


Diamond Tube Segments



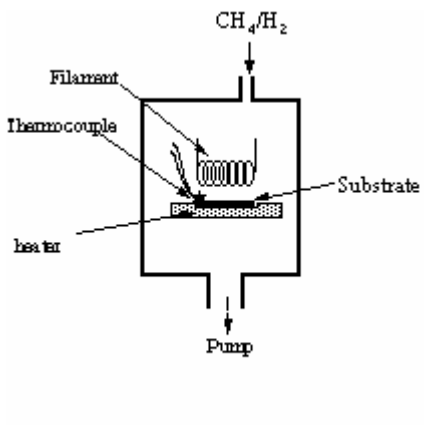




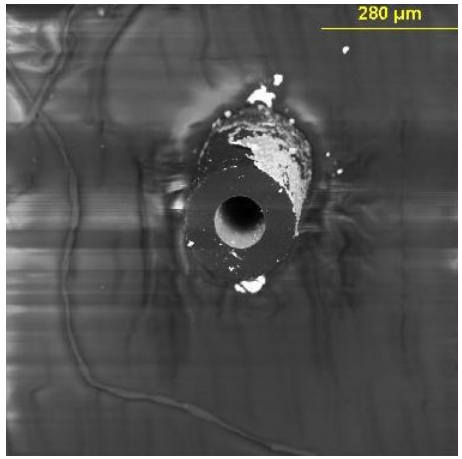


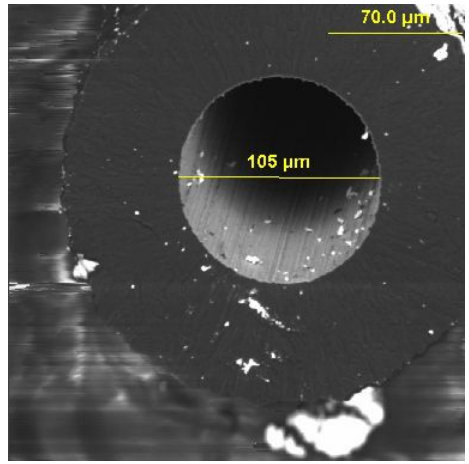
*Developed for Euclid Techlabs by Coating Technology Solutions, Inc. Somerville, MA

THz Scale Diamond Tubes



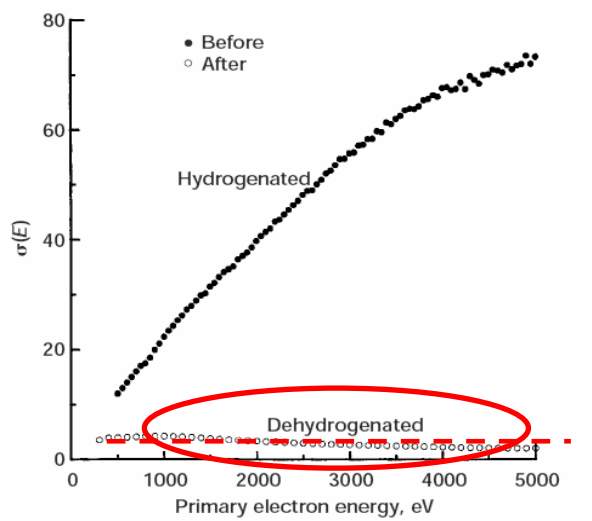
Schematic drawing of a hot filament CVD reactor.





Scanning electron microscope images of a THz diamond microstructure produced using the hot wire deposition technique.

SEE COEFFICIENT



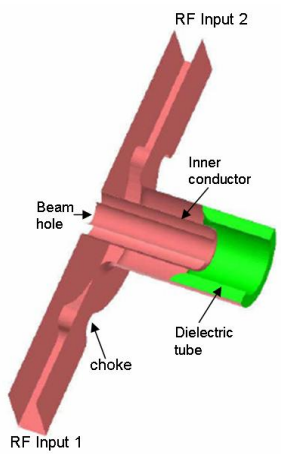
I.L. Krainsky et al. NASA Report/TP—1999-208692, (1999)

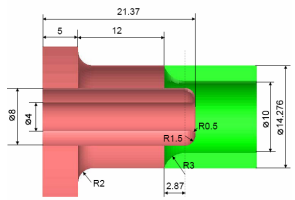
Collaboration:

- NRL, Surface Chemistry (J.Butler)
- Genvac Aerospace Inc./NASA
- Coating Technology Solutions, Inc.

Multipacting is suppressed by treating the diamond surface during the CVD growth of the diamond, in particular, dehydrogenation of the surface to decrease the secondary electron yield. SEE coefficient is reduced from 60 to 1.

NEW COAXIAL-TYPE COUPLER FOR THE DIELECTRIC-BASED ACCELERATOR*

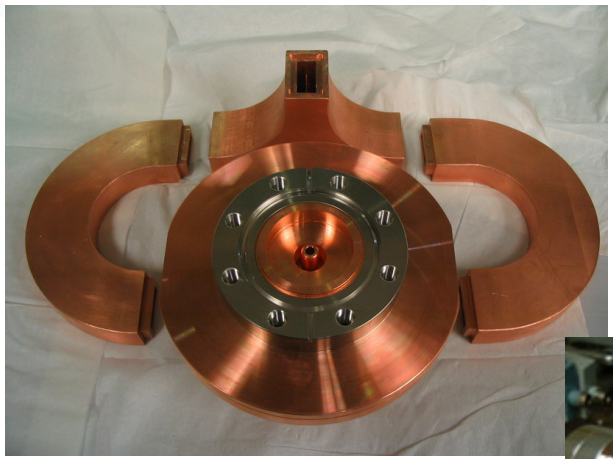


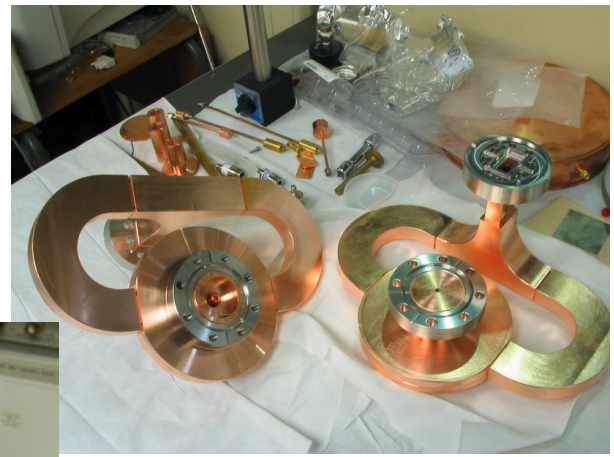


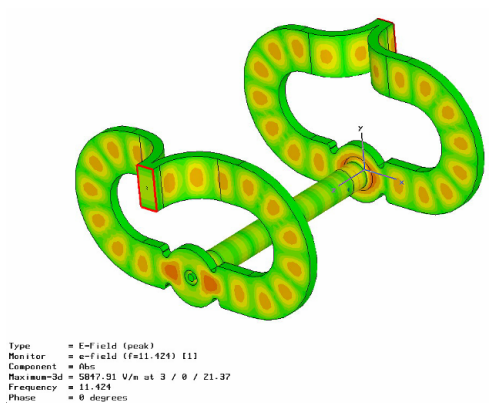
PROJECT IN COLLABORATION WITH ANL/AWA

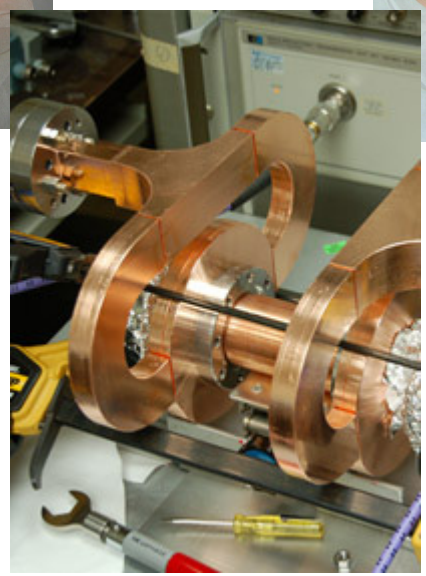
* Talk by C. Jing

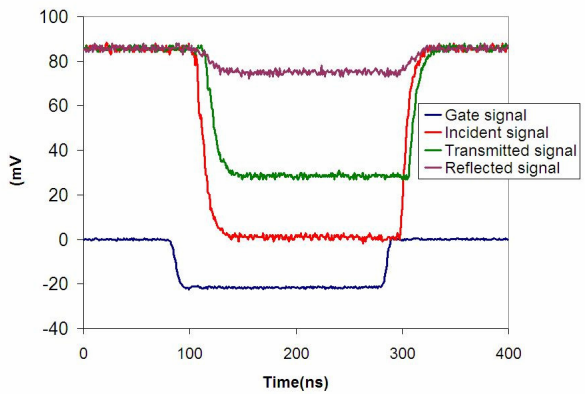
New Coupler Design for DLA Structures







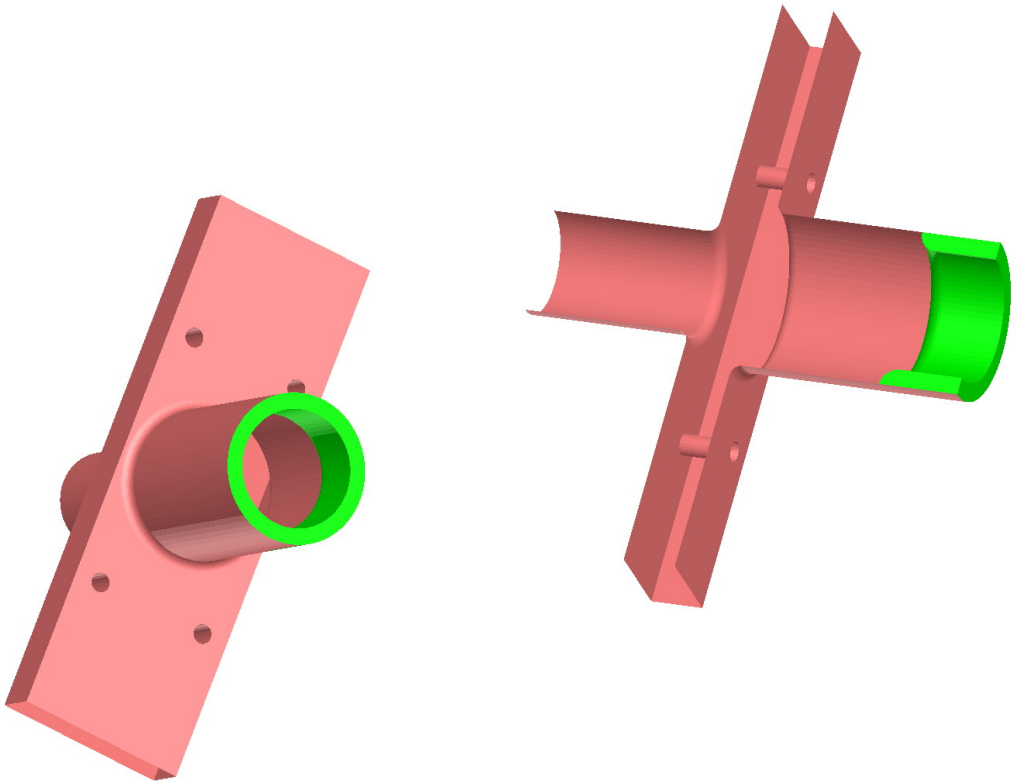


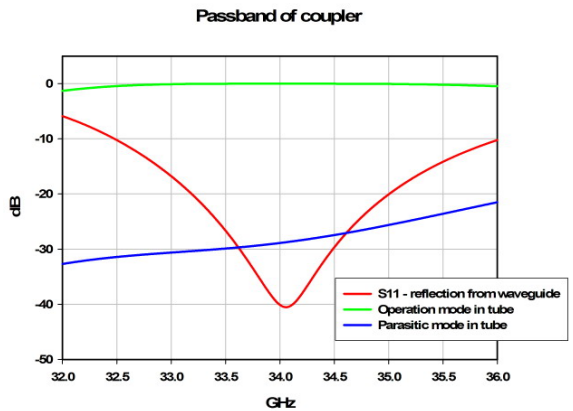


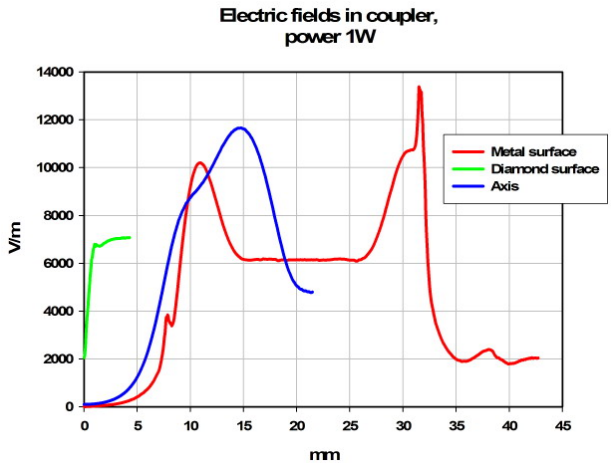
Euclid Techlabs LLC

US HG Research Collaboration Workshop
SLAC, 2007

Coupling of the Diamond DLA







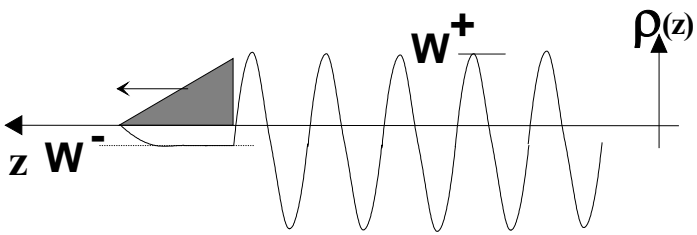
TRANSFORMER RATIO ENHANCEMENT EXPERIMENT FOR THE DIELECTRIC-BASED ACCELERATOR*

PROJECT IN COLLABORATION WITH ANL/AWA

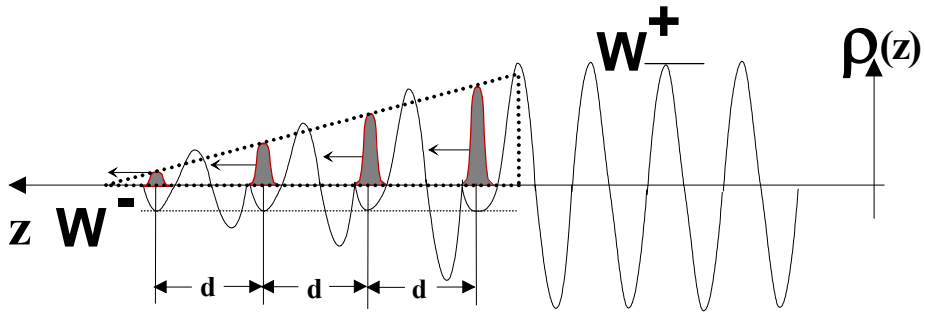
Euclid Techlabs LLC

US HG Research
Collaboration Workshop
SLAC, 2007

Transformer Ratio Experiment



Reference: K.Bane, P.Chen, P.Wilson, IEEE Trans. Nucl. Sci. NS-32, 3524 (1985)



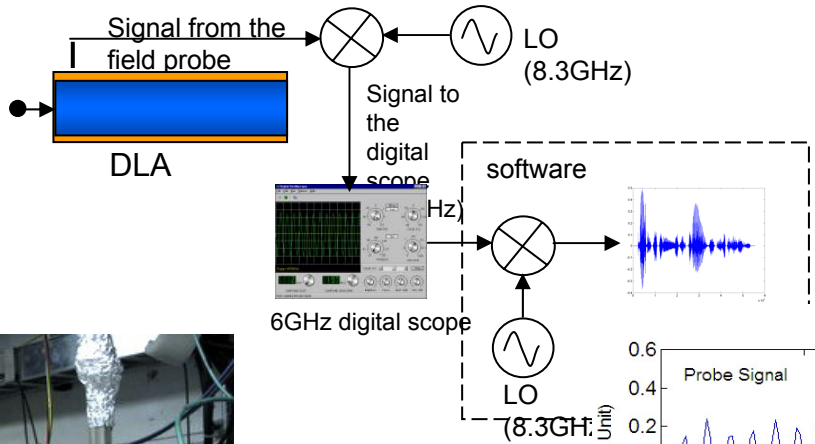
Reference: Schutt ,Tsakanov, Vaganyan, Nor Ambred, Armenia, (1989)

Transformer Ratio

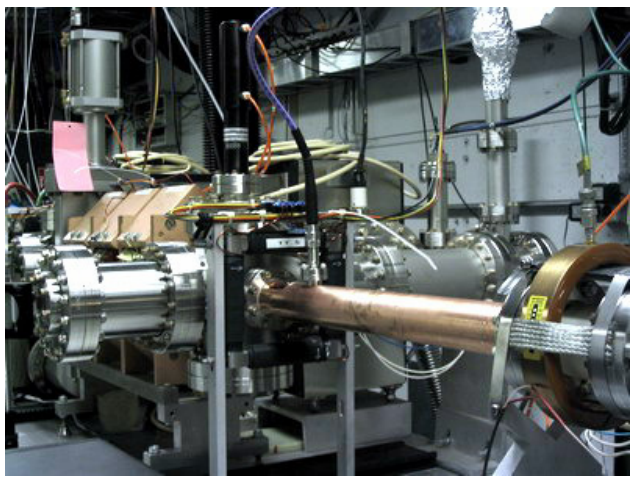
R = (Max. energy gain behind the bunch) / (Max. energy loss inside the bunch).

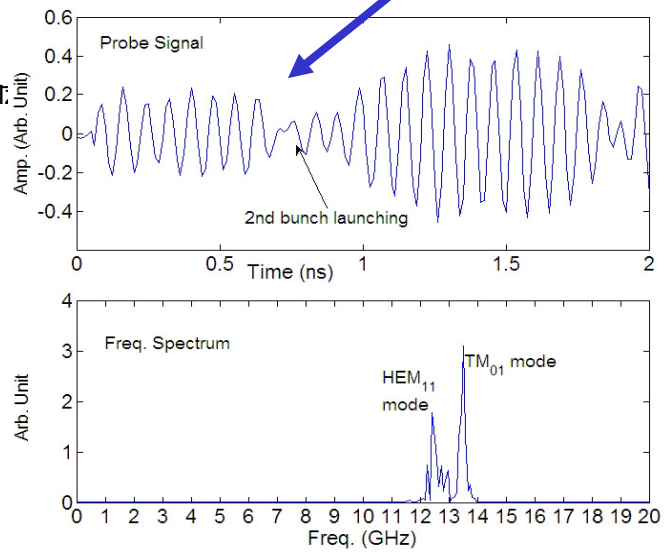
Wakefields measurements

two-bunch wakefield experiment setup

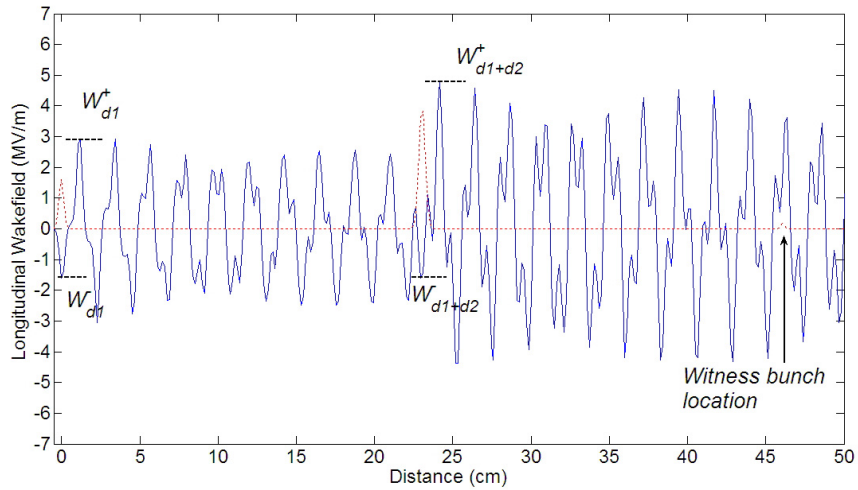


The field probe signal from the RBT in the 13.625 GHz DLA

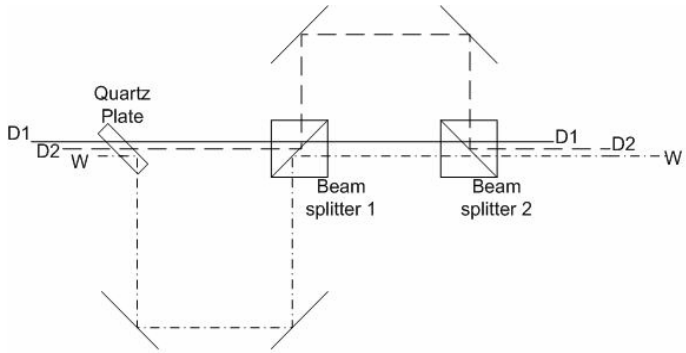




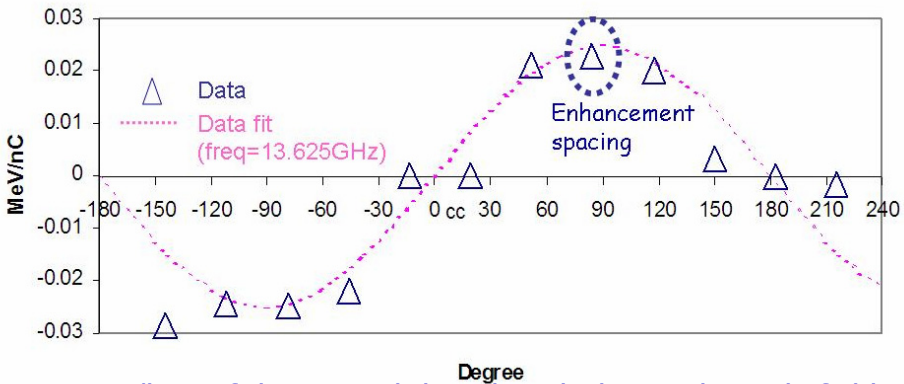
Energy Gain in Collinear Wakefield Experiment



Numerical simulation of the experiment of transformer ratio enhancement experiment carried on the AWA facility.



The configuration of laser system for transformer ratio enhancement experiment



Normalized energy gain/loss of the second drive bunch due to the wakefield behind the first drive bunch at varying spacing between them.

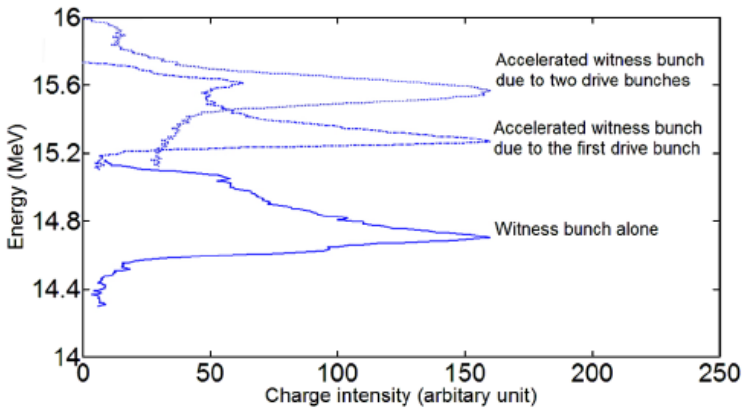
Enhanced Transformer Ratio in Collinear Wakefield Experiment

PRL 98, 144801 (2007) PHYSICAL REVIEW LETTERS week ending 6 APRIL 2007

Observation of Enhanced Transformer Ratio in Collinear Wakefield Acceleration

C. Jing,[1] A. Kanareykin,[1] J. G. Power,[2] M. Conde,[2] Z. Yusof,[2] P. Schoessow,[1] and W. Gai[2]
[1]*Euclid Techlabs LLC, Solon, Ohio 44139, USA*
[2]*High Energy Physics Division, Argonne National Laboratory, Argonne, Illinois-60439, USA*
(Received 3 November 2006; published 2 April 2007)

In a w
leading, l
bunch or
a trailing



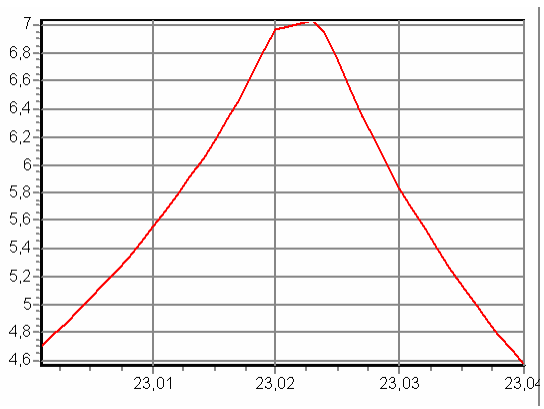
discussed
o key pa-
the trans-
rge ratios

enhancement factor of 1.31

R~2.3

Future experiments:

We plan 4-bunch train experiment with 26 GHz structure, R ~ 6-7 →



Transformer Ratio Enhancement for PWFA

In this demonstration experiment a dielectric structure was used as the wakefield accelerator; however, the use of an RBT to improve the transformer ratio is applicable to other accelerators, most importantly to beam-driven plasma wakefield accelerators that can now be operated at extremely high gradients [1] but still limited to $R < 2$. Recent publications in this area have emphasized the importance of the transformer ratio factor for the success of plasma high gradient accelerators [2-3].

[1]. M. J. Hogan et al., *Physical Review Letters*, vol. 95, Issue 5, id. 054802J. B.
[2]. J.Rosenzweig. *Proceedings PAC 2001*, pp. 100-103. (2001).
[3]. R. Maeda, T. Katsouleas, P. Muggli et al. Physical Review ST-AB, v.7, p. 111301, (2004).

A recent review for the Office of Science of the US Department of Energy by the National Task Force on High Energy Density Physics includes “Large Transformer Ratio” as part of its “Scientific Objectives and Milestones”.

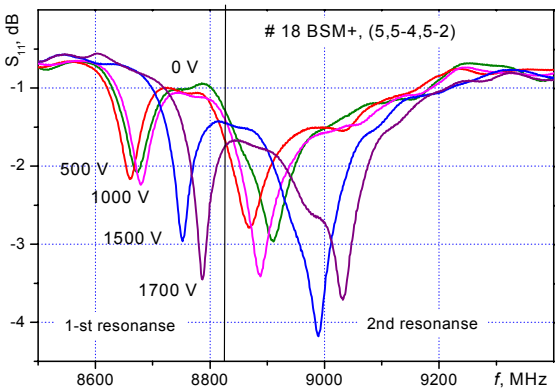
[4] National Task Force on High Energy Density Physics Review. 2004.
http://www.ingentaconnect.com/content/klu/jofe/2005/00000024/F0020001/00006922

FERROELECTRIC MATERIALS FOR:

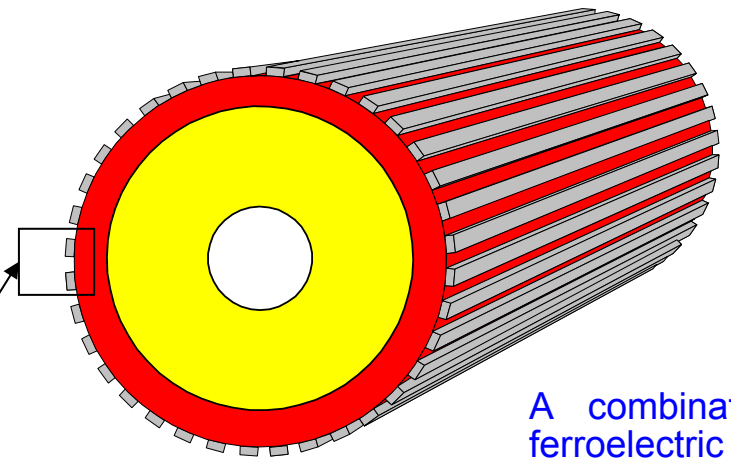
- FREQUENCY TUNING FOR DIELECTRIC BASED ACCELERATORS
- SC CAVITY COUPLING ADJUSTMENTS FOR ILC
- PULSE COMPRESSION AND POWER DISTRIBUTION FOR LINEAR COLLIDER

PROJECT IN COLLABORATION WITH YALE/OMEGA-P, INC AND ANL/AWA

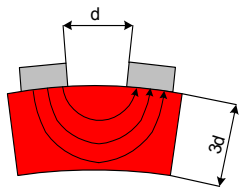
Tunable Dielectric Loaded Accelerator



permittivity of the ceramic and ferroelectric of 20 and 481 respectively, frequency shift of 162 MHz (second resonance) at 1.7 V/ μm bias field.



Microstrip electrodes

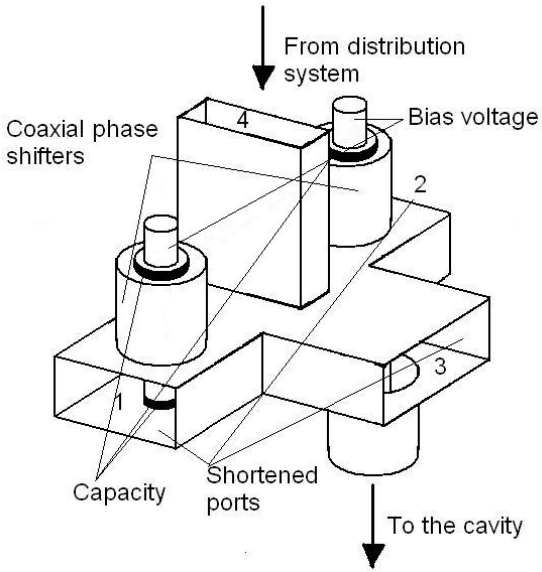


$d = 60\mu m$

A combination of ferroelectric and ceramic layers have been used to implement tuning of a composite waveguide.

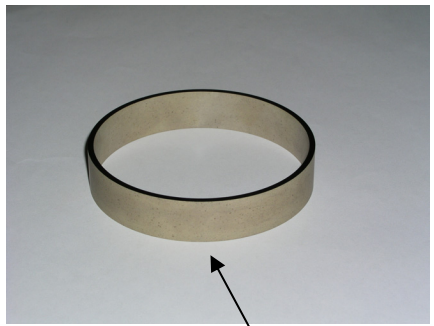
Dielectric constant variation with DC electric field allows control of the matching between the longitudinal wakefield phase and the witness beam position for acceleration efficiency.

FAST ACTIVE L-BAND HIGH POWER TUNER FOR ILC



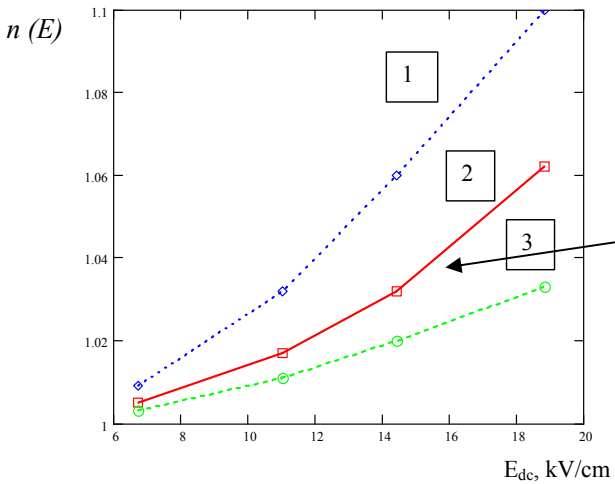
Schematic of the L-band tuner to produce fast ILC cavity coupling changes based on a magic-T and two phase shifters containing ferroelectric elements*.

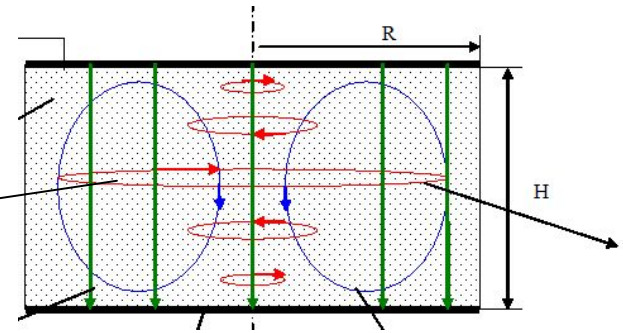
* Developed by Omega-P, Inc., New Haven, CT



Ferroelectric ring elements for the X-band high power phase shifter. The same technology will be used for the L-band tuner fabrication.

Transverse Bias Field





The BST(M)-3 dielectric-ferroelectric composite has been studied experimentally with respect to the dielectric response on the applied transverse and parallel bias fields. The absolute tunability vs. transverse and parallel biasing voltages has been measured. The theoretical analysis of the transverse bias applied to ferroelectric materials has been carried out. Finally, feasibility of the use of transverse bias configurations for ferroelectric based accelerator component tuning has been demonstrated

FERROELECTRIC PROPERTIES

- very short intrinsic response time of ~10^{-10} - 10^{-11} sec (1 ns for circuits)
- high dielectric breakdown strength of 15-20 V/μm (150-200 kV/cm)
- high vacuum compatibility
- easy mechanical treatment (similar to conventional ceramic)

Ferroelectrics should have the following properties to operate in high-power rf switching and tuning devices:

- ε - 300-500 [500-600 current, can be reduced to 150-250]
- dielectric constant ε variation-10%-20% at 5 V/μ, [15% - $E^{\perp}$, >30% $E^{\parallel}$]
- DC field - 10's of kV/cm loss factor [20 kV/cm air, tested]
- $\tan\delta$~10^{-2}-10^{-3} at 11-35 GHz [5×10^{-3} at X-band, 5×10^{-4} 760 MHz, ring]

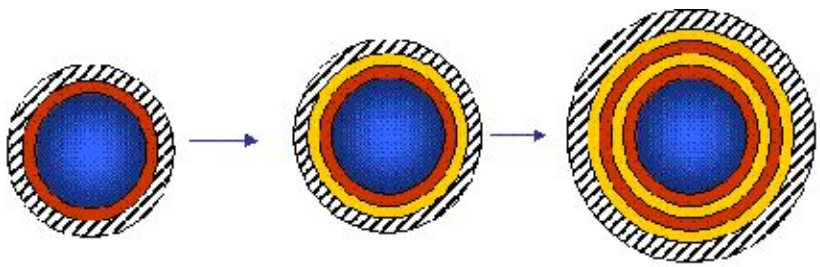
MULTILAYER DIELECTRIC BASED ACCELERATOR

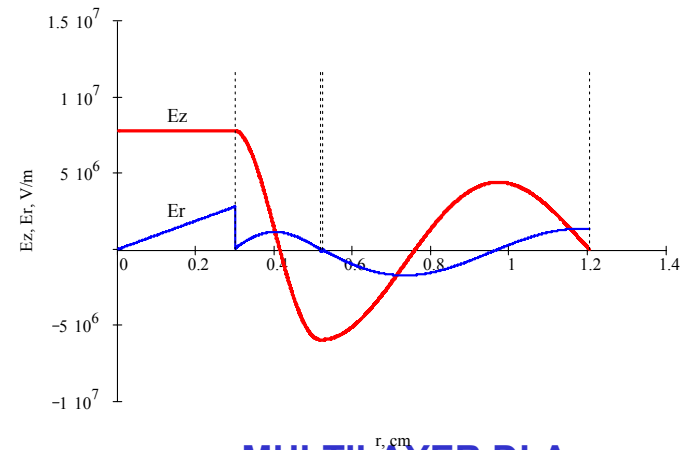
PROJECT IN COLLABORATION WITH ANL/AWA

Euclid Techlabs LLC

US HG Research
Collaboration Workshop
SLAC, 2007

Multilayer DLA structure





Layers	SINGLE	SINGLE	DOUBLE	4-LAYER
Frequency, GHz	11.424	11.424	11.424	11.424
Mode TM_{0n}	TM_{01}	TM_{03}	TM_{03}	TM_{03}
Group Velocity	0.055	0.033	0,069	0.056
Q	2249	5102	6984	8501
r(MO/m)	15	8.72	15.00	22,00
r/Q	8756	1708	2143	2585
Power Attn (dB/m)	**-14.4**	**-5.86**	**-2.14**	**-2.20**

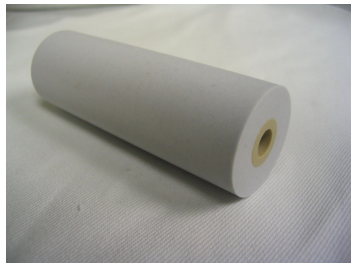
MULTILAYER DLA:

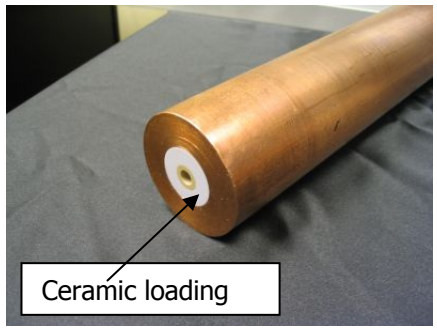
- ALLOWS TO CONFINE E/M FIELDS.

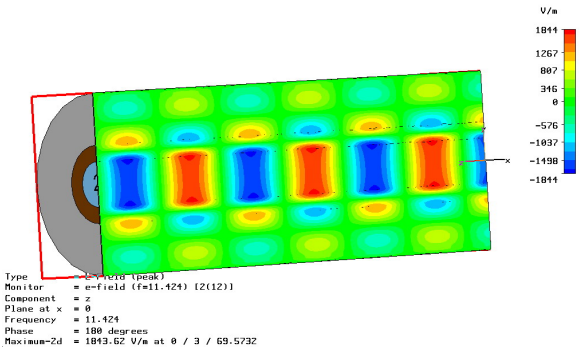
- REDUCES LOSSES DRAMATICALLY

Q×f=constant, f is up, tanδ is up as well.

Multilayer DLA structure
DLA fabrication

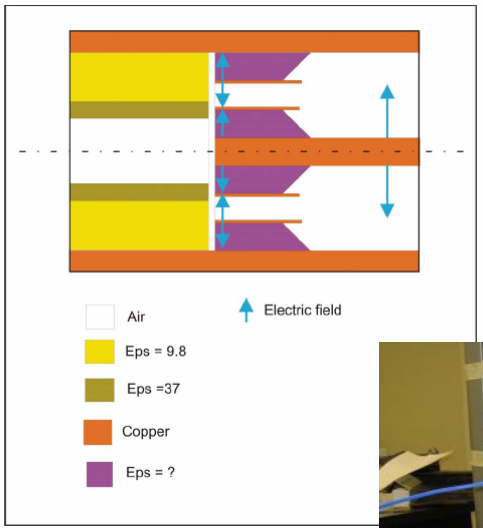


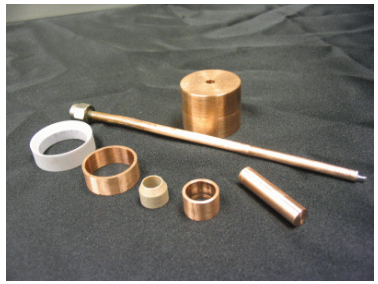


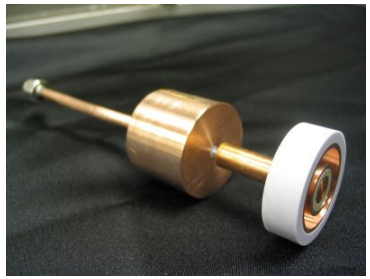


PARAMETERS	Value
Frequency	11.424GHz
Inner Radius	3mm-5.17mm
Outer Radius	12.02mm
Dielectric Constant	37-9.7
Dielectric tube length	70mm/piece
Group Velocity	0.064c
R/Q	2040Ω/m
Shunt Impedance	12.5 MΩ/m
Power ATTN	**2.7dB/m**

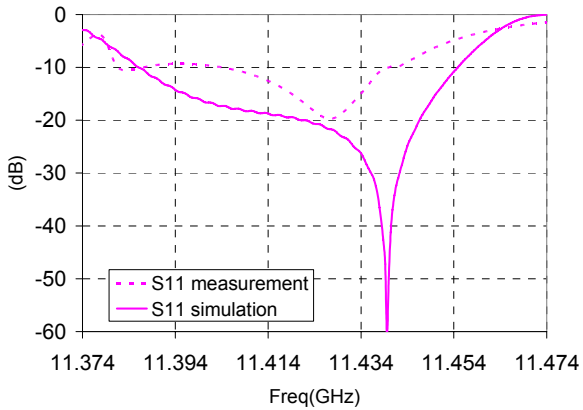
Multilayer DLA structure
TM03 Launcher/Bench Test







Dual layer DLA bench testing



Power attenuation < 4 dB/m, S11< -15 dB

ACTIVE MEDIA

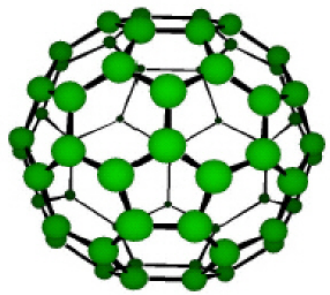
MASER CONCEPTS FOR ADVANCED ACCELERATOR:

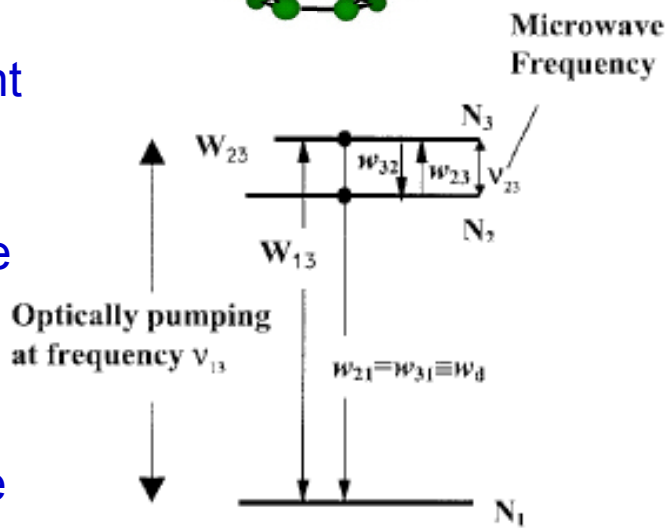
- BASED ON FULLERENE TPhP-C_{60} IN LC SOLUTION
- OPTICAL PUMPING
- ALL BENEFITS OF CONVENTIONAL ACCELERATOR

PROJECT IN COLLABORATION WITH ANL/AWA

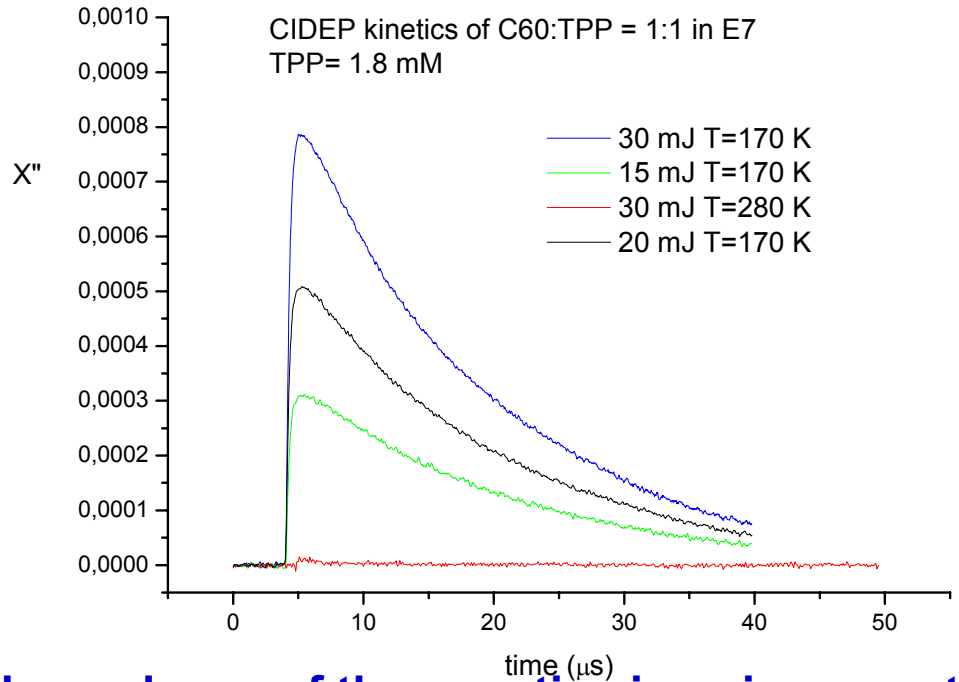
Activity in Fullerenes

- Active medium: TPhP-C_{60}-LC solution
- Photoexcitation of triplet states of C_{60} by optical pump
- Effect of the nematic liquid crystal component (rodlike molecules aligned to exhibit long range 1D order) is to introduce a symmetry breaking and allow the spin energy levels of the fullerene to become selectively populated.
- Operating temperature ~ 150 K
- Frequency of microwave transition is tunable by adjusting the applied magnetic field.





ESR Measurements of New Active Materials

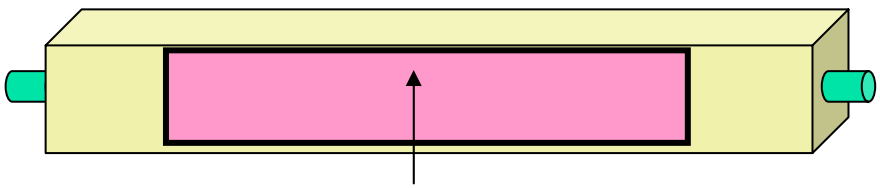


Time dependence of the negative imaginary part of the magnetic susceptibility for different pump energies. X''=10^{-4} corresponds to ~10^{17} spins/cc.

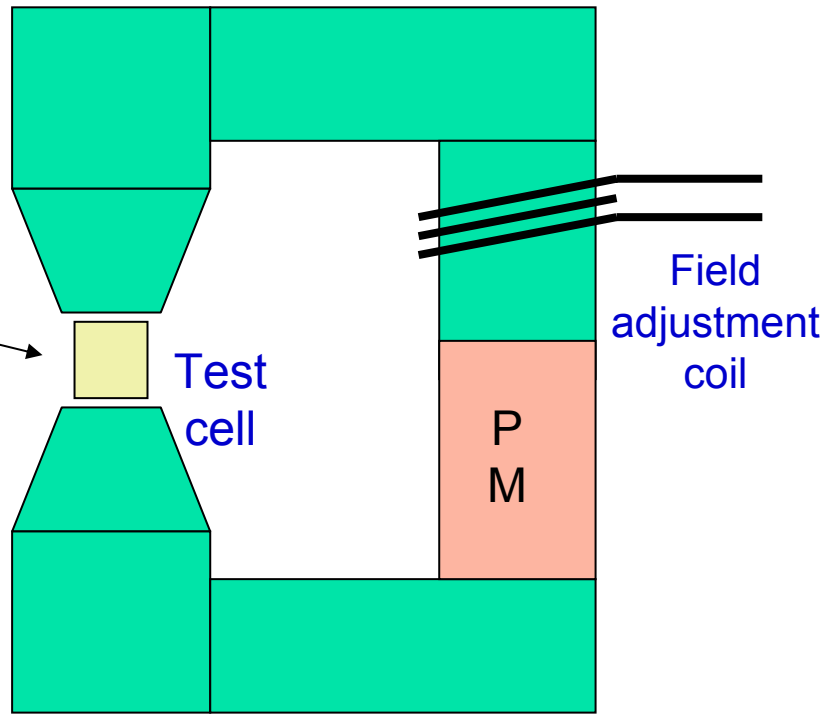
Activity in Fullerenes

- The achievable spin density impacts the total volume of active media required for these measurements.
- We use as a reference the maximum estimated number of 10^{17} spins/cm^3 for the E7-C_{60} -TPhP solution.
- This implies a stored energy in the medium of 6.6 erg/cm^3 excited by an optical pulse energy of 37 mJ/cm^3. (G=660 keV/cm for 1 pC bunch)
- Measurements have been made at lower temperatures than originally planned. (150 K)

Bench Test System



90% transmission mesh window for pump input



- Rectangular cell
- PM dipole
  - Physically smaller than solenoid
  - Cool in LN_2 bath
  - Adaptable to beam experiment

Bench Test/Acceleration Experiment

- Redesign of bench test system from the original proposal to accommodate the beam acceleration experiment with minor modifications.
- Use PM dipole to produce uniform 3 kG field across 1 cm X 5 cm test cell. (Under design using Poisson/Pandira)
- Tuning coil to provide required ~400 G field swing
- Pump signal from flashlamp input via fiber optics or lucite light guide
- 3D FDTD simulation code being developed using active medium model, auxiliary differential equation technique.

SUMMARY

euclid TECHLABS

NEW MATERIALS and technologies FOR ADVANCED CONCEPTS:

- CVD DIAMOND DEPOSITION HAS BEEN USED FOR THE 34 GHZ DLA STRUCTURE DEVELOPMENT. THE DIAMOND WAVEGUIDE HAS BEEN FABRICATED AND THE MATERIAL HAS BEEN RF TESTED.
- RF COUPLING SECTION FOR THE CERAMIC-BASED AND DIAMOND-BASED DLA HAS BEEN DESIGNED.
- TRANSFORMER RATIO GREATER THAN 2 HAS BEEN DEMONSTRATED. THE FOUR-BUNCH EXPERIMENT IS PLANNED FOR 2007-2008.
- TUNABLE LOW LOSS FERROELECTRIC FOR TUNABLE DLA, PULSE COMPRESSION AND POWER DISTRIBUTION FOR LINEAR COLLIDERS HAS BEEN DEVELOPED. ILC COUPLING TUNER IS UNDER DEVELOPMENT.
- FULLERENE BASED ACTIVE MEDIA FOR SOLID STATE MASER POWER SOURCE FOR ADVANCED ACCELERATOR HAS BEEN STUDIED. EXPERIMENTAL SETUP IS UNDER DEVELOPMENT.