DEVELOPMENT OF DIELECTRIC DISK ACCELERATORS FOR ARGONNE 500MEV SHORT PULSE TWO BEAM DEMONSTRATOR

Alexei Kanareykin/ Chunguang Jing

for ANL AWA/Euclid Techlabs collaboration

4th European Advanced Accelerator Workshop

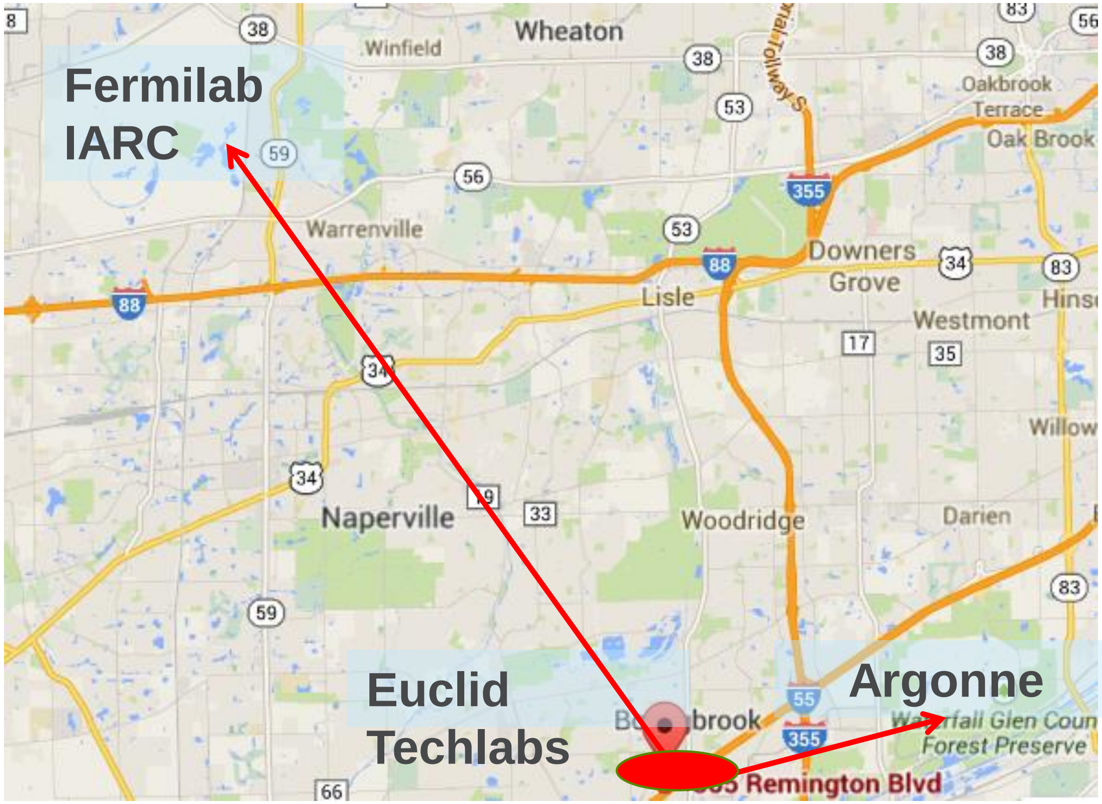
EAAC'19, 15-21 September 2019

Isola d'Elba, Italy

Euclid Techlabs LLC

Euclid TechLabs LLC, founded in 1999 is a company specializing in the development of advanced materials and new designs for beam physics and high power/high frequency applications. Additional areas of expertise include dielectric structure based accelerators, pulsed electron microscopy, and "smart" materials technology and applications.

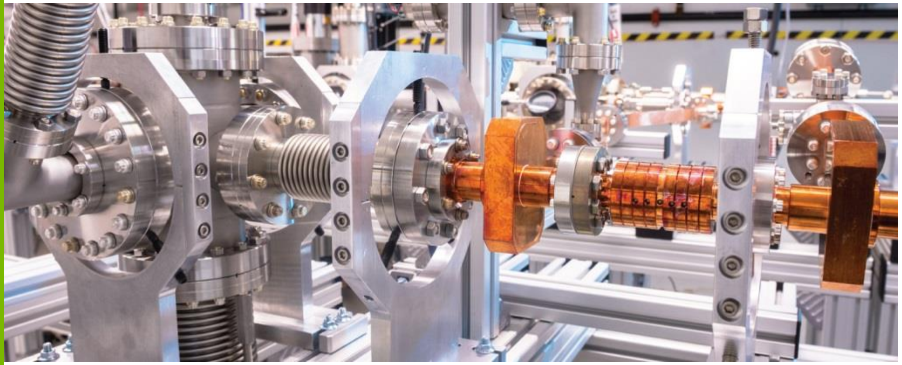
- 2 offices: Bolingbrook, IL (lab) and Gaithersburg MD (administrative).
- Tight collaborations with US National Labs: Argonne, Fermi, BNL, JLab.
- Actively collaborate with CERN



LAB FACILITY IN BOLINGBROOK IL, USA

euclid TECHLABS

- Compact electron accelerator test facility (bunker)
- Time resolved TEM beamline
- Clean room/magnetron sputtering (TiN, copper, dielectrics)
- Field Emission cathode DC test stand
- Femtosec laser
- RF lab
- …other beam physics related equipment

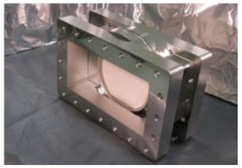


16 PhDs,
25 staff total

11,000 sq ft - total
2,000 sq ft – office
9,000 sq ft - lab

2 locations: Chicago and Washington

ANL/AWA accelerator, ANL/CNM - cathodes, ANL/APS- diamond based X-ray optics, Jlab and Fermi: SRF tests

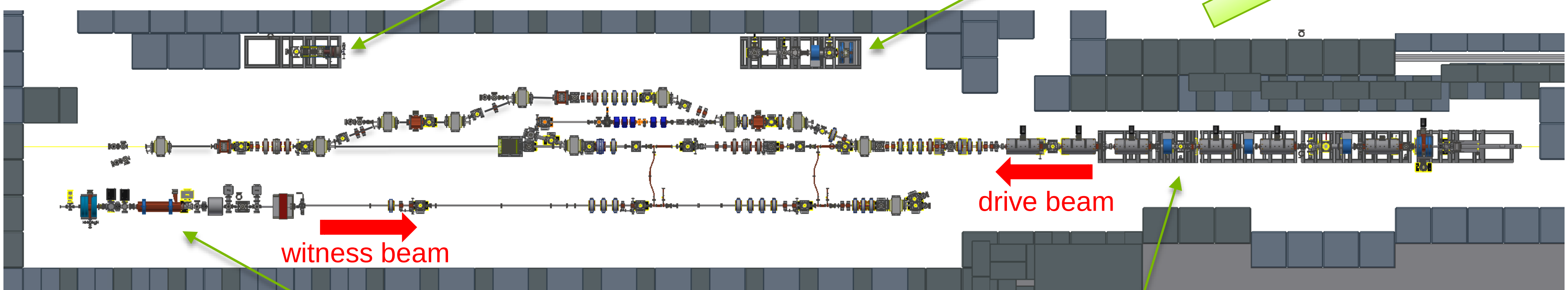


BEAMLINES AND TEST-STANDS AT AWA, ARGONNE

Manoel Conde talk, Wednesday, WG3, 10am

20 MW RF power station
RF gun studies and conditioning

ACT
Cathode studies
Breakdown studies



Witness beamline
4 – 15 MeV
0.001 – 20 nC

Drive beamline
8 – 70 MeV
0.001 – 100 nC (single bunch)
Bunch trains (up to 32 bunches with 600 nC total)

Unique capabilities of AWA:

- Two independent linacs
- Emittance exchange beamline
- Wide range of bunch charge (highest)

& flexibility →

Ideal test-stand for beam driven wakefield studies

MOTIVATION

Talk J. Power, WG8 Tuesday 5.10 pm

- In order to validate the dielectric-based short-pulse wakefield Two Beam Accelerator concept, the AWA/ANL plans to demonstrate a ~**500-MeV module**.
- A new **high shunt impedance** dielectric wakefield accelerator is the key element for this experiment. A dielectric-lined waveguide cannot provide high shunt impedance.
- Starting from 2019, Euclid /AWA collaborates to develop a new dielectric-disk accelerator (DDA). With 5x10^-4 of loss tangent dielectric material (eps=50), one can achieve **~200MΩ/m shunt impedance at 26GHz** traveling wave operation, which **is 4 times higher** than those of the conventional dielectric-lined accelerating structures.
- This will **meet the requirements** of the proposed 500MeV demonstrator. We report here on the progress on this project.

DIELECTRIC BASED ACCELERATOR. WHY ?

All metal structures: pulse 150–400 ns and gradients of ~100 MV/m

- A short pulse (~20 ns), high gradient (>300 MV/m) accelerator is an alternative technology to meet the requirements for future high-energy machines

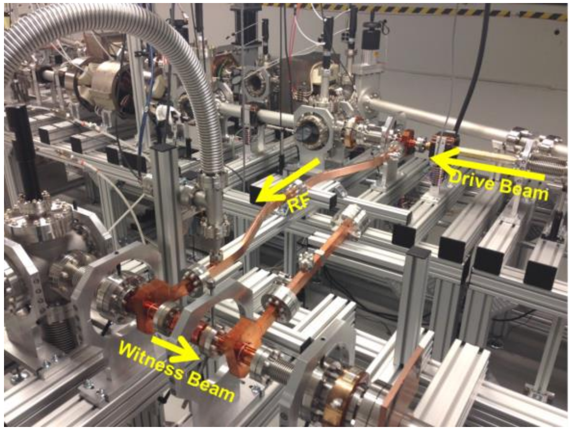
- A **fast rise time (<3 ns), high power (GW level), short rf pulse** needs to be generated.

The **traveling-wave Two-Beam Accelerator** scheme meets these requirements.

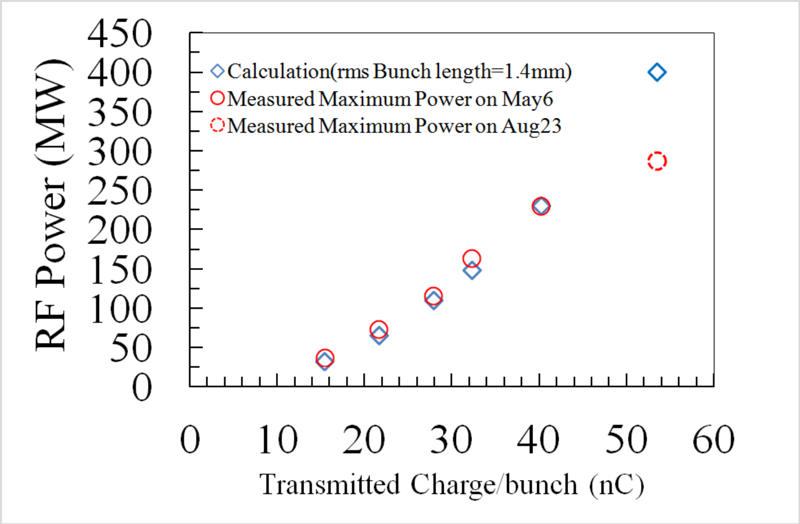
- **simplicity of manufacture**
- **expected high breakdown threshold,**
- **dielectric is “transparent” to the rf propagation;**
- **it is a broadband device (broadband coupling scheme !)**

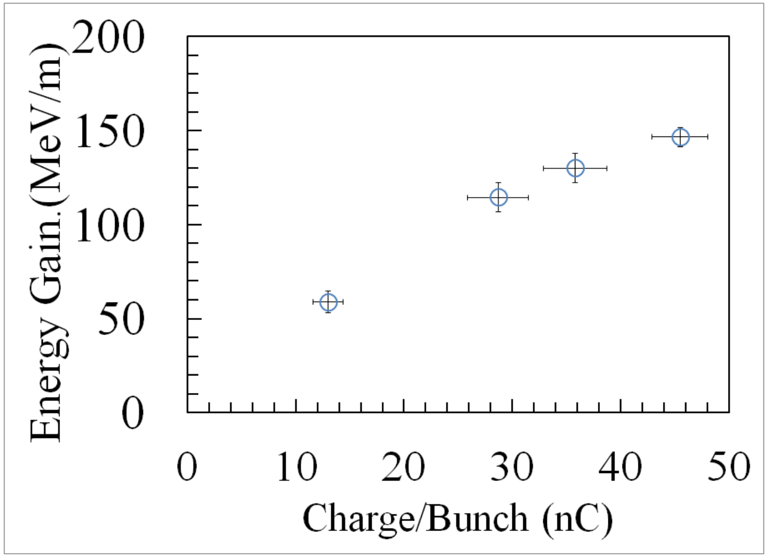
PREVIOUS EXPERIENCE

TWO-BEAM ACCELERATION EXPERIMENT



- 11.7 GHz metallic iris loaded structure
- 300 MW
- 150 MeV/m

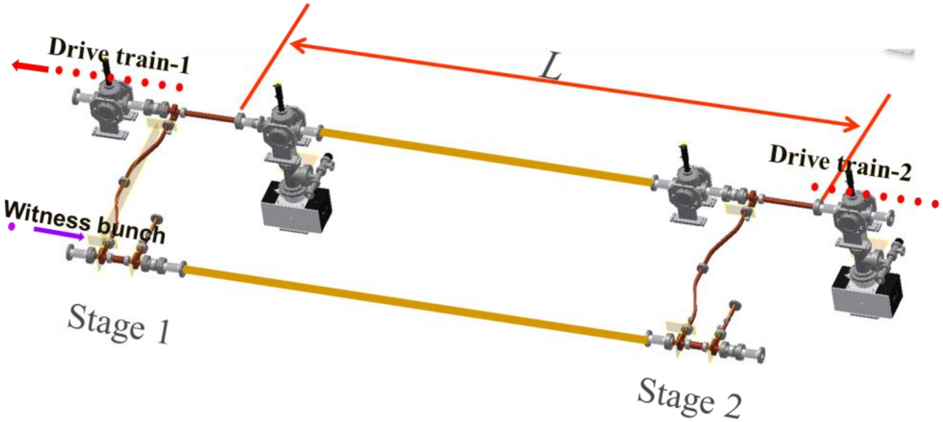




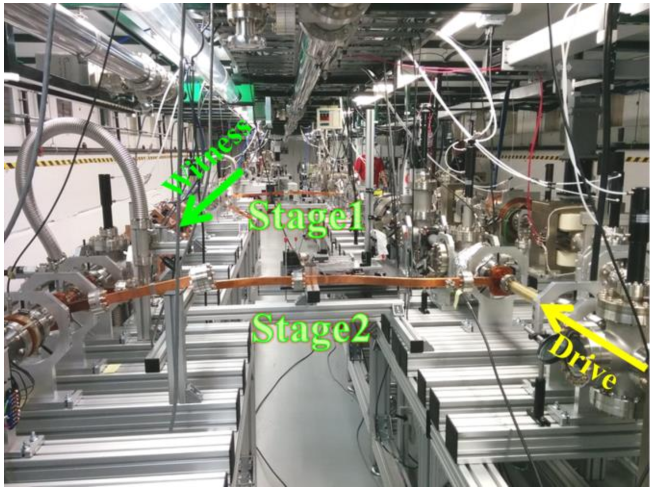
C. Jing et al., Nucl. Instr. Meth. in Phy. Res. A 898, 72-76 (2018)

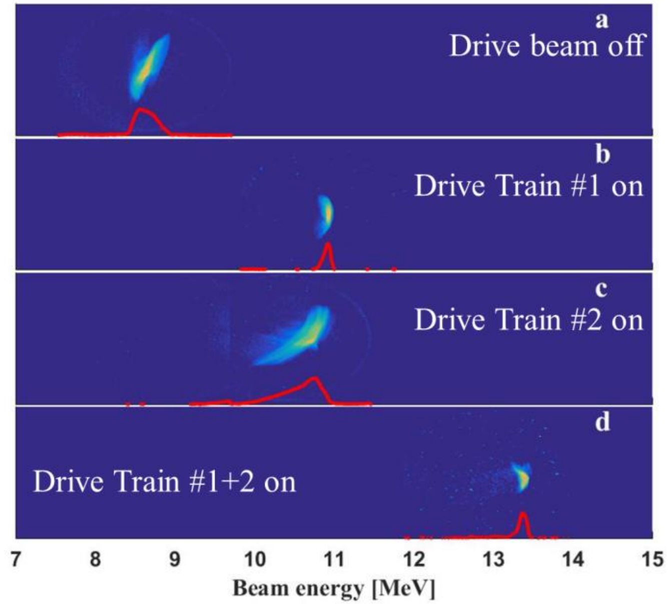
PREVIOUS EXPERIENCE

STAGING DEMONSTRATION AT AWA



- 11.7 GHz metallic iris loaded structures
- 70 MeV/m

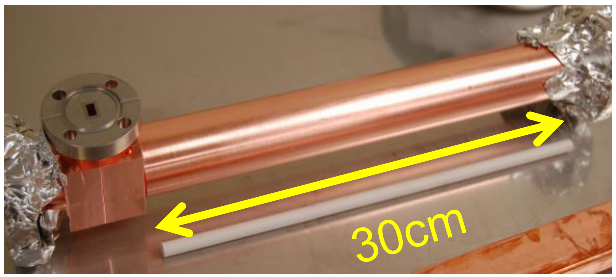




C. Jing et al., Nucl. Instr. Meth. in Phy. Res. A 898, 72-76 (2018)

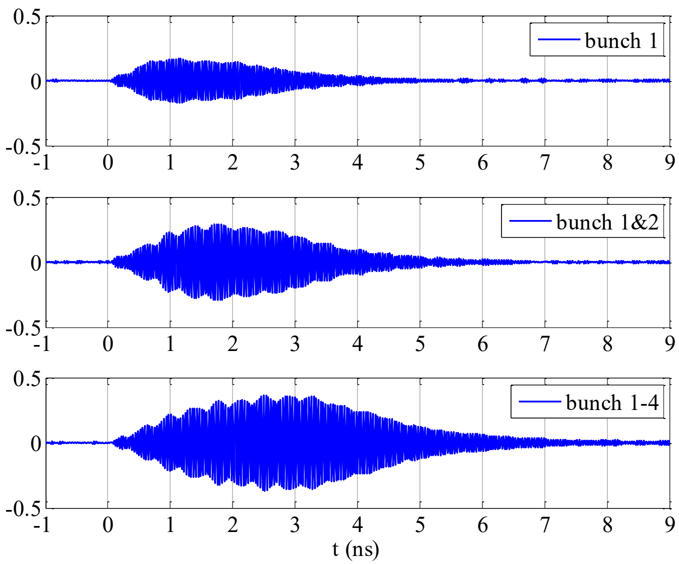
K-BAND 26 GHZ STRUCTURES

- **All-dielectric TBA**



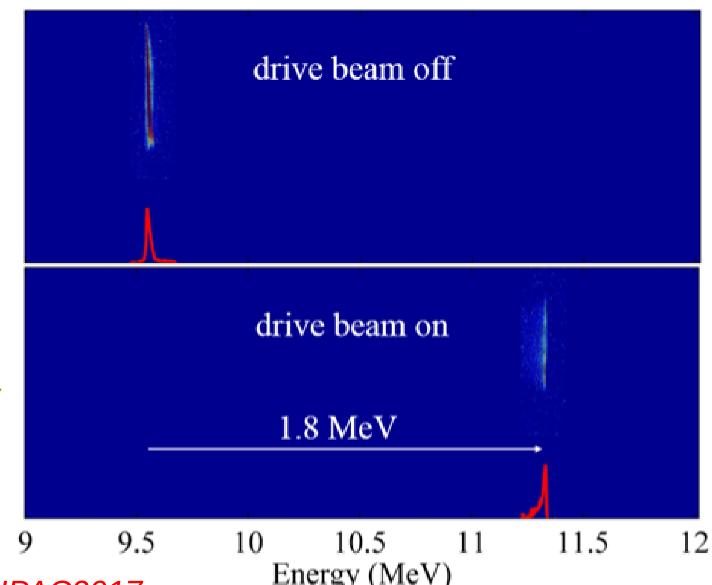
power extractor

accelerator



55 MW
generated power

28 MeV/m
acceleration



J. Shao, *et al, in Proceedings of IPAC2017*

PREVIOUS EXPERIENCE

X-BAND DIELECTRIC-LOADED POWER EXTRACTOR

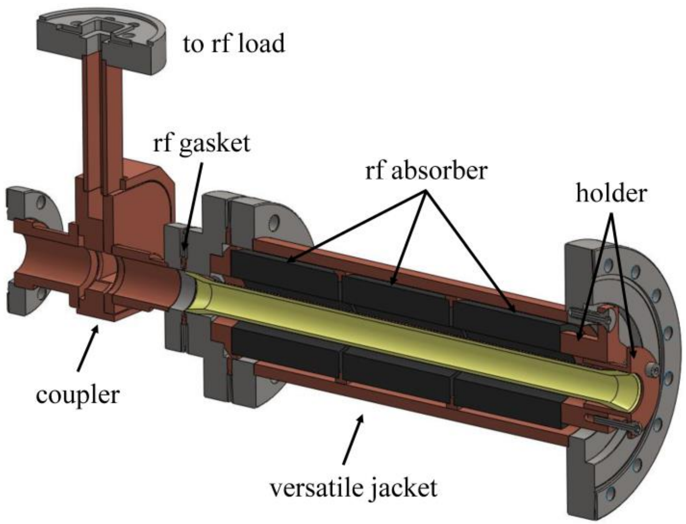
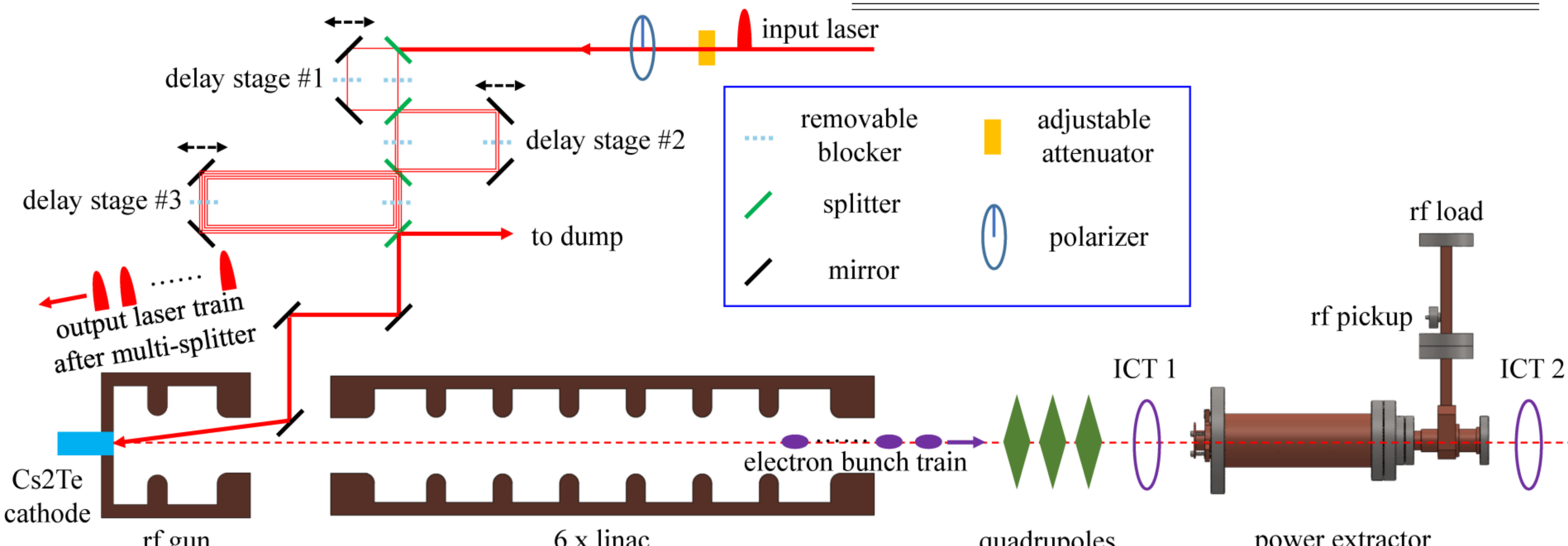


TABLE I. Parameters of the uniform section.

Parameter	Value
Material	Alumina
Dielectric constant	9.8
Loss tangent	1×10^{-4}
Inner radius	7.50 mm
Outer radius	9.40 mm
Length	26 cm
Quality factor	3393
r/Q	4.32 kΩ/m
Group velocity	0.20 c
$E_{surface,max}/E_{axis}$	1
Flat-top duration (8-bunch train)	3.1 ns

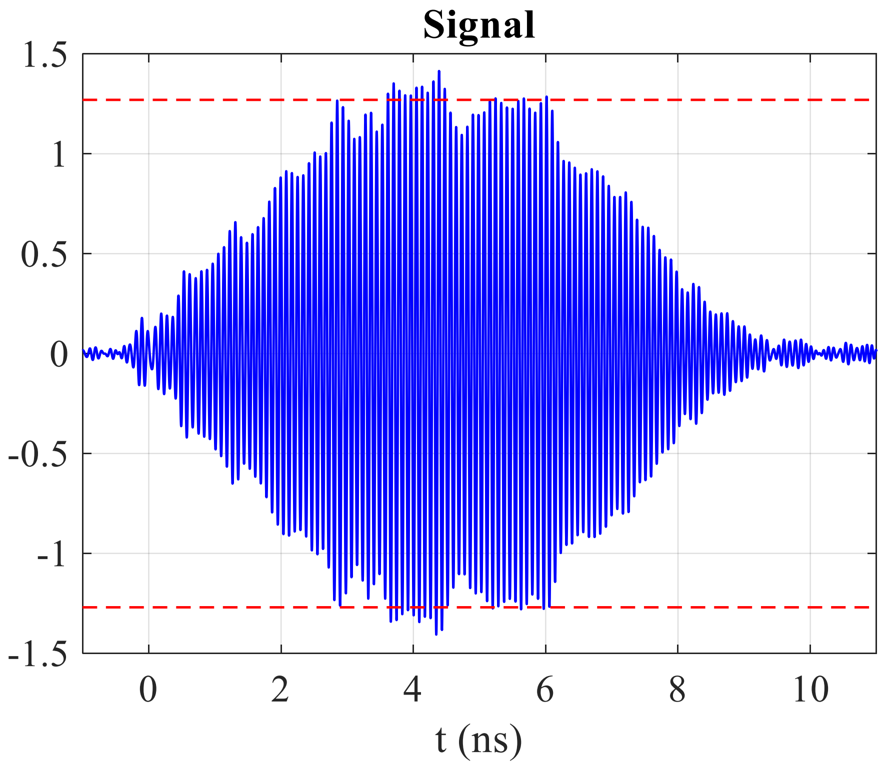


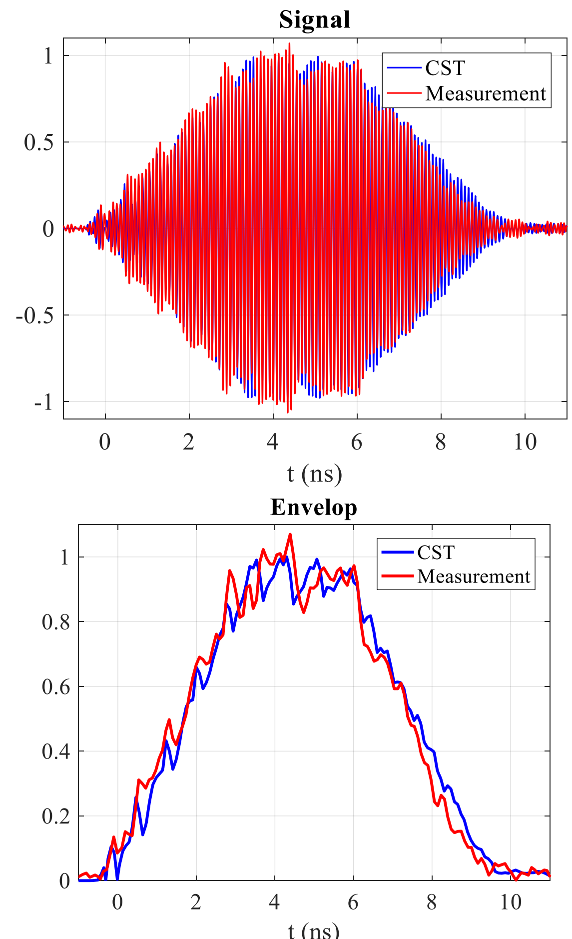
PREVIOUS EXPERIENCE

POWER LEVEL

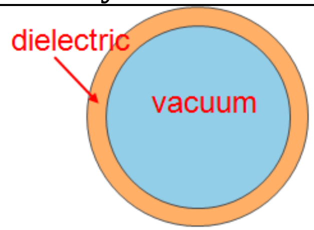
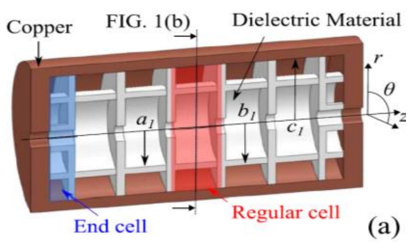
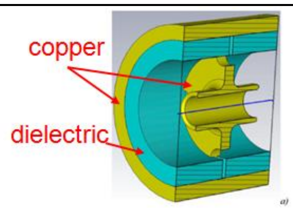
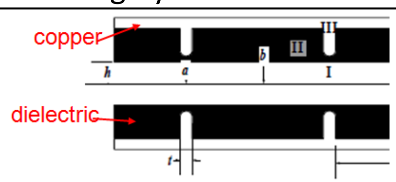
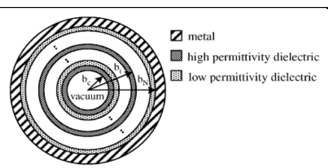
- **8-bunch train**

- Transmitted charge: ~350 nC with 100% transmission
- Power level: ~200 MW (assuming the coupling of the pickup is 71 dB)
- Flat-top: ~3 ns





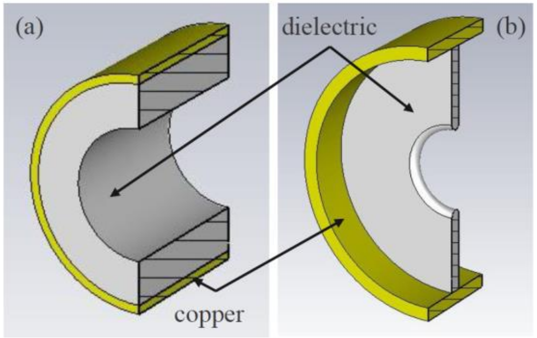
SURVEY OF DIELECTRIC BASED STRUCTURES

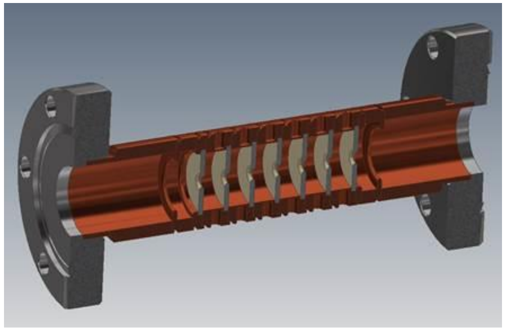
Variety of dielectric structures	Pros	Cons
 Dielectric-loaded accelerator	- Most developed structure - High group velocity, low surface fields	- Moderate r/Q - Weak points: tapered section
 Dielectric-assisted accelerator	- Very high shunt impedance - Low group velocity - Prototype fabricated	- No high group velocity optimization yet - Current prototype is clamped together, and may not hold high gradient - Weak points: high surface fields at joint of copper and dielectric
 Disk-Ring hybrid accelerator	- High group velocity - Various parameters for optimization	- Moderate r/Q - No prototype yet - Weak points: high surface fields at joint of copper and dielectric
 Hybrid dielectric accelerator	- Low surface fields, high r/Q - Prototype reported	- Low group velocity - May be difficult to fabricate dielectric piece with desired shape - Weak points: joint of copper and dielectric
 Multilayer dielectric accelerator	- Higher r/Q than DLA - High group velocity - Low surface fields	- Hard to eliminate the gap between dielectric layers - Weak points: joint of layers

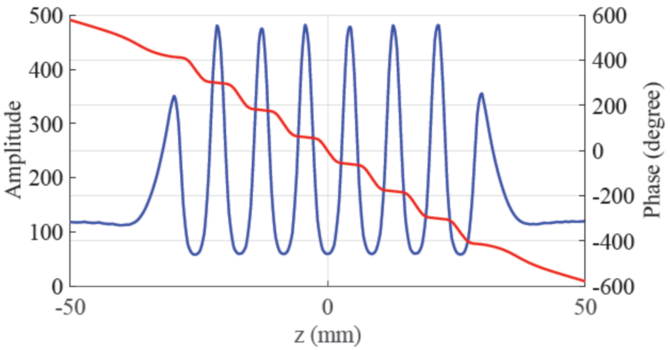
NOVEL STRUCTURES

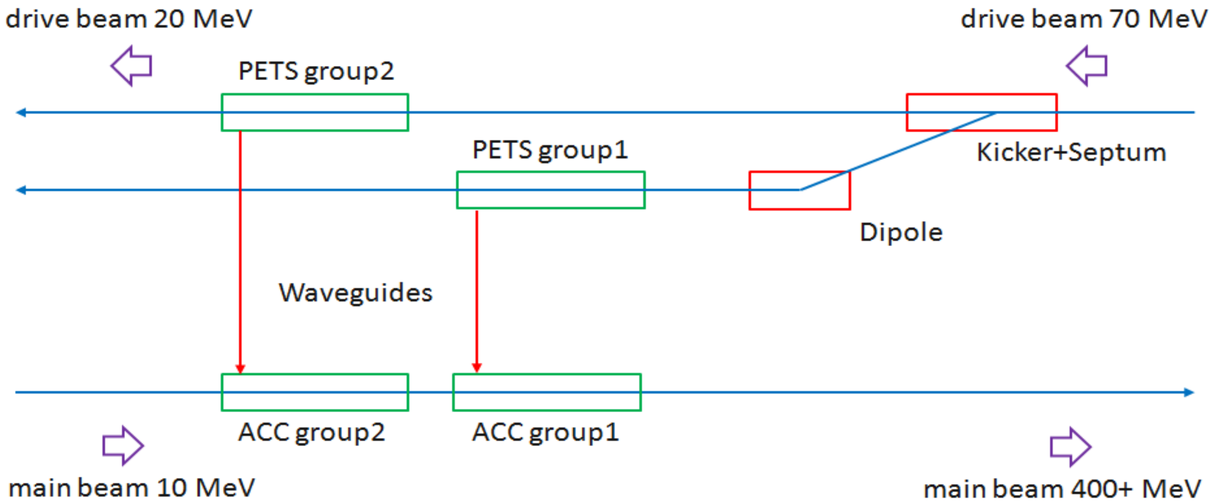
▪ Dielectric-disk accelerator

J. Shao, *et al, in Proceedings of IPAC2018,* (2018)





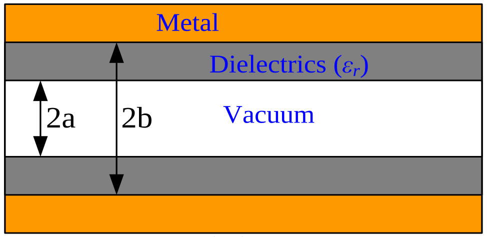




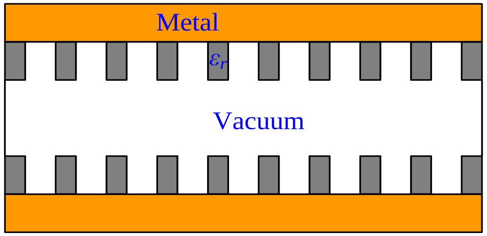
DIELECTRIC DISK ACCELERATOR

Talk J. Power, WG3
Tuesday 5.10 pm

- **26 GHz** structure
- **22 ns** short pulse
- **1 GW** RF power
- **270 MV/m** gradient



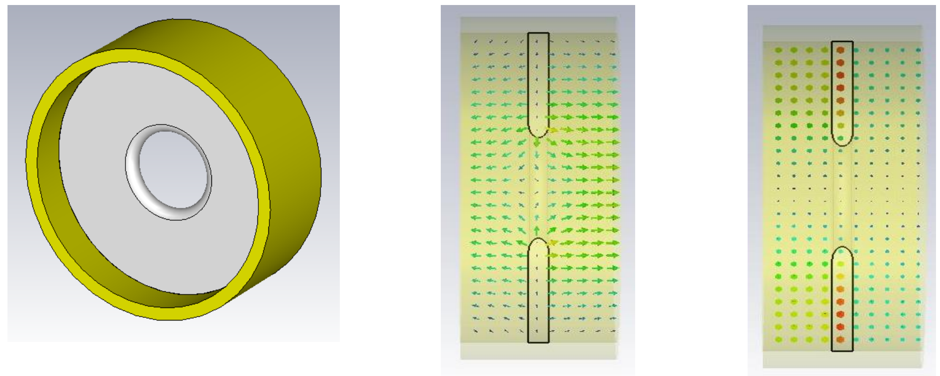
(a)



(b)

(a) dielectric-lined circular waveguide, and (b) dielectric disk-loaded circular waveguide.

J. Shao et al. Proc. IPAC'18, p.640

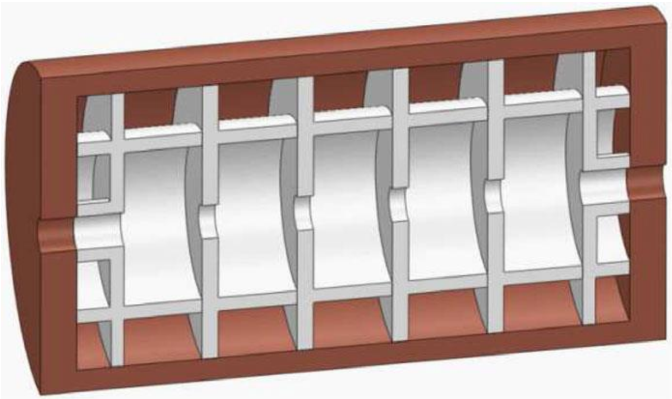


A Dielectric Disk cell: a) geometry; b) electric and c) magnetic fields of the accelerating mode;

	Dielectric-loaded	Dielectric-disk	Copper-disk*
Aperture	3 mm	3 mm	3 mm
Outer diameter	4.99 mm	9.23 mm	9.27 mm
Dielectric thickness	1 mm (wall)	0.5 mm (disk)	0.5mm (copper disk)
Dielectric constant	10	50	N/A
Tangent loss	1e-4	5e-4	N/A
Group velocity, Vg	0.11c	0.16c	0.017c
Shunt impedance, r	50MΩ/m	208MΩ/m	139MΩ/m
Q	2300	6400	4300
Input power	1.22 GW	0.96 GW	N/A
$\eta_{drive\text{-}main}$	19.8 %	28.5 %	N/A
Gradient, Ez	363 MV/m	363 MV/m	N/A
Max surface field, E_{max}	363 MV/m	660 MV/m	N/A
Tuning	Difficult	Easy	Easy

Dielectric Disk Accelerating (DDA) structures operating at TM02 π-mode

Yelong Wei, Alexej Grudiev



The DAA structure has high quality factor and a very high shunt impedance at room temperature since the electromagnetic field distribution of accelerating mode can be controlled by dielectric parts so that the wall loss on the metallic surface is greatly reduced: C-band (5.712 GHz), Q_0~119,314 shunt impedance~ 617 MΩm, TM_{02} mode.

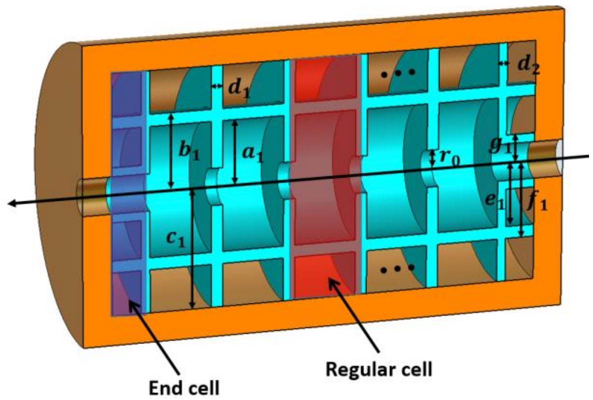
D. Satoh, M. Yoshida, and N. Hayashizaki. PRAB, 20, 091302 (2017)

The magnesia ceramic (MgO) which was used for the prototype model has the purity of 3N class. From the resonant characteristics of a dielectric resonator made with the same material, we have estimated its relative permittivity ε_r and tan δ near 10 GHz as **ε=9.64** and **tanδ=6.0×10^{-6}** (!) at room temperature.

Thus, studies on the following subjects will have to be conducted: ….(3) sintering of some ceramic materials for reasonably **high dielectric permittivity (ε_r > 20) and low loss tangent (tan δ < 10^{-4}).**

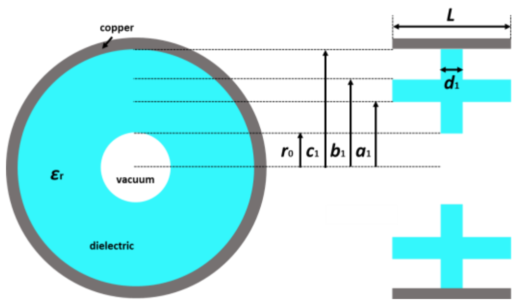
Design of a broadband mode launcher

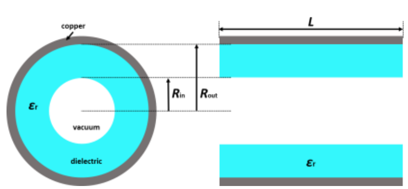
Yelong Wei, Alexej Grudiev

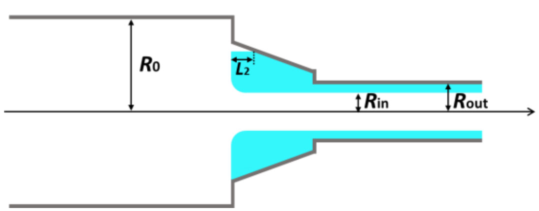


- High order mode operation reduces the wall power loss;
- The electromagnetic fields can be controlled by dielectric parts;
- High power efficiency.

Optimum parameters	Original	Modified
Dielectric constant εr	9.64	9.64
Dielectric loss tangent δ	6E-6	6E-6
Inner radius r0 [mm]	3.15	3.15
Outer radius c1 [mm]	20.5	20.5
a1 [mm]	11.10	11.10
b1 [mm]	13.16	13.50
d1 [mm]	2.0	2.0
L1 [mm]		5.0
x1 [mm]		0.9
z1 [mm]		0.7
Structure period length L [mm]	12.50	12.50
Phase advance	180°	180°
Acceleration mode	TM02 π-mode	TM02 π-mode
Frequency [GHz]	11.9969	11.9949
Unloaded *Q*0	134542	112639
r'/*Q*0 [Ω/m]	6089	5488
r' [MΩ/m]	819	618

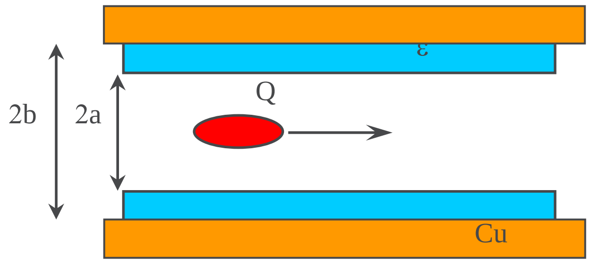






MATERIALS FOR A DIELECTRIC-BASED ACCELERATOR

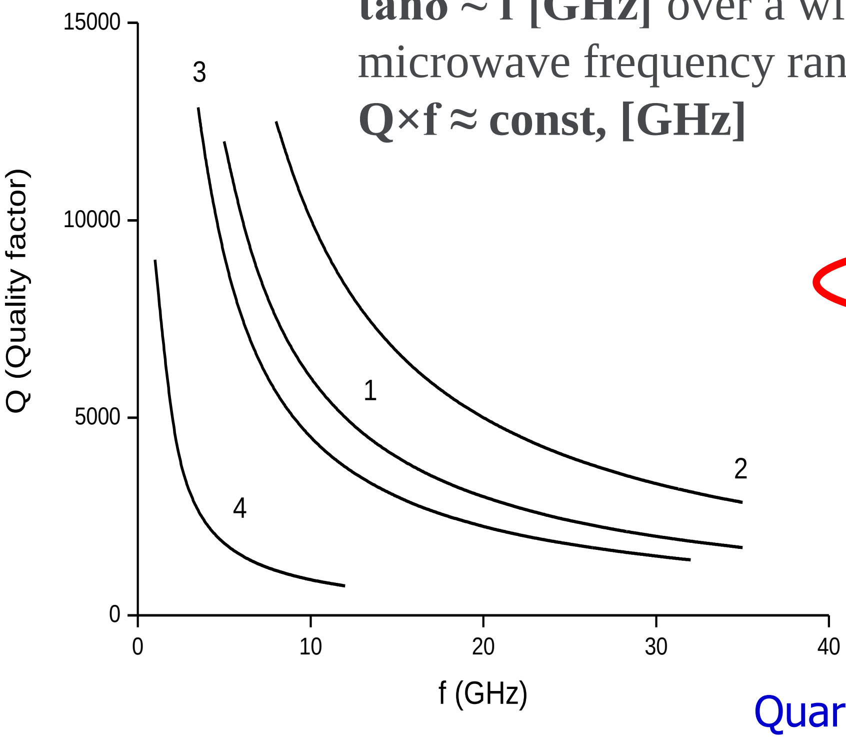
A.Kanareykin, Poster, Wednesday 7 pm



Low-loss high breakdown strength ceramic for the dielectric structures

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%	$\leq 3\times10^{-4}$

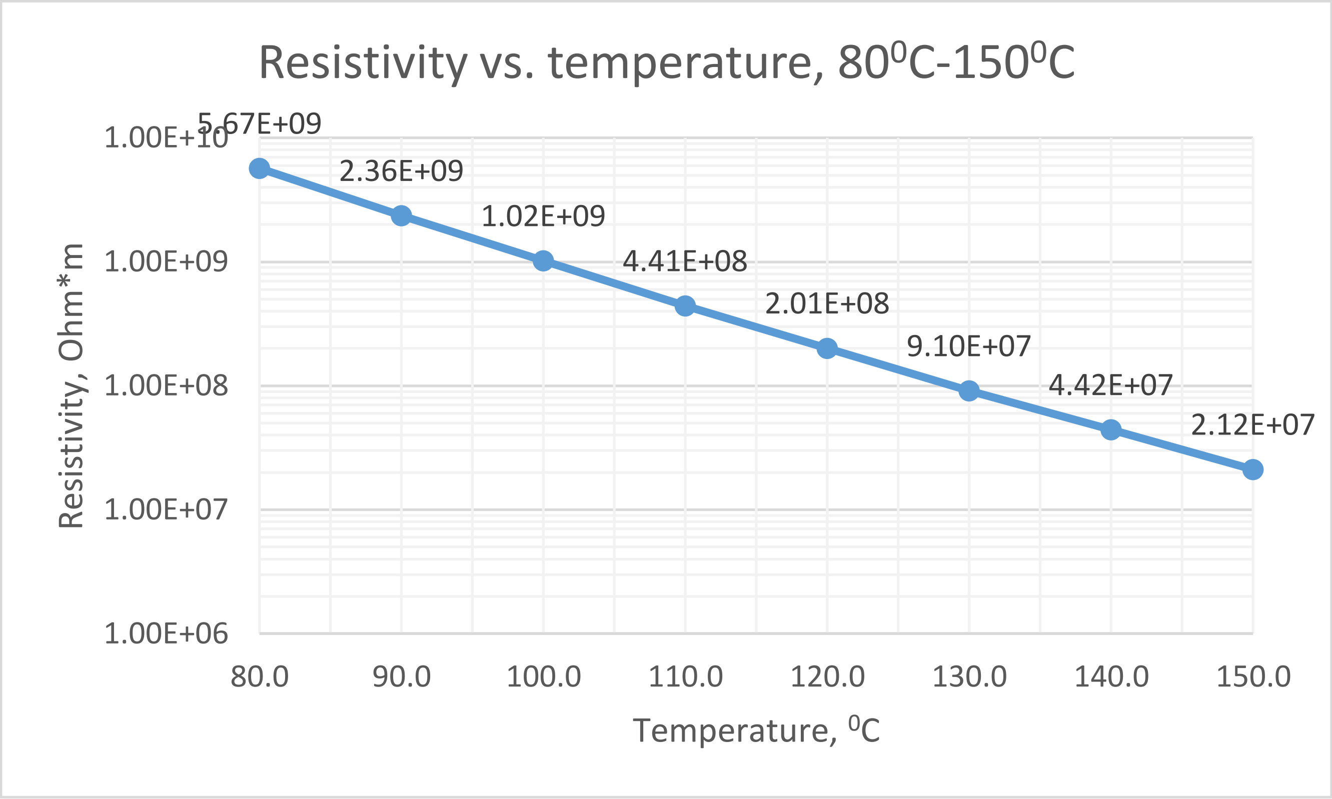
tanδ ~ f [GHz] over a wide microwave frequency range.
Q×f ≈ const, [GHz]



Quartz, ε~ 3.75, tanδ~10^{-4} Diamond, ε~ 5.7, tanδ<10^{-4}

CERAMIC STRUCTURES: CONDUCTIVITY

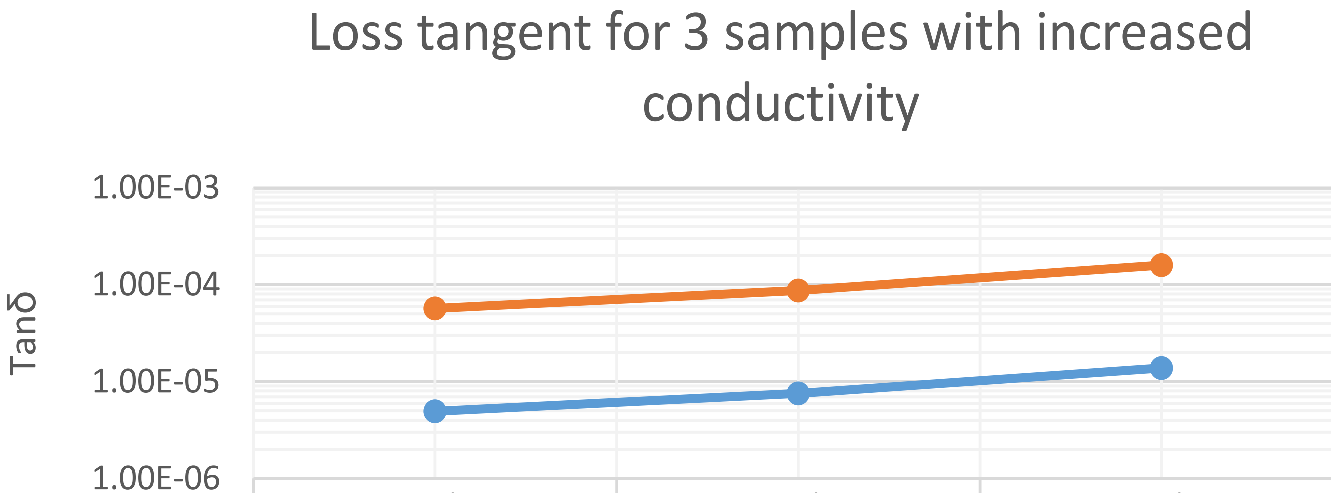
- **(Mg,Ti) ceramic** materials with very low dielectric loss, **if modified** (Euclid, 2018) exhibiting **2–3 orders of magnitude increased conductivity** (100–1000 times reduced volumetric resistivity).



- Same time, **~10^4 conductivity increase** of the developed (Mg,Ti) ceramic in the 25^0C–100^0C temperature range, while the loss tangent variation still **~20%** change to the room temperature value

Ceramic Structures: Conductivity vs. tanδ

Loss tangent change with increased conductivity



	sample 1	sample 2	sample 2
650 MHz	4.93E-06	7.56E-06	1.39E-05
7.5 GHz	5.68E-05	8.72E-05	1.60E-04

tanδ=5.8×10^{-5}
at 7.5 GHz

1.66×10^{-4}
at 7.5 GHz

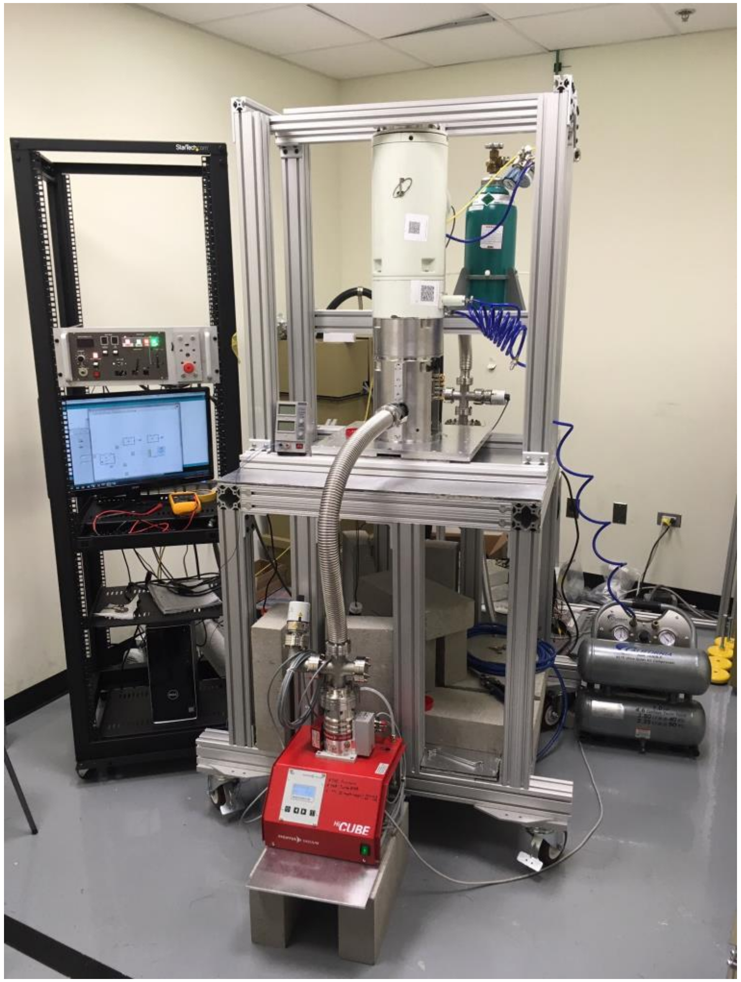
650 MHz 7.5 GHz

Loss tangent change with temperature

the **loss tangent** variation at 100^0C did not exceed a **20%** change compared to the room temperature value. This ability to tune the conductivity will allow one to effectively discharge high power RF windows by controlling their operating temperature.

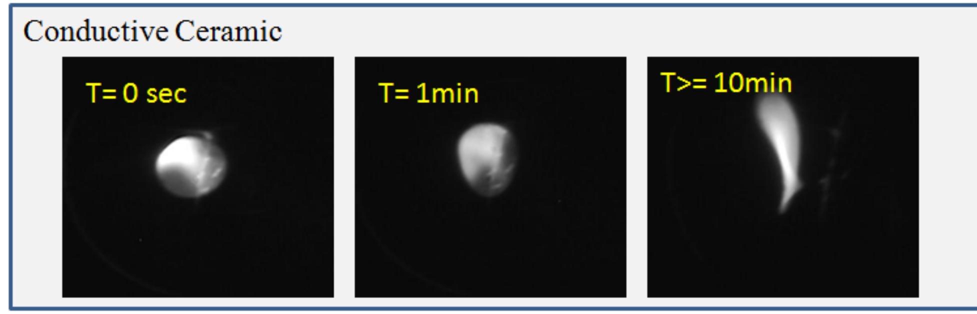
DC 200 kV BEAM CHARGING TEST OF CERAMIC

DC beam test using TEM DC gun:

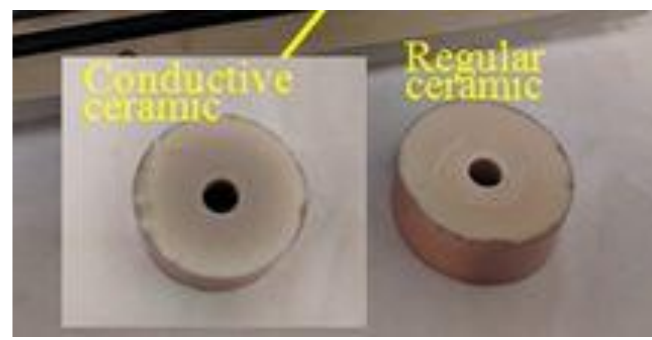


DC 200 kV electron beam
For charging testing

DC conductive ceramic with excellent microwave properties: **no charging !**



Beam test under 200 kV DC gun. The regular ceramic is charged < 1 sec. The DC beam test of the new ceramic demons-trated its self-discharge during ~ 1 hour test.

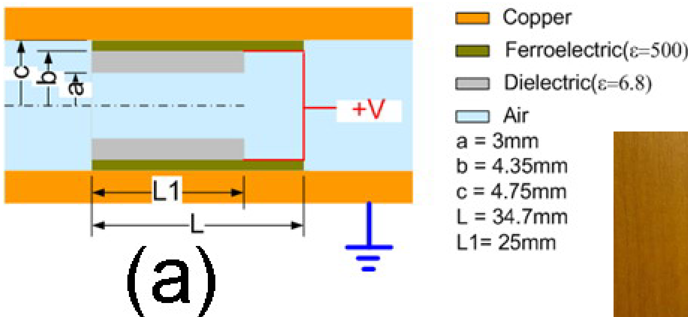


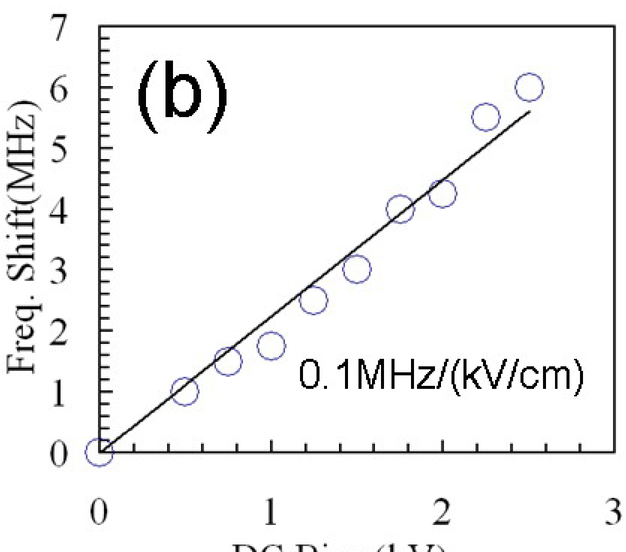
TUNABLE DIELECTRIC MATERIALS

Materials ferroelectrics (tunable ceramic) are used for beam driven acceleration experiment and various accelerator components when fast tuning is needed

Where this materials have been used: Beam driven structures - >250 MV/m surface field tested, short pulse < 30 ns is needed.

Tunable Dielectric-Based Accelerator

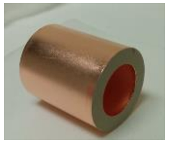


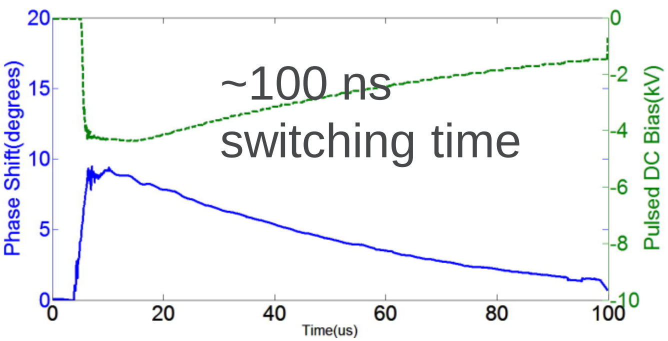


US patent 7,768,187

US patent 8,067,324

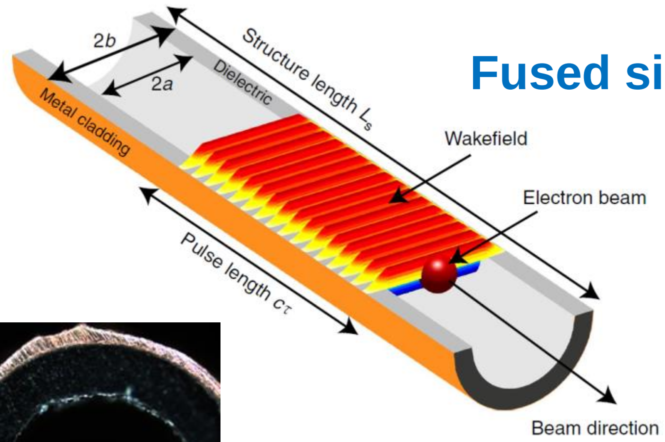
Fast ferroelectric based tuner for CERN



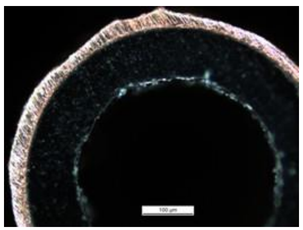


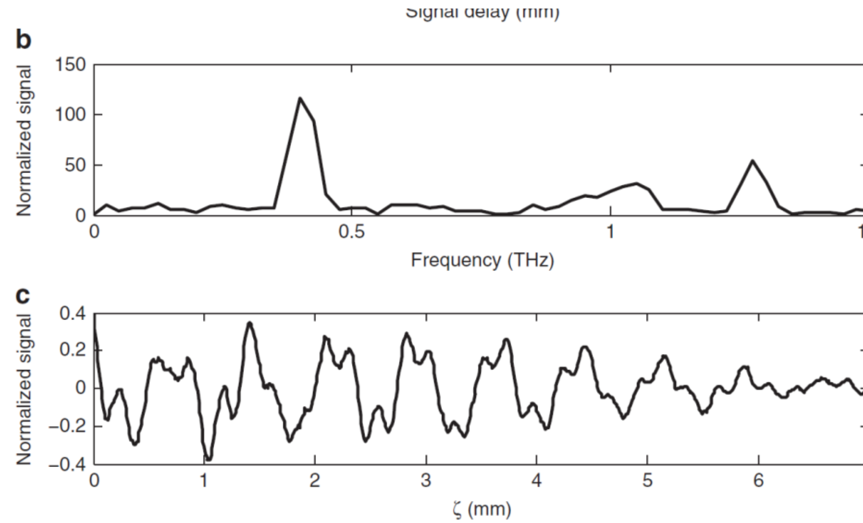
FACET DIELECTRIC TESTING

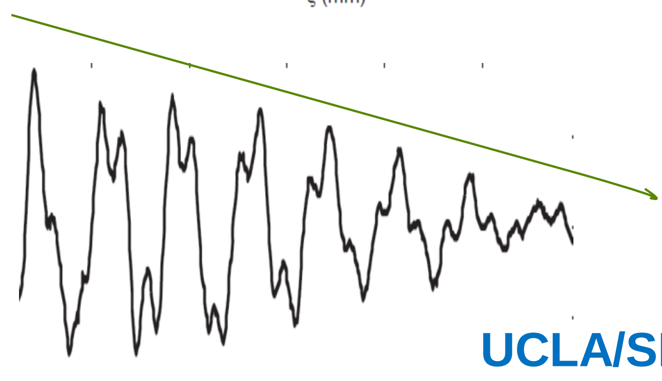
Wakefield Damping at ~ GV/M



Fused silica







Unusual sharp fall off in field strength- the pulse is too short. Expected 18 mm, measured – 5 mm at ~ 1 GV/m range. High field induced conductivity at THz ?

UCLA/SLAC

the observed damping in experiment is much larger than that ascribable to dielectric or metallic losses under the conditions used in these experiments. This damping is an unexpected feature—comparison with previous studies makes it clear **that the observed damping is introduced by use of a very intense, short pulse electron beam.**

B. O'Shea et al. Nature Communications,7,12763, 2016

History: the starting era (1947-1960)

Theoretical papers (1947---)

$TM_{0,1}$ Mode in Circular Wave Guides with Two Coaxial Dielectrics

SIDNEY FRANKEL
Federal Telecommunication Laboratories, Inc., New York, New York
(Received February 3, 1947)

Field components for a transverse magnetic wave in a wave guide with two coaxial dielectrics are computed. A typical phase velocity to a prea

Slow Transverse Magnetic Waves in Cylindrical Guides

G. G. BRUCK AND E. R. WICHER
Specialties, Inc., Syosset, Long Island, New York
(Received March 24, 1947)

The fundamental physical phenomenon upon which linear electron accelerators and traveling beam tubes de-

The authors propose that, for the purposes of t the well-established proposition concerning the equiv

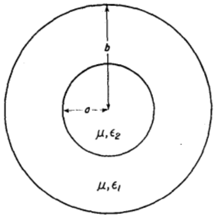


FIG. 1. Cross section of wave guide having two coaxial dielectrics.

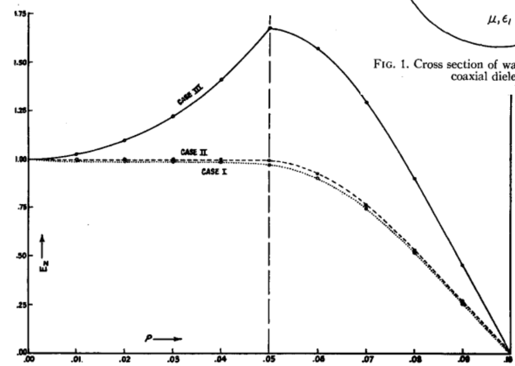


FIG. 1. Distribution of the longitudinal component of electric field strength through a cross section of the tube.

Experimental Work(1948-1958)

Research Group	Scientists	References	Research Scope
Atomic Energy Research Establishment (AERE), UK	R.B. R.-Shersby-Harvie, etc.	1. R.B. R.-Shersby-Harvie, Nature, 162 (1948) 890. 2. R.B. R.-Shersby-Harvie,etc., Proc. I.E.E. B., 104 (1957) 273.	Constructed and Tested a 4MeV Traveling wave Dielectric Disk Loaded Accelerator. Beam Acceleration. Discovered Multipactor in DLA.
Queen Mary College, Uni. of London, UK	G.B. Walker, etc.	1. G.B.Walker and N.D.West, Proc. I.E.E. C., 104 (1957) 381. 2. G.B.Walker and E.L.Lewis, Nature, 181 (1958) 38.	Constructed and Tested Dielectric Disk Loaded Wavguide Cavities. Tested Dielectric Breakdown.
IIT, USA	G.I. Cohn and G.T. Flesher	1. G.T.Flesher and G.I.Cohn, A.I.E.E. C., 70 (1951) 887. 2. G.I.Cohn and G.T.Flesher, IIT Report, 2 (1952).	Constructed and Tested a Quartz Tube Based Dielectric Loaded Accelerator.

History: waiting years(1960-1985)

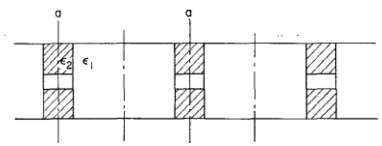
IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES, VOL. MTT-16, NO. 1, JANUARY 1968

Two Examples of "Confluence" in Periodic Slow Wave Structures

DON R. McDIARMID, MEMBER, IEEE, AND GEORGE B. WALKER, MEMBER, IEEE

Abstract—The properties that result from the elimination of a stop-nd of a lossless periodic slow wave structure are discussed. For two par-ular structures, it is shown that theory predicts a nonzero group veloc- at the point of confluence of the two passbands. This confluence is sirable for linear accelerator structures operating at the π-mode since produces increased mode separation.

Certain characteristics of zero and π-mode confluence are also dis-



IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES, VOL. MTT-20, NO. 8, AUGUST 1972 517

Circular Waveguides Lined With Artificial Anisotropic Dielectrics

CHRISTOPHER T. M. CHANG

Abstract—The propagation of electromagnetic waves inside circular waveguides lined with artificial anisotropic dielectric is investigated. Our investigation shows that the dominant hybrid electromagnetic (HEM_{11}) mode possesses a transverse deflecting field over the aperture of the structure and can be used as a transverse deflecting mode in a particle separator with ultrahigh energy. Expressions for power, attenuation, and transverse shunt impedance are obtained, and the effects of changing in loading on these various quantities are studied and presented in graphs.

INTRODUCTION

THE PROPAGATION of electromagnetic waves

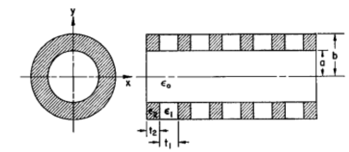


Fig. 1. Geometry of an anisotropic-dielectric-lined circular waveguide. The anisotropic dielectric is simulated by using spaced lamination of two different isotropic dielectric disks.

V. A. Vagin and V. I. Kotov, "Investigation of hybrid waves in a circular waveguide partially filled with dielectric," *Sov. Phys.—Tech. Phys.*, vol. 10, pp. 987–991, Jan. 1966.

H. Hahn, "Dielectric loaded circular deflecting waveguide," *Z. Angew. Phys.*, vol. 29, no. 5, pp. 318–323, 1970.

C. T. M. Chang and J. W. Dawson, "Propagation of electromagnetic waves in a partially dielectric filled circular waveguide," *J. Appl. Phys.*, vol. 41, pp. 4493–4500, Oct. 1970.

R. L. Kustom, C. T. M. Chang, and J. W. Dawson, "Dielectric loaded waveguides as particle separators," *Nucl. Instrum. Methods*, vol. 87, pp. 19–27, Oct. 1970.

C. T. M. Chang, J. W. Dawson, R. E. Fuja, R. L. Kustom, R. M. Lill, and J. J. Peerson, "Long pulse synchronous traveling wave separator," *IEEE Trans. Nucl. Sci.*, vol. NS-18, pp. 764–768, Mar. 1971.

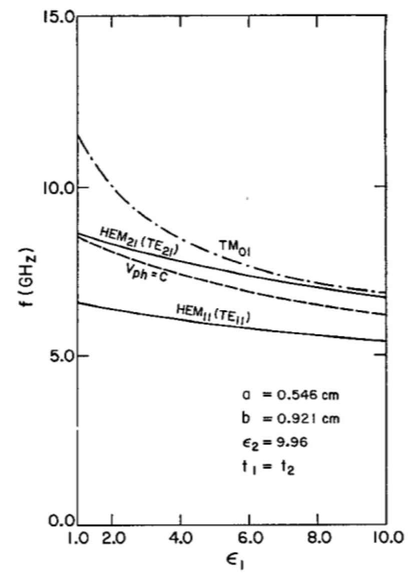


Fig. 3. The changes of cutoff frequencies of HEM_{11}, HEM_{21}, and TM_{01} modes and the operating frequency of HEM_{11} mode at $v_{ph} = c$ (the dashed curve) with ϵ_1.

History: the reviving era (1988-present)

VOLUME 61, NUMBER 24 PHYSICAL REVIEW LETTERS 12 DECEMBER 1988

Experimental Demonstration of Wake-Field Effects in Dielectric Structures

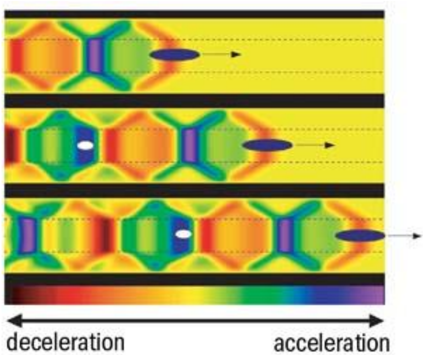
W. Gai, P. Schoessow, B. Cole,[a] R. Konecny, J. Norem, J. Rosenzweig, and J. Simpson
High Energy Physics Division, Argonne National Laboratory, Argonne, Illinois 60439
(Received 10 August 1988)

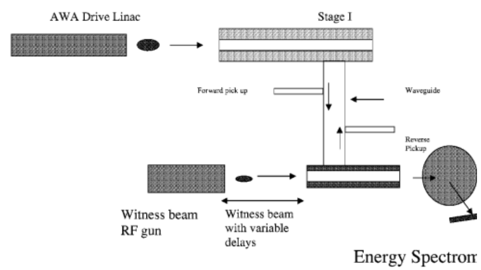
We have measured the wake fields induced by short, intense relativistic electron bunches in a slow-wave structure consisting of a dielectric-lined tube, as a test of the dielectric wake-field acceleration mechanism. These fields were used to accelerate a second electron bunch which followed the driving bunch at a variable distance. Results are presented for different dielectrics and beam intensities, and are compared with theoretical predictions.

Measurement of deflection-mode damping in an accelerating structure

E. Chojnacki, W. Gai, C. Ho, R. Konecny, S. Mtingwa, J. Norem, M. Rosing, P. Schoessow, and J. Simpson
Argonne National Laboratory, Argonne, Illinois 60439
(Received 10 October 1990; accepted for publication 25 January 1991)

We have directly measured the damping of wake-field deflection modes in a slow-wave accelerating structure consisting of a dielectric-lined waveguide with segmented conducting boundaries wrapped with rf absorbing material. Such damping of deflection modes is desired to prevent beam breakup instabilities. Attenuation *e*-folding times of 246 ps were recorded for deflection modes at the Advanced Accelerator Test Facility while the quality of the desired accelerating mode remained unaffected.





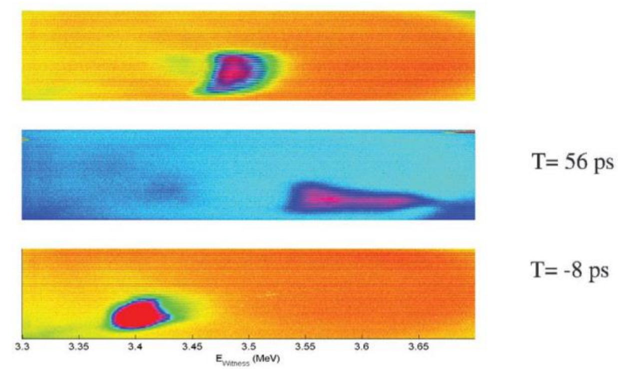


Figure 4. Measured energy change of the witness beam. The top is with drive beam off and middle is with drive beam on and with acceleration phase of beam delay at 56 ps. The bottom shows the deceleration.

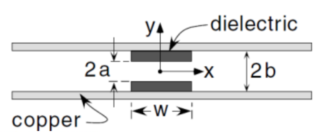
VOLUME 87, NUMBER 9 PHYSICAL REVIEW LETTERS 27 AUGUST 2001

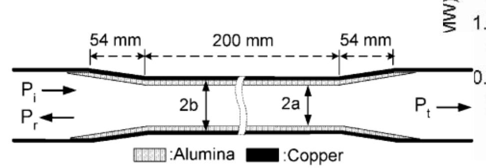
High-Gradient Millimeter-Wave Accelerator on a Planar Dielectric Subs

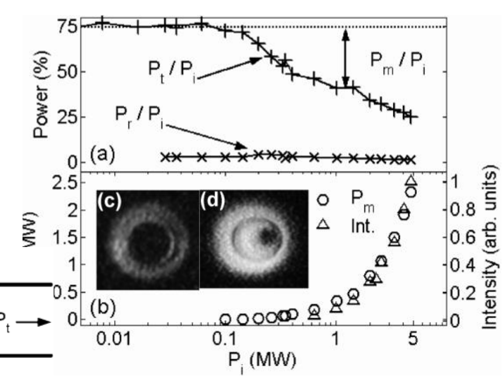
Marc E. Hill*
Department of Physics, Harvard University, Cambridge, Massachusetts 02138

Chris Adolphsen, W. Baumgartner, Richard S. Callin, Xintian E. Lin, Mike Seidel, Tim Slaton, and D
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94309
(Received 27 October 2000; published 10 August 2001)

We report the first high-gradient studies of a millimeter-wave accelerator, employing for the first time a planar dielectric accelerator, powered by means of a 0.5-A, 300-MeV, 11.424-GHz drive electron beam, synchronous at the 8th harmonic, 91.392 GHz. Embedded in a ring-resonator circuit within the electron beam line vacuum, this structure was operated at 20 MeV/m, with a circulating power of 200 kW, for 2×10^5 pulses, with no sign of breakdown, dielectric charging, or other deleterious high-gradient phenomena. We also present the first measurement of the quadrupolar content of an accelerating mode.







SUMMARY

- A short pulse (~20 ns), high gradient (>300 MV/m) accelerator is an alternative technology to meet the requirements for future high-energy machines

- A fast risetime (<3 ns), high power (GW level), short rf pulse needs to be generated.

The Dielectric Disk Accelerating (DDA) structure for the **Two-Beam Accelerator** scheme meets these requirements.

- **simplicity of manufacture**
- **expected high breakdown threshold,**
- **broadband device (broadband coupling scheme)**
- **excellent Q and shunt impedance are visible**

Low loss at RF and DC increased conductivity materials are available

Short pulse is critical

New smart designs and new materials are welcome !