DIELECTRIC BASED STRUCTURES FOR ADVANCED LINEAR COLLIDER

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for ANL AWA/Euclid Techlabs collaboration

ALEGRO Workshop

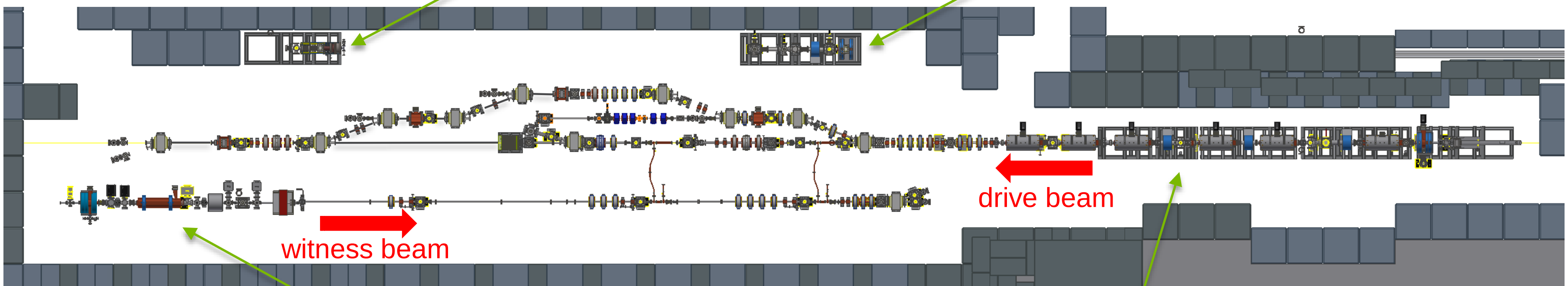
26-29 March 2019

CERN

BEAMLINES AND TEST-STANDS AT AWA

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)

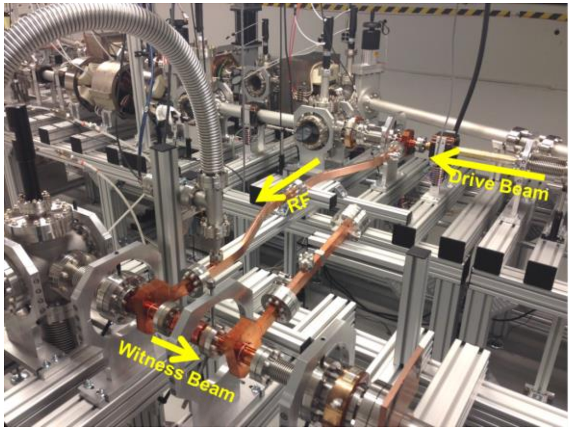
Unique capabilities of AWA:

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

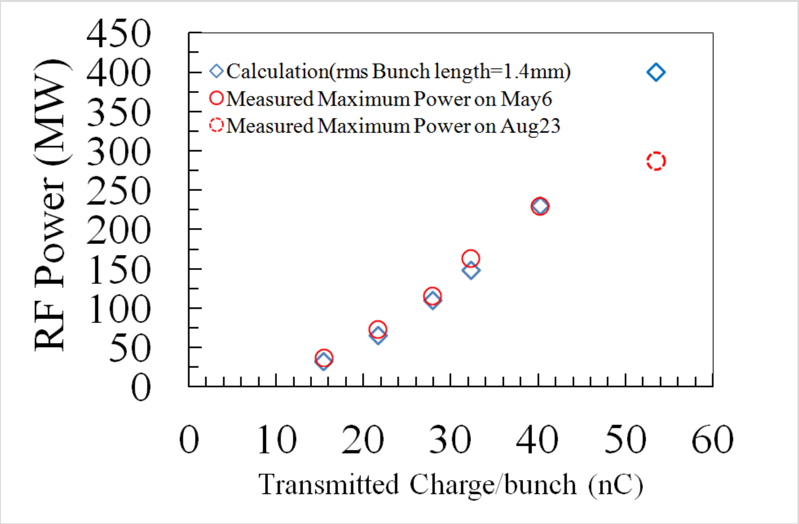
& flexibility →

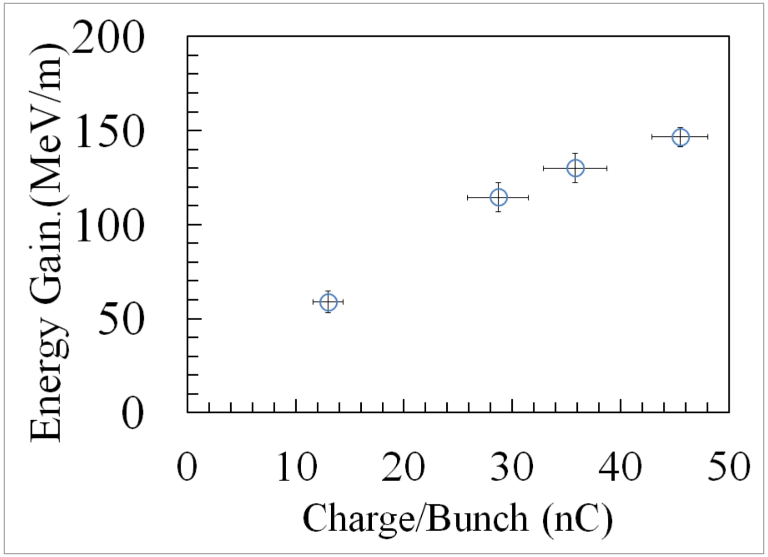
Ideal test-stand for beam driven wakefield studies

TWO-BEAM ACCELERATION EXPERIMENT



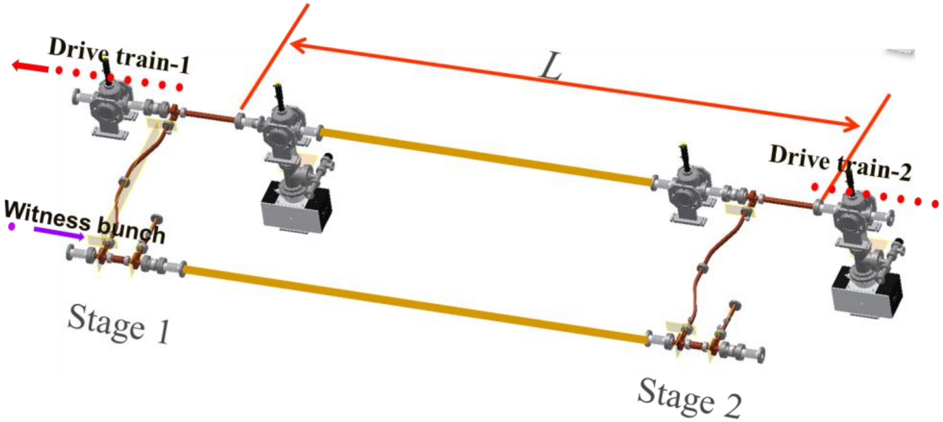
- 11.7 GHz metallic iris loaded structure
- 300 MW
- 150 MeV/m



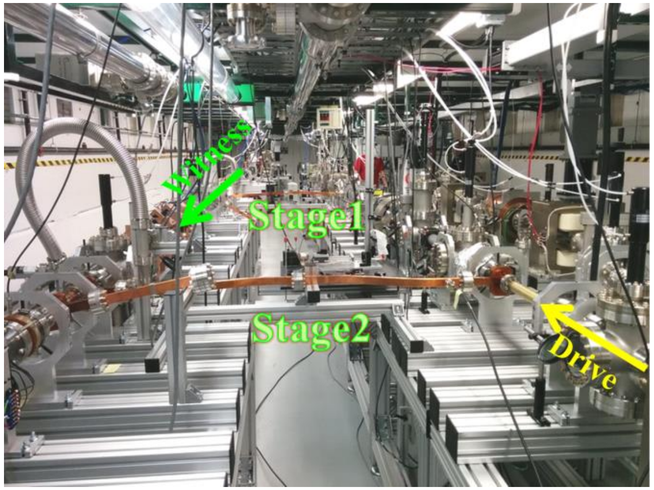


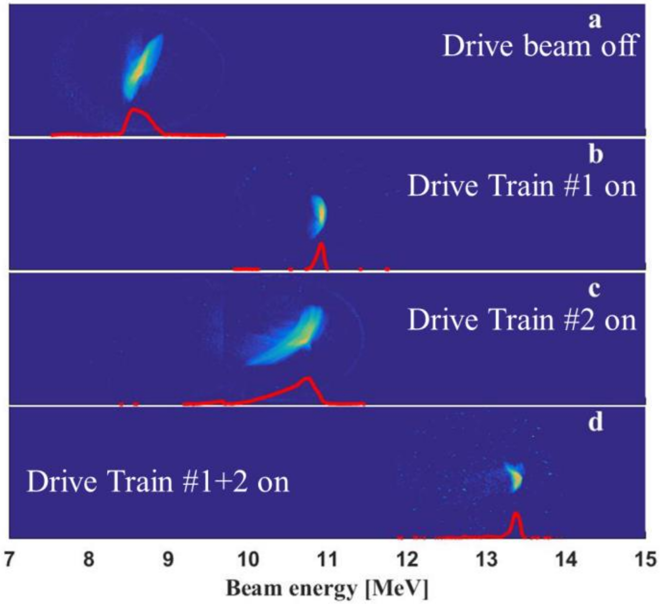
C. Jing et al., Nucl. Instr. Meth. in Phy. Res. A 898, 72-76 (2018)

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)

DIELECTRIC BASED ACCELERATOR. WHY ?

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

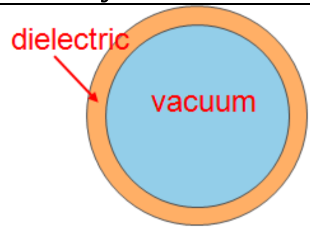
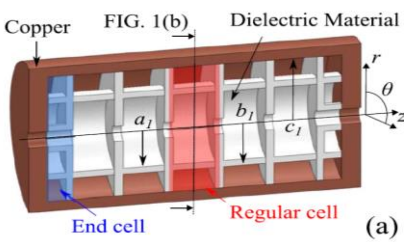
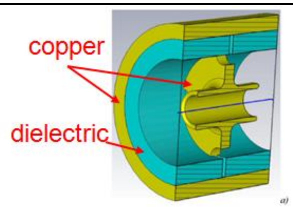
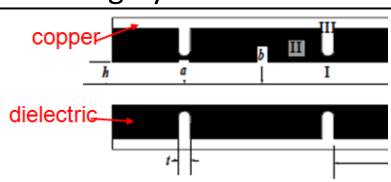
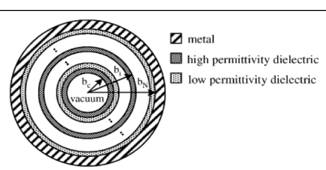
- A short pulse (~20 ns), high gradient (>300 MV/m) accelerator is an alternative technology to meet the requirements for future high-energy machines

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

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

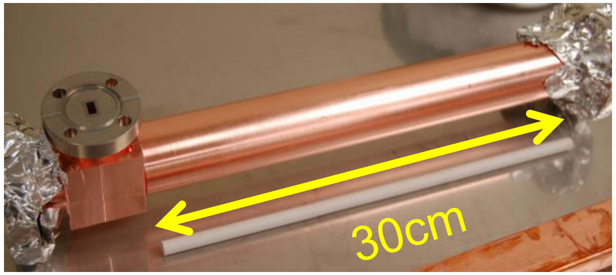
- **simplicity of manufacture**
- **expected high breakdown threshold,**
- **dielectric is “transparent” to the rf propagation;**
- **it is a broadband device (broadband coupling scheme !)**

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

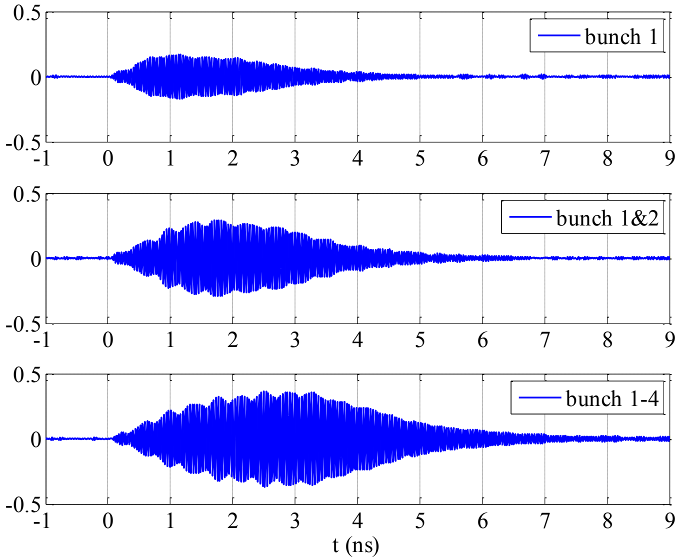
K-BAND 26 GHZ STRUCTURES

- **All-dielectric TBA**



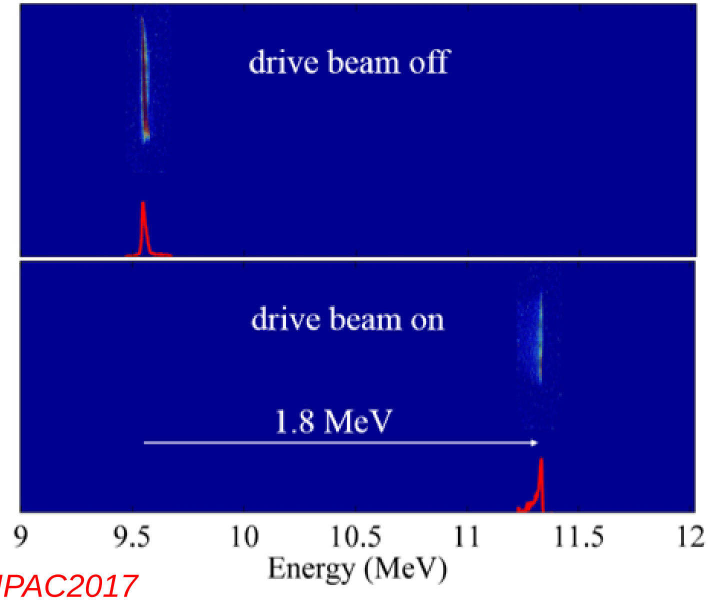
power extractor

accelerator



55 MW
generated power

28 MeV/m
acceleration

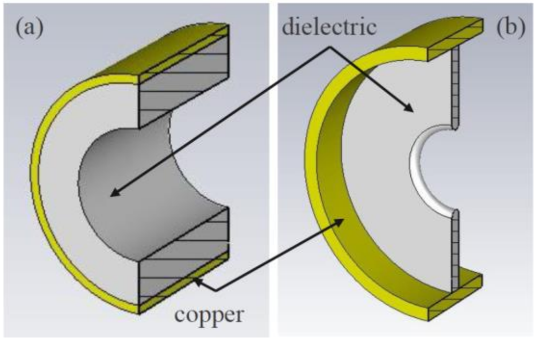


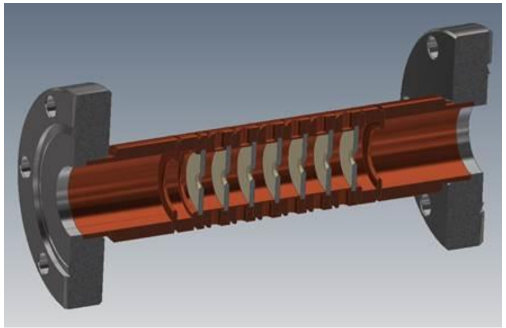
J. Shao, *et al, in Proceedings of IPAC2017*

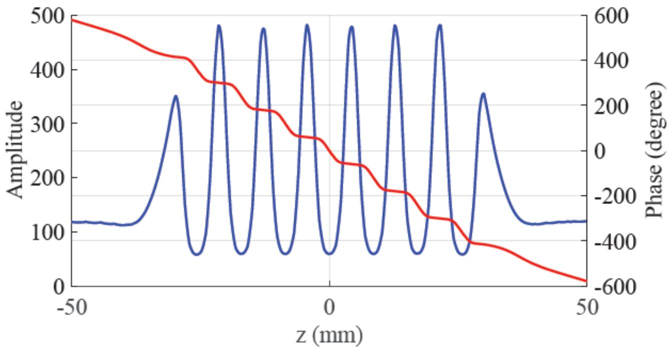
NOVEL STRUCTURES

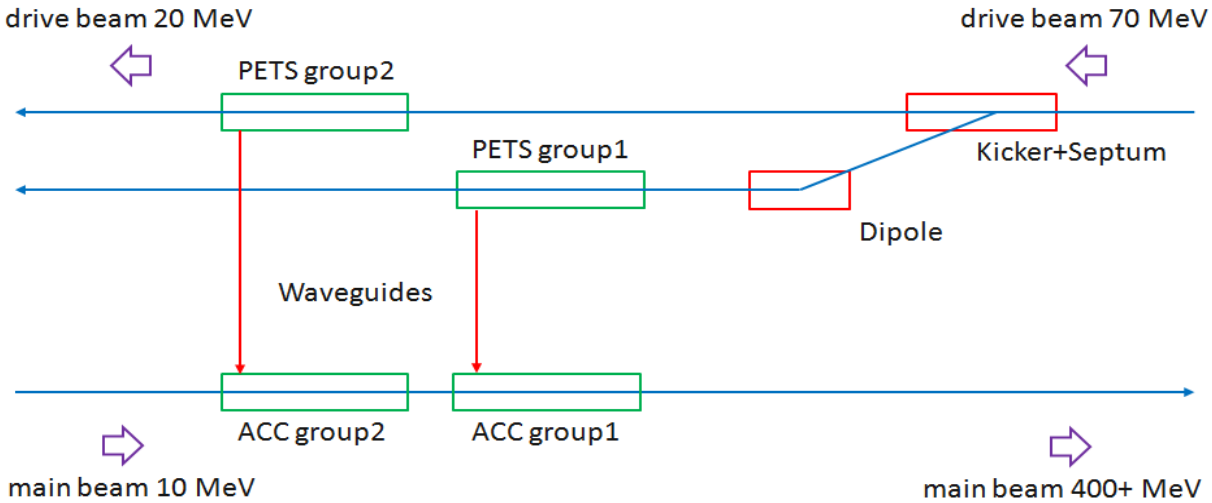
- **Dielectric-disk accelerator**

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

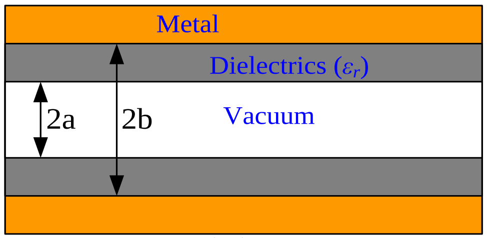




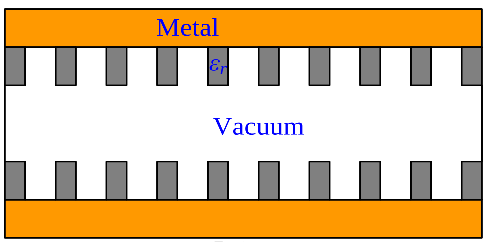




DIELECTRIC DISK ACCELERATOR



(a)



(b)

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

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

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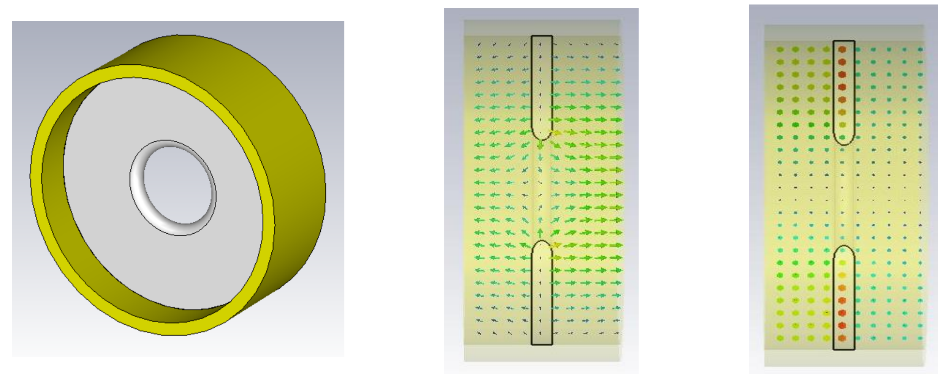


A Dielectric Disk cell: a) geometry; b) electric and c) magnetic fields of the accelerating mode;

	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

X-BAND DIELECTRIC-LOADED POWER EXTRACTOR

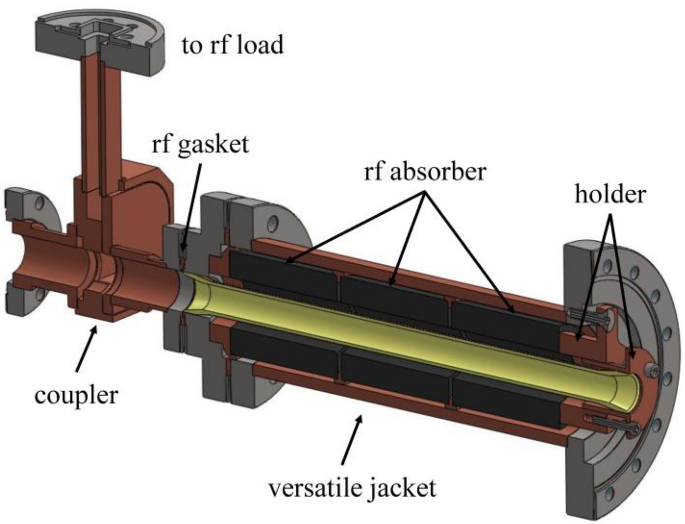
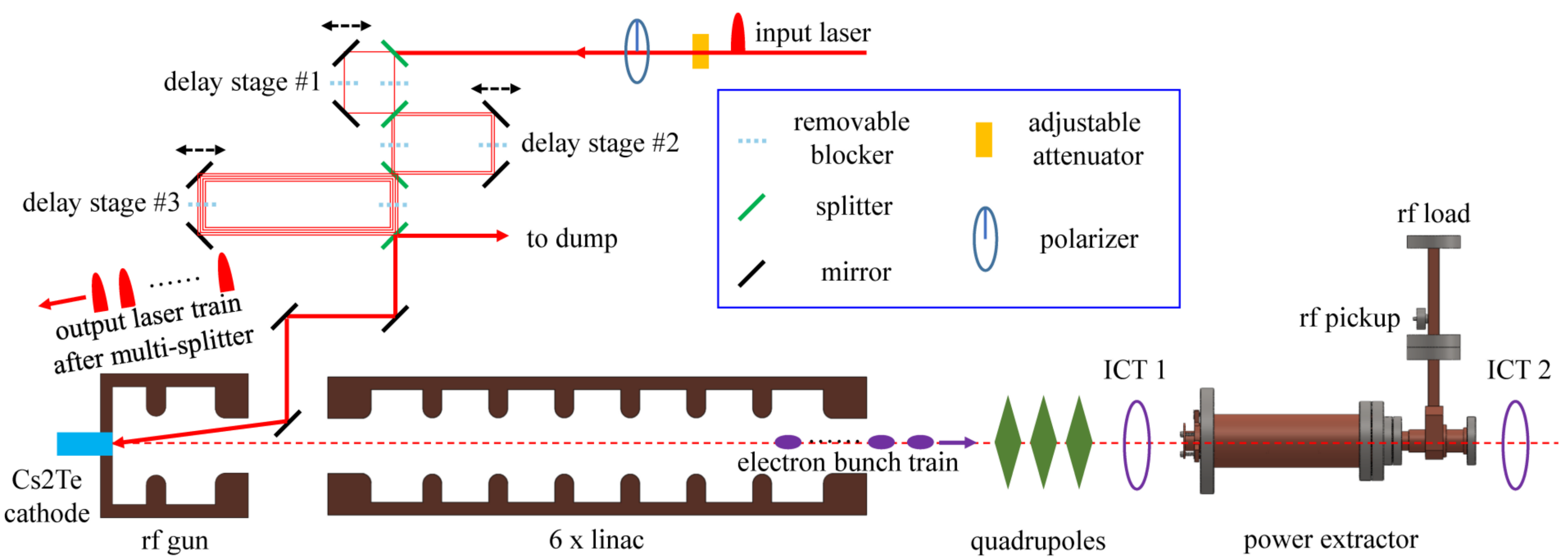


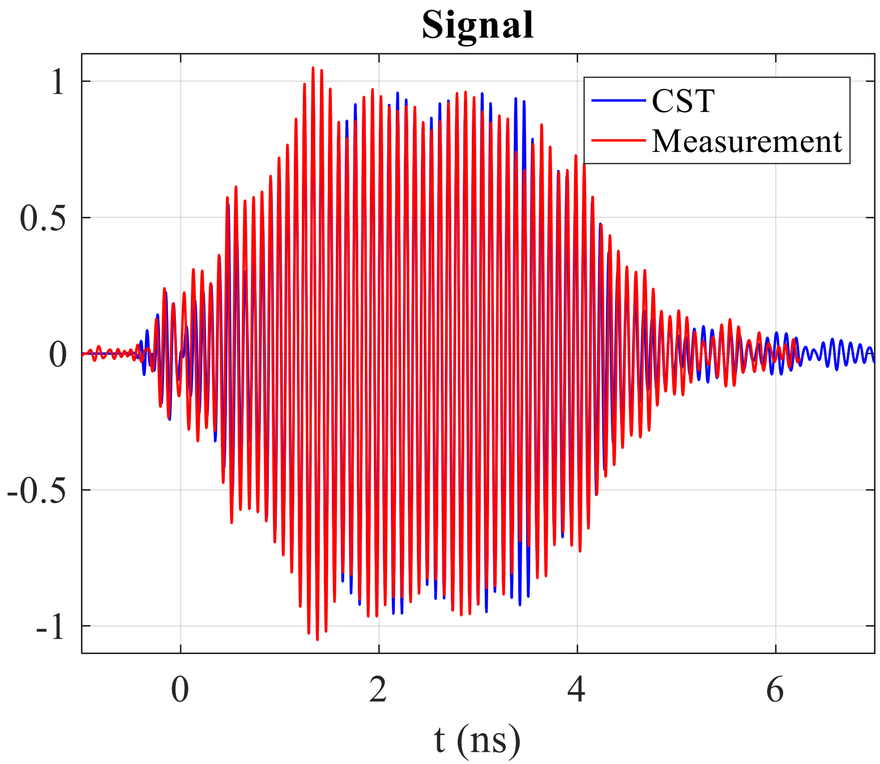
TABLE I. Parameters of the uniform section.

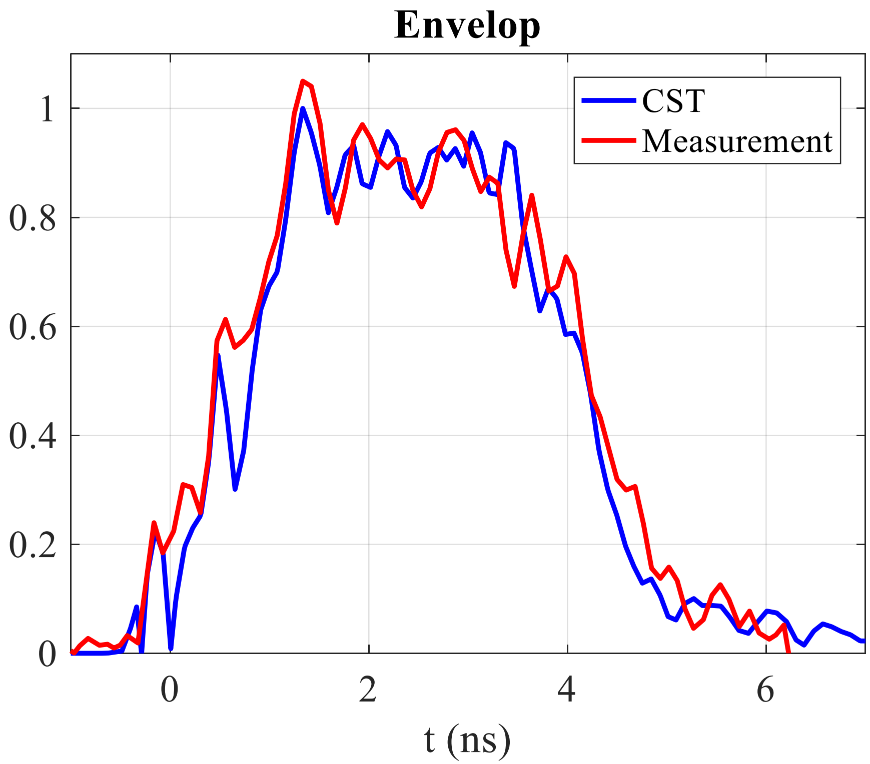
Parameter	Value
Material	Alumina
Dielectric constant	9.8
Loss tangent	1×10^{-4}
Inner radius	7.50 mm
Outer radius	9.40 mm
Length	26 cm
Quality factor	3393
r/Q	4.32 kΩ/m
Group velocity	0.20 c
$E_{surface,max}/E_{axis}$	1
Flat-top duration (8-bunch train)	3.1 ns



RF PULSE SHAPE

- **2-bunches**
  - CST simulation with full structure including the coupler, based on the realistic charge balance
  - A 5 GHz band-pass filter applied to the measurement results to reduce noise





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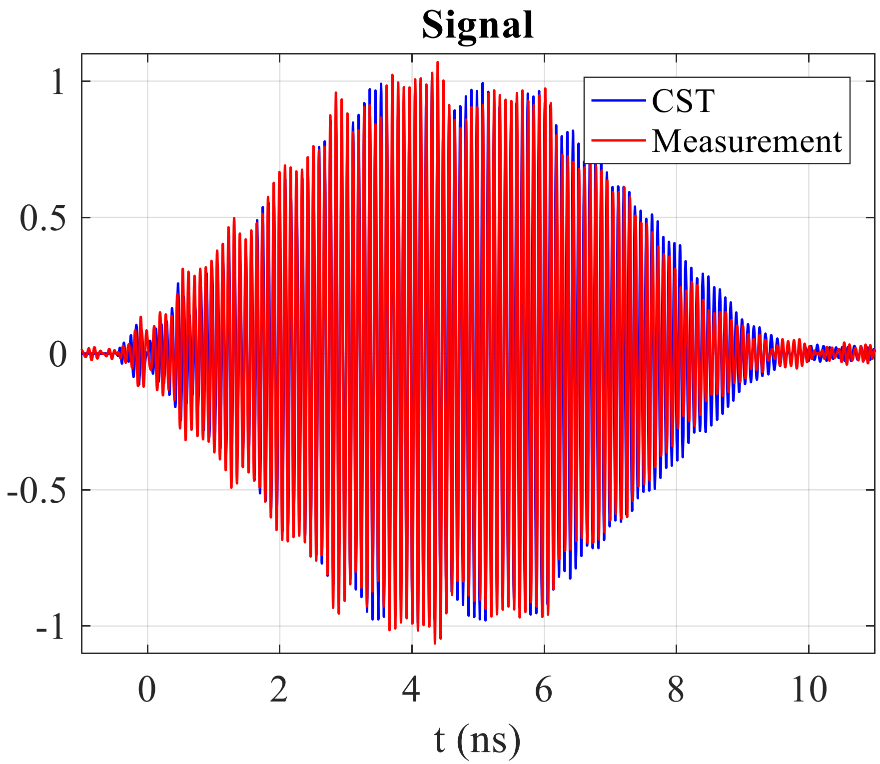
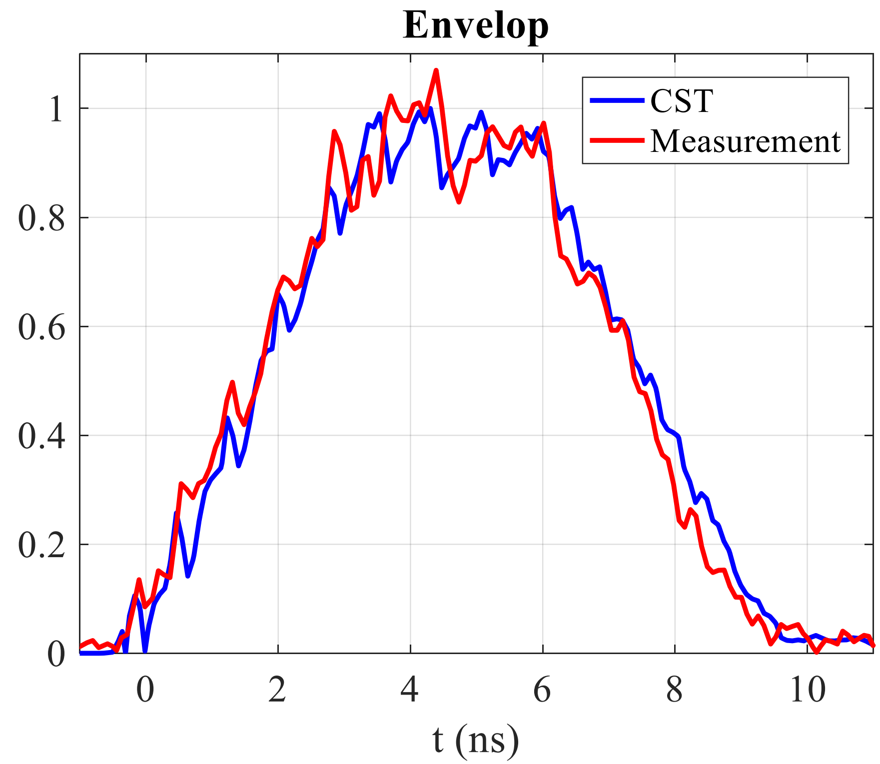
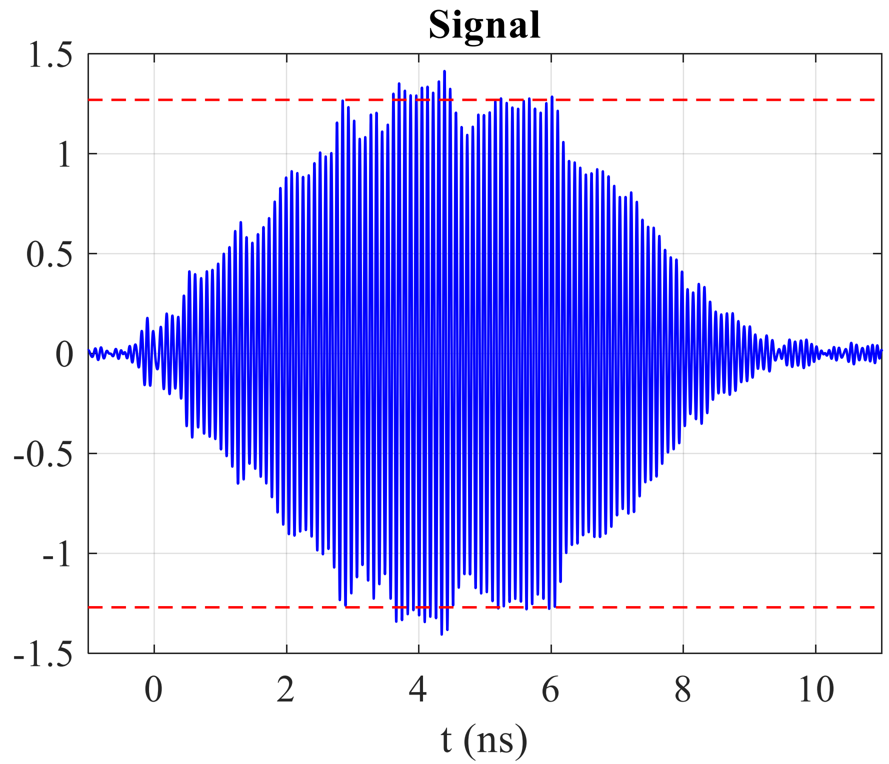


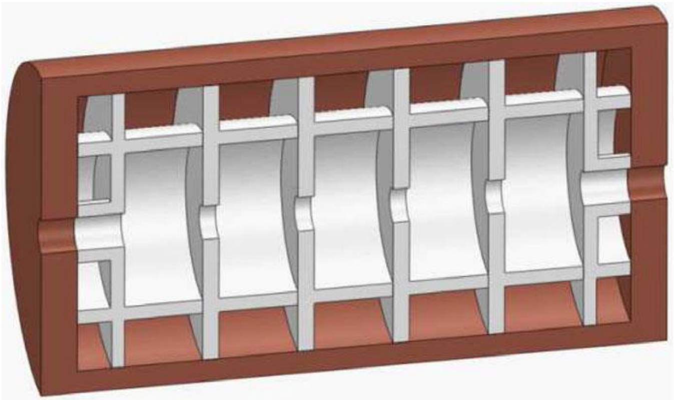


POWER LEVEL

- **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



Extreme Dielectric Losses of MgO 3N ?



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.

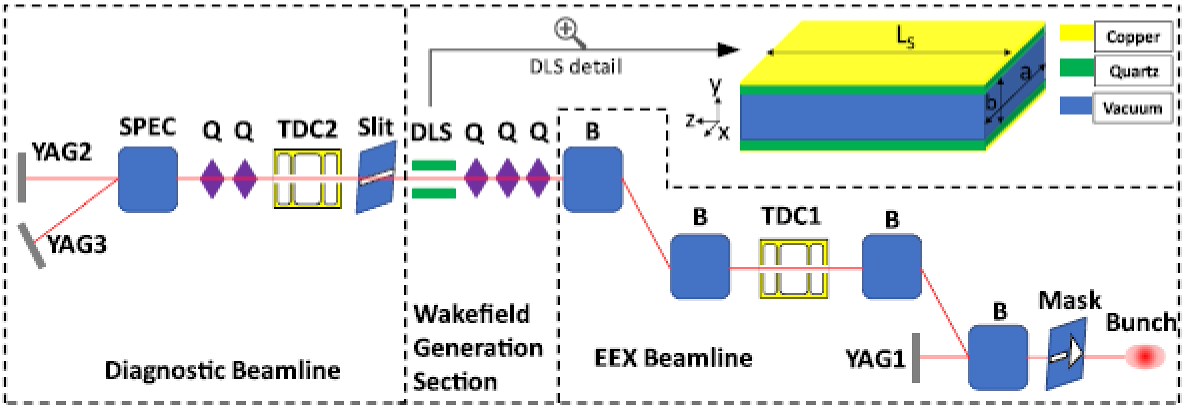
Thus, studies on the following subjects will have to be conducted: ….(3) sintering of some ceramic materials for reasonably **high dielectric permittivity (ε_r > 20) and low loss tangent (tan δ < 10^{-4}).**

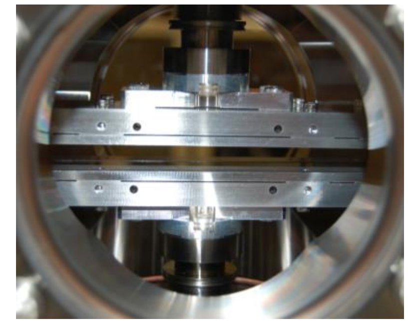
See also **Yelong Wei, this Workshop**.

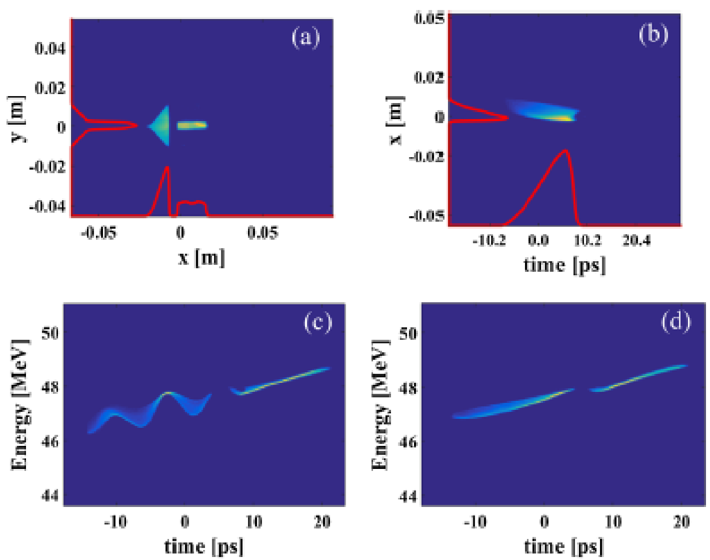
euclid TECHLABS

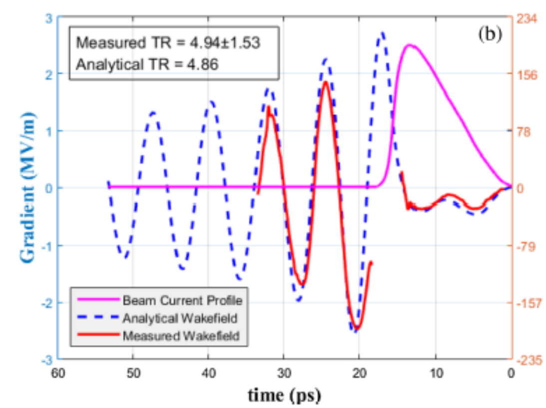
TOWARDS HIGH EFFICIENCY

- **High transformer ratio with EEX technology**





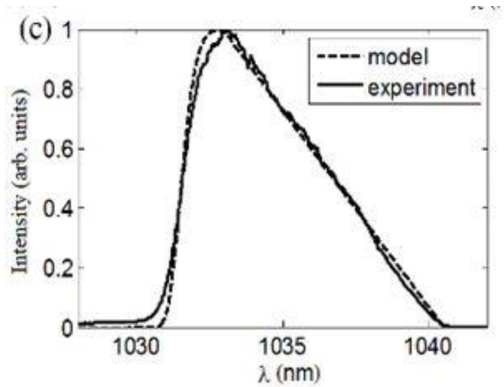




Tunable structure
Transformer ratio ~ 5

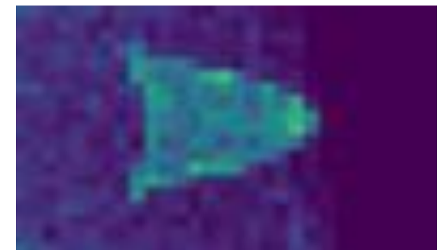
Q. Gao, *et al*, *Phys. Rev. Lett.*, 120, 114801 (2018)

LASER PULSE SHAPING FOR TRANSFORMER RATIO ENHANCEMENT

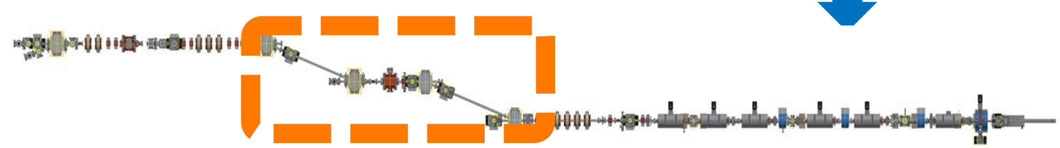


Spectrum shaped as a right triangle: Experiment and modeling

Modeling of electron beam distribution for AWA gun



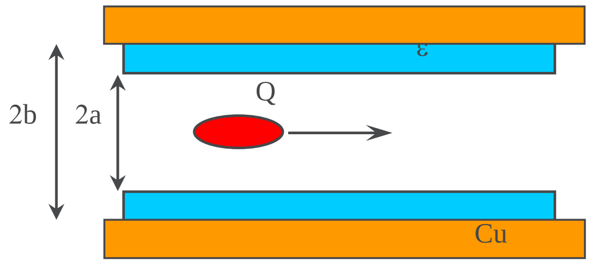
EEX line with pre-shaped bunch



- *mathematical models were developed to provide triangular and quasi-triangular (smooth) temporal laser beam shaping,*
- *the generation of laser pulses following a temporal linear shape were experimentally produced*
- *the resulting electron distribution in a RF gun and corresponded space charge effects were studied.*

Next – experimental demonstration of laser pulse shaping, triangular bunch generation in combination with the EEX beam line.

CERAMIC MATERIALS
FOR A DIELECTRIC-BASED ACCELERATOR



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

Nonlinear ceramic material for the tunable DLA structure

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

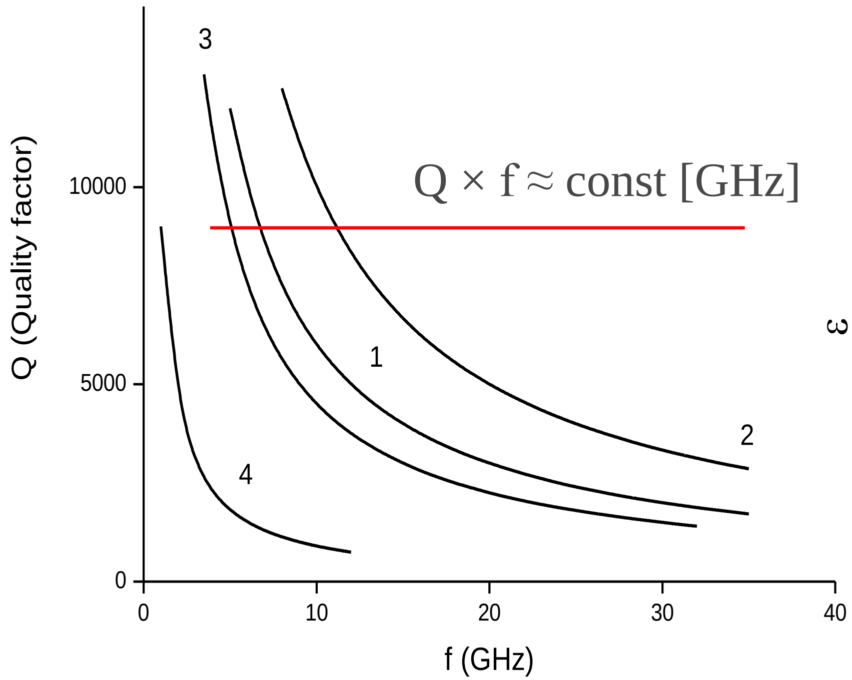
Coating,TiN, AlN

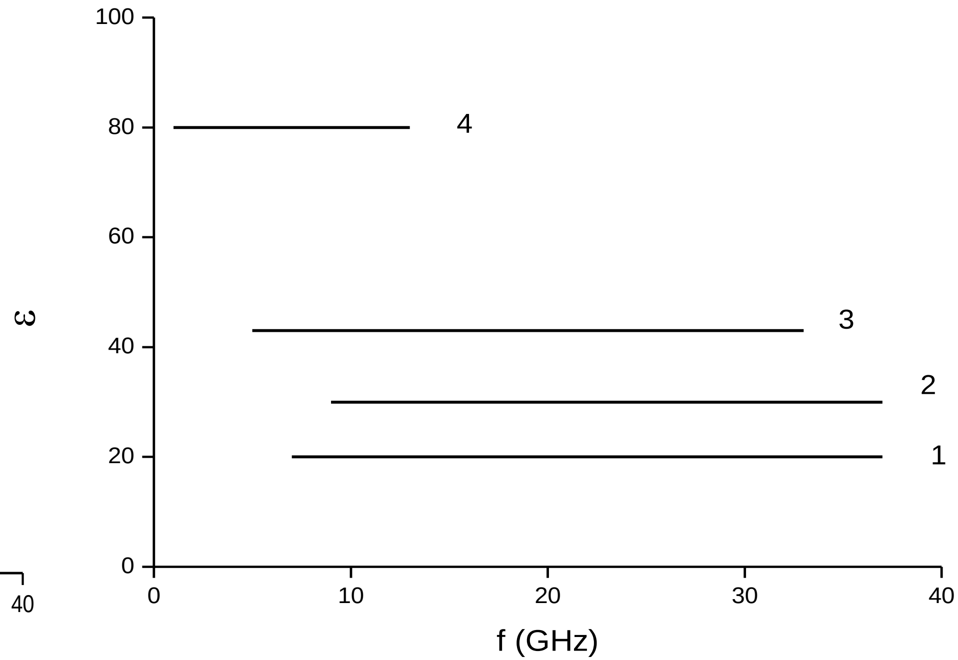
material	ε	tanδ, X-band	thermo-conductivity
TiN, AlN	9.8	3×10^{-3}	180 W/m^{0}K

Quartz, ε~ 3.75, tanδ~10^{-4}

Diamond, ε~ 5.7, tanδ<10^{-4}

Loss Tangent and Dielectric Constant of Microwave Ceramic





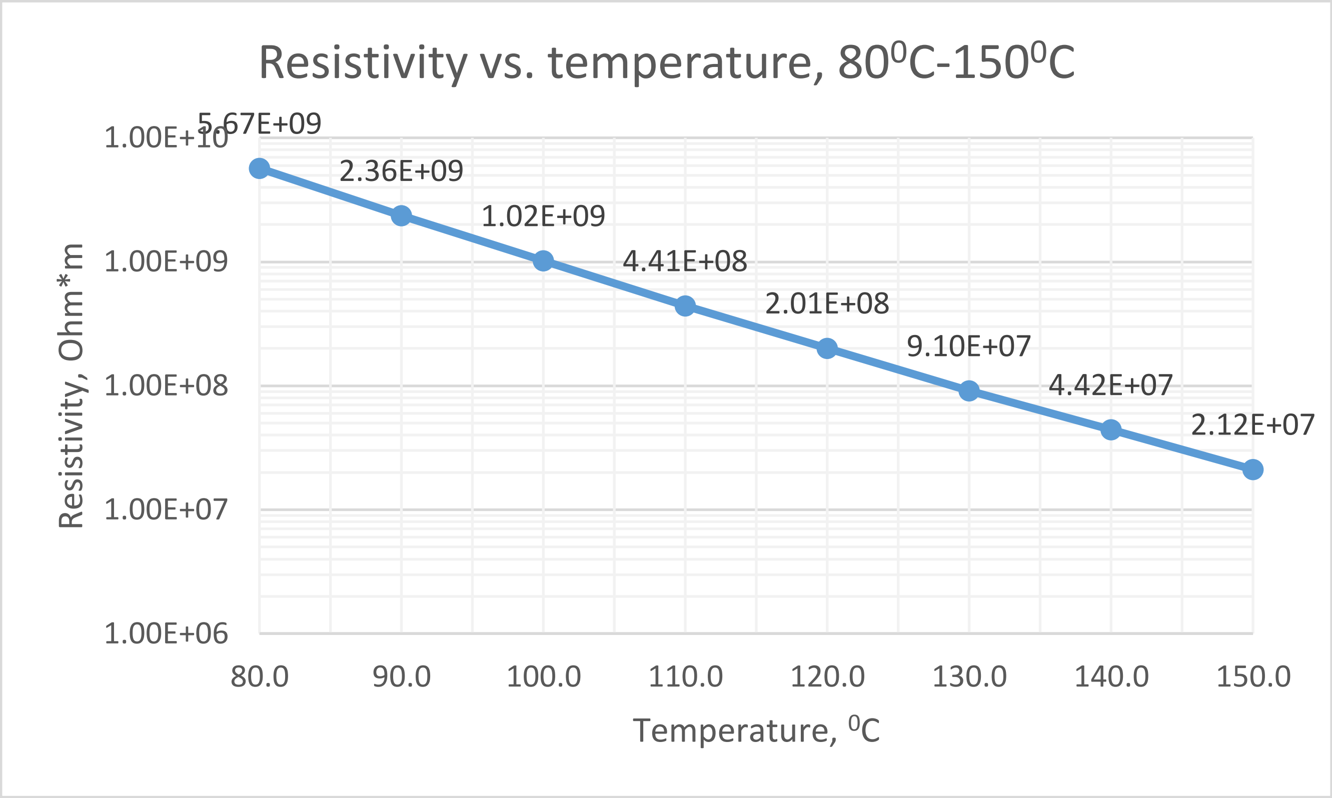
tanδ ~ f [GHz] over a wide microwave frequency range. **Q×f ≈ const, [GHz], Q=1/tanδ.** The product of frequency and dielectric quality is a constant. **This relation is a very important characteristic of linear microwave ceramics**

Best Q*f is in the range 150,000-180,000 (MgTi)

tanδ~5*10^-5 at X band (10 GHz)

CERAMIC STRUCTURES: CONDUCTIVITY

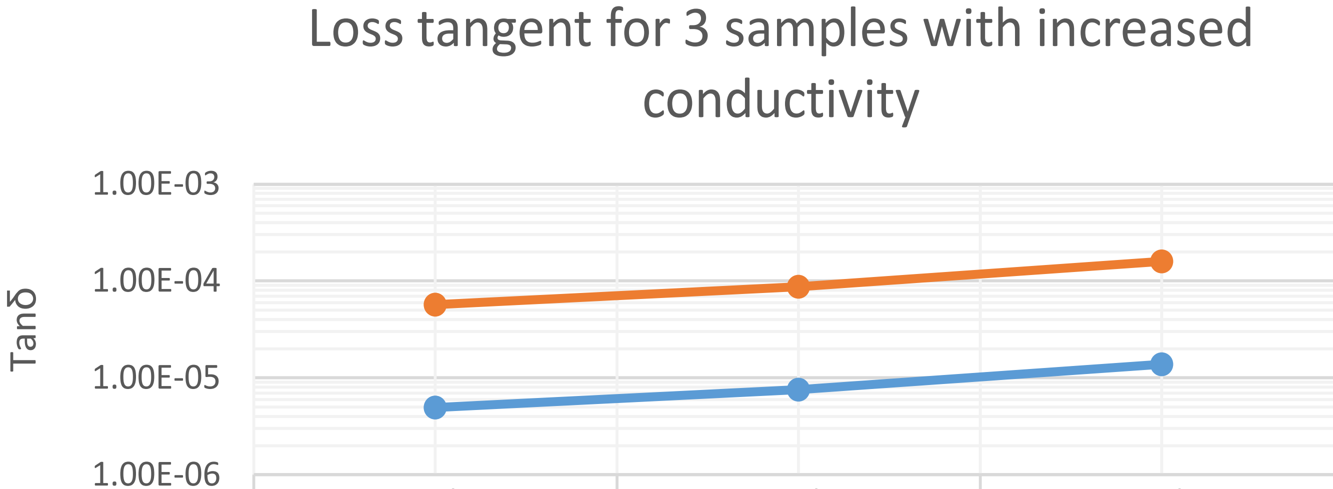
- **(Mg,Ti) ceramic** materials with very low dielectric loss, **if modified** (Euclid, 2018) exhibiting **2–3 orders of magnitude increased conductivity** (100–1000 times reduced volumetric resistivity).



- 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

content of oxygen

650 MHz 7.5 GHz

$\tan\delta = 5.8 \times 10^{-5}$ at 7.5 GHz

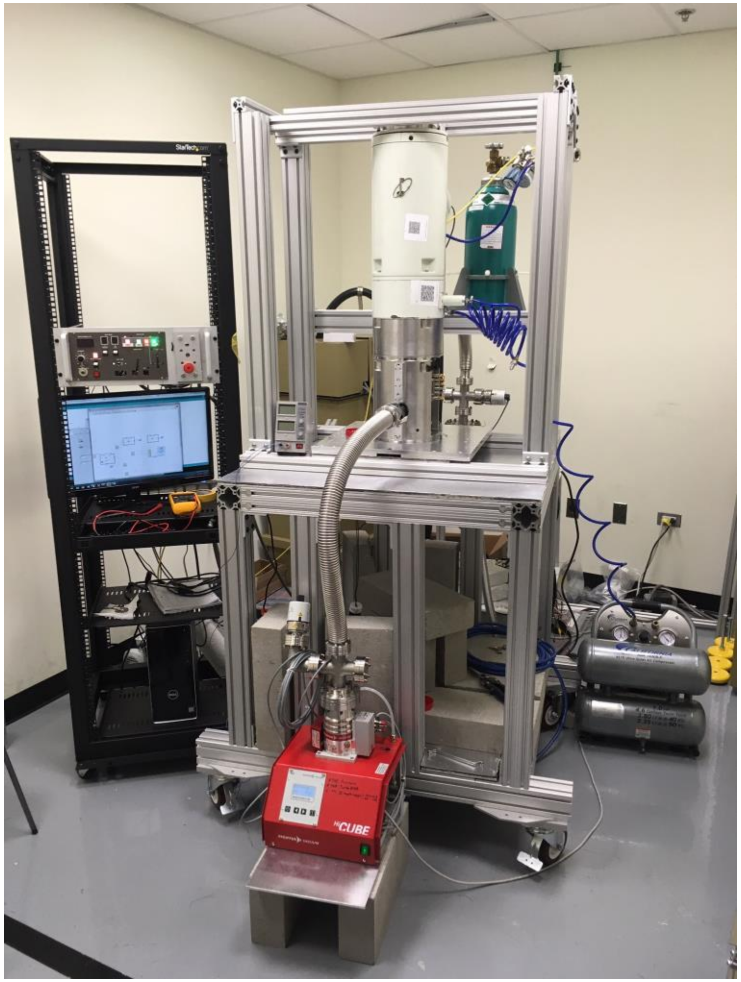
1.66×10^{-4} at 7.5 GHz

Loss tangent change with temperature

the **loss tangent** variation at 100^{0}C 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.

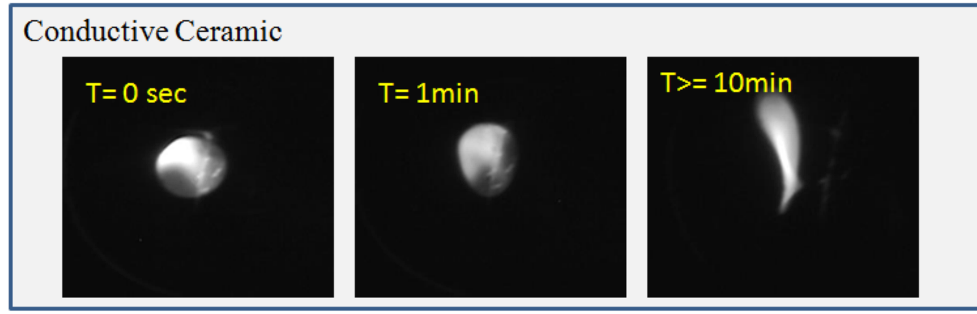
DC 200 kV BEAM CHARGING TEST OF CERAMIC

DC beam test using TEM DC gun:

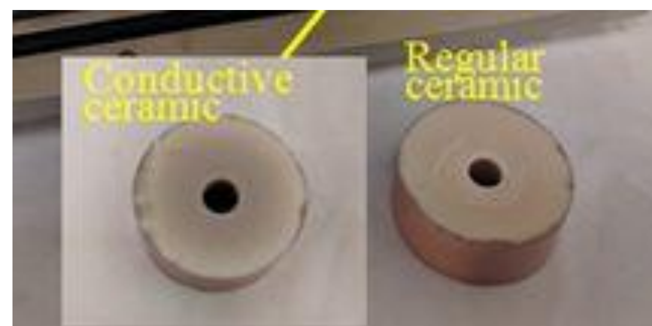


DC 200 kV electron beam
For charging testing

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



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

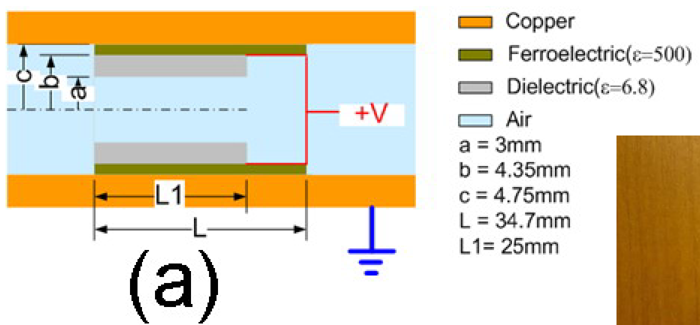


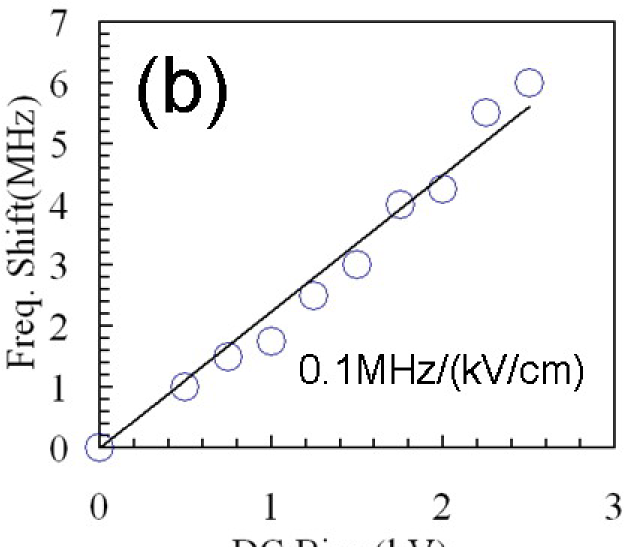
TUNABLE DIELECTRIC MATERIALS

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

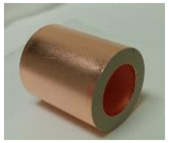
Where this materials have been used: Beam driven structures - >250 MV/m surface field tested, short pulse < 30 ns is needed.

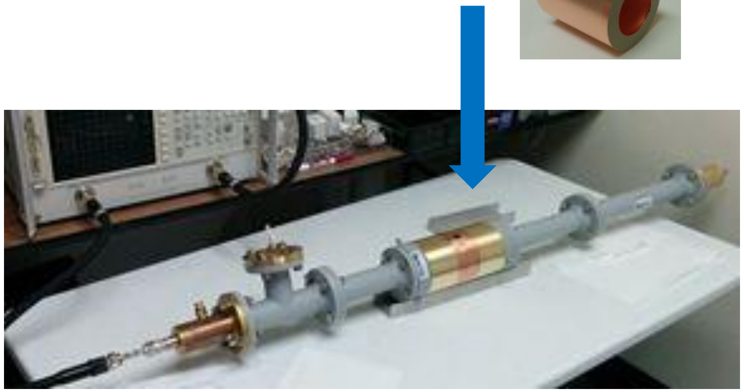
Tunable Dielectric-Based Accelerator

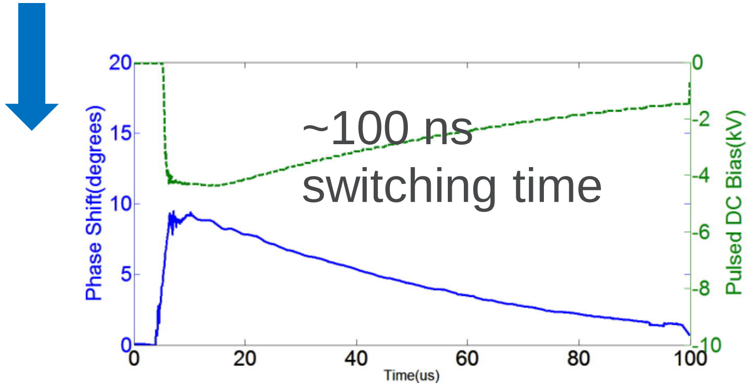




Fast ferroelectric based tuner for CERN





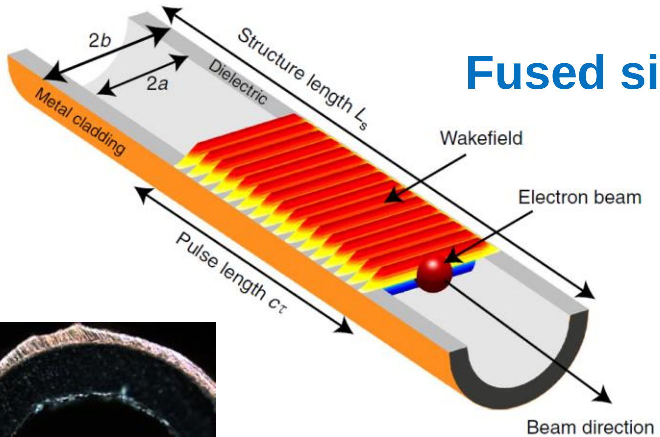


US patent 7,768,187

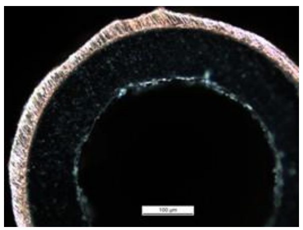
US patent 8,067,324

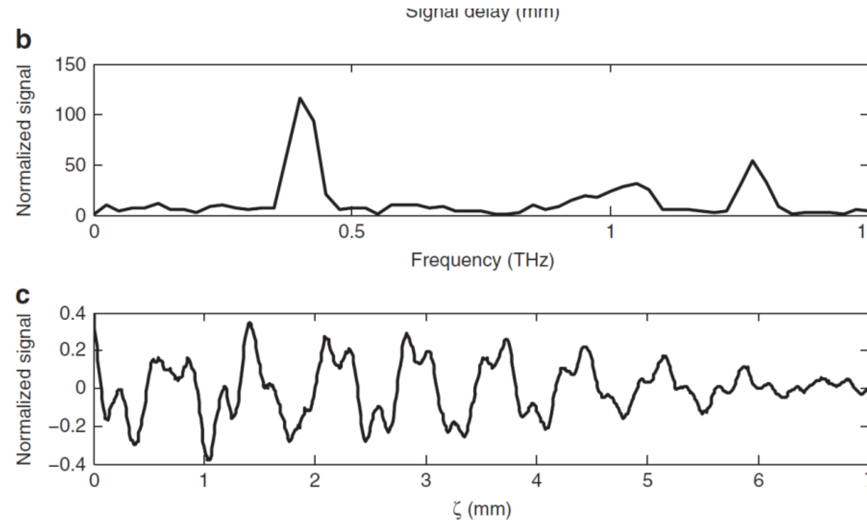
FACET DIELECTRIC TESTING

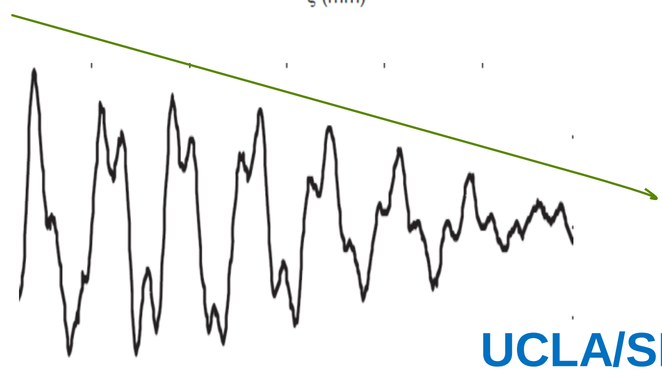
Wakefield Damping at ~ GV/M



Fused silica







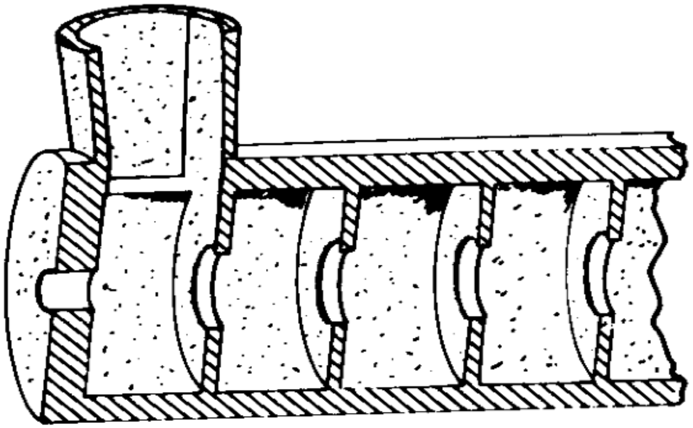
Unusual sharp fall off in field strength- the pulse is too short. Expected 18 mm, measured – 5 mm at ~ 1 GV/m range. High field induced conductivity at THz ?

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

AND SOME HISTORY…

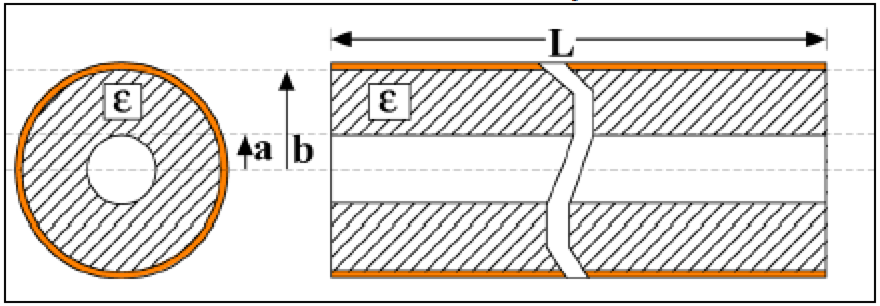


History, 1947 – first DLA linac paper

Frankel S. TM01 Mode in Cylindrical Waveguide with Two Dielectrics // J. App. Phys. 1947. V.18. P. 650.

First electron linac at Stanford (1947)

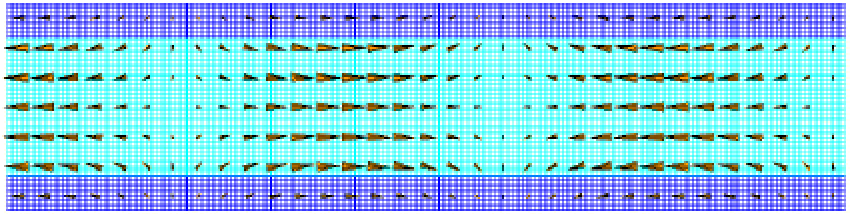
Geometry



Advantages

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

Electric Field Vectors



Major concerns

- Multipactor
- Breakdown

Mind the gaps, mind the steps !

Papers on Dielectric Accelerator published before 1960

- Frankel S. TM01 Mode in Cylindrical Waveguide with Two Dielectrics // J. App. Phys. 1947. V.18. P. 650-655.
- Bruck G.C., E.R.Wicher Slow Transverse Magnetic Modes in Cylindrical Waveguides // J. App. Phys. 1947. V. 18. P. 766-769.
- Shersby-Harvie R. B. R. A Proposed New Form of Dielectric-loaded Wave-Guide for Linear Electron Accelerators // Nature. 1948. V. 162. P. 890-890.
- Oliner A.A., Remarks of Slow Wave Cylindrical Waveguides // J. App. Phys. 1948. V. 19. P. 109-110.
- Flesher G., Cohn G. Dielectric Loading for Waveguide Linear Accelerator // AIEE Transactions. 1951. V.70. P. 887-893.
- Shersby-Harvie R. B. R. et al. Theoretical and Experimental Investigation of Anisotropic Dielectric Loaded Linear Electron Accelerator // Proceedings of the IEE - Part B: Radio and Electronic Engineering. 1957. V. 104. P. 273-290.
- Walker G. B. and West N.D. Mode Separation at the π-Mode in a Dielectric Waveguide Cavity // Proceedings of the IEE - Part C: Monographs. 1957. V. 104. P.381-387.
- Walker G. B., Lewis E. L. Vacuum Breakdown in Dielectric-loaded Wave-guides // Nature. 1958. V. 181. P. 38 – 39.

Again some history: now 1988

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.

PACS numbers: 41.80.−

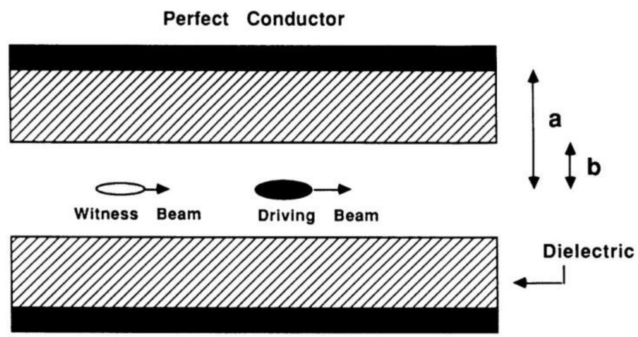


FIG. 1. Sketch of the dielectric cavity.

But before in Russia: theory of Cherenkov radiation in waveguide:

B. M. Bolotvskii, Usp. Fiz. Nauk., 75, 295 (1961) [Sov. Phys. Usp. 4, 781 (1962)]

Short pulse !

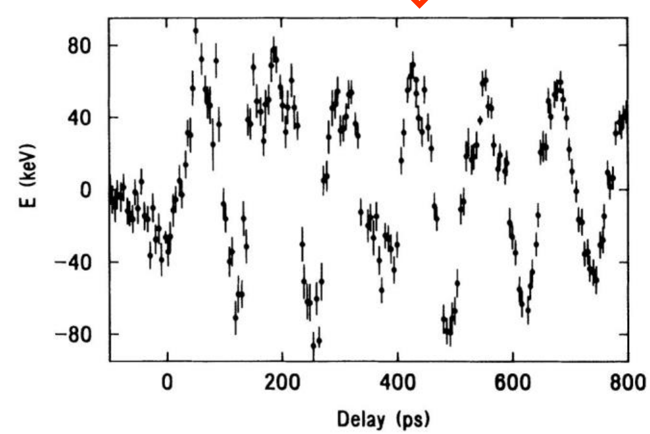


FIG. 4. Nylon scan: Wake potential measured as a function of witness-bunch delay.

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 traveling-wave 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

Tunable ceramic can be used

Short pulse is critical

New smart designs and new materials are needed !