WG 2. High Gradient Structures

Sami Tantawi, Valery Dolgashev

Mission Statement:

The purpose of this Working Group is to survey and discuss technologies for high-gradient electromagnetic structures. We need to leverage past and ongoing research efforts towards high gradient acceleration and high power generation in order to identify the highest practical accelerating gradient and to establish a working accelerator frequency for a multi-TeV linear collider. While the primary application for these developments is a technology for a multi-TeV linear collider, broader benefits are foreseen.

WG 2. High Gradient Structures

The charge to the Working Group is:

1. Survey the state-of-the-art in high-gradient electromagnetic structures to include:
   - performance achievements to date,
   - experiments on the basic physics of rf breakdown
   - theoretical modeling and simulations
2. Discuss developments towards understanding of the rf breakdown phenomenon:
   - Frequency scaling,
   - Geometry dependence,
   - Energy, power and pulse length,
   - Materials,
   - Surface processing technique,
   - Theory

RF Technologies and Sources for High Gradient Studies

1-Steve Russell - MM-Wave Source Development at Los Alamos National Laboratory
2-Jay Hirshfield-Advanced Rf Sources For High Gradient R&D
3-Lawrence Ives - High Power RF Sources for Accelerators and High Gradient Research.
Applications
4- Gregory Nusinovich-Phase sensitivity of relativistic gyrotrons to voltage deviation
5- Jiquan Guo - Active RF Pulse Compression Using Electrically controlled Semiconductor Switch
6- Alexei Kanareykin - Low-Loss Ferroelectrics for Accelerator Application
7- Sergei Kazakov - Electrically-Controlled Fast Ferroelectric Tuner for ILC
8- Slava Yakovlev-Novel Components For Rf Pulse Manipulation
9- Michael LaPointe-Ka-Band Test Facility For High-Gradient Accelerator R&D

MM-Wave Source Development at Los Alamos National Laboratory

S. J. Russell, K. A. Bishofberger, R. W. Brown, B. E. Carlsten, R. Carlson, L. M. Earley, M. V. Fazio, W. B. Haynes, C. E. Heath, H. C. Kirbie, F. L. Krawczyk, F. P. Romero, F. E. Sigler, E. I. Smirnova, Z. -F. Wang, R. M. Wheat
Los Alamos National Laboratory

S. Humphries, Jr.
Field Precision, Albuquerque, NM

P. Ferguson
MDS Company, Oakland, CA

J. M. Potter
JP Accelerator Works, Los Alamos, NM

Summary

- Motivation for planar geometries.
- Goal – 95 GHz sheet beam traveling wave tube (TWT).
- “Conventional” planar RF structures we have designed and tested.
- Dielectric photonic band gap (PBG) structures that may replace our conventional copper circuits.
- Sheet beam generation and transport.
- Beam cooling as a path to very high frequency devices (~300 GHz).

Source Development at CCR

- 91 GHz 10 MW Gyroklystron
- 30 GHz 25 MW Gyroklystron
- 50 MW X-Band Multiple Beam Klystron
- L-Band 1.5 GHz Klystron for JLAB
- L-Band Annular Beam Klystron

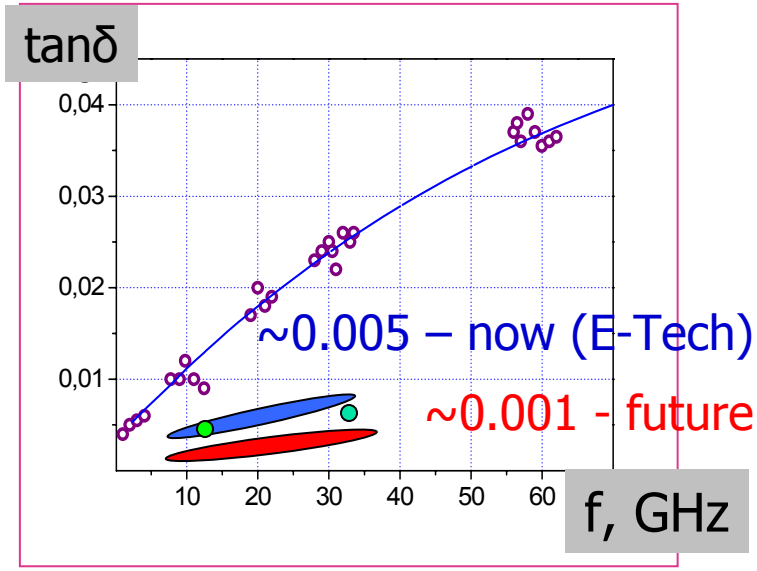
BST Ferroelectric Parameters

E-Tech

- Dielectric constant 400- 2000 ;
- Tunability K= e(0)/e(Emax) – 1.5, E_{max} = 5 V/μ;
- loss factor *tan* d – 0,005 - 0,01 at 10 ГГц ;
- high power ;

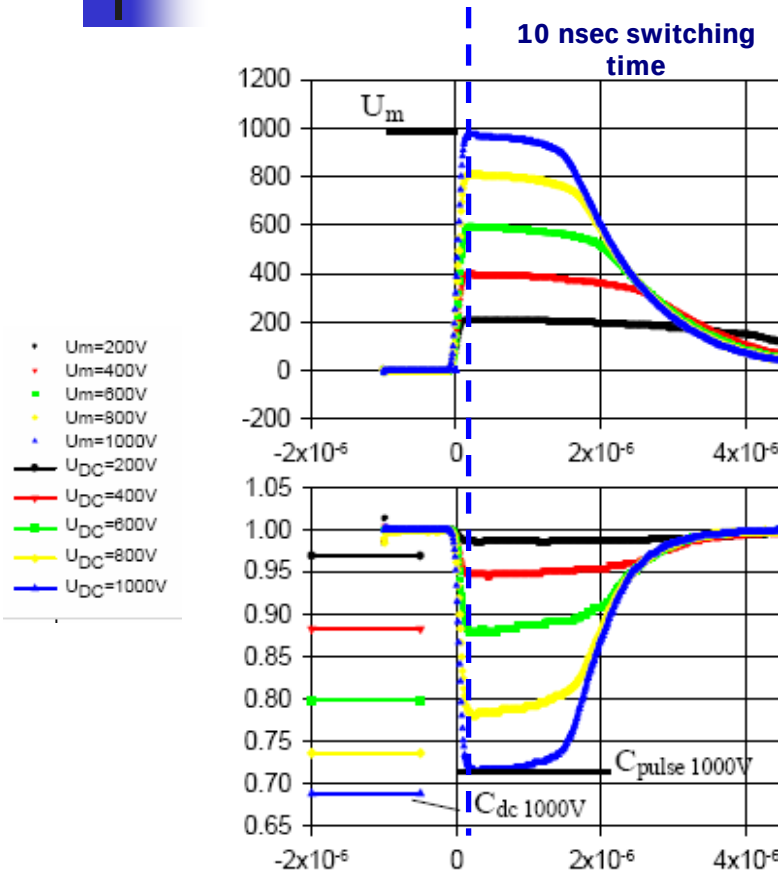
.

$Ba_xSr_{1-x}TiO_3$ (BST)

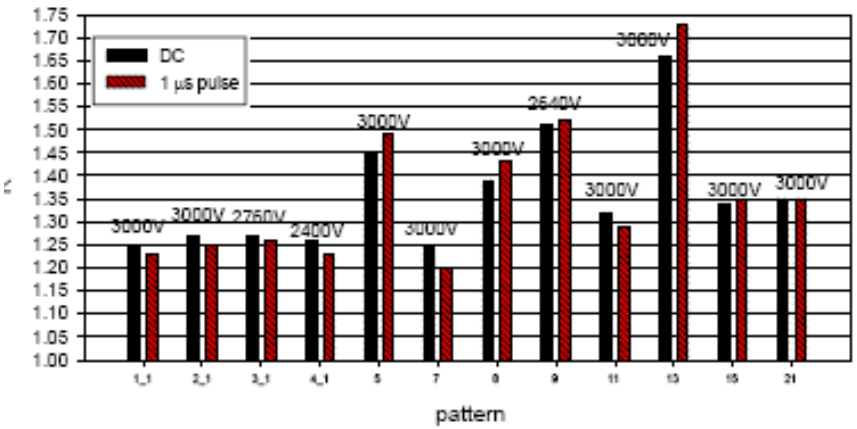


Microwave applications require BST composition at paraelectric phase and maximum nonlinear of the dielectric constant ε. x = 0, 5 – 0,6 composition parameter corresponds this requirements at room temperature. Technology procedure of the BST composition sintering and additives of (Mn, Mg, Ca) crucially defines the tunability and loss factor parameters. High transmitted power requires thick films 50-100 μm or bulk BST.

Switching Time of 10 ns for the Bulk Ferroelectric



Biasing pulse and phase response of the BSM ferroelectric material



- Note that with this experiment a short response time of less that 10 ns has been demonstrated for the bulk BSM ferroelectric at a high tunability exceeding 30% at 4 V/µm bias field in pulse mode .

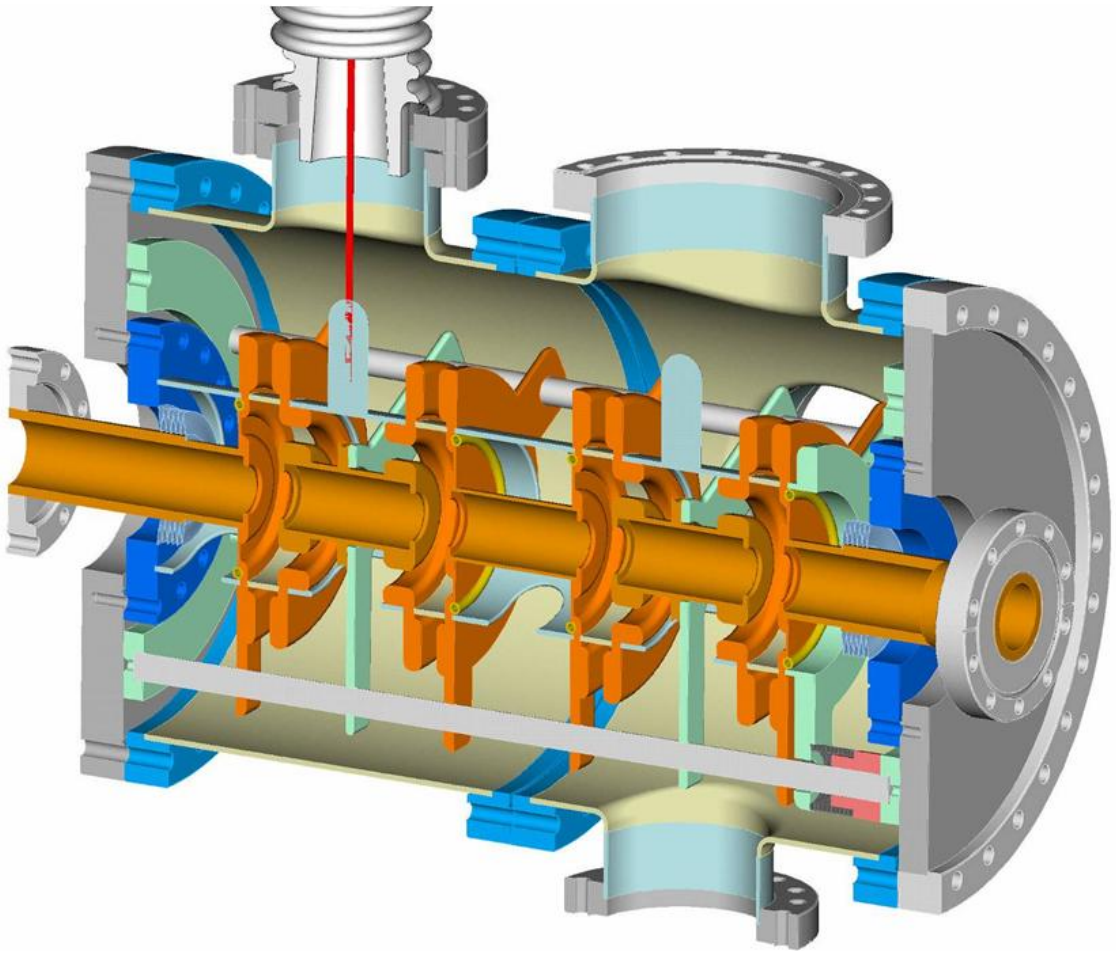
12th Advanced Accelerator Concepts Workshop, AAC 2006
Grand Geneva Resort, Lake Geneva, Wisconsin
July, 2006

NOVEL COMPONENTS FOR RF PULSE MANIPULATION*

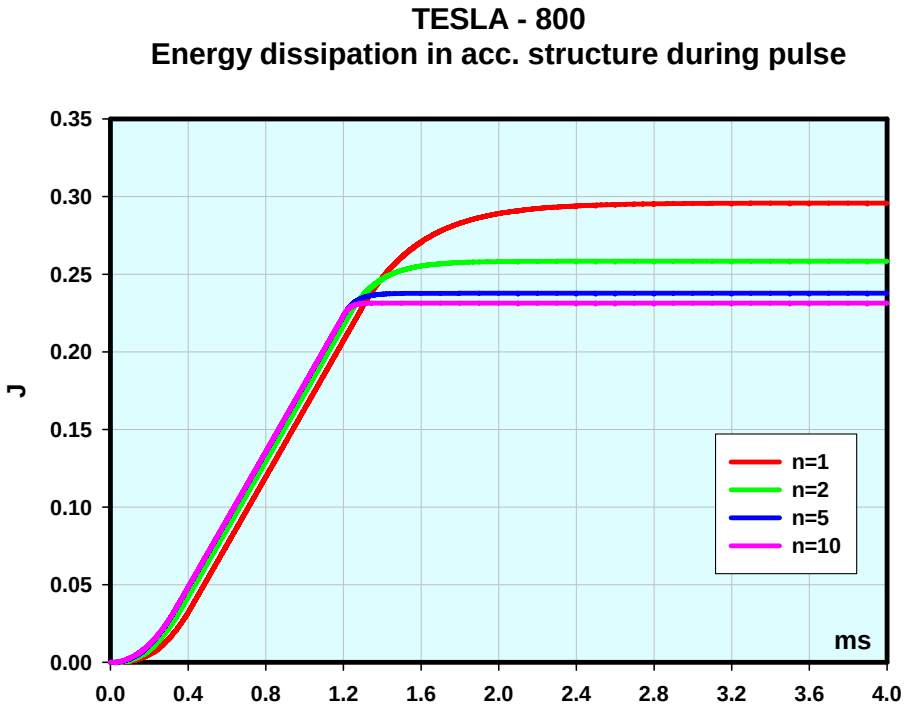
V.P. Yakovlev[1], Yu.Yu. Danilov[2], A.M. Gorbachev[2], J.L. Hirshfield[1,3], Yu.I. Koshurinov[2], S.V. Kuzikov[2], O.A. Nezhevenko, V.G. Pavelyev[2], M.I. Petelin[2], M.E. Plotkin[2], A.L. Vikharev[2]

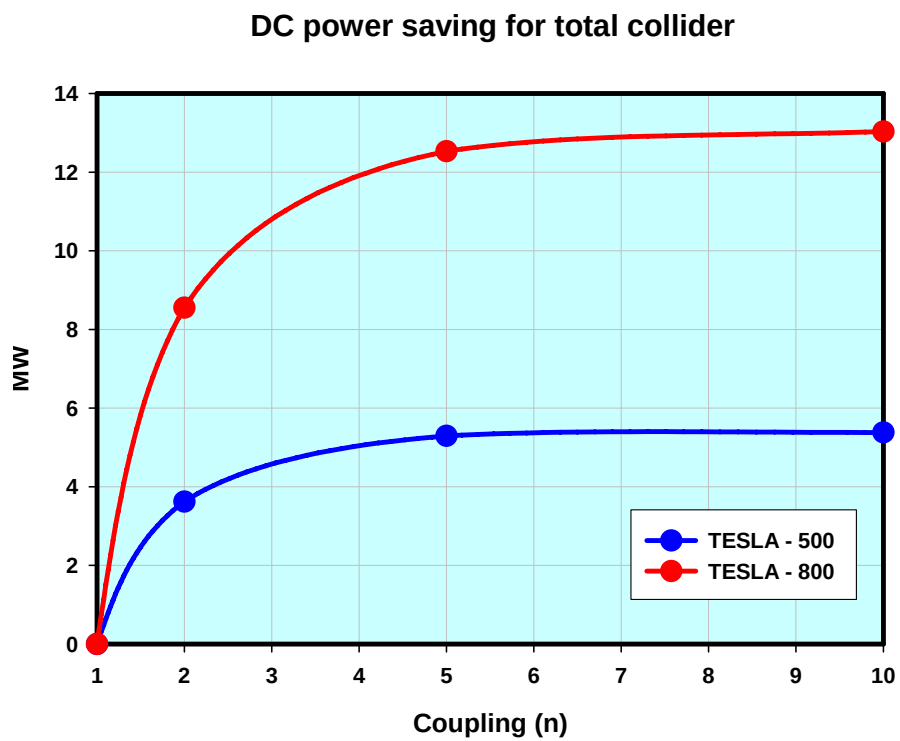
[1]Omega-P, Inc., New Haven, CT 06511
[2]Institute of Applied Physics, Nizhny Novgorod, 603600 Russia
[3]Yale University, New Haven, CT 06520

* Work supported by the U.S. Department of Energy



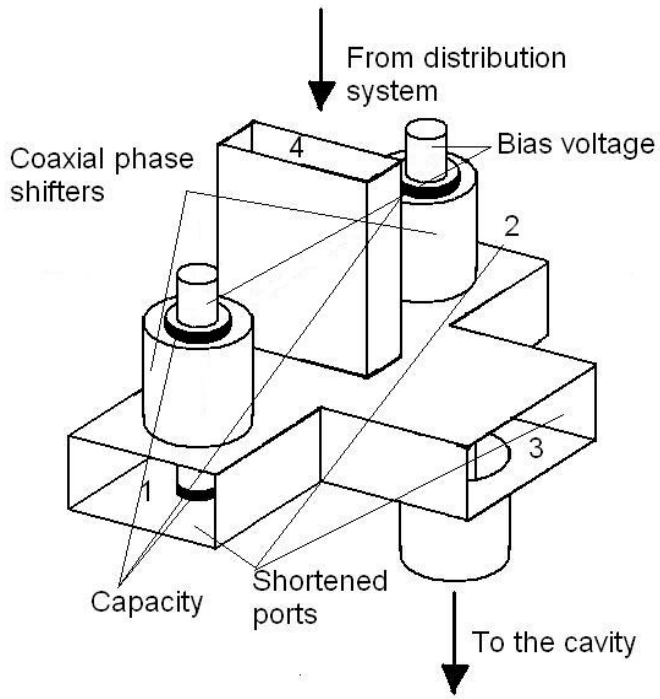
Design of the X-band ferroelectric phase shifter made for Omega-P by AES.





Coupling	t1, ms	t2, ms	t3. ms	$t3_1$-$t3_n$ ms	Saving, cryo. MW	Saving, RF MW	Total MW
1	---	0.420	1.288	0	0	0	0
2	0.25	0.361	1.229	0.059	3.39	5.16	8.55
5	0.150	0.336	1.204	0.084	5.18	7.35	12.53
10	0.09	0.3375	1.206	0.0825	5.80	7.23	13.03

Possible solution for tuner:



Advantage of phase-shifter with full reflection:
no need to worry abut good SWR;
easy to apply bias voltage

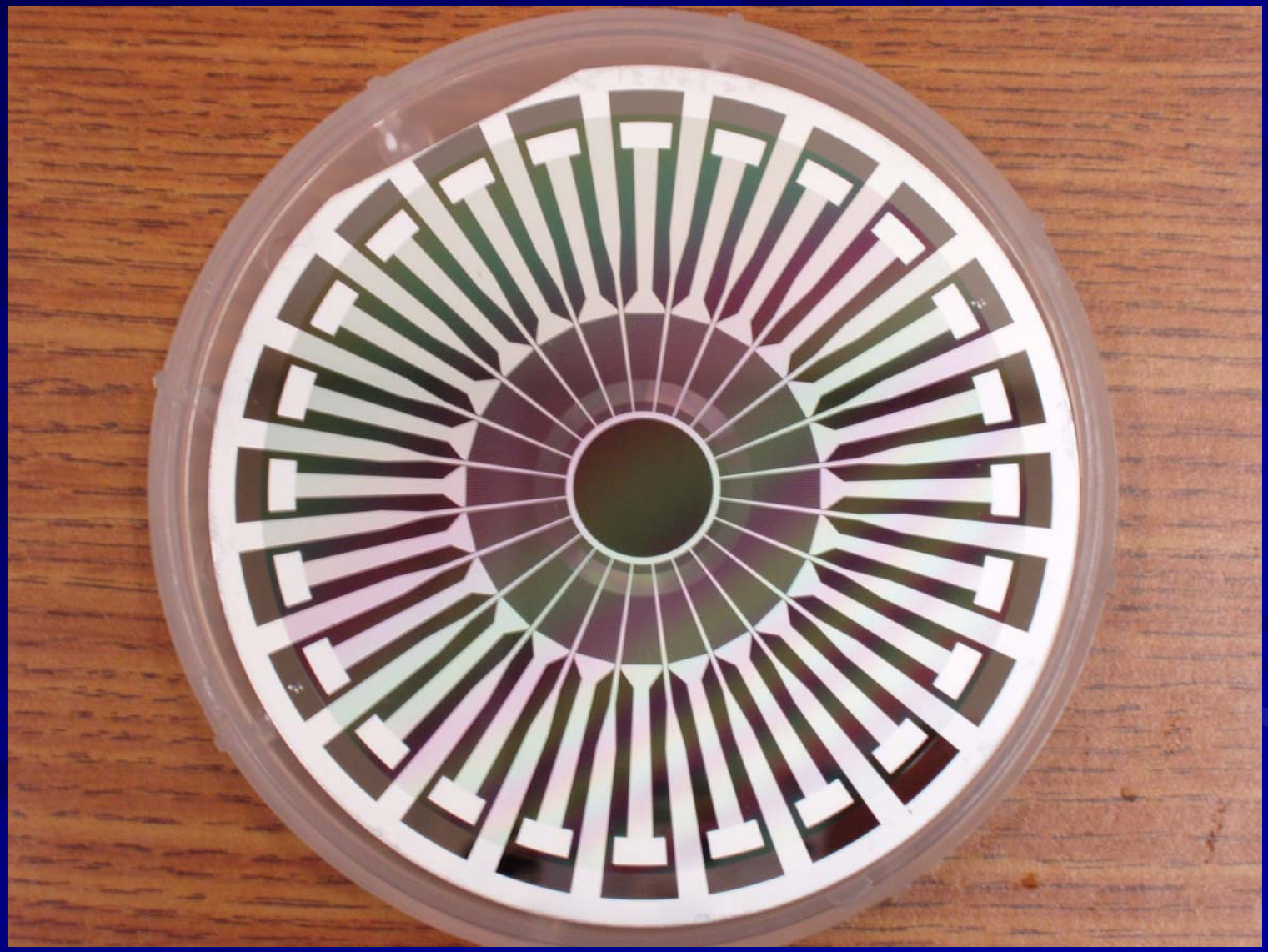
Summary

- **The theory describing the phase stability of free-running and phase-locked gyrotrons is developed**
- **Phase sensitivity of free-running and phase-locked relativistic gyrotrons to the voltage deviation is studied with the use of non-stationary code MAGY**
- **Results indicate that for providing required phase stability in microsecond pulses the voltage should be stabilized with about 0.1% accuracy**

Gregory Nusinovich

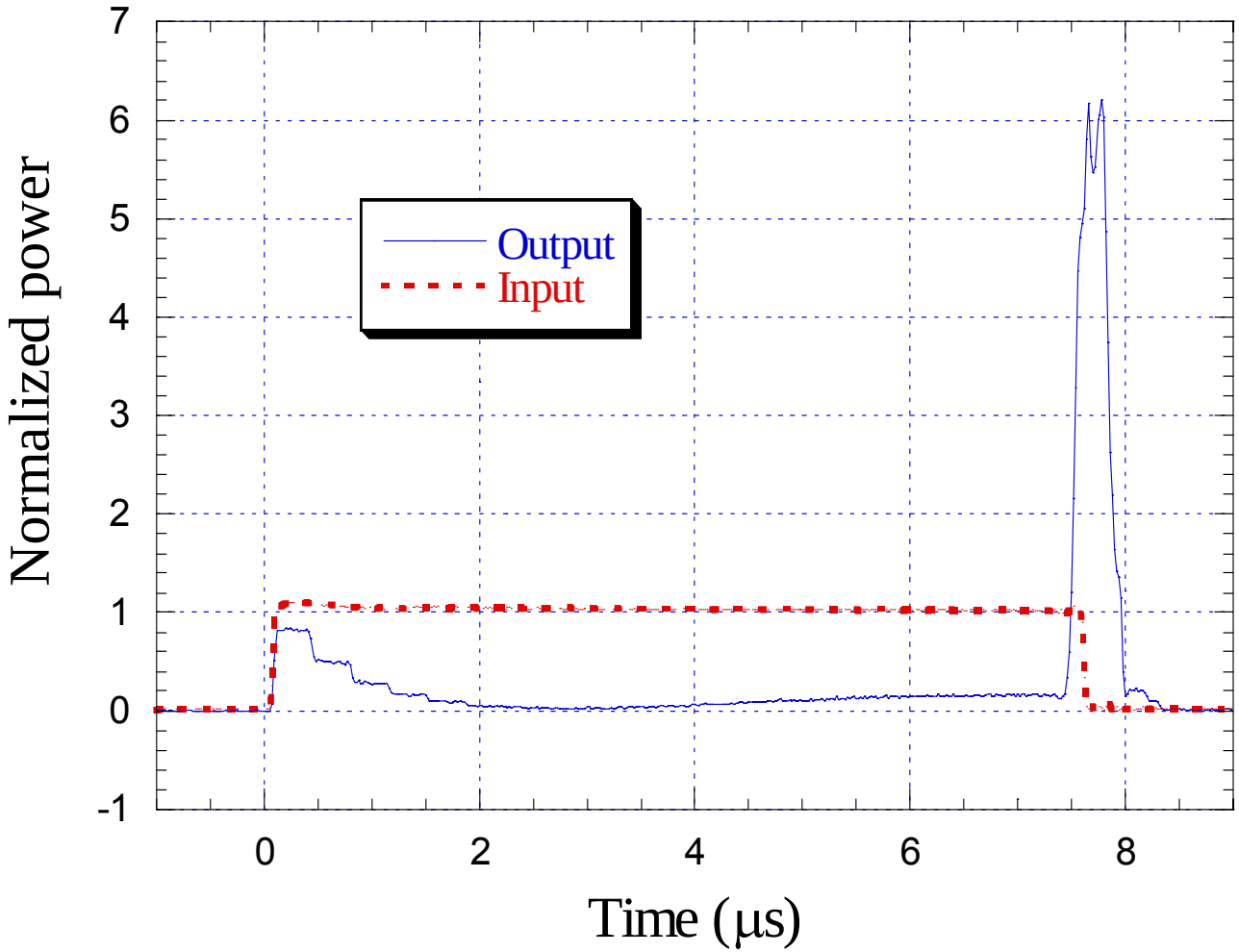
Jiquan Guo
Stanford University

Diode array



Jiquan Guo
Stanford University

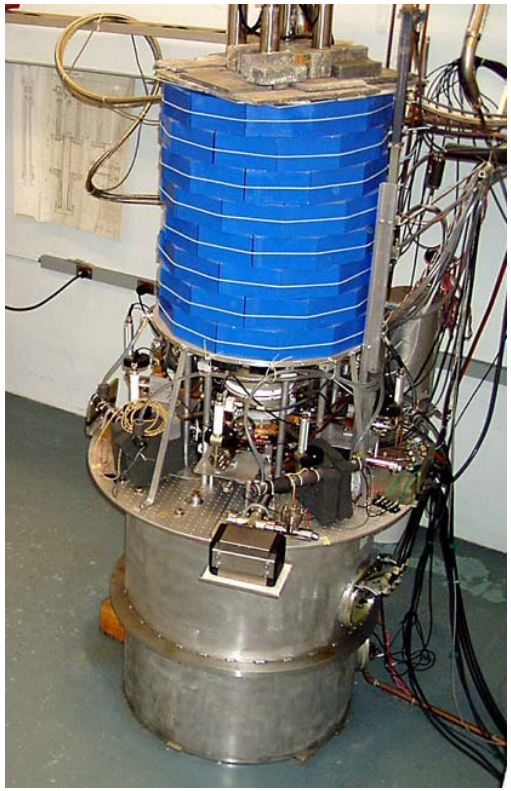
Low Power Active Pulse Compression Test Without Input Phase Flipping

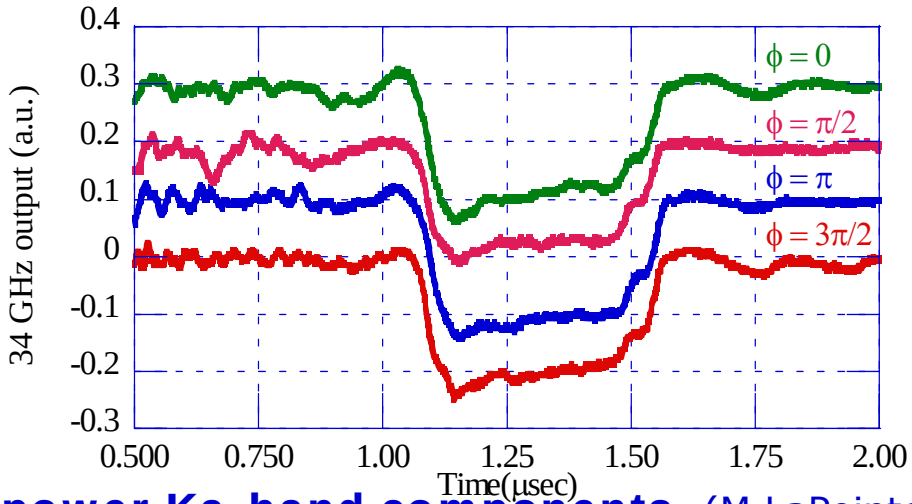


34 GHz Magnicon at Yale Beam Physics Lab

34-GHz magnicon is the first (and only) mm-wave amplifier suitable for high-gradient AARD that has been built & operated.

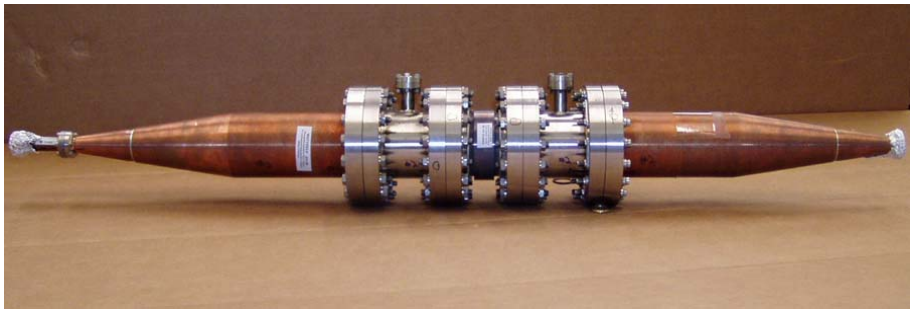
beam power:up to 95 MW (475 kV, 200 A); beam diam ~1 mm
drive frequency: 11.4 GHz (this is a 3rd harmonic device)
RF power: 26 MW, 450 ns; 30 MW, 100 ns; 4 WR-28 outputs





High-power Ka-band components (M.LaPointe, V.Yakovlev, *this meeting*)

Mode converters, windows, pulse compressors, power combiner, transmission lines, and couplers to mm-wave test structures are already developed and built. Components are essential if RF source is to be used for R&D on breakdown and pulsed heating basic studies, and component and structure development.



63-mm Ø window assembly (1 of 4)

Ka-BAND TEST FACILITY FOR HIGH-GRADIENT ACCELERATOR R&D*

M.A. LaPointe,[1] A.A. Bogdashov,[4] A.V. Chirkov,[4]
G.G. Denisov,[3,4] J.L.Hirshfield,[1,3] E.V. Kozyrev,[1,5]
S.V. Kuzikov,[4] A.G. Litvak,[3,4] D.A. Lukovnikov,[4]
V.I. Malygin,[4] O.A. Nezhevenko, M.I. Petelin,[3,4]
Yu.V. Rodin,[4] S. Shchelkunov,[2] M.Y. Shmelyov,[4]
V.P. Yakovlev[3]

[1]Department of Physics, Yale University, New Haven, CT 06511
[2]Department of Applied Physics, Columbia University, New York, NY 10027
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[5]Budker INP SB RAS, Novosibirsk, Russia

*Research supported by Office of High Energy Physics, U.S. Dept. of Energy

(Opinionated) Summary

- 34-GHz magnicon shows slow but steady progress: 26 MW in 675 nsec; 1 μs pulses now demonstrated; expect to reach 9 MW in each of four WR-28 outputs soon. This is the only mm-wave amplifier proven and (soon-to-be) available for AARD.
- Window and transmission lines are scheduled for installation in September.
- First two AARD experiments to be installed in Fall 2006.
- Lessons learned from 7.0, 11.4, 34.3 GHz experimental magnicons can be applied to build a 50 MW, 30 GHz, 1.2 μs, 100 Hz industrial magnicon for AARD. This tube is the only proven candidate to be the 30-GHz stand-alone source for high-gradient AARD for fundamental studies, and for tests of CLIC structures. An industrial partner is essential for construction and processing of these tubes.
- The harmonic multiplier is the "cheapest and quickest" route to a multi-MW phase-coherent high-power microwave source at a selection of harmonic multiples of 11.424 GHz. This source would use existing SLAC gun and beam collector, and other technology that is well-developed and understood; it is a minimal risk enterprise.

One could configure 1 klystron and 3 harmonic multipliers (or one multiplier with inter-changeable output cavities) using two SLAC klystron modulators, and have one grand test stand supplying multi-10's-MW power at 11.4, 22.8, 34.3, and 45.7 GHz, having good phase stability and some frequency tunability. One source could be operating in 2 years, given sufficient resources and a commitment from SLAC.

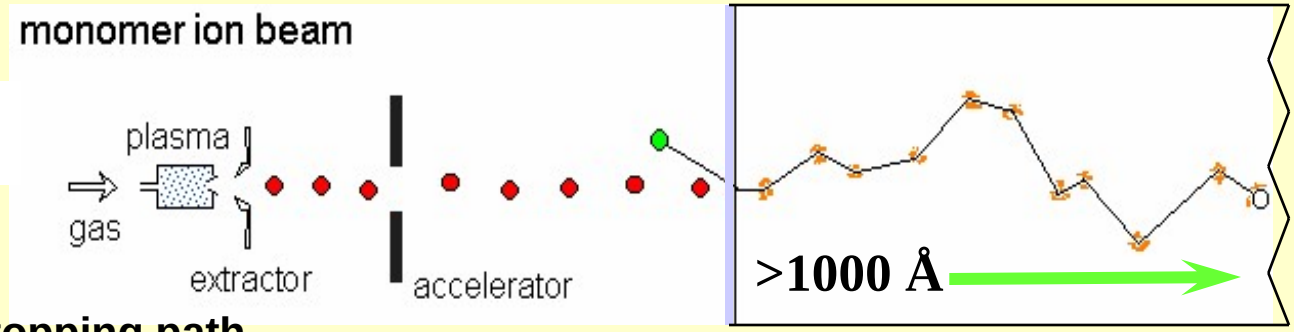
– The magnicon and harmonic multiplier show great promise as mm-wave RF sources for high-gradient AARD. <u>*No other*</u> advanced mm-wave source concept has yet been demonstrated with performance suitable for AARD.

Superconducting Material Studies

1-Jim Norem - Materials Science Problems of the SCRF Q-slope
2-D.R. Swenson - Surface Characterization of Nb SRF Cavity Material Treated with Gas Cluster Ion Beams
3-Chris Nantista-Materials Testing with a High-Q RF Cavity

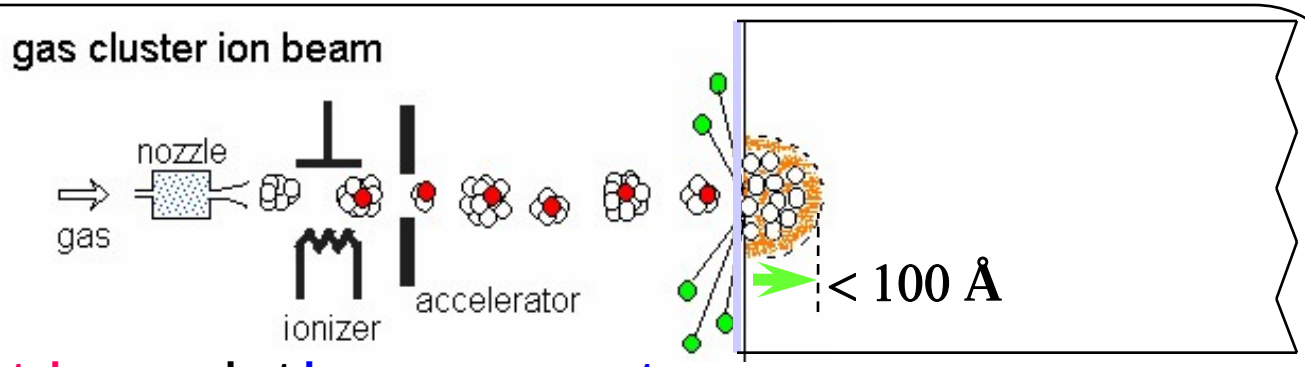
Surface processing with Gas Cluster Ion Beams (GCIB)

Conventional ions



- **deep penetration**
- **thermal spike along stopping path**
- **'normal' sputtering distribution**

Gas cluster ions

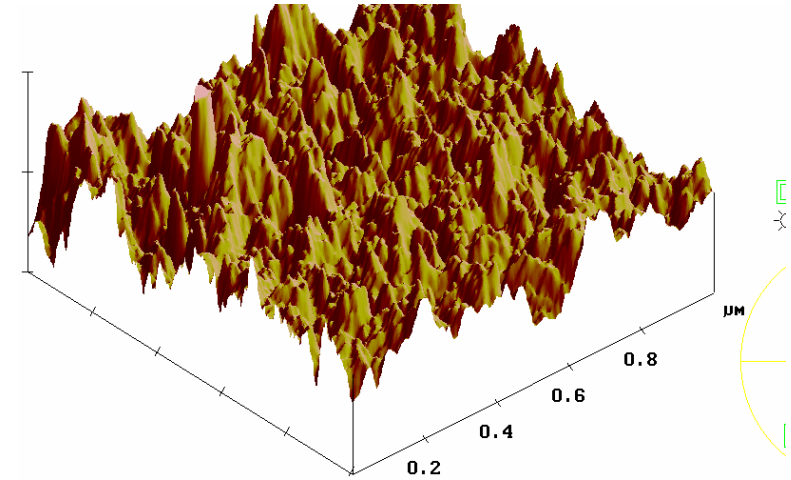


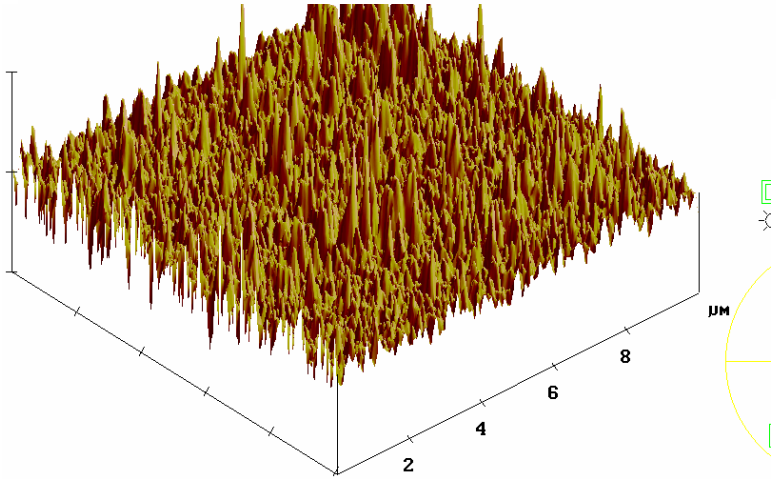
- **clusters have high total energy but low energy per atom**
- **extremely shallow penetration into target surface**
- **energy deposition into localized region**
- **'lateral' sputtering distribution**
- **inherent smoothing action**

Possible mechanisms of Q-slope

- **Contamination in surface layers produces a “weak” superconductor.**
- **Grain edges become are subject to magnetic field enhancements.**
- **Flux penetration into the superconductor can be affected by surface conditions**
- **Surface oxides can absorb energy from sub-gap electrons.**
- **Thermal feedback from local “hot spots” causes losses that limit the maximum field.**
- **Grain boundaries comprise a “weak link” that causes losses at high fields.**

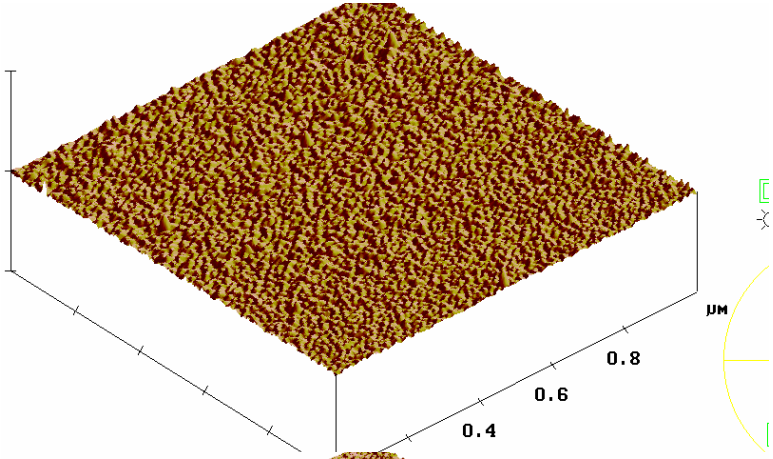
Surface smoothing by GCIB-- example SiC

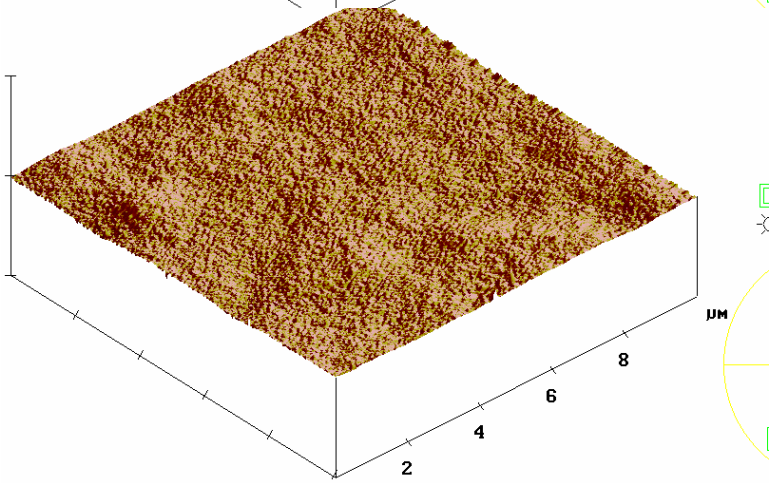




X 2.000 µm/div
Z 50.000 nm/div

36011001.a03





X 2.000 µm/div
Z 50.000 nm/div

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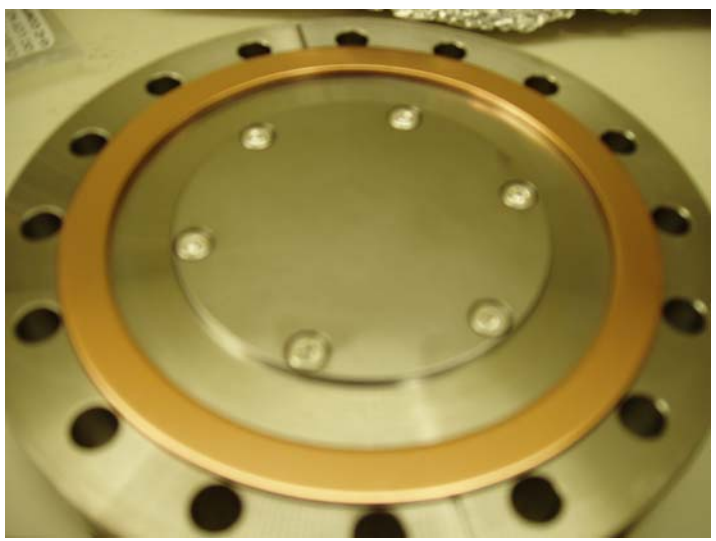
SBIR collaboration with Epion

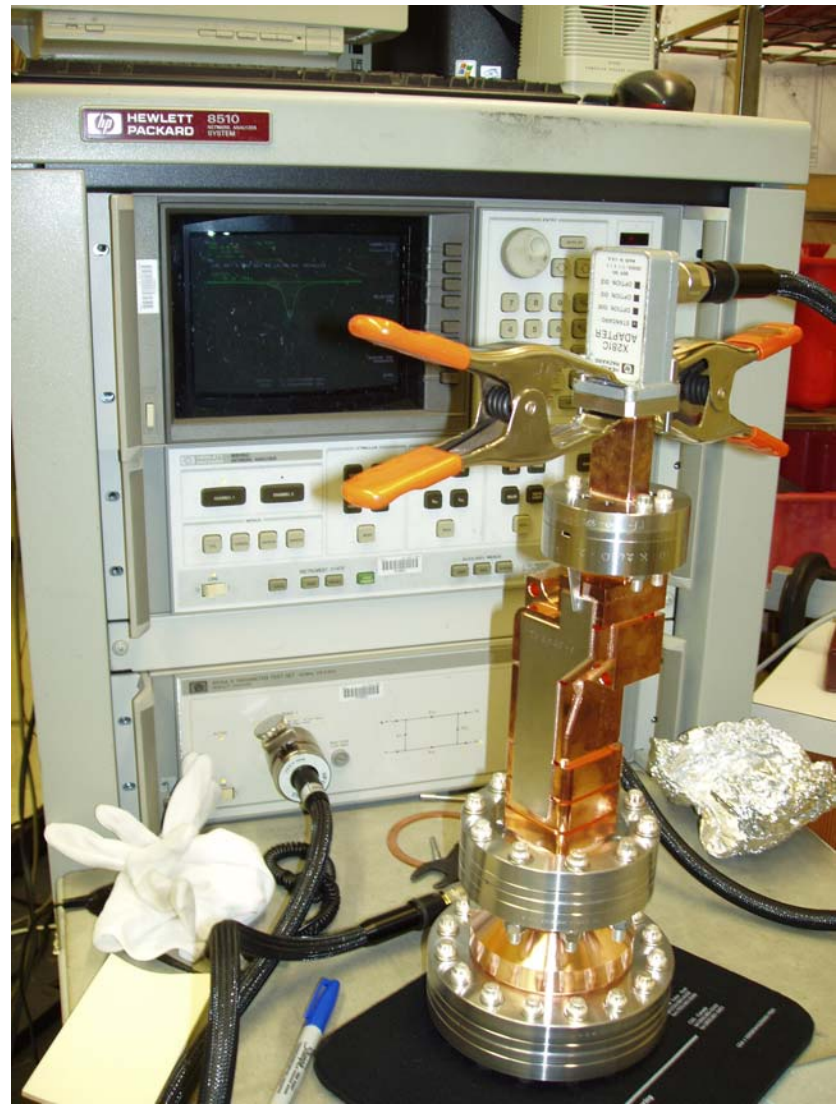
“Cold” Tests (Room Temperature)

room temp. measurements

	HFSS (Cu)	Copper	Niobium
f_r	11.424	11.4072	11.4061
Q_L	30,991	29,961	20,128
β	0.4383	0.4611	0.2728
Q_0	44,575	43,775	25,619
Q_e	101,694	94,944	93,906

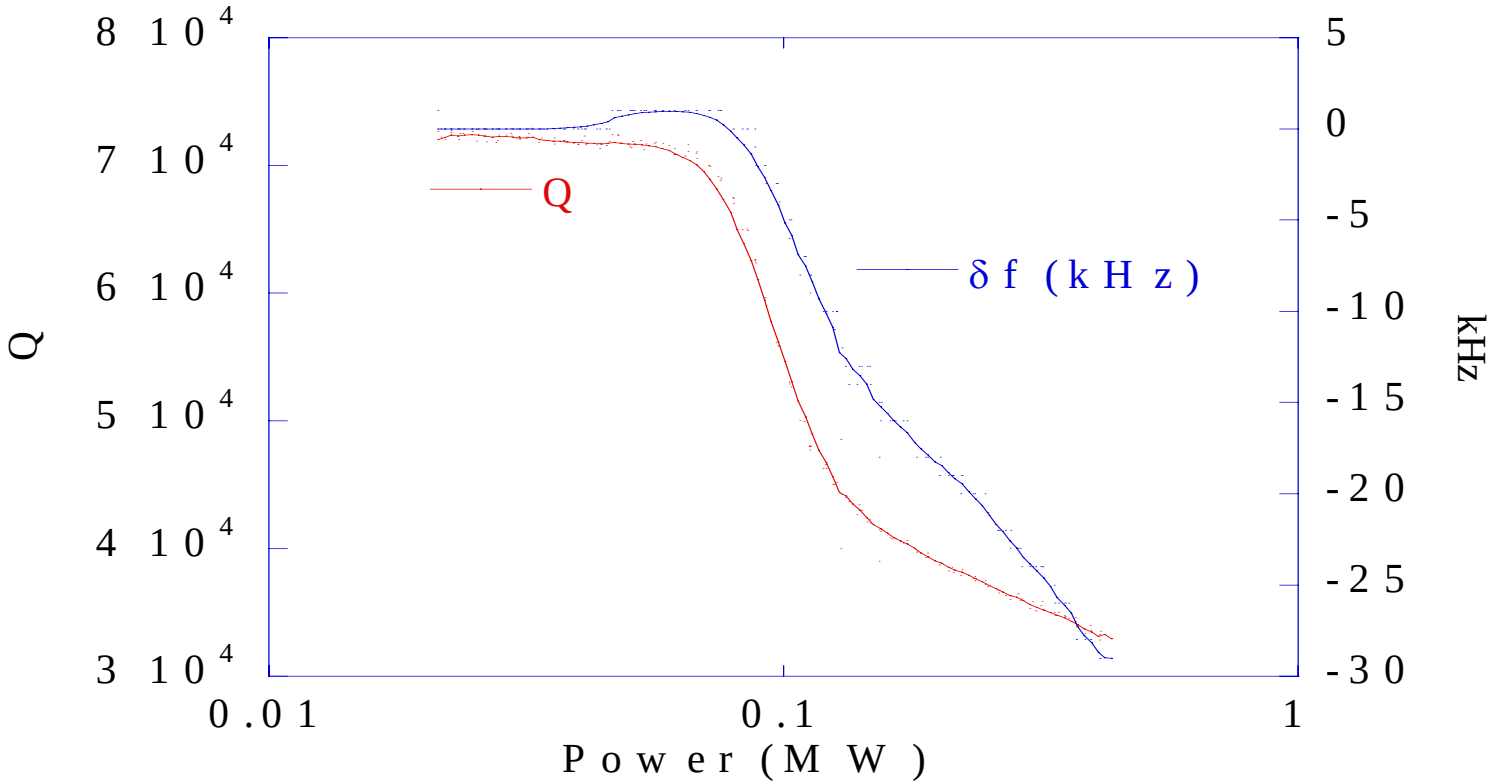


Nb sample mounted in bottom flange



HP 8510C Network Analyzer

High Power Test of Niobium at 4.2K

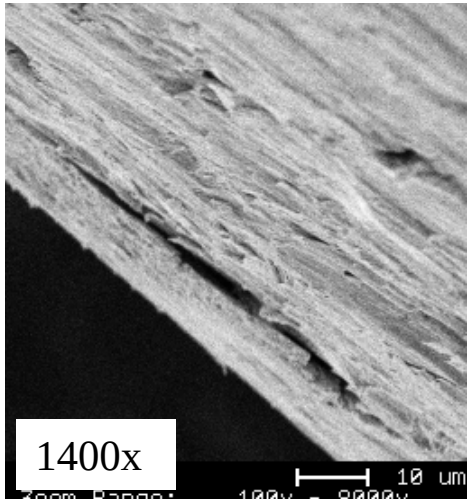


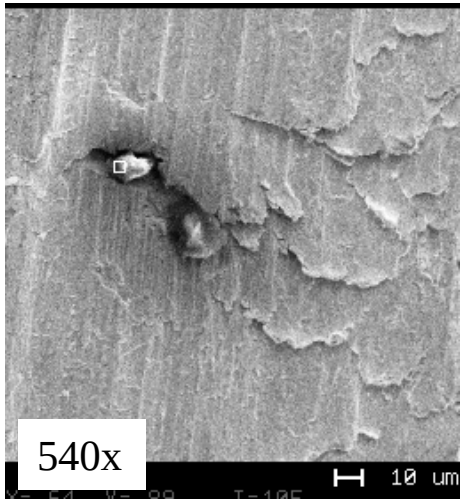
New test setup for inexpensive accurate characterization of high-field RF properties of materials and processing techniques

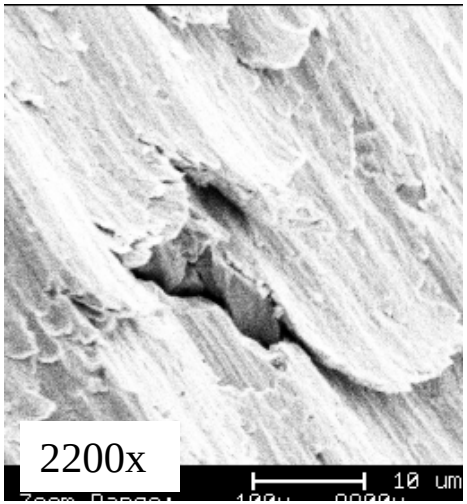
Experiments on High Gradient Structures and Materials

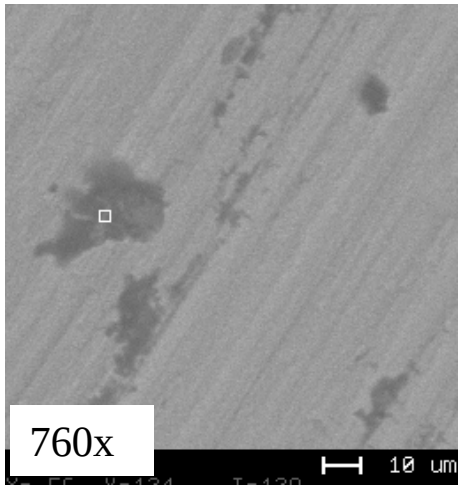
1- Lisa Laurent -Experimental Testing of NLC Structures
2- Valery Dolgashev- Study of RF Breakdown in Normal Conducting Structures with Various Geometries and Materials.
3- Valery Dolgashev-Experiments on Metal surface damage using 120 KeV beam
4-Zikiri Yusof – Field Enhancement and Breakdown Studies at the Argonne Wakefield Accelerator Facility
5-Steven Gold - Development of a 20-MeV Dielectric-Loaded Test Accelerator.
6-Chunguang Jing - Development of Dielectric-Based High Gradient Accelerating Structures

SEM Images of a Tungsten Iris Insert

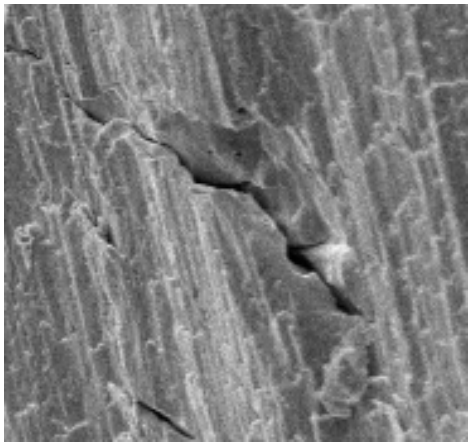








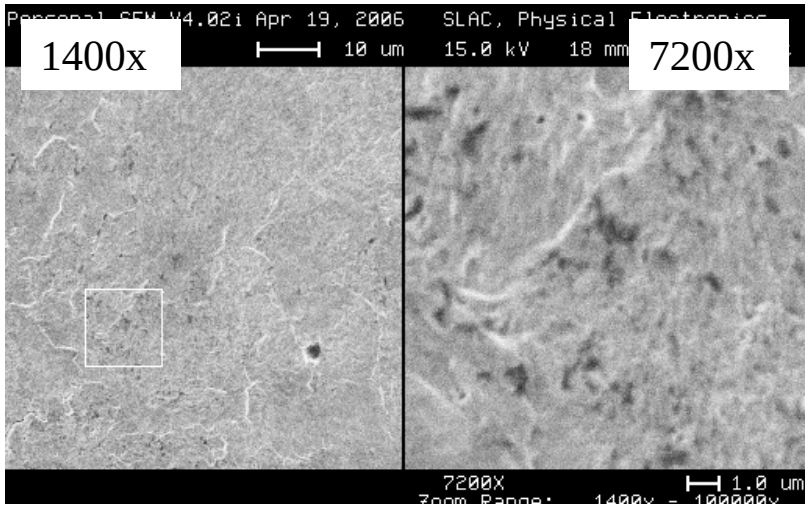
Lisa Laurent



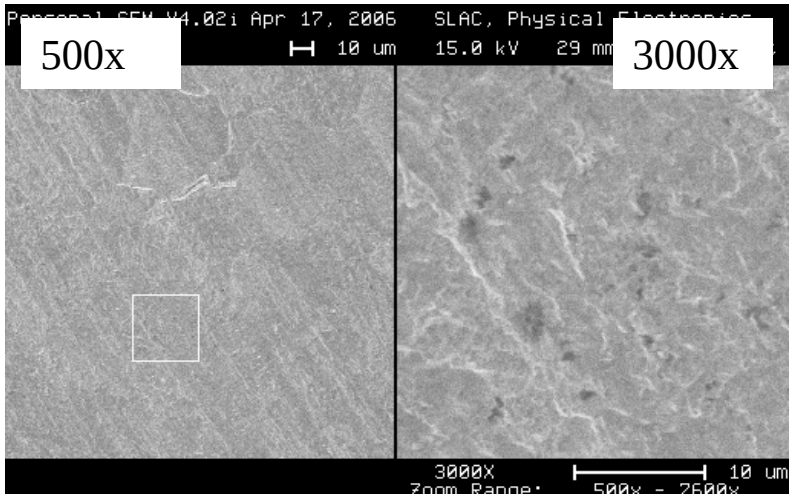
Tungsten Rod Machined at Philip-Elmet and Hand Polished using a Lathe at SLAC

Before Etching

After 5 Second Chemical Etch



Philip-Elmet Polished Tungsten Rod After 30 Second Chemical Etch



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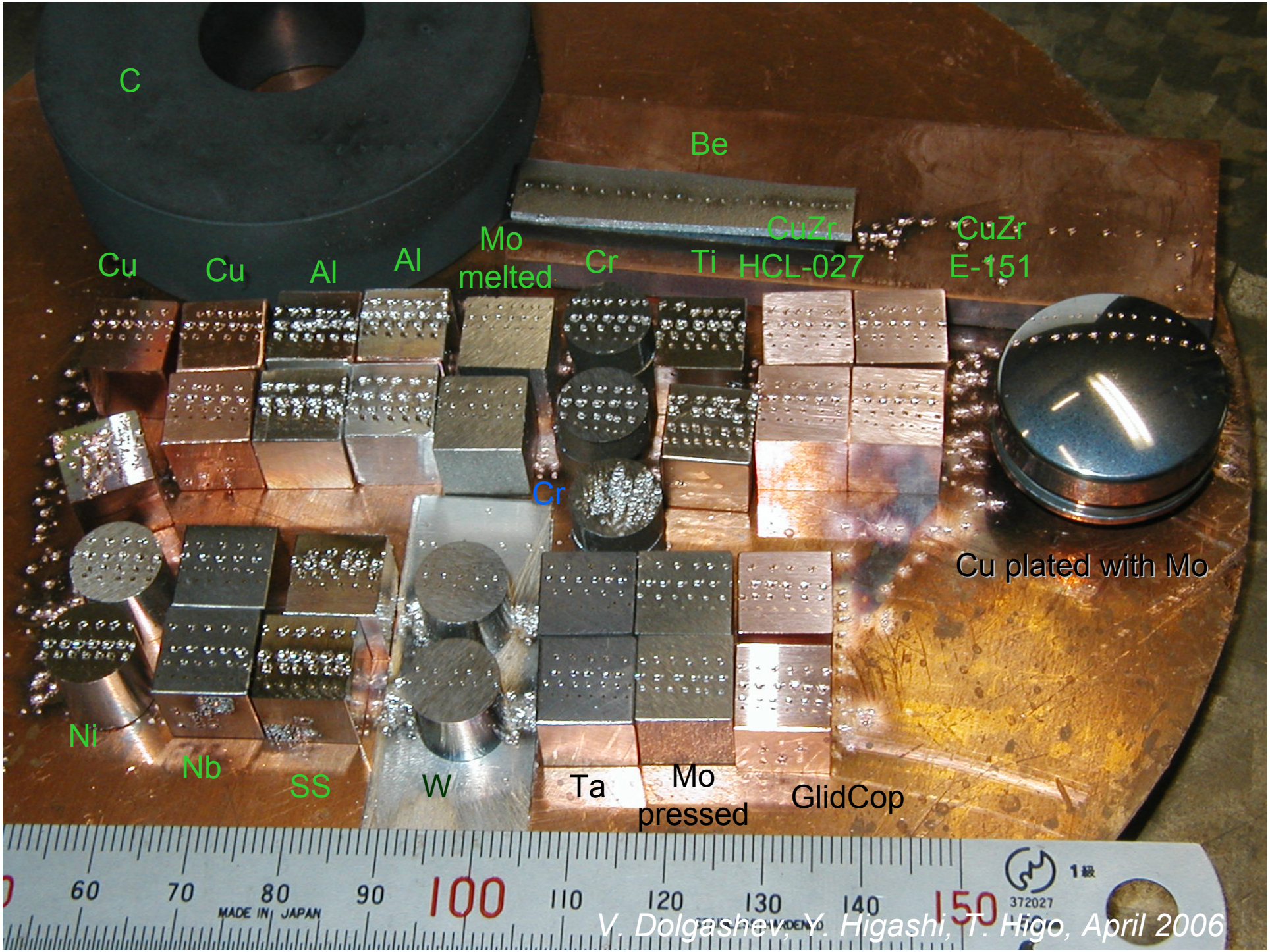
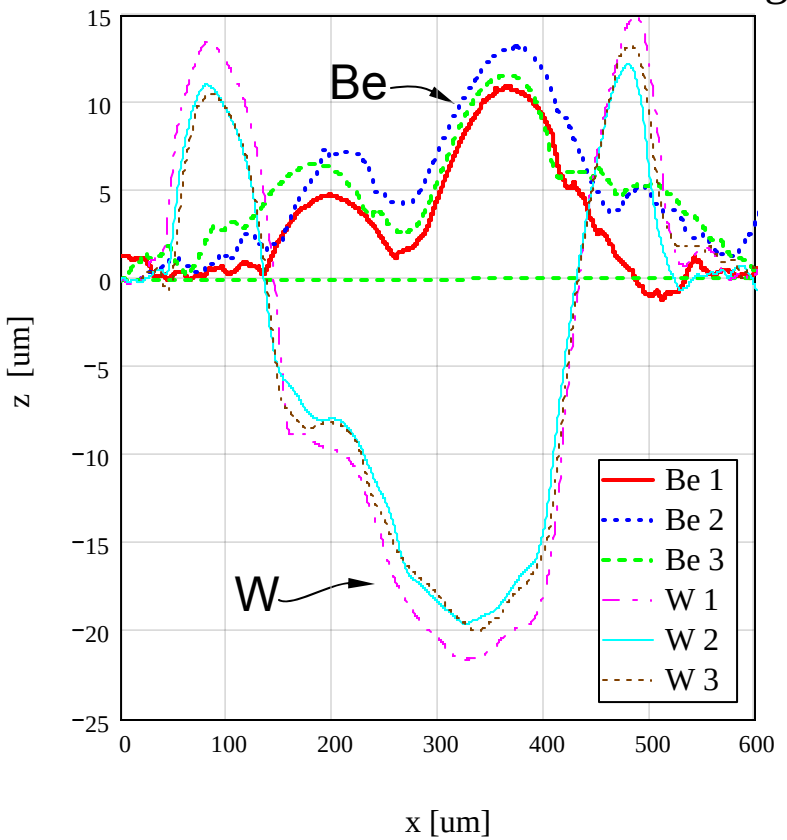
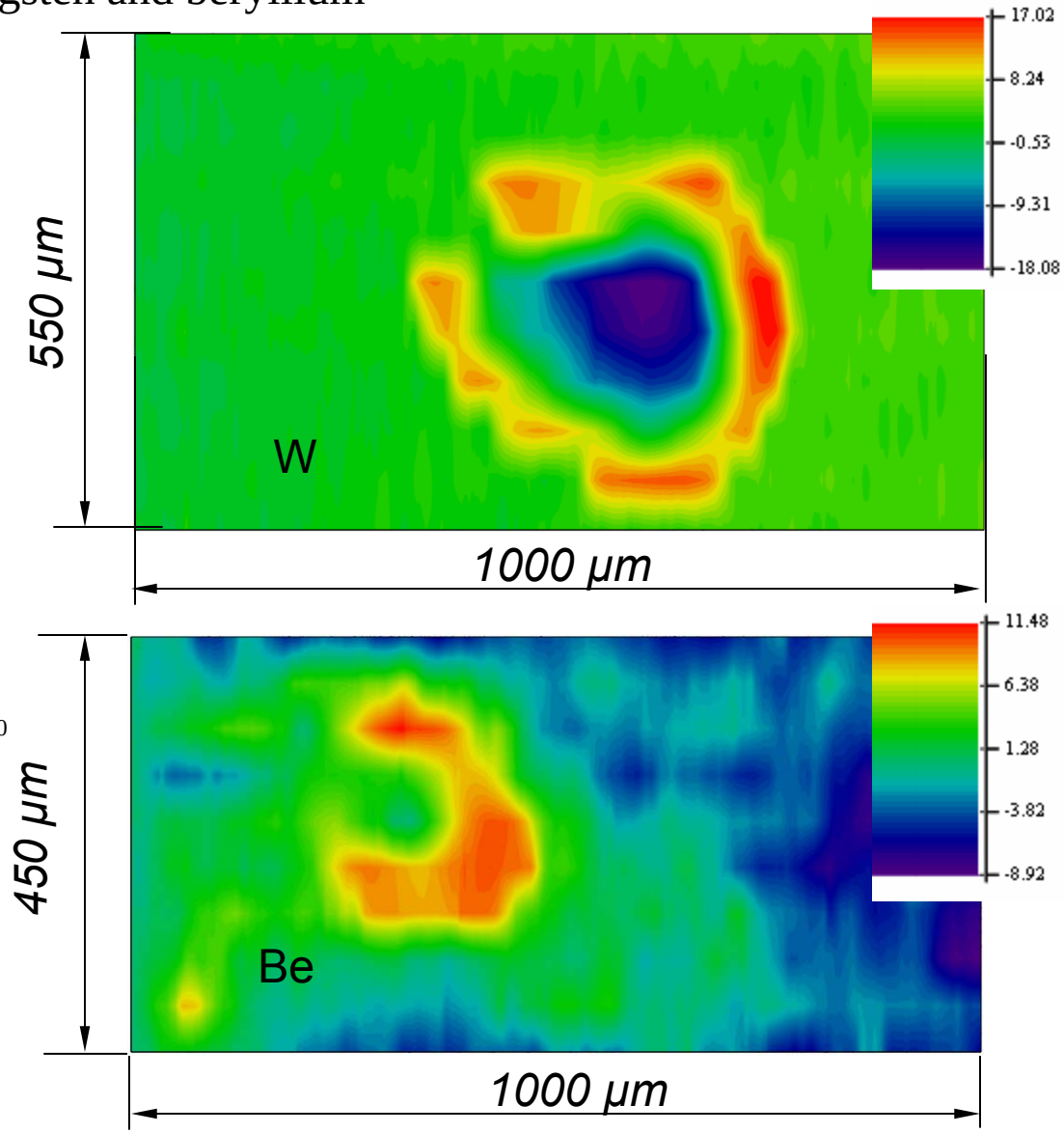


V. Dolgashev, Y. Higashi, T. Higo, April 2006

Profile measurements of impact spot of 120 kV electron beam with same power density for tungsten and beryllium



1D profile
through middle of the spot
for 6 different spots:
3 beryllium and 3 tungsten.

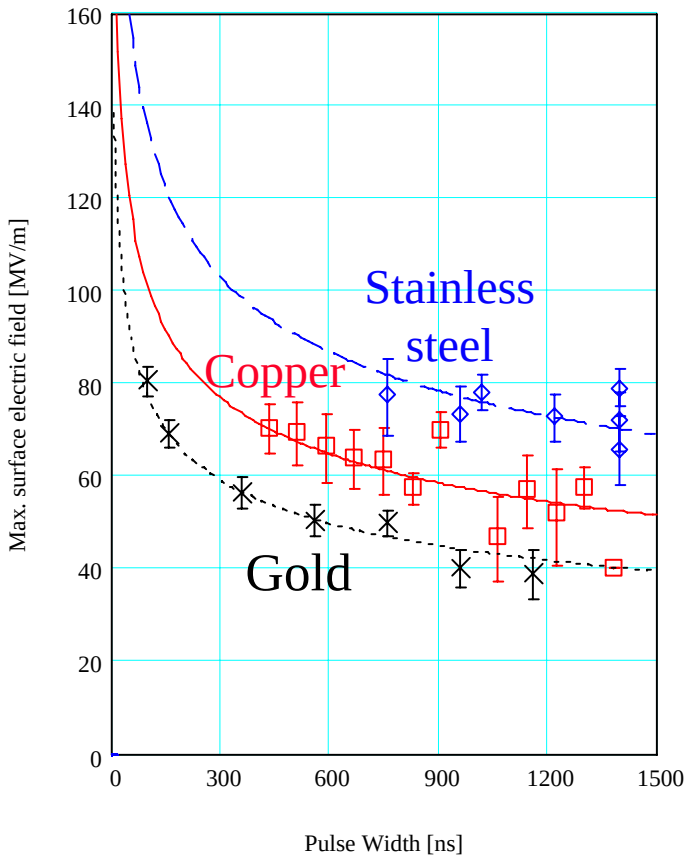


2D profile

Profiles measured using Dektak Bench-Top Surface Profiler

V. Dolgashev, Y. Higashi, T. Higo, April 2006

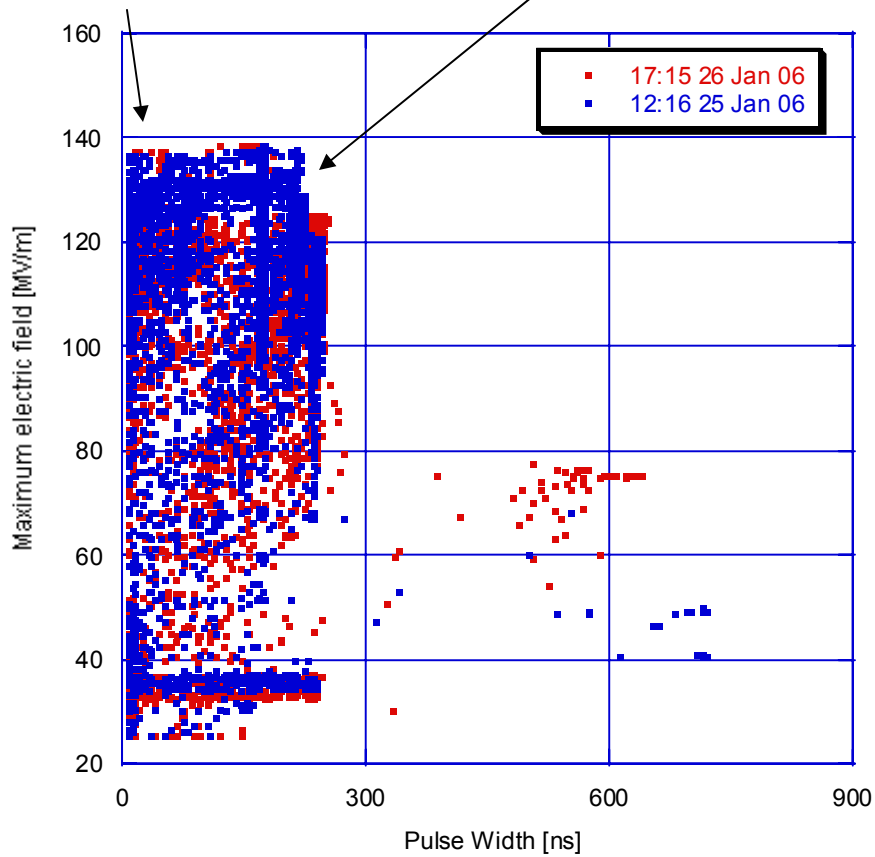
Low magnetic field waveguides with different surface materials



Breakdown threshold measurements for low-magnetic-field waveguides with different materials

No breakdowns, limited by available power

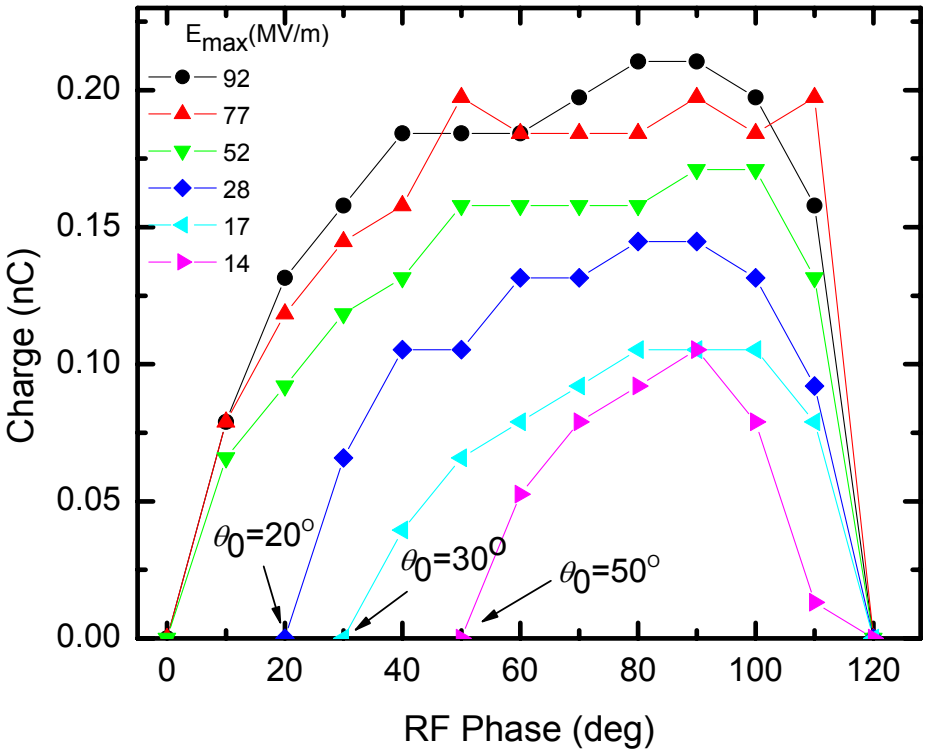
Limited by breakdowns in SLED



Peak power *vs.* pulse width during processing of molybdenum waveguide

V. Dolgashev

DETERMINATION OF FIELD EHANCEMENT FACTOR



$h\nu$ = 3.3 eV; Φ = 3.6 eV

$$Q \propto \left[h\nu - \Phi + \alpha\sqrt{\beta E(\theta)}\right]^2$$

$$E(\theta) = E_{max}\sin(\theta)$$

$$\alpha = \sqrt{e/4\pi\varepsilon_0}$$

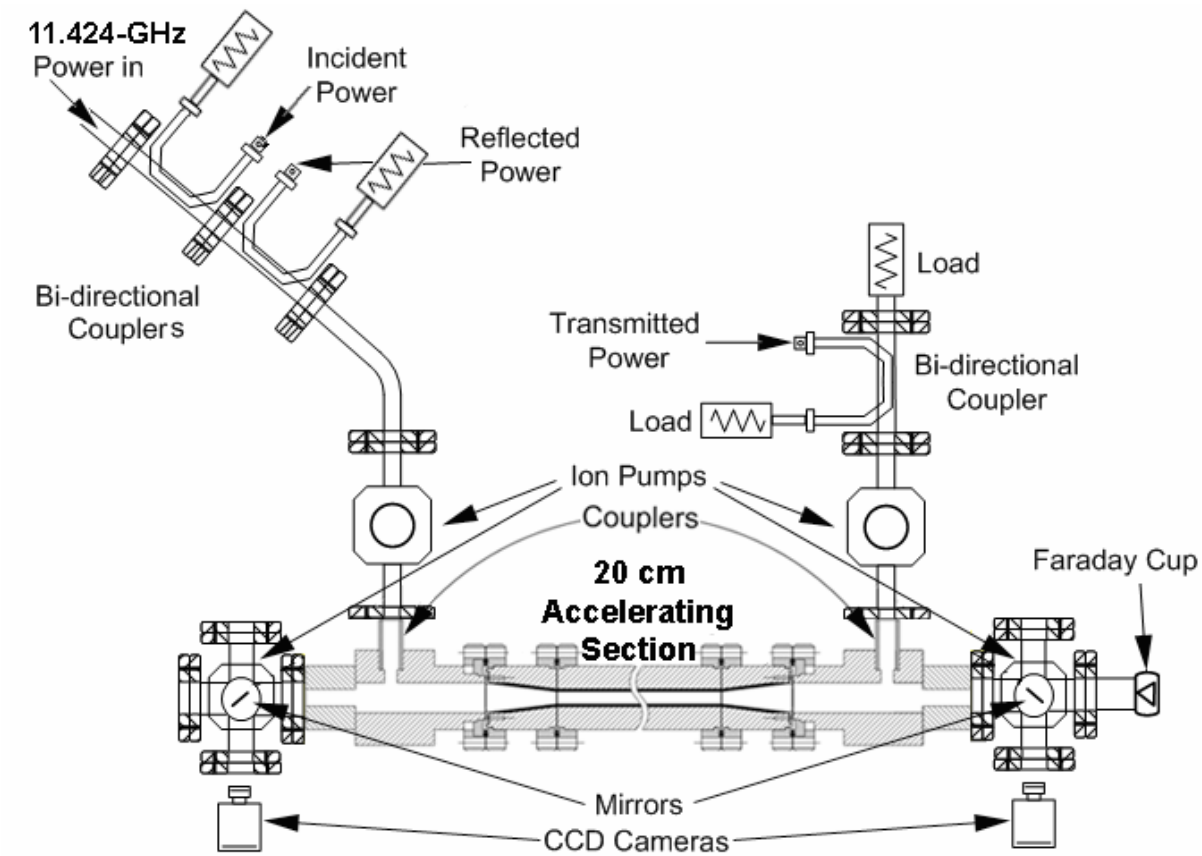
At threshold, Q = 0. This allows us to make a reasonable estimate of the maximum β.

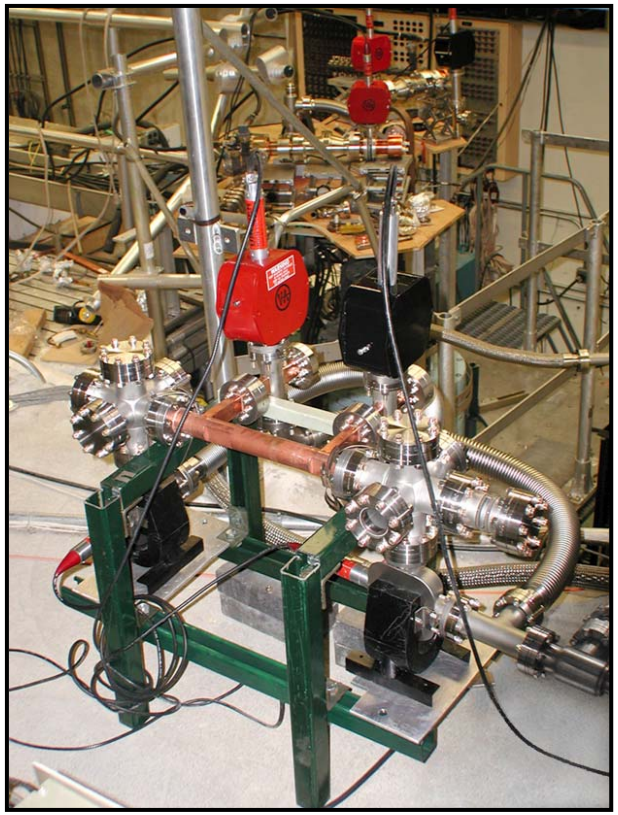
θ_0 (deg)	E_{max} (MV/m)	$E_0 = E_{max}\sin(\theta_0)$ (MV/m)	β
20	28	9.2	6.8
30	17	8.5	7.3
50	14	11	5.8

This is a *new* and viable technique to realistically determine the field enhancement factor of the cathode in a photoinjector

Z. Yousef

Experimental Setup for High Power Tests of DLA Structures





S. Gold

Accompanying Papers

- Summary of results from DLA structures
- Development of a theoretical multipactor model

} **J. Power**

- Recent test results for quartz DLA structure
- Design of improved DLA structures with lower rf fields, decreased loss

} **C. Jing**

RF Breakdown Theory

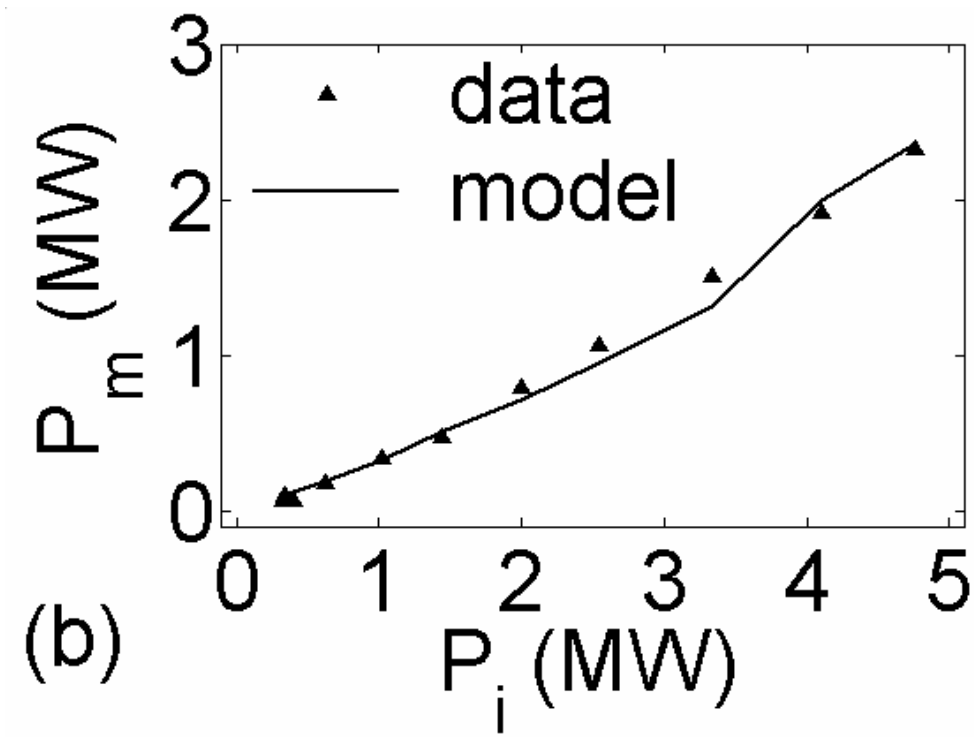
1-John Power - Multipactor Modeling in Cylindrical Dielectric-Loaded Accelerators
2-Jim Norem - The Interactions Between rf and Structure Parameters in High Gradient
1-Walter Wuensch- Highlights from recent CLIC high-power test results

Thursday 3:30-5 Joint session with computational working group
Open discussion on breakdown theory and scaling and simulation moderated by G. Nusinovich, J. Norem and V. Dolgashev

Comparison of Multipactor Model and Experiment

Excellent Agreement

$$P_m = N K_i / \tau$$



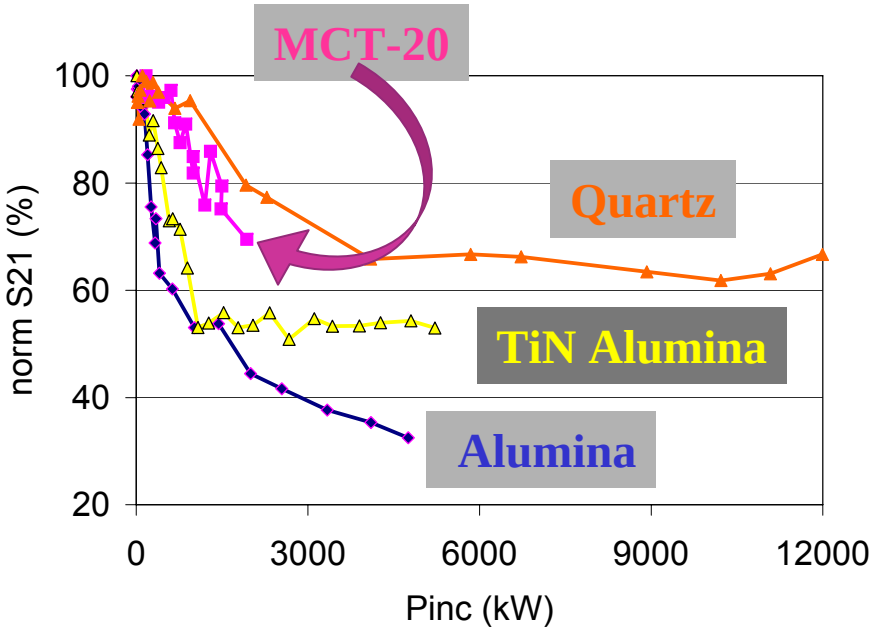
Fit Parameters

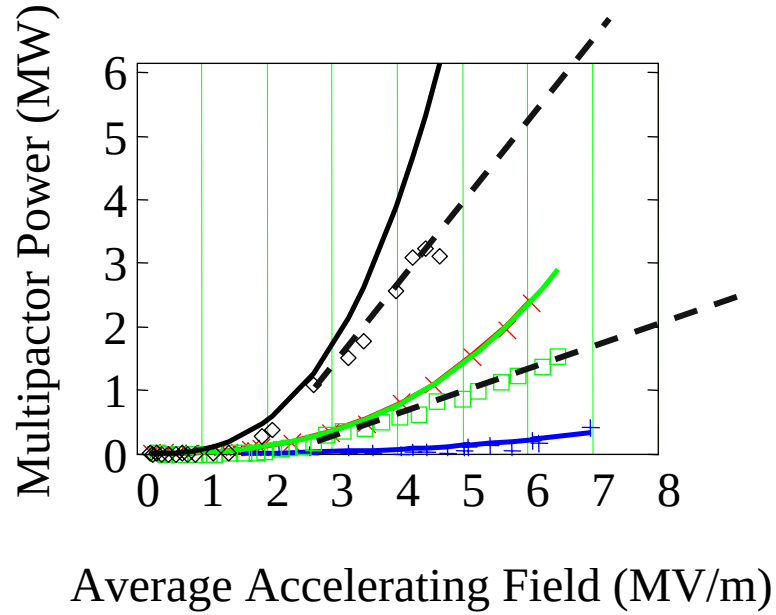
e_0 = 2 eV
e_1 = 60 eV
L = 250 mm

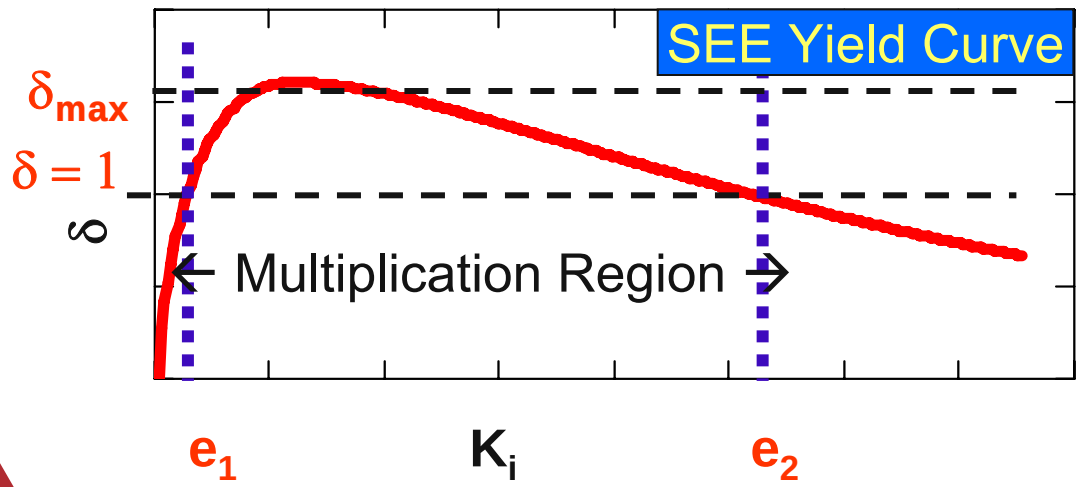
Saturation →
E_{DC}/E_{z0} ~30%

J. Power

Can we explain 'saturation' (slope change)? …back to 2D numerical model







MCT & Alumina → ceramics

Quartz and TiN coated → Different e_0, e_1, e_2??

J. Power

Objective: present the case for a material dependent rf-breakdown limit scaling of

$$\frac{P\,\tau^{1/\alpha}}{C}$$

P is power flow, *τ* is pulse length, *C* is the structure circumference and *α* is around 1.5 (Mo) to 3 (Cu).

Walter Wuensch

Fixed frequency (30 GHz), variable geometry, fixed material (Cu), different pulse lengths (Argh!), all 'damaged'

	F [GHz]	V_g/c	E_{acc} [MeV/m]	E_{surf} [MeV/m]	P [MW]	T [ns]	D [mm]	$\frac{P\tau^{1/3}}{C}$
30 GHz Cu, CTF3	30	0.047	116	253	34	70	3.5	13
CTF2 PETS	30	0.500			240	16	16	12
CTF3 PETS	30	0.398	30	116	100	50	9	13

Walter Wuensch

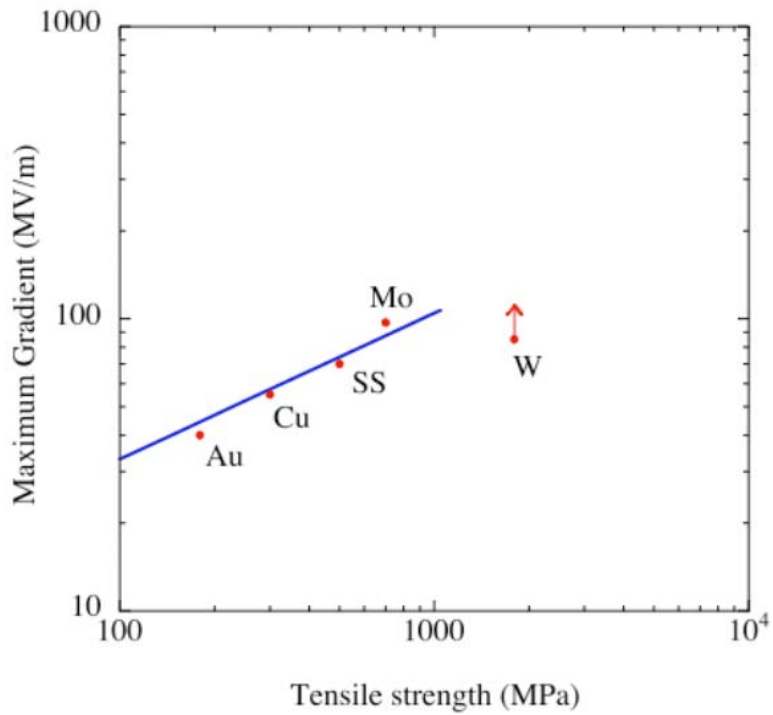
Variable frequency, variable geometry, Cu

	F [GHz]	V_g/c	E_{acc} [MeV/m]	E_{surf} [MeV/m]	P [MW]	T [ns]	D [mm]	$\frac{P\tau^{1/3}}{C}$
CERN X-band	11.424	0.011	153	326	69	150	6	20
NLC Conditioning limit	11.424	Around 0.05	75	Around 180	120	400	8.9	40
30 GHz Cu	30	0.047	116	253	34	70	3.5	13
CTF3 PETS	30	0.398	30	116	100	50	9	13

Walter Wuensch

Using the model: II) Materials

- Only materials change, everything else constant.
- The model argues that tensile strength is the dominant effect.
- $E_{surf} = \frac{E_{local}}{\beta} \approx -\frac{\sqrt{2T/\varepsilon_0}}{\ln(b/a)/b}$



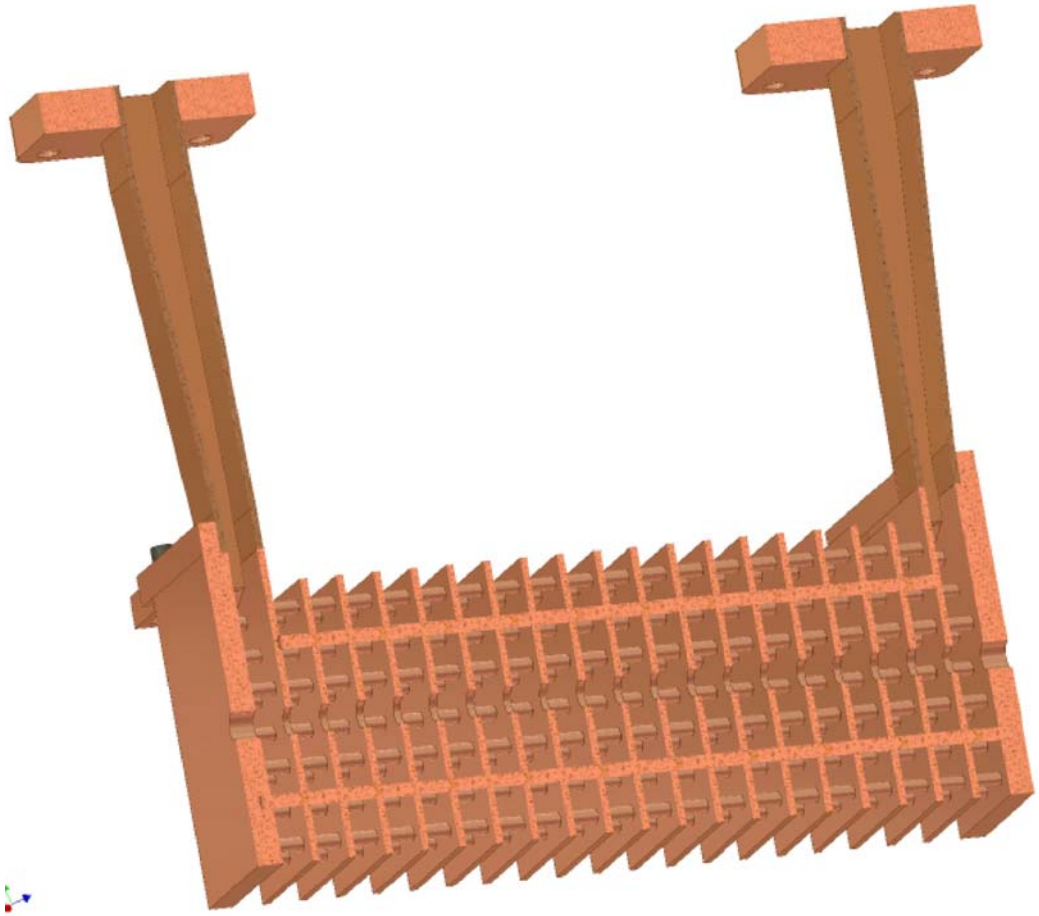
SLAC and CERN data

J. Norem

Photonic Band Gap

1- Galewood C; Photonic Band Gap Structures
2- B. Cowan PBG structures for optical acceleration
3-J. Cary Vorpal simulations of PBGs
4- M. Shapiro PBG Structures in Metals and Dielectrics at X-band

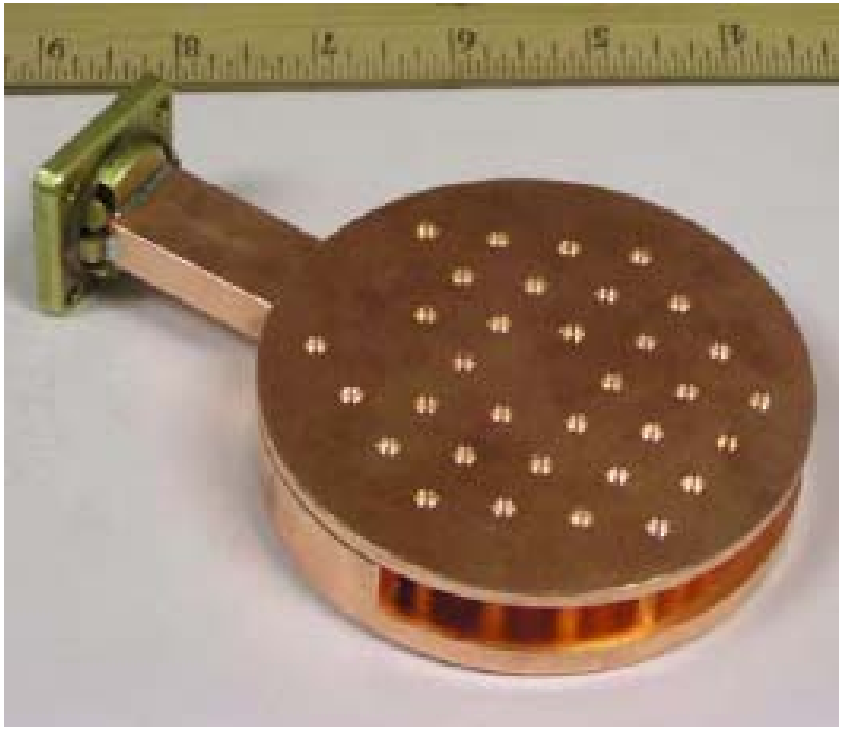
Advanced PBG structure



- 20 cells
- Input power up to 10 MW
- Large beam holes ($a/\lambda=0.179$ as in NLC)
- Easier to tune

M. Shapiro

Brazed PBG structure



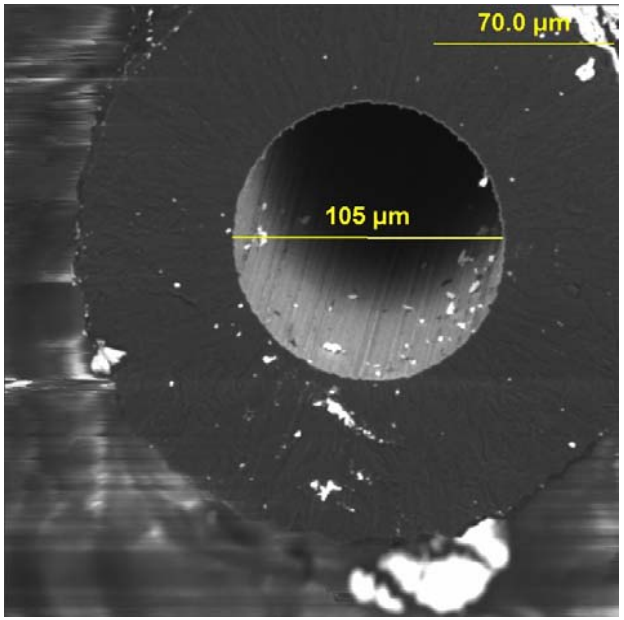
- Goal is study breakdown and pulsed heating with novel materials in simple configuration
- Three rods removed for coupling
- Open structure, simplified breakdown diagnostics
- Use different materials for rods in first row (Molybdenum, SS)

M. Shapiro

High Gradient RF Dielectric Structures

1-Alexei Kanareykin - High-Gradient Cylindrical Diamond-Based Accelerating Structure.
2-Changbiao Wang - Rectangular Dielectric-Lined Structures for Achieving High Acceleration Gradients
3-Manoel Conde - High Gradient Wakefields in Dielectric Loaded Structures

Diamond Waveguide of THz range

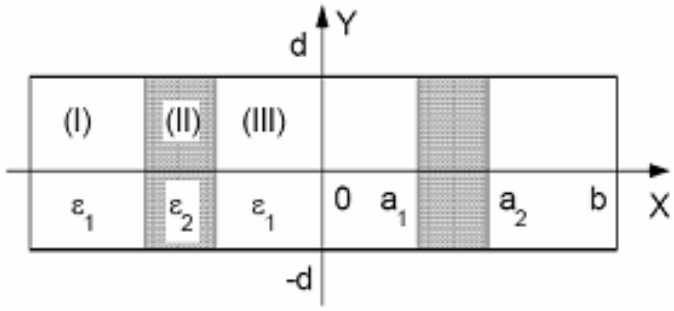


Diamond tubes of 500-800 GHz frequency range have been developed, ID is of 105 µm, OD is of 245 µm

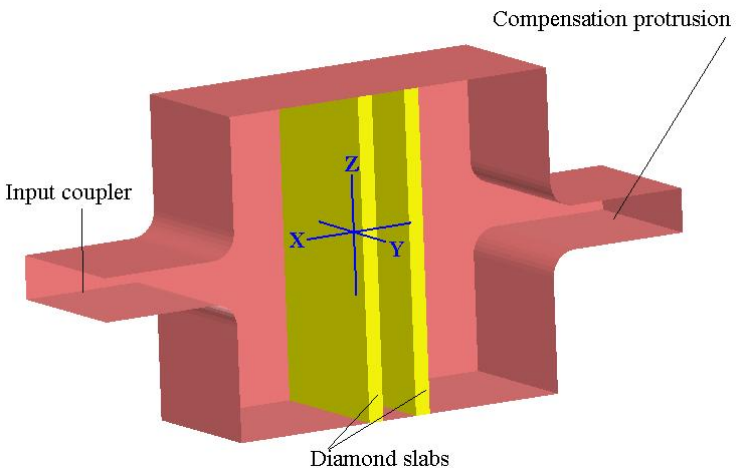
Diamond waveguides can be fabricated of 2-3 mm in diameter with the wall thickness is of 500-800 µm.

Alexei Kanareykin

Topic 1. Test cavity design for measuring diamond breakdown limit



(a) Cross section for theoretical analysis.



(b) 3D picture in coupler simulations.

Table 1: Parameters for diamond-lined cavity structure.

operating frequency for LSM_{216} mode	34.272 GHz
equivalent phase velocity v_{phase}	c
cavity height $2d$ (along y)	12.0 mm
cavity width $2b$ (along x)	29.6 mm
cavity length L (along z)	26.2 mm
beam aperture width $2a_1$	3.0 mm
width of dielectric slabs $a_2 - a_1$	1.29 mm
relative dielectric constant	5.7
loss tangent $\tan\delta$	3×10^{-5}
wall quality factor Q_w	51,000
dielectric quality factor Q_d	140,000
overall quality factor Q	37,000
characteristic shunt impedance R/Q	53.8 Ω
shunt impedance R	1.99 MΩ
input RF power	10 MW
peak RF electric field on axis	340 MV/m

Figure 1: Sketch of cavity design. Seen are two diamond slabs surrounding the beam channel, the input coupler, and the opposing compensation protrusion to symmetrize the fields. Parameters for the example discussed in this paper are given in Table 1.

C. Wang

High Gradient Wakefields in Dielectric Loaded Structures

2006 AAC Workshop

Manoel Conde

A U.S. Department of Energy laboratory managed by The University of Chicago

Research at 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

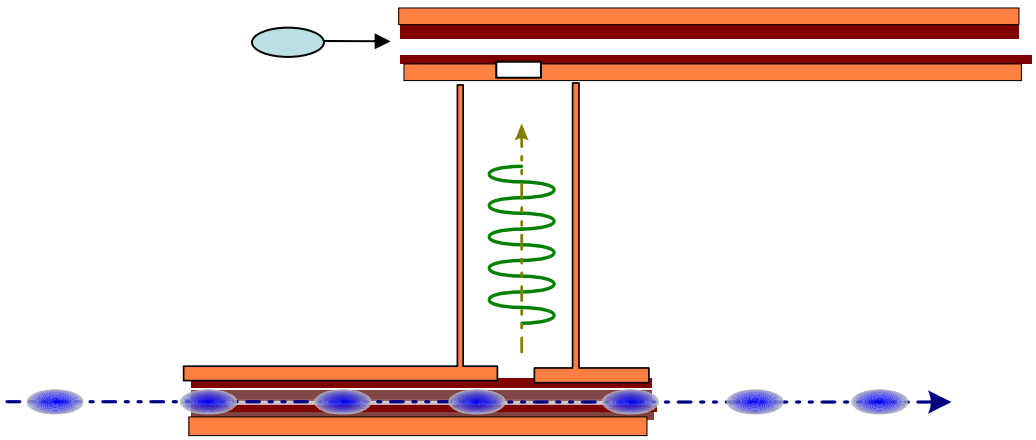
High brightness beam generation and propagation, and development of novel beam diagnostics.

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**.

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.



Final Remarks

- There are several possibilities for the realization of RF sources in the range between 11 GHz to 34 GHz.
- Basic efforts in understanding material properties for high gradient RF structure is becoming more visible and getting more attention. However, this effort is still in its infancy.
- There is also an effort on basic understanding of materials for supper conduction accelerator structures.
- Dielectric materials and dielectric accelerator structure are drawing much attention. Material developments and technologies for such structure is being developed.
- Advances in microwave materials such as ferroelectrics could lead to efficient RF sources and systems at frequencies between 11 to 30 GHz
- There is a strong experimental effort, around the world, on normal conducting accelerator structure.
- A concrete theory and basic understanding of the underplaying physics for RF breakdown in normal conducting structures does not exist.
  - Several ideas, simulations and conjectures are floating around.
  - A strong experimental effort to examine these theories is needed.
  - Also, these ideas need to mature and become more than a back of the envlop calculations.