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# PULSED SURFACE HEATING AND RF BREAKDOWN TESTS ON CANDIDATE MATERIALS FOR HIGH-GRADIENT ACCELERATOR STRUCTURES\*

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# MOTIVATION

- Feasibility for a future multi-TeV collider rests on experimental proof that “high working gradients” can be sustained in a practical room-temperature accelerator structure, where “high”  $\approx 150$  MeV/m.
- To progress beyond the 60-90 MeV/m regime shown with X- and Ka-band structures at SLAC, CERN, and KEK, deeper understanding is required of processes that limit RF electric and magnetic fields at material surfaces.
- RF breakdown limits  $E$  fields, while surface fatigue limits  $H$  fields. Thus, basic experiments are needed, over a range of frequencies, on breakdown and surface fatigue on metals (Cu + others), alloys, and composites.
- This talk outlines experiments planned at Yale at Ka-band.

# PULSED HEATING

A dedicated test cell has been built for measuring a maximum achievable surface  $H$ -field limit imposed by pulsed heating and metal fatigue. Beyond such a limit, the structure lifetime would be less than, for example,  $2.6 \times 10^{10}$  pulses, or  $\sim 15$  years, @4000 hrs/yr, 120 pps.

The RF source to drive the test device is the Yale/Omega-P 34-GHz pulsed magnicon. Utilization of a few MW,  $\mu$ s-width pulsed excitation is expected to bring about pulsed heating excursions exceeding  $600^\circ\text{C}$ . [Measurements of the number of pulses to failure, for a range of pulsed temperature excursions, should allow extrapolation to the temperature excursion that can be tolerated for a 15-year structure lifetime.]

The test cell is designed to allow measurements for copper, for other candidate structure materials, and for different procedures of surface preparation.

Pulsed heating is caused by the pulsed eddy currents during a high-power RF pulse.

Mechanical stress arises from localized thermal expansion in a thin surface layer due to a pulsed temperature rise  $\Delta T$ .

When the rise in temperature is above a "safe" value  $\Delta T_s$  the mechanical stress grows large enough to create microscopic damages in the metal.

The damage accumulates with each succeeding pulse and the cavity surface is essentially destroyed after a certain number of pulses.

For Cu, estimates give a safe threshold for temperature rise  $\Delta T_s$  of about  $110\text{ C}^\circ$ .\* But measurements are needed to confirm this, and to determine  $\Delta T_s$  for other materials.

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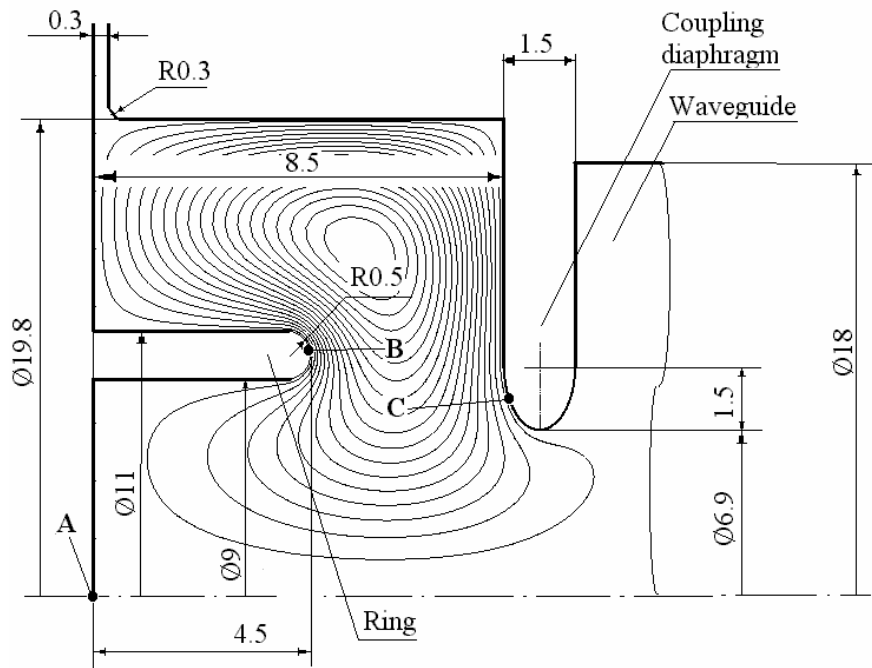
\*D.P. Pritzkau and R.H. Siemann, "Results on an RF Pulse Heating Experiments at SLAC", SLAC-PUB-8554, August 2000.

The structure life-time drops exponentially when the temperature rise increases; thus in order to make reliable measurements within a reasonable time (hours or days) one needs a high temperature rise, up to 500-600 °C.

Tests at 34 GHz can produce such high temperature rises.

The asymptotic behavior of the surface degradation may be determined based on measurements for different temperature rises that will allow firm conclusions to be drawn as to structure life-time for different metals, alloys, composites, fabrication technique, surface preparation, etc.

The  $TE_{011}$  test cell schematic layout and the RF magnetic field pattern are shown in the figure. The cell consists of two main parts, the cavity body which is coupled to an input waveguide, and the removable end cap (test sample), the left-most element.

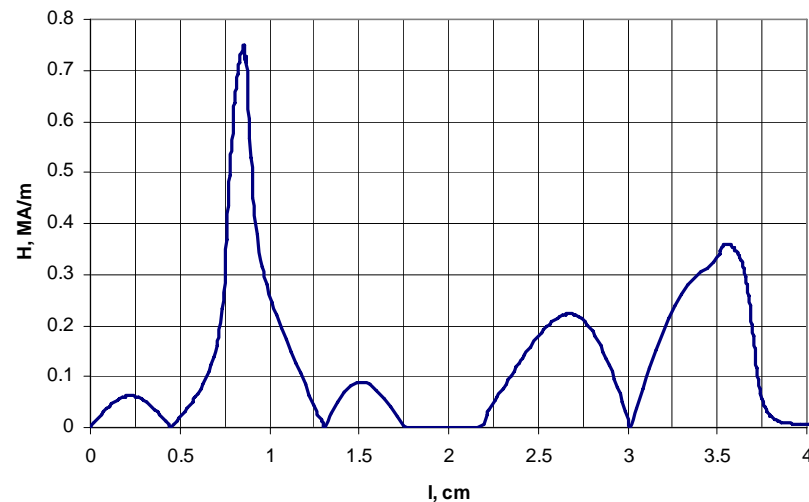


### Cavity parameters

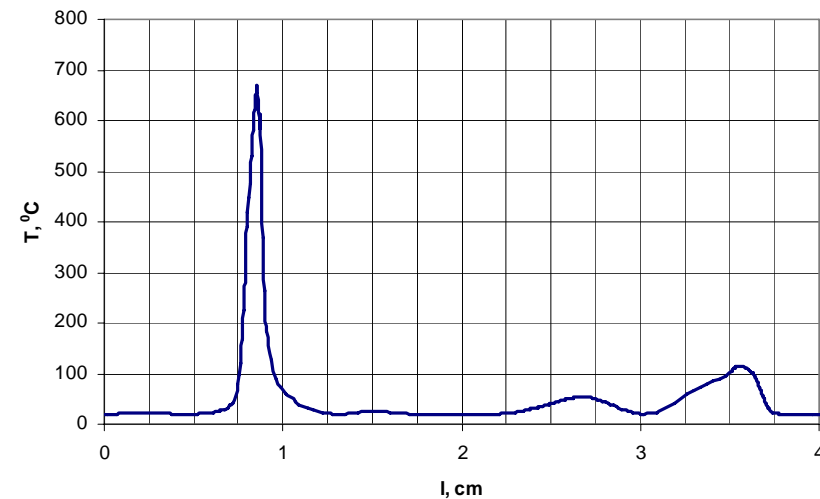
operating frequency	34.272 GHz
operating mode	$TM_{011}$
unloaded quality factor	7000
input power	1.5 MW
maximum surface field	0.82 MA/m
RF pulse duration	1 $\mu$ sec
temperature rise	650 $^{\circ}$ C
input waveguide mode	$TE_{01}$

Cavity schematic layout and RF magnetic field pattern. Dimensions are in mm.

The cavity design has to satisfy two main requirements: (a) the cavity geometry including input coupling must be axially symmetric in order to keep surface electric fields negligibly small, and consequently to avoid breakdown problems, and (b) the temperature rise at any point (except for the end cap) should not exceed the "safe" value of  $110^{\circ}\text{C}$ , in order not to damage the main part of the cavity surface.

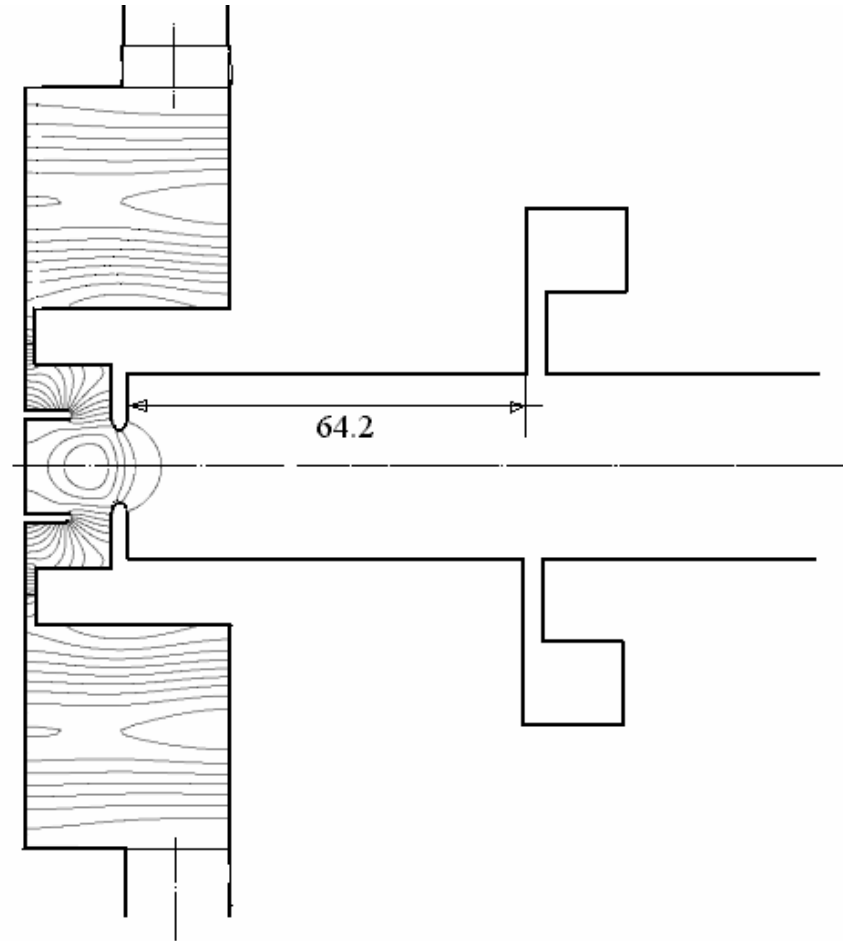


(a)



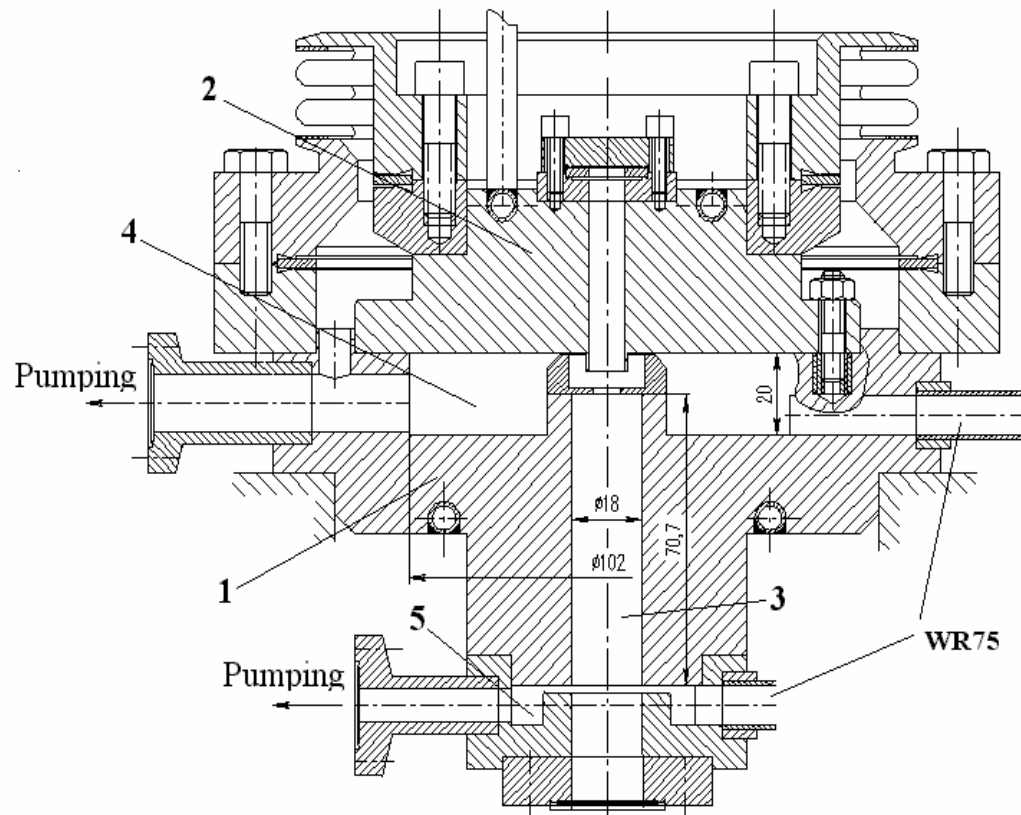
(b)

(a)  $H$ -field and (b)  $\Delta T$  distributions over perimeter of the cavity surface, with input power = 1.5 MW, and pulse width =  $1 \mu\text{s}$ .



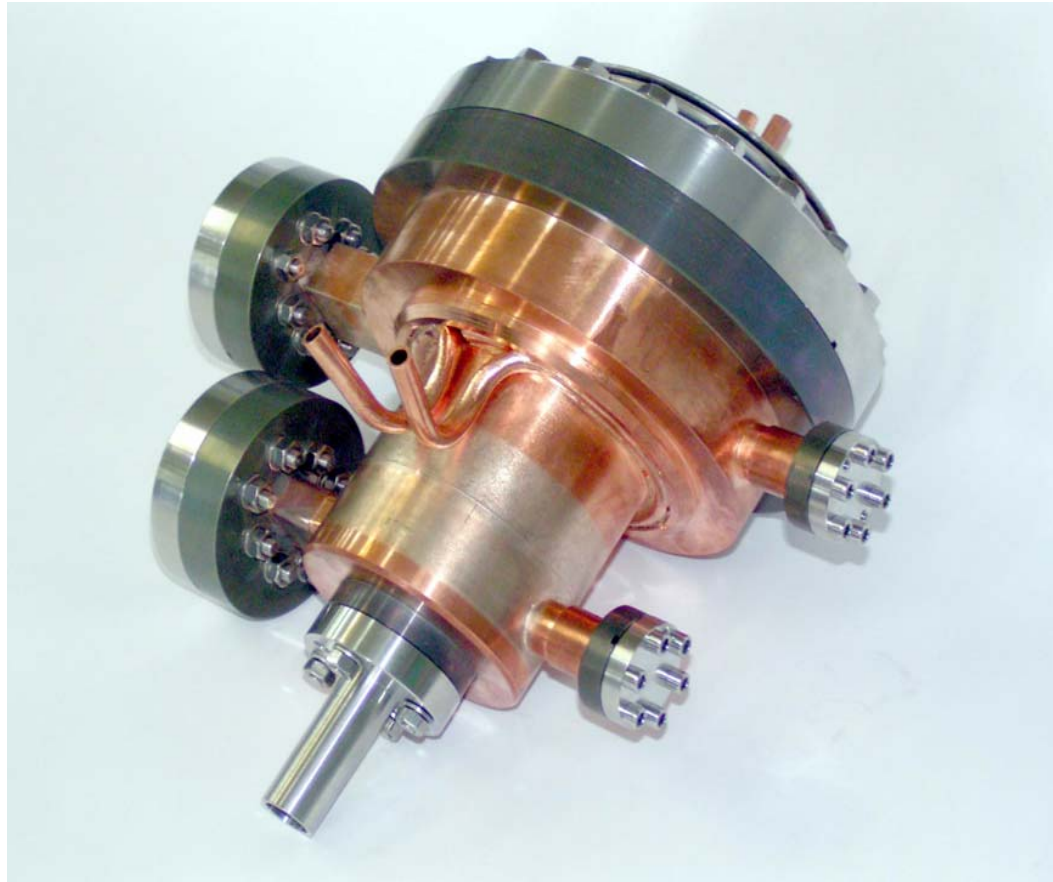
Field pattern of the hybrid dipole mode at 13.27 GHz, to be used for diagnostics, via "real time"  $Q$  measurements. Insulating cavity is shown as well.



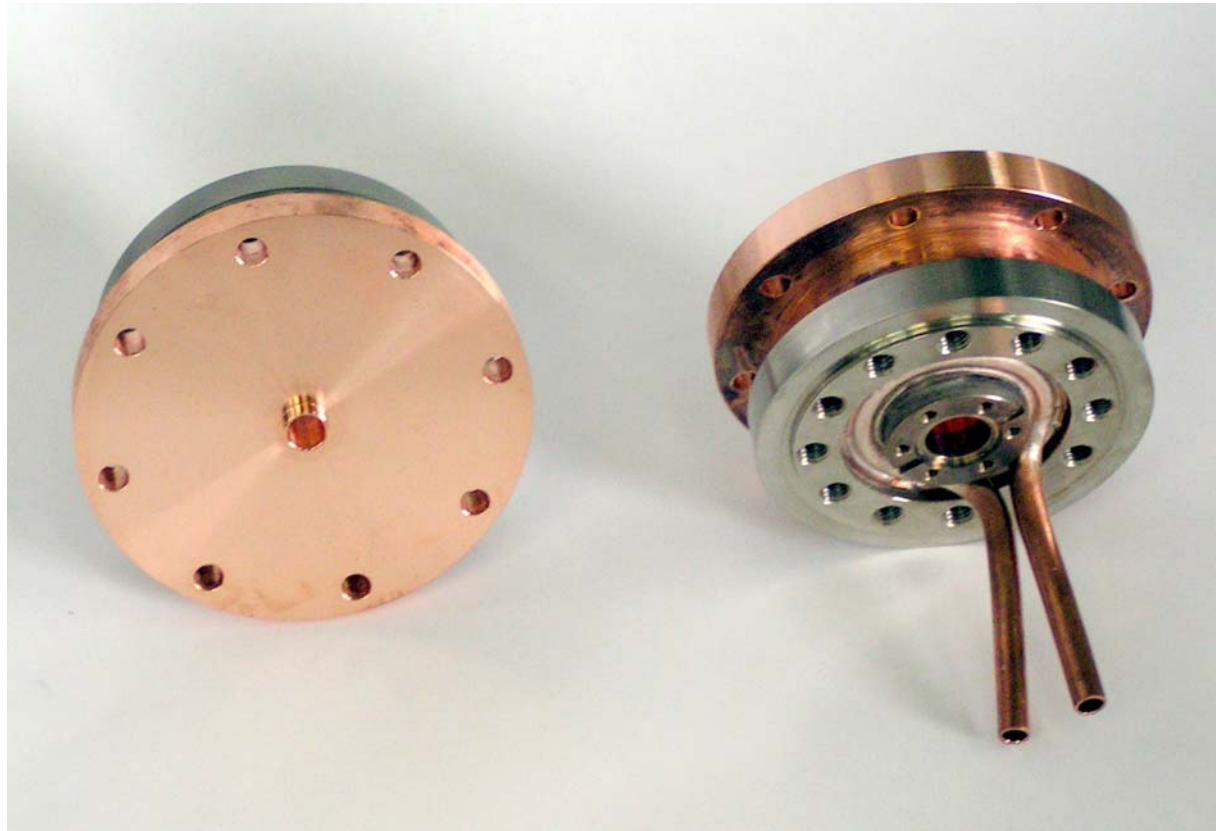


## TEST CAVITY DESIGN

1- cavity body; 2- end cap test sample; 3- TE<sub>01</sub>-mode 34-GHz input waveguide; 4- coaxial chamber; 5- insulating cavity for 13.3-GHz diagnostic signal coupled *via* WR-75 waveguides.



**TEST CAVITY**



**REMOVABLE END CAP** *(one of many)*

# RF BREAKDOWN

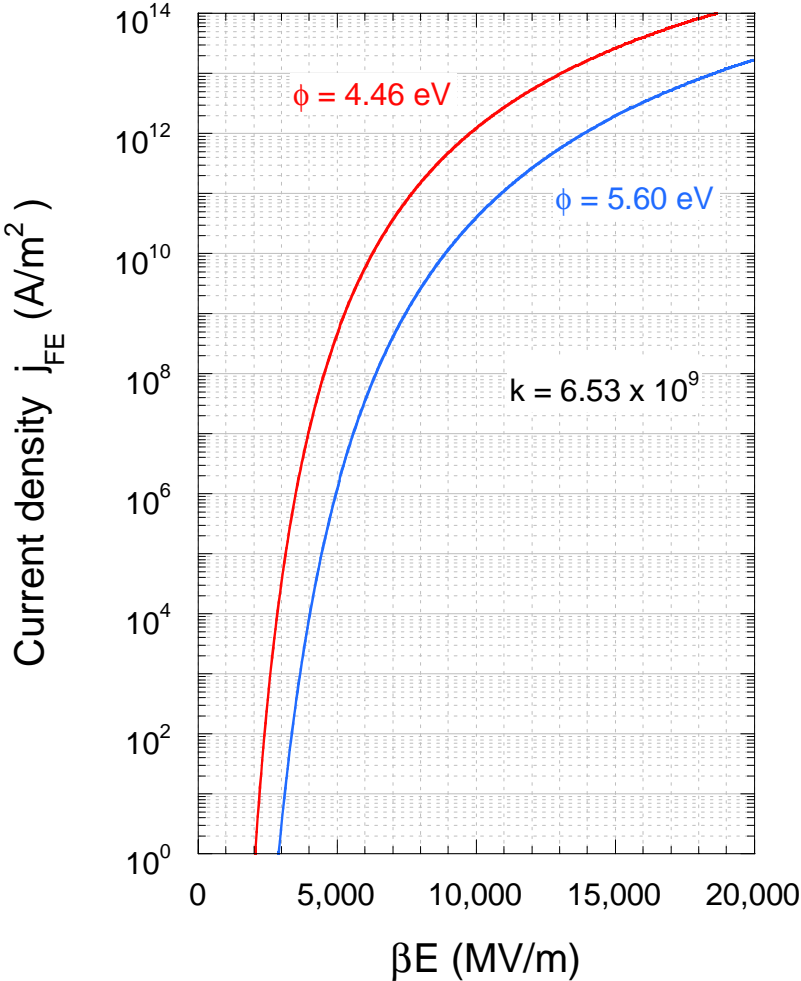
- One of the major obstacles to the achievement of high acceleration gradients in room-temperature high-energy particle accelerators is electron field emission (dark current), widely believed to be the precursor to vacuum breakdown of copper.
- RF vacuum breakdown is accompanied by formation of a plasma burst that absorbs or reflects the microwaves, thereby terminating the acceleration of the beam.
- It would thus appear desirable to reduce field emission from the Cu surfaces, to try to raise the onset threshold for breakdown.
- Experiments are planned aimed at suppressing field emission in intense RF fields found in accelerator structures and components, by increasing the surface electron work function  $\phi$  in regions of high  $E$  fields, while retaining high RF conductivity (not much less than for Cu) in regions of high  $H$  fields.
- First experiments are to determine whether work function has a significant influence on breakdown thresholds, mindful of the likely influence of other material properties besides work function.

## COMPARATIVE PROPERTIES OF CANDIDATE HIGH WORK-FUNCTION METALS

	$\phi$ (eV)	lattice constant (Å)	electrical resistivity ( $\mu\Omega$ -cm)	thermal expansion coef (ppm)	thermal conductivity cal/cm <sup>2</sup> /cm/ sec/°C	cost (\$/oz) (at 3/05)
Pt	~5.7	3.9310	10.6	8.9	0.165	868
Ir	~ 5.3	3.8389	5.3	6.8	0.14	185
Pd	~ 5.1	3.8902	10.8	11.8	0.168	208
Au	~ 5.2	4.0780	2.35	14.2	0.71	433
Ni	~ 5.2	3.5238	6.84	13.3	0.22	0.46
Cu	~ 4.65	3.6153	1.67	16.5	0.94	0.10

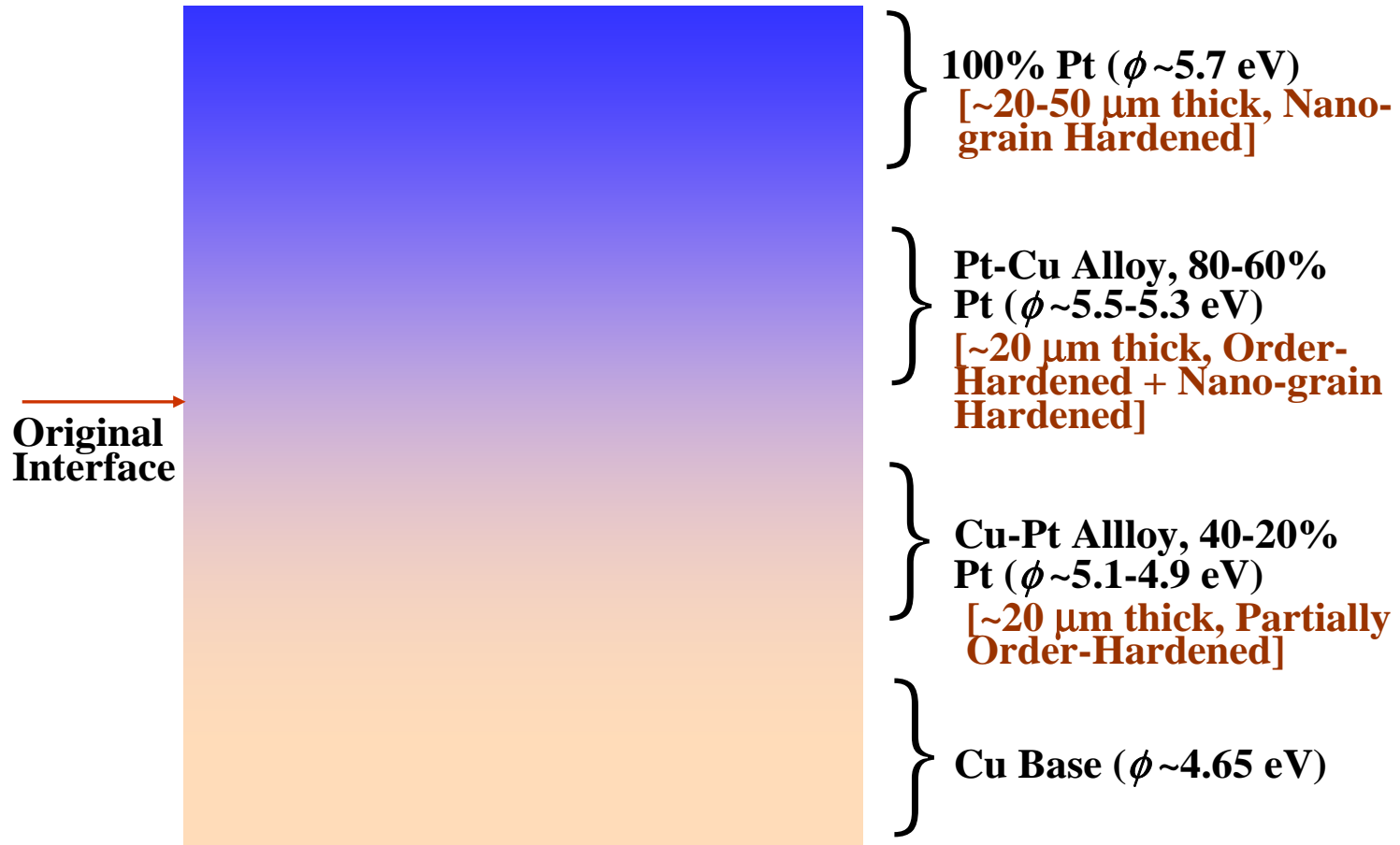
# Field emission current density for Cu (red) and Pt (blue)

[Melting temperature for (Cu, Pt) is (1083, 1769) °C.]



% Cu	% Pt	$\phi$ (eV)
0	100	5.65
20	80	5.4
40	60	5.3
100	0	4.65

## High-Work-Function, Gradient-Hardened, Fatigue-Resistant, Pt Based Surface Coating



Another possible remedy: a graded, high adhesion, very high melting point, thin, insulating coating

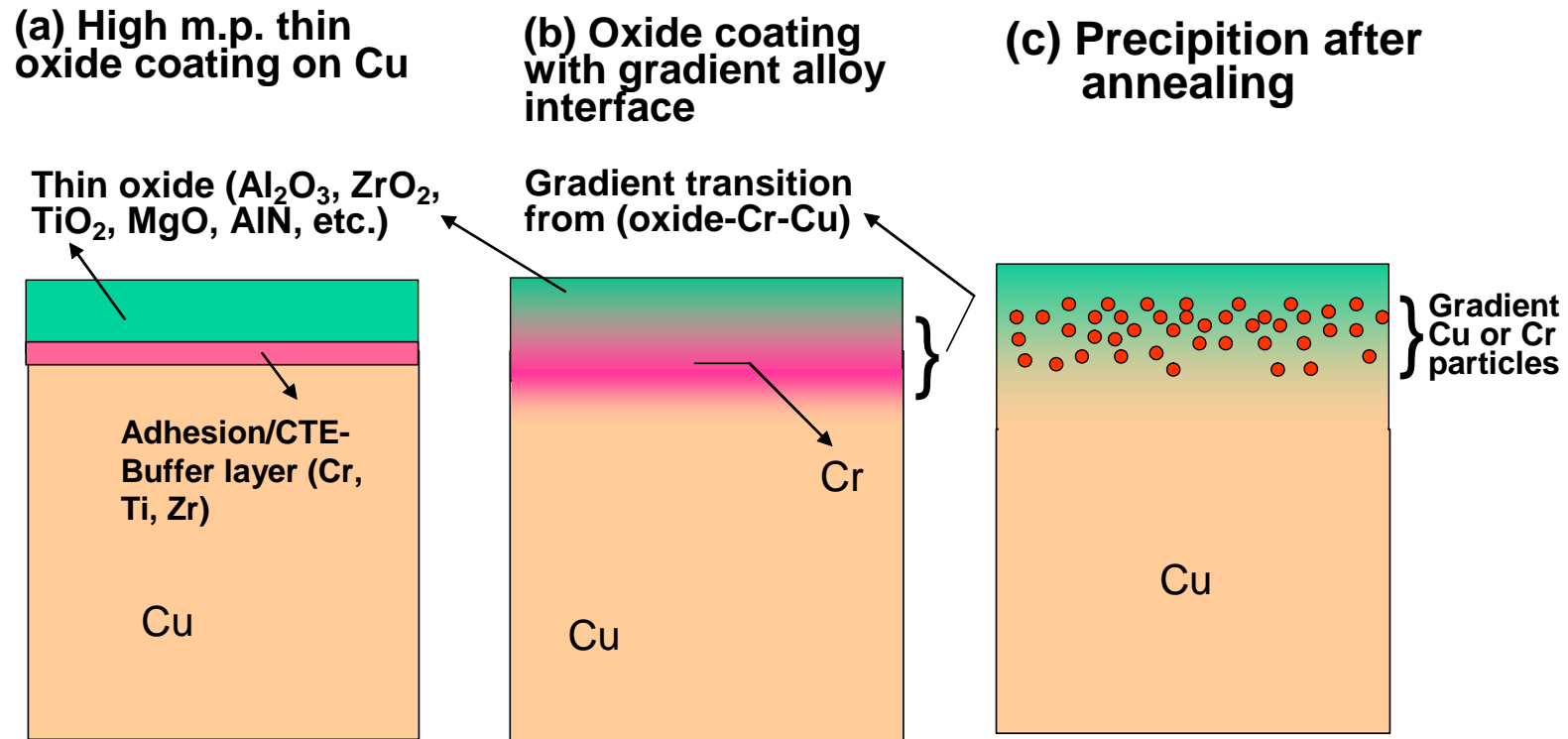


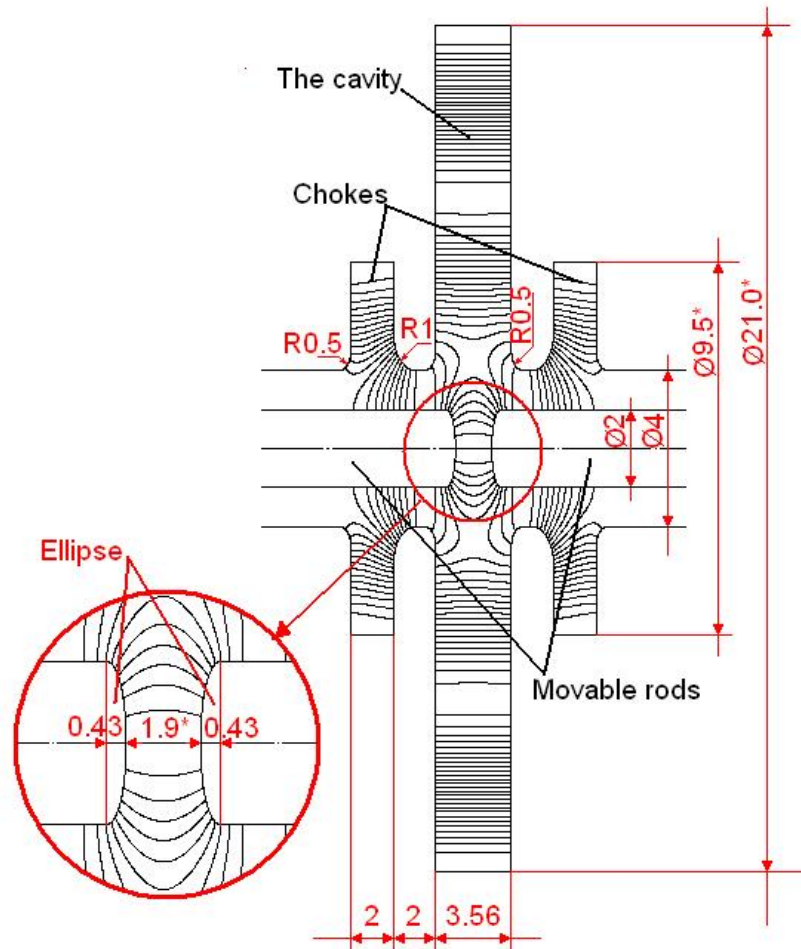
Fig.1



## Comparative properties of some nitride and oxide candidate coating and buffer layer metals

	melting temperature (°C)	thermal expansion coefficient (ppm)	thermal conductivity (W/m°K)	electrical resistivity (Ω-cm)
<u>base metal Cu</u>	1083	16.5	401	1.67
<u>adhesion/buffer</u>				
Ti	1668	8.4	22	12.9
Cr	1875	6.2	68	42
Zr	1852	5.8	79	46
Ni	1453	13.3	83	6.8
<u>nitride or oxide coating layer</u>				
AlN (Y <sub>2</sub> O <sub>3</sub> doped)	1900	4.9	200	>10 <sup>14</sup>
BN	3033	2.3	24	~10 <sup>13</sup>
Al <sub>2</sub> O <sub>3</sub>	2054	8.1	40	>10 <sup>14</sup>
ZrO <sub>2</sub>	2710	13.5	2.5	~10 <sup>10</sup>
TiO <sub>2</sub>	1736	6.0	11.7	~10 <sup>12</sup>
MgO	2800	10.8	42	>10 <sup>14</sup>
diamond	3000	0.5	2100	>10 <sup>14</sup>

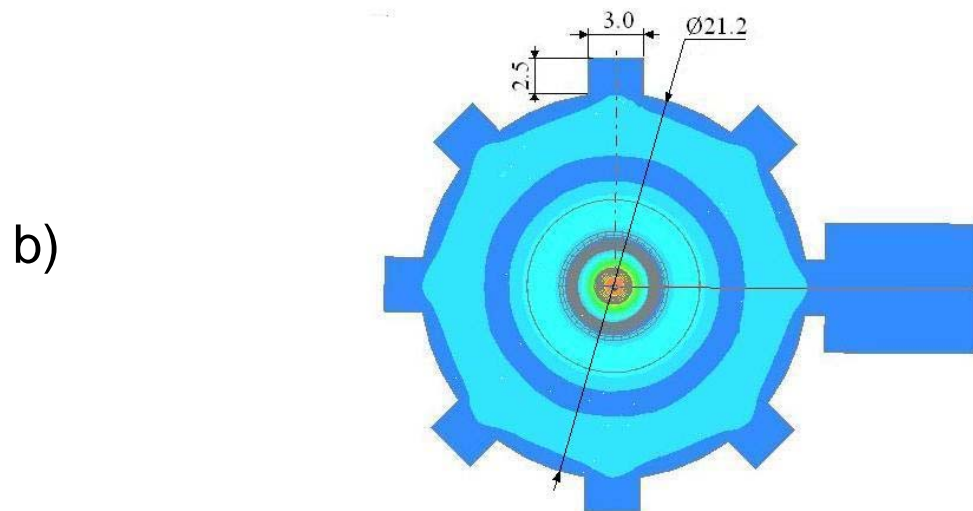
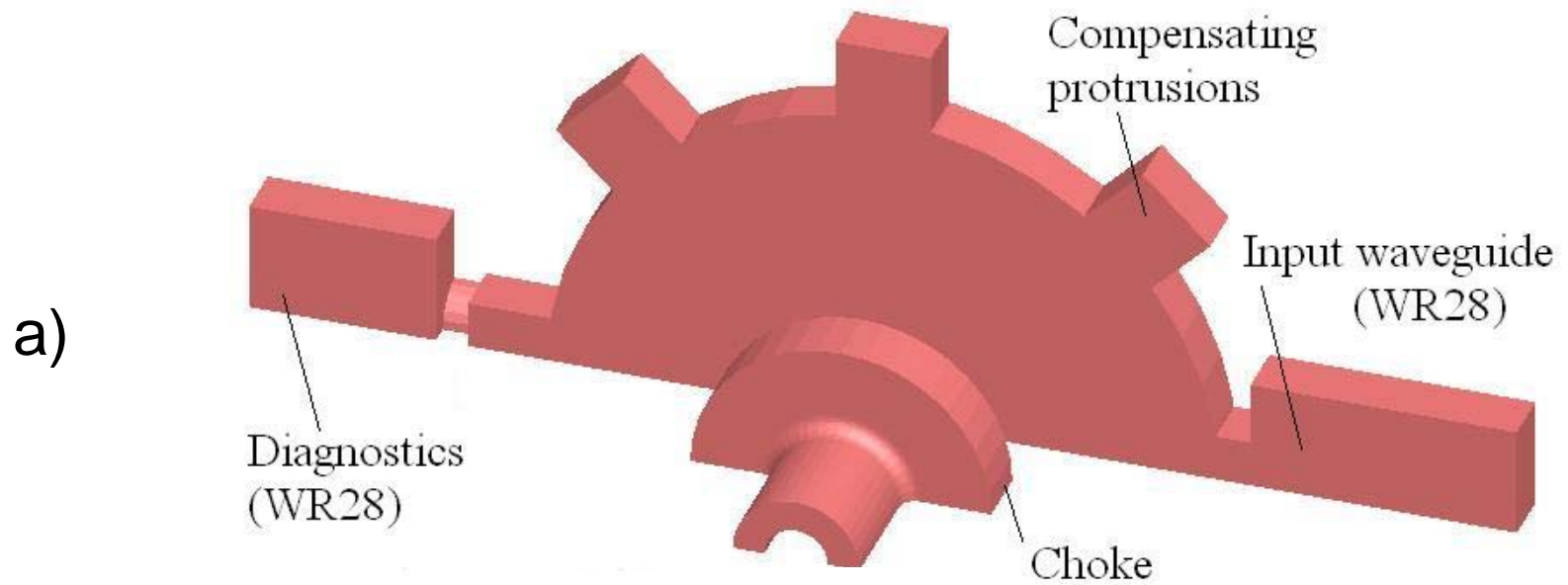
The  $TM_{030}$  test cavity schematic layout and the RF magnetic field pattern are shown in the figure. The cavity consists of three main parts, the cavity body, which is coupled to an input waveguide, and two removable rods that have the elliptically shaped ends of modified copper or other materials.



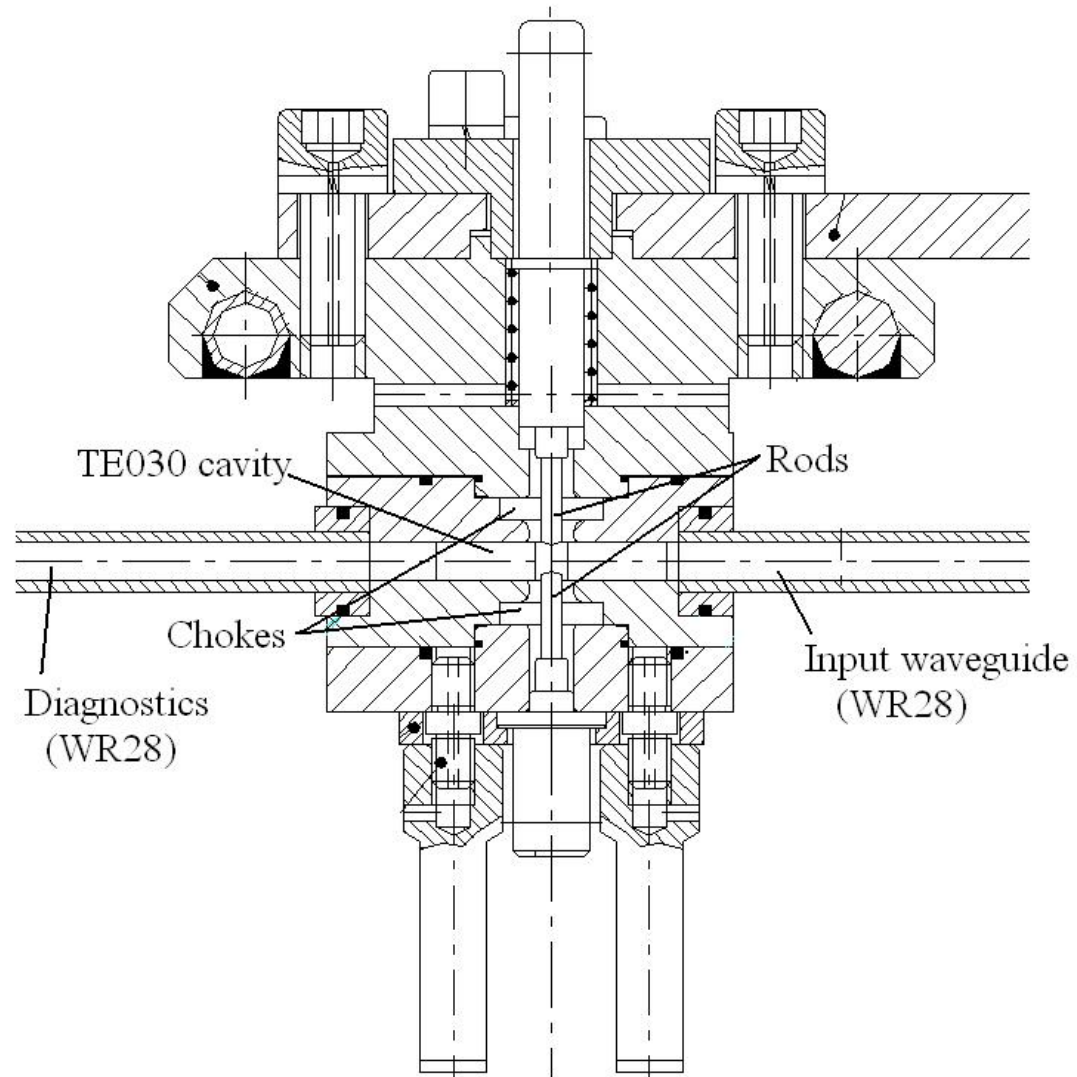
### Cavity parameters

operating frequency	34.272 GHz
operating mode	$TM_{030}$
quality factor (unloaded)	4500
input power	1.3 MW
maximum surface field (rod)	500 MV/m
maximum surface field (cavity body)	~150 MV/m
RF pulse duration	up to 1 $\mu$ sec

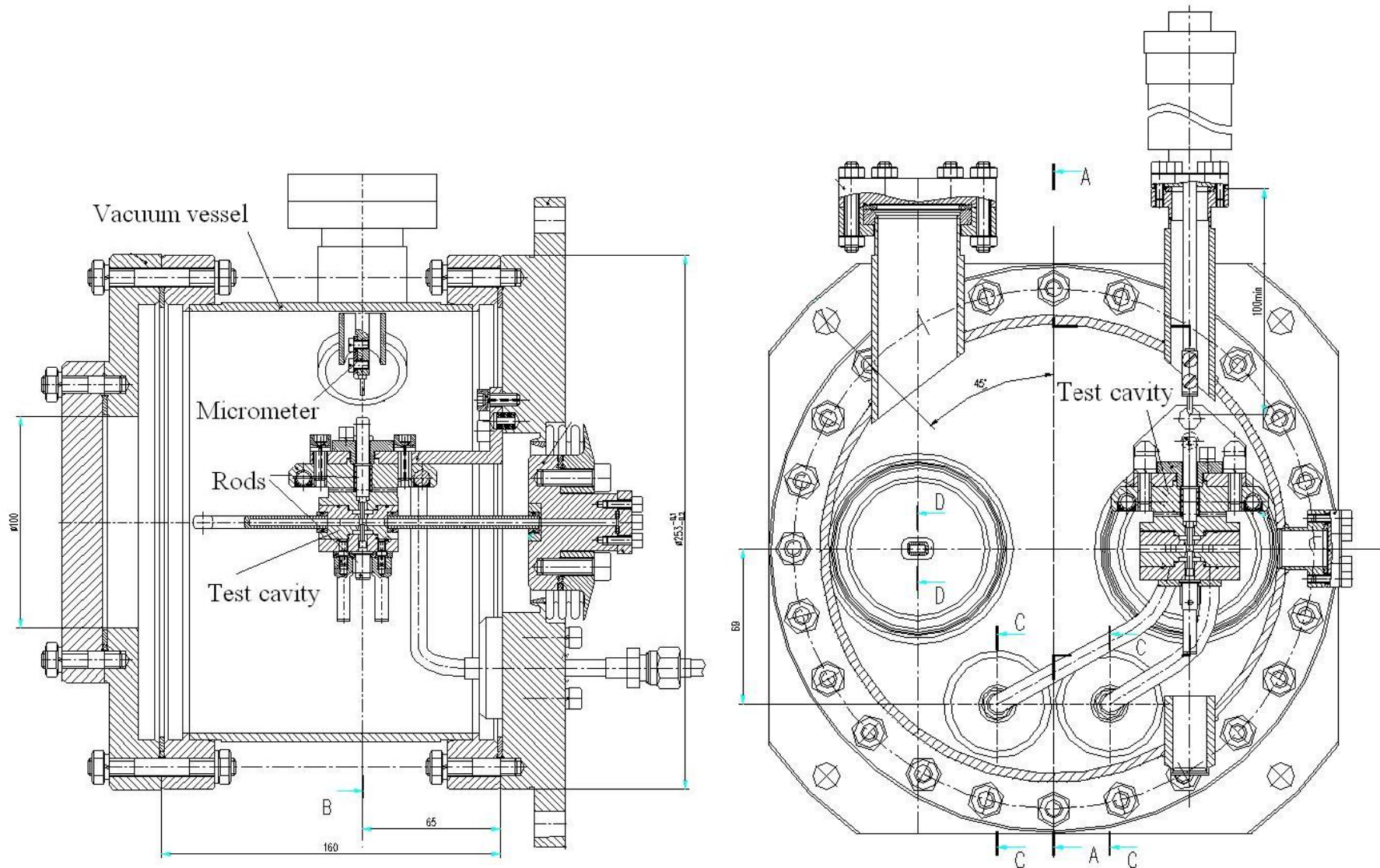
The cavity schematic layout and the RF magnetic field pattern. All dimensions are in mm



3D simulations of the test cavity: the cavity layout with the input and diagnostics waveguides and compensating protrusions (a) and field pattern in transverse cross section (b).



**The test cavity design**



The test cavity assembly layout in different projections. The cavity is placed in a vacuum vessel that can easily be opened in order to replace test rod samples. Ready in December 2006.



## Something different: rectangular dielectric-loaded structures

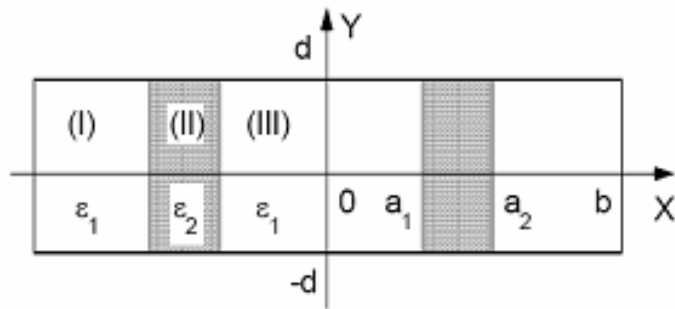
Motivation: Dielectrics may sustain higher surface fields than metals or alloys. Published DC breakdown for CVD diamond is 2 GV/m!

As for rectangular geometry, advantages are:

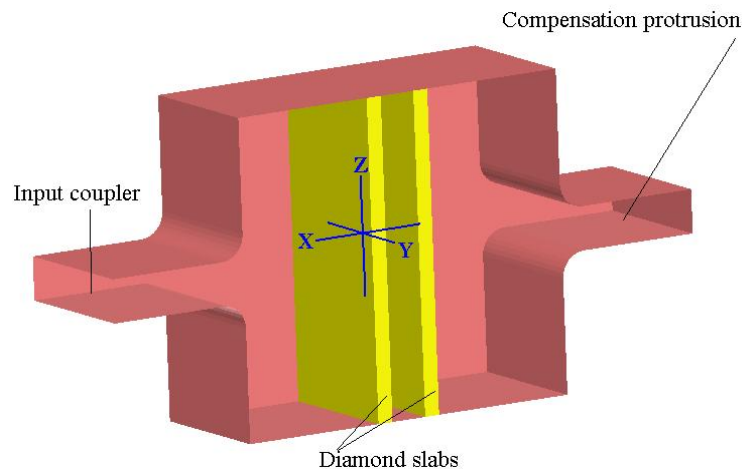
- Precision fabrication is more easily achievable than for cylindrical geometry, especially since dielectric slabs can be ground and polished, and—if necessary—have uniform coatings applied.
- Symmetry planes allow insertion of longitudinal slots, providing ease of assembly, suppression of HOM's, and continuous pumpout.
- At least one additional spatial degree-of-freedom is available for optimizing dimensions of structure, as compared with cylindrical structures.
- Possible use of sheet beams.
- Peak fields can be on dielectrics, rather than on metal walls.

But, until RF breakdown and other materials limits of candidate dielectrics are measured in realistic settings, the potential for this class of structures for achievement of high acceleration gradients remains speculative. Diamond is the first material destined for tests, at 34 GHz.

## Test cavity design for measuring diamond breakdown limit



(a) Cross section for theoretical analysis.



(b) 3D picture in coupler simulations.

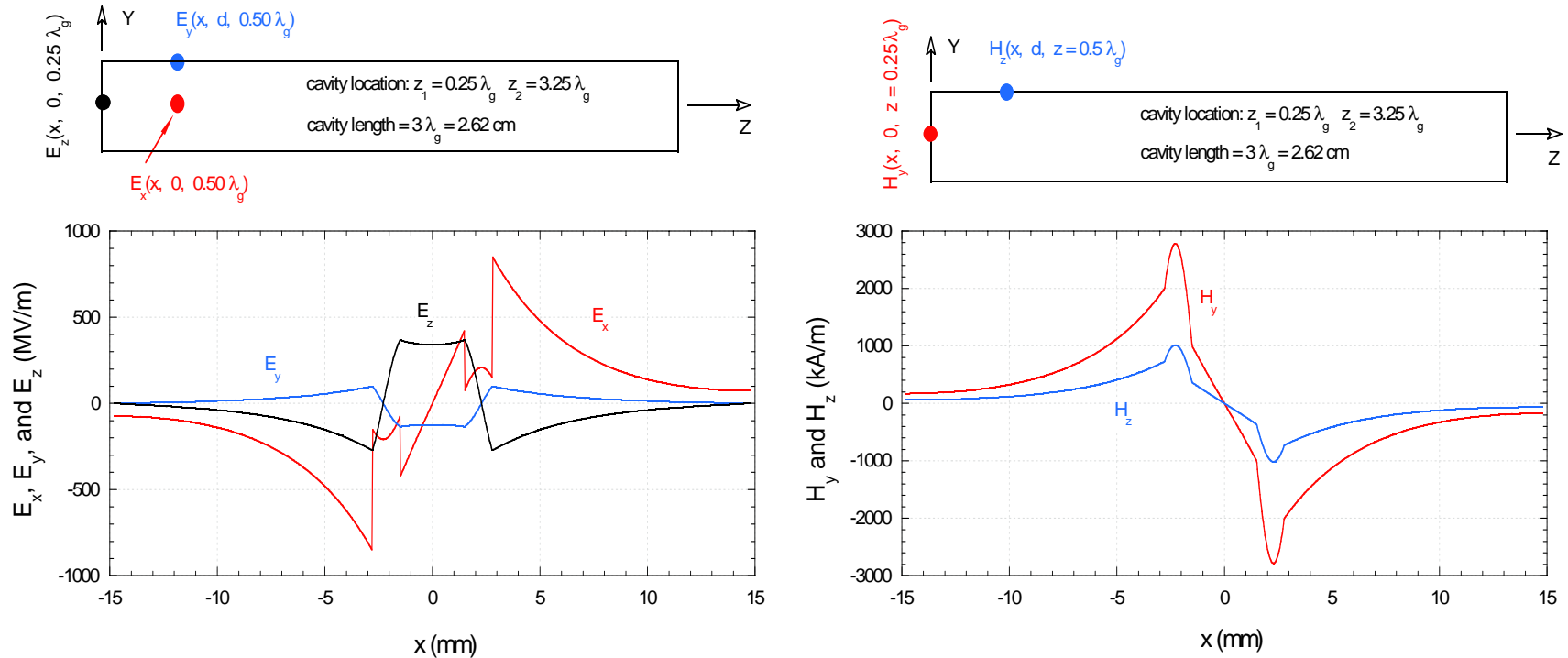
Table 1: Parameters for diamond-lined cavity structure.

operating frequency for LSM <sub>216</sub> mode	34.272 GHz
equivalent phase velocity $v_{\text{phase}}$	$c$
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 $\tan \delta$	$3 \times 10^{-5}$
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 $\Omega$
shunt impedance $R$	1.99 M $\Omega$
input RF power	10 MW
peak RF electric field on axis	340 MV/m

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.

# ANALYTIC RESULTS FOR RF FIELDS IN TEST CAVITY



RF field profiles for the idealized LSM<sub>216</sub> cavity mode with parameters as in Table 1 for an input power of 10 MW, at (y,z) coordinates shown in the accompanying diagrams.

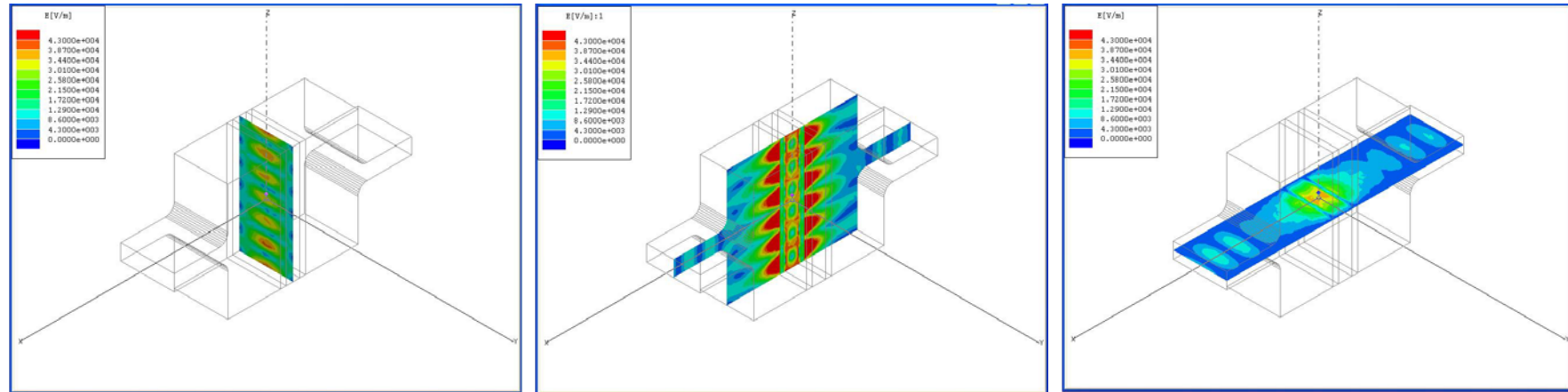
Left figure shows peak  $E$ -fields at the diamond surfaces of  $E_{y\text{-max}} = 133\text{ MV/m}$ , and  $E_{x\text{-max}} = 848\text{ MV/m}$ ;  $E_z$  on the axis is  $340\text{ MV/m}$ .

Right figure shows  $H$ -field profiles with  $H_{y\text{-max}} = 2783\text{ kA/m}$  and  $H_{z\text{-max}} = 1014\text{ kA/m}$ .

The fields on the end walls must be greatly reduced in the test cavity. Intention is to use of wall tapers and profiled slots to achieve reductions.



## FIELD DISTRIBUTIONS IN TEST CAVITY, INCLUDING INPUT COUPLER

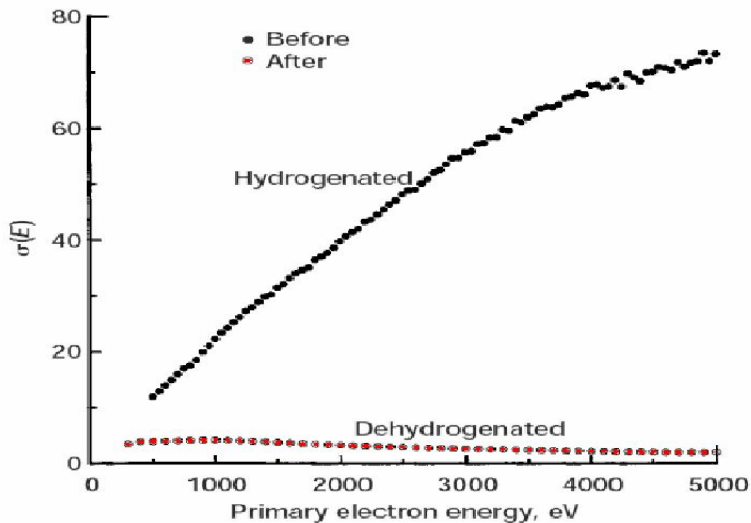


*on y-z plane*

*on x-z plane*

*on x-y plane*

Field pattern in each of the symmetry planes of the operating  $LSM_{216}$  mode with an input coupler and a compensating protrusion. For operation with short pulses (e.g., 50-100 ns) the coupling factor would be about 4 in order to achieve reasonable energy flow during the pulse, and the temperature rise on the copper side walls would be about 170 °C (for a 50-ns pulse).



De-hydrogenation to reduce SEEC.  
 [I. L. Krainsky, V.M. Asnin, and A.G. Petukhov,  
 NASA/TP-1999-208692 (1999)]

Polished diamond disk, with diameter 75 mm and thickness 1.35 mm developed by collaborator A.L. Vikharev *et al*/at IAP. Measured dielectric constant and loss tangent at 36 GHz are 5.7 and  $3 \times 10^{-5}$ .

(a). Secondary electron emission coefficient *versus* primary electron energy for diamond with and without de-hydrogenation. It is seen, removal of the hydrogen by exposure of the finished diamond sample is seen to have a remarkable influence on the secondary yield. (b). Sample CVD diamond disk developed at IAP.

## SUMMARY

- A rational pathway towards achievement of high gradients in warm structures should include fundamental experimental studies of RF breakdown and pulsed surface fatigue for candidate structure materials, including Cu and other metals, alloys, and composites.
- Experiments should be conducted over a range of frequencies, e.g., 11.4, 17.1, 22.8, 30, 34.3, ...GHz. Pending experiments at 34.3 GHz were described:
  - a. pulsed heating and surface fatigue for Cu and other materials, for extrapolation to determine material lifetime as a function of pulsed temperature rise;
  - b. breakdown on a wide variety of test samples, under comparable conditions, including samples with work functions greater than for Cu, alloy samples with m.p. greater than for Cu, and samples with a thin high m.p. insulating layer;
  - c. tests to determine breakdown limits for dielectrics, beginning with CVD diamond (H and de-H), to assess potential of rectangular accelerator structure geometry with highest field on dielectric.