US High Gradient Research and Progress at SLAC

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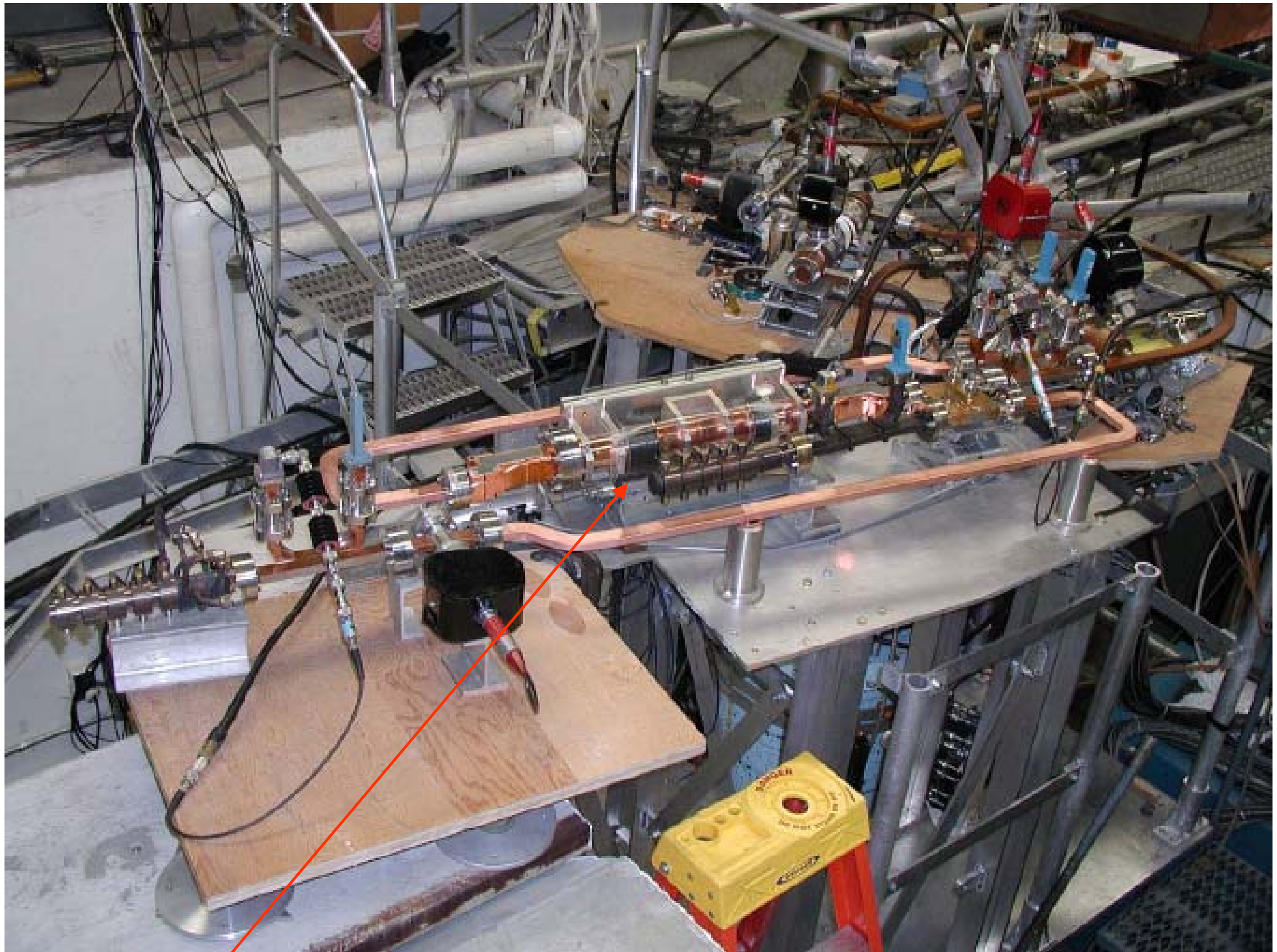
10/16/2007

Outline

We will consider aspects of the US High Gradient Collaboration with direct impact on CLIC.

- Experimental Programs that address fundamental gradient issues around the US.
- Facilities and components at SLAC
  - Test Stands in the klystron department
  - ASTA
  - Two-PAC
  - NLCTA
  - MIT/NRL/CERN
- Experimental program at SLAC in practicalar and collaborative programs with CERN and KEK.
  - Single cell structure testing
  - Full structure testing
  - Pulsed heating
  - Material testing
- On going research Planned Experiments.

X-band Setup at NRL

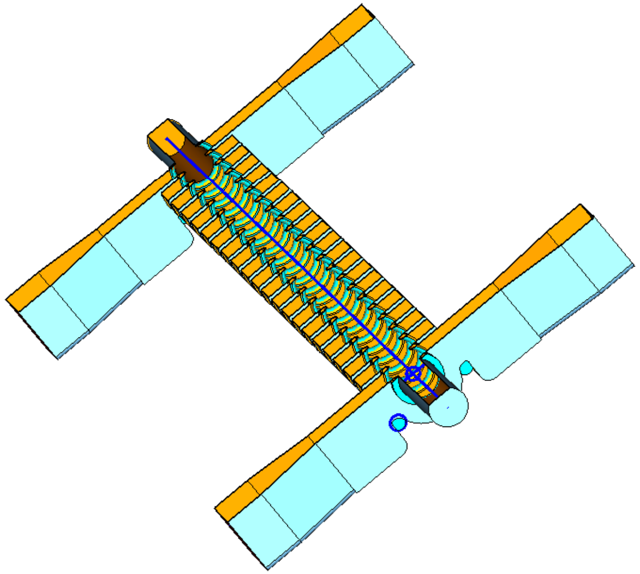


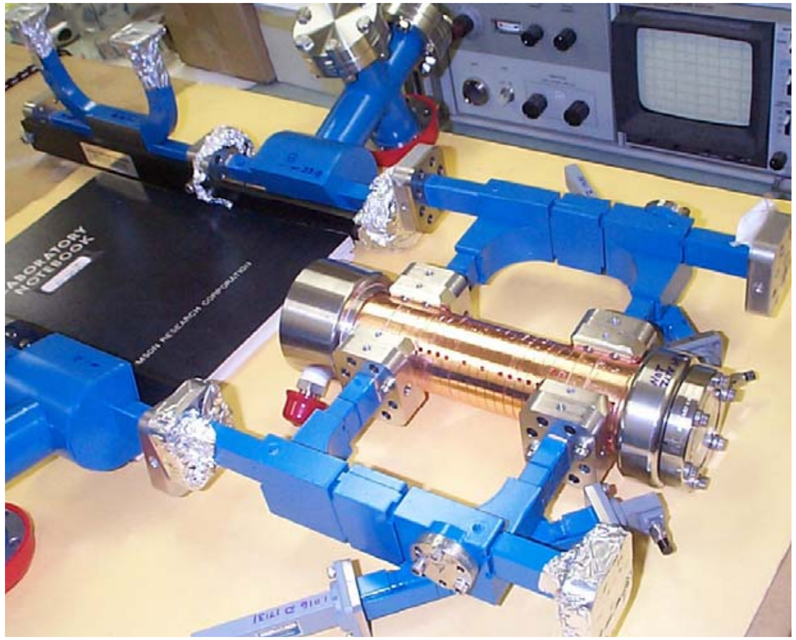
SLAC components (A combiner specifically designed and build for NRL)

MIT User Facility

- Planned collaborations through the High Gradient Collaboration:
  - Continue long term collaboration with Haimson Research
  - Testing of Univ. CO dielectric PBG structures, part of High Gradient Collaboration (G. Werner, J. Cary)
  - Proposed collaboration with SLAC / CERN
- Test RF breakdown, novel structures
- Facility Upgrade:
  - Phase I: Purchase new DC power supply, 65 kV, 30 kJ/s for higher repetition rate operation; funded by supplement in 2006.
  - Phase II: Design and procurement of modulator components to complete the upgrade – Funded August 2007.

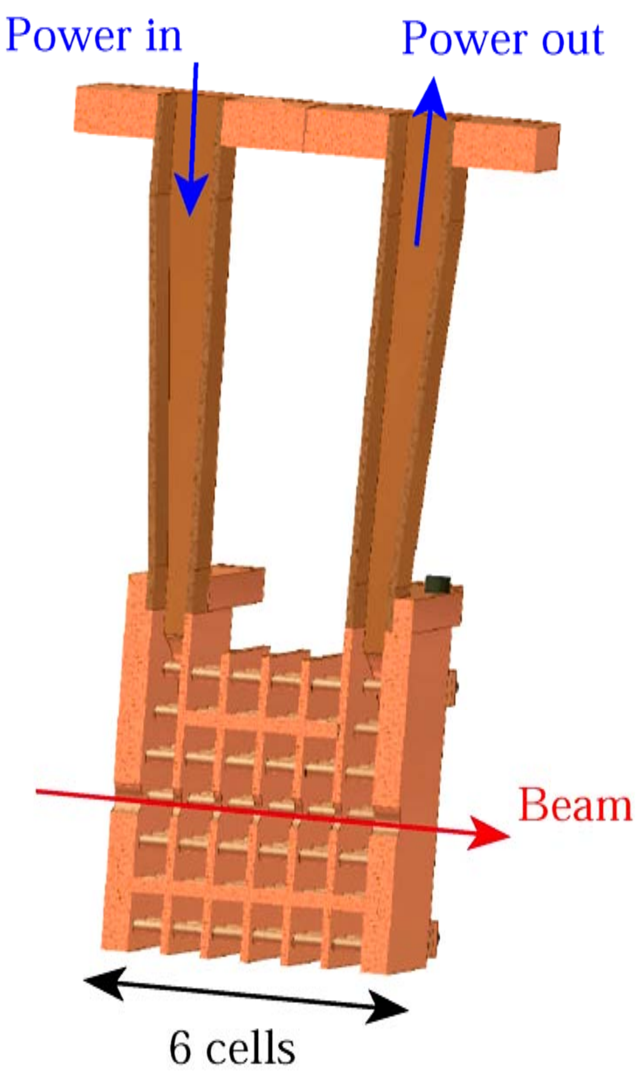
HRC: Test of 22 Cell Cu Linac Test Structure

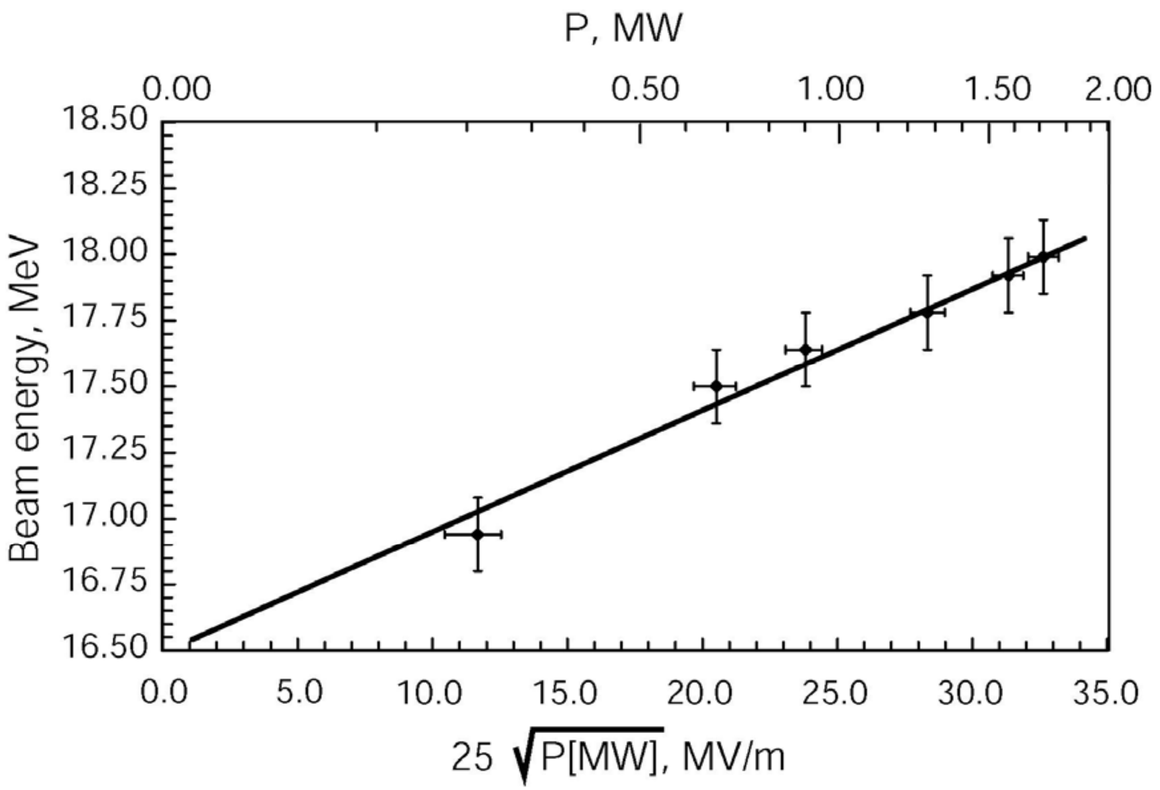




- 17 GHz Test structure built in 2002
  - Structure was located at Univ. MD for many years.
- **STATUS: Arrived at MIT late 2006, Installed May 07**
- **FIRST TESTS: Started Summer 2007**
- **GOAL: Measure breakdown limit of pure Cu structure**
  - Baseline for comparison with “hardened” structures

Accomplishments: PBG Accelerator Expt.





- First successful experimental PBG accelerator demonstration.

E. I. Smirnova et al., Physical Review Letters (2005).

Future Work with test facilities in the US and CERN

- Frequency Scaling Studies
  - It is conjectured that the frequency scaling for copper structures is fundamentally due to incidental pulse length parameters which favor higher frequencies because of the shorter filling time.
  - However to date a systematic study which uses the same geometry at different frequencies have never been conducted.
  - We are now at position that will allow us to do this and we should take the chance and conduct such a series of experiments. At SLAC 11.424 frequency sources are available, at MIT, soon there will be a high repetition rate reliable source at 17 GHz, and finally at CERN there is a room for testing structures at 30 GHz (May be also possible at Yale).
  - We intend to build a set of reusable couplers and a set of single cell standing wave accelerator structures with a/λ of about 0.21 to test at different frequencies. The test at 11.424 is under way at SLAC; we will duplicate its geometry at 17 and 30 GHz.

High Gradient Research at SLAC

- As the host, we concentrated on being accessible to the rest of the collaboration:
  - Improve our test facilities at 11.424 GHz
    - 2-pack, ASTA and individual stations
  - Cost effective testing:
    - SLAC can provide their reusable couplers and supply compatible flanges. Hence, other groups need only to worry about the design of the accelerator structure “proper”
    - We are introducing new types of gate valve to minimize, time, effort and cost for installation of different experiments
    - We are introducing a new test stand for low temperature high power measurements

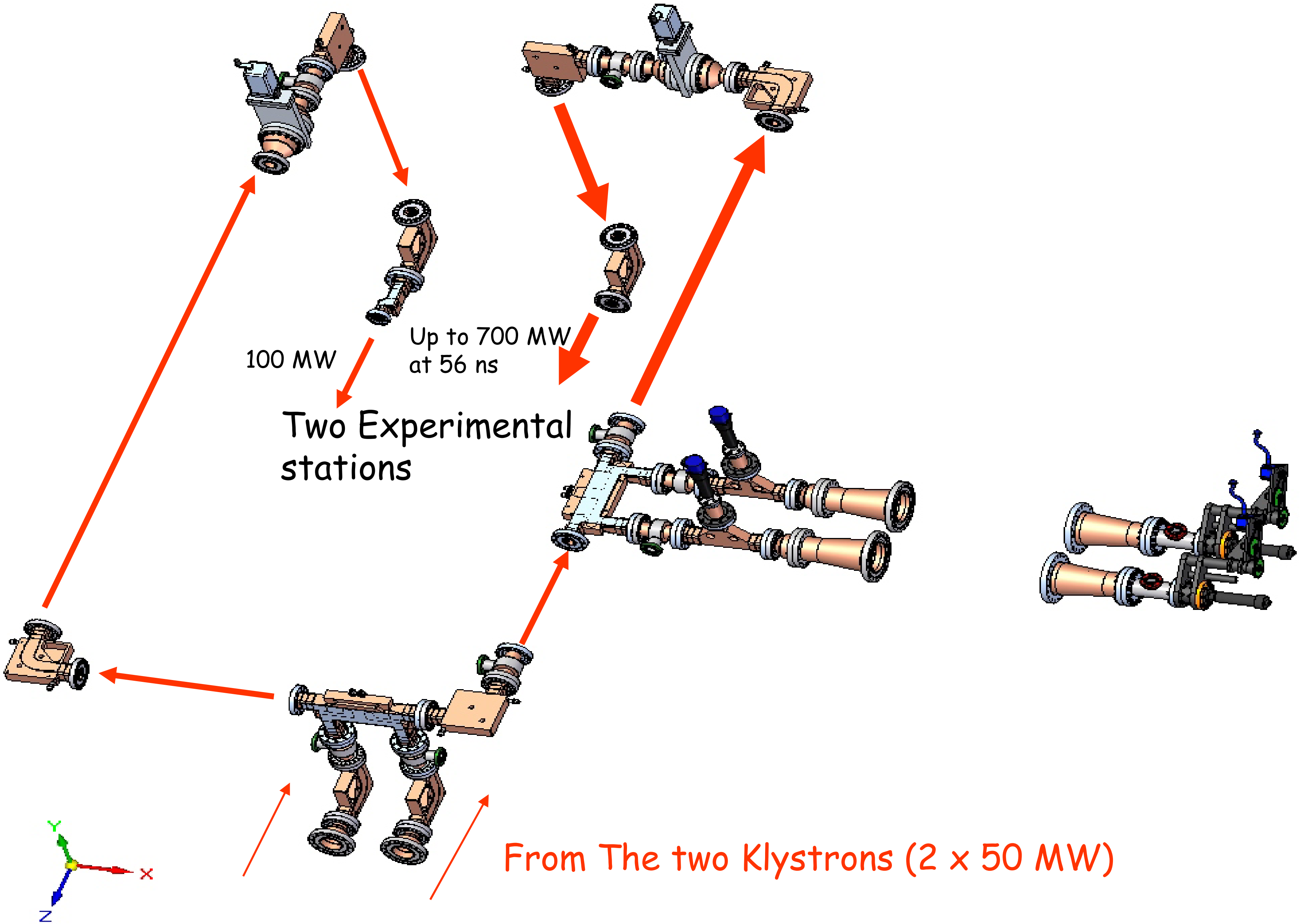
High Gradient Research at SLAC

- As the host, we tried to unify the on going efforts:
  - We encouraged groups to take advantage of the available resources at SLAC for building and manufacturing accelerator structures. This could considerably save time and element mistakes.
  - Encourage a coherent theoretical modeling efforts, this is going to materialize soon through our collaboration with the University of Maryland
  - We started a collaborative efforts with MIT, ANL, … on novel structures.
  - We are also working with CERN, LANA and SNS on material characterizations with our novel cavities

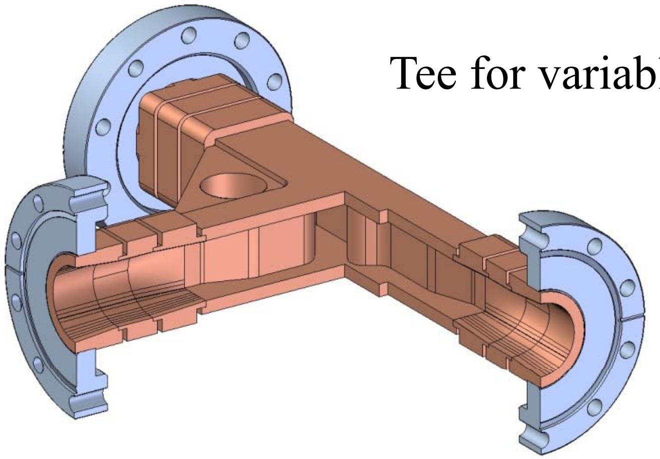
Pulse compressors at ASTA and Two-Pack

- All New overmoded components for high reliability (So that we are testing structure rather than RF system)
- Flexible pulse length and gain
- High efficiency
- Each is powered by two klystrons

ASTA Pulse Compressor

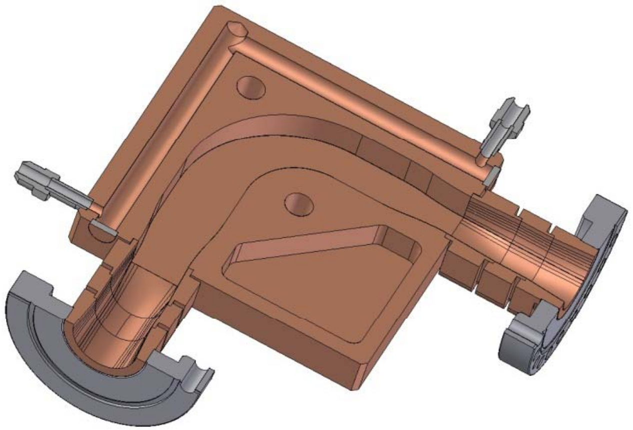


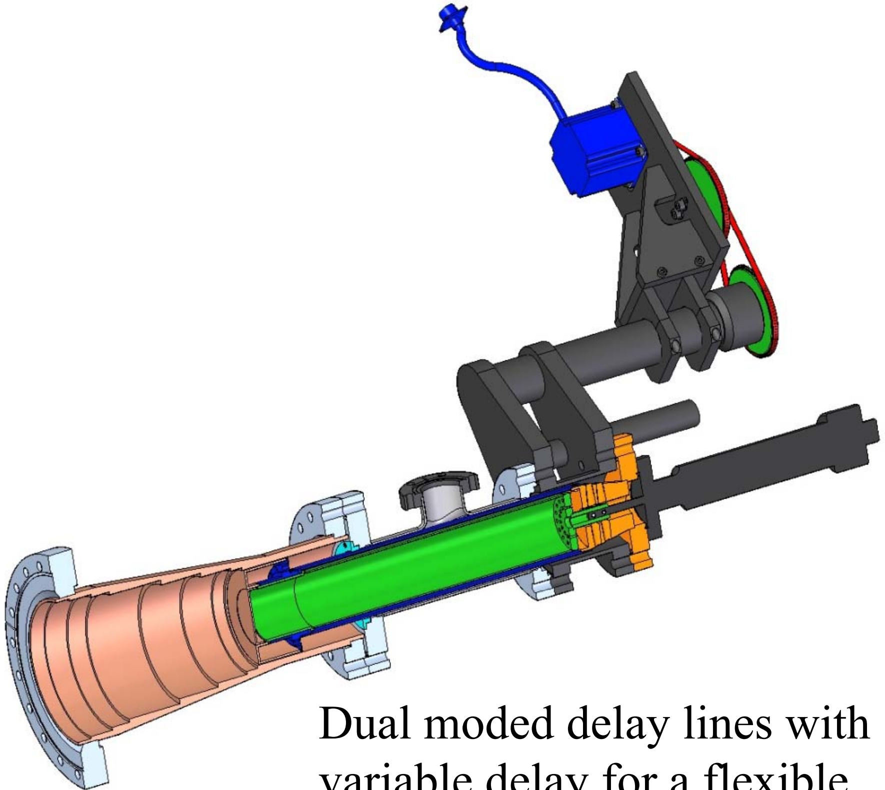
Components To Support The Experimental Facilities



Tee for variable iris

Bends for low loss transmission and reliable RF systems

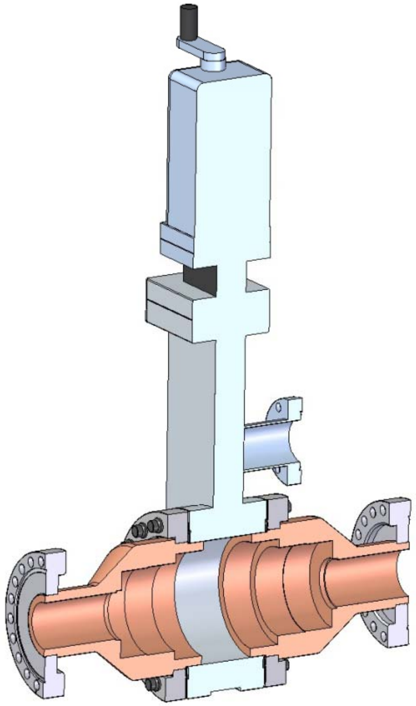


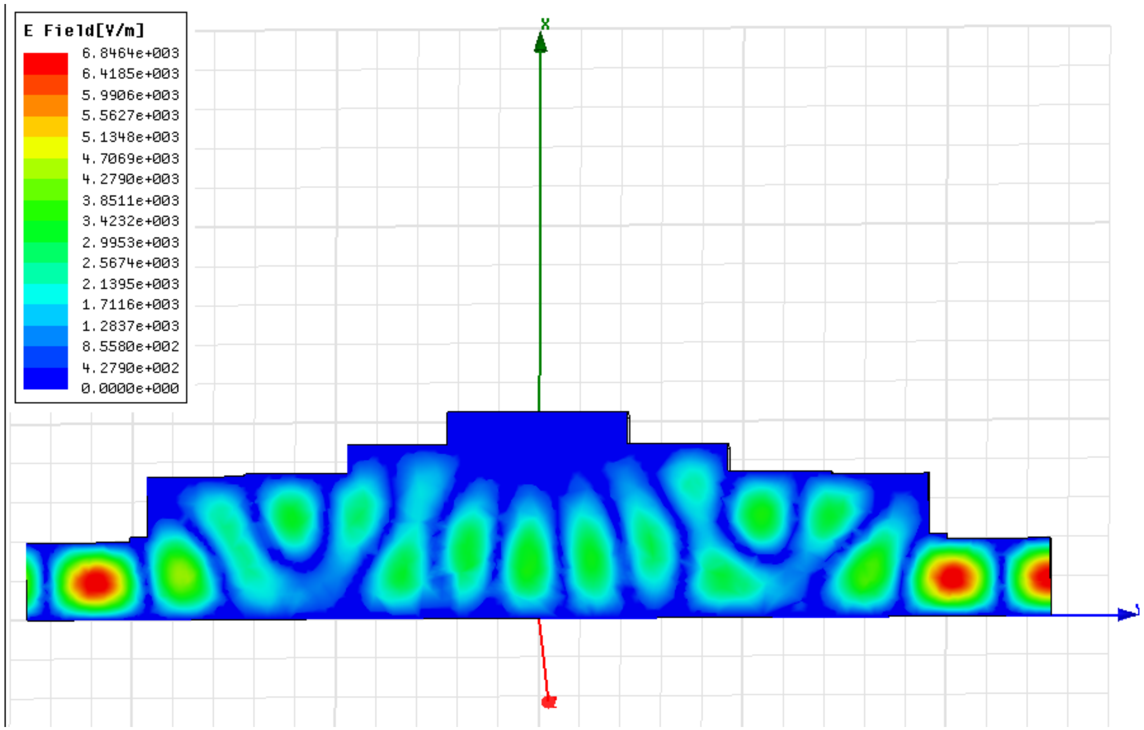


Dual moded delay lines with variable delay for a flexible pulse width

All these components have designed and in different stages of manufacturing

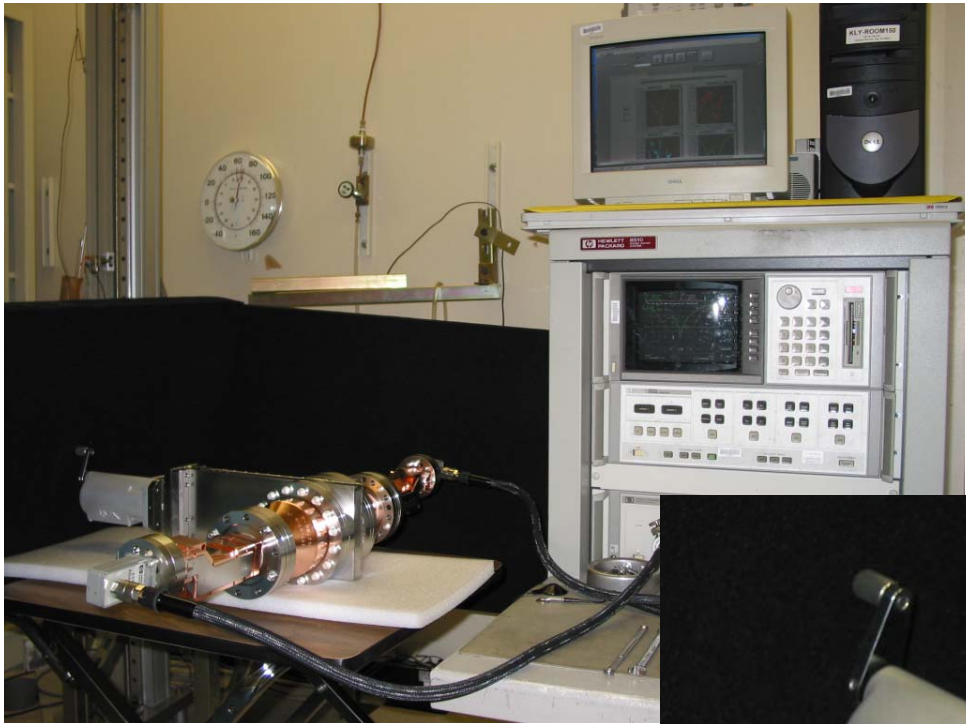
Gate Valve

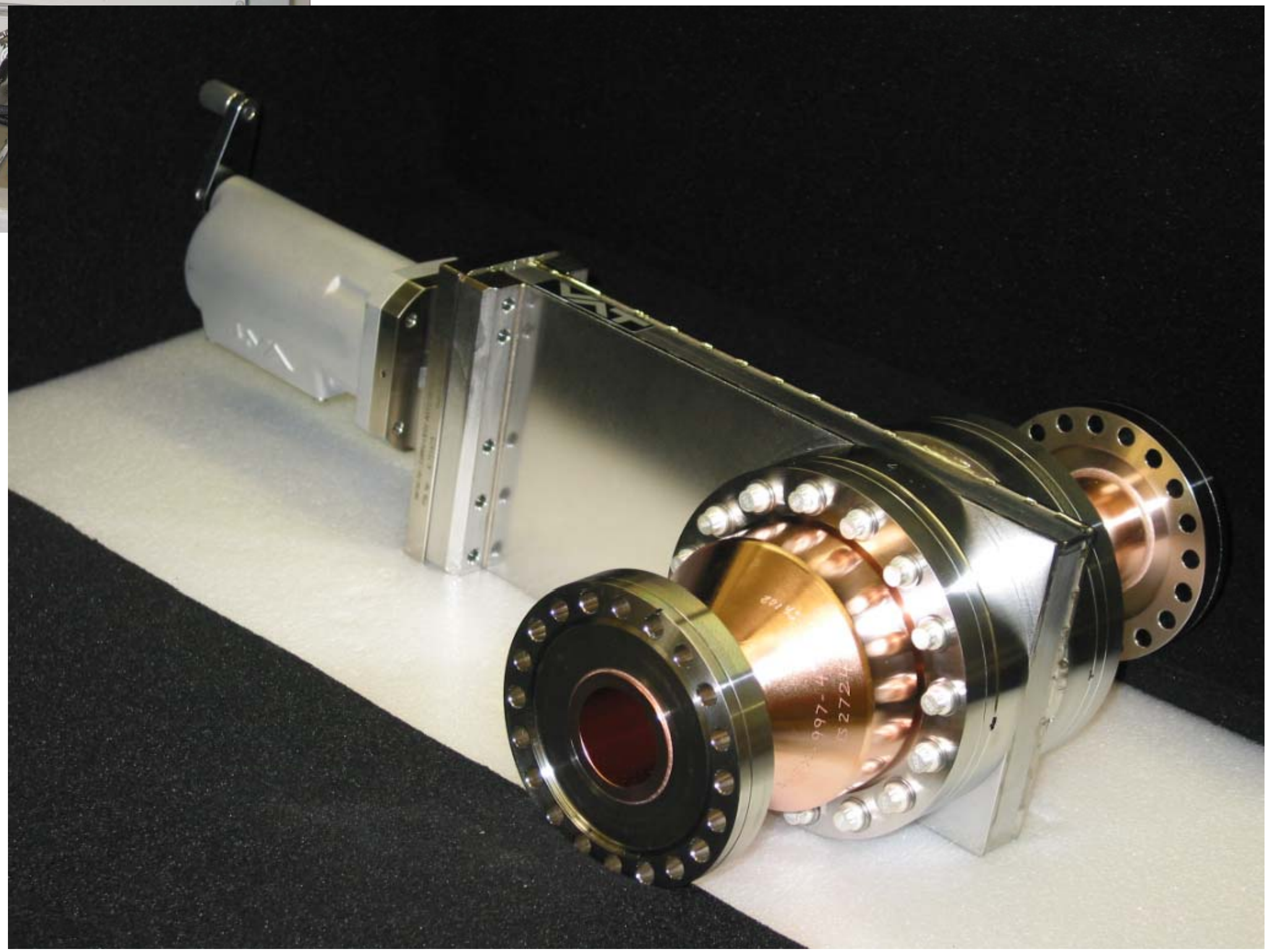


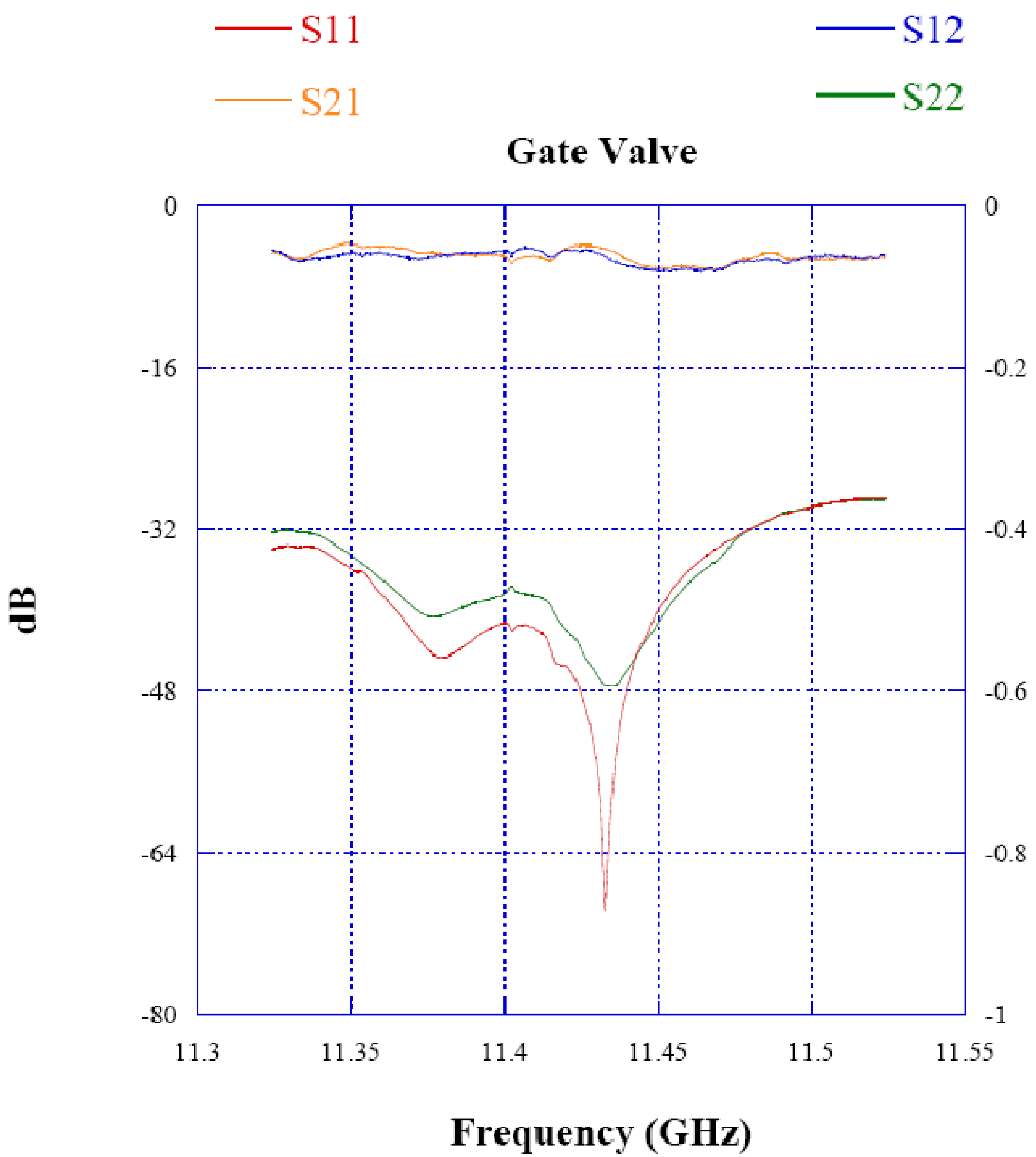


We have designed a new type of gate valves to allow fast exchange of experimental structure. This will cut the change time from a week to one day

A. Grudiev, “Development Of A Novel Rf Waveguide Vacuum Valve,” Proceedings of EPAC 2006, Edinburgh, Scotland

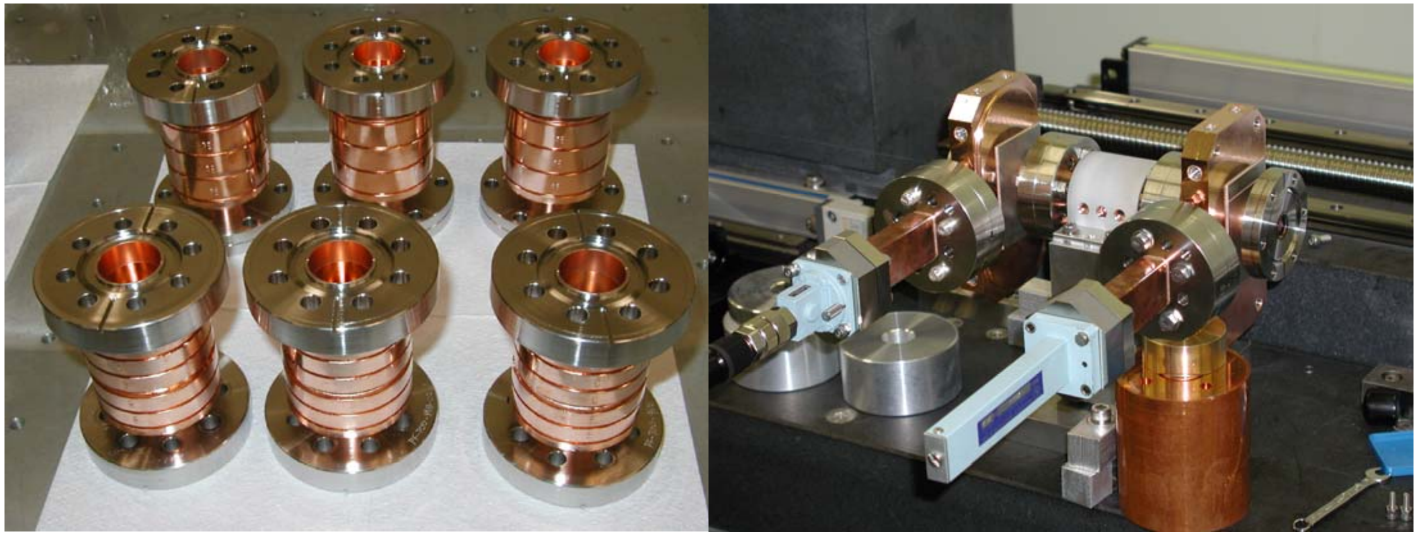

KLY-ROOM150




S11
S12
S21
S22
Gate Valve
0
-16
-32
-48
-64
-80
0
-0.2
-0.4
-0.6
-0.8
-1
dB
11.3
11.35
11.4
11.45
11.5
11.55
Frequency (GHz)

Basic Physics Experimental Studies

- There are three basic vehicles for these studies:
  - traveling- wave single cell accelerator structures,
  - single-cell standing-wave accelerator structures,
  - waveguide structures



Single Cell Accelerator Structure Motivations

Goals

- Study rf breakdown in practical accelerating structures: dependence on circuit parameters, materials, cell shapes and surface processing techniques

Difficulties

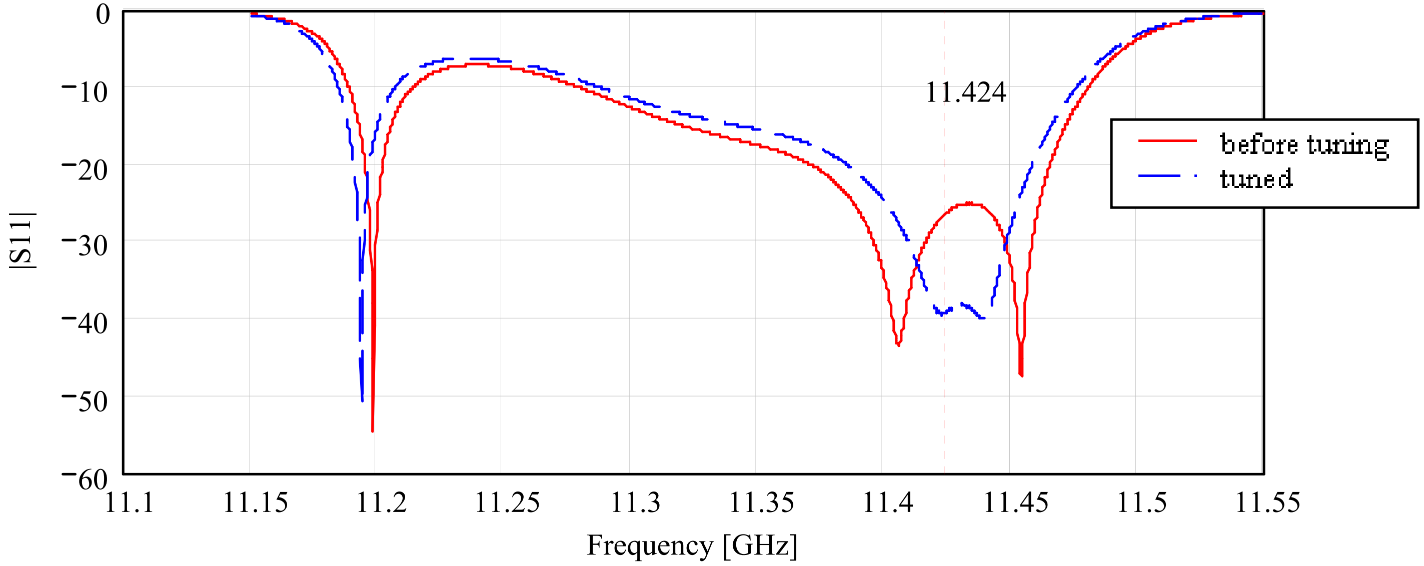
- Full scale structures are long, complex, and expensive

Solution

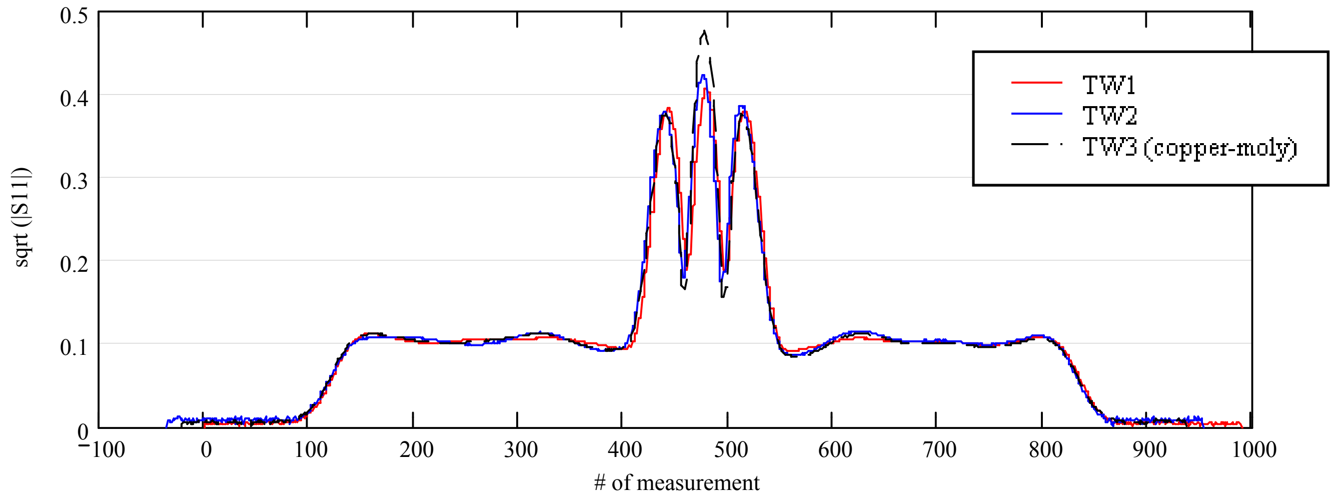
- *Single cell Traveling wave (TW)* and *single cell standing wave (SW)* structures with properties close to that of full scale structures
- Reusable couplers

This program, now, has a strong participation from both KEK and CERN.

Cold Test With Single Cell Traveling Wave Structure



Reflection from single cell TW structure before and after tuning

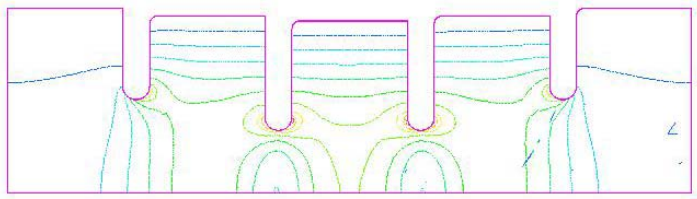


On axis field profile for three single cell TW structures

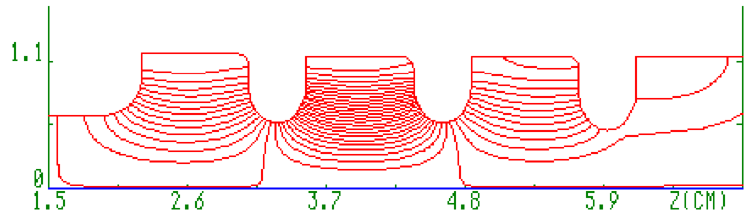
Single cell traveling (TW) and standing wave (SW) structure 11.4 GHz high gradient study

Goals:

•RF breakdown *vs.* circuit parameters (SW *vs.* TW)
•RF breakdown *vs.* different surface processing technique (etching, baking)
•RF breakdown *vs.* different materials: copper, molybdenum, molybdenum-copper



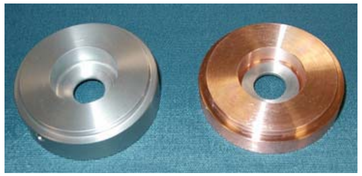
Electric field lines in single cell **traveling** wave structure



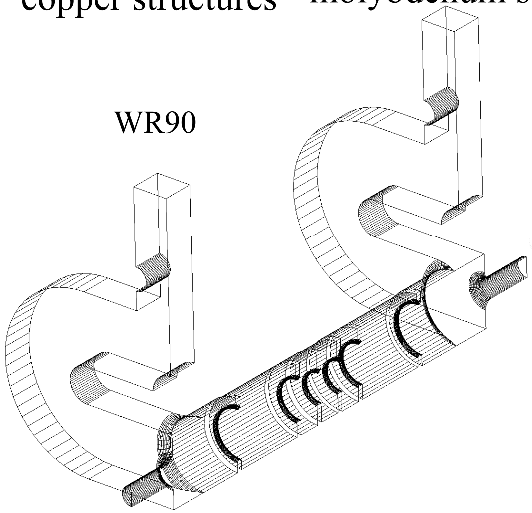
Electric field lines in single cell **standing** wave structure

TW SW
copper structures

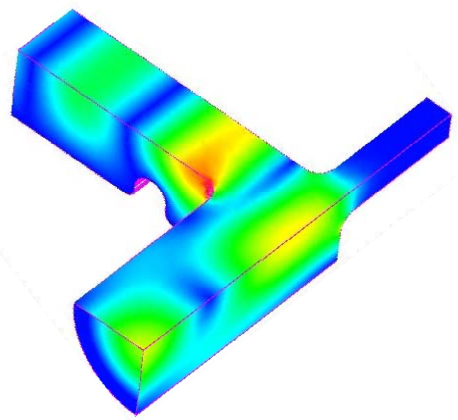
TW SW
molybdenum structures



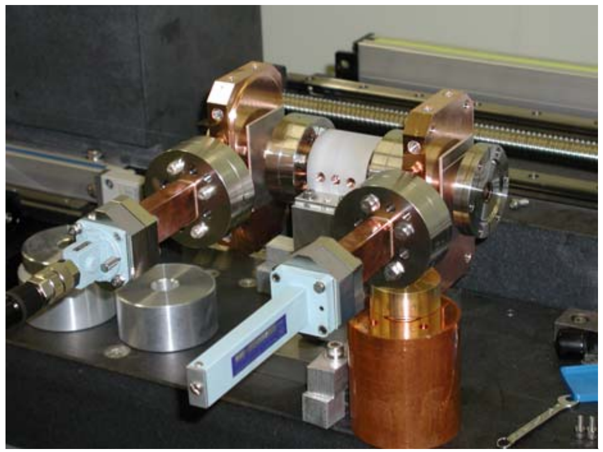
SW moly TW moly-copper cells



Single cell TW structure with mode-launchers



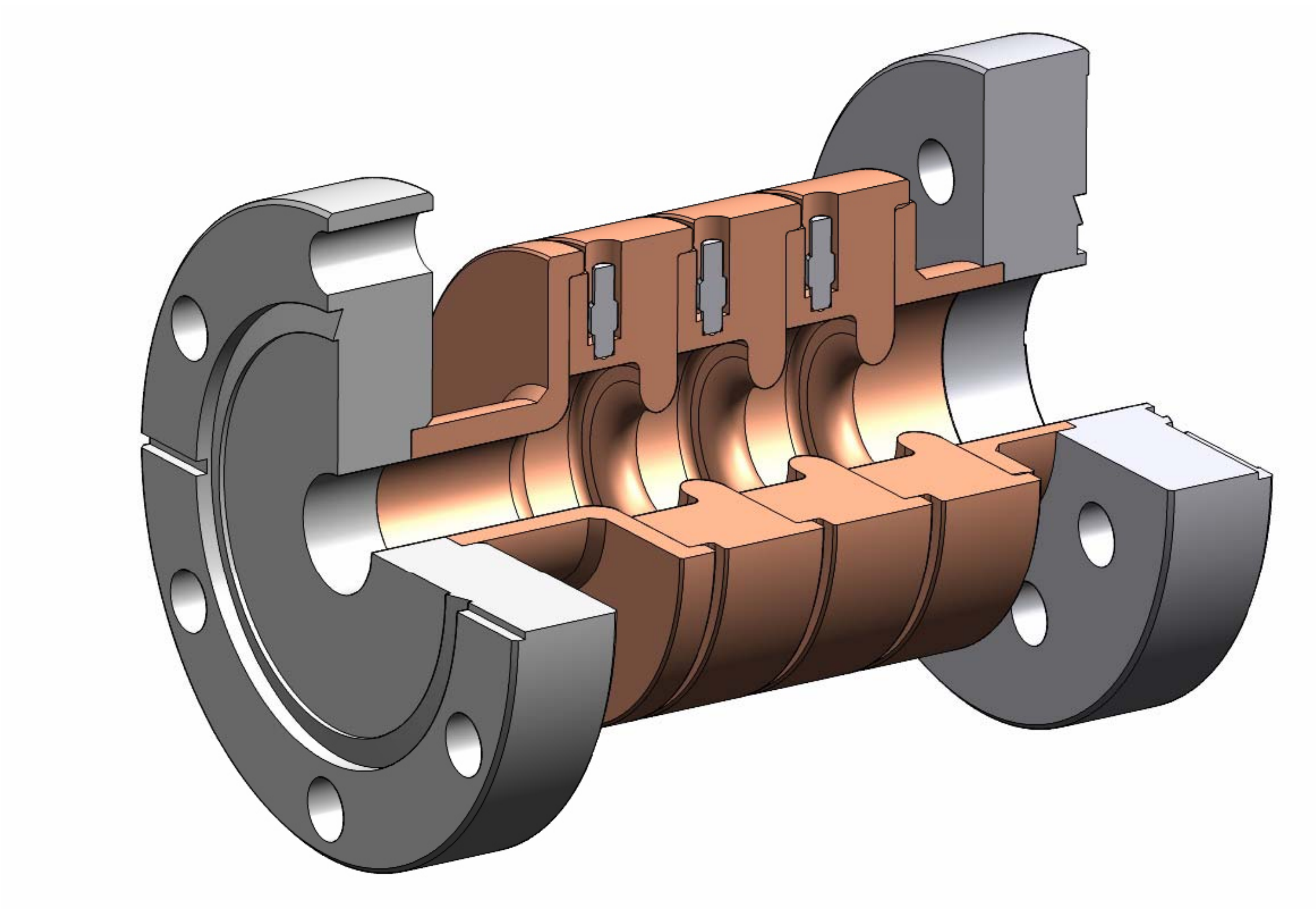
Surface electric fields in the final mode launcher E max.= 49 MV/m for 100 MW



Bead-pull measurements of single cell TW structure

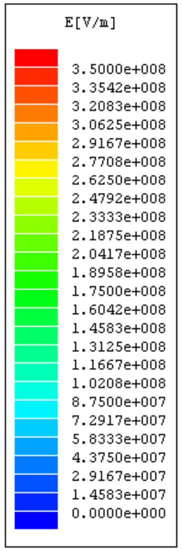
S .Tantawi, V. Dolgashev, C. Nantista (SLAC), Y.Higashi, T.Higo (KEK)

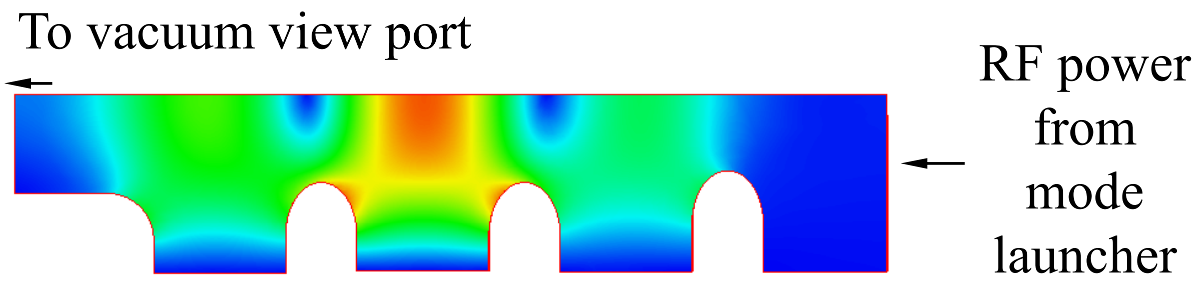
3D model of single cell SW structure



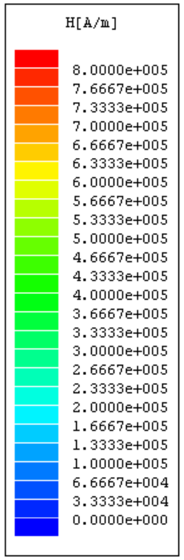
David Martin

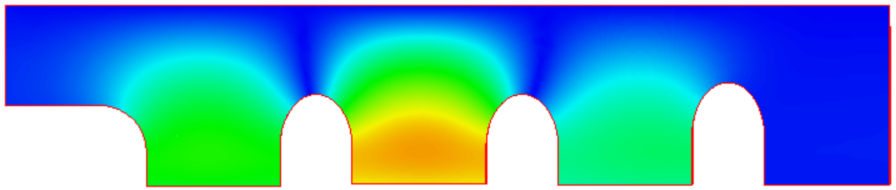
Single Cell Standing Wave Structure
HFSS Calculation





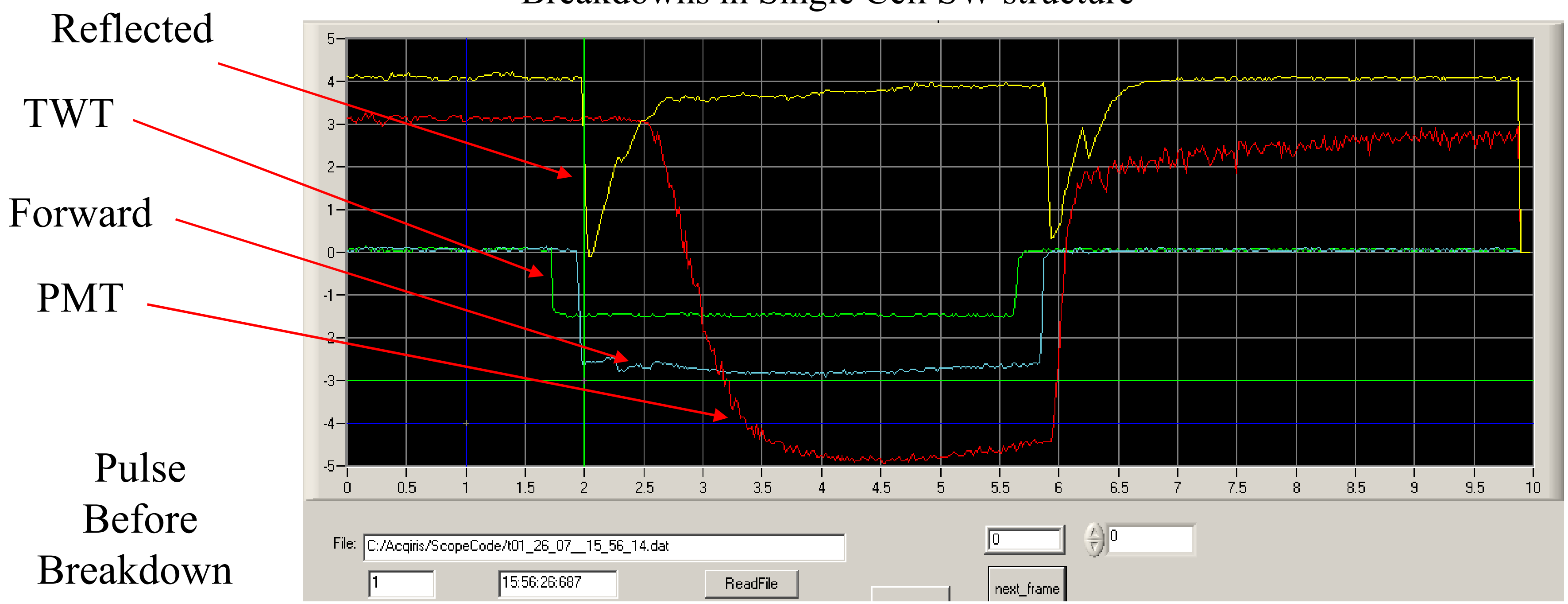
Amplitude of electric fields for 10 MW input power, maximum surface field 310 MV/m



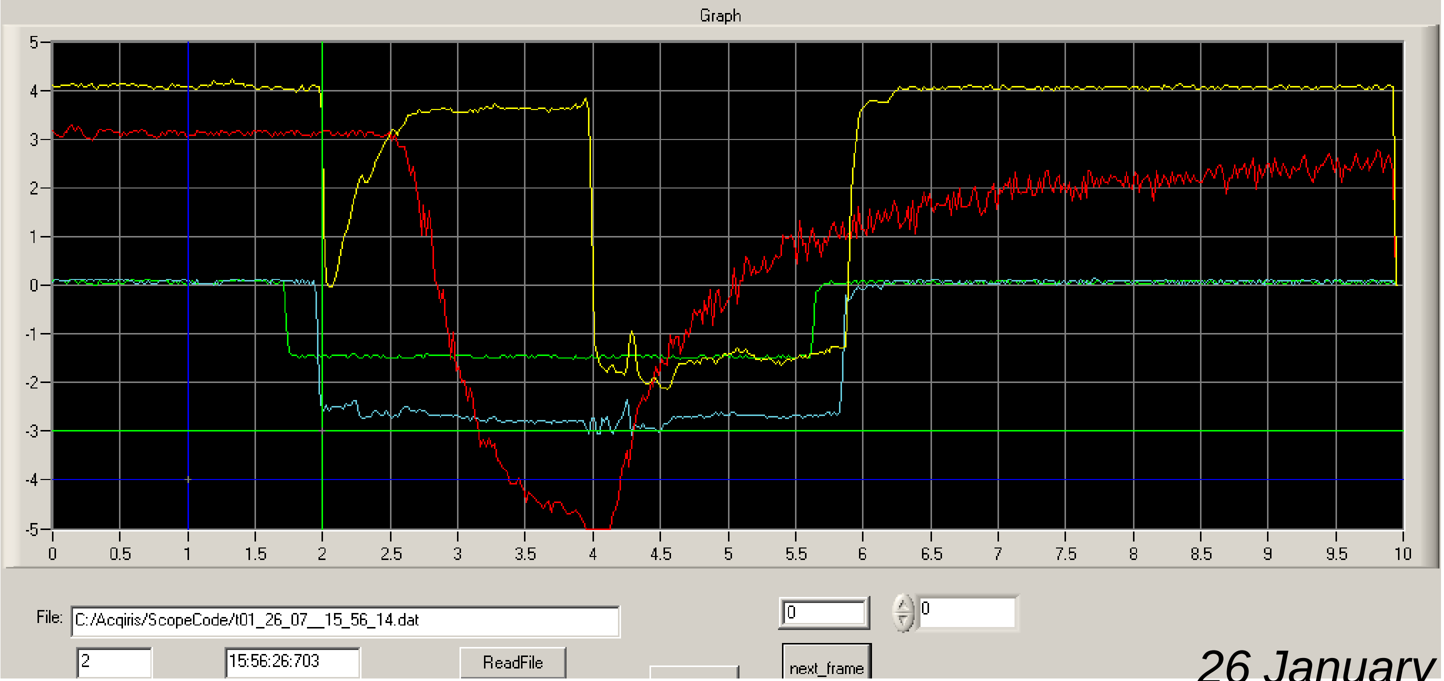


Amplitude of magnetic fields for 10 MW input power , maximum magnetic field 634.5 kA/m

Breakdowns in Single Cell SW structure

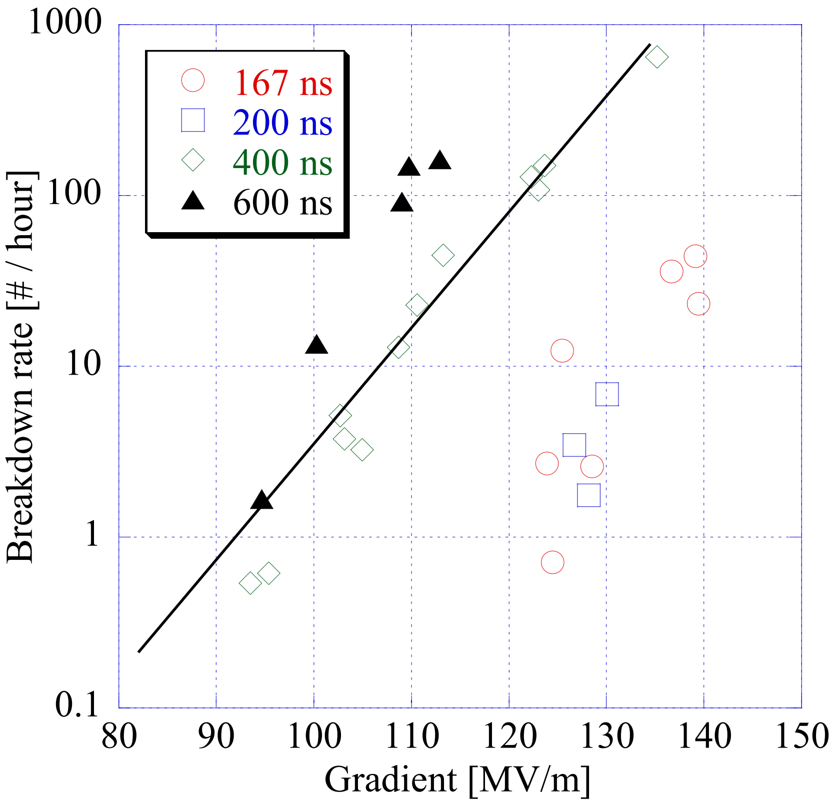


Pulse Before Breakdown

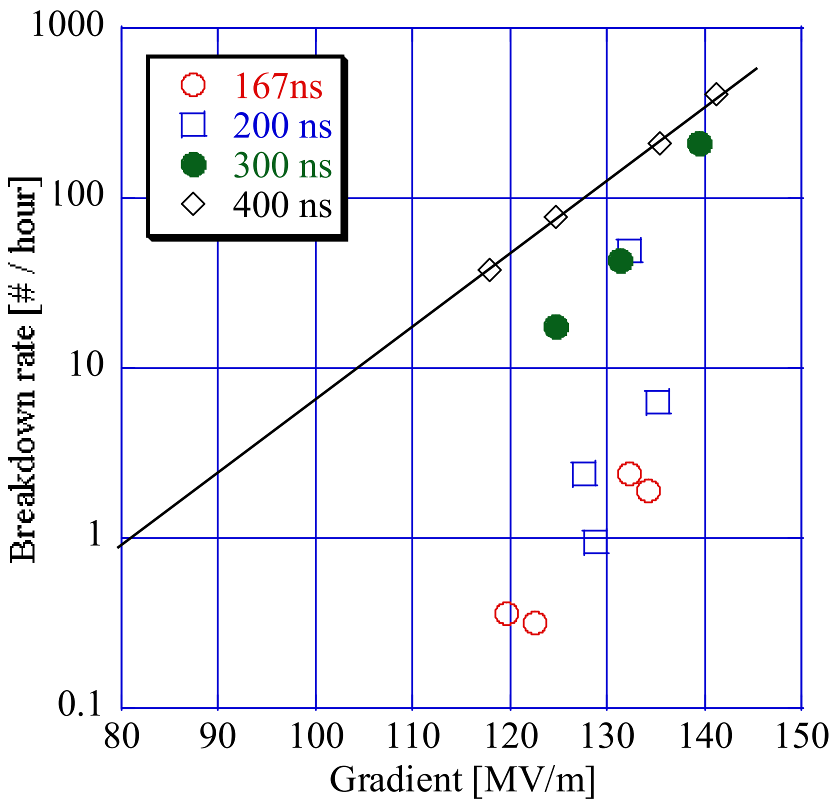


Breakdown

Breakdown rate *vs.* accelerating gradient, all breakdowns, standard pulse

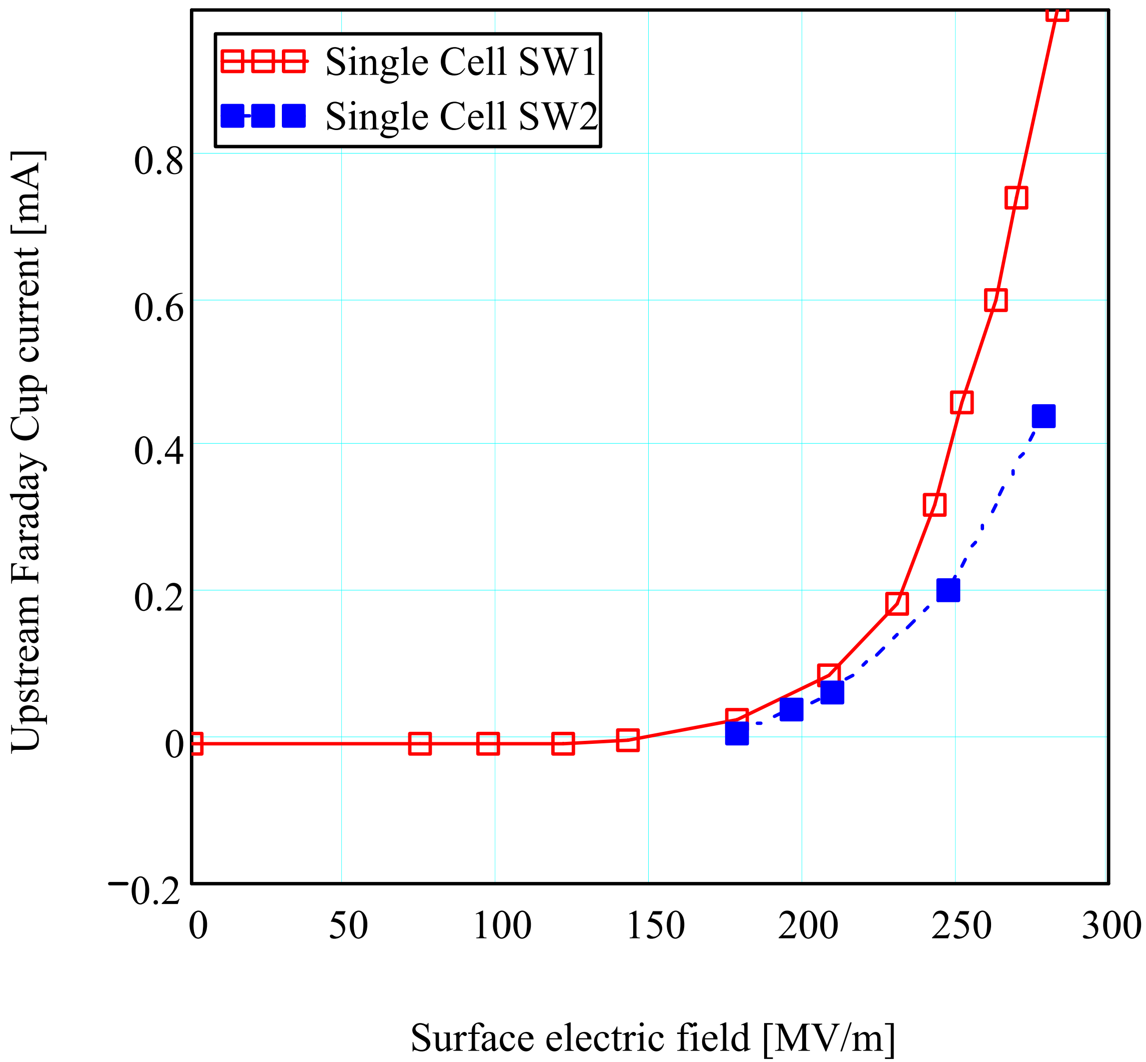


Single Cell SW1

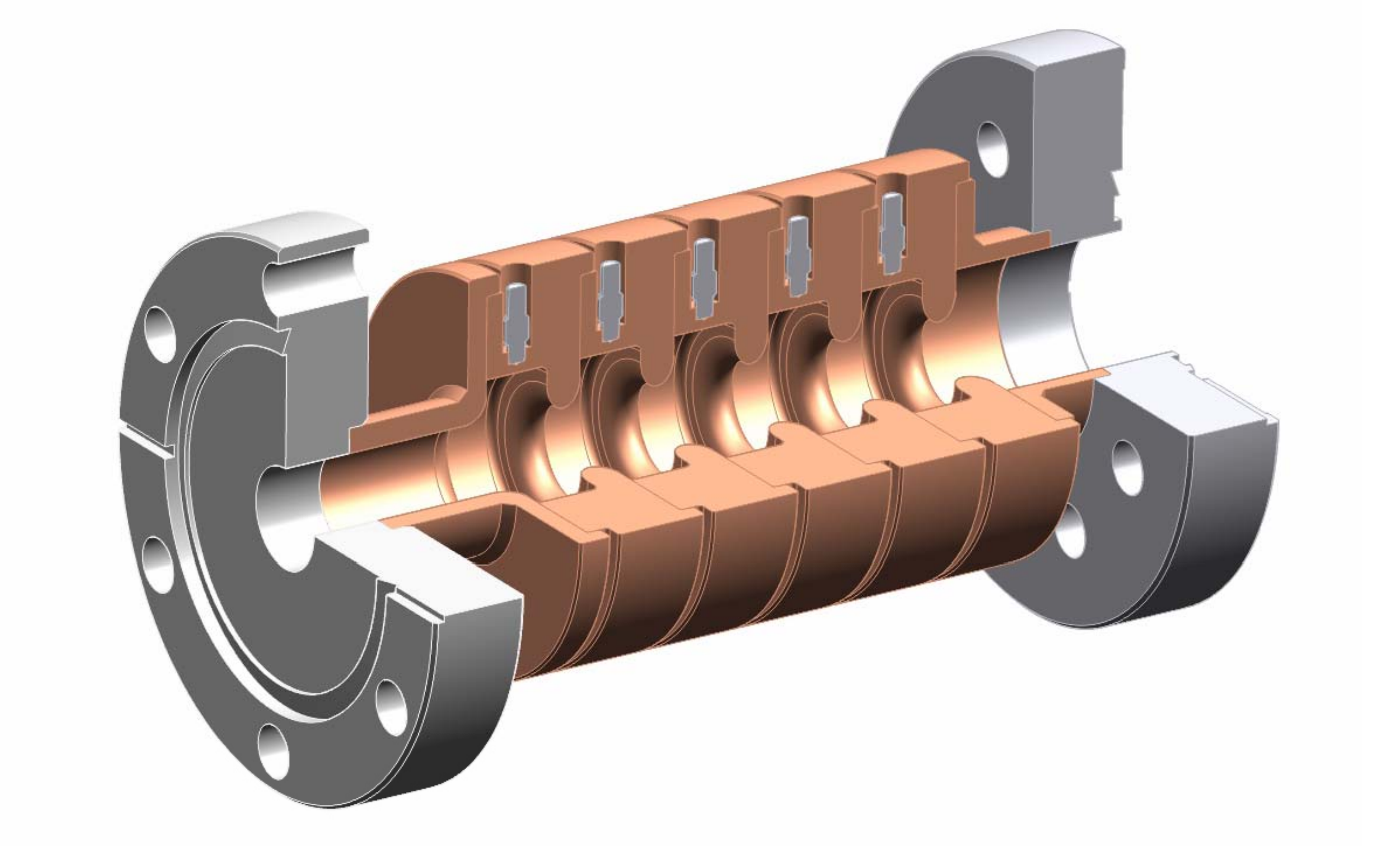


Single Cell SW2

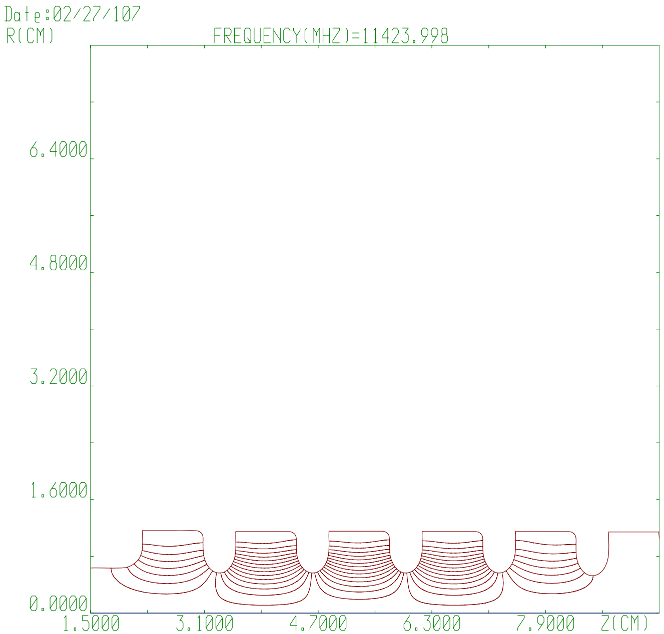
Dark current measured by upstream Faraday Cup at the end of processing of the Single Cell SW structures



3 Cell Standing Wave Structure



Tuned for **equal fields on the axis**, normalized for 10 MW losses, maximum electric field 230 MW/m; maximum magnetic field 4.57A/m



MODE	K**2	K(1/cm)	F(MHz)	EPS
3	5.23725E+00	2.28850E+00	1.09192E+04	2.46944E-05
4	5.33816E+00	2.31045E+00	1.10239E+04	1.32425E-05
5	5.45269E+00	2.33510E+00	1.11416E+04	2.80533E-05
6	5.62500E+00	2.37171E+00	1.13162E+04	9.89956E-06
7	5.73264E+00	2.39429E+00	**1.14240E+04**	5.10727E-05
10	1.60569E+01	4.00711E+00	1.91193E+04	1.14853E-02

S_matrix result:

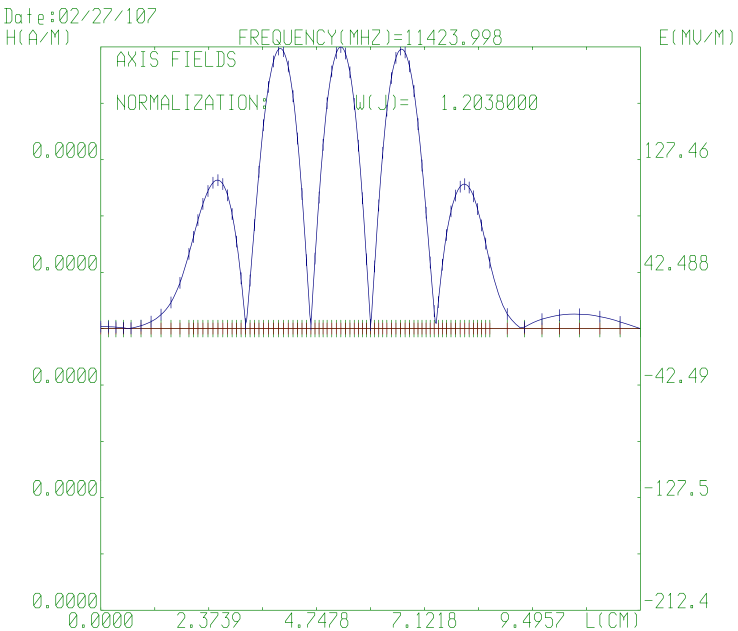
$$\text{Result} = \begin{pmatrix} 0.1378387906 \\ 1.1423912\times 10^{4} \\ 8.0388277901\times 10^{3} \end{pmatrix} \begin{matrix} \\ [\text{MHz}] \\ Q \end{matrix}$$

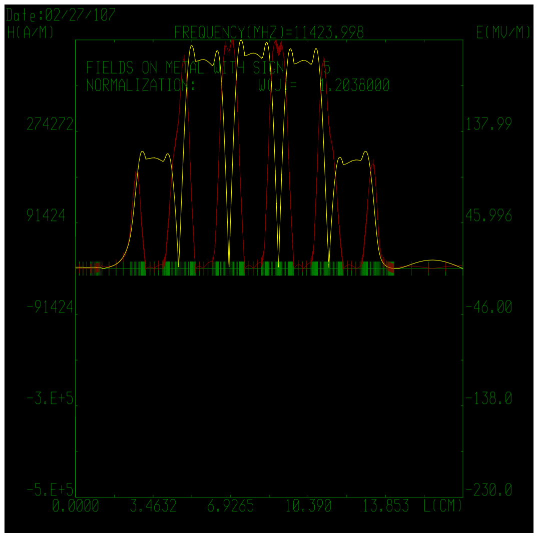
SLANS NUMBER OF MODE 7; ACCURACY 5.107E-06
CAVITY RADIUS 1.1621 CM, LENGTH 11.8696 CM
FREQUENCY .... 1.1424E+04 MHZ
LENGTH OF WAVE .... 2.62423 CM
WAVE VALUE 2.3942926 1/CM
QUALITY FACTOR .... 8.6412E+03
STORED ENERGY .... 1.2038E+00 J
TRANSIT TIME FACTOR .... -.6233E+02
EFFECTIVE IMPEDANCE .... 1.812E+02 OHM
SHUNT IMPEDANCE .... 1.56602 MOHM
MAXIMUM MAG. FIELD ..... 4.571E+05 A/M
NEAR POINT R= .990 CM , Z= 4.853 CM
MAXIMUM ELEC.FIELD ..... 2.300E+02 MV/M
NEAR POINT R= .628 CM , Z= 4.757 CM
ACCELERATION .... 5.596E+00 MEV
ACCELERATION RATE ...... 4.715E+01 MEV/M
AVERAGE E.FIELD ON AXIS 7.564E-01 MV/M
KM (Emax/Accel.rate).... 4.87775
KH (Hmax*Z0/Accel.rate). 3.65253

Q_s_matrix/Q_copper

$$\left(\frac{8038.8}{8641.2}\right)^{-1} = 1.075$$

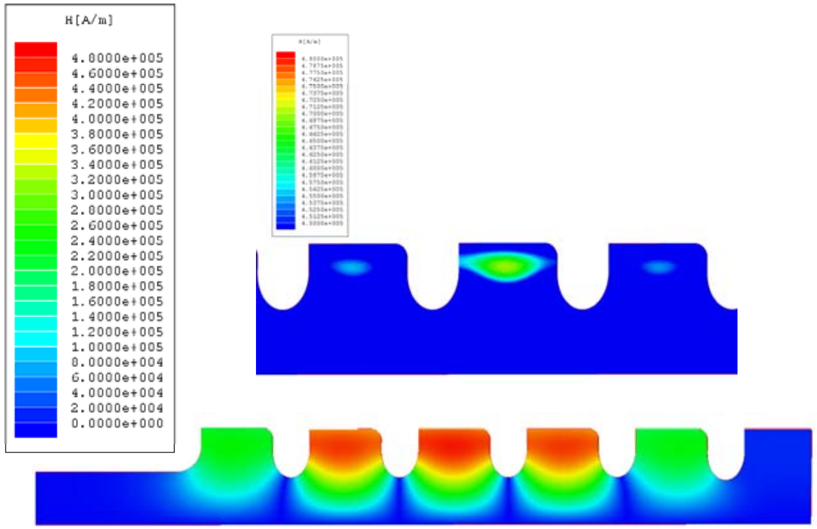
SLANS geometry file:sw3cl_cu.ge0



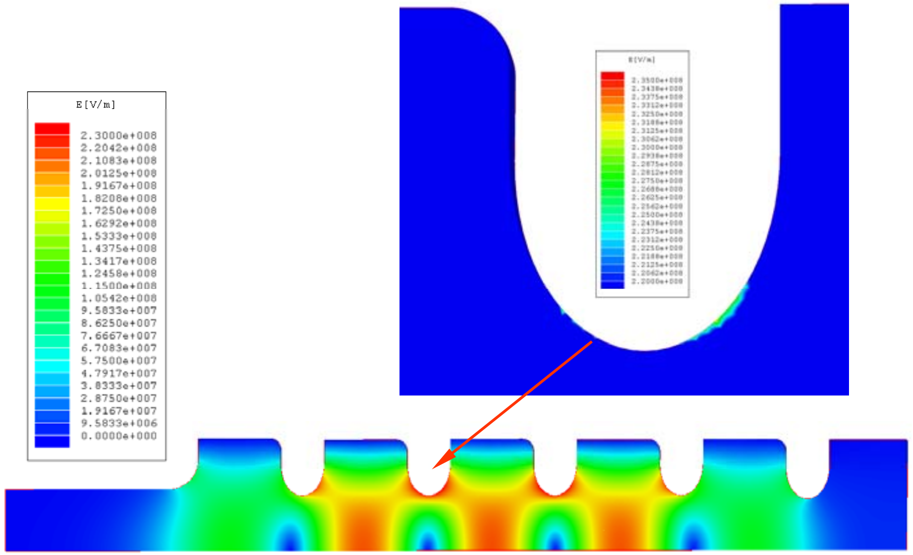


V.A. Dolgashev 27 February 2007, 17:07

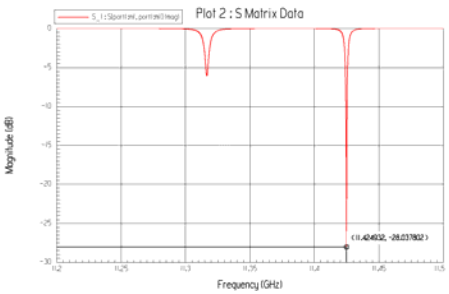
Verification of SLANS results with HFSS, 10 MW input



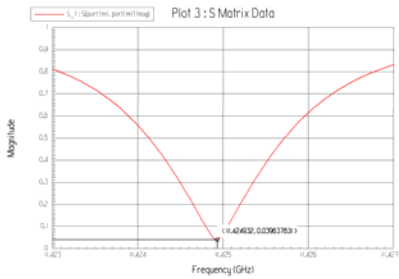
Maximum magnetic field 458 kA/m
(SLANS 457 kA/m)



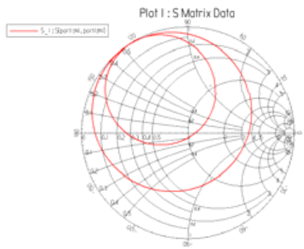
Maximum magnetic field 230 MV/m
(SLANS 230 MV/m)

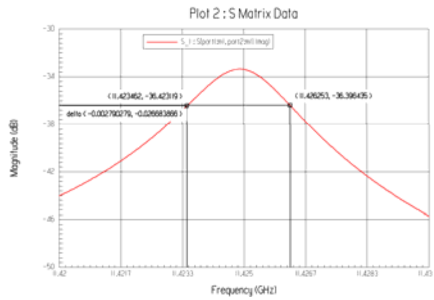


Resonance at 11.4249 GHz
(SLANS 11.424 GHz)



$\beta = 1.083$
(SLANS 1.075)





Over-coupled loaded Q

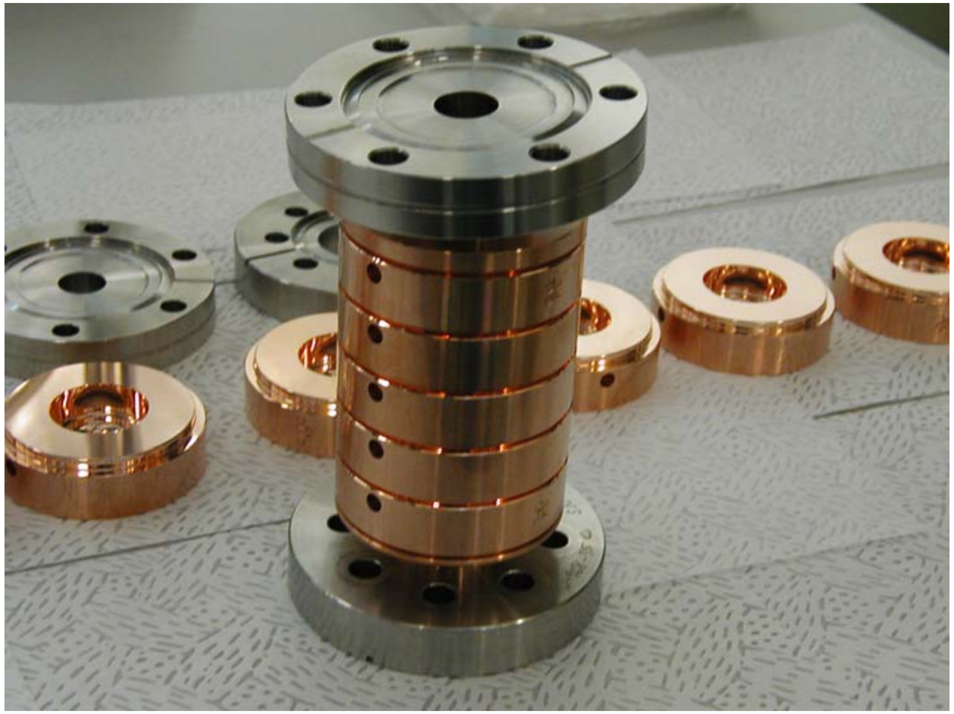
$$\frac{11.4249}{0.00279027} = 4.095\times 10^{3}$$

Unloaded Q
(SLANS 8.64e3)

$$4.095(1 + 1.083)\cdot 10^{3} = 8.53\times 10^{3}$$

V.A. Dolgashev, 2 March 2007

Manufacturing of 3-cell SW structure at KEK



Yasuo Higashi, KEK

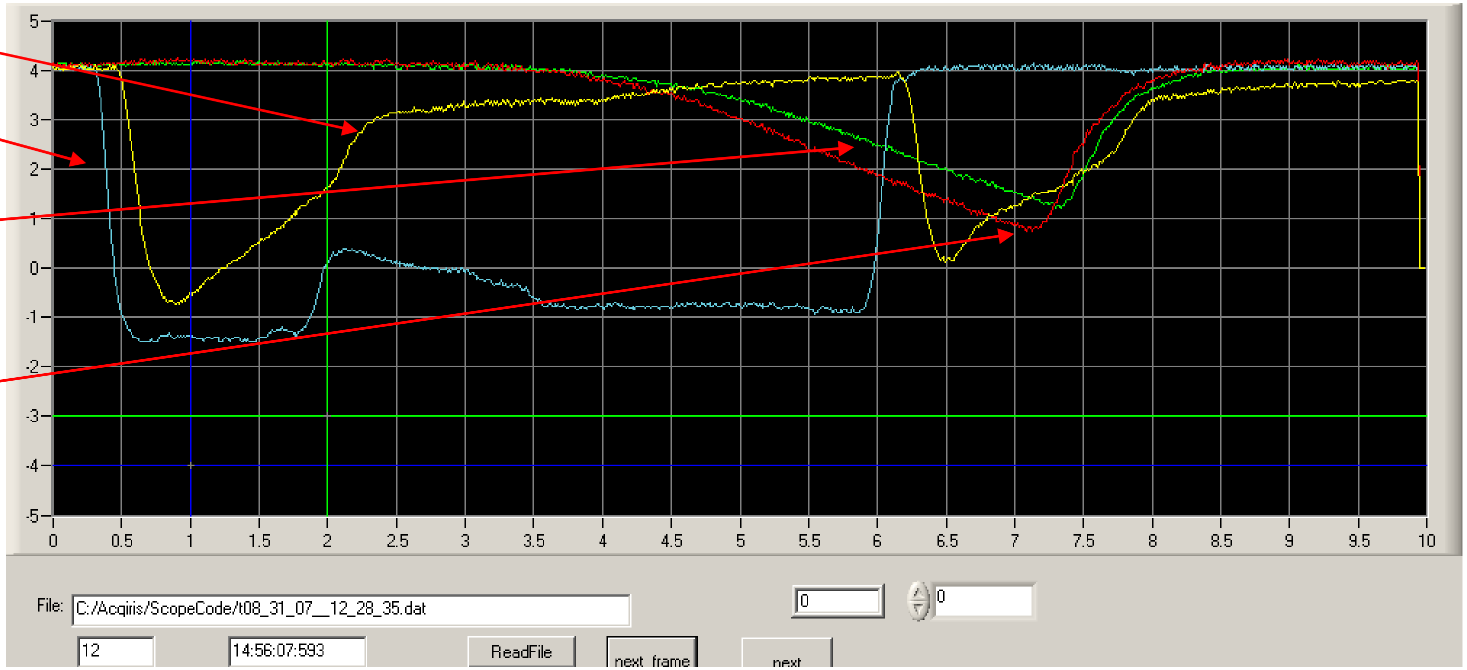
Breakdowns in 3-Cell Cell SW structure, pulse length 300 ns

Reflected

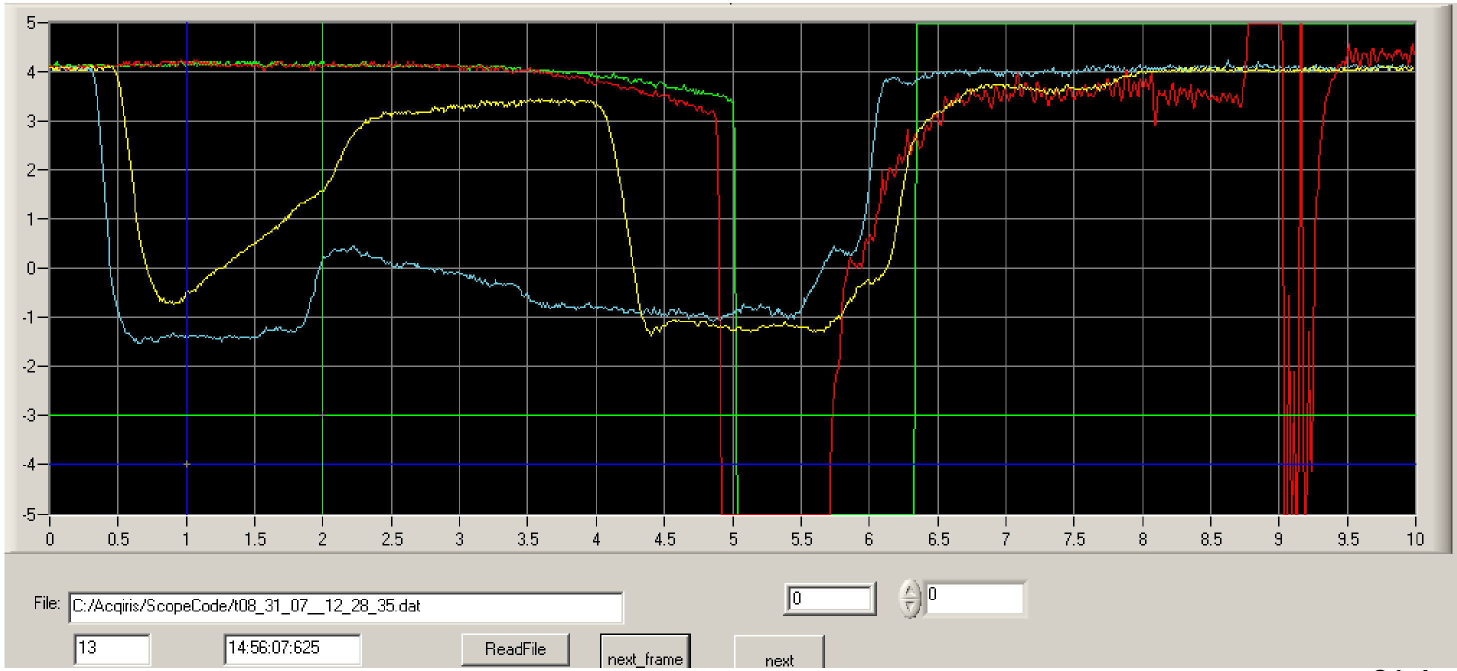
Forward

Upstream Faraday Cup

Downstream Faraday Cup



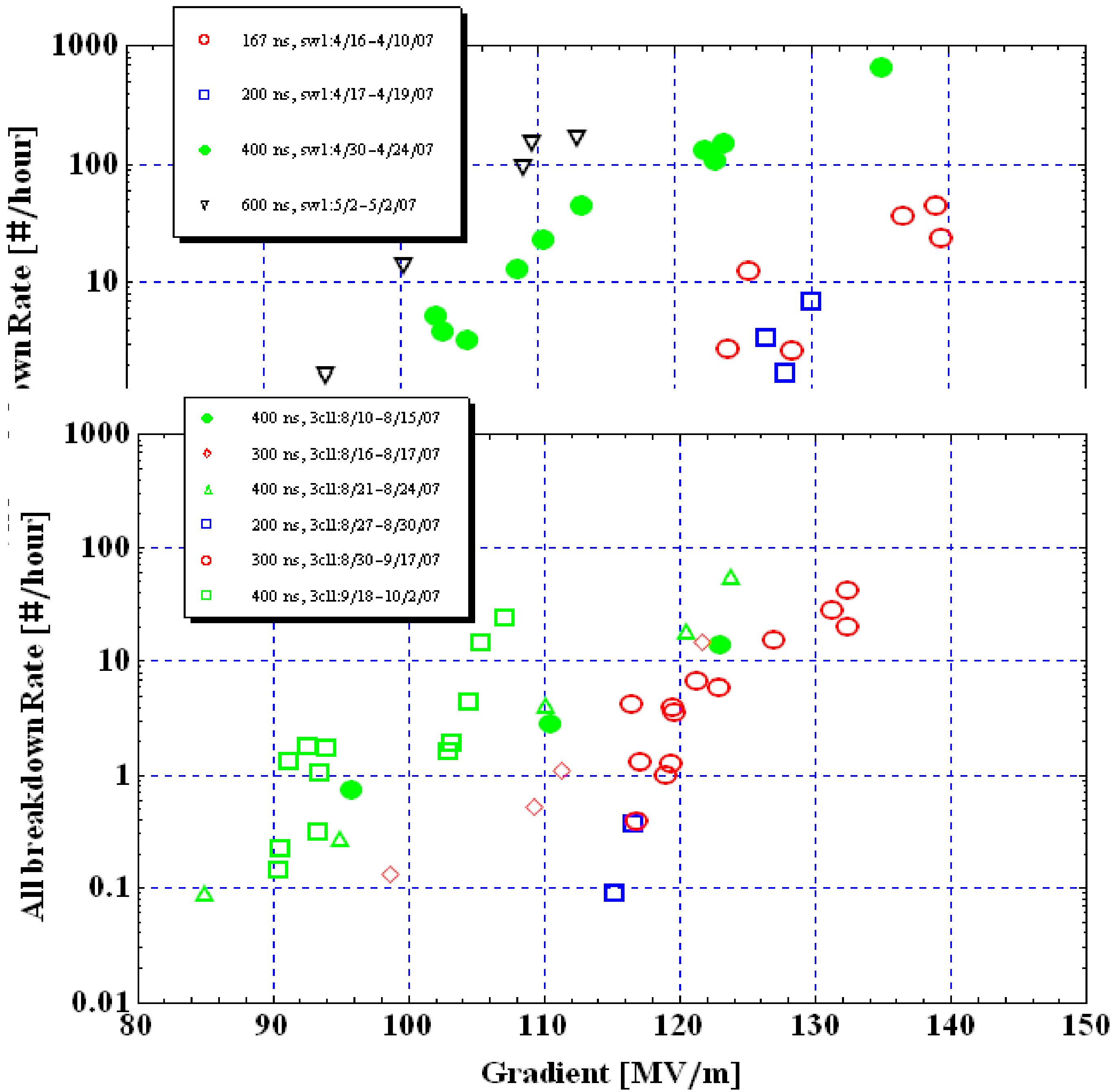
Pulse Before Breakdown



Breakdown

31 August 07

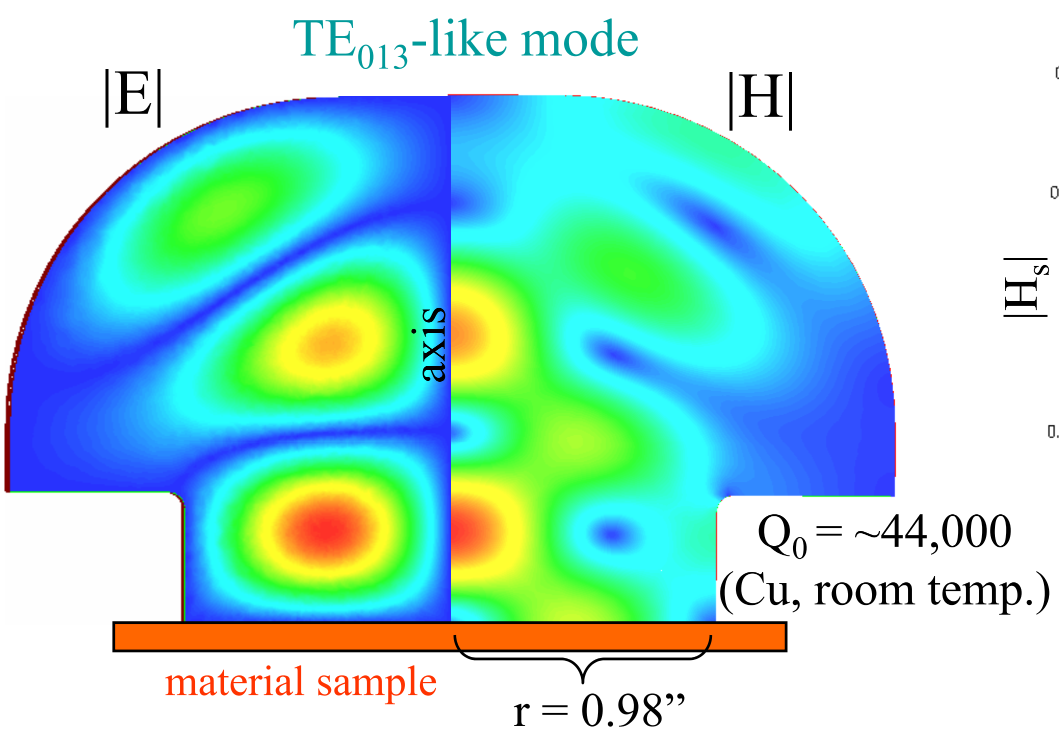
Breakdown rate *vs.* accelerating gradient (a/λ~0.2)

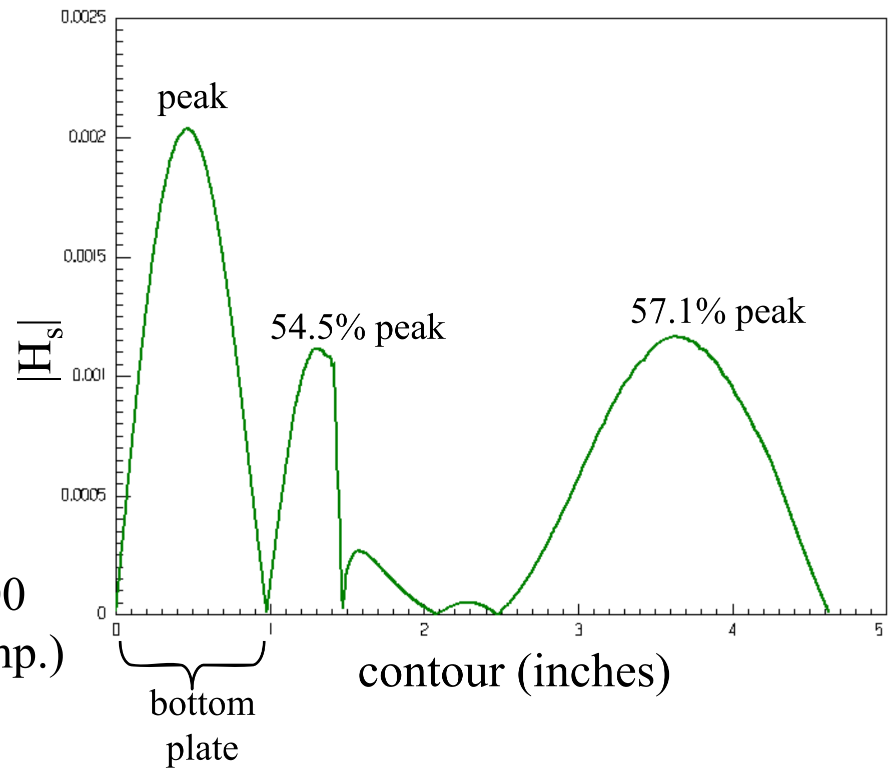


Single cell
SW1

3 cell SW

The Mushroom Cavity





<u>Why X-band</u> (~11.424 GHz)?:

- •high power & rf components available
- •fits in cryogenic dewar
- •small (3") samples required

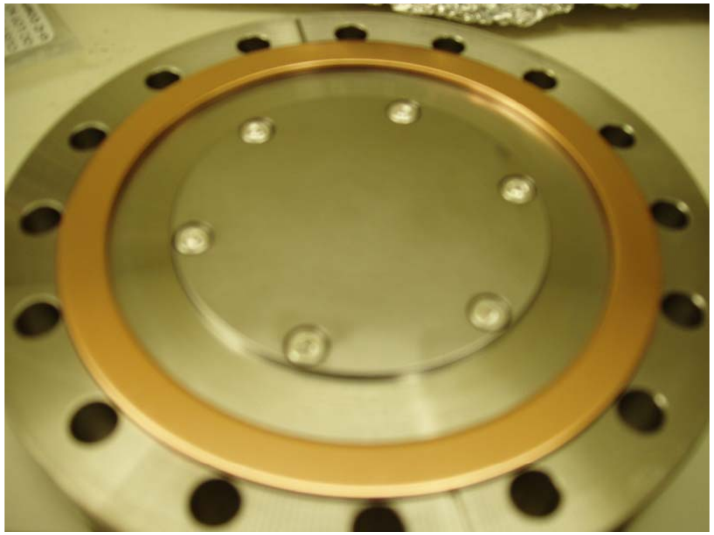
<u>Features:</u>

•No surface electric fields (no multipactor)

•Magnetic field concentrated on bottom (sample) face (75% higher than anywhere else)

•Purely azimuthal currents allow demountable bottom face (gap).

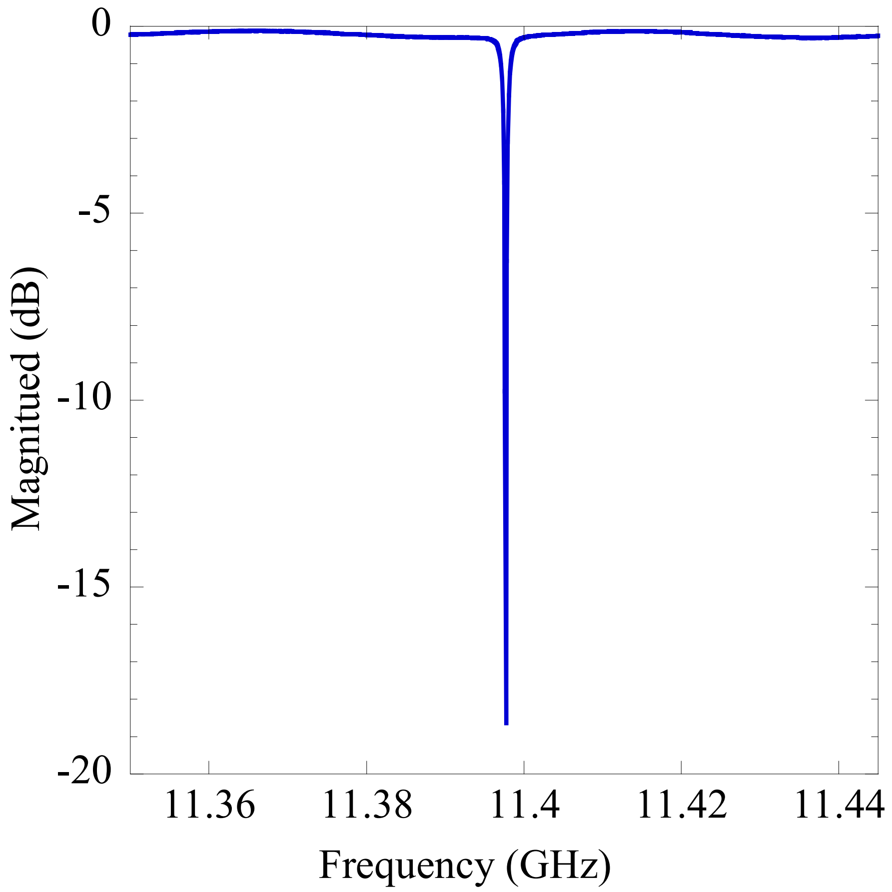
Pulsed Heating Cavity

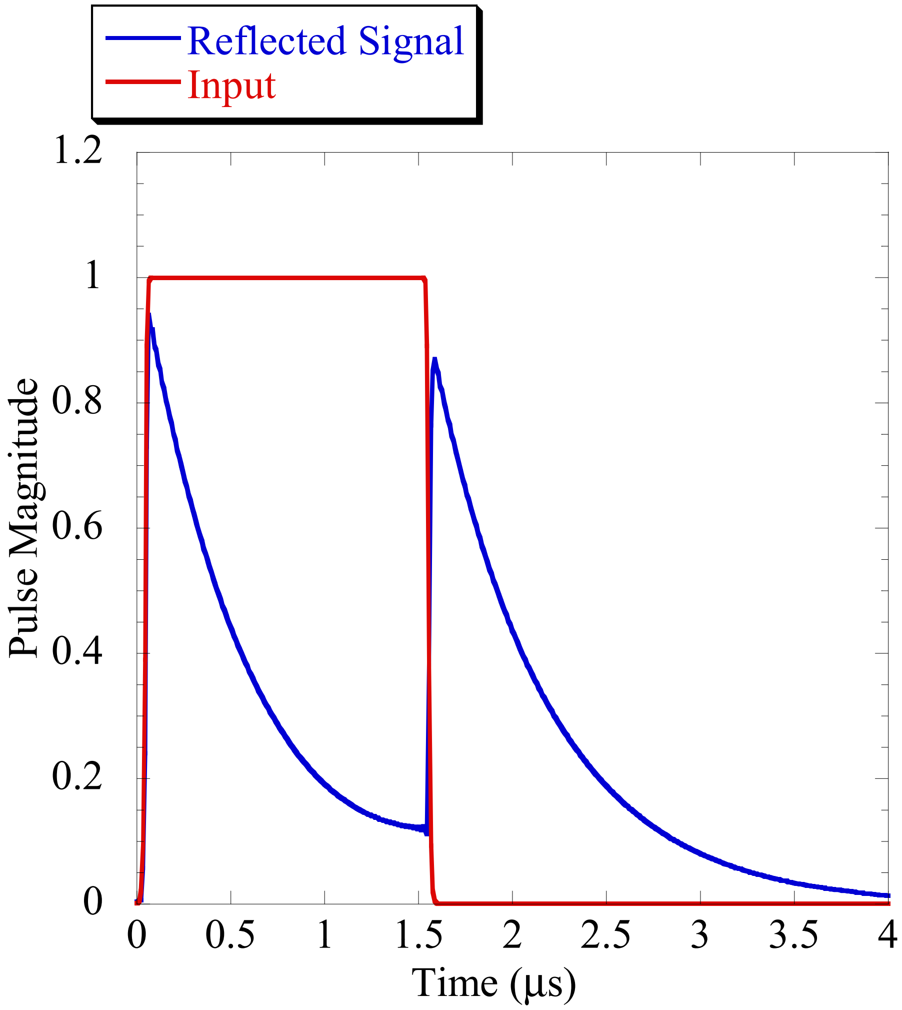


Nb sample mounted in bottom flange

HP 8510C Network Analyzer

Pulsed Heating Copper Sample

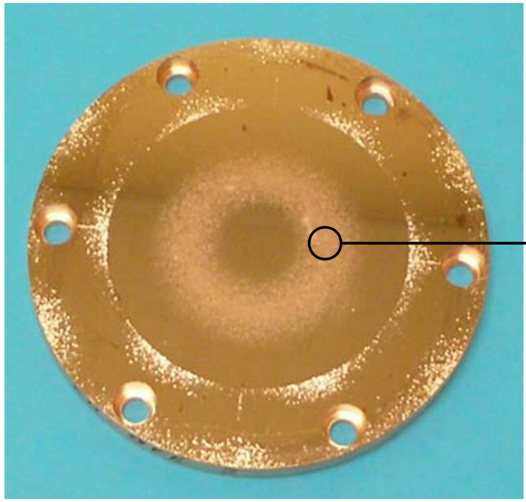




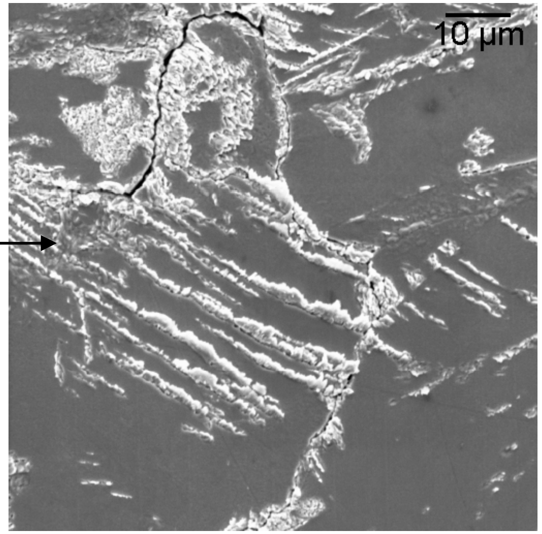
High Power Tests

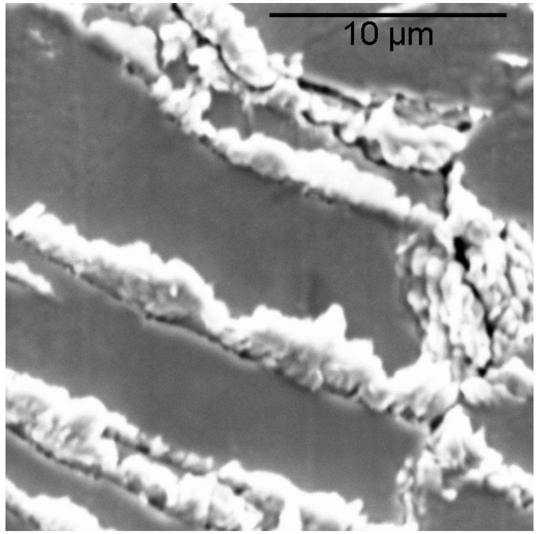
- Anomalies
  - Resonant Frequency increases as the cavity gets hot then decreases.
  - Q factor drops from 45000 to ~27000 over long period of time and then recovers when the cavity is off for about ~ 3 hour.
  - Cavity exhibits gas bursts similar to that of breakdown phenomenon.
- Thermo-mechanical analysis is needed

Pulsed Heating Experiments



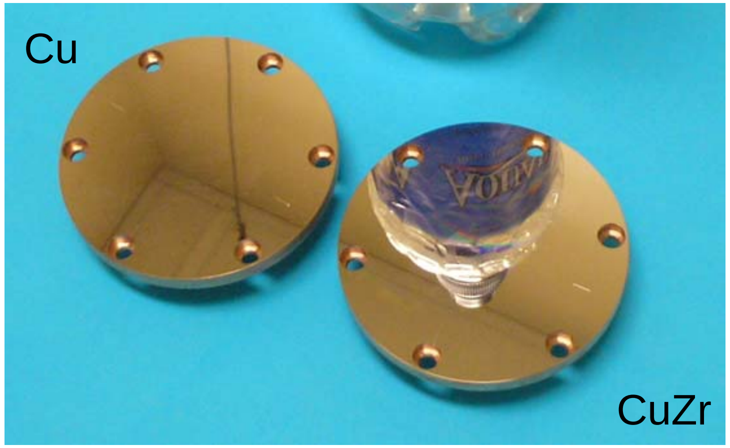
Photograph of pulse heating sample Cu OFE 2 after rf processing



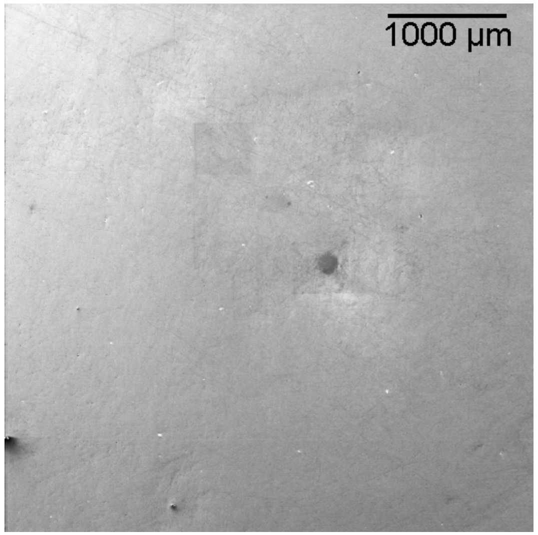


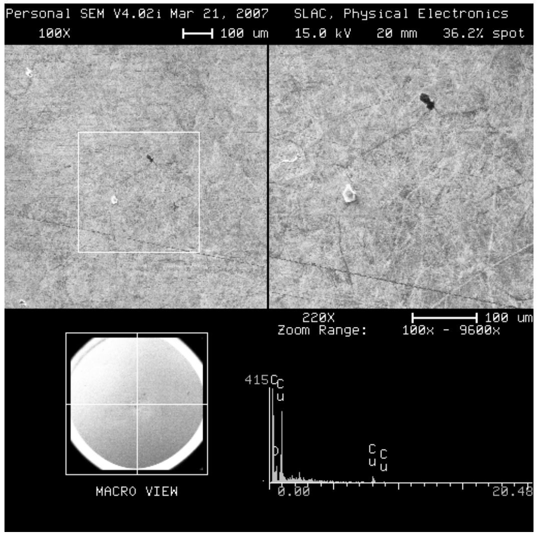
SEM image showing large amounts of copper has apparently erupted through the cracks.

Pulsed Heating Experiments



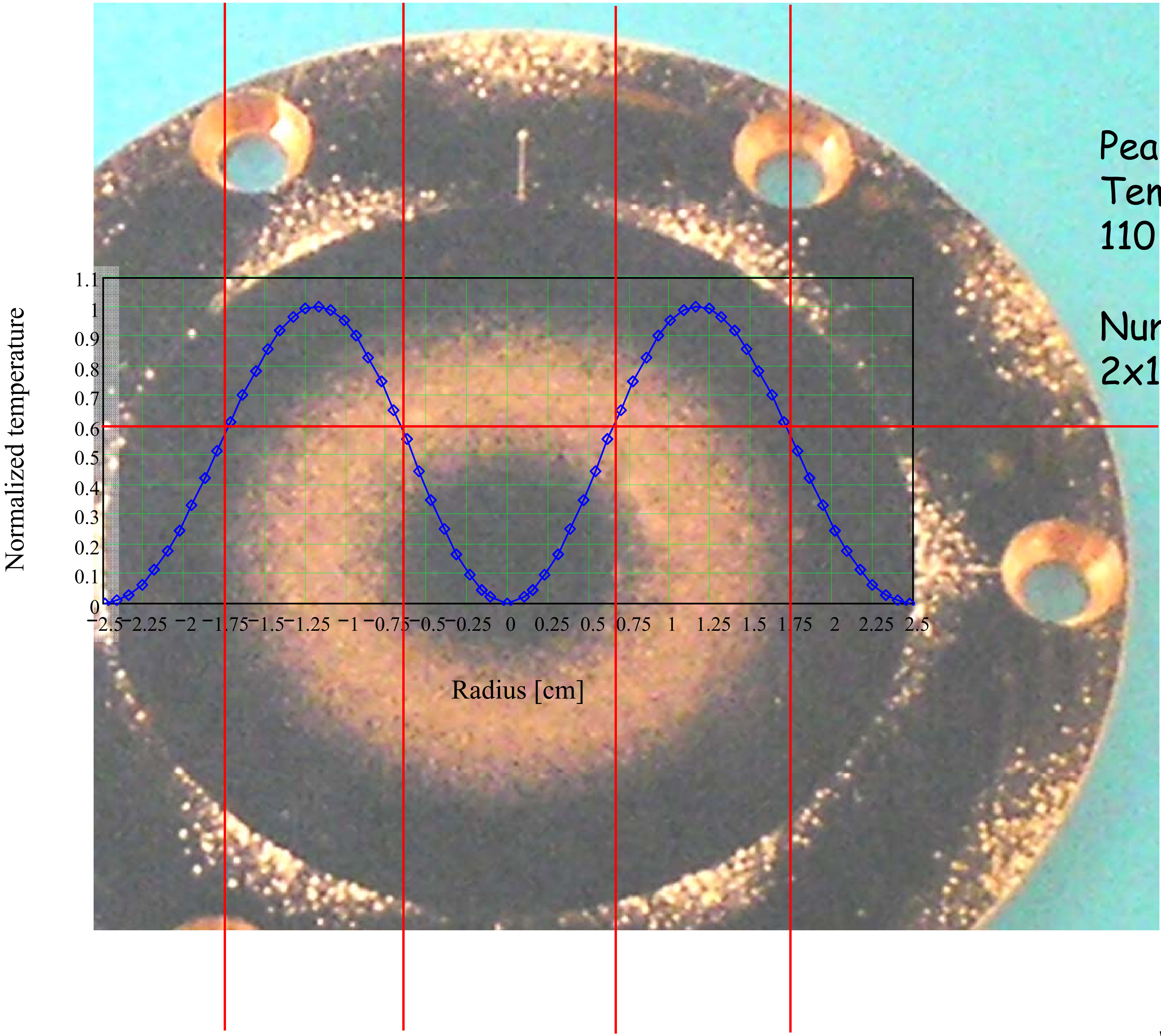
Digital picture of copper and copper zirconium sample before rf processing





SEM images prior to rf processing (center of sample). Dark spot at center is carbon

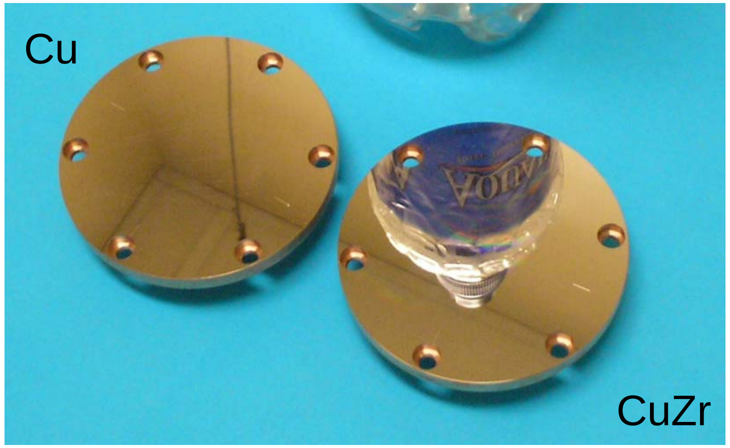
Pulse heating temperature and visible damage



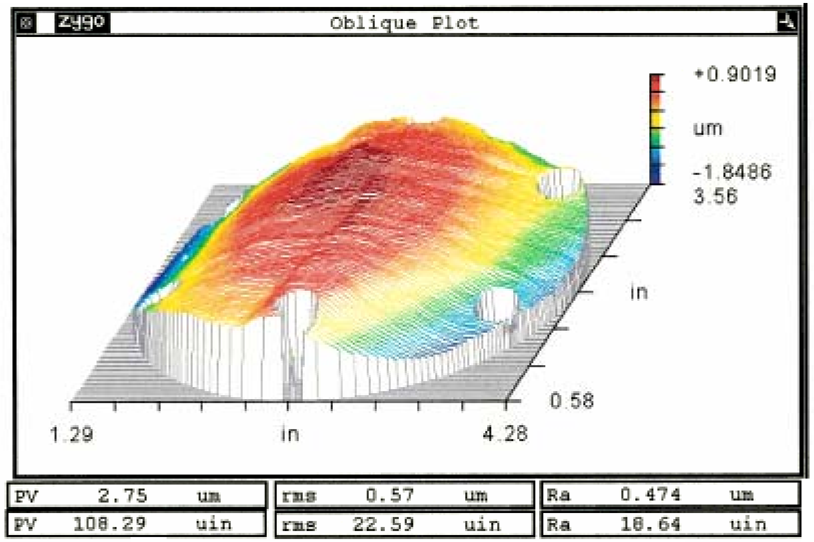
Peak transient
Temperature rise
110 degree Celsius

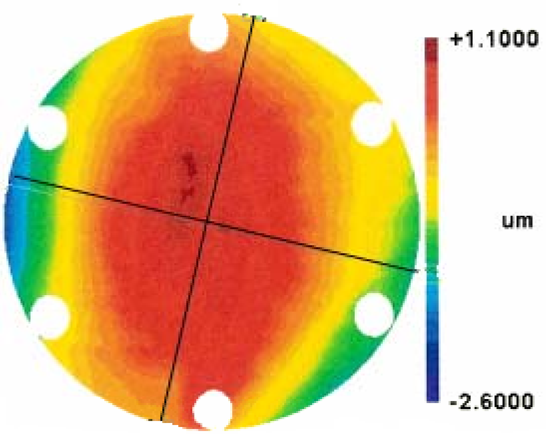
Number of pulses
2×10^6

Pulse Heating Experiment: Cu and CuZr



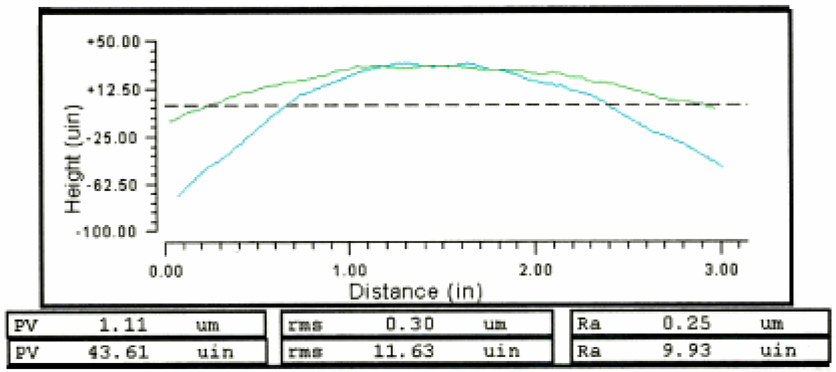
Surface Profilometry: Copper



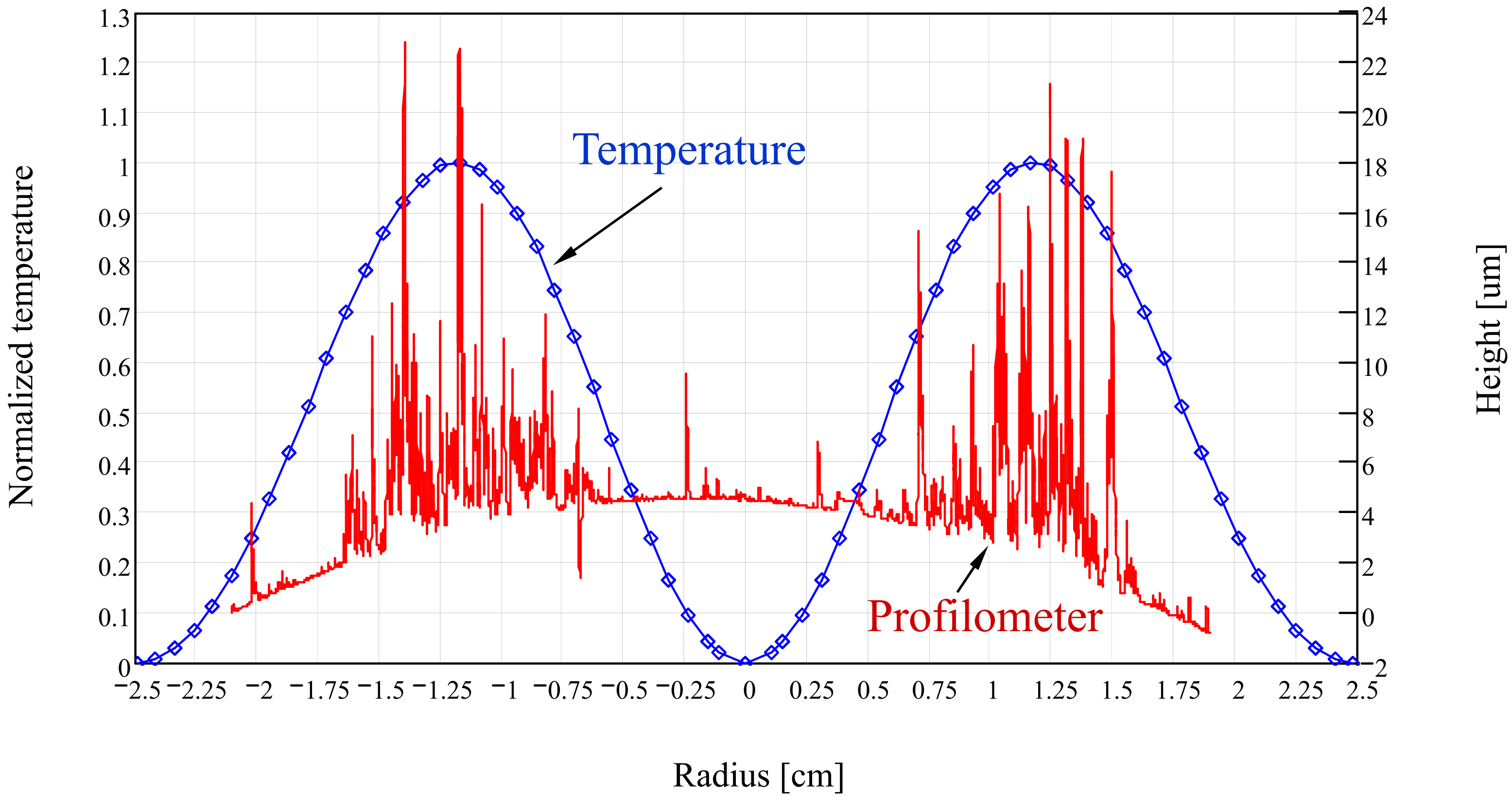


Cross Section

Surface Profile



Stylus profilometer data and normalized pulse heating temperature, pulse heating experiment, first copper sample

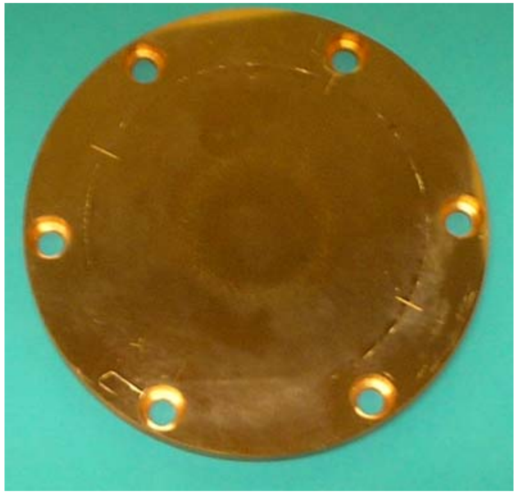


Profilometer data – Lisa Laurent

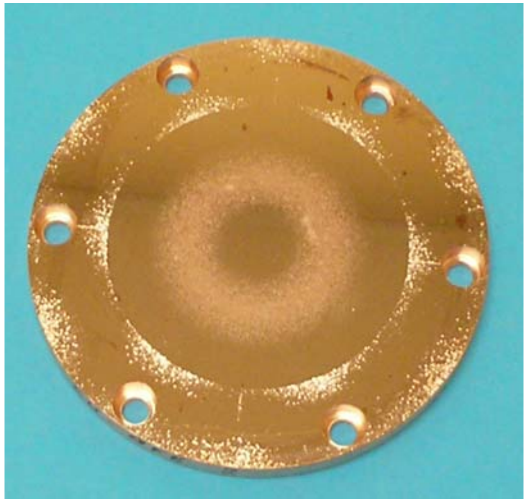
11 October 2007

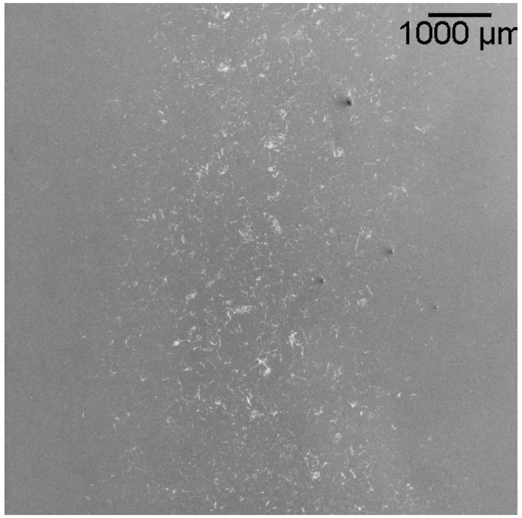
Pulse Heating Samples After RF Test

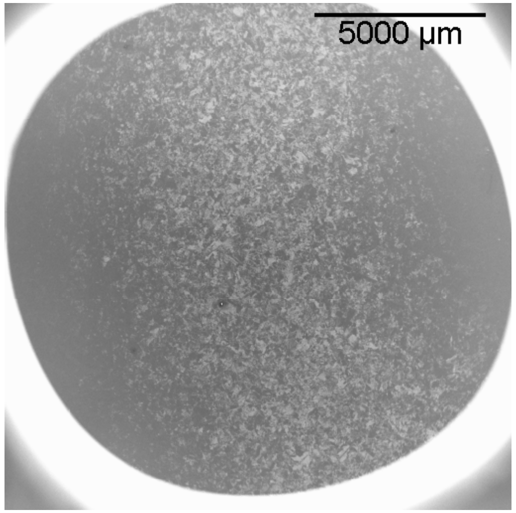
OFE_Cu1



OFE_Cu2

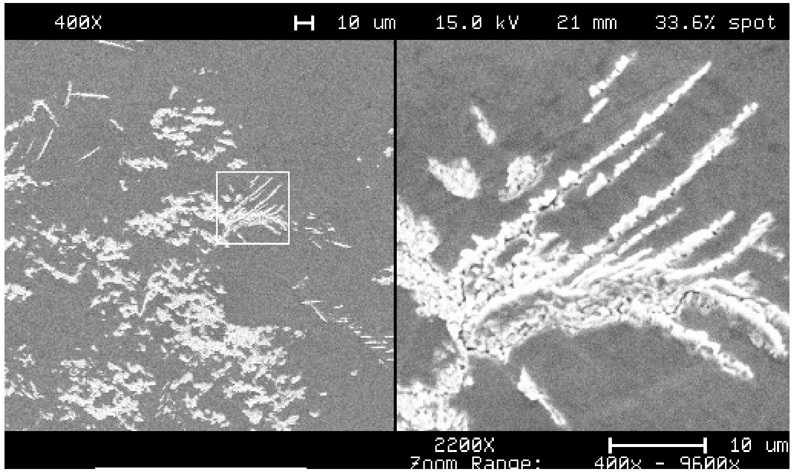


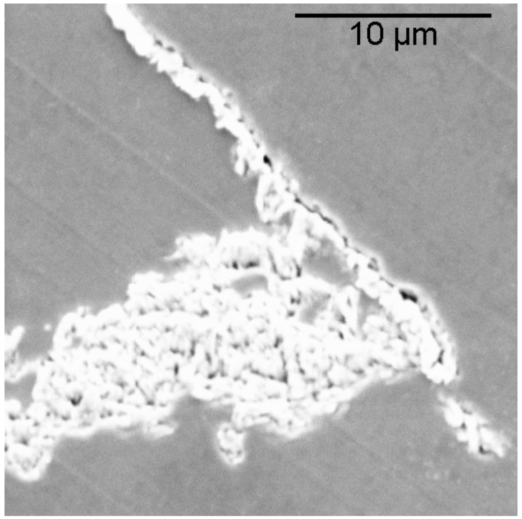


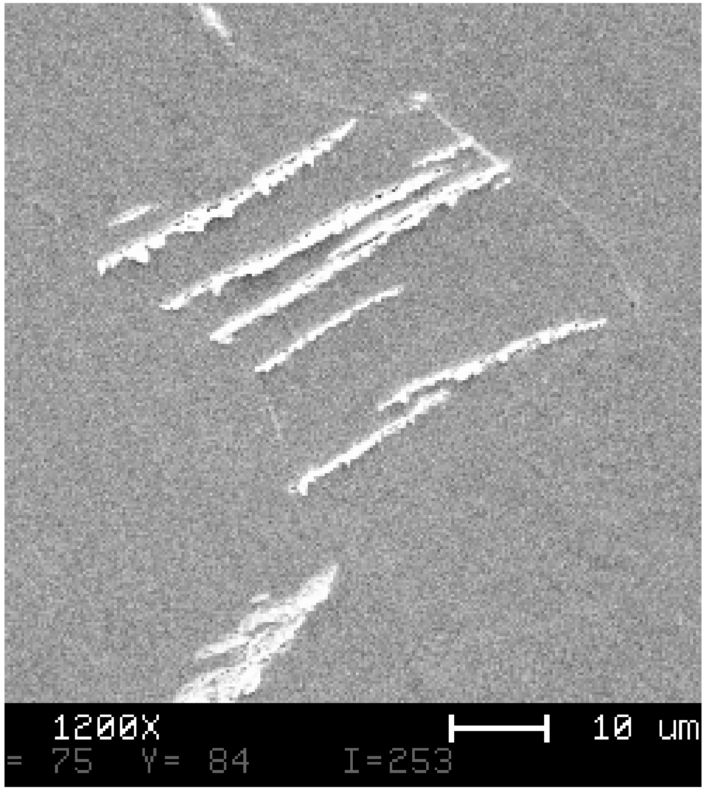


Low magnification SEM Images showing approximate width of pulse heating ring

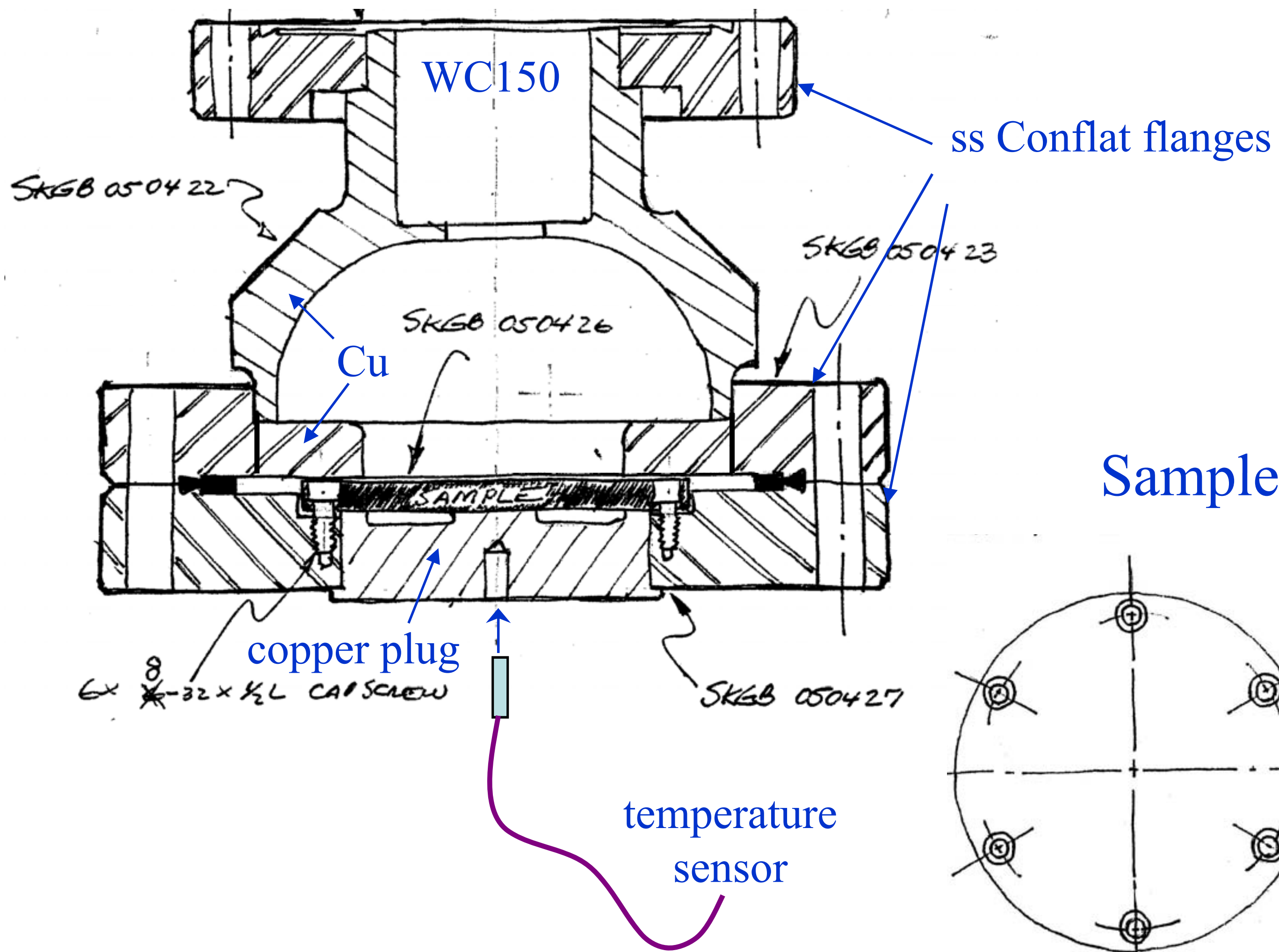
SEM Images of Pulse Heating Sample OFE_Cu1 After RF Test



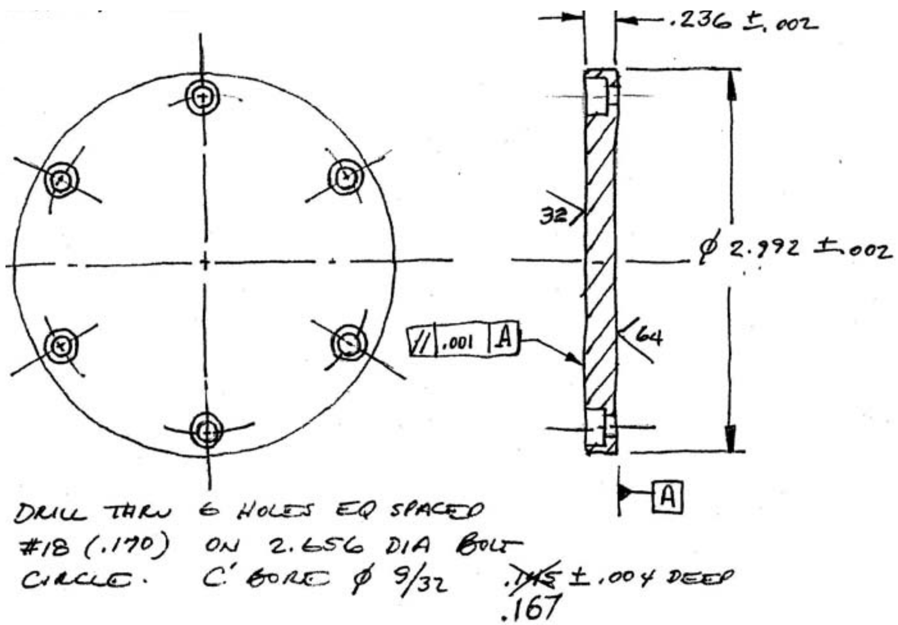




Mechanical Design



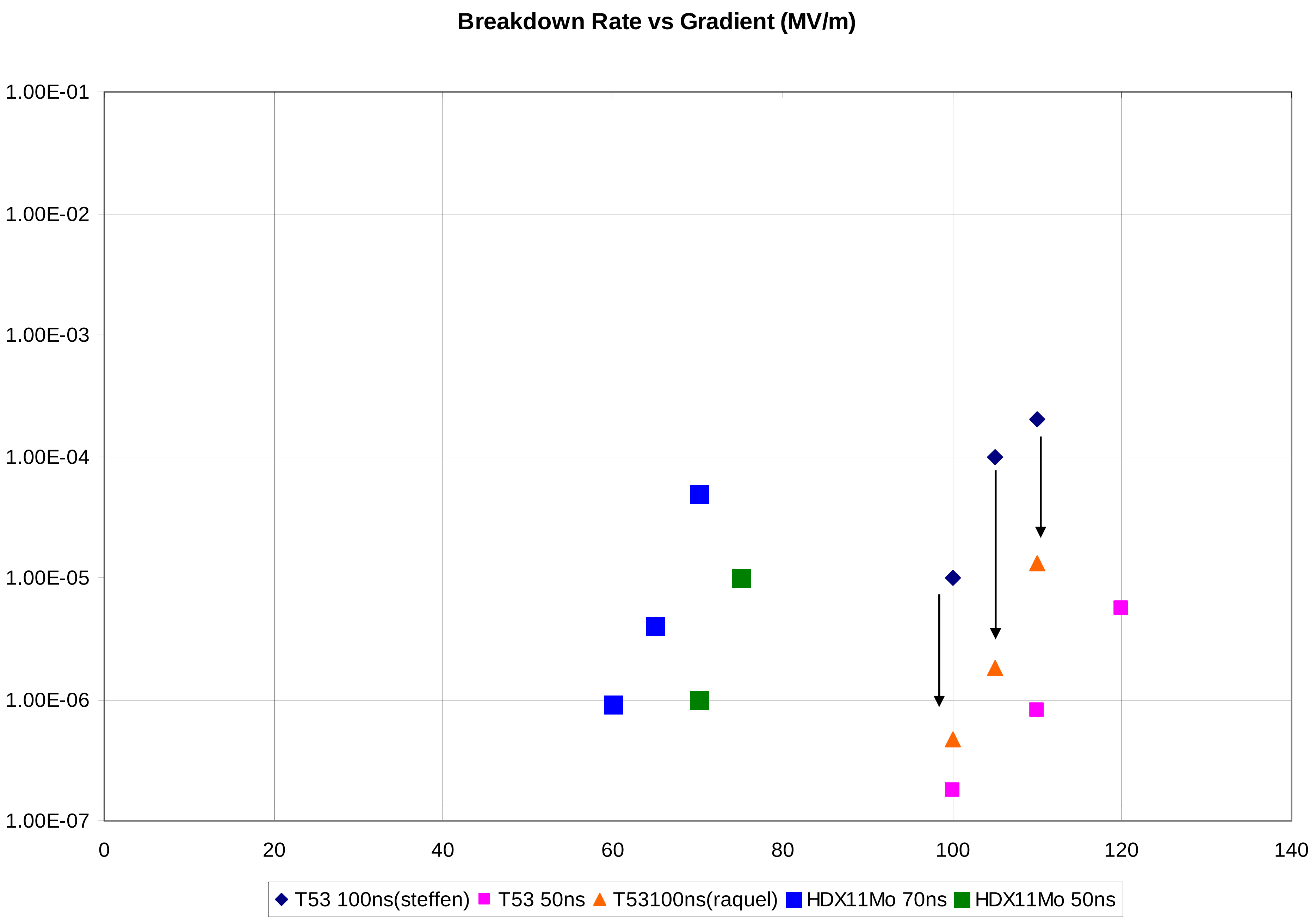
Sample Dimensions



G. Bowden

Four Quadrants of a Novel Structure Design Developed by the CLIC group at CERN

(X-band version being Tested at NLCTA)



Breakdown Rate vs Gradient (MV/m)
1.00E-01
1.00E-02
1.00E-03
1.00E-04
1.00E-05
1.00E-06
1.00E-07
0
20
40
60
80
100
120
140
T53 100ns(steffen)
T53 50ns
T53100ns(raquel)
HDX11Mo 70ns
HDX11Mo 50ns

Summary of Structure Testing Results

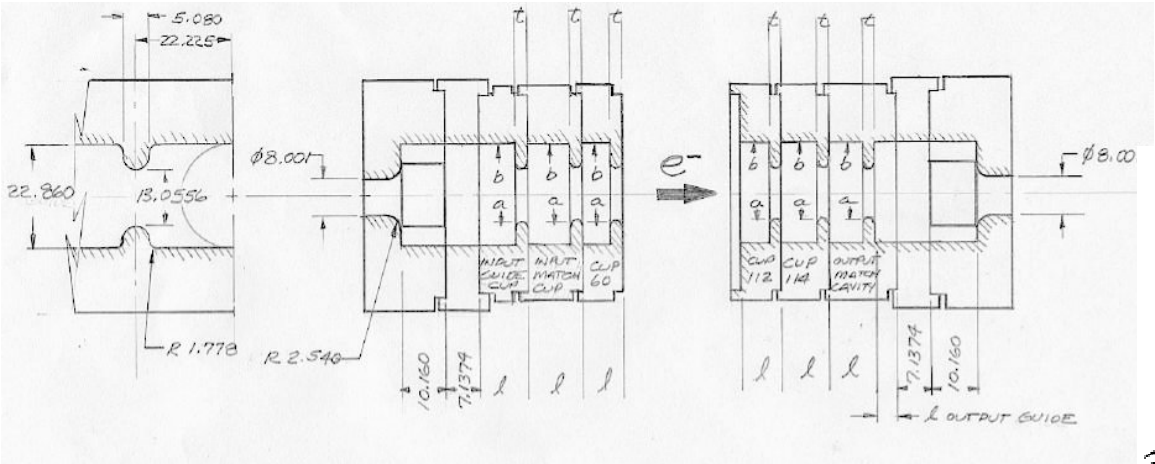
- Standing wave structure > 100 MV/m for very low breakdown rate at 100 ns flat pulse width after the filling time (equivalent 180 ns for TW structures) $a/\lambda \sim 0.21$

- H75vg4S18, it is < unity at 94 MV/m with 150 ns pulses. $a/\lambda \sim 0.17$

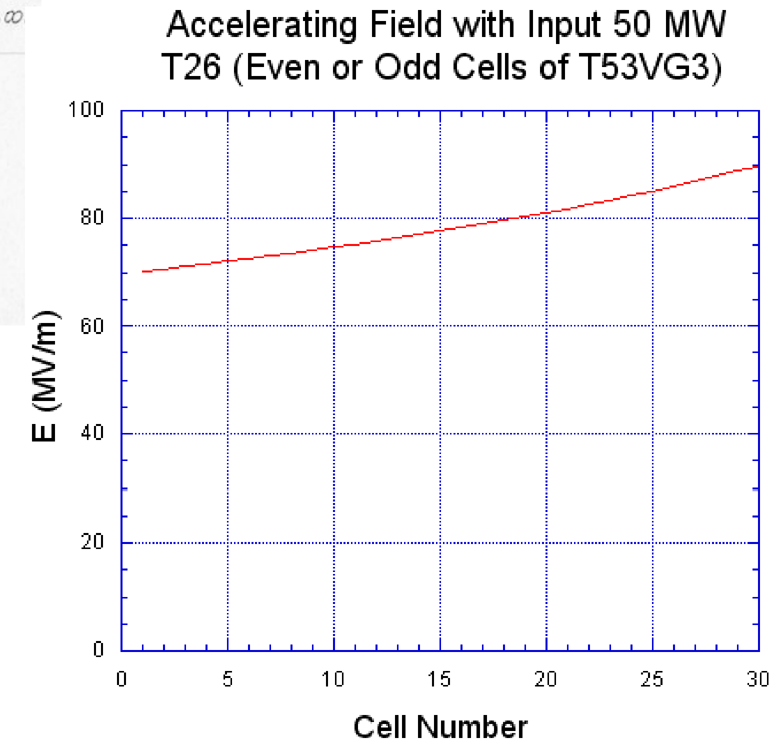
- T53VG3MC, it is < unity at 100 MV/m with 150 ns pulses. $a/\lambda \sim 0.13$

Work in Progress

Design for T28_VG2.9 (T26) Structure



Structure Layout

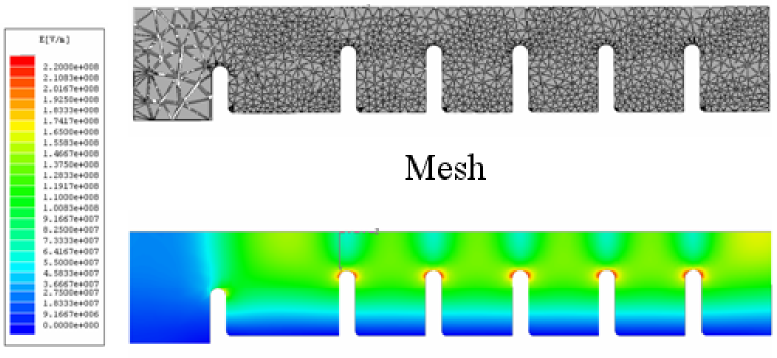


- Input: existing universal coupler assembly.
- Input matching:
- Regular cups: 28 even number cups from T53.
- Output matching:
- Output: existing universal coupler assembly
- Total 30 accelerating cells in the structure.

Work in Progress

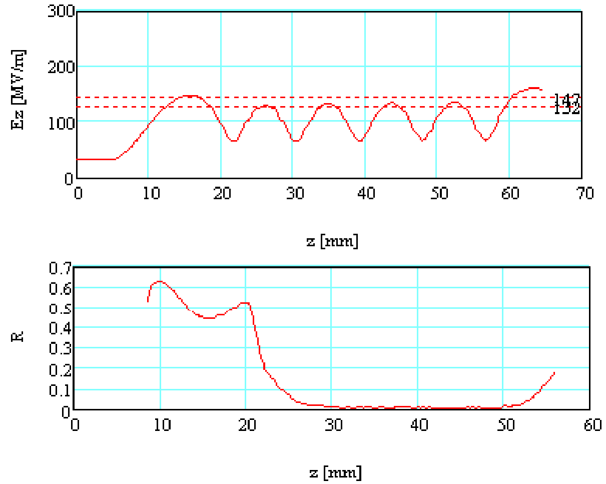
Status and Schedule for T28_VG2.9 (T26) Structure

1. Re-designed of the input matching region.



Mesh

Surface electric field, max. field 220 MV/m



On-axis field and “local” R

2. All new RF parts under fabrication will be completed by the end of October.

3. The final assembly will be completed by the end of 2007

4. Design modification of strongback is underway.

Work in Progress

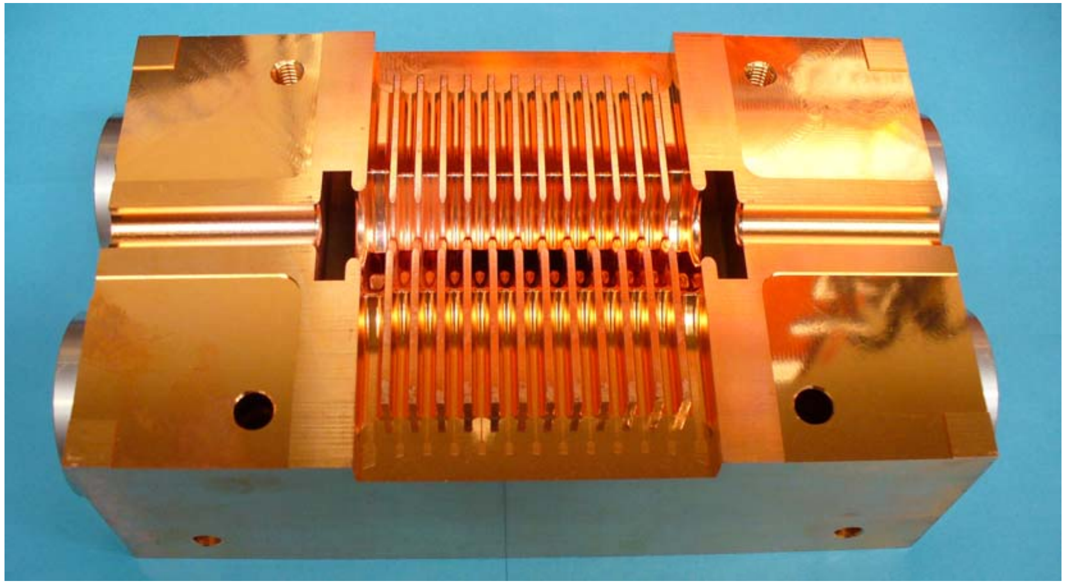
Other Collaboration Issues

1. T18_VG2.4_DISC
   - Two sets of RF Parts are under fabrication at KEK.
   - Diffusion bonding and brazing work will start from the end of November, 2007.
   - Final assemblies and tuning of two section will be done at SLAC. One of the completed section will be tested at SLAC and one will be sent to KEK by the end of 2008.

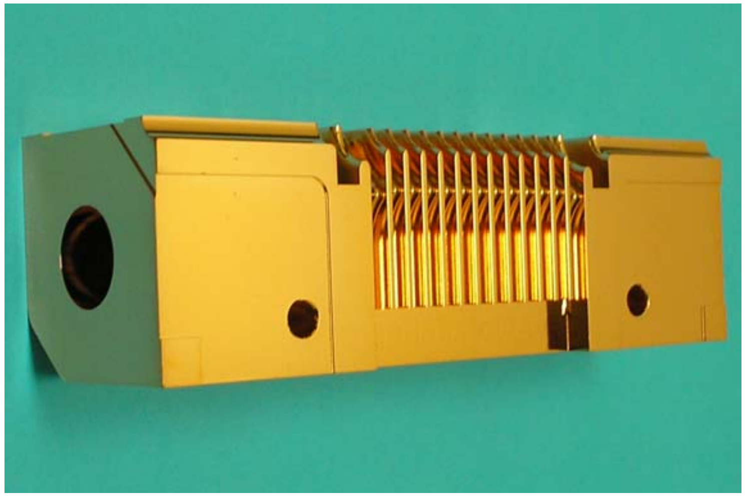
2. TD18_VG2.4_QUAD
   - Providing RF feed components and assisting its shipping to SLAC.
   - High power test will be at Station I of the NLCTA in the early of 2008.

Work in Progress

C11VG5Q16 After RF Testing



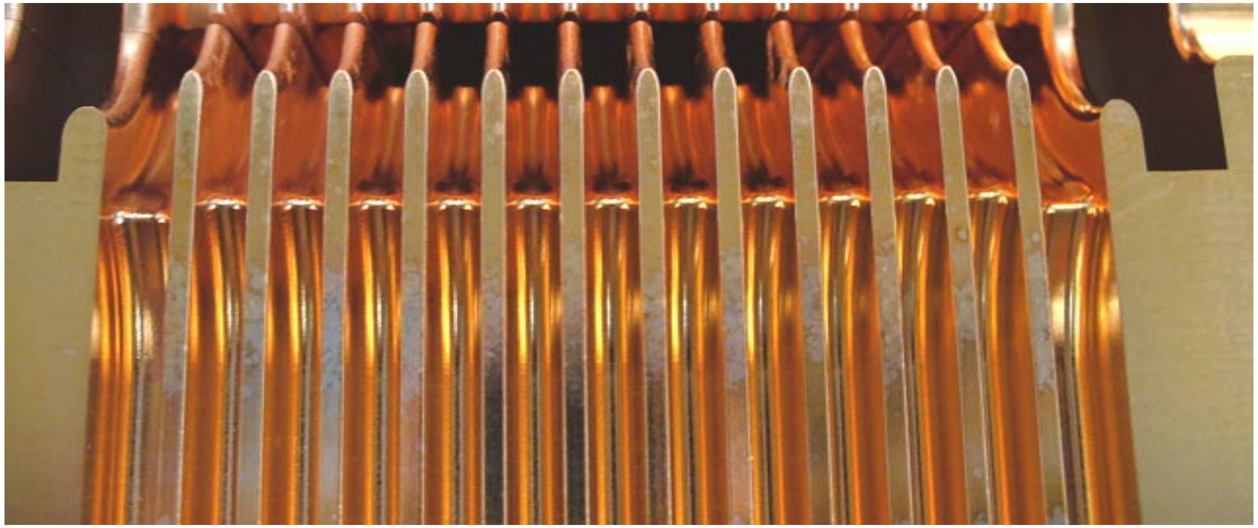
After RF Testing, the water fittings were machined off and each quadrant was electropolished.



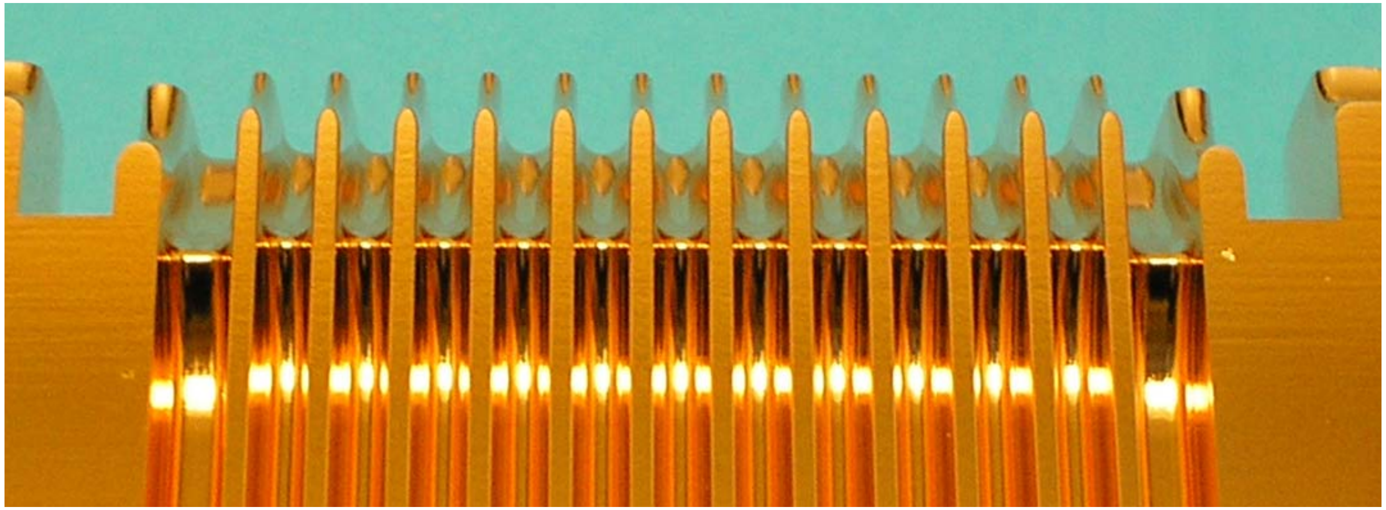
Work in Progress

C11VG5Q16

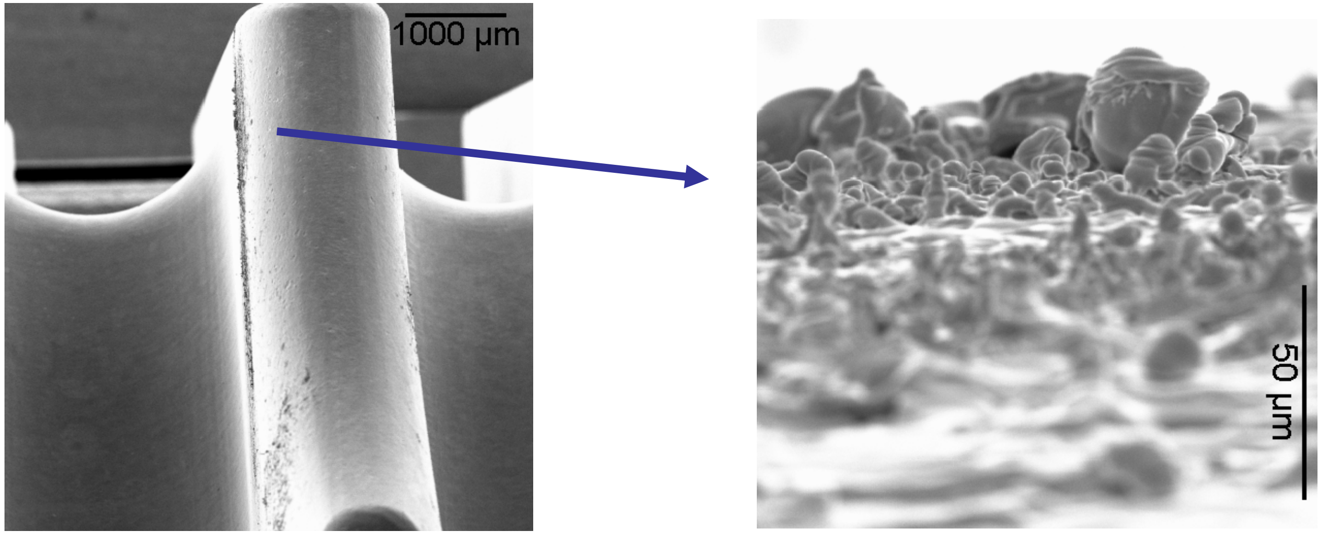
Before Electropolish



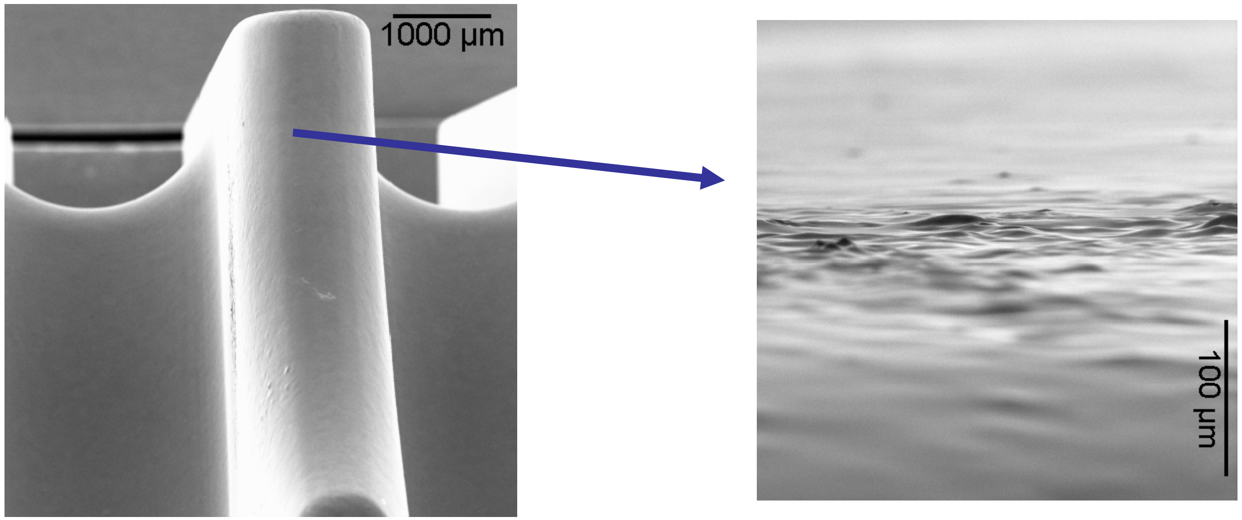
After 7-minute Electropolish



C11VG5Q16 Iris 9



Before Electropolish



7-minute electropolish

Future Work

- Geometry Studies
  - Standing wave structures, traveling waves structures with different phase advances and iris shapes. In this category, we are planning to test 4 structures in the immediate future:
    - Three cell standing wave structure
    - Standing wave structure with optimized cell shape to minimize magnetic field
    - Standing wave structure with optimized cell shape to minimize the peak magnetic field times the electric field on the surface
    - Standing wave structures with reduced a/l
  - Heavily damped structures, 3 different types that are under studies:
    - Choked structures
    - Bi-periodic standing wave structures
    - The MIT photonic band gap structures

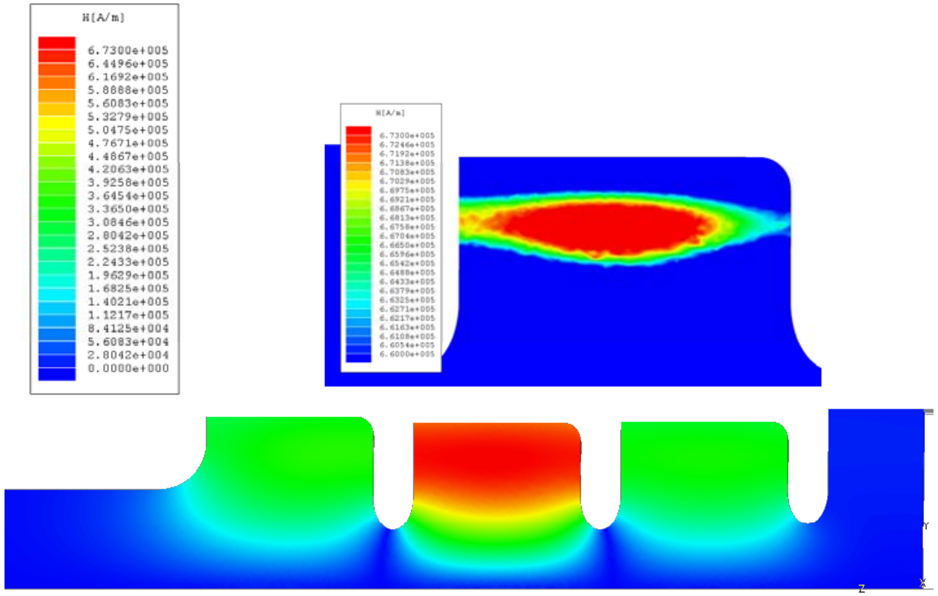
Future Work

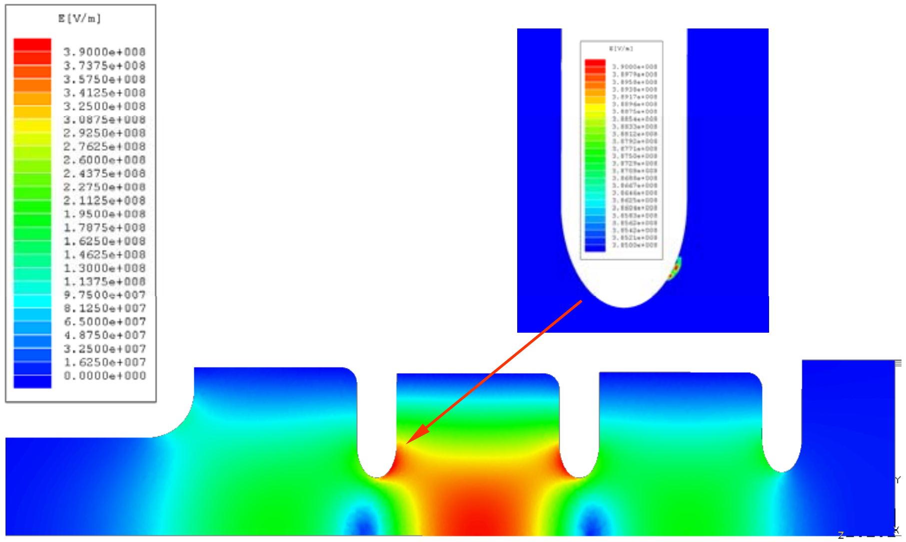
- Material Studies

  Materials is one of the key parameter that hold the potential for a breakthrough for high gradient accelerator structures. Initially we intend to concentrate on cupper alloys and processing of copper surfaces we are going to study:

  - Copper Zirconium
  - Copper Beryllium
  - Copper silver

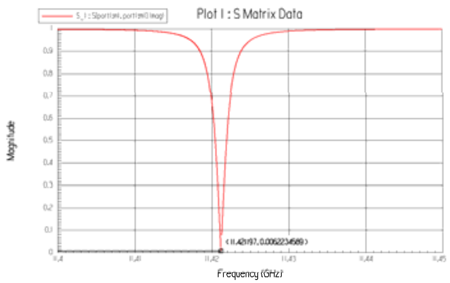
Single Cell SW375
Verification of SLANS results with HFSS, 10 MW input

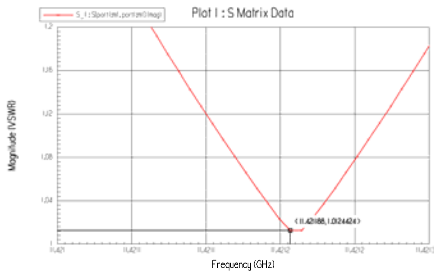


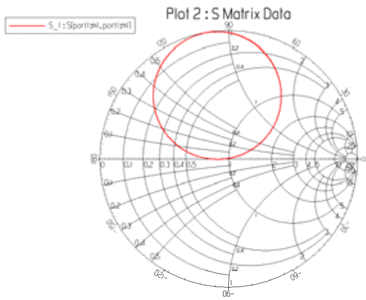


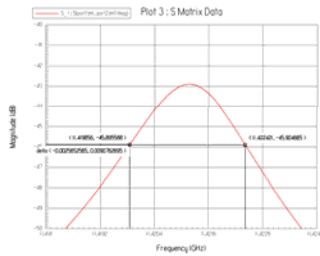
Maximum magnetic field 672 kA/m
(SLANS 668.0 kA/m)

Maximum magnetic field 390 MV/m
(SLANS 398.9 MV/m)









Resonance at 11.4212 GHz

(SLANS 11.4241 GHz)

$\beta = 0.988$

(SLANS 1.032356)

Under-coupled loaded Q

Unloaded Q=8,849.8

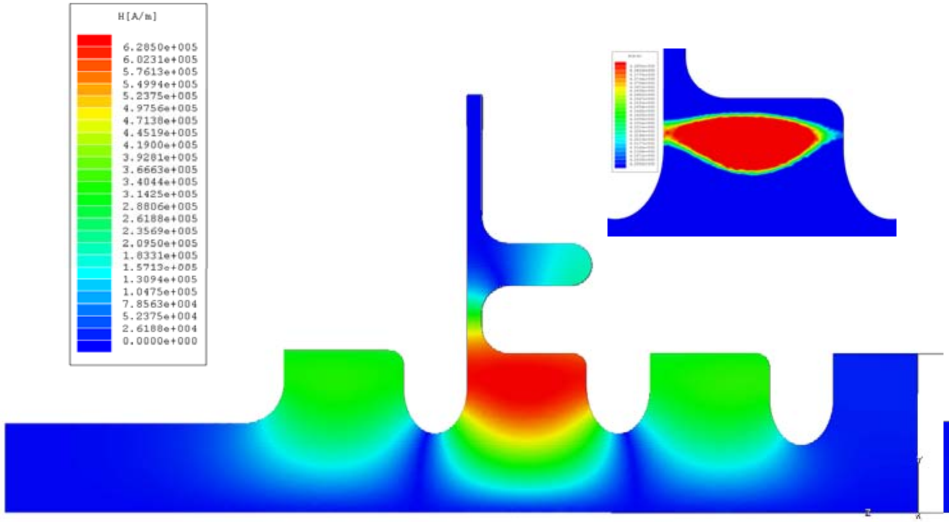
(SLANS 8,912.5)

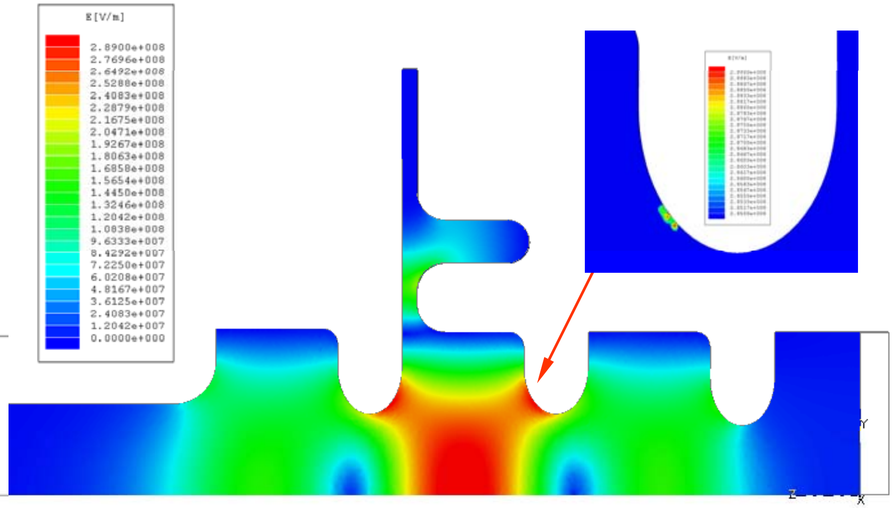
$$\frac{11.4212}{0.00256526} = 4.452\times 10^{3}$$

$$\frac{11.4212}{0.00256526}\cdot(1 + 0.987710) = 8.8498\times 10^{3}$$

V.A. Dolgashev, 25 September 2007

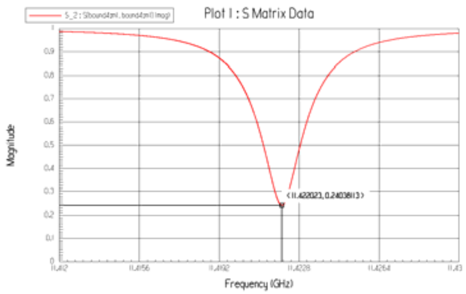
Single Cell SW565 with choke
Verification of SLANS results with HFSS, 10 MW input

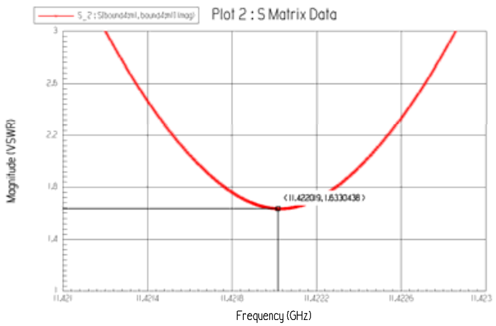


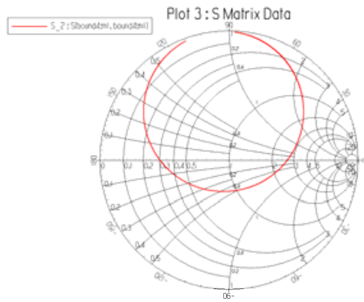


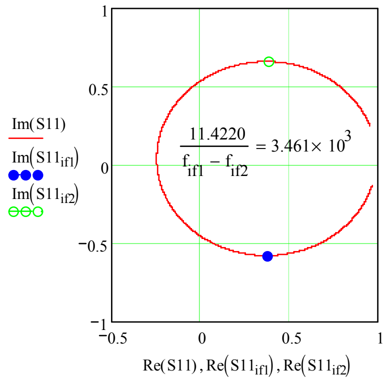
Maximum magnetic field 628.5 kA/m
(SLANS 627.5 kA/m)

Maximum magnetic field 289 MV/m
(SLANS 297.7 MV/m)









Resonance at 11.4220 GHz
(SLANS 11.4240 GHz)

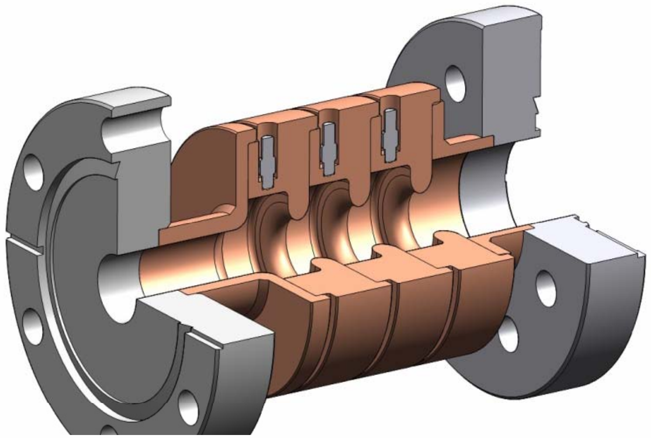
$\beta = 1.633$
(SLANS 1.788)

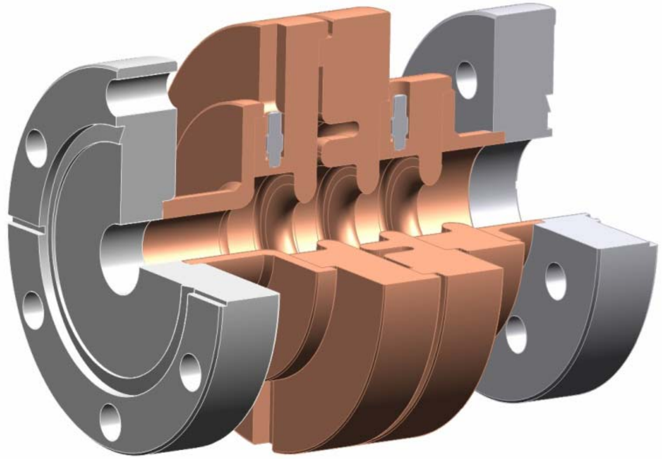
Over-coupled loaded Q
Unloaded Q=9.112
(SLANS 9,183.4)

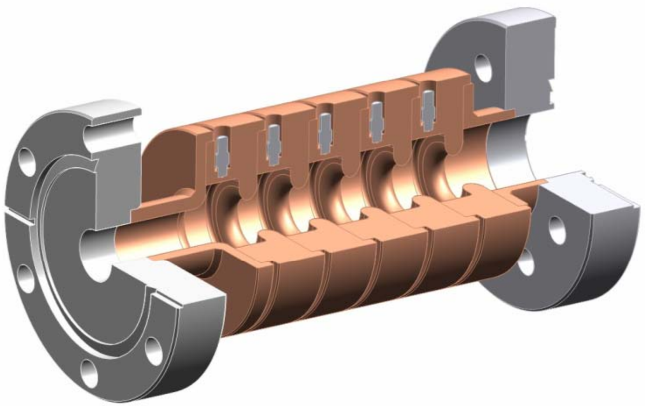
$$\frac{11.4220}{\left(3.30033\times 10^{-3}\right)}\cdot(1 + 1.633) = 9.112\times 10^{3}$$

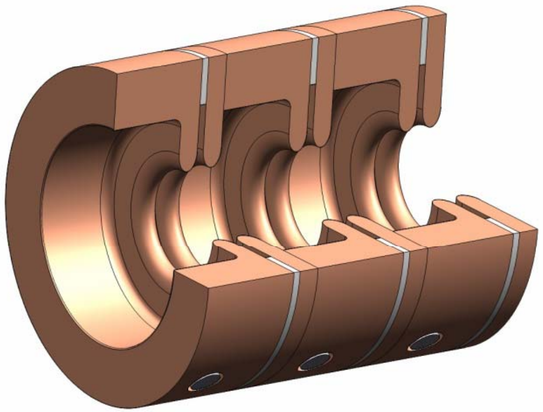
V.A. Dolgashev, 25 September 2007

Structure Shapes









Summary

- We have made significant progress on our facilities
- We have made significant progress in test facilities around the country
- The collaboration is taking off with SLAC as the Host
- We have made progress with copper test structure
- We are about to embark on the experimental program which includes materials, geometries, frequency scaling, and strong wake field damping.
- The theoretical effort taking shape within the collaboration and will by tied to the experimental program.
- A US High Gradient Research Workshop will be held at the University of Maryland on January 24-25, 2008. Hope to see you there.

Acknowledgment

This work is made possible by the efforts of

- V. Dolgashev, G. Bowden, P. Wilson, R. Miller, J. Wang, A. Nguyen, J. Lewandowski
- C. Pearson, J. Eichner, D. Martin, C. Yoneda, L. Laurent et. al., C. Adolphsen