Research and Development for Ultra High Gradient Accelerator Structures

S. Tantawi

For the SLAC team and collaborators

SLAC
NATIONAL ACCELERATOR LABORATORY

LELAND STANFORD JUNIOR UNIVERSITY
1891

This work is made possible by the efforts of SLAC’s

- V. Dolgashev, J. Lewandowski, J. Neilson, J. Wang, A. Yeremian, C. Guo *of Accelerator Technology Research*
- E. Jongewaard, C. Pearson, A. Vlieks, J. Eichner, D. Martin, C. Yoneda, L. Laurent, A. Haase, R. Talley, J. Zelinski, J. Van Pelt, R. Kirby and staff *of Klystron Lab.*
- S. Weathersby, C. Hast, *ARD Test Facilities*
- Z. Li, *Advanced Computation*

In close collaboration with:

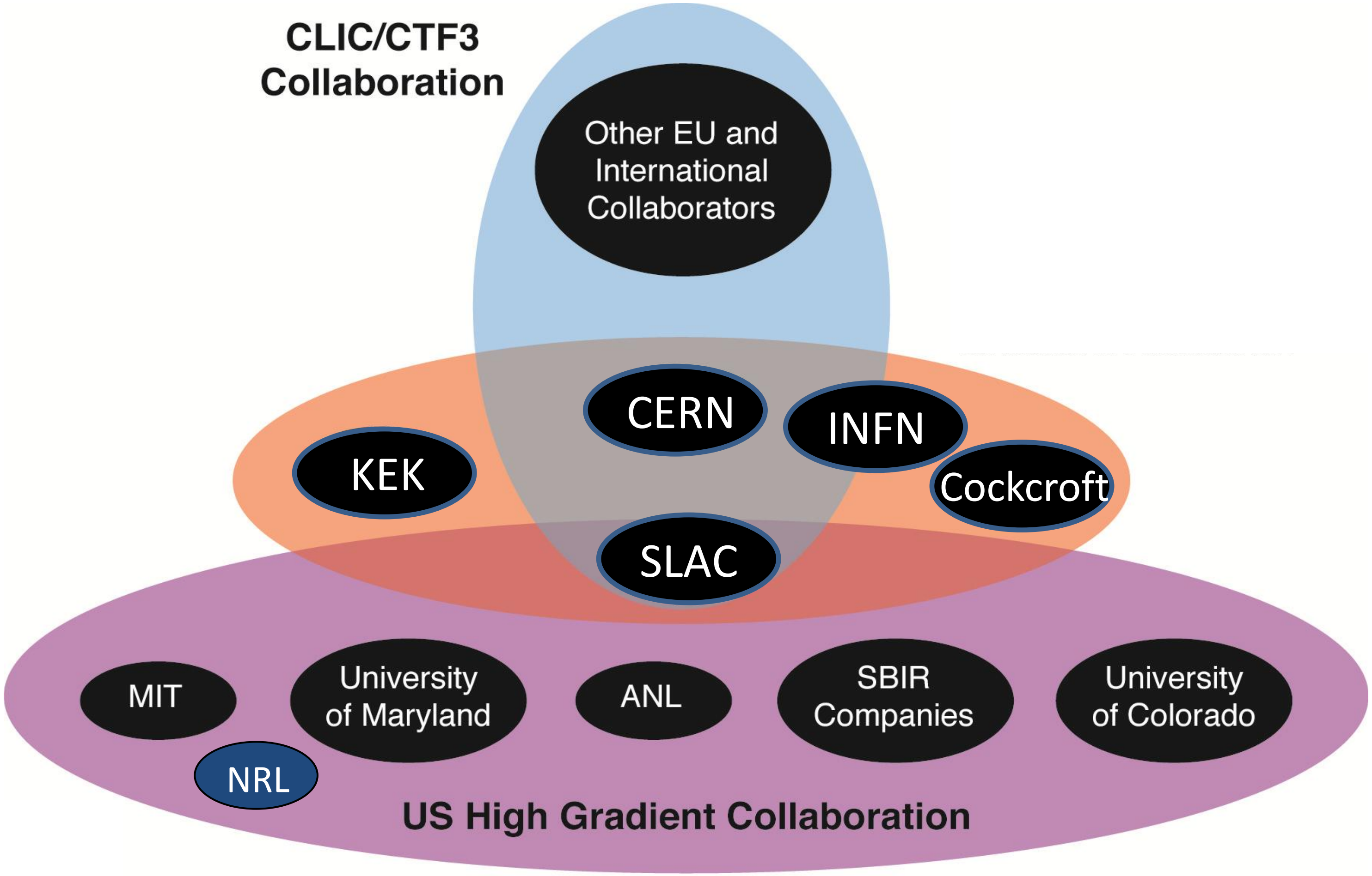
- Y. Higashi, *KEK*, *Tsukuba*, *Japan*
- B. Spataro, *INFN*, *Frascati*, *Italy*

Single-Cell-PBG structures done in collaboration with R. Temkin, B. Munroe, R. Marsh, *MIT*

TW structures done in collaboration with W. Wuensch and CERN CLIC team, T. Higo and the KEK team

T18+resonat ring done in collaboration with J. Haimson and Haimson Research Corporation, data processing A. Palaia from Uppsala University

International Collaboration on High Gradient Research



The Challenge

What gradient can be reliably achieved using warm technology?

- The original, optimistic view (PAC 1986) : E. Tanabe, J. W. Wang and G. A. Loew, "Voltage Breakdown at X-Band and C-Band Frequencies," :
  - The authors report experimental results showing that the Surface Electric Field limit at 9.3 GHz (X-Band) exceeds 572 MV/m in pulses of up to 4.5 microseconds
  - Results predict an on-axis gradient of at least 250 MV/m
- Reality sets in (by 2001):
  - The operating limit determined by experiments on the NLC Test Accelerator showed that high gradient accelerator structure operating at X-band would not survive long term operation without computer/feedback protection and the breakdown rate above 65 MV/m can not be tolerated for a collider application.
- **The challenge**: we wish to ***understand*** the limitations on accelerator gradient in warm structures

- **Our goal** is to push the boundaries of the design to achieve:
  - Ultra-high-gradient; to open the door for a multi-TeV collider
  - High rf energy to beam energy efficacy, which leads to an economical, and hence feasible designs
  - Heavily damped wakefield

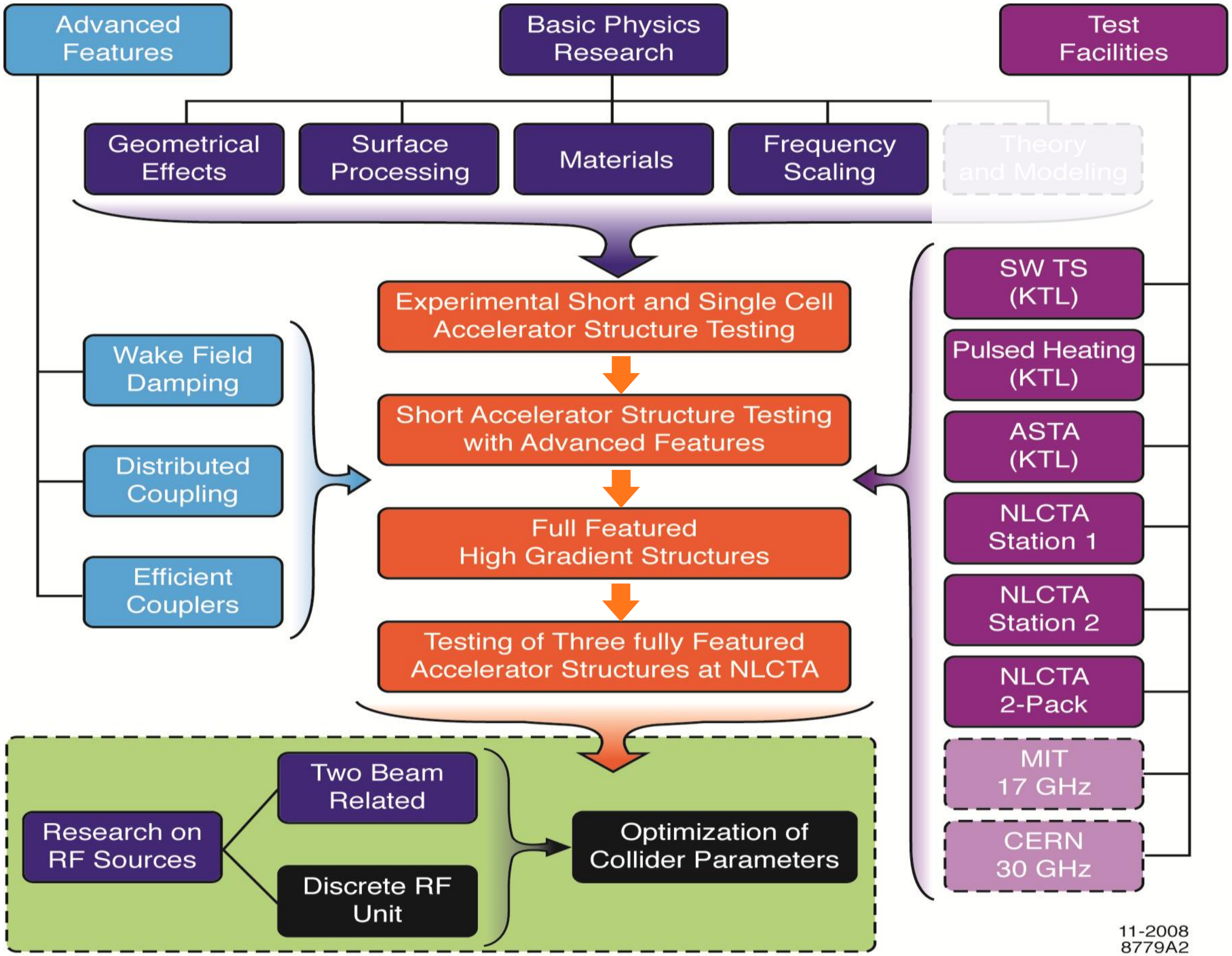
Introduction and Motivations

- The collaboration started at the wake of the Cold vs warm decision that led to the creation of the ILC organization.

- Traditionally linear collider programs dictated the performance of accelerator structures. Our collaboration started with a different philosophy; we would like to find the fundamental limitations on structures and design a collider around an optimized structure.

- We had to address fundamentals early; these include, but are not limited to:
  - Frequency scaling
  - Geometry dependence
  - Materials
  - Surface processing techniques (etching, baking, etc.)
  - Theory

Research and Development Plan



Advanced Features

Basic Physics Research

Test Facilities

Geometrical Effects

Surface Processing

Materials

Frequency Scaling

Theory and Modeling

Experimental Short and Single Cell Accelerator Structure Testing

Short Accelerator Structure Testing with Advanced Features

Full Featured High Gradient Structures

Testing of Three fully Featured Accelerator Structures at NLCTA

Wake Field Damping

Distributed Coupling

Efficient Couplers

SW TS (KTL)

Pulsed Heating (KTL)

ASTA (KTL)

NLCTA Station 1

NLCTA Station 2

NLCTA 2-Pack

MIT 17 GHz

CERN 30 GHz

Research on RF Sources

Two Beam Related

Discrete RF Unit

Optimization of Collider Parameters

11-2008
8779A2

Basic Physics Research Short/Compact Accelerator Structures

- Brazed Structures
  - Geometrical Studies
    - Standing wave structures have been studied extensively
    - Travelling wave structures are ongoing
    - Structures with wake field damping features
      - Photonic band gap
      - Choked structures
      - Slotted structures
  - Material studies
    - Limited to what one can get for the brazed structure
  - Low temperature normal conducting structures
- Clamped Structures
  - Material Studies
  - Mixed material structures
  - Surface coatings
- Joined Structures
  - Plated Joints
  - Electron Beam welding
  - Low Temperature brazing
- Structures with View Ports for Fast Diagnostics for Breakdown Phenomenon

Basic Physics Research Full Size Accelerator Structures

- Resonant Ring Structures
  - Geometrical Studies
  - Martial studies
- CERN Structures
- Dielectric Structures
- New Distributed Coupling Standing Wave Accelerator Structures

Basic Physics Research Others

- Pulsed Heating Setup
  - Material Studies
- Mixed E&H Setup
- Superconducting Material/Low Temperature Material Testing
  - Novel RF materials
  - Stratified materials

RF Sources Research

- Overmoded Magnetrons
- Massively Multimoded Klystrons
- Large signal codes
- Novel RF sources

There are other efforts in the group which is not the subject of this presentation

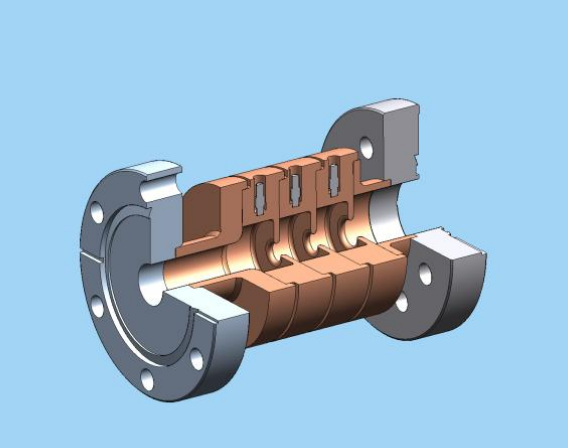
High Power Tests of Single Cell Standing Wave Structures

- Low shunt impedance, *a/lambda* = 0.215, *1C-SW-A5.65-T4.6-Cu*, 5 tested
    - *KEK=#1…KEK-#4*
    - *Frascati-#2*
- Low shunt impedance, TiN coated, *1C-SW-A5.65-T4.6-Cu-TiN-KEK-#1*, 1 tested
- Three high gradient cells, low shunt impedance, *3C-SW-A5.65-T4.6-Cu,* 2 tested
    - *KEK-#1…KEK-#2*
- High shunt impedance, elliptical iris, *a/lambda* **=** 0.143, *1C-SW-A3.75-T2.6-Cu-SLAC-#1*, 1 tested
- High shunt impedance, round iris, *a/lambda* **=** 0.143, *1C-SW-A3.75-T1.66-Cu-KEK-#1*, 1 tested
- Low shunt impedance, choke with 1mm gap, *1C-SW-A5.65-T4.6-Choke-Cu*, 2 tested
    - *SLAC-#1*
    - *KEK-#1*
- Low shunt impedance, made of CuZr, *1C-SW-A5.65-T4.6-CuZr-SLAC-#1,* 1 tested
- Low shunt impedance, made of CuCr, *1C-SW-A5.65-T4.6-CuCr-SLAC-#1,* 1 tested
- Highest shunt impedance copper structure *1C-SW-A2.75-T2.0-Cu-SLAC-#1***,** 1 tested
- Photonic-Band Gap, low shunt impedance, *1C-SW-A5.65-T4.6-PBG-Cu-SLAC-#1,* 1 tested
- Low shunt impedance, made of hard copper *1C-SW-A5.65-T4.6-Clamped-Cu-SLAC#1,* 1 tested
- Low shunt impedance, made of molybdenum *1C-SW-A5.65-T4.6-Mo-Frascati-#1,* 1 tested
- Low shunt impedance, hard copper electroformed *1C-SW-A5.65-T4.6-Electroformed-Cu-Frascati-#1,* 1 tested
- High shunt impedance, choke with 4mm gap, *1C-SW-A3.75-T2.6-4mm-Ch-Cu-,* 2 tested
    - SLAC-#1
    - KEK-#1
- High shunt impedance, elliptical iris, ultra pure Cu, *a/lambda* **=** 0.143, *1C-SW-A3.75-T2.6-6NCu-KEK-#1*, 1 tested
- High shunt impedance, elliptical iris, HIP treated, *a/lambda* = 0.143, *1C-SW-A3.75-T2.6-6N-HIP-Cu-KEK-#1*, 1 tested
- High shunt impedance, elliptical iris, ultra pure Cu,, *a/lambda* **=** 0.143, *1C-SW-A3.75-T2.6-7N-Cu-KEK-#1*, 1 tested
- Low shunt impedance, made of soft CuAg, *1C-SW-A5.65-T4.6-CuAg-SLAC-#1,* 1 tested
- High shunt impedance hard CuAg structure *1C-SW-A3.75-T2.6-LowTempBrazed-CuAg-KEK-#1,* 1 tested
- High shunt impedance soft CuAg, *1C-SW-A3.75-T2.6-CuAg-SLAC-#1*, 1 tested
- High shunt impedance hard CuZr, *1C-SW-A3.75-T2.6-Clamped-CuZr-SLAC-#1*, 1 tested
- High shunt impedance dual feed side coupled, *1C-SW-A3.75-T2.6-2WR90-Cu-SLAC-#1,* 1 tested

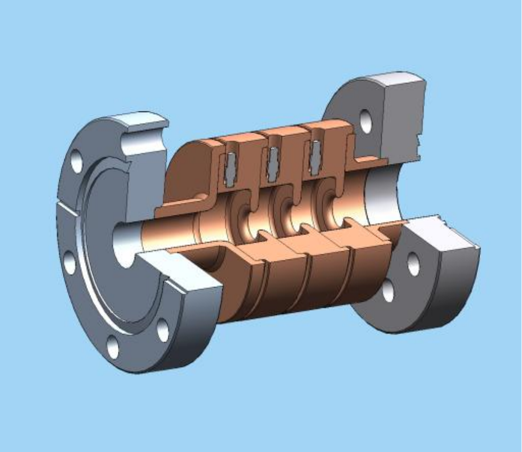
Now 30th test is ongoing,
single feed side coupled
1C-SW-A3.75-T2.6-1WR90-Cu-SLAC-#1

Geometrical Studies

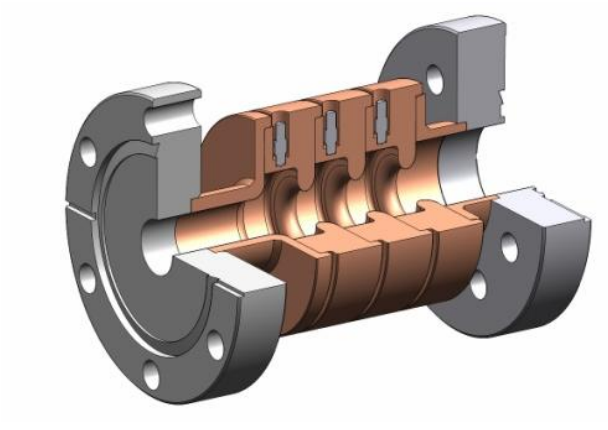
Three Single-Cell-SW Structures of Different Geometries



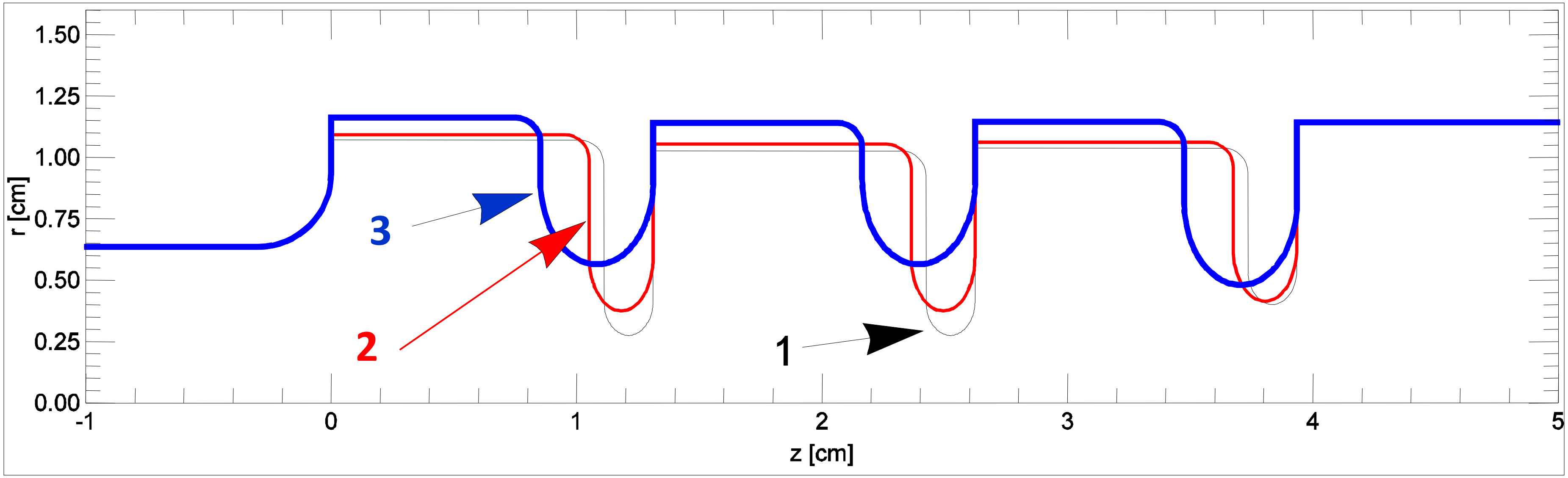
1)1C-SW-A2.75-T2.0-Cu



2) 1C-SW-A3.75-T2.0-Cu

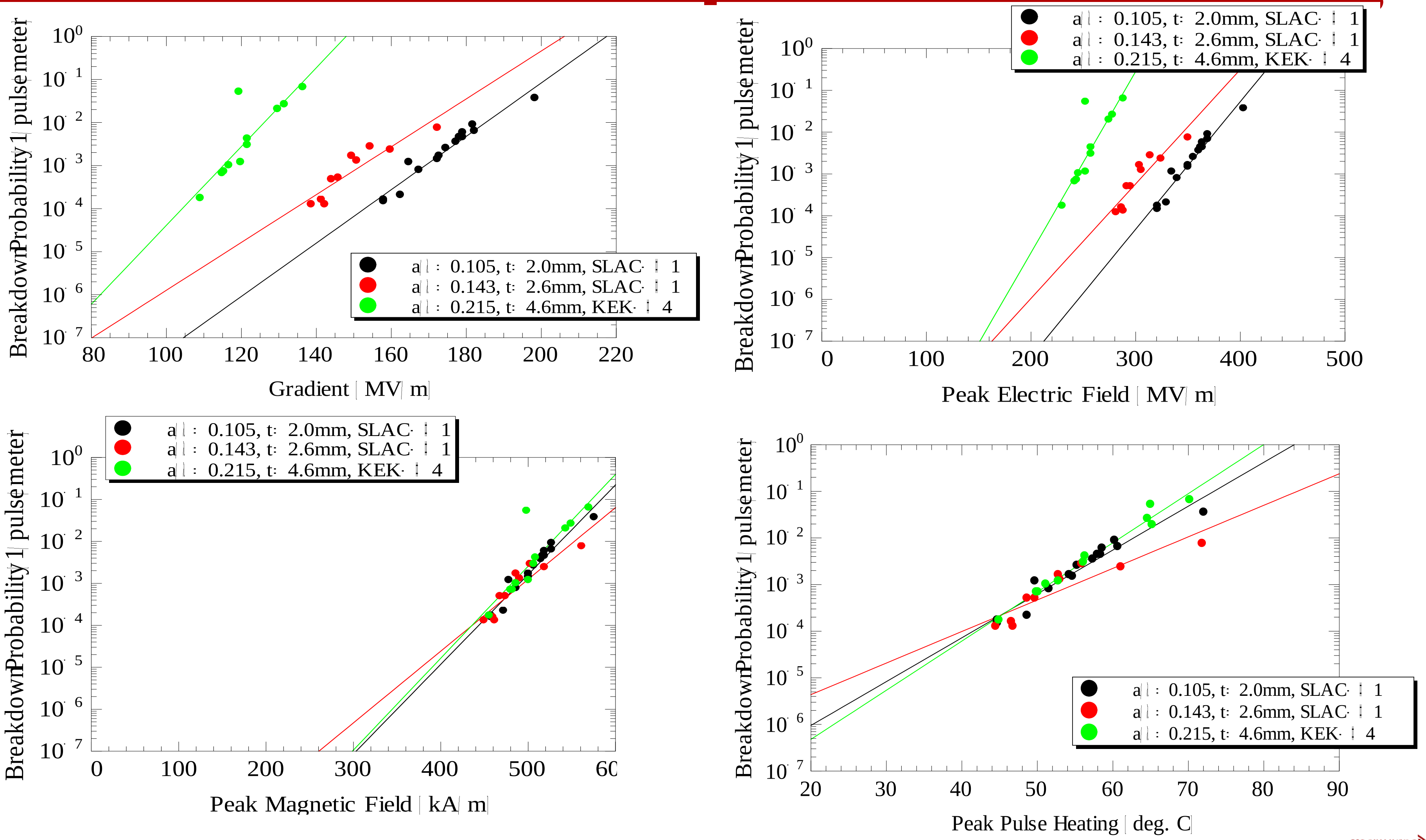


3) 1C-SW-A5.65-T4.6-Cu



Geometrical Studies

Different single cell structures: Standing-wave structures with different iris diameters and shapes; $a/\lambda=0.215$, $a/\lambda=0.143$, and $a/\lambda=0.105$

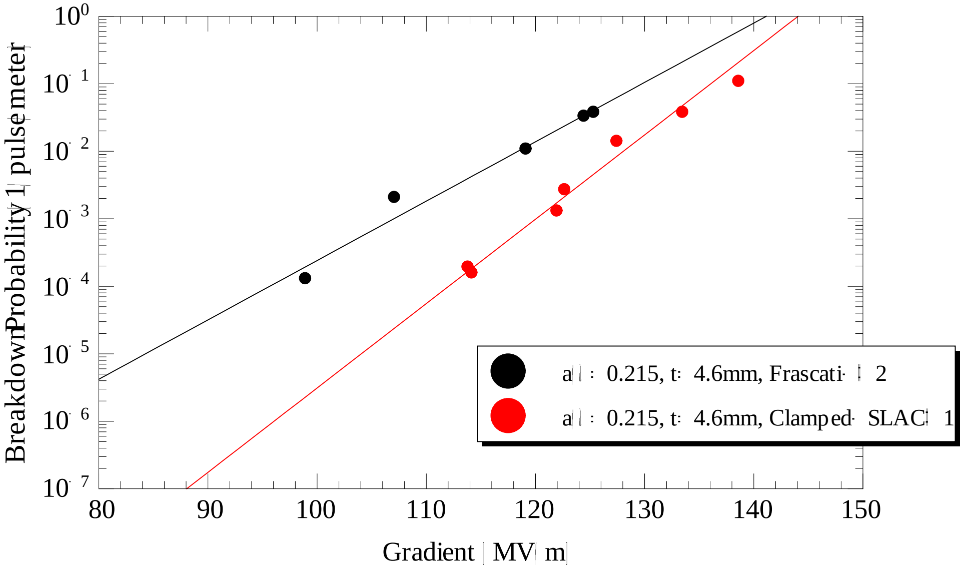


Global geometry plays a major role in determining the accelerating gradient, rather than the local electric field.

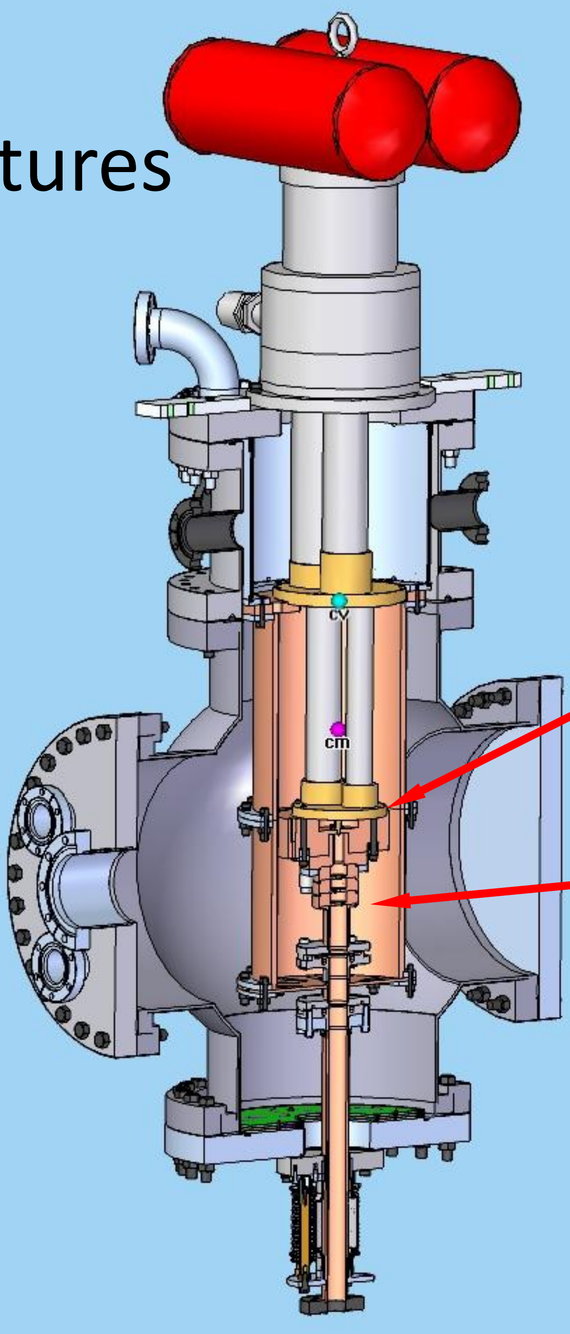
Test of Hard Copper

Hard Copper showed an observable improvements of annealed brazed

Clamped Structure with Hard Copper cells



Experiments at cryo temperatures



Refrigerator head

Accelerating structure

RF in

Solid model: David Martin, 10 January 2011

Material Testing (Pulsed heating experiments)

Special cavity has
designed to focus
magnetic field into
that can be replac

method

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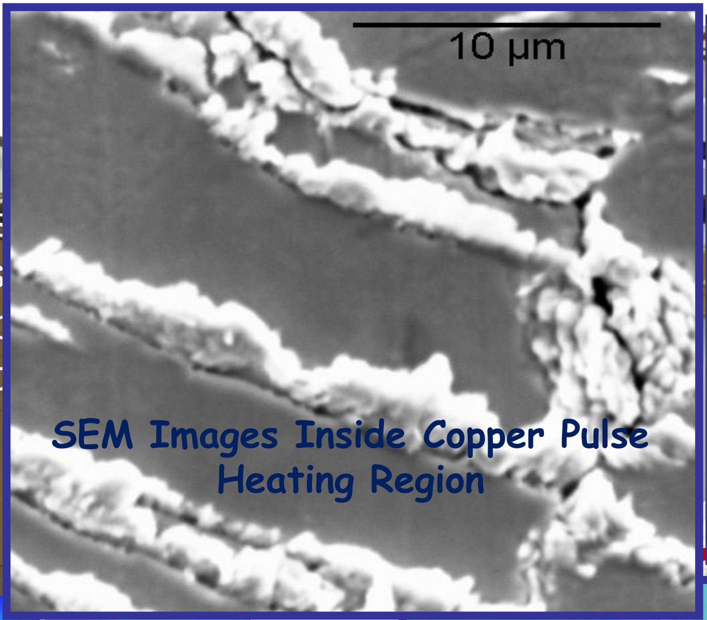
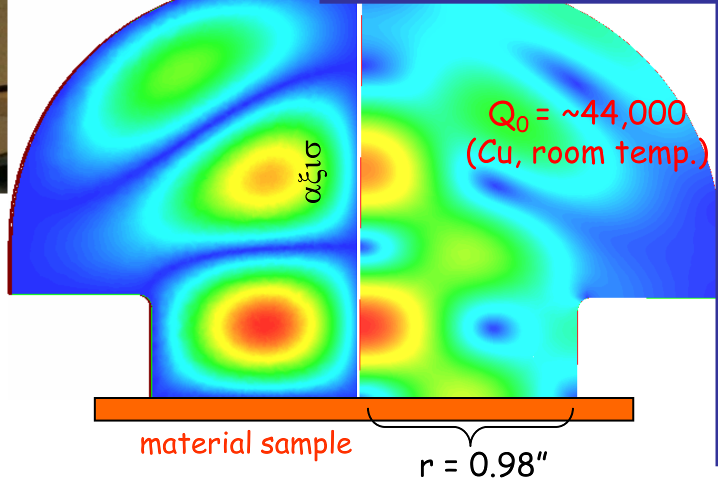
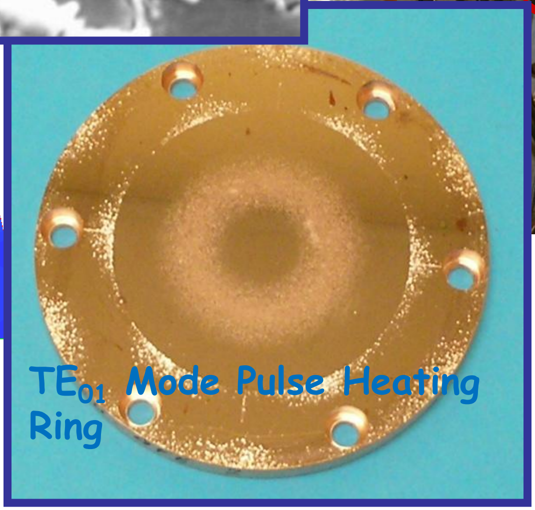


SEM Images Inside Copper Pulse Heating Region

Metallography: Intergranular fractures 500X

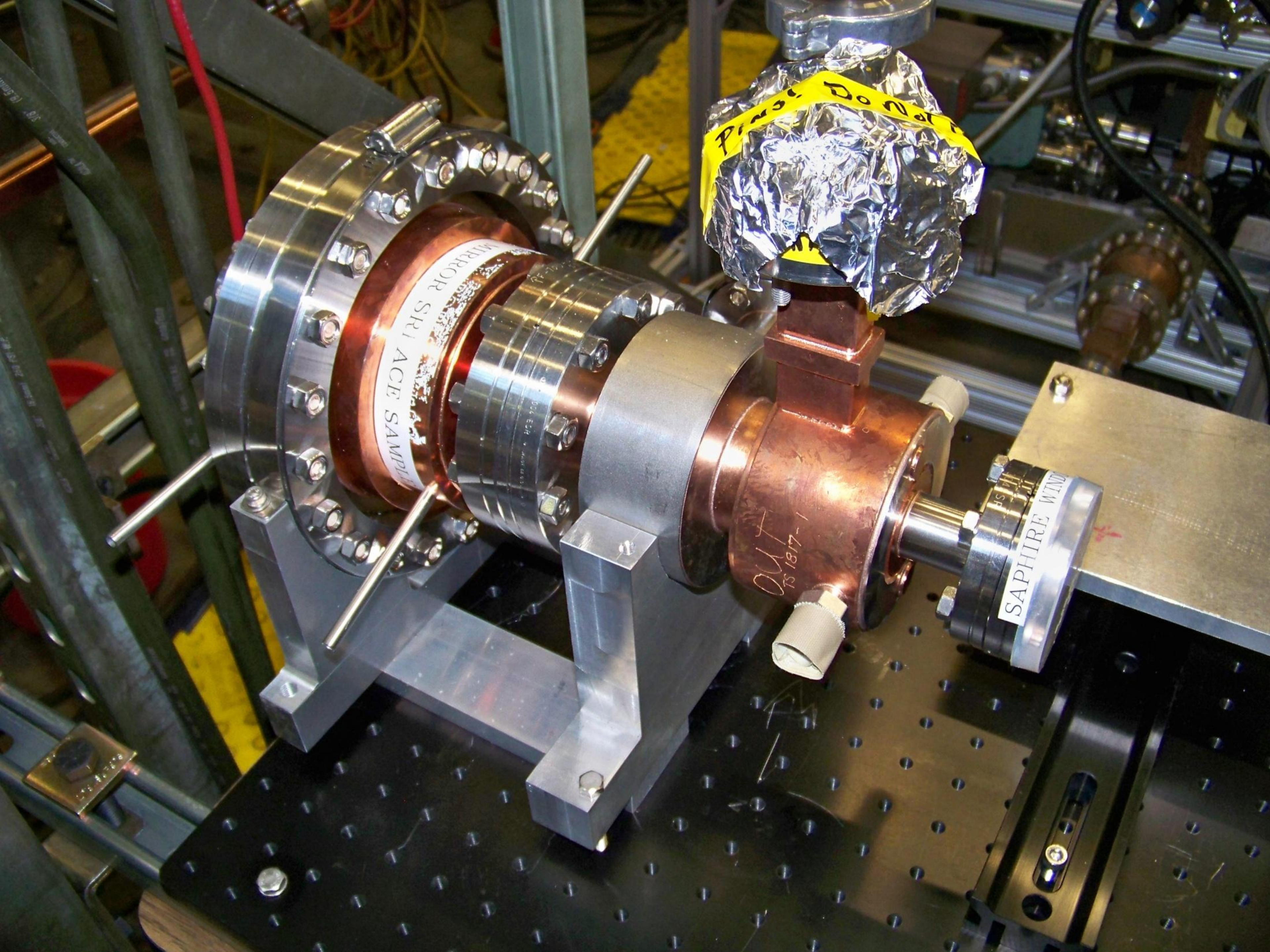


Q_0 = ~44,000 (Cu, room temp.)



TE$_{01}$ Mode Pulse Heating Ring

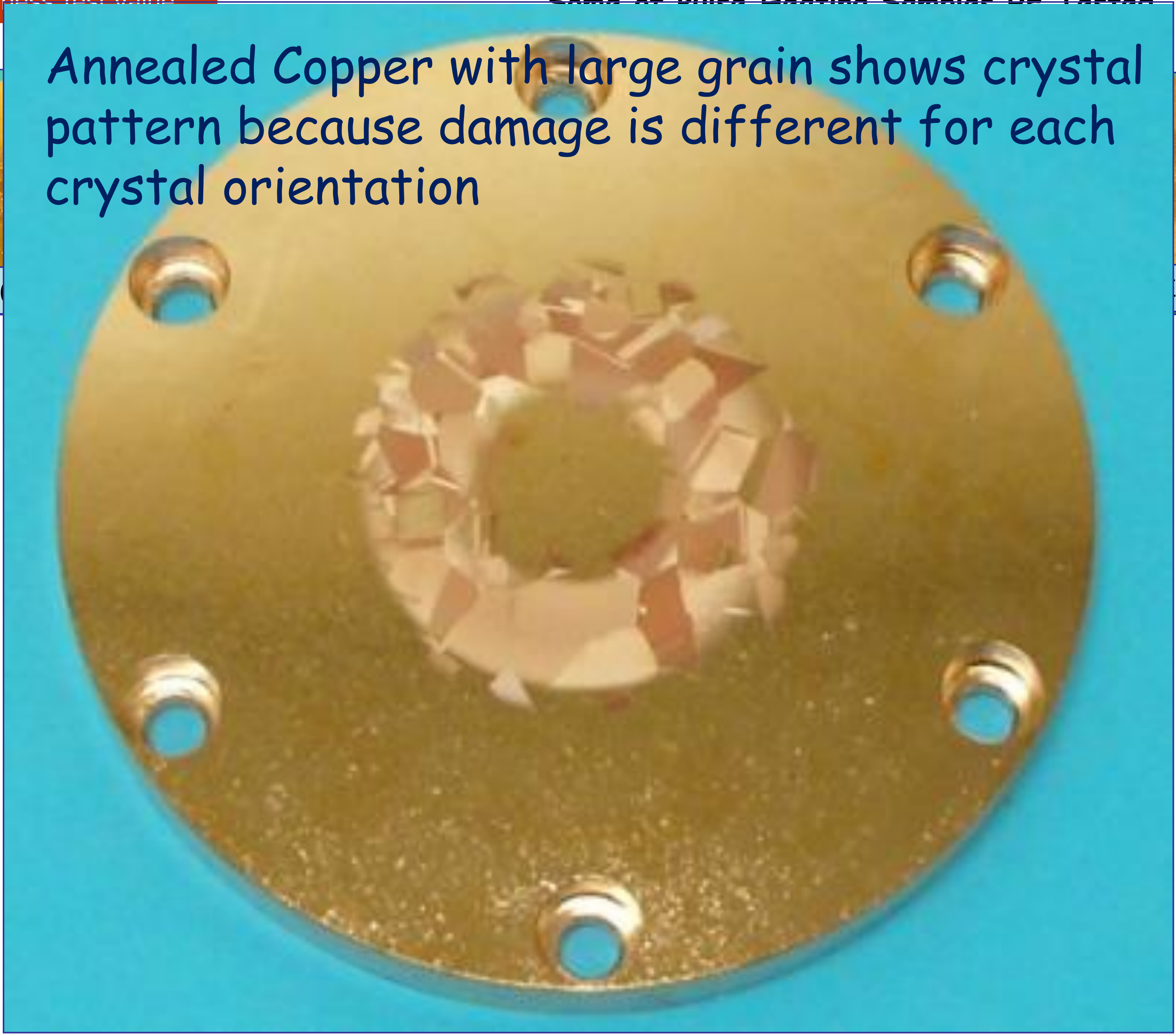
Max Temp rise during pulse = 110°C


MIRROR SURFACE SAMPL
Pins, Do Not
OUT
TS 1817-1
SAPHIRE WIND

Hardness Test Value

Some of Pulse Heating Samples RF Tested

Cu101 (

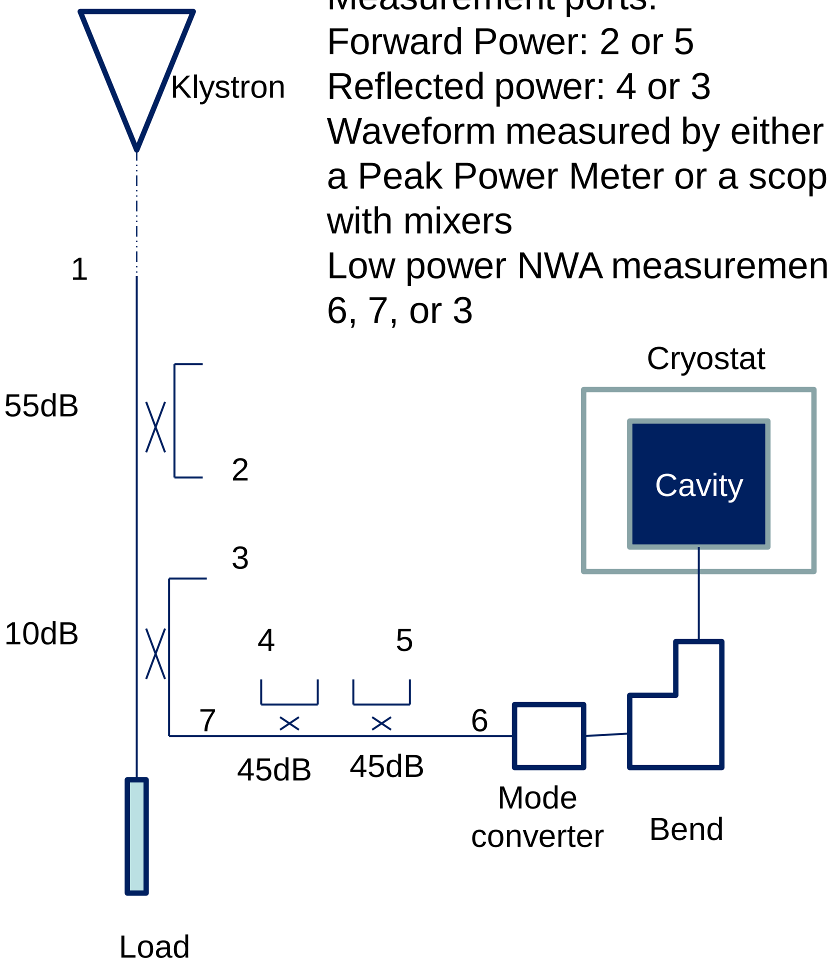


Annealed Copper with large grain shows crystal pattern because damage is different for each crystal orientation

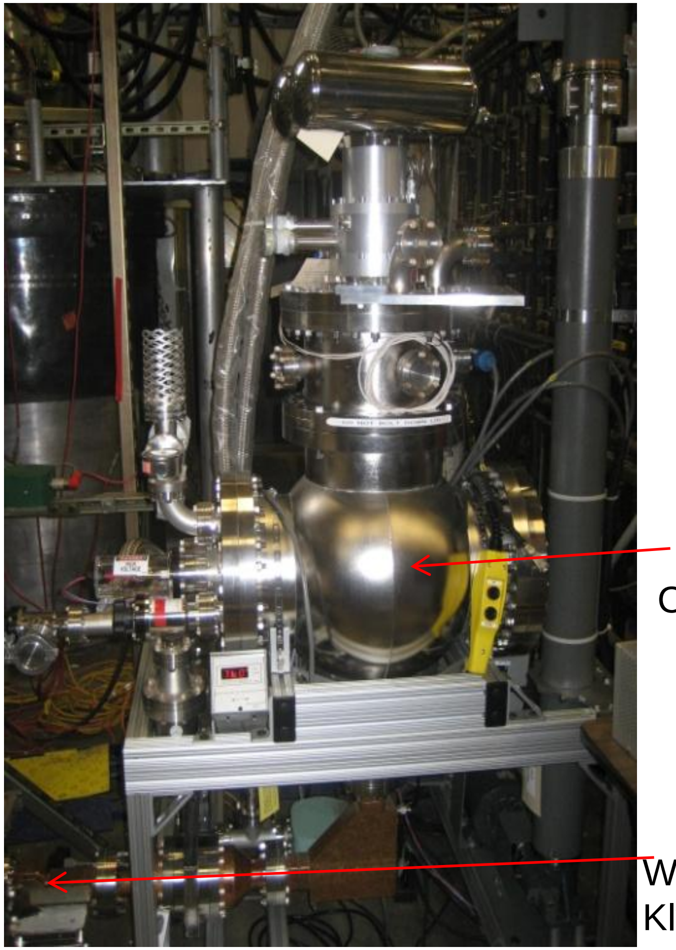
RN)

System overview

Measurement ports:
Forward Power: 2 or 5
Reflected power: 4 or 3
Waveform measured by either a Peak Power Meter or a scope with mixers
Low power NWA measurement: 6, 7, or 3

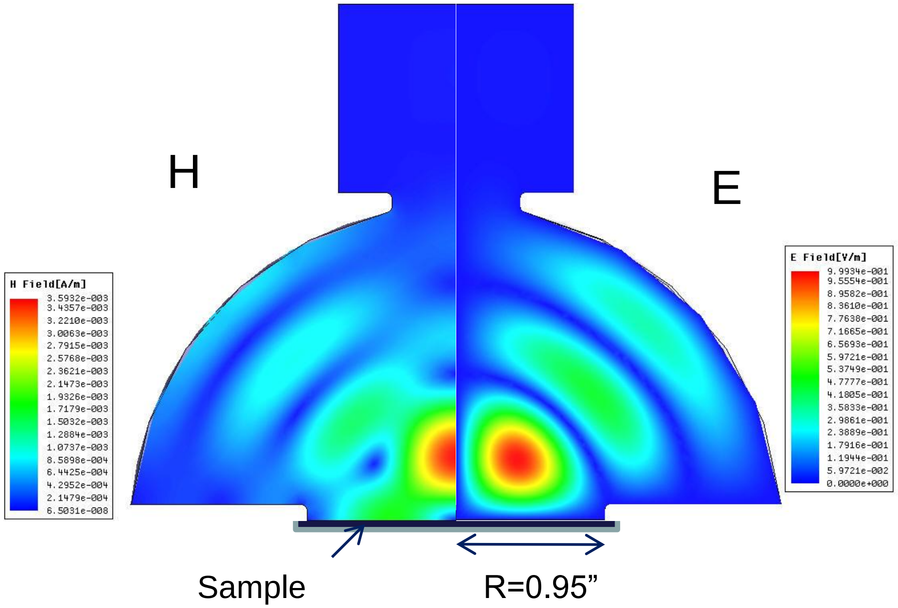


System Diagram



Cavity Design

High-Q cavity under TE013 like mode



$F_{res,\ design}$=~11.399GHz
$F_{res,\ 290K}$=~11.424GHz
$F_{res,\ 4K}$=~11.46GHz

Tc~3.6µs(using Q value for copper at 4K)

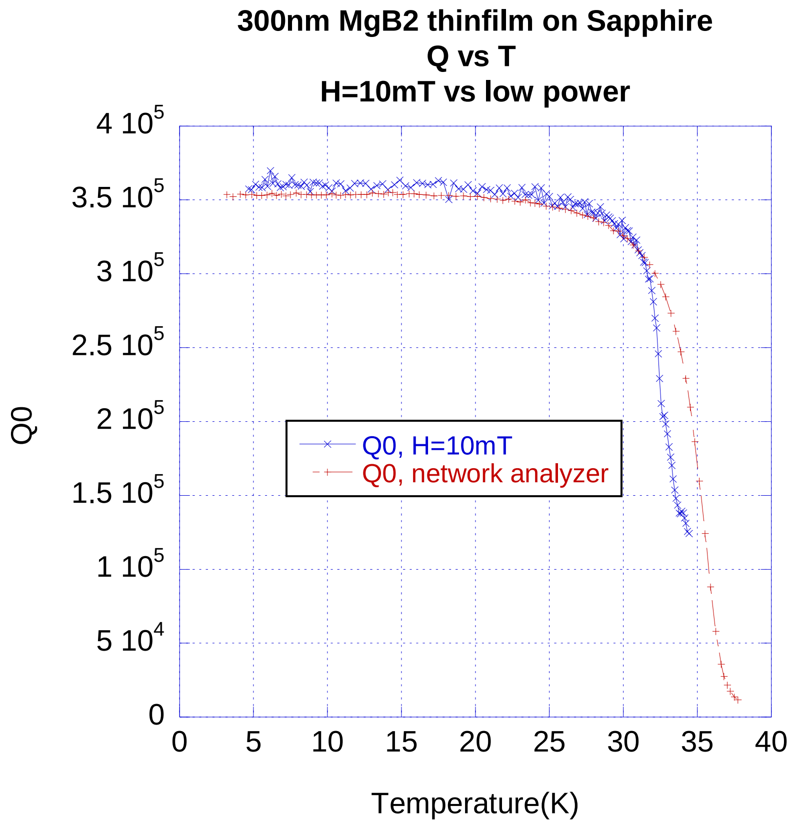
$Q_{0,4K}$=~224,000
$Q_{0,290K}$=~50,000
(measured from bulk Cu samples)

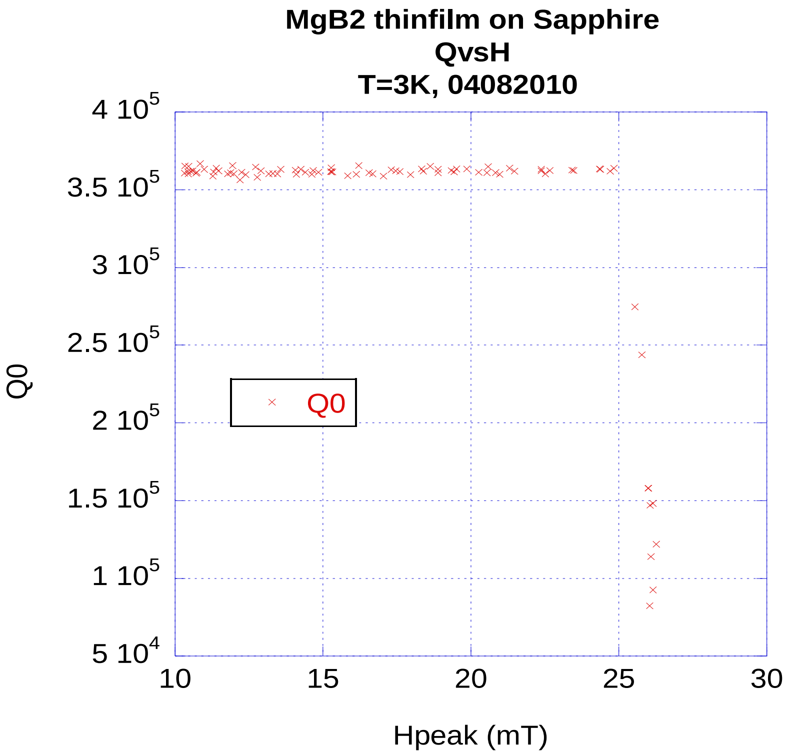
Qe~310,000

$Q_{0,4K}$=~342,000
(Estimated for zero resistivity samples, using measured Cu sample results)

- High-Q hemispheric cavity under a TE_{013} like mode
  - Zero E-field on sample
  - Maximize H-field on the sample, H_{peak} on bottom is 2.5 times of peak on dome
  - Maximize loss on the sample, 36% of cavity total
  - No radial current on bottom
- Copper cavity body
  - No temperature transition or quenching
  - Higher surface impedance
  - Coupling sensitive to iris radius
- Possible future Nb cavity body
  - More precise R_s characterization

Measurement results: 300nm MgB_2 on Sapphire

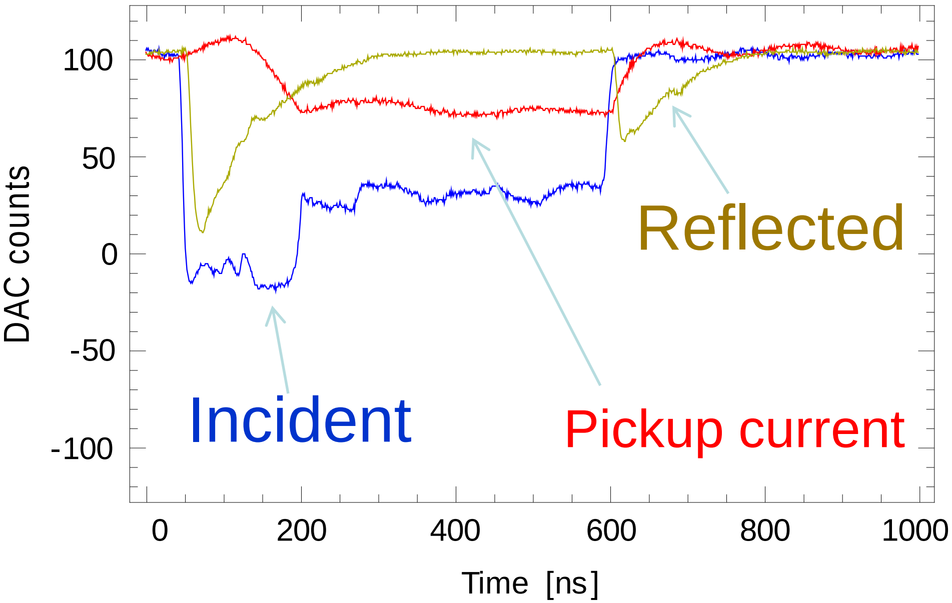




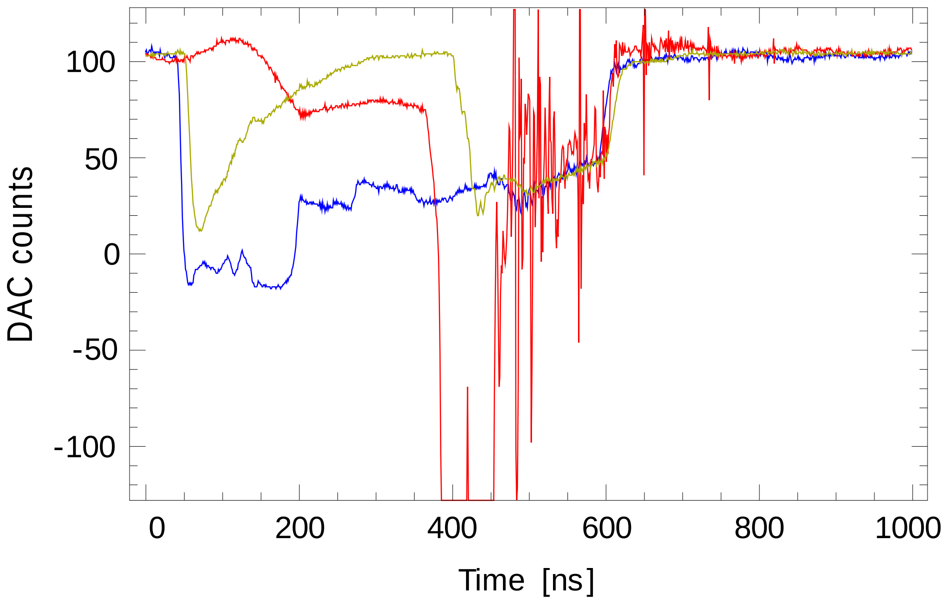
300nm MgB2 thin film on Sapphire substrate, provided by LANL and deposited at STI.

RF signals for breakdown in single-cell-SW structure

1C-SW-A3 .75-T2 .6-6N-HIP-Cu-KEK-#1



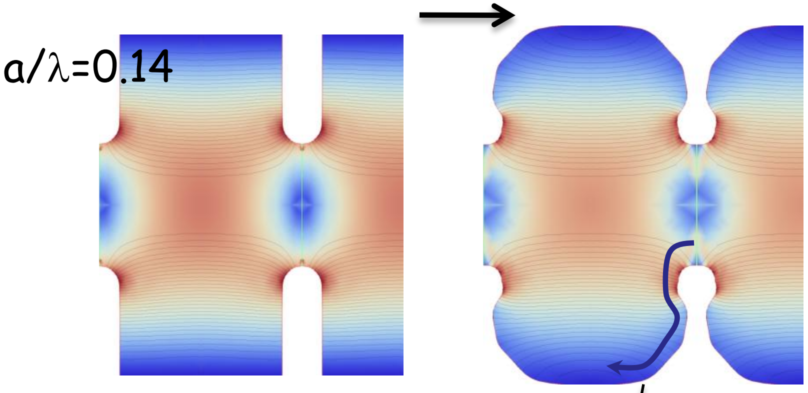
File: t04_09_10__09_41_24.dat Shot: 9 Time Stamp: {9,44,6,203}

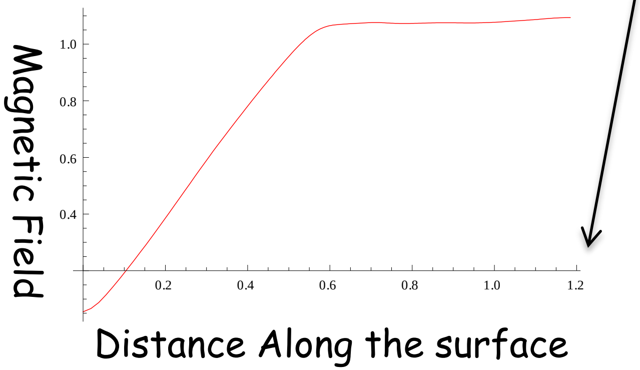


File: t04_09_10__09_41_24.dat Shot: 10 Time Stamp: {9,44,6,218}

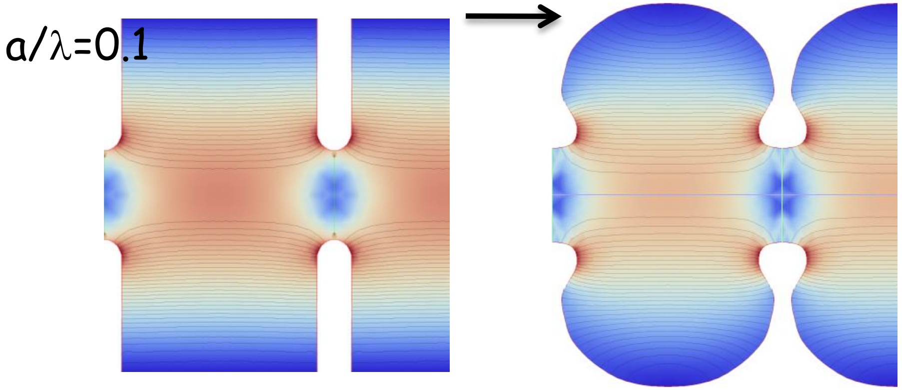
Iris shaping for Standing-Wave π-mode structures

Shunt Impedance	83 MΩ/m	Shunt Impedance	104 MΩ/m
Quality Factor	8561	Quality Factor	9778
Peak E_s/E_a	2.33	Peak E_s/E_a	2.41
Peak Z_0H_s/E_a	1.23	Peak Z_0H_s/E_a	1.12



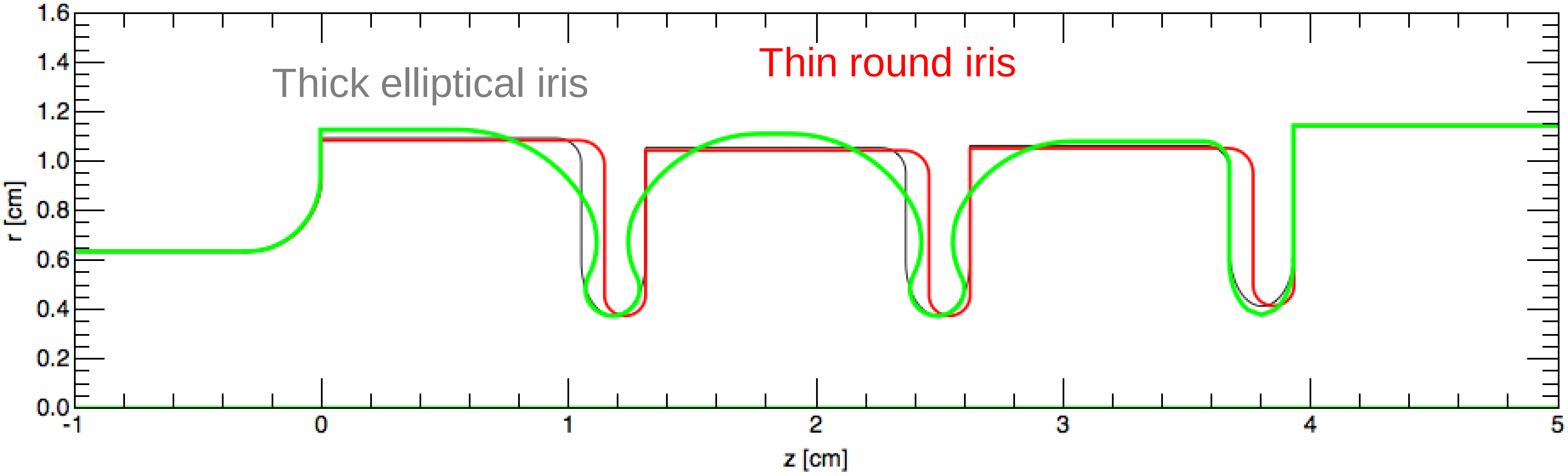


Shunt Impedance	102 MΩ/m	Shunt Impedance	128 MΩ/m
Quality Factor	8645	Quality Factor	9655
Peak E_s/E_a	2.3	Peak E_s/E_a	2.5
Peak Z_0H_s/E_a	1.09	Peak Z_0H_s/E_a	1.04



Shape optimization reduces magnetic field on the surface, and hence, we hope to improve breakdown rate with the enhanced efficiency

Shaped Iris

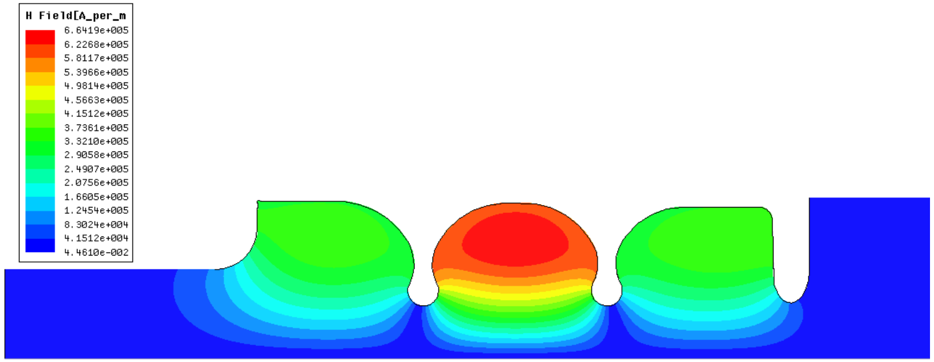


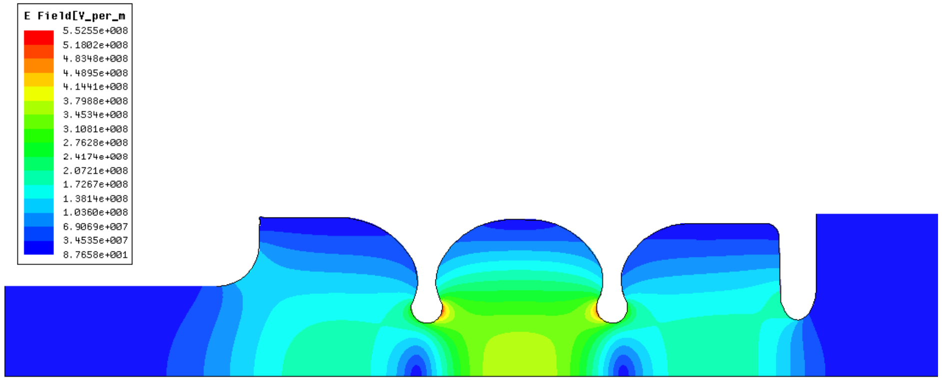
- Iris profile designed to maximize shunt impedance, minimize peak surface magnetic field

SW Cells a/λ =0.143, π Phase Shift Field Normalized for 100MeV/m Acceleration

Parameter	**T=1.66 Round Iris**	**T=2.6mm Elliptical Iris**	**T=2.2mm Shaped Iris**
Stored Energy [J]	0.189	0.189	0.186
Q-value	8820	8560	10090
Shunt Impedance [MOhm/m]	**85.2**	**82.6**	**99.2**
Max. Mag. Field [KA/m]	**314**	**325**	**294**
Max. Electric Field [MV/m]	266	203	268
Losses in one cell [MW]	1.54	1.59	1.32
Hmax*ZO/Eacc	1.18	1.22	1.11
Max. Im{E x H*} W/μm^2	**42.8**	**44.4**	**56.5**
Max. Im{E x H*}/H^2	417	407	650

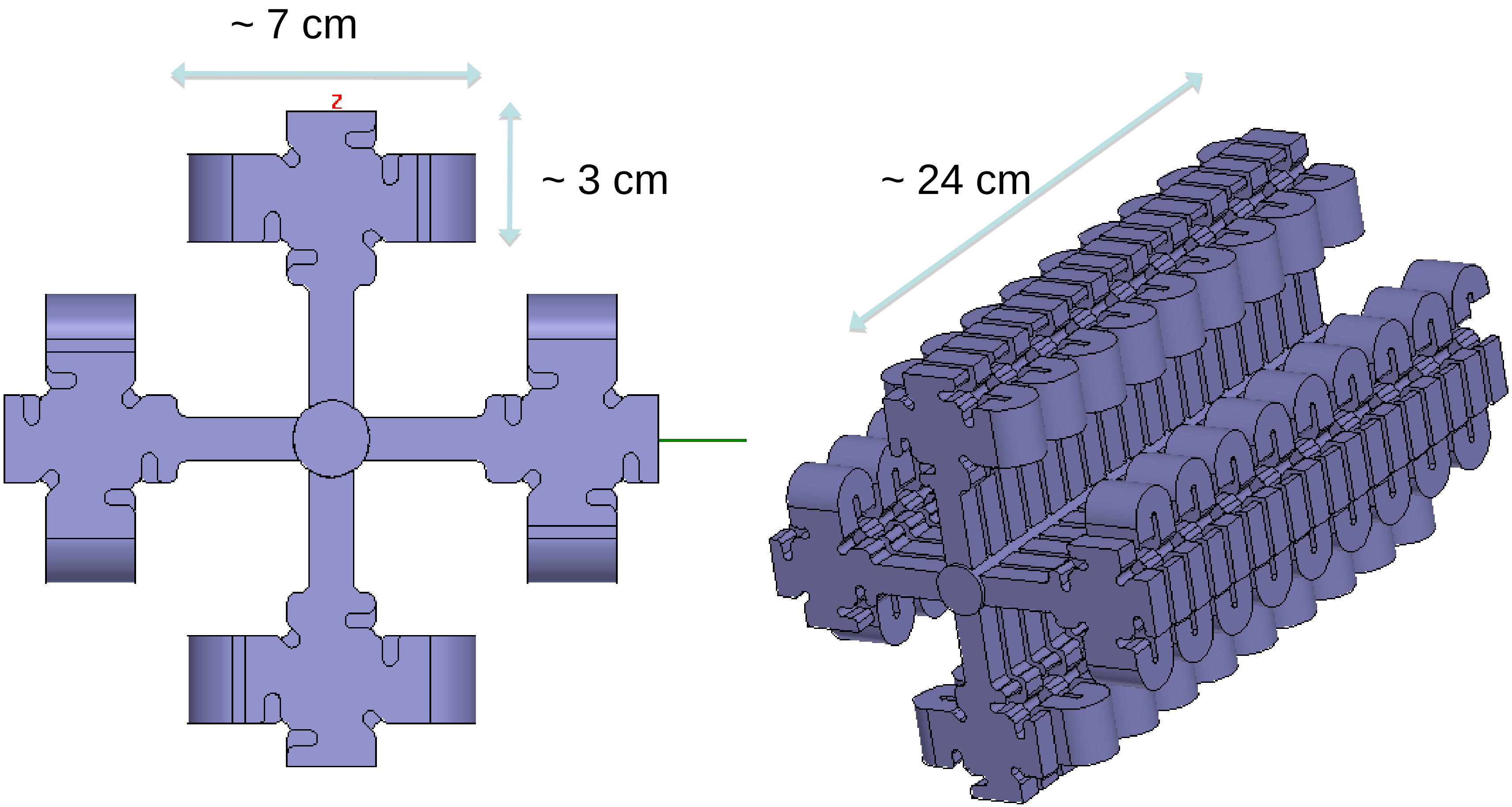
1C-SW-A3.75-T2.2-Cu
10 MW input



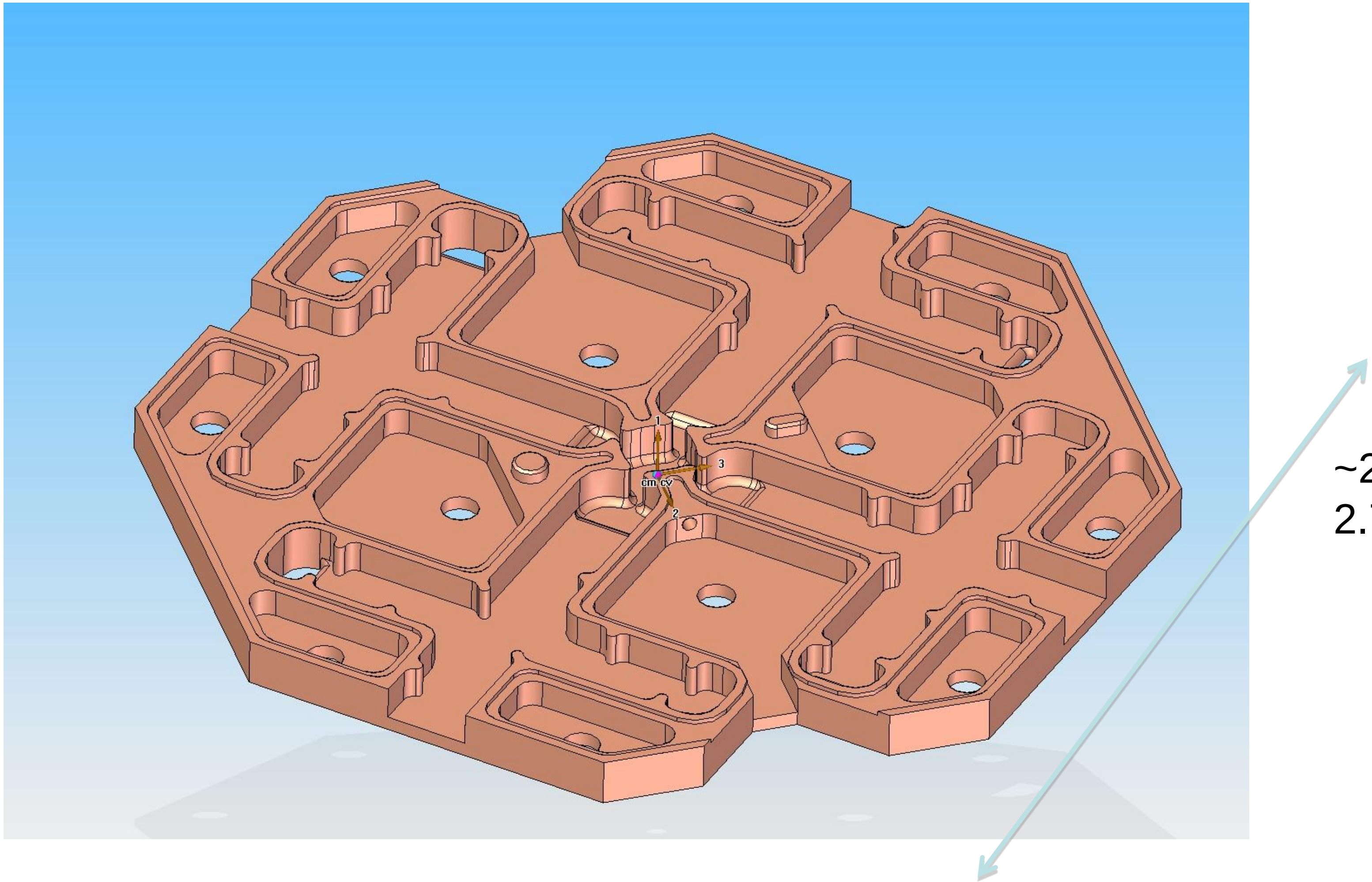


Resonance at 11.424 GHz β = 1.007

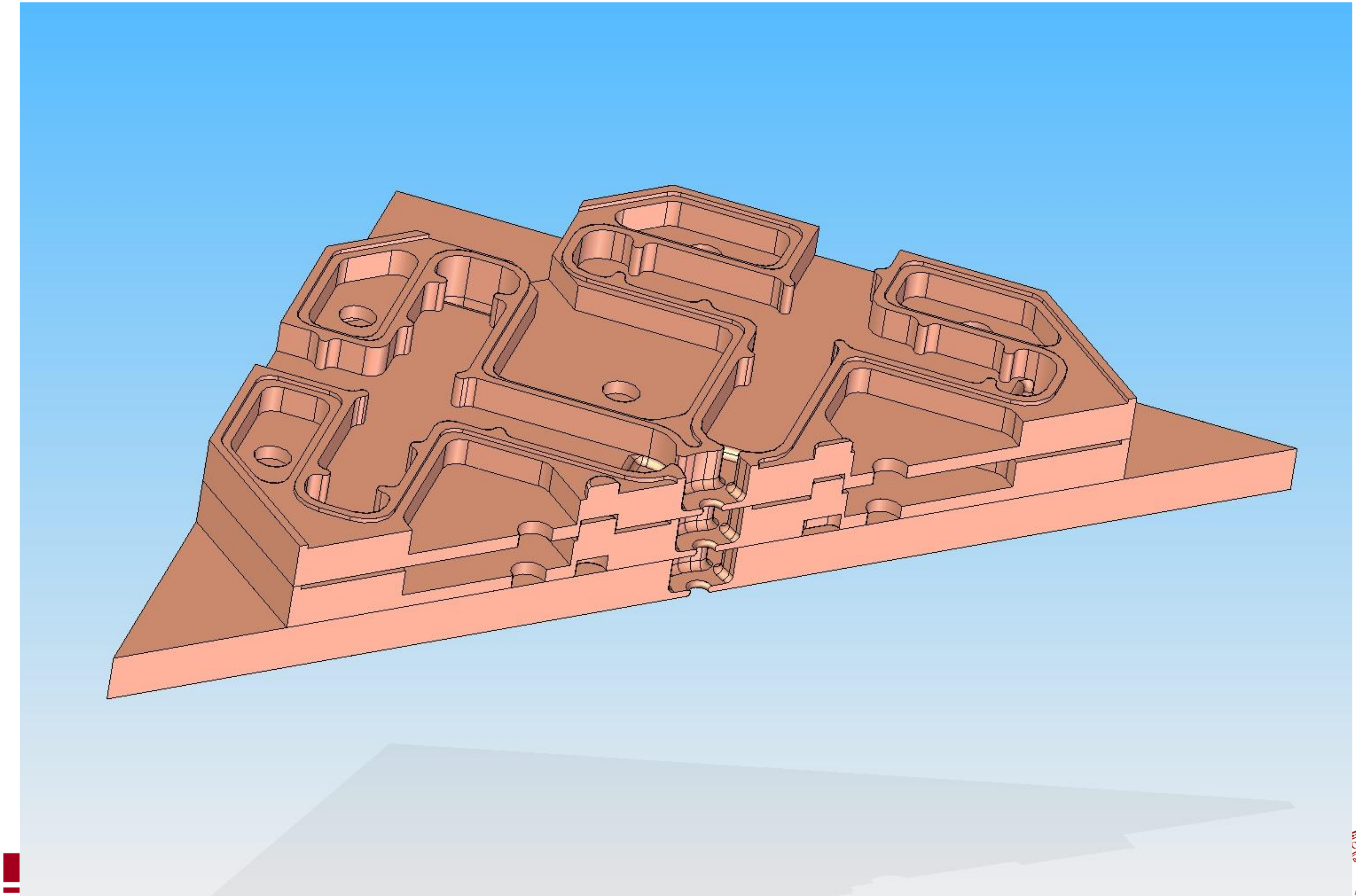
RF Feed Using Biplanar Coupler



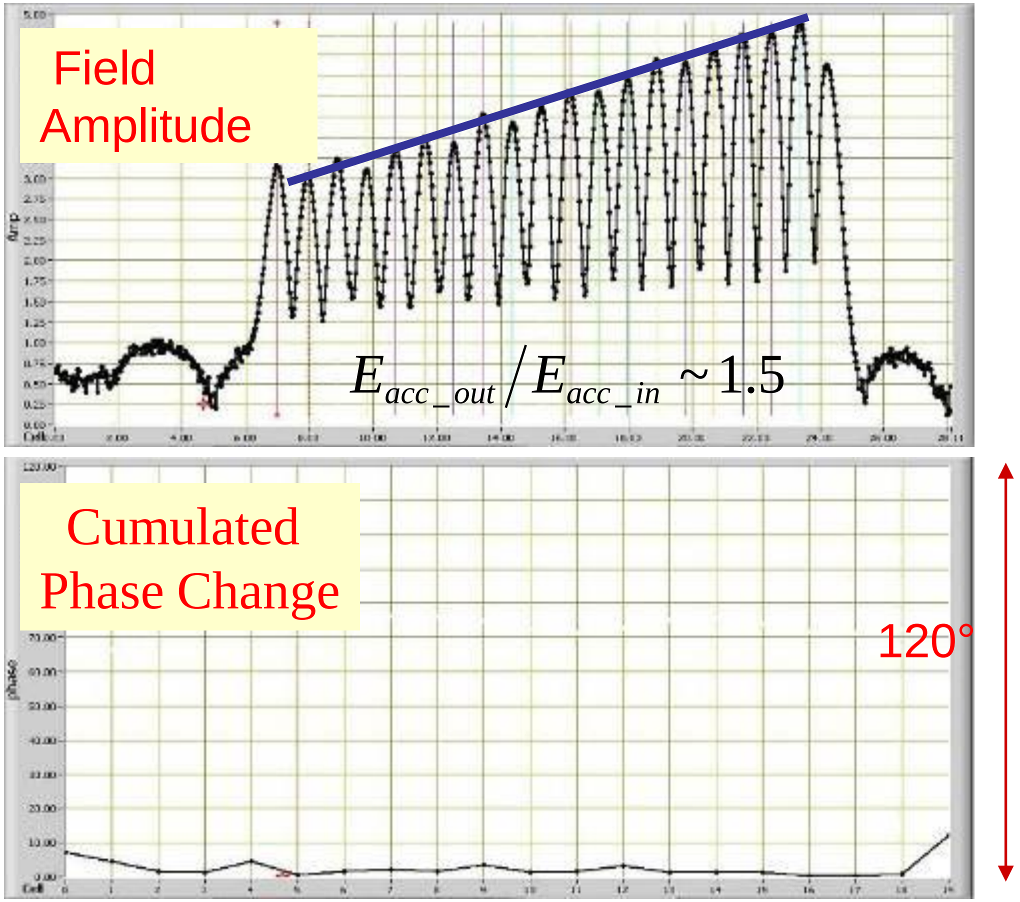
Current Mechanical Design



~25 cm
2.7 kg



T18_VG2.4_DISC Structure Test



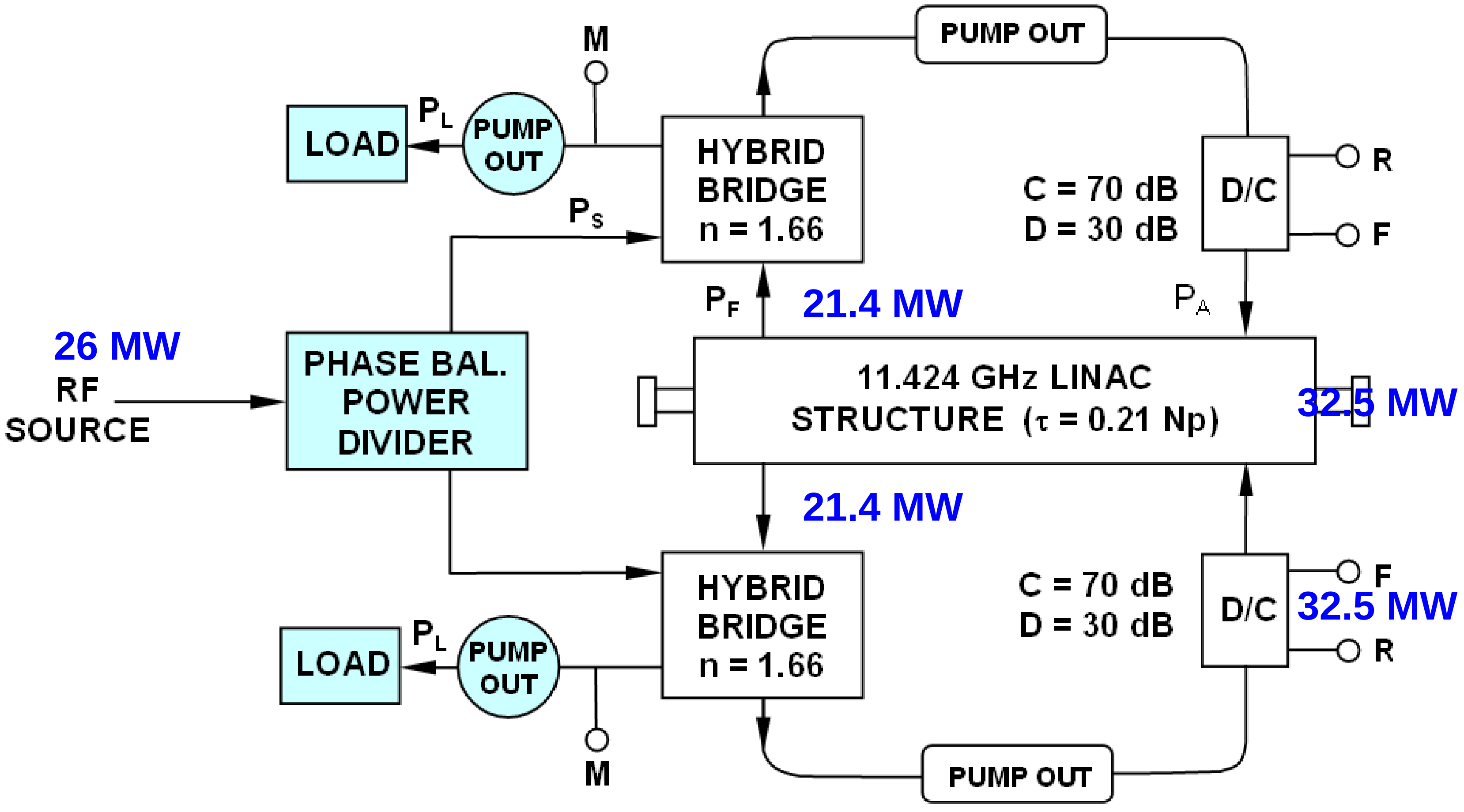
$$E_{acc\_out} / E_{acc\_in} \sim 1.5$$

Microwave Tuning and test

J. Wang

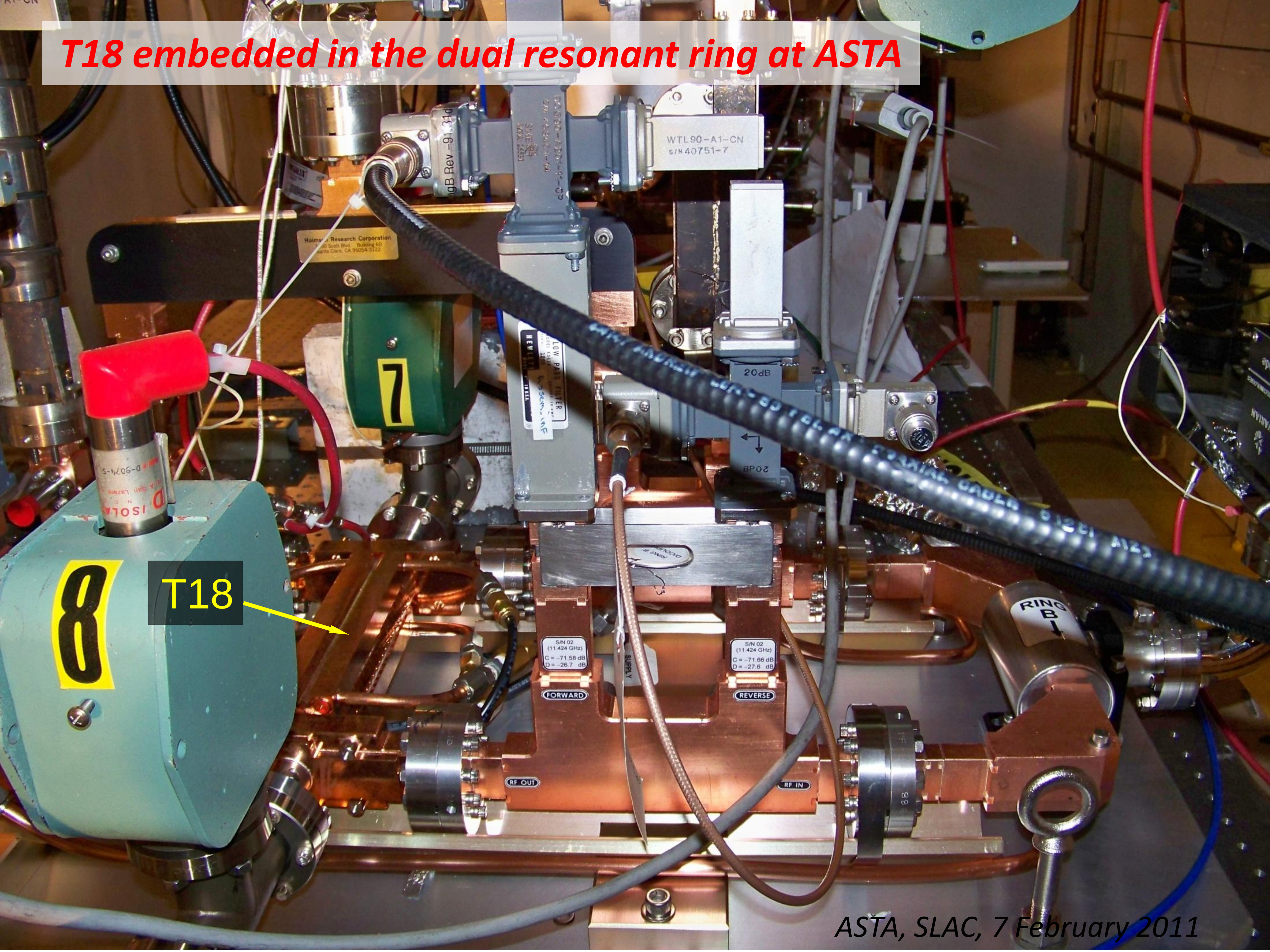
An 11.424 MHz Dual Resonant Ring System for High Gradient Testing CLIC/KEK/SLAC T18 Structures

Power Distribution to Achieve an Unloaded Accelerating Gradient of 108 MV/m



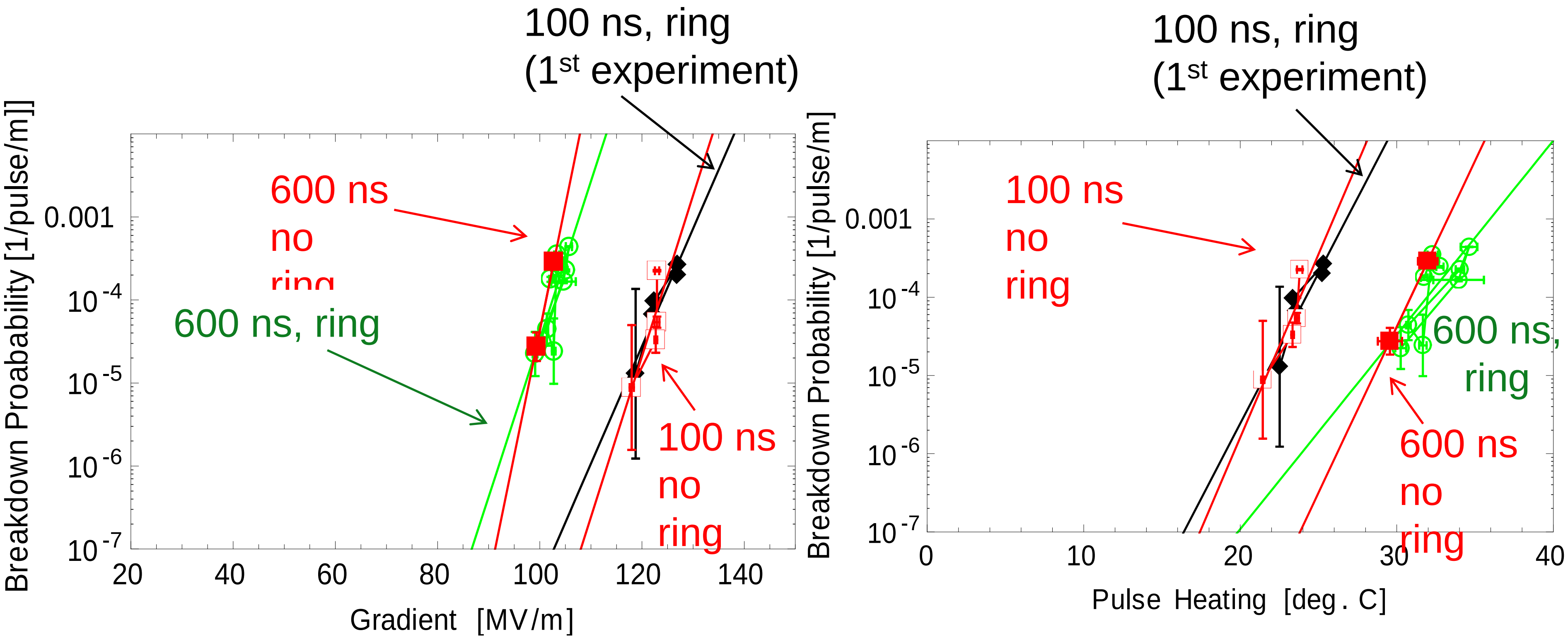
Jake Haimson

T18 embedded in the dual resonant ring at ASTA



ASTA, SLAC, 7 February 2011

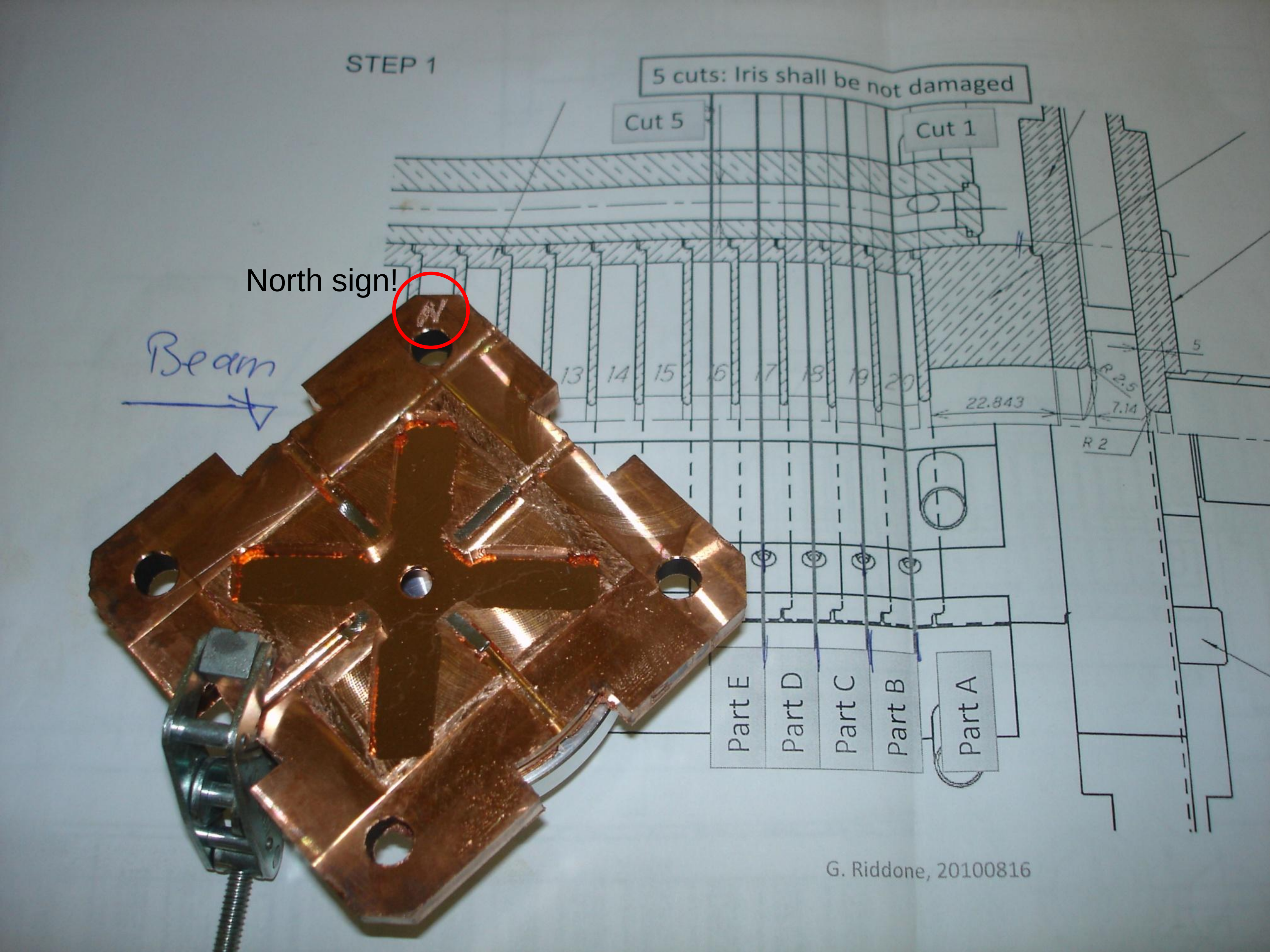
Summary of T18 in resonant ring up to 21st of June 2011



Valery Dolgashev, Jim Lewandowski and Stephen Weathersby, 1 June 2011

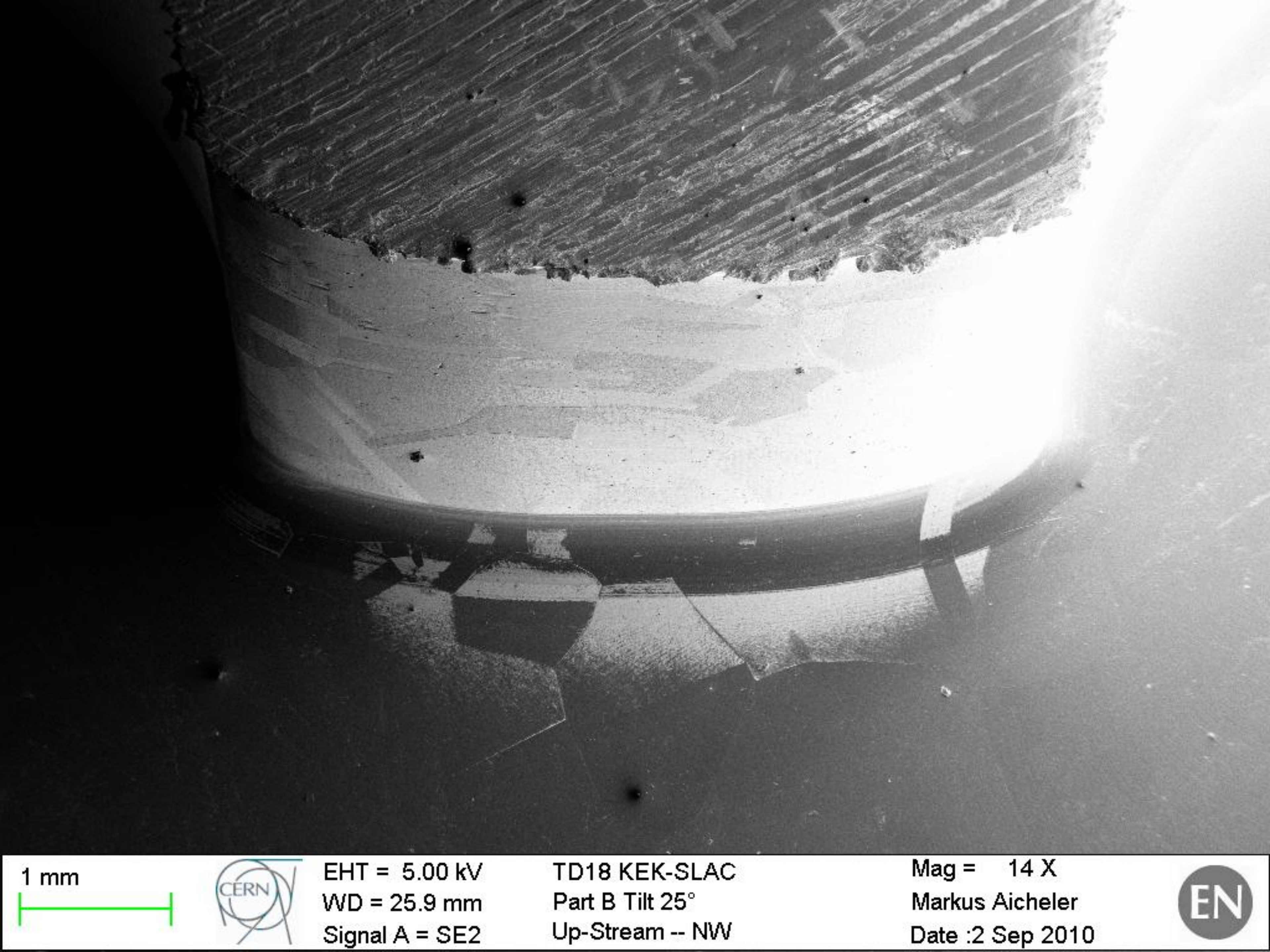
Results of tests of T18 with and without Jake Haimson's resonant ring

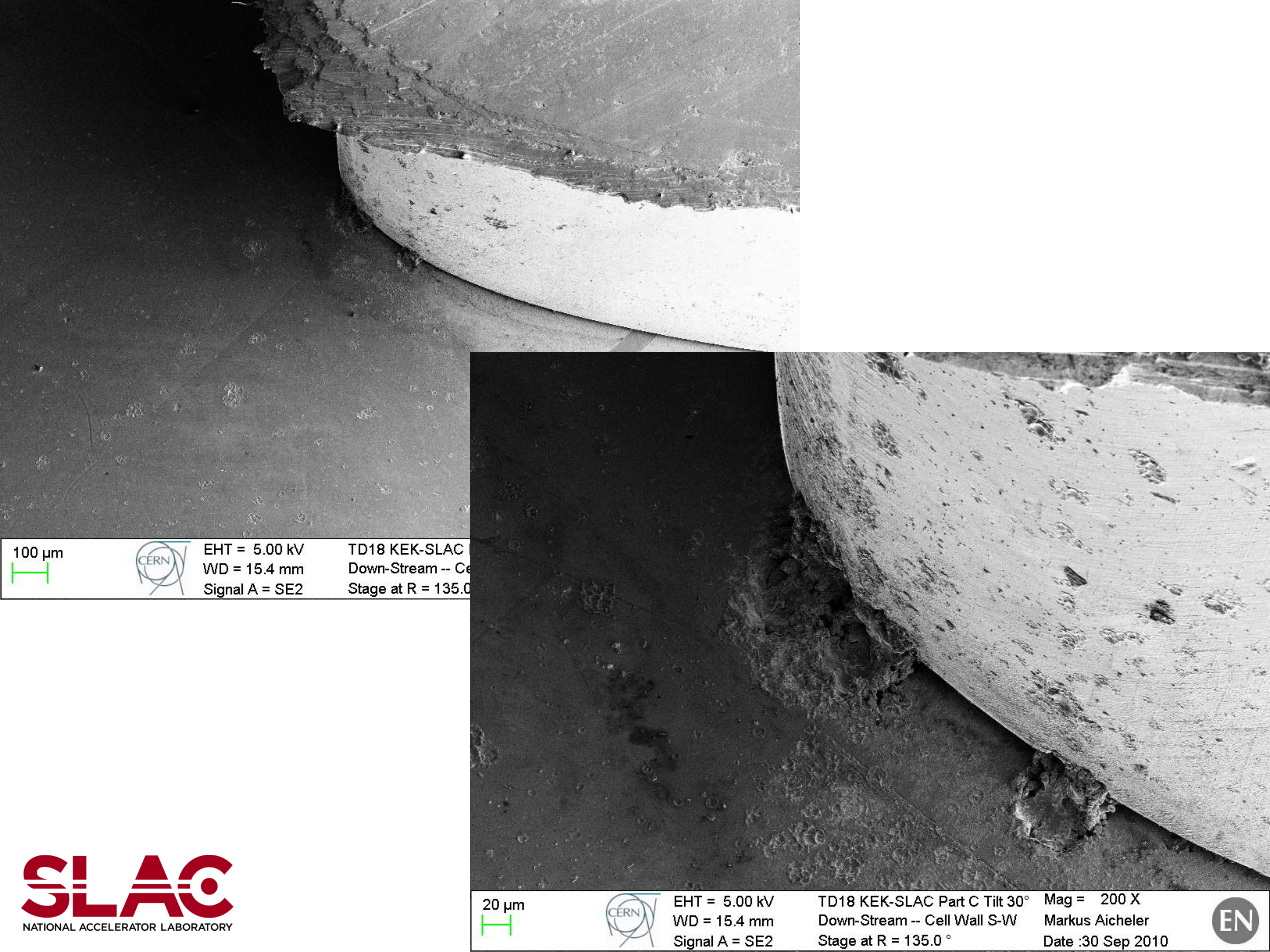
- Structure in a ring recovers has less number of destructive breakdowns and recovers faster from such breakdowns.
- It seems that during stable operation (between destructive breakdowns and breakdown chains) the breakdown probability is the same with the ring and without it.
- In the current experiment structure with ring needed about 3 time less power for the same gradient then with the ring, with may help testing similar structure with moderate rf power.



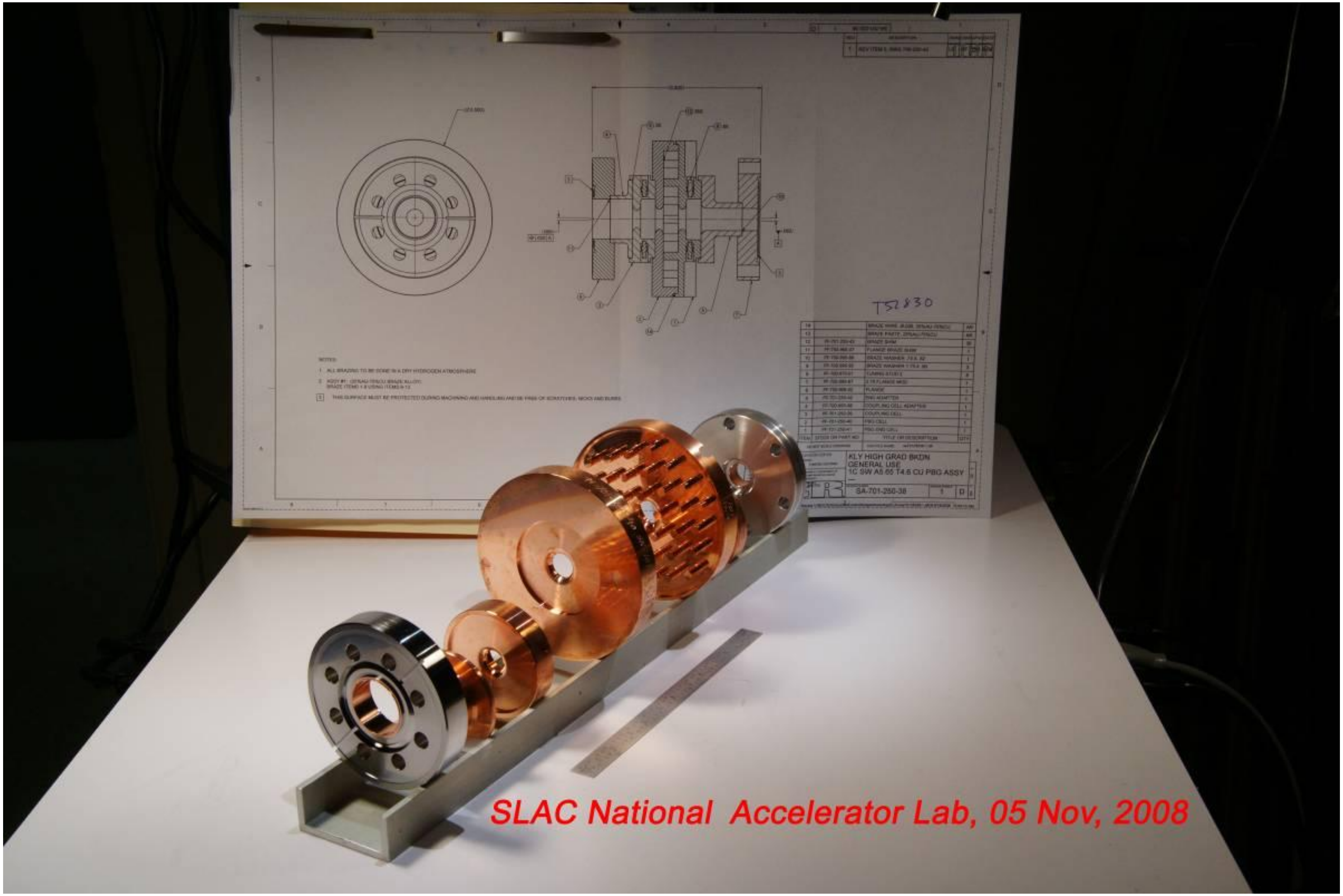
North sign!

STEP 1
5 cuts: Iris shall be not damaged
Cut 5
Cut 1
Beam
N
13
14
15
16
17
18
19
20
22.843
R 2.5
7.14
5
R 2
Part E
Part D
Part C
Part B
Part A
G. Riddone, 20100816


1 mm
CERN
EHT = 5.00 kV
WD = 25.9 mm
Signal A = SE2
TD18 KEK-SLAC
Part B Tilt 25°
Up-Stream -- NW
Mag = 14 X
Markus Aicheler
Date :2 Sep 2010
EN

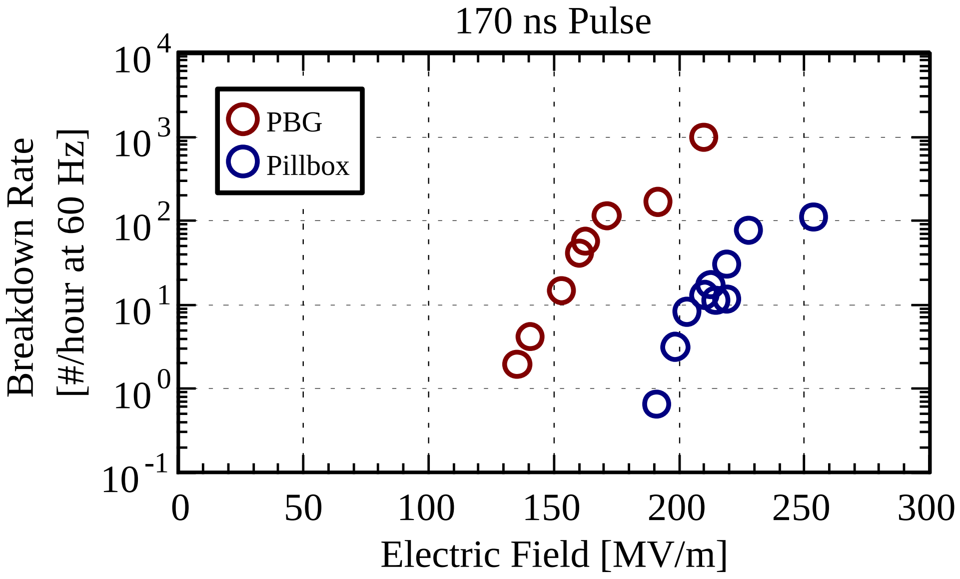

100 µm
CERN
EHT = 5.00 kV
WD = 15.4 mm
Signal A = SE2
TD18 KEK-SLAC
Down-Stream -- Ce
Stage at R = 135.0
20 µm
CERN
EHT = 5.00 kV
WD = 15.4 mm
Signal A = SE2
TD18 KEK-SLAC Part C Tilt 30°
Down-Stream -- Cell Wall S-W
Stage at R = 135.0 °
Mag = 200 X
Markus Aicheler
Date :30 Sep 2010
EN

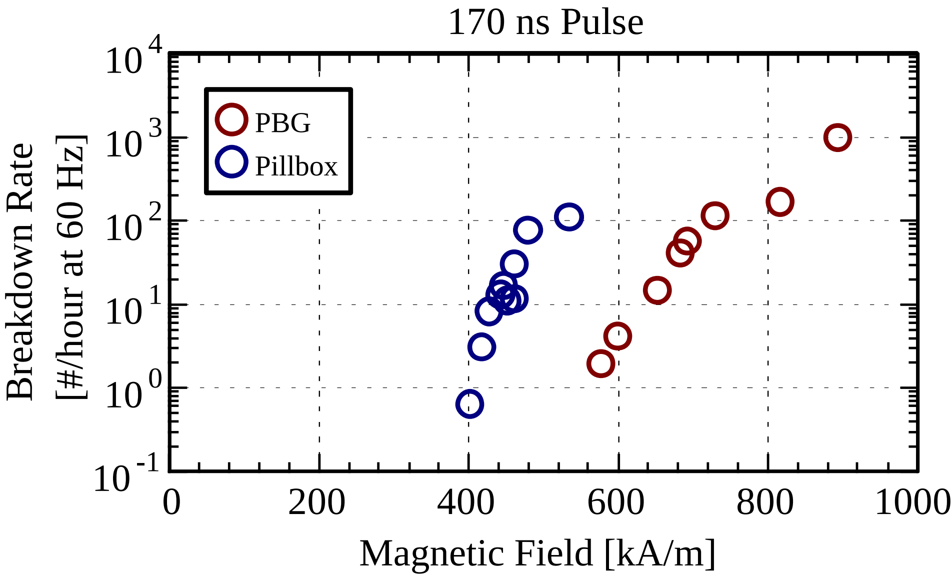
PBG Structure Fabricated at SLAC

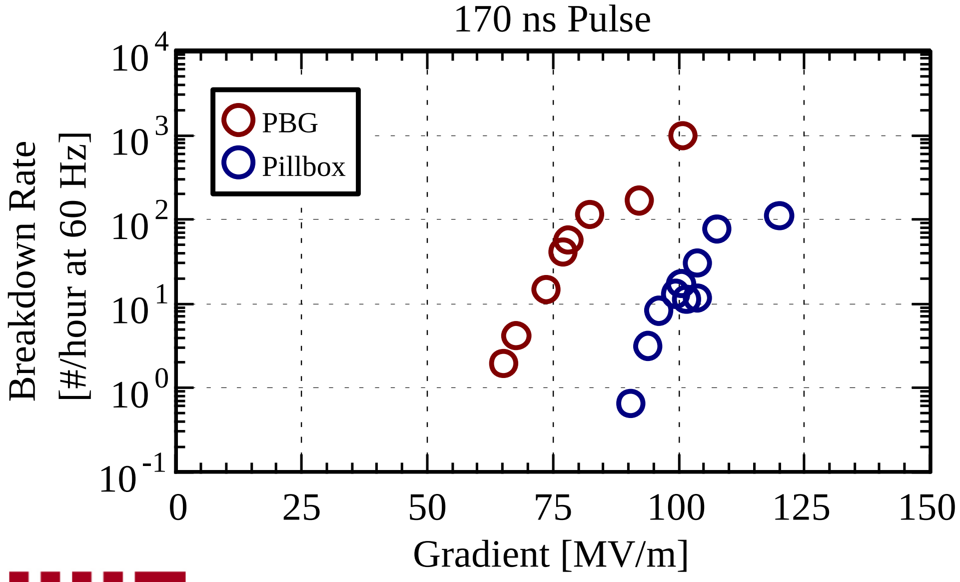


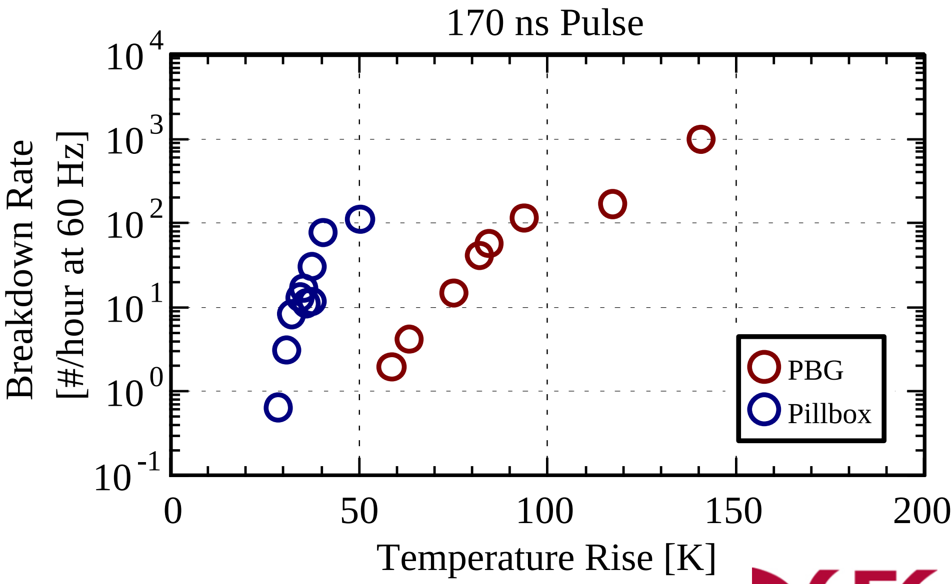
SLAC National Accelerator Lab, 05 Nov, 2008

Breakdown Data



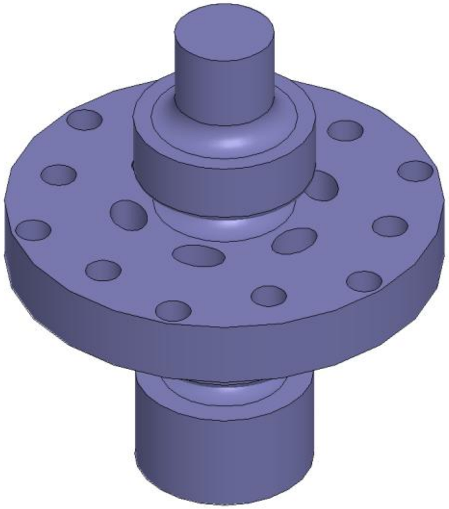




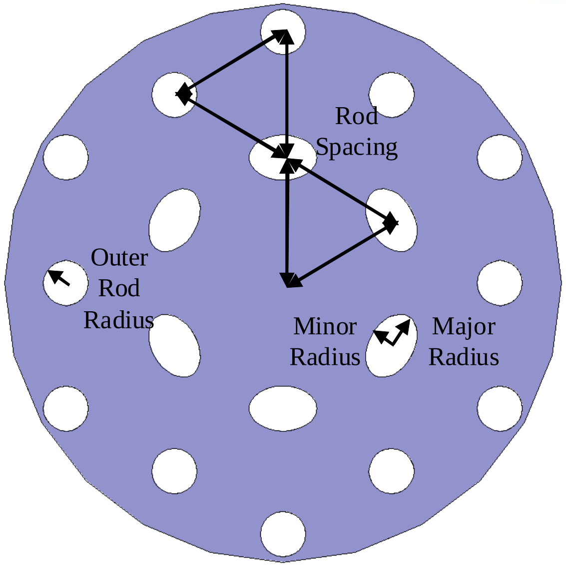


Elliptical-rod Design at 11 GHz

- Standing wave design with 2 matching cells, one test cell
- Axially powered via TM_{01} mode launcher
- Structure has elliptical inner rods
  - Spread large H field over larger region → reduce pulsed heating



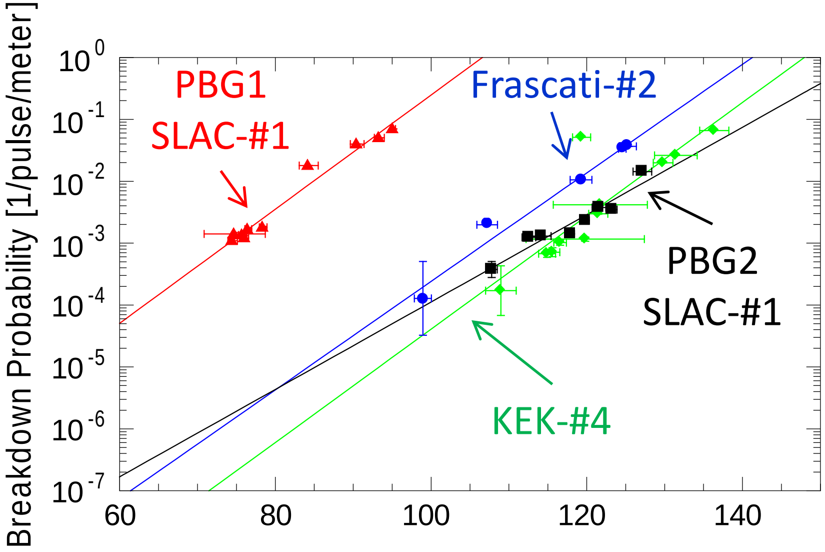
Performance at 100 MV/m		
	Round	Elliptical
Power	5.9 MW	4.4 MW
Peak Surface E Field	208 MV/m	207 MV/m
Peak Surface Magnetic Field	**890 kA/m**	**713 kA/m**
Pulsed Heating for 150ns Flat Pulse	131 K	84 K

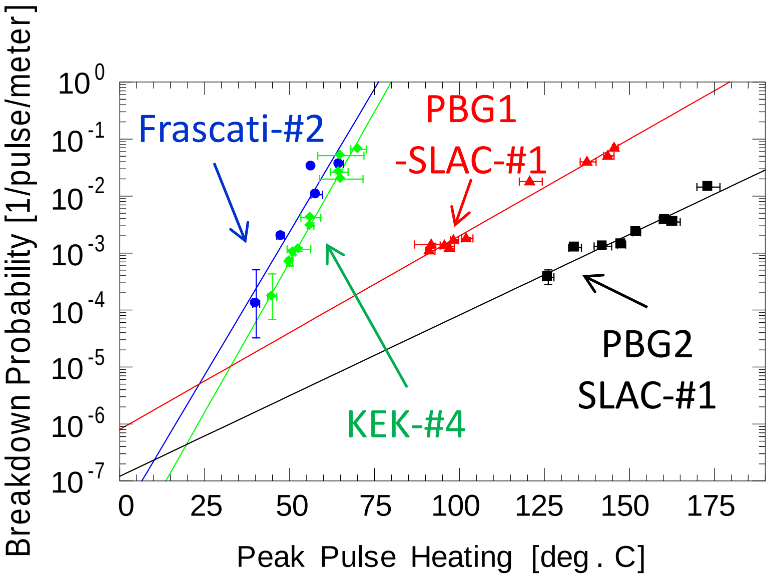


B. J. Munroe, MIT

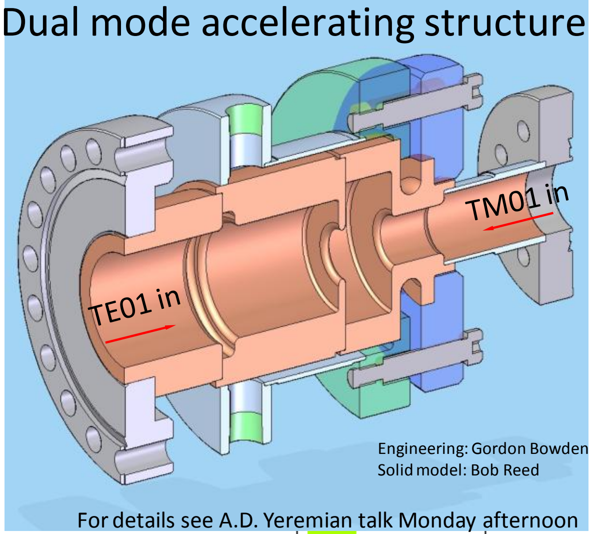
Breakdown rate vs. gradient and pulse heating for 2 disc-loaded and two PBG single-cell structures, *shaped* pulse 150 ns

(A5.65-T4.6-KEK-#4, A5.65-T4.6-Frascati-#2, A5.65-T4.6-PBG-SLAC-#1, , A5.65-T4.6-PBG2-SLAC-#1)





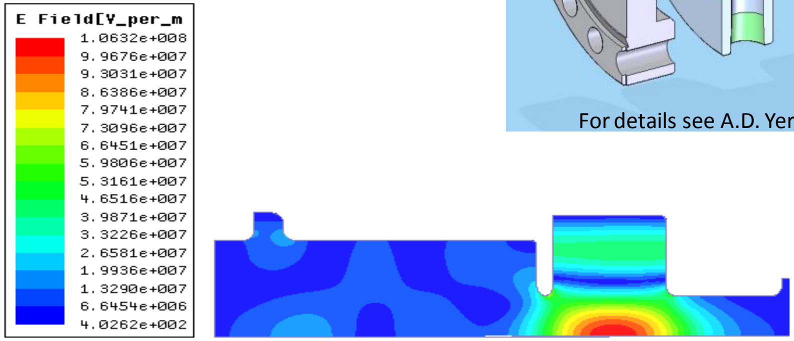
Dual Moded RF Cavity for Studying Electric and Magnetic Field Mixing



Engineering: Gordon Bowden
Solid model: Bob Reed

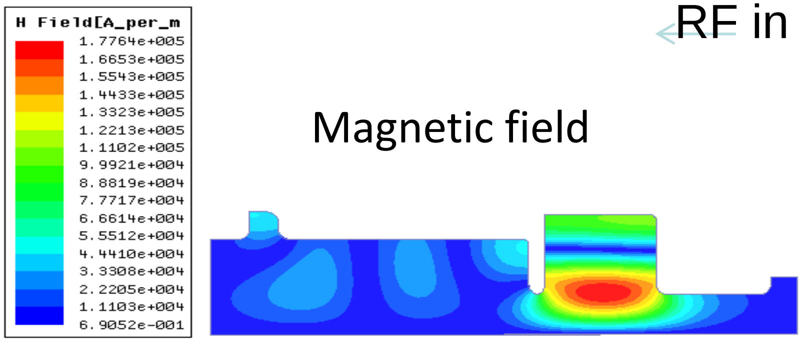
For details see A.D. Yeremian talk Monday afternoon

TM01 mode



RF in

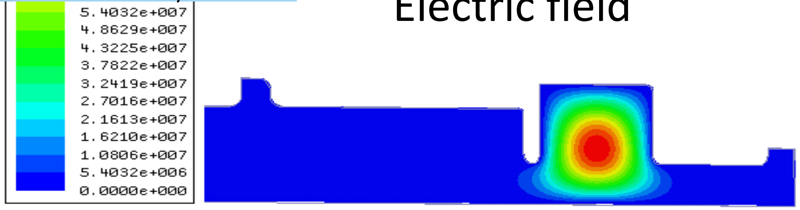
Magnetic field



RF in

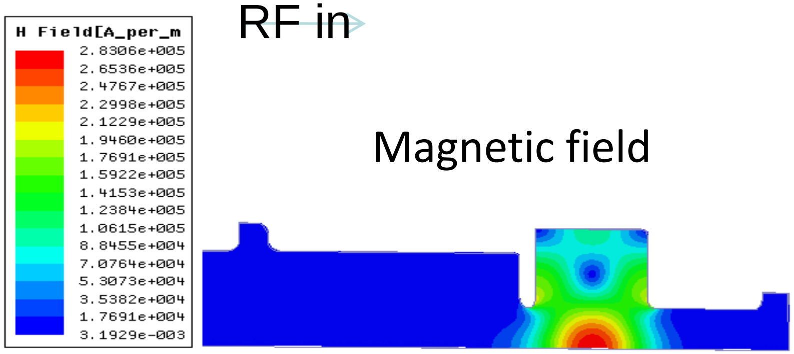
TE01 mode

Electric field



RF in

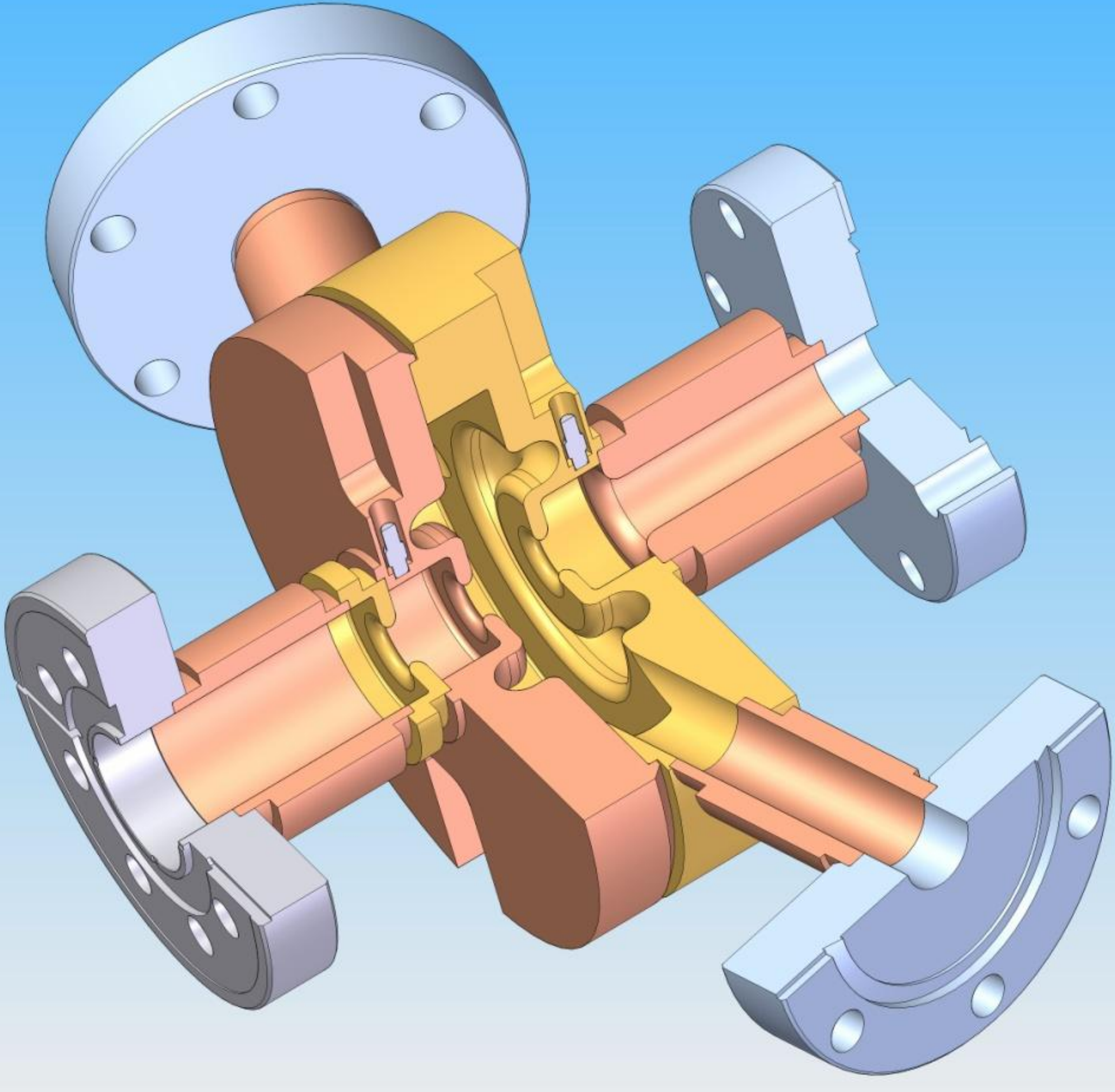
Magnetic field



RF in

A.. D. Yeremian, V. A. Dolgashev, S. G. Tantawi 2011

X Band Full Choke Structure 1C-SW-A3.75-T2.6 View Port-Cu



Solid model by David Martin

Future work/Open Problems

- Full length accelerator structures based on standing wave cells:
  - These are being theoretically designed and modeled. The structure will feature parallel coupling and would look matched like any other traveling wave structure from the outside.
  - We hope to prove a structure capable of exceeding 140 MV/m gradient
- Wakefield damping features are being studied theoretically and experimentally.
- Accelerator structures made of copper alloys are being studied
- The effect of beam-loading on gradient needs to be verified.
- The development of theoretical understanding and Modeling of the RF breakdown phenomena is starting to take shape. however, this is still at its infancy.

Future work/Open Problems

- Future Developments of advanced concepts such as multimoded and multi-frequency structure, Photonic band gap, and dielectric structures will pave the way for a revolution in the art.
- We have to pay attention to these development and create the proper environment that enable its development. This needs sources and enhanced test facilities
- Ultra High Gradient accelerator structures will be not live to its potential without the development of *efficient* RF sources to drive them. The development of these sources has to be given attention in the near future
    - These sources need to have high efficiency
    - operate at low modulator voltages, in hope of an in expensive modulators with short and fall and rise times.
    - Possibly with pulse shapes that mimic that needed for standing wave accelerator structures
    - Possibly with multi frequency output.
- To this end we need expand our collaborative research towards transformational RF source technology.
- We would go about this with the similar philosophy; we would like to open the door for fundamentally new ideas for RF sources, find the fundamental limitations on source designs and adopt around them the design of the system.

Summary

- The work being done is characterized by a strong national and international collaboration. This is the only way to gather the necessary resources to do this work.
- Magnetic field plays a very important role in determining the breakdown probability in a given structure
- The experimental program to date has paved the ground work for the theoretical developments.
- With the understanding of geometrical effects, we have demonstrated standing and traveling wave accelerator structures that work above 100 MV/m loaded gradient.
- Standing wave structures have shown the potential for gradients of 150 MV/m or higher
- Further understanding of materials properties may allow even greater improvements
- We still have not demonstrated a full featured accelerator structure including wakefield damping. This is expected in the near future.

Summary (Continued)

- We have followed our published working plane and our effort is now paving the way for a new understanding of the gradient limits of room temperature accelerators and will allow us to break these barriers for the development of ultra-high gradient structures.

- The availability of SLAC facilities which was developed over the years due to healthy RF technology developments were essential and continue to be essential for these research activity.

- For this to have a healthy future it should be accompanied by a developmental and industrialization program that will maintain and enhance our essential capabilities.

- The effort reported here is just a representative sample of our effort.