Study of Basic Breakdown Phenomena in High Gradient Vacuum Structures

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SLAC National Accelerator Laboratory

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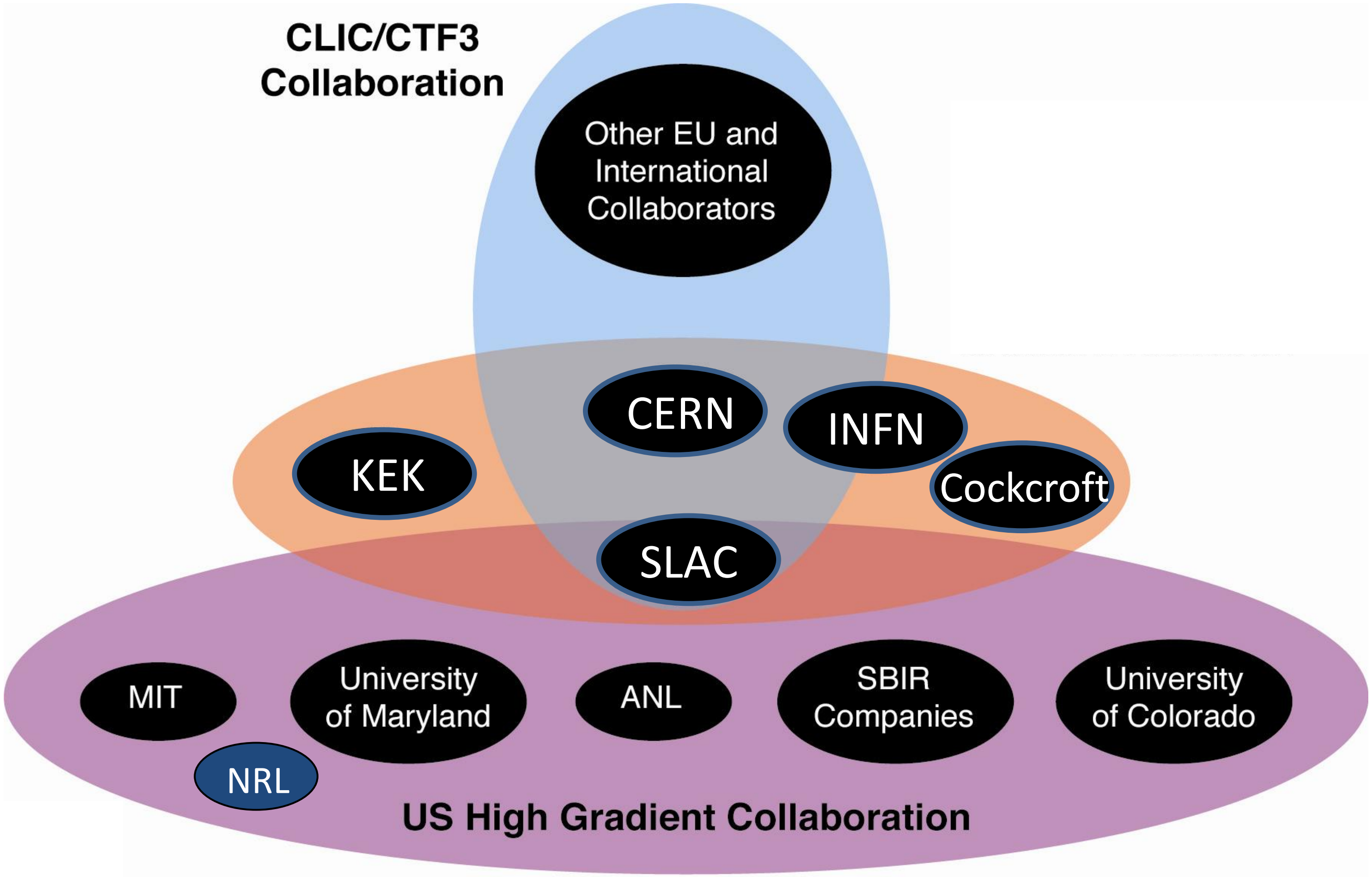
Tsukuba, Japan

International Collaboration on High Gradient Research



- LINAC10: **MOP002, MOP022, MOP023, MOP067, MOP068, MOP069, MOP070, MOP072, MOP074, MOP075, MOP076, MOP077, MOP079, FR104**
- 14th Advanced Accelerator Workshop, Annapolis, Maryland , June 13 - June 19, 2010
- 4th Annual X-Band Structure Workshop, CERN, 3-5 May 2010
- Breakdown Physics Workshop , CERN, 6-7 May 2010

This work is made possible by the efforts

- S. Tantawi, A. Yeremian, J. Lewandowski , J. Wang, C. Adolphsen, F. Wang, C. Nantista, 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, Z. Li, S. Weathersby *of SLAC*
- Y. Higashi *et al., KEK, Tsukuba, Japan*
- B. Spataro *et al., INFN, Frascati, Italy*
- W. Wuensch *et. al., CERN's CLIC team*

Outline

- General approach: simple structures with fast turn around
- Surface processing
- Reproducibility
- Breakdown behavior *vs.* geometry
- Pulse length dependence
- Pulse heating studies
- Breakdown behavior *vs.* materials
- Future directions

Basic Physics Research on RF breakdown

Study dependence of rf breakdown properties on

- Surface Processing Techniques
- Geometry
- Material
- Frequency Scaling
- Circuit
- …

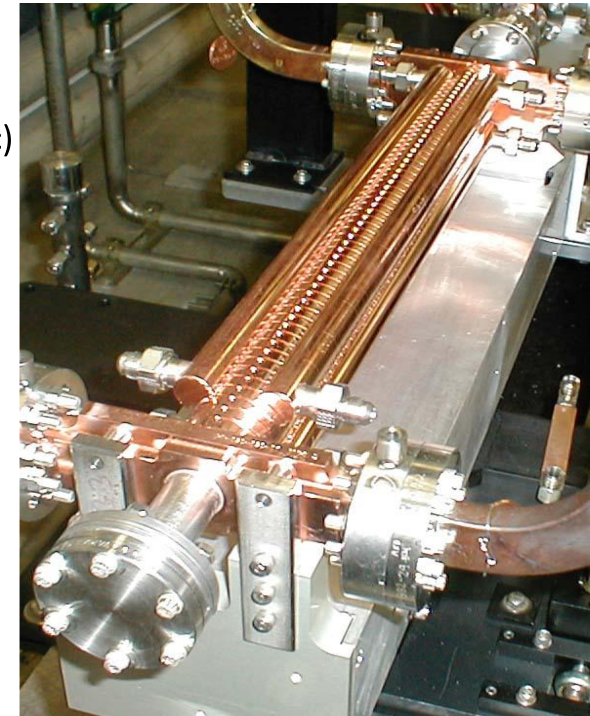
Theoretical developments

Goal: We want to understand and predict breakdown behavior for practical structures

Experimental Studies of Basic RF Breakdown Physics at 11 GHz

T53VG3

(v_g from 3.3% to 1.6% c)



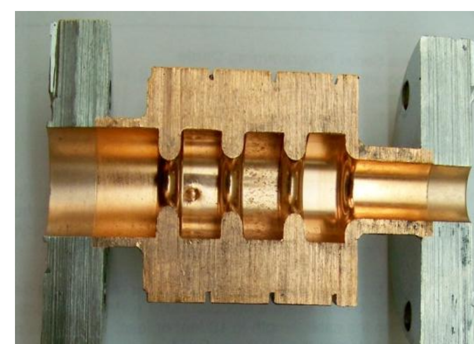
Difficulties:

- Full scale structures are long, complex, and expensive

Solution:

Short Accelerating Structures

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

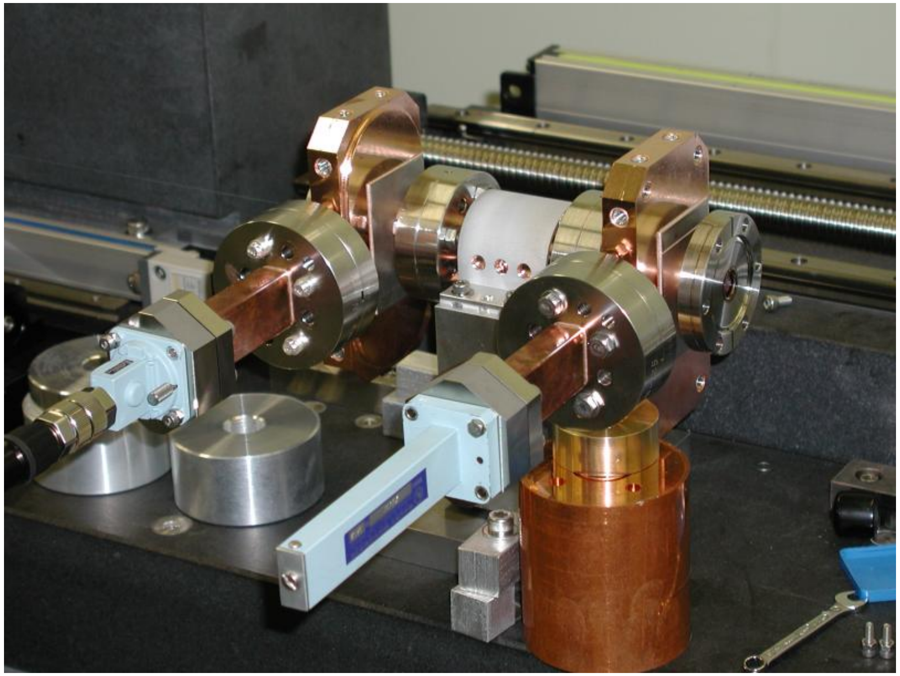


Pulsed Heating Cavity with easy-to-replace samples

Experimental Studies of Basic RF Breakdown Physics at 11 GHz

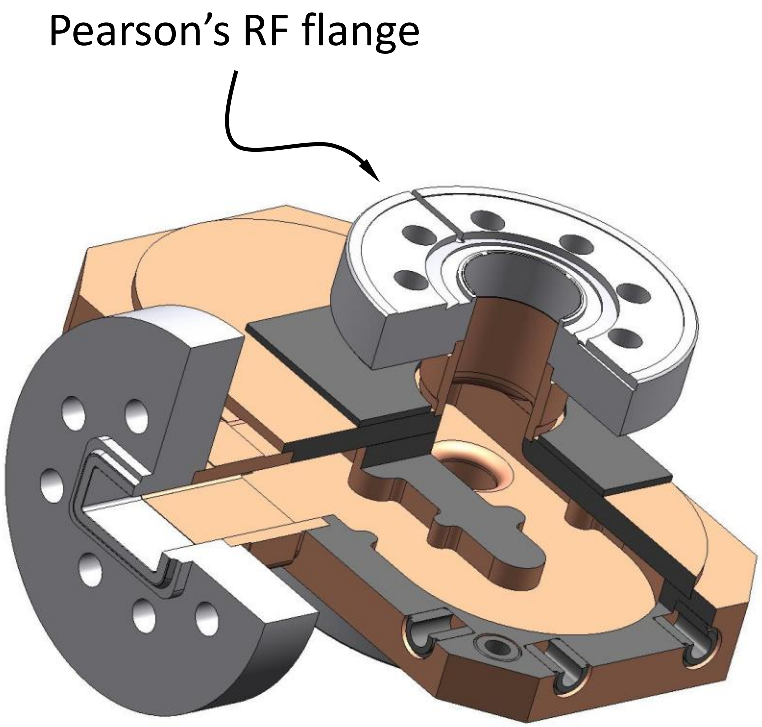
- Single Cell Accelerator Structures
  - standing-wave (SLAC, KEK, INFN-Frascati)
  - traveling-wave (SLAC, KEK, CERN)

SW and TW structures

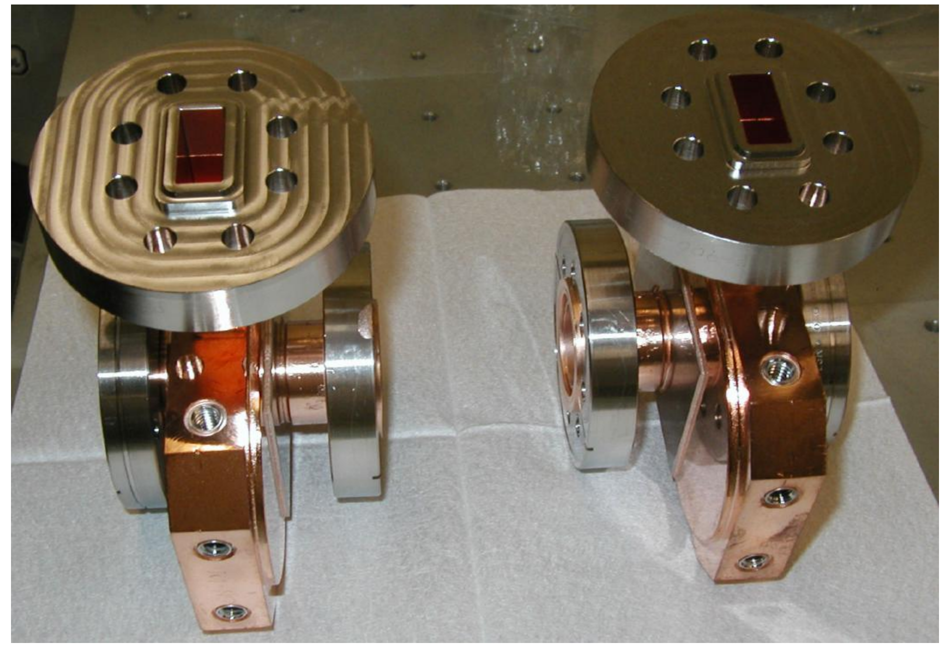


Bead-pull of TW structure

Reusable coupler: TM_{01} Mode Launcher



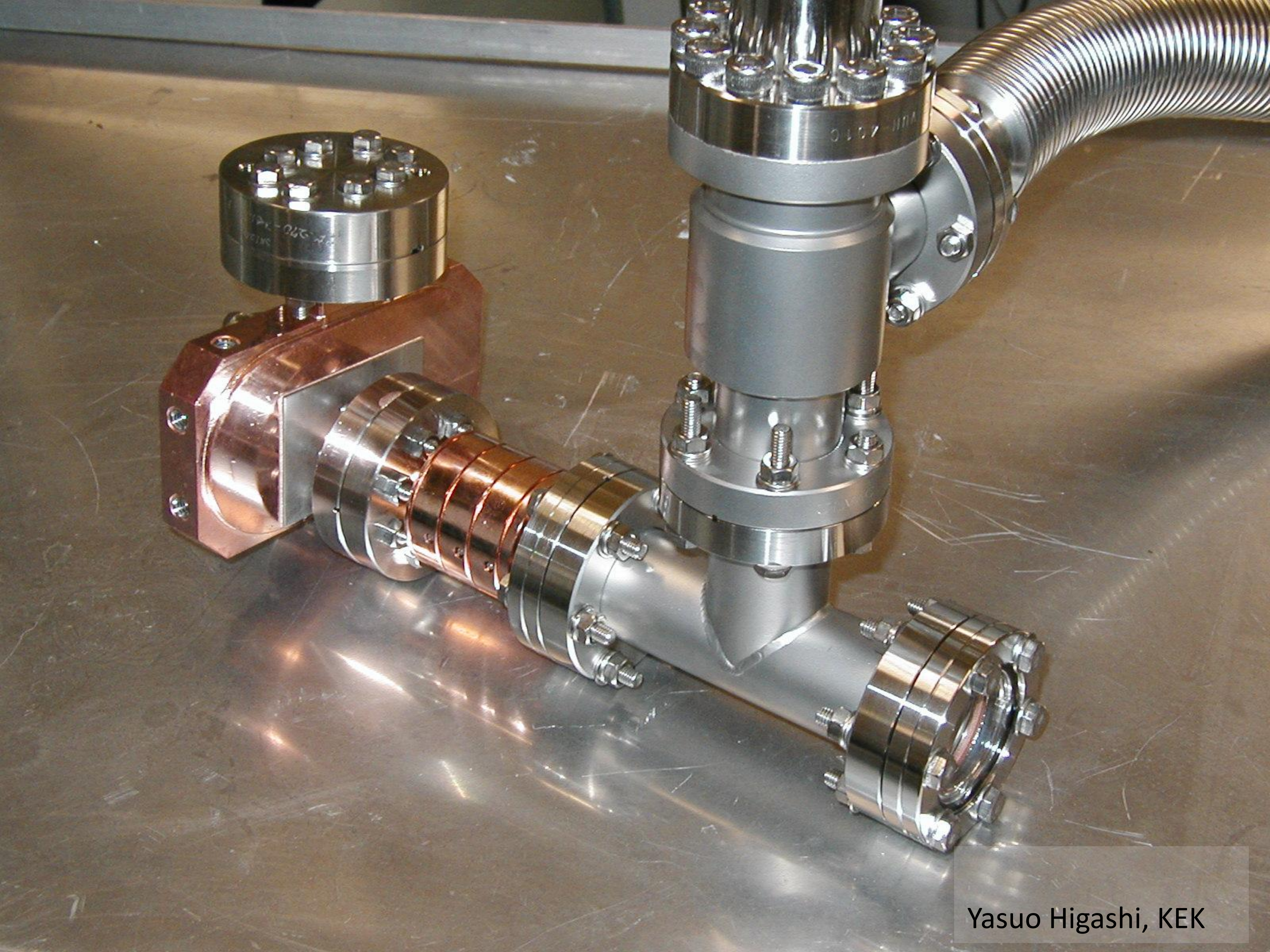
Cutaway view of the mode launcher



Two mode launchers

Surface electric fields in the mode launcher
E_{max}= 49 MV/m for 100 MW

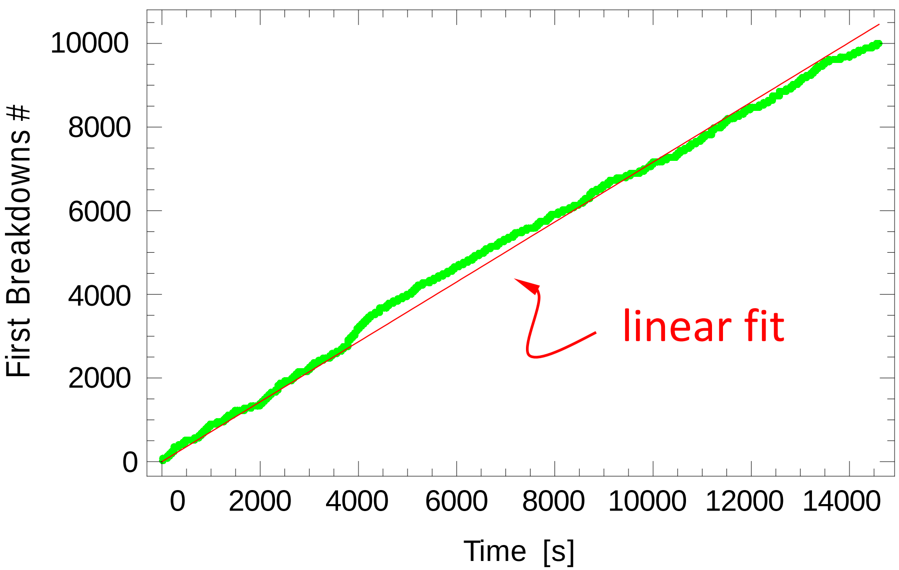
S. Tantawi, C. Nantista


Yasuo Higashi, KEK

Breakdown rate

We use a well defined parameter to characterize rf breakdown behavior:
breakdown rate (# breakdowns/pulse/meter)

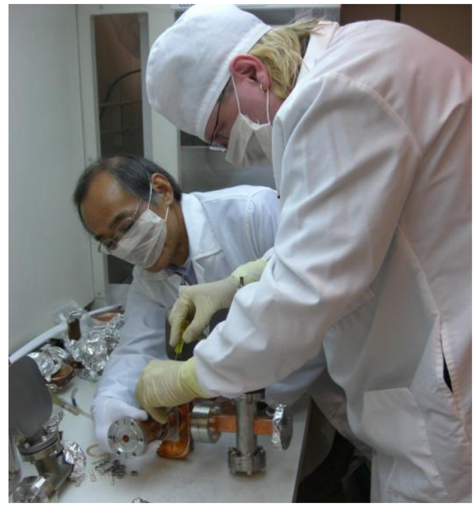
For reference, linear collider CLIC has to have $<10^{-7}$ breakdowns/pulse/meter

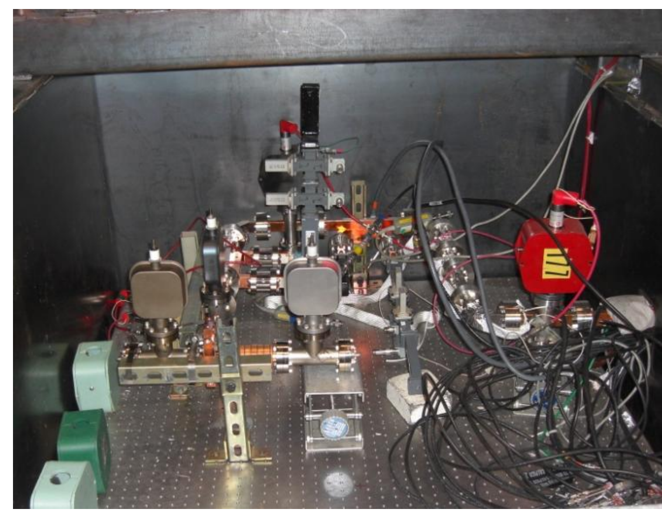


Gradient ~147 MV/m,
pulse heating temperature ~80 deg. C,
breakdown rate ~1/per pulse/meter (2600 per hour at 60 Hz rep rate),
flat part of pulse 200 ns,
data from June 4th, 2008

Surface Processing

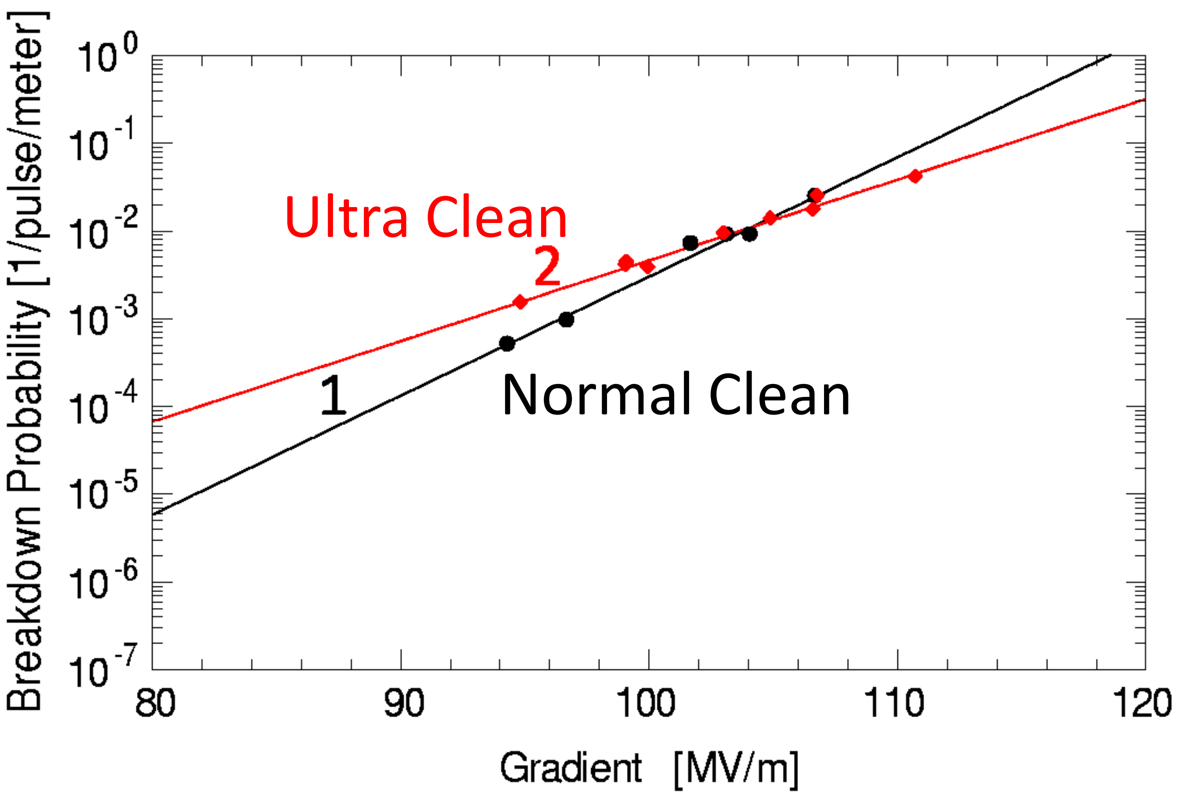
Dr. Yasuo Higashi and Richard Talley assembling 3C-SW-A5.65-T4.6-Cu-KEK-#2





A special structure was built and processed (with best cleaning and surface processing we can master) at KEK and hermetically sealed, then assembled at SLAC at the best possible clean conditions

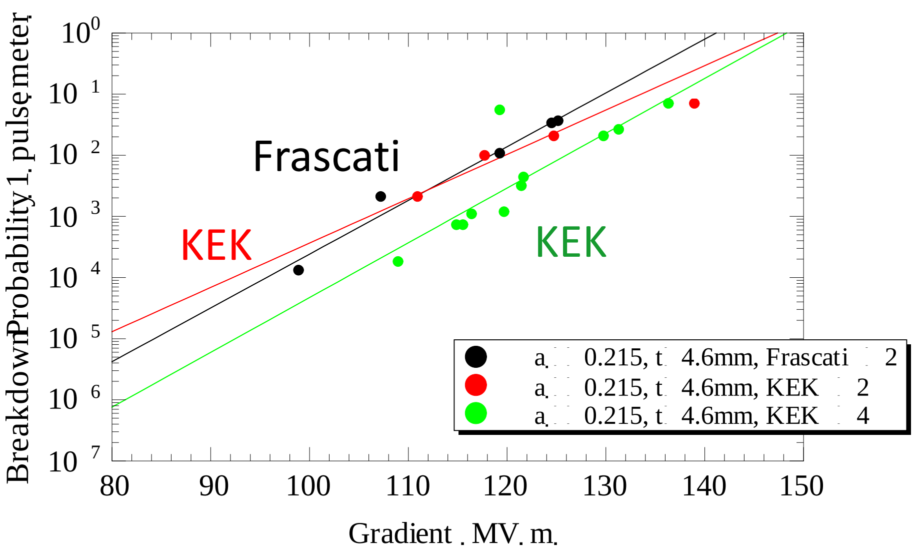
Two structures #1 processed normally and #2 processed similar to superconducting accelerator structures



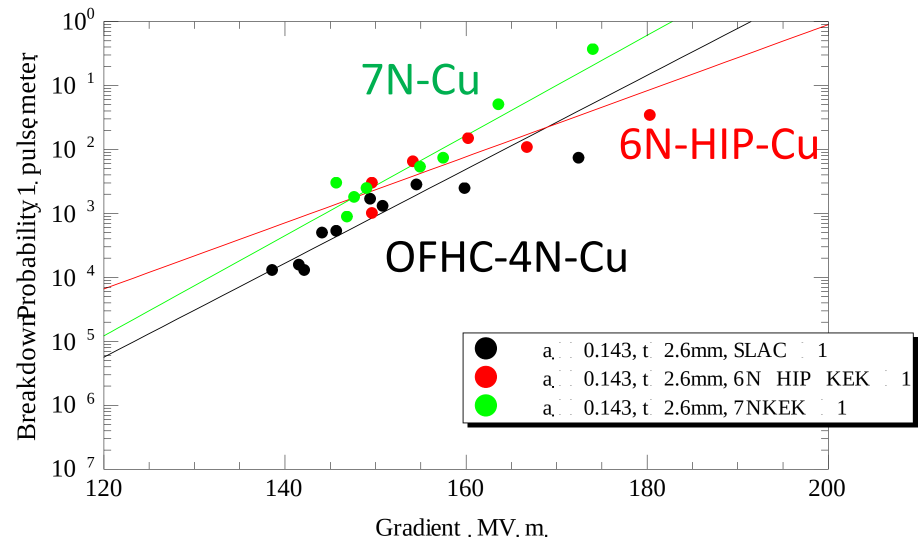
The near perfect surface processing affected only the processing time: the ultra-clean structure was processed in our system in 2.4 10^5 pulses with an accumulated 260 breakdowns in contrast to a 5 10^5 minutes and an accumulated 2000 breakdowns for the normal structure.

Reproducibility of Ultiamate Breakdown Properties for Brazed Copper Structures

Accelerator structures manufactured by different laboratories



Accelerator structures manufactured with different grades of copper purity



Reproducibility

We found that ultimate breakdown rate is reproducible among structures of the same geometry and material.

Practical consequences:

•Because of this reproducibility we can interpolate breakdown performance data to new geometries. We found that extrapolation of the data is often invalid.

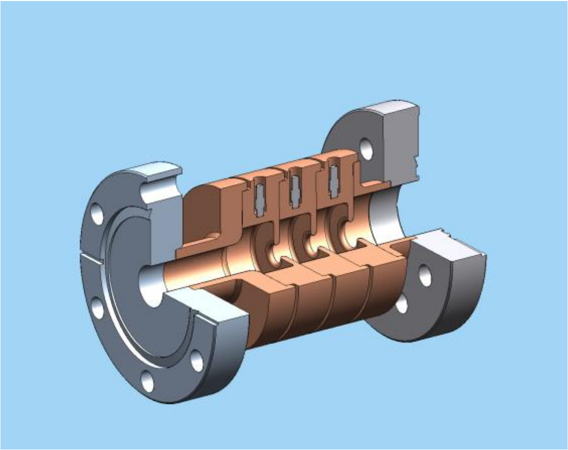
•To predict the breakdown rate a physical model of breakdown performance should have structure drawings and material properties as main (and may be only) inputs.

Dependence of Gradient on Geometry

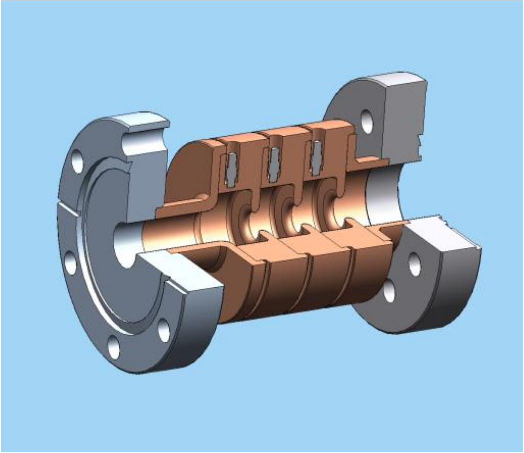
Surface Electric Field *vs.* Surface Magnetic Field

Geometrical Studies

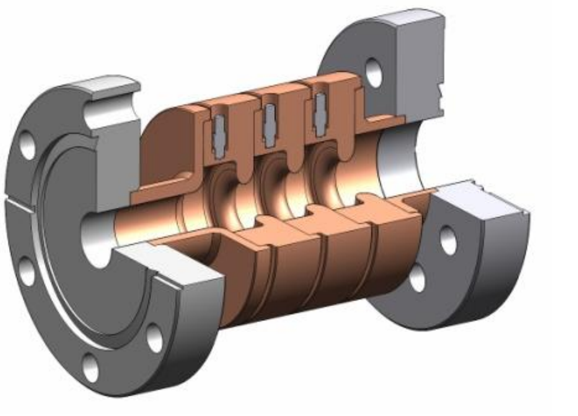
Three Single-Cell-SW Structures of Different Geometries



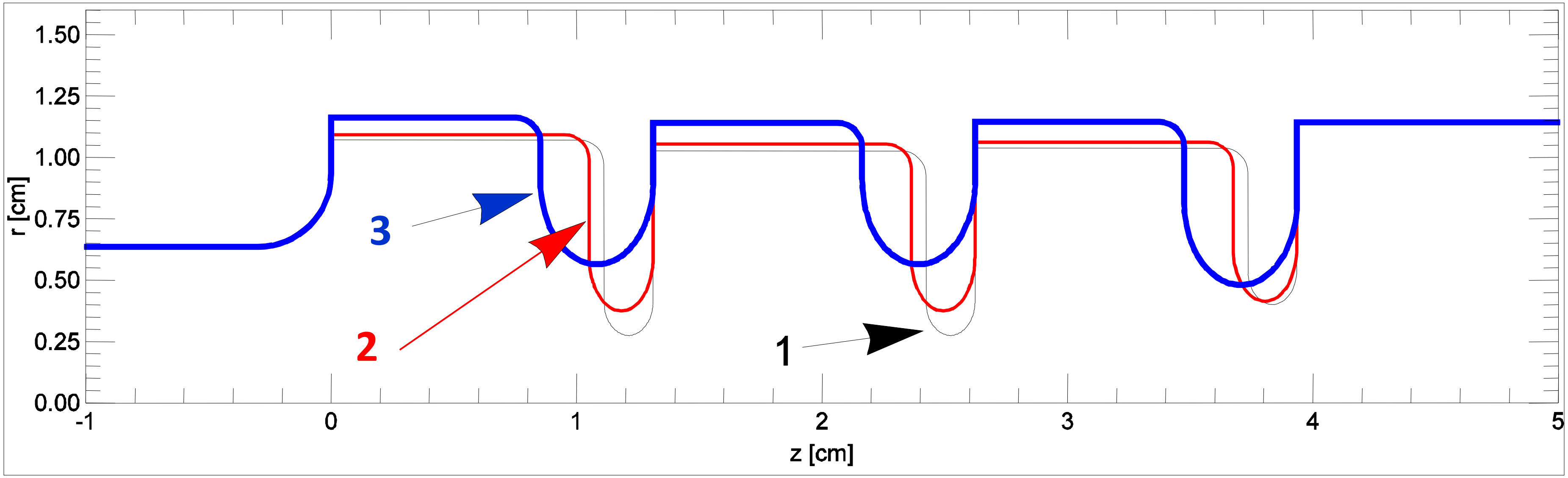
1)1C-SW-A2.75-T2.0-Cu



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

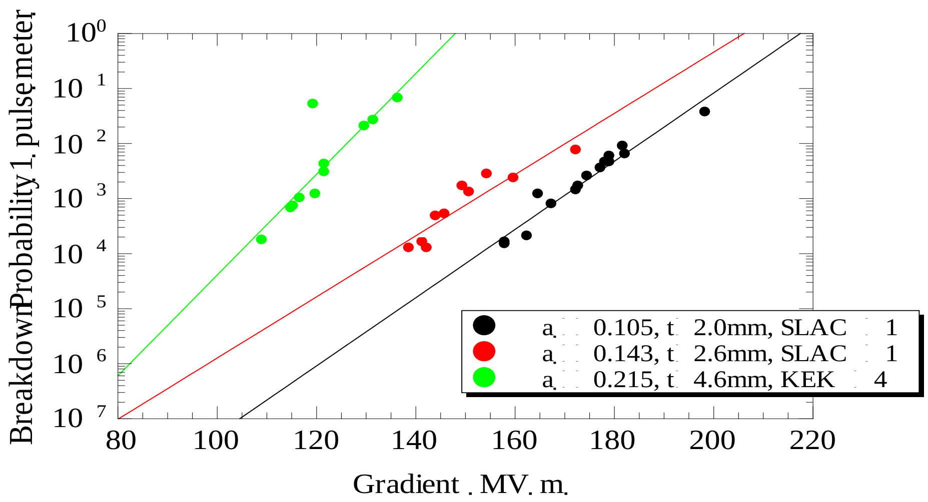


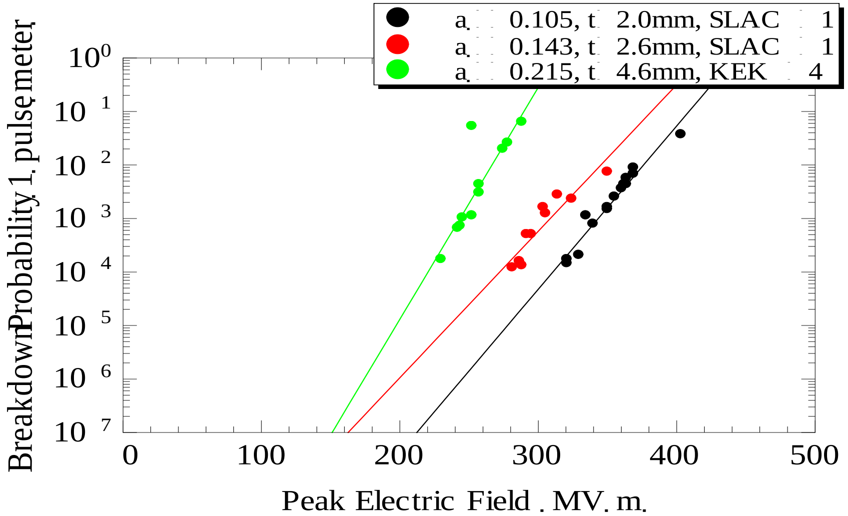
3) 1C-SW-A5.65-T4.6-Cu

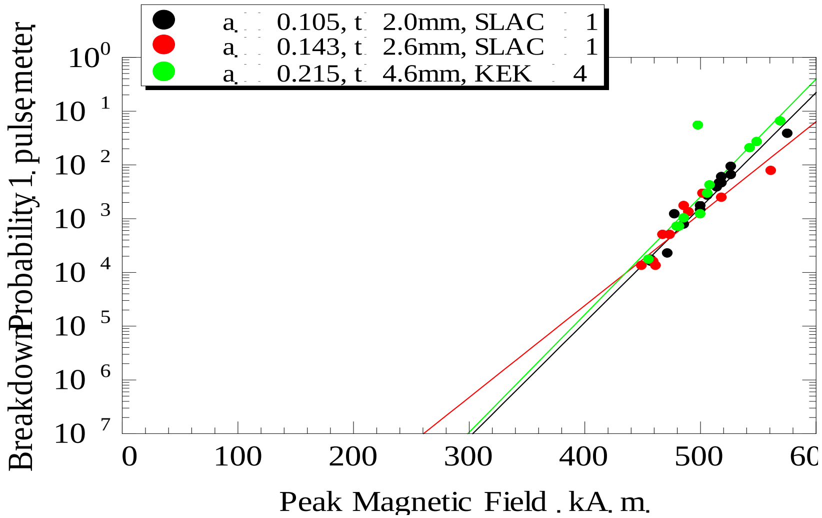


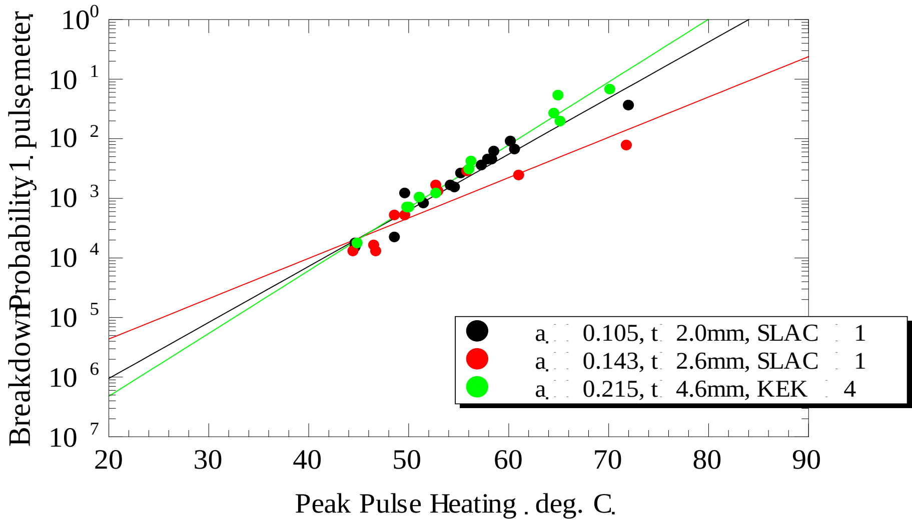
Geometrical Studies

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

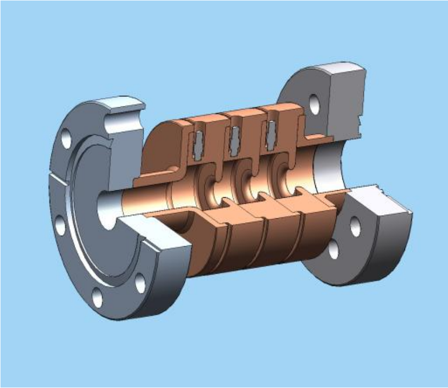




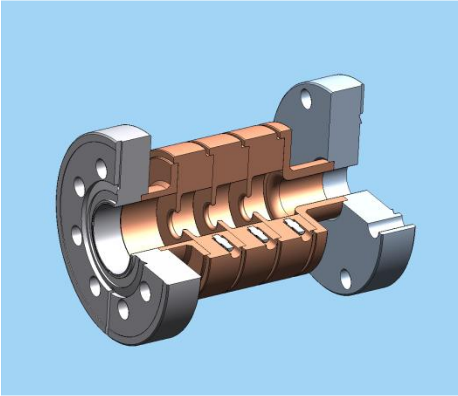




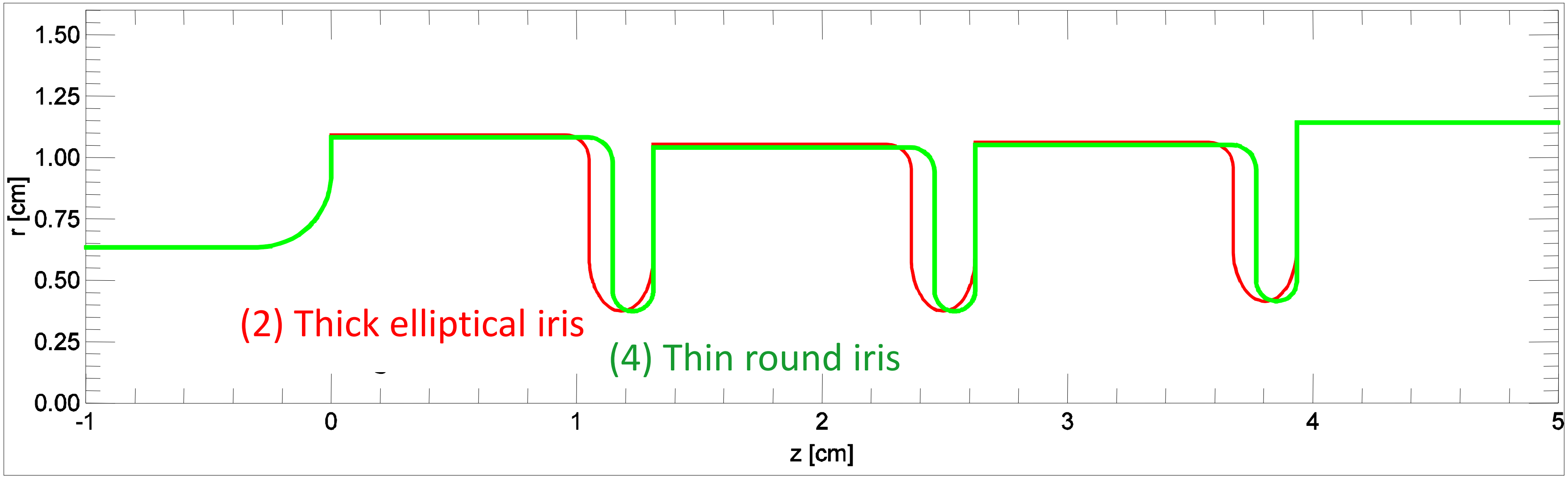
Geometrical Studies
Two Single-Cell-SW Structures with same magnetic but different electric fields



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

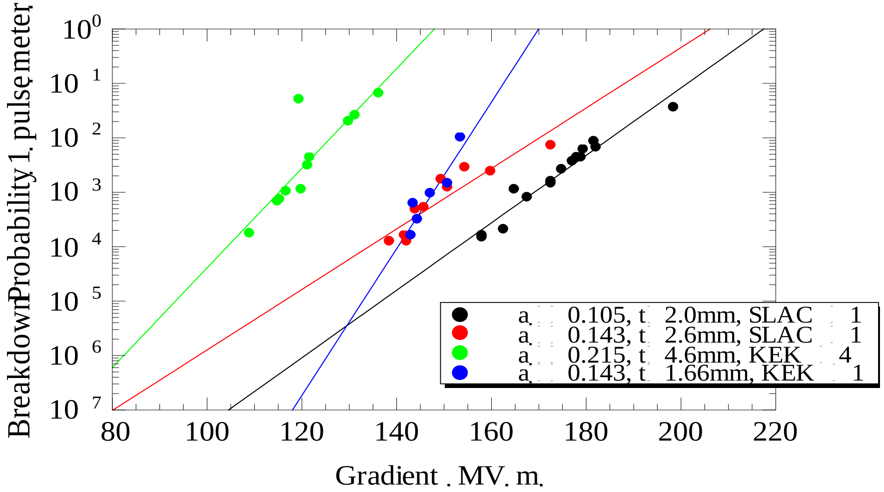


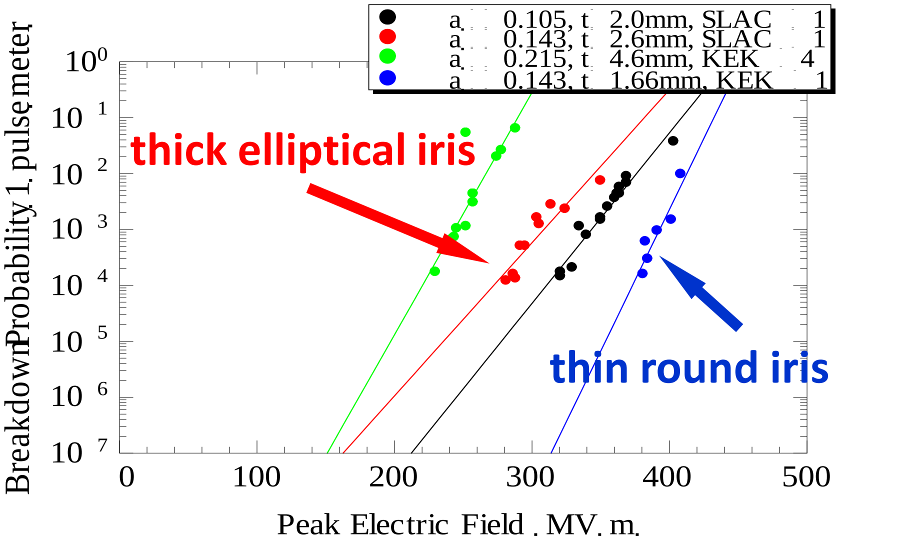
4) 1C-SW-A3.75-T1.66-Cu

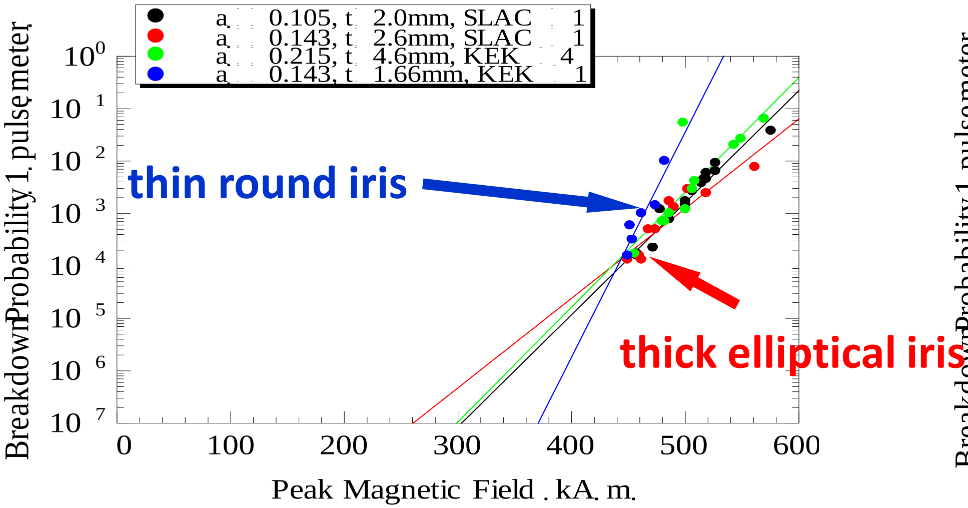


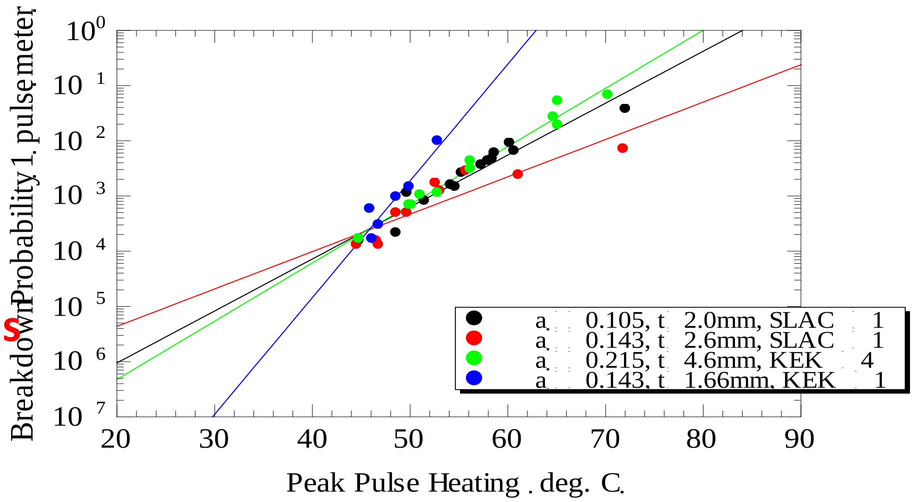
Geometrical Studies

Different single cell structures: Standing-wave structures with different iris diameters and shapes; **a/λ =0.215**, **a/λ =0.143**, and **a/λ =0.105**, and **a/λ=0.143 thin round iris**









Geometry plays a major role in determining the accelerating gradient and breakdown performance:

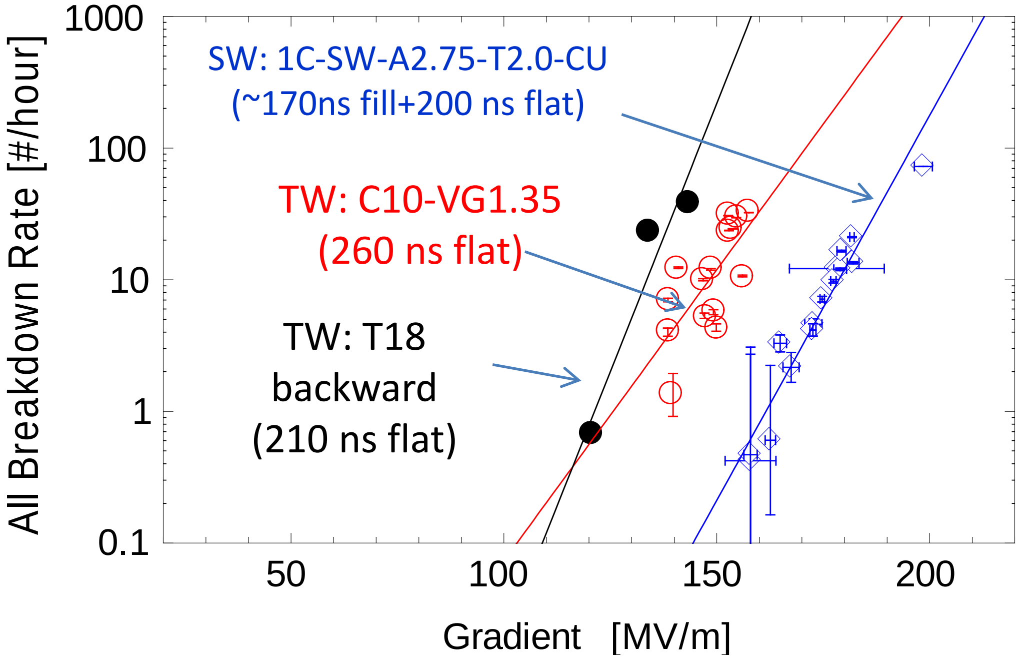
Local electric field seems to have less importance than magnetic field in disk-loaded-waveguide type SW structures

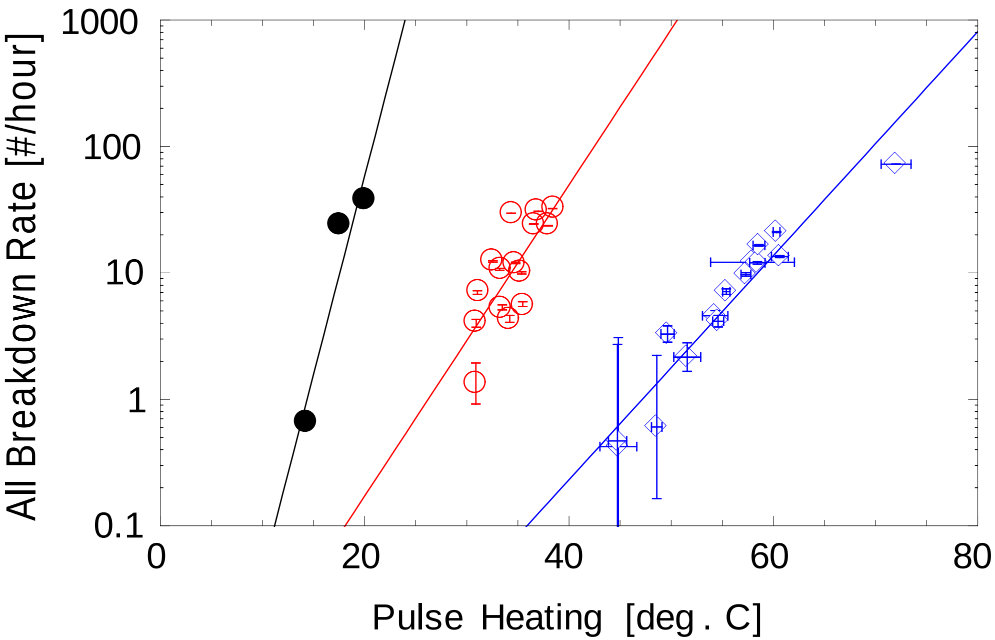
Geometrical Studies

TW *vs.* SW with Breakdowns in One Cell

Geometrical studies

TW *vs.* SW: At low breakdown rate < 5 *10^{-5}/per pulse/meter (<10 per hour@60Hz) the statistical behavior of the SW and low group velocity TW structures is very similar but TW structures has ~20-30% lower gradient and about 2 times lower peak pulse heating.



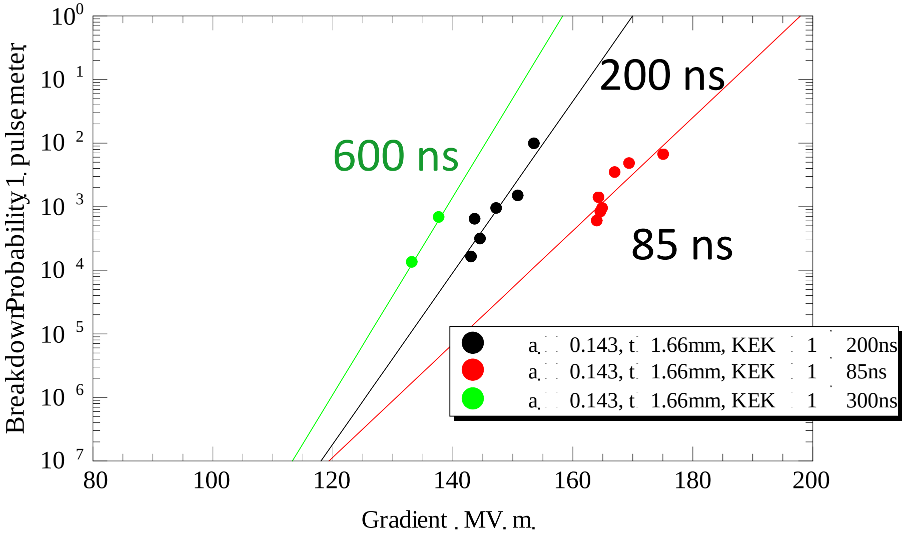


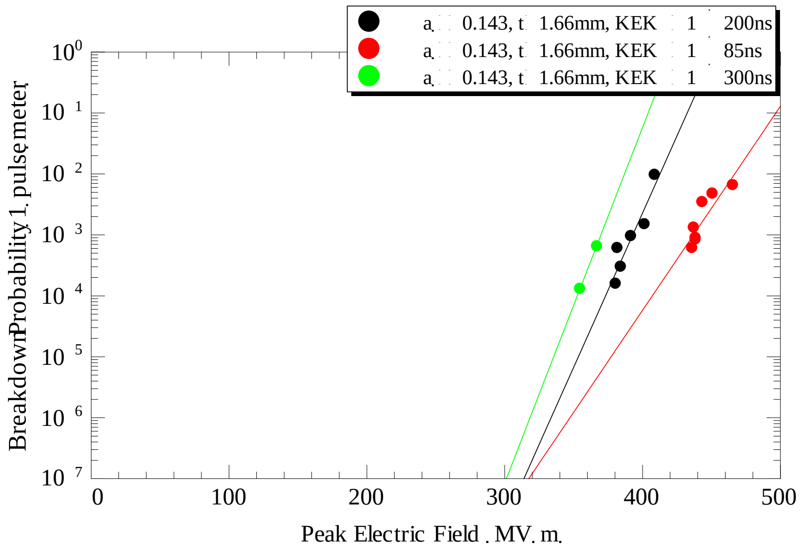
Breakdown rate *vs.* gradient and pulse heating for one SW and two TW structures with ~3mm aperture

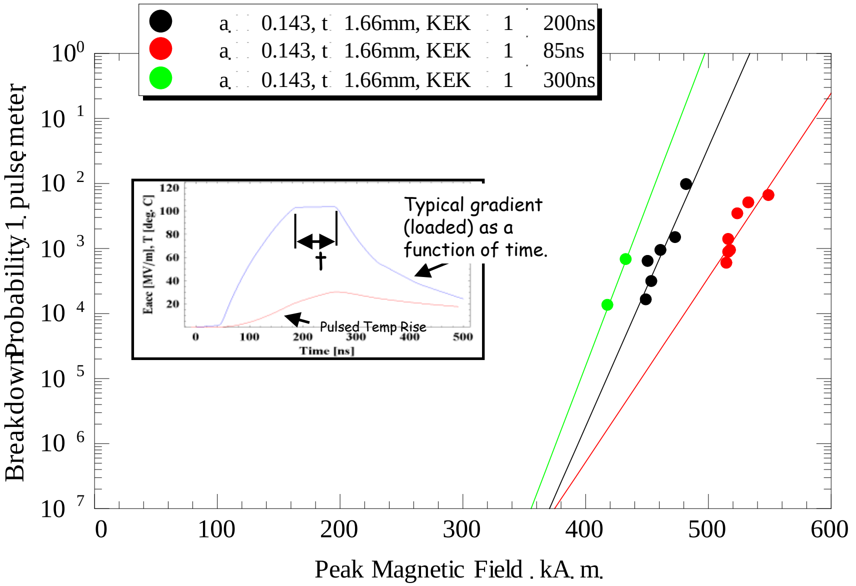
C10 and T18 TW structures: R. Zennaro *et al., Design and Fabrication of CLIC test structures*, LINAC08

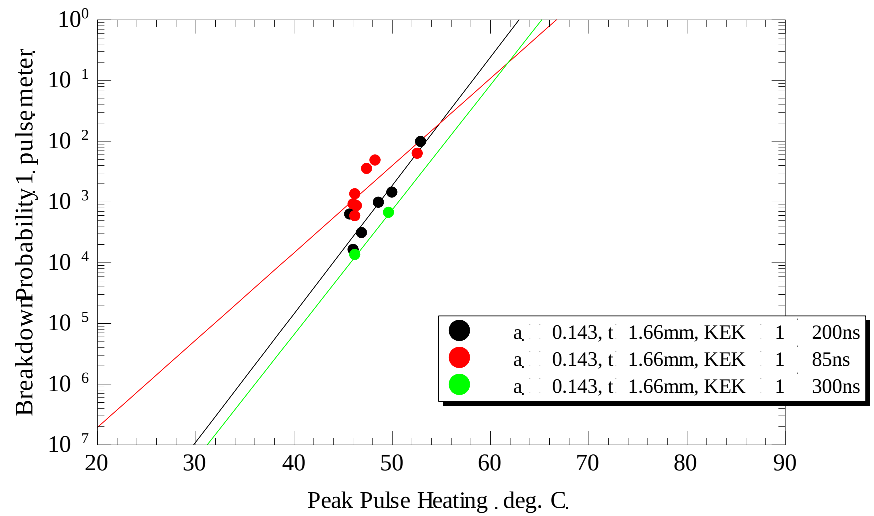
Pulse Length Dependence

Peak Pulse Heating correlate better with breakdown rate than peak magnetic field









RF Magnetic Fields and Pulse Heating

- Experimental and theoretical evidence points to the rf magnetic field as an important factor in determining the breakdown behavior in given structure.
  - Magnetic field can be responsible for:
    - Geometrical effects
    - Effective field enhancement
    - Extreme heating of small metal particles (*model of exploding copper dust)*
  - Surface fatigue may contribute to the low statistics phenomena of breakdown: why a breakdown occurs after thousands and millions of *quiet* pulses.

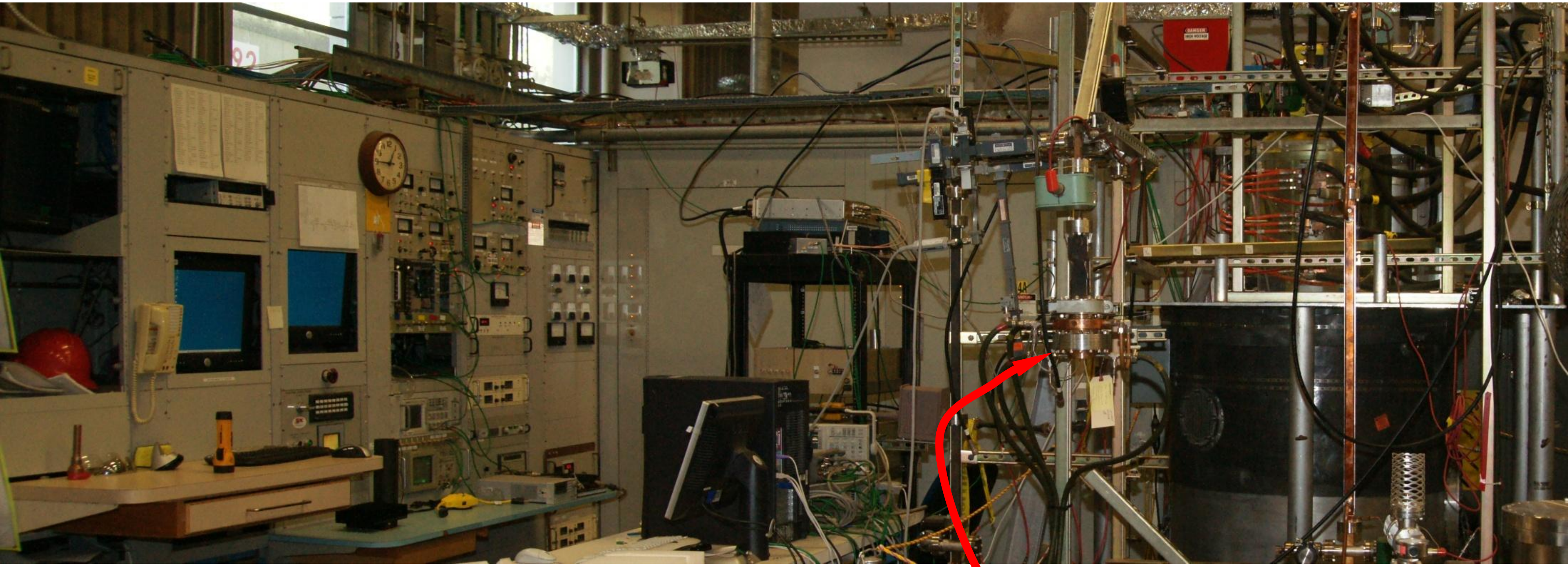
- Surface fatigue is particularly important in areas where peak magnetic field is enhanced and can cause damage, such as in coupling slots for wakefield damping

•V. A. Dolgashev and S. G. Tantawi, ***RF Breakdown in X-band Waveguides***, EPAC'02, 2002, Paris, France
•V. A. Dolgashev, ***High Magnetic Fields in Couplers of X-band Accelerating Structures***, in Proc. of IEEE PAC 2003, Portland, Oregon, 2003, pp. 1267–1269, SLAC-PUB-10123.
•G. S. Nusinovich D. Kashyn, and J. T. M. Antonsen, ***Possible Role of RF Melted Microparticles on the Operation of High-Gradient Accelerating Structures***, *Phys. Rev. ST Accel. Beams 12, 101001 (2009).*
•A. Grudiev, S. Calatroni, and W. Wuensch, ***New Local Field Quantity Describing the High Gradient Limit of Accelerating Structures***, Phys. Rev. ST Accel. Beams 12, 102001 (2009).
•A. Pohjonen, F. Djurabekova, K. Nordlund, and S. Fitzgerald*.,* ***Dislocation Nucleation on Near Surface Void Under Tensile Stress in Cu,*** in *CERN Breakdown Physics Workshop, May, 2010.*

Material Testing

Pulse Heating Cavity Experiments

Material Testing (Pulsed Heating Experiments)

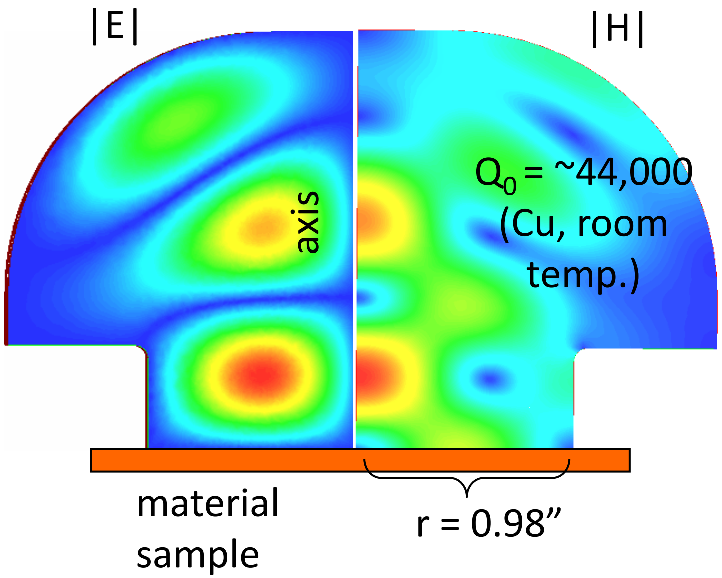


Pulse heating cavity

- Lisa Laurent, **MOP076**
- S. Heikkinen, *Study of High Power RF Induced Thermal Fatigue in the High Gradient Accelerating Structures, Ph.D. thesis,* Helsinki University of Technology, Finland (2008).

Material Testing (Pulsed Heating Experiments)

TE_{013}-like mode (no surface electric fields)

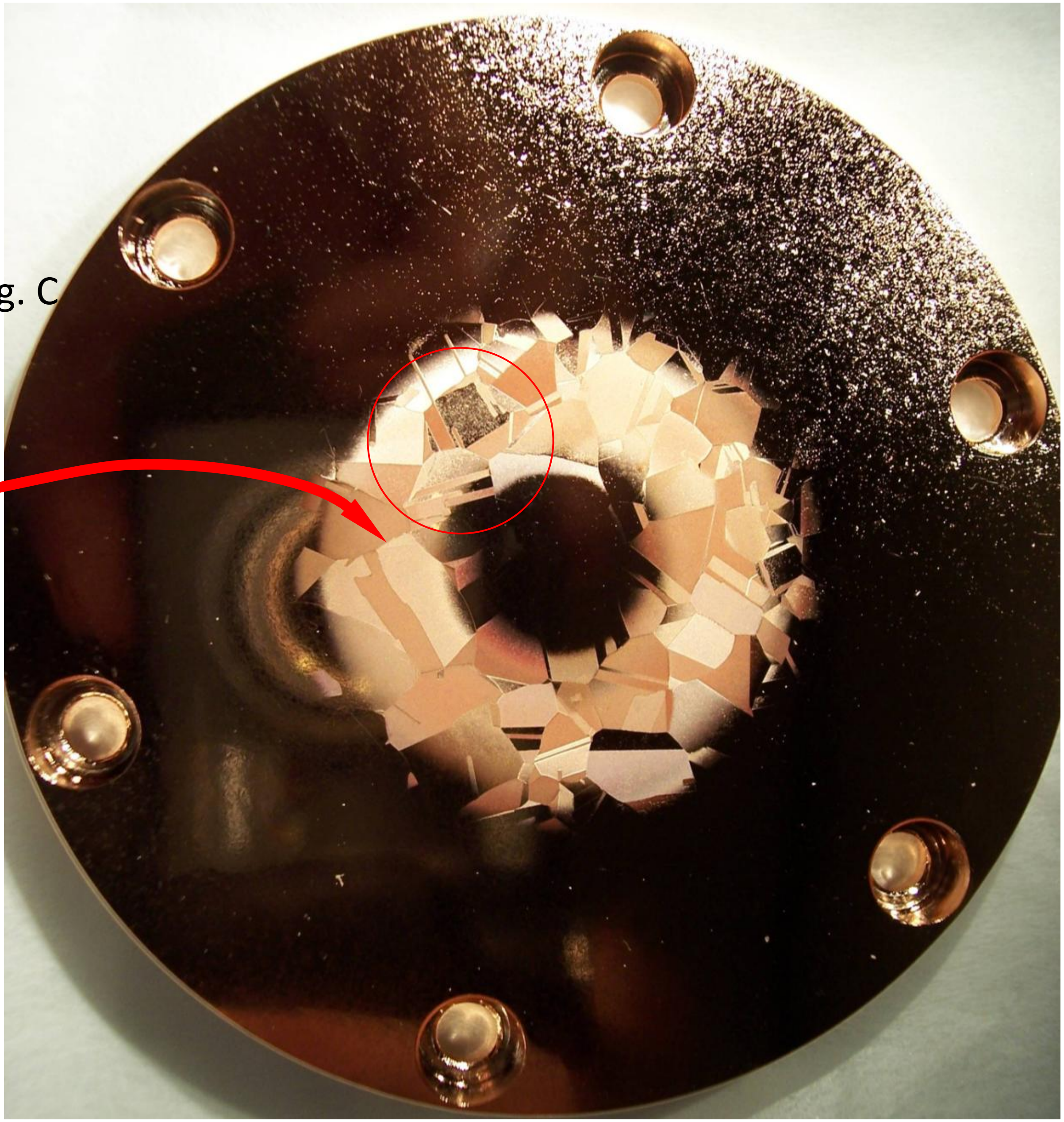


Special cavity has been designed to focus the magnetic field into a flat plate that can be replaced.

S. Tantawi, C. Nantista

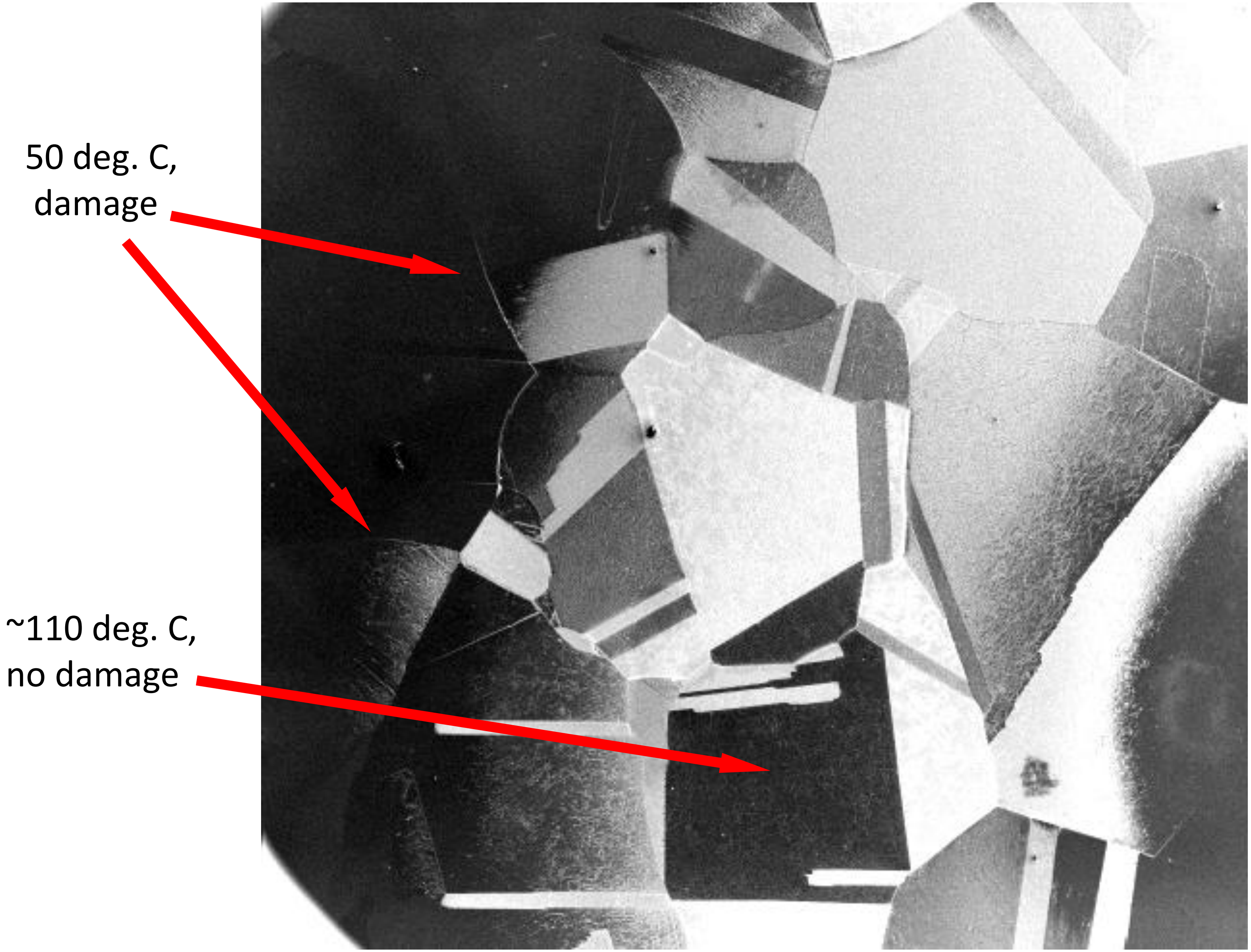
Pulse Heating Sample

Pulse heating ring,
peak temperature 110 deg. C



Sample manufactured by Y. Higashi, KEK

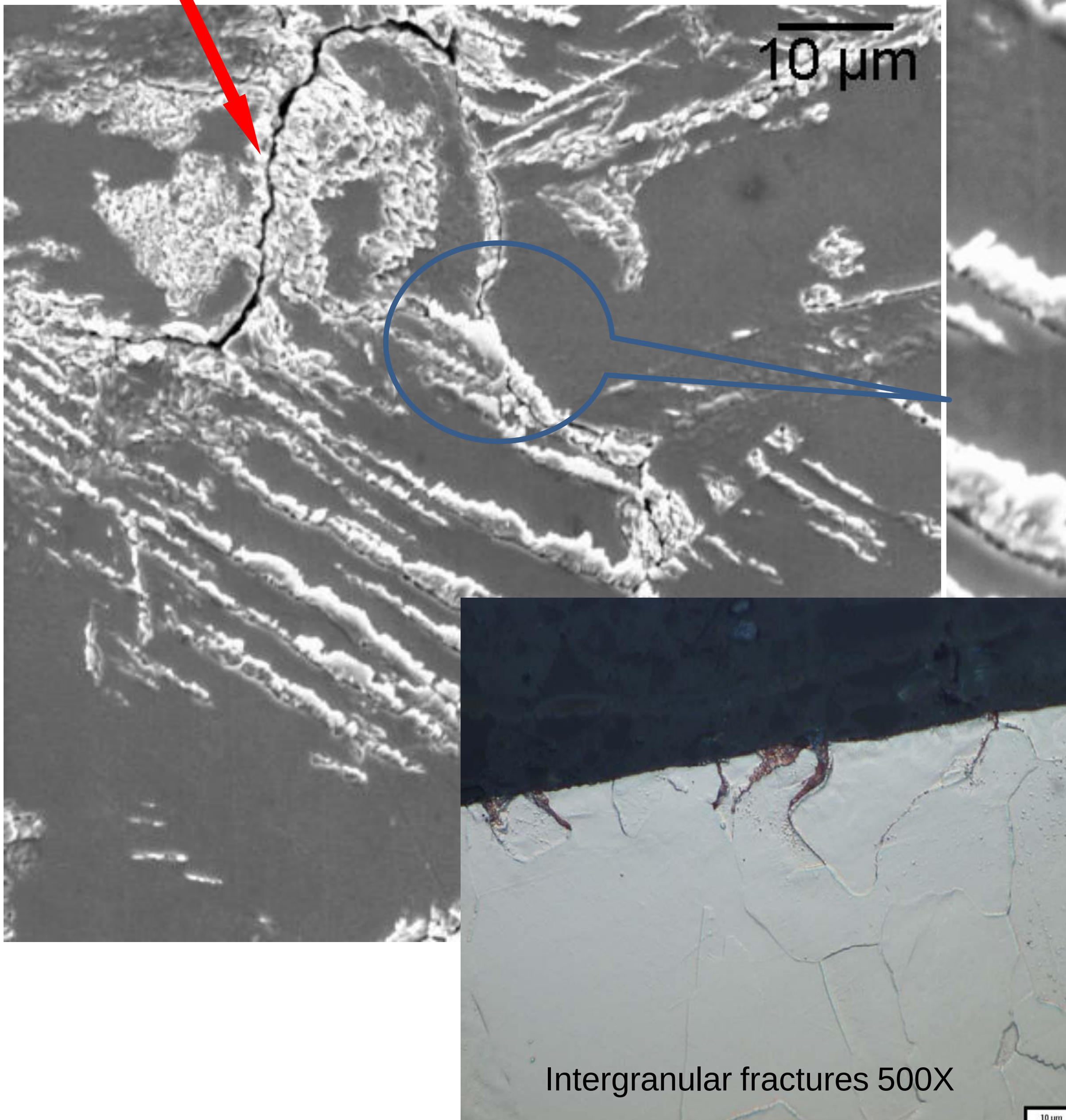
Pulse Heating Damage Strongly Depends on Crystal Grain Orientation and Starts at Grain Boundaries

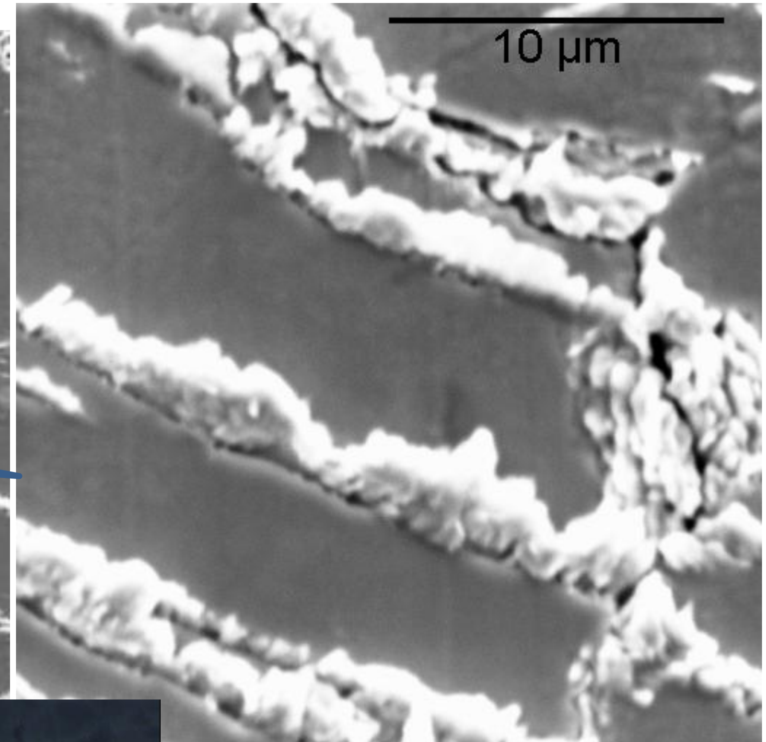


L. Laurent

Pulse Heating Damage

Inter-granular fracture





Trans-granular fractures

L. Laurent

Hardness Test Value

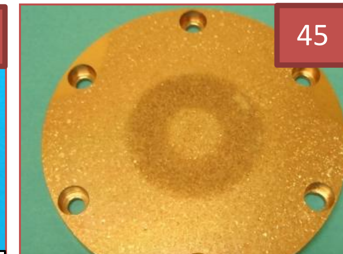
Pulse Heating Test Samples


10
Copper (SLAC)

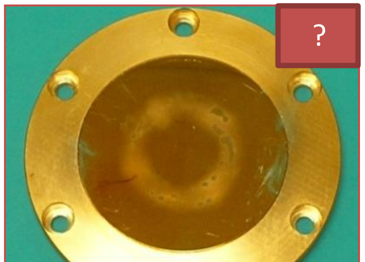

19
SPDT Copper (KEK)


33
HIP2 Copper (KEK)


36
HIP1 Copper (KEK)

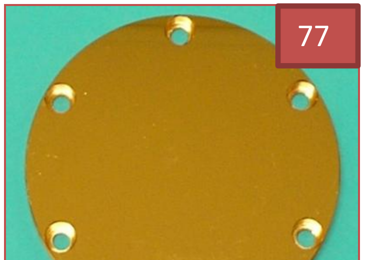

45
CuZr Annealed (CERN)


54
CuCr Annealed (SLAC)

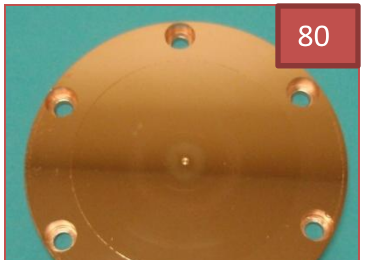

?
Single Crystal Cu (KEK)


62
E-Deposited Cu (KEK)


64
Silver Plated Cu (KEK)


77
CuZr Cold Worked (CERN)


78
Copper Silver (SLAC)


80
Copper Silver (KEK)


83
CuCr Non-Annealed (SLAC)

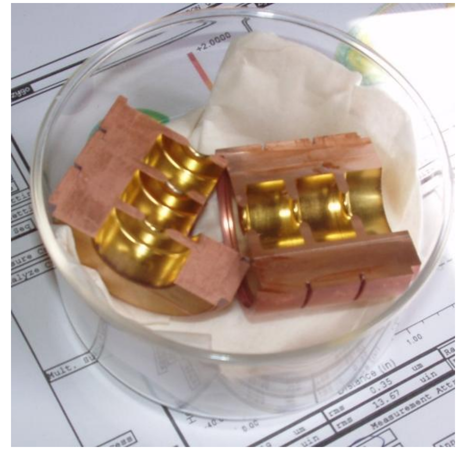

85
Glidcop (CERN)

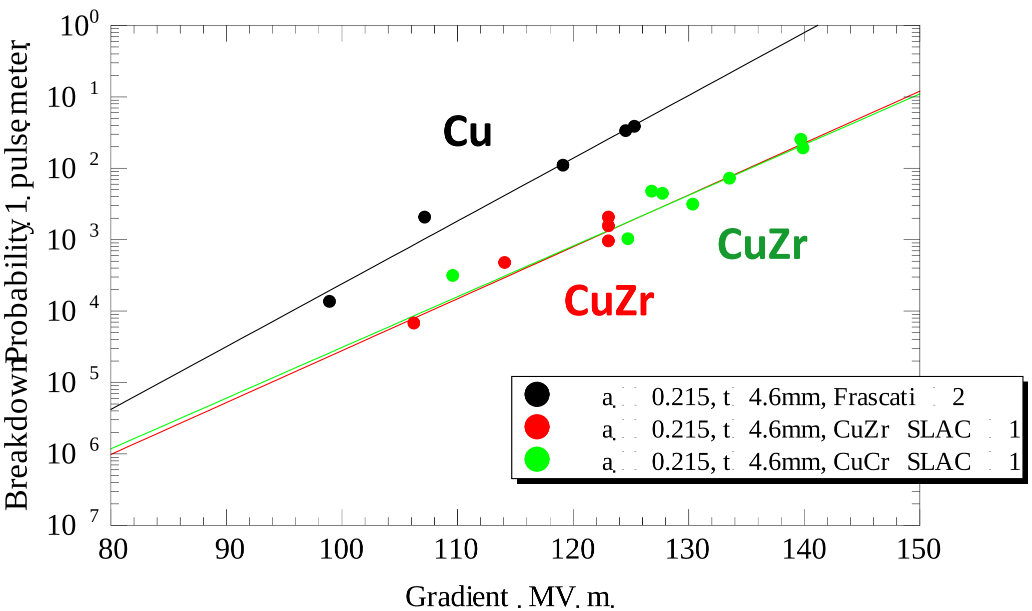
L. Laurent, **MOP076**

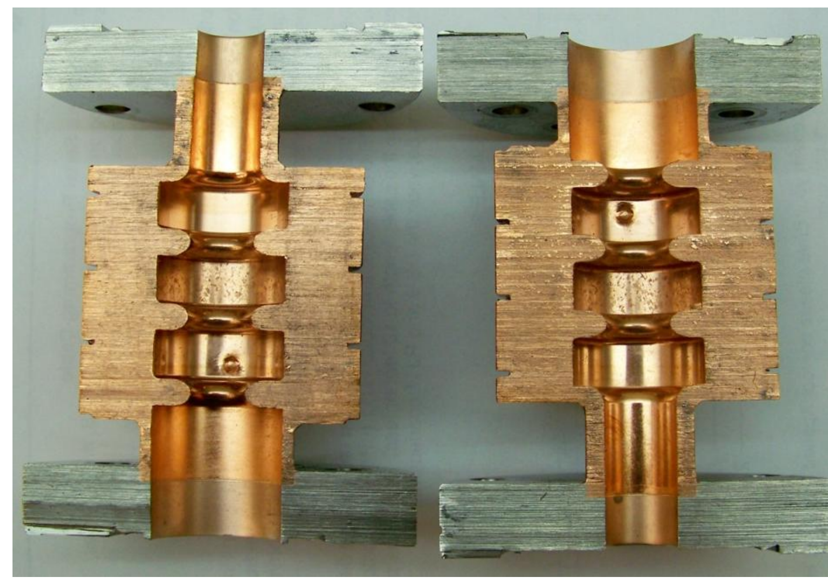

Breakdown and pulsed heating effects on an standing wave accelerating structure iris
Photo John Van Pelt

Material Tests
Vacuum Brazed CuZr and CuCr Structures

Trials of diffusion bonding and brazing of CuZr at SLAC.



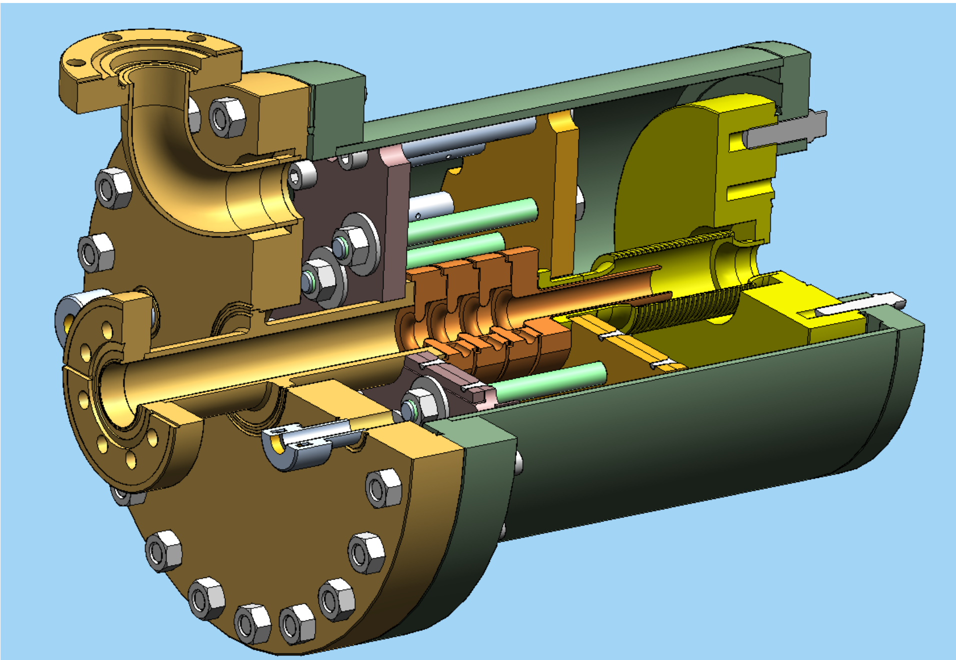


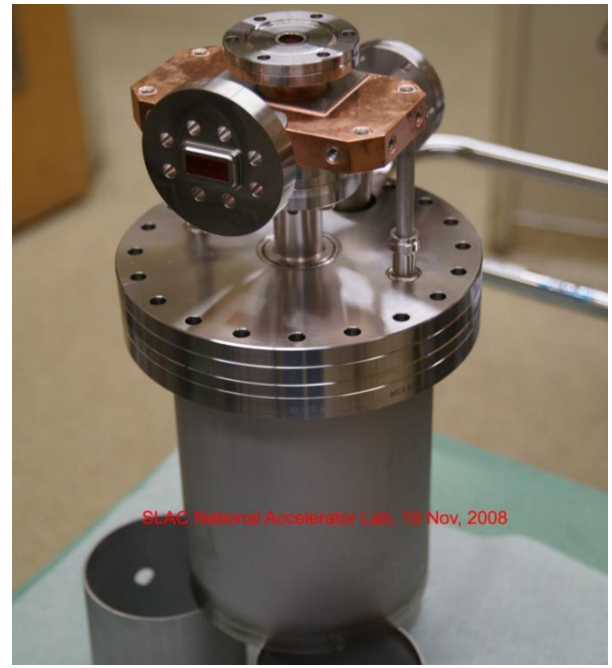


1C-SW-A5.65-T4.6-CuZr-SLAC-#1

Material Tests Without Brazing
Clamped Structure

Clamping Structure for testing accelerating structures made of copper alloys

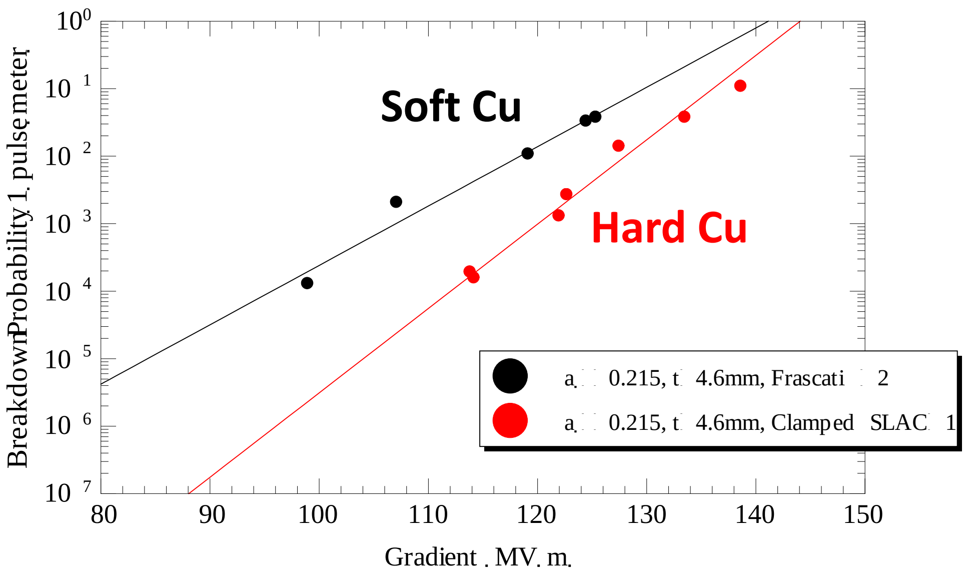


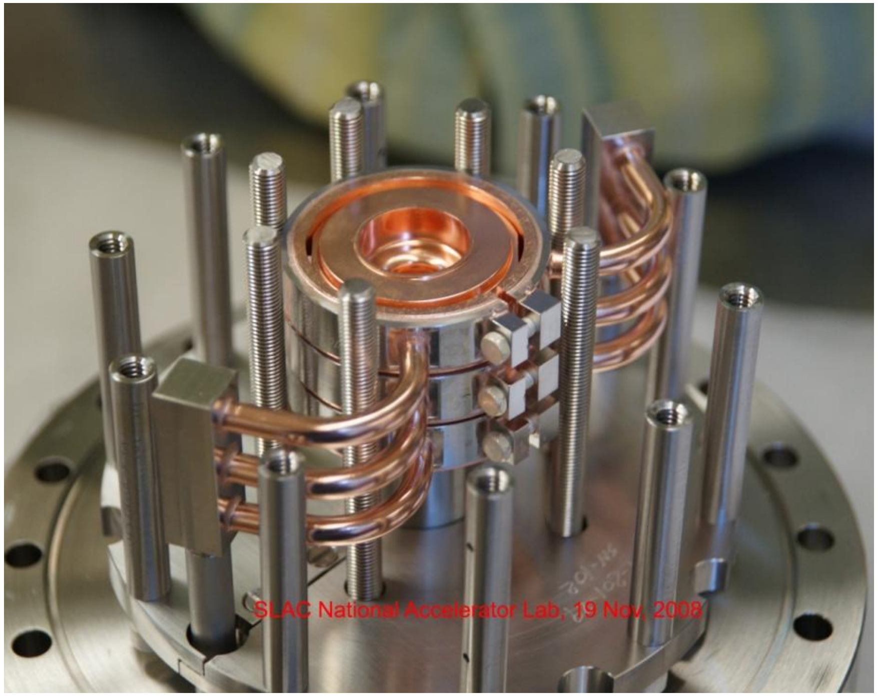


- The clamped structure will provide a method for testing materials without the need to develop all the necessary technologies for bonding and brazing them.
- Once a material is identified, we can devise constriction methods to building structures.
- Furthermore, it will provide us the opportunity to test hard materials without annealing which typically accompany the brazing process

Material Tests
Hard Copper

Clamped Structure with Hard Copper cells



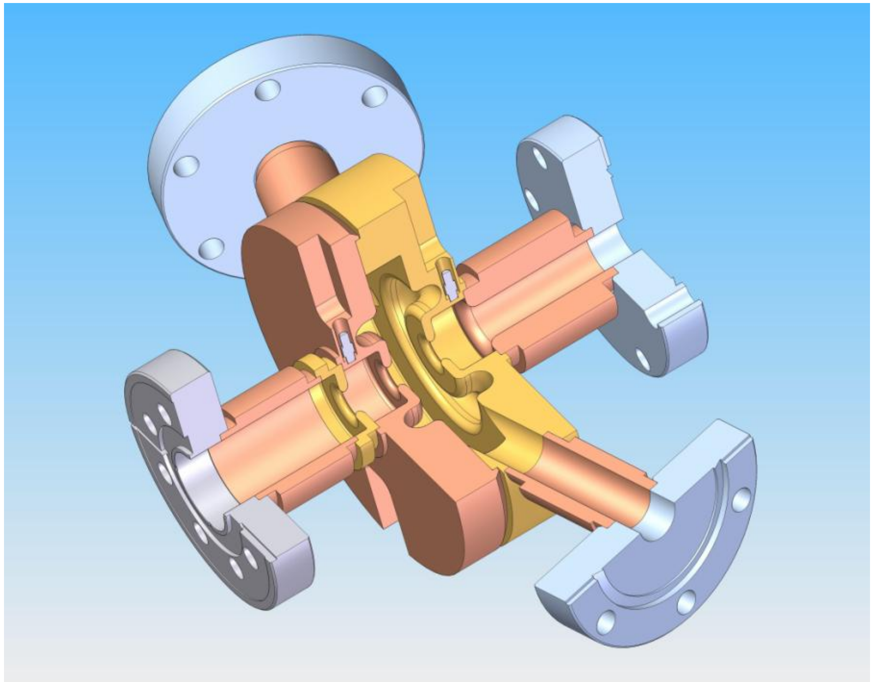


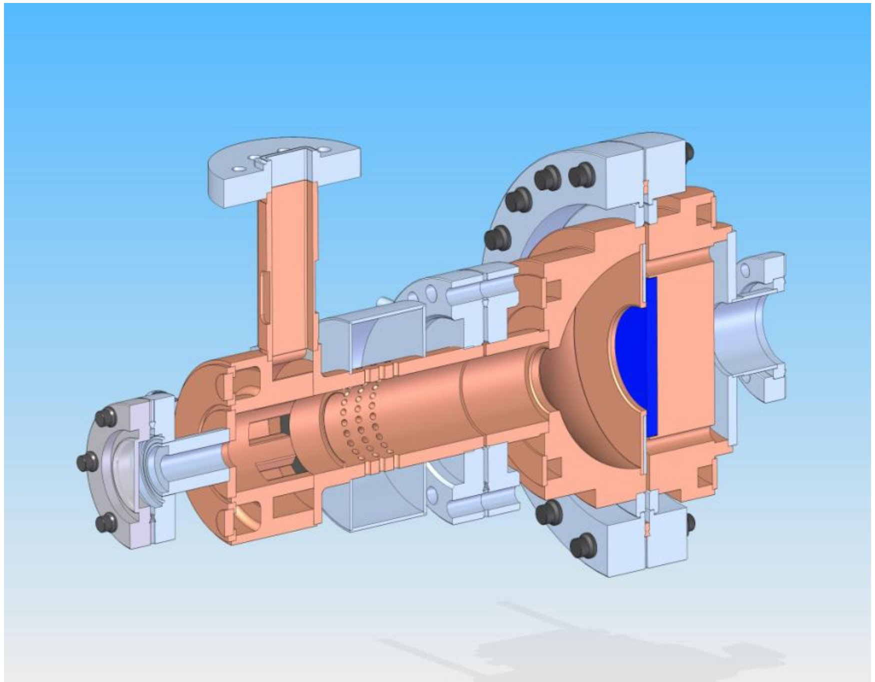
Next Steps

In Situ Observation of Microscopic Surface Properties

In-Situ Observation of Metal Surface (KEK, SLAC)

- Crystal migration due to pulse heating
  - Interferometer (ready)
  - High resolution microscopy (ready)
- Pulse temperature measurement by High-Speed Radiation Thermometer (under development)
- Particles observation by Laser scattering (under development)


SW structure


New pulse heating cavity

Summary

- **This work is done by a strong international collaboration. This is the only way to gather the necessary resources. New participants are welcome.**
- Short SW structures have higher gradient then short TW structures for the same aperture and breakdown rate.
- Geometry and material are determining ultimate rf breakdown behavior in short SW structures.
- Peak rf magnetic field has stronger effect on the rf breakdown then peak electric field which contradicts commonly accepted model of the rf breakdown.
- When soft copper is exposed RF magnetic field alone some grain boundaries show signs of damage at about 50 deg. C pulse heating.
- Pulse heating damage in hard metals is strongly suppressed which consistent with models of stress induced fatigue.
- Breakdown behavior of hard materials is different from soft materials which suggest connection between the fatigue and the breakdown trigger.
- We started building and debugging experimental setups that may allow in situ microscopic observation of metal surface.
- We designing cavities in which we decouple rf magnetic and rf electric fields.