Recent High Gradient Tests at SLAC

Presented on behalf of collaboration by

Valery Dolgashev,

SLAC National Accelerator Laboratory

3rd International Workshop on Mechanisms of Vacuum Arcs (MeVArc 2012)
October 01, October 04, 2012, Albuquerque, New Mexico

U.S. DEPARTMENT OF ENERGY
Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

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

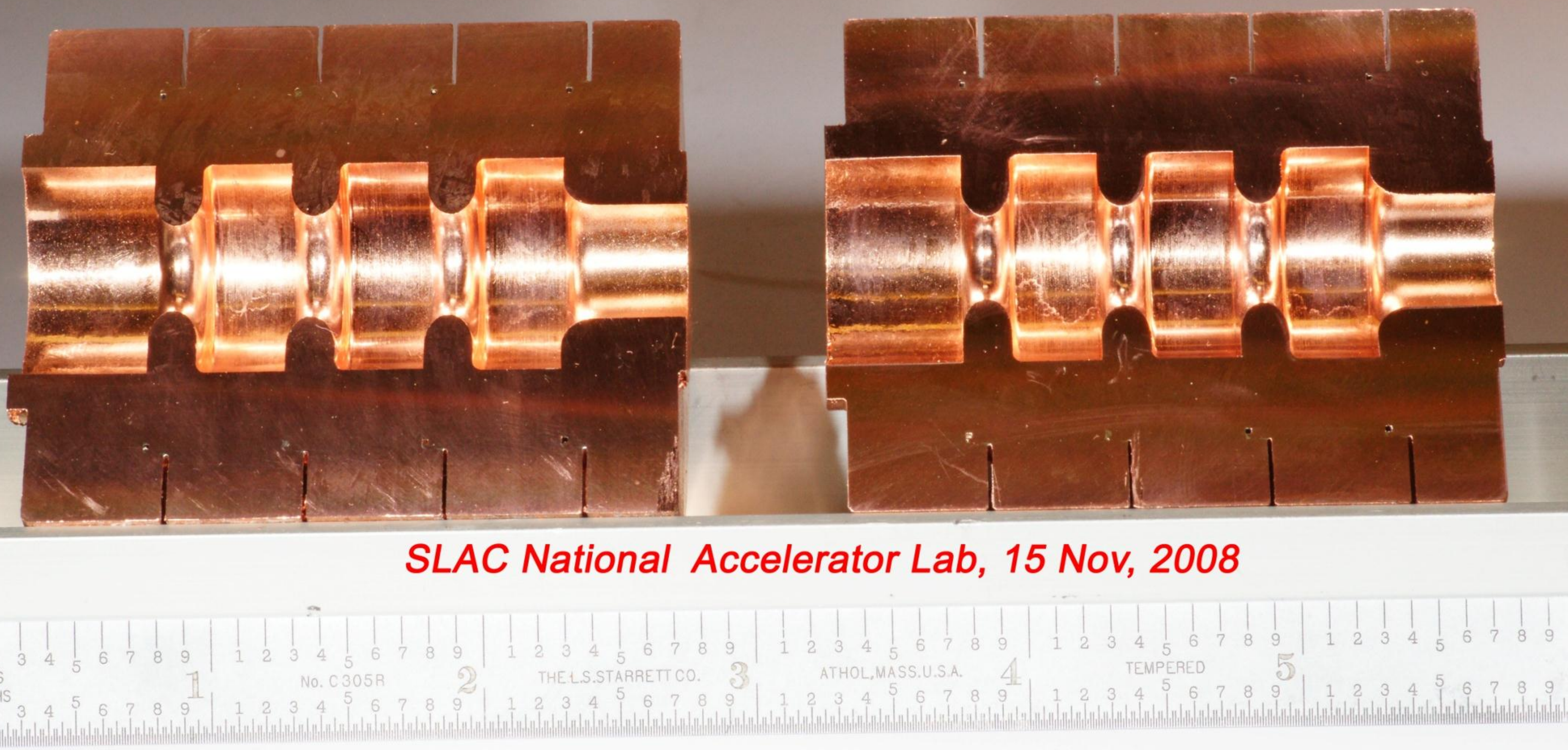
- S. Tantawi , J. Wang, *of Advanced Accelerator Research*
- E. Jongewaard, J. Neilson, C. Pearson, A. Vlieks, J. Eichner, D. Martin, C. Yoneda, L. Laurent, A. Haase, R. Talley, J. Van Pelt, A. Yeremian and staff *of RFARED.*
- J. Lewandowski, S. Weathersby, C. Hast, *ARD Test Facilities*
- Z. Li*, Advanced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

In close collaboration with:

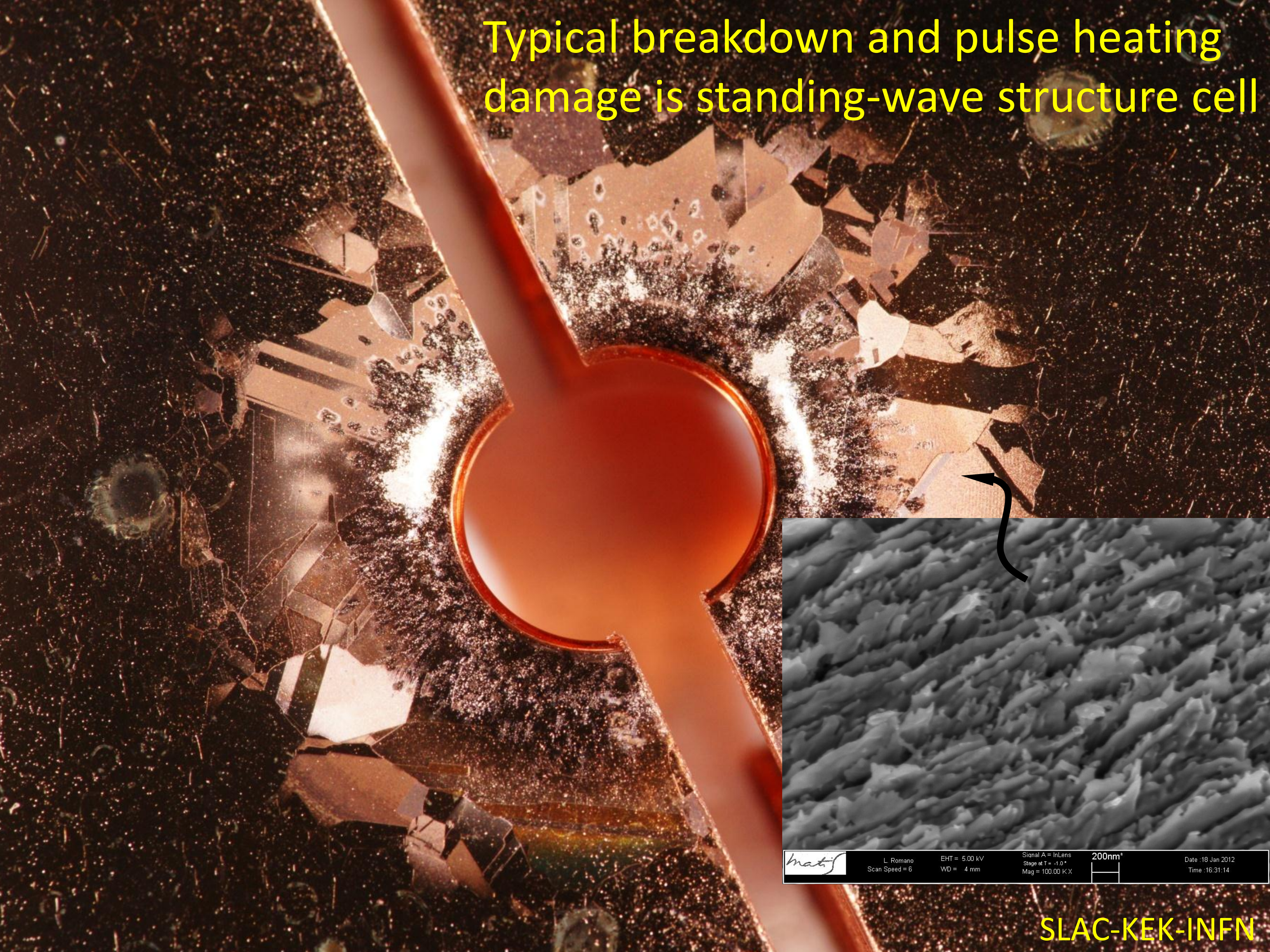
- Y. Higashi, *KEK, Tsukuba, Japan*
- B. Spataro, *INFN, Frascati, Italy*

11.4GHz, Standing Wave-Structure

1C-SW-A5.65-T4.6-Cu-Frascati-#2



SLAC-KEK-INFN


Typical breakdown and pulse heating damage is standing-wave structure cell
L. Romano
Scan Speed = 6
EHT = 5.00 kV
WD = 4 mm
Signal A = InLens
Stage at T = -1.0 °
Mag = 100.00 K X
200nm*
Date :18 Jan 2012
Time :16:31:14
SLAC-KEK-INFN

Outline

- Motivation
- Overview of recent experimental results
  - Reproducibility test Standing Wave structure with optimized shape that reduces peak magnetic fields,
  - Clad Copper-Molybedenum structure
  - Copper-on-Stainless Steel
  - 100 GHz structure
  - Dual mode accelerating cavity (ongoing test)
- Planned experiments

Single Cell SW and short TW Accelerating Structures

Goals

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

Difficulties

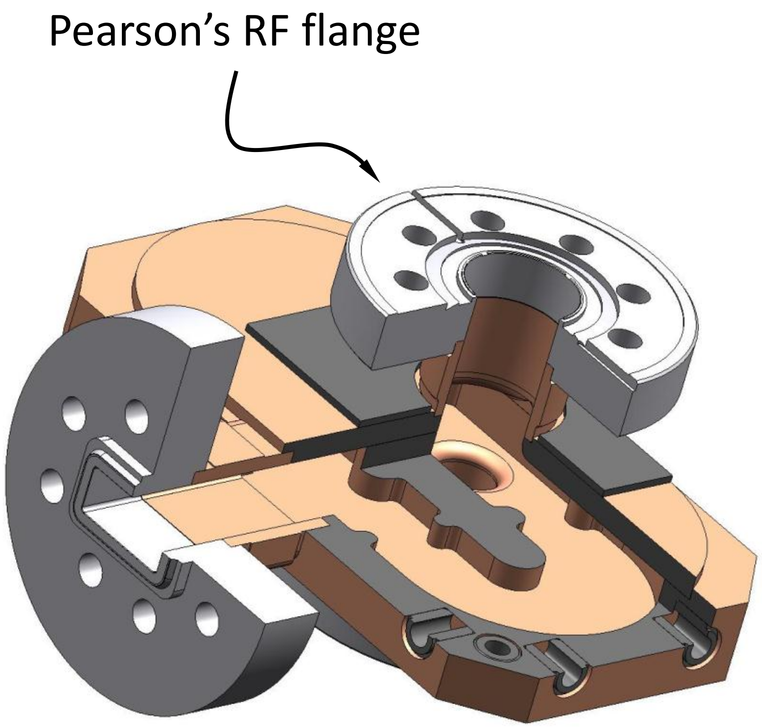
- Full scale structures are long, complex, and expensive

Solution

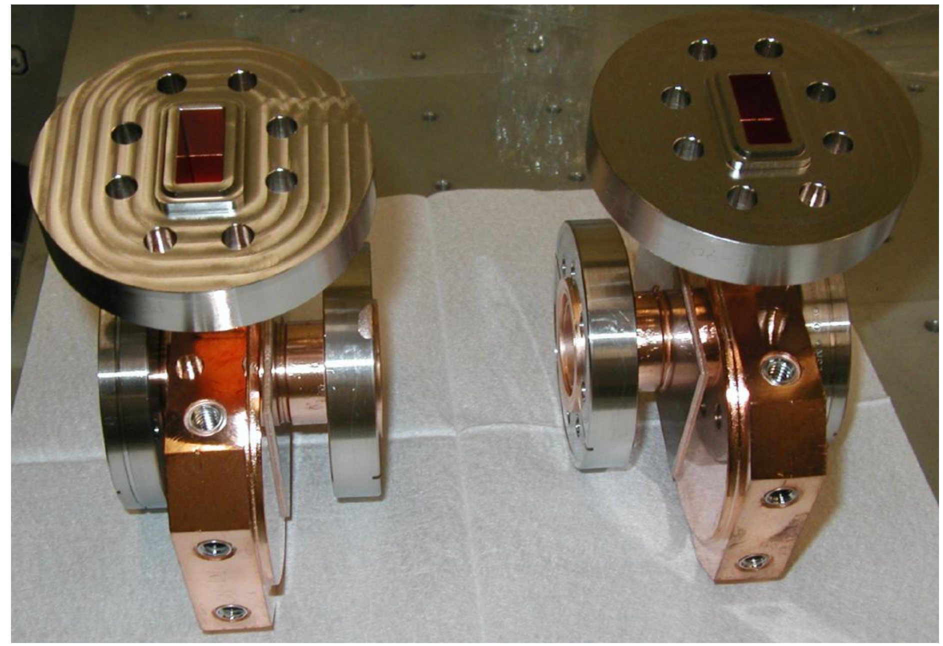
- *Single cell standing wave (SW)* structures with properties close to that of full scale structures
- *Short traveling wave (TW) structures*
- Reusable couplers

We want to predict breakdown behavior for practical structures

Reusable coupler: TM_{01} Mode Launcher



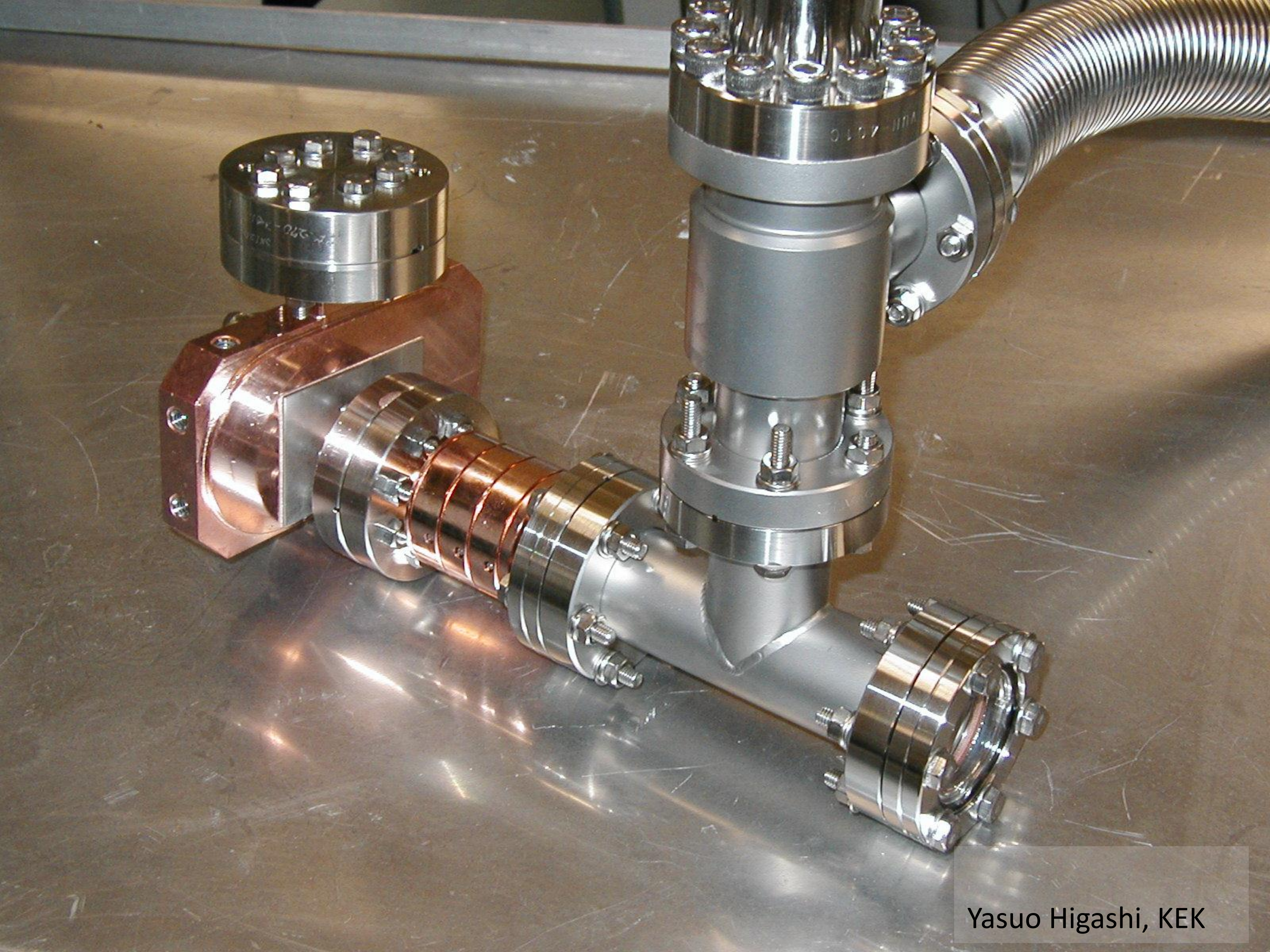
Cutaway view of the mode launcher

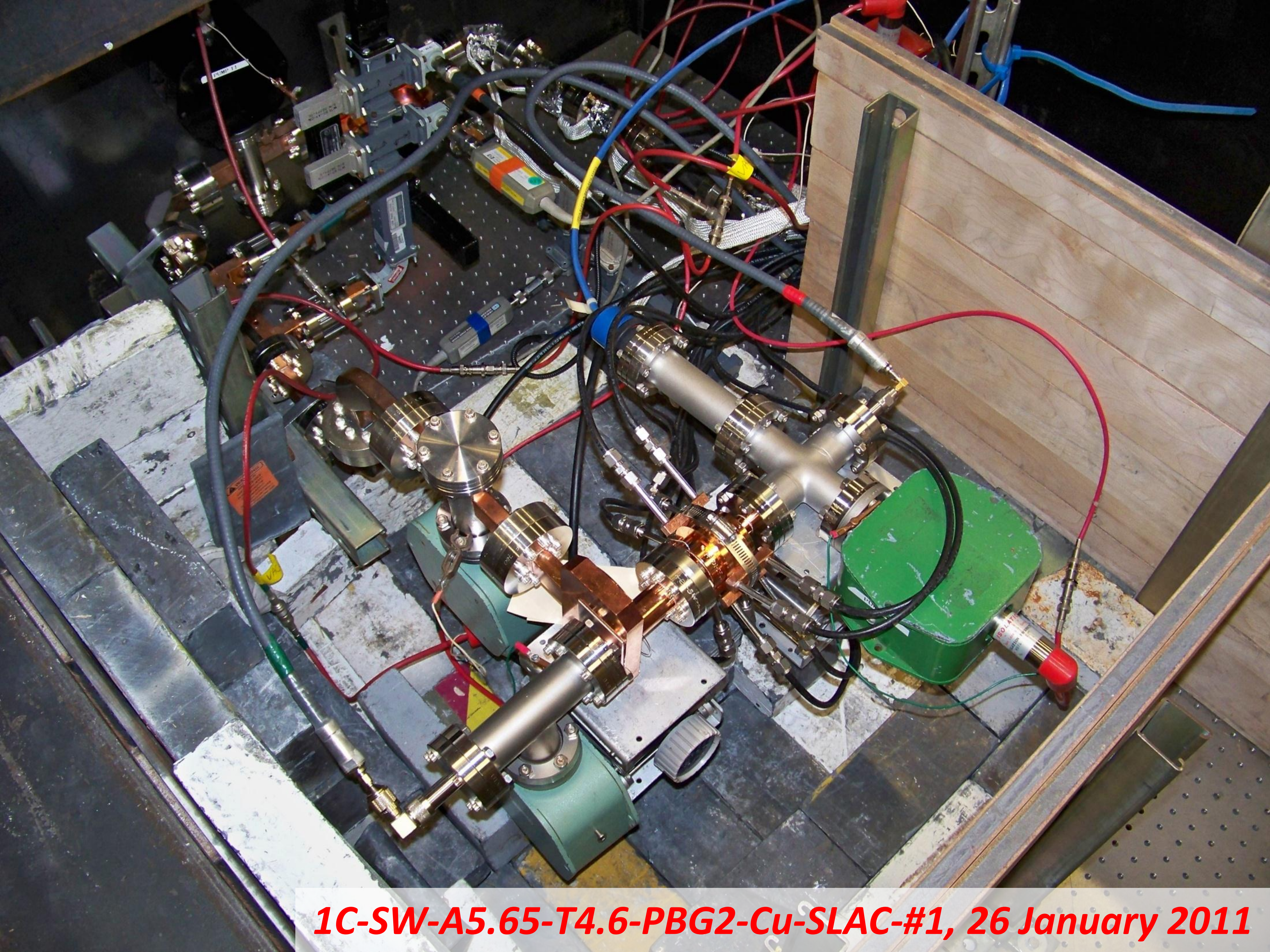


Two mode launchers

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

S. Tantawi, C. Nantista


Yasuo Higashi, KEK



1C-SW-A5.65-T4.6-PBG2-Cu-SLAC-#1, 26 January 2011

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
- Low shunt impedance, TiN coated, *1C-SW-A5.65-T4.6-Cu-TiN*, 1 tested
- Three high gradient cells, low shunt impedance, *3C-SW-A5.65-T4.6-Cu,* 2 tested
- High shunt impedance, elliptical iris, *a/lambda* = 0.143, *1C-SW-A3.75-T2.6-Cu*, 1 tested
- High shunt impedance, round iris, *a/lambda* = 0.143, *1C-SW-A3.75-T1.66-Cu*, 1 tested
- Low shunt impedance, choke with 1mm gap, *1C-SW-A5.65-T4.6-Choke-Cu*, 2 tested
- Low shunt impedance, made of CuZr, *1C-SW-A5.65-T4.6-CuZr,* 1 tested
- Low shunt impedance, made of CuCr, *1C-SW-A5.65-T4.6-CuCr,* 1 tested
- Highest shunt impedance copper structure *1C-SW-A2.75-T2.0-Cu*, 1 tested
- Photonic-Band Gap, low shunt impedance, *1C-SW-A5.65-T4.6-PBG-Cu,* 1 tested
- Low shunt impedance, made of hard copper *1C-SW-A5.65-T4.6-Clamped,* 1 tested
- Low shunt impedance, made of molybdenum *1C-SW-A5.65-T4.6-Mo,* 1 tested
- Low shunt impedance, hard copper electroformed *1C-SW-A5.65-T4.6-Electroformed-Cu,* 1 tested
- High shunt impedance, choke with 4mm gap, *1C-SW-A3.75-T2.6-4mm-Ch-Cu,* 2 tested
- High shunt impedance, elliptical iris, *a/lambda* = 0.143, *1C-SW-A3.75-T2.6-6NCu*, 1 tested
- High shunt impedance, elliptical iris, *a/lambda* = 0.143, *1C-SW-A3.75-T2.6-6N-HIP-Cu*, 1 tested
- High shunt impedance, elliptical iris, *a/lambda* = 0.143, *1C-SW-A3.75-T2.6-7N-Cu*, 1 tested
- Low shunt impedance, made of 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,* 1 tested
- High shunt impedance soft CuAg, *1C-SW-A3.75-T2.6-CuAg*, 1 tested
- High shunt impedance hard CuZr, *1C-SW-A3.75-T2.6-Clamped-CuZr*, 1 tested
- High shunt impedance single feed side coupled, 1C-SW-A3.75-T2.6-1WR90-Cu, 1 tested
- High shunt impedance hard CuCr, *1C-SW-A3.75-T2.6-Clamped-CuCr*, 1 tested
- High shunt impedance double feed side coupled 3C-SW-A3.75-T2.6-2WR90-Cu, 2 tested
- Highest shunt impedance hard copper structure *1C-SW-A2.75-T2.0-Clamped-Cu,* 2 tested
- Low shunt impedance Photonic-Band Gap with elliptical rods *1C-SW-A5.65-T4.6-PBG2-Cu*, 1 tested
- Highest shunt impedance, copper coated stainless steel *1C-SW-A2.75-t2.0-Clamped-SS, 1 tested*
- Optimized shape, high shunt impedance, *1C-SW-A3.75-T2.2-Cu*, 2 tested
- High shunt impedance coated with ZrO2, *1C-SW-A3.75-T2.6-Clamped-Coated*, 1 tested
- High shunt impedance, clad Mo-Copper 1C-SW-A3.75-t2.6-Cu-Mo-KEK-#2, 1 tested
- Highest shunt impedance, stainless steel coated with copper, *1C-SW-A3.75-A2.6-Clamped-Cu-Coated-SS-KEK-#1*

To be able to rely on our experimental results a great deal of effort have been geared towards:

- Material origin and purity
- Surface treatments
- Manufacturing technology
- **Consistency and reproducibility of test results**

The 42^{th} test is about to start, highest shunt impedance hard copper-silver structure *1C-SW-A2.75-A2.0-Clamped-CuAg-SLAC#1*

Next experiments, as for 4 October 2012

In-situ diagnostics:

High shunt impedance, full choke cell with a viewport, 1C-SW-A3.75-T2.6-Ch-View-Port-Cu

Geometry tests:

High shunt impedance, triple choke, copper, *1C-SW-A3.75-T2.6-4mm-TripleCh-Cu*

Materials:

Highest shunt impedance, made of hard CuAg, *1C-SW-A2.75-T2.0-Clamped-CuAg*

Highest shunt impedance, cryogenic test, *1C-SW-A2.75-T2.0-Cryo-Cu*

Highest shunt impedance, made of hard CuCr, CuAg, CuZr, *1C-SW-A2.75-T2.0-Clamped-CuCr, CuAg, CuZr*

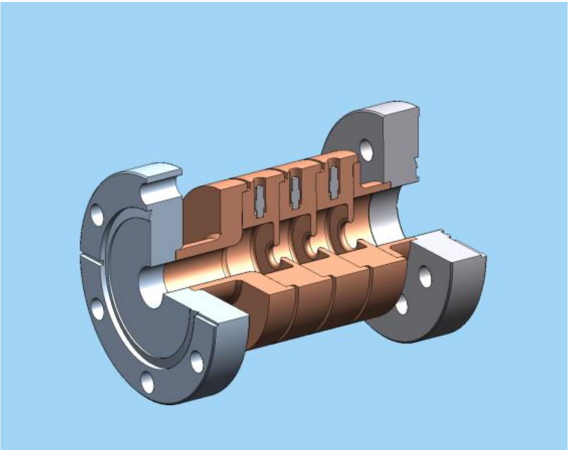
High shunt impedance, triple choke, Molybdenum, *1C-SW-A3.75-T2.6-4mm-TripleCh-Mo*

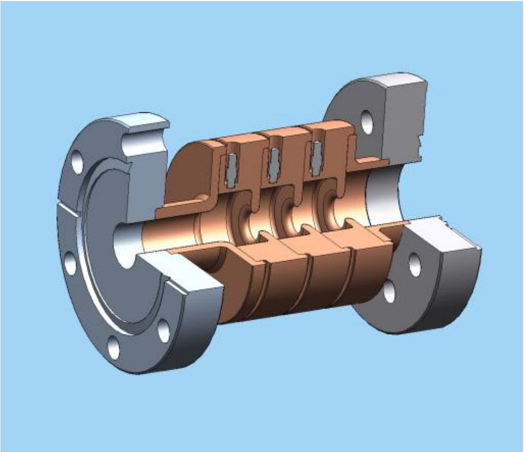
Reproducibility tests:

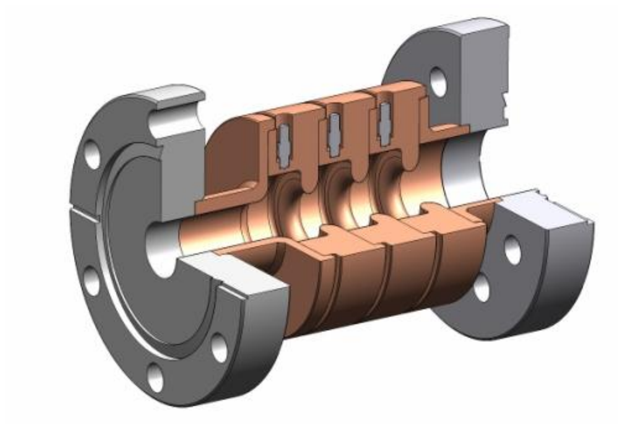
High shunt impedance, round iris, *1C-SW-A3.75-T1.66-Cu*

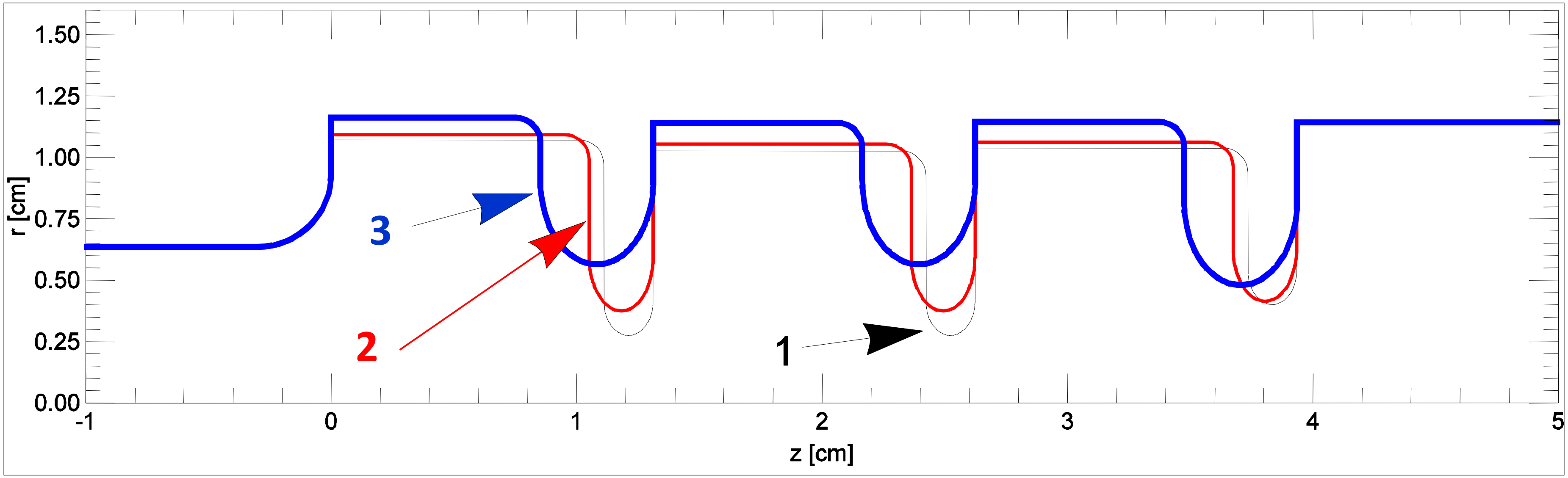
Three high gradient cells, low shunt impedance, *3C-SW-A5.65-T4.6-Cu*

Geometrical Studies
Three Single-Cell-SW Structures of Different Geometries

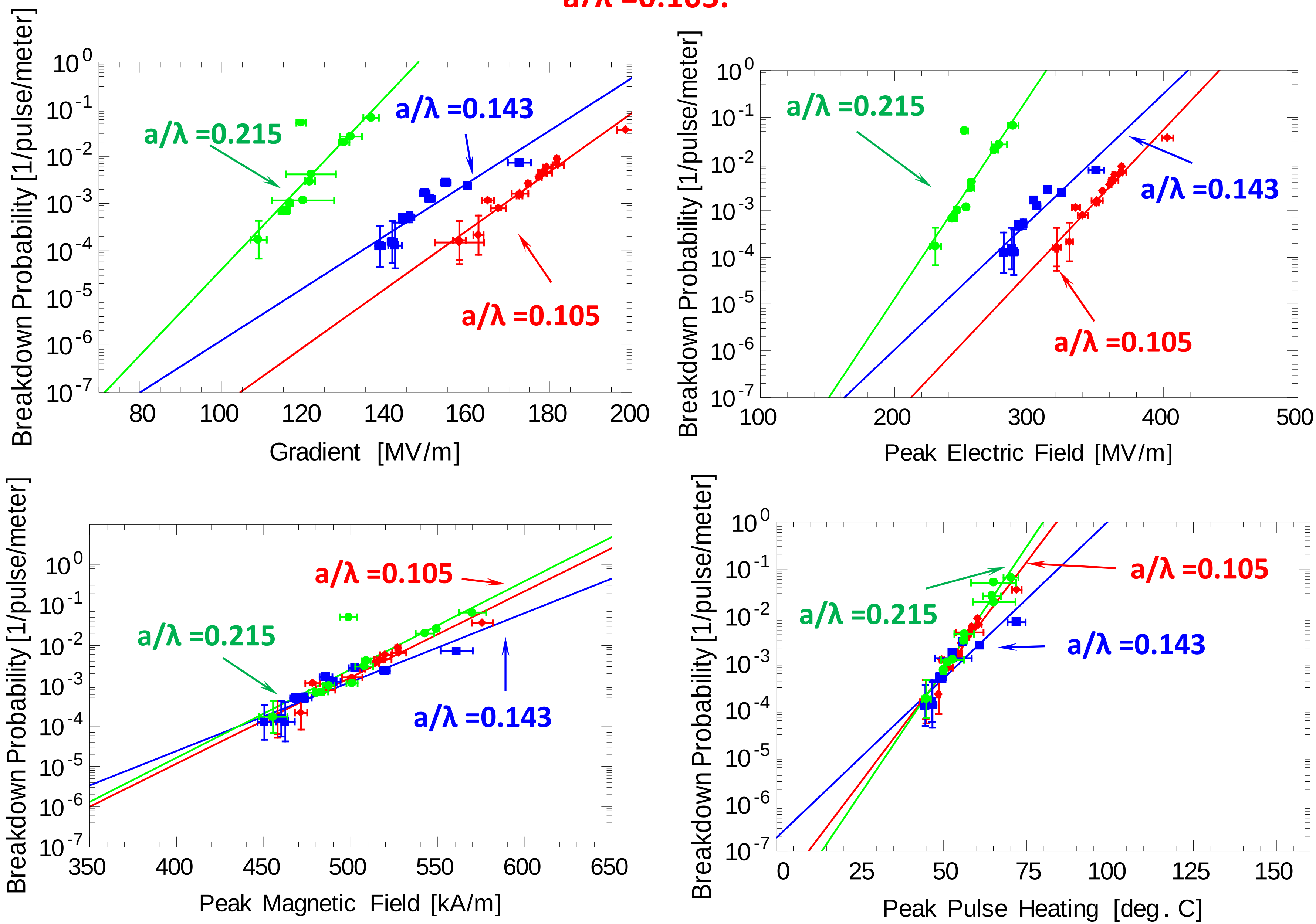

1)1C-SW-A2.75-T2.0-Cu


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

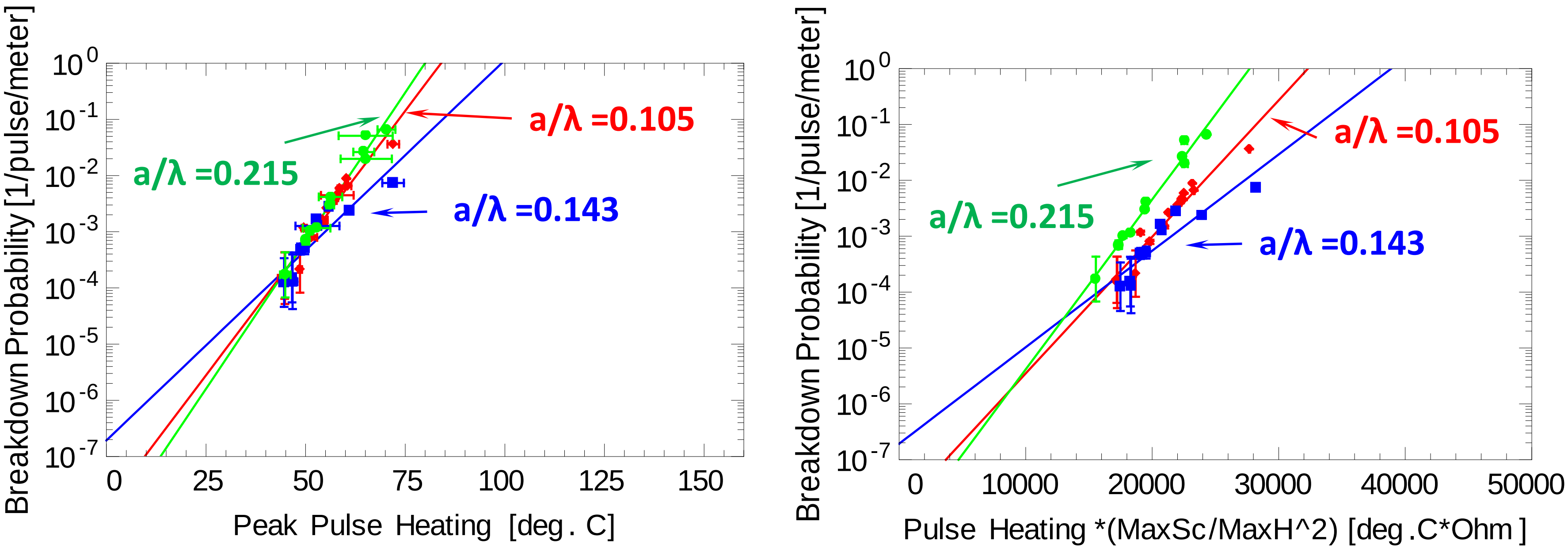

3) 1C-SW-A5.65-T4.6-Cu



Standing-wave structures with different iris diameters: a/λ =0.215, a/λ =0.143, and a/λ =0.105.



Breakdown rate *vs.* peak pulse heating and peak Pointing vector
Standing-wave structures with different iris diameters: **a/λ =0.215, a/λ =0.143**, and **a/λ =0.105.**

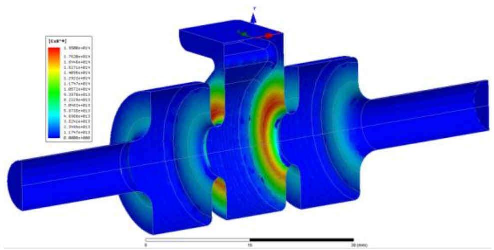


Analysis of experimental data from multiple structures (including these) finds that peak Poynting vector is correlated with breakdown rate:

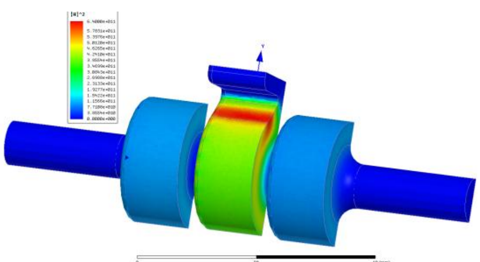
A. Grudiev, S. Calatroni, and W. Wuensch,
New local field quantity describing the high gradient limit of accelerating structures,
Phys. Rev. ST Accel. Beams **12,** 102001 (2009).

Structures that have different ratio between peak Poynting vector and peak H^2

1C-SW-A3.75-T2.6-1WR90-Cu



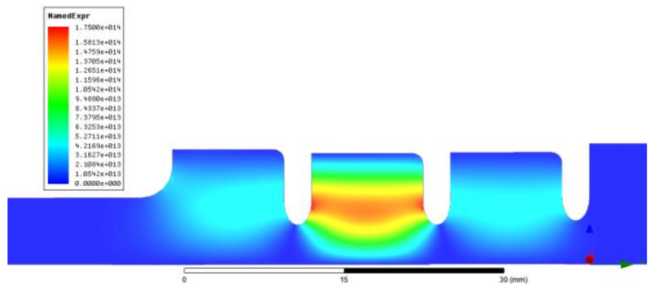
Max. Poyning Vector
1.93 e14 W/m^2



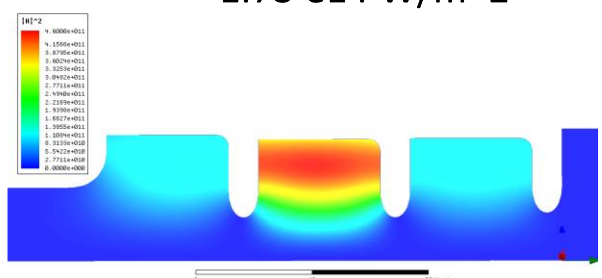
Max. |H^2| 6.4e11 (A/m)^2

Ratio is **301 Ohm**

1C-SW-A3.75-T2.6-Cu



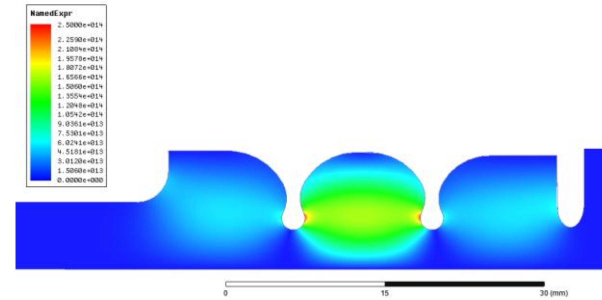
Max. Poyning Vector
1.73 e14 W/m^2



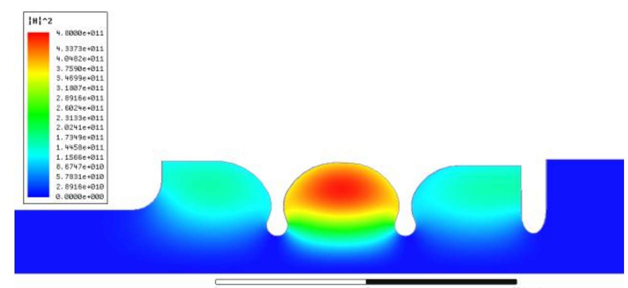
Max. |H^2| 4.44e11 (A/m)^2

Ratio is **390 Ohm**

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



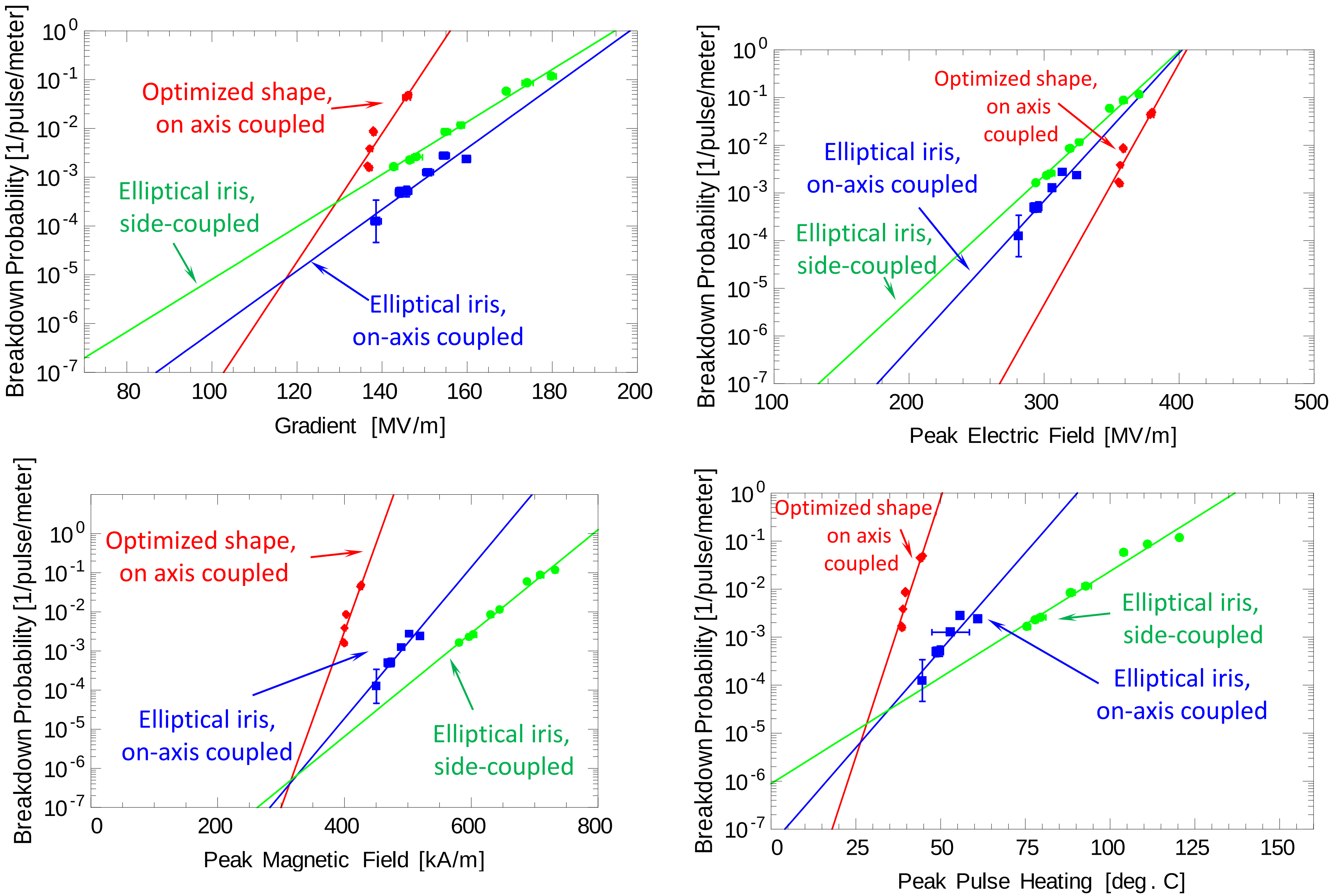
Max. Poyning Vector
2.4e14 M/m^2



Max. |H^2| 3.8e11 (A/m)^2

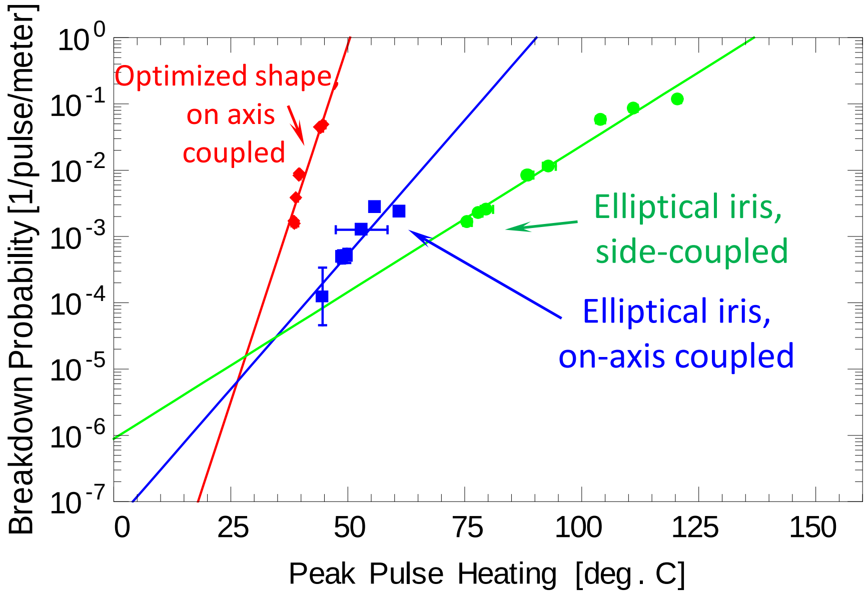
Ratio is **632 Ohm**

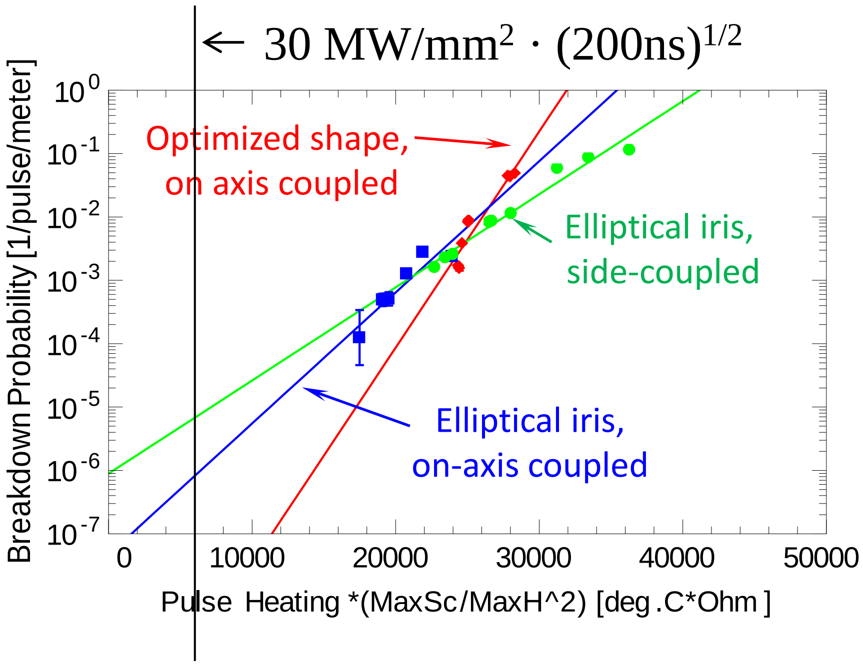
Comparison of two on-axis coupled structures and one side-coupled structure of 3.75 mm aperture, shaped pulse with 200 ns flat part



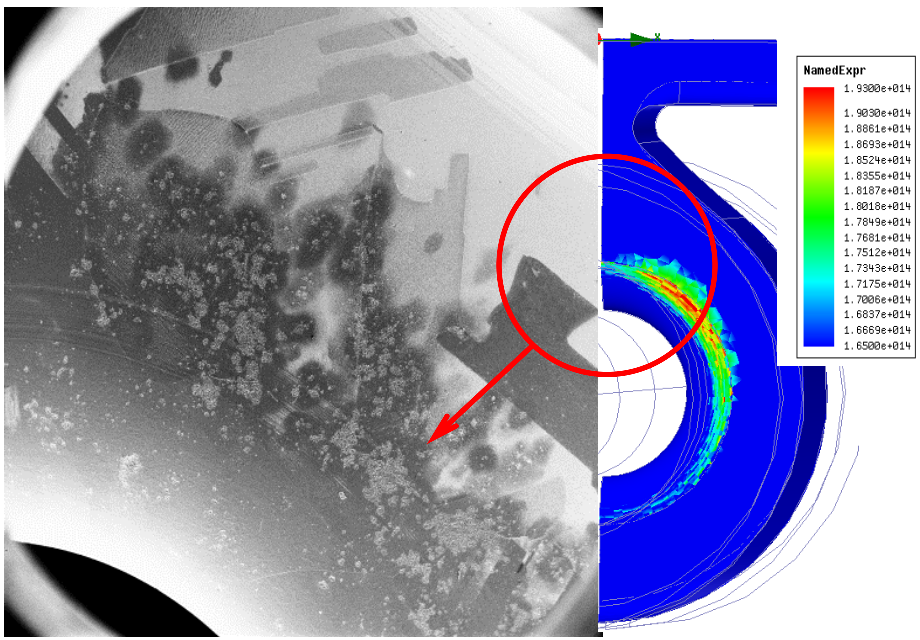
Pulse heating vs. Poynting vector

Comparison of two on-axis coupled structures and one side-coupled structure of 3.75 mm aperture, shaped pulse with 200 ns flat part

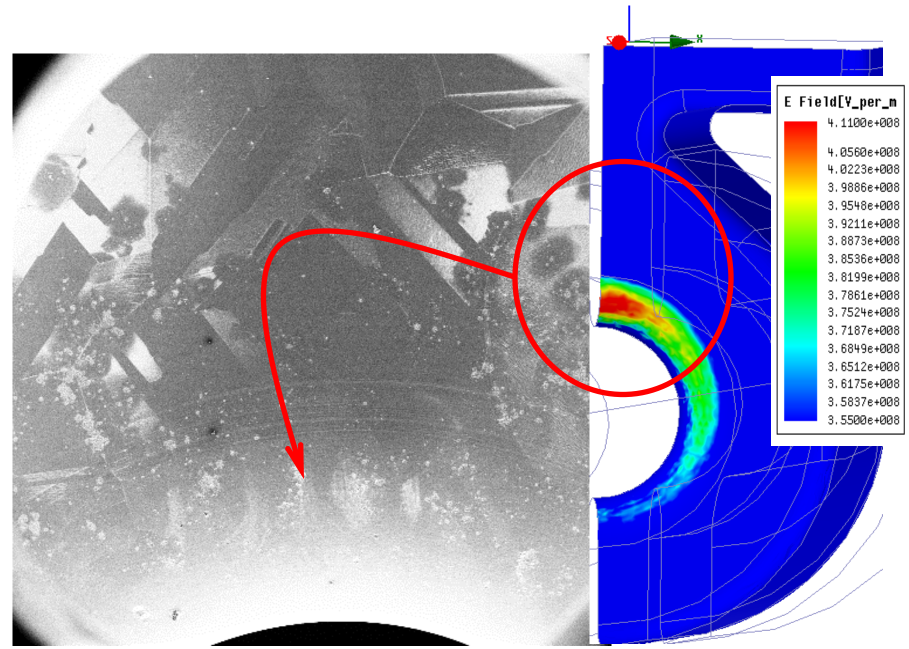




SEM inspection of single-feed 1C-SW-A3.75-T2.6-1WR90-Cu-SLAC-#1



Area with maximum peak Poyniting vector **with intense breakdown damage.**



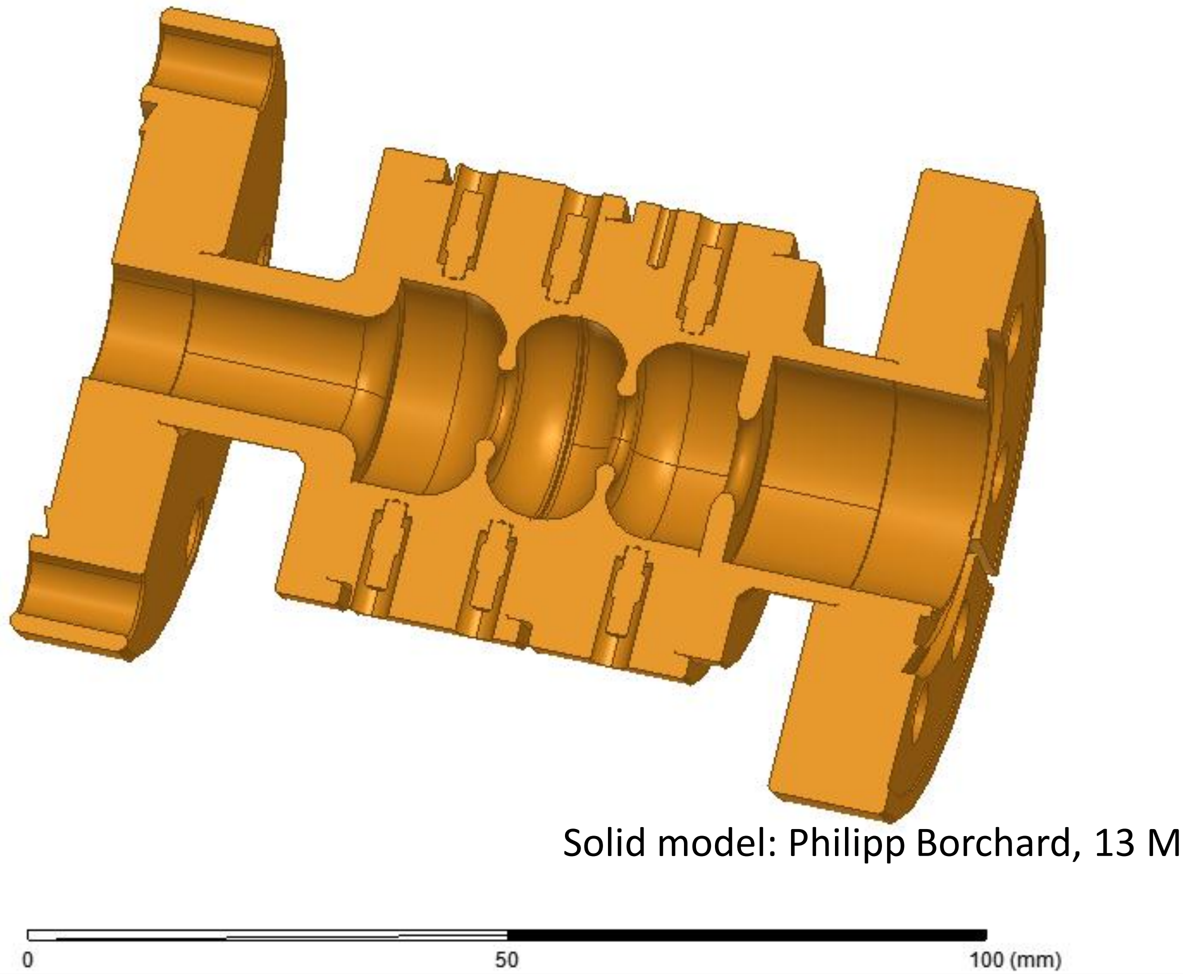
Area with maximum peak electric fields **with little breakdown damage.**

The breakdown damage in this structure was correlated more with the location of the peak Poyning vector than with the location of the peak electric or magnetic fields field.

Results

For structures of disc-loaded waveguide type, with high fields in one cell, with same beam aperture the breakdown rate correlates more with peak Poyniting vector integrated with 1/Sqrt (pulse length) *then with either peak electric fields or peak pulse heating*.

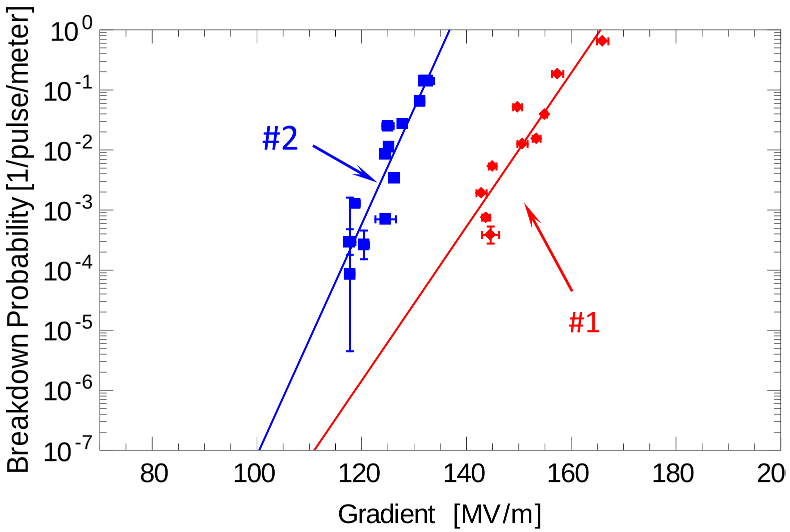
Reproducibility test, Optimized shape, high shunt impedance, *1C-SW-A3.75-T2.2-Cu*

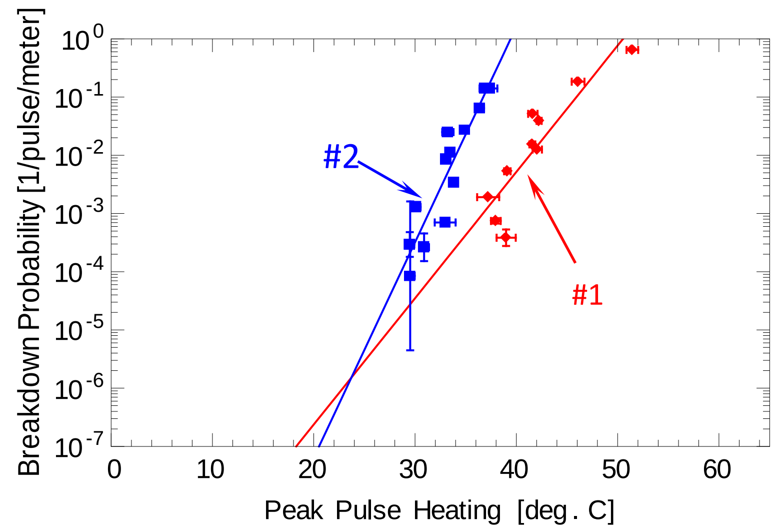


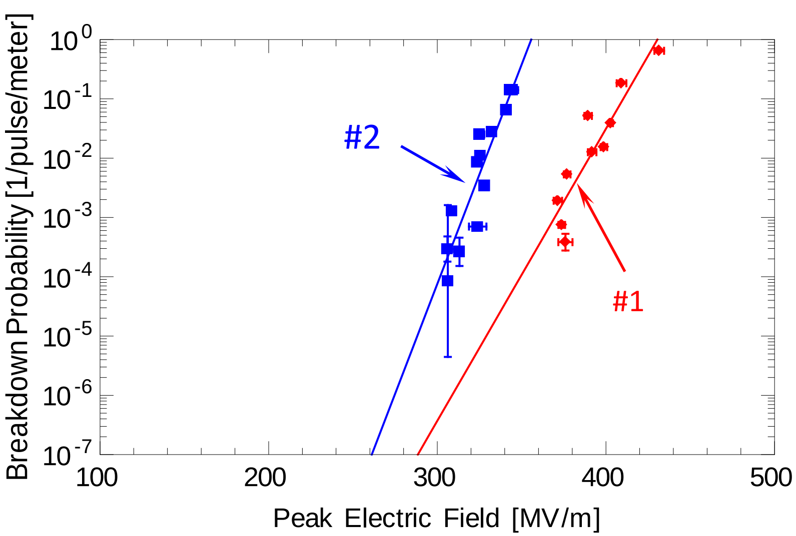
Solid model: Philipp Borchard, 13 May 2011

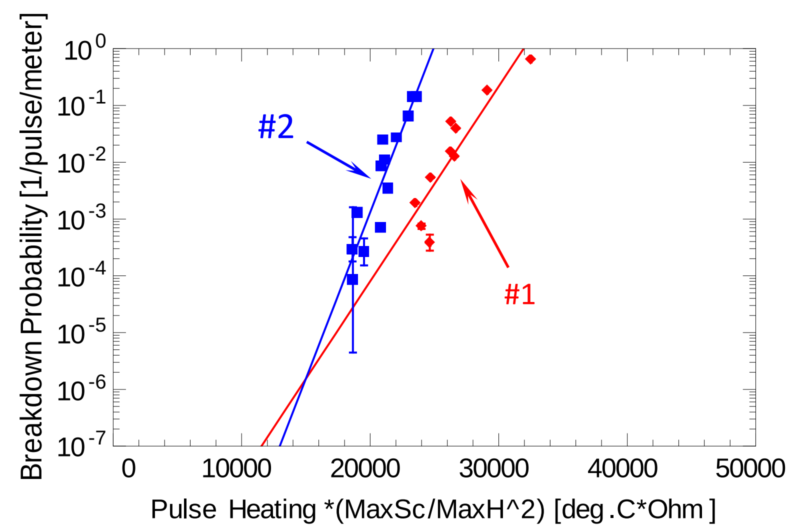
Jeff Neilson and Sami Tantawi

Breakdown data for two versions of optimized shape 1C-SW-A3.75-T2.2-Cu-SLAC, #1 and #2, 150 ns shaped pulse, 2nd 150ns run



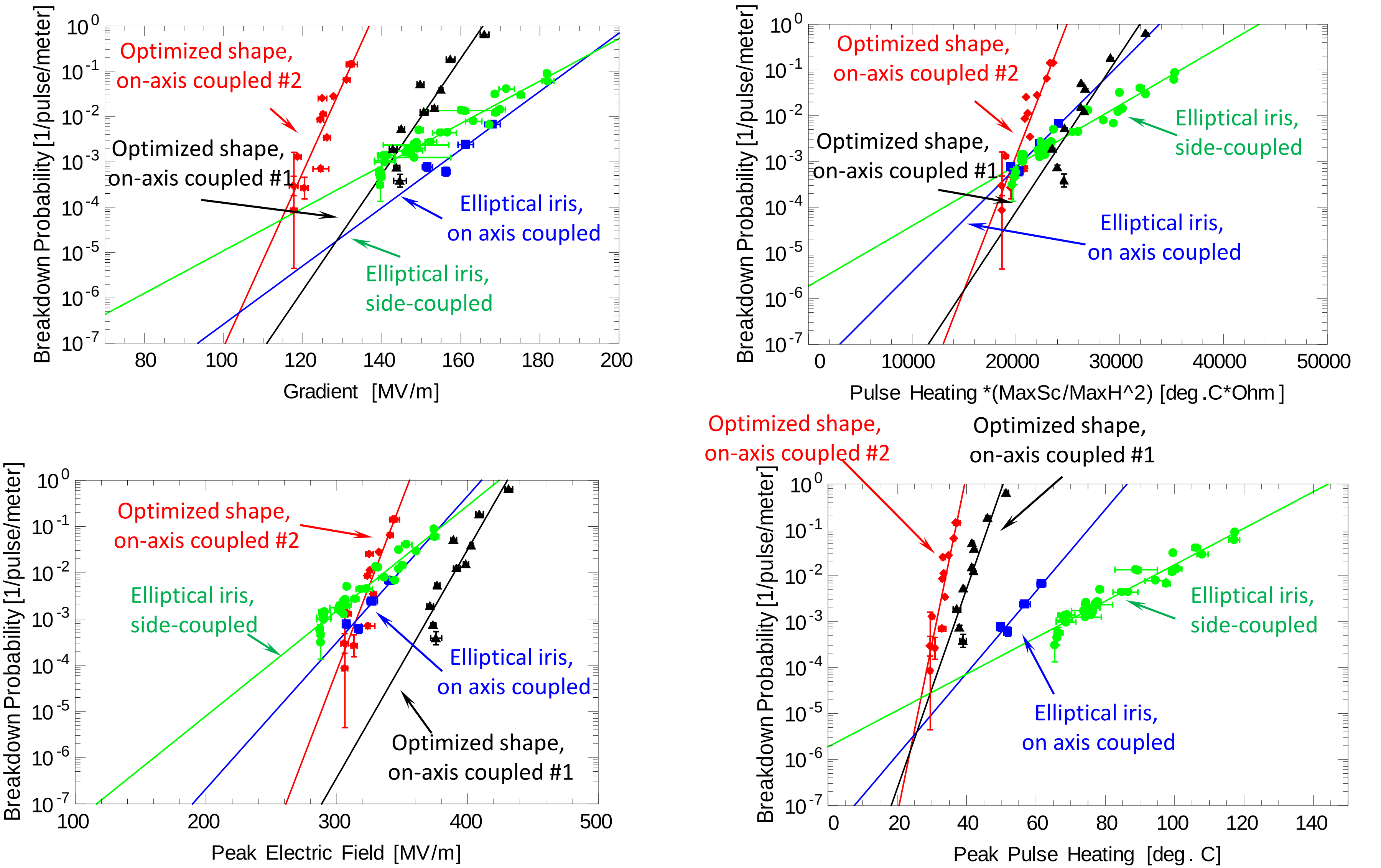






V.A. Dolgashev, 27 September 2012

Breakdown data for two optimized shape 1C-SW-A3.75-T2.2-Cu-SLAC-#1 and #2, their comparison with 2 structures of 3.75 mm aperture and different geometries, 150 ns shaped pulse

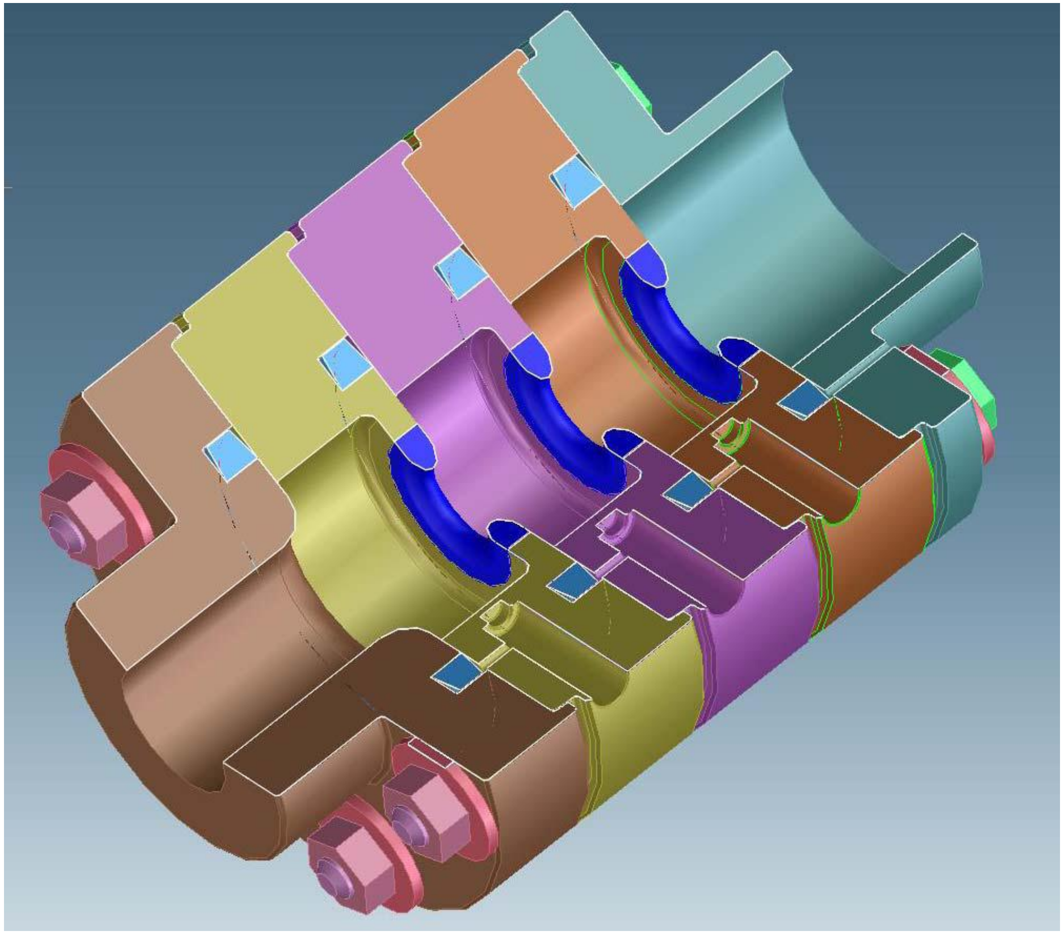


Material studies

Copper-Molybdenum Clad structure
1C-SW-A3.75-A2.6-Clad-Cu-Mo-KEK-#1

Material studies

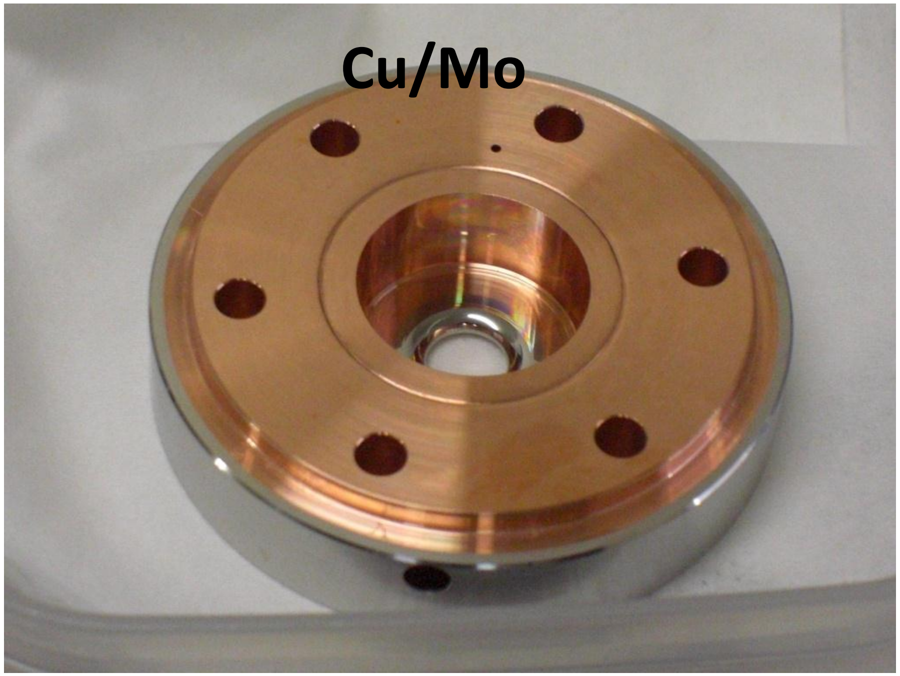
Copper-Molybdenum Clad structures

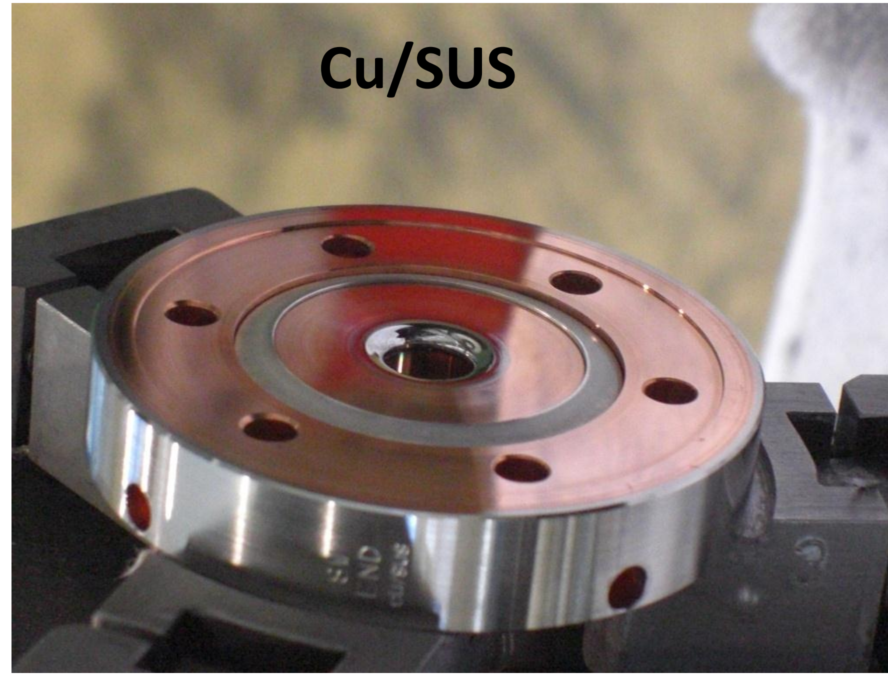


1C-SW-A3.75-T2.6-Clad-Cu-Mo-KEK

Both peak surface electric field and peak Poynting vector located on the iris insert.

1C-SW-A3.75-T2.6-Clad-Cu/SUS, Cu/Mo surface polished cell





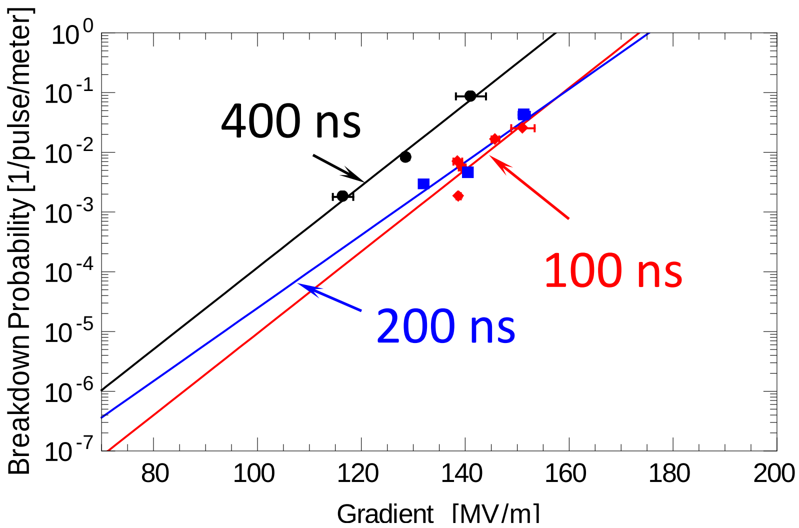
	Bulk resistivity (Ohm-m)	surface resistivity (Ohm)	skin depth (mm)
Cu	1.724x10E-8	0.034	0.505
SUS 304	6.4 x10E-7	0.208	3.07
Mo	5.7x 10E-8	0.062	0.918

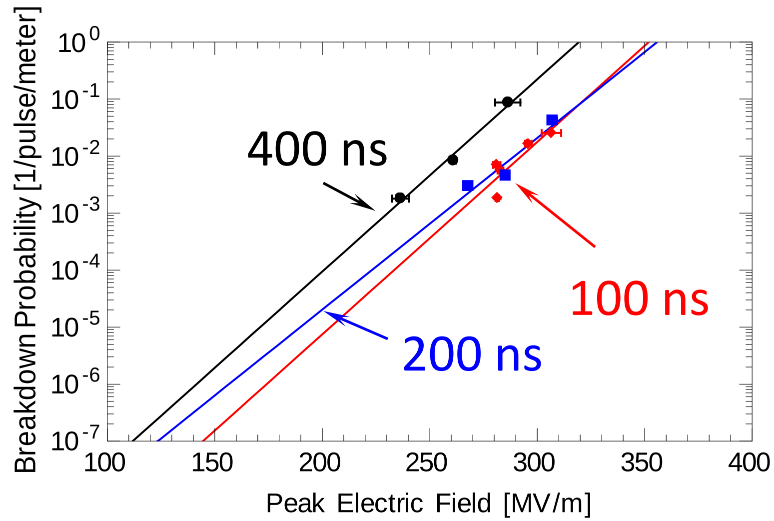
Yasuo Higashi, KEK, September 2011

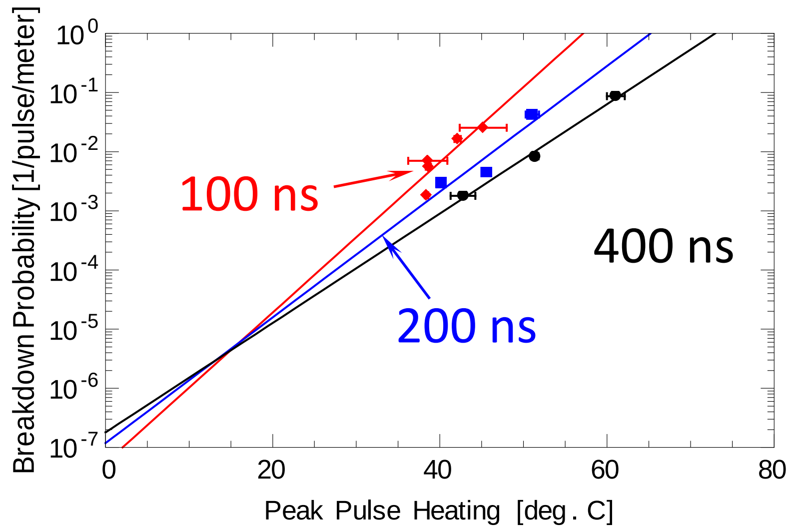
Two Single cell SW structures, one with Mo another one with stainless steel tips before shipping to SLAC

Yasuo Higashi, KEK

Breakdown data for high shunt impedance Clad Mo-Cu
1C-SW-A3 .75-T2 .6-Clad-Cu-Mo-KEK-#1, different length of shaped pulse

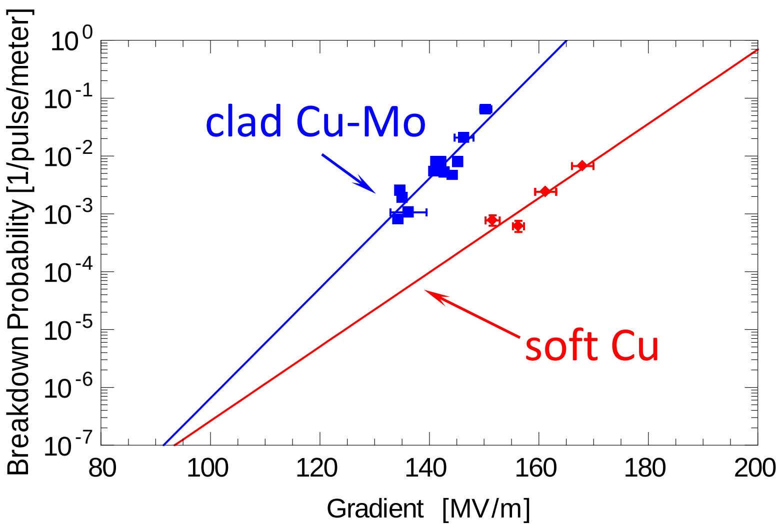


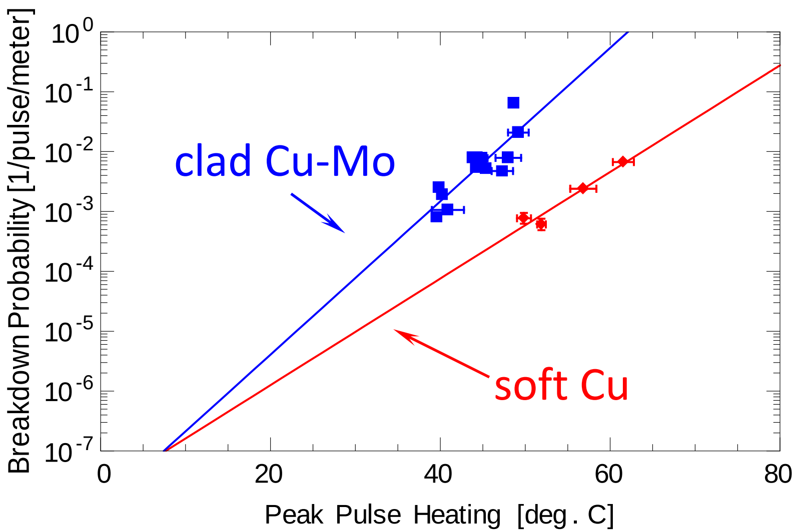


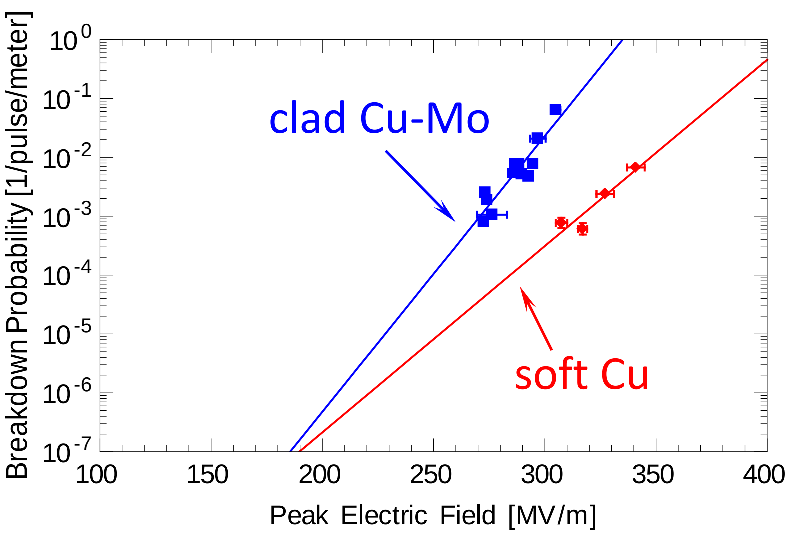


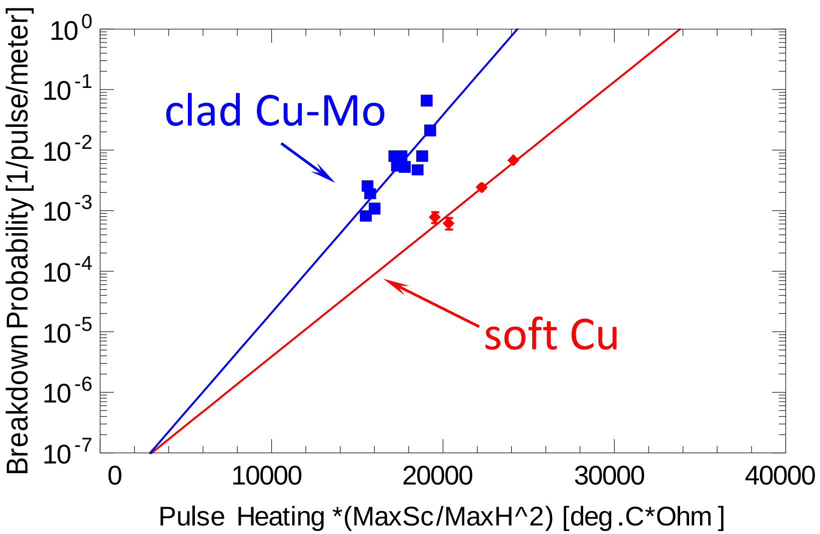
Cu-Mo clad structure shows pulse length dependence of the rf breakdown rate which is characteristic for structures limited **by field amplitude**, not pulse heating.

Breakdown data for two structures of same shape but different materials , 1C-SW-A3.75-T2.6, soft Cu and clad Cu-Mo, 150 ns shaped pulse

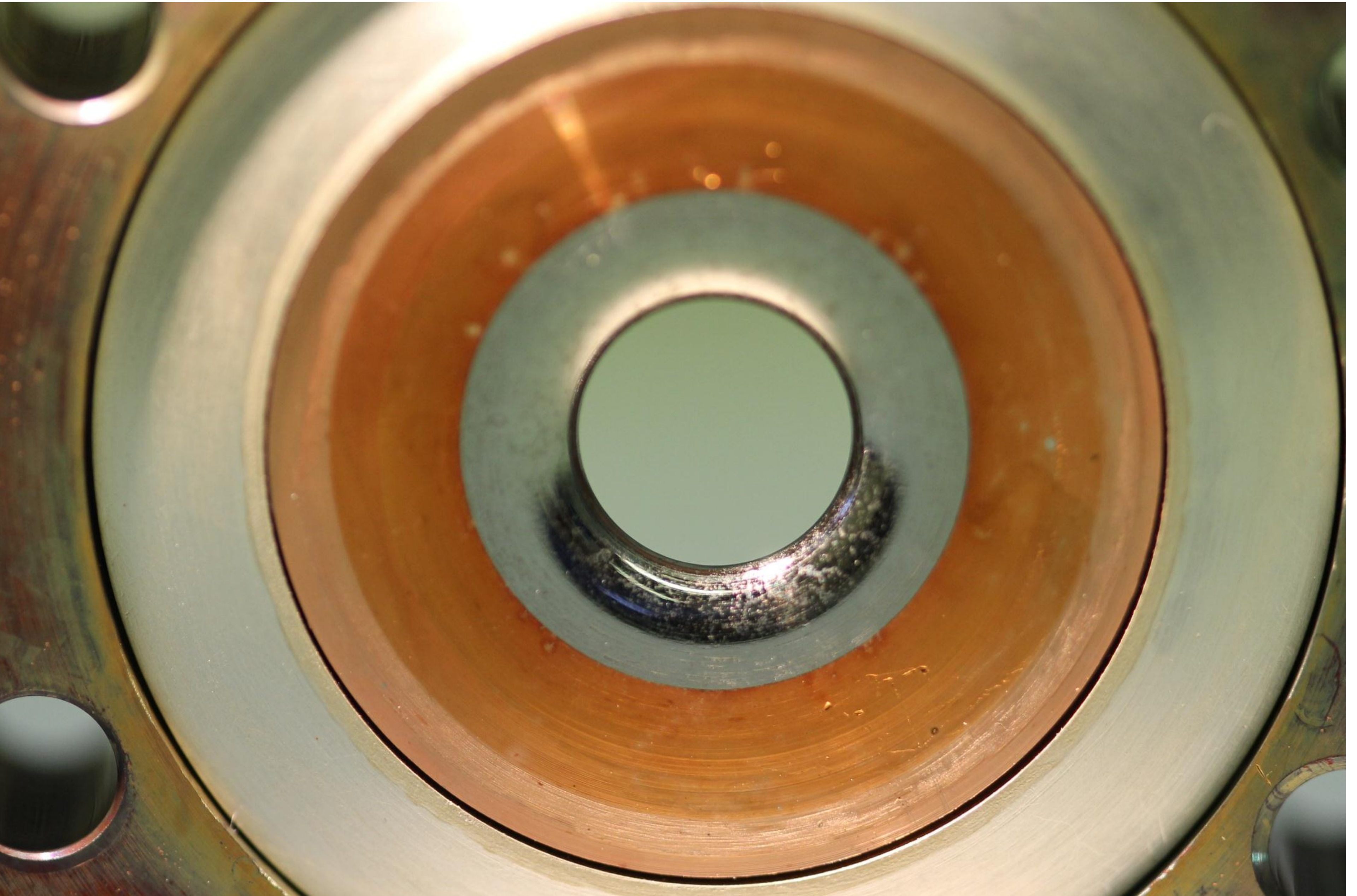






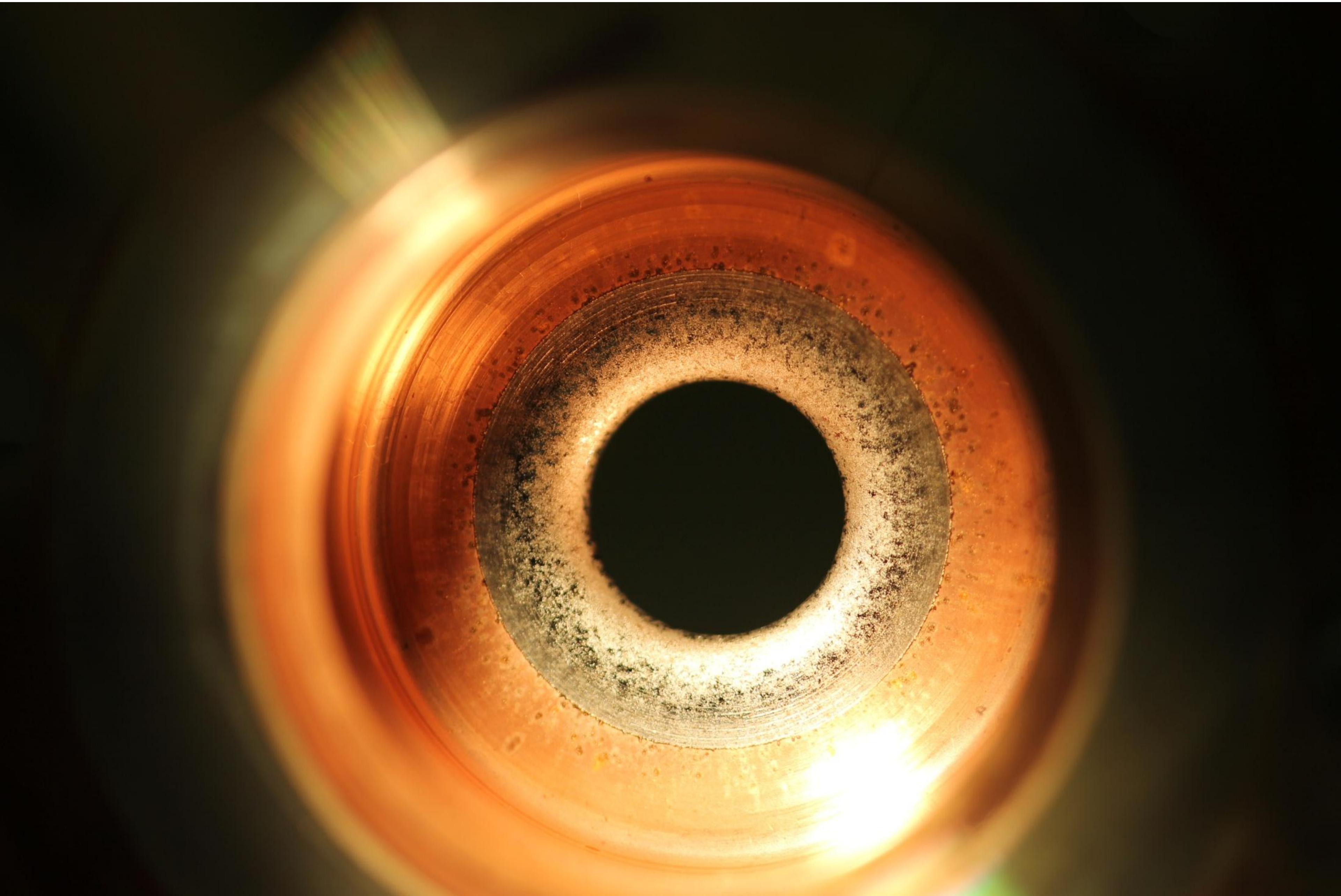


Low gradient side of central cell of Cu-Mo clad structure
1C-SW-A3.75-A2.6-Clad-Cu-Mo-KEK-#1



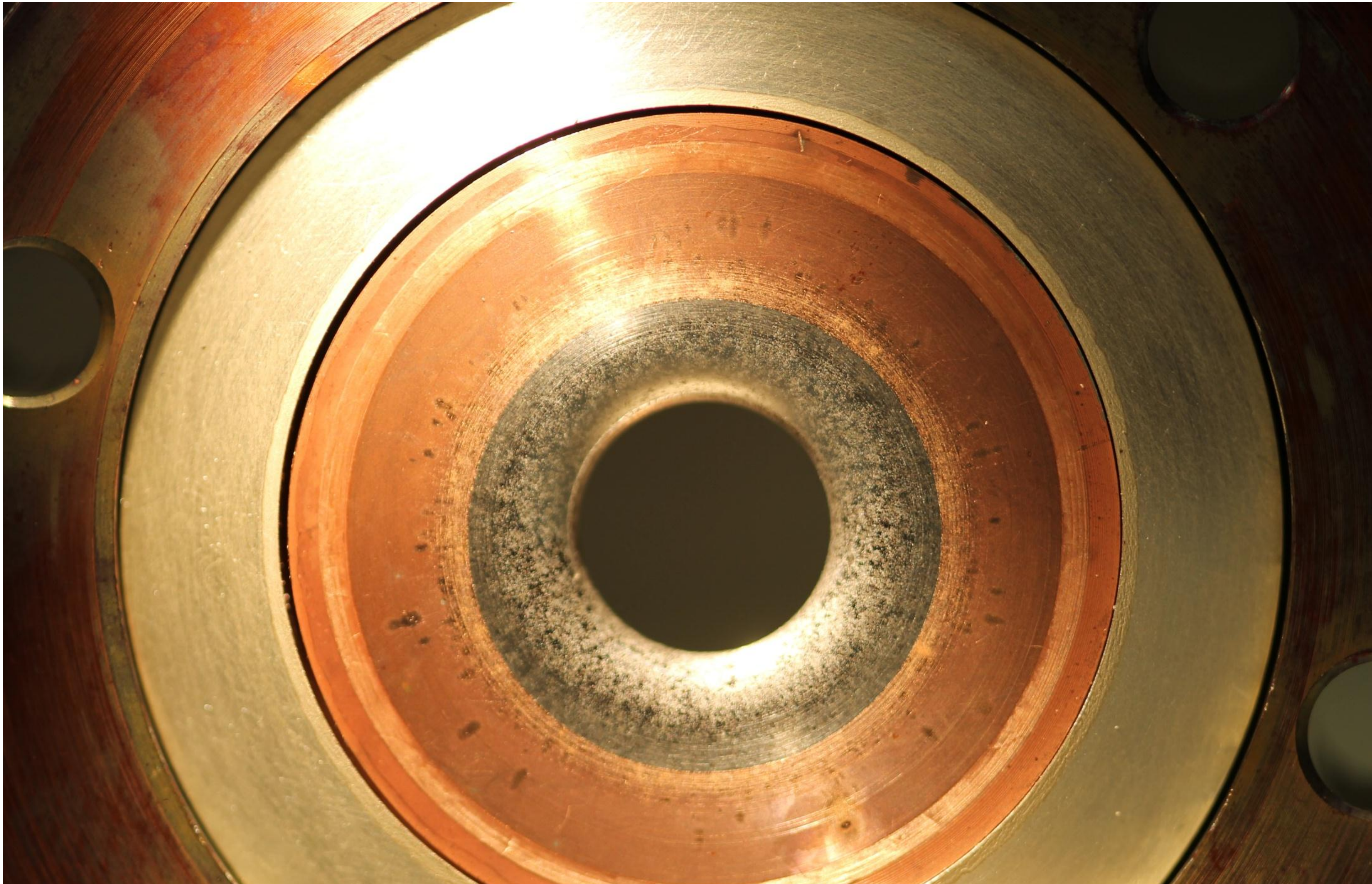
High gradient side of *central cell* of Cu-Mo clad structure

1C-SW-A3.75-A2.6-Clad-Cu-Mo-KEK-#1



High gradient side of *end cell* of Cu-Mo clad structure

1C-SW-A3.75-A2.6-Clad-Cu-Mo-KEK-#1



Results of clad Mo-Cu structure

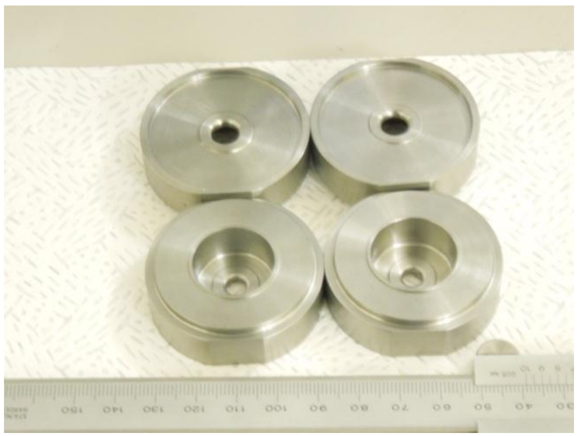
- We successfully tested clad structure built without high temperature brazing to avoid damage of the Mo-Cu joint.
- Cu-Mo clad structure shows pulse length dependence of the rf breakdown rate which is characteristic for structures limited by field amplitude, not pulse heating.
- For the same breakdown rate, gradient in clad Cu-Mo structures is about 20% lower than in soft copper structures.

Material studies

Stainless Steel-Cu Clad structure

1C-SW-A2.75-T2.0-Cu-on-SS-Clamped-KEK-#1

Clad single cell SW structures made with electroplating for testing in SLAC vacuum-can



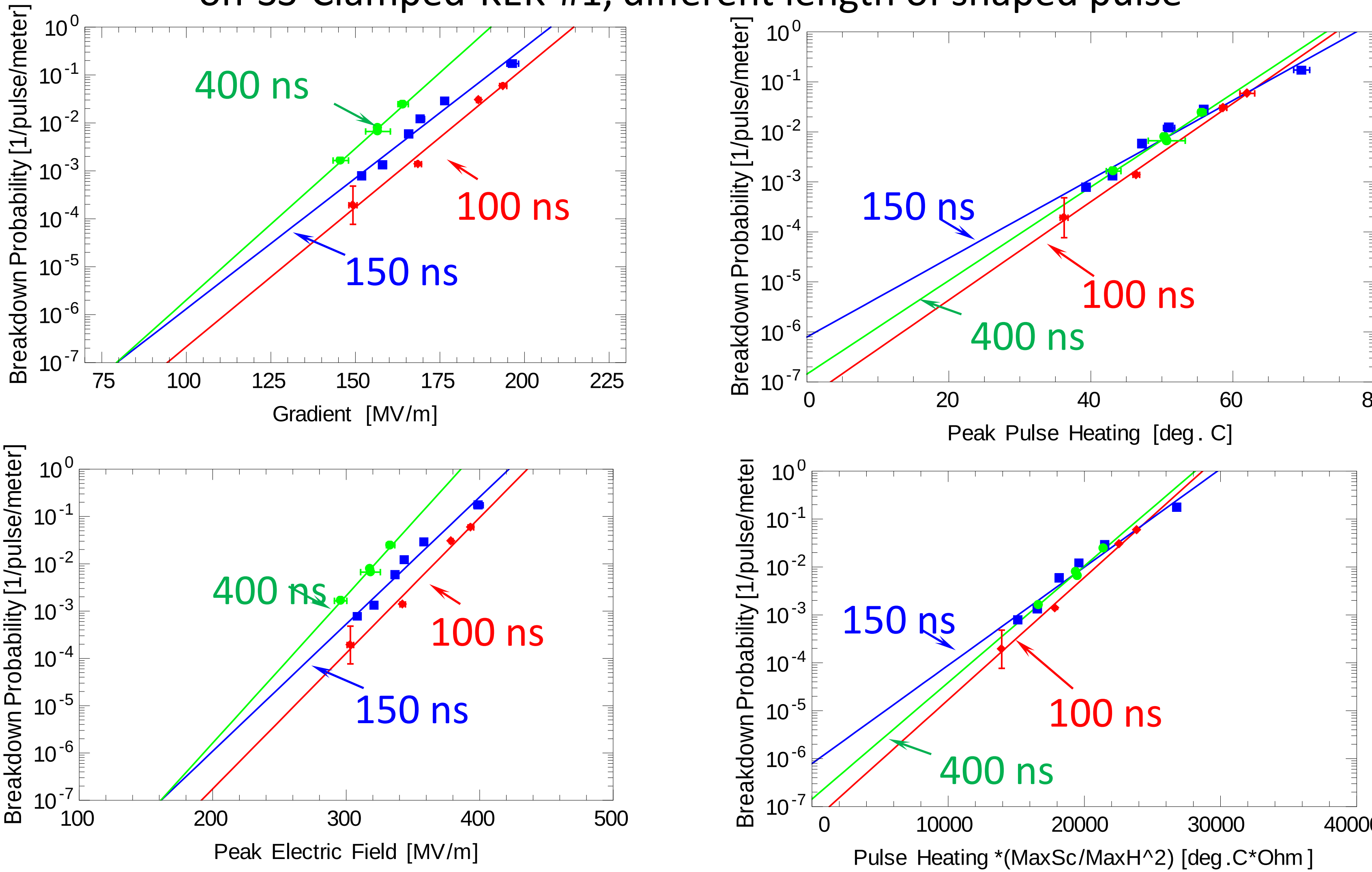
Stainless steel base

Stainless steel base plated with copper

Cells after final machining

Y. Higashi, KEK

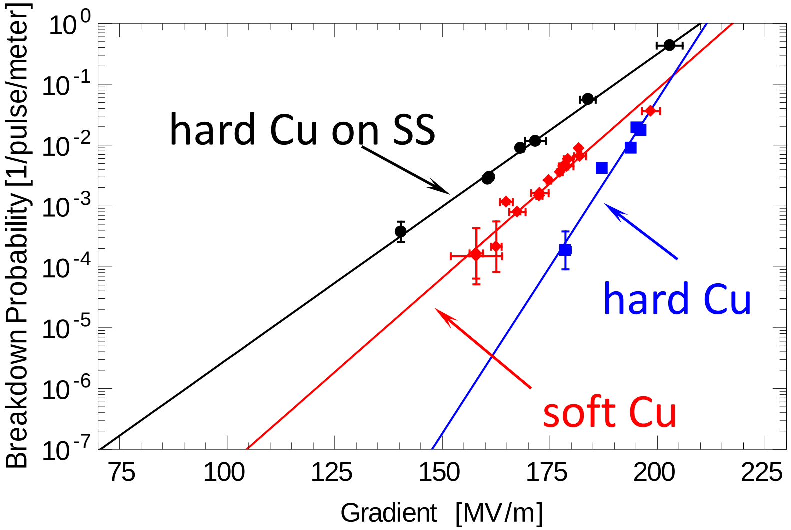
Breakdown data for highest shunt impedance Cu-on-SS 1C-SW-A2.75-T2.0-Cu-on-SS-Clamped-KEK-#1, different length of shaped pulse

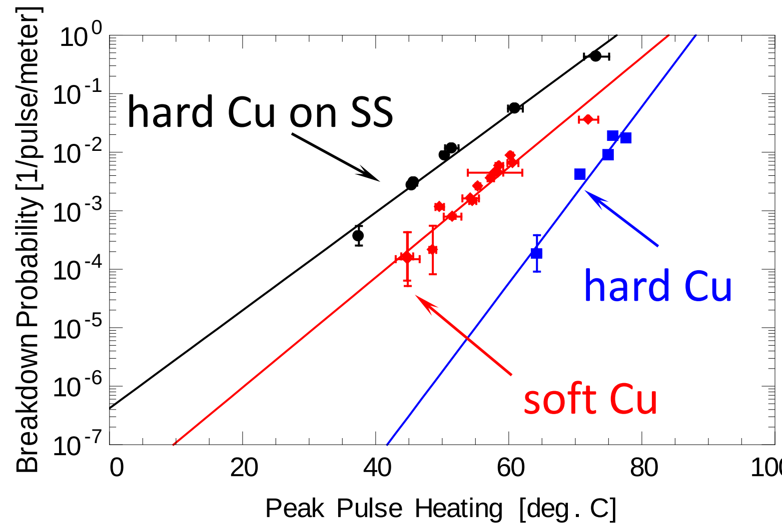


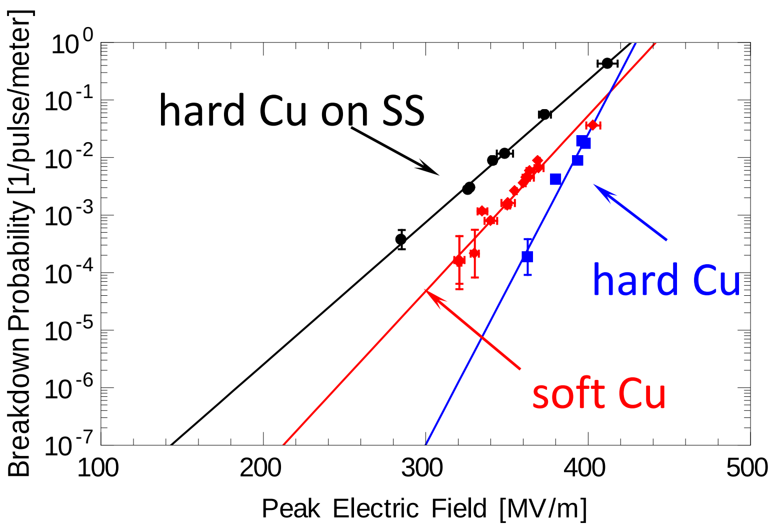
Clad structure shows pulse length dependence of the rf breakdown rate which is typical for copper structures.

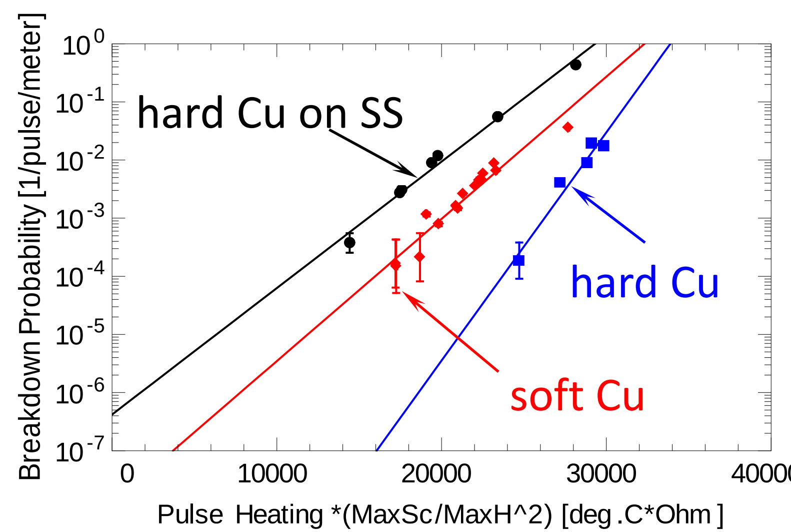
V.A. Dolgashev, 28 September 2012

Breakdown data for three structures of same shape but different materials , 1C-SW-A2.75-T2.0, soft Cu, hard Cu, and Cu on Stainless Steel, 200 ns shaped pulse



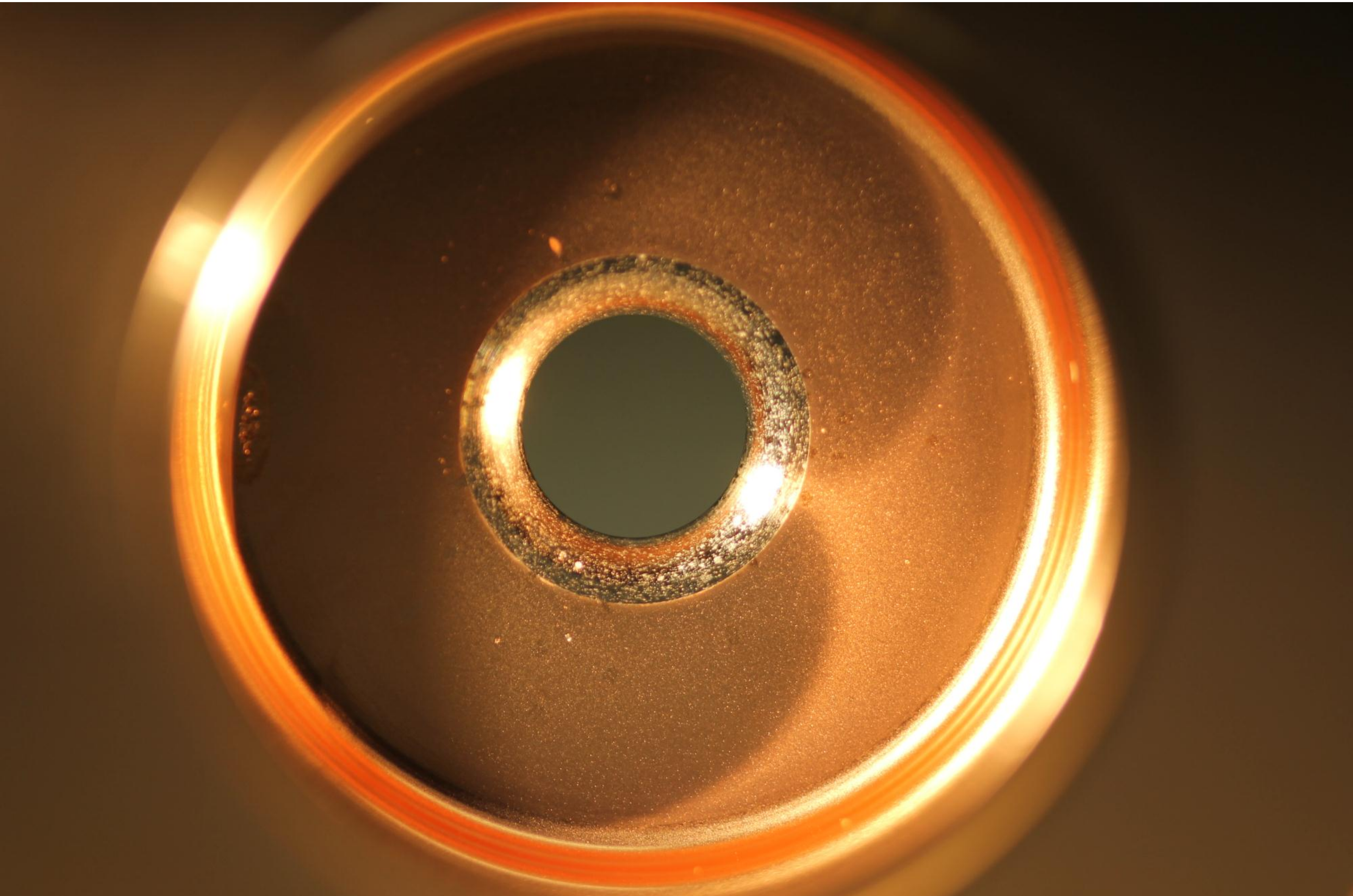




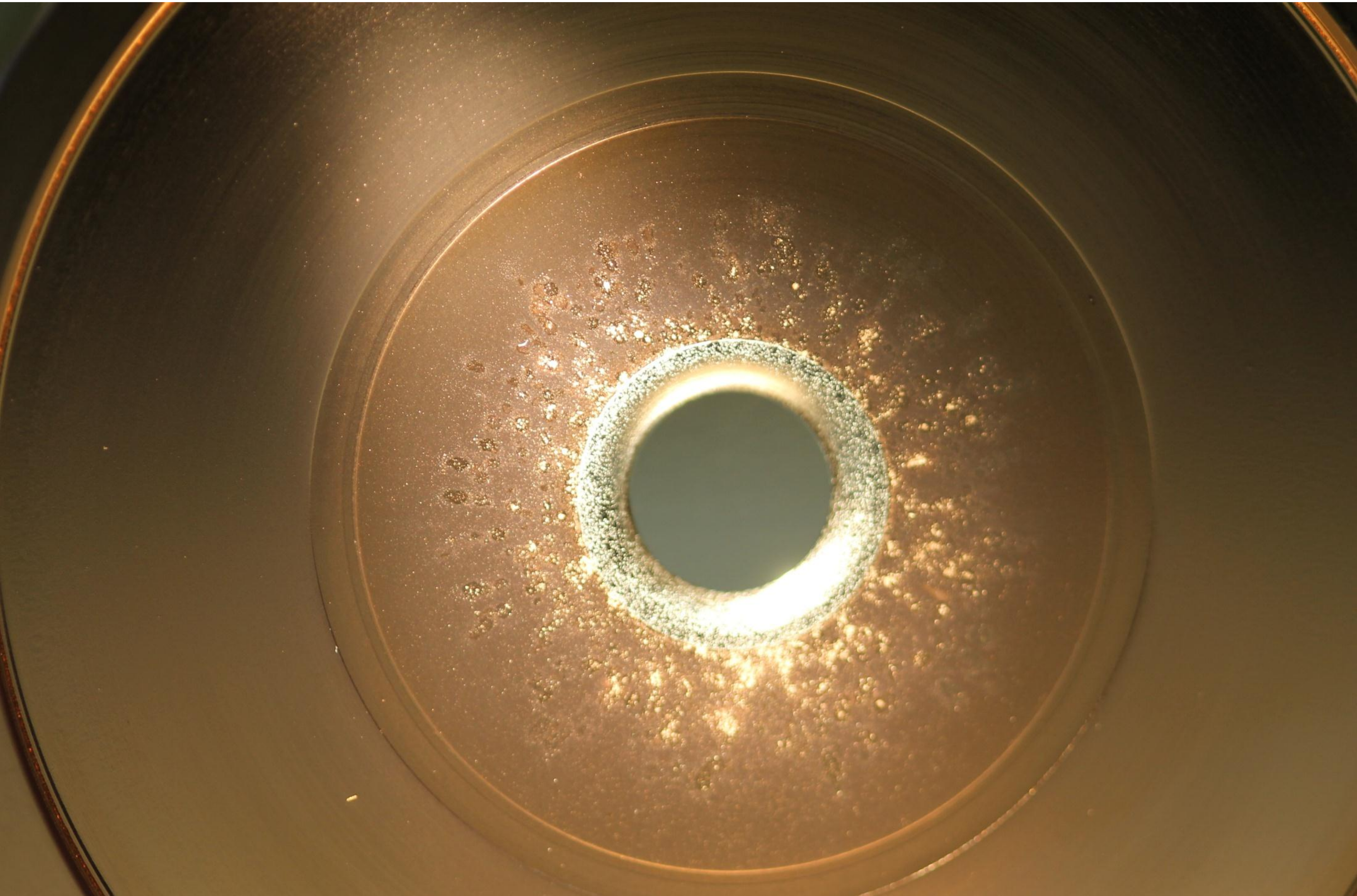


V.A. Dolgashev, 28 September 2012

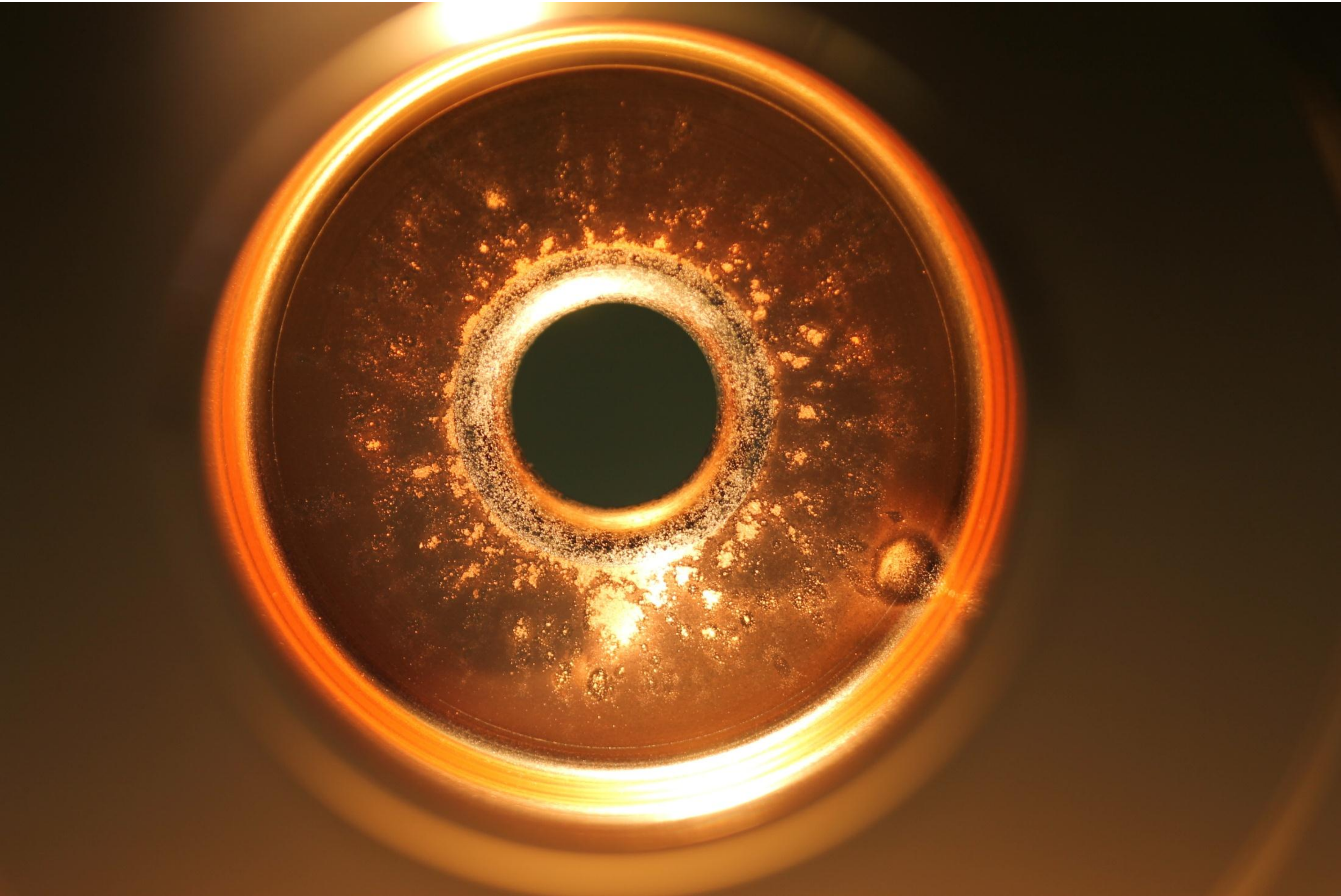
Low gradient side of *end cell* of 1C-SW-A2.75-T2.0-Cu-on-SS-Clamped-KEK-#1



High gradient side of *end cell* of 1C-SW-A2.75-T2.0-Cu-on-SS-Clamped-KEK-#1



High gradient side of *central cell* of 1C-SW-A2.75-T2.0-Cu-on-SS-Clamped-KEK-#1



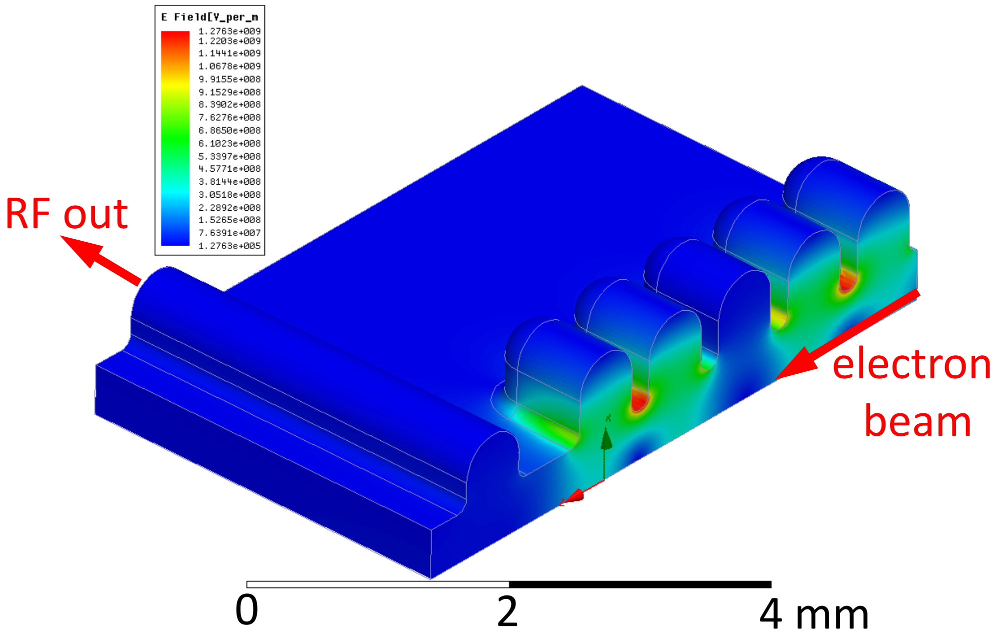
Results of the test of highest shunt impedance Cu-on-SS structure

1. This is successful test of the clad-cell technology potentially suitable for brazed structures
2. Statistical behavior of the rf breakdowns in the structure is very similar to rf breakdowns in soft copper structures
3. For the same breakdown rate the gradient is about 10% lower in the Cu-coated structure than in soft-Cu structure, while the clad structure has significantly lower dark currents

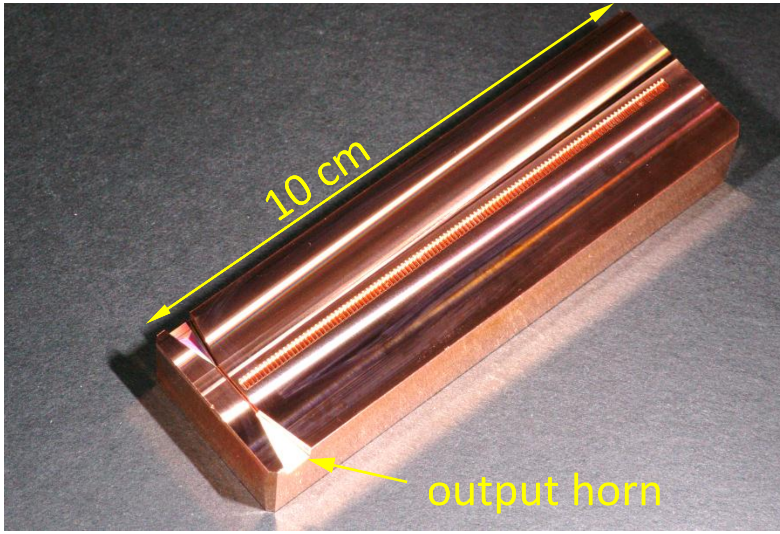
Beam tests of 100 GHz copper structure at FACET

Motivation:
Study rf frequency dependence of rf breakdowns properties in metal structures

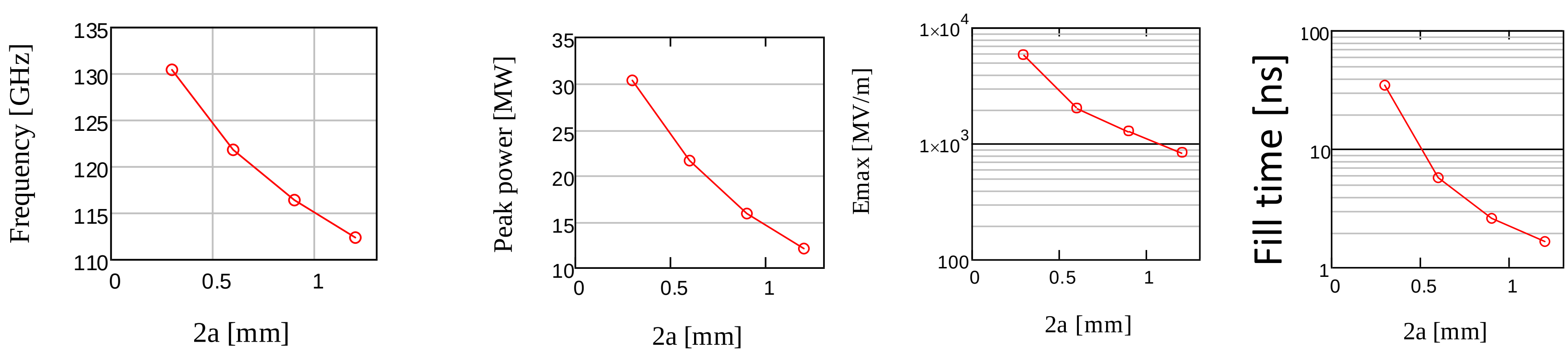
RF Breakdown Test of Metal Accelerating Structure at FACET



HFSS model of 1/4th of output part of accelerating structure, beam gap 0.9 mm, frequency 116 GHz, excitation 1.6 nC, peak electric field ~1.3 GV/m



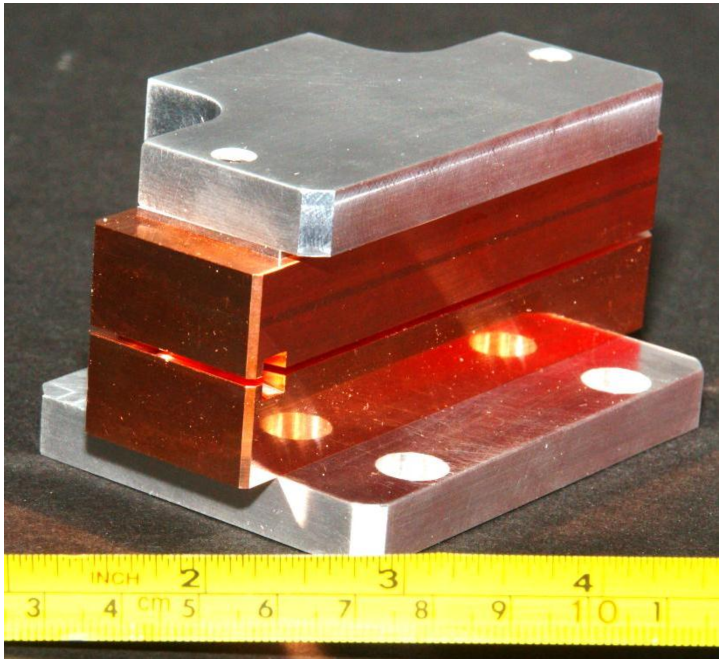
Accelerating structure manufactured by Makino



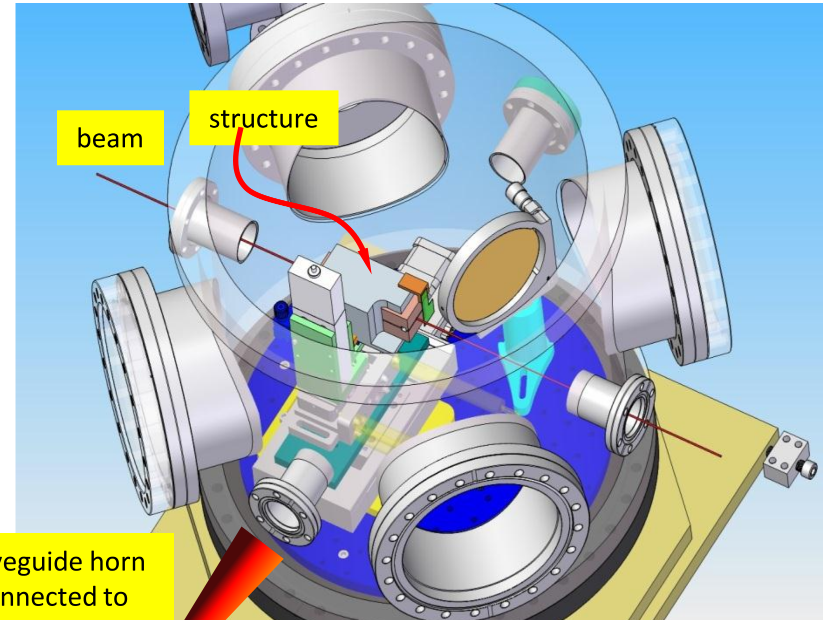
Parameters of accelerating structure with changing beam gap, excited by 1.6 nC bunch

Valery Dolgashev, Sami Tantawi, SLAC

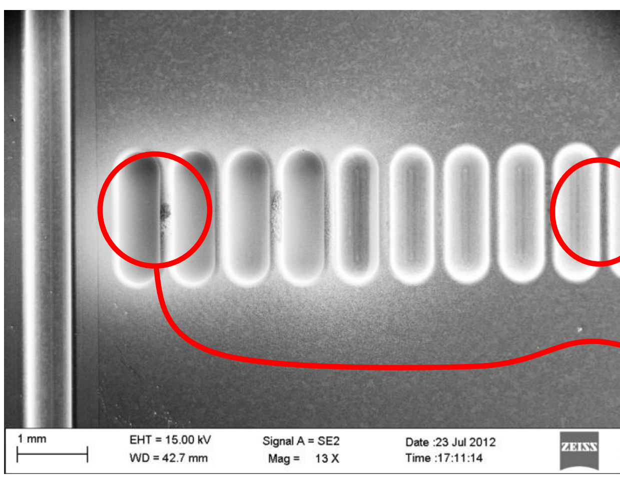
RF Breakdown Test of Metal Accelerating Structure at FACET



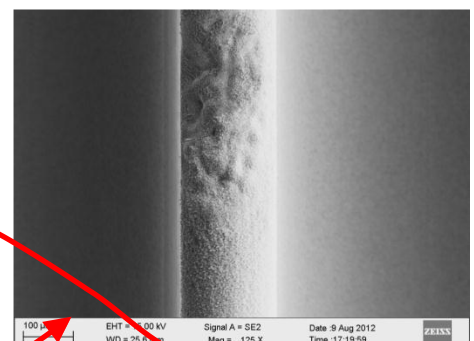
Assembled structure, beam gap set to 0.9mm



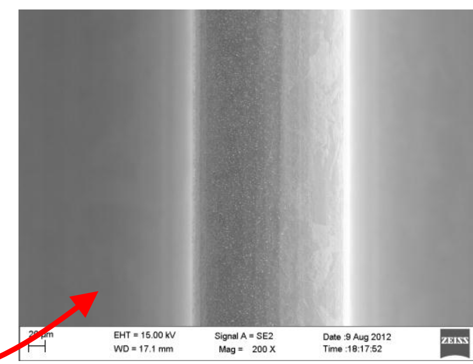
Structure in FACET vacuum chamber



Autopsy of output part of the structure



1^{st} iris – breakdown damage, peak surface fields <1.3 GV/m



9^{th} iris – no breakdown damage, peak surface fields > 0.64 GV/m, pulse length ~3ns

Valery Dolgashev, Sami Tantawi, SLAC

Dual Mode Cavity

Motivation:

The goal for a dual mode cavity is to study the effect of the rf magnetic field on the operational *accelerating gradient determined by rf breakdowns in a geometry as close as practical to a standing wave accelerator cell.*

S. Tantawi, "Experimental Evaluation of Magnetic Field Effects on Breakdown Rates", CERN Breakdown Physics Workshop, May 2010

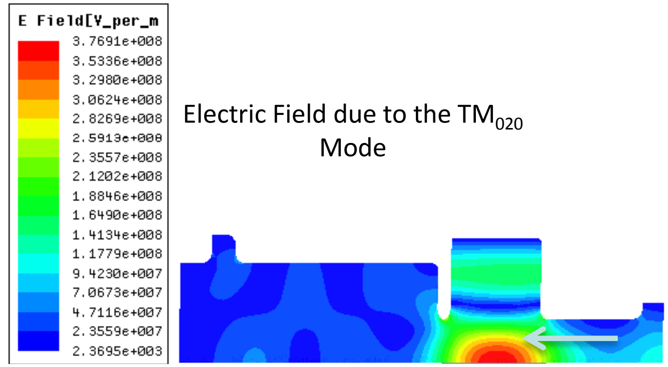
A. D. Yeremian et al., *A Dual-mode Accelerating Cavity to Test RF Breakdown Dependence on RF Magnetic Fields, MOPC073,* Proc. of IPAC´11, San Sebastian, Spain, 2011

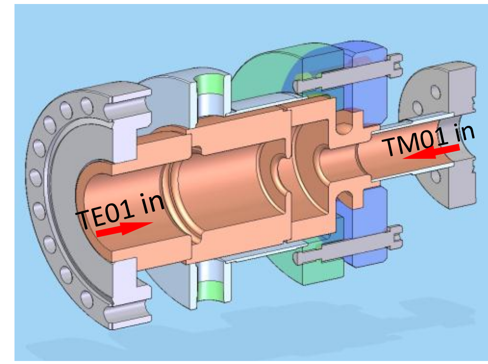
Dual Mode Accelerating Cavity for studying the relative effects of electric and magnetic fields

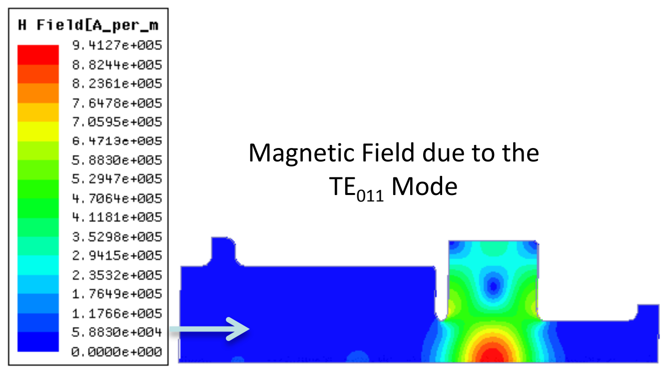
- This experiment is ongoing we are in the process of collecting statistics.

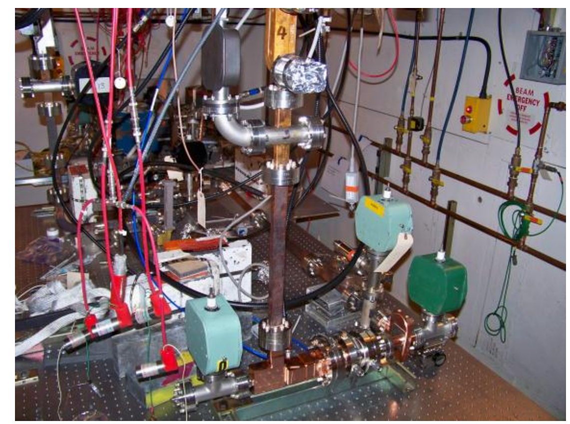
- The experiment is very flexible, we change the independently electric and magnetic field, timing between fields , and relative amplitude and phase

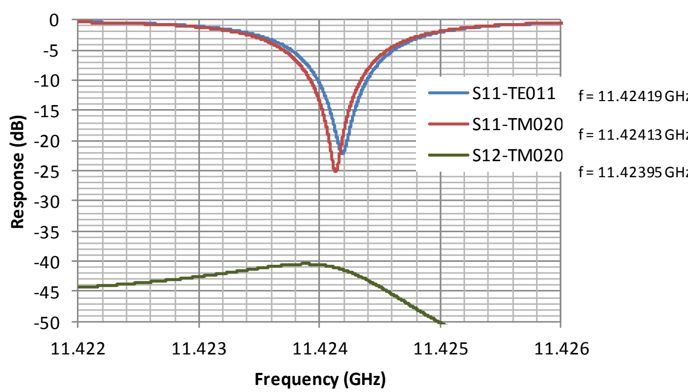
- We are already seeing very interesting results that could have an impact on our understanding of the phenomena



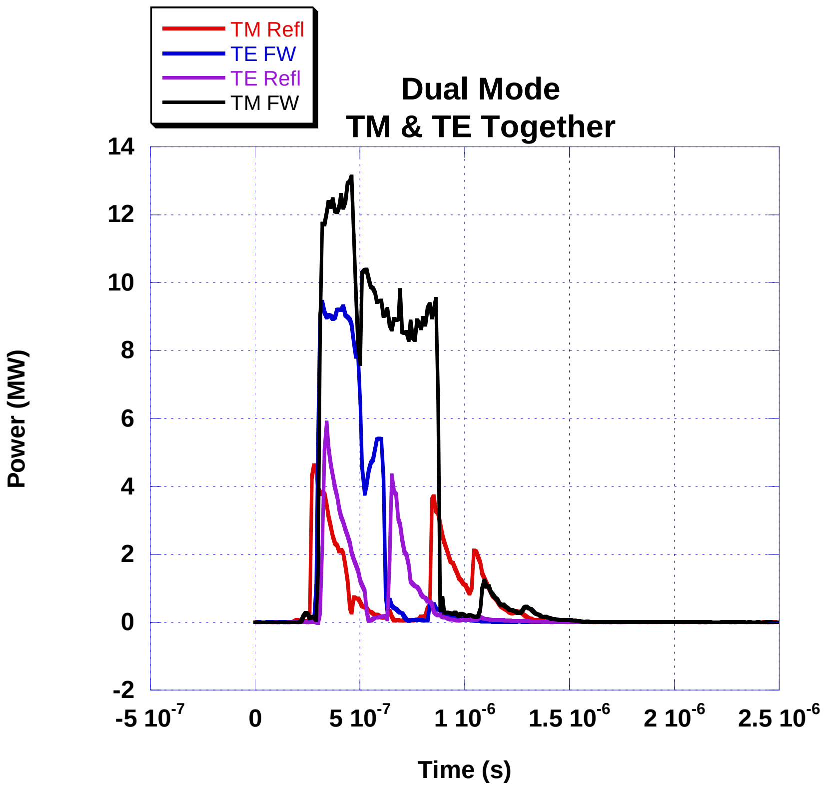


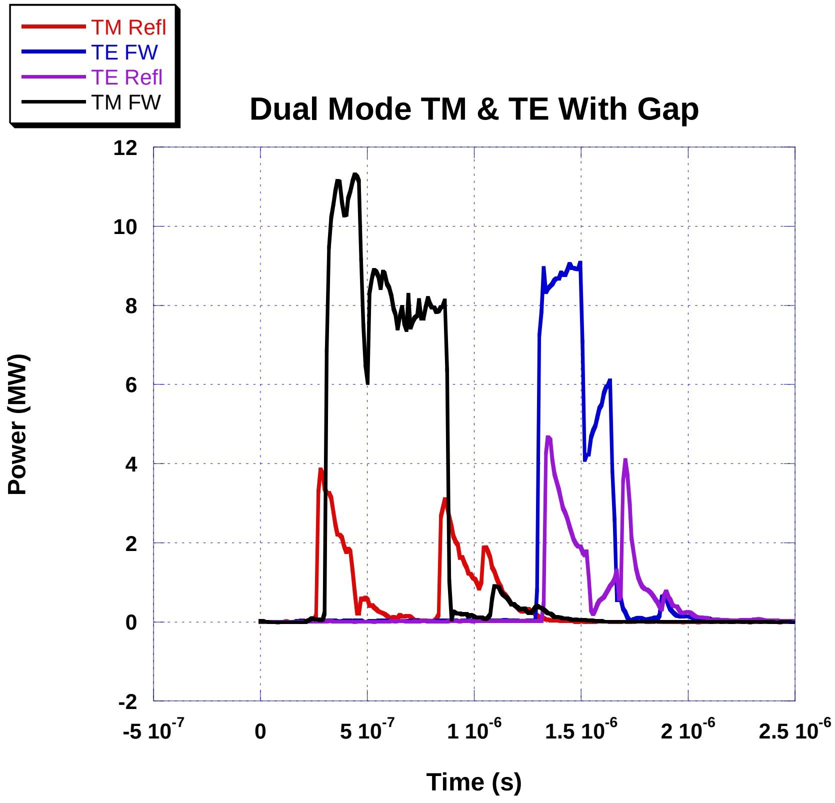






Changing relative position of TM and TE modes



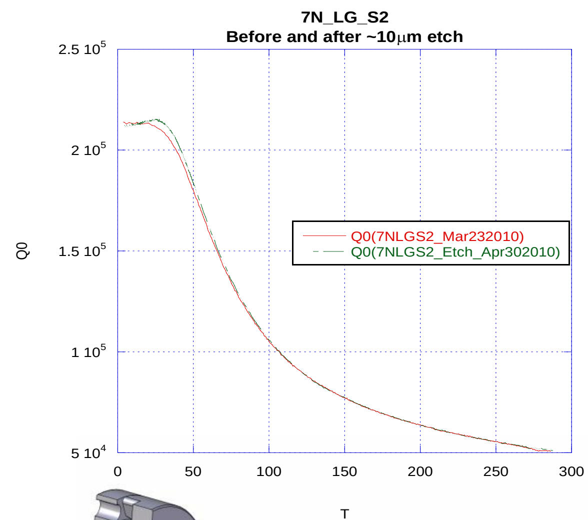


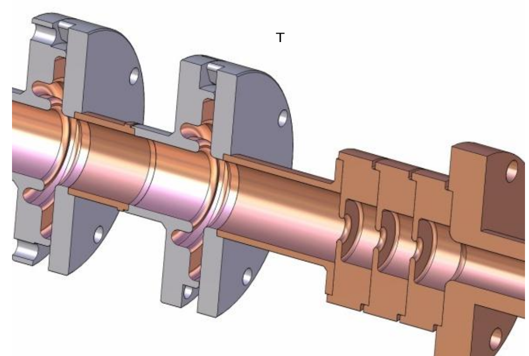
J. Lewandowski, 12 April 2012

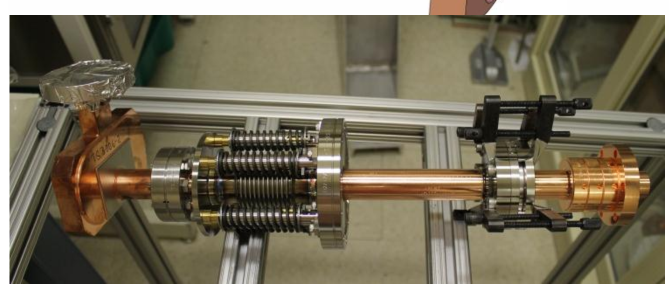
Future experiments

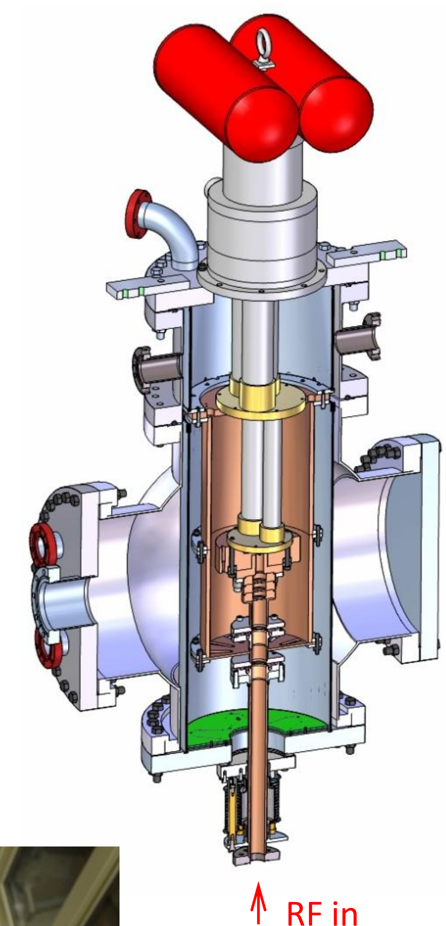
Cryogenic Testing of normal conducting accelerating structures

- We made detailed measurements for copper conductivity at 11.424 GHz using specialized cavities
- Conductivity increases (by a factor of 17.6 at 25K), enough to reduce cyclic stresses.
- The yield strength of copper also increases.
- The experiment is ready and will be executed in a month or so as soon as there is a time slot in ASTA









Dolgashev *et al.*, IPAC12

Parallel-fed Standing Wave structure

Potential advantages of parallel fed, π mode standing wave structures over travelling-wave structures

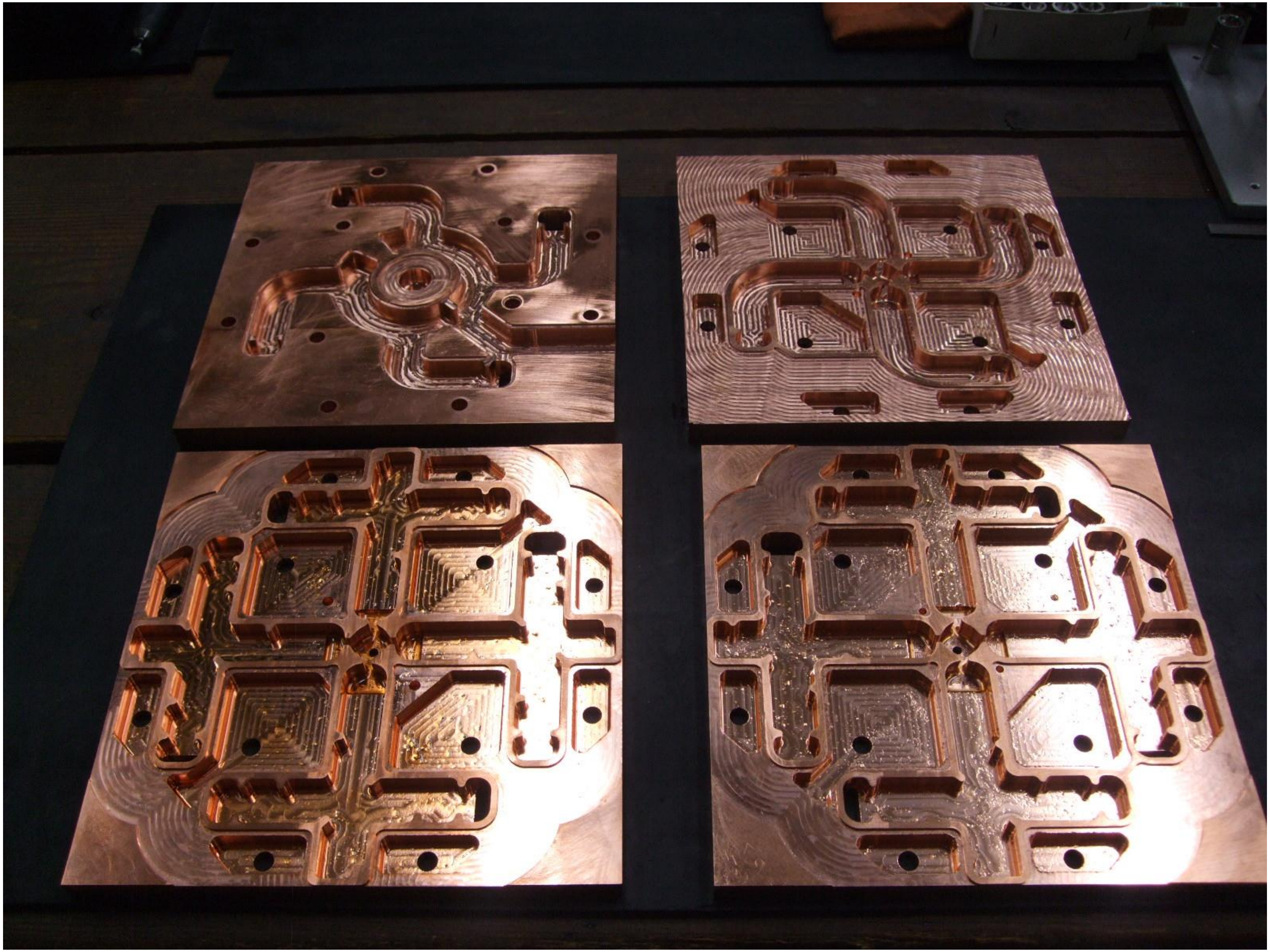
– minimizes energy available during breakdown

– maximizes power distribution efficiency

– enhanced vacuum pumping conductance

Jeffrey Neilson, Sami Tantawi, Valery Dolgashev, "Design of RF feed system and cavities for standing-wave accelerator structure," Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, Volume 657, Issue 1, 21 November 2011, Pages 52-54.

Manufacturing of Parallel fed Standing Wave structure

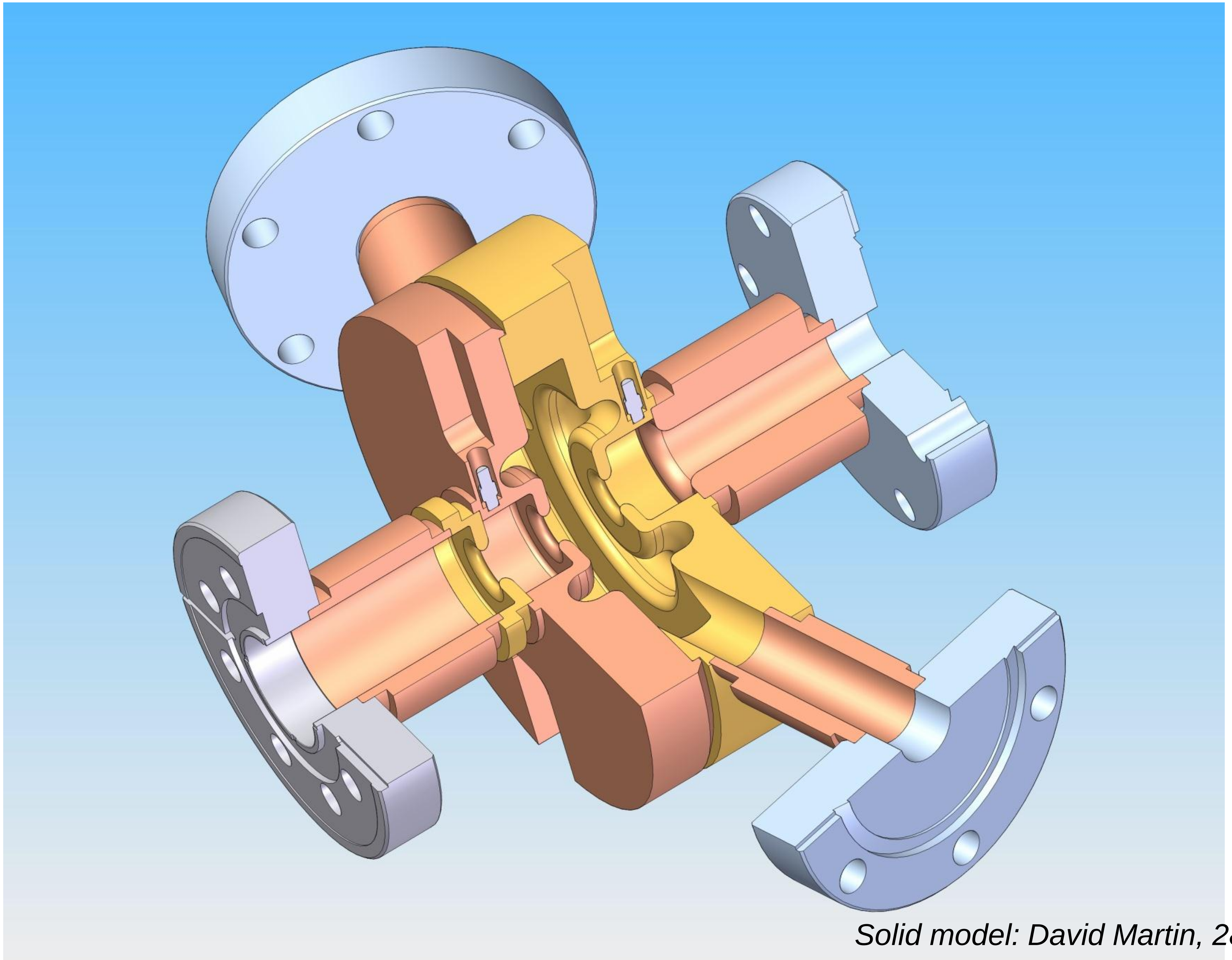


Yasuo Higashi, KEK

New diagnostics

In-situ microscopic observation of surface change and rf breakdowns:

Full cell choke and two view ports *1C-SW-A3.75-T2.6-Ch-View-Port-Cu-SLAC-#1,2*



Solid model: David Martin, 28 April 2010

Conclusion

- We continue high-power tests of with focus on understanding breakdown physics and developing technologies suitable for practical structures of new shapes and materials.