Recent High Gradient Tests at SLAC

Presented on behalf of collaboration by

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SLAC National Accelerator Laboratory

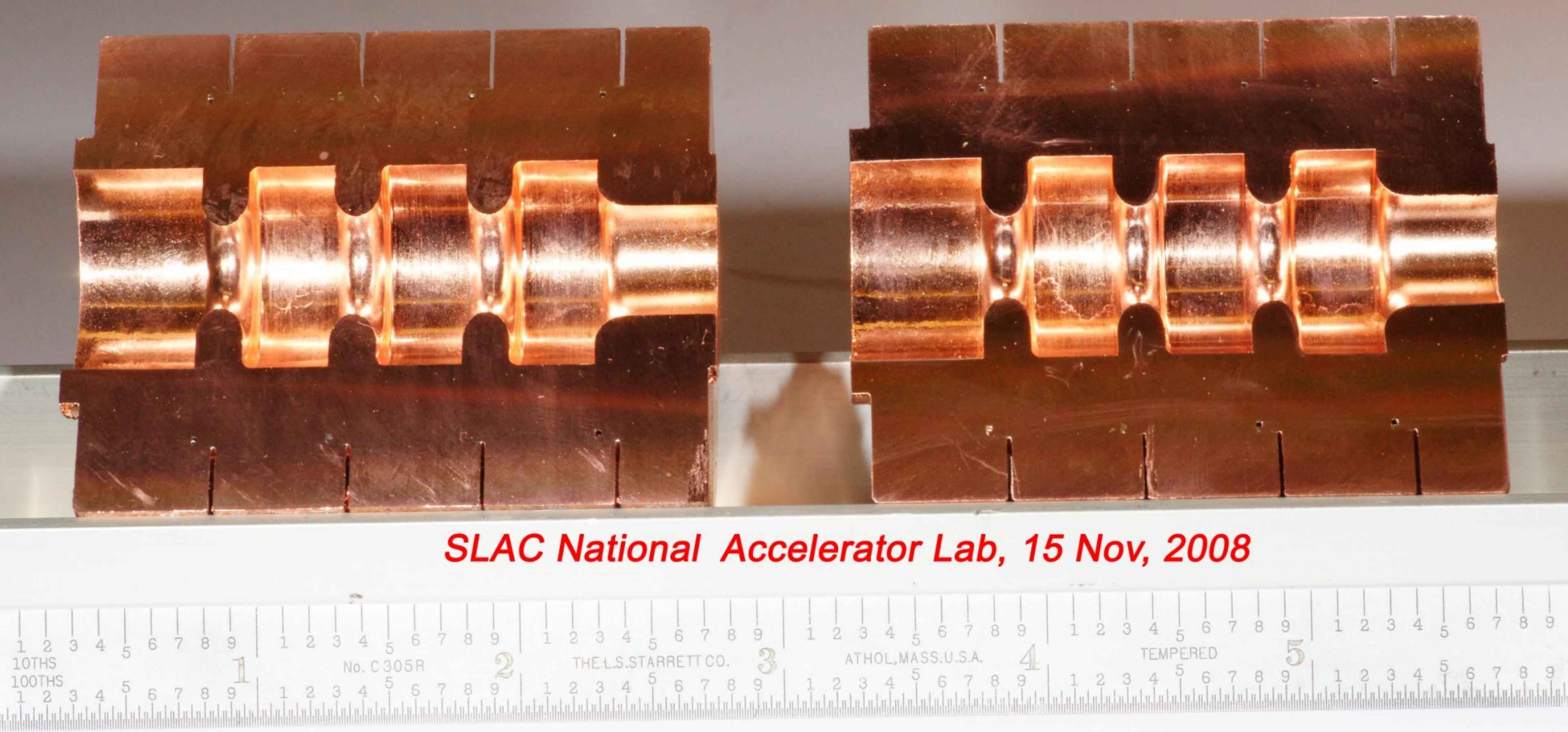
the 4th International Workshop on Mechanisms of Vacuum Arcs,
MeVArc 2013, 4-7 November, Hotel Les Aiglos, France

U.S. DEPARTMENT OF ENERGY Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

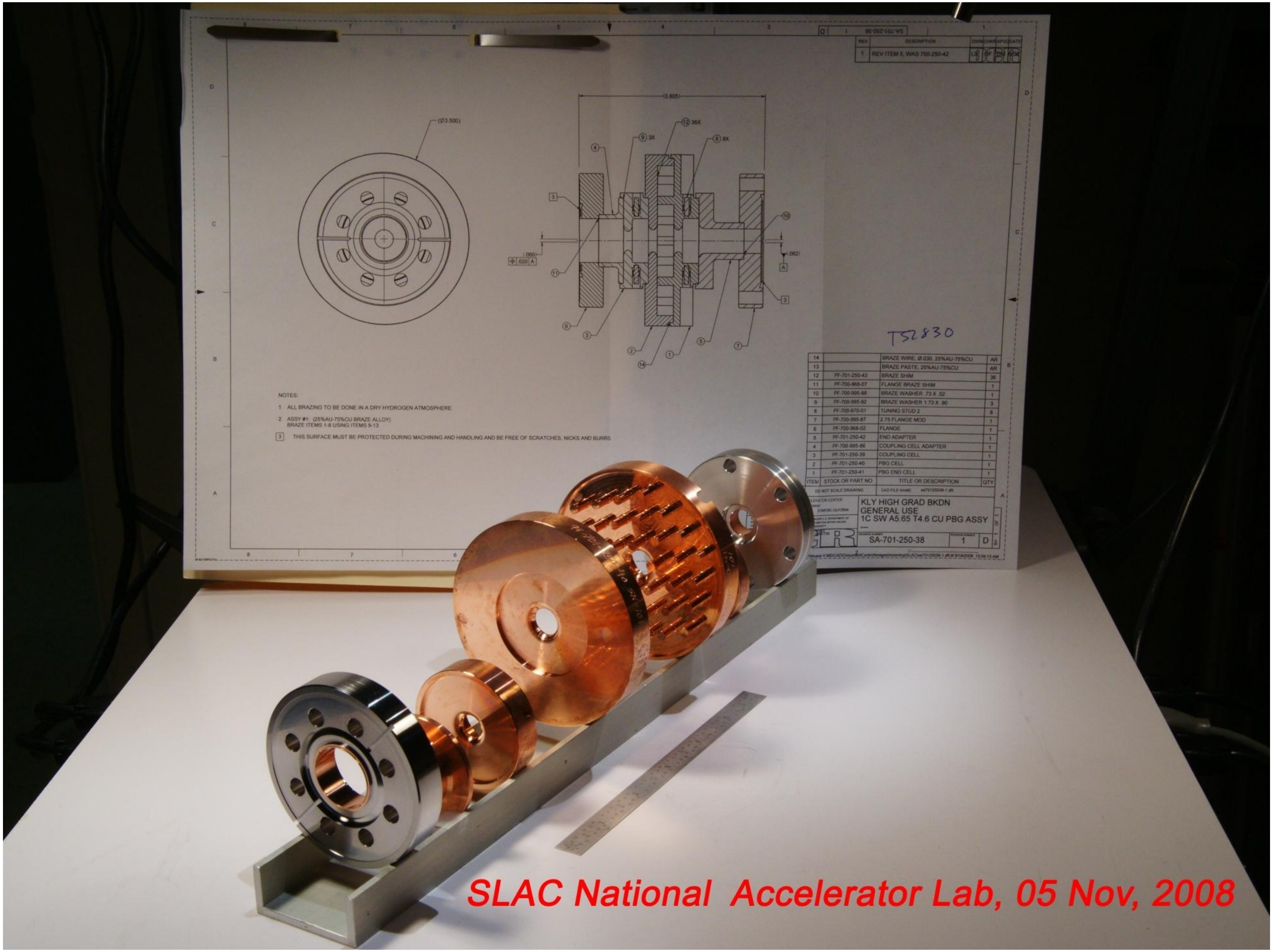
11.4 GHz, Standing Wave-Structure

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



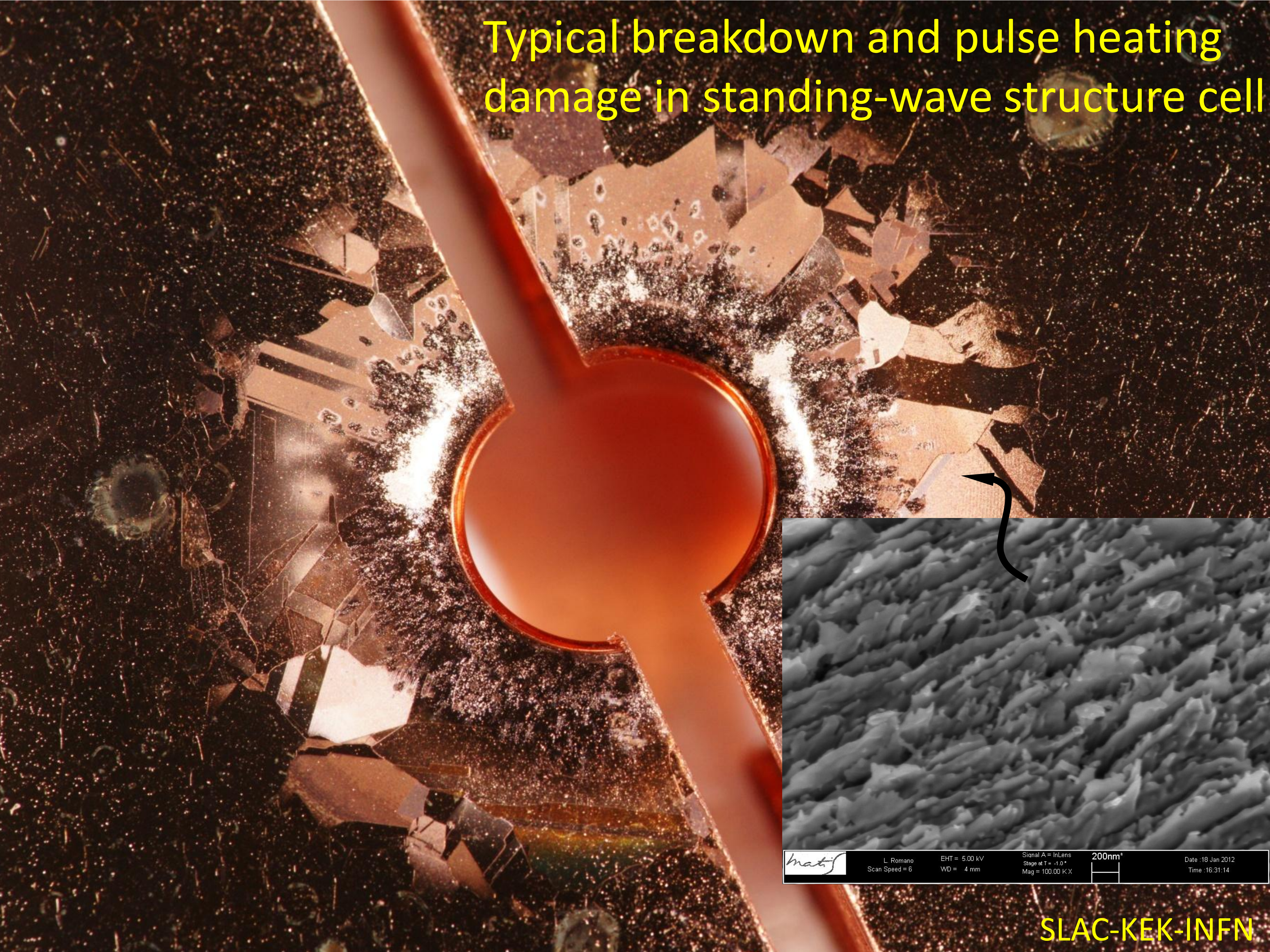
SLAC-KEK-INFN

11.4 GHz Standing Wave Structure with Photonic-Band Gap cell



SLAC-MIT

Typical breakdown and pulse heating damage in standing-wave structure cell



SLAC-KEK-INFN

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, 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 and now OIST, Okinawa, Japan*
- B. Spataro (spokesperson), C. Marcelli, V. Rigato, *INFN, Italy, NORCIA program*

Outline

- Motivation

- Overview of recent experimental results
  - Hard CuAg
  - Clad Cu-Mo and Cu-SS structures
  - Cryo Cu structure

- Planned experiments
  - 100 GHz structure
  - NORCIA’s structures

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

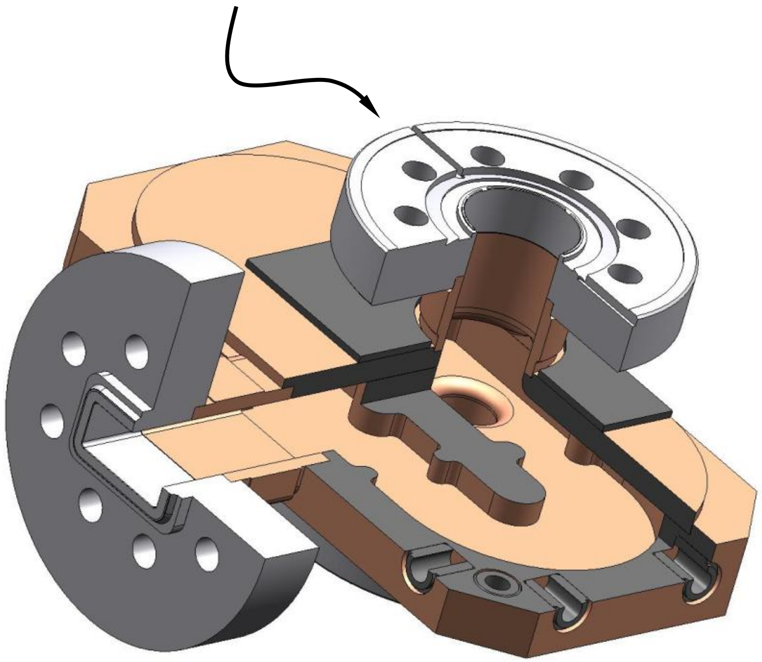
Solution

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

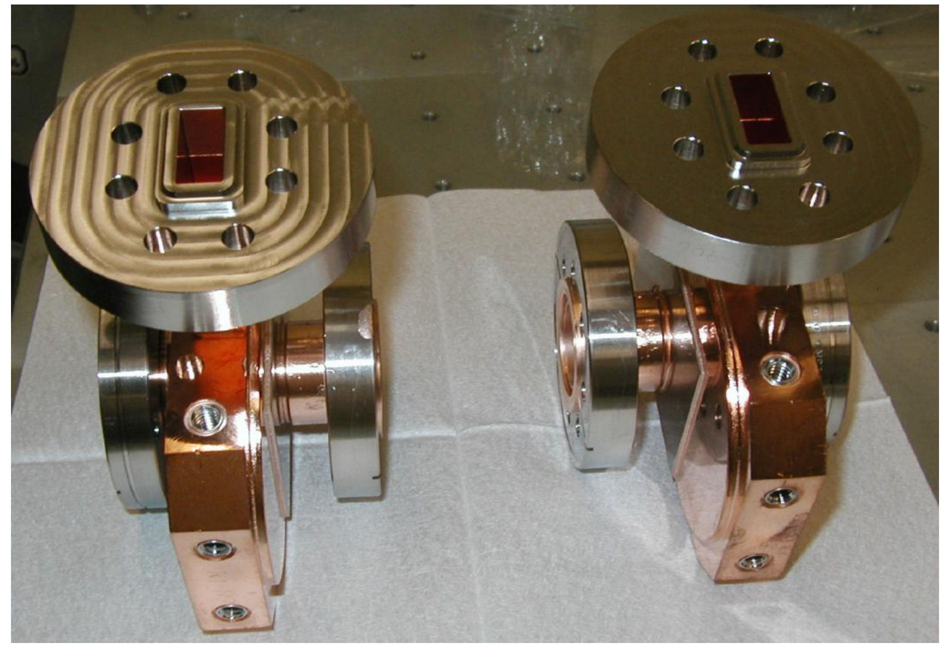
We want to predict breakdown behavior for practical structures

Reusable coupler: TM_{01} Mode Launcher

Pearson's RF flange



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

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, 1 tested
- Highest shunt impedance, stainless steel coated with copper, *1C-SW-A3.75-A2.6-Clamped-Cu-Coated-SS-KEK-#1*
- highest shunt impedance hard copper-silver structure *1C-SW-A2.75-A2.0-Clamped-CuAg-SLAC#1*
- High shunt impedance, clad Stainless Steel -Copper 1C-SW-A3.75-t2.6-Cu-SS-KEK, 1 tested

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 44th test is ongoing, highest shunt impedance, cryogenic test, 1C-SW-A2.75-T2.0-Cryo-Cu and 45th test is about to finish, highest shunt impedance hard copper-silver structure 1C-SW-A2.75-T2.0-Clamped-CuAg-SLAC-#2

Current “state of the art”

- We practically can predict performance heat-treated soft copper structures from drawings.
  - We found peak pulse heating to be good predictor of breakdown rate in simple, disk-loaded-waveguide type geometries.
  - We found “modified Poynting vector” to be practical predictor of breakdown rate in more complex geometries.
- Motivated by correlation of peak pulse heating and breakdown rate we study hard cooper alloys and methods of building structures out of them.
  - We found hard Cu and hard CuAg have better performance then soft copper.
  - As for now, hard CuAg had records performance.
- We study clad metal and multi-layered structures and their construction methods. Idea is to study materials with designed properties.
- We started looking at process of initial conditioning.
- We study new methods of breakdown diagnostics and autopsy, specifically on ion-beam-milling and X-ray microscopy.
- We started looking at breakdown physics at 100 GHz frequencies.

Next experiments, as for 4th November 2013

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:

High shunt impedance, gold–plated, *1C-SW-A3.75-T2.6-Electroformed-Au*
High shunt impedance, ultra-hard copper *1C-SW-A3.75-T2.6-Clamped-Hardenerd-Cu*
Highest shunt impedance, ultra-hard copper *1C-SW-A2.75-T2.0-Clamped-Hardenerd-Cu*

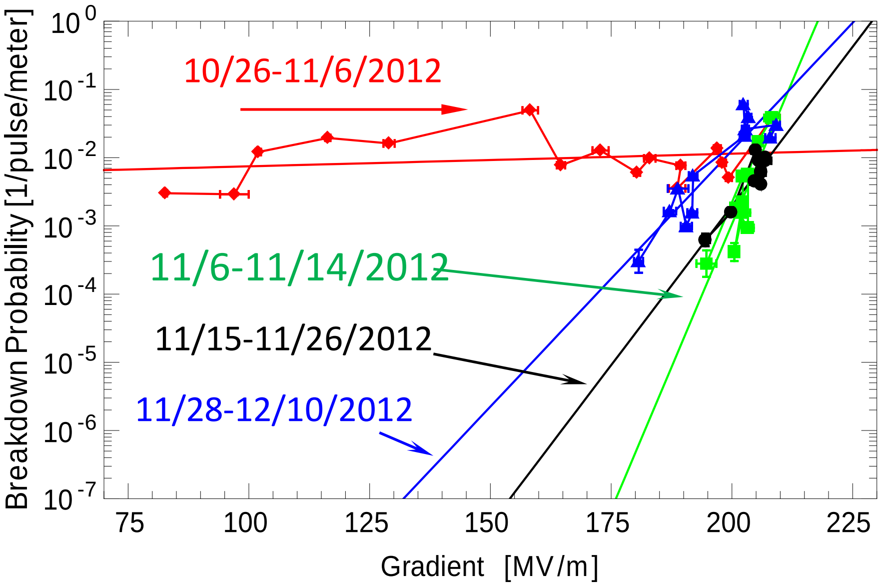
Reproducibility tests:

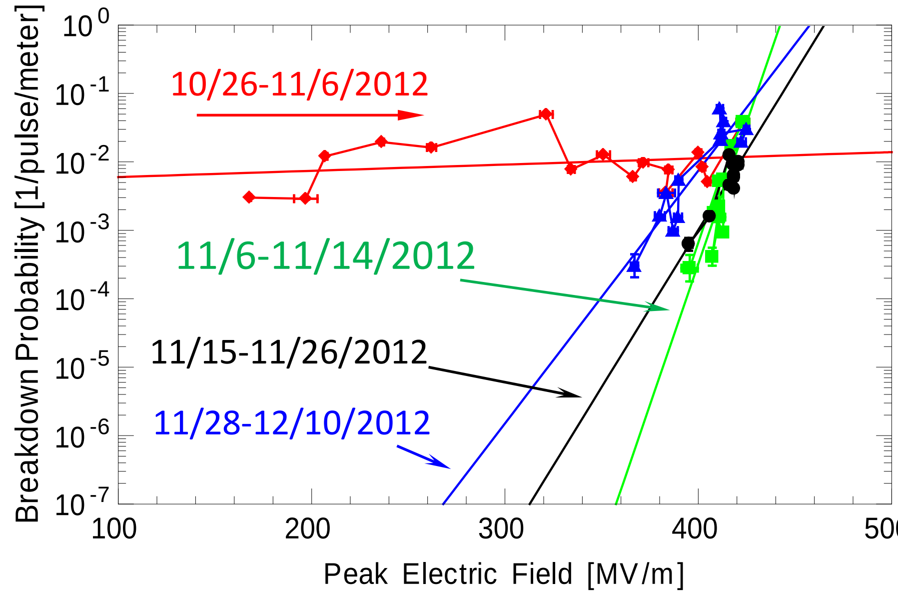
Highest shunt impedance, made of hard CuAg, 1C-SW-A2.75-T2.0-Clamped-CuAg
Optimized shape, high shunt impedance, 1C-SW-A3.75-T2.2-Cu
High shunt impedance, round iris, *1C-SW-A3.75-T1.66-Cu*
Three high gradient cells, low shunt impedance, *3C-SW-A5.65-T4.6-Cu*

Material Studies

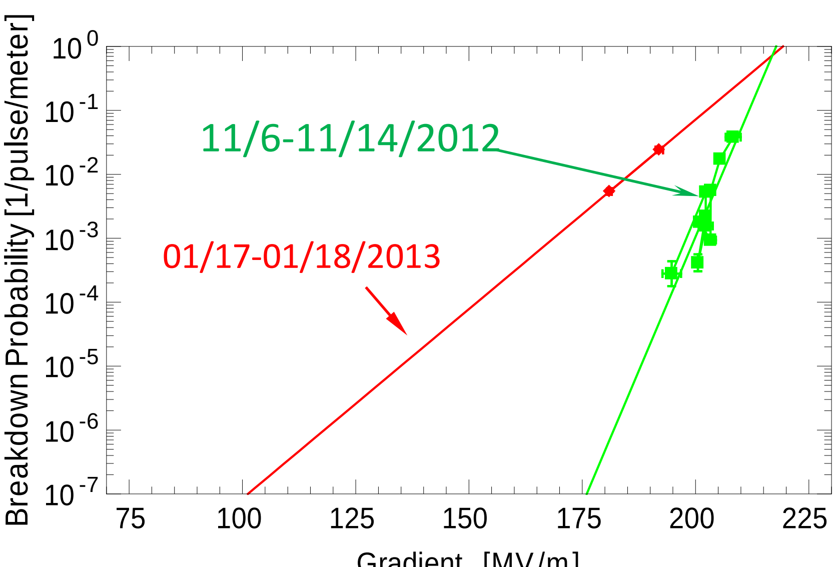
Hard CuAg highest shunt impedance,
1C-SW-A2.75-T2.0-Clamped-CuAg-SLAC-#1,
and first results from
1C-SW-A2.75-T2.0-Clamped-CuAg-SLAC-#2
CuAg spec: Silver wt 0.08 %

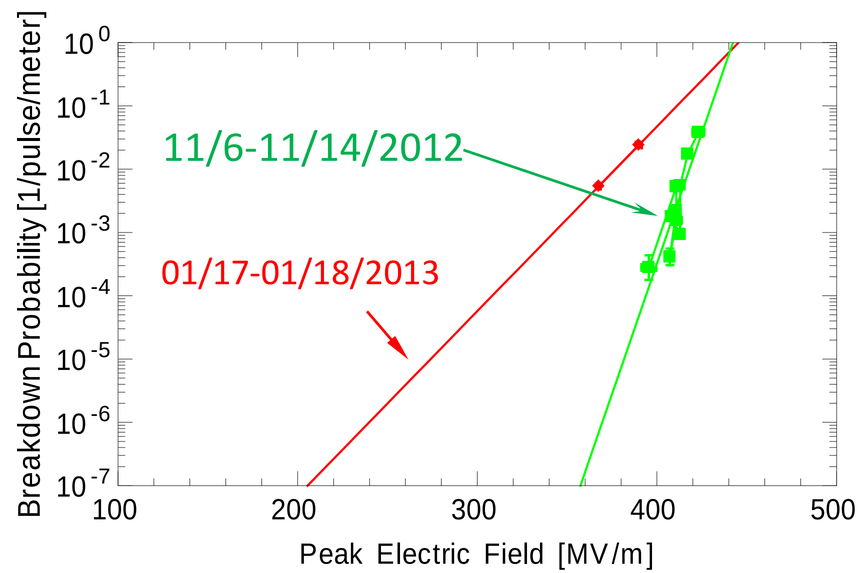
Evolution of breakdown performance 1C-SW-A2.75-T2.0-Clamped-CuAg-SLAC-#1 during conditioning using 150 ns shaped pulse





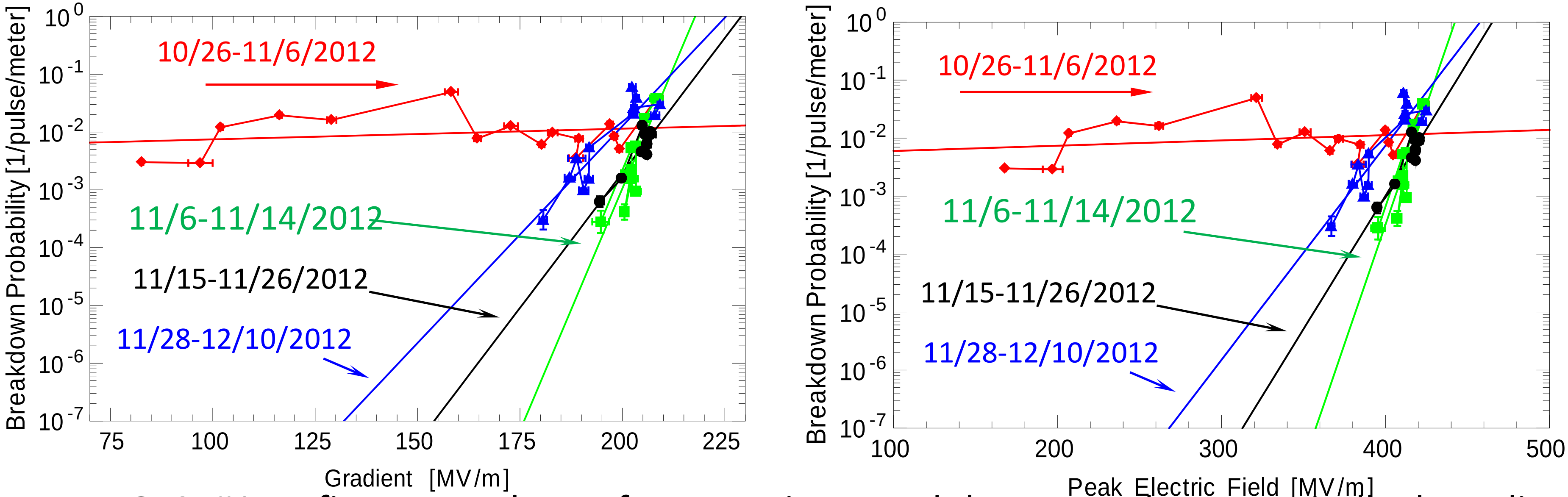
at first stage, the performance improved then started systematically degrading



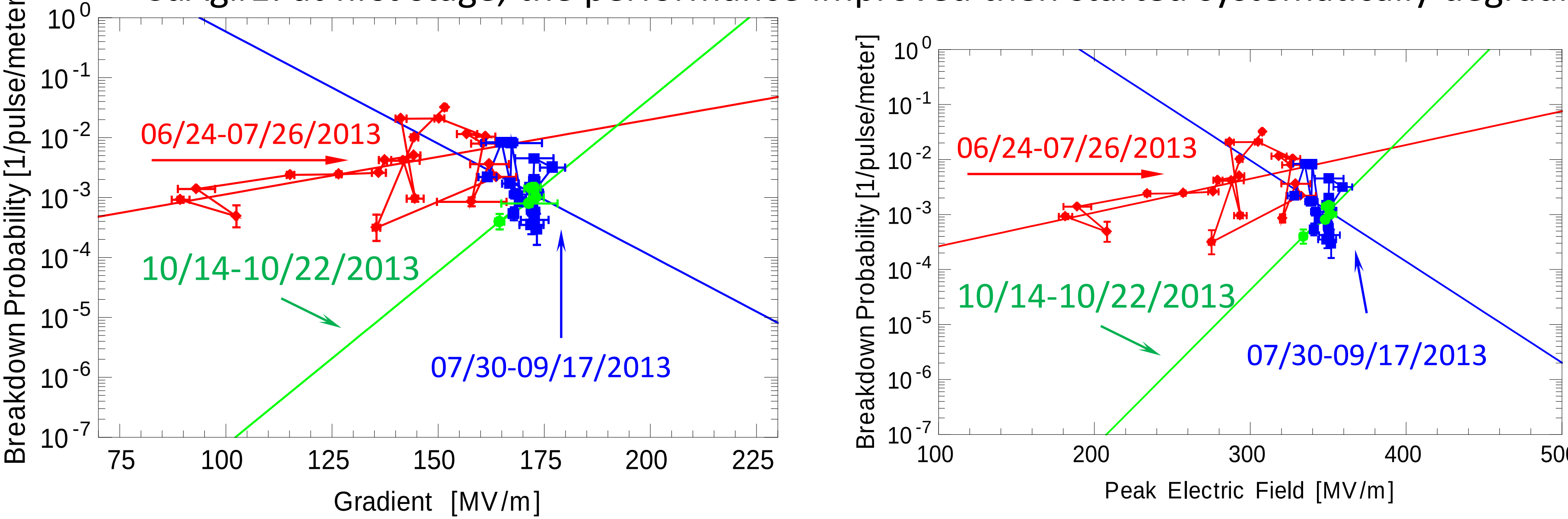


The structure shows atypically large difference between initial and final performance

Evolution of breakdown performance for 2 hard structures 1C-SW-A2.75-T2.0-Clamped-CuAg-SLAC-#1 and #2, during conditioning using 150 ns shaped pulse

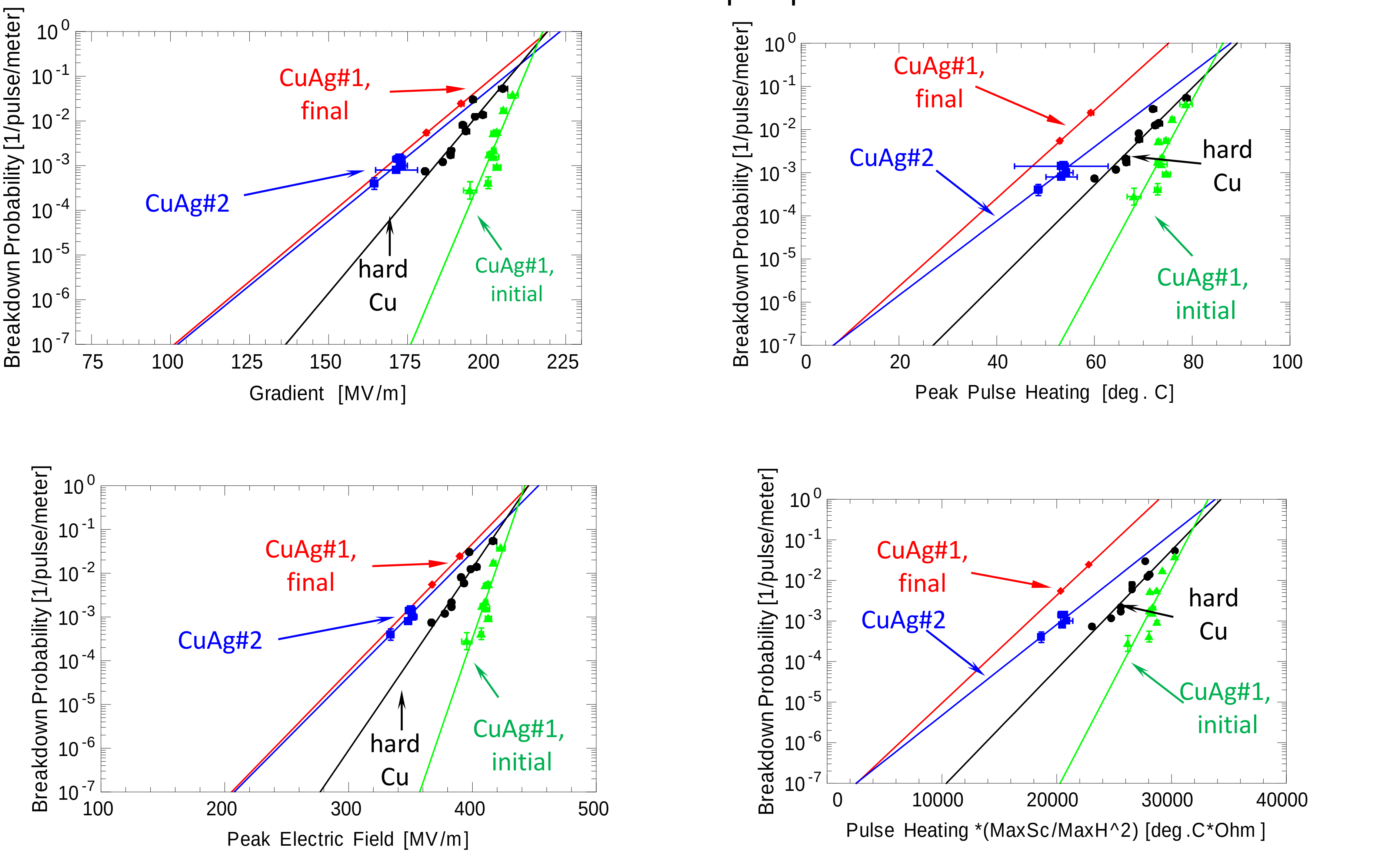


CuAg#1: at first stage, the performance improved then started systematically degrading



CuAg#2: “typical” processing behavior, the performance improved then saturated at the same level as final performance of CuAg#1

Reproducibility: Breakdown data for three 1C-SW-A2.75-T2.0-structures made of hard Cu and hard CuAg (initial and final performance for CuAg#1 and final for CuAg#2), 150 ns shaped pulse



Gradient performance of CuAg#1 is practicaly identical to “final” CuAg#1

Results of hard CuAg tests

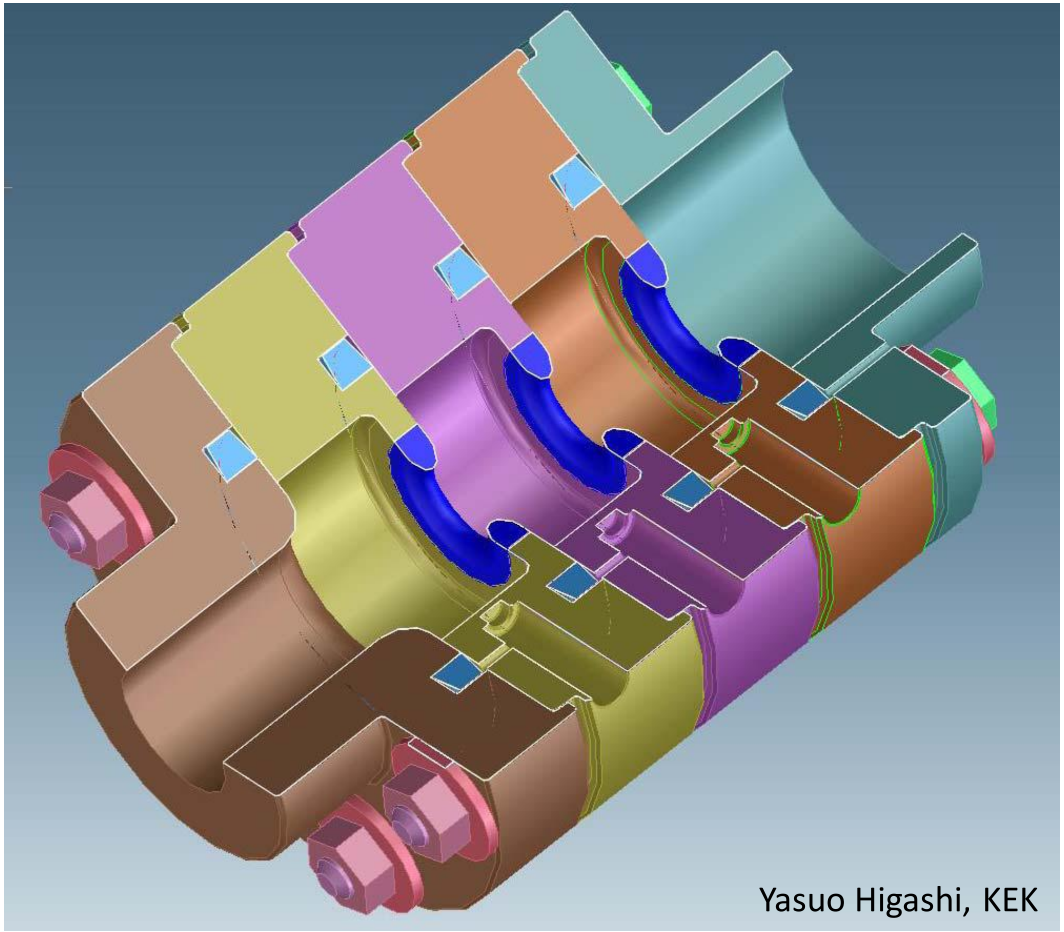
1. CuAg#1 is one few structures that had clear better performance at initial stages of conditioning, at this initial stages it had record performance compared with any other structure we tested.
2. Conditioning of second structure was typical, performance improved until saturated at level very similar to final performance of CuAg#1. Suspect in this case long storage of cells in ambient air before their cleaning and assembly.
3. We plan to test another CuAg structure, this time minimizing exposer to air.

Material Studies

Clad Structures

- High shunt impedance Clad Copper-Moly 1C-SW-A3.75-A2.6-Clad-Cu-Mo-KEK-#1
- High shunt impedance Clad Copper-Stainless Steel 1C-SW-A3.75-A2.6-Clad-Cu-SS-KEK-#1

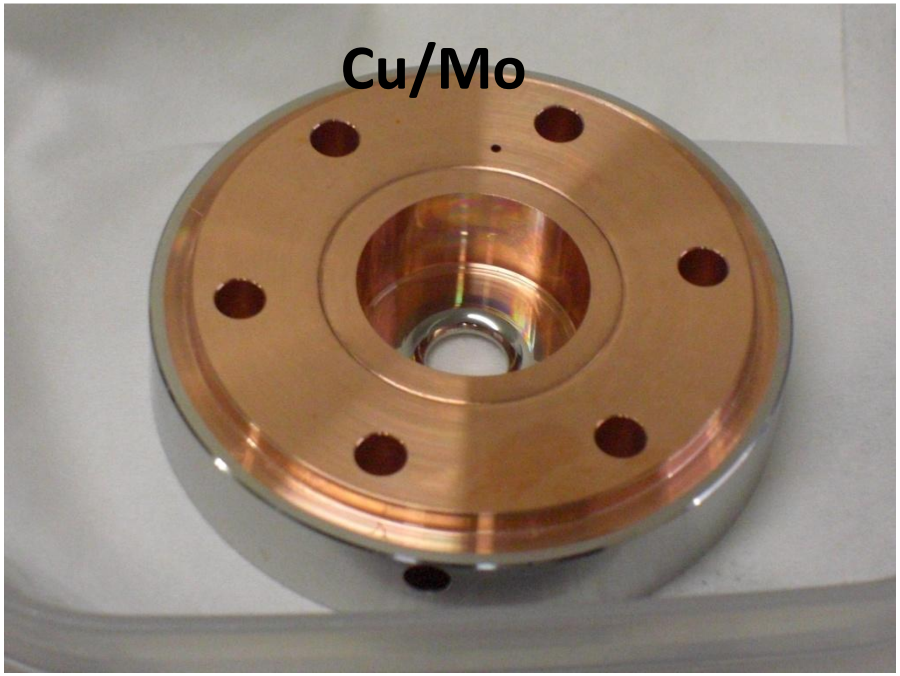
Clad Structures

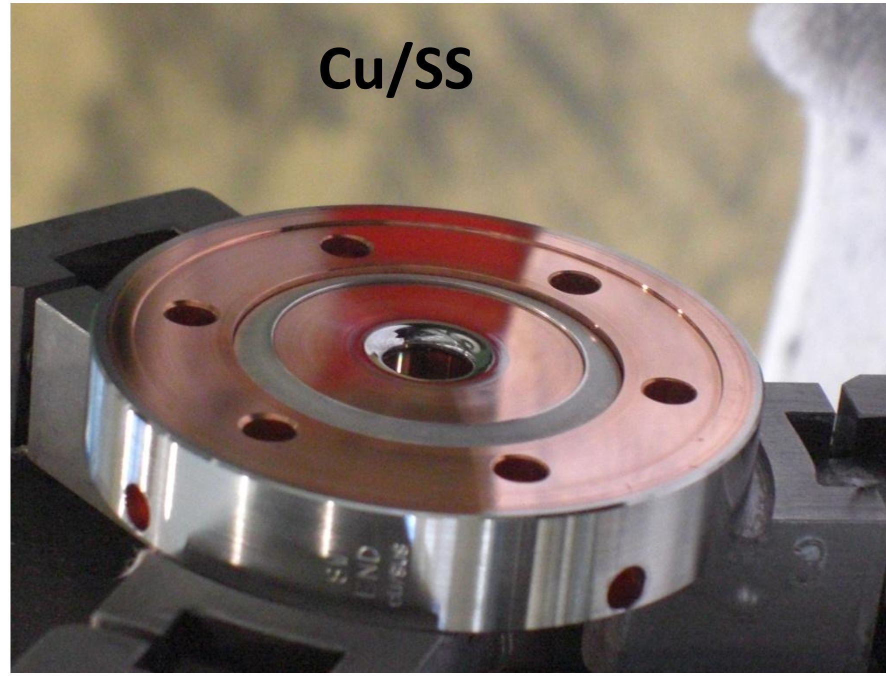


1C-SW-A3.75-T2.6-Clad-Cu-Mo, Cu-SS

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

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





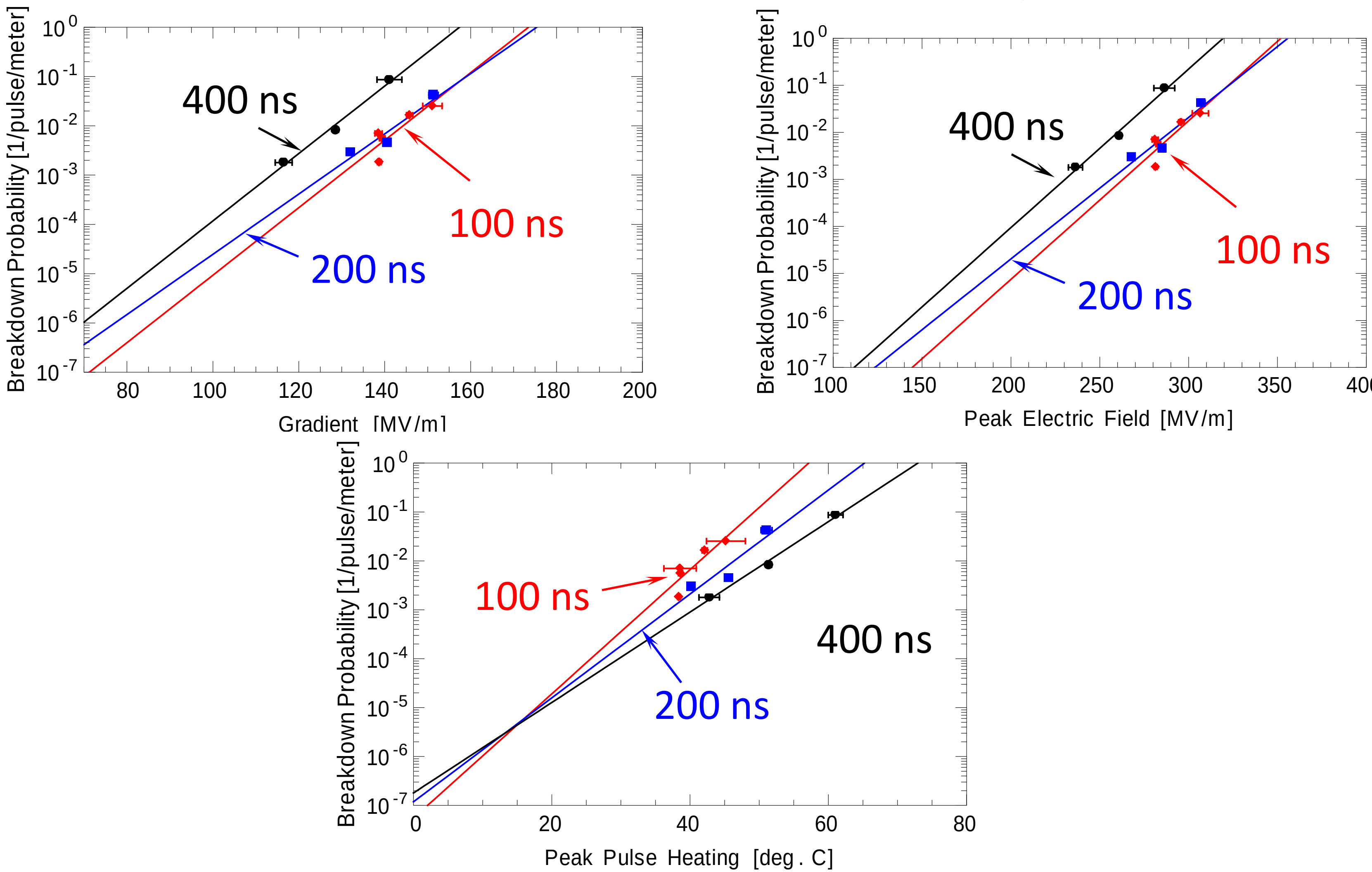
	Bulk resistivity (Ohm-m)	surface resistivity (Ohm)	skin depth (mm)
Cu	1.724x10E-8	0.034	0.505
SUS 304	6.4 x10E-7	0.208	3.07
Mo	5.7x 10E-8	0.062	0.918

Yasuo Higashi, KEK, September 2011

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

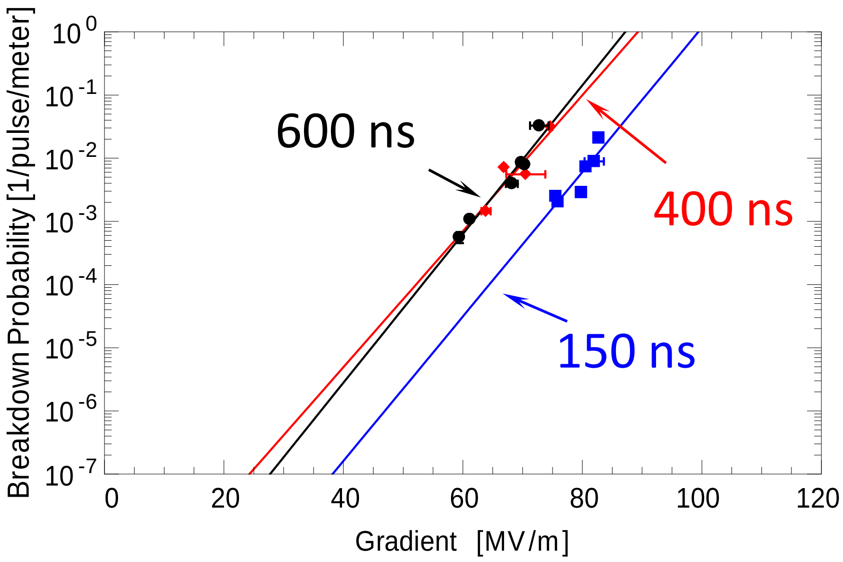
Yasuo Higashi, KEK

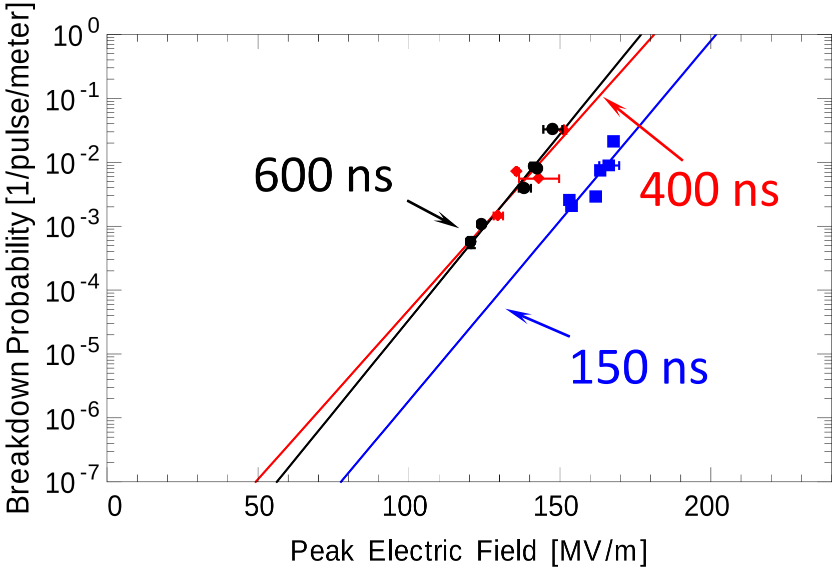
Breakdown data for high shunt impedance Clad Mo-Cu
1C-SW-A3 .75-T2 .6-Clad-Cu-Mo-KEK-#1, different length of shaped pulse

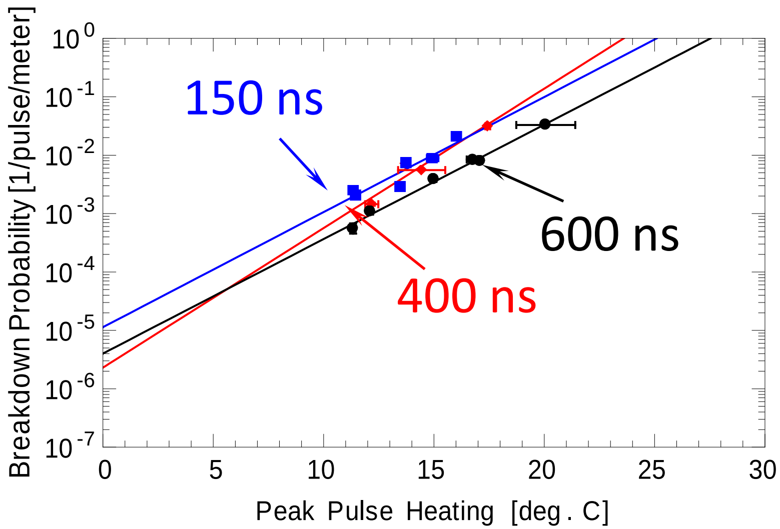


Cu-Mo clad structure shows pulse length dependence of the rf breakdown rate which is characteristic for structures limited **by field amplitude**, not pulse heating.

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

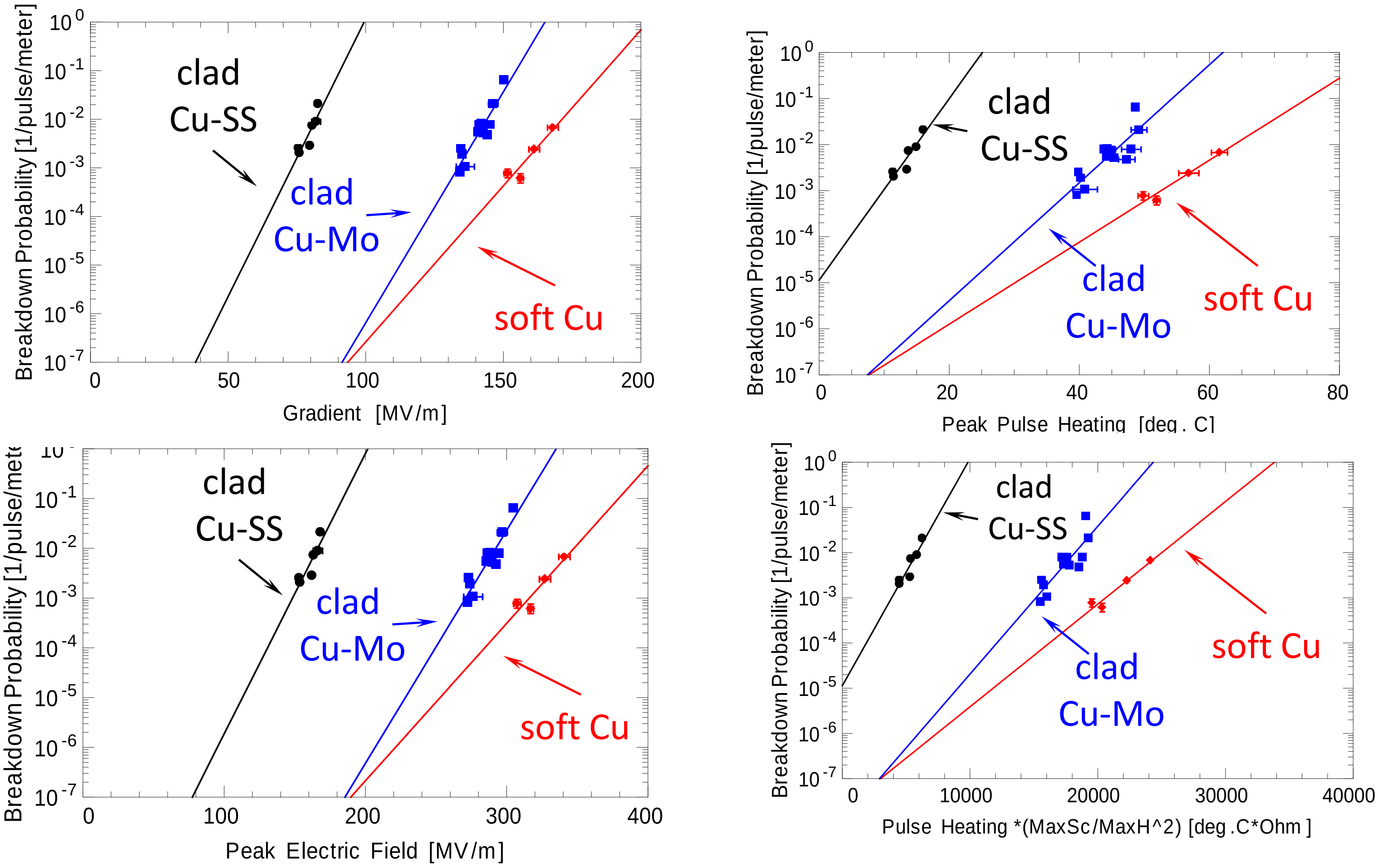




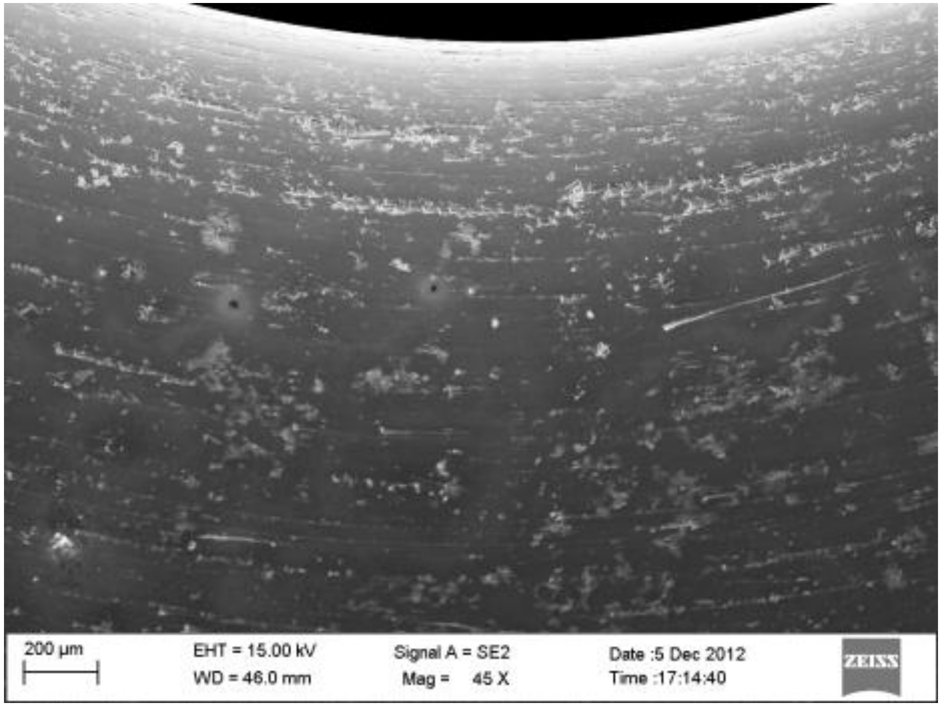


Cu-SS clad structure does not show clear correlation with either field or pulse heating.

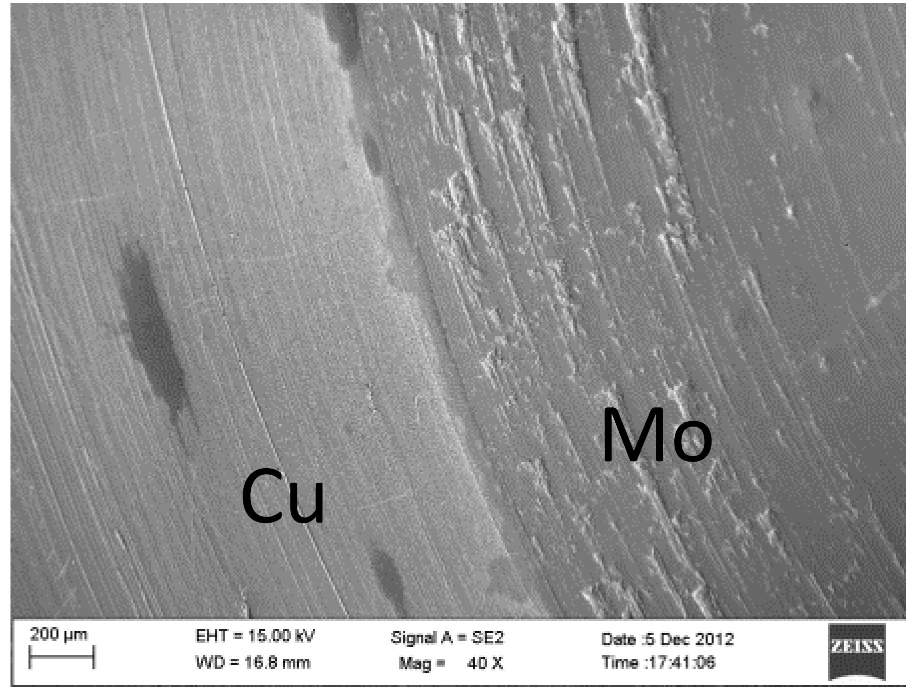
Breakdown data for three structures of same shape but different iris-tip materials , 1C-SW-A3.75-T2.6, soft Cu, clad Cu-Mo, clad Cu-SS, 150 ns shaped pulse



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

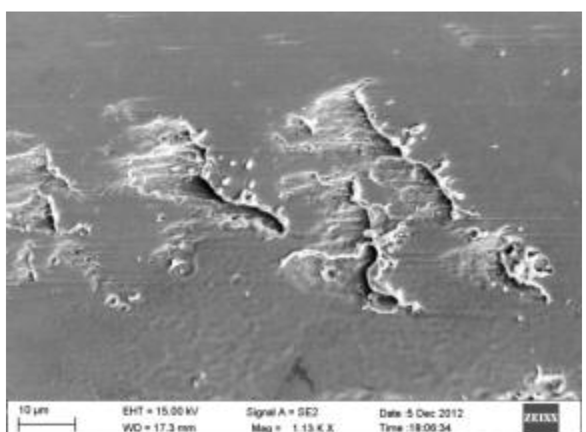


Scratches on Mo surface

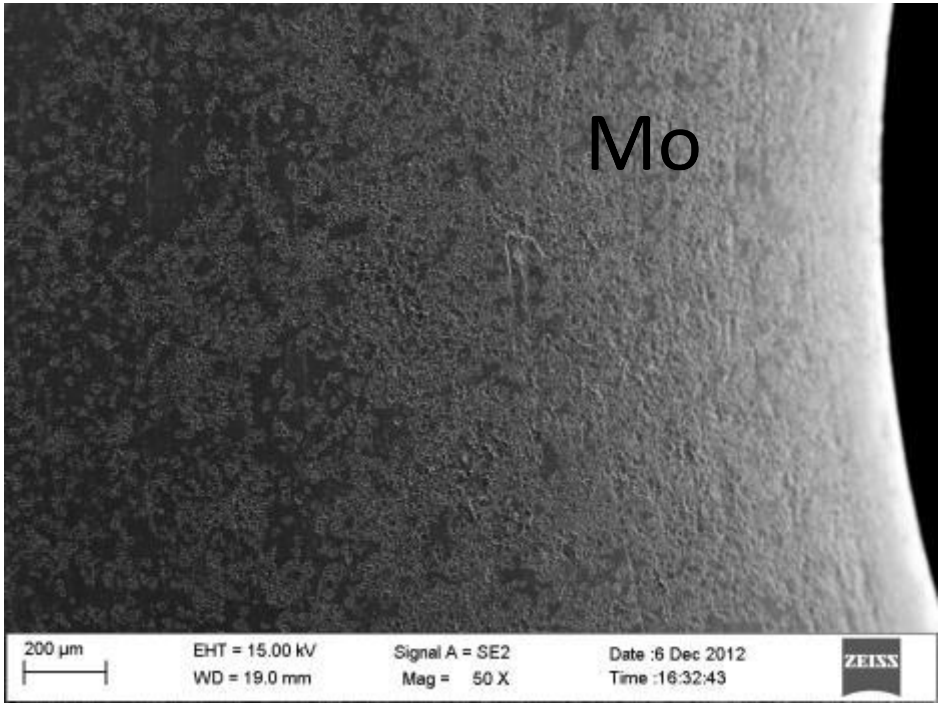


Seamless joint between Cu and Mo

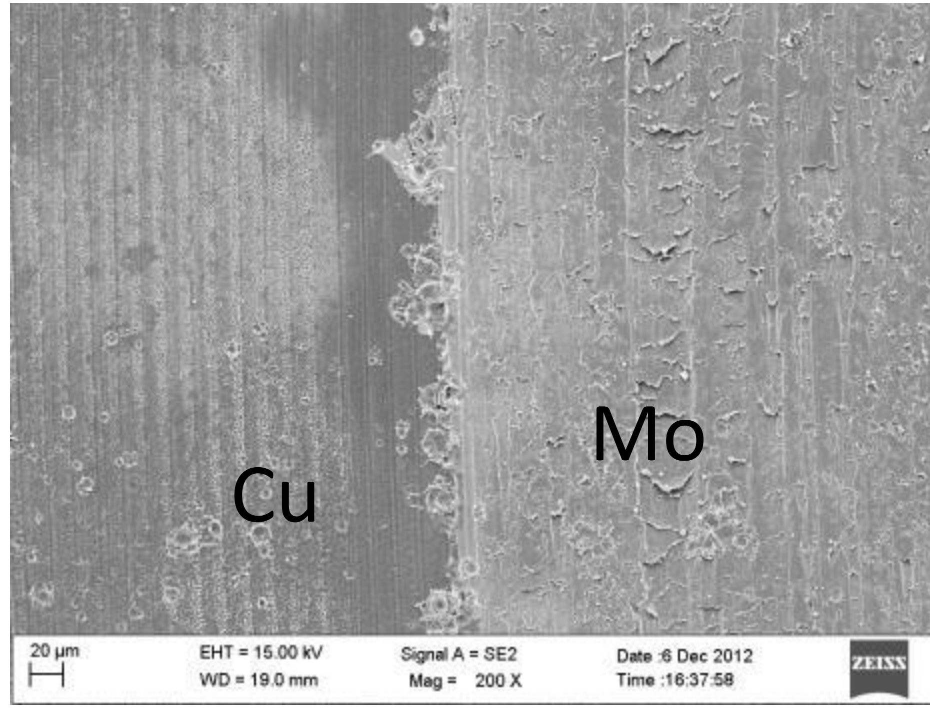
Melted edges of Mo scratches



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

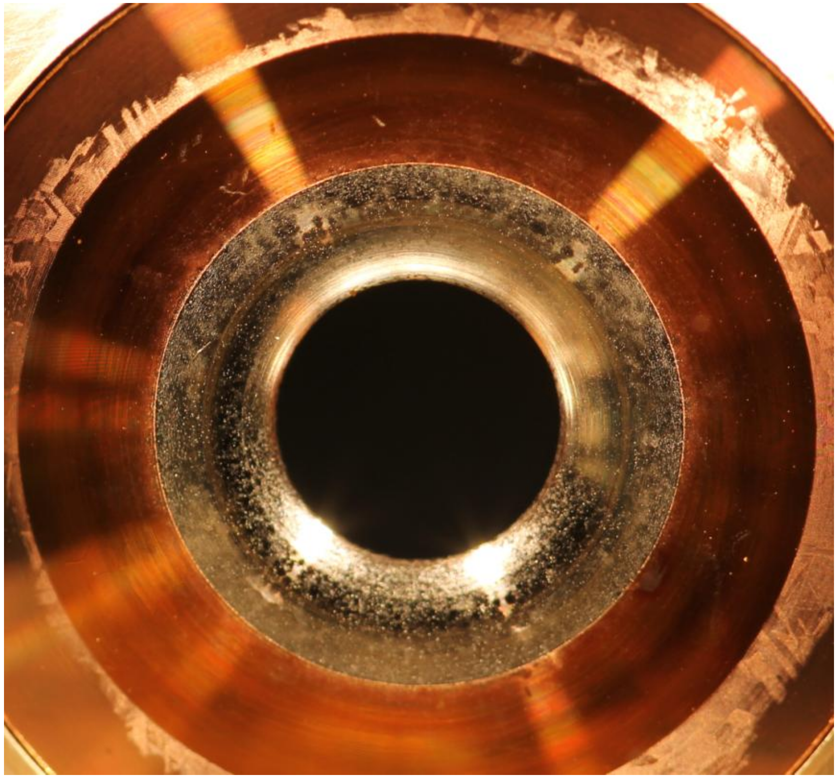


Massive breakdown damage of Mo surface

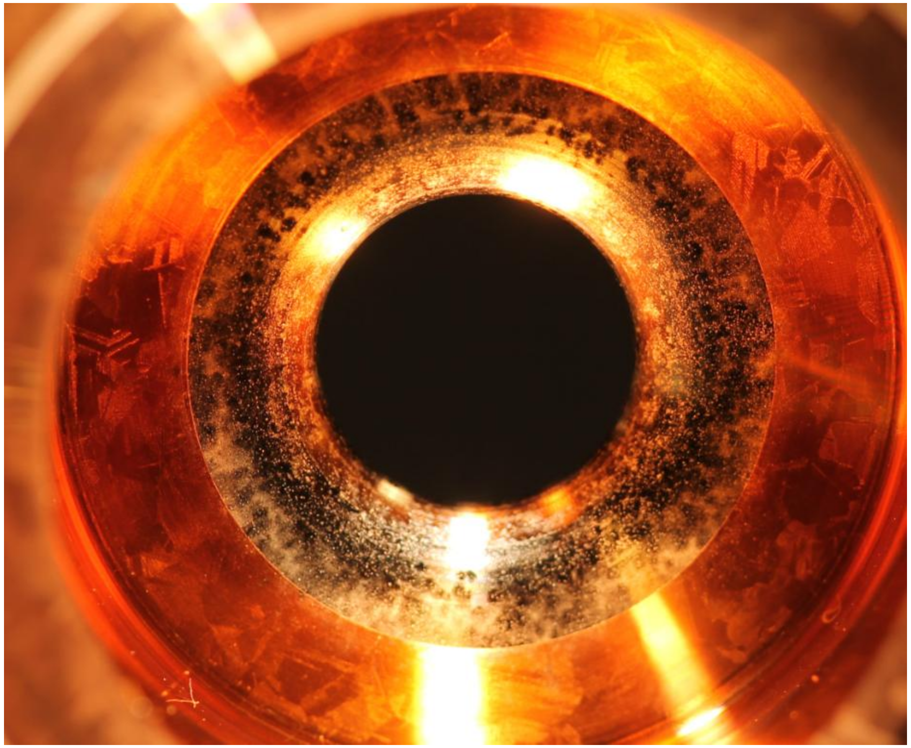


Moderate damage of Cu-Mo joint

Autopsy of Clad Cu-SS
1C-SW-A3 .75-T2 .6-Clad-Cu-SS-KEK-#1

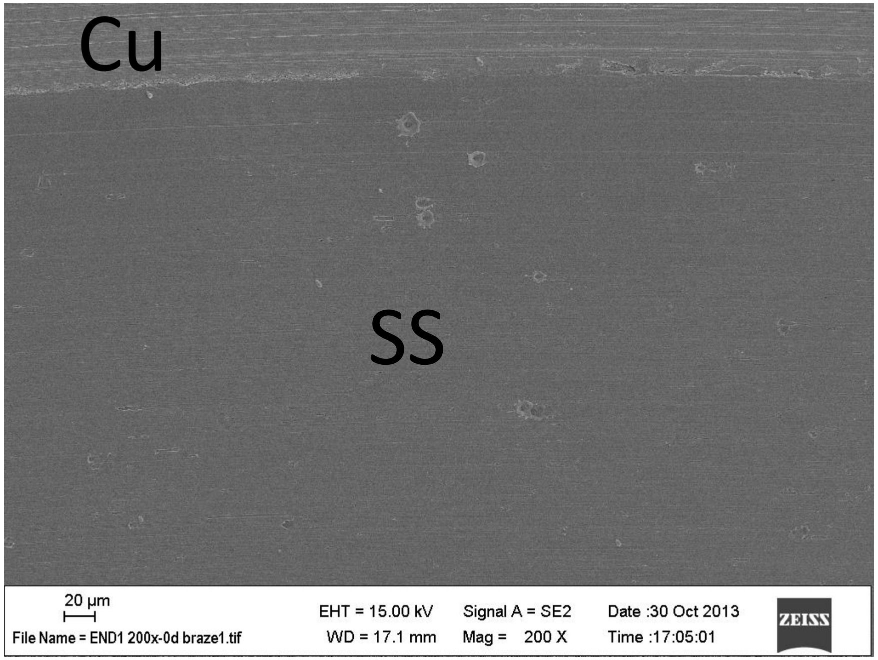


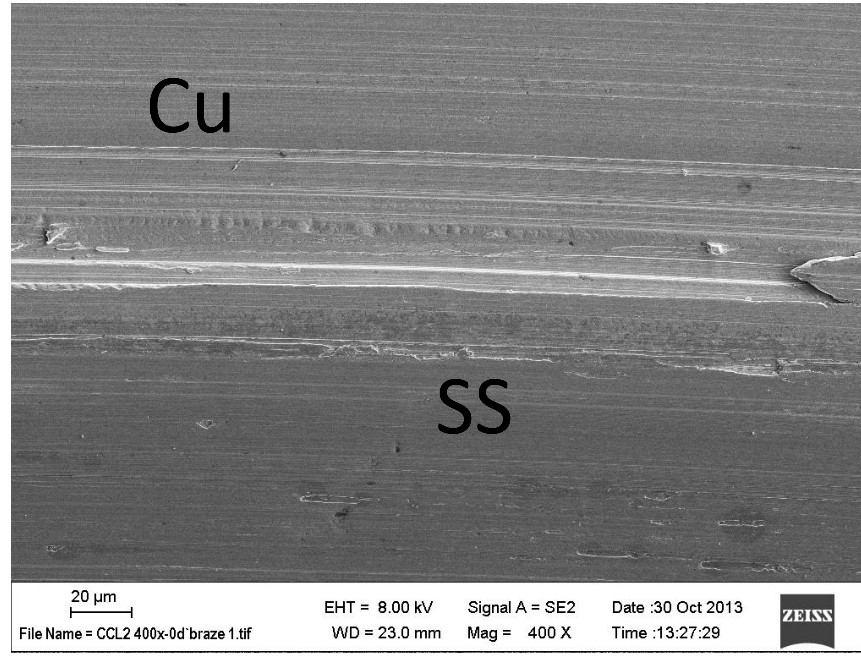
High gradient side of "end cell"



High gradient side of "middle cell"

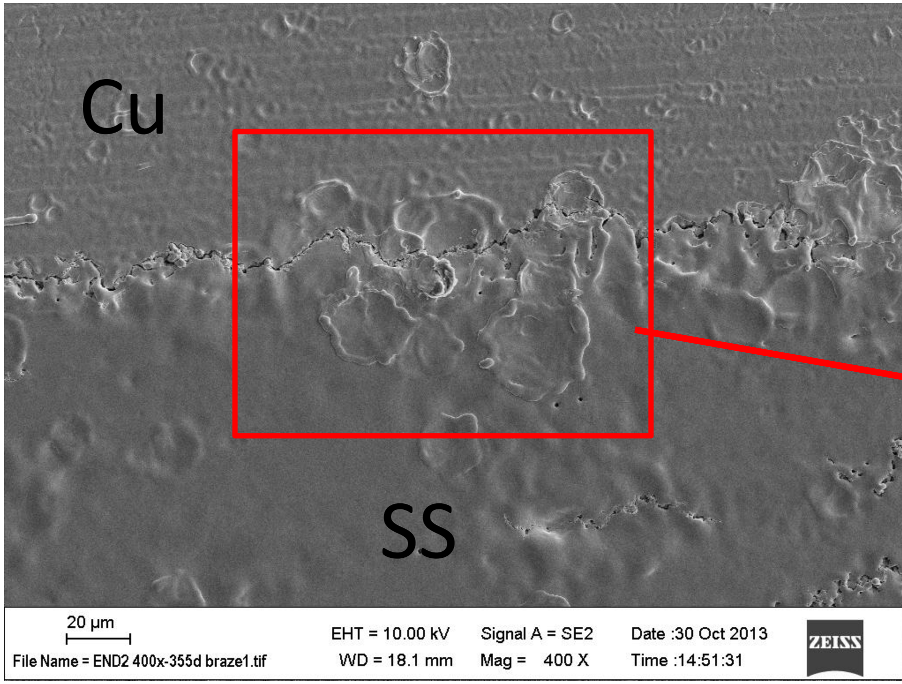
Autopsy of SS-Cu joint, low gradient side

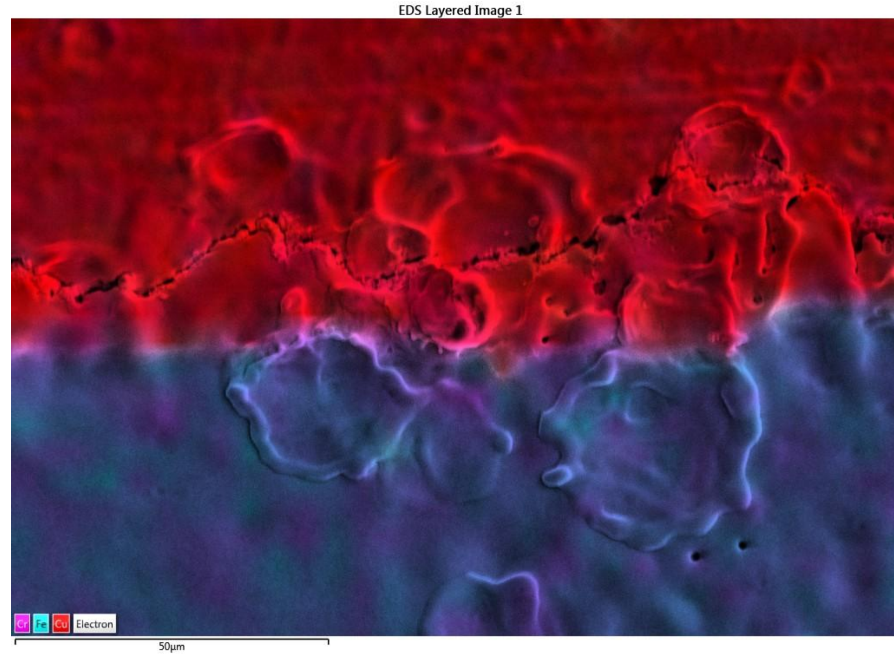




Seamless joint between SS and Cu, good SS surface finish

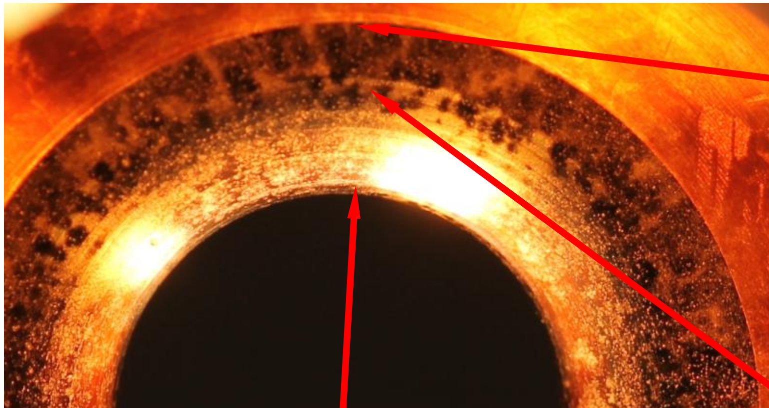
Autopsy of SS-Cu joint on high gradient side of end cell

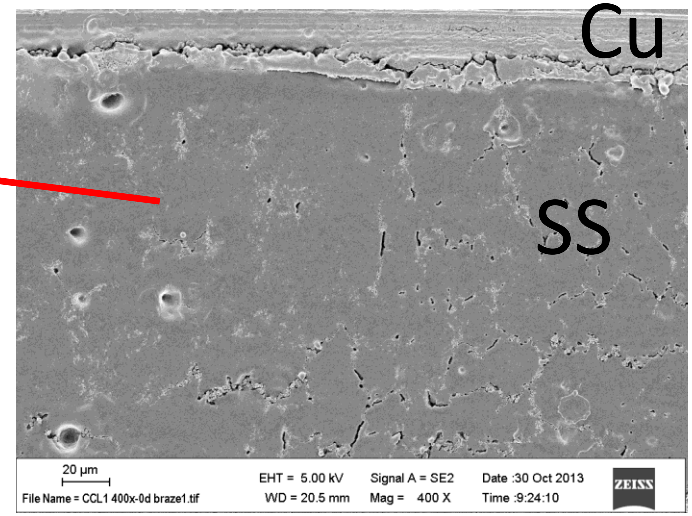




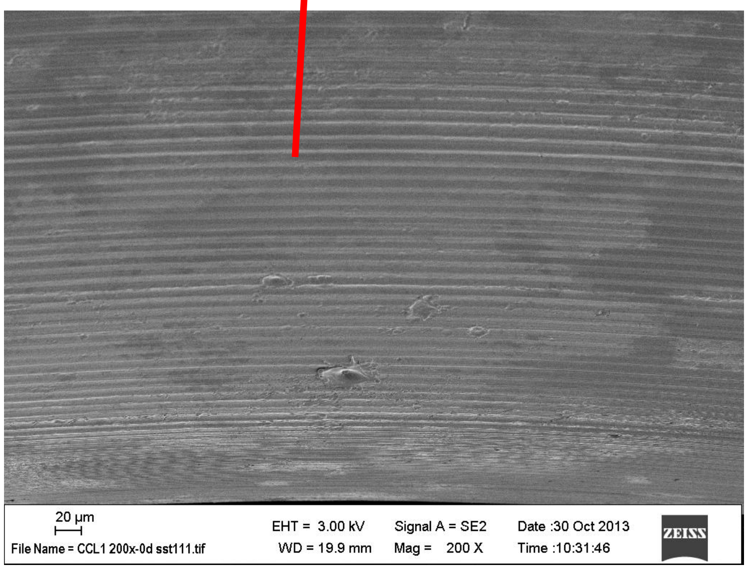
Massive damage on SS side of the joint, little damage on copper side, Crack appeared on copper side, about 10 um from Cu-SS joint.

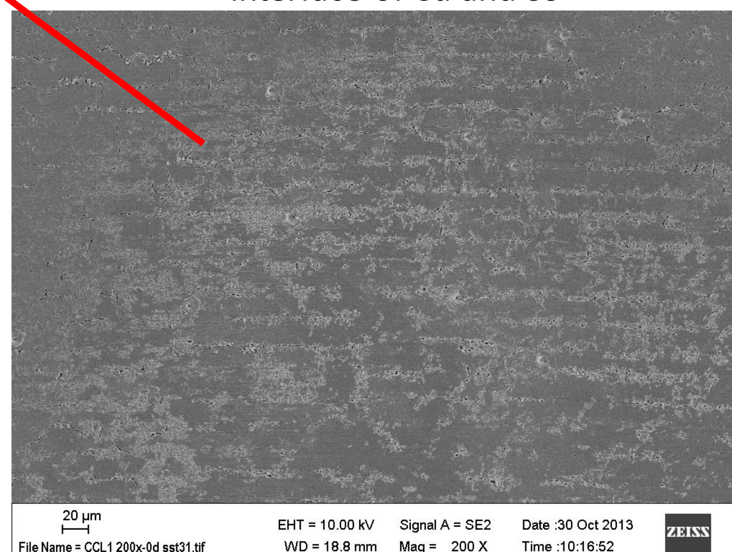
Autopsy of high gradient side of middle cell





Melted pulse heating damage and crack near interface of Cu and SS





Little damage near iris tip

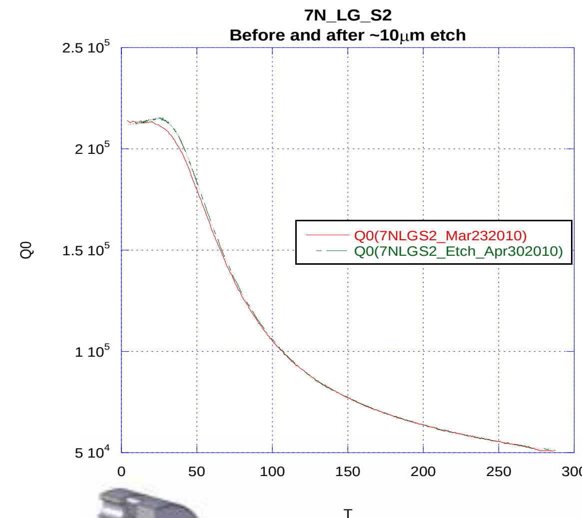
Pulse heating damage in the middle of SS insert

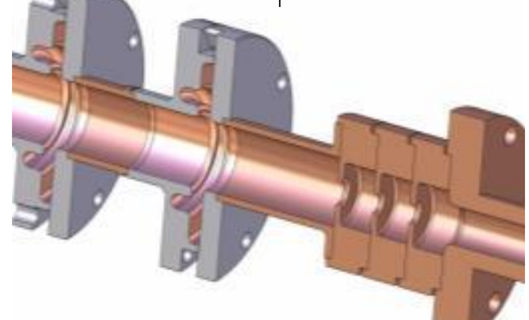
Results of Clad Cu-Mo and Cu-SS Structures

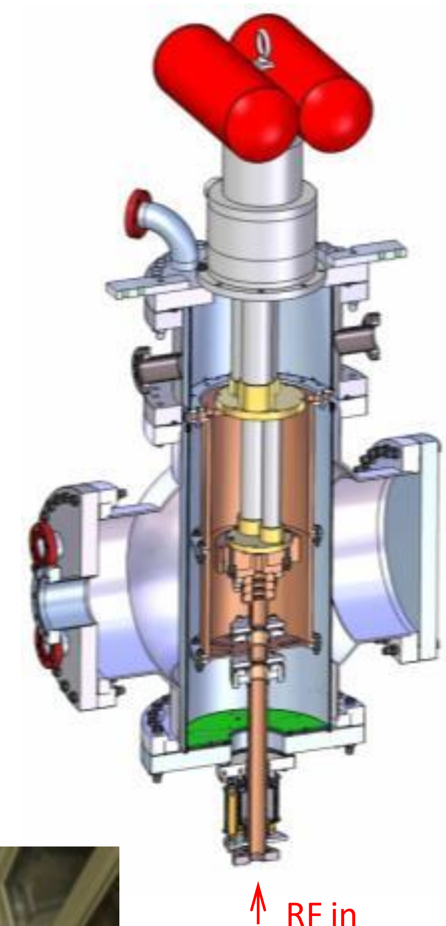
- We successfully tested clad structure built without high temperature brazing to avoid damage of the bi-metal Mo-Cu and SS-Cu joint during manufacturing.
- For the same breakdown rate, gradient in clad Cu-Mo structures is about 20% lower than in soft copper structures and Cu-SS about two times lower
- Electron-Microscope inspection of Clad Cu-Mo cells allows us to speculate that the performance was limited by scratches on Mo surface, not by Cu-Mo joint as initially suspected.
- Autopsy of Clad Cu-SS structure showed massive pulse heating damage on SS near the Cu-SS joint. The breakdown damage appears on top of SS pulse heating damage. There is little breakdown damage on copper. This is our first data on combined pulse heating and breakdown damage in stainless steel.
- We speculate that with improved surface quality of Mo type of structure could have better performance then copper

Ongoing test: Cryogenic Testing of normal conducting accelerating structures

- To design the structure we used our 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.

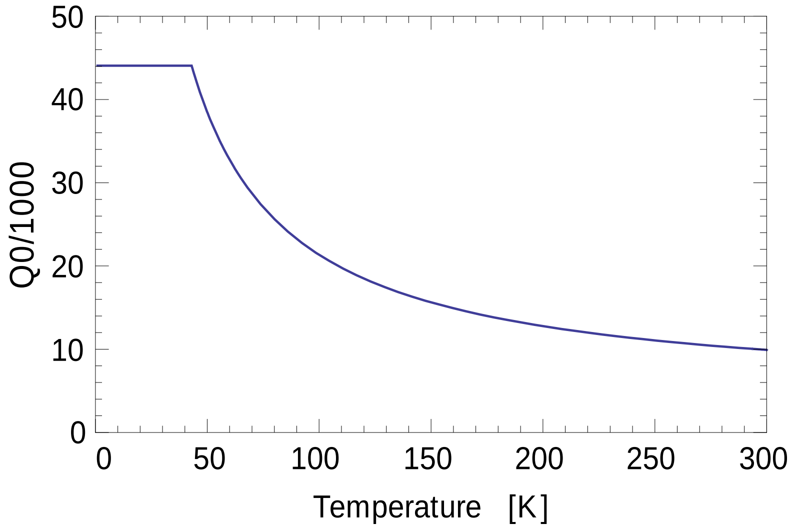


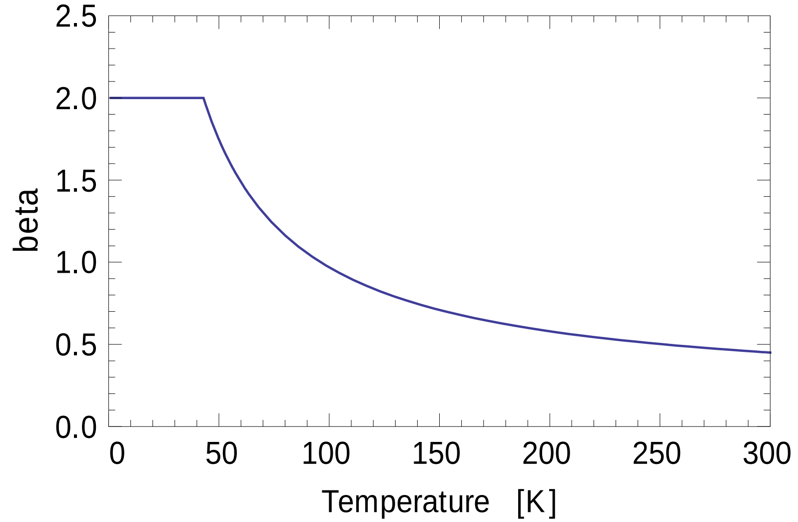


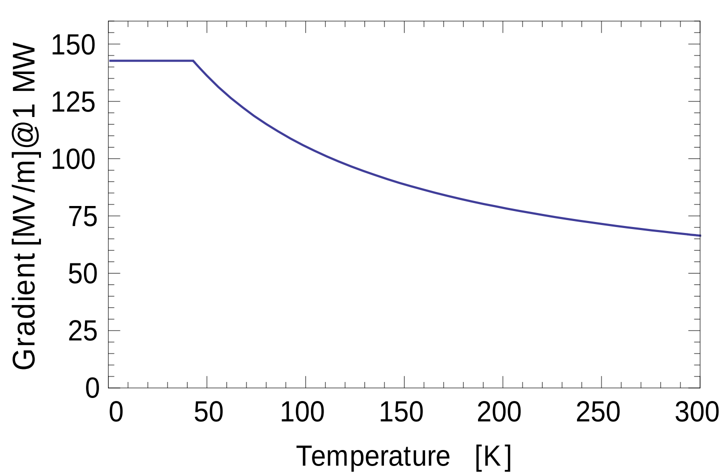


Dolgashev *et al.*, IPAC12

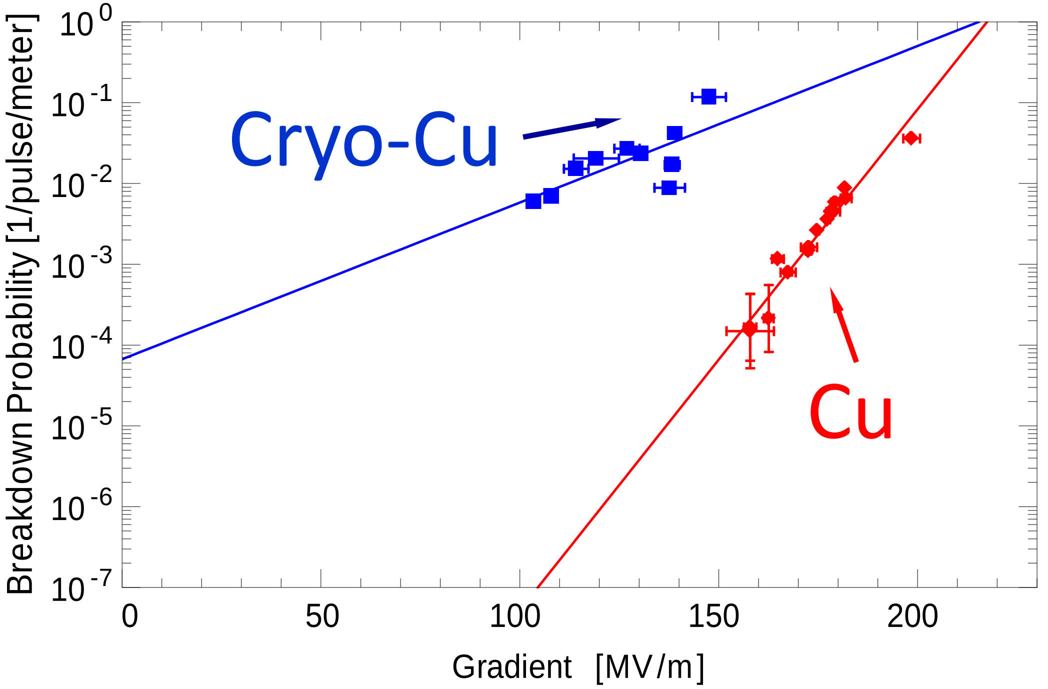
Q_o, coupling and gradient *vs.* temperature



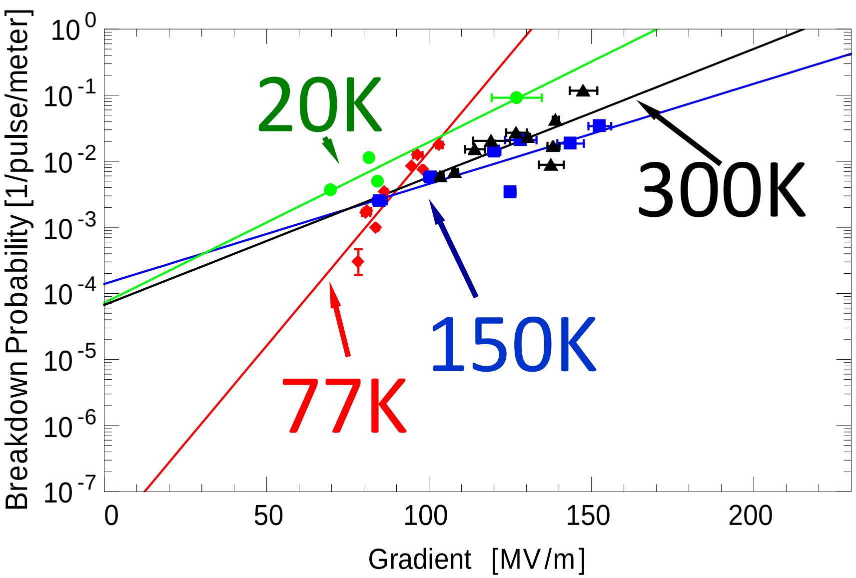


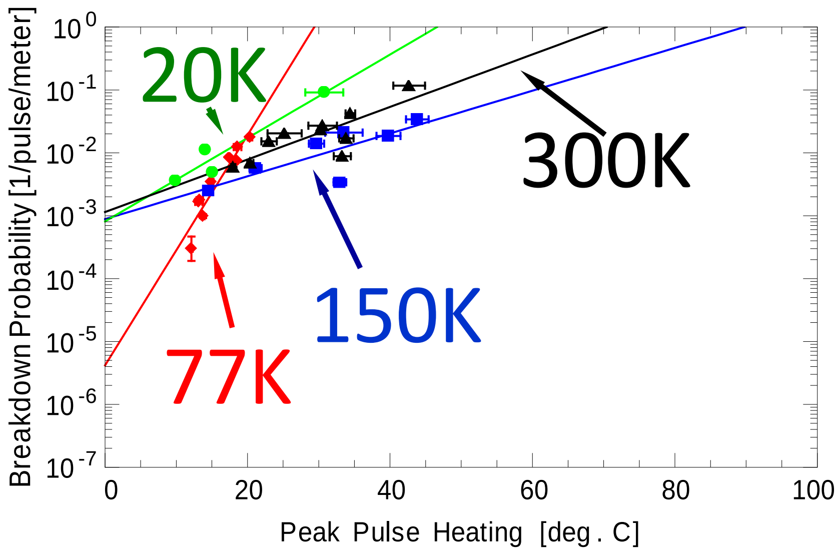


Preliminary: Comparison of two highest shunt impedance structures: one “standard” heat treated copper another Cryo, both at room temperature, and both at 200 ns flat pulse



Preliminary: Breakdown data for Cryo structure 1C-SW-A2.75-T2.0-Cryo-Cu-SLAC-#1 at different temperatures





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.*

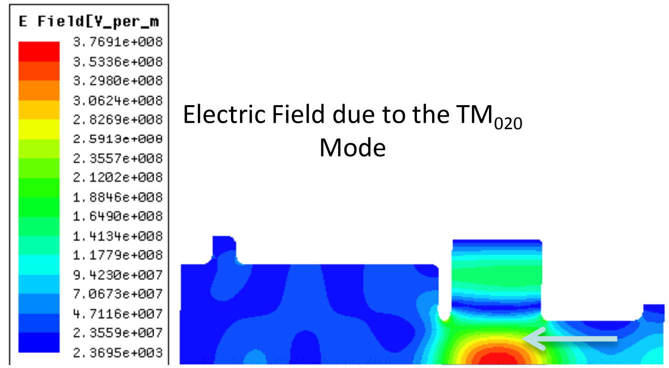
S. Tantawi, "Experimental Evaluation of Magnetic Field Effects on Breakdown Rates", CERN Breakdown Physics Workshop, May 2010

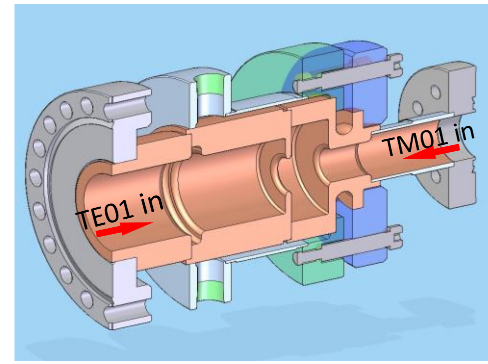
A. D. Yeremian et al., *A Dual-mode Accelerating Cavity to Test RF Breakdown Dependence on RF Magnetic Fields, MOPC073,* Proc. of IPAC´11, San Sebastian, Spain, 2011

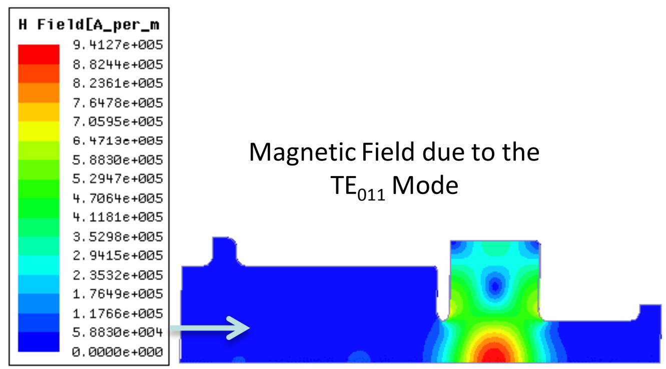
Dual Mode Accelerating Cavity for studying the relative effects of electric and magnetic fields

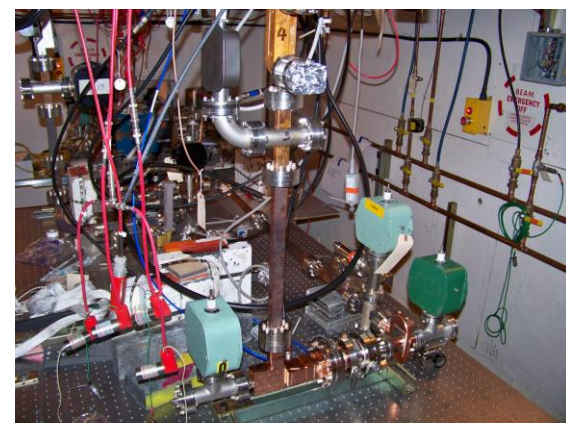
- In this experiment we changed the independently electric and magnetic field, timing between fields, and relative amplitude and phase

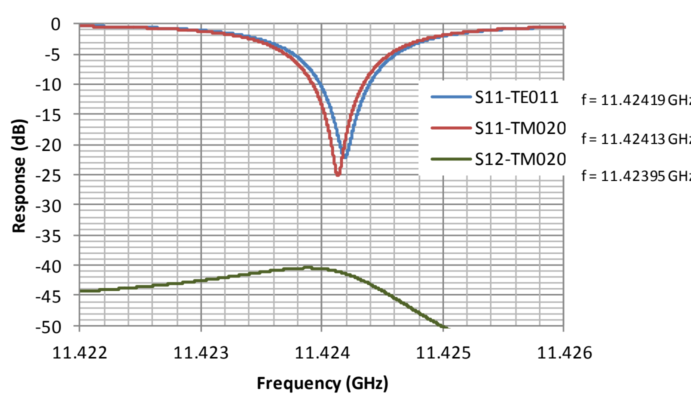
- This experiment is finished we are processing data









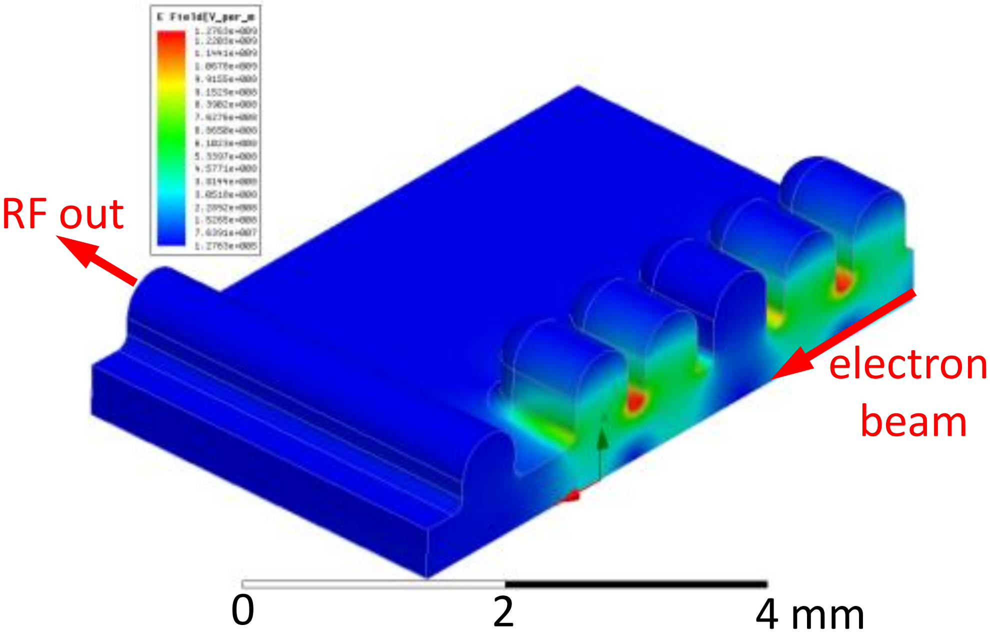


Future experiments

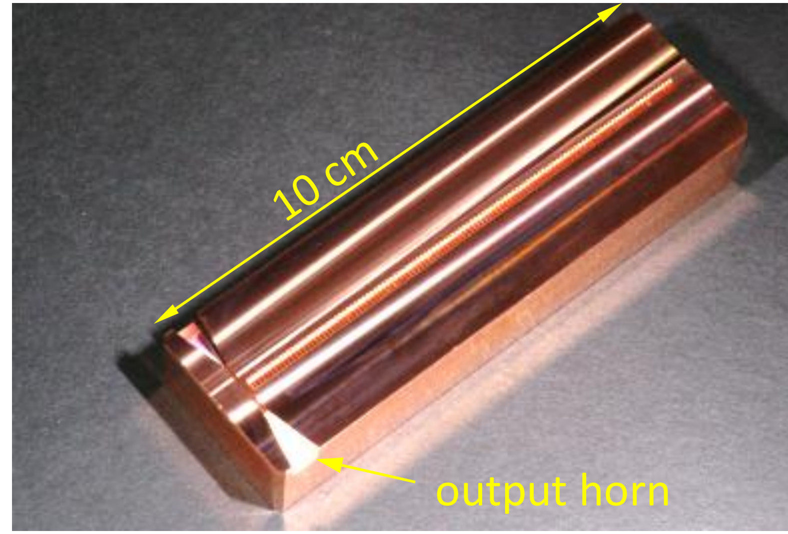
Beam tests of 100 GHz copper structure at FACET

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

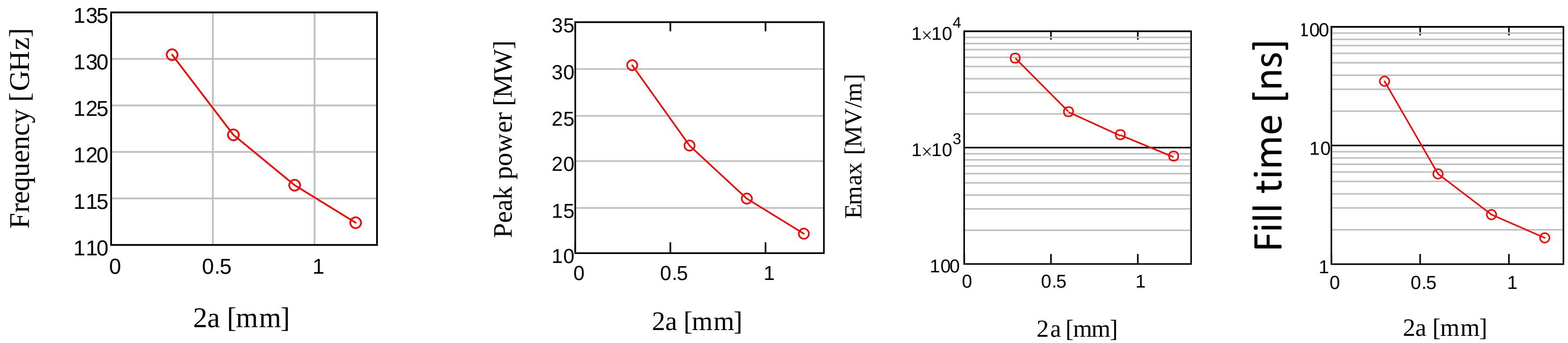
RF Breakdown Test of Metal Accelerating Structure at FACET



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



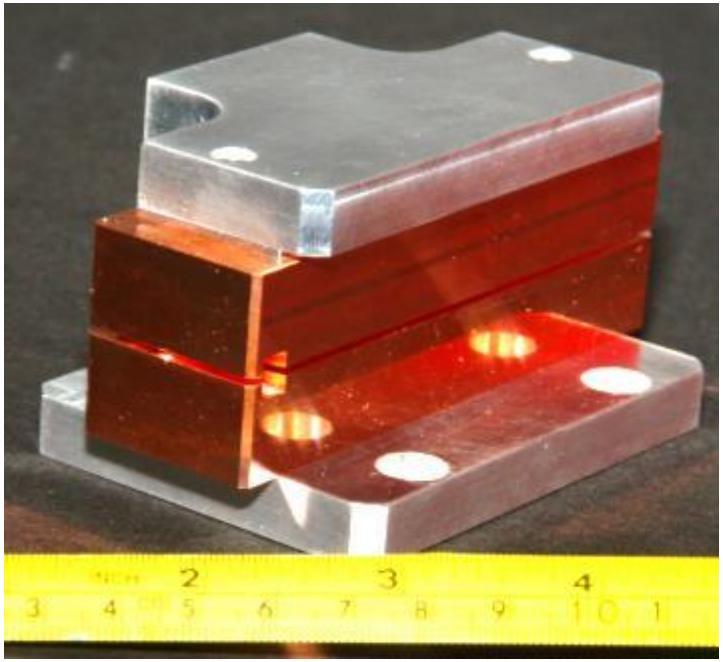
Accelerating structure manufactured by Makino



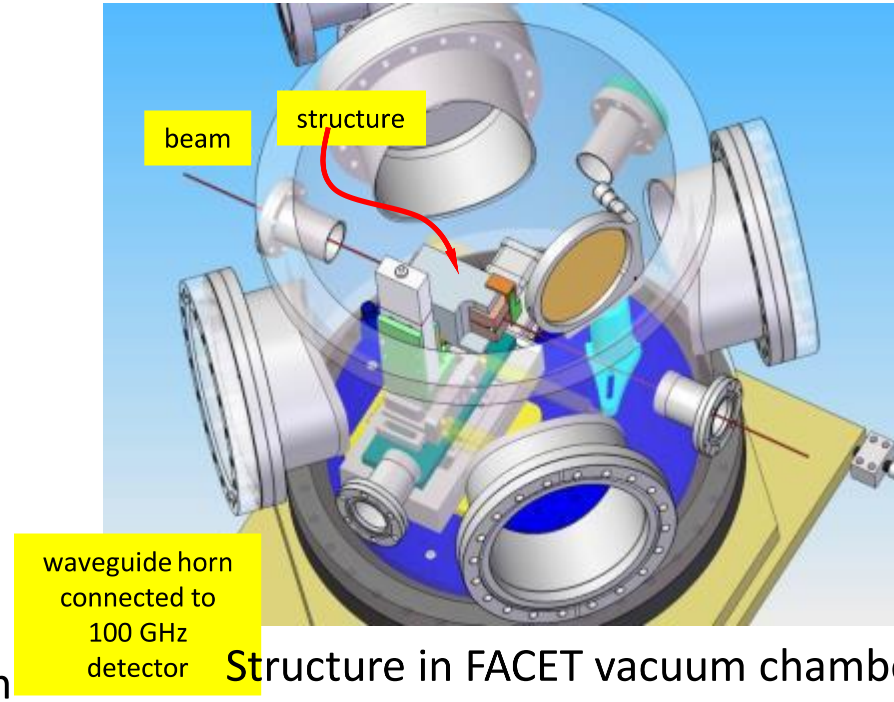
Parameters of accelerating structure with changing beam gap, excited by 1.6 nC bunch

Valery Dolgashev, Sami Tantawi, SLAC

RF Breakdown Test of Metal Accelerating Structure at FACET

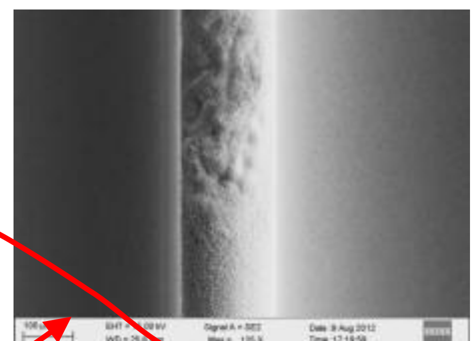


Assembled structure, beam gap set to 0.9mm

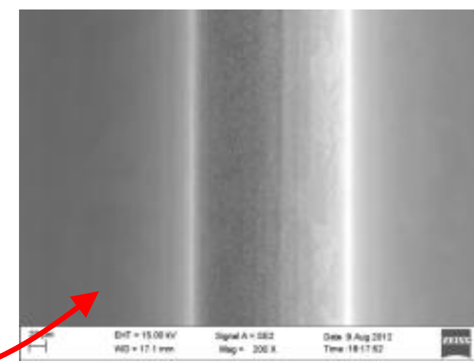


Structure in FACET vacuum chamber

Autopsy of output part of the structure



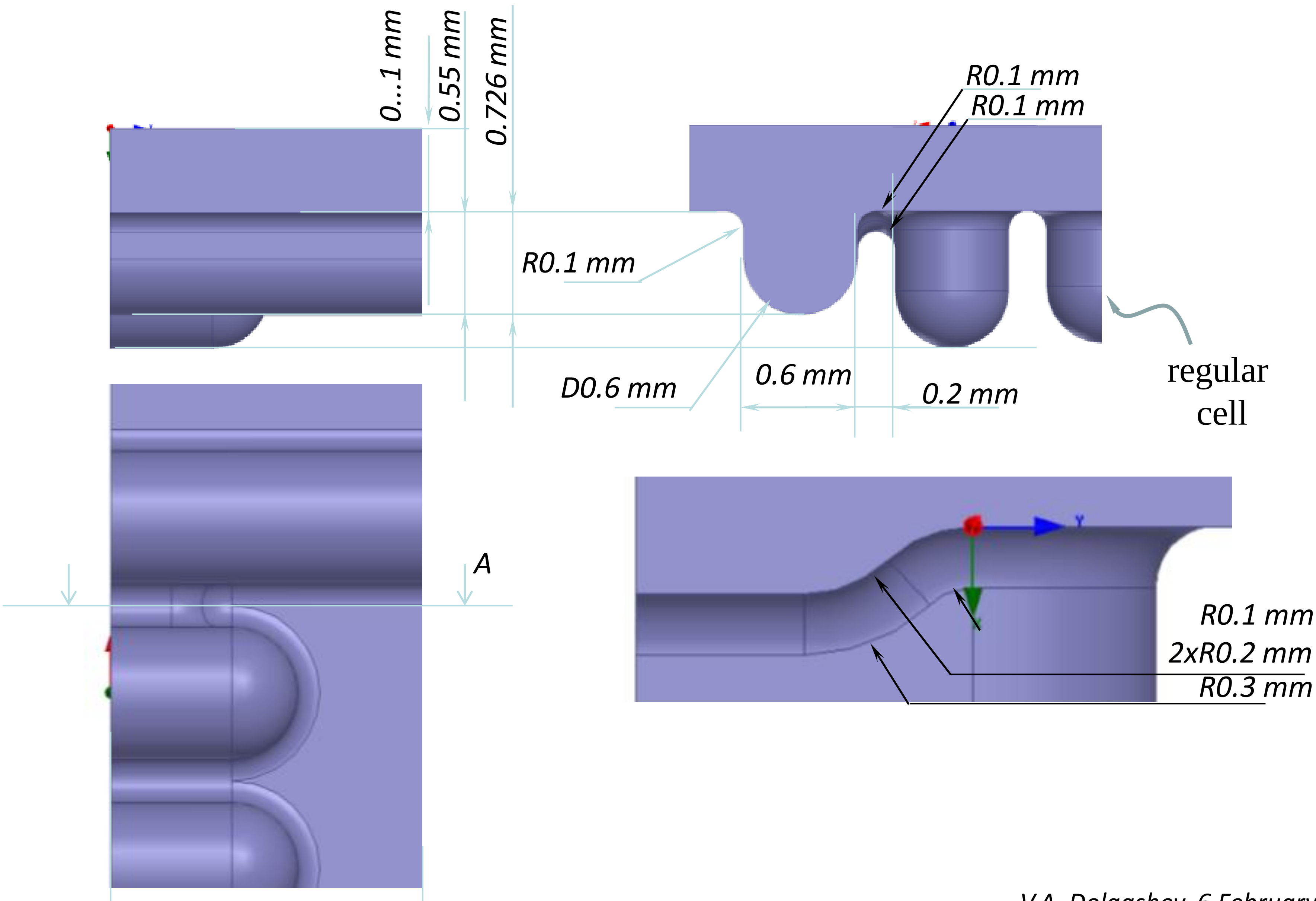
1st iris – breakdown damage, peak surface fields <1.3 GV/m



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

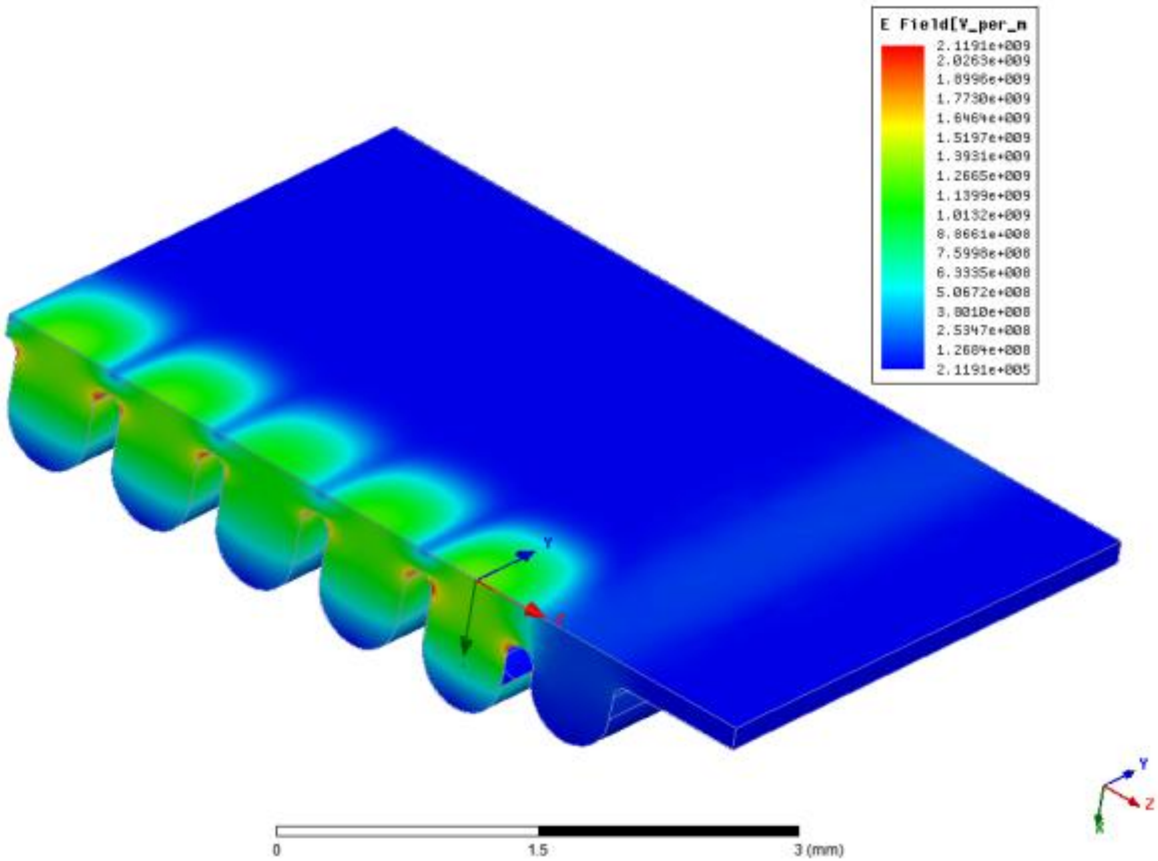
Valery Dolgashev, Sami Tantawi, SLAC

New, matched coupler



V.A. Dolgashev, 6 February 2013

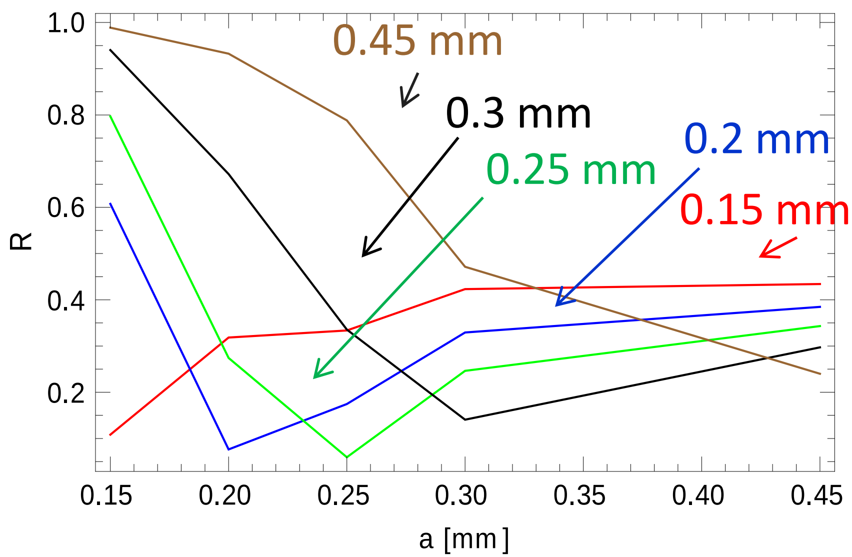
Accelerating structure, aperture 2a = 0.3 mm, synchronous frequency 136 GHz,
fields normalized to 10 MW of input power, coupler reflection R=0.09

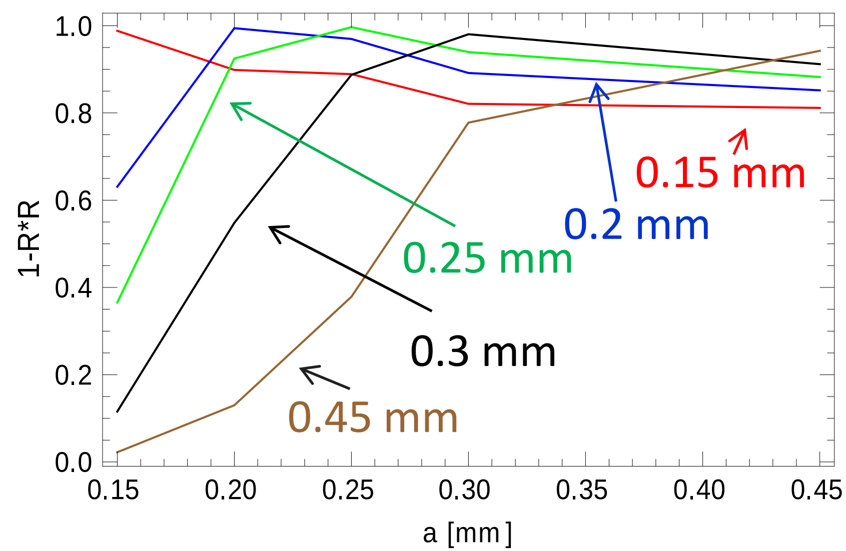


Surface electric fields, Emax = 2.1 GV/m

V.A. Dolgashev, 7 January 2013

Result of aperture-scan with different couplers, the couplers are matched as good as practical to correspondent gap

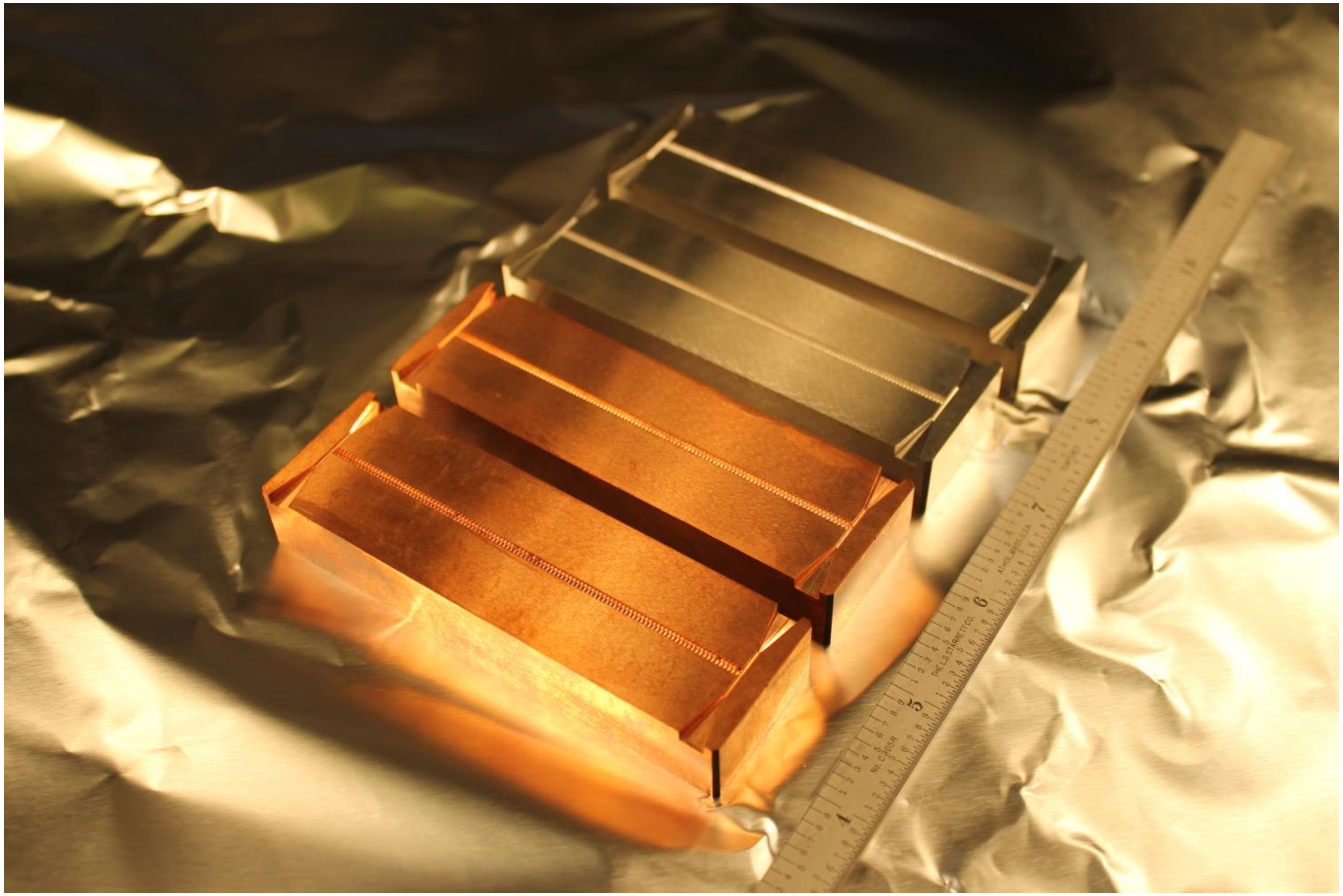




a [mm]	0.15	0.2	0.25	0.3	0.45
f_synch [GHz]	136.33	133.045	130.36	127.5	122.5

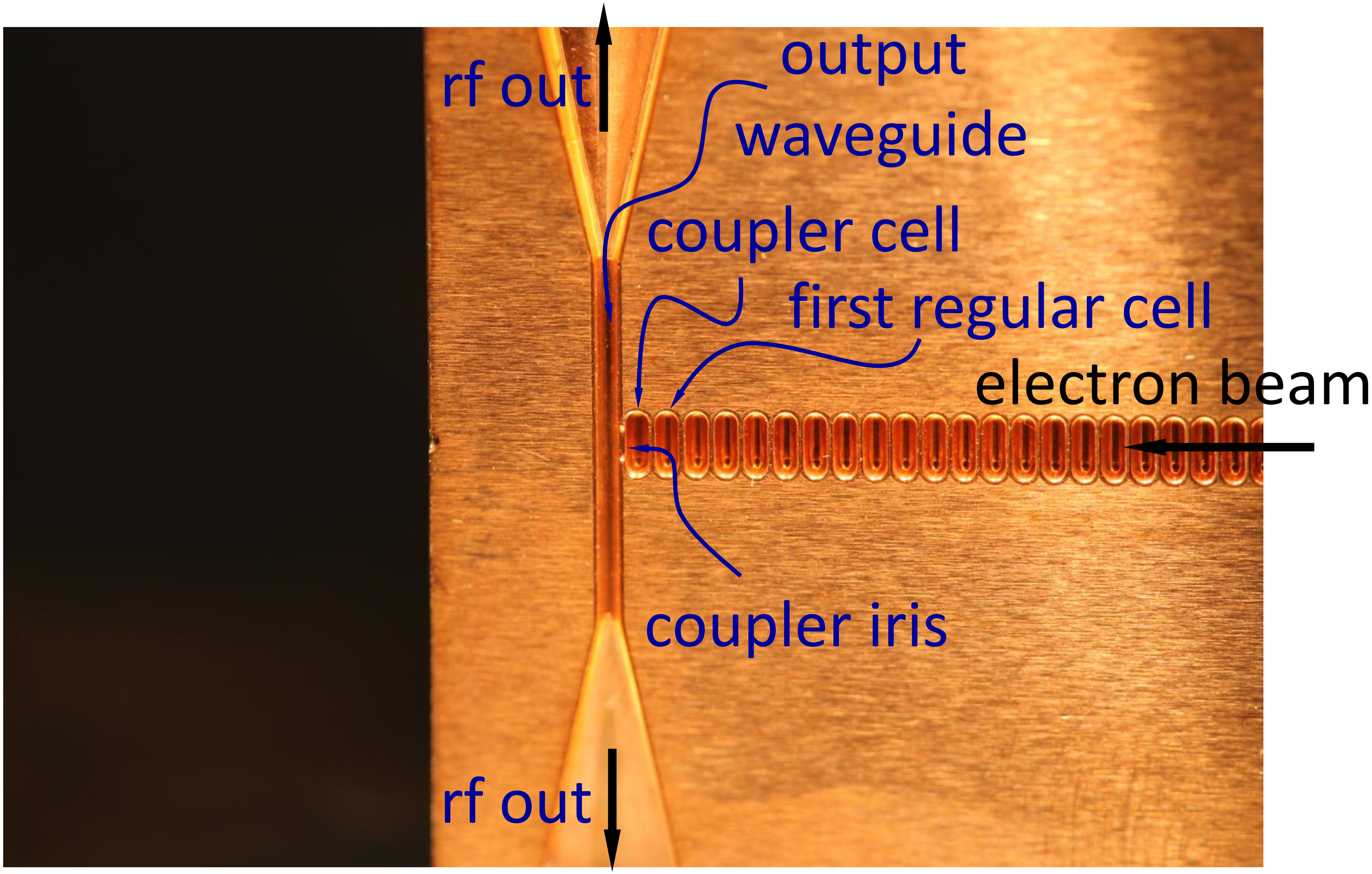
V. A. Dolgashev, 6 February, 2013

Cooper and stainless steel structures to study effect of material on rf breakdown at short pulse, 100 GHz



Manufacturing: EDM Department Inc.

Power coupler of the 100 GHz structure

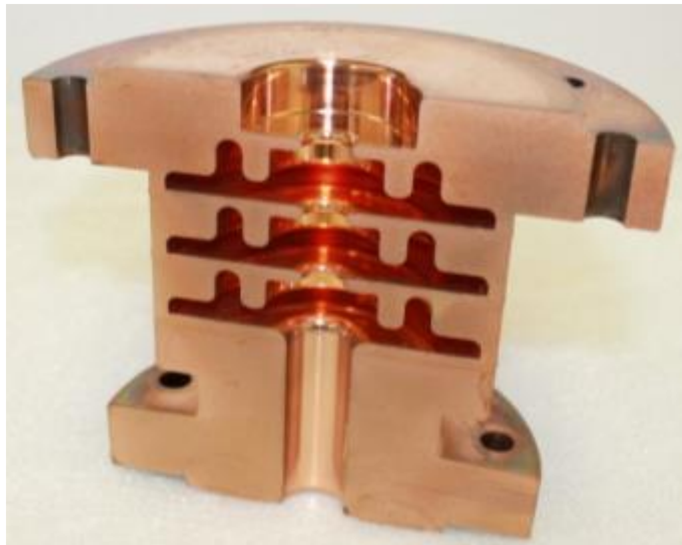


Manufacturing: EDM Department Inc.

NOvel Researches Challenges In Accelerators

http://www.lnf.infn.it/gr5/website_norcia/home.html

Molybdenum brazed



Triple-choke
Cu electron-beam welded

Cu electroplated

NORCIA

Bruno Spataro, INFN Frascati

NOvel Researches Challenges In Accelerators

http://www.lnf.infn.it/gr5/website_norcia/home.html

INFN

New technologies are required for multi-TeV line*ar* colliders, ν’ s facilities, x-ray FELs, etc.

The research project is devoted to the R&D of key components for existing accelerators and for the next generation of accelerators

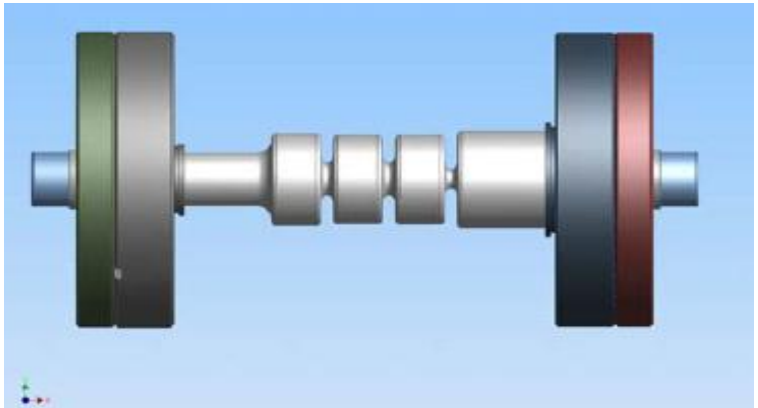
Approach:

New materials and manufacturing techniques including single- and multi-layer surfaces with precision-controlled properties

NORCIA

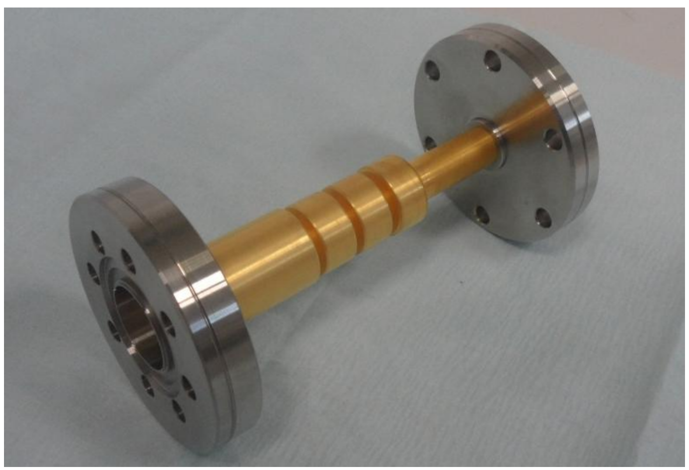
Bruno Spataro, INFN Frascati

NORCIA’s prototypes



Prototype mandrel
for the electroforming

3 µm thick Au coating



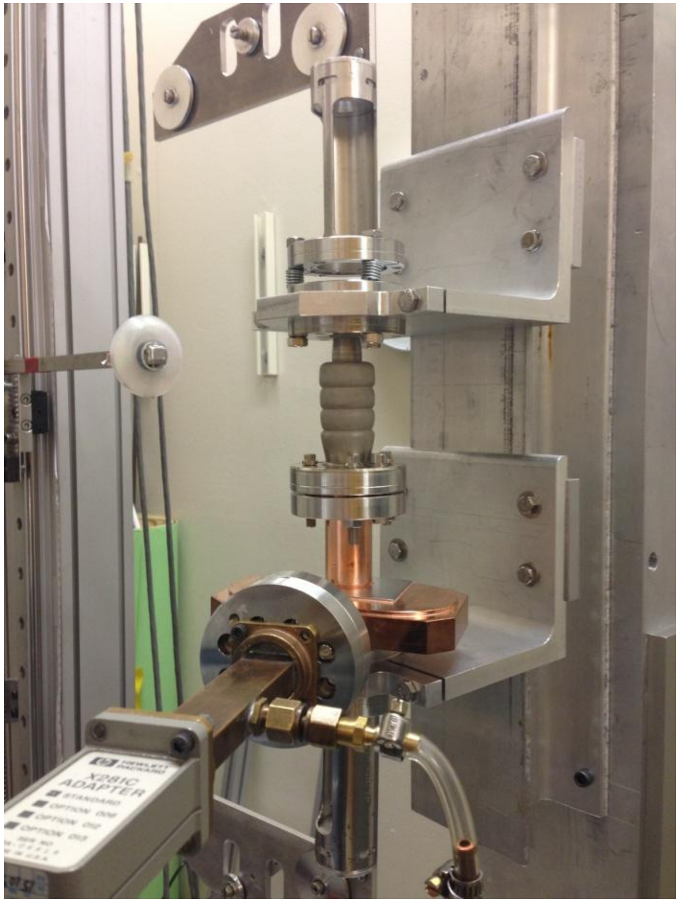
Fitting test between mandrel
and CF flanges

Au coated structure with
a 4 mm thick Nickel coating

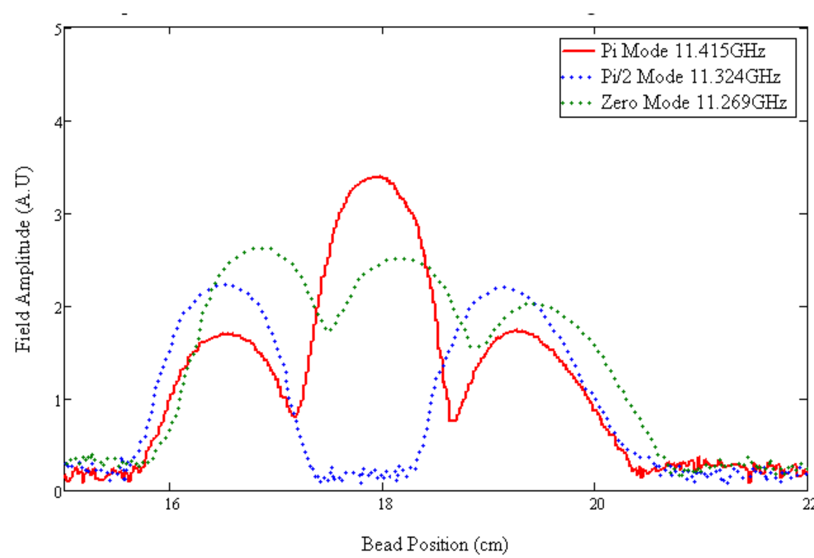
Bruno Spataro, INFN Frascati

Summary of RF QC for NORCIA's prototype 1C-SW-A3.75-T2.6-Electroformed-Au-Frascati-#1

	Pi Mode	Pi/2 Mode	Zero Mode
$F(GHz)_{Measured}$ *$F(GHz)_{Calculated}$*	11.4154 *11.42388*	11.3241 *11.33004*	11.2692 *11.27766*
$Q\ zero_{Measured}$ *$Qzero_{Calculated}$*	5786 *9177*	6621 *9389*	7090 *9110*
$Q\ loaded_{Measured}$	3486	1874	1949
$Q\ ext_{Measured}$	8774	2561	2688
$Beta_{Measured}$	.659	2.58	2.64



Beadpull setup



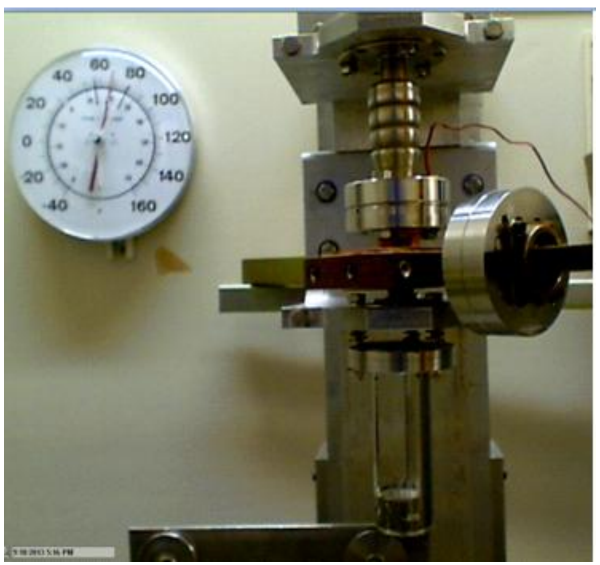
On-axis field amplitude for 0. Pi/2 and Pi- modes

Jim Lewandowski, SLAC , 31 May 2013

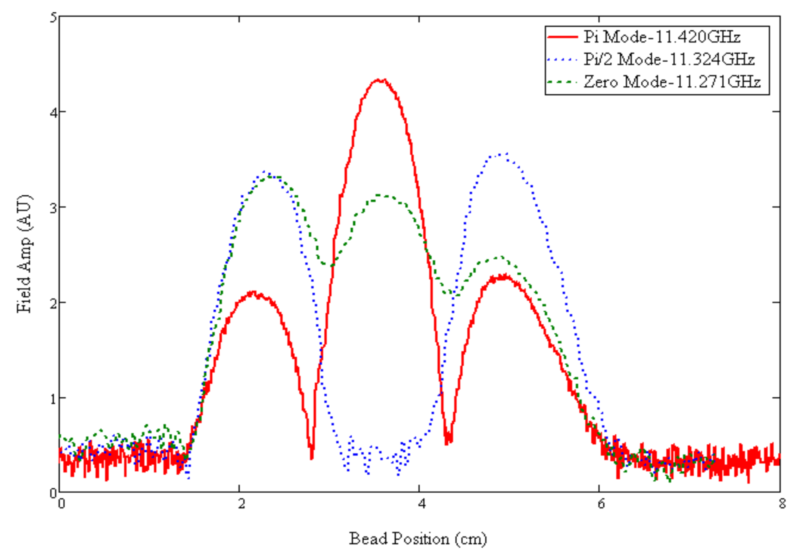
Summary of RF QC for NORCIA's prototype 1C-SW-A3.75-T2.6-Electroformed-Au-Frascati-#2

Coupling iris

	Pi Mode	Pi/2 Mode	Zero Mode
$F(GHz)_{Measured}$ *$F(GHz)_{Calculated}$*	11.4200 *11.42388*	11.3241 *11.33004*	11.27088 *11.27766*
$Q\ zero_{Measured}$ *$Qzero_{Calculated}$*	5130 *9178*	6467 *9388*	5981 *9110*
$Q\ loaded_{Measured}$	3077	1874	1938
$Q\ ext_{Measured}$	7315	2351	2867
$Beta_{Measured}$	.726	2.75	2.08



Beadpull setup



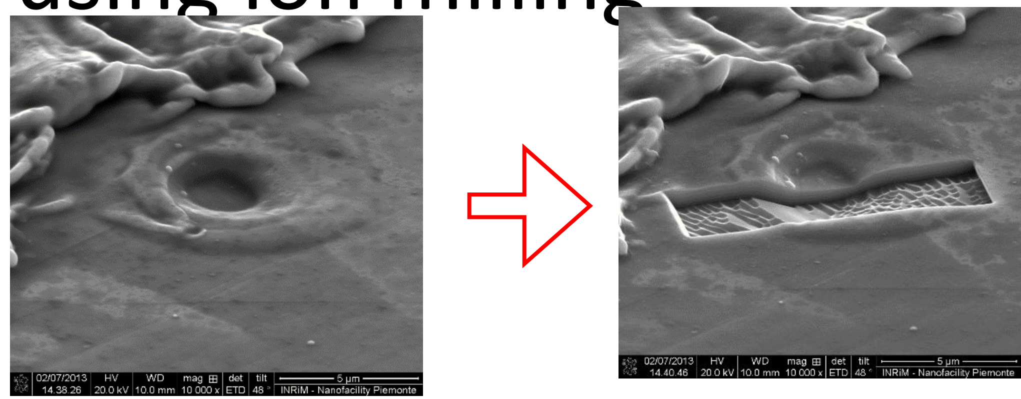
On-axis field amplitude for 0. Pi/2 and Pi- modes

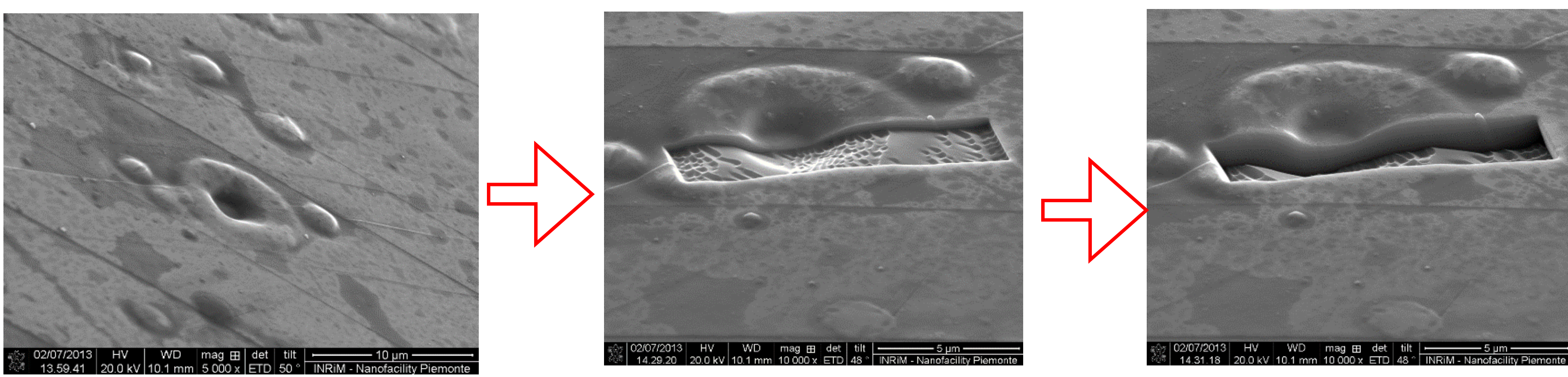
NORCIA

Jim Lewandowski, SLAC , 31 October 2013

First results on microscopic study of high-gradient cells using ion milling

- FIB cross sections may shed light on interpretation of dynamics of Copper flow caused by localized heating; (possible causes: electron heating i.e. e- trajectory driven, microwave hot spots...)





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.