Summary of RF Breakdown Studies using Single Cell Standing Wave Accelerating Structures

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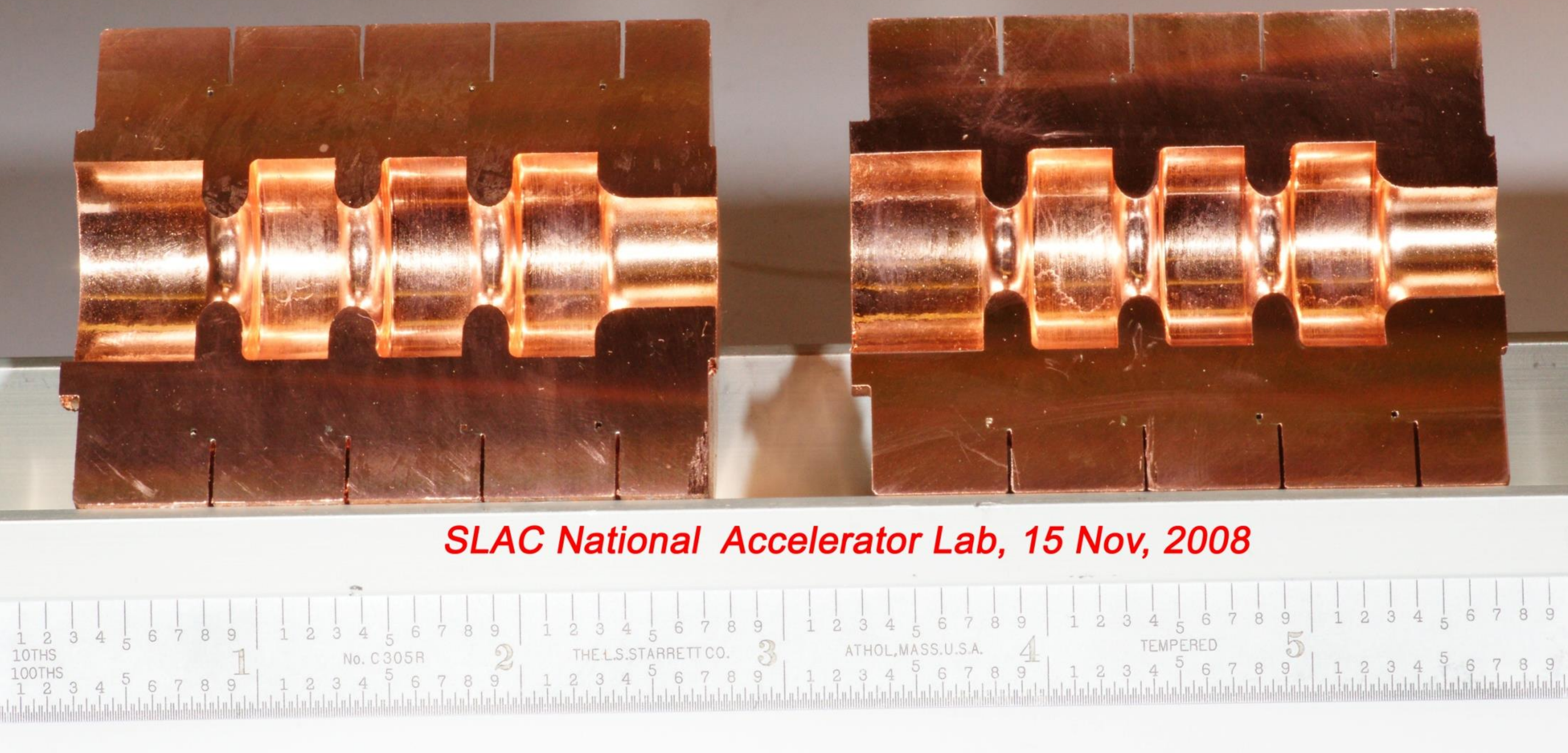
U.S. DEPARTMENT OF ENERGY Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

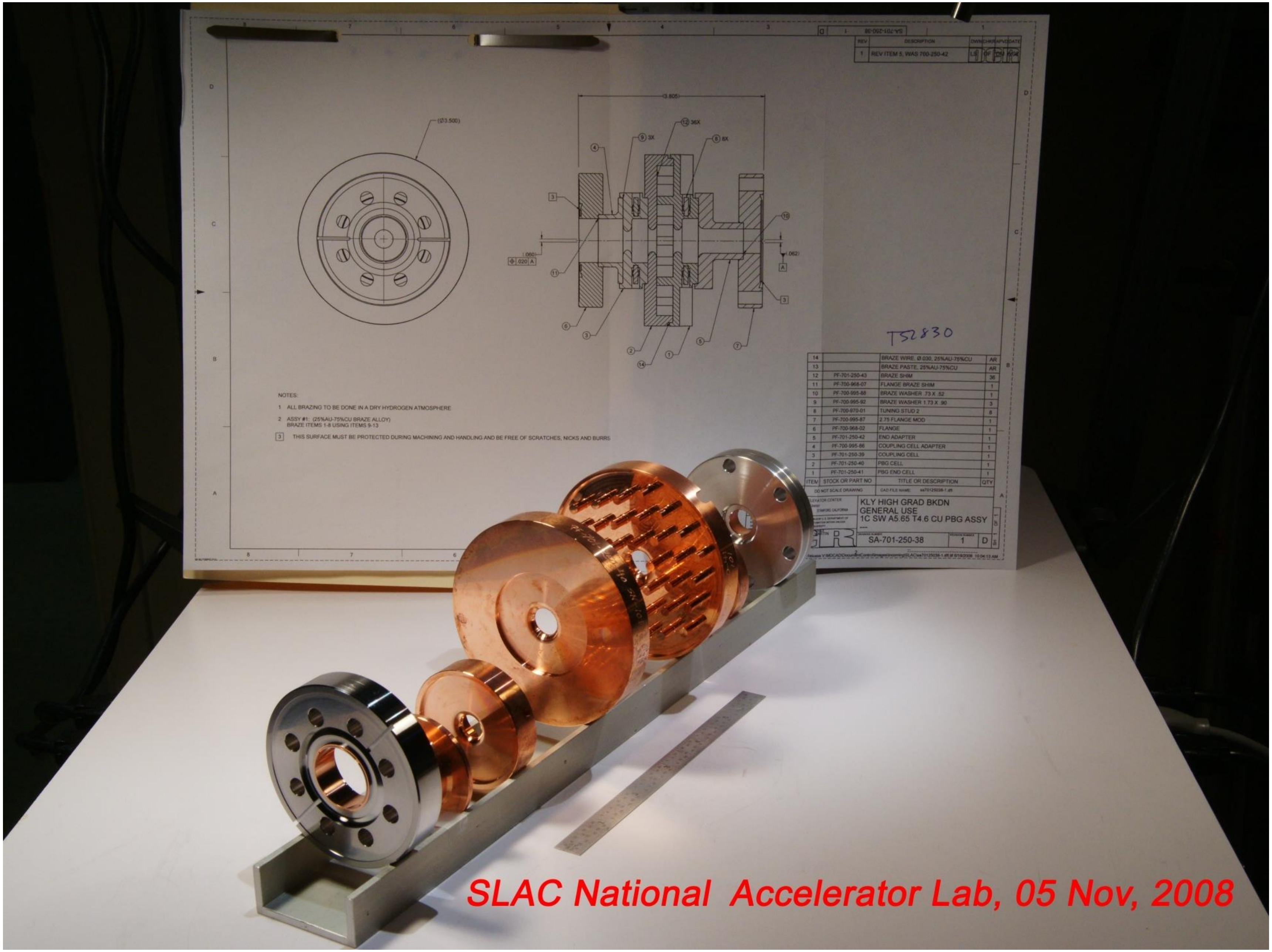
11.4 GHz, Standing Wave-Structure

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



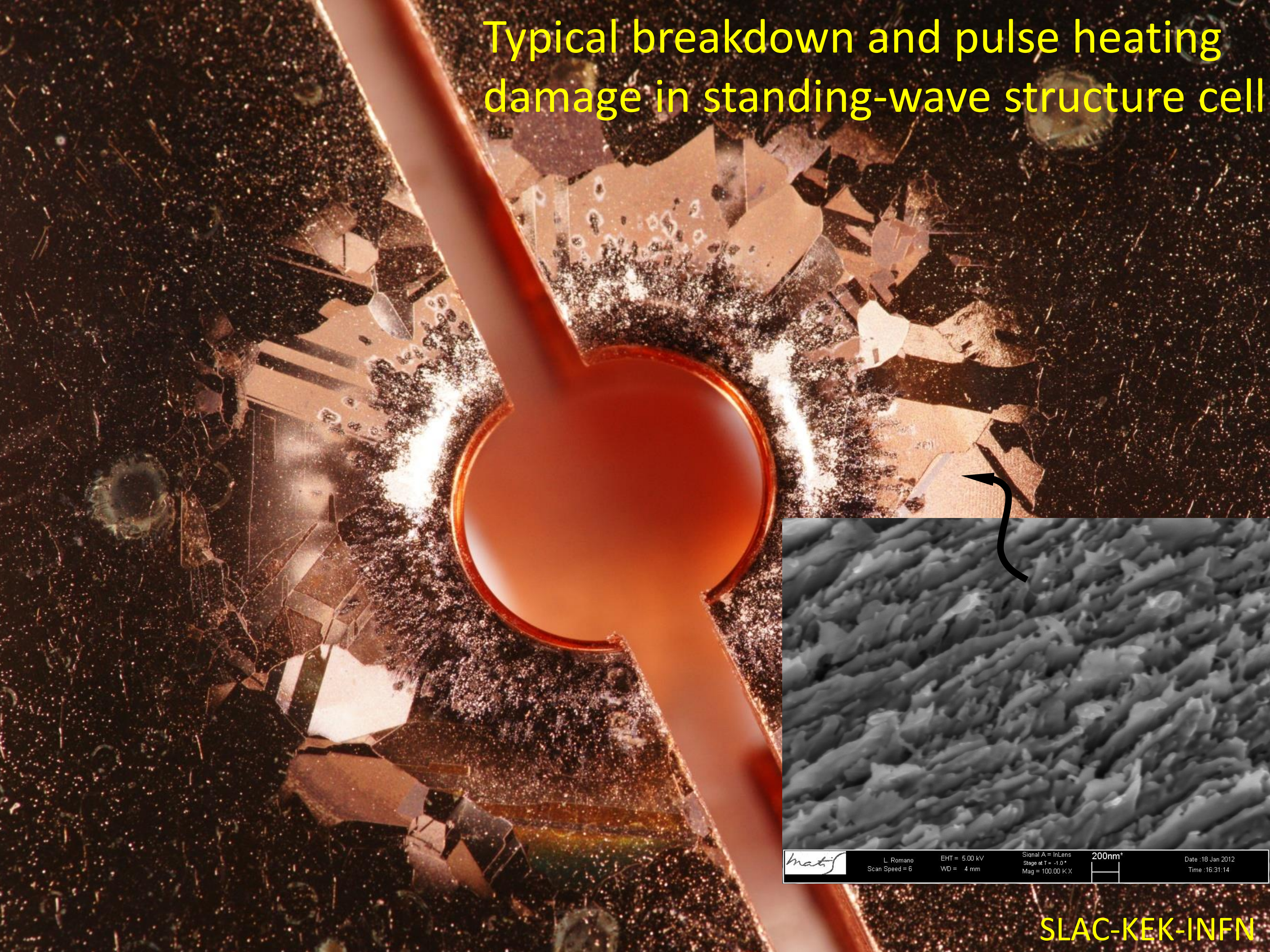
SLAC-KEK-INFN

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

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- Z. Li*, Advanced Computation*

In close collaboration with:

- T. Abe, *KEK, Tsukuba, Japan*
- C. Marcelli, V. Rigato, *INFN, Italy*

Outline

- Motivation
- Geometries
- Materials
  - Hard copper
  - Hard copper alloys
  - Cryo
- Construction techniques
  - Electron Beam Welding
  - TIG welding

Single Cell SW Accelerating Structures

Goals

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

- Development of new manufacturing techniques

Difficulties

- Full scale structures are long, complex, and expensive

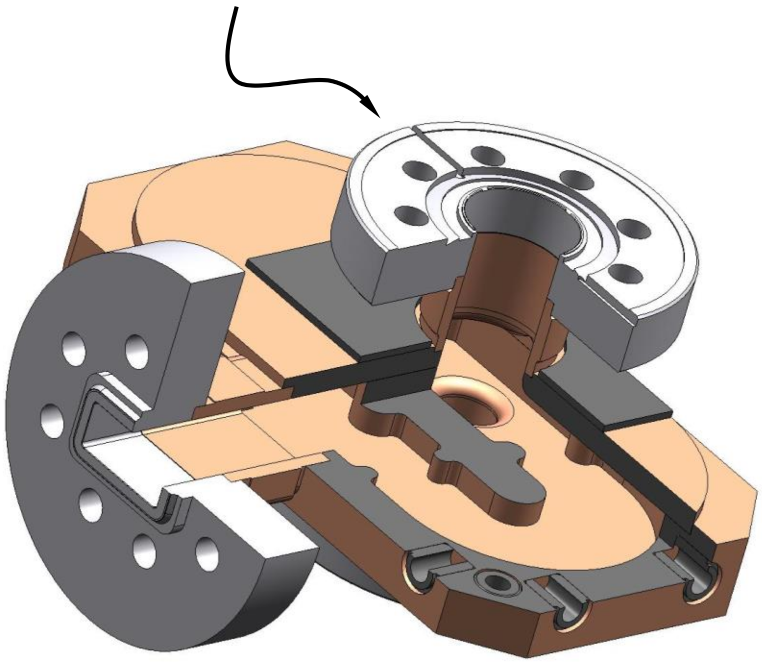
Solution

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

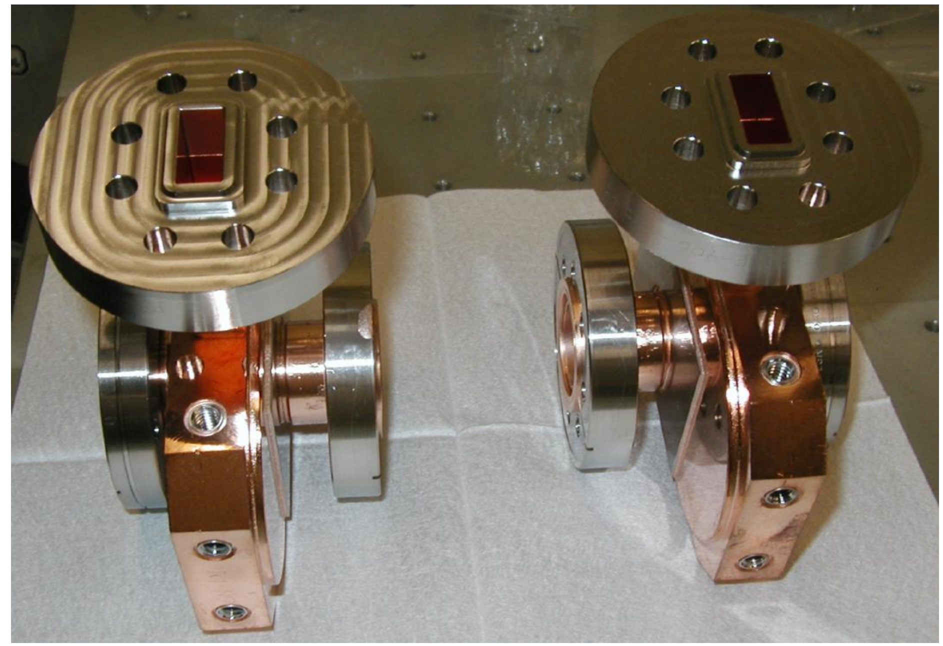
We want to predict breakdown behavior for practical structures

Reusable coupler: TM_{01} Mode Launcher

Pearson's RF flange



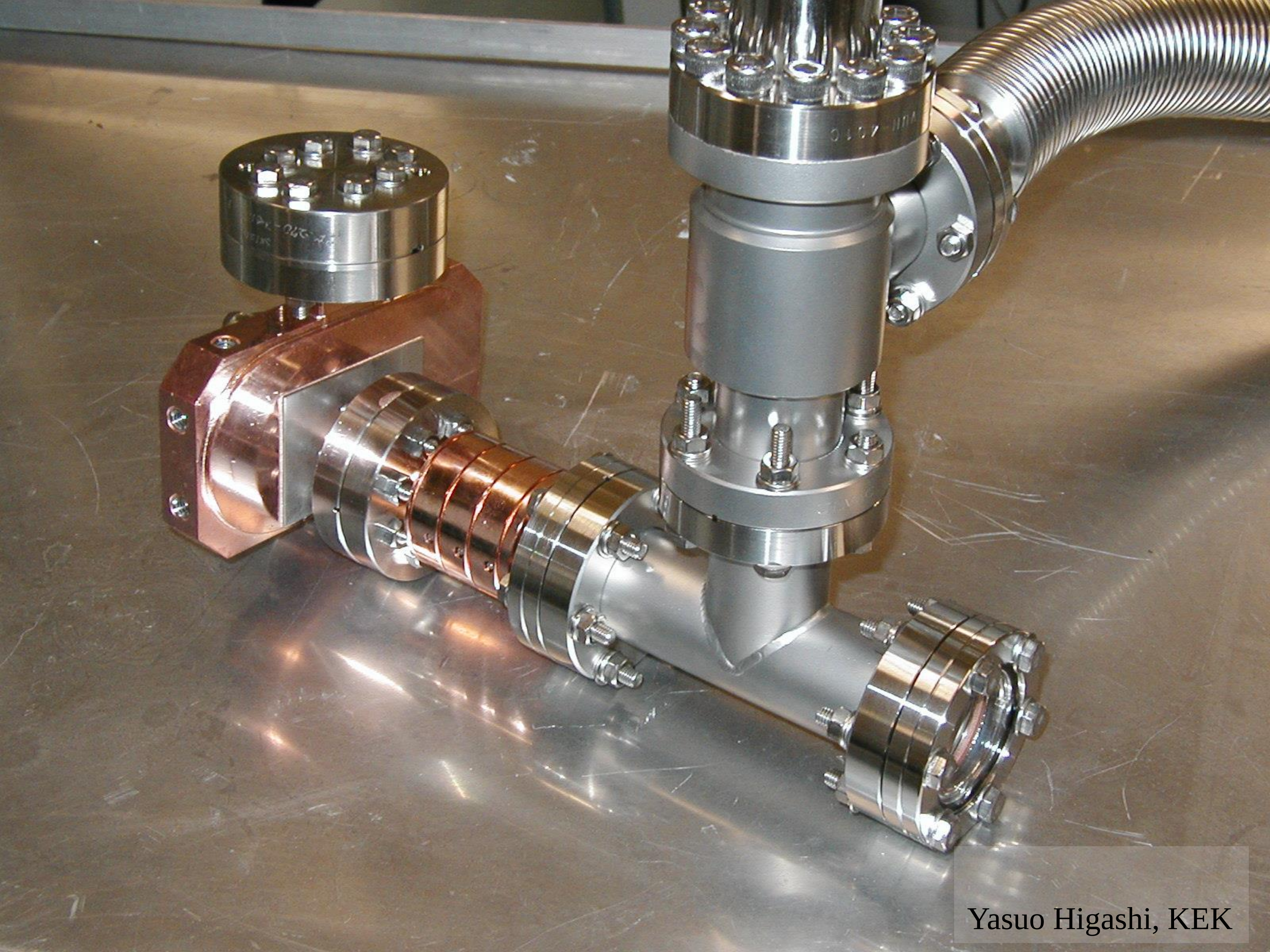
Cutaway view of the mode launcher



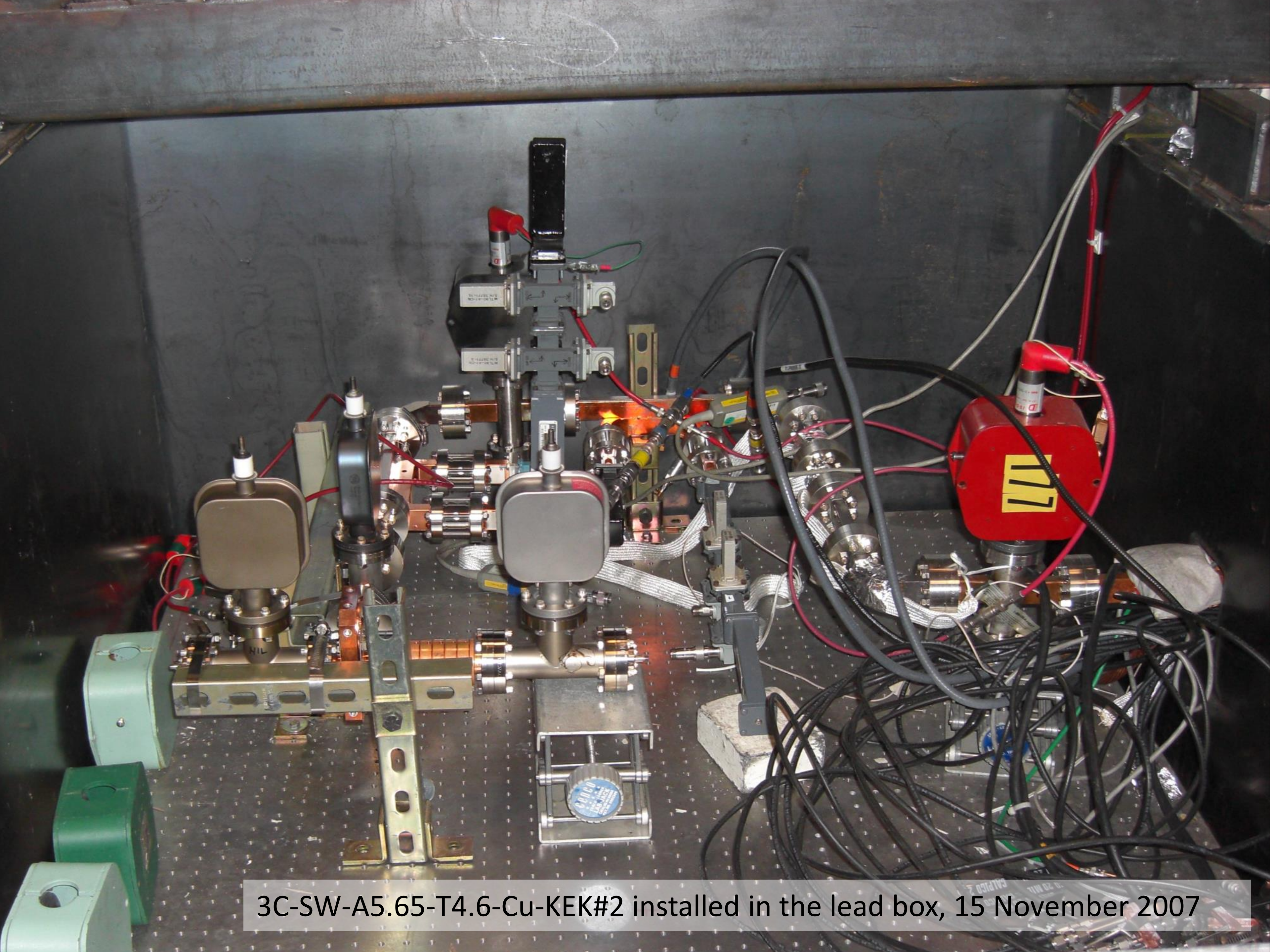
Two mode launchers

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

S. Tantawi, C. Nantista, SLAC



Yasuo Higashi, KEK



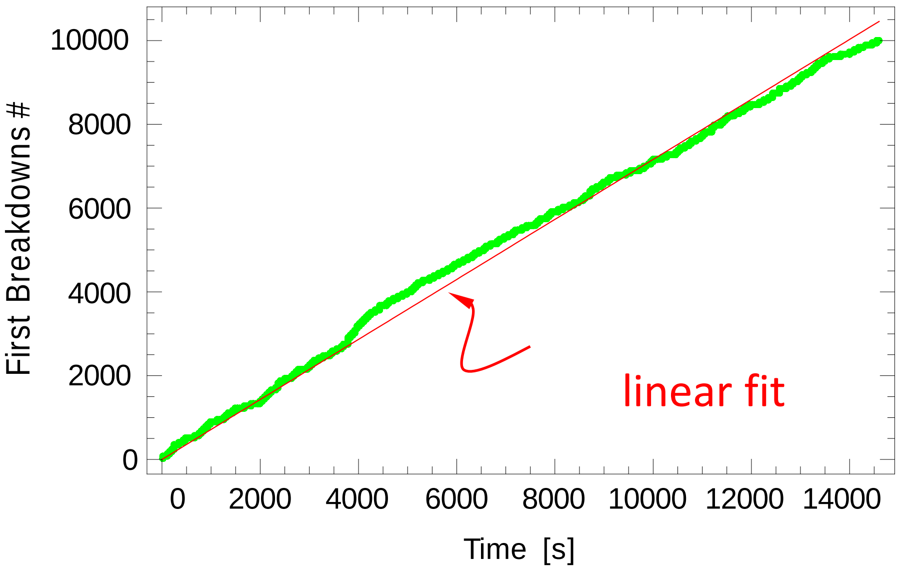
3C-SW-A5.65-T4.6-Cu-KEK#2 installed in the lead box, 15 November 2007

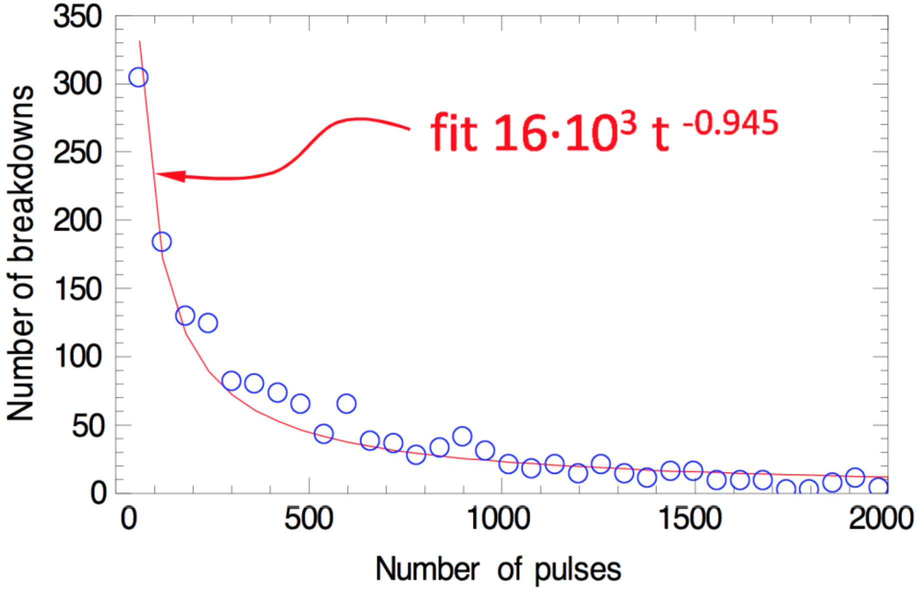
Breakdown rate

Instead of “breakdown limit” or “breakdown threshold” 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.

We found that the breakdown rate is reproducible for different structures of same geometry and bulk material.





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

V.A. Dolgashev, LINAC2010

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-3 tested*
- High shunt impedance, clad Stainless Steel -Copper 1C-SW-A3.75-t2.6-Cu-SS-KEK, 1 tested
- High shunt impedance, electroformed 1C-SW-A3.75-t2.6-Electroformed-Au-Frascati-#1, 1 tested,
- Highest shunt impedance, Cryo copper, *1C-SW-A3.75-A2.6-Cryo-Cu, 2 tested,*
- Highest shunt impedance, ZrO2 coated, 1C-SW-A2.75-T2.0-Coated-ZrO2-Clamped-SLAC-#1, 1 tested,
- Highest shunt impedance, hard CuAg, Electron Beam Welded, *1C-SW-A2.75-T1.5-CuAg-EBW-Radiabeam,* 1 tested,
- Highest shunt impedance, hard copper, Electron Beam Welded, *1C-SW-A2.75-T2.0-EBW-Cu-Frascati-#1,* 1 tested,
- Highest shunt impedance, hard copper, TIG welded, *1C-SW-A2.75-T2.0-TIG-Cu-Frascati-#1,* 1 tested,
- *Side coupled, hard copper, clamped, 3C-SW-A1.5-T3.03-Brazless-Cu-Euclid-#1,* 1 tested,
- Highest shunt impedance, clamped, Tin plated, *1C-SW-A2.75-T2.0-Clamped-Tin-Plated-SLAC-#1,* 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

Toal of 54 structures tested in up to date

Current “state of the art”

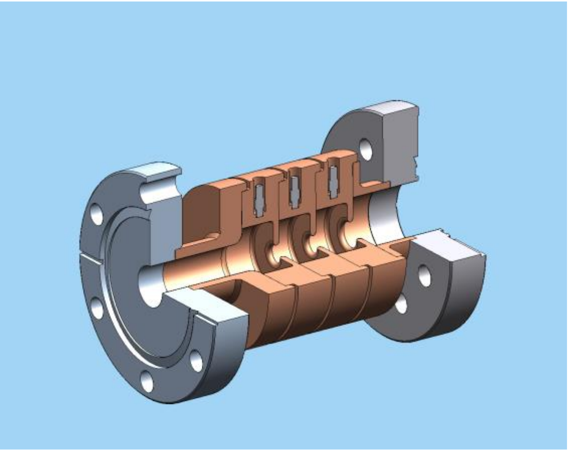
- We practically can predict performance of heat-treated soft copper X-band structures from drawings.
  - We found peak pulse heating to be good predictor of breakdown rate in simple, disk-loaded-waveguide type geometries.
  - We found “modified Poynting vector”(Sc) to be a practical predictor of breakdown rate in more complex geometries.
- Motivated by correlation of peak pulse heating and breakdown rate we study hard cooper alloys and methods of building practical structures out of them.
  - We found hard Cu and hard CuAg have better performance then soft heat-treated copper.
  - As for now, hard CuAg had record performance for room temperature structures.
- We study breakdown in cryo normal conducting structures, as for now, such accelerating structure holds absolute record for X-band accelerating structure
  of ~250 MV/m (0.5 GV/m peak surface) at 10^{-3}/pulse/m breakdown probability.
- We study clad metal and multi-layered structures and their construction methods. Idea is to study materials with designed properties.
- We started looking at a complex process of initial conditioning:
  - In 3 CuAg experiments (1 soft and 2 hard) we observed unusual conditioning: breakdown performance on initial stages of conditioning was better than at final stage. Note that at this final stage the performance is better then in common soft-copper structures

Geometrical studies

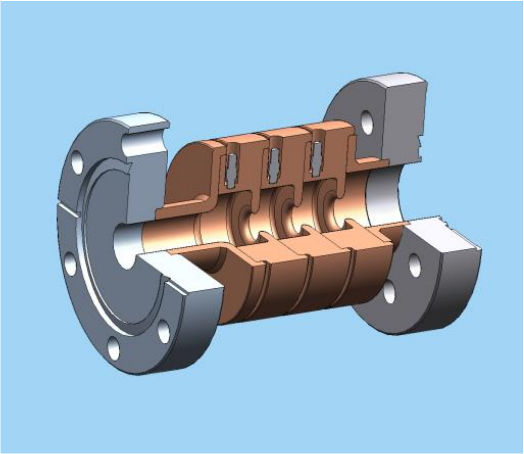
In beginning stages of the program, we have found out that “as conditioned” breakdown rates weakly depend on initial surface condition and reproducible for the same geometries and bulk materials. Therefore, we could carry out comparative studies of different geometries.

Geometrical Studies

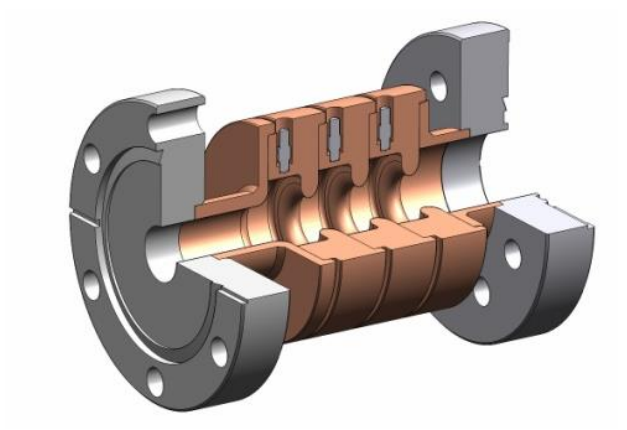
Three Single-Cell-SW Structures of Different Geometries



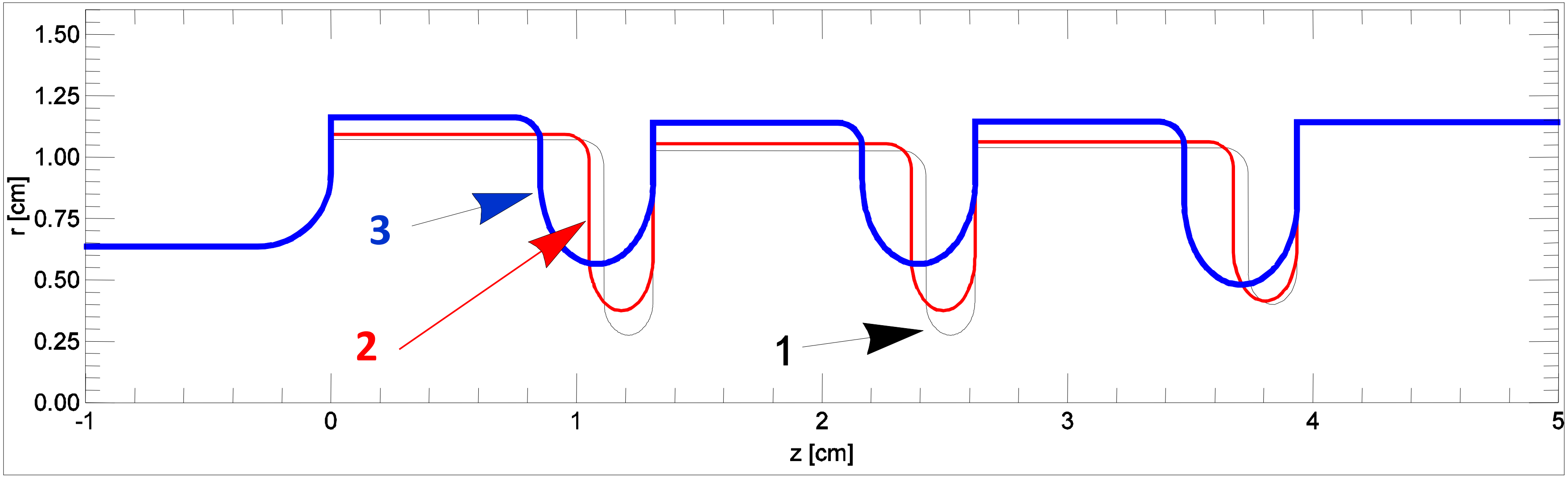
1)1C-SW-A2.75-T2.0-Cu



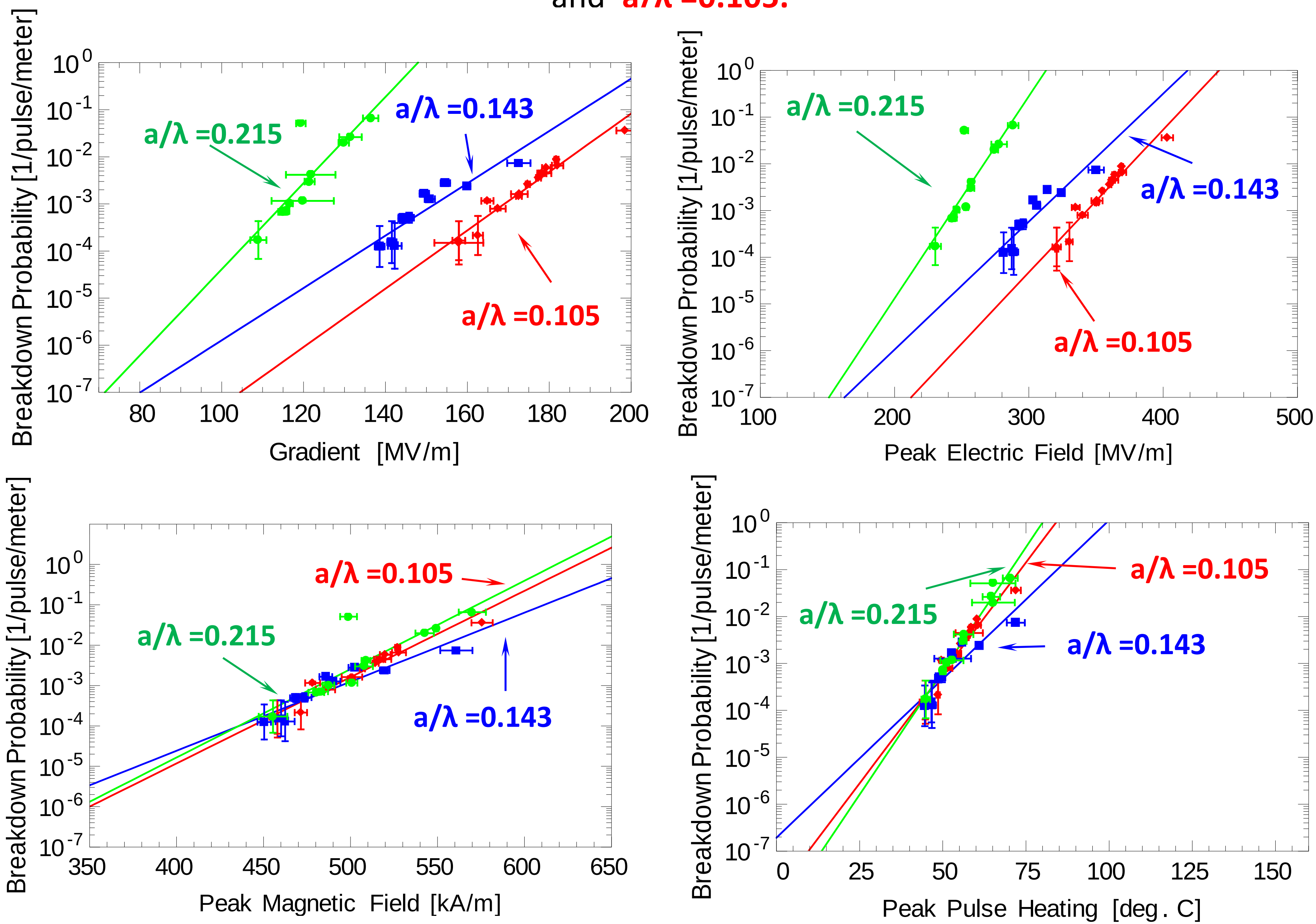
2) 1C-SW-A3.75-T2.0-Cu



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.



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

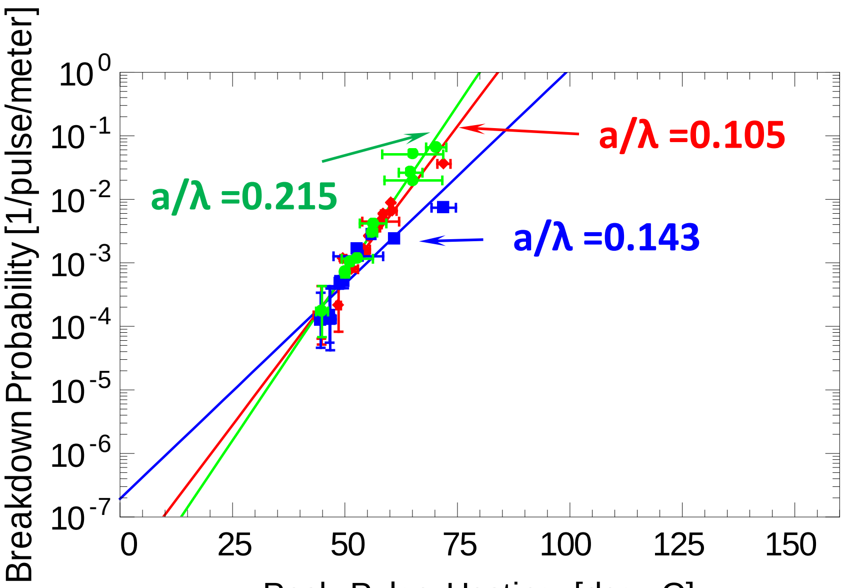
Peak electric field seems to have less importance than magnetic field

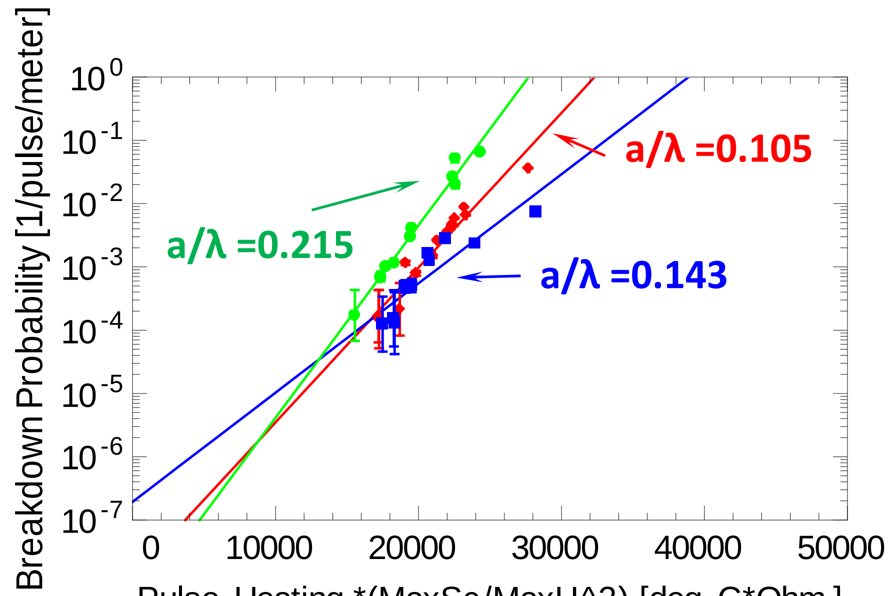
Consequences :

- New geometries optimized for low pulse heating
- Experiments that uncouple rf electric and magnetic fields

- Dedicated study of pulse heating
  - Lisa Laurent et al., *Experimental study of rf pulsed heating,* Phys. Rev. ST Accel. Beams 14, 041001 (2011)
  - 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).
- Hard copper allows resistant to pulse heating damage
- Clad materials
- Cryo-experiments with normal conducting structures
- Methods of building structures without extreme heat treatment

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.**



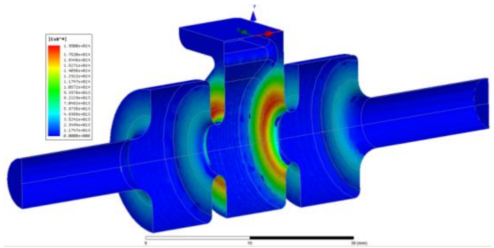


Analysis of experimental data from multiple structures (including these) finds that peak Poynting vector is correlated with breakdown rate:

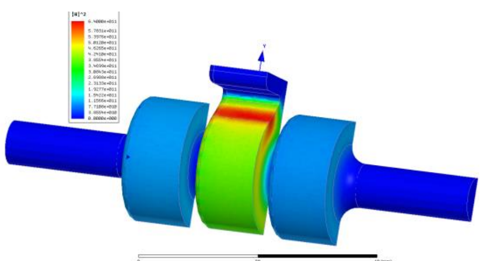
A. Grudiev, S. Calatroni, and W. Wuensch,
New local field quantity describing the high gradient limit of accelerating structures,
Phys. Rev. ST Accel. Beams **12,** 102001 (2009).

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

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



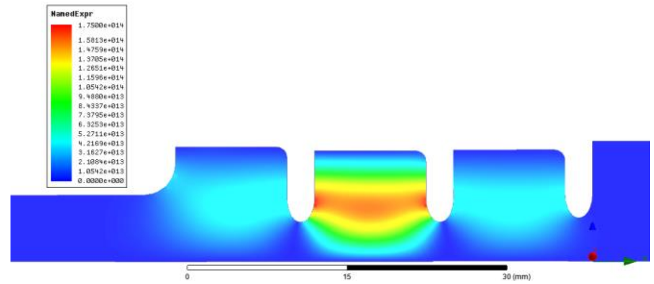
Max. Poyning Vector 1.93 e14 W/m^2



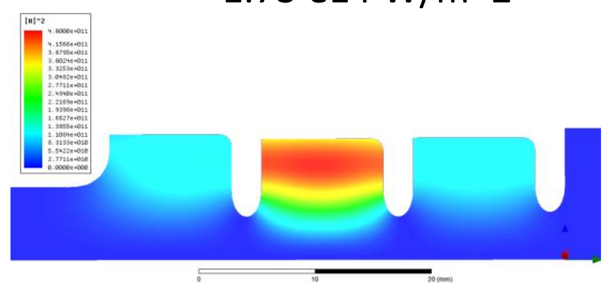
Max. |H^2| 6.4e11 (A/m)^2

Ratio is 301 Ohm

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



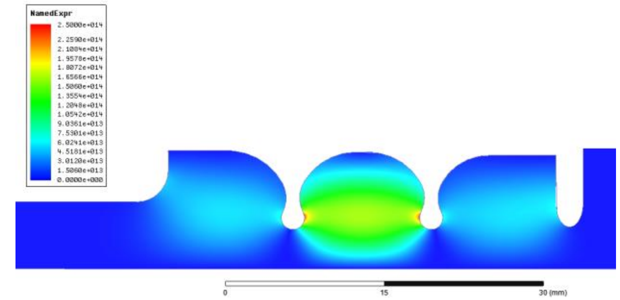
Max. Poyning Vector 1.73 e14 W/m^2



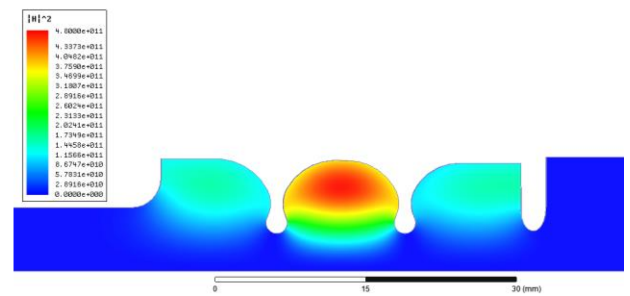
Max. |H^2| 4.44e11 (A/m)^2

Ratio is 390 Ohm

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



Max. Poyning Vector 2.4e14 M/m^2

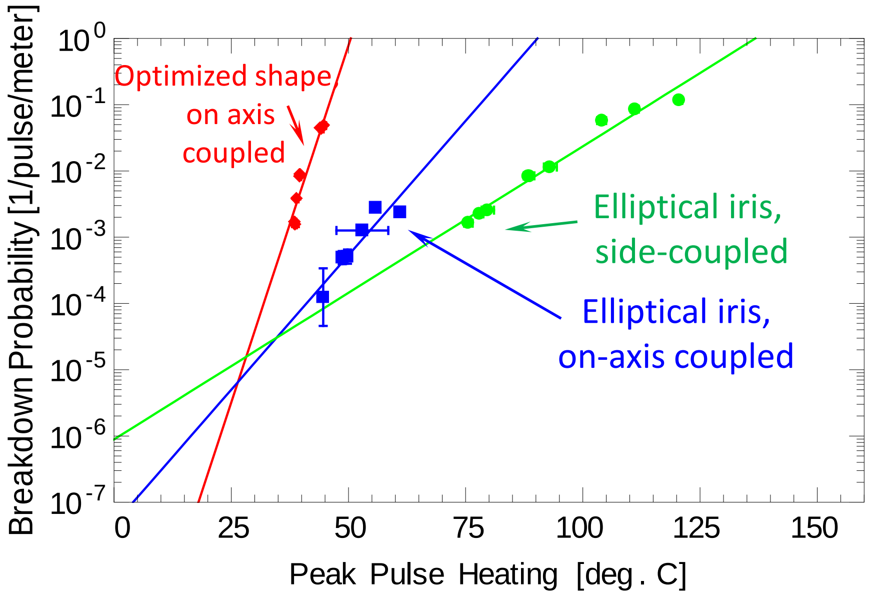


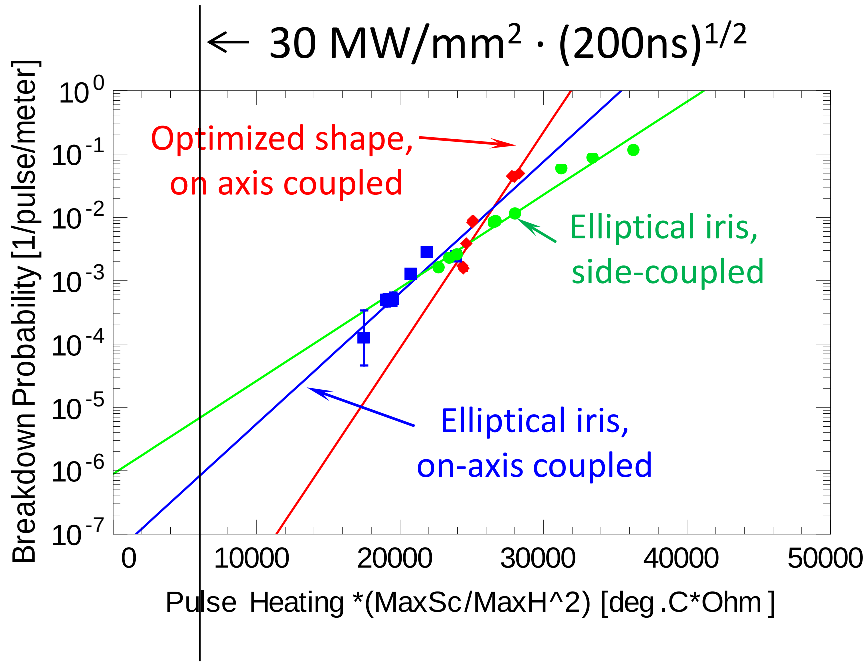
Max. |H^2| 3.8e11 (A/m)^2

Ratio is 632 Ohm

Pulse heating vs. Poynting vector

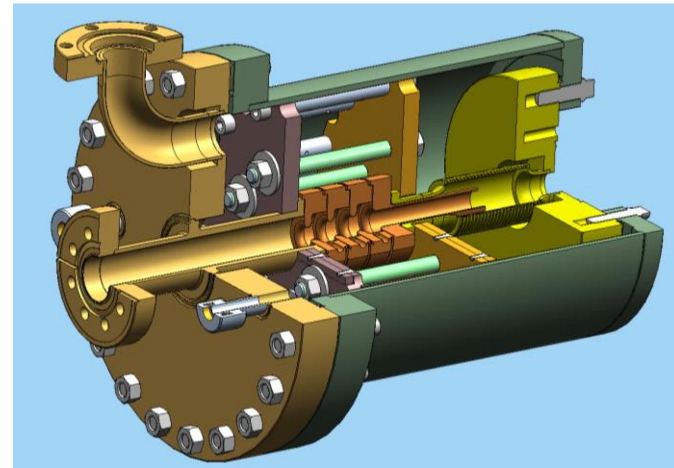
Comparison of two on-axis coupled structures and one side-coupled structure of 3.75 mm aperture, shaped pulse with 200 ns flat part



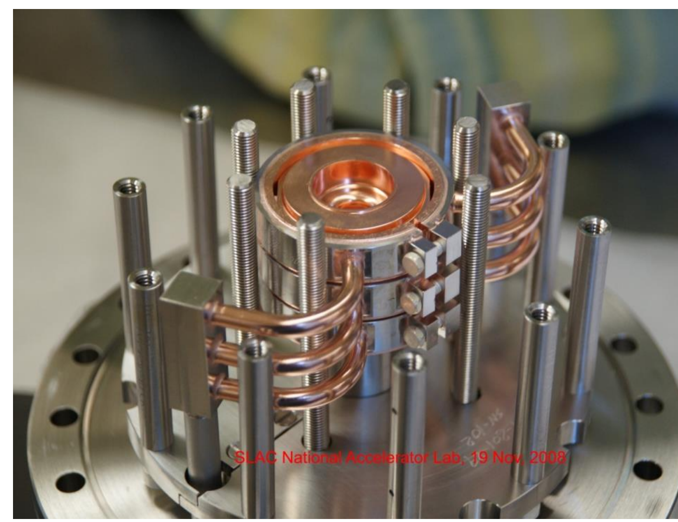


For structures of significantly different geometries breakdown rate better correlated more with peak Poynting vector than with peak surface pulse heating.

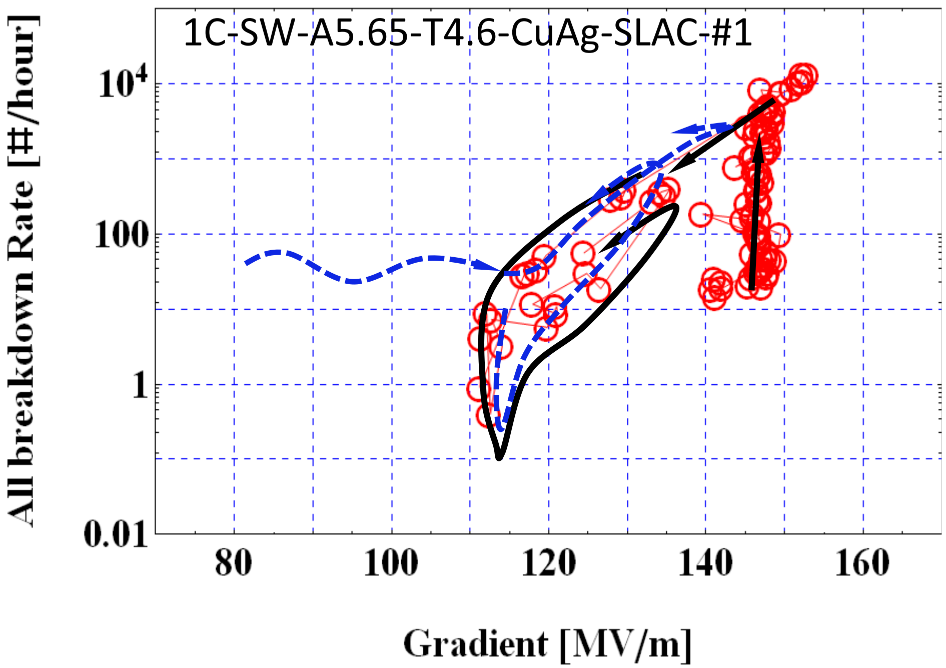
Development of Hard Copper and Copper Alloy Structures



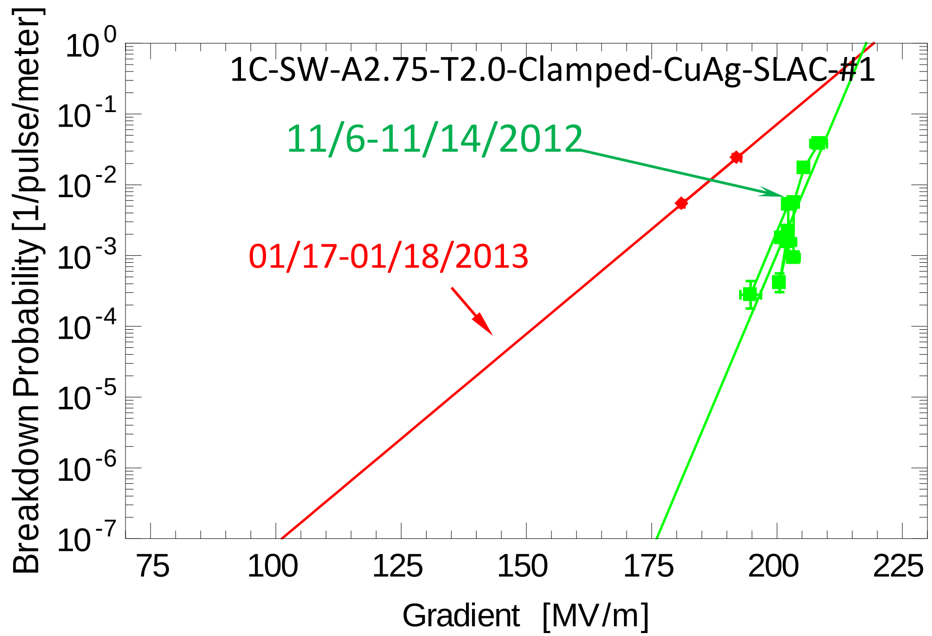
- We had to develop an apparatus for testing accelerator structure without brazing
- The results shows a great improvement of possible gradients at very low breakdown rates
- It is now possible to talk about reliable gradient higher than 150 MV/m



Discovery of atypical conditioning behavior of both soft and hard CuAg alloys

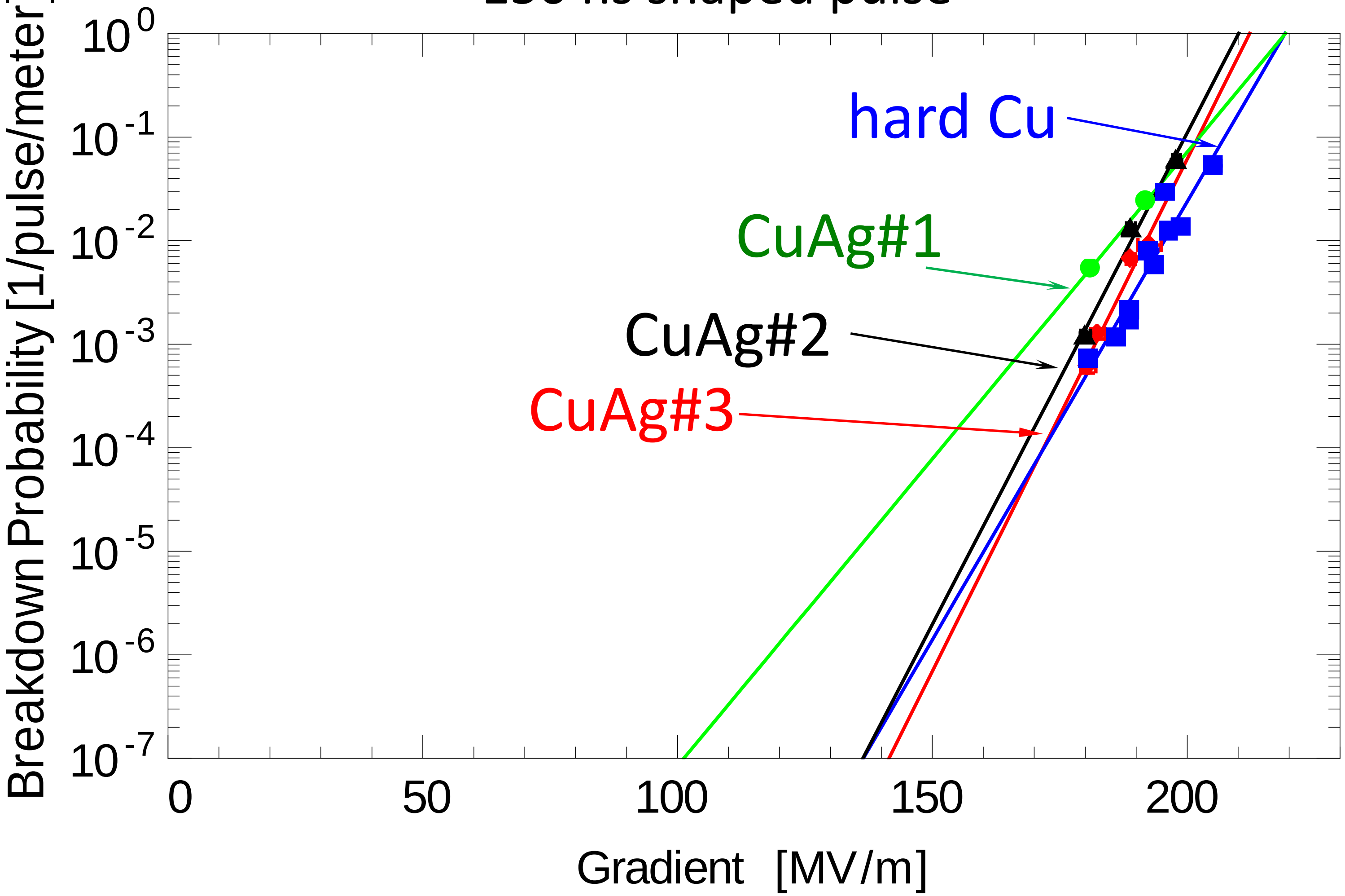


Unusual conditioning soft CuAg, starting with very good performance, then degrading



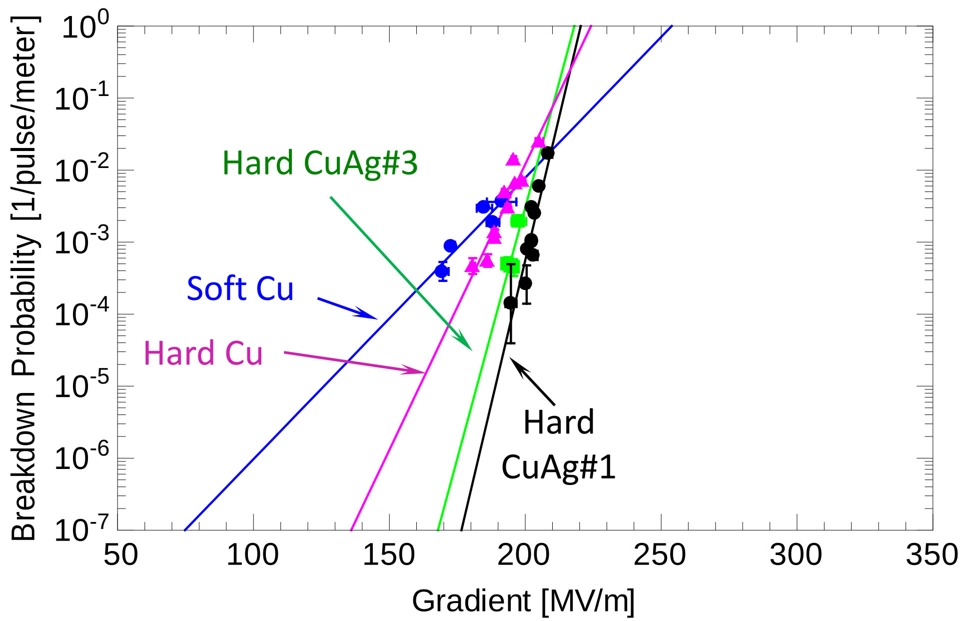
Unusual conditioning hard CuAg, again starting with very good performance, then degrading

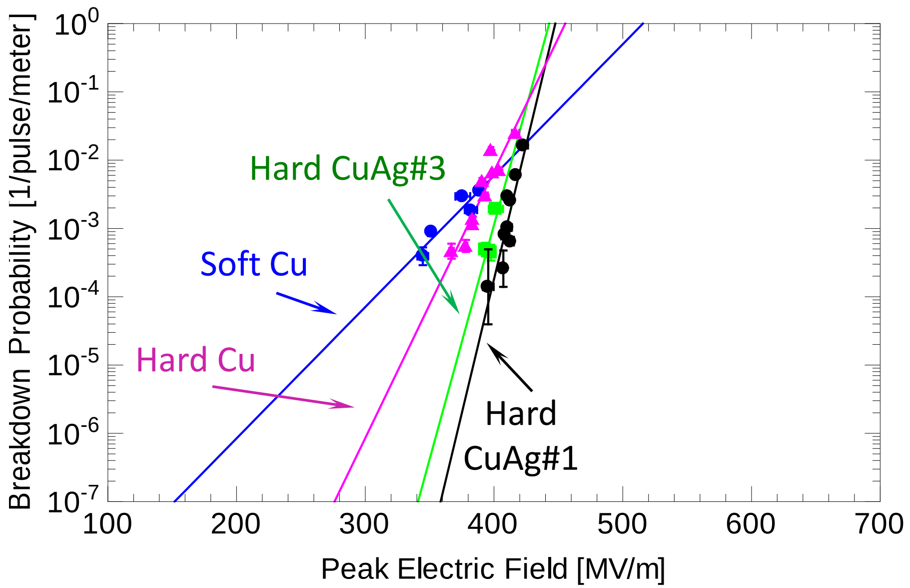
Reproducibility of final performance : Breakdown data for three1C-SW-A2.75-T2.0-structures made out of hard Cu and hard CuAg, 150 ns shaped pulse



“Final” gradient performance of all CuAg structures is very similar and practically identical to hard Cu

Breakdown probability for four **a/λ =0.105** structures (1C-SW-A2.75-T2.0), one made of made of soft–heat treated Cu, one hard Cu, and two hard CuAg, 150 ns shaped pulse



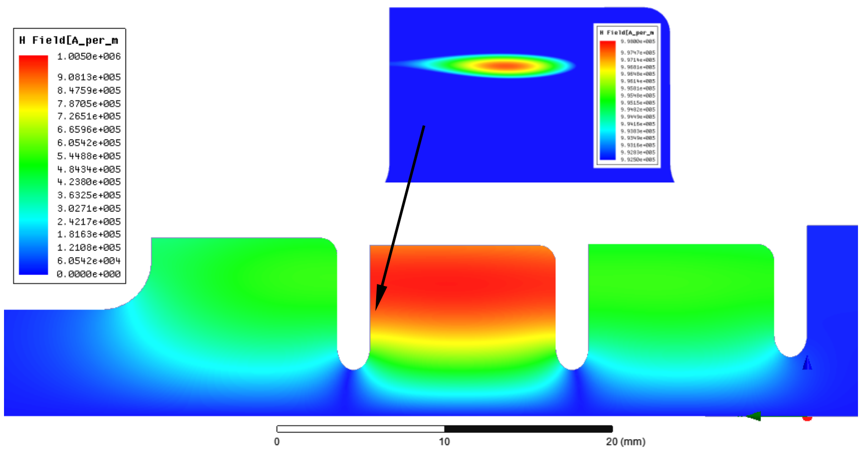


We found that hard copper and hard copper-silver have better high gradient performance then soft, heat-treated copper. In addition to that, at initial stages of conditioning CuAg clearly outperforms hard copper.

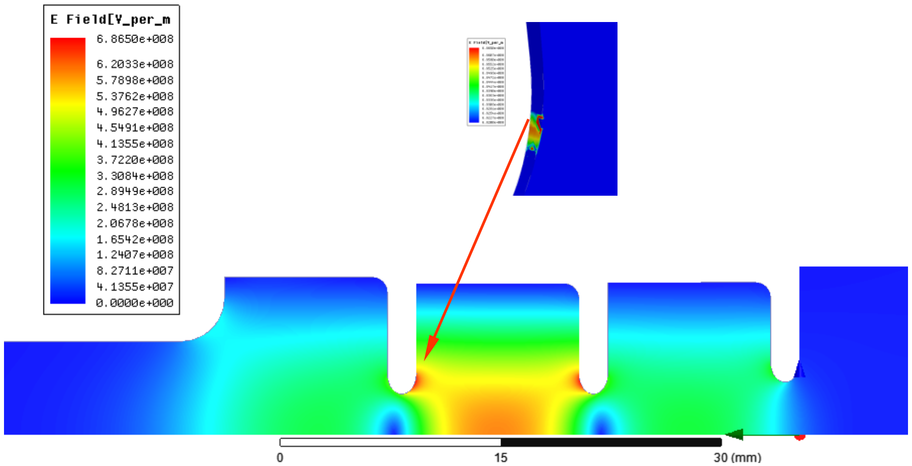
Freezing crystal defects: Normal Conducting Cryogenic Structure

- We conjecture that the breakdown rate is linked to movements of crystal defects induced by periodic stress. Pulse heating creating some or, possibly major part of this stress. So, by decreasing crystal mobility and increasing yield stress we will reduce the breakdown rate for the same gradient. We want to do this by cooling a cavity to to 4…100 K.
- Pros:
  - Mobility of the crystals decreased, yield stress increases.
  - Resistivity decreased thus reducing rf power required to sustain the gradient.
  - Vacuum pumping between breakdowns is improved.
- Cons:
  - Since the cavity acts as a cryogenic vacuum pump any vacuum leak or other source of gasses could contaminate high field surfaces.
  - Due to reduced cooling efficiency at low temperature, overall efficiency of the system decreased and makes high repetition-rate operation problematic.
  - Due to rapid increase of the resistivity with the temperature effective temperature of the cavity may be much higher then its average temperature thus reducing advantages of cryo operation.

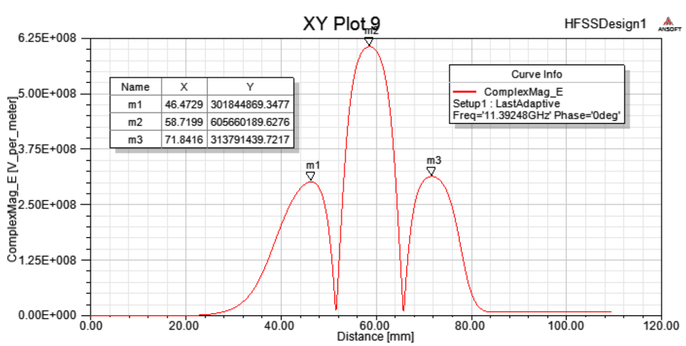
Design of cryo accelerating structure, 1C-SW-T2.75-A2.0-Cryo-Cu, 11.3925 GHz, 10 MW rf input



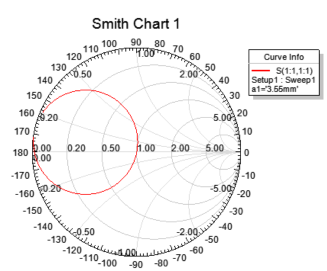
Maximum magnetic field 992.5 kA/m
(SLANS 993.2 kA/m)



Maximum electric field 686 MV/m
(SLANS 678 MV/m)



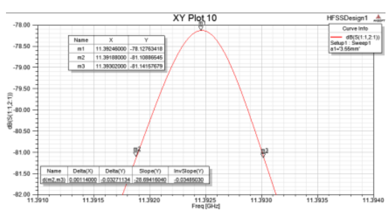
Coupler-cell on-axis field is ~4% high vs. end-cell field,
Peak field on axis 605.7 MV/m (SLANS 605.7 MV/m)

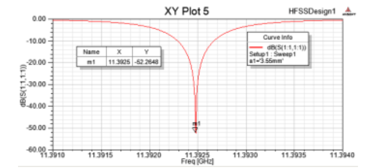


Slightly over coupled with beta= 1.00488

$$Q := \frac{11.394}{0.00114}$$

$$Q = 9.995 \times 10^{3}$$

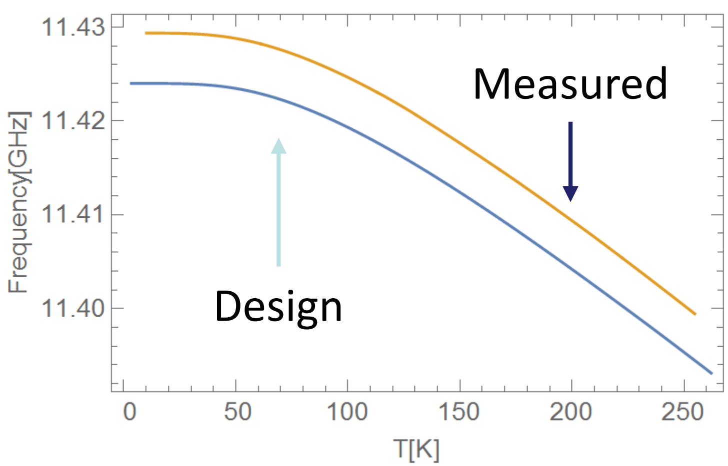


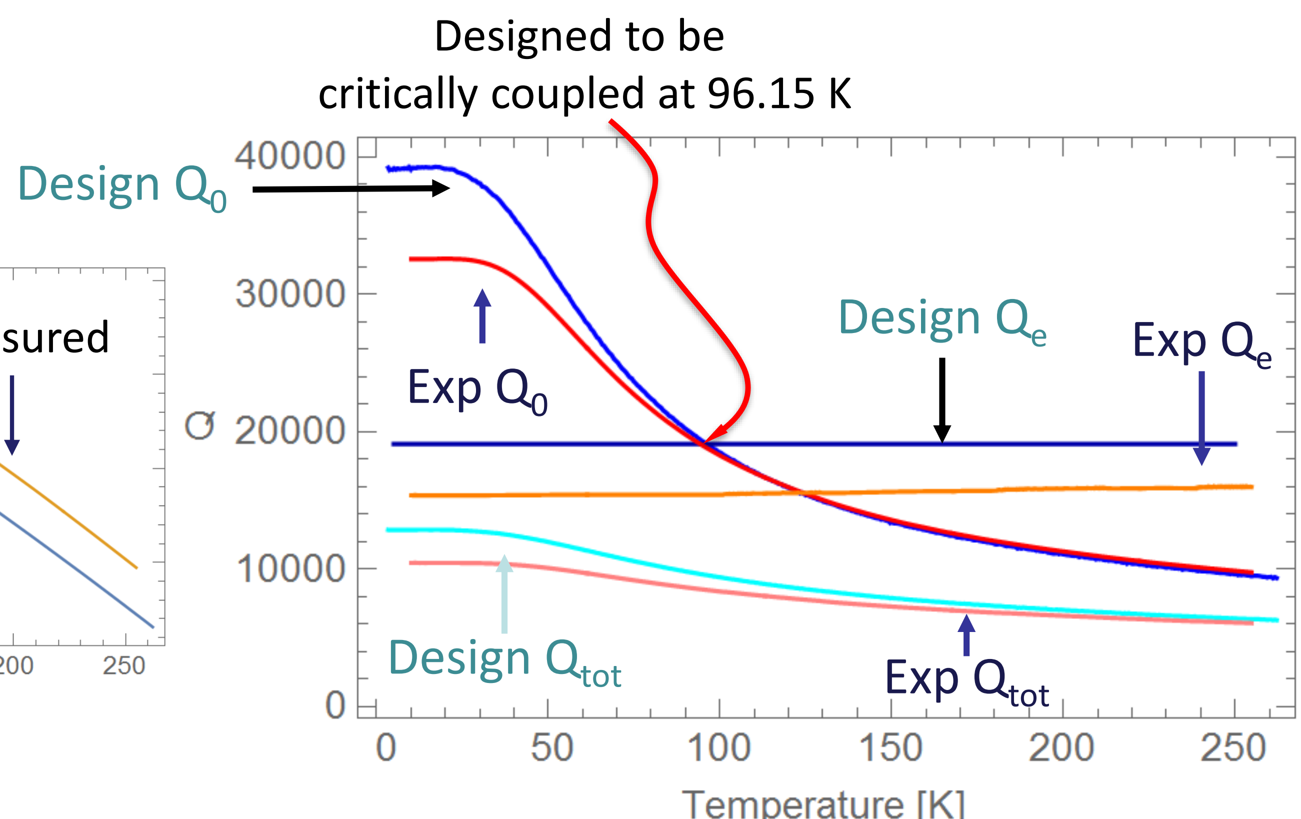


F=11.39**25** GHz (SLANS 11.93**40** GHz)

V.A. Dolgashev, SLAC, 14 March 2011

Results of Low Power Measurements, 1C-SW-A2.75-T2.0-cryo-cu-SLAC-#2: Qo of accelerating structure is lower then Qo of dome cavity, but the difference is not as dramatic as expected from high power data

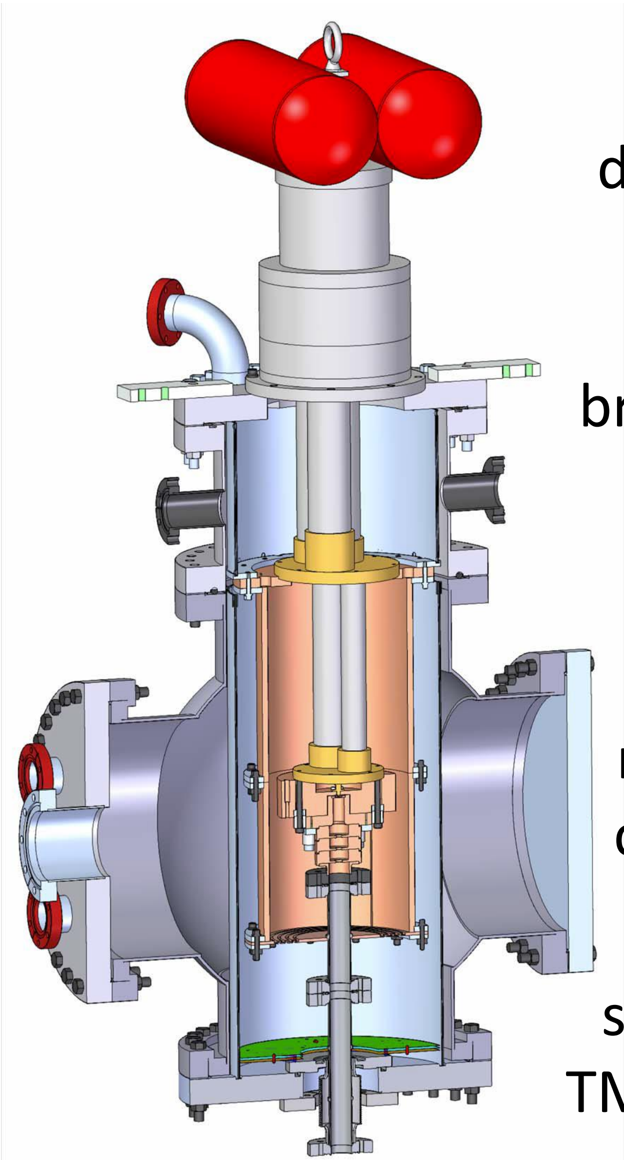




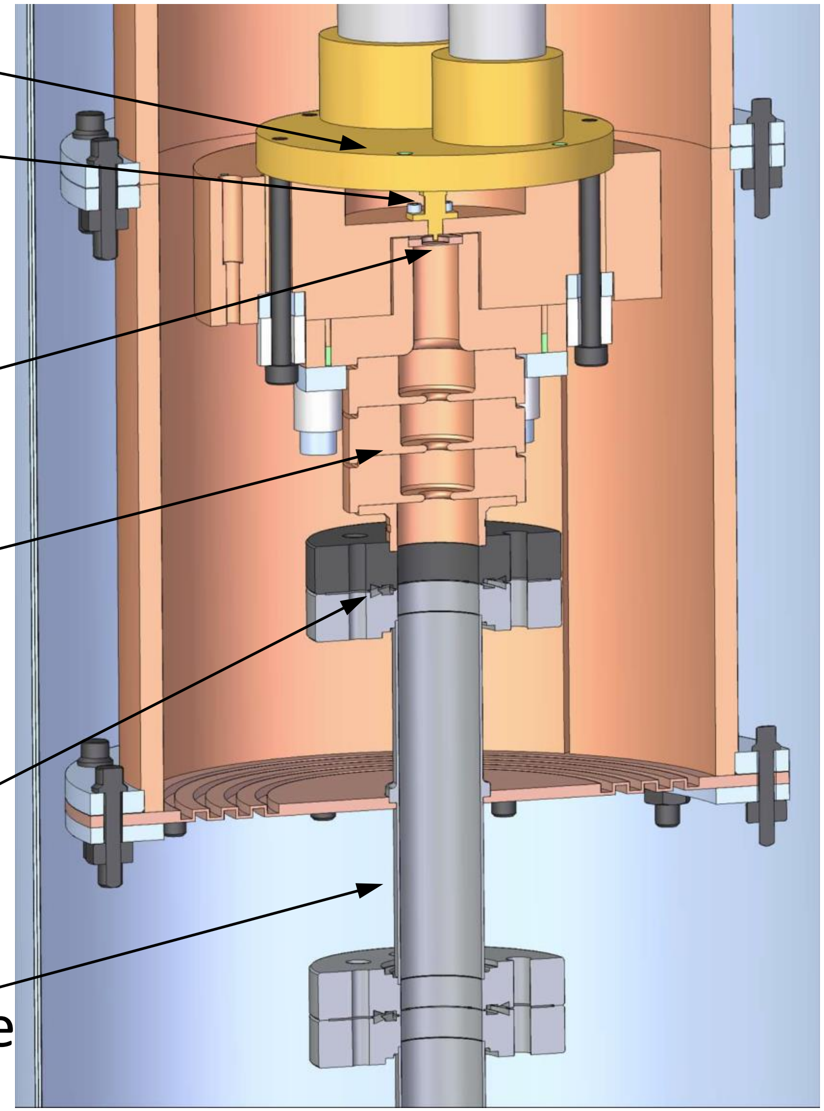
Design parameters versus measured

Alex Cahill (UCLS), Matt Franzi, Jim Lewandowski

Cryo structure setup with rf vacuum isolated from cryo vacuum

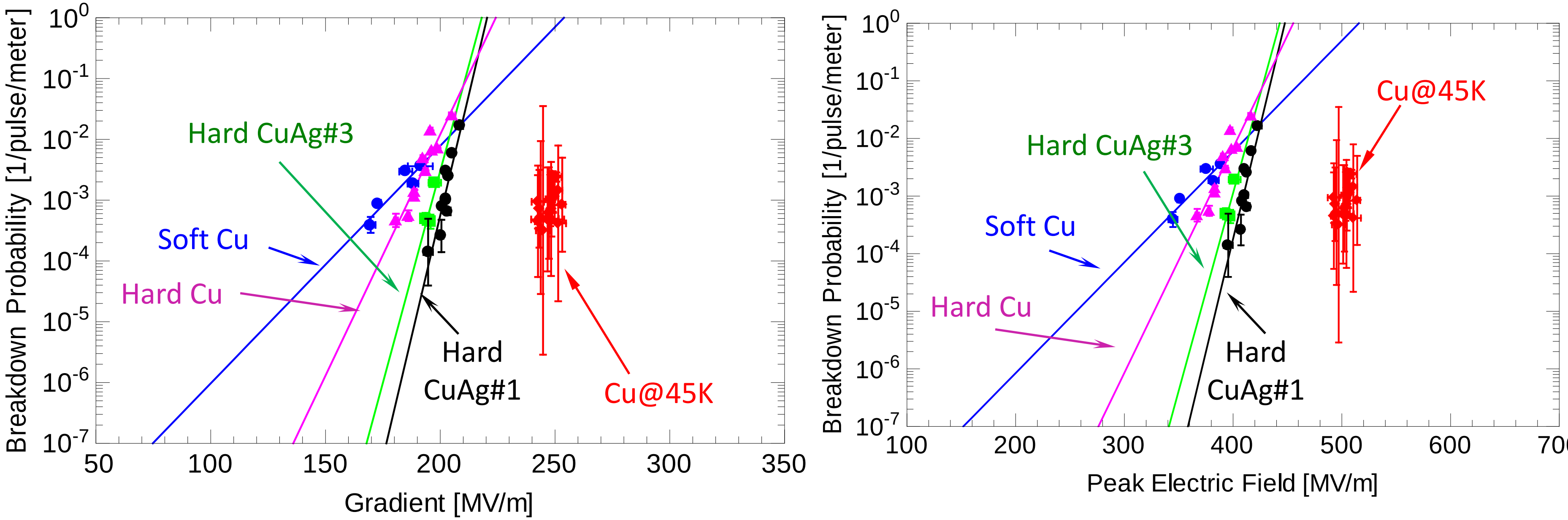


Cryostat assembly



V. A. Dolgashev et al., IPAC2012

RF breakdown performance of normal conducting cryo structure at 45 deg. K assuming Qo from fitting of the power signals, *first breakdowns*



For the breakdown probability 10^{-3} .. 10^{-4} 1/pulse/m cryo structure clearly outperforms record data from hard CuAg obtained in initial stages of conditioning. CuAg on final stages of conditioning very similar to hard Cu.

News construction techniques which preserve hardens of the meatal

- Electron Beam Welding
- Tungsten Inert Gas Welding
- Clamping

1. V. Dolgashev, L. Faillace, B. Spataro, and R. Bonifazi, Innovative compact braze-free accelerating cavity, Journal of Instrumentation 13 (09), P09017. 2018.
2. V.A. Dolgashev, L. Faillace, B. Spataro, S. Tantawi, and R. Bonifazi, *“High-Gradient RF Tests of Welded X-band Accelerating Cavities,”* PRAB, Published 10 August 2021.
3. R Agustsson, P Carriere, O Chimalpopoc, V A Dolgashev, M A Gusarova, S V Kutsaev and A Yu Smirnov, "*Experimental Studies of a High-Gradient X-band Welded Hard-Copper Split Accelerating Structure*", December 2021, Journal of Physics D: Applied Physics, JPhysD-129173.R2
4. Bruno Spataro, Mostafa Behtouei, Fabio Cardelli, Martina Carillo, Valery Dolgashev, Luigi Faillace, Mauro Migliorati, Luigi Palumbo, *“A hard copper open X-band RF accelerating structure made by two halves,”* MDPI Instruments, published 15 January 2022.
5. V.A. Dolgashev, L. Faillace, M. Migliorati, and B. Spataro, *Investigations on the multiple-sector hard-copper X-band accelerating structures*, Volume 1063, June 2024, 169272.

The first approach: welded cells

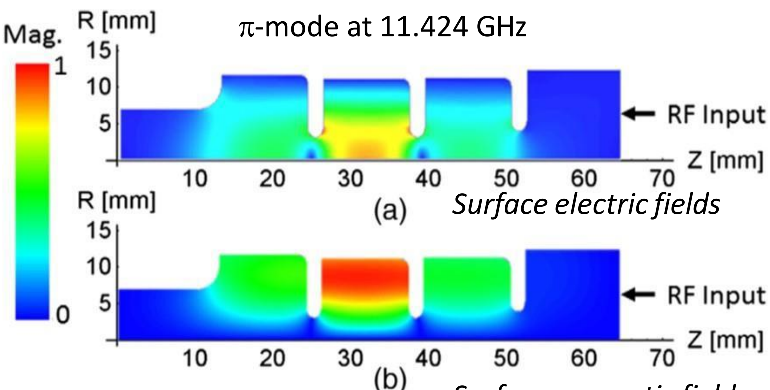
Approach

- Structure made traditionally, out of metal cups or cells
- Instead of high temperature brazing it is welded with electron beam

Braze-Free Cavity – Construction and Clamping System

Main RF parameters of the structure normalized to 100 MV/m accelerating gradient.

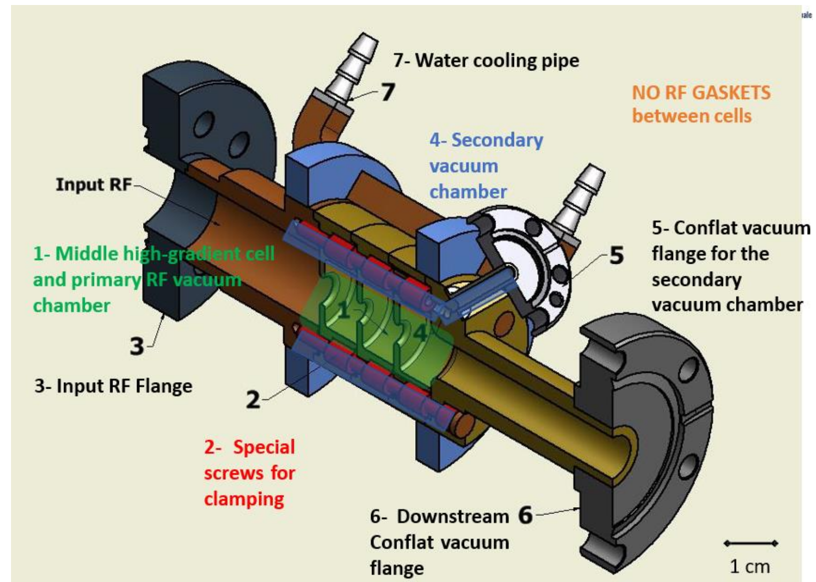
Parameter	Value
Resonant frequency, f [GHz]	11.424
Stored energy [J]	0.153
Quality factor Q	8590
Shunt impedance [MΩ/m]	102.894
H_{max} [MA/m]	0.29
E_{max} [MV/m]	203.1
Power loss per cell [MW]	1.275
a [mm]	2.75
a/λ	0.105
$H_{max}Z_0/E_{acc}$	1.093
t [mm]	2
Iris ellipticity	1.385
Phase advance per cell [deg.]	180



Surface electric fields

Surface magnetic fields

Solid model, one-half of the single-cell X-Band (11.424 GHz) cavity



1 cm

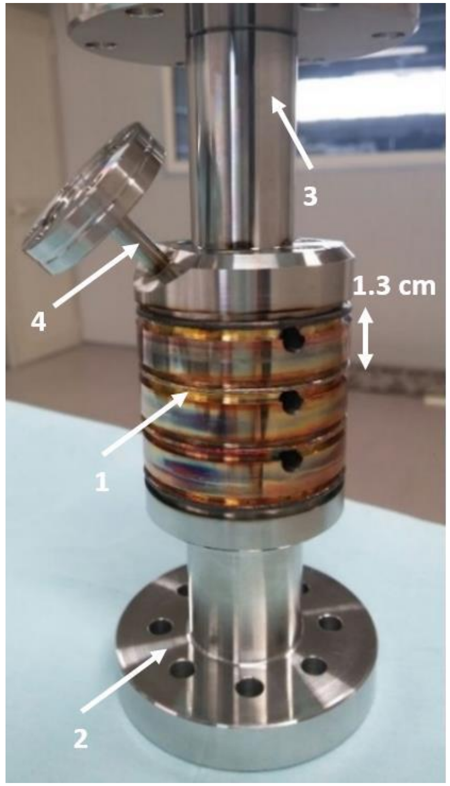
SLAC-INFN/LNF-Comeb

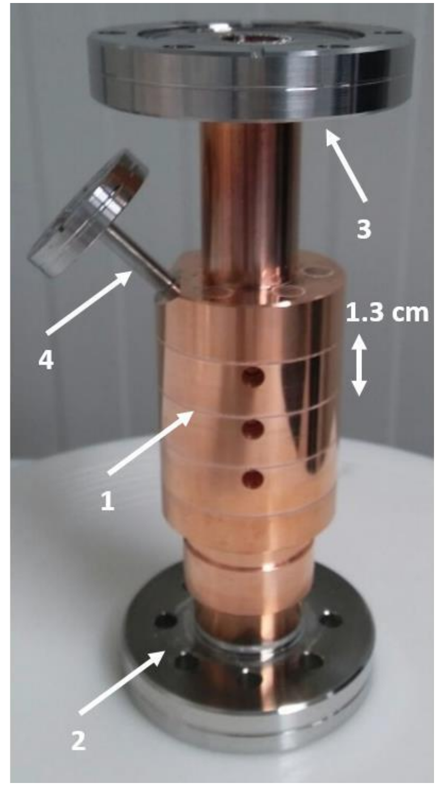
V. Dolgashev, L. Faillace, B. Spataro, and R. Bonifazi, Innovative compact braze-free accelerating cavity, Journal of Instrumentation 13 (09), P09017.

First successfully tested welded single-cell cavities

TIG cavity

Tungsten Inert Gas welded Single Cell Standing Wave structure, 1C-SW-A2.75-T2.0-TIG-Cu-Frascati-#1





EBW cavity

Electron Beam Welded Single Cell Standing Wave structure, 1C-SW-A2.75-T2.0-EBW-Cu-Frascati-#1

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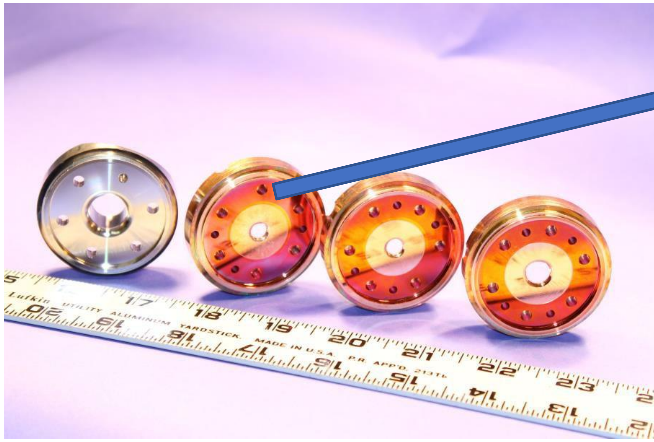
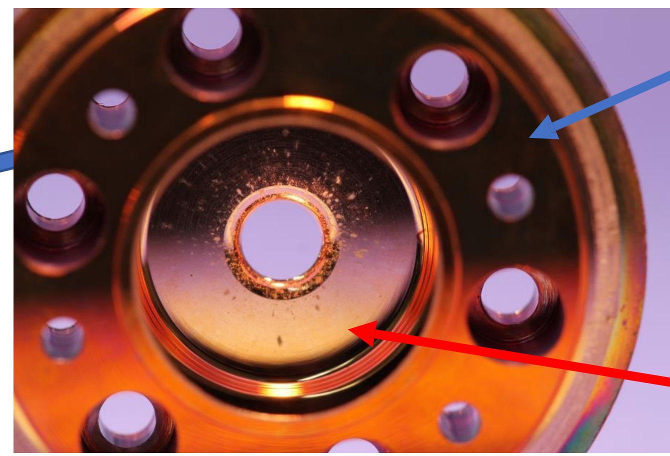
(1) Welding joints, (2) input RF flange, (3) downstream Conflat vacuum flange, (4) Conflat flange for pumping the secondary vacuum chamber.

TIG cavity after high-power tests



High RF breakdown activity in middle cell, as expected.



Oxidation inside the secondary vacuum chamber (as expected during the TIG process)

No oxidation observed inside the primary chamber, on the high-field surfaces!

The second approach: halves and multi-sector cavities

- Structure milled out of halves, quadrants, or multiple sectors
- The structures is welded with electron beam or TIG welded

Goal: Develop techniques to build practical multicell structures out of hard copper alloys

“Hard” Open structure out or two halves

INFN SLAC

Istituto Nazionale di Fisica Nucleare

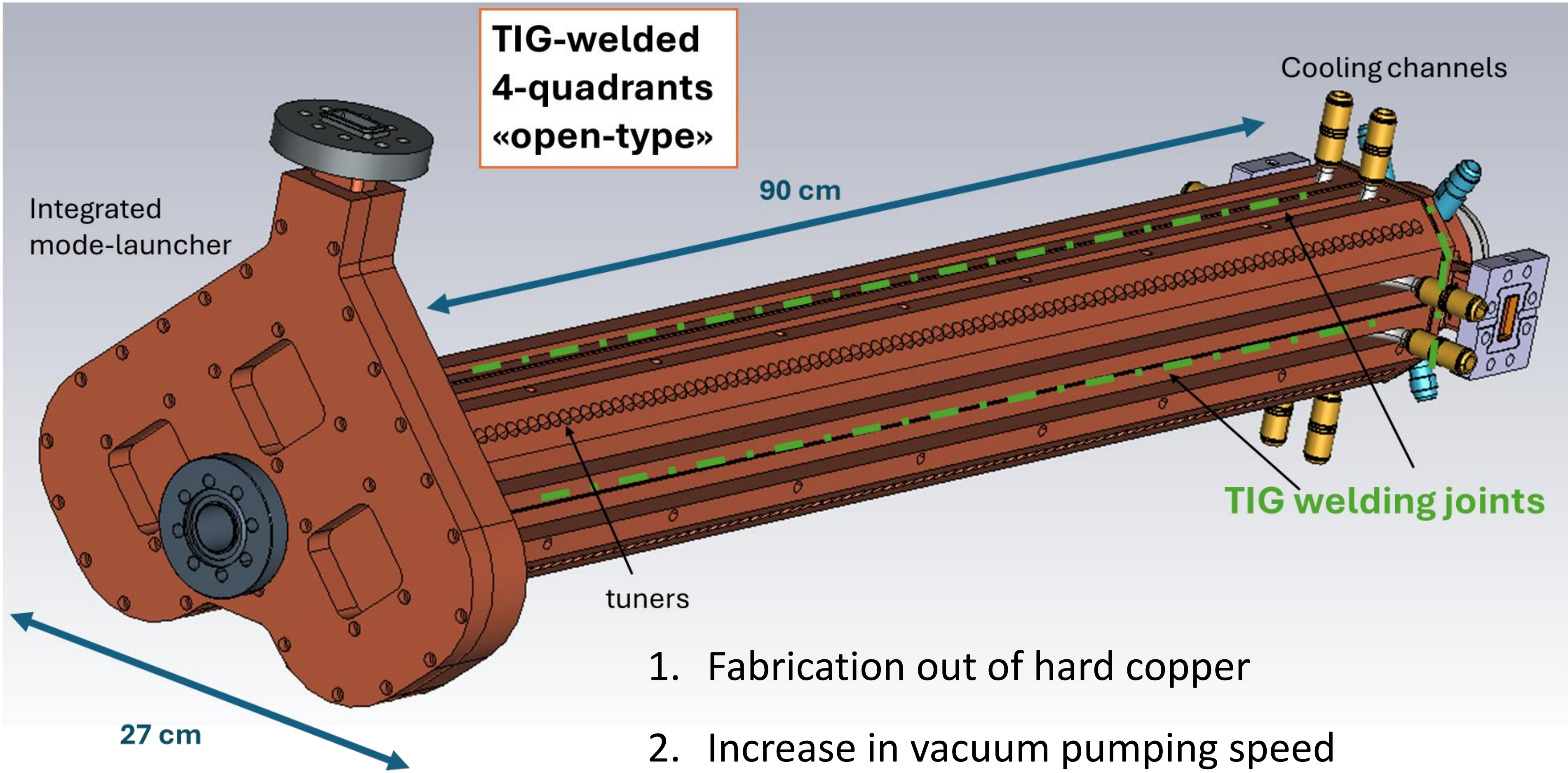
- The two cavity halves are aligned clamped together by means of a male-female matching surface.
- Clamping is obtained with stainless-steel screws.
- The structure is eventually TIG welded on the outer surface

Bruno Spataro, Mostafa Behtouei, Fabio Cardelli, Martina Carillo, Valery Dolgashev, Luigi Faillace, Mauro Migliorati, Luigi Palumbo, “*A hard copper open X-band RF accelerating structure made by two halves,*” MDPI Instruments, published 15 January 2022.

Full TW multi-cell X-band structure

Luigi Faillace (INFN-LNF),

Accelerating **ST**ructures made of multipl**E** secto**R**s **I**n ***X***-Band, **ASTERIX**



1. Fabrication out of hard copper
2. Increase in vacuum pumping speed
3. Overall reduction of the fabrication costs
4. Easy insertion of HOM absorbing materials

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Conclusion

- In systematic experiments to study the fundamental physics of vacuum RF breakdown, we tested more than fifty single-cell standing wave structures at high power.
- One of the main results of this study is the large amount of reproducible quantitative data, which allows for rapid evaluation of any future experimental results.
- This program is an excellent example of close international cooperation that has spanned over two decades and is still ongoing.

Valery Dolgashev, *"Design Criteria for High Gradient RF Linacs,"* Applied Sciences, Published 29 September 2023