Progress on High Gradient Research at SLAC

Presented on behalf of collaboration by

Valery Dolgashev,

SLAC National Accelerator Laboratory

US High Gradient Research Collaboration Workshop 2011
February 9-10, 2011
SLAC National Accelerator Laboratory

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

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

In close collaboration with:

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

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

TW structures done in collaboration with W. Wuensch and CERN CLIC team

T18+resonat ring done in collaboration with J. Haimson and Haimson Research Corporation

Outline

- Motivation
- Planned experiments
- Recent results
  - SW structures
    - Geometry
    - Hard materials
  - TW structures
    - T18 in resonant ring
    - C10

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

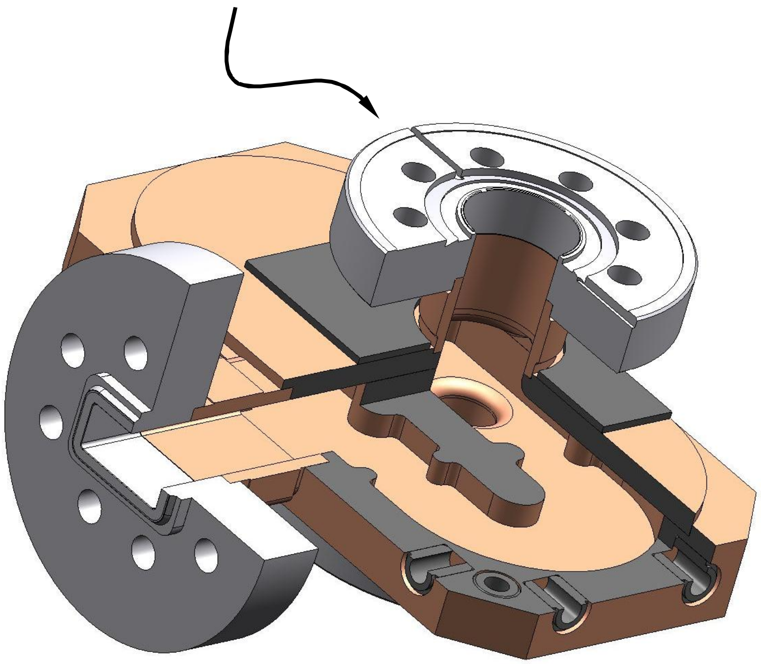
Solution

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

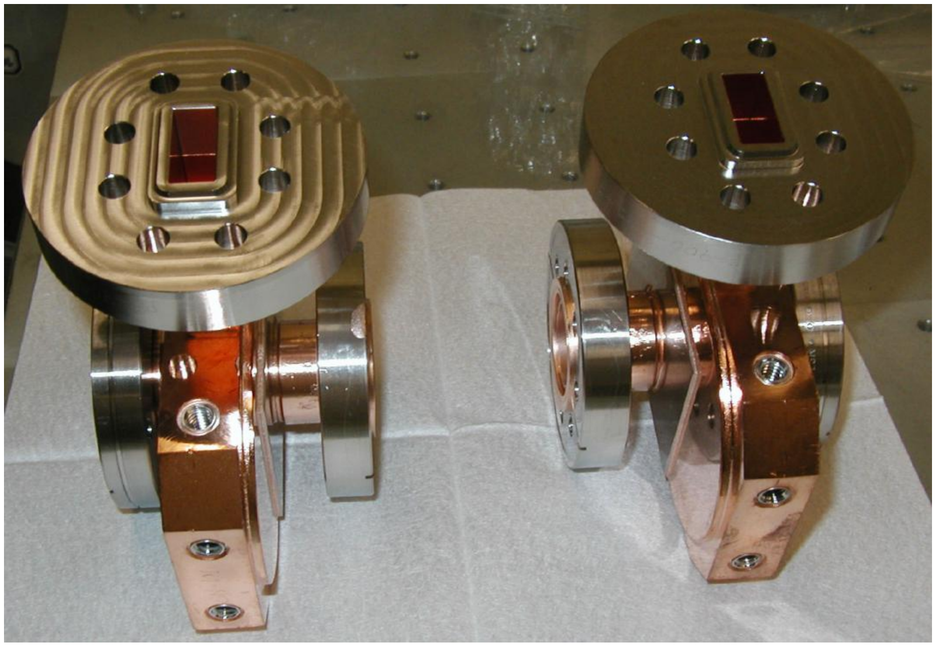
We want to predict breakdown behavior for practical structures

Reusable coupler: TM_{01} Mode Launcher

Pearson's RF flange



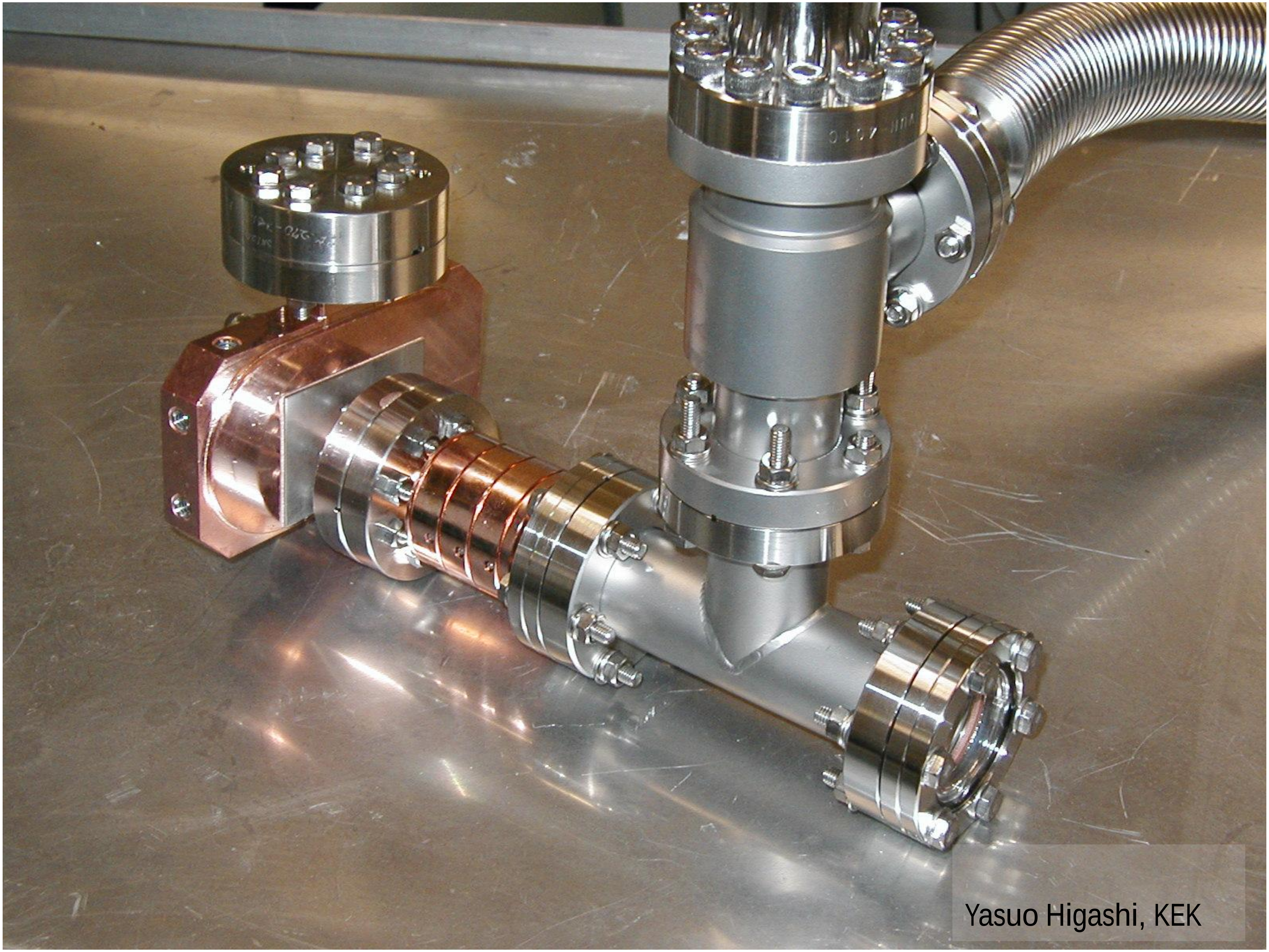
Cutaway view of the mode launcher



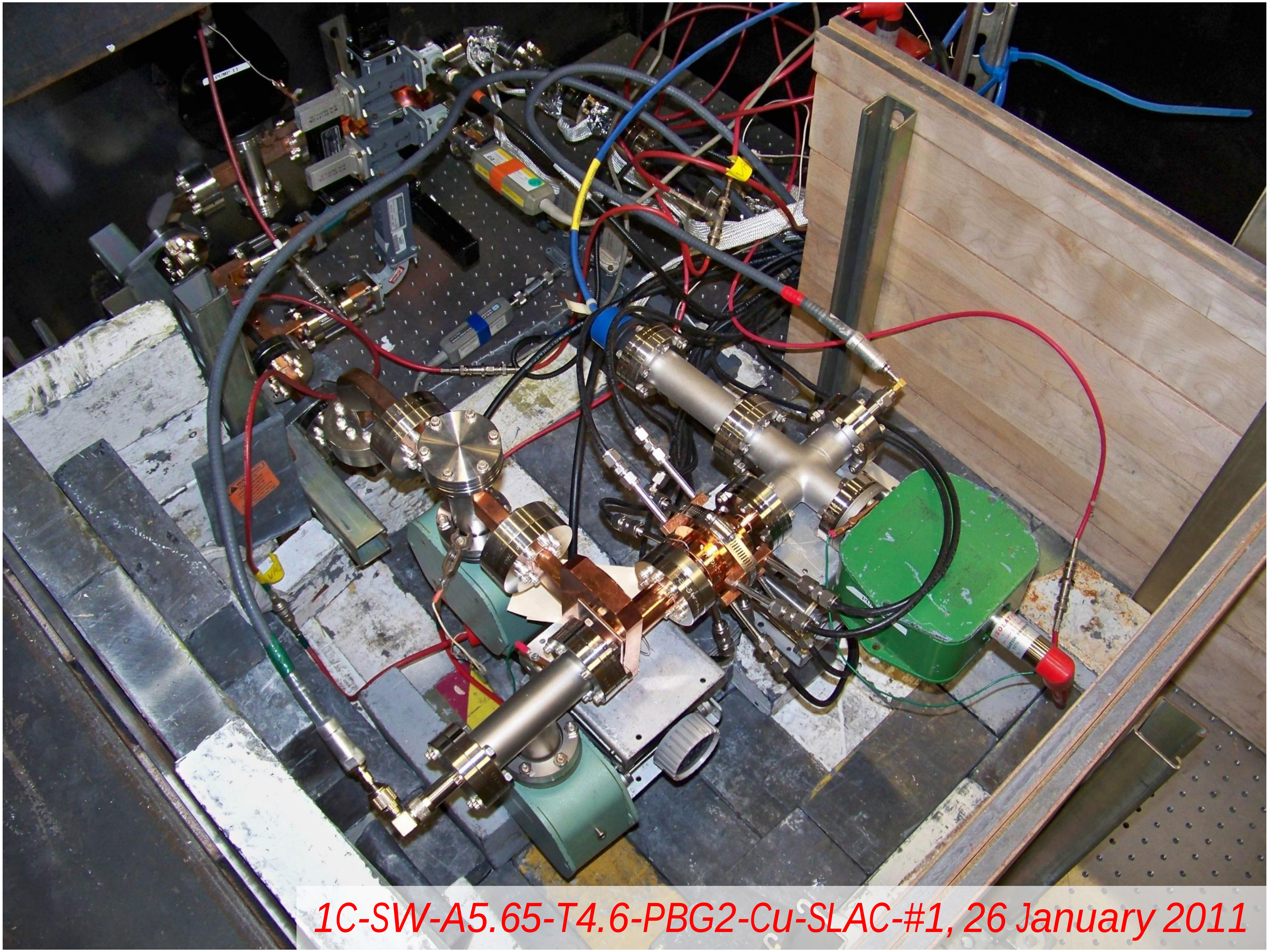
Two mode launchers

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

S. Tantawi, C. Nantista



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 Tested

- 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-SLAC-#1, 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-SLAC, 2 tested
- Highest shunt impedance hard copper structure *1C-SW-A2.75-T2.0-Clamped-Cu,* 1 tested

Now 34th test is ongoing,

Low shunt impedance Photonic-Band Gap with elliptical rods *1C-SW-A5.65-T4.6-PBG2-Cu-SLAC-#1*

Next experiments, as for February 2010

New 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*

High shunt impedance, reduced magnetic field, copper *1C-SW-A3.75-T2.2-Cu*

Materials:

High shunt impedance, made of hard CuAg, *1C-SW-A3.75-T2.6-Clamped-CuAg,*

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*

High shunt impedance, Cu-Mo, *1C-SW-A3.75-T2.6-Cu-Mo*

High shunt impedance, Cu-Stainless Steel, *1C-SW-A3.75-T2.6-Cu-SUS*

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

High shunt impedance, Stainless Steel coated with copper, *1C-SW-A3.75-T2.6-SUS-Coated-Cu*

Reproducibility tests:

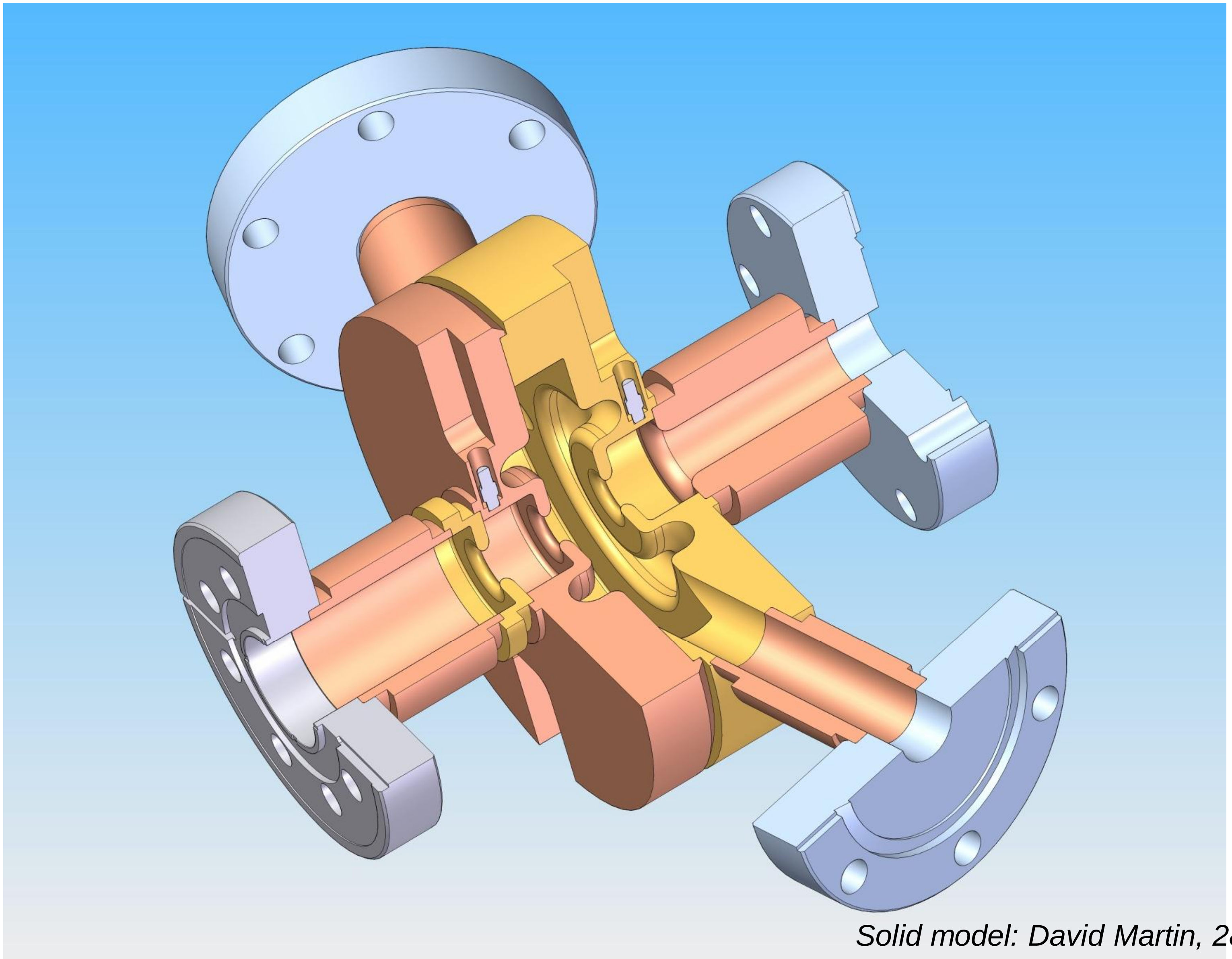
High shunt impedance, round iris, *1C-SW-A3.75-T1.66-Cu*

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

New diagnostics

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

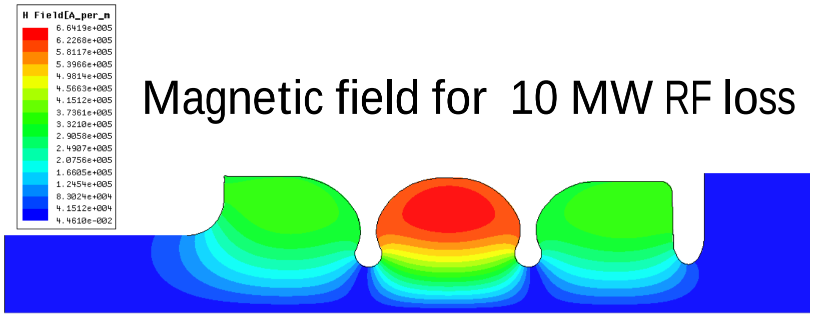
Full cell choke and two view ports *1C-SW-A3.75-T2.6-Ch-View-Port-Cu-SLAC-#1,2*



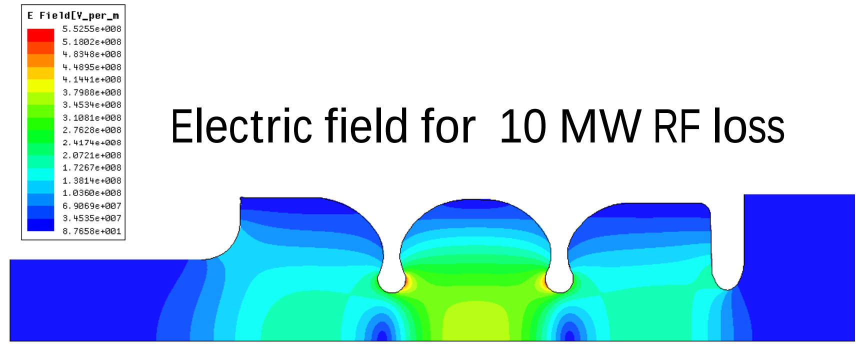
Solid model: David Martin, 28 April 2010

Geometry Test
Highest shunt Impedance, reduced magnetic field,
1C-SW-A3.75-T2.2-Cu

Magnetic field for 10 MW RF loss



Electric field for 10 MW RF loss

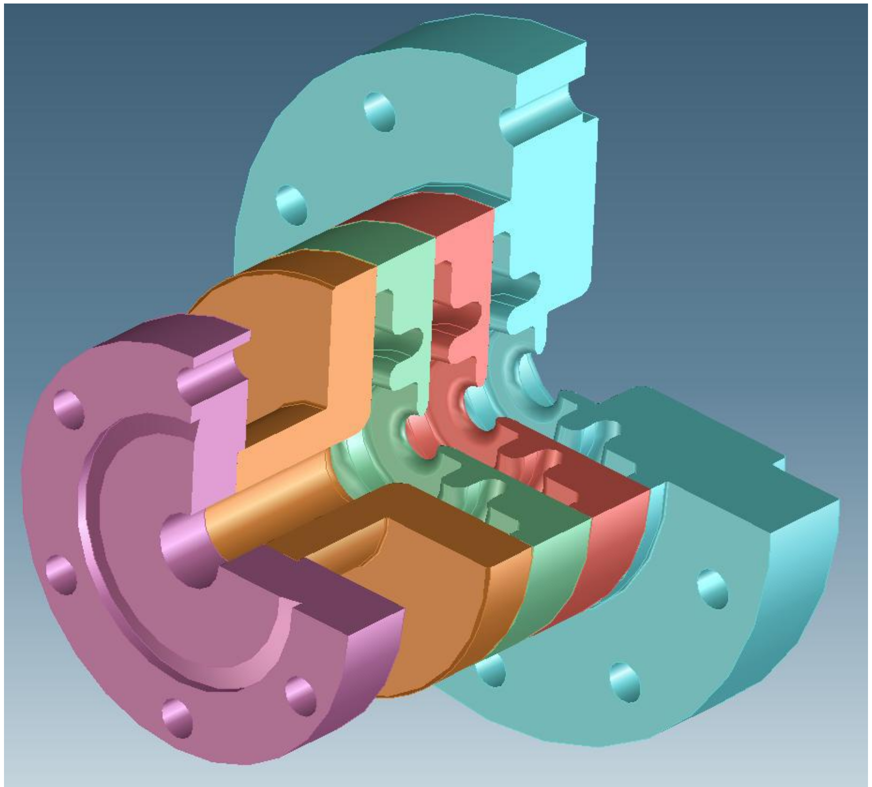


SW Cells a/λ =0.143, π Phase Shift
Field Normalized for 100MeV/m Acceleration

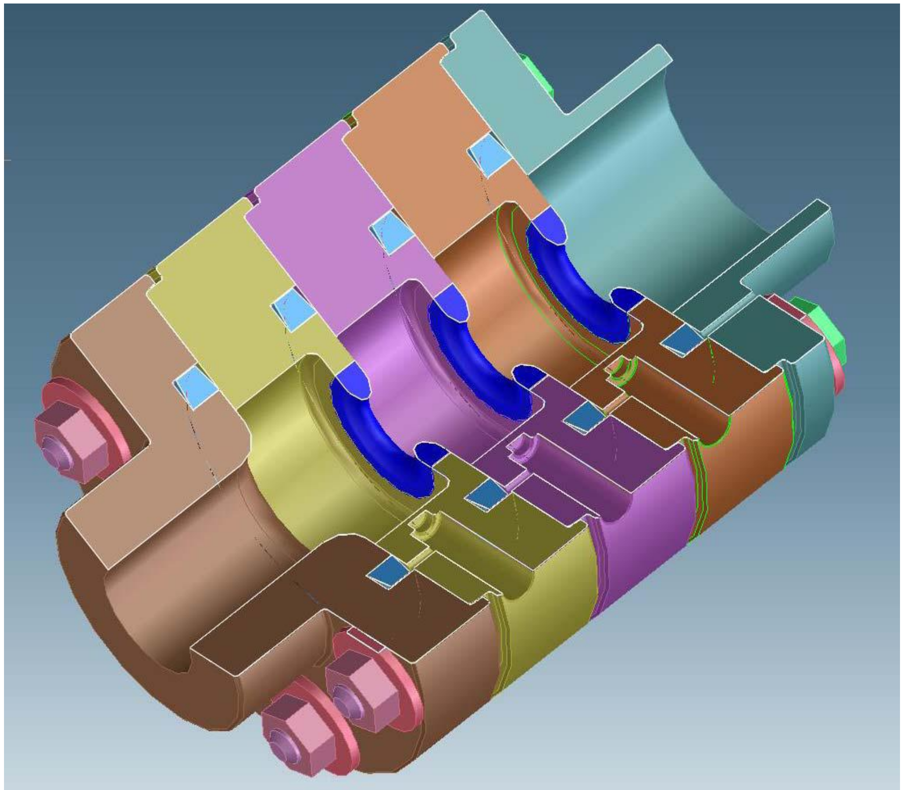
Parameter	T=1.66 Round Iris	T=2.6mm Elliptical Iris	T=2.2mm Shaped Iris
Stored Energy [J]	0.189	0.189	0.186
Q-value	8820	8560	10090
Shunt Impedance [MOhm/m]	85.2	82.6	99.2
Max. Mag. Field [KA/m]	314	325	294
Max. Electric Field [MV/m]	266	203	268
Losses in one cell [MW]	1.54	1.59	1.32
Hmax*Z0/Eacc	1.18	1.22	1.11
Max. Im{E x H*} W/μm^2	42.8	44.4	56.5
Max. Im{E x H*}/H^2	417	407	650

J. Neilson

Geometry and material test
Structure joining techniques that avoid high temperature treatment



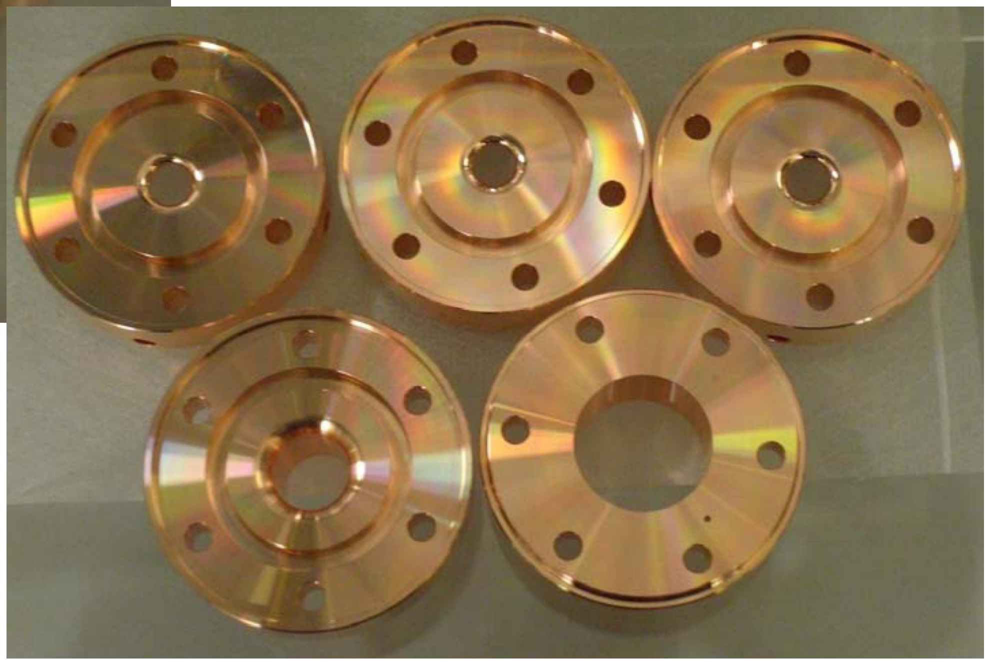
1C-SW-A3.75-T2.2-Cu,Mo-KEK, similar configuration is under development in INFN-Frascati



1C-SW-A3.75-T2.6-Clamped-CuAg-KEK

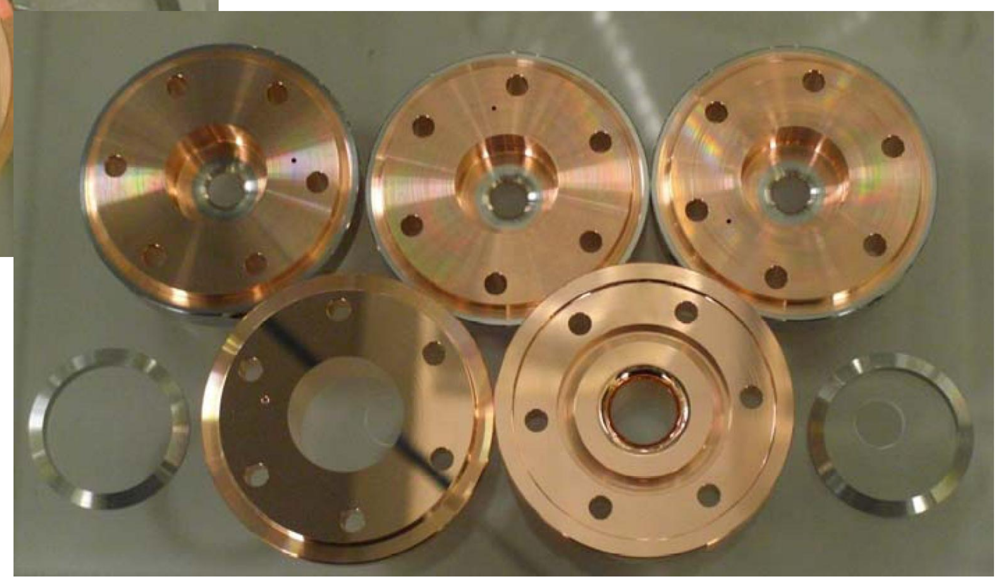
Y. Higashi, KEK

Material test
1C-SW-A3.75-T2.6-Clamped-CuAg-KEK



Y. Higashi, KEK

Material test
1C-SW-A3.75-T2.60-Cu-SUS-Clamped-KEK



Ag coated SUS gaskets

Y. Higashi, KEK

Material test
1C-SW-A3.75-T2.60-Cu-Mo-Clamped-KEK

Y. Higashi, KEK

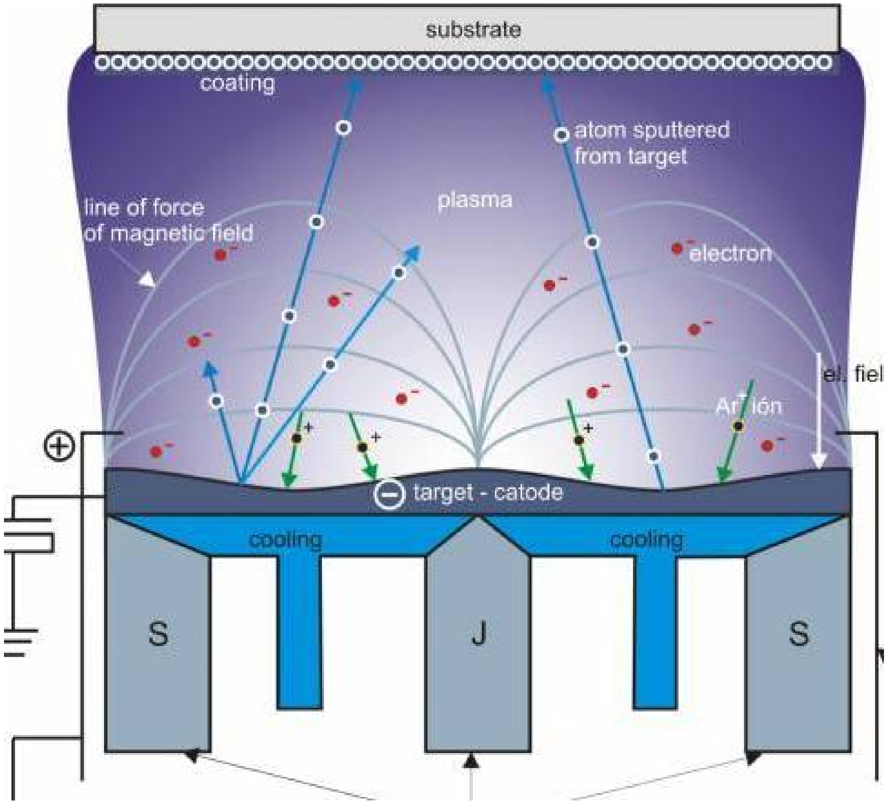
Material test, electropolishing

Before electropolishing

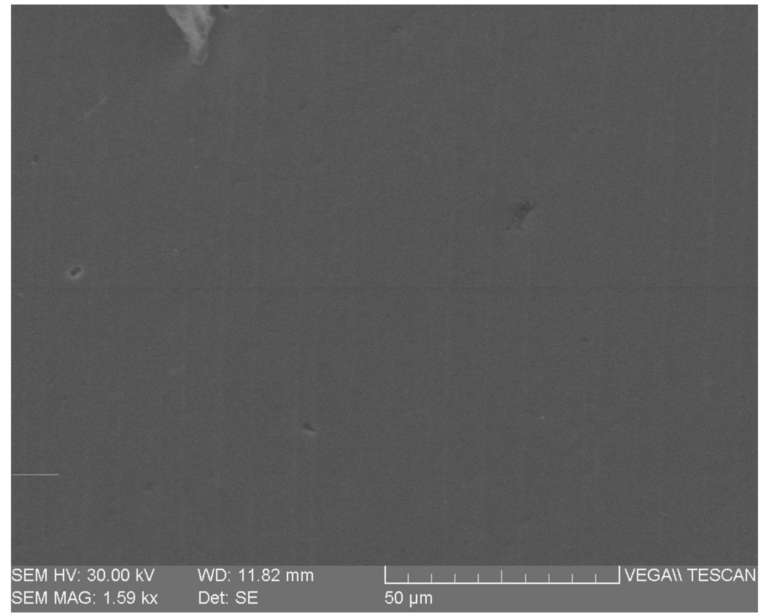
After

Y. Higashi, KEK

Material testing, Mo spattering on Cu



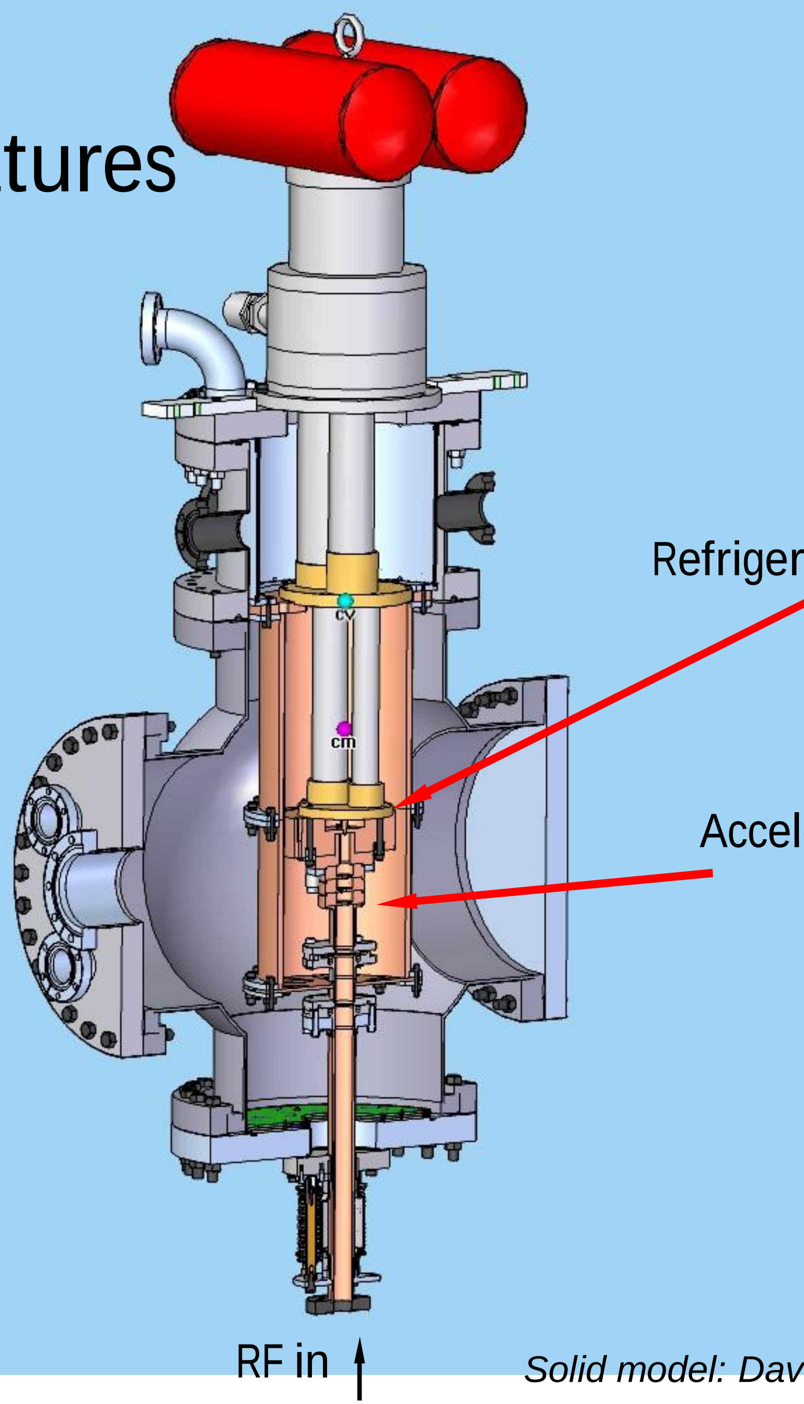
Schematic diagram of a DC magnetron plasma source



SEM Picture of copper dish machined at very low roughness sputtered with 300nm of Molybdenum after a thermal treatment of 2 hours at 300 °C.

B. Spataro, INFN-Frascati

Experiments at cryo temperatures



Solid model: David Martin, 10 January 2011

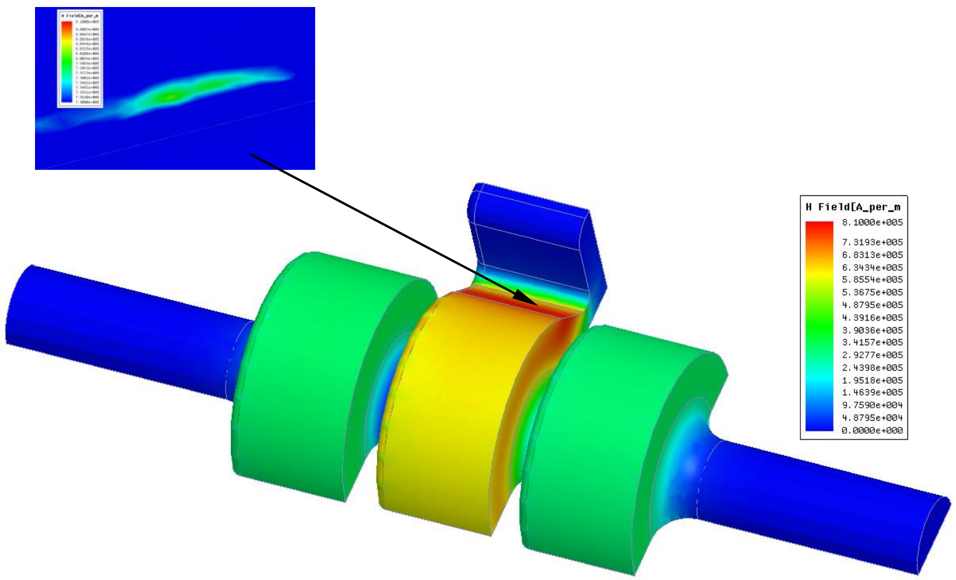
Single Cell Standing Wave Structures Results

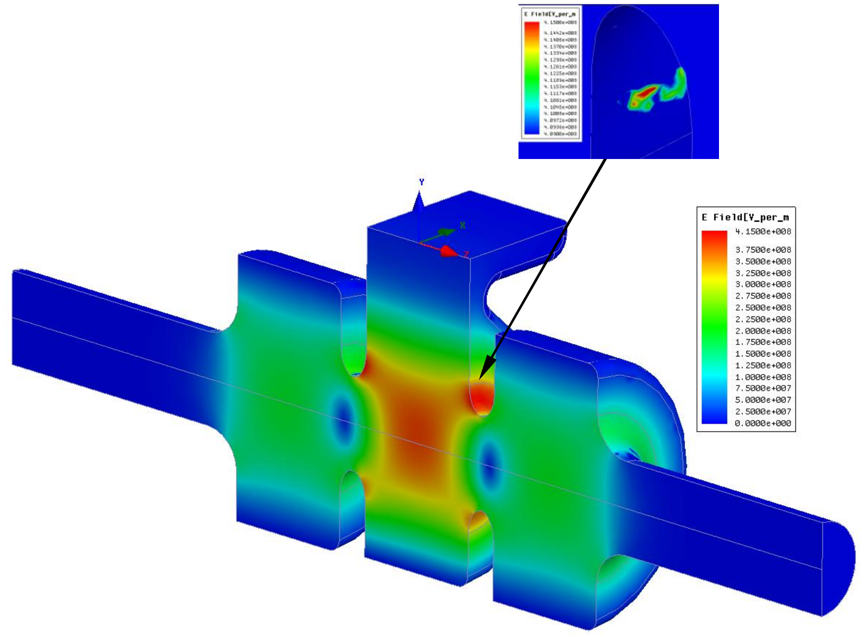
- Geometry test
  - 1C-SW-A3.75-T2.6-1WR90-Cu-SLAC-#1
  - 3C-SW-A3.75-T4.6-2WR90-Cu-SLAC-#2
- Material test
  - 1C-SW-A3.75-T2.6-Clamped-CuCr-SLAC-#1
  - 1C-SW-A2.75-T2.0-Clamped-Cu-SLAC-#1

Geometry test
High shunt-impedance single-feed side-coupled
1C-SW-A3.75-T4.6-1WR90-Cu-SLAC-#1

This is test toward practical parallel-coupled standing wave structures,
see Jeff Neilson talk

Side-coupled ingle feed 1C-SW-A3.75-T2.6-1WR90-Cu-SLAC-#1
Calculating Zenghai's geometry with HFSS, driven, 10 MW input



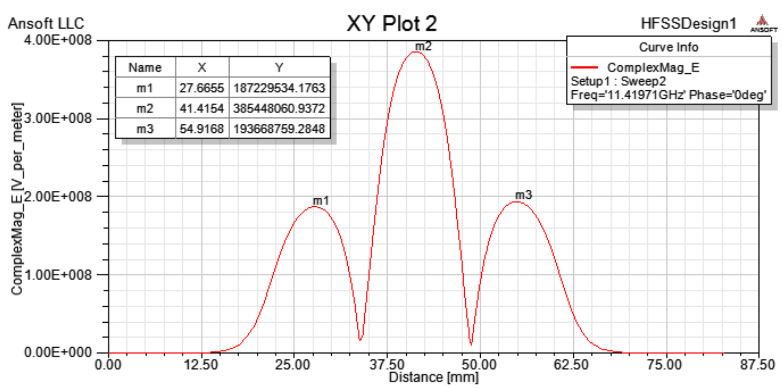


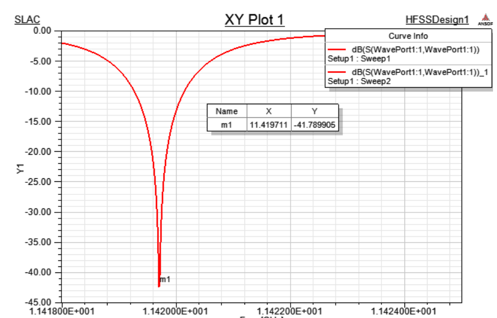
Maximum magnetic field 800 kA/m, H_{1WR90} / H_{SLANS}= $\frac{800}{668} = 1.198$

(SLANS 1C-SW-T3.75-A2.6-Cu 668.0 kA/m)

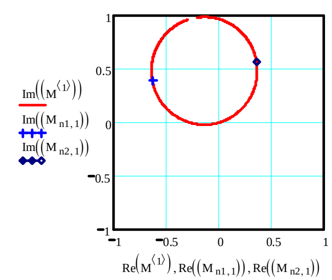
Maximum electric field 412 MV/m, E_{1WR90} / E_{SLANS}= $\frac{412}{398.9} = 1.033$

(SLANS 398.9 MV/m)





Resonant frequency 11.4197 GHz



Maximum on axis peak electric field 385 MV/m, field balance $\frac{3854}{1872 + 1936} = 1.012$

(SLANS 384 MV/m)

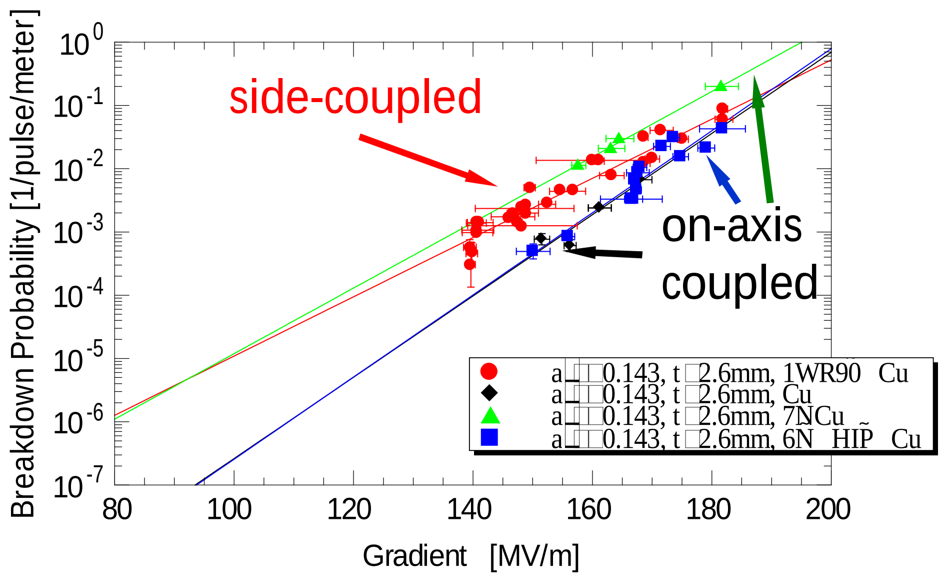
$$\frac{f_{floor\left(\frac{n1+n2}{2}\right)}}{f_{n1} - f_{n2}} = 4.309 \times 10^3$$

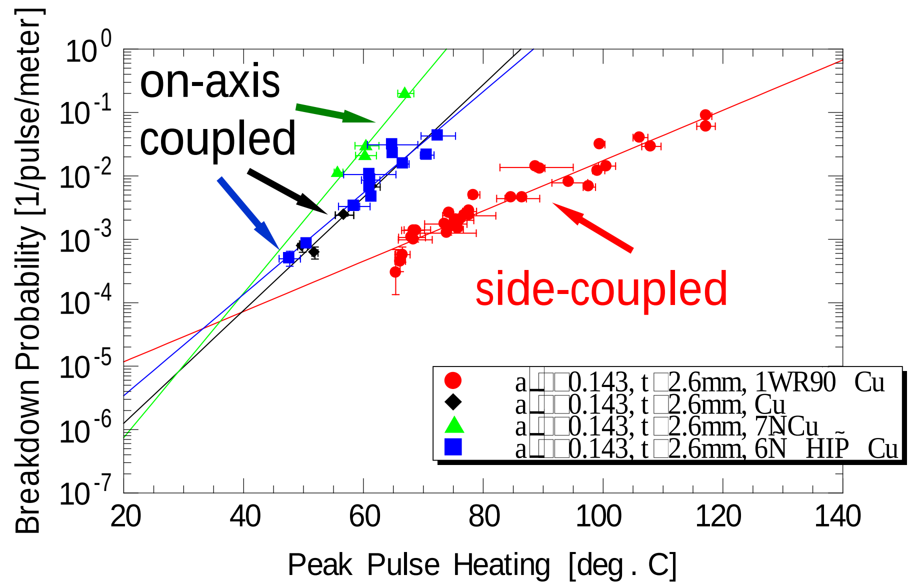
$$Qo := 2\cdot\left(4.309 \times 10^3\right)$$

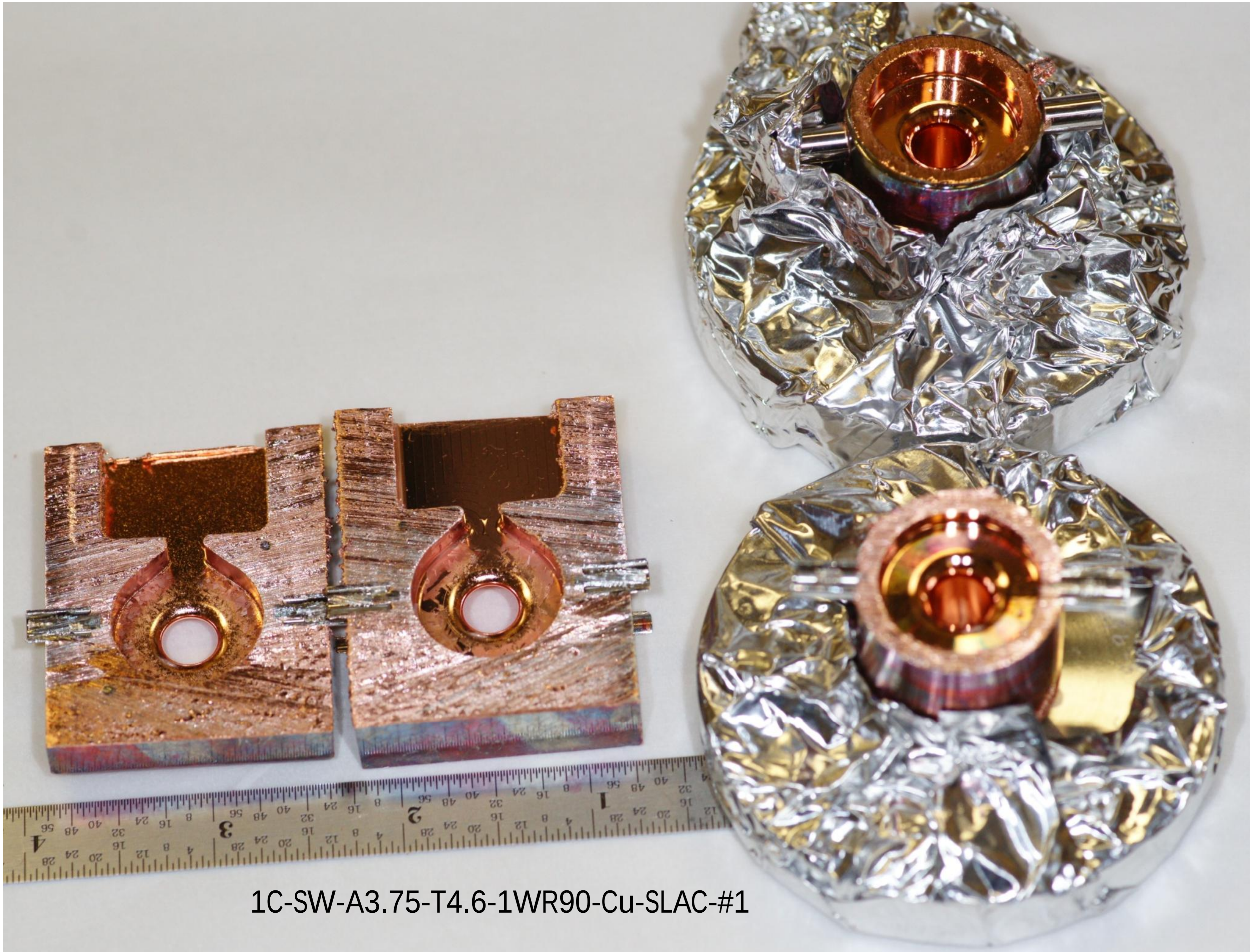
$$Qo = 8.618 \times 10^3$$

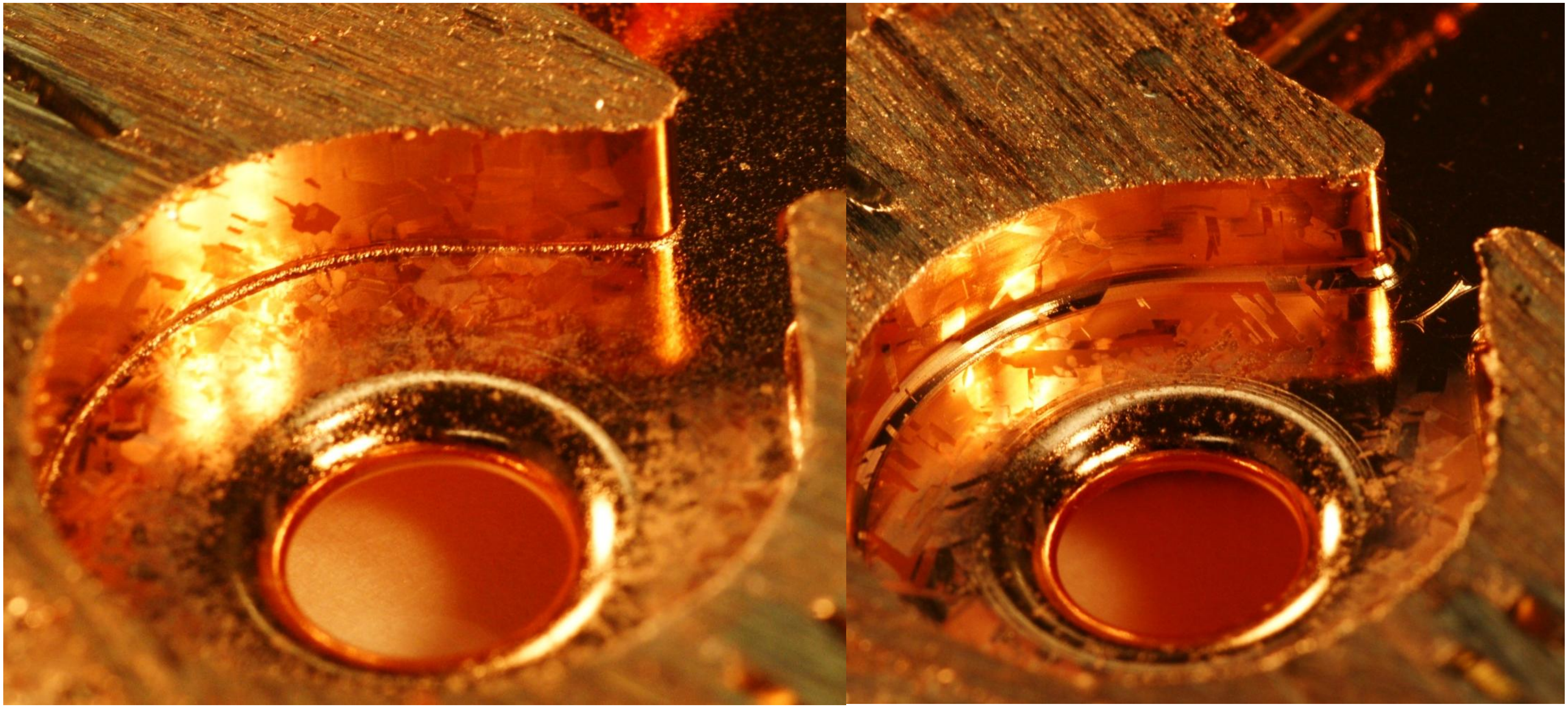
V.A. Dolgashev, 7 June 2010

Comparison of one side-coupled copper structure with three on-axis coupled copper structures of same iris geometry (1C-SW-A3.75-T2.6-Cu), shaped pulse with 150 ns flat part

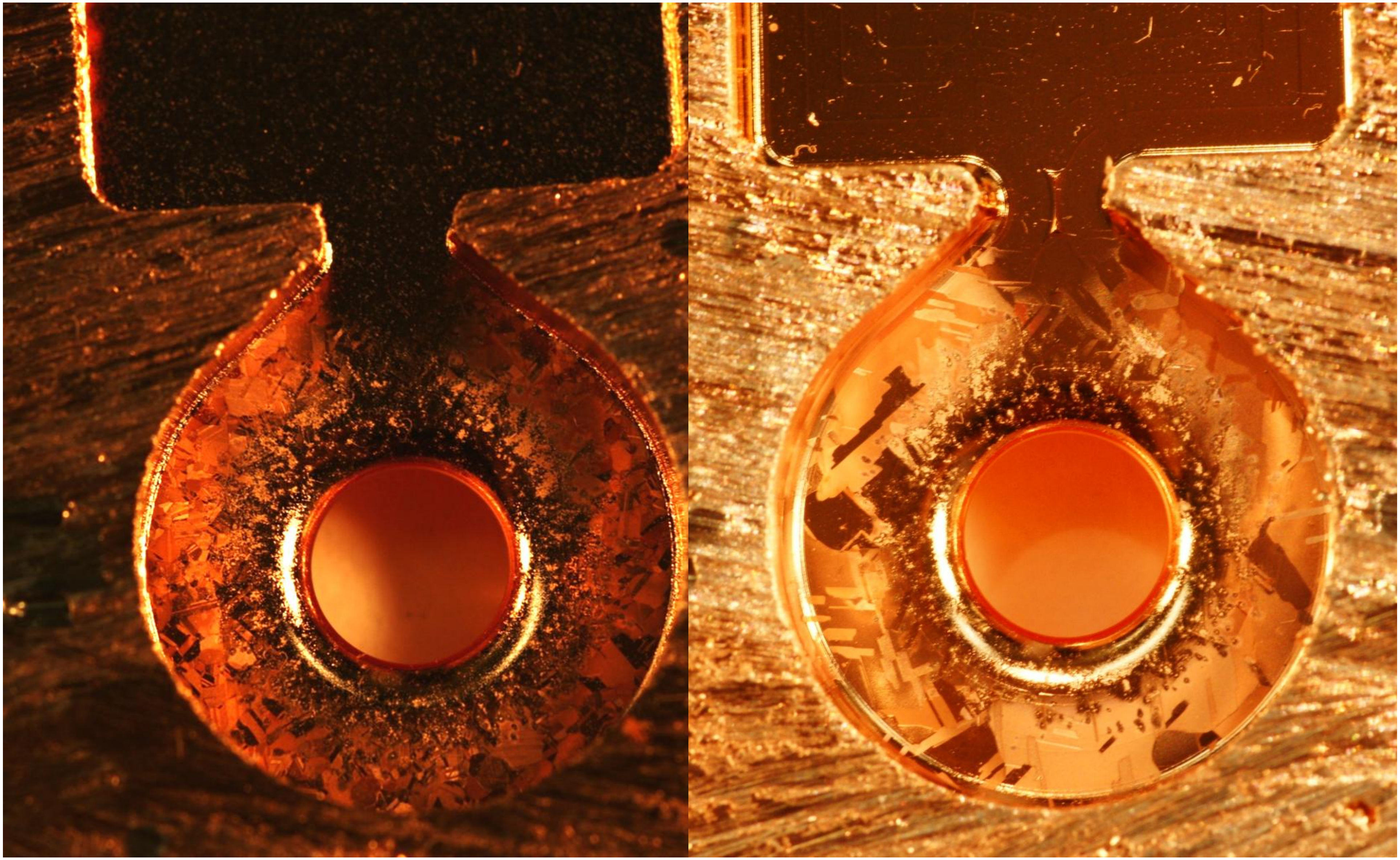




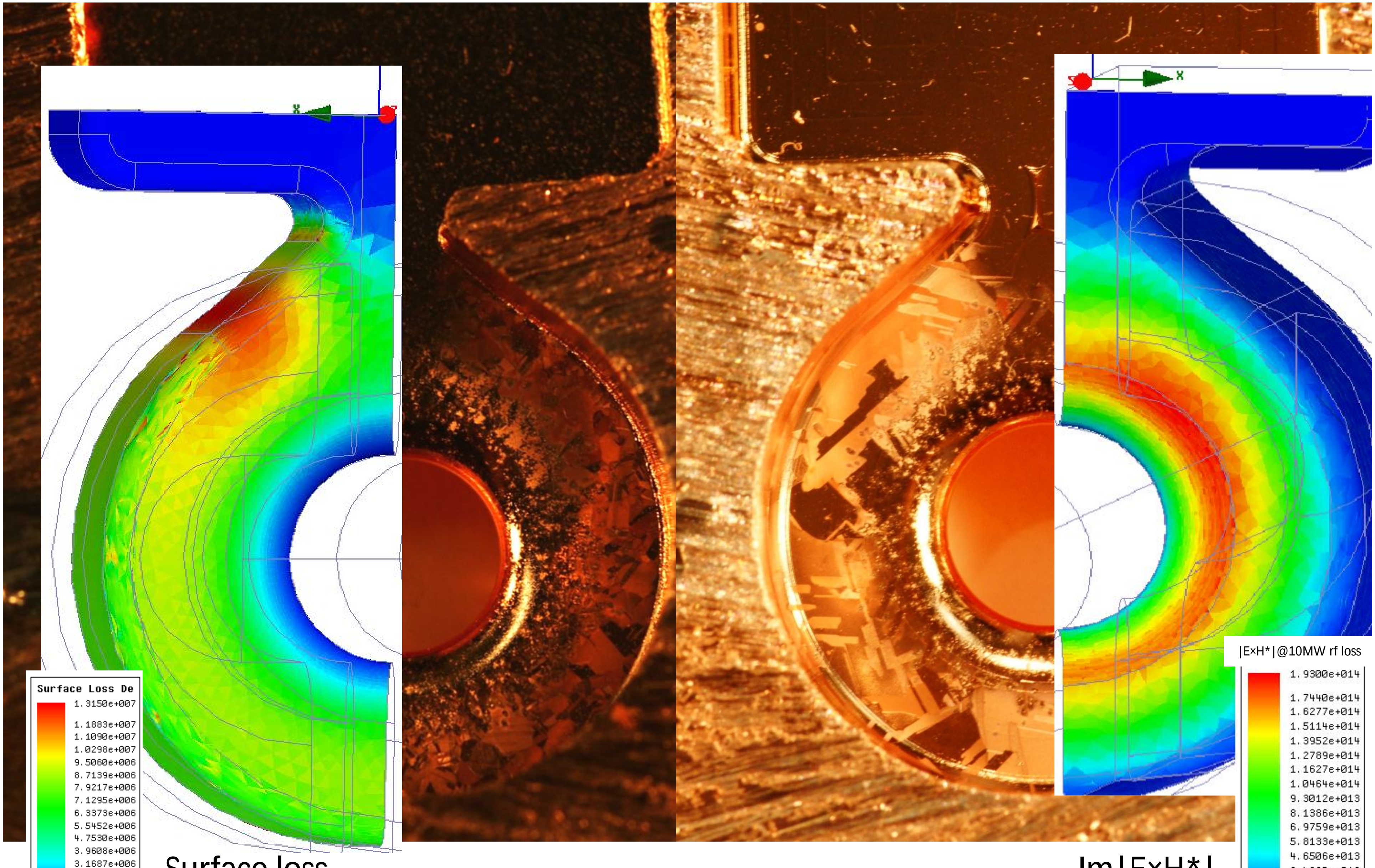

1C-SW-A3.75-T4.6-1WR90-Cu-SLAC-#1



Coupling cell of 1C-SW-A3.75-T4.6-1WR90-Cu-SLAC-#1

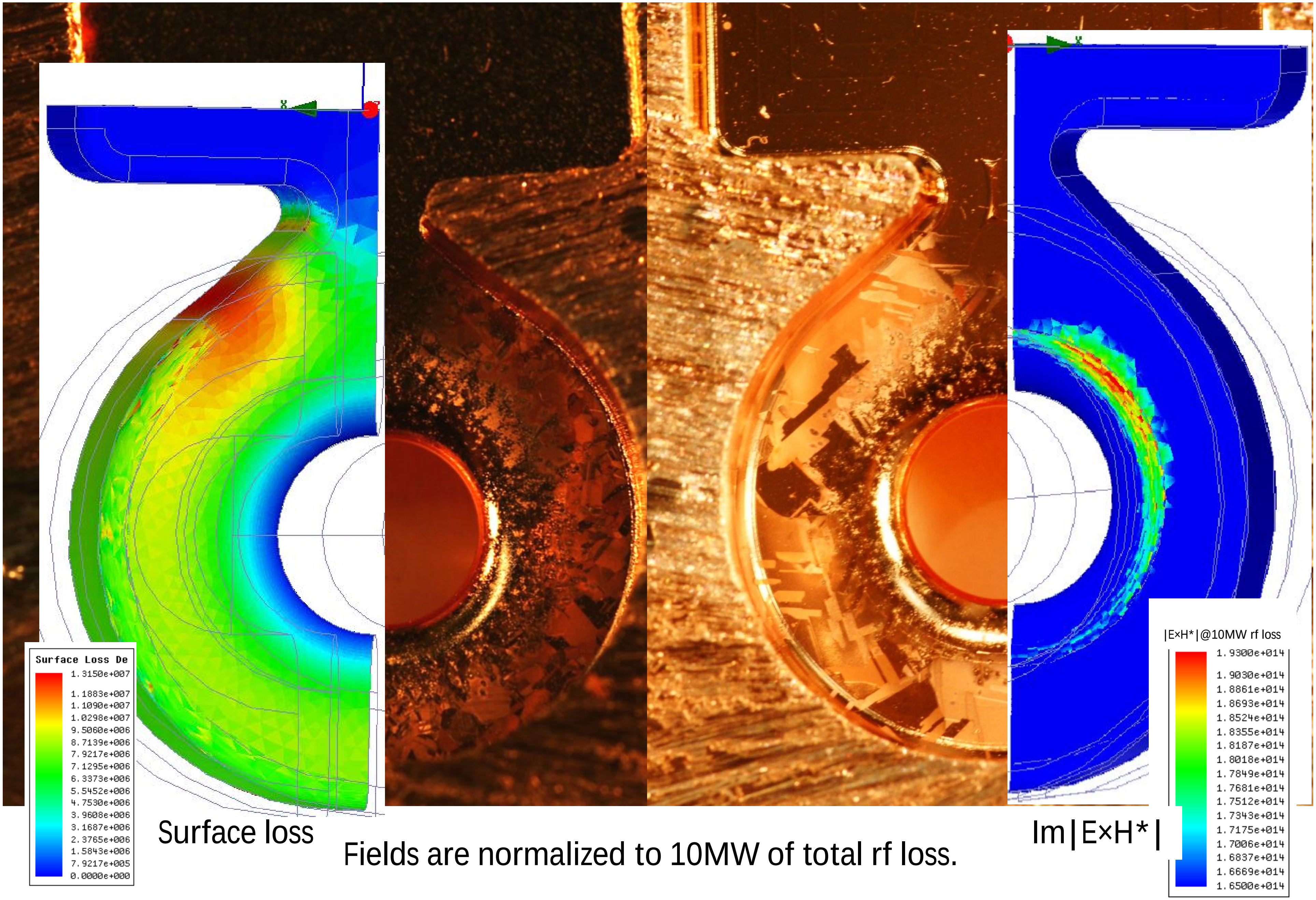


Coupling cell of 1C-SW-A3.75-T4.6-1WR90-Cu-SLAC-#1



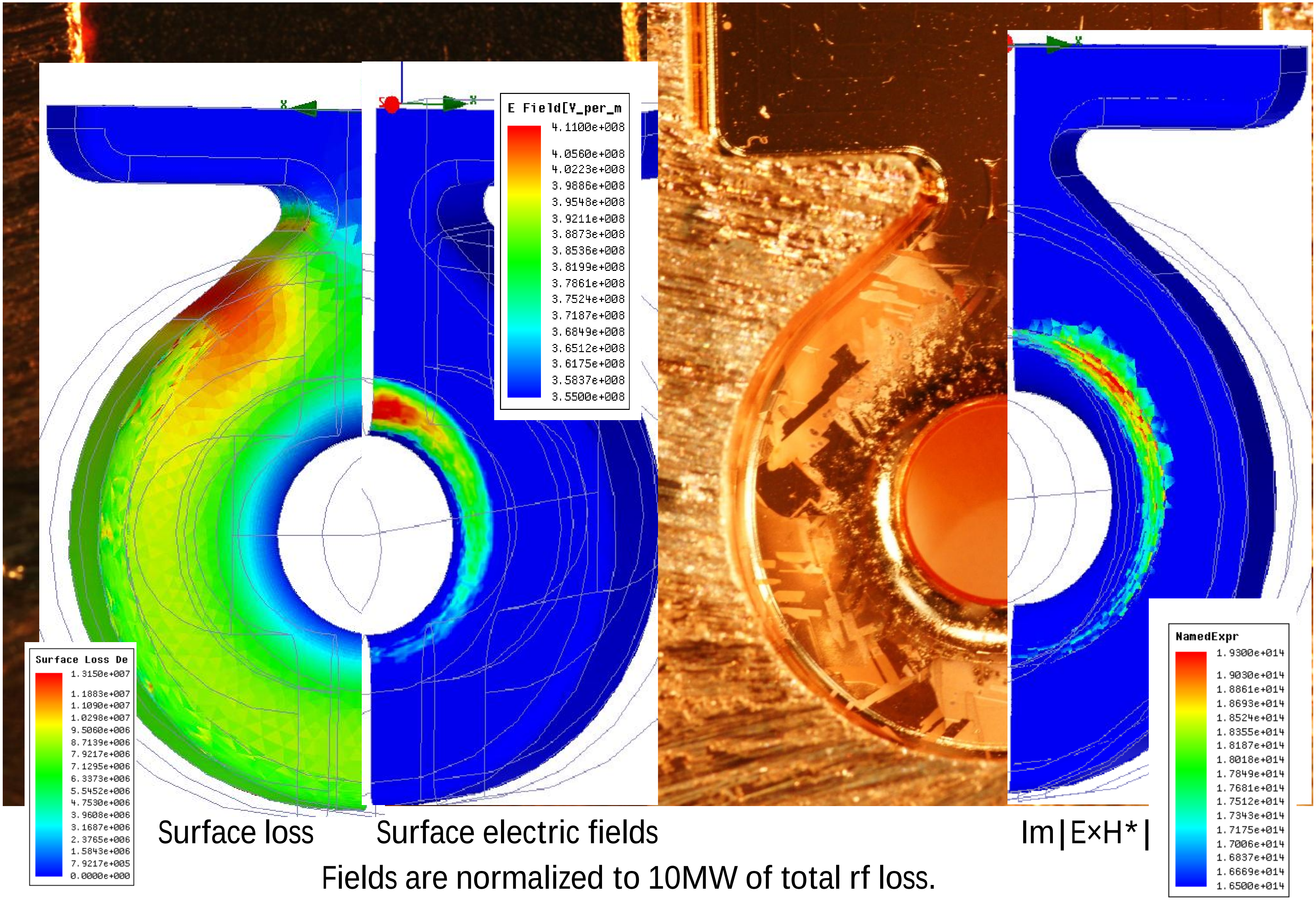
Fields are normalized to 10MW of total rf loss.

Coupling cell of 1C-SW-A3.75-T4.6-1WR90-Cu-SLAC-#1



Fields are normalized to 10MW of total rf loss.

Coupling cell of 1C-SW-A3.75-T4.6-1WR90-Cu-SLAC-#1



Fields are normalized to 10MW of total rf loss.

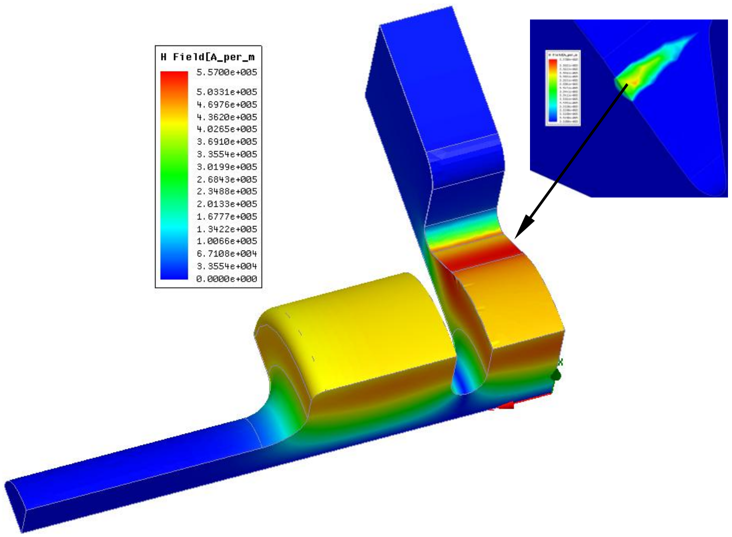
Coupling cell of 1C-SW-A3.75-T4.6-1WR90-Cu-SLAC-#1

Geometry Test
High shunt Impedance dual symmetric feed
3C-SW-A3.75-T4.6-2WR90-Cu-SLAC-#2

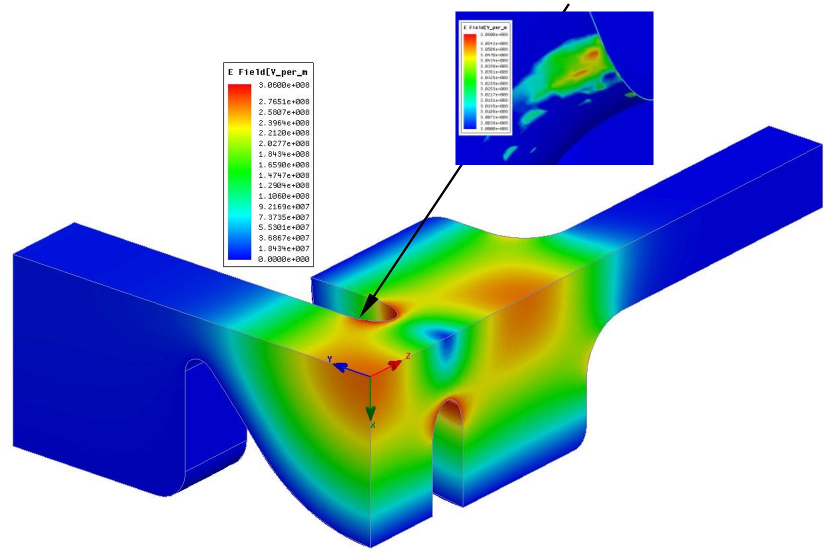
This is prototype structure for parallel-coupled standing wave structures

1C-SW-A3.75-T2.6-2WR90-Cu-SLAC-#2

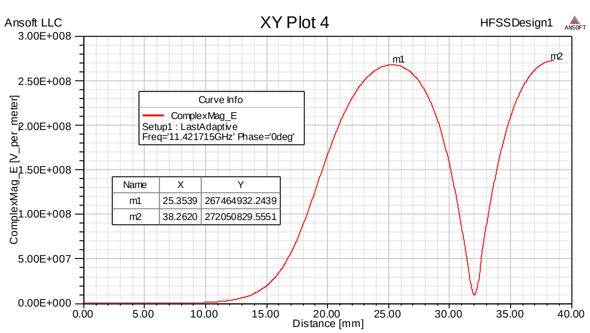
Calculating Zenghai's geometry with HFSS, first order elements, driven, 10 MW input, gradient over central cell 148 MV/m, Eacc/Emax=2.06 (2D SLANS=2.03)



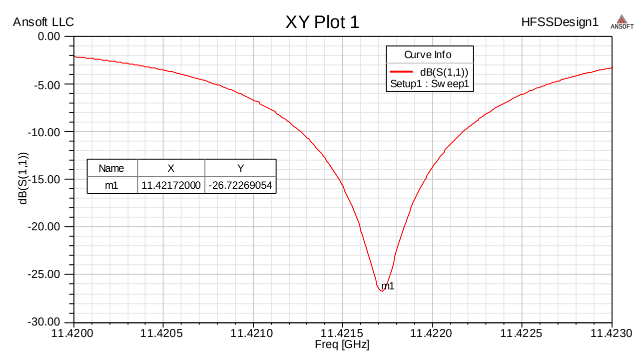
Maximum magnetic field 556 kA/m,
Hmax*Z0/Eacc= 1.415, (2D SLANS =1.224)



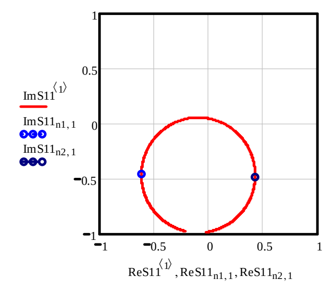
Maximum electric field 305 MV/m



Maximum on axis peak electric field 272.05 MV/m,
field balance 272.05/267.465 = 1.017



Resonant frequency 11.421715 GHz,
slightly over coupled



$$Qo := 4.079\times 10^{3}\cdot\left(\frac{1+s11}{1-s11}+1\right)$$

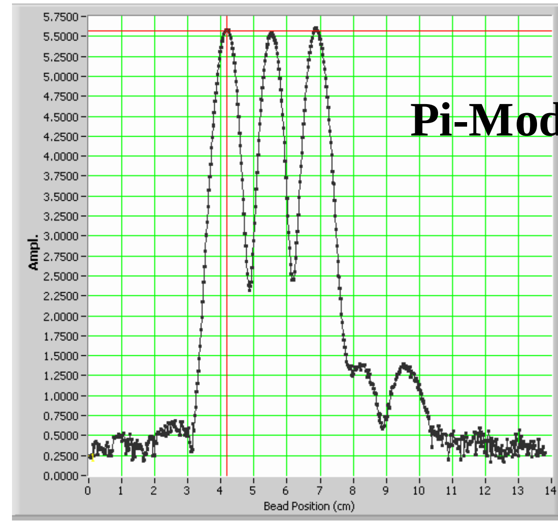
$$s11 = 0.04612$$

$$Qo = 8.552\times 10^{3}$$

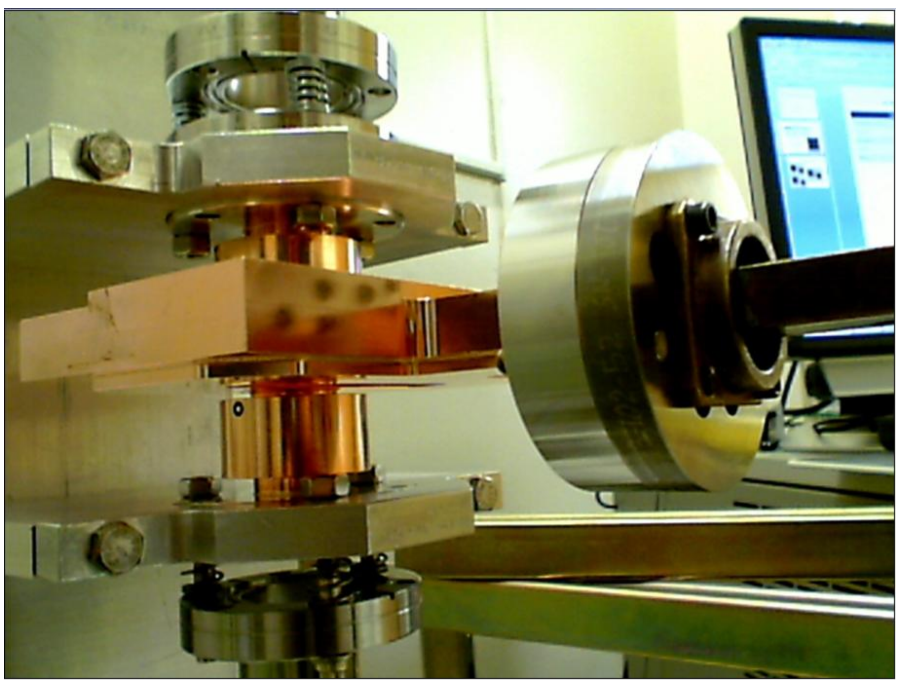
V.A. Dolgashev, 12 Nov 2010

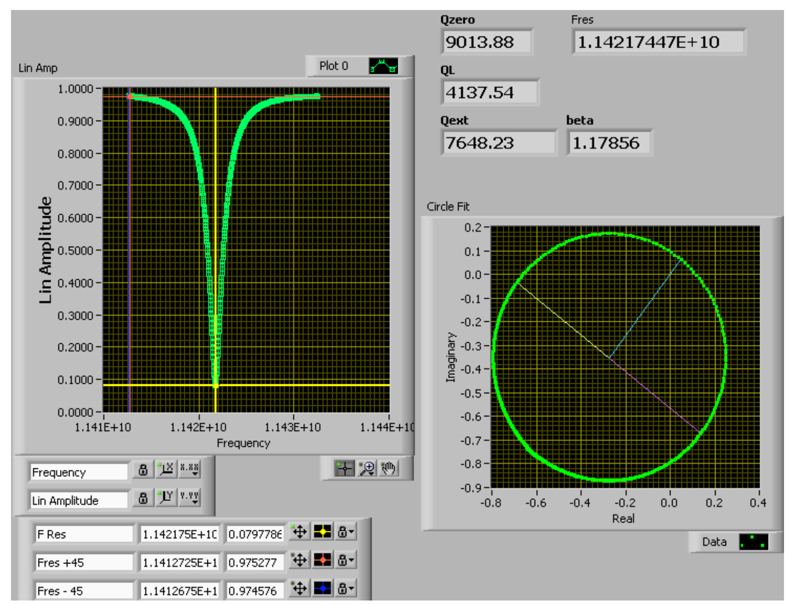
Bead-pull

	Pi Mode	Zero Mode
Frequency (GHz)	11.42174	11.2647
Q zero	9013	8861
Q loaded	4137	2790
Q ext	7648	4073
Beta	1.17	2.17



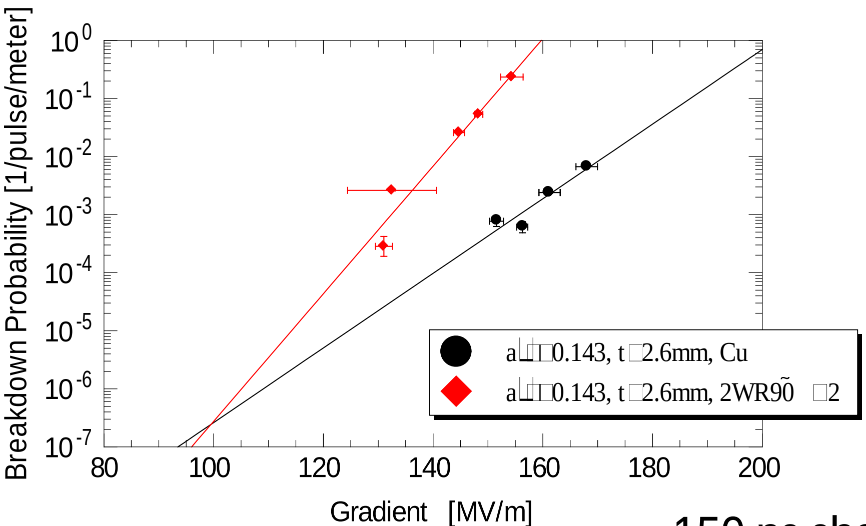
On-axis fields

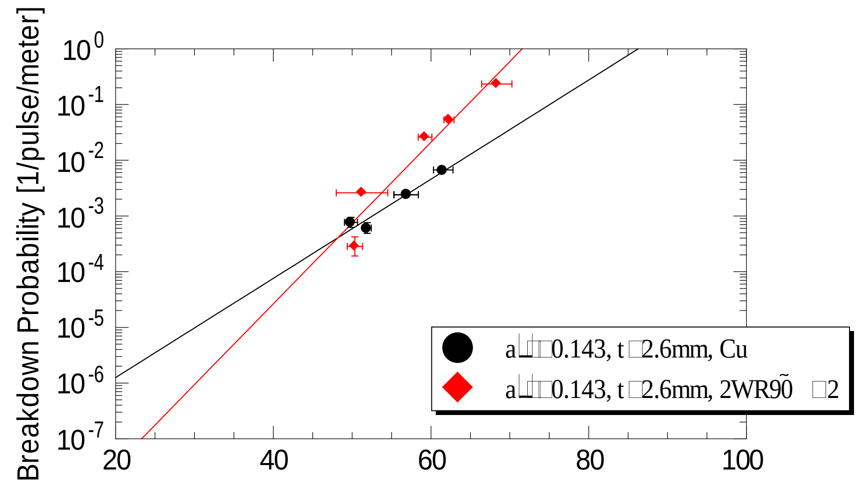




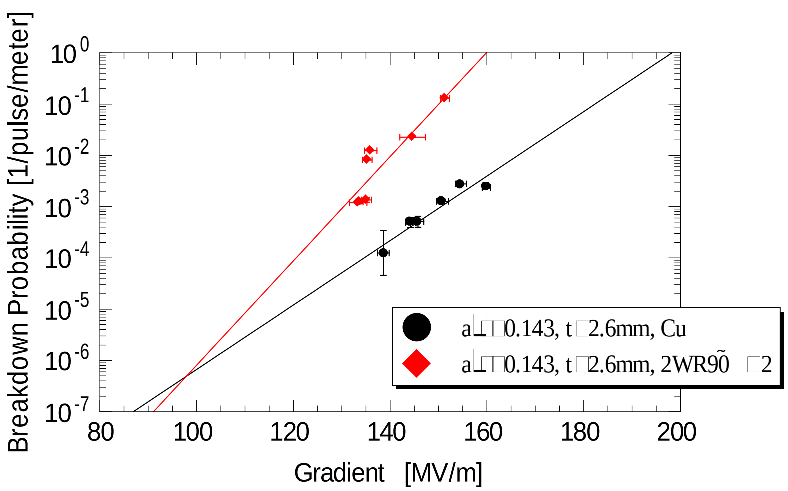
Jim Lewandowski, 7 October 2010

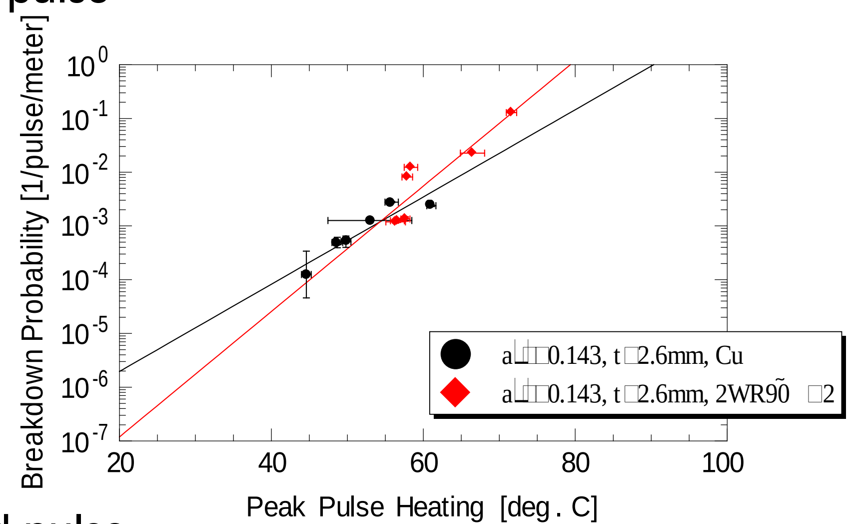
Comparison with on-axis coupled structure





150 ns shaped pulse





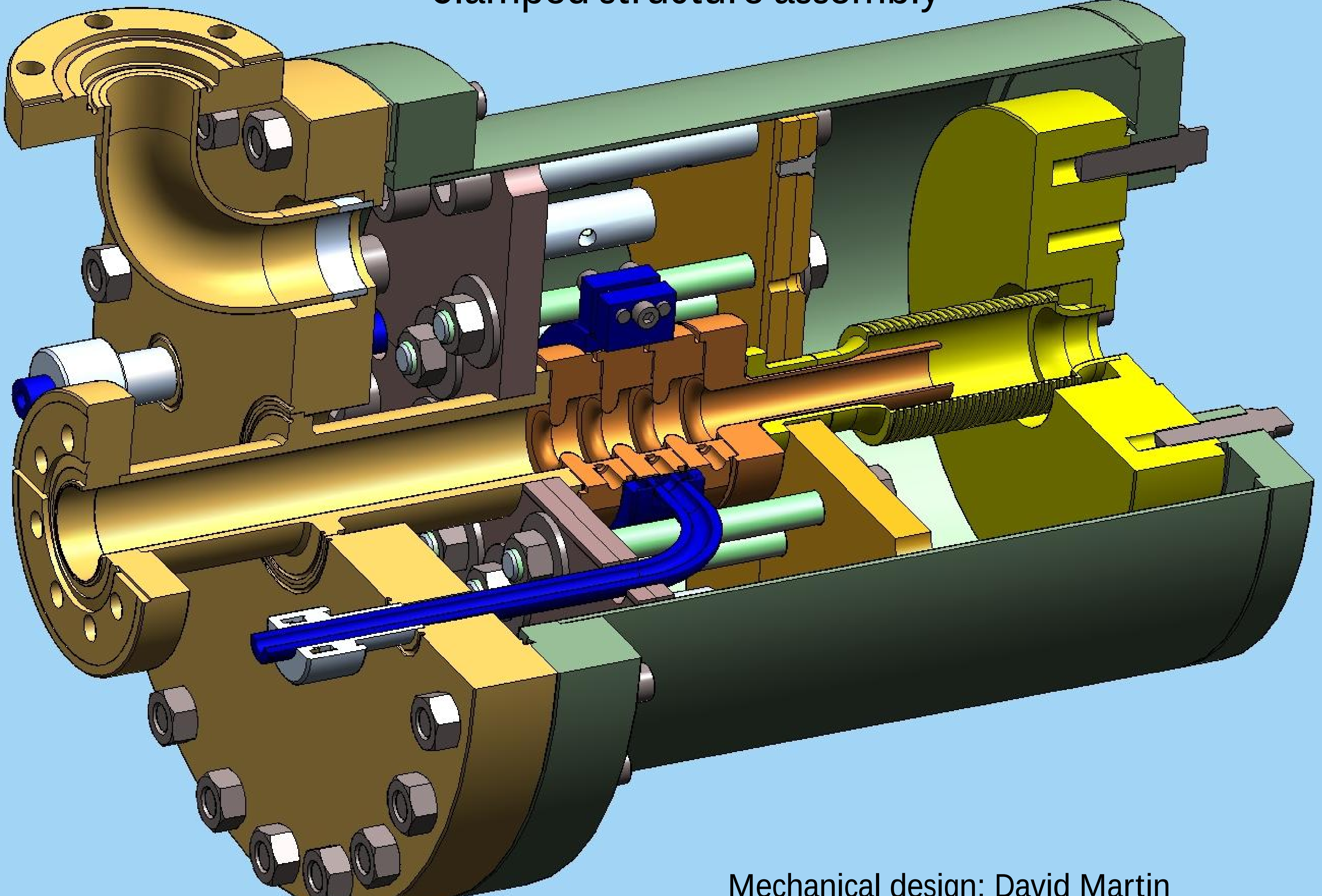
200 ns shaped pulse

Material test

High shunt-impedance, hard-CuCr,

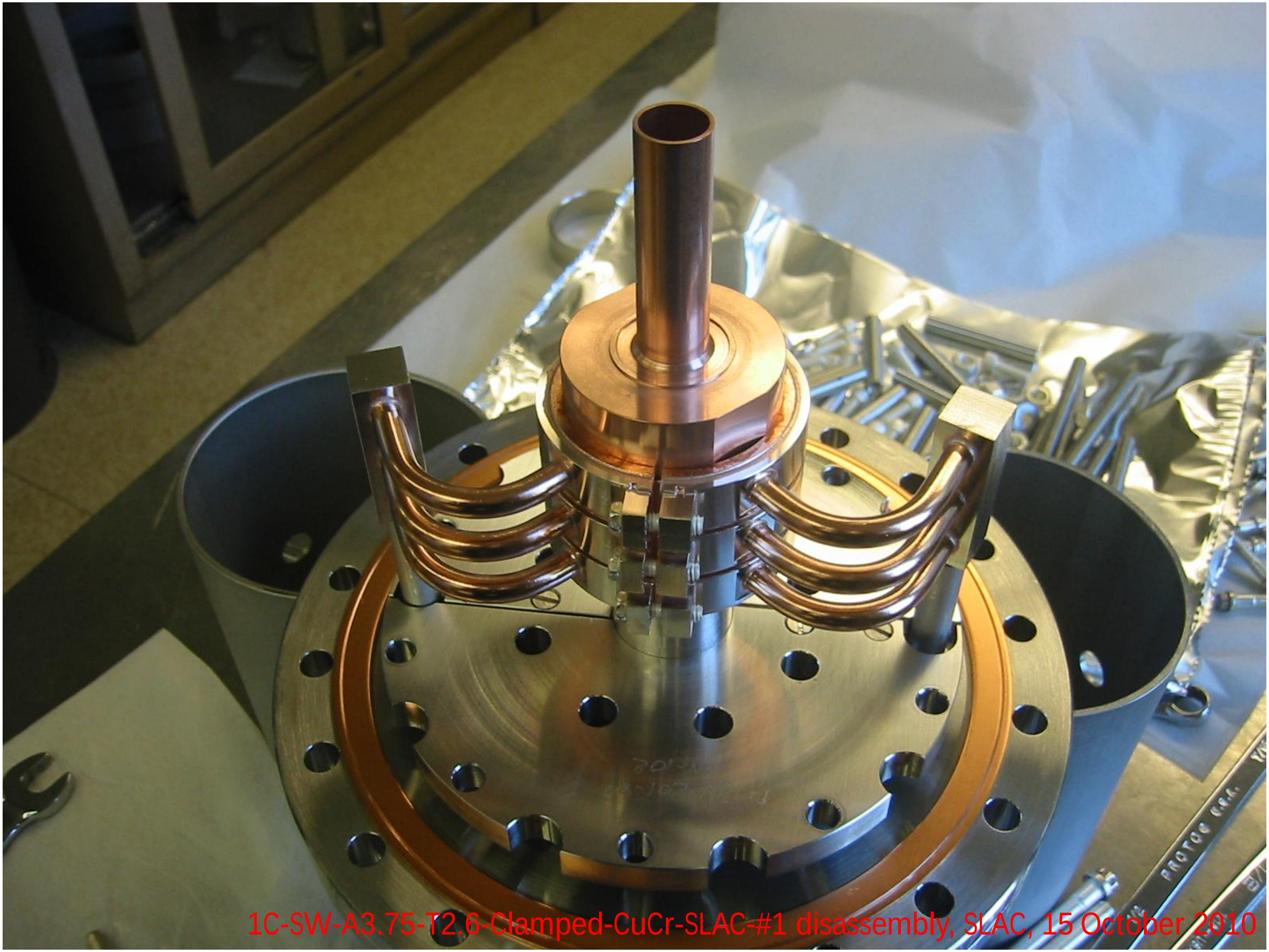
1C-SW-A3.75-T2.6-Clamped-CuCr-SLAC-#1

Clamped structure assembly

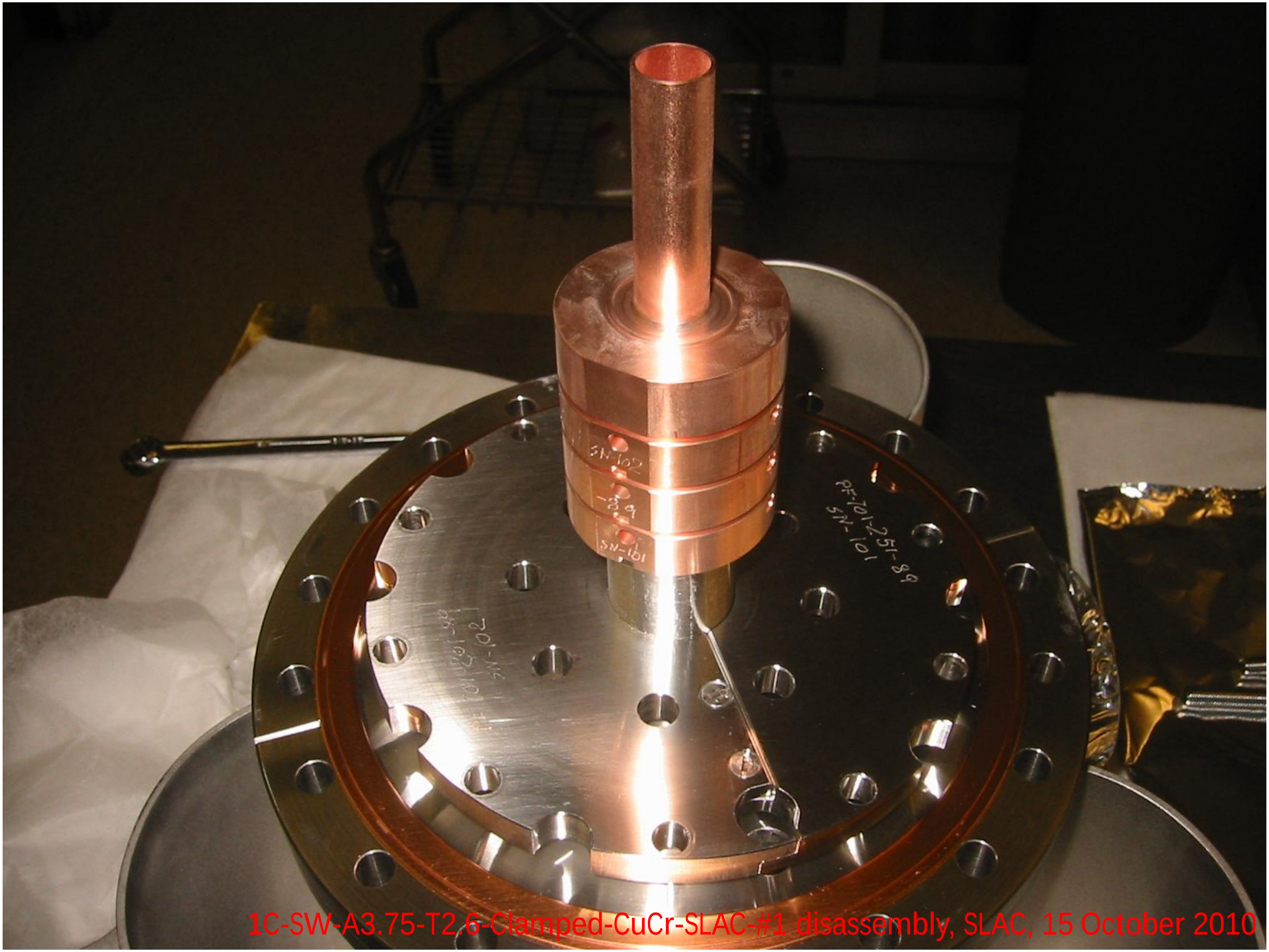


Mechanical design: David Martin

1C-SW-A3.75-T2.6-Clamped-CuCr-SLAC-#1 disassembly, SLAC, 15 October 2010



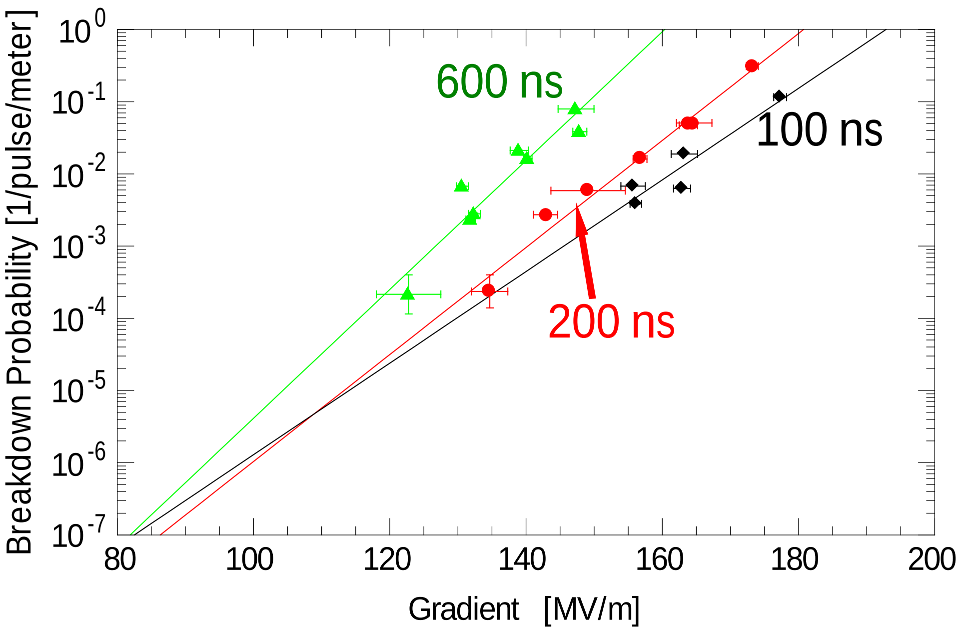
1C-SW-A3.75-T2.6-Clamped-CuCr-SLAC-#1 disassembly, SLAC, 15 October 2010

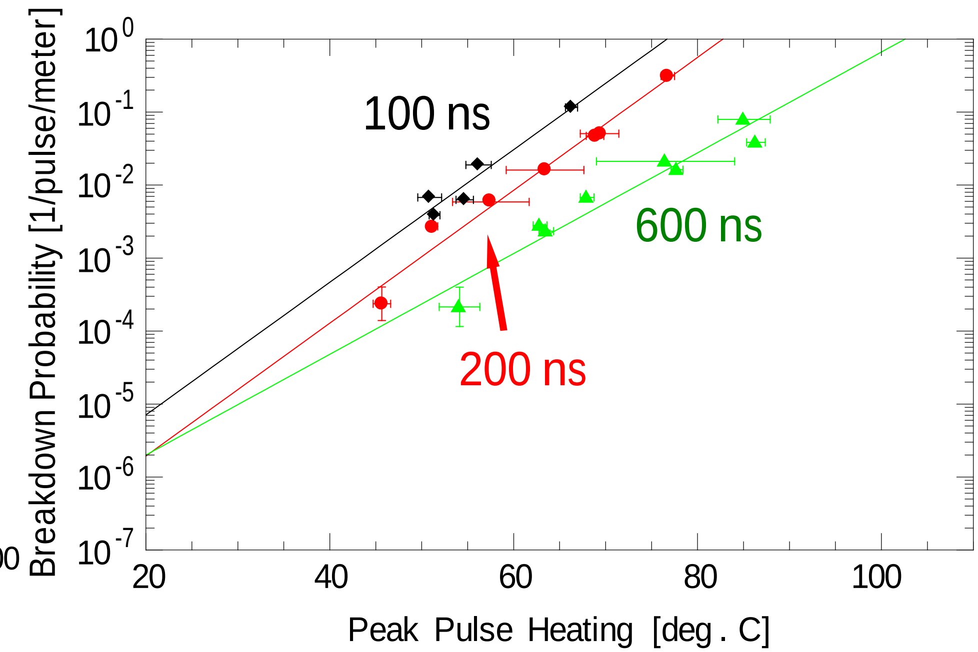


1C-SW-A3.75-T2.6-Clamped-CuCr-SLAC-#1 disassembly, SLAC, 15 October 2010

1C-SW-A3.75-T2.6-Clamped-CuCr-SLAC-#1 after test

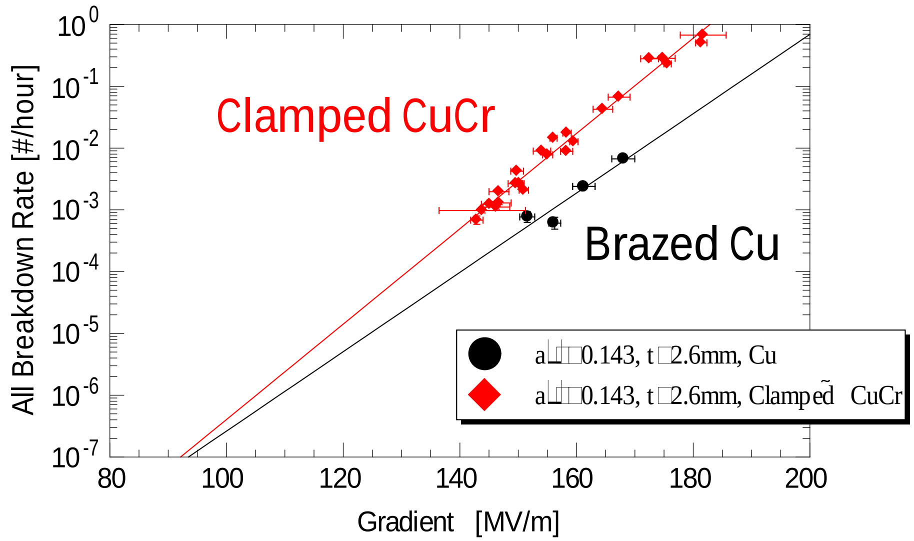
High shunt impedance structure made of hard CuCr, 1C-SW-A3.75-T2.6-Clamped-CuCr-SLAC- #1, Dependence of breakdown rate for different pulse length of flat part of the shaped pulse.

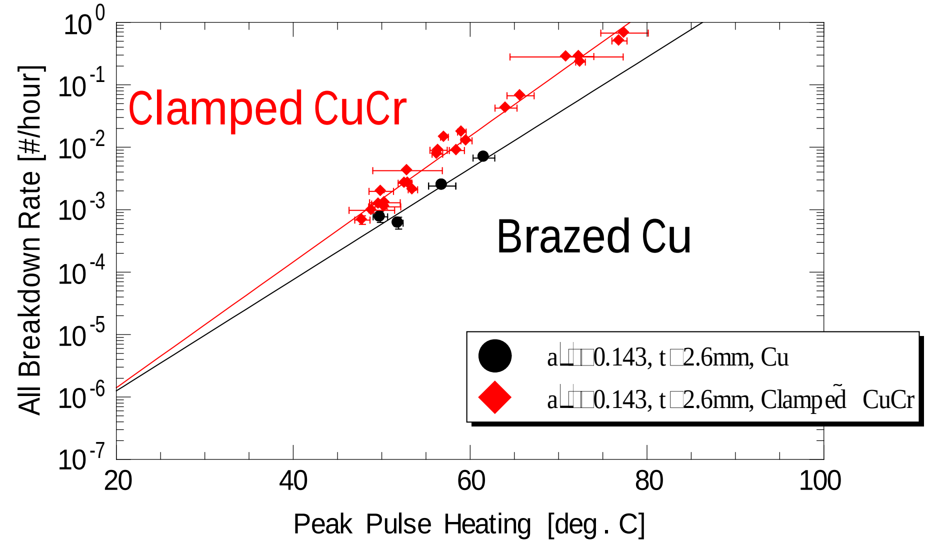




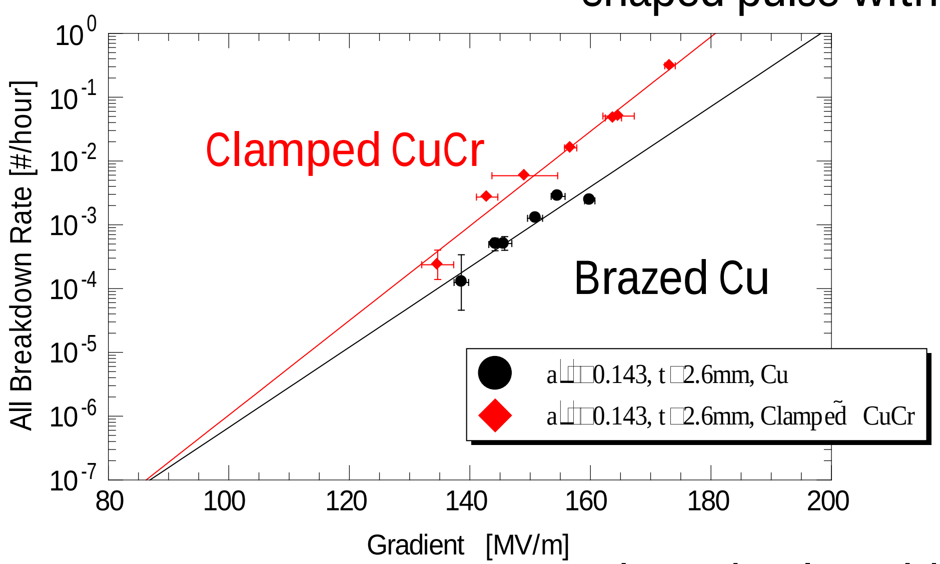
No obvious correlation with pulse heating.

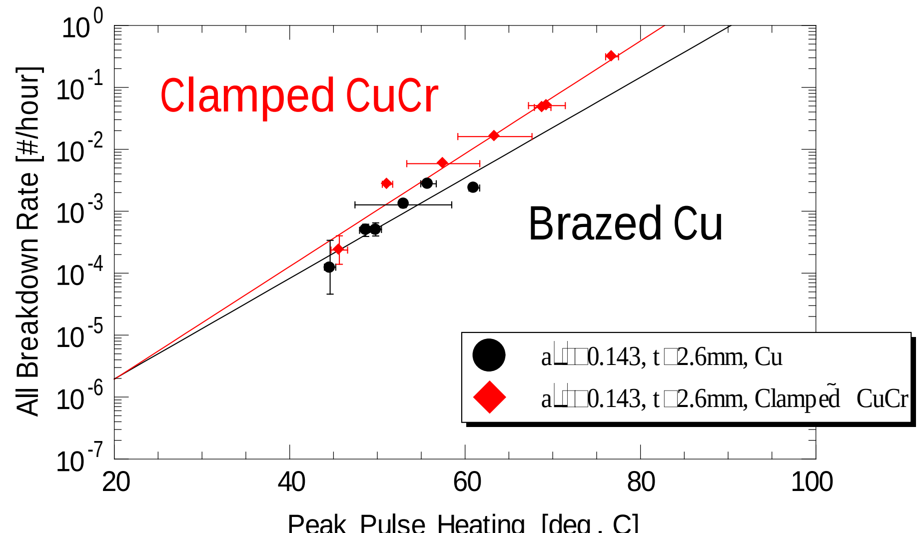
Comparison of two structures same geometry, one brazed Cu another clamped CuCr





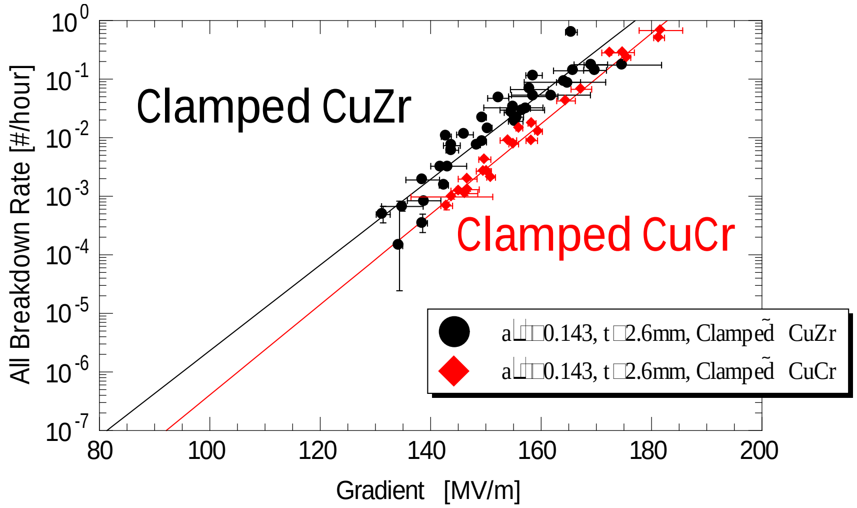
Shaped pulse with 150 ns flat part

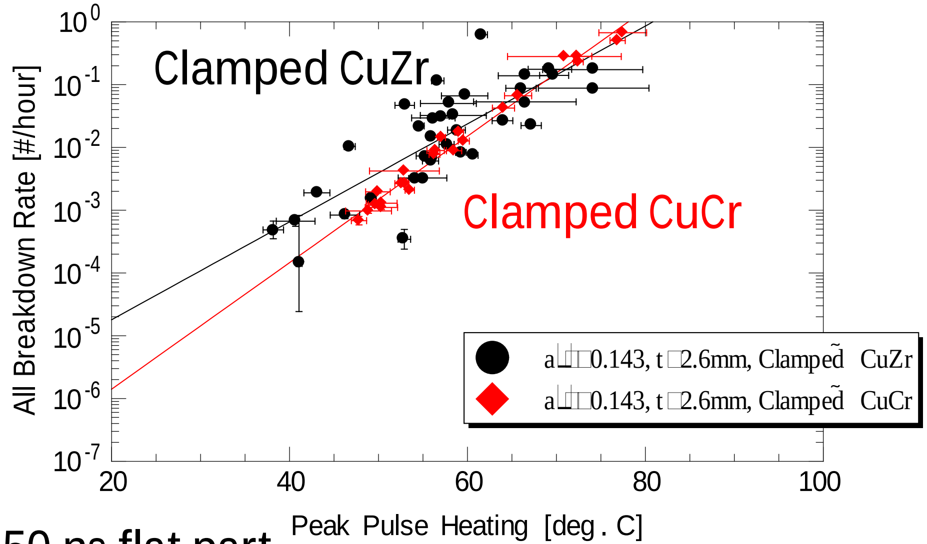




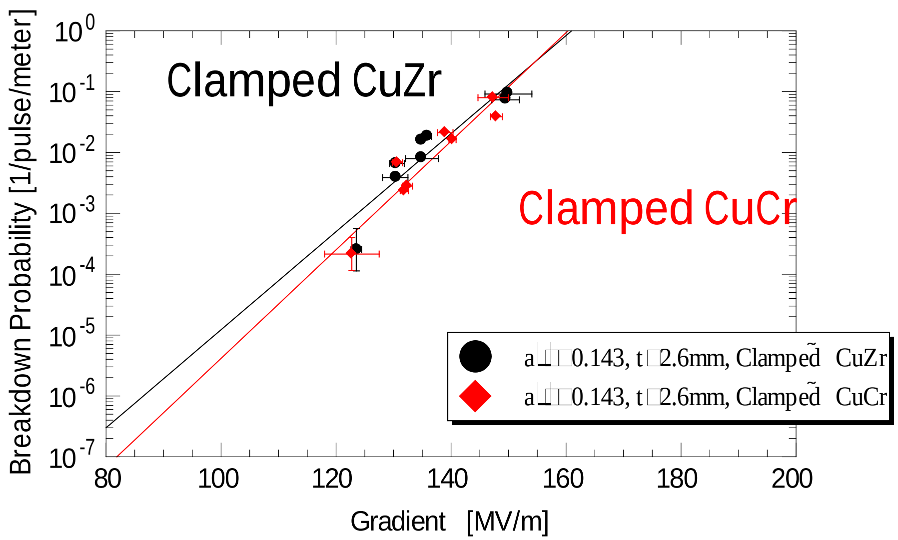
Shaped pulse with 200 ns flat part

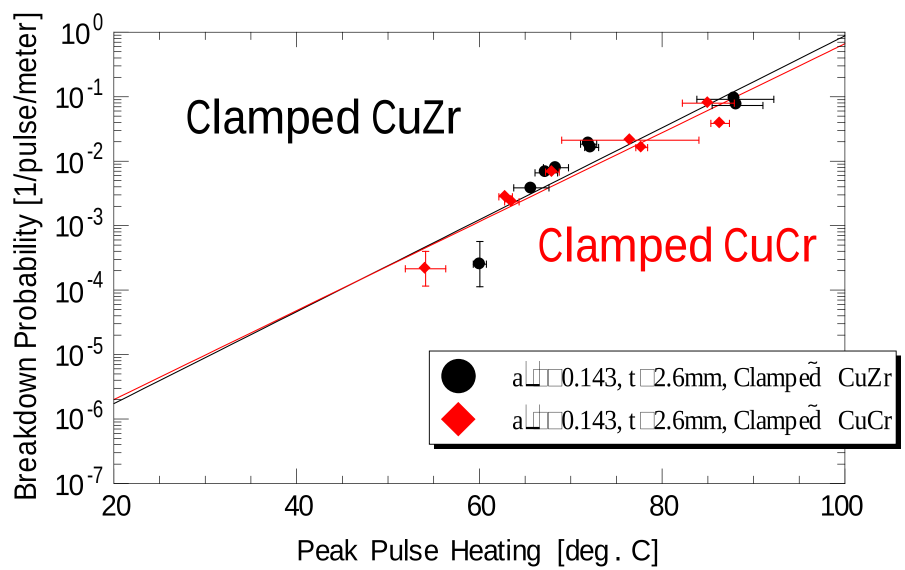
Comparison of two clamped structures with the same geometry made of hard CuCr and CuZr





Shaped pulse with 150 ns flat part

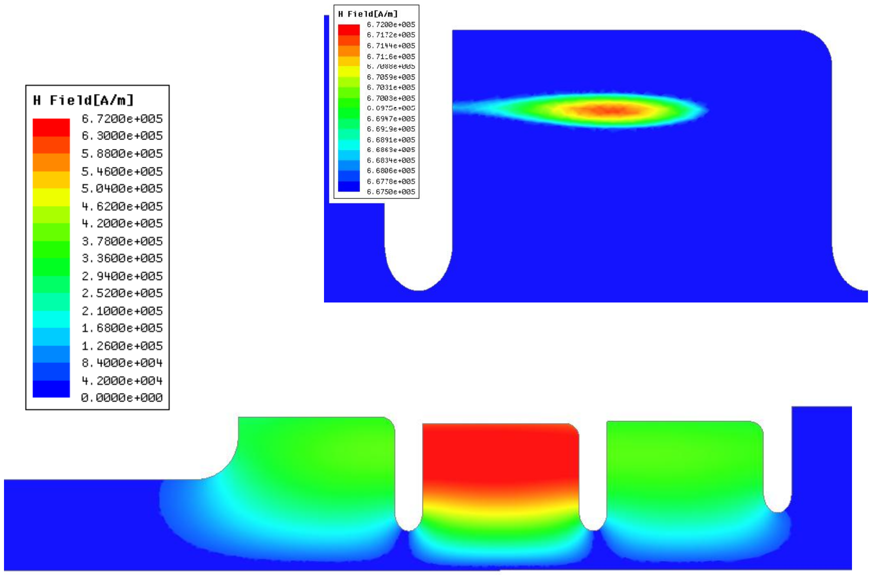




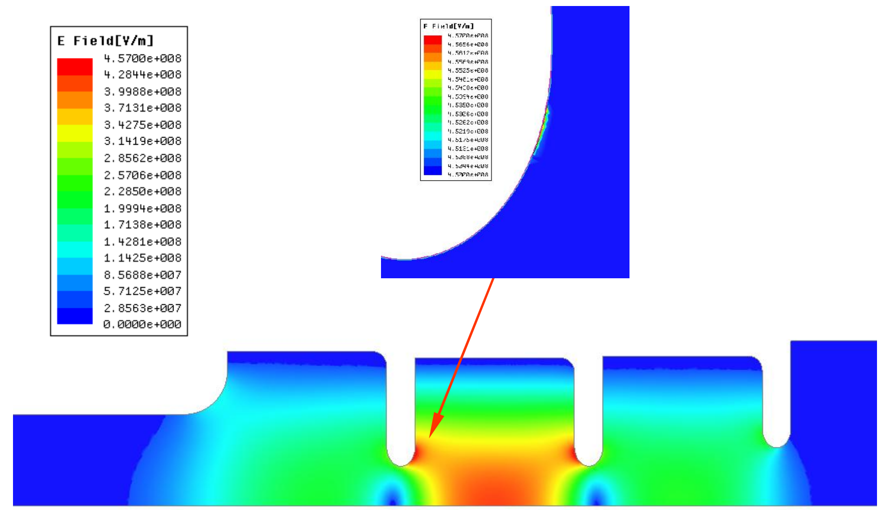
Shaped pulse with 600 ns flat part

Material test
Hard copper highest shunt impedance
1C-SW-A2.75-T2.0-Clamped-Cu-SLAC-#1

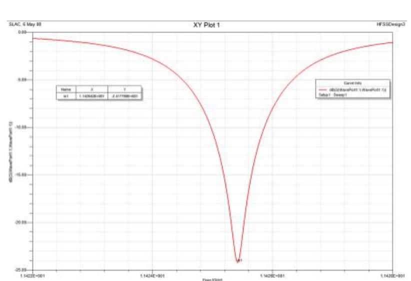
SW-A2.75-T2.0-Cu
Verification of SLANS results with HFSS11, 10 MW input



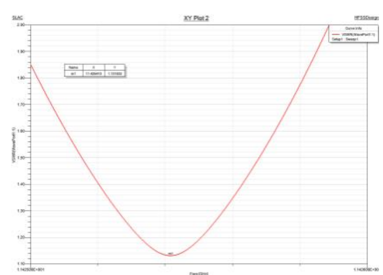
Maximum magnetic field 667.5 kA/m
(SLANS 666.8 kA/m)



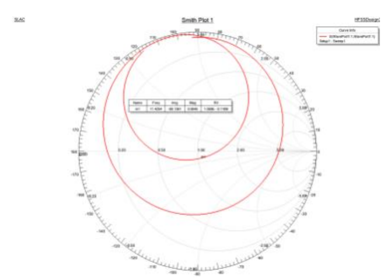
Maximum electric field 457 MV/m
(SLANS 456.3 MV/m)



Resonance at 11.42542 GHz
(SLANS 11.42398 GHz)

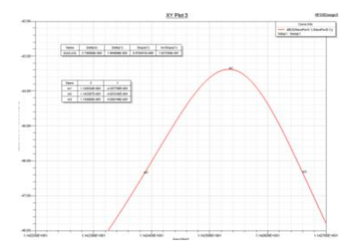


$\beta = 1.131$
(SLANS 1.164)



Over-coupled loaded Q

Unloaded Q=8,919
(SLANS 8,9594)



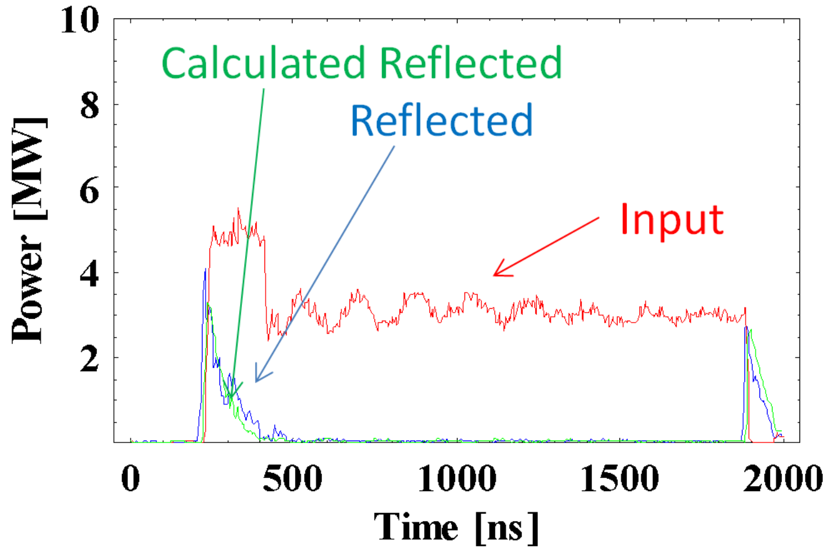
$$\frac{11.42542\,\text{GHz}}{2.73\,\text{MHz}} = 4.185\times 10^3$$

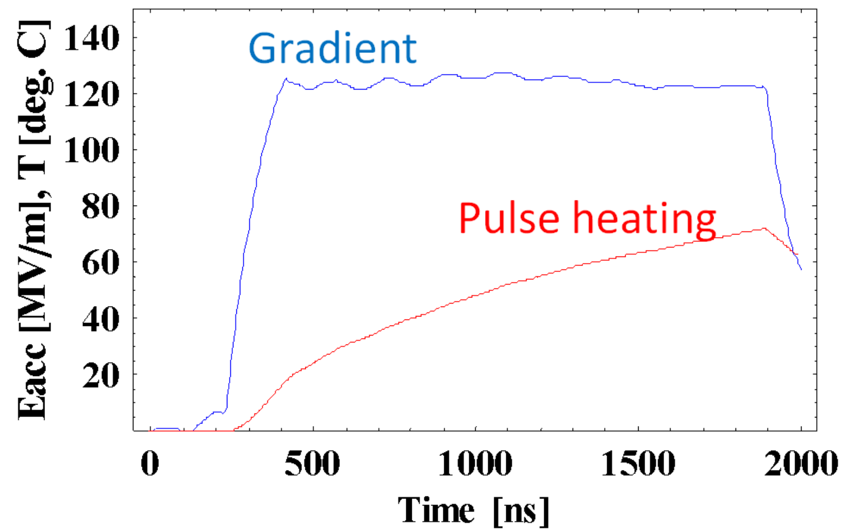
$$\frac{11.42542\,\text{GHz}}{2.73\,\text{MHz}}(1 + 1.131) = 8.919\times 10^3$$

V.A. Dolgashev, 6 May 2008

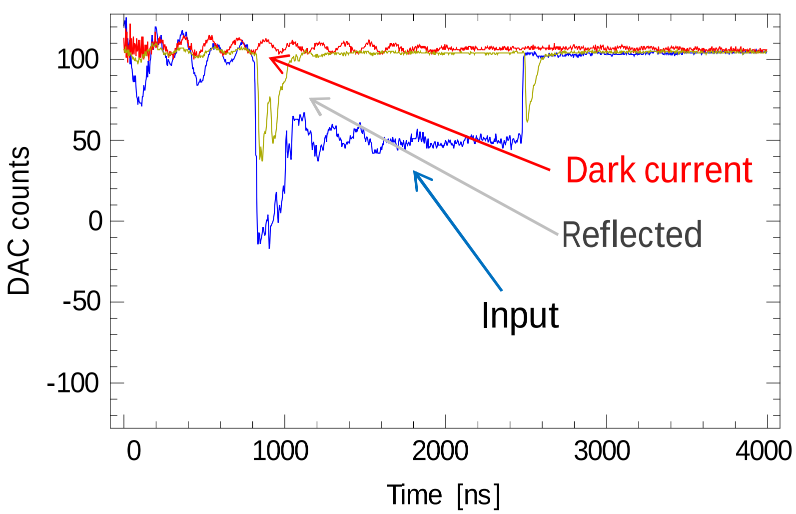
RF Signals

1199 {5,1,2011,10,43,16,765} MaxE: 255.987 MaxT: 70.7841



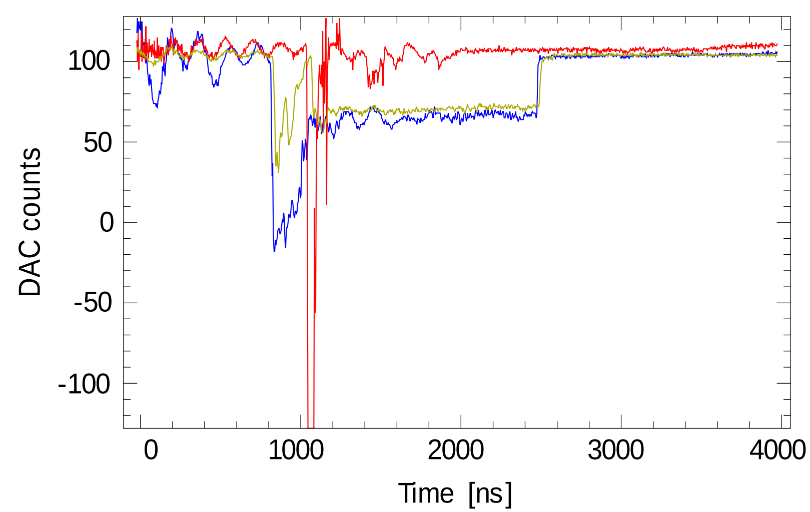


File: t01_06_11__08_37_08.dat Shot: 5 TimeStamp: {17,39,42,796}



Before rf breakdown

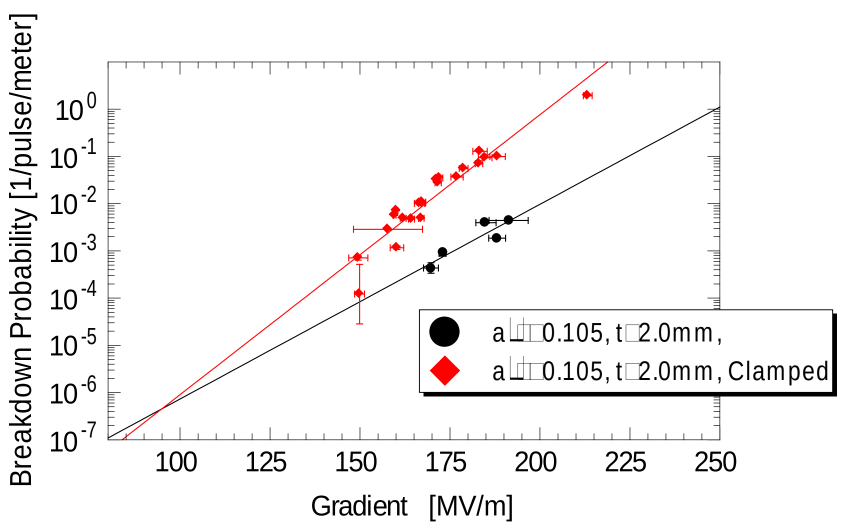
File: t01_06_11__08_37_08.dat Shot: 6 TimeStamp: {17,39,42,812}



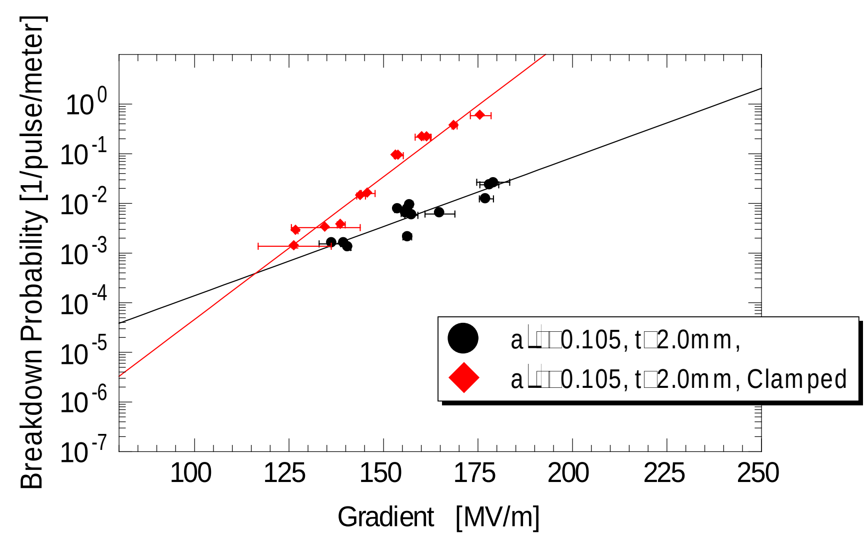
RF breakdown

V.A. Dolgashev 31 January 2011

Comparison of soft and hard copper 1C-SW-A2.75-T2.0 structures, different pulse length



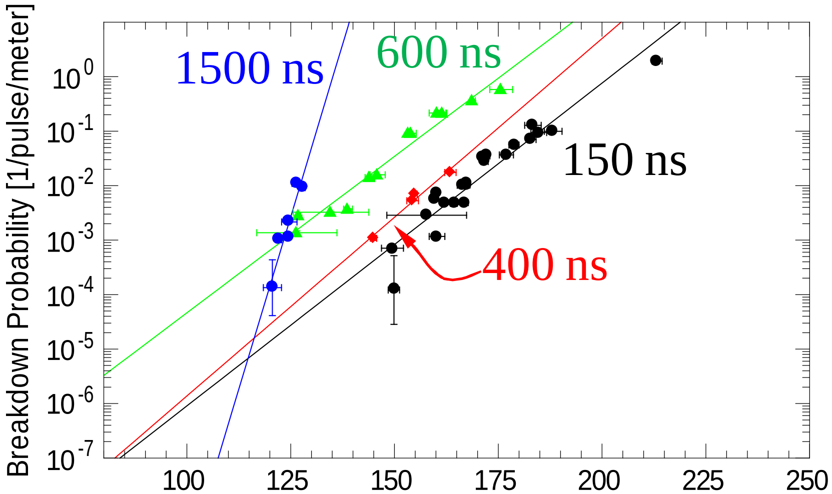
150 ns



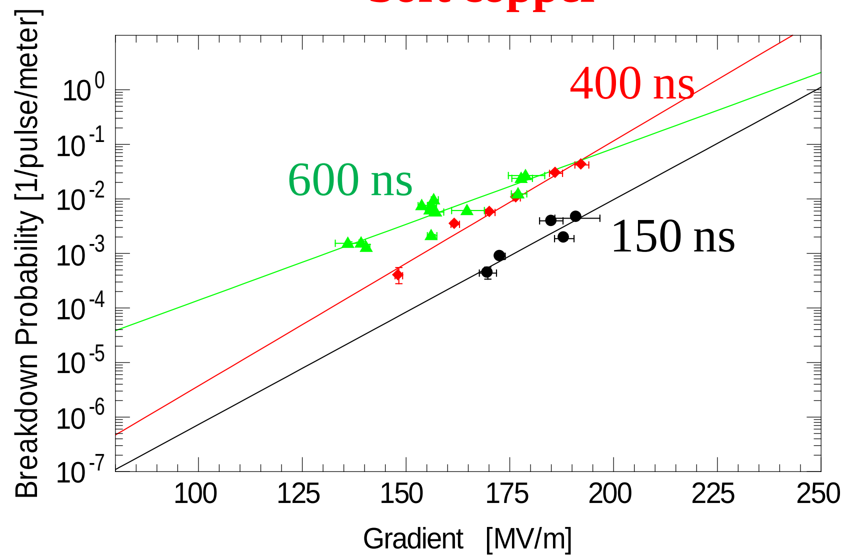
600 ns

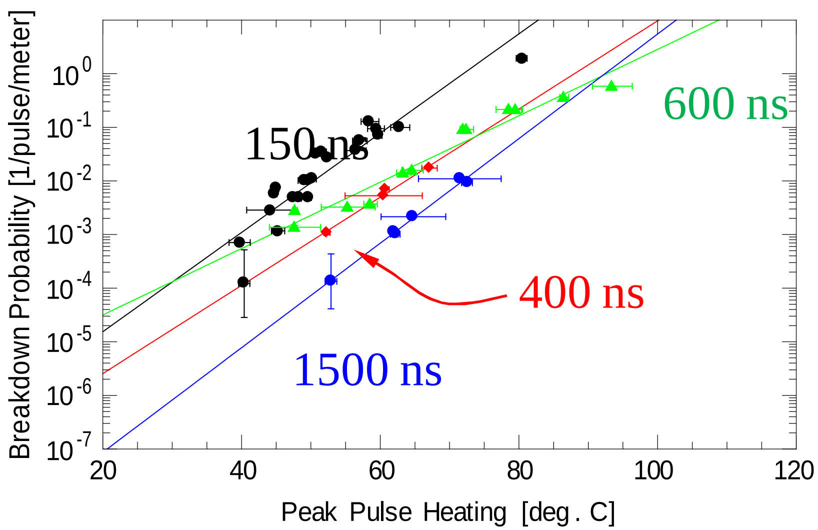
Comparison of soft and hard copper 1C-SW-A2.75-T2.0 structures, different pulse length

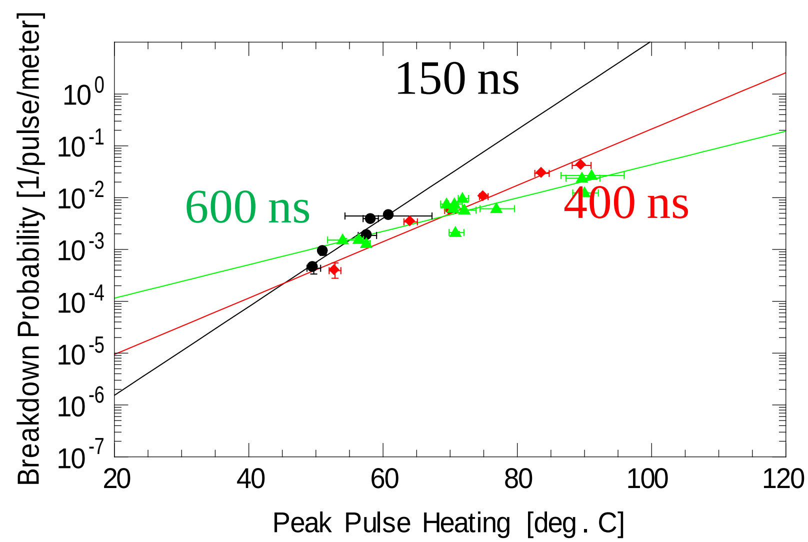
Hard copper



Soft copper







No obvious correlation with pulse heating

Traveling Wave Structures

- T18 in resonant ring
- Ten cell TW structures, C10

Traveling Wave T18 in a resonant ring

- T18 is designed by CERN, built at KEK, assembled and bonded in SLAC, first tested at SLAC (NLCTA), assembled with Jake Haimson's resonant ring and now tested at ASTA

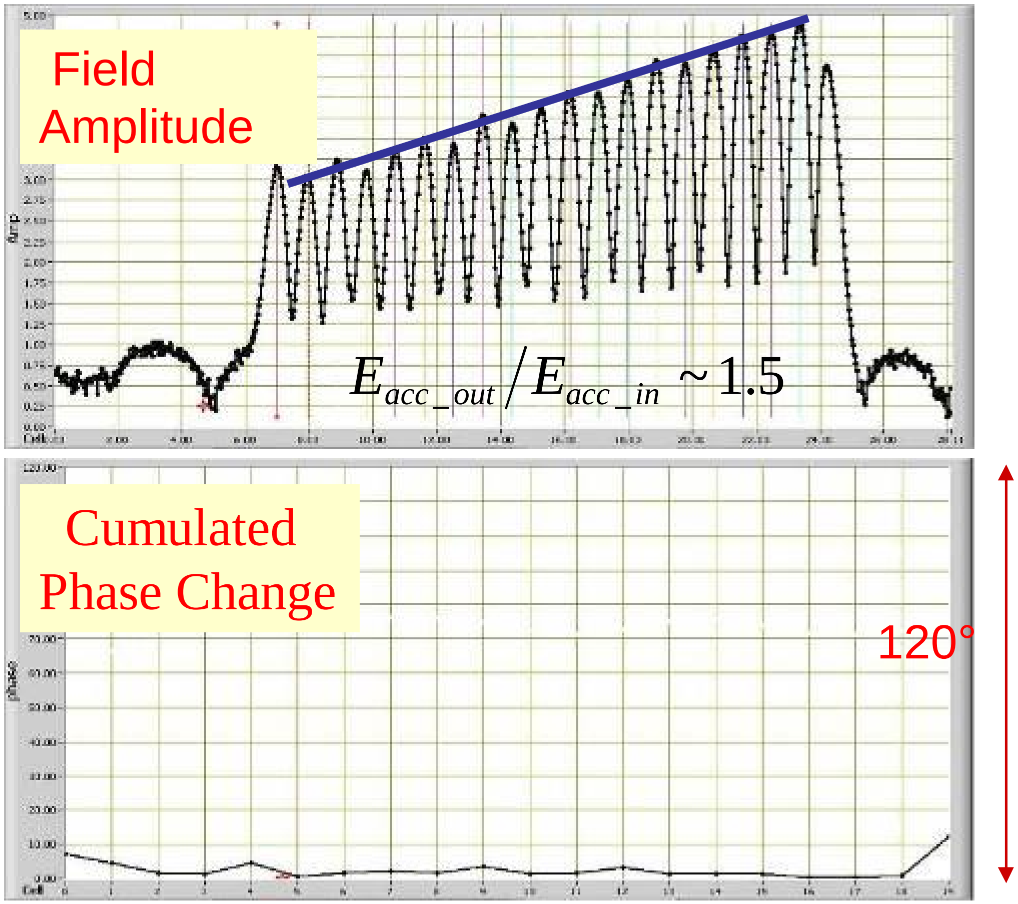
- Resonant ring is made by Haimson Research Corporation, *see*
Jake Haimson's talk this afternoon.

T18_VG2.4_DISC Structures

Frequency.	11.424GHz
Cells	18+input+output
Attenuation Factor τ	0.23
Filling Time	36ns
a_{in}/a_{out}	4.06/2.66 mm
Vg_{in}/Vg_{out}	2.61/1.02 (%c)
S_{11}	0.035
S_{21}	0.8
Phase Advance / Cell	120°
Pulse Heating ΔT	2.5 /17.5 °K (55.5 MW, 200ns)
Average Unloaded Gradient	55.5MW→100MV/m

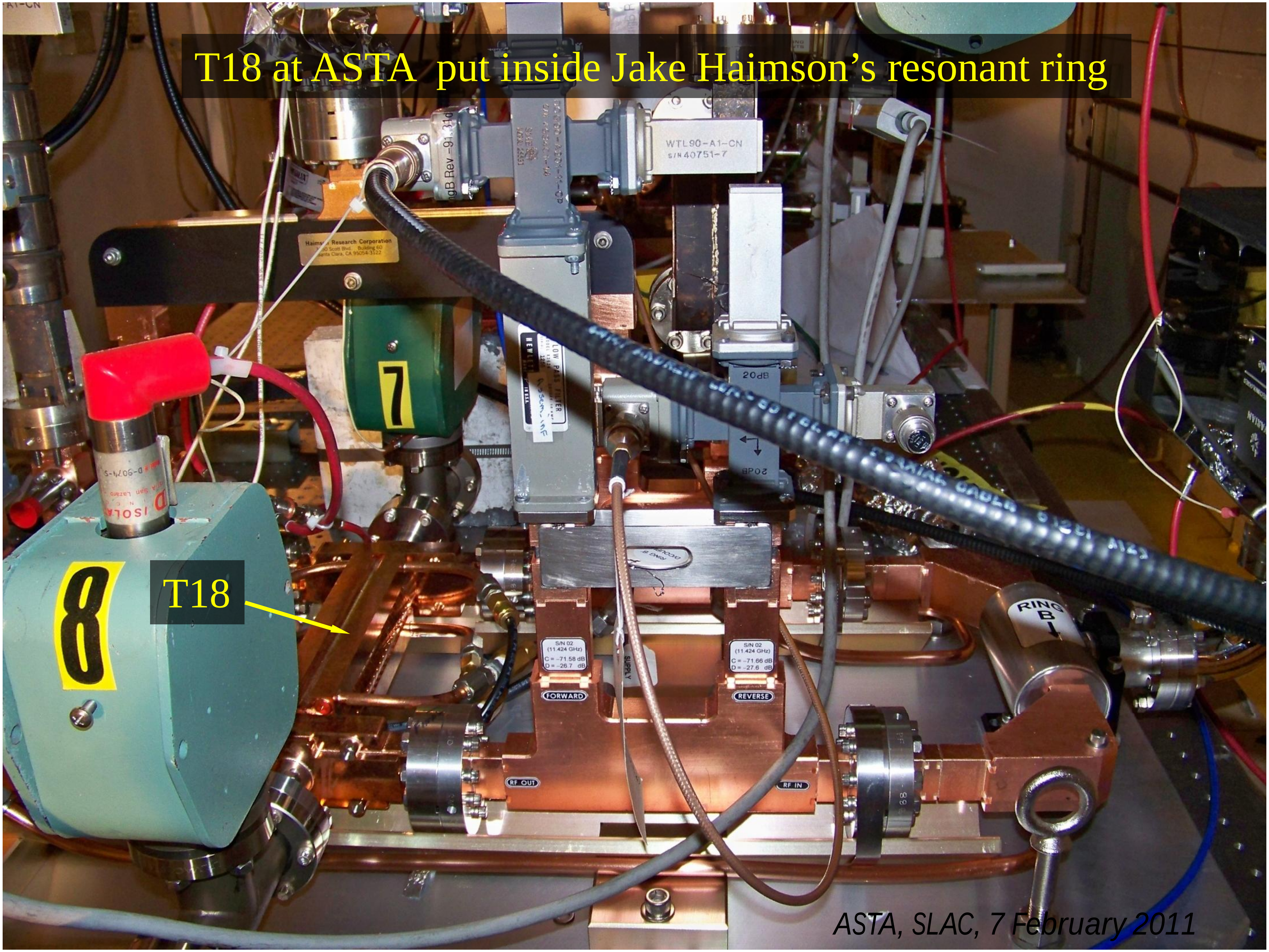
J. Wang

T18_VG2.4_DISC Structure Test

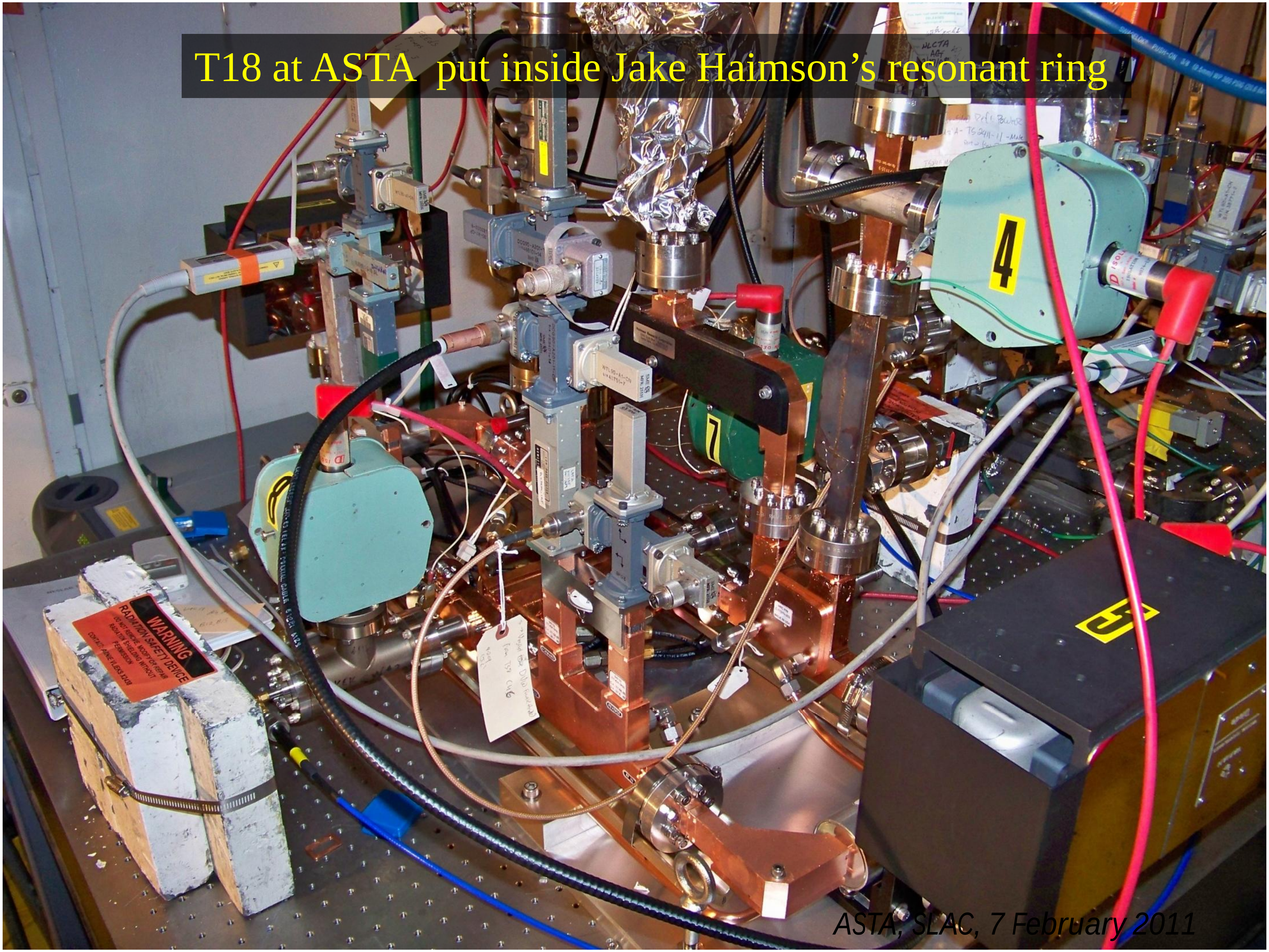


Microwave Tuning and test

J. Wang

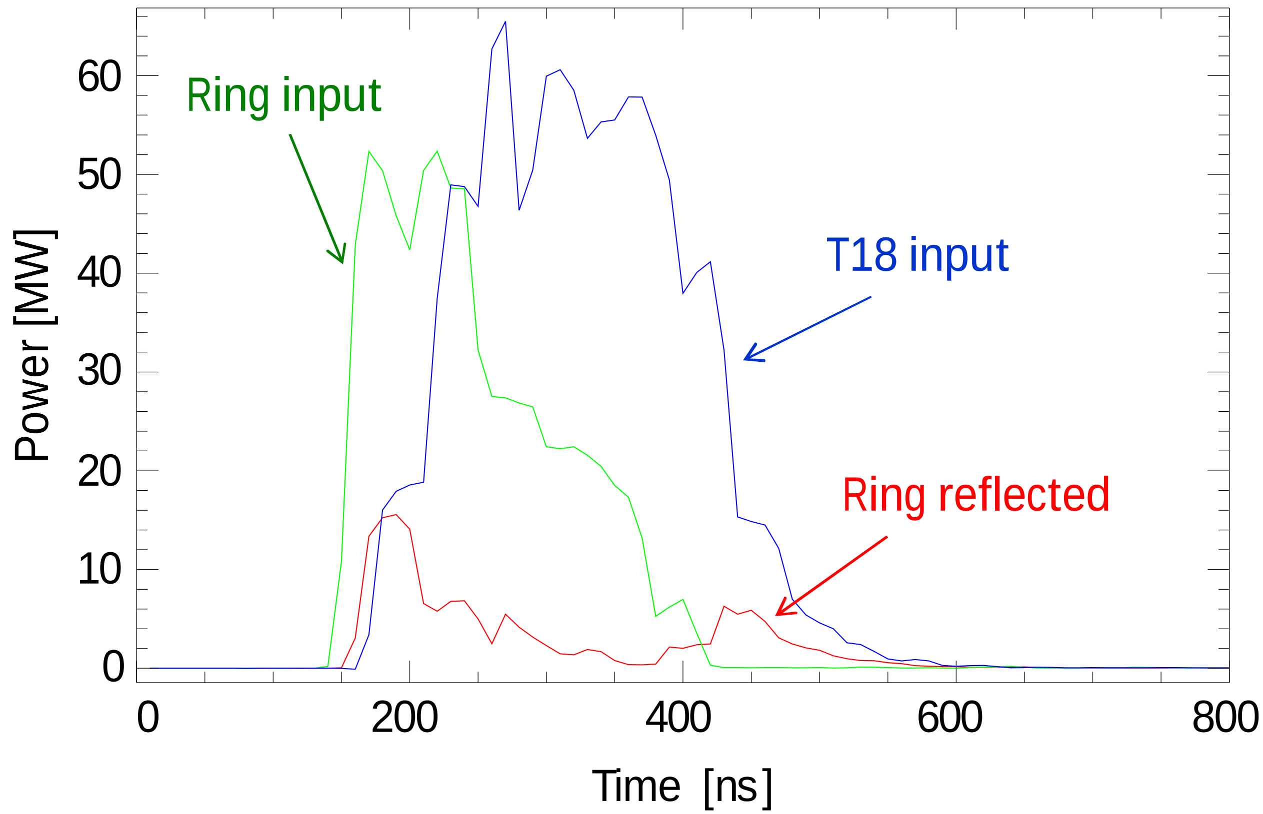

T18 at ASTA put inside Jake Haimson's resonant ring
T18
WTL90-A1-CN
S/N 40751-7
20dB
FORWARD
REVERSE
RF OUT
RF IN
RING B
S/N 02
(11.424 GHz)
C = -71.58 dB
D = -26.7 dB
S/N 02
(11.424 GHz)
C = -71.66 dB
D = -27.6 dB
Haimson Research Corporation
7
8
ASTA, SLAC, 7 February 2011

T18 at ASTA put inside Jake Haimson's resonant ring



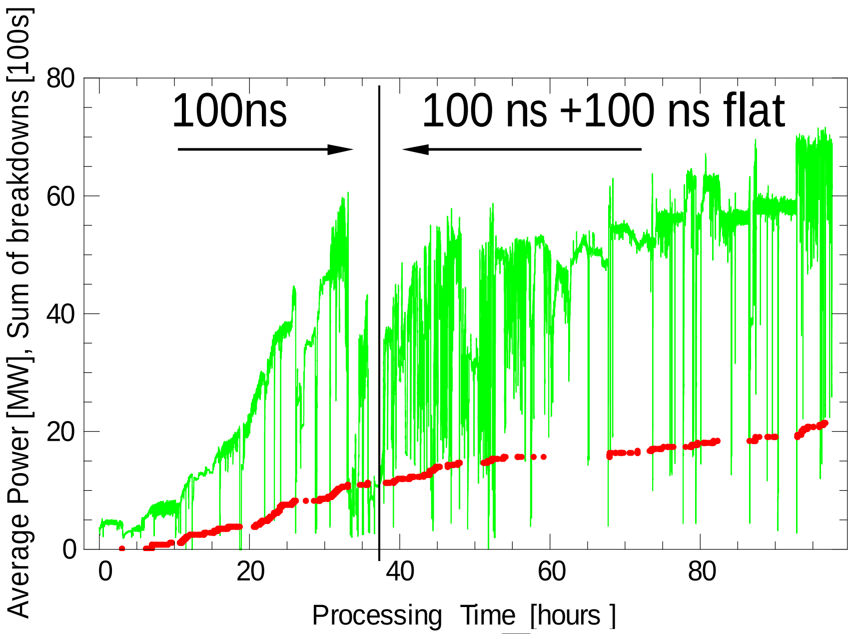
ASTA, SLAC, 7 February 2011

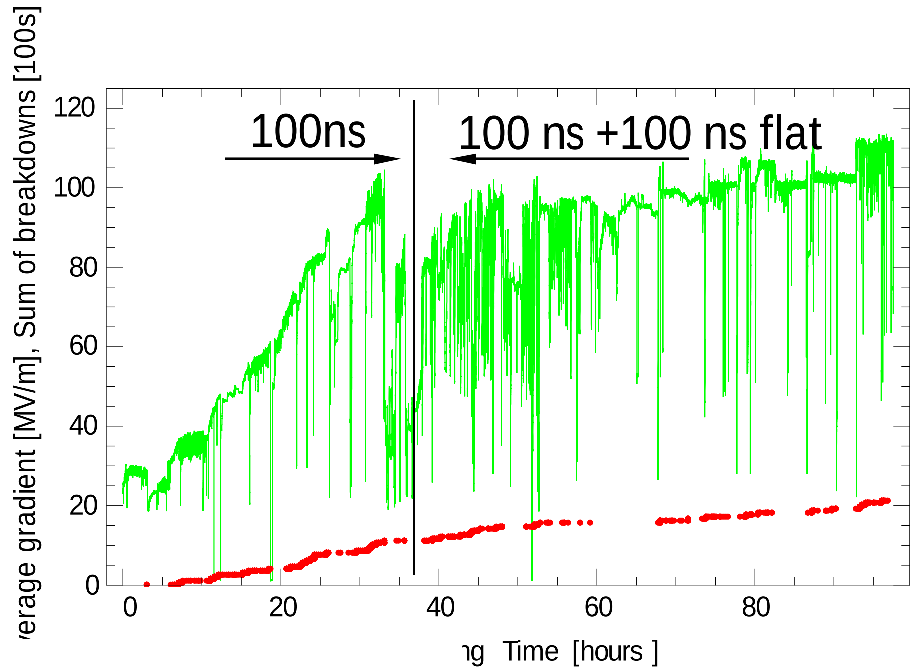
T18 in resonant ring

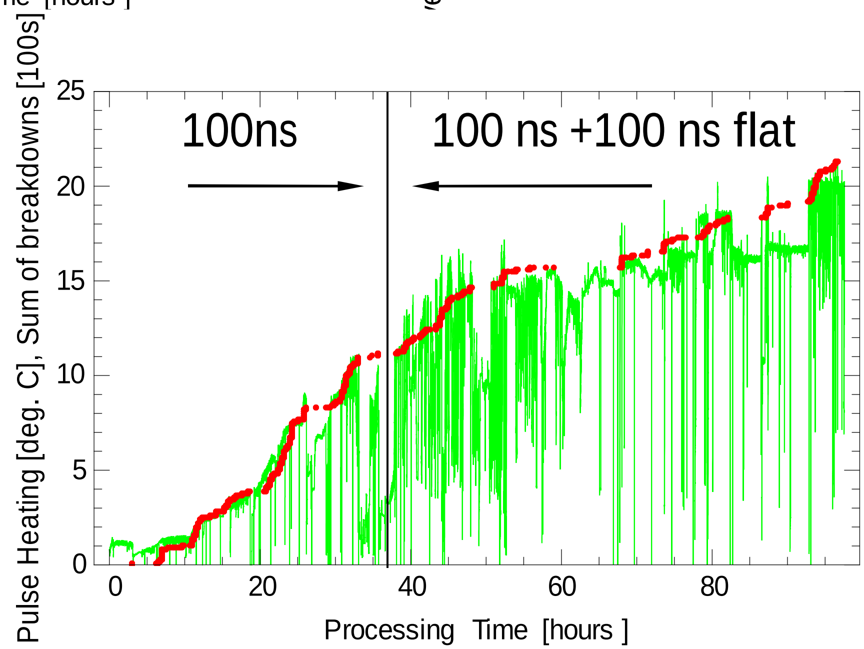


Structure is powered by shaped pulse with ~100 ns charging and ~100 ns flat part

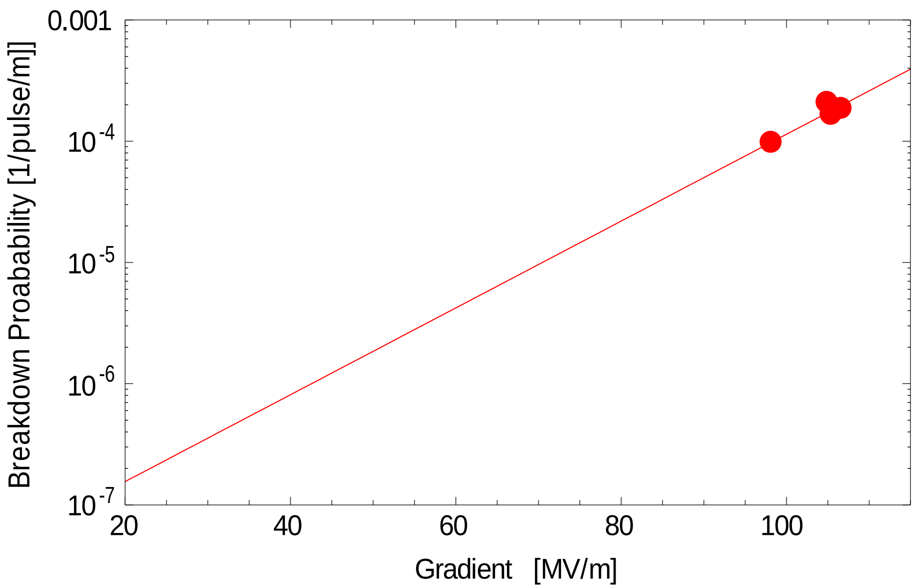
Processing of T18 in resonant ring up to 4th February 2011

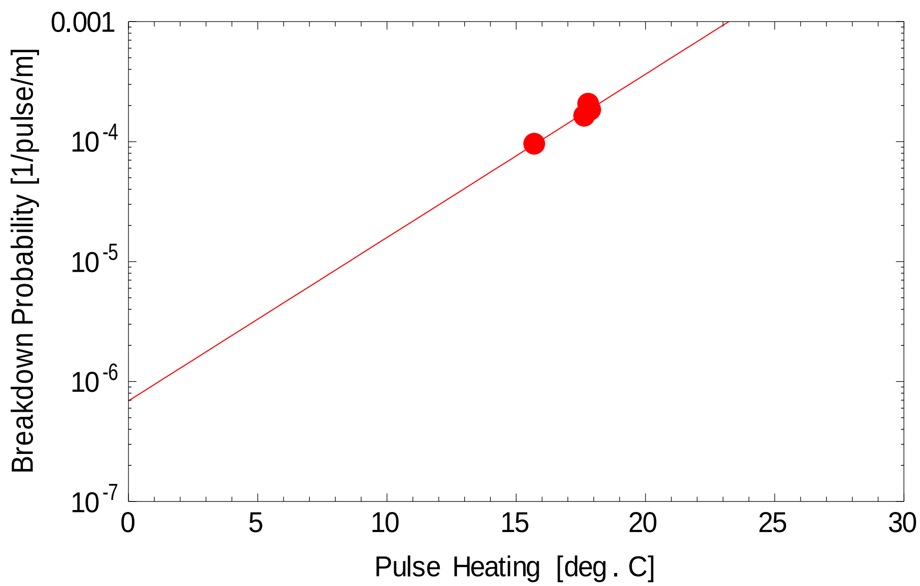






Initial breakdown rate, T18 in resonant ring, Data up to 4 February 2011, Shaped pulse 100 ns charging and 100 ns flat





Status (7 February 2011)

- Structure processed with ~100 ns input pulse (no flat part) up to ~60 MW peak power at the input of the structure (104 MV/m).
- Pulse shape changed to ~100 ns charging time and ~100 ns flat part. The structure run at up to ~70 MW at the input of the structure (~112 MV/m). System mostly limited not by rf breakdowns in the structure but by outgassing in transport line.

10 Cell Traveling Wave Structures

C10-VG135

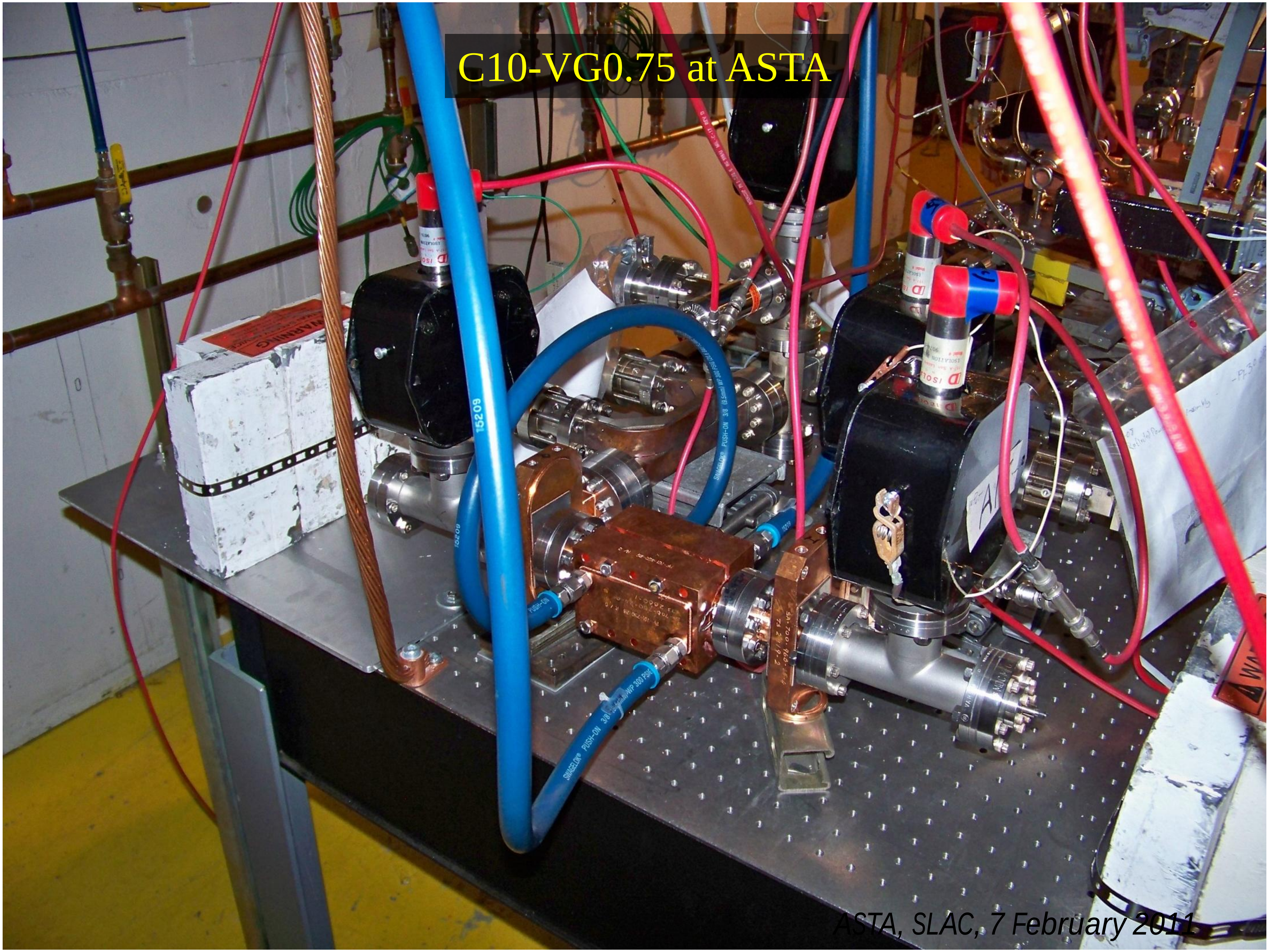
(10C-TW-A3.00-T1.66-Cu-SLAC-#1)

C10-VG07

(10C-TW-A2.53- T1.66-Cu-SLAC-#1)

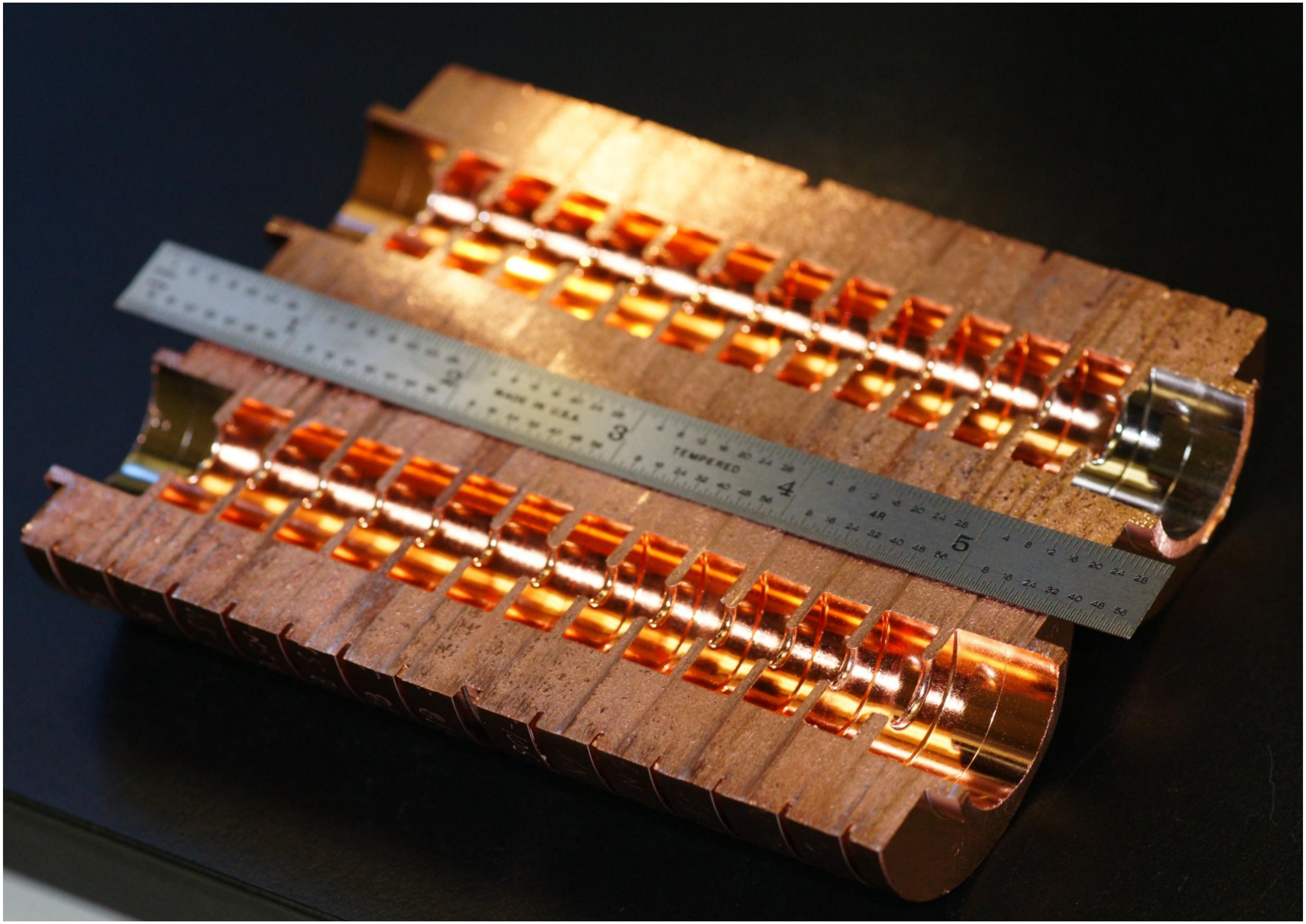
This work is done in collaboration with CERN

C10-VG0.75 at ASTA



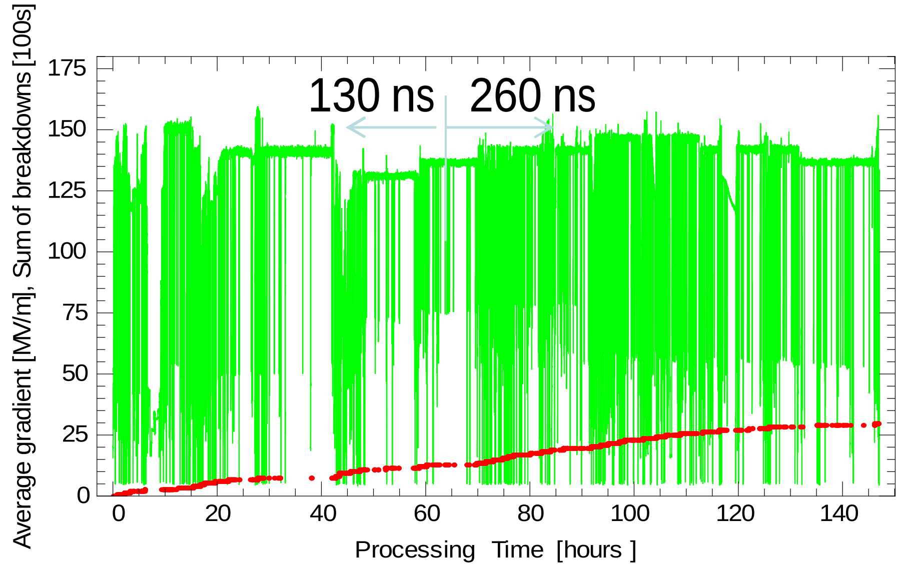
ASTA, SLAC, 7 February 2011

10 cell Traveling Wave Structure C10-VG135 Cut After High Power Test

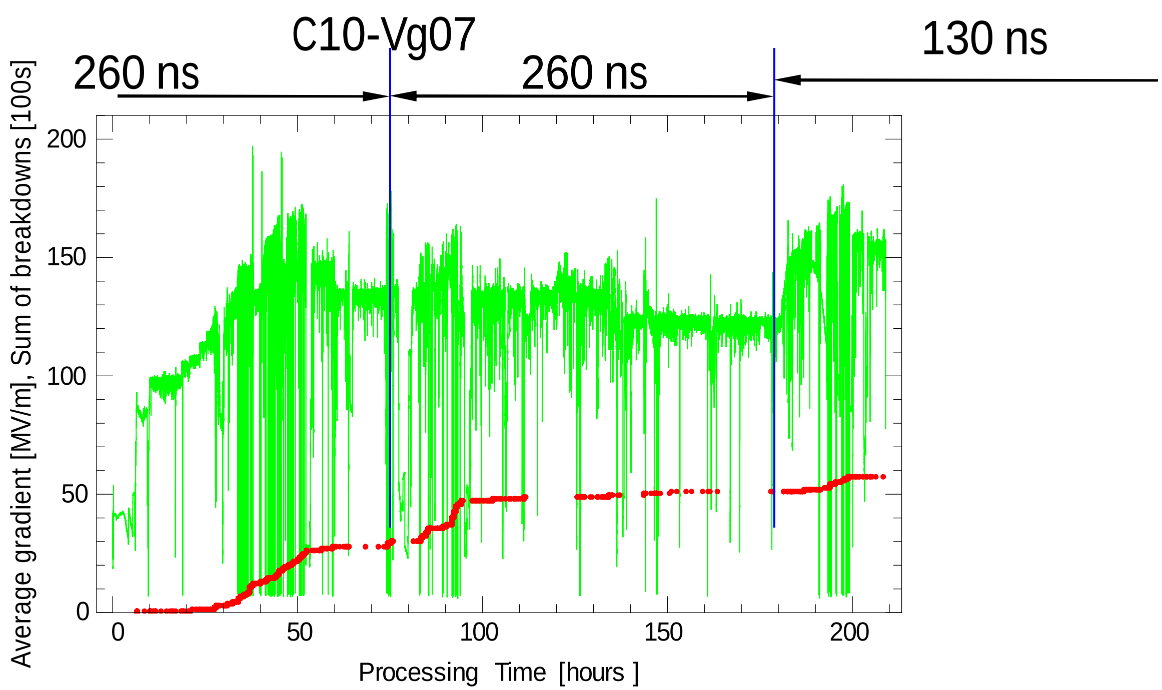


Processing of two 10 cell TW structures, C10-Vg1.35 and C10-Vg0.7

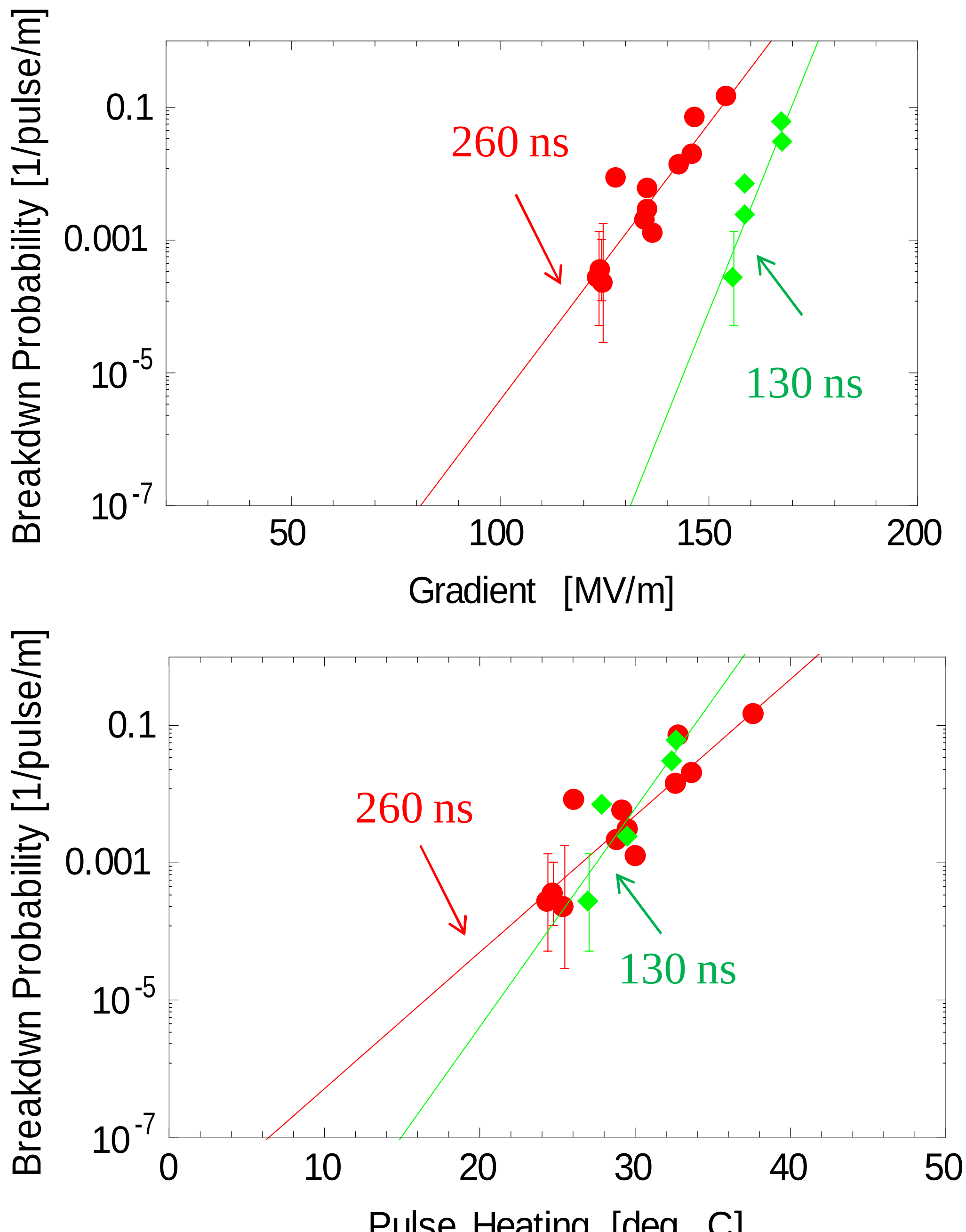
C10-Vg1.35



C10-Vg0.7

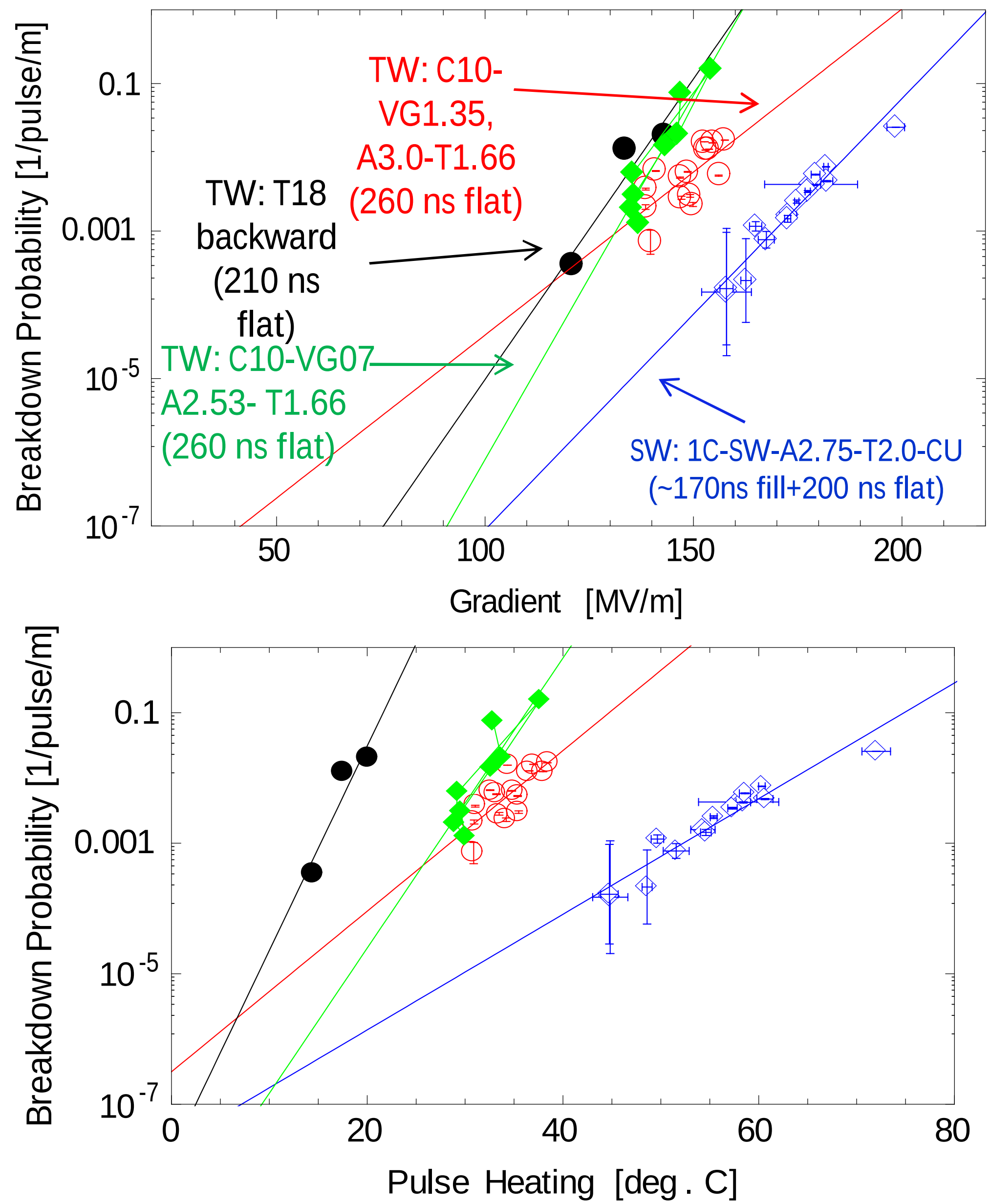


Breakdown rate *vs.* pulse length for C10-VG07

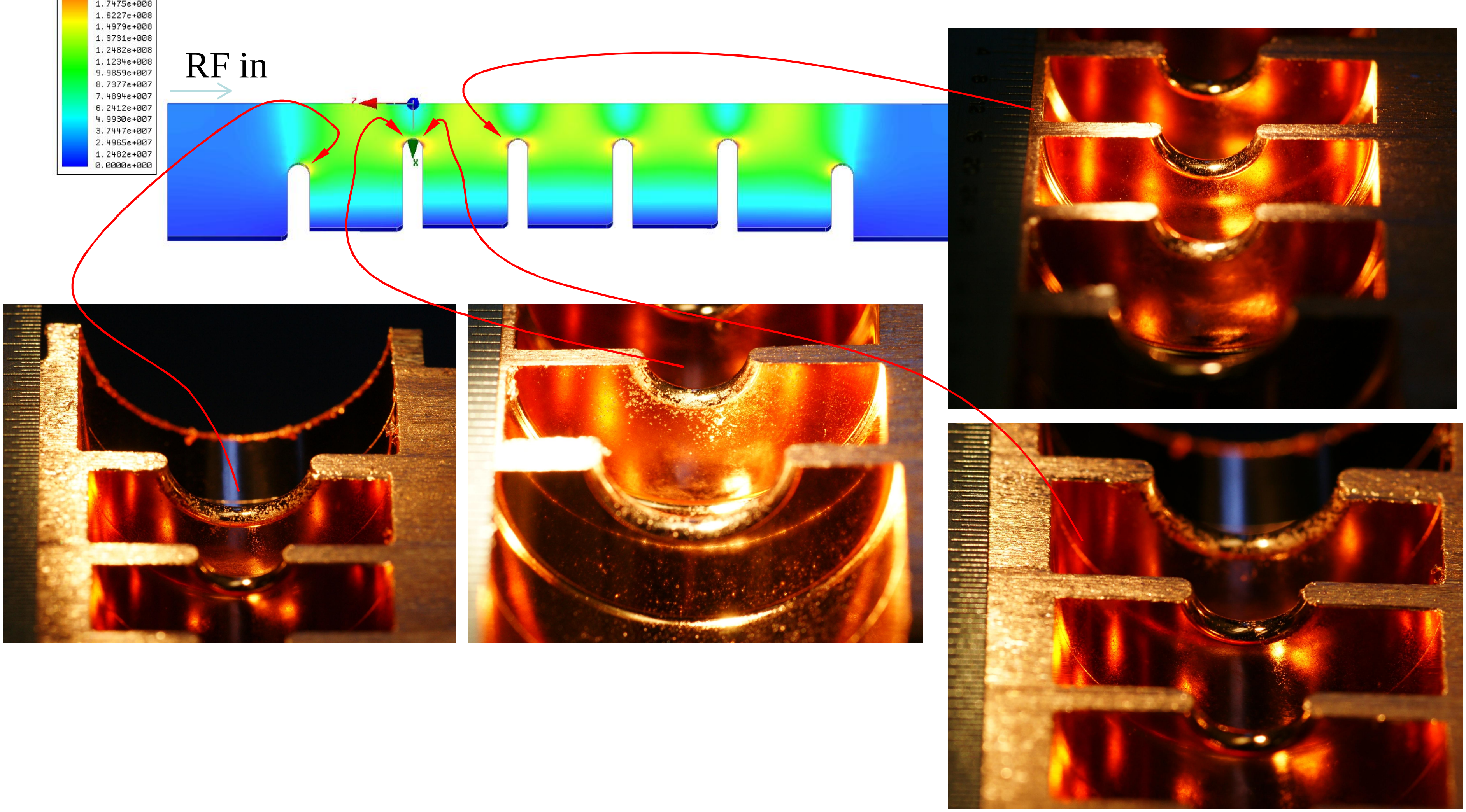


V.A. Dolgashev, S. Tantawi

Breakdown rate *vs.* gradient and peak pulse heating for three TW and one SW structure



Breakdown Damage in Coupler of 10 cell TW Structure C10-VG135



Summary

- Test results of two side coupled SW structures are opening possibility of building parallel-coupled SW structures capable of well above 100 MV/m gradients with apertures satisfactory for a linear collider.
- Test results of hard materials show that change in hardness for the Cu and Cu alloy changed response of the breakdown to pulse length: the breakdown rate lost correlation with Sqrt(pulse_length). This property is another proof that hardness of the material is of importance for breakdown physics.
- Test of 10 Cell TW structures showed gradients above 130 MV/m for ~260 ns pulse length with less than 10^{-3} breakdowns per pulse per meter. The breakdowns were observed in couplers of the structures. We think that by eliminating coupler effects we may be able to improve the performance of the structures.
- Test of T18 in a resonant ring is exploring circuit dependence of rf breakdowns due to external circuit which should automatically shut off breakdowns.

Parameters of *periodic* structures, Eacc=100 MV/m

Name	A2.75-T2.0-Cu	A3.75-T1.66-Cu	A3.75-T2.6-Cu	A3.75-T2.6-Ch-4mm-Cu	A5.65-T4.6-Choke-Cu	A5.65-T4.6-PBG-Cu	A5.65-T4.6-Cu	*T53VG3*
Stored Energy [J]	0.153	0.189	0.189	0.294774	0.333	0.311	0.298	*0.09*
Q-value [x1000]	8.59	8.82	8.56	8.39	7.53	6.29	8.38	*6.77*
Shunt Impedance [MOhm/m]	102.891	85.189	82.598	52.03	41.34	36.46	51.359	*91.772*
Max. Mag. Field [A/m]	2.90E+05	3.14E+05	3.25E+05	3.45E+05	4.20E+05	8.95E+5	4.18E+05	*2.75E+05*
Max. Electric Field [MV/m]	203.1	266	202.9	210.4	212	212	211.4	*217.5*
Losses in one cell [MW]	1.275	1.54	1.588	2.521	3.173	3.60	2.554	*0.953*
a [mm]	2.75	3.75	3.75	3.75	5.65	5.65	5.65	*3.885*
a/lambda	0.105	0.143	0.143	0.143	0.215	0.215	0.215	*0.148*
Hmax*Z0/Eacc	1.093	1.181	1.224	1.300	1.581	3.371	1.575	*1.035*
t [mm]	2	1.664	2.6	2.6	4.6	4.6	4.6	*1.66*
Iris ellipticity	1.385	0.998	1.692	1.692	1.478	1.478	1.478	*1*
Ph. advance/cell [deg.]	180	180	180	180	180	180	180	*120*

V.A. Dolgashev, 12 May 2009