Status of High Gradient Tests of Normal Conducting Single-Cell Structures

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X-Band RF Structure and Beam Dynamics Workshop, 1-4 December, 2008 at The Cockroft Institute, UK

Outline

- Introduction
- Strategy
- Structures
- Results

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

- A. Yeremian, J. Lewandowski *of Accelerator Technology Research*
- C. Pearson, J. Eichner, D. Martin, C. Yoneda, L. Laurent, R. Talley, J. Zelinski and staff *of Klystron Lab.*
- Z. Li, *Advanced Computation*

In collaboration with :

- R. Marsh, *MIT*
- B. Spataro, *INFN, Frascati*

Single Cell Accelerator 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

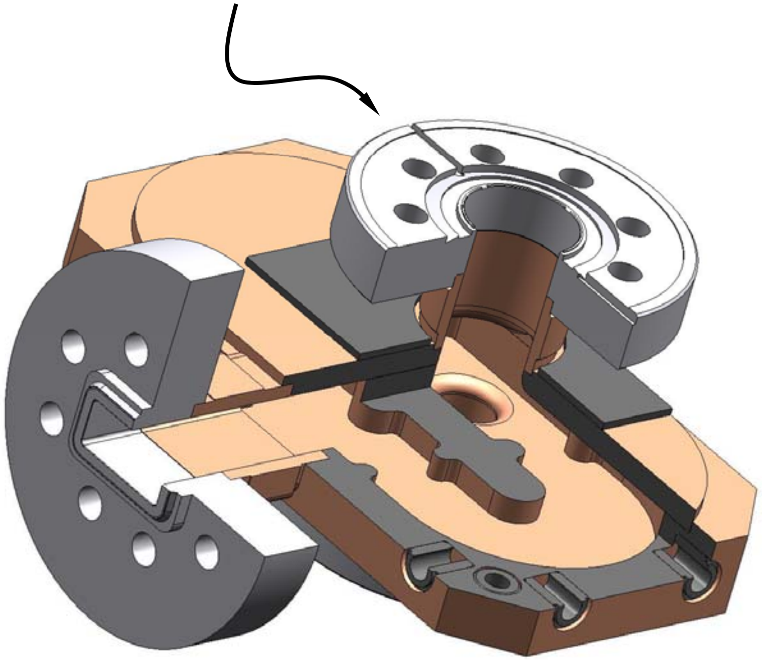
Solution

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

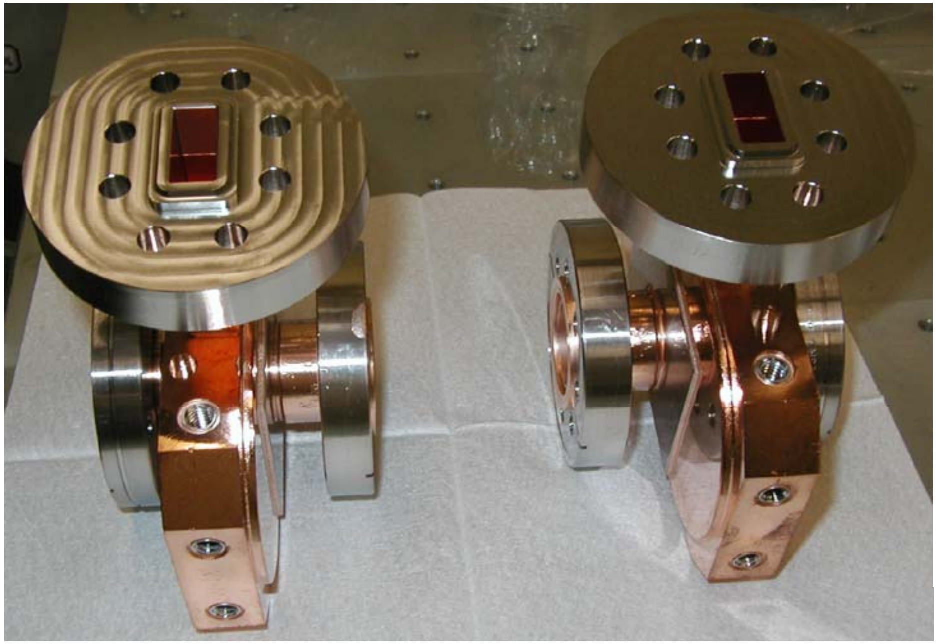
We want to predict breakdown behavior for practical structures

Reusable coupler: TM_{01} Mode Launcher

Pearson's RF flange



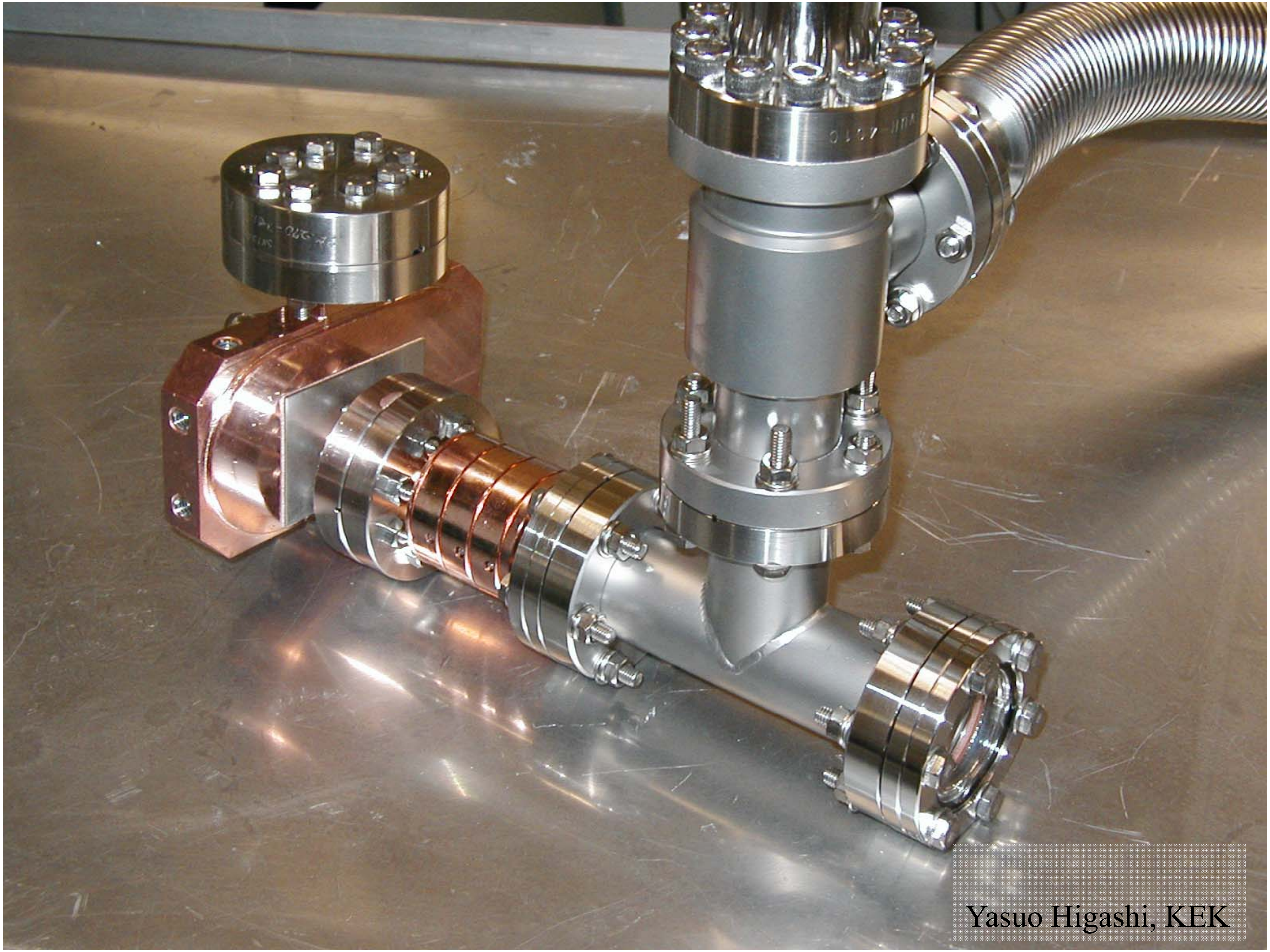
Cutaway view of the mode launcher



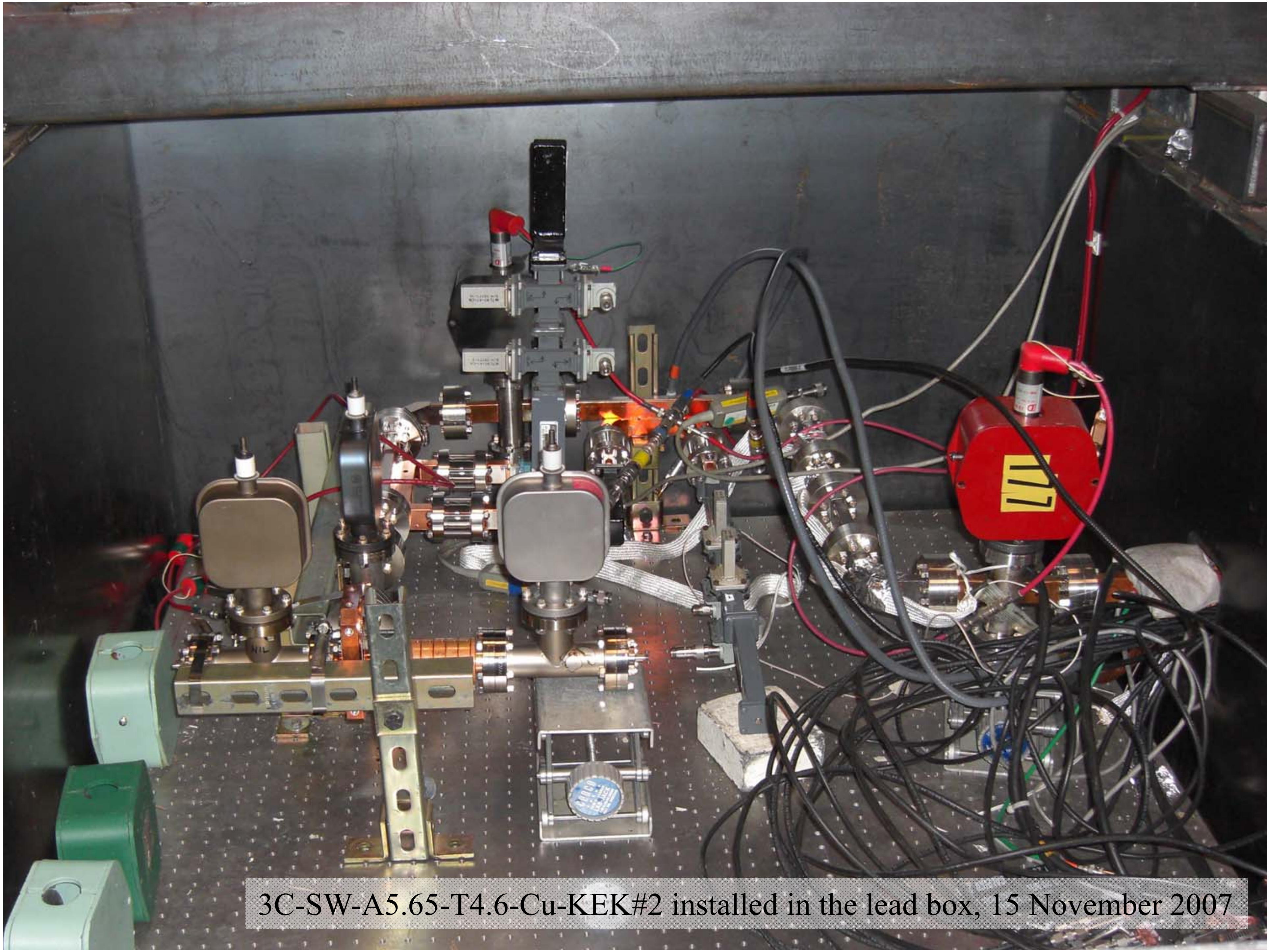
Two mode launchers

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

S. Tantawi, C. Nantista



Yasuo Higashi, KEK



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

Strategy

Geometry

- Stored energy, 1-cell vs. 3-cell
- Electric field for same magnetic field
- Choke 1 mm
- Choke 4 mm
- PBG
- Choke WR90 coupler
- Shunt impedance, iris size, etc.
- …

Materials

- CuZr
- CuCr
- CuAg
- Molybdenum

…

Coatings

- TiN
- …

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
- Choke with 1mm gap in high gradient cell, *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

Now 15th test under way,
highest shunt impedance copper structure
1C-SW-A2.75-T2.0-Cu-SLAC-#1

Next experiments, as for 30th November 2008

Reproducibility tests:

High shunt impedance, elliptical iris, *1C-SW-A3.75-T2.6-Cu*
High shunt impedance, round iris, *1C-SW-A3.75-T1.66-Cu*
Low shunt impedance, made of CuZr, *1C-SW-A5.65-T4.6-CuZr*
Three high gradient cells, low shunt impedance, *3C-SW-A5.65-T4.6-Cu*

Geometry tests:

Photonic-Band-Gap in high gradient cell, *1C-SW-A5.65-T4.6-Cu-PBG*
Three cells, WR90 1mm gap choke coupling to power source,
3C-SW-A5.65-T4.6-Cu-WR90
High shunt impedance, choke with 4mm gap, *1C-SW-A3.75-T2.6-Choke-Cu*
Choke with 4mm gap in high gradient cell, *1C-SW-A5.65-T4.6-Choke-Cu*

Materials:

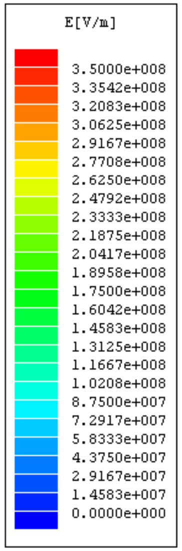
High shunt impedance, elliptical iris, 6N copper, *1C-SW-A3.75-T2.6-6N-Cu*
High shunt impedance, made of CuZr, *1C-SW-A3.75-T2.6-CuZr*
High shunt impedance, made of CuAg, *1C-SW-A3.75-T2.6-CuAg*
Low shunt impedance, made of CuAg, *1C-SW-A5.65-T4.6-CuAg*

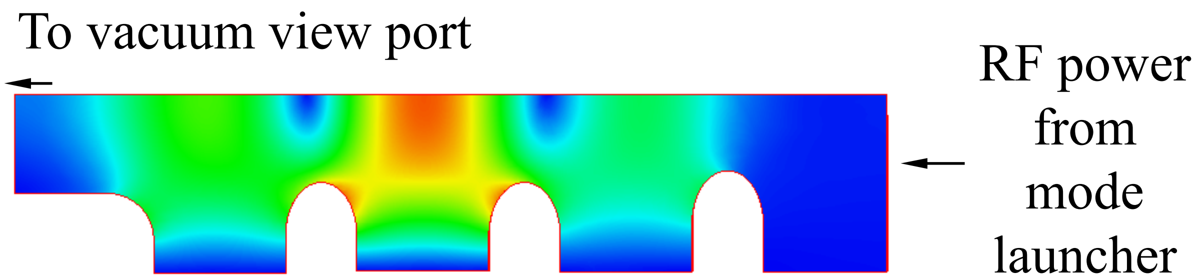
Parameters of *periodic* structures, Eacc=100 MV/m

Name	A2.75-T2.0-Cu	A3.75-T1.66-Cu	A3.75-T2.6-Cu	A5.65-T4.6-Choke-Cu	A5.65-T4.6-Cu	*T53VG3*
Stored Energy [J]	0.153	0.189	0.189	0.333	0.298	*0.09*
Q-value	8.59E+03	8.82E+03	8.56E+03	7.53E+03	8.38E+03	*6.77E+03*
Shunt Impedance [MOhm/m]	102.891	85.189	82.598	41.34	51.359	*91.772*
Max. Mag. Field [A/m]	2.90E+05	3.14E+05	3.25E+05	4.20E+05	4.18E+05	*2.75E+05*
Max. Electric Field [MV/m]	203.1	266	202.9	212	211.4	*217.5*
Losses in one cell [MW]	**1.275**	**1.54**	**1.588**	**3.173**	**2.554**	***0.953***
a [mm]	2.75	3.75	3.75	5.65	5.65	*3.885*
a/lambda	**0.105**	**0.143**	**0.143**	**0.215**	**0.215**	***0.148***
Hmax*Z0/Eacc	1.093	1.181	1.224	1.581	1.575	*1.035*
t [mm]	2	1.664	2.6	4.6	4.6	*1.66*
Iris ellipticity	1.385	0.998	1.692	1.478	1.478	*1*
Ph. advance/cell [deg.]	180	180	180	180	180	*120*

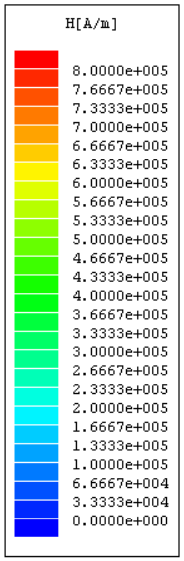
Single-Cell-SW-A5.65-T4.6-Cu

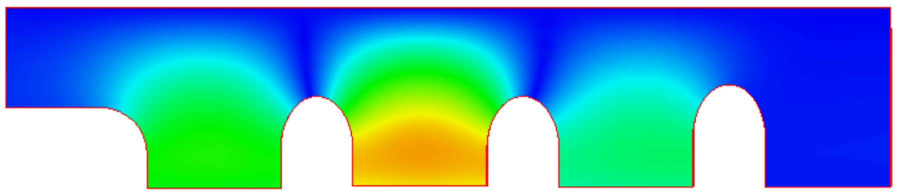
10 MW input





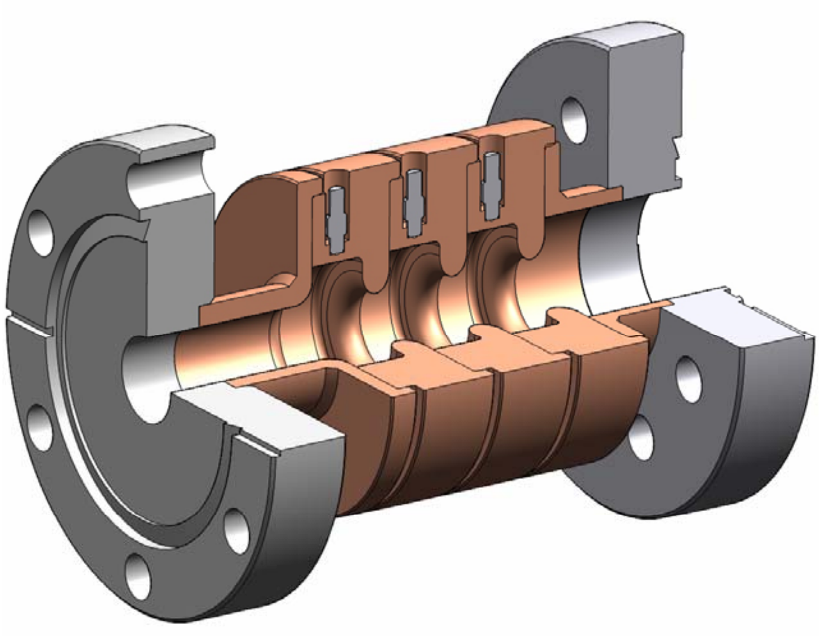
Amplitude of electric fields, maximum surface field **310 MV/m**



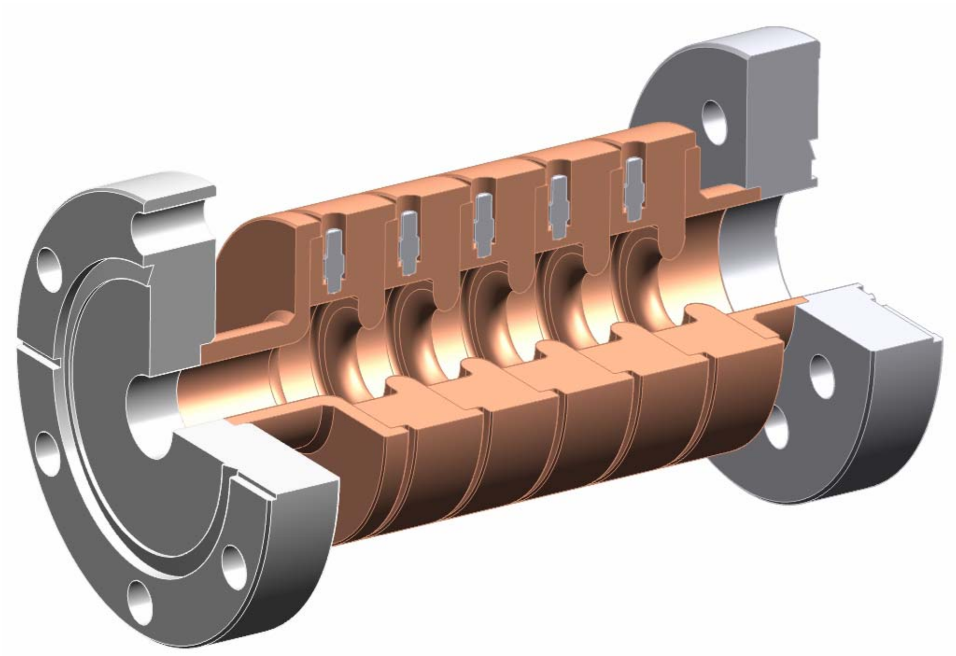


Amplitude of magnetic fields, maximum magnetic field **634.5 kA/m**

Low shunt impedance structures, a/λ=0.215



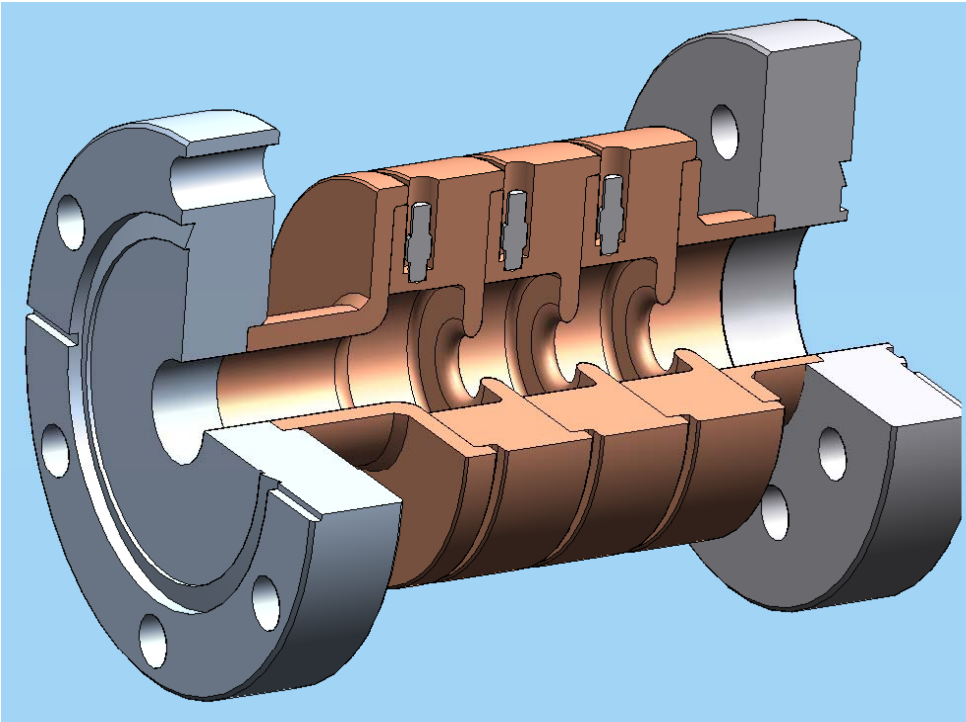
1C-SW-A5.65-T4.6-Cu



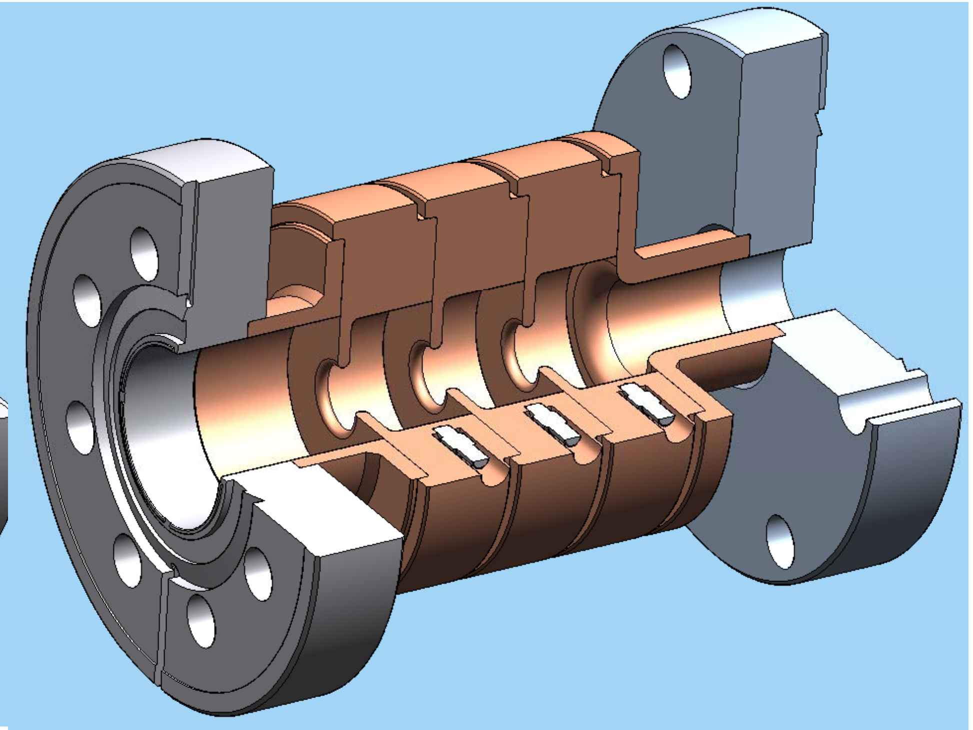
3C-SW-A5.65-T4.6-Cu

Solid Model: David Martin

High shunt impedance structures, $a/\lambda=0.143$



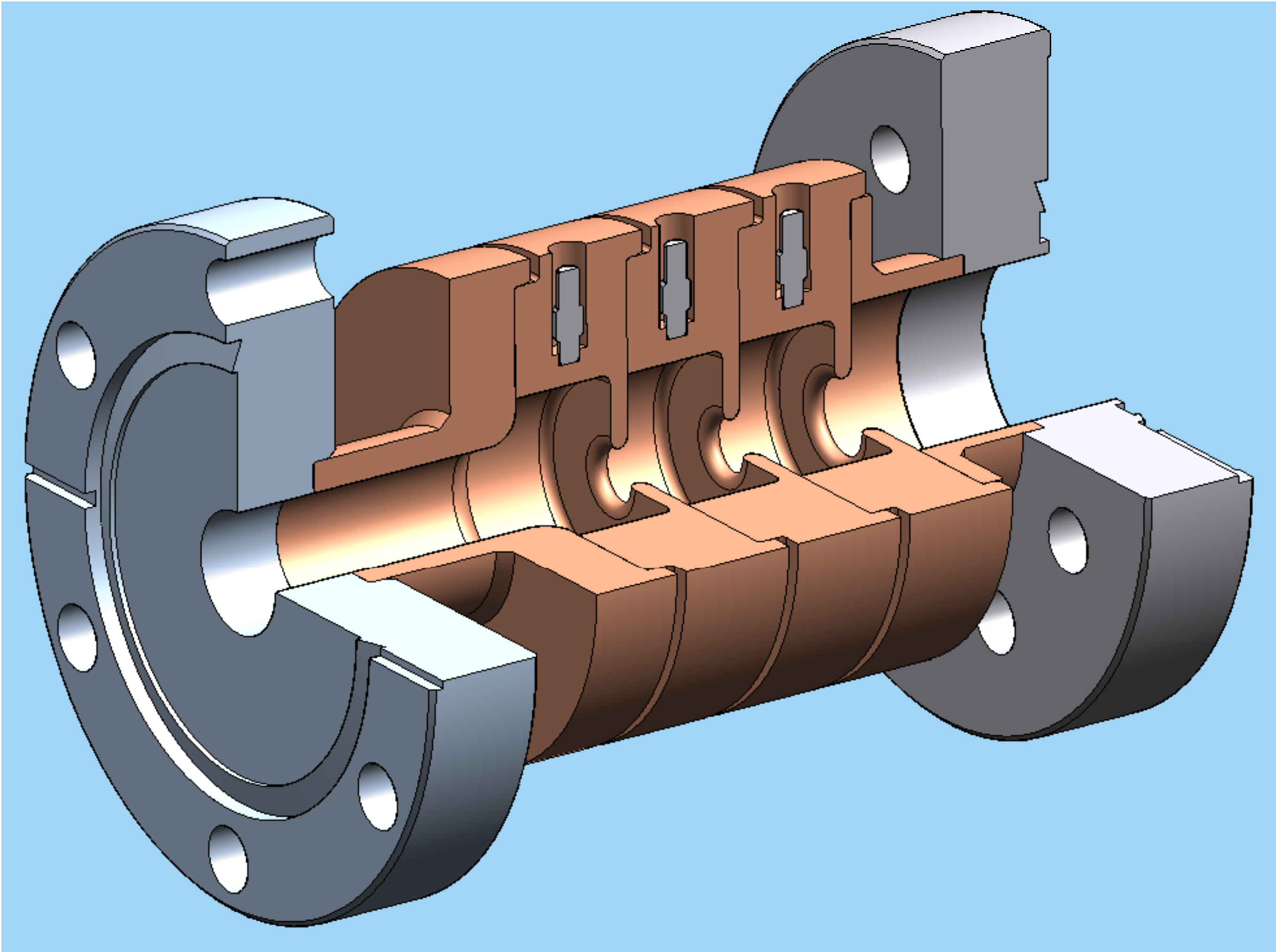
1C-SW-A3.75-T2.6-Cu



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

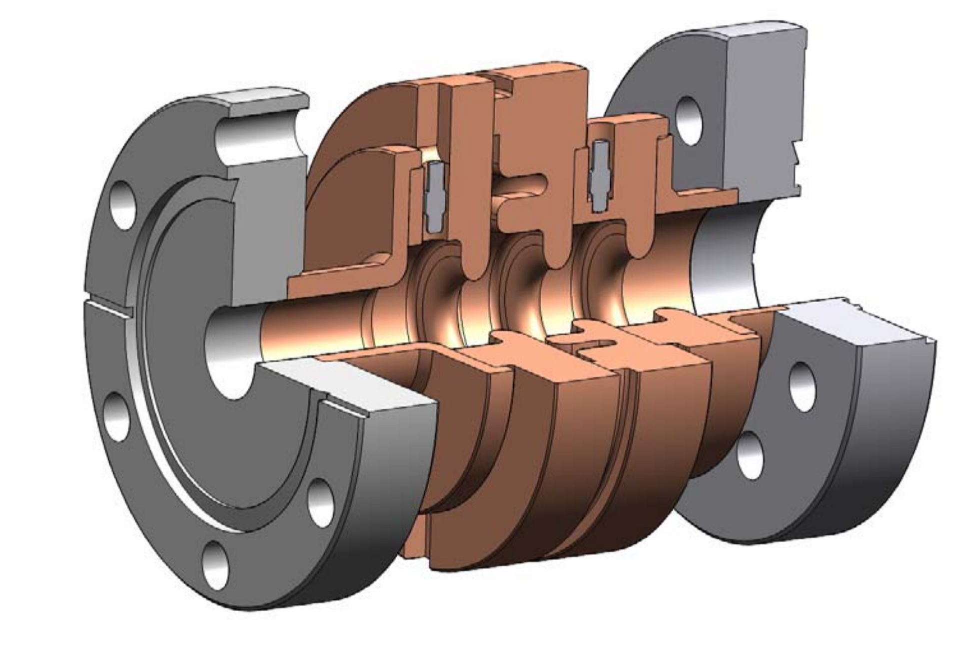
Solid Model: David Martin

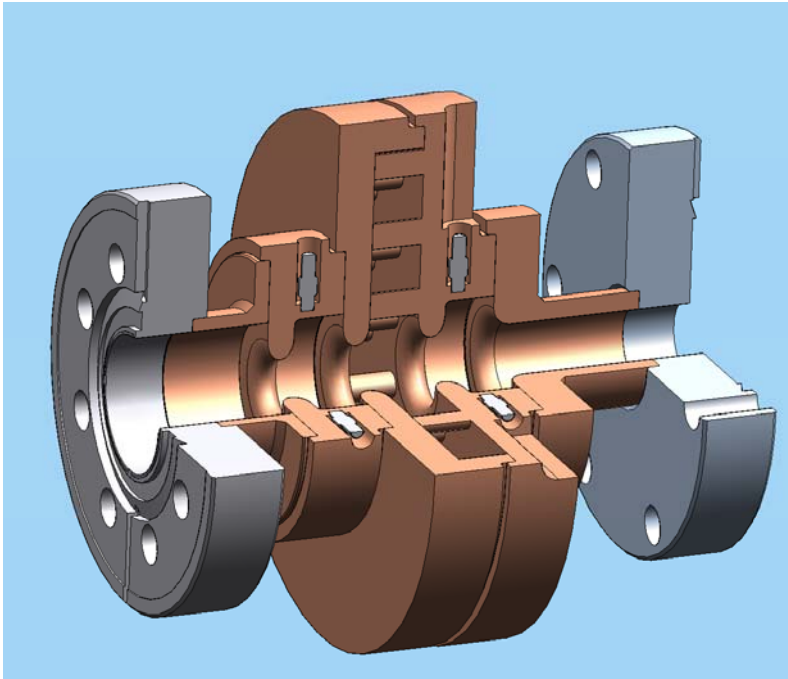
Highest shunt impedance structure, $a/\lambda = 0.105$



1C-SW-A3.75-T2.6-Cu *Solid Model: David Martin*

Wakefield damping “ready” structures, a/λ=0.215



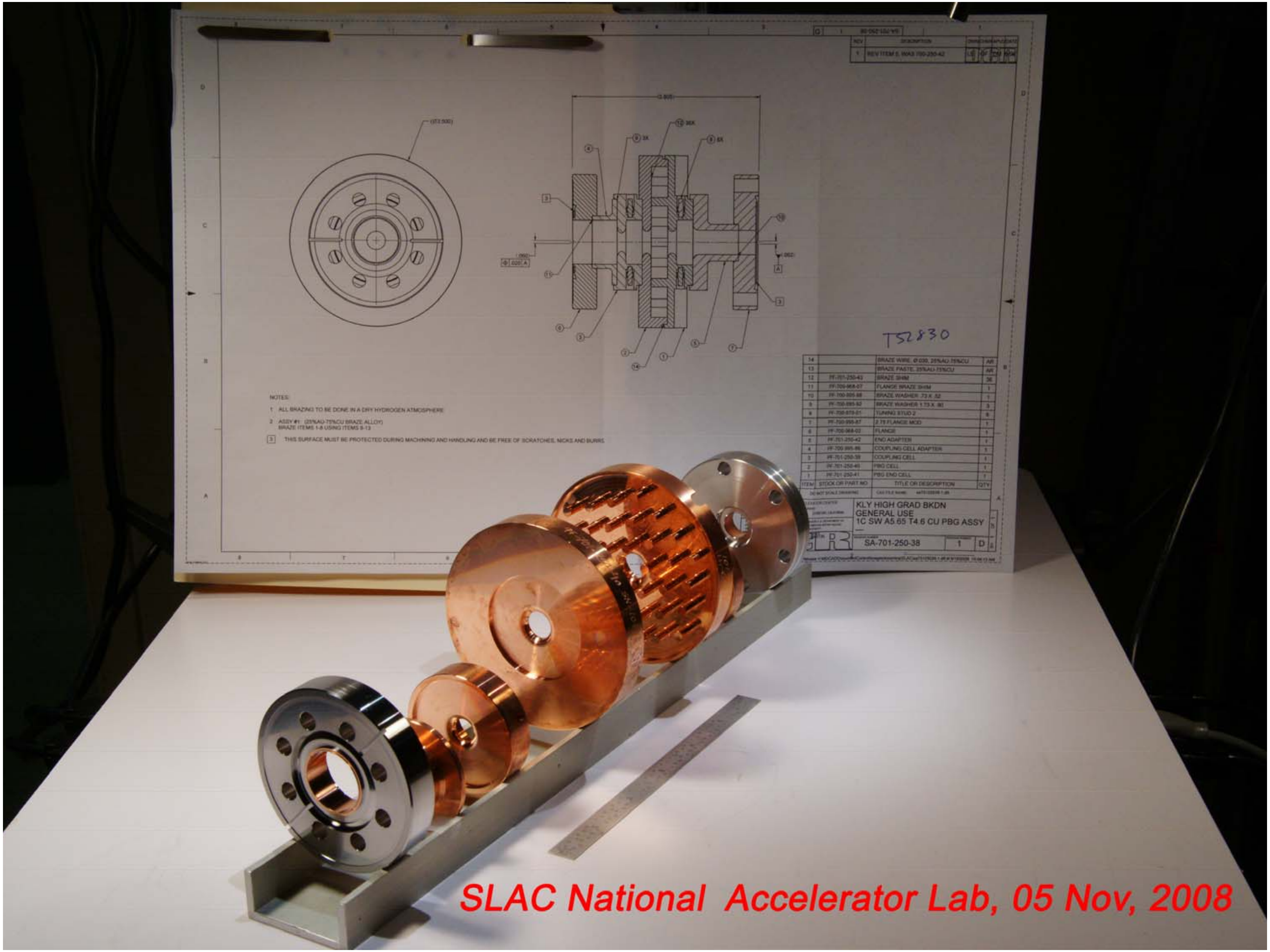


Electrical design: Roark Marsh, MIT

1C-SW-A5.65-T4.6-Cu-Choke

1C-SW-A5.65-T4.6-Cu-PBG

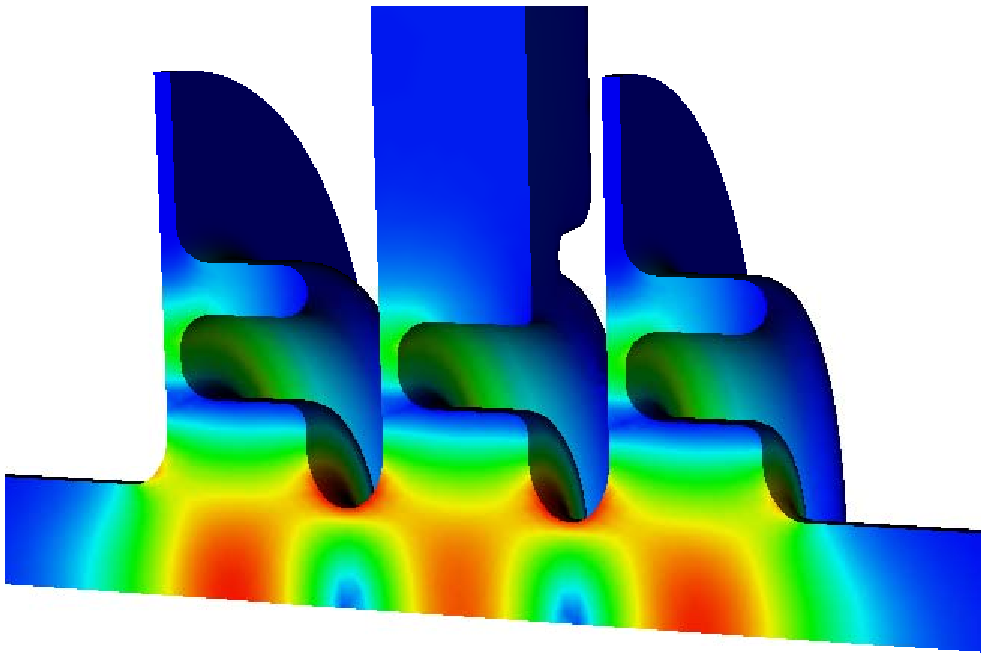
Solid Models: David Martin


T52830
KLY HIGH GRAD BKDN
GENERAL USE
1C SW A5.65 T4.6 CU PBG ASSY
SA-701-250-38
SLAC National Accelerator Lab, 05 Nov, 2008

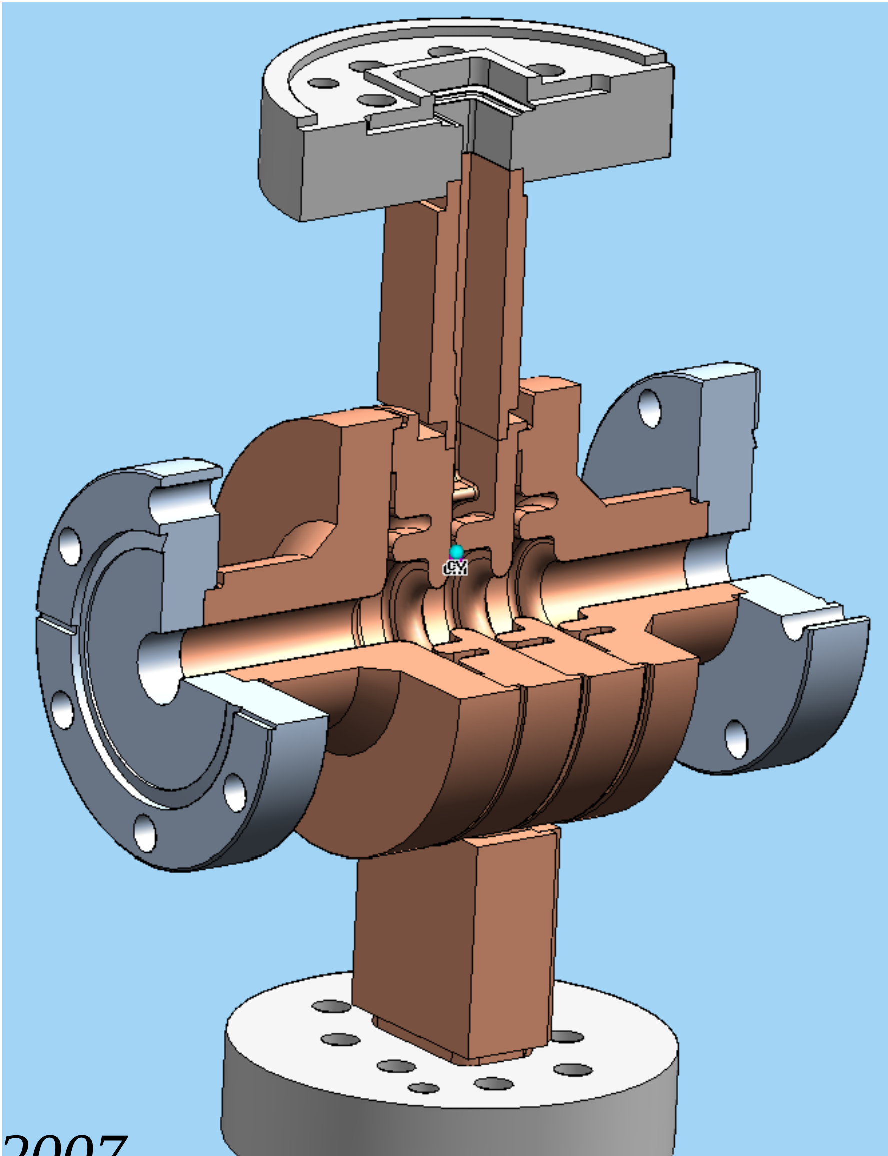

SLAC National Accelerator Lab, 05 Nov, 2008

3-Cell structure with choke coupler and WR90 inputs

3C-SW-A5.65-T4.6-Cu-WR90, $a/\lambda=0.215$



Surface electric fields

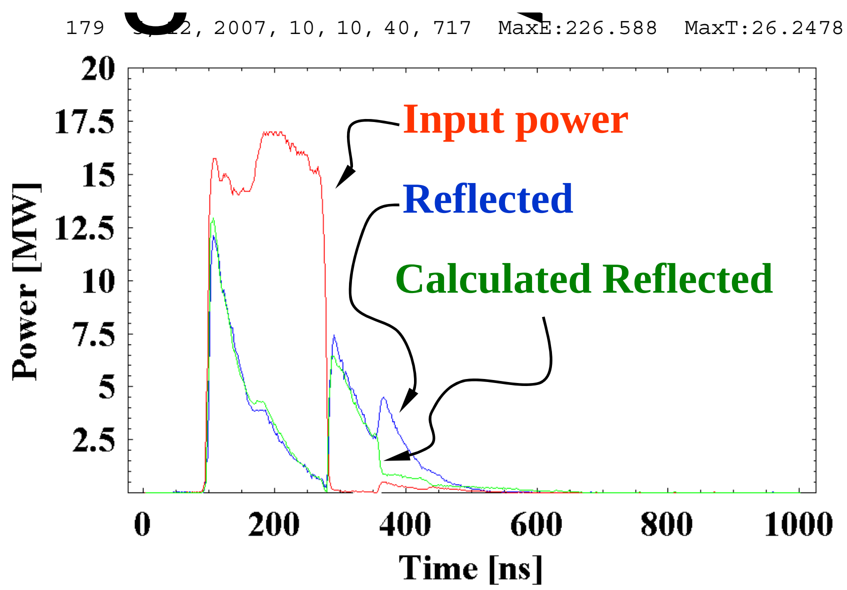


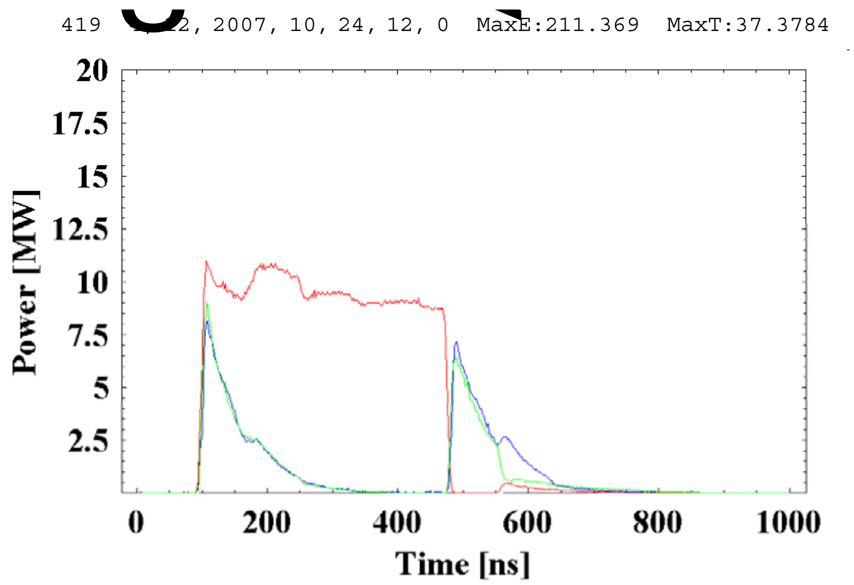
Electrical design: Z. Li, 8 November 2007

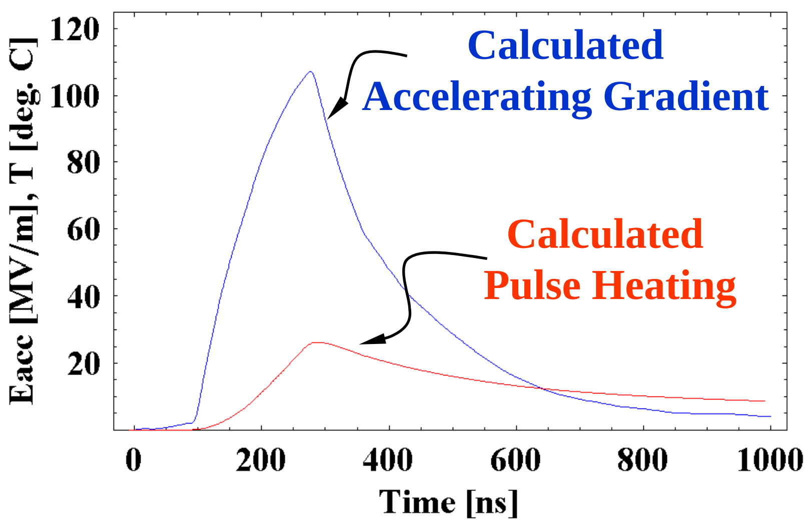
Solid Model: David Martin

Results

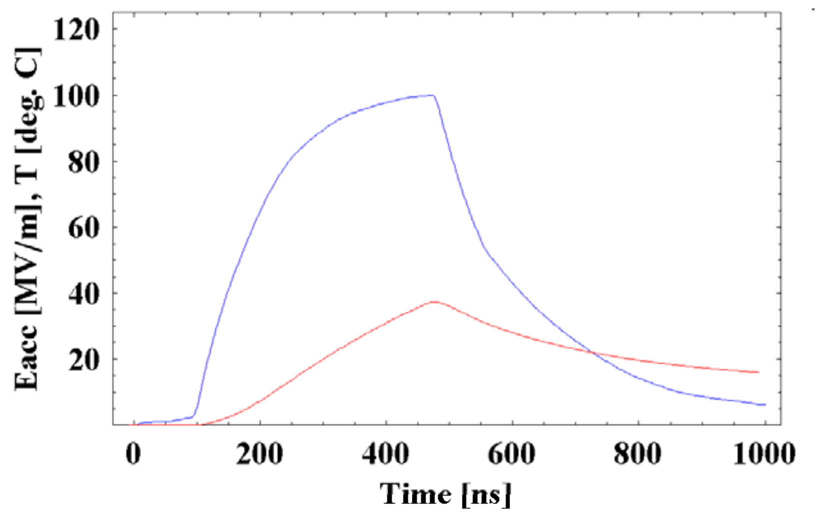
RF pulse profile: “square” pulse





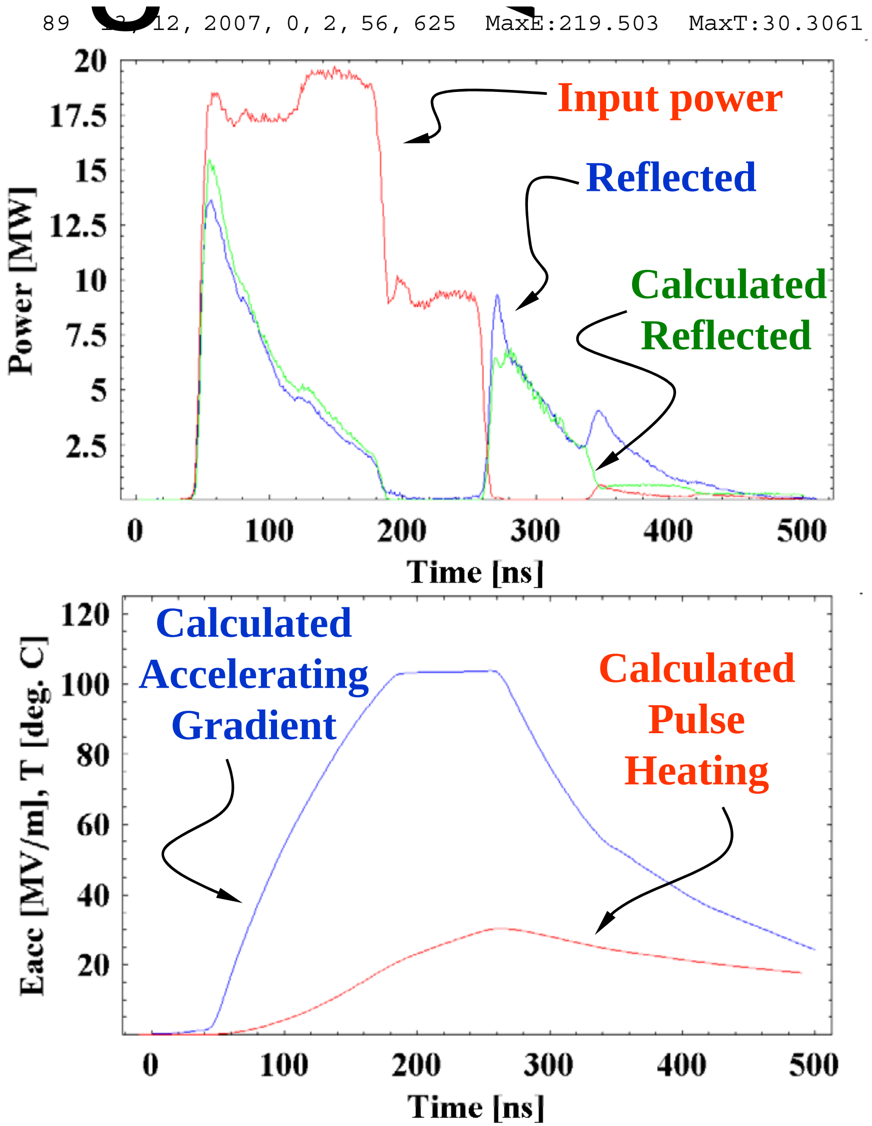


Input pulse length ~175 ns

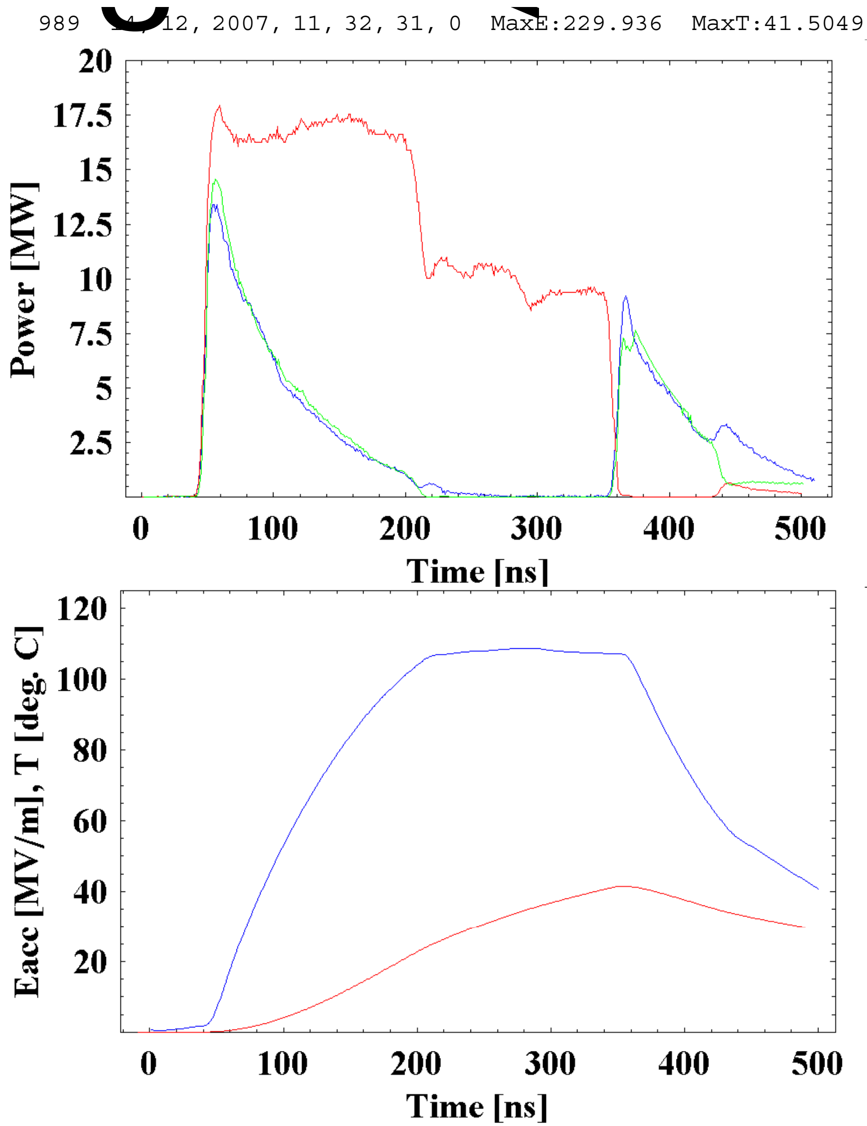


Input pulse length ~380 ns

RF pulse profile: “shaped” pulse



Total input pulse length ~215 ns,
flat part ~80 ns

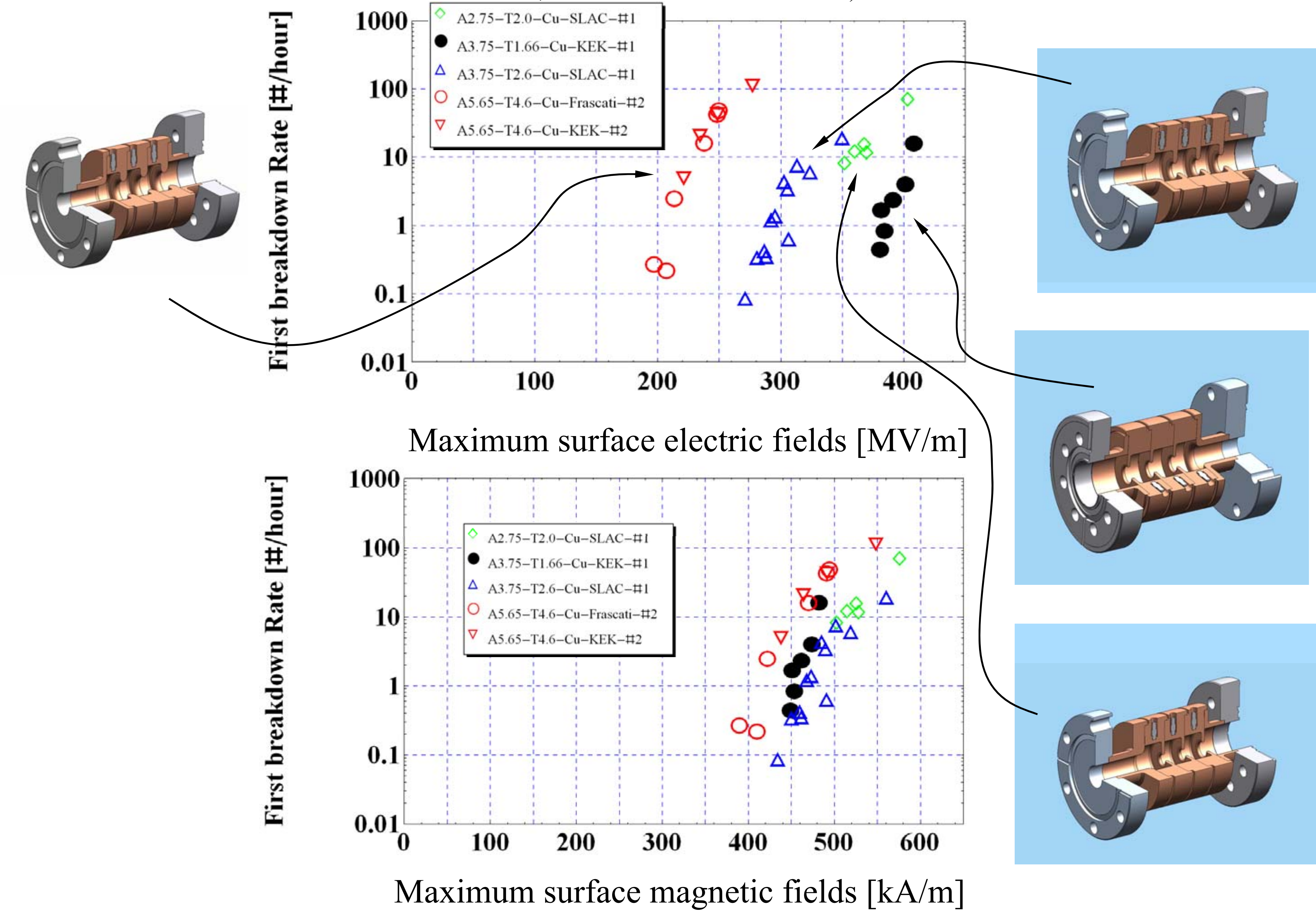


Total input pulse length ~310 ns,
flat part ~150 ns

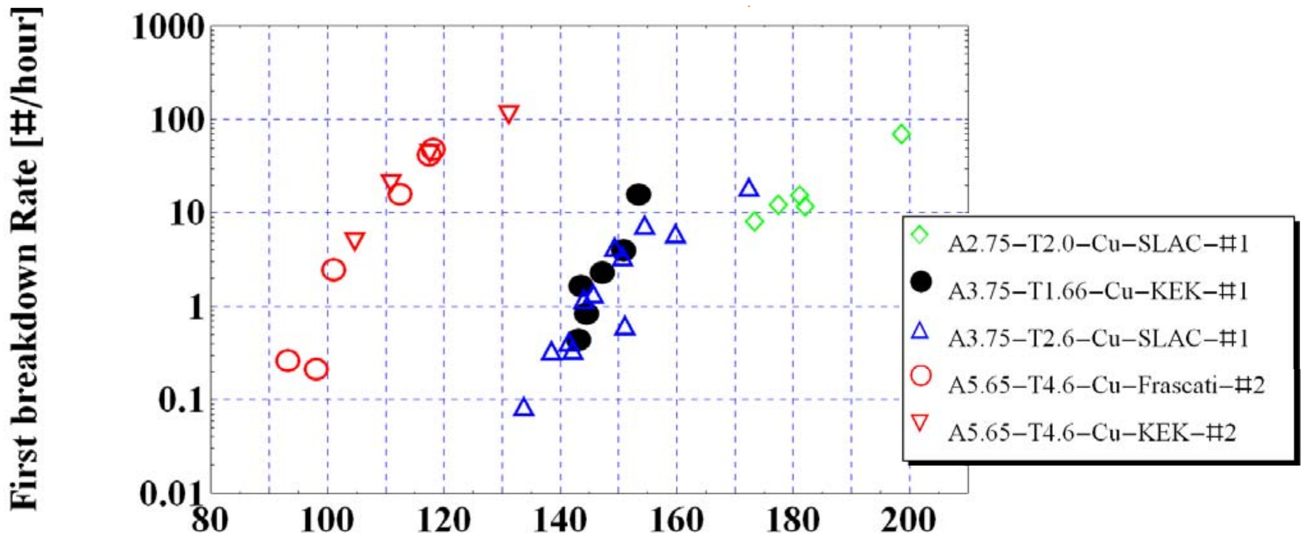
Geometries

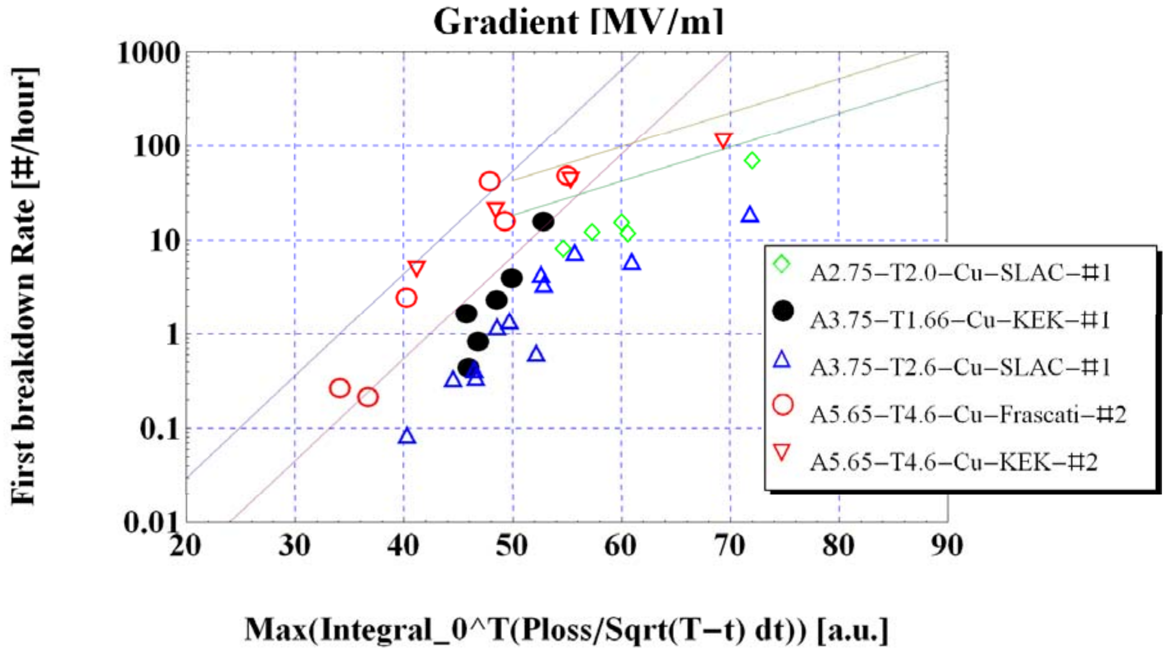
Surface fields for 5 different single cell structures, *shaped* pulse

(*flat* part: A5.65-T4.6-KEK-#1- 150 ns, A5.65-T4.6-Frascati-#2- 150 ns, A3.75-T2.6-Cu-SLAC-#1: 150 ns, A3.75-T1.66-Cu-KEK-#1 200 ns, A2.75-T2.0-Cu-SLAC-#1 200 ns)

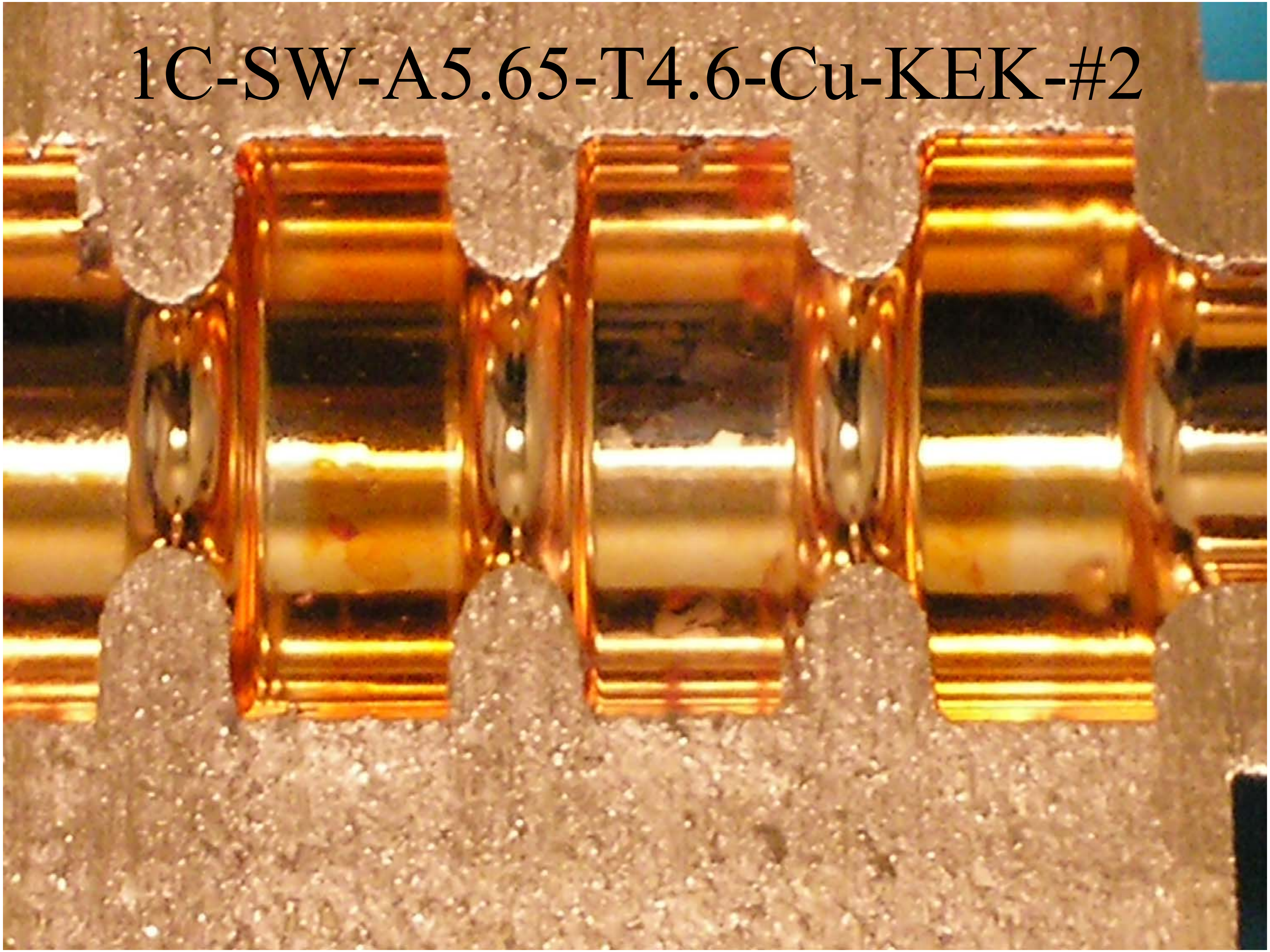


Gradient and pulse heating for 5 different single cell structures, *shaped* pulse (*flat* part: A5.65-T4.6-KEK-#1- 150 ns, A5.65-T4.6-Frascati-#2- 150 ns, A3.75-T2.6-Cu-SLAC-#1: 150 ns, A3.75-T1.66-Cu-KEK-#1 200 ns, A2.75-T2.0-Cu-SLAC-#1 200 ns)

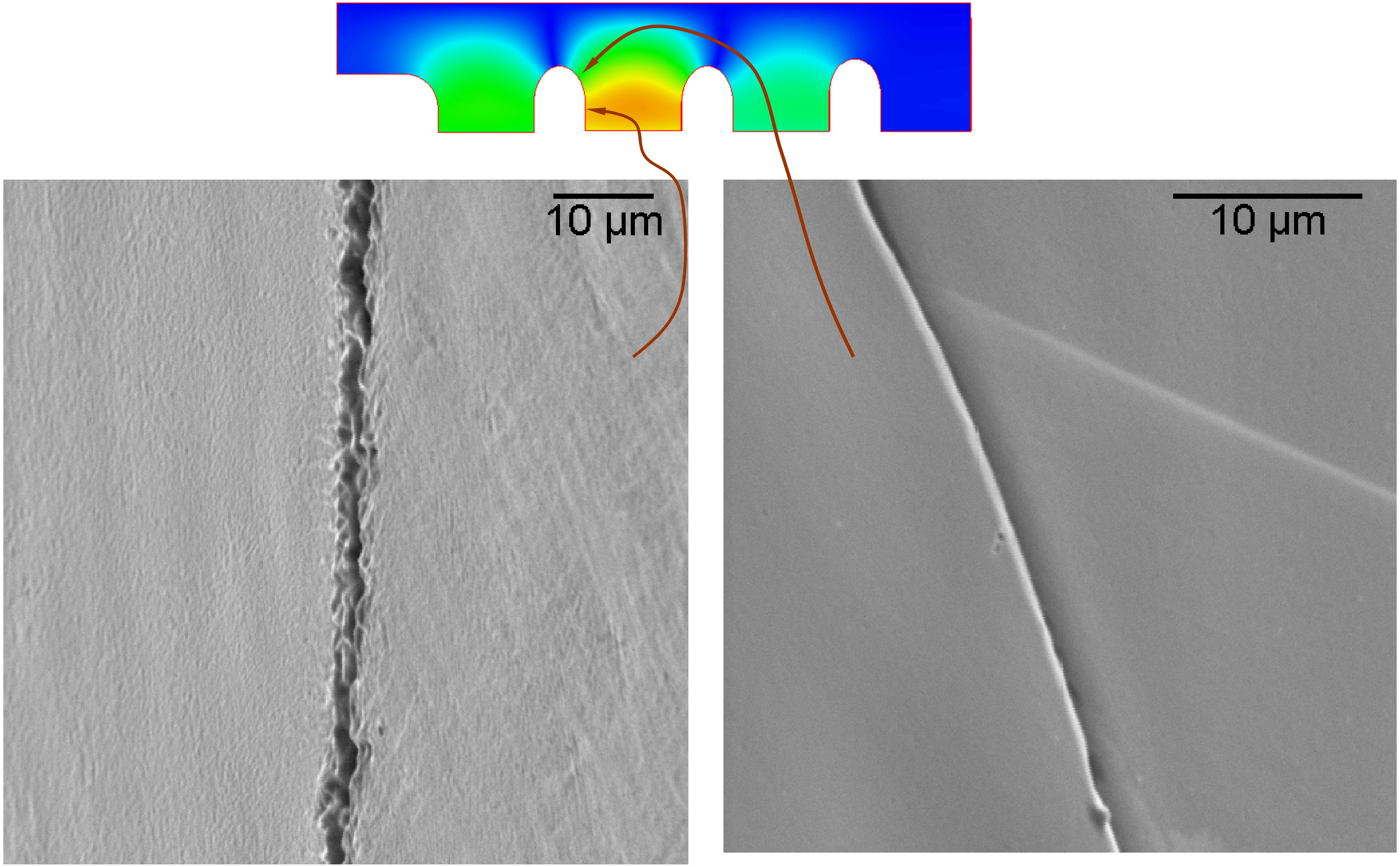




Pulse heating damage in copper structures


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

Grain boundary on iris of 1C-SW-A5.65-T4.6-Cu-KEK-#2

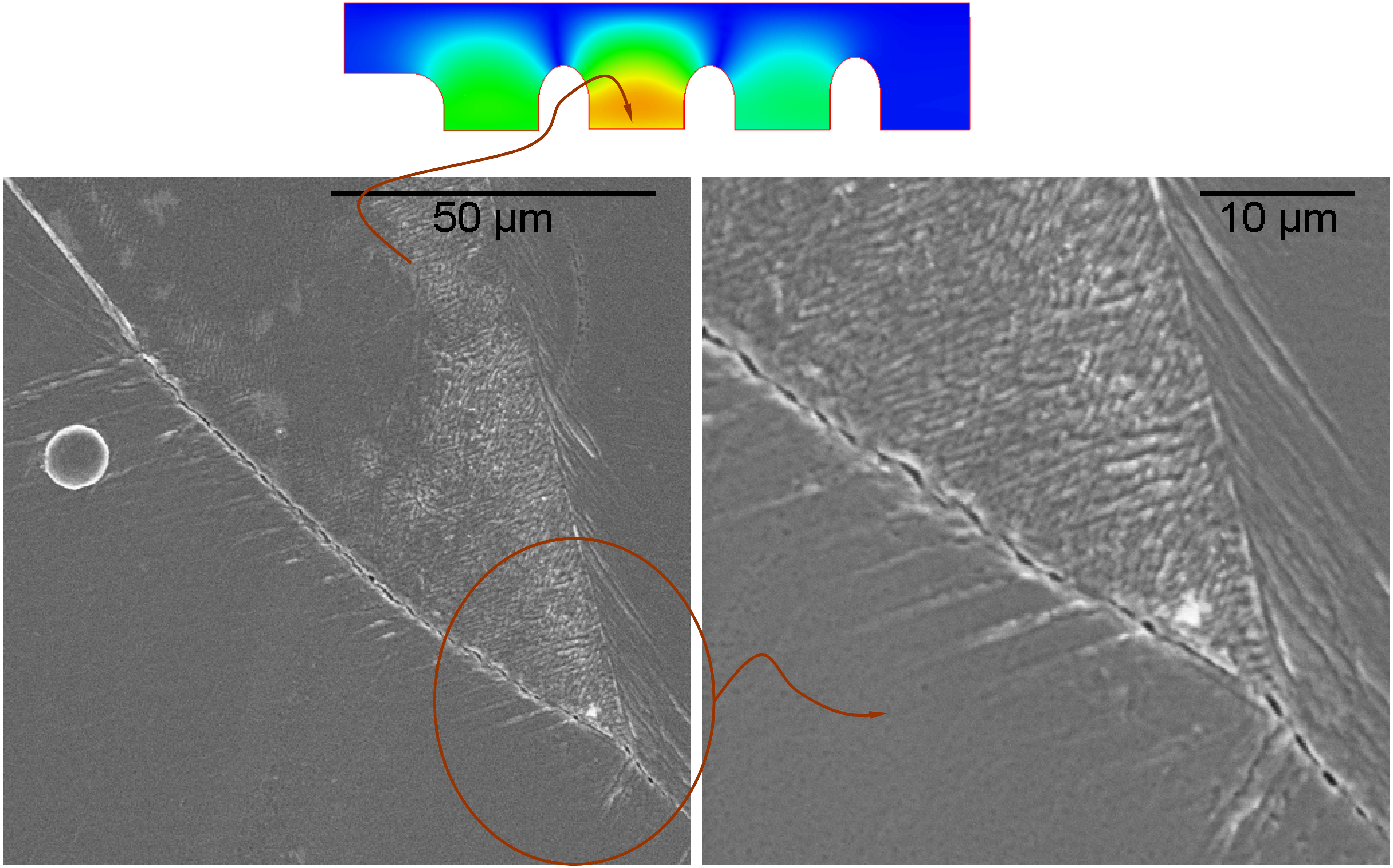


Grain boundary in high **magnetic** field area

Grain boundary in high **electric** field area

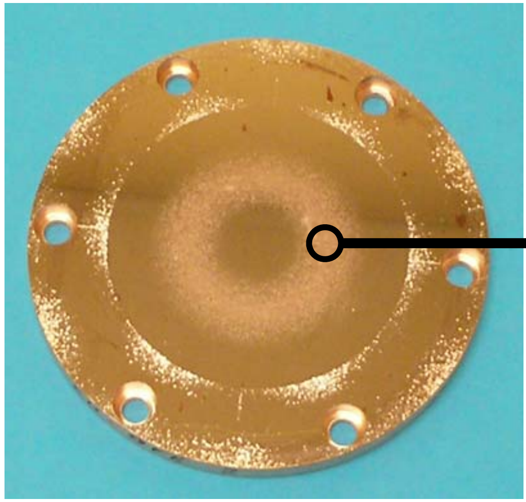
Lisa Laurent, 20 March 2008

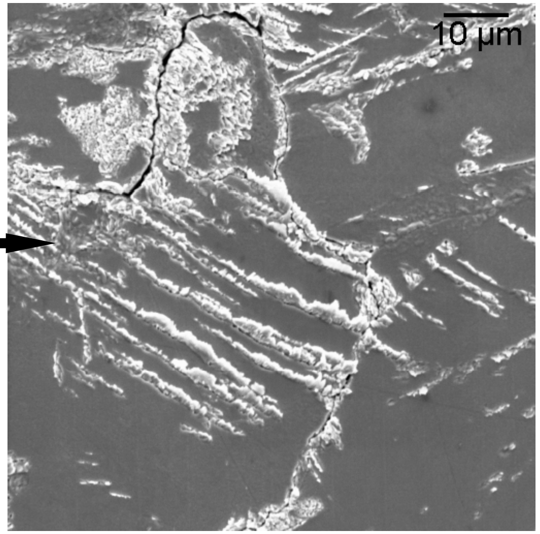
Cracks between grains and deformation of the grain on outside wall of 1C-SW-A5.65-T4.6-Cu-KEK-#2

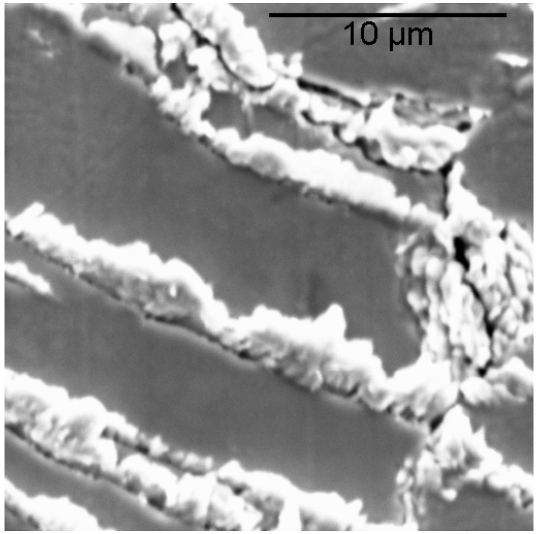


Lisa Laurent, 20 March 2008

Pulsed Heating Experiments



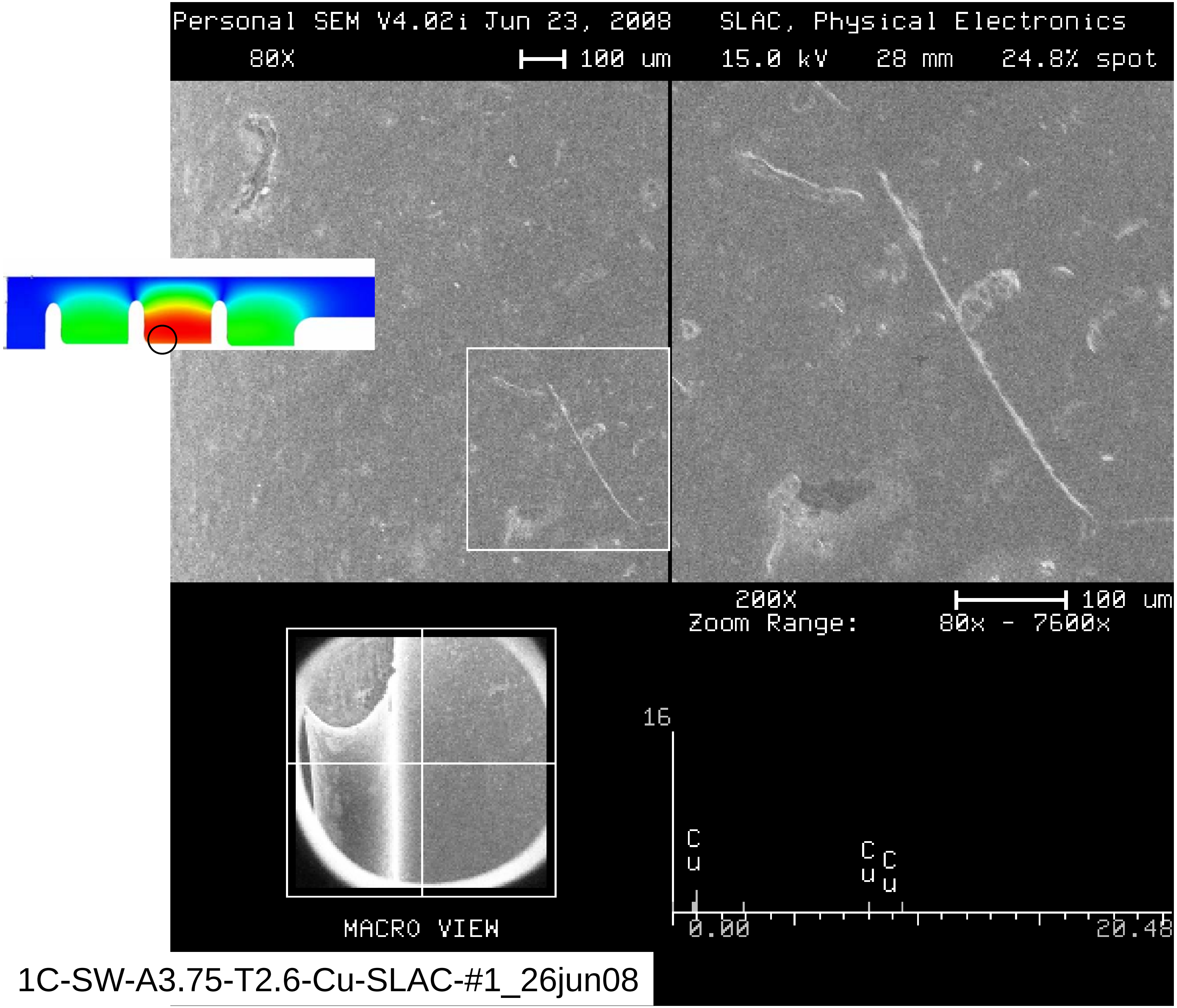




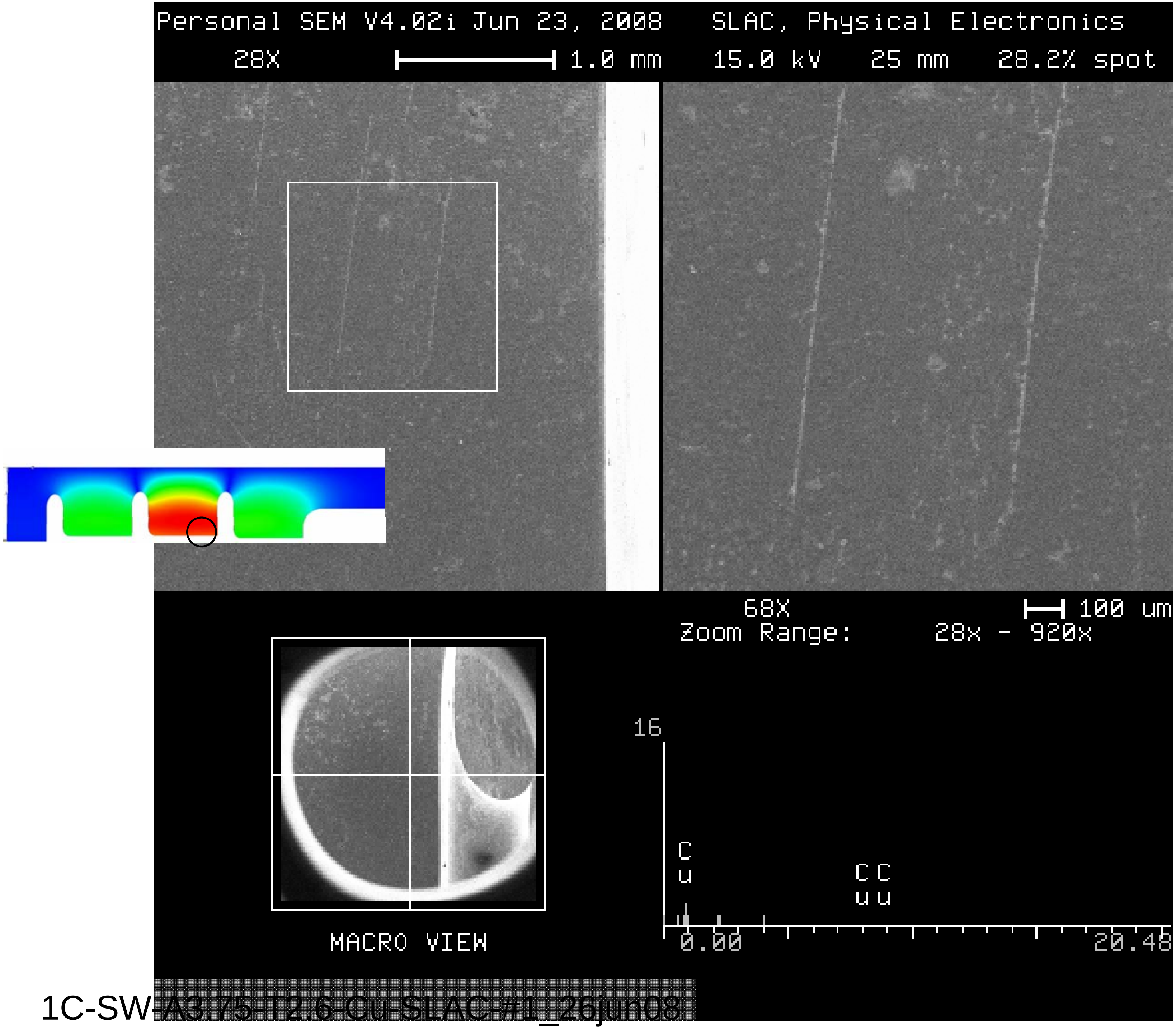
Photograph of pulse heating sample Cu OFE 2 after rf processing

SEM image showing large amounts of copper has apparently erupted through the cracks.

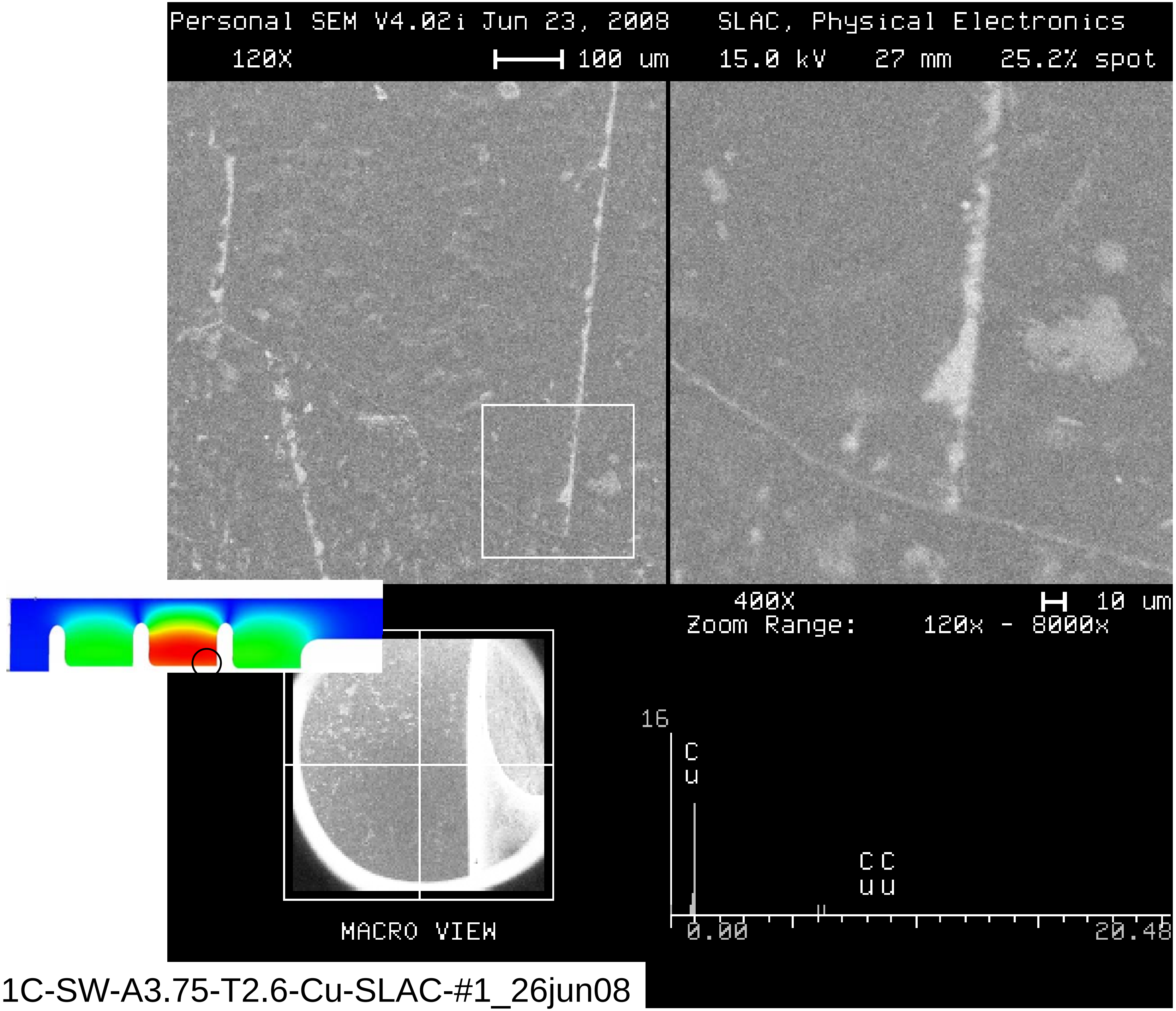
SEM - Lisa Laurent



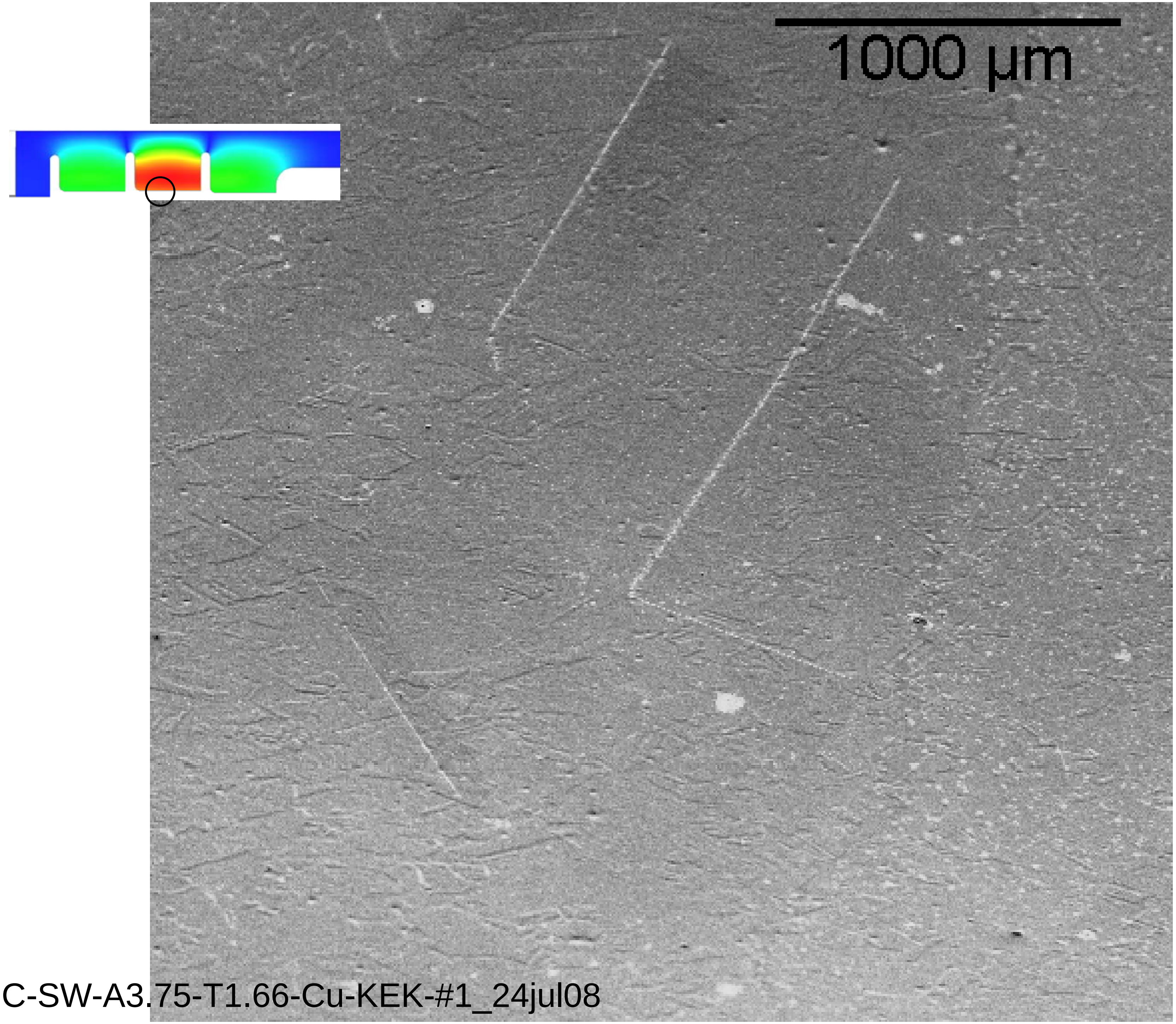
1C-SW-A3.75-T2.6-Cu-SLAC-#1_26jun08



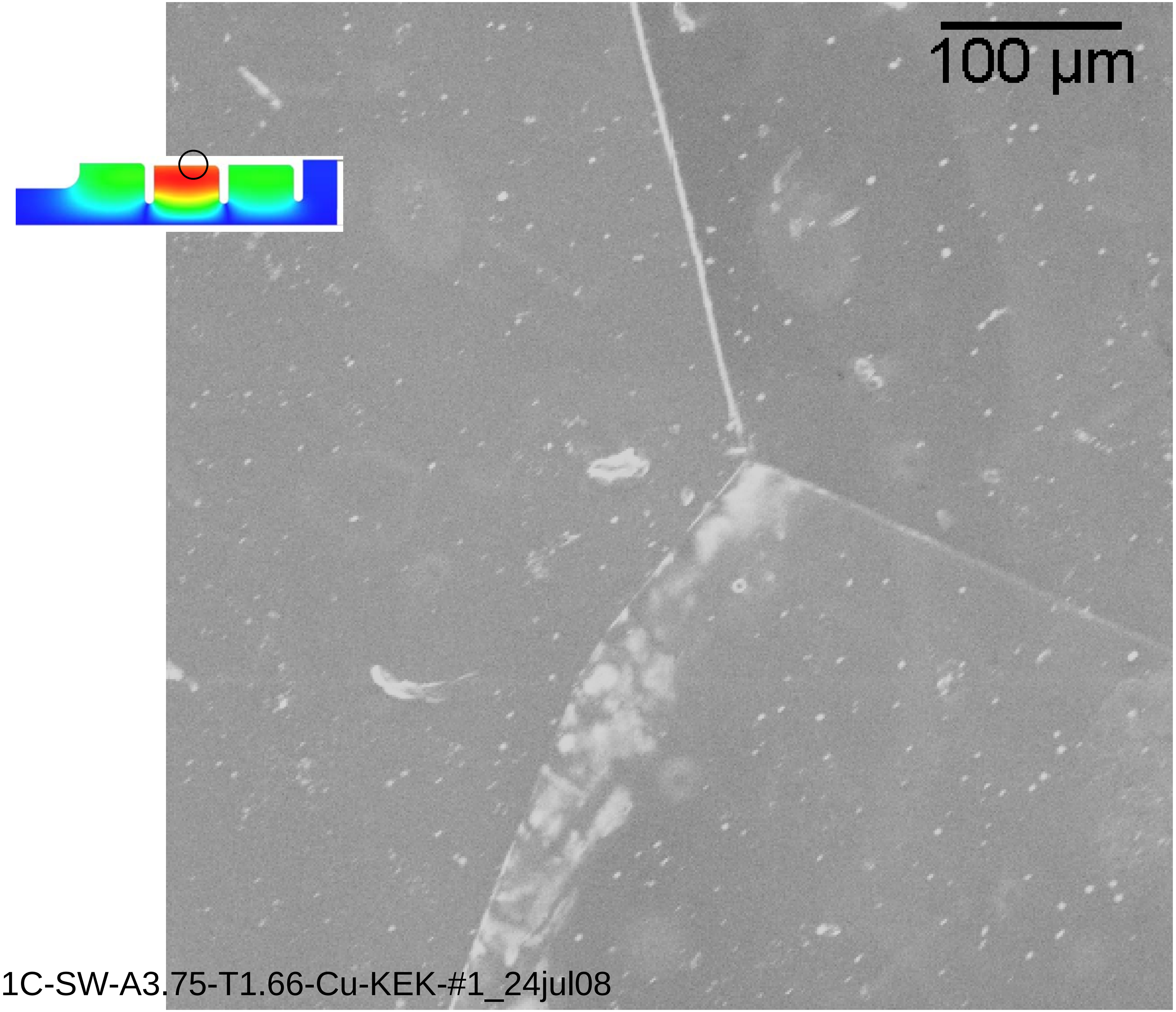
1C-SW-A3.75-T2.6-Cu-SLAC-#1_26jun08



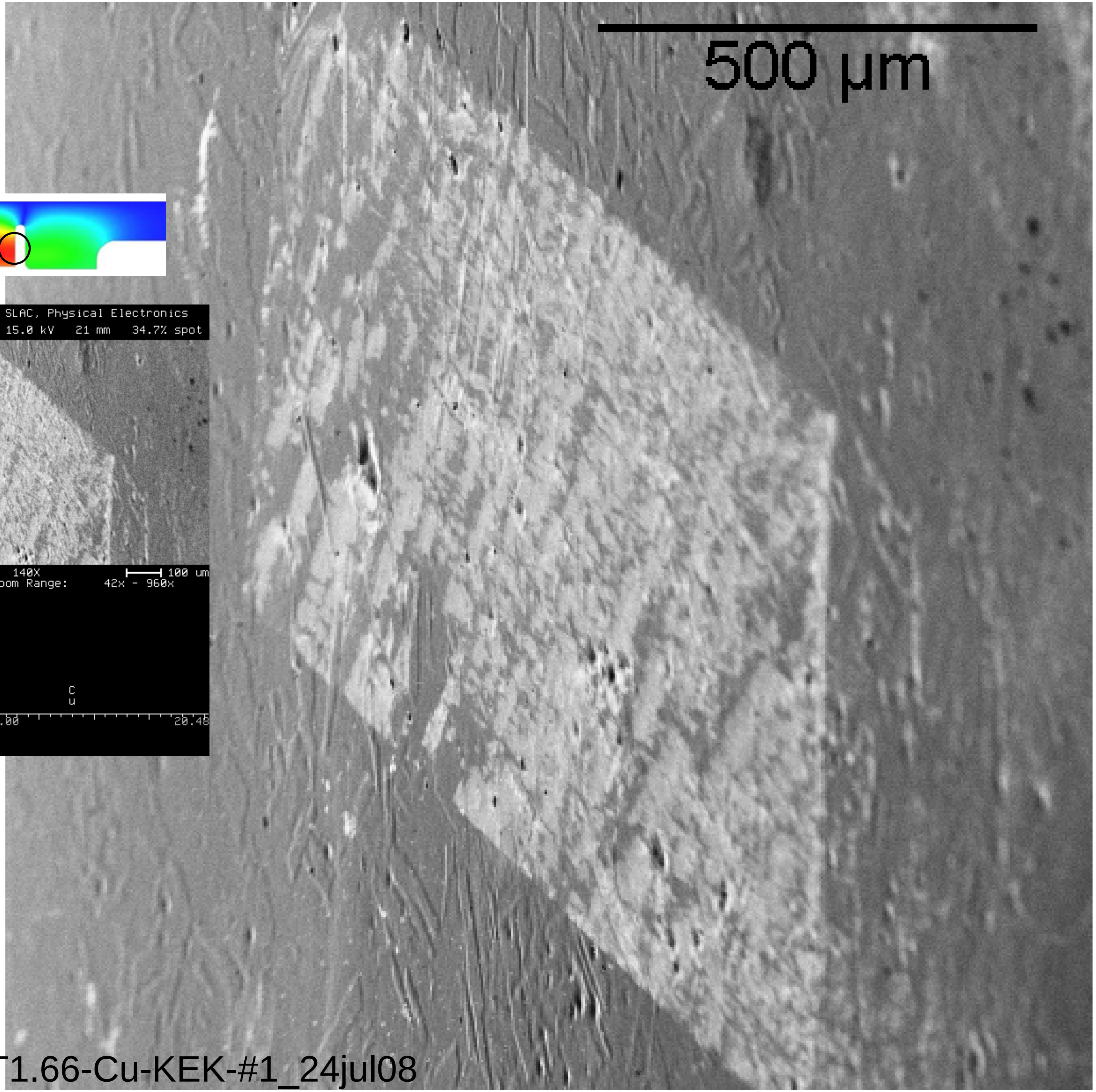
1C-SW-A3.75-T2.6-Cu-SLAC-#1_26jun08

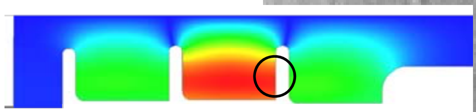


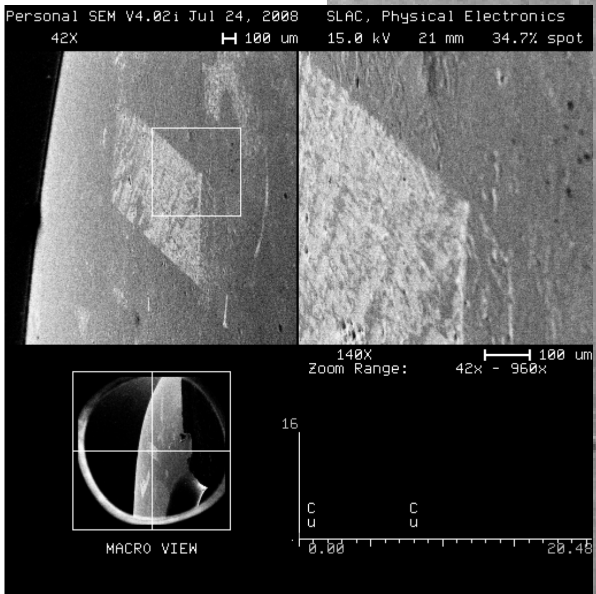
1C-SW-A3.75-T1.66-Cu-KEK-#1_24jul08



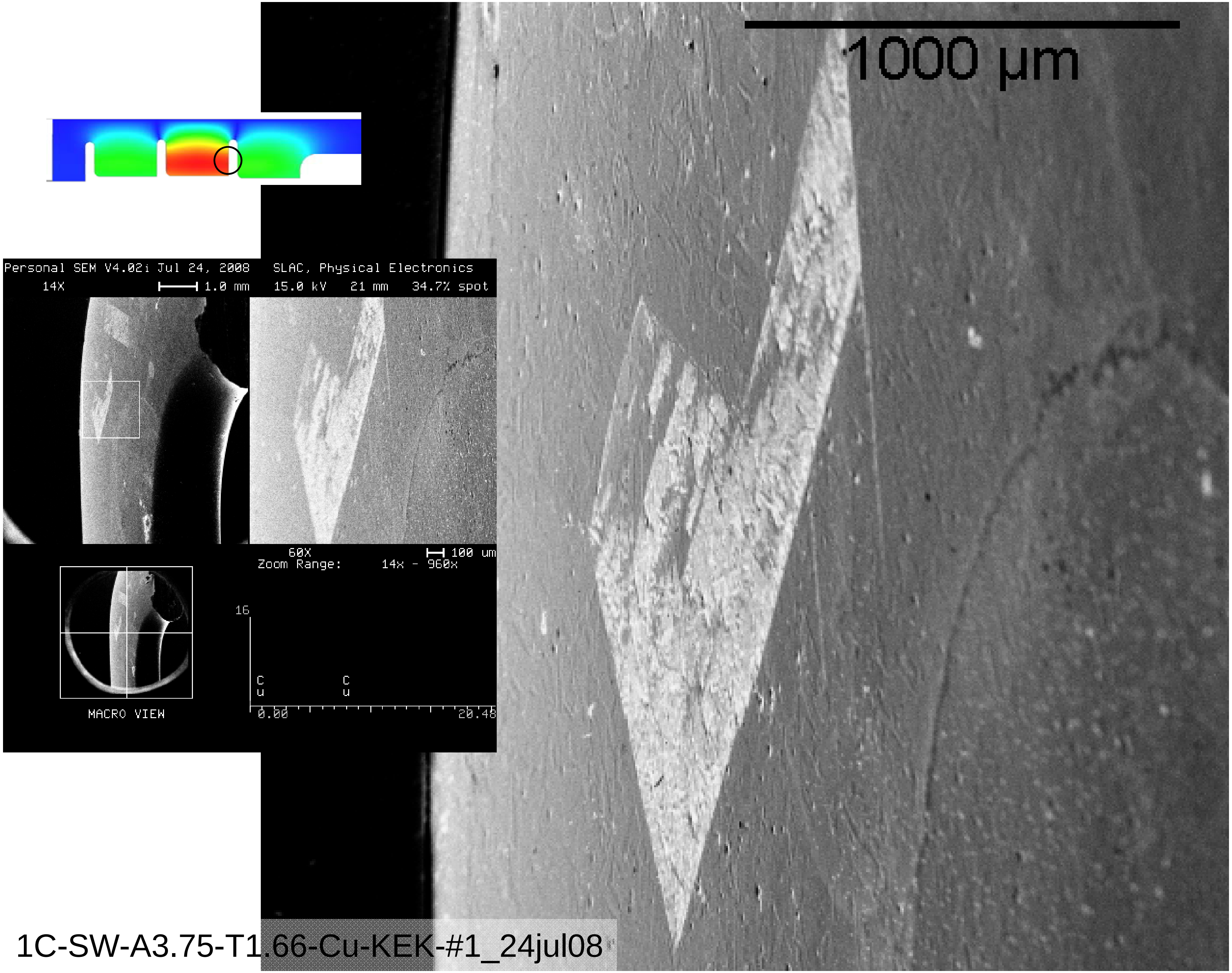
1C-SW-A3.75-T1.66-Cu-KEK-#1_24jul08



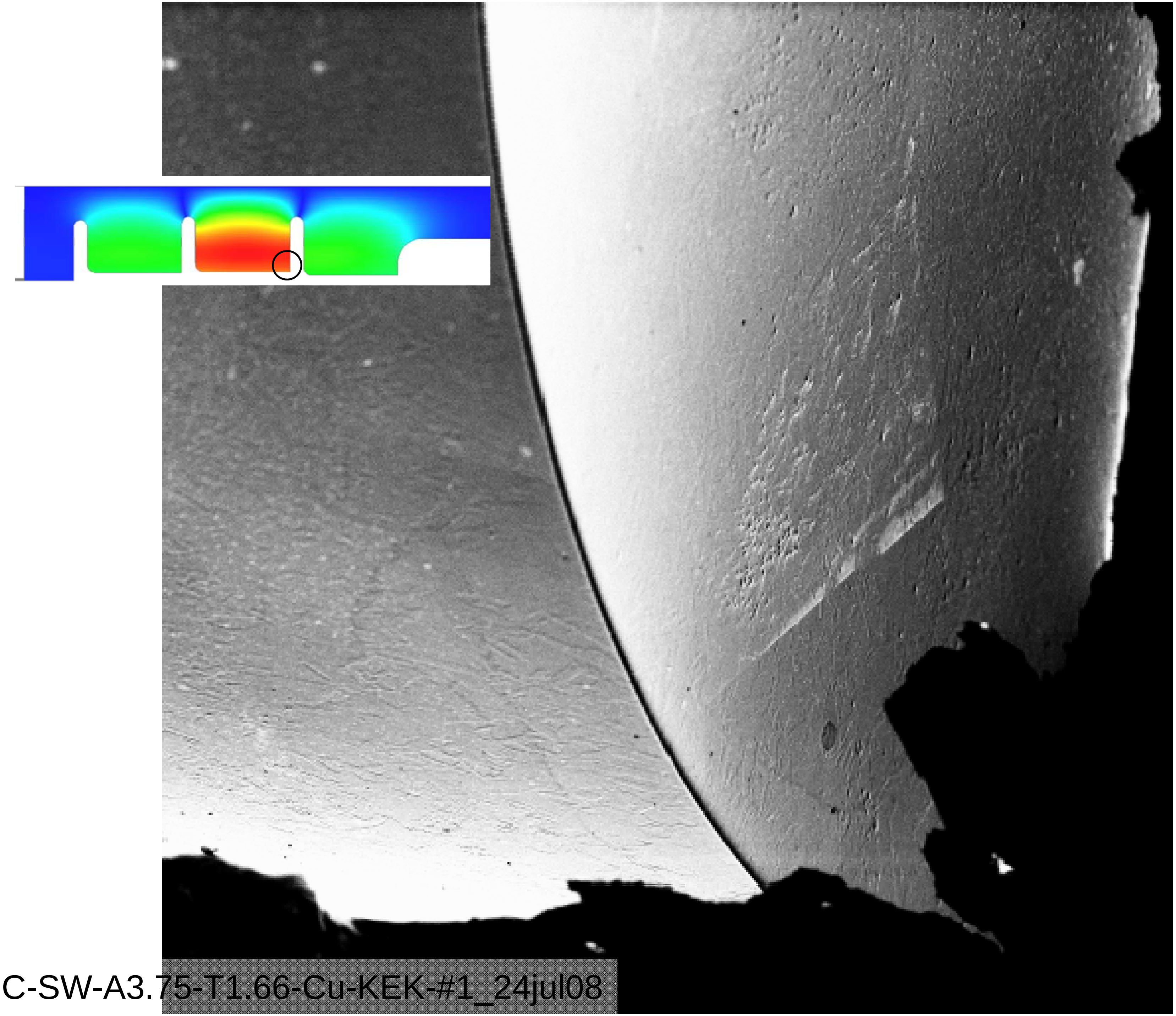




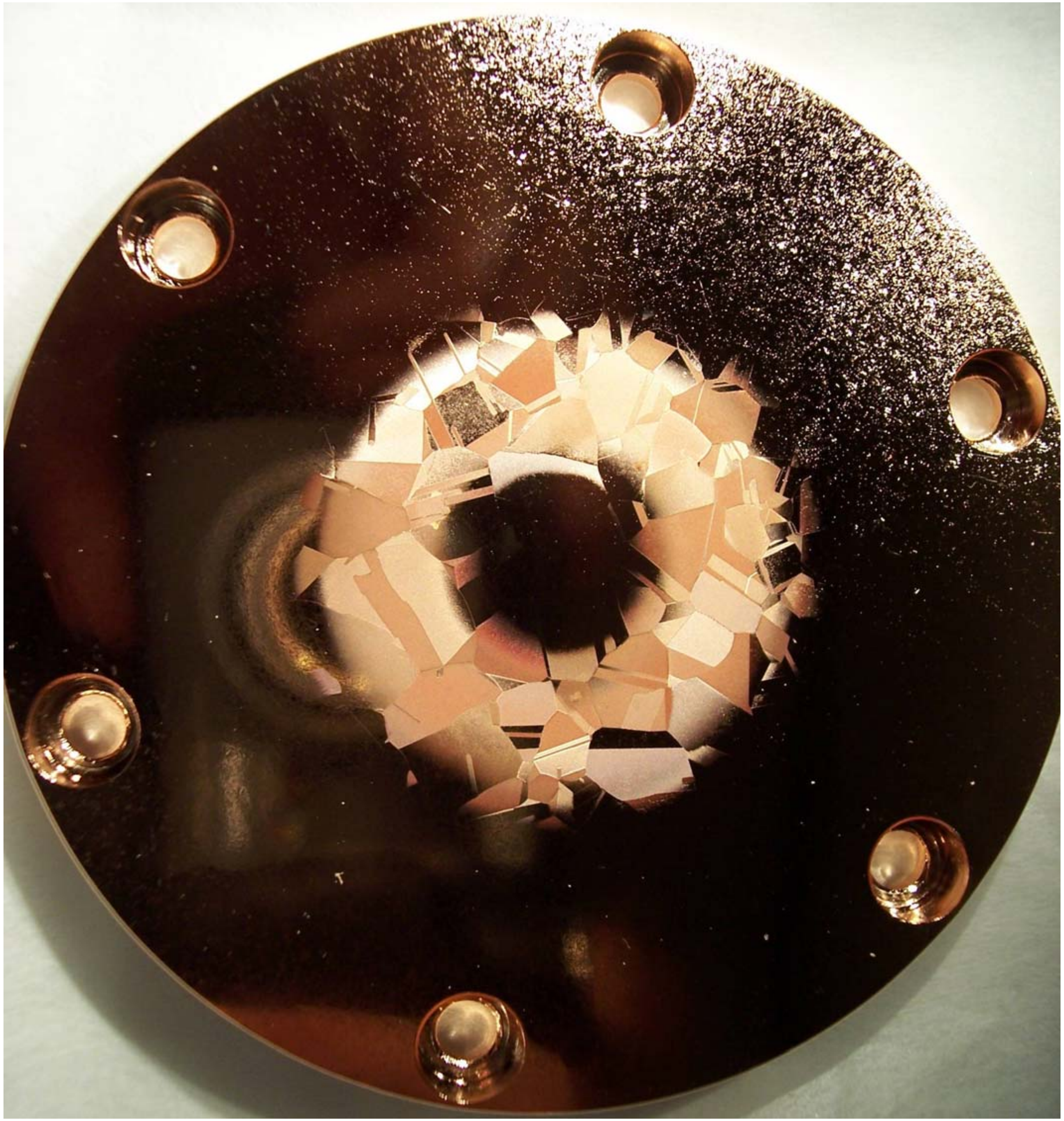
1C-SW-A3.75-T1.66-Cu-KEK-#1_24jul08

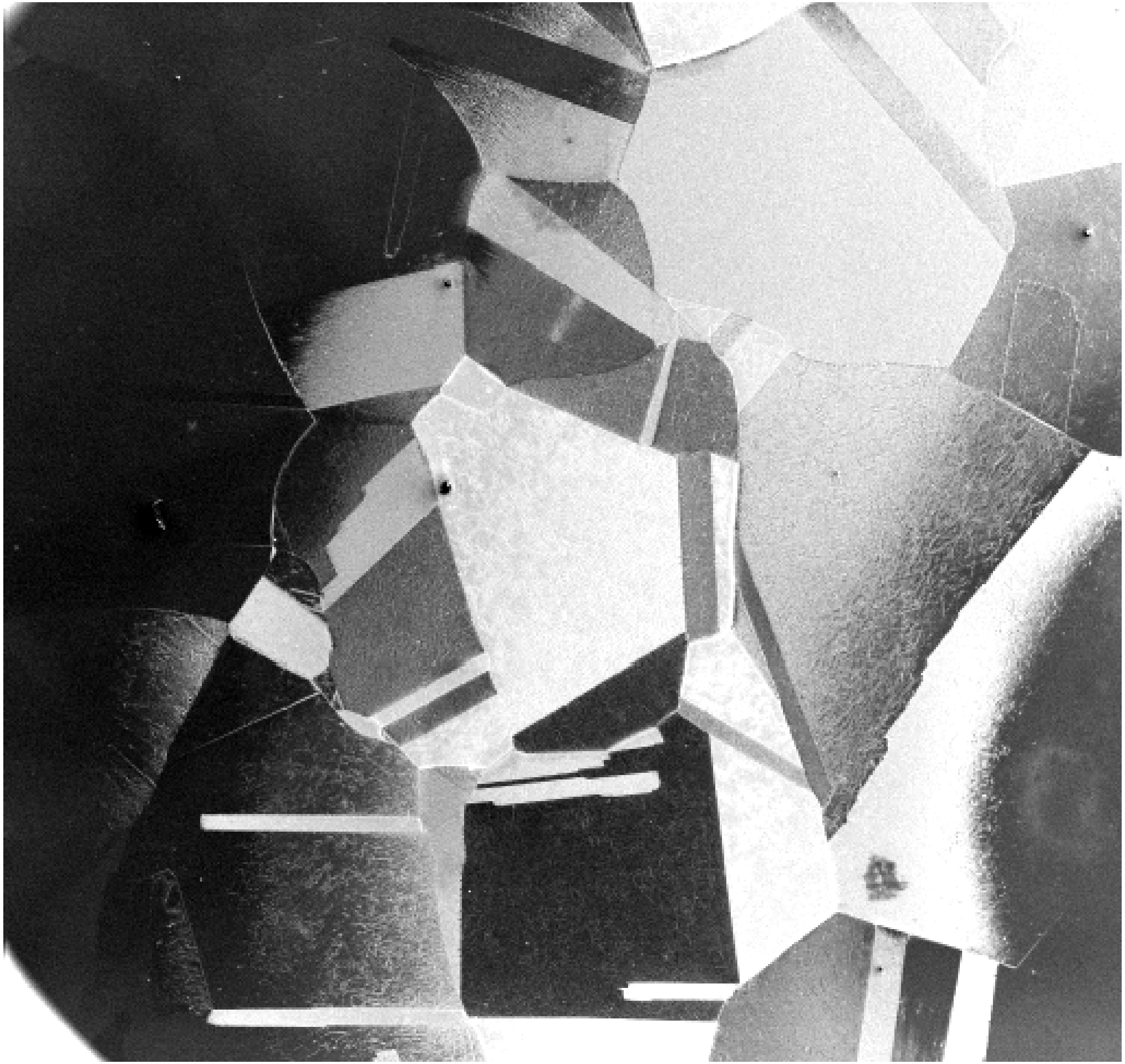


1C-SW-A3.75-T1.66-Cu-KEK-#1_24jul08

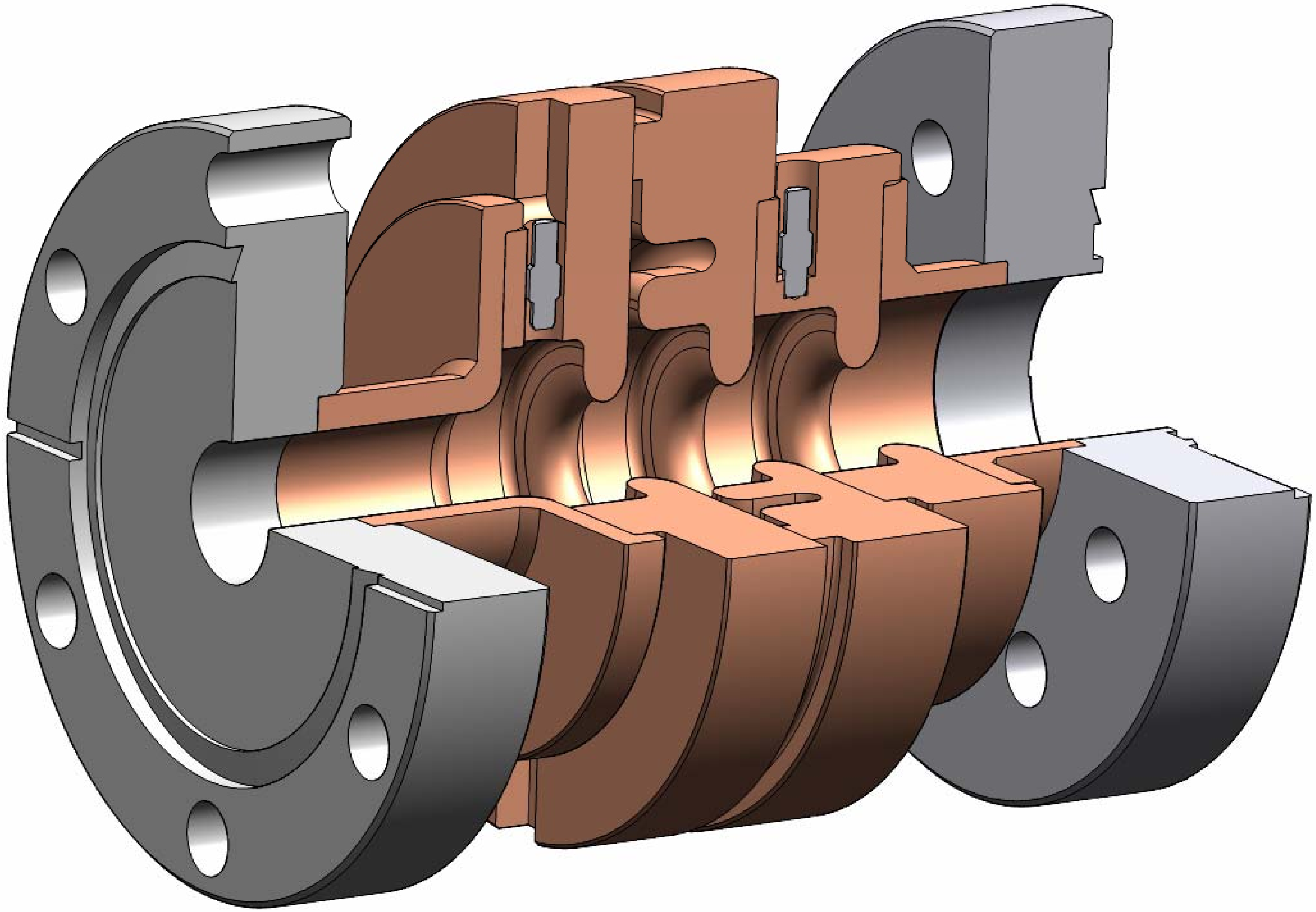


1C-SW-A3.75-T1.66-Cu-KEK-#1_24jul08





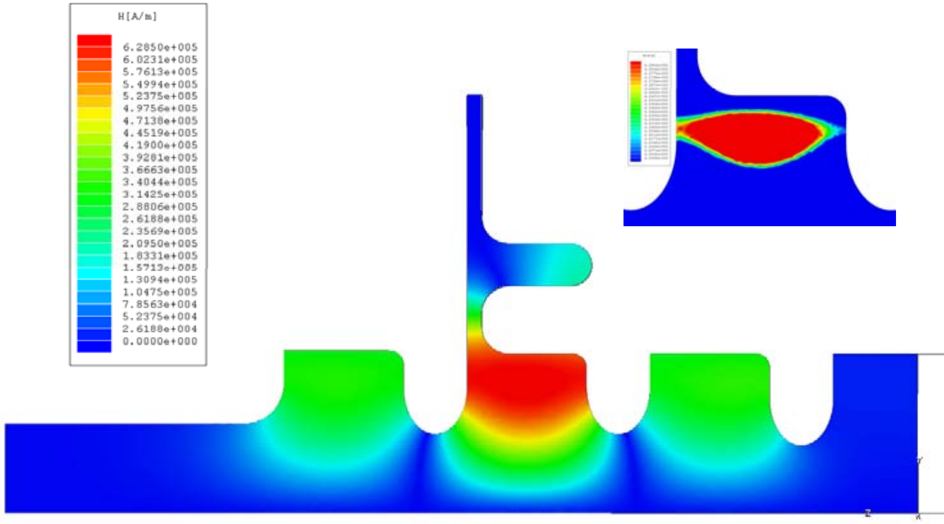
Choke Structure Results

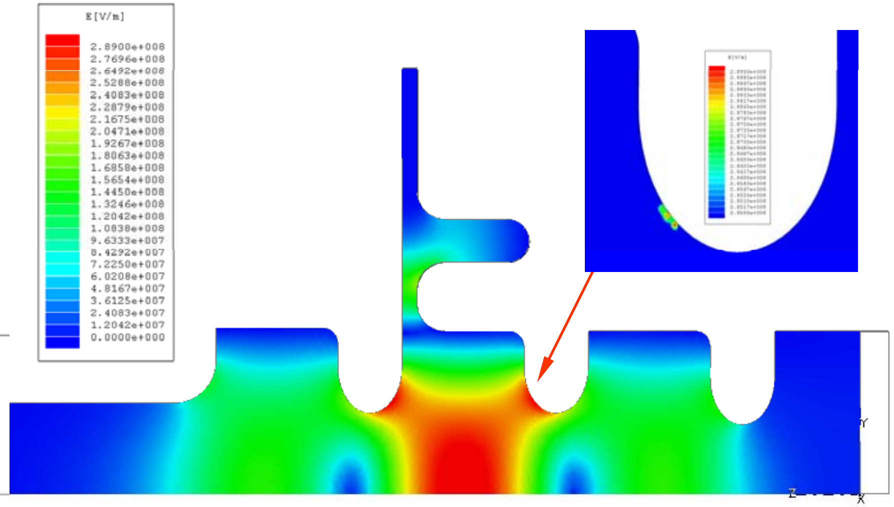


1C-SW-A5.65-T4.6-Cu-Choke

1C-SW-A5.65-T4.6-Cu-Choke

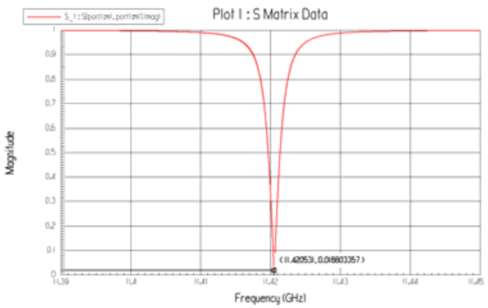
10 MW input

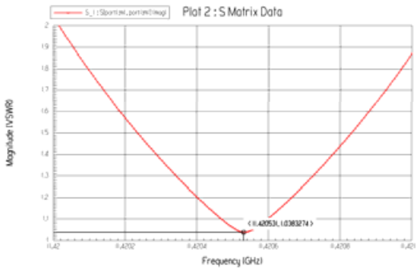


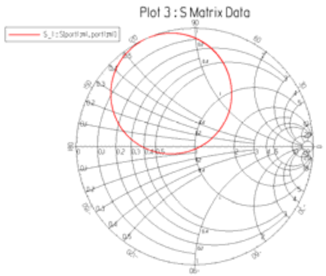


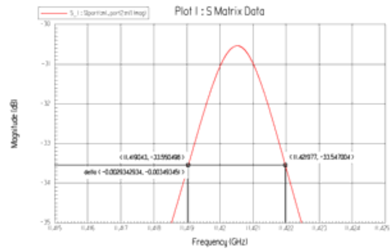
Maximum magnetic field 628.5 kA/m
(SLANS 627.5 kA/m)

Maximum electric field 289 MV/m
((SLANS 297.7 MV/m)









Resonance at 11.42053 GHz $\beta = 1.03832$

(SLANS 11.424 GHz) (SLANS 1.045)

Over-coupled loaded Q

$$\frac{11.42053}{0.00293429} = 3.892 \times 10^{3}$$

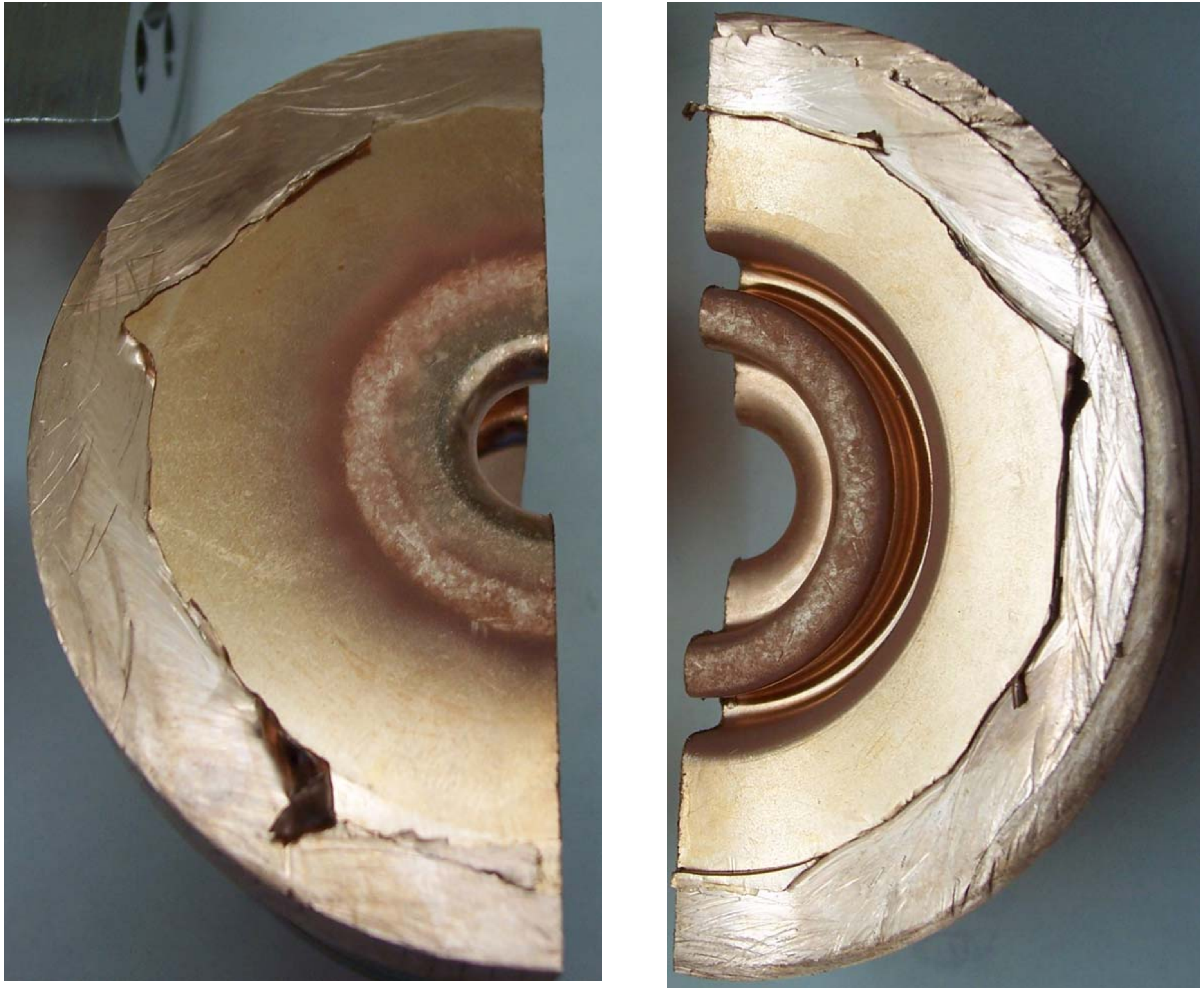
Unloaded Q=7,933

(SLANS 7,933.5)

$$\frac{11.42053}{0.00293429} \cdot (1 + 1.03832) = 7.933 \times 10^{3}$$

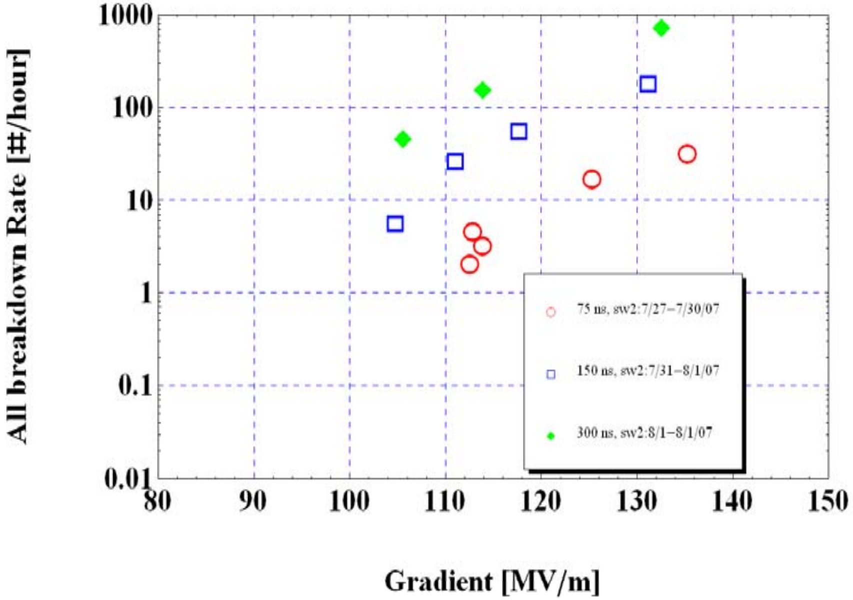
V.A. Dolgashev, 25 September 2007

1C-SW-A5.65-T4.6-**Ch**-Cu-SLAC-#1

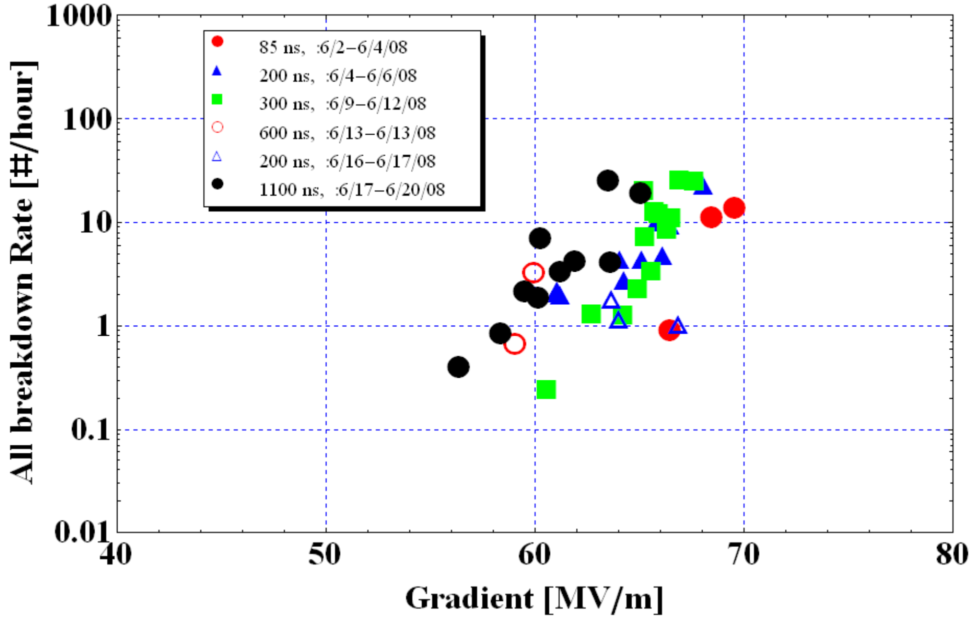


1C-SW-A5.65-T4.6-**Ch**-Cu-SLAC-#1

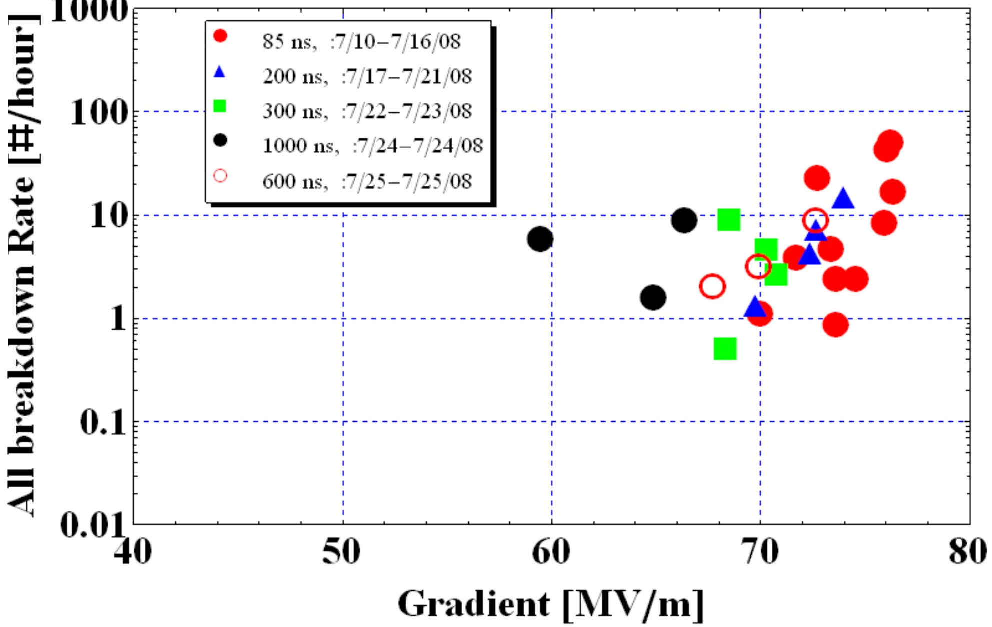
Two structures with chokes



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

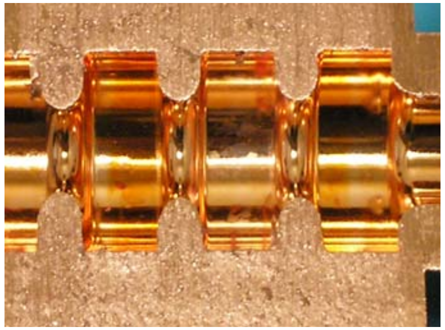


1C-SW-A5.65-T4.6-**Ch**-Cu-SLAC-#1

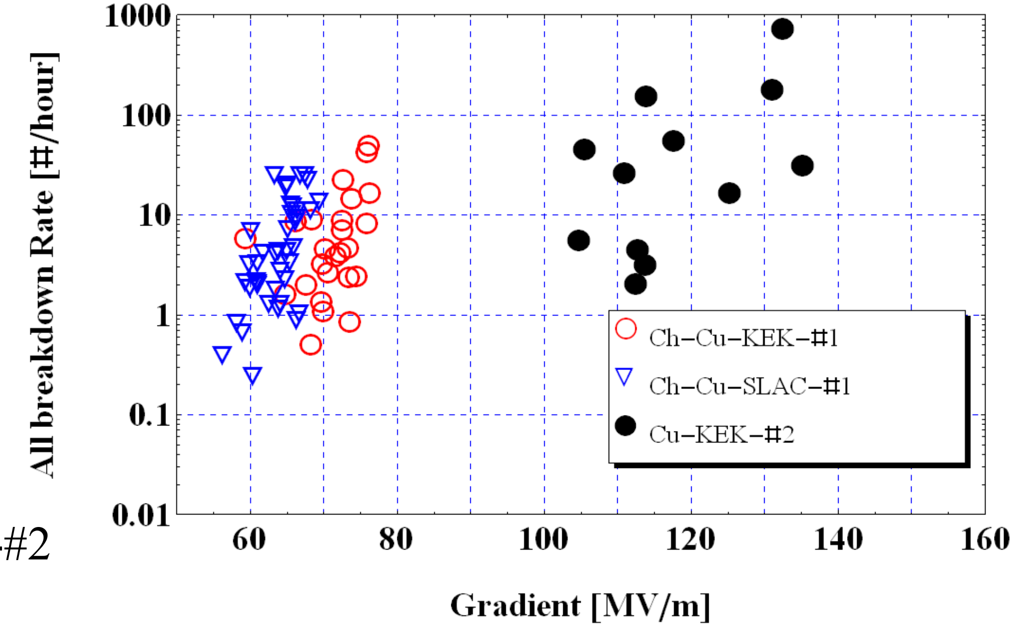


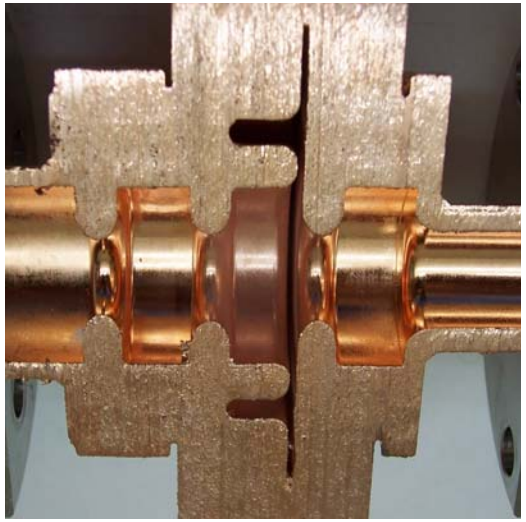
1C-SW-A5.65-T4.6-**Ch**-Cu-KEK-#1

Choke *vs.* no Choke

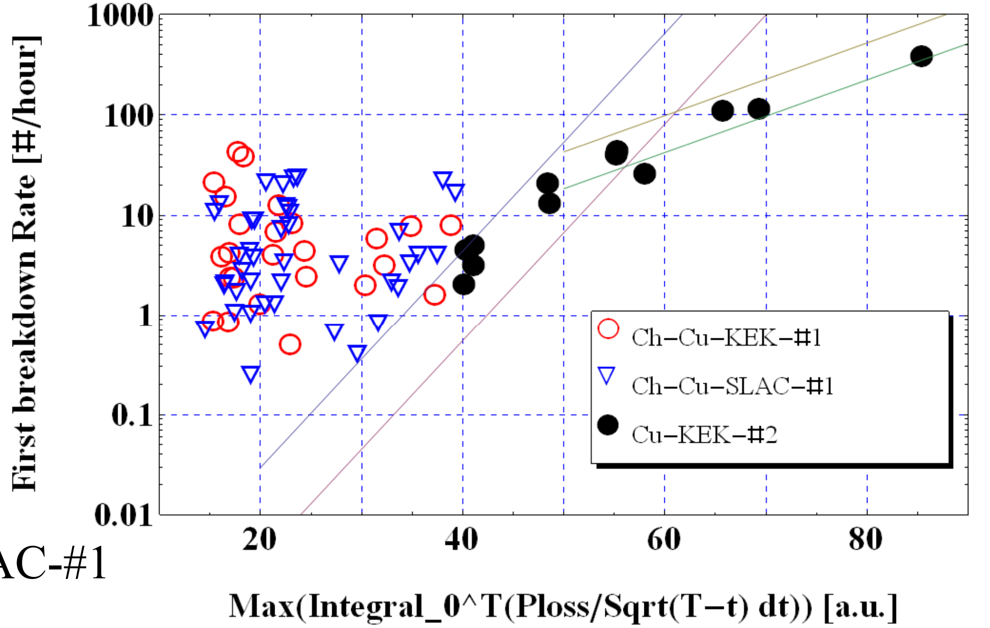


1C-SW-A5.65-T4.6-Cu-KEK-#2

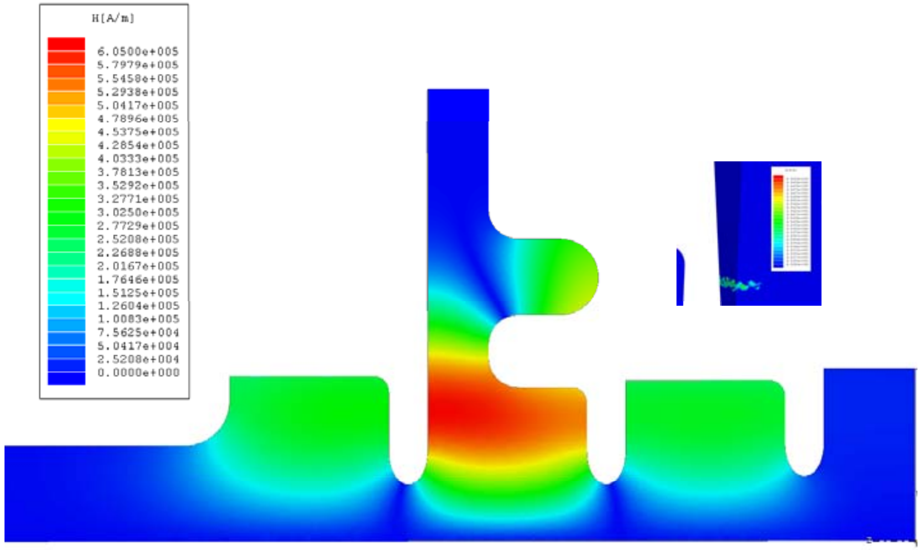


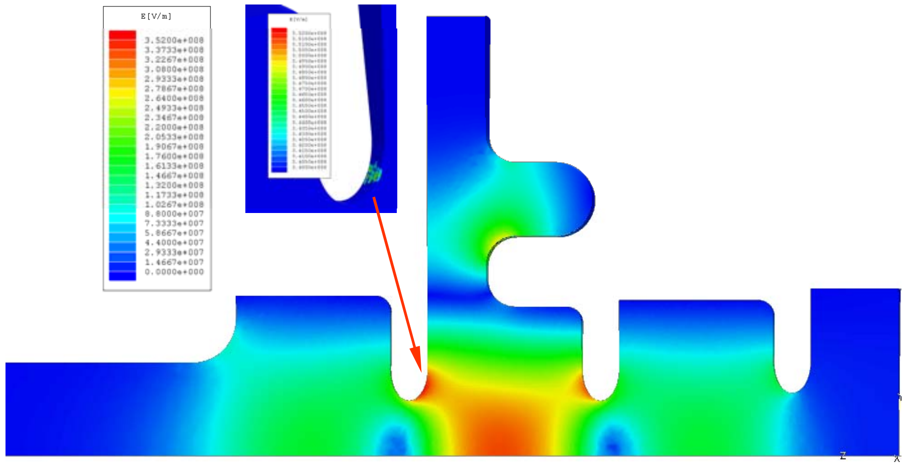


1C-SW-A5.65-T4.6-**Ch**-Cu-SLAC-#1



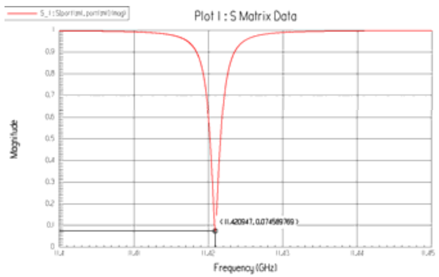
Next choke structure: 1C-SW-A3.75-T2.6-Cu-4mm-Choke, 10 MW losses

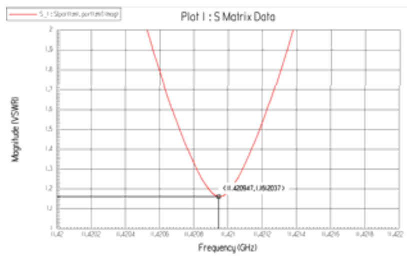


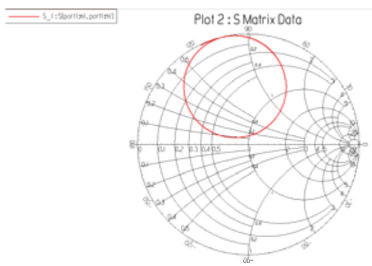


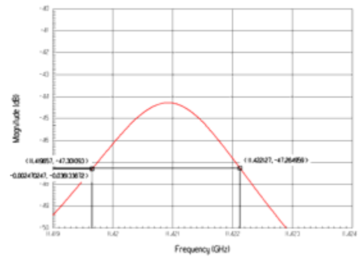
Maximum magnetic field 604 kA/m
(SLANS 602.065 kA/m)

Maximum electric field 347 MV/m
(SLANS 350.85 MV/m)









$$\frac{11.421}{0.002470247} = 4.6234243\times 10^{3}$$

Resonance at 11.420947 GHz β = 0.861

(SLANS 11.42391 GHz) (SLANS 1.04952)

Under-coupled loaded Q
Unloaded Q=8,605
(SLANS 8,668)

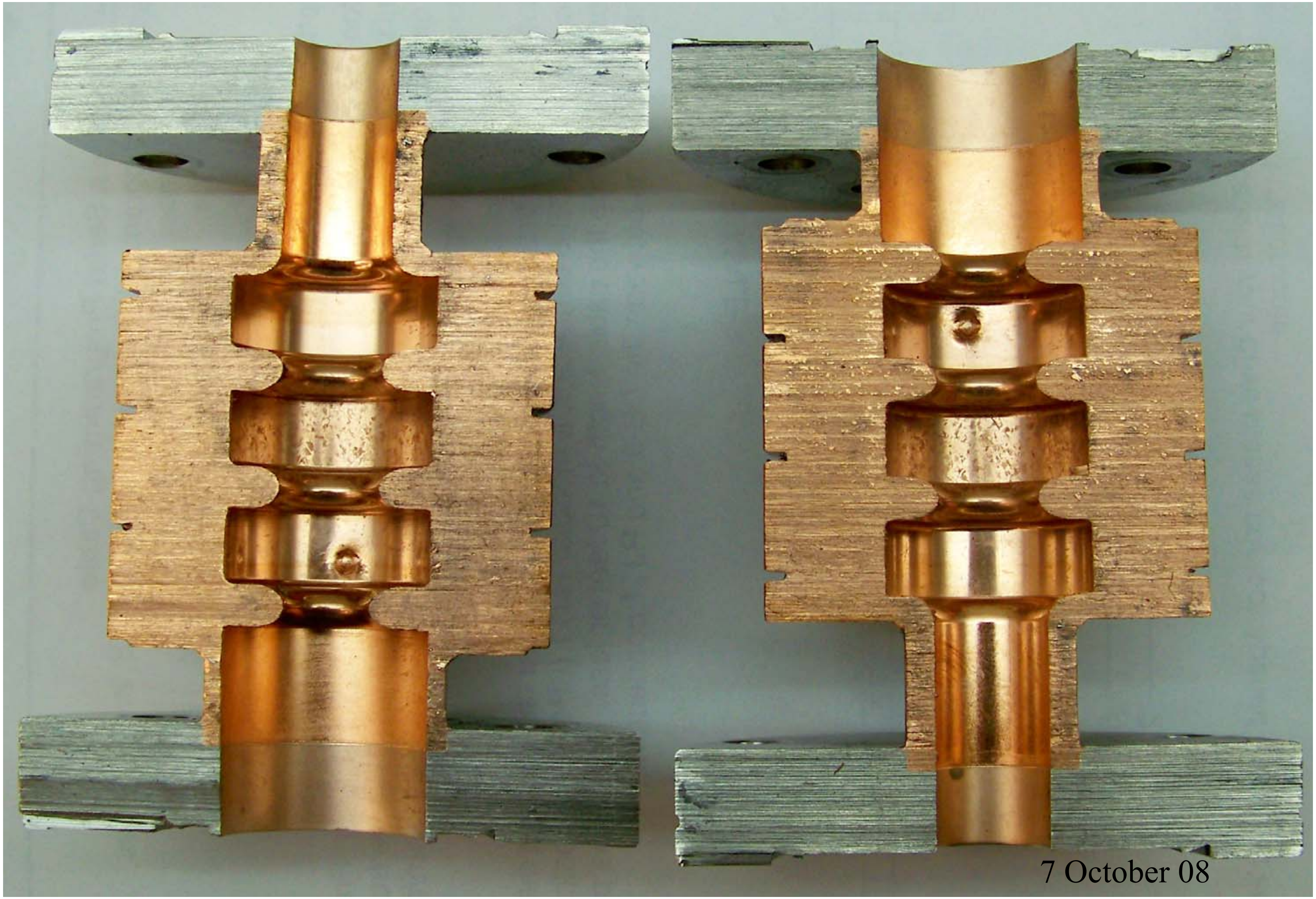
$$\frac{11.421}{0.002470247}\cdot\left(1 + 1.1612037^{-1}\right) = 8.605\times 10^{3}$$

V.A. Dolgashev, 18 September 2008

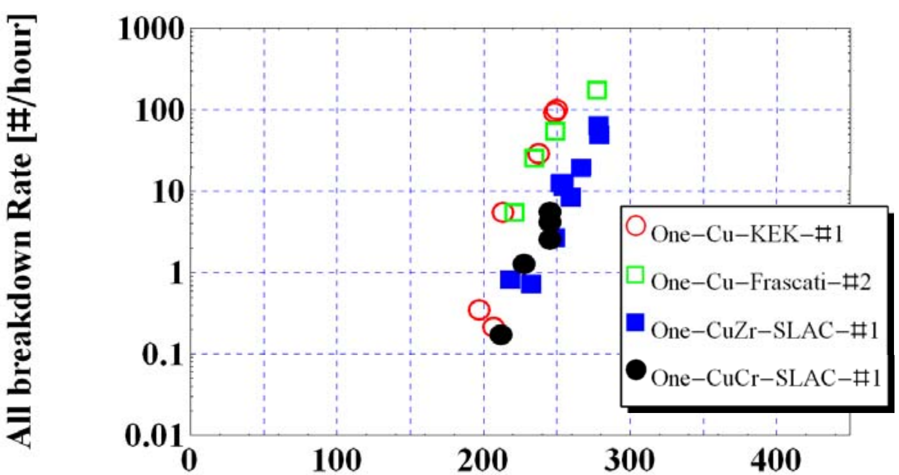
Copper alloys

CuZr and CuCr structures

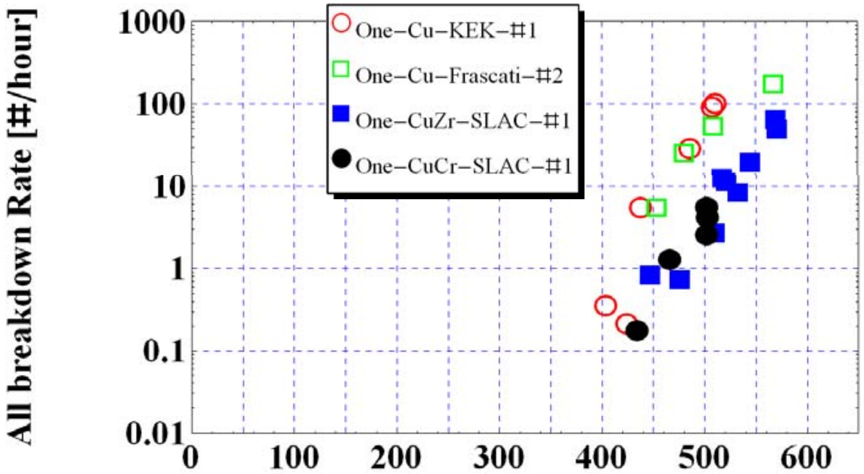
1C-SW-A5.65-T4.6-CuZr-SLAC-#1



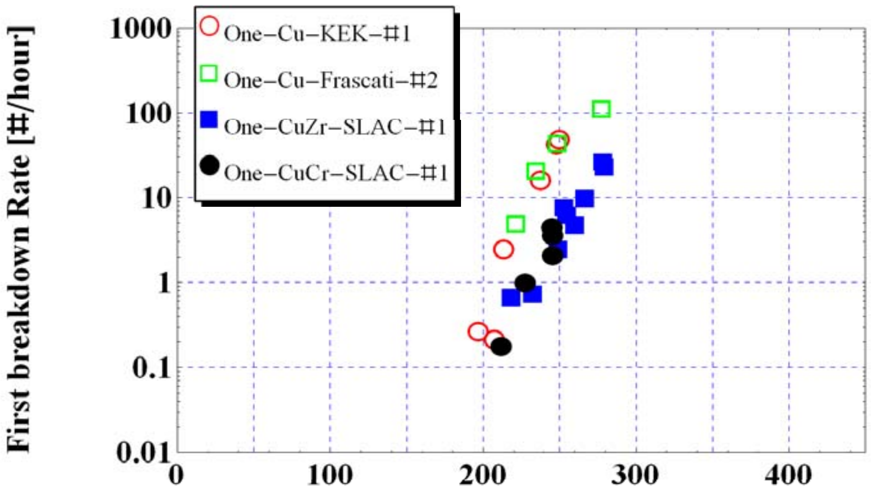
150 ns shaped pulse for 1C-SW-A5.65-T4.6 structures



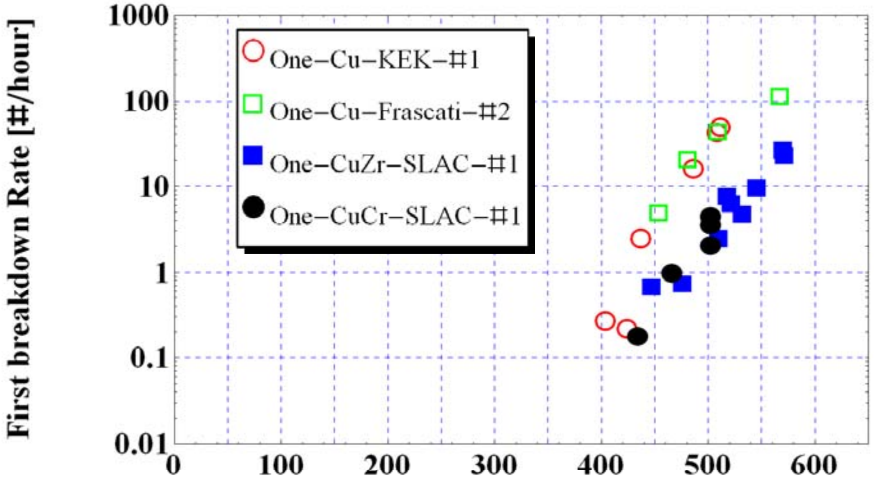
Maximum surface electric field [kA/m]



Maximum surface magnetic field [kA/m]



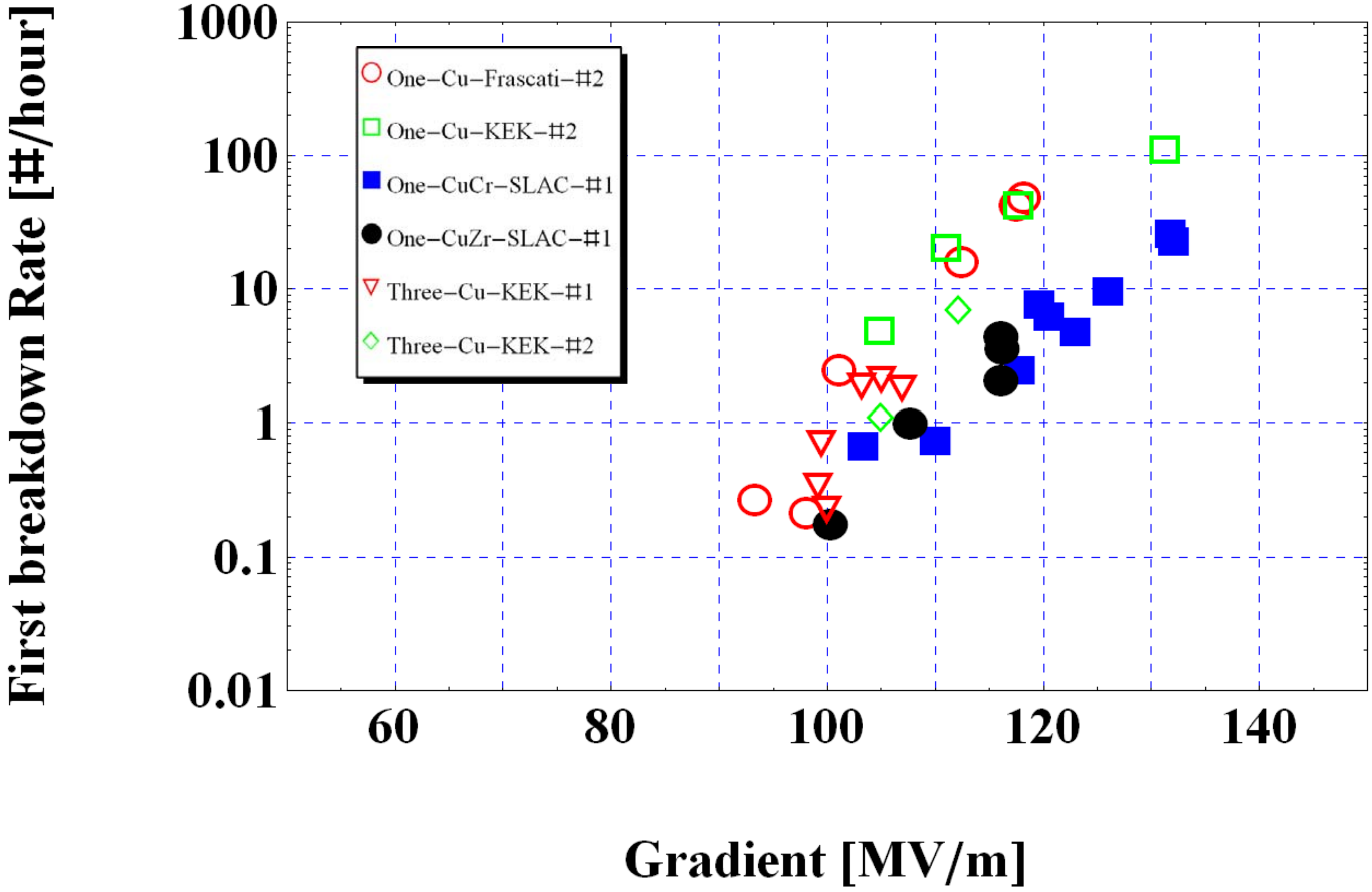
Maximum surface electric field [kA/m]



Maximum surface magnetic field [kA/m]

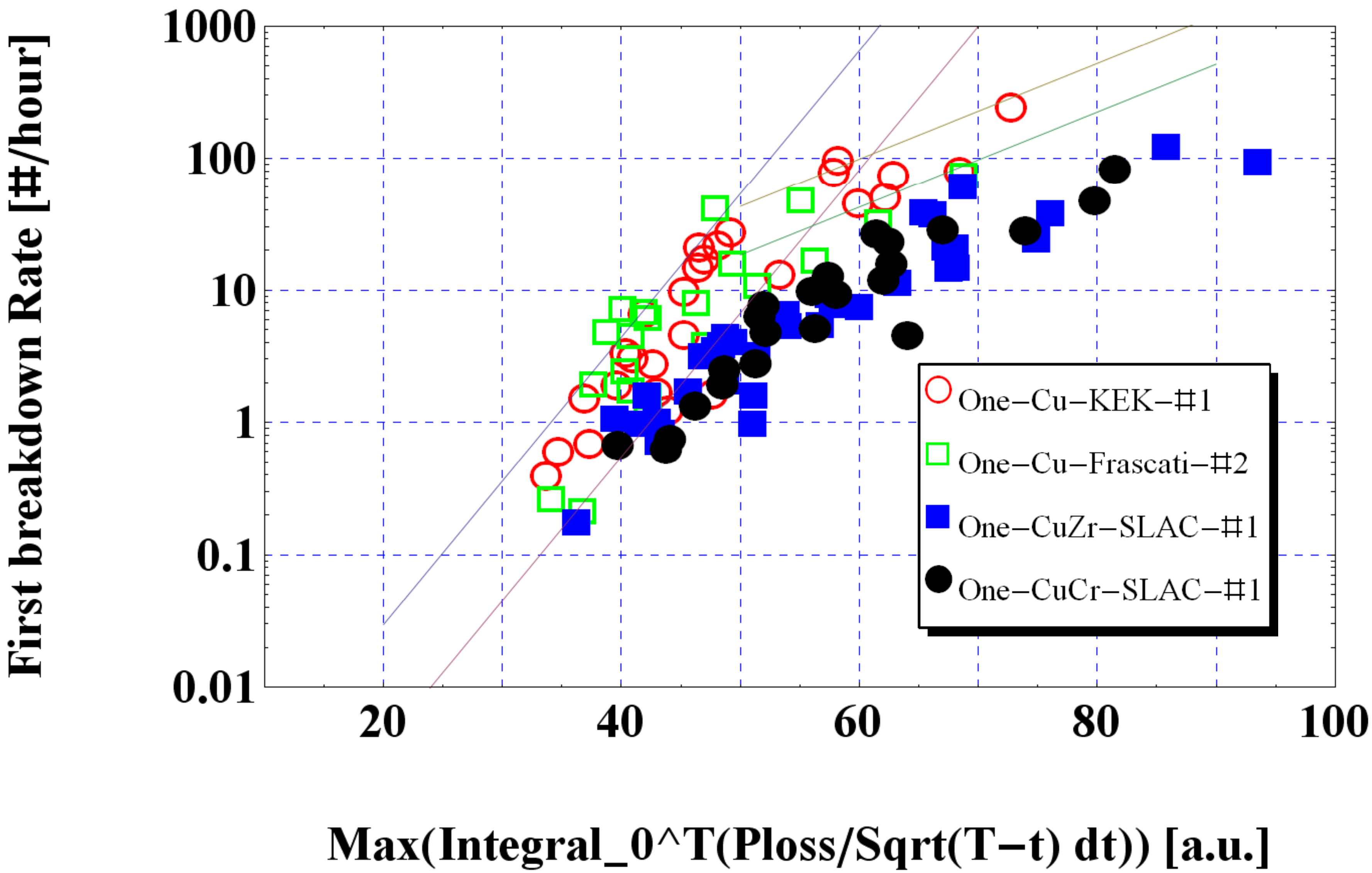
V.A. Dolgashev, 12 November 2008

150 ns shaped pulse for 1C and 3C SW-A5.65-T4.6 structures

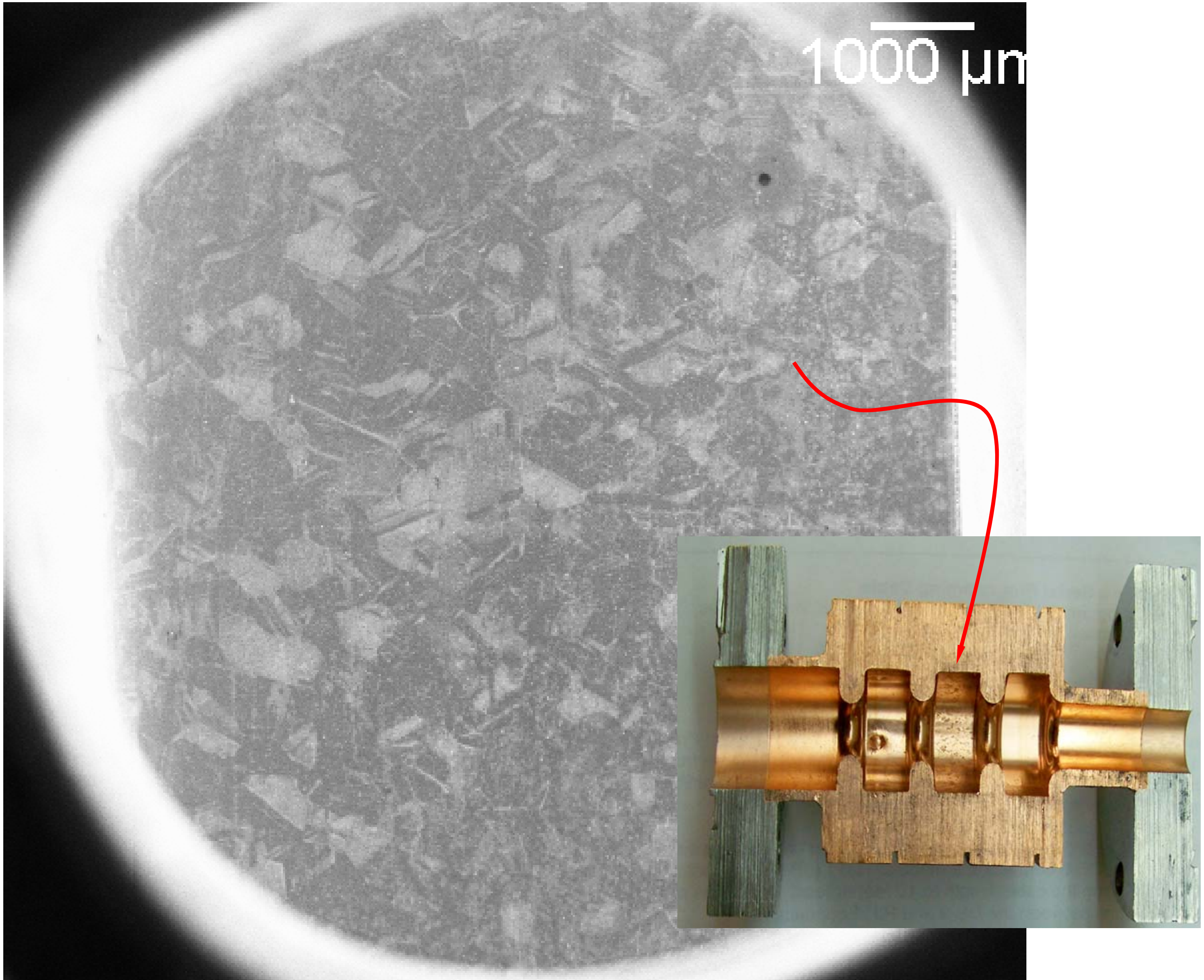


V.A. Dolgashev, 12 November 2008

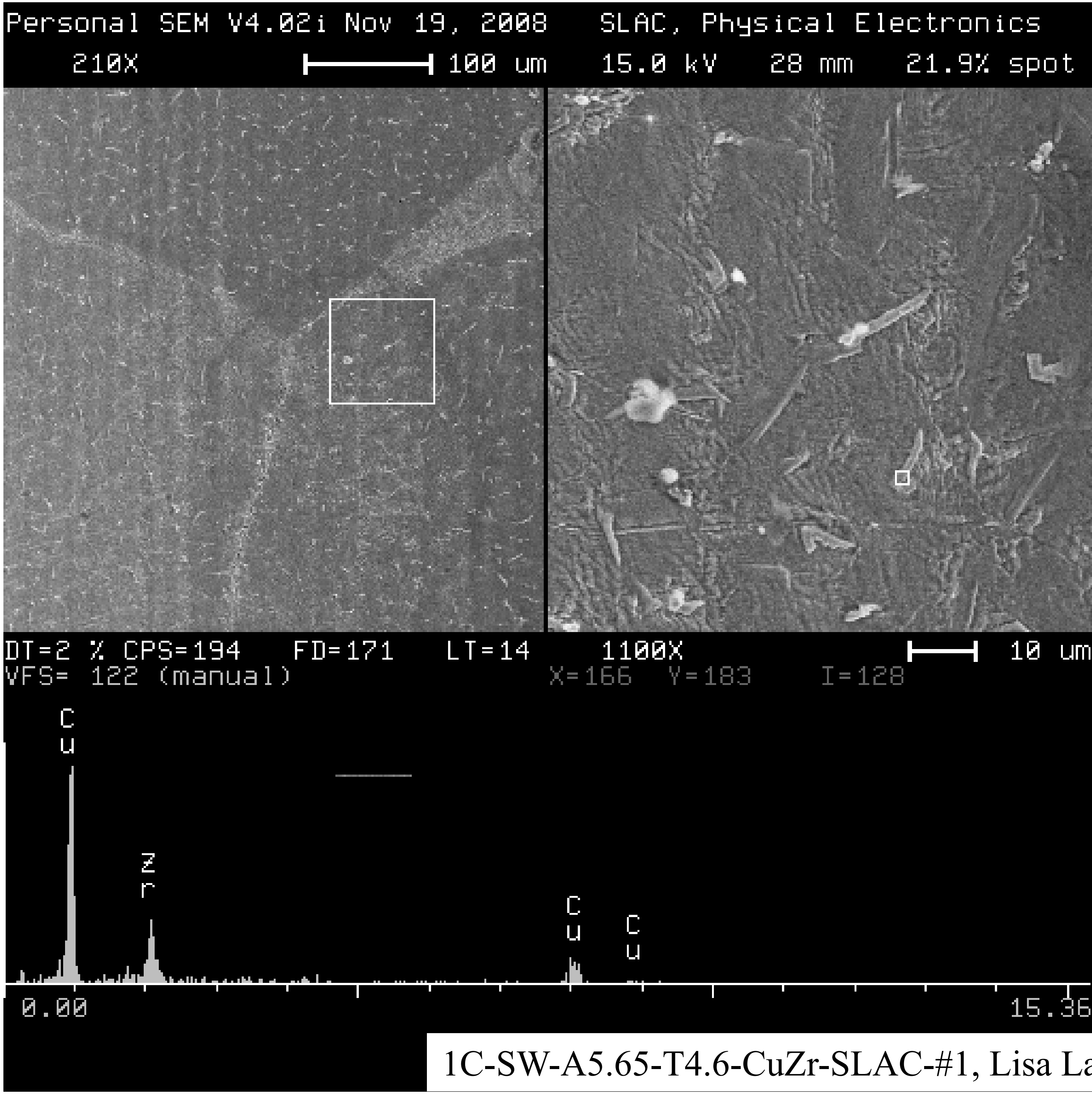
Cu, CuZr, CuCr in1C-SW-A5.65-T4.6 structures



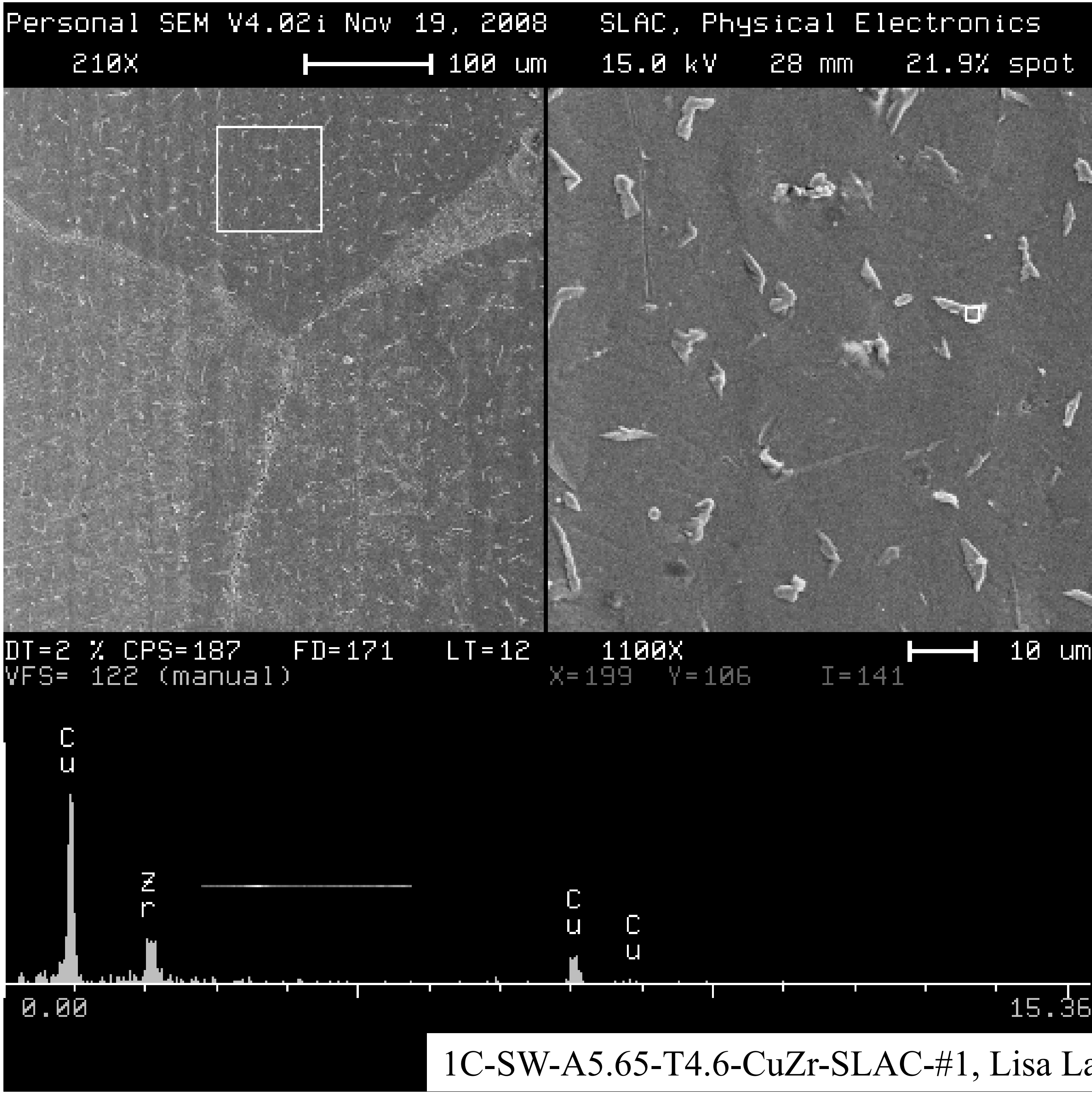
V.A. Dolgashev, 12 November 2008



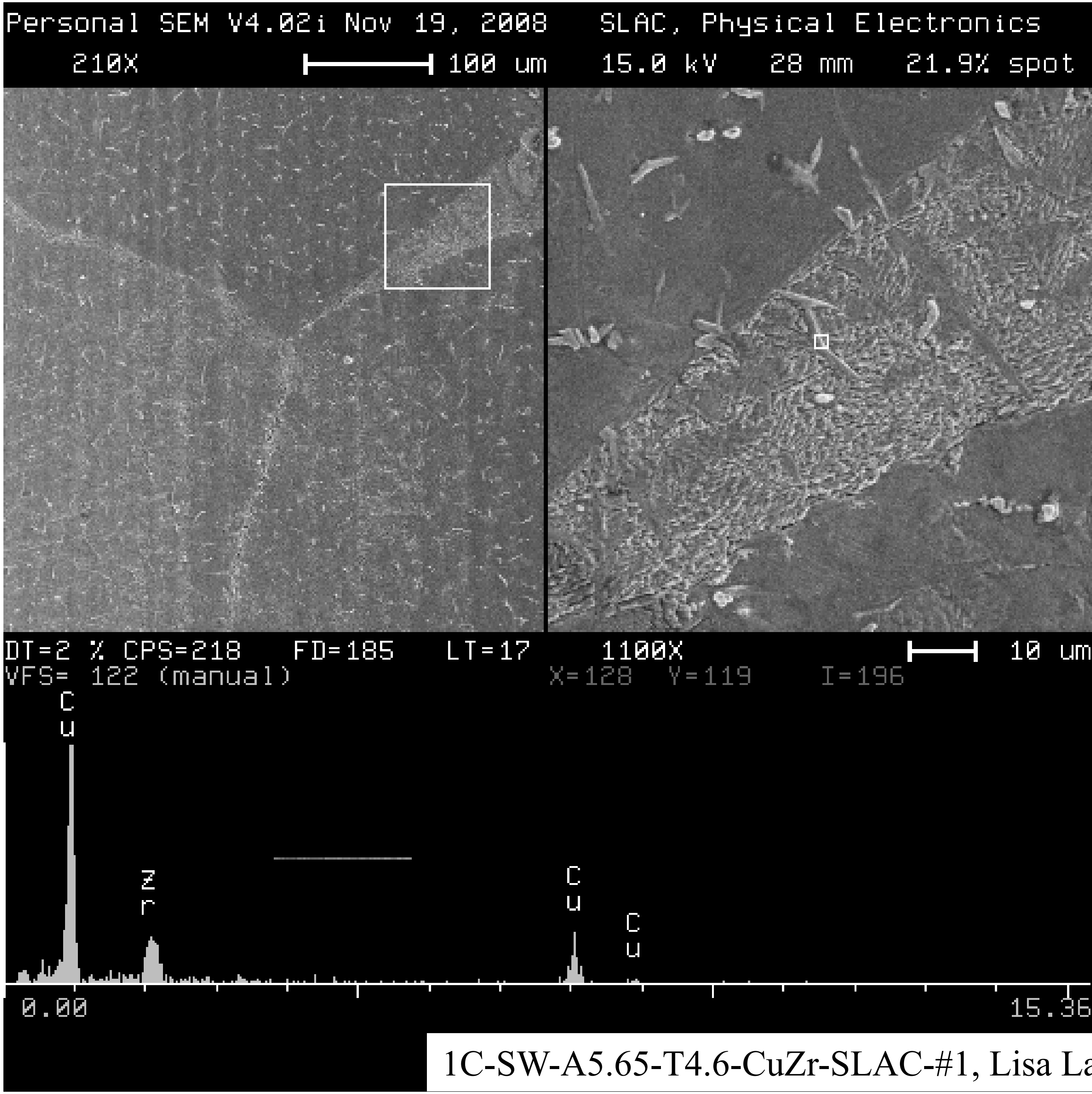
1C-SW-A5.65-T4.6-CuZr-SLAC-#1, Lisa Laurent



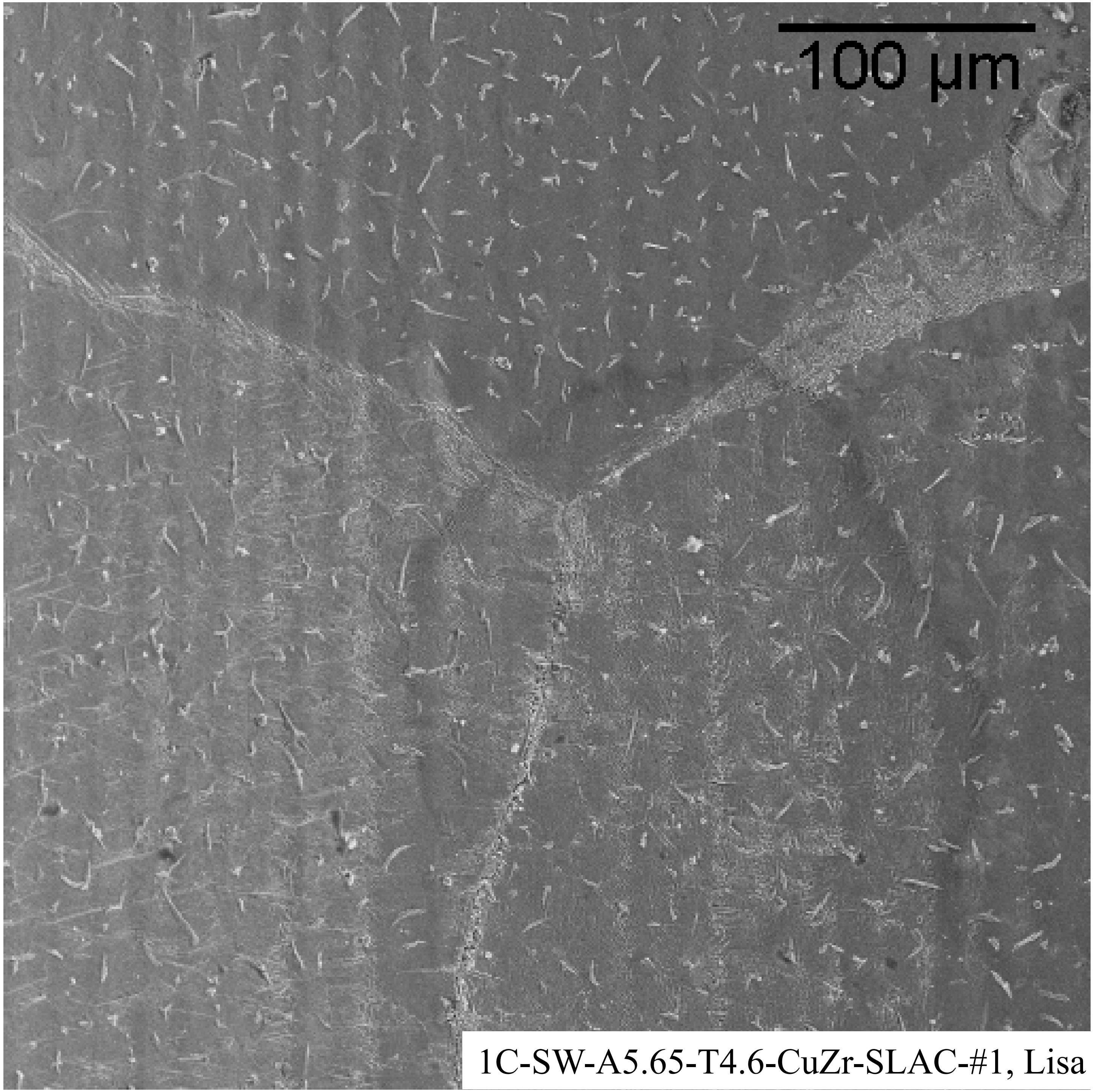
1C-SW-A5.65-T4.6-CuZr-SLAC-#1, Lisa Laurent



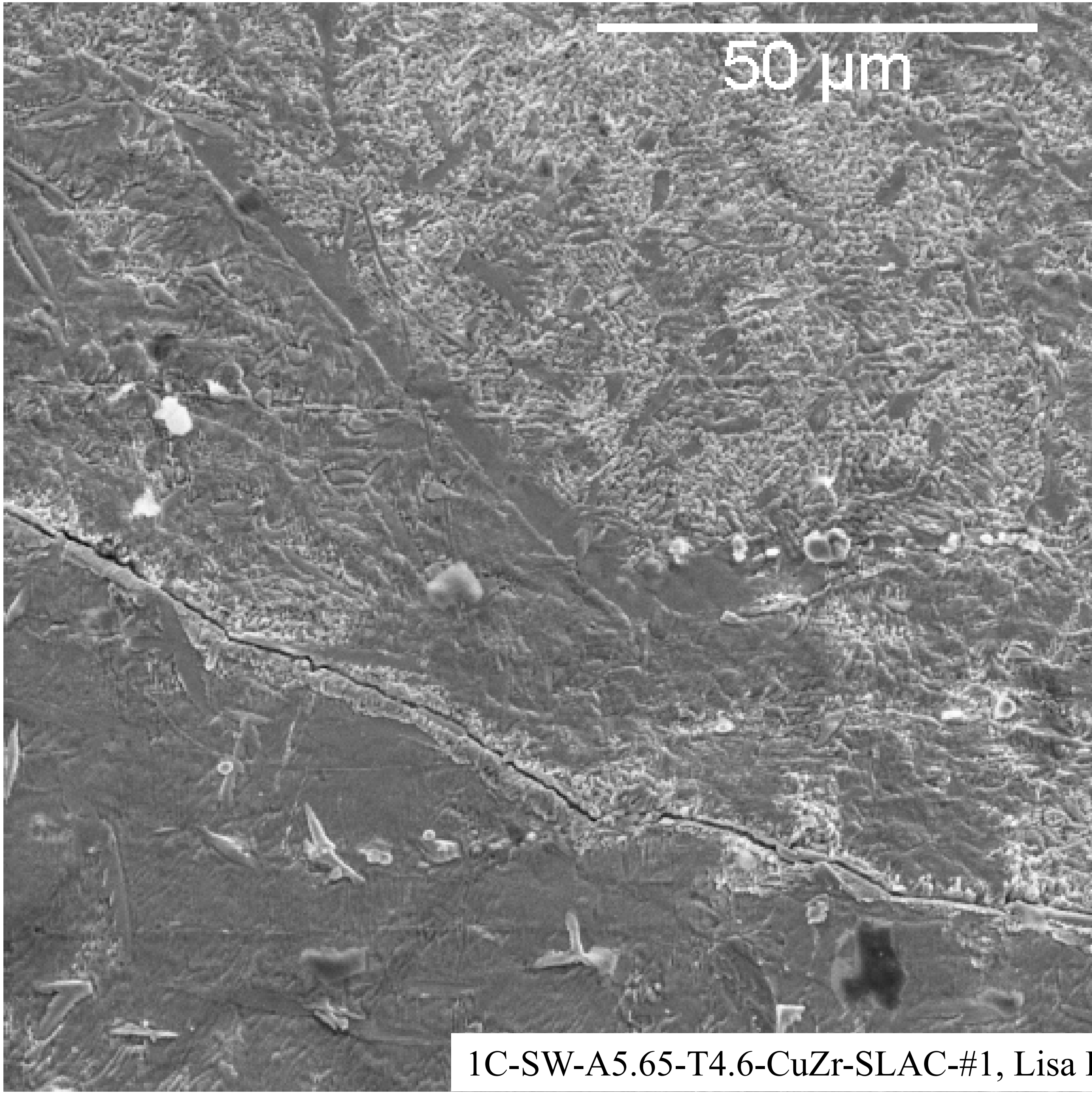
1C-SW-A5.65-T4.6-CuZr-SLAC-#1, Lisa Laurent



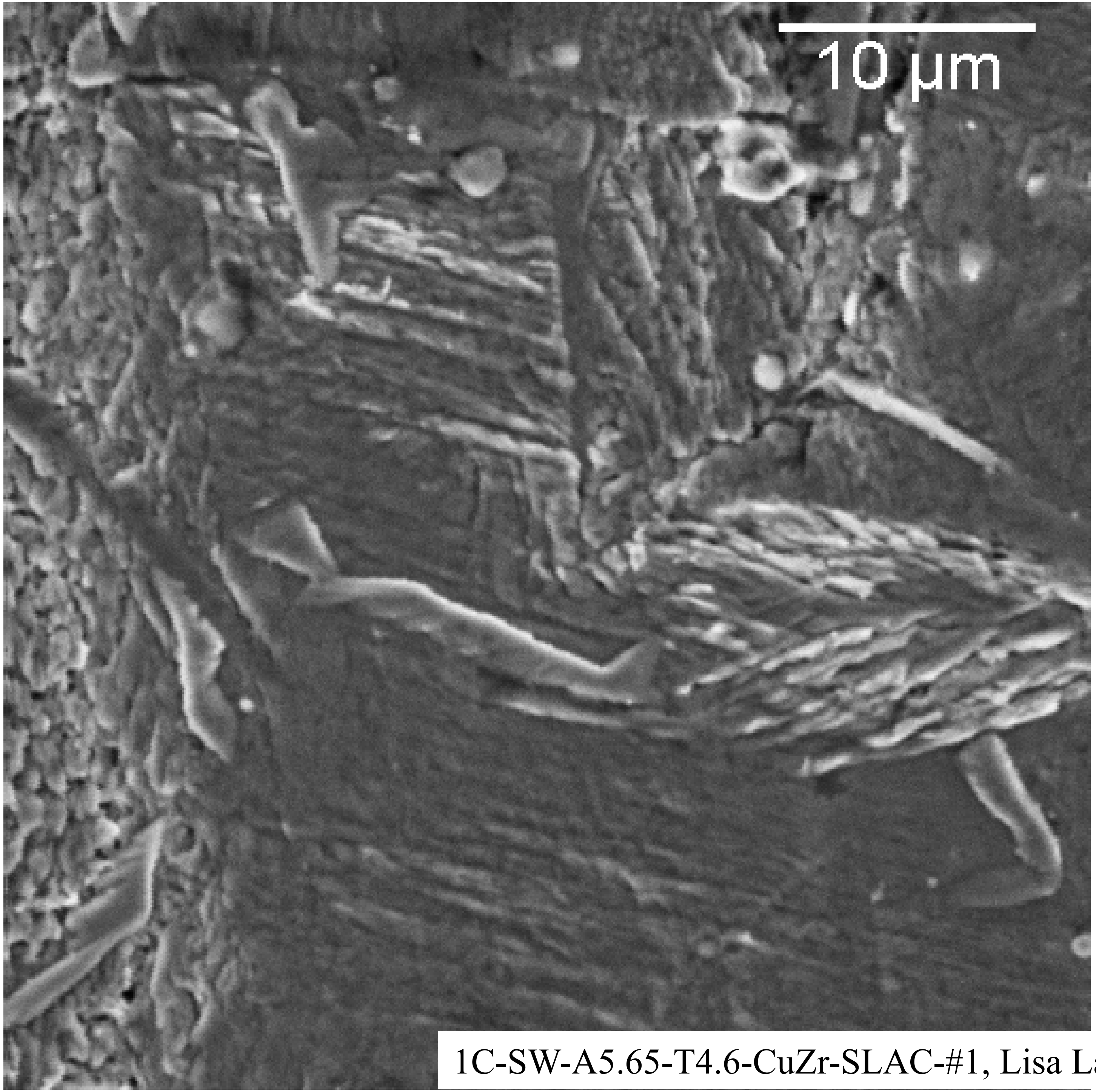
1C-SW-A5.65-T4.6-CuZr-SLAC-#1, Lisa Laurent



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



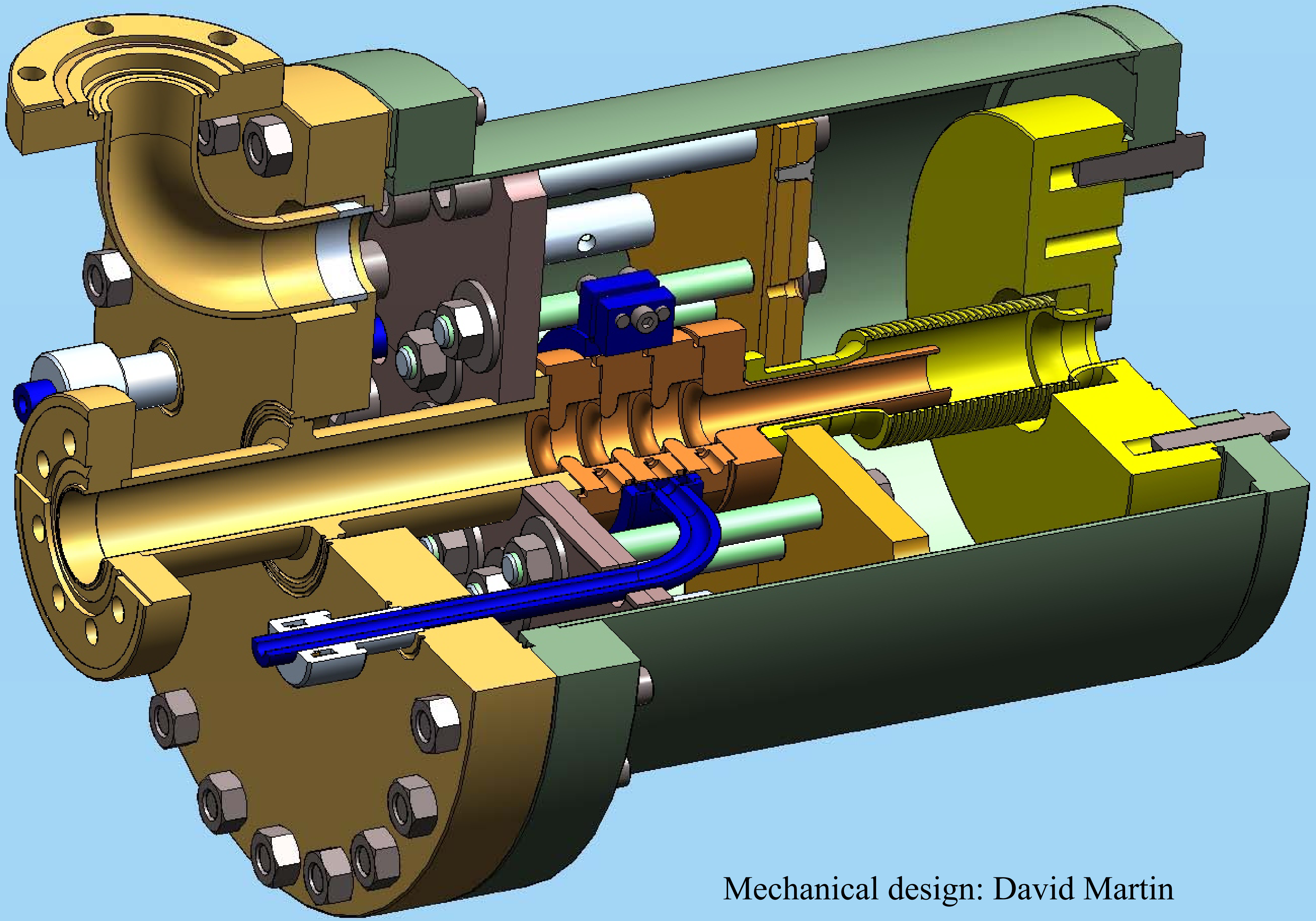
1C-SW-A5.65-T4.6-CuZr-SLAC-#1, Lisa Laurent



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

Copper alloys

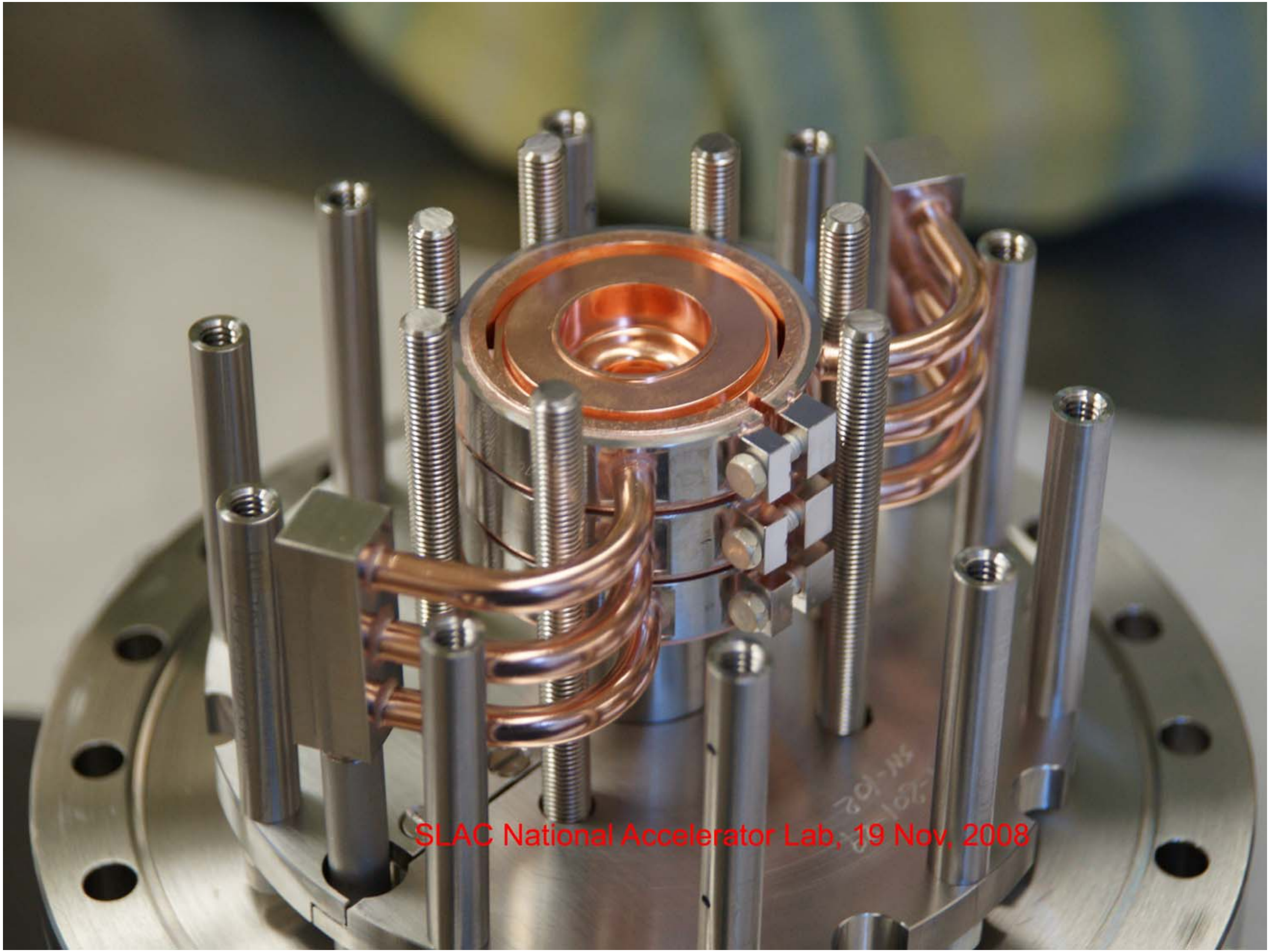
Clamped structure

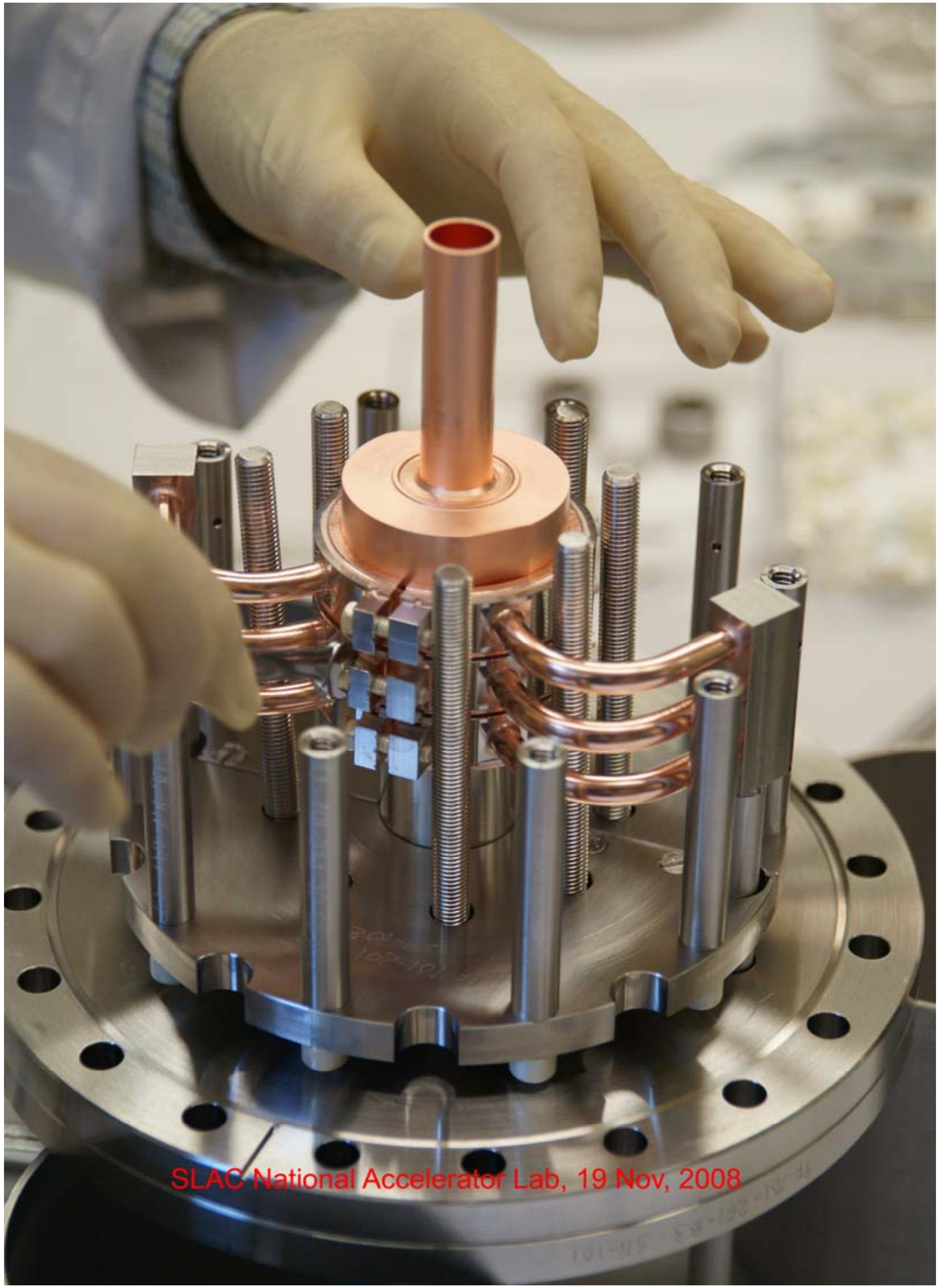


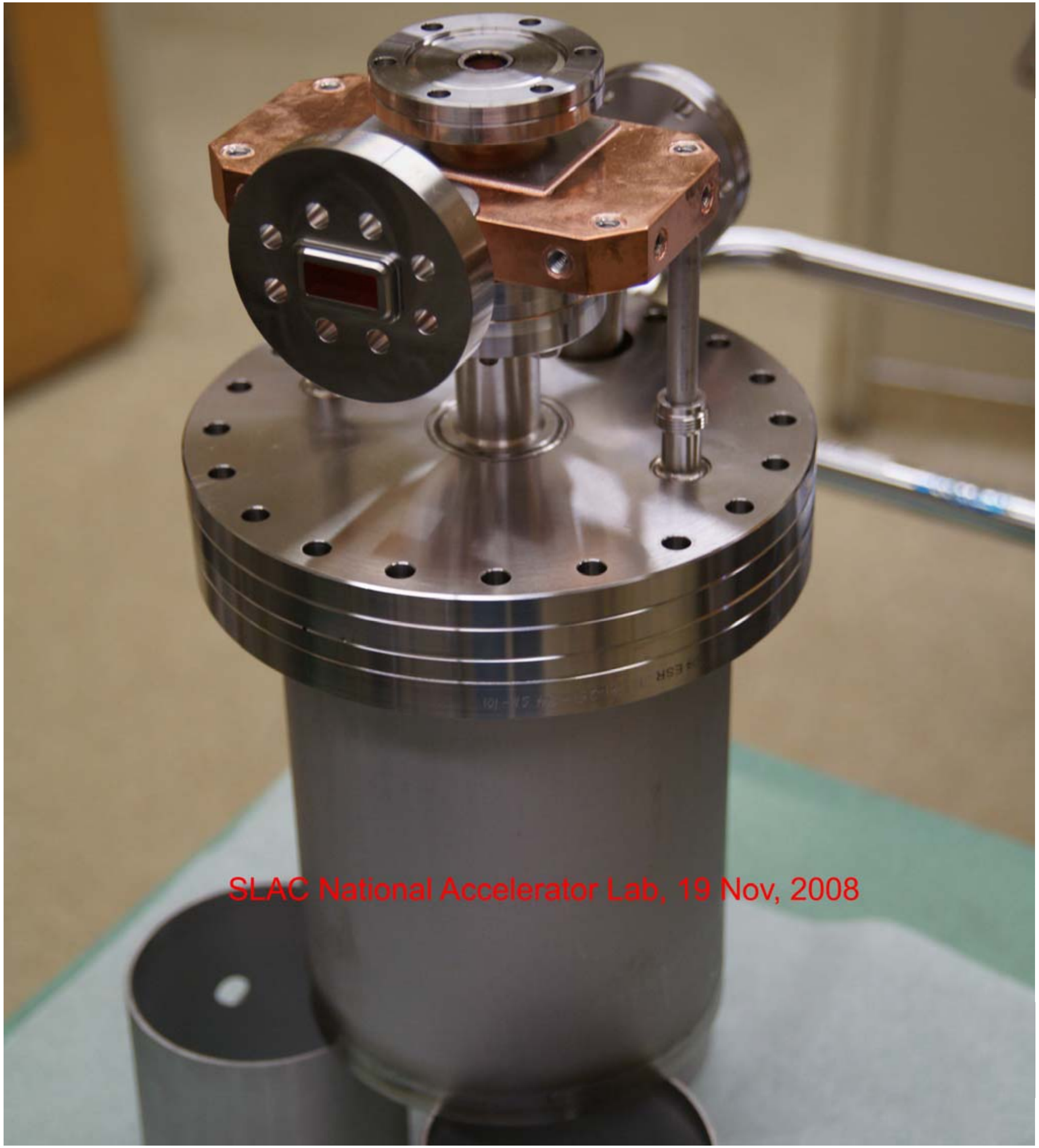
Mechanical design: David Martin


SLAC National Accelerator Lab, 19 Nov, 2008


SLAC National Accelerator Lab, 19 Nov, 2008


SLAC National Accelerator Lab, 19 Nov, 2008


SLAC National Accelerator Lab, 19 Nov, 2008

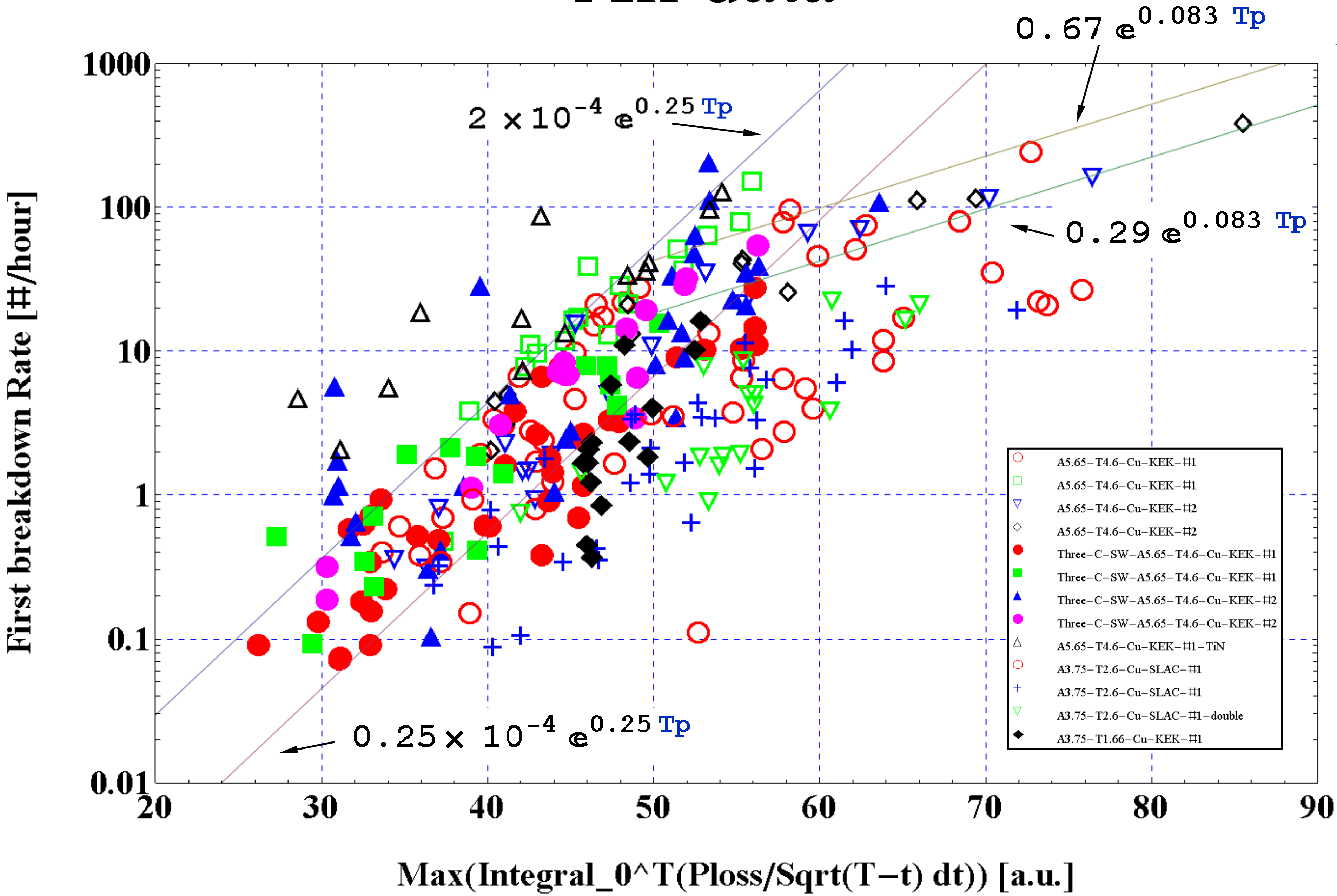

SLAC National Accelerator Lab, 19 Nov, 2008

Summary

We have a test setup with short turn-around time that produces useful data. The stand started working January 2007 and now running15th structure, smallest iris, *1C-SW-A2.75-T2.0-Cu-SLAC-#1*.

More slides

All data



0.67 e^0.083 Tp
2 × 10^-4 e^0.25 Tp
0.29 e^0.083 Tp
0.25 × 10^-4 e^0.25 Tp
First breakdown Rate [#/hour]
1000
100
10
1
0.1
0.01
20
30
40
50
60
70
80
90
Max(Integral_0^T(Ploss/Sqrt(T−t) dt)) [a.u.]
A5.65−T4.6−Cu−KEK−#1
A5.65−T4.6−Cu−KEK−#1
A5.65−T4.6−Cu−KEK−#2
A5.65−T4.6−Cu−KEK−#2
Three−C−SW−A5.65−T4.6−Cu−KEK−#1
Three−C−SW−A5.65−T4.6−Cu−KEK−#1
Three−C−SW−A5.65−T4.6−Cu−KEK−#2
Three−C−SW−A5.65−T4.6−Cu−KEK−#2
A5.65−T4.6−Cu−KEK−#1−TiN
A3.75−T2.6−Cu−SLAC−#1
A3.75−T2.6−Cu−SLAC−#1
A3.75−T2.6−Cu−SLAC−#1−double
A3.75−T1.66−Cu−KEK−#1

Some Observations

- In all structures but one, coated with TiN and choke structure, *breakdown rate increases exponentially with either input power or pulse width*. For structure coated with TiN and the choke structure the pulse-width dependence is weak.
- There is no dramatic difference in breakdown rate for same electro-magnetic field and pulse width between single-cell and 3-cell structures. Same time, stored energy and input power ~2 times different.
- At certain field and pulse width the 3-cell structure shows obvious run-away behavior.
- All structures but one – coated with TiN conditioned in few hours with few vacuum trips. During further operation, the vacuum trips were very rare, even at high breakdown rate. TiN structure took a week to condition. Choke structures took few days to condition.
- All structures had different amplitude of dark current (measured by Faraday cups) for the same field levels and pulse width. There was no obvious correlation between the dark current amplitude for the different structures and the breakdown rate.