High gradient, X-band and above, metallic RF structures

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U.S. DEPARTMENT OF ENERGY
Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

I with to thank *direct contributors* to this report

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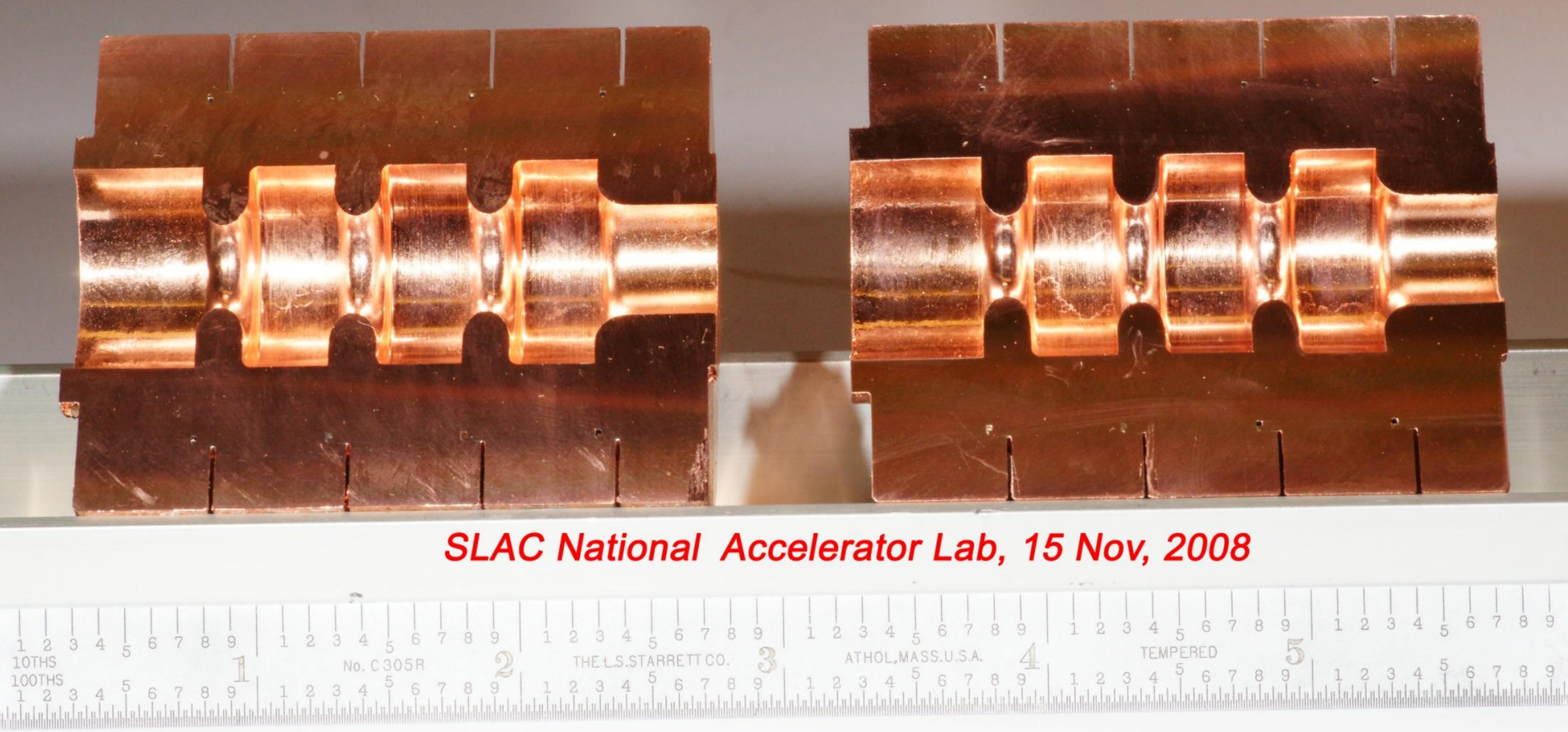
Most recent information:

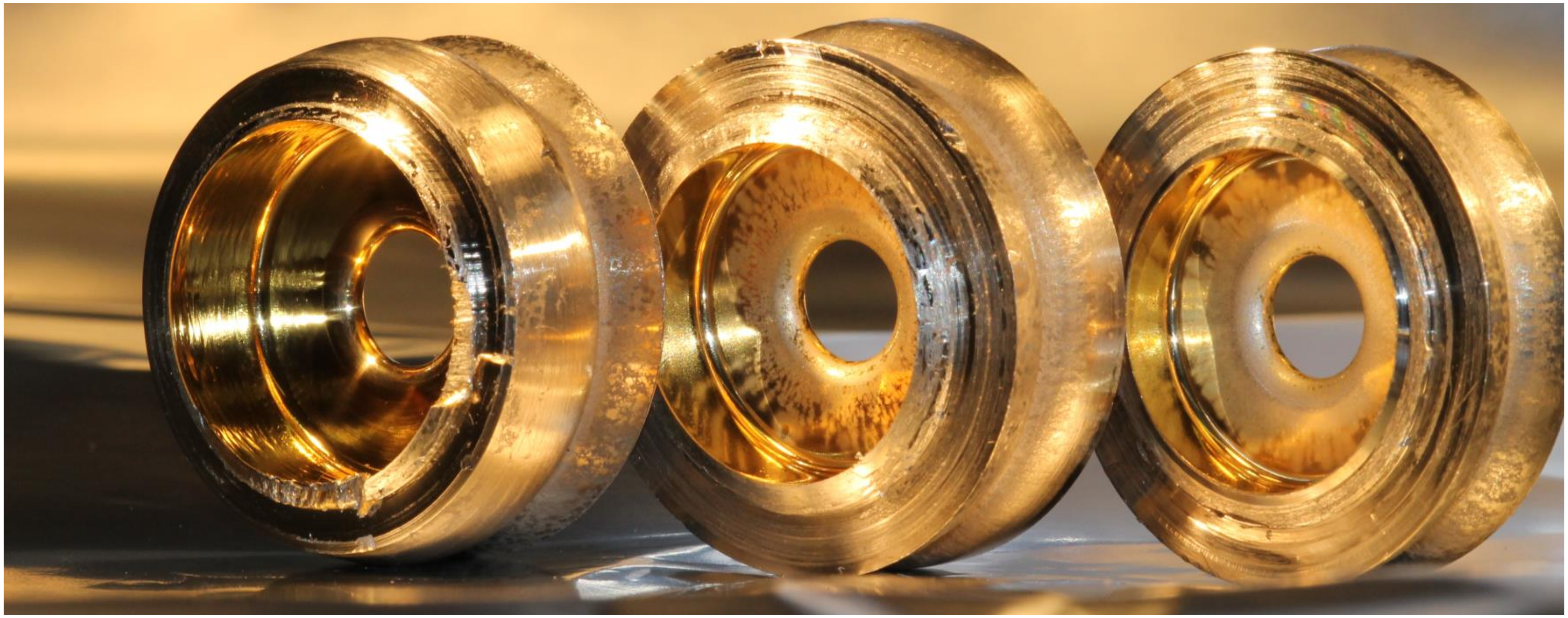
- International Workshop on Breakdown Science and High Gradient Technology (HG2015) Tsinghua University, Beijing , China, 16-19 June 2015.
- 5th International Workshop “Mechanisms of Vacuum Arcs”, MeVArc-5,, in Saariselkä, Finnish Lapland, September 2-4, 2015.

11.4 GHz Standing Wave Accelerating Structure, Copper, 1C-SW-A5.65-T4.6-Cu-Frascati-#2



SLAC-KEK-INFN

11.4 GHz Standing Wave Accelerating Electroformed Structure, Nickel-Gold, after-test autopsy



Input side of *Coupler cell*

High gradient side of *End cell*

High gradient side of *Center cell*

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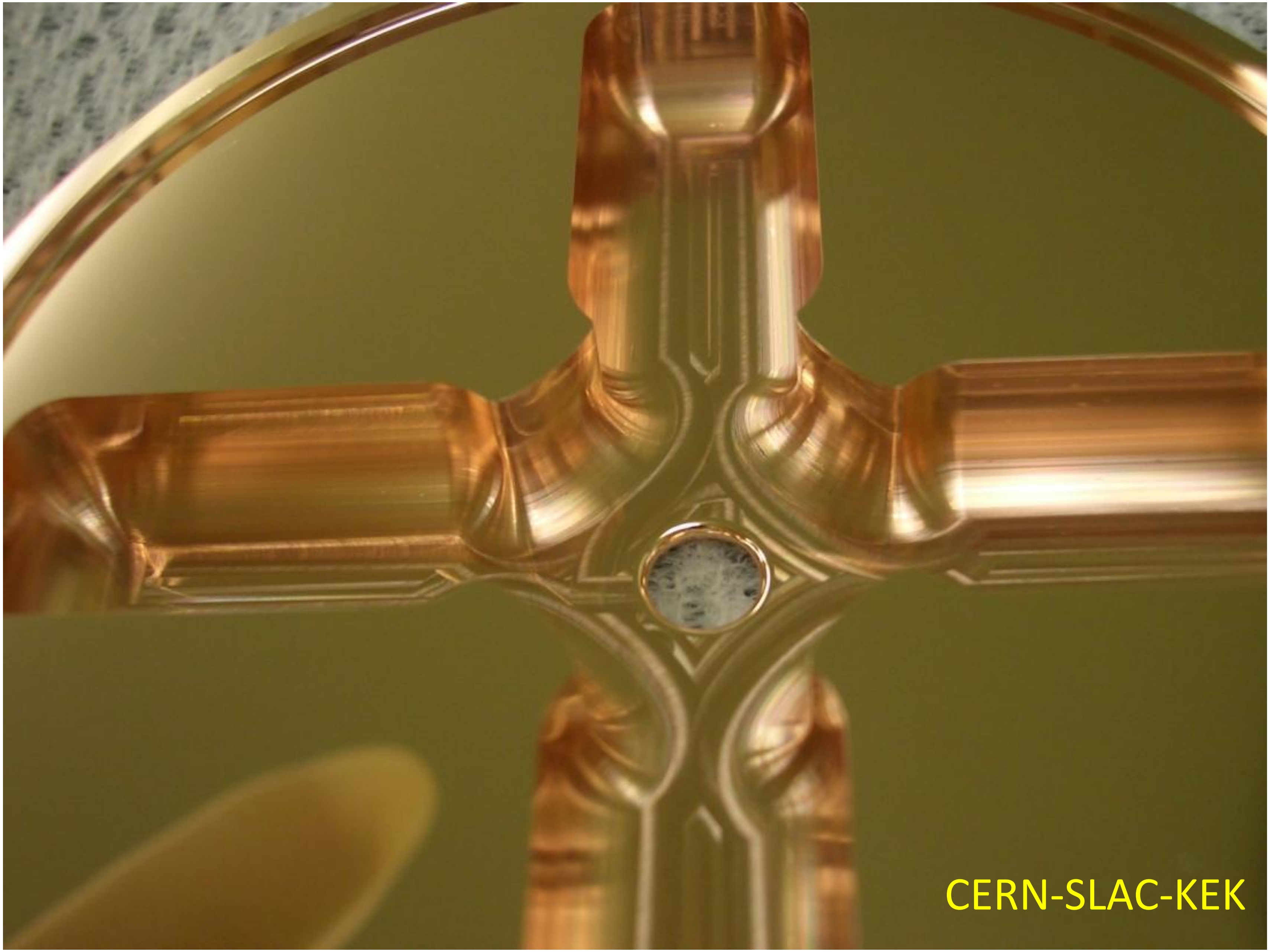
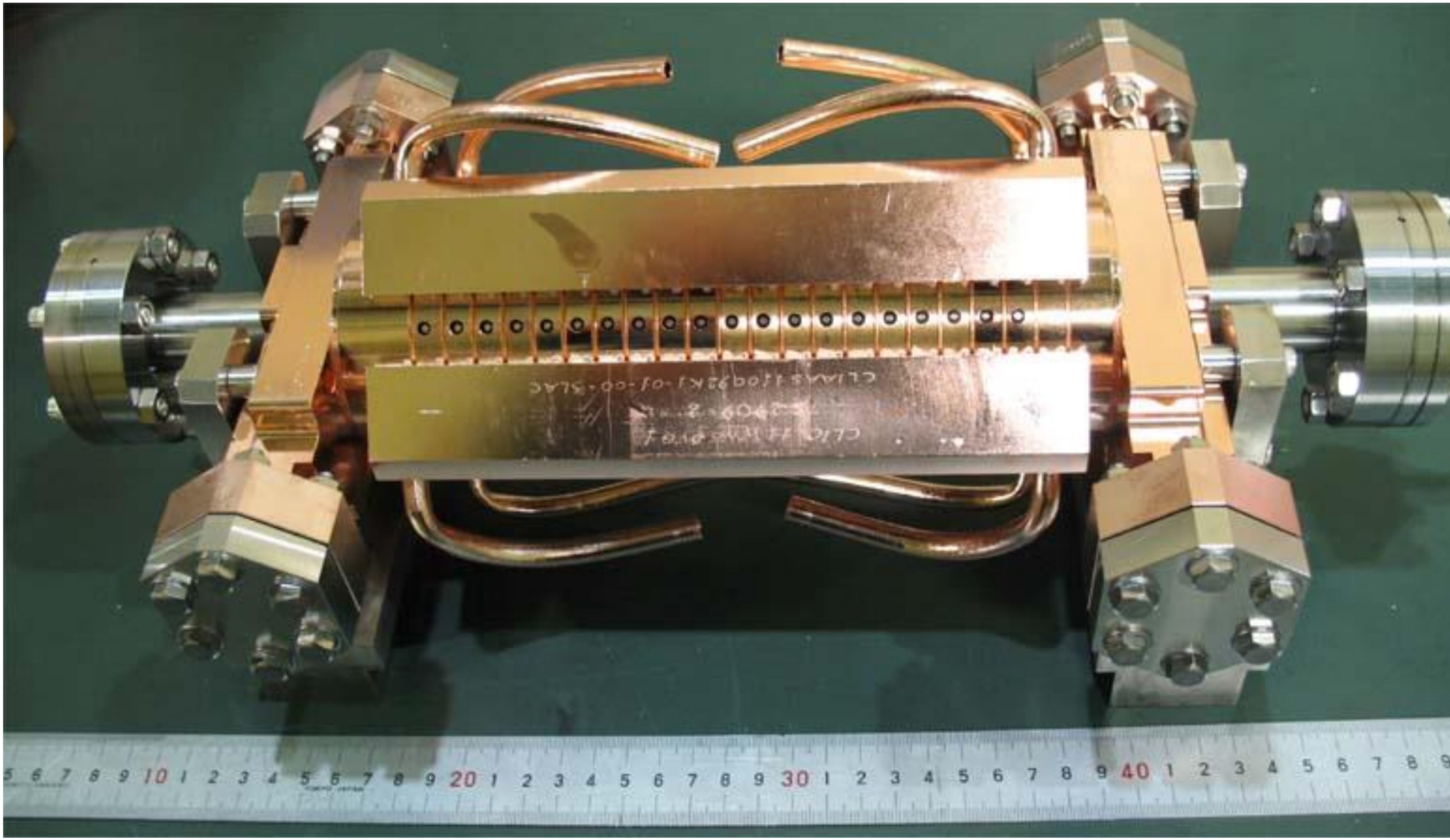
Cell of 11.4 GHz Traveling Wave Accelerating Structure with damping waveguides, CLIC prototype TD24



Traveling Wave Accelerating Structure with damping waveguides, 11.4 GHz , CLIC prototype TD18

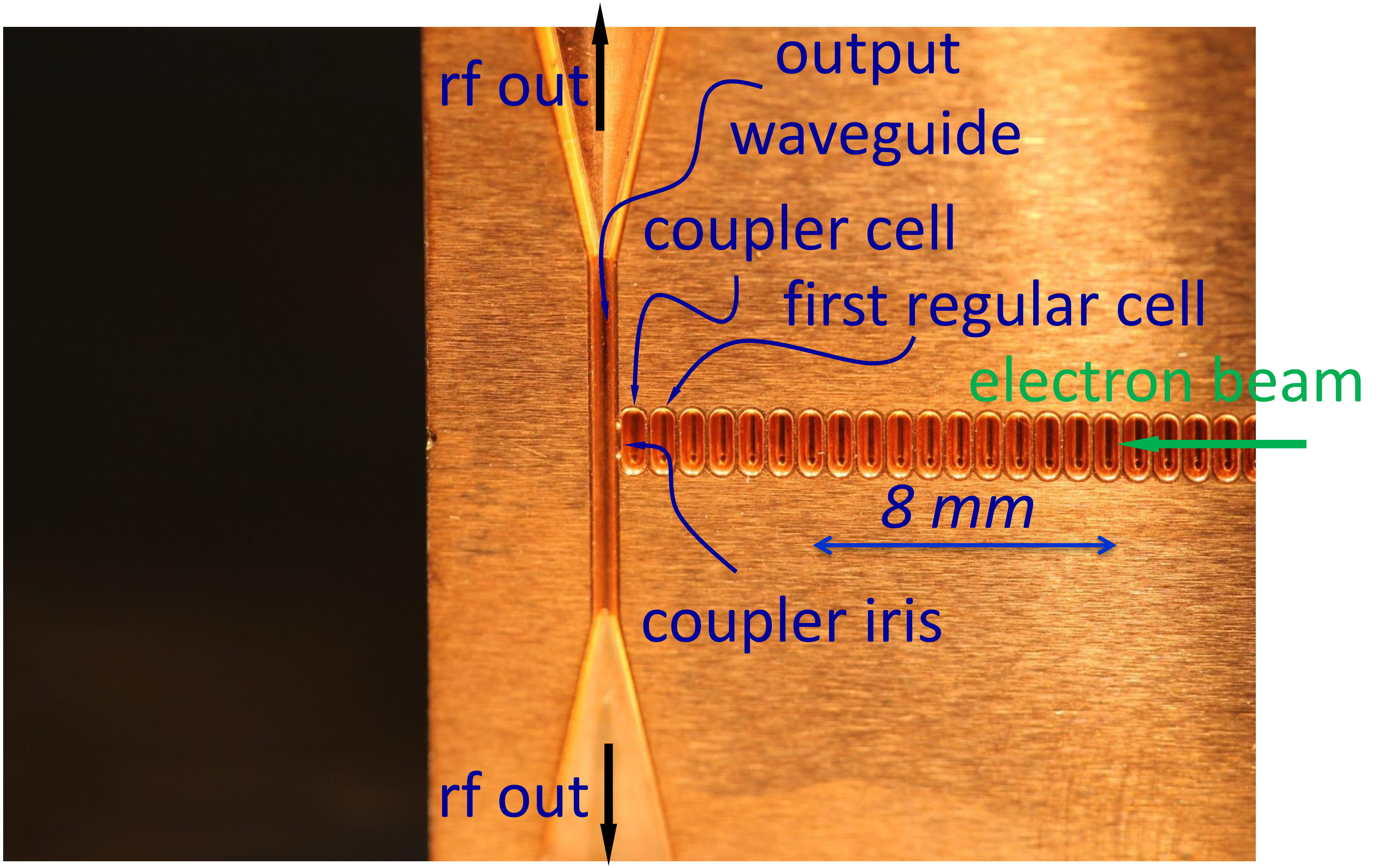


CERN- SLAC-KEK

12 GHz Open-Travelling Wave accelerating structure made by milling, copper, CLIC-G-OPEN

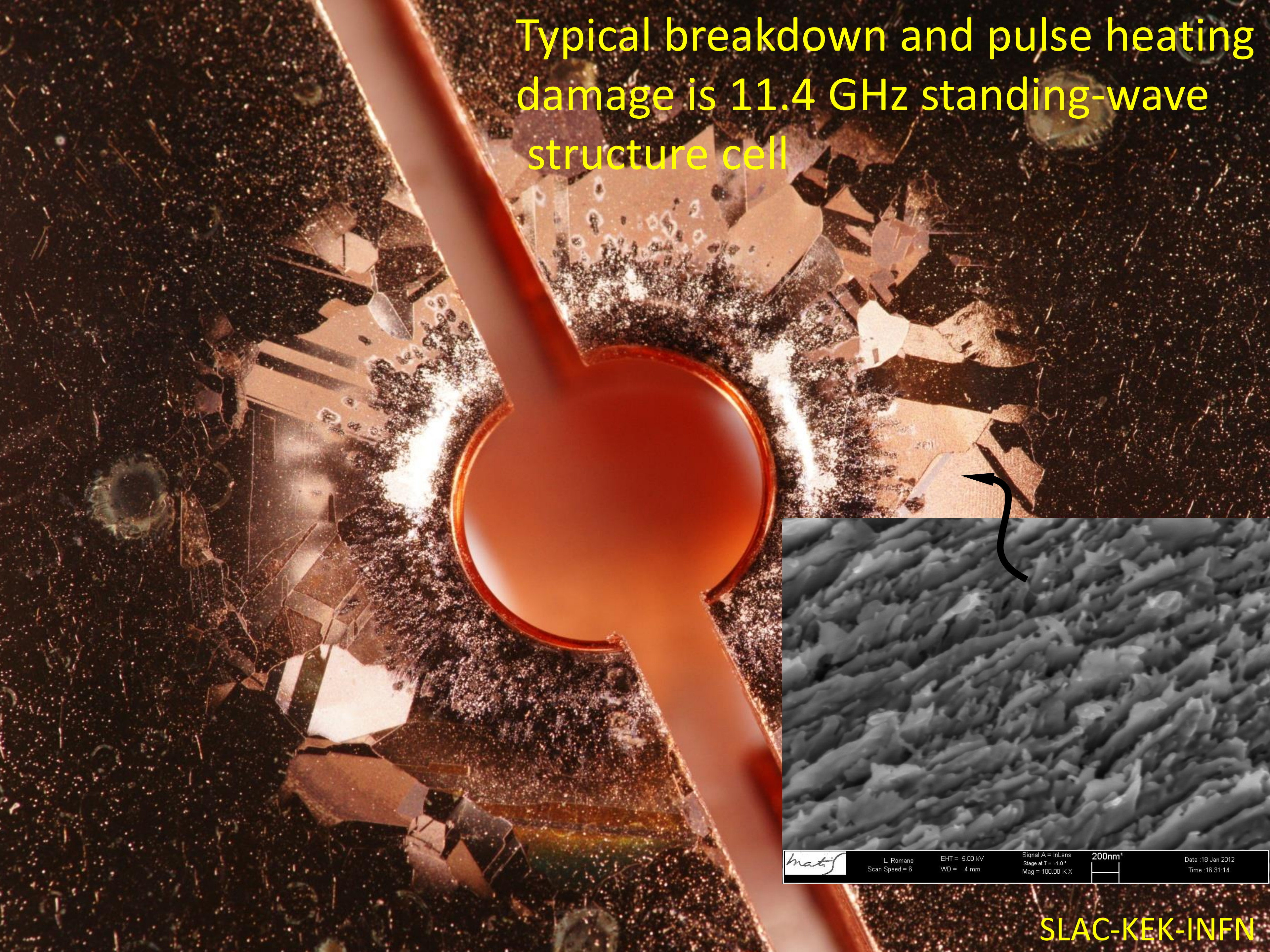
CERN-SLAC

Output Part of the Open 100 GHz Copper Traveling Wave Accelerating Structure



SLAC-INFN

Typical breakdown and pulse heating damage is 11.4 GHz standing-wave structure cell

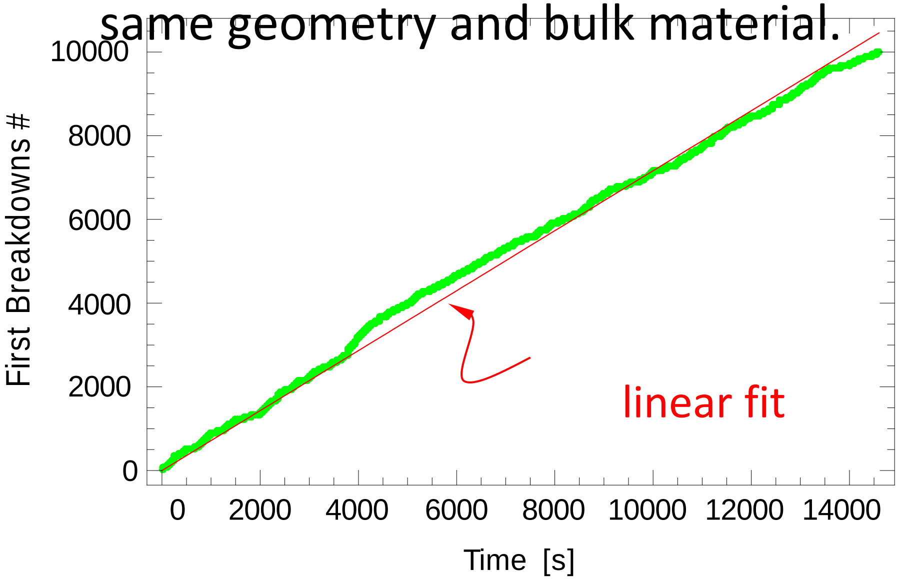


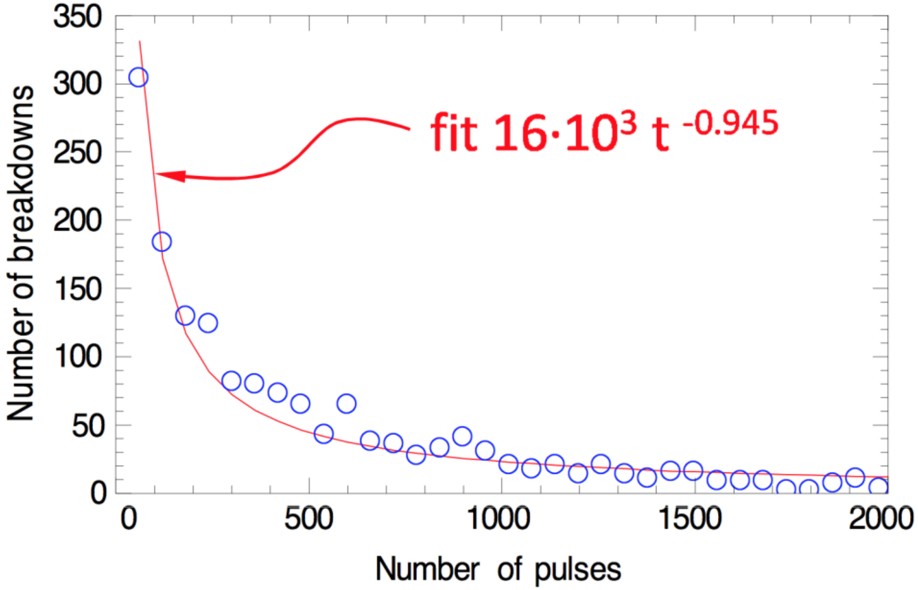
Breakdown rate

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

Current “state of the art”

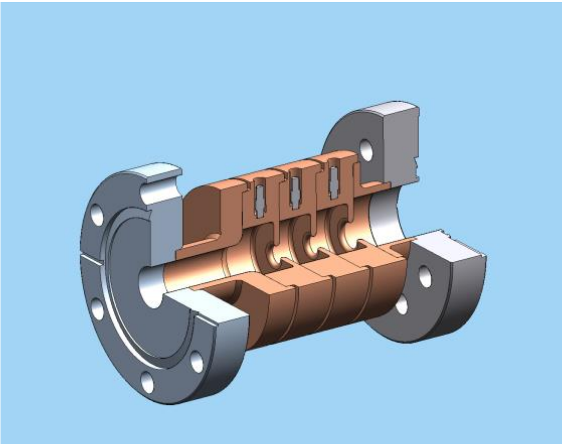
- We practically can predict performance of heat-treated soft copper X-band structures from drawings.
  - We found peak pulse heating to be good predictor of breakdown rate in simple, disk-loaded-waveguide type geometries.
  - We found “modified Poynting vector”(Sc) to be a practical predictor of breakdown 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 breakdown physics in 100 GHz and 200 GHz
- 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

Outline

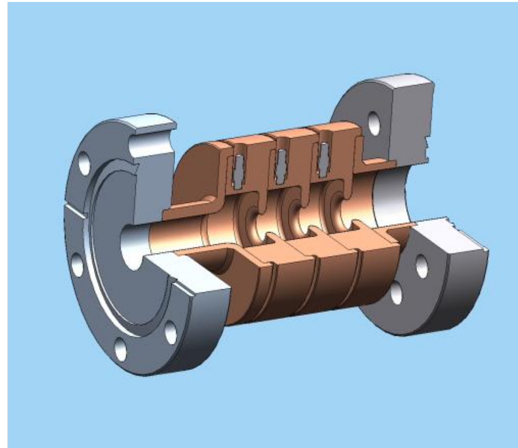
- Experiments on Basic physics of rf breakdown
  - Geometry
    - Peak Pulse Surface Heating
      - Hard copper and Copper Alloys
    - Dual mode structure
    - Peak Poynting Vector
  - Material
    - Normal conducting cryo structure
- New manufacturing techniques
  - Clamped rf gun
  - Open traveling wave structures
- Frequency scaling
    - 90 GHz
    - 120 GHz
    - 235 GHz
- Resent Full structure tests
- Dislocation dynamics

Geometrical Studies

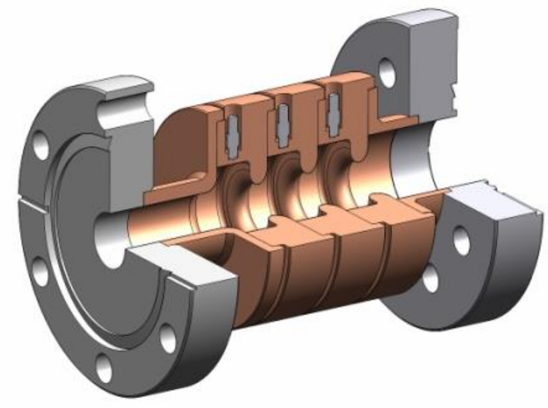
Three Single-Cell-SW Structures of Different Geometries



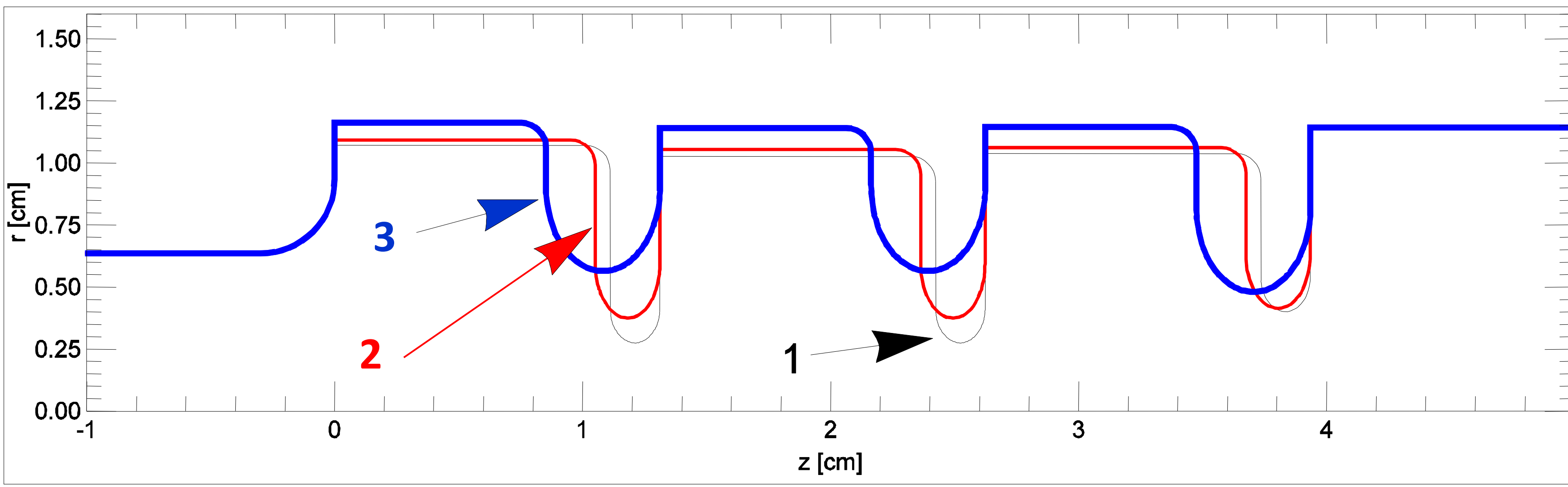
1)1C-SW-A2.75-T2.0-Cu



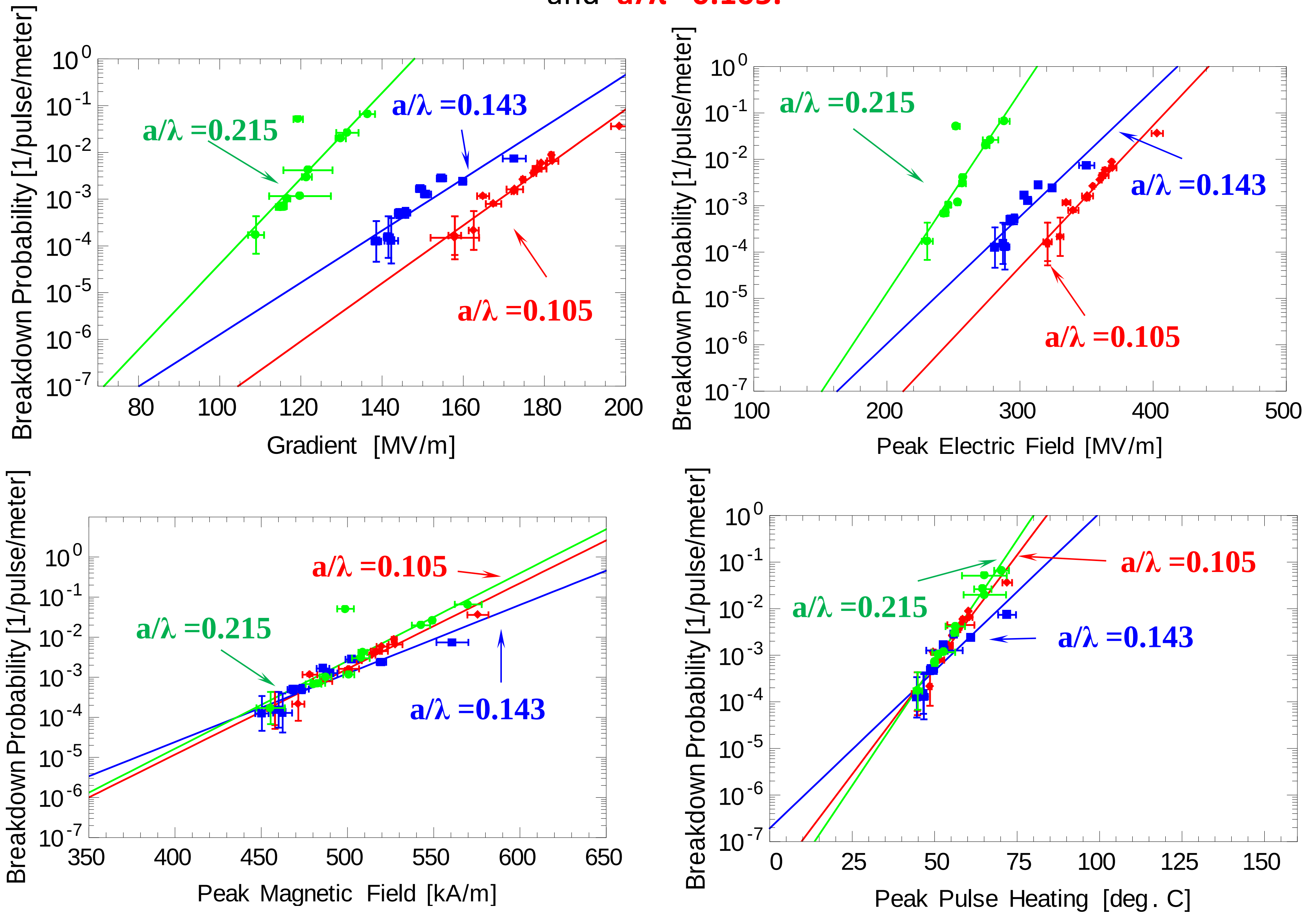
2) 1C-SW-A3.75-T2.0-Cu



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:

Local electric field seems to have less importance than magnetic field

Consequences :

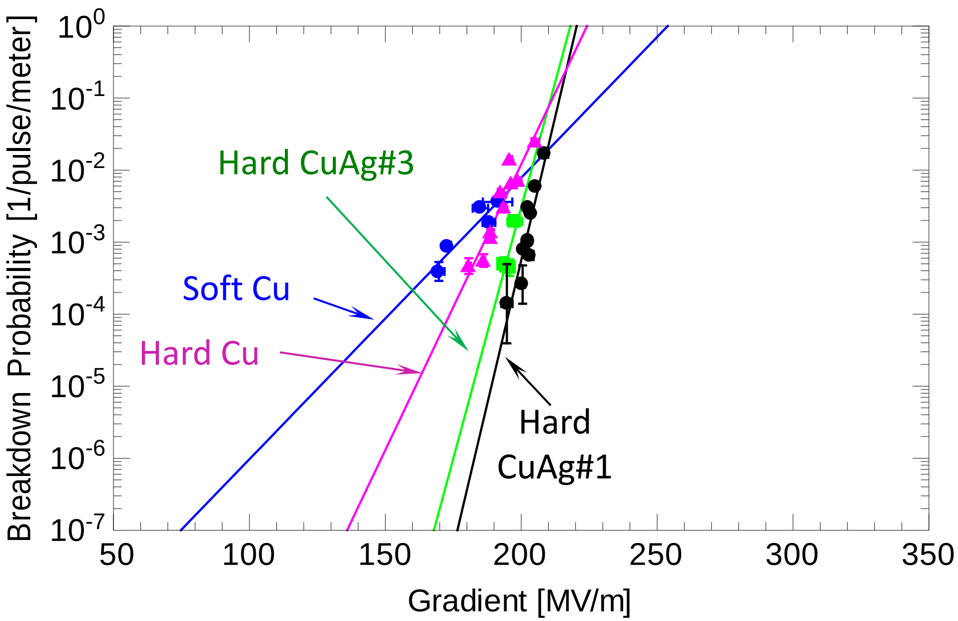
- New geometries optimized for low pulse heating
- Experiments that uncouple rf electric and magnetic fields

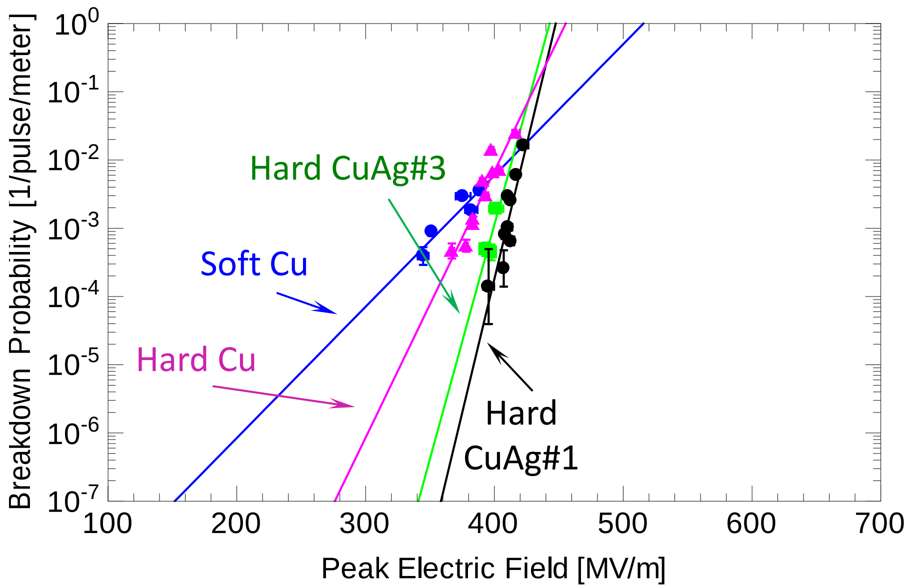
- Dedicated study of pulse heating
  - Lisa Laurent et al., *Experimental study of rf pulsed heating,* Phys. Rev. ST Accel. Beams 14, 041001 (2011)
  - S. Heikkinen, *Study of High Power RF Induced Thermal Fatigue in the High Gradient Accelerating Structures, Ph.D. thesis,* Helsinki University of Technology, 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

Development of Hard Copper and Coper 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

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



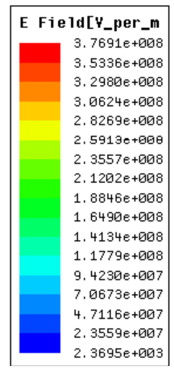


We found that hard copper and hard copper-silver have better high gradient performance then soft, heat-treated copper.
In addition to that, at initial stages of conditioning CuAg clearly outperforms hard copper.

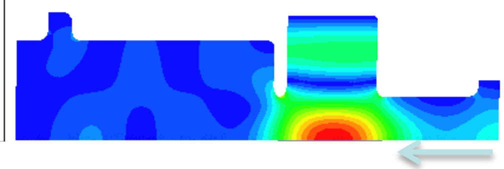
Dual Mode Accelerating Cavity for studying the relative effects of electric and magnetic fields

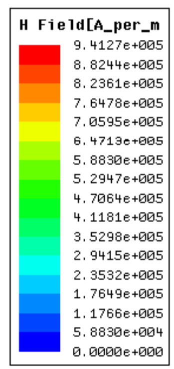
•The experiment is very flexible, we change the independently electric and magnetic field, timing between fields , and relative amplitude and phase

•This experiment is finished we are in the process of understanding the data

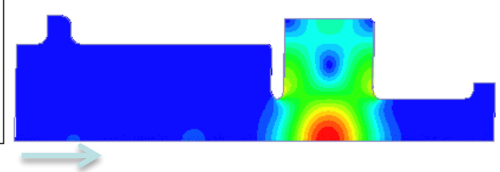


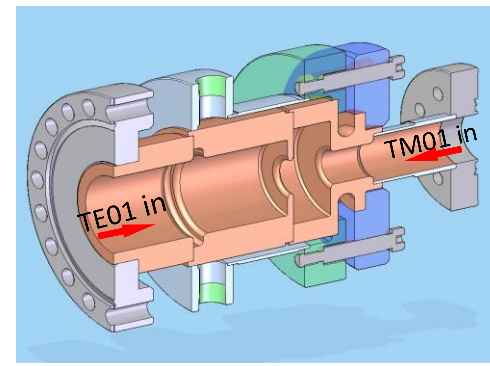
Electric Field due to the TM_{020} Mode

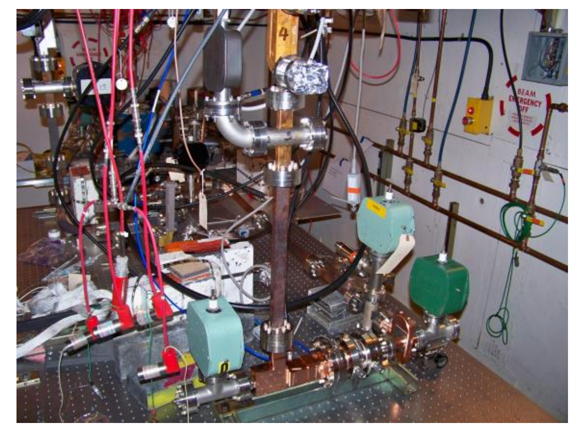


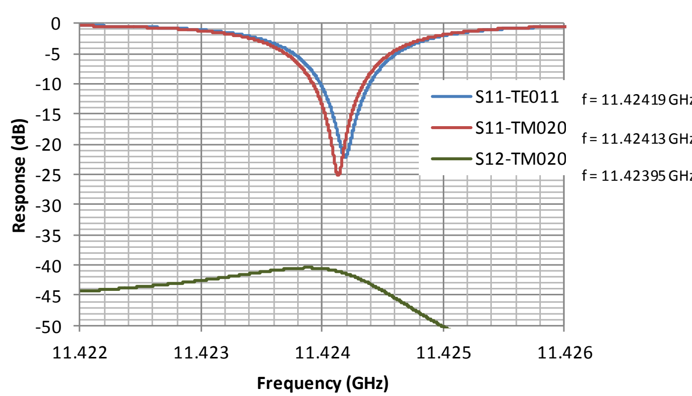


Magnetic Field due to the TE_{011} Mode



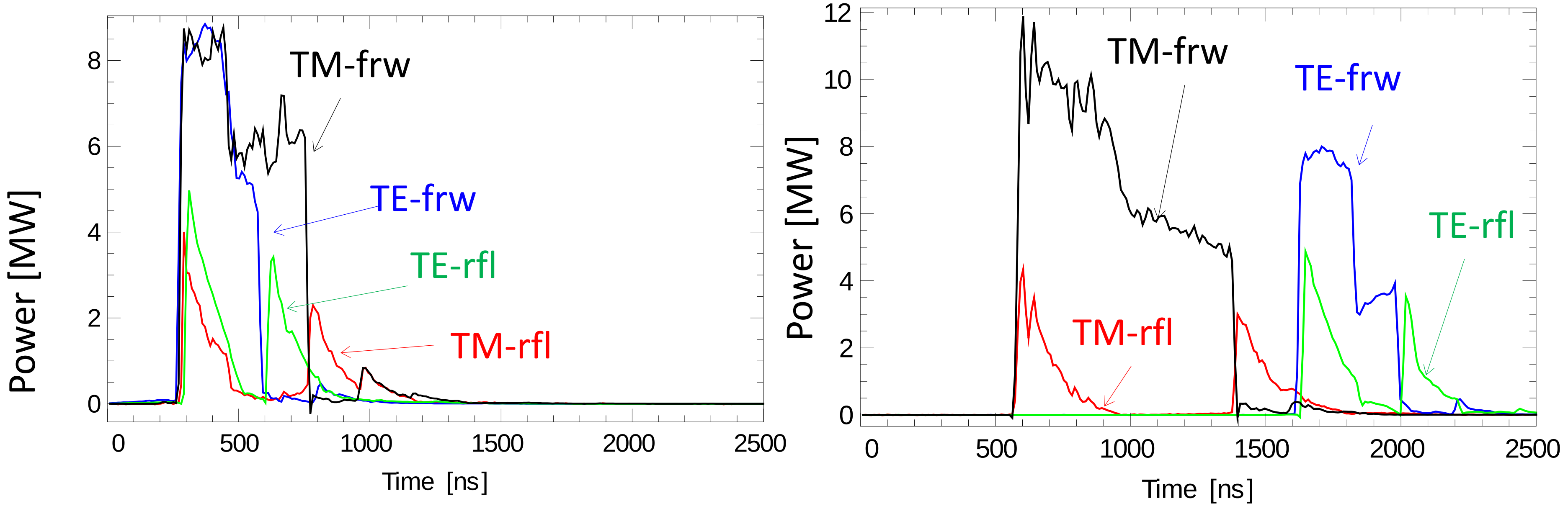




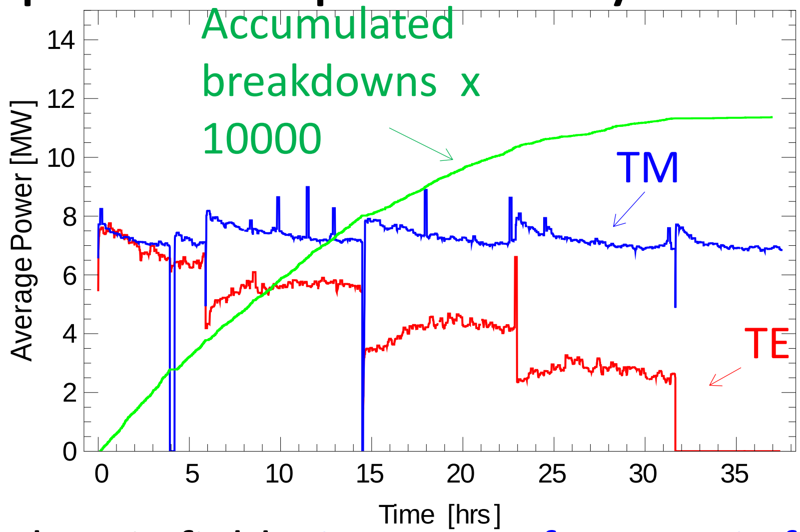


Dolgashev *et al.*, IPAC12

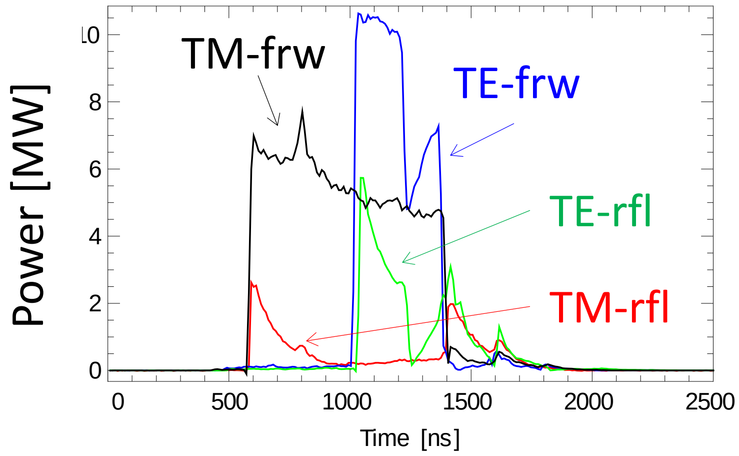
Independent control of two klystrons allows arbitrary relative timing of the modes

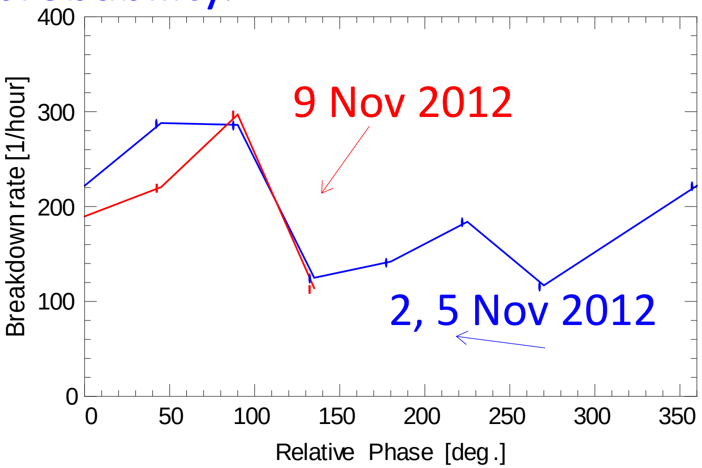


Effect of surface magnetic field and its relative-to-electric filed phase on probability of RF breakdowns



With constant surface electric fields, increase of magnetic fields dramatically increases breakdown probability.

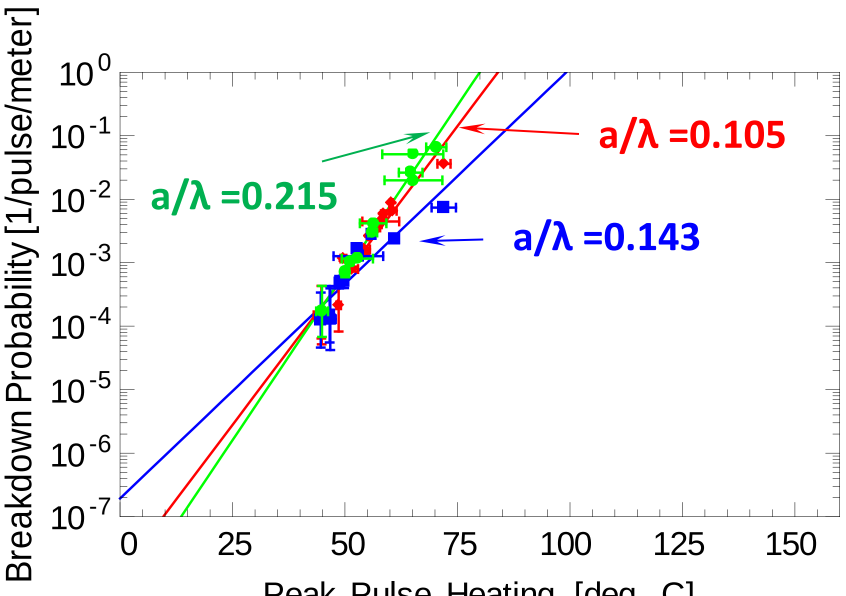


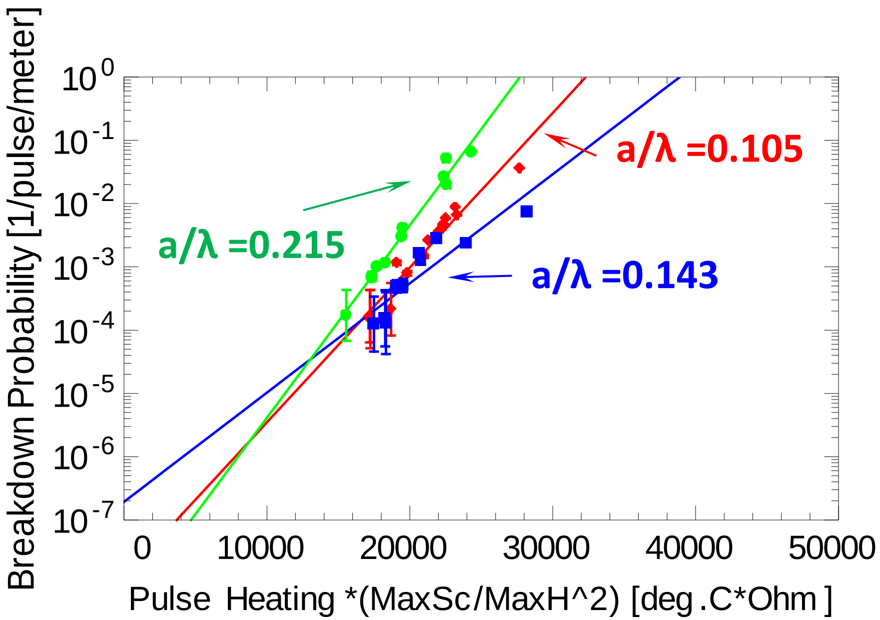


Breakdown probability is clearly correlated with relative phase between surface electric and magnetic fields.

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:

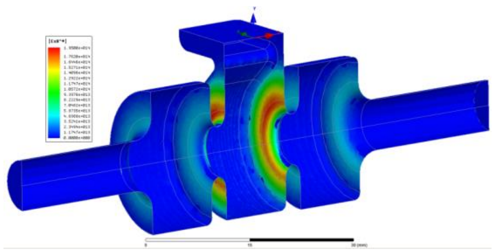
A. Grudiev, S. Calatroni, and W. Wuensch,
New local field quantity describing the high gradient limit of accelerating structures,
Phys. Rev. ST Accel. Beams **12,** 102001 (2009).

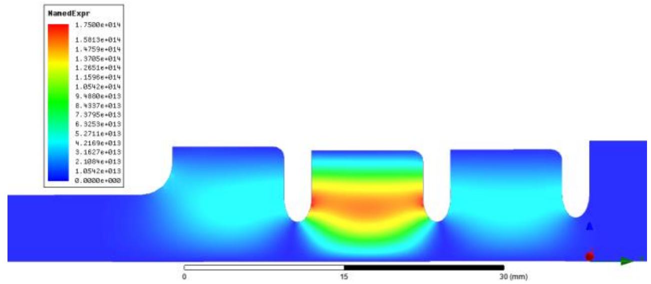
Structures that have different ratio between peak Poynting vector and peak H^2

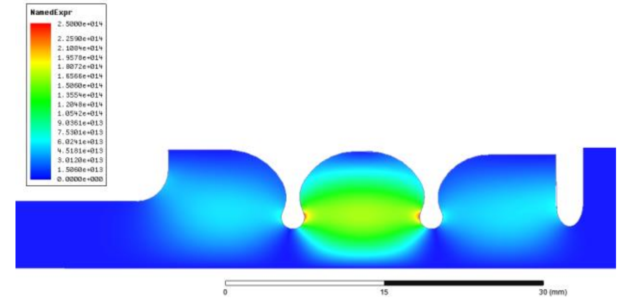
1C-SW-A3.75-T2.6-1WR90-Cu

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

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



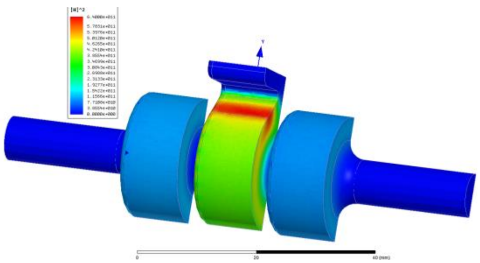


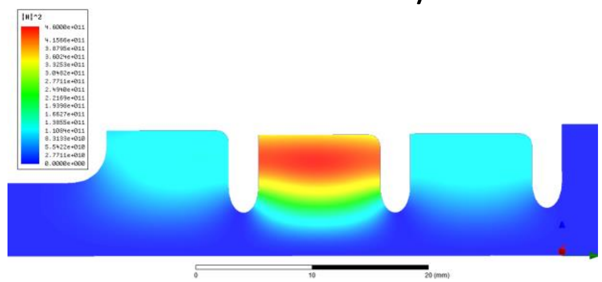


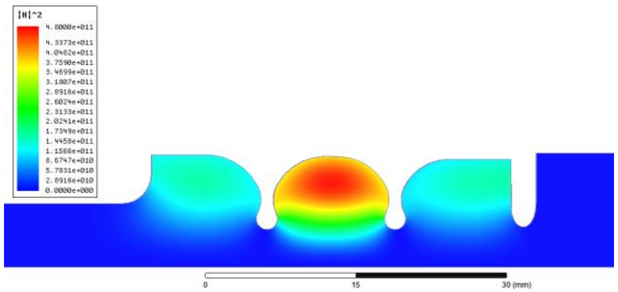
Max. Poyning Vector
1.93 e14 W/m^2

Max. Poyning Vector
1.73 e14 W/m^2

Max. Poyning Vector
2.4e14 M/m^2







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

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

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

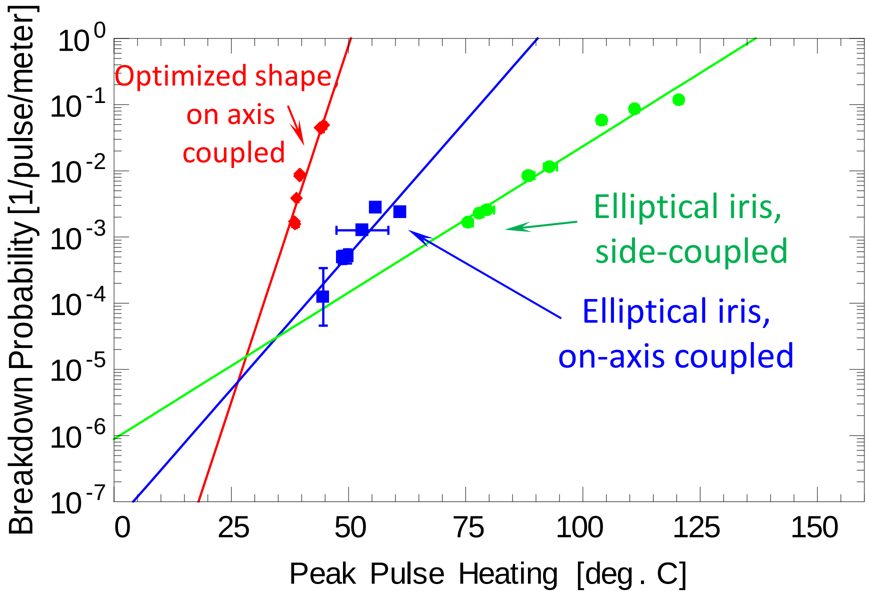
Ratio is **301 Ohm**

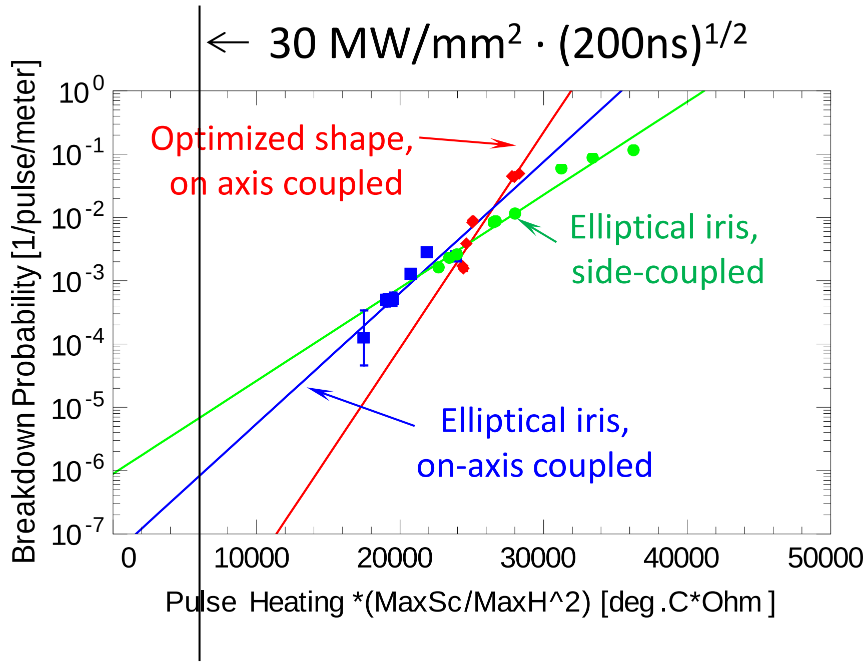
Ratio is **390 Ohm**

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





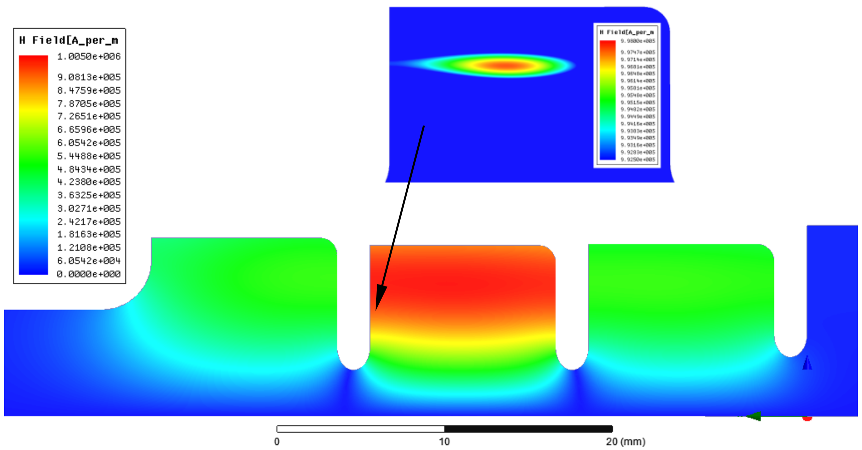
For structures of significantly different geometries breakdown rate better correlated more with peak Poynting vector than with peak surface pulse heating.

Freezing crystal defects: Normal Conducting Cryogenic Structure

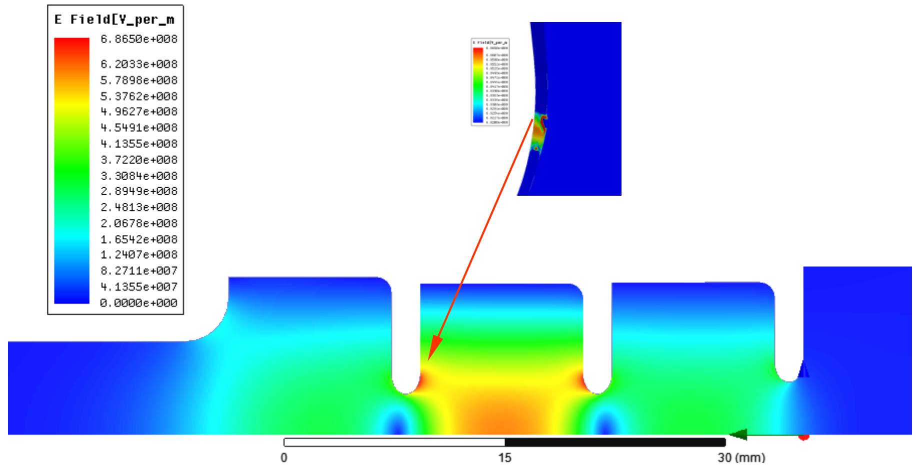
- We conjecture that the breakdown rate is linked to movements of crystal defects induced by periodic stress. Pulse heating creating some or, possibly major part of this stress. So, by decreasing crystal mobility and increasing yield stress we will reduce the breakdown rate for the same gradient. We 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.

See talk at HG2015, Tsinghua University, Beijing, China, 16-19 June 2015

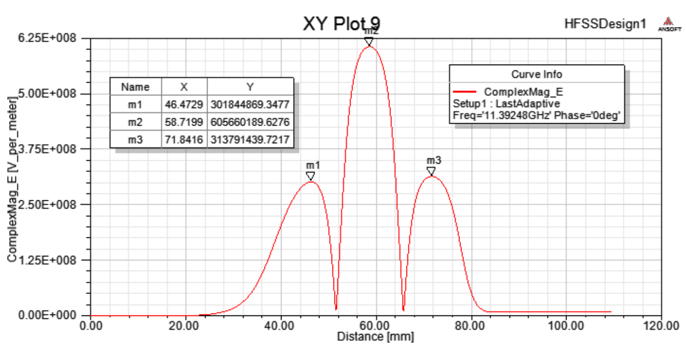
Design of cryo accelerating structure, 1C-SW-T2.75-A2.0-Cryo-Cu, 11.3925 GHz, 10 MW rf input



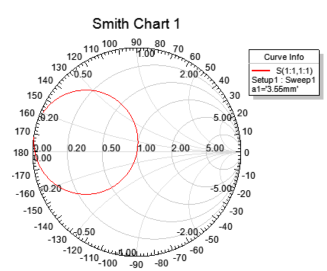
Maximum magnetic field 992.5 kA/m
(SLANS 993.2 kA/m)



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



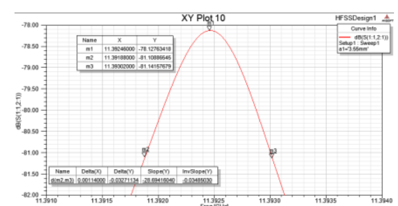
Coupler-cell on-axis field is ~4% high vs. end-cell field,
Peak field on axis 605.7 MV/m (SLANS 605.7 MV/m)

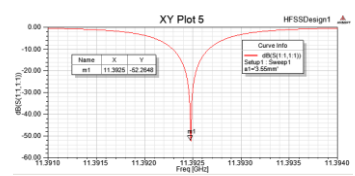


Slightly over coupled with beta= 1.00488

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

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

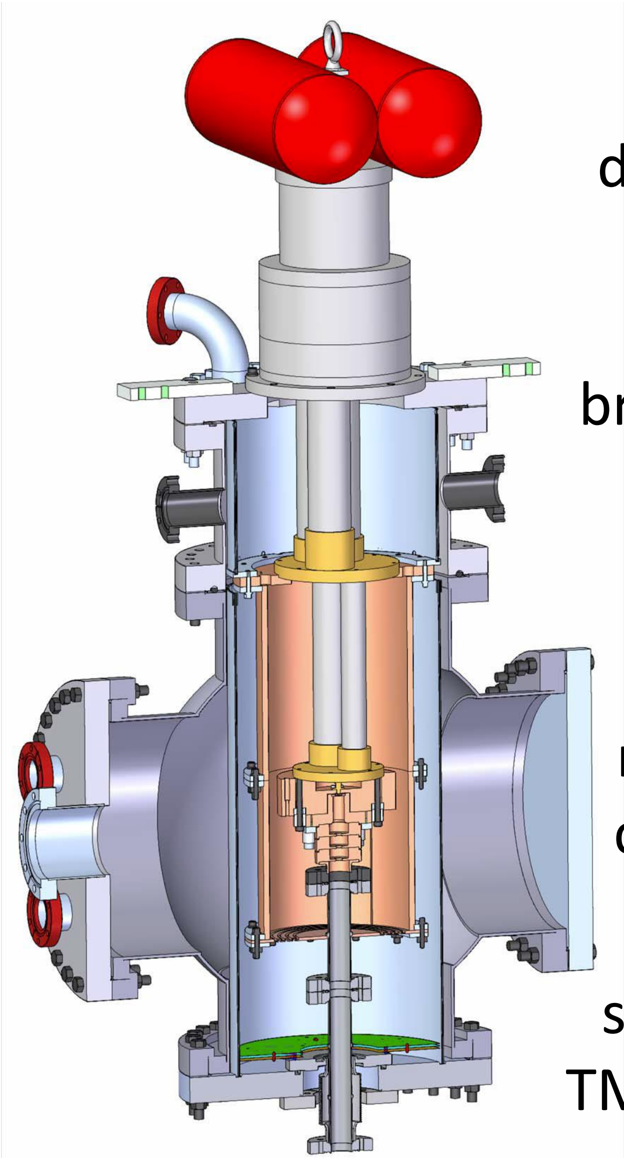




F=11.39**25** GHz (SLANS 11.93**40** GHz)

V.A. Dolgashev, SLAC, 14 March 2011

Cryo structure setup with rf vacuum isolated from cryo vacuum



Cryostat assembly

cold head

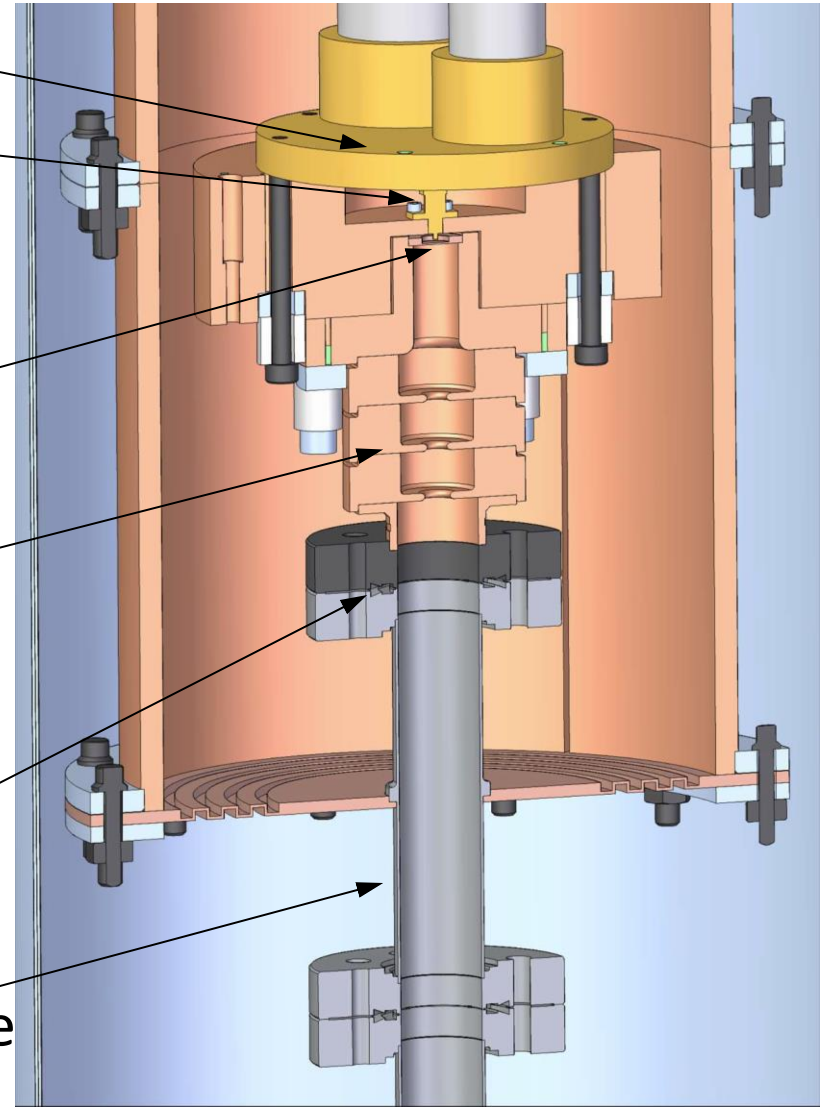
dark-current monitor

brazed-in metal foil

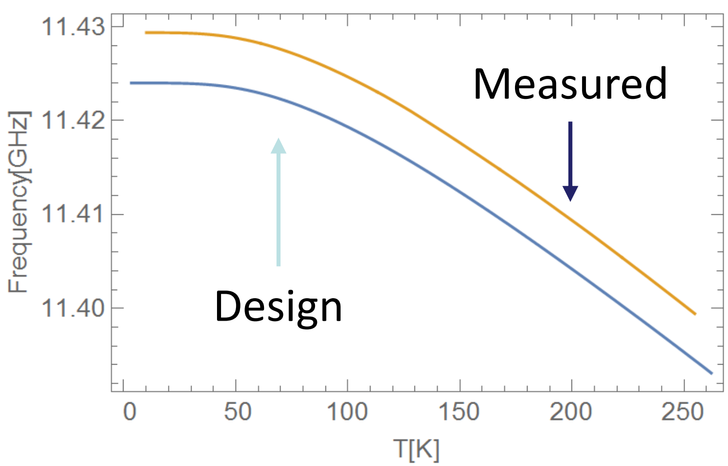
accelerating structure

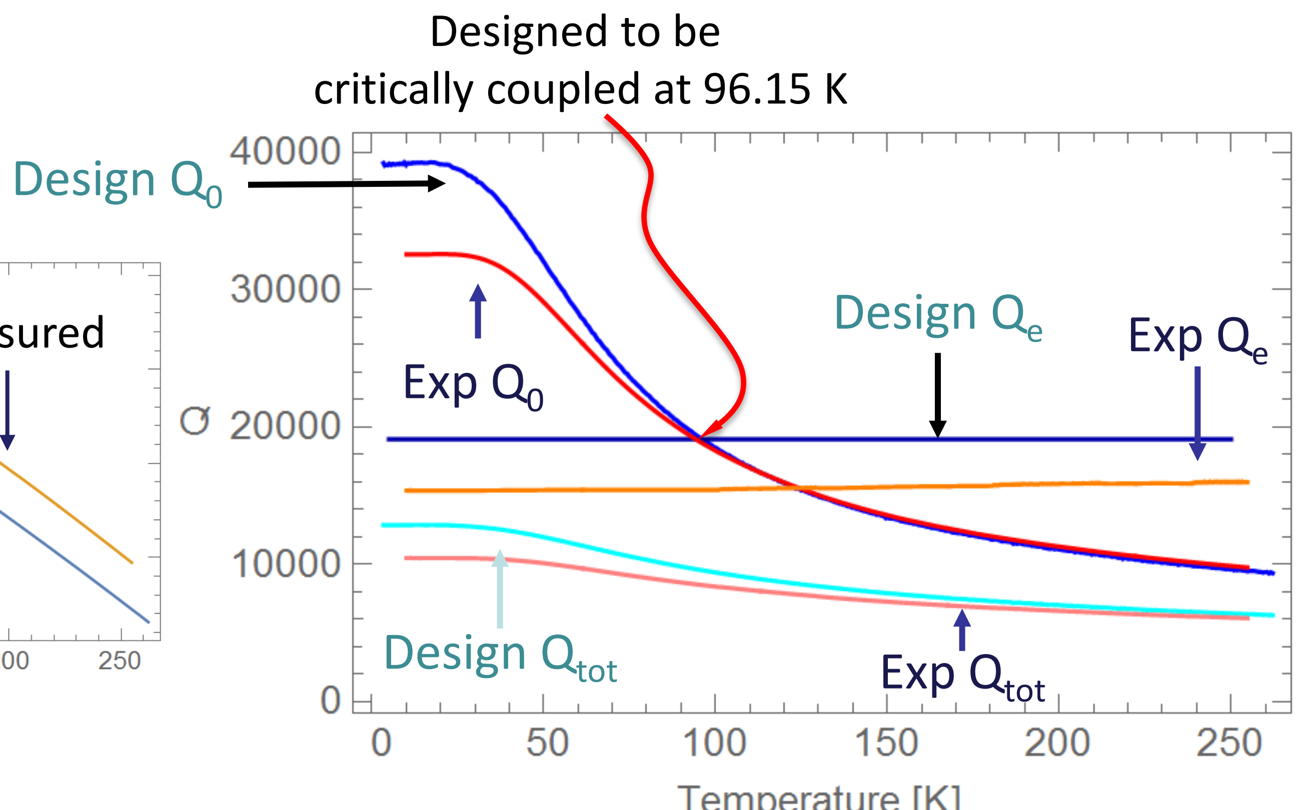
rf flange with crashed metal gasket

stainless steel TM01 waveguide



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

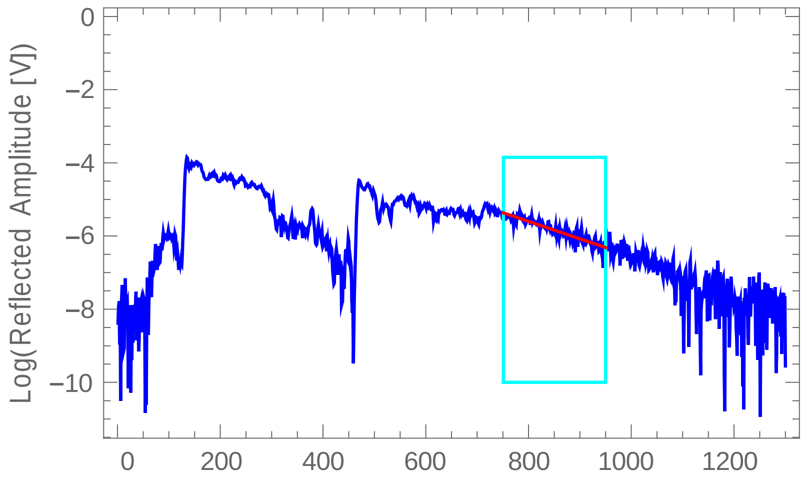




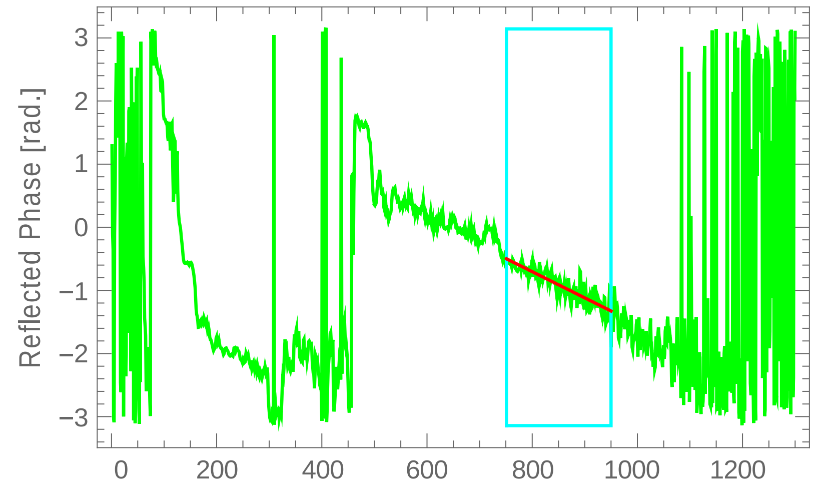
Design parameters versus measured

Alex Cahill (UCLS), Matt Franzi, Jim Lewandowski

Obtaining Q_{loaded} from decay of downmixed reflected signal

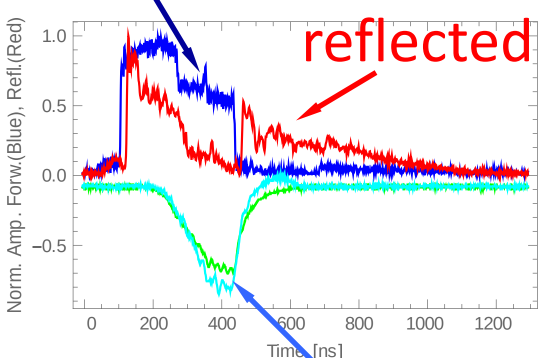


Amplitude of reflected signal

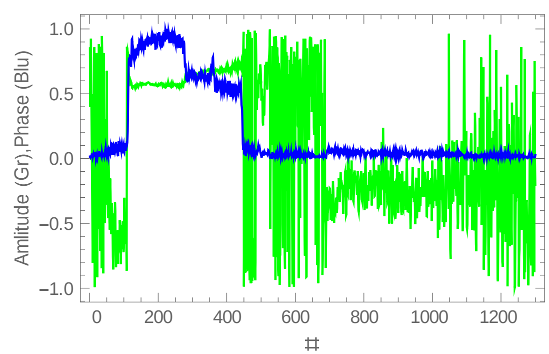


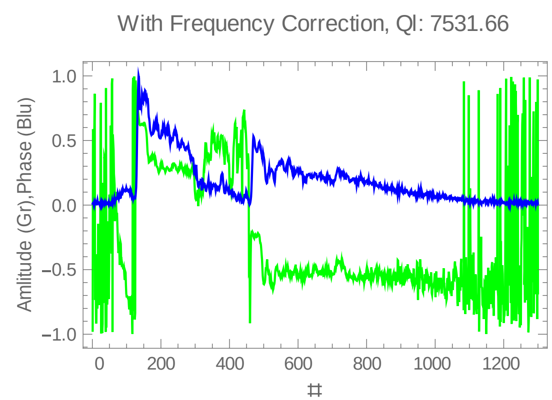
Phase of reflected signal, raw data

forward



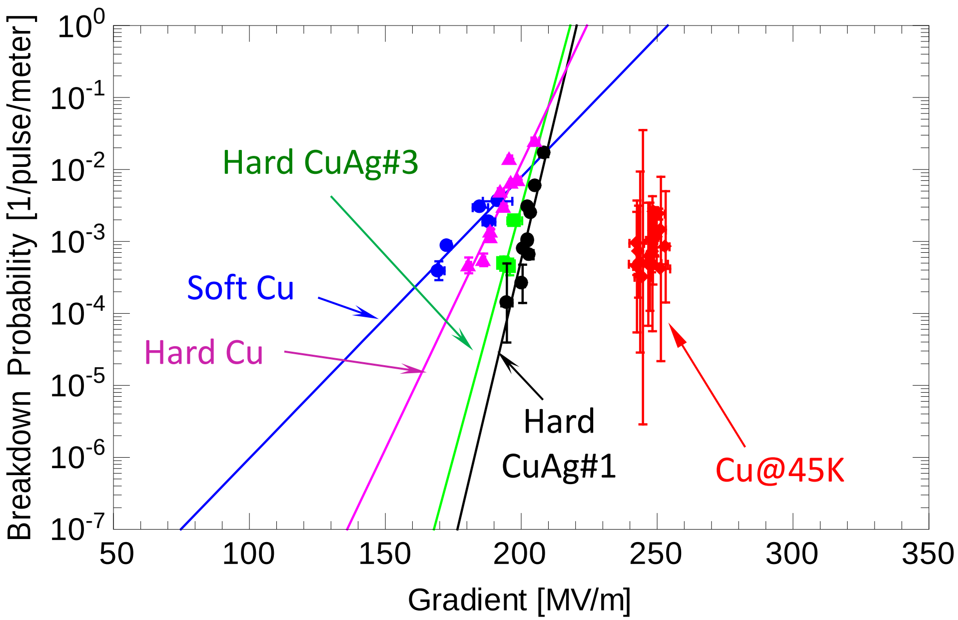
dark current

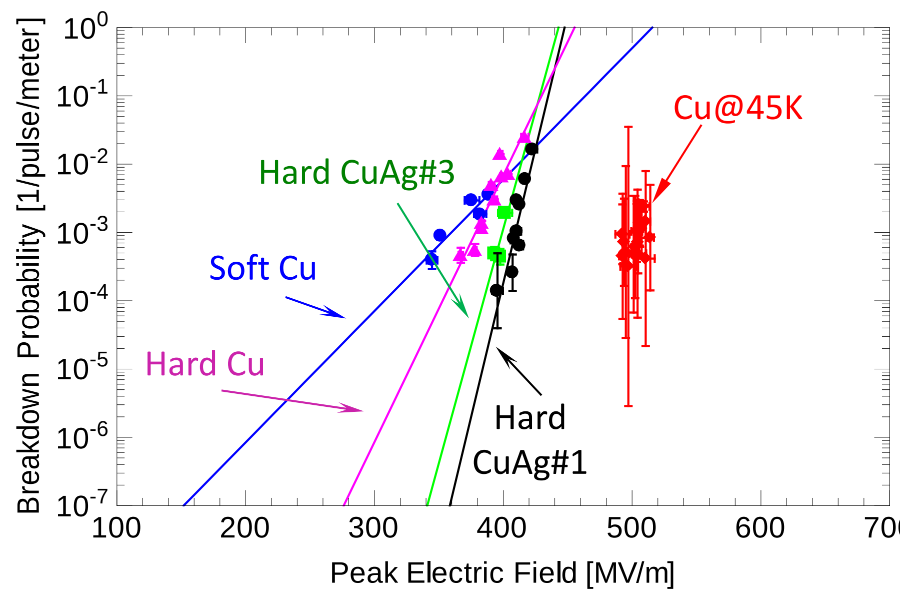




Q_{loaded} = 7531 is consistent with fit of peak-power meter signals

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.

Current Status of our Cryo experiment

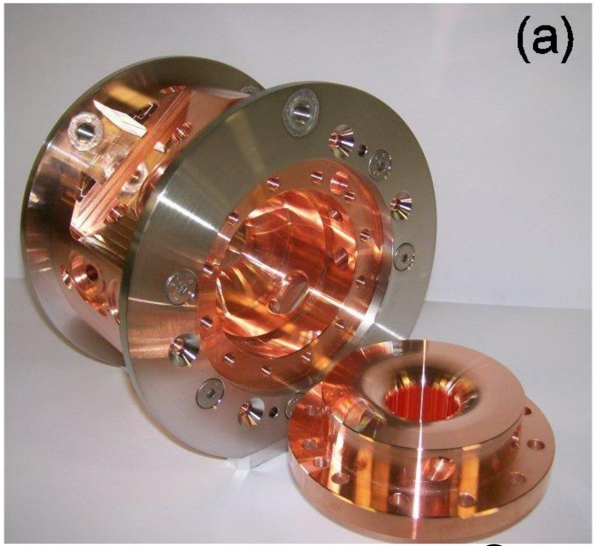
Preliminary analysis indicates that breakdown probability in our cryo single-cell structure is lower then in any other cavity we have tested. This show potential of practical structures with accelerating gradients above 250 MV/m.

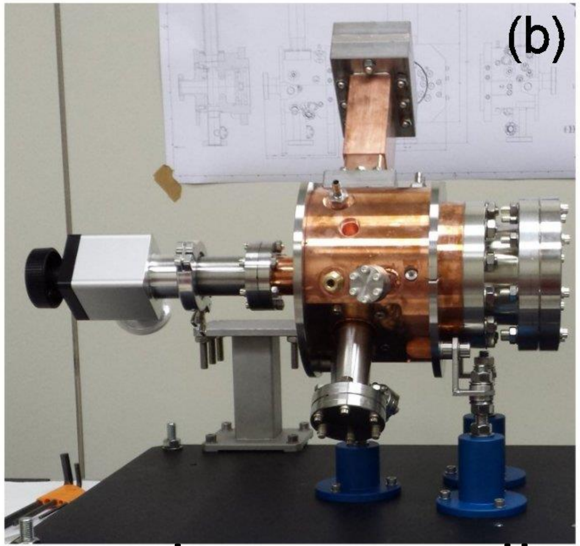
We found that rf losses in the cryo structure are higher then we measured using network analyzer. We are working on understanding of physics behind this reduction: We plan to systematically measure Qo at high power *vs.* temperature, repetition rate, pulse length, pulse shape, dark current. We also want to see whether Qo changes during the rf pulse.

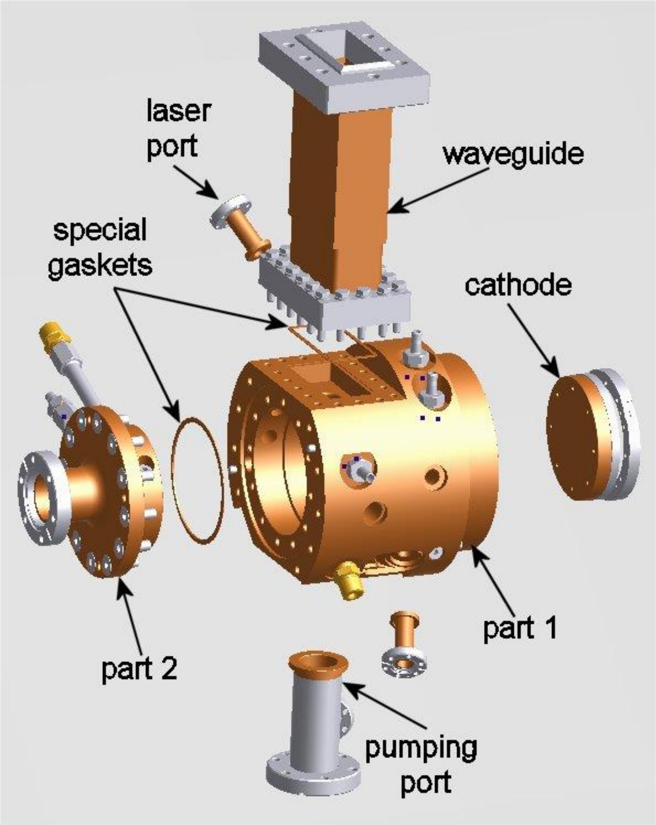
Hard copper alloys outperform soft, heat treated copper, so manufacturing techniques need to be developed that does not use high temperature brazing

Clamped photo-rf gun

The new SPARC GUN has been realized without brazing using a novel process recently developed at LNF-INFN involving the use of special gaskets that guarantee (simultaneously) the vacuum seal and perfect RF contact when the structure is clamped.





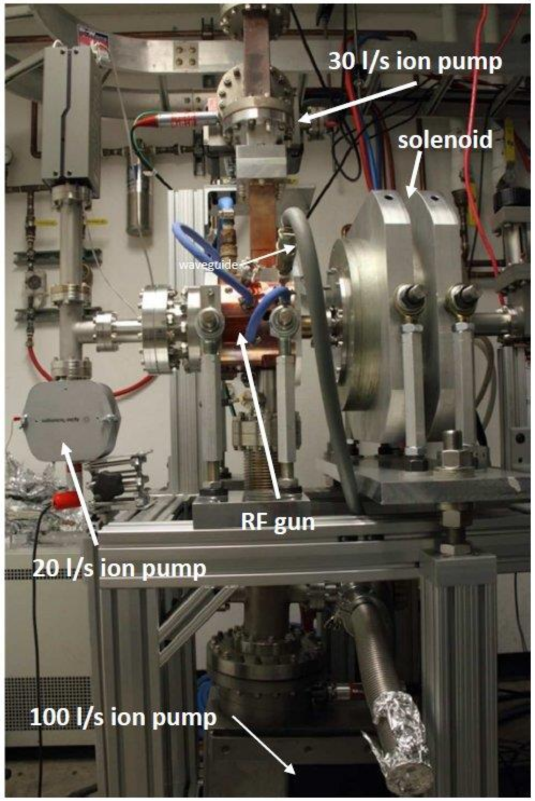


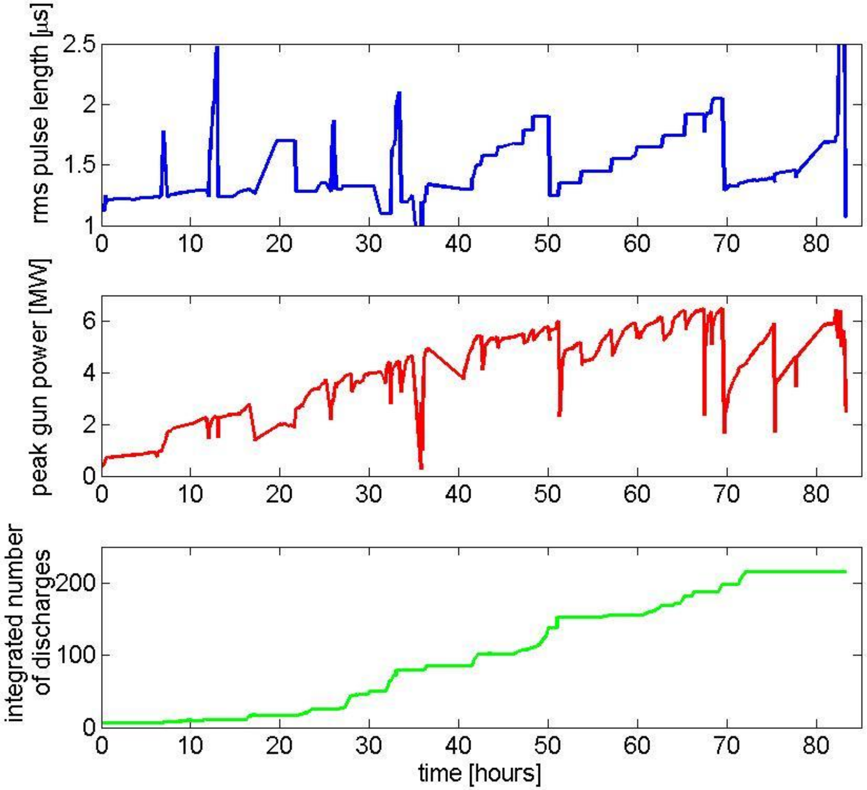
INFN

See Monday WG3 talk of David Alesini

High Power Test of Clamped Photo-Gun

The gun has been successfully tested at high power at UCLA (Pegasus Laboratory). The gun reached about 92 MV/m cathode peak field with an rms pulse length of 2 μs. It is currently used for experiment with photoelectron beam at UCLA.





INFN-UCLA

Open Traveling Wave Accelerating Structure

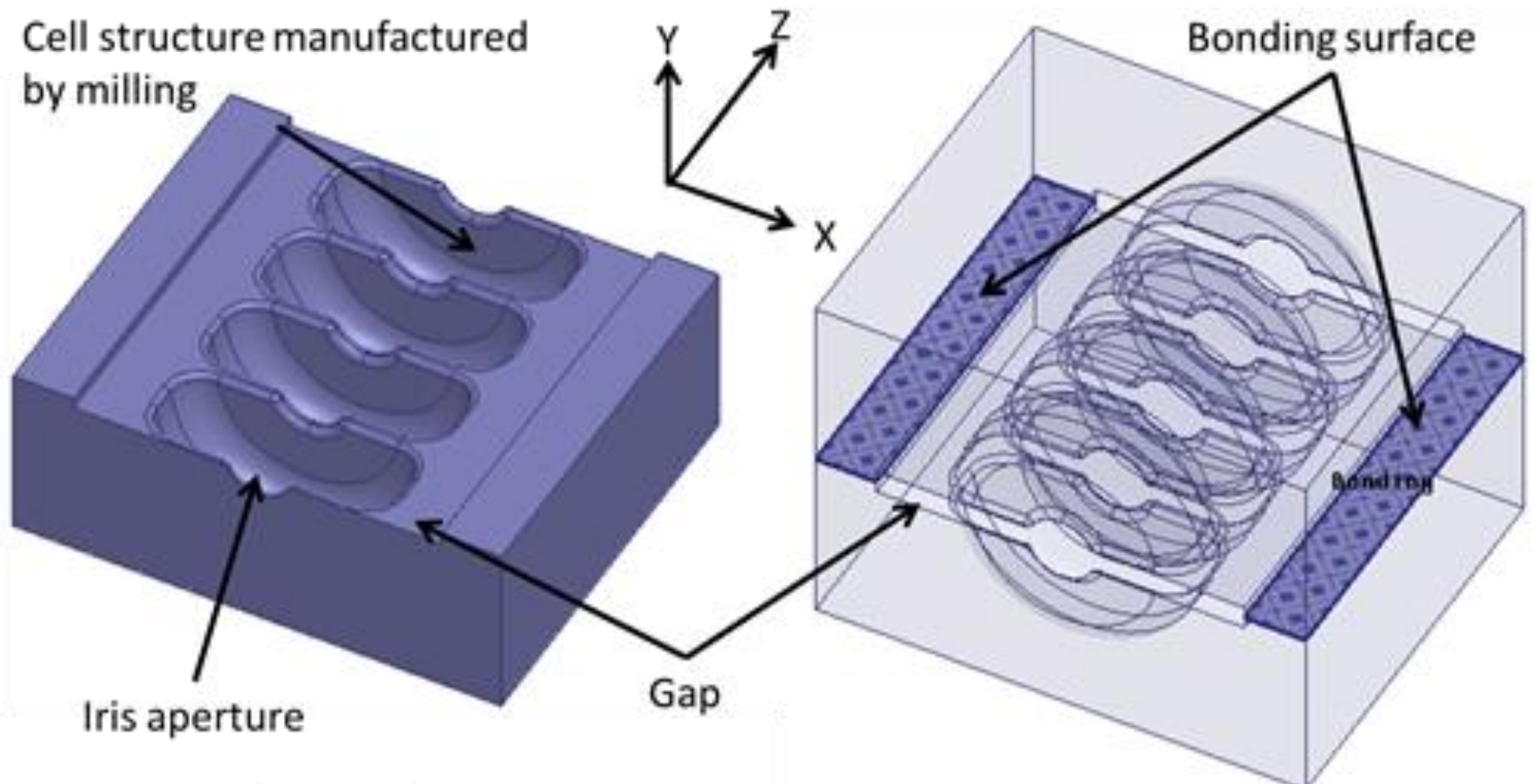
Motivation

- Novel geometry: open structure – no rf currents flowing through the metal-to-metal joint
- Novel manufacturing technique: milling structure out of two halves instead of machining and then brazing single cells
- Develop approach consistent with manufacturing accelerating structures out of hard copper alloys – it is possible to avoid high temperature brazing that softens metal

SLAC-CERN

See talk at HG2015, Tsinghua University, Beijing , China, 16-19 June 2015

Concept of brazed version



Solid mode of one-half structure

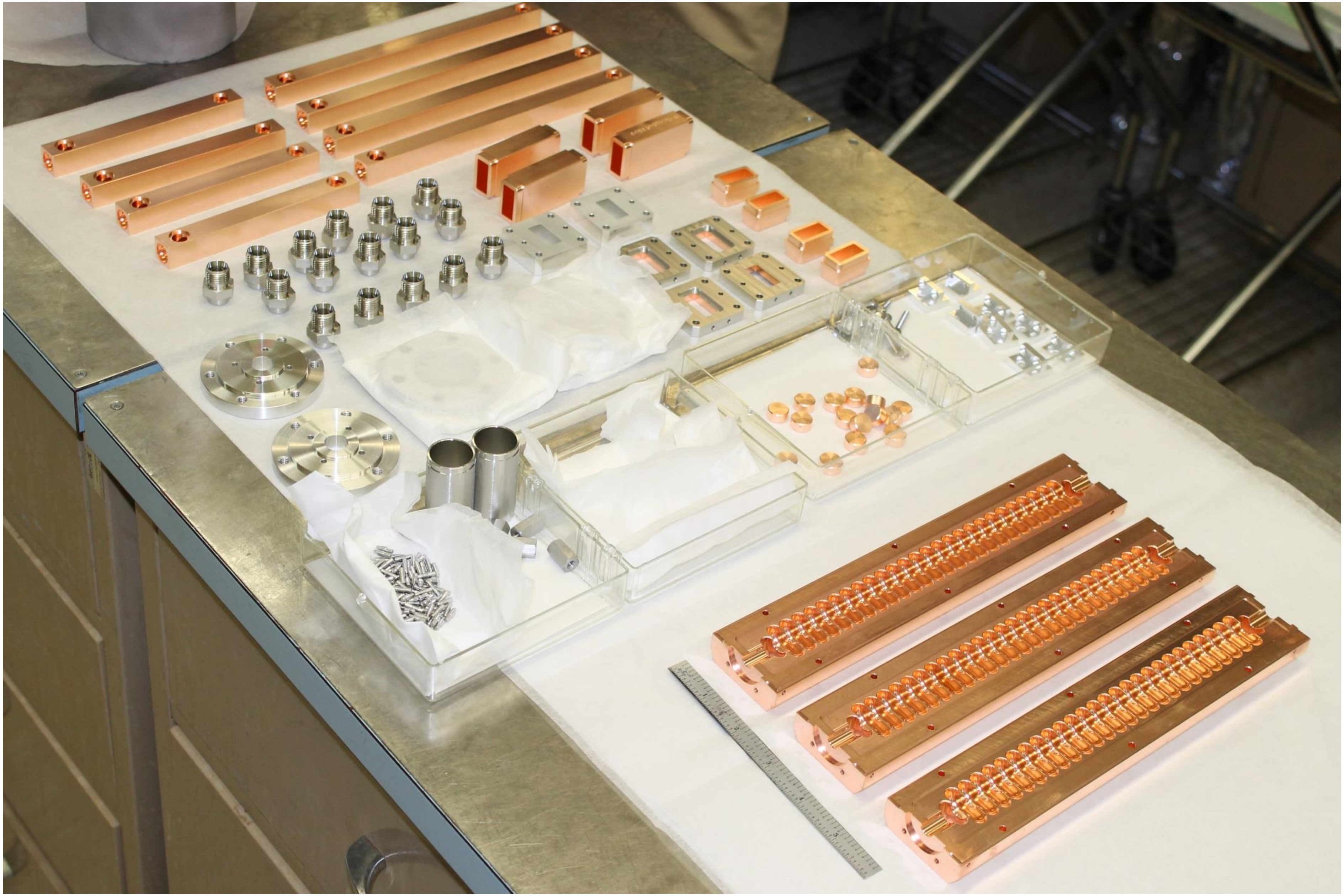
Two halves bonded together

Accelerating structure parameters

Loaded gradient* [MV/m]	100
Working frequency [GHz]	11.994
Phase advance per cell	2π/3
Active structure length [mm]	217
Input/output radii [mm]	3.15/2.35
Input/output iris thickness [mm]	1.67/1.00
Q factor [Cu]	7112/7445
Group velocity [%c]	1.99/1.06
Shunt impendence [MΩ/m]	107/137
Peak input power [MW]	60.9
Filling time [ns]	49.5
Maximum E-field [MV/m]	313
Maximum modified Poynting vector[MW/mm^2]	7.09
Maximum pluse heating temperature rise [K]	35

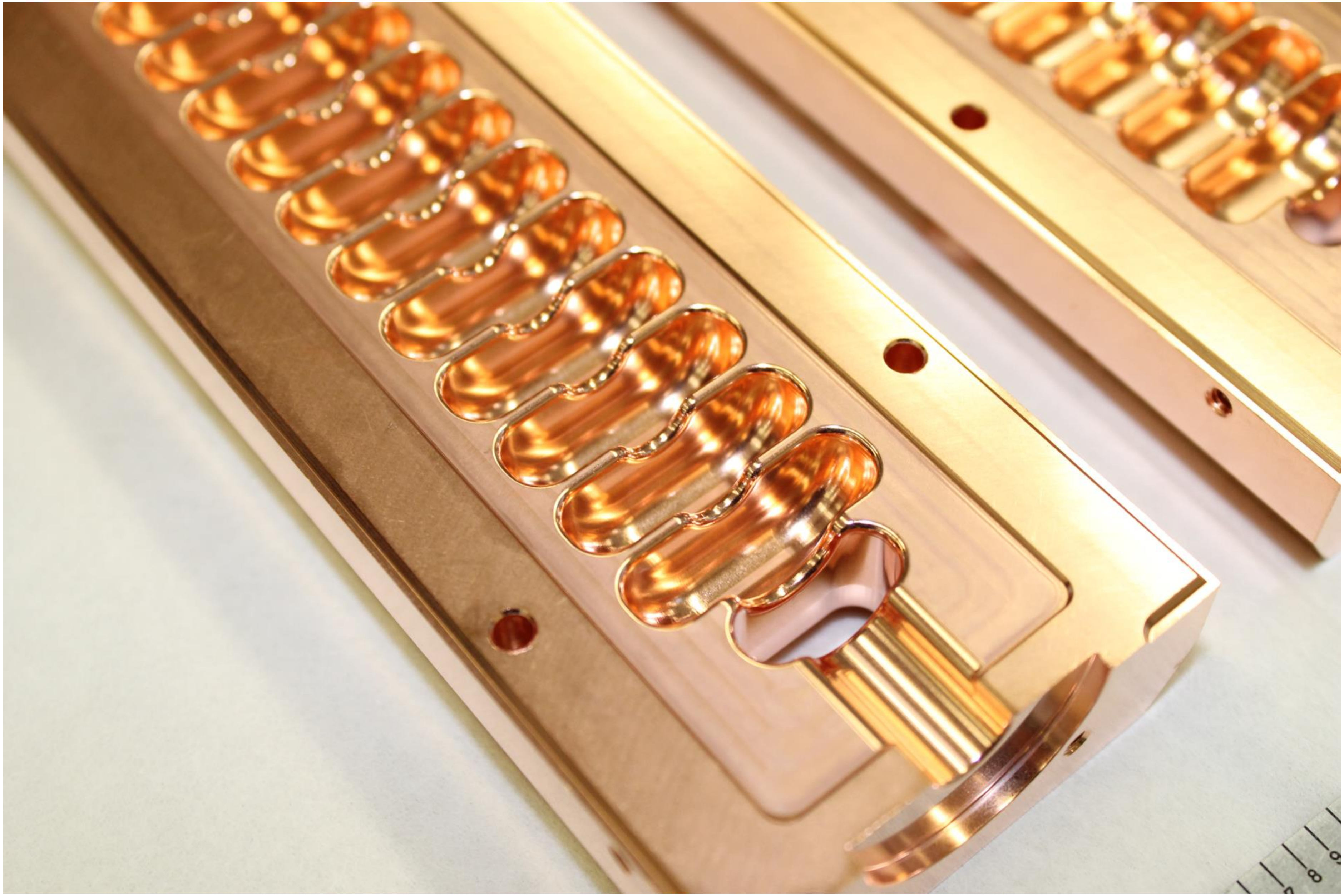
SLAC-CERN

CLIC-G-Open parts ready for pre-brazing cold test



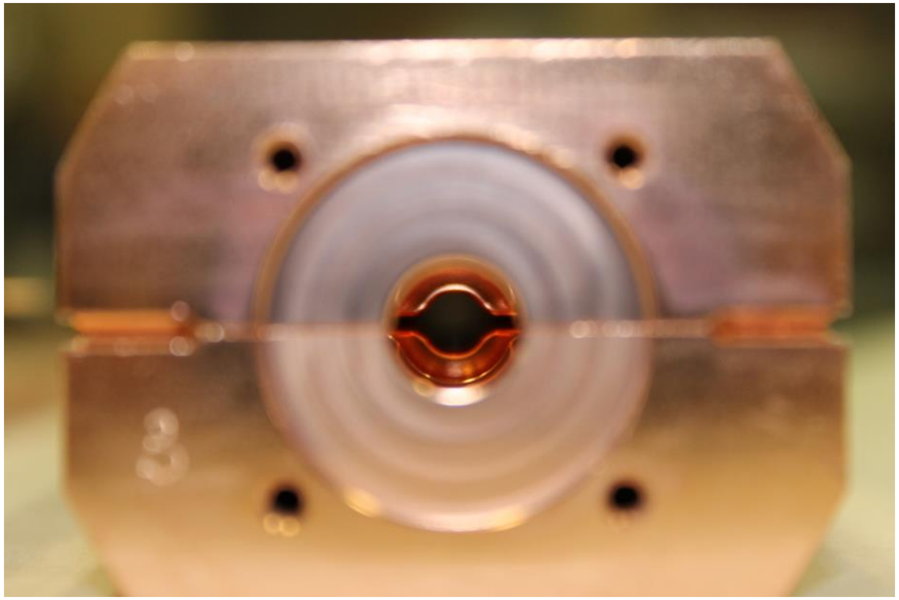
SLAC-CERN

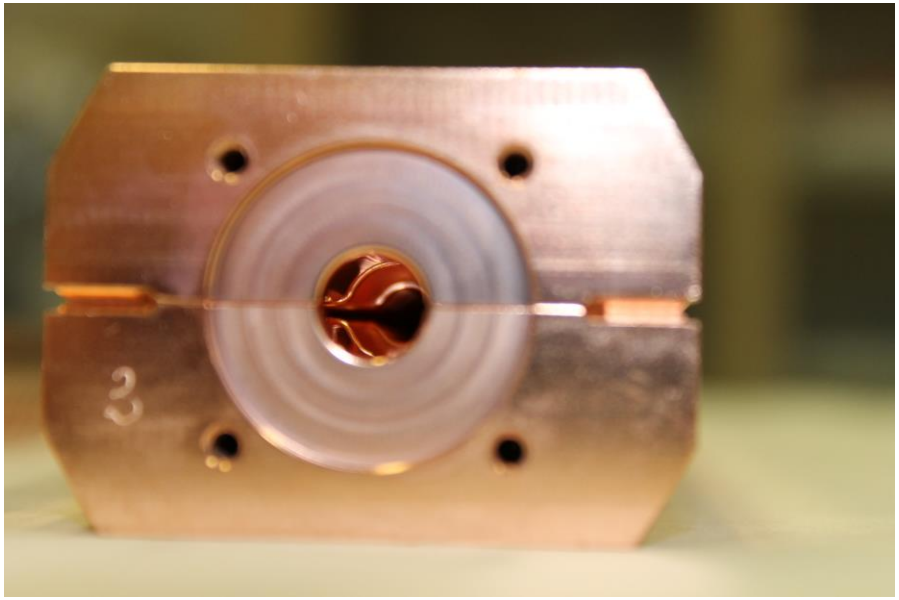
Input Part of the Half-Structure



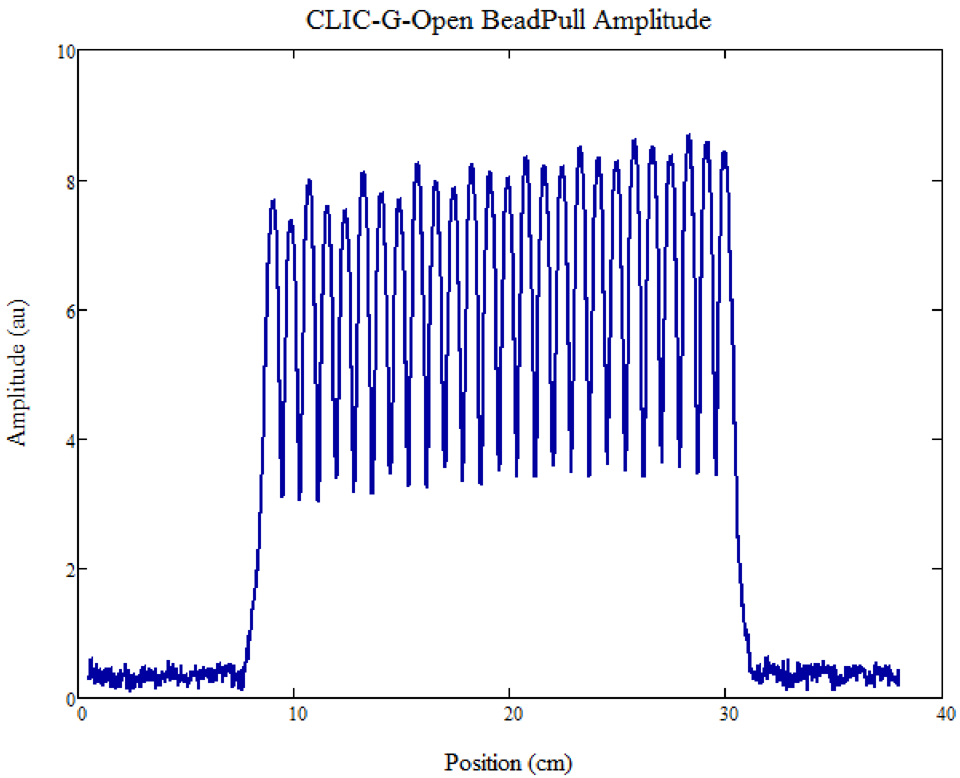
SLAC-CERN

Output Beam Pipe

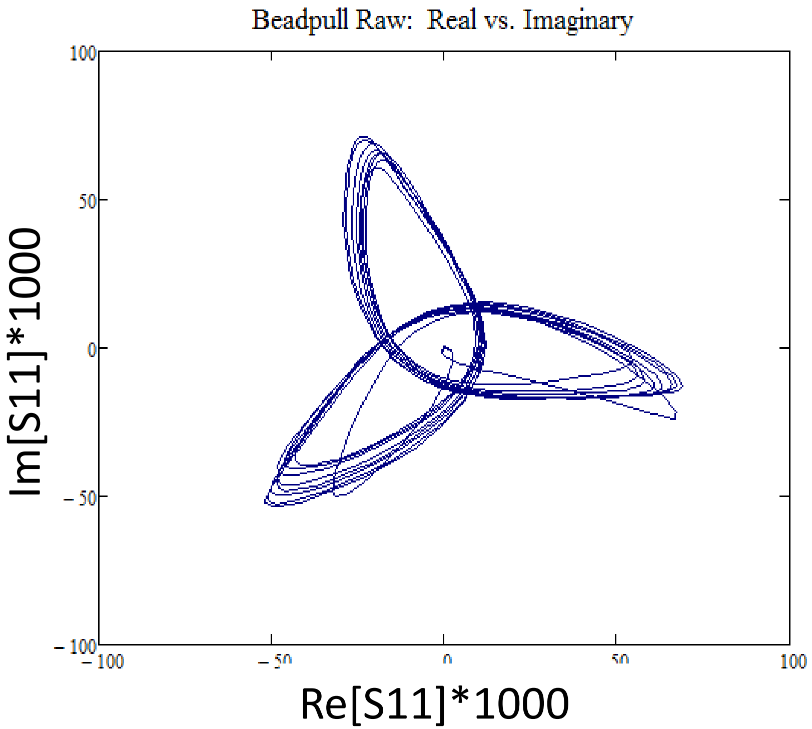




Final beadpull of tuned CLIC-G-OPEN



On-axis field amplitude.

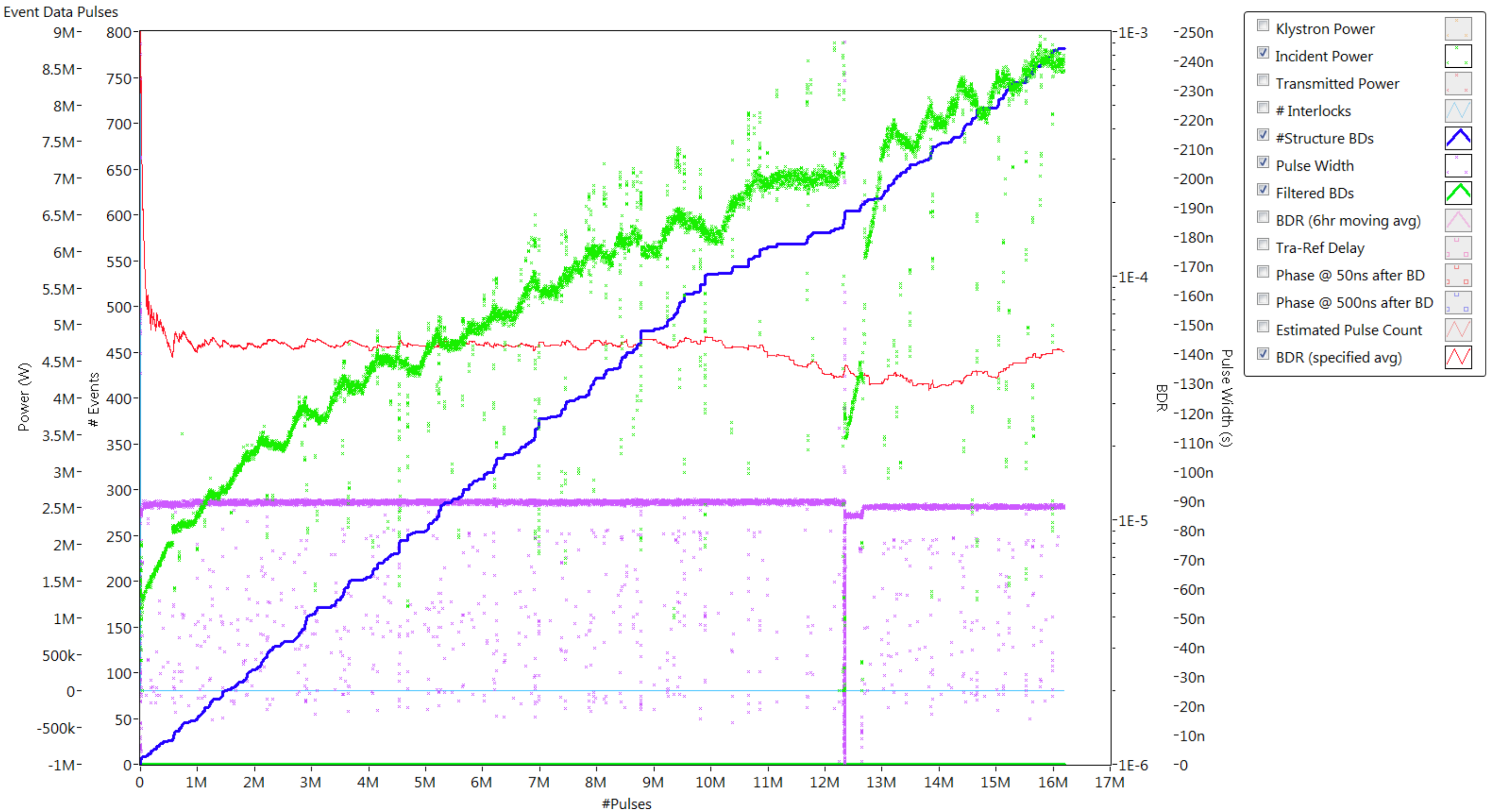


Polar plot of beadpull data.

SLAC-CERN

High Power Test at CERN (Xbox-2)

- Started Friday with RF (4th Sept).
- Normal constant BDR conditioning software used BDR set-point 5e-5.
- ~8.5MW reached



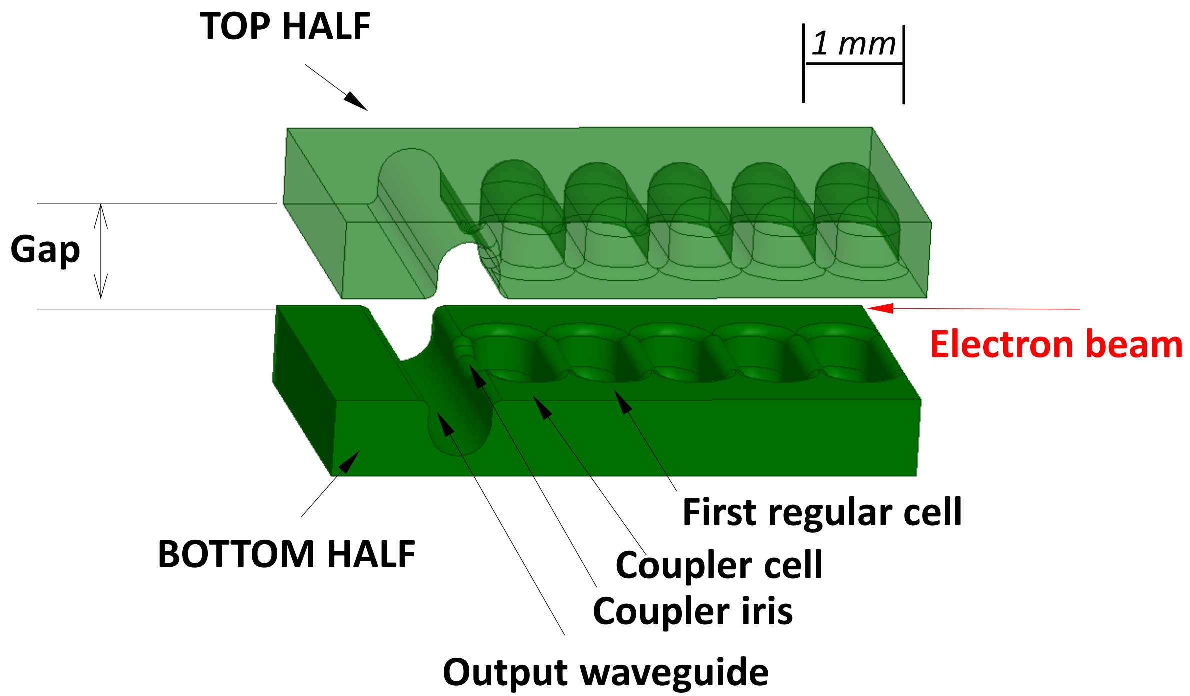
Ben Woolley, CERN, 9 September 2015

Basic Physics of RF Breakdown

Experiments on frequency scaling of RF breakdown probability

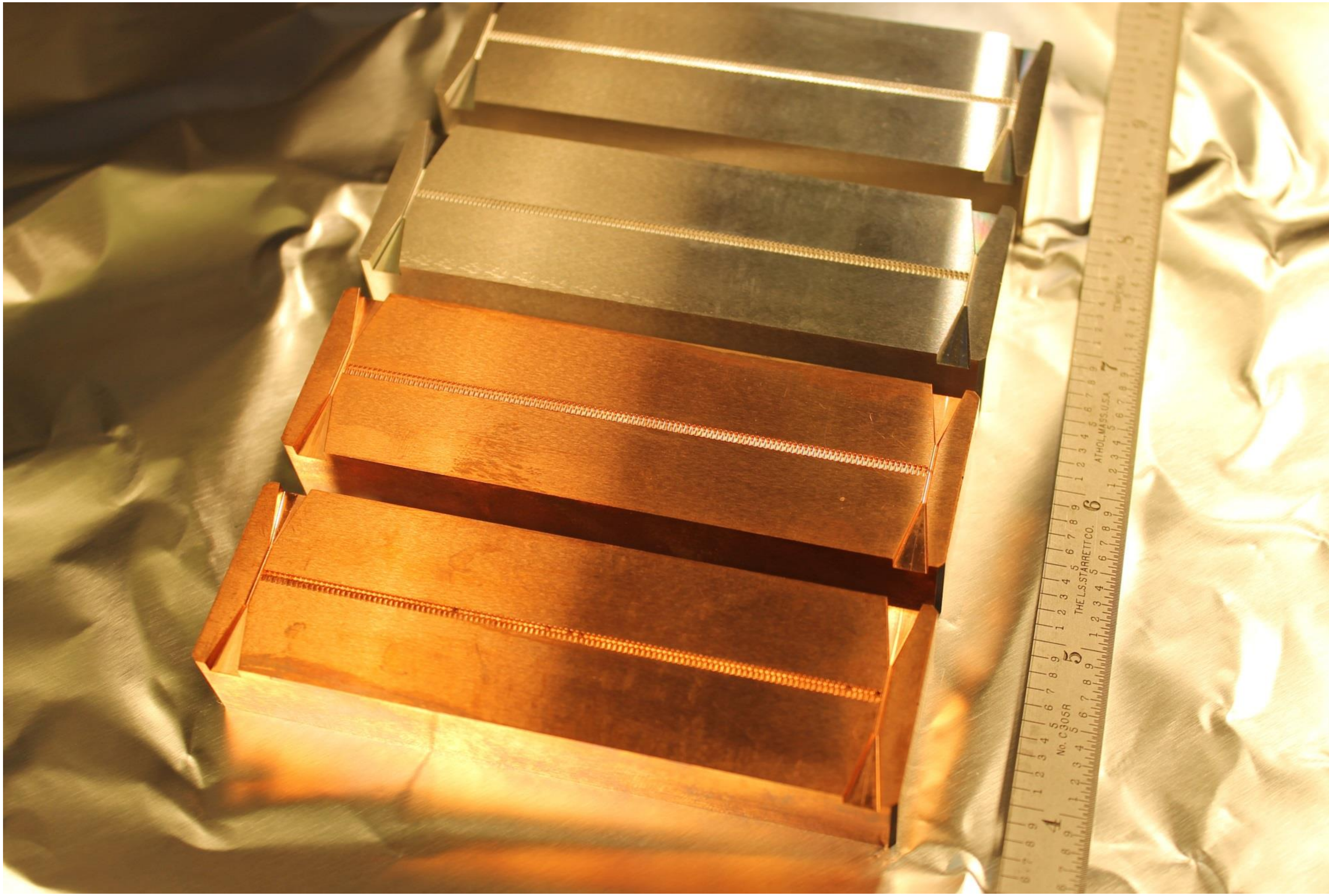
- 90 GHz (Argonne)
- 120 GHz (FACET –E204, SLAC-INFN)
- 235 GHz (FACET – E204, SLAC-INFN)

Output part of the *120 GHz open travelling wave accelerating structure*, including coupler and output waveguides.



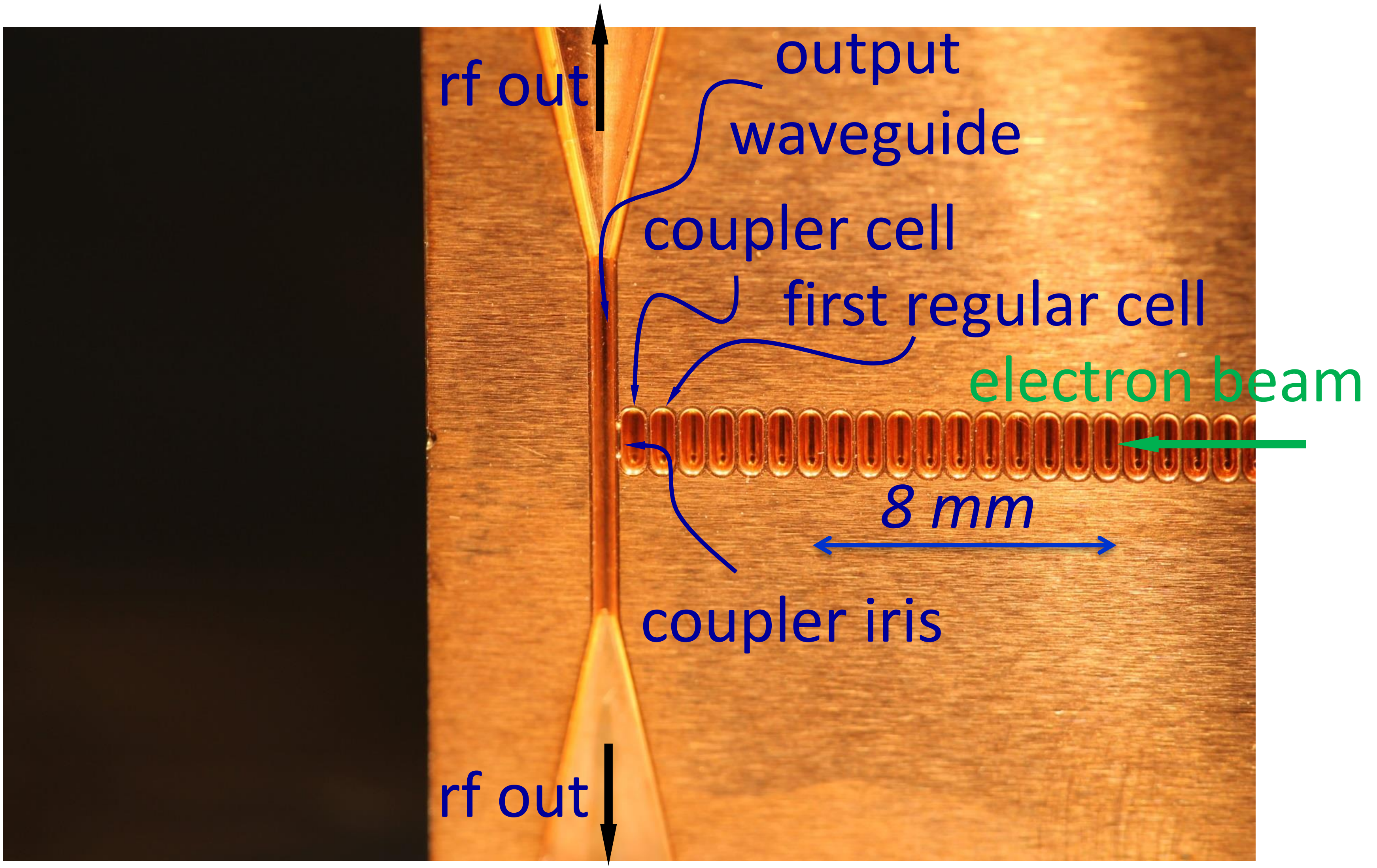
SLAC-INFN

100 GHz copper and stainless steel traveling wave accelerating structures, as received from vendor



Manufacturing: EDM Department Inc.

Output Part of the Open 100 GHz Copper Traveling Wave Accelerating Structure



SLAC-INFN

Goal – of E-204

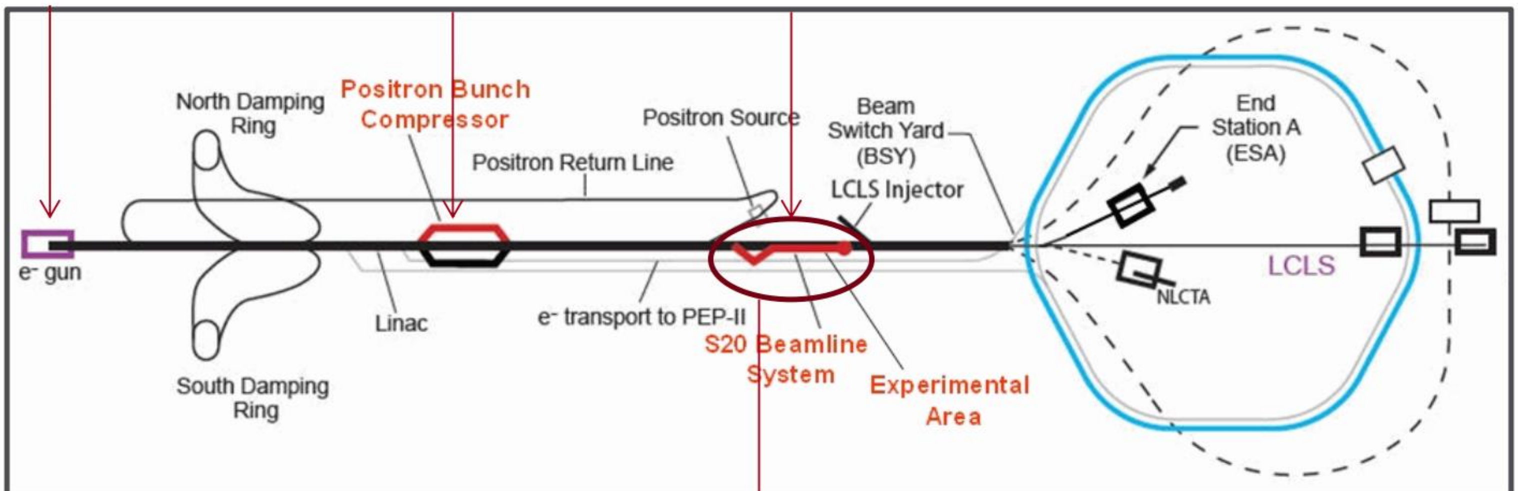
Determine statistical properties of rf breakdown in metal accelerating structures *vs.* structure geometry, material, accelerating gradient and pulse length at 100 GHz and 200 GHz frequencies.

Method

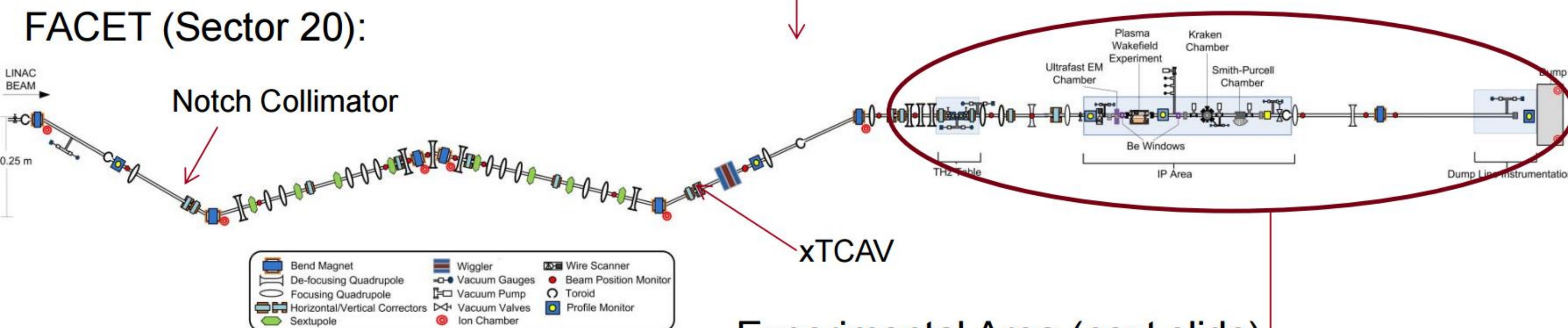
- We apply our X-band experience in manufacturing, surface preparation and testing to these sub-THz accelerating structures.
- We start from beam-excited structures (E204 at FACET), develop diagnostics and testing approach and move to structures powered by rf sources.

- DoE HEP National User Facility

Linac: Sector 0 Sector 10 Sector 20



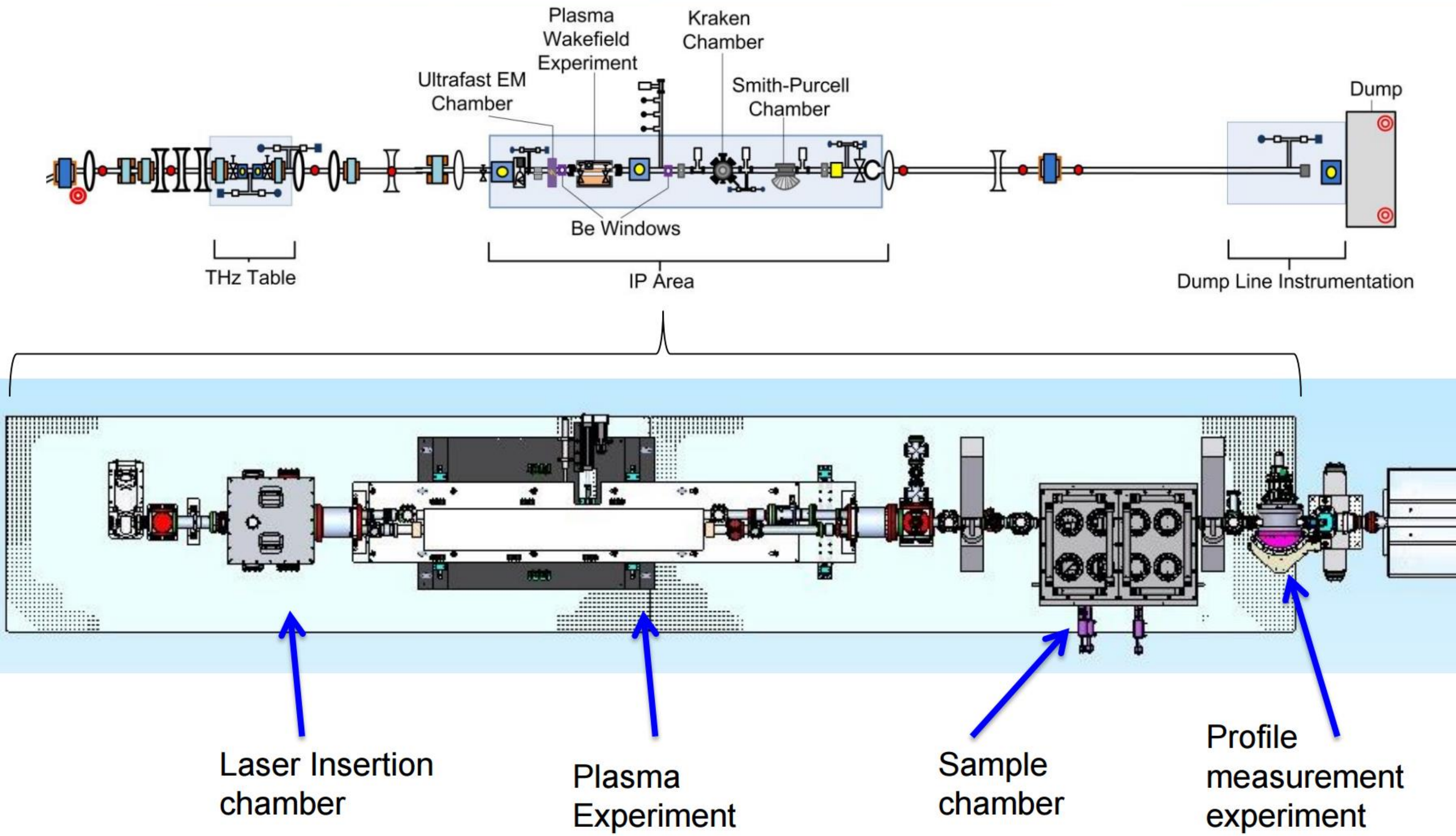
FACET (Sector 20):



Experimental Area (next slide)

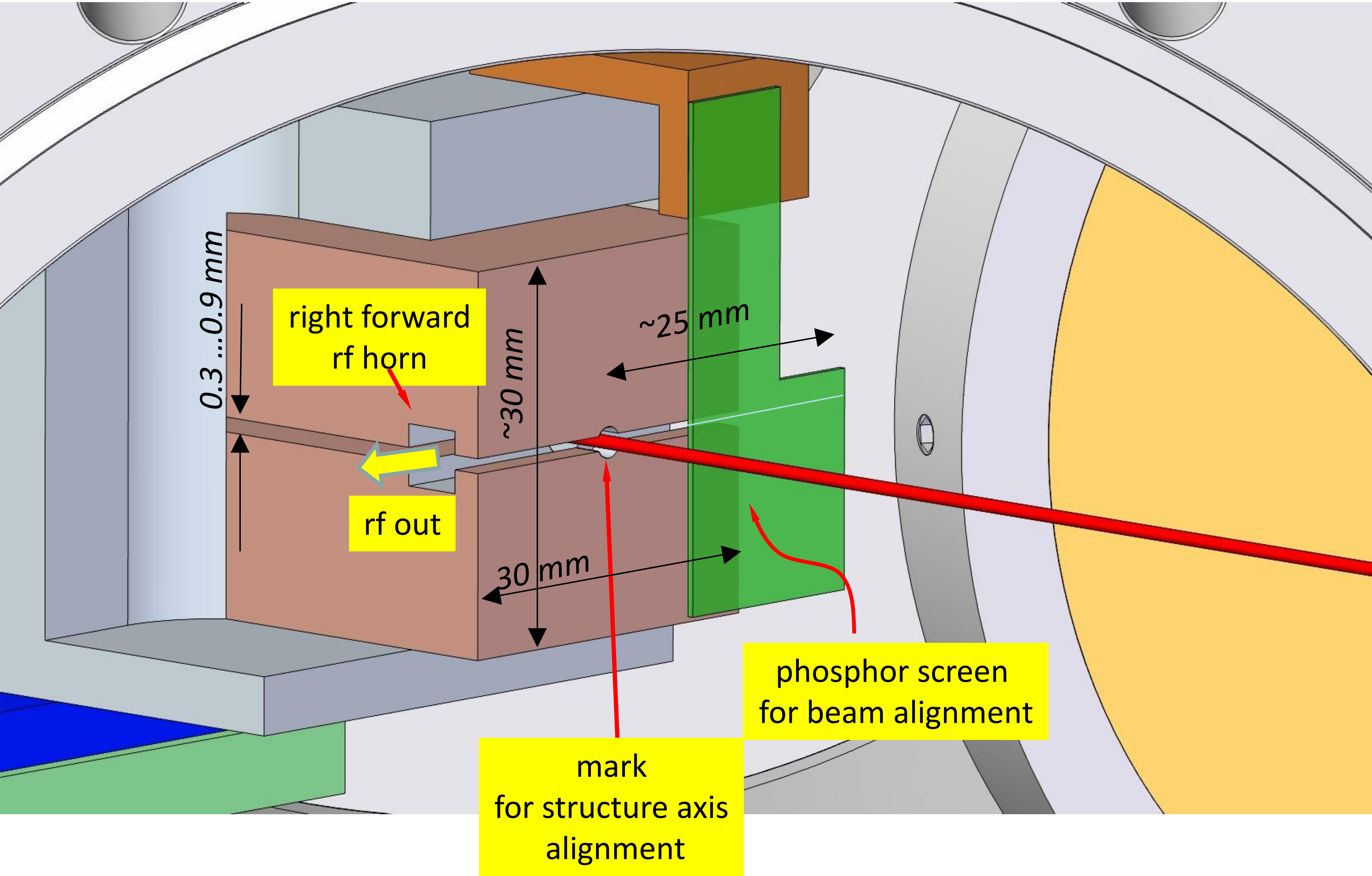
C. Hast, SLAC Electron Beam Test Facilities 5 MeV to 20 GeV, SLAC SiD Workshop, Oct. 15th, 2013

FACET's Experimental Area

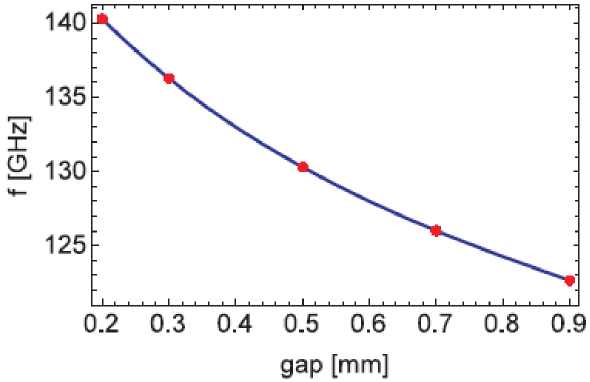


C. Hast, SLAC Electron Beam Test Facilities 5 MeV to 20 GeV, SLAC SiD Workshop, Oct. 15th, 2013

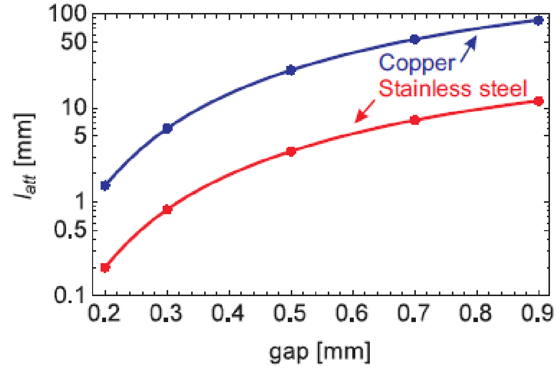
First experiment: alignment camera view



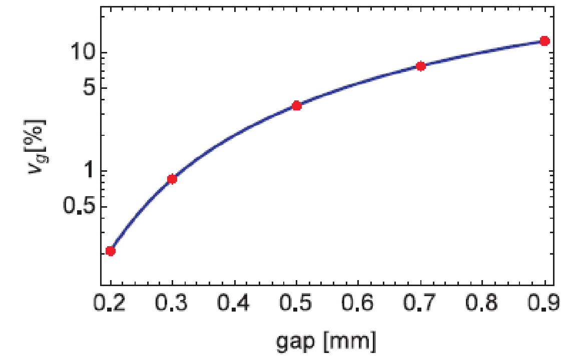
Results of the simulations for the travelling wave copper and stainless steel structures *vs.* gap size, for 3.2 nC and 50 μm long bunch.



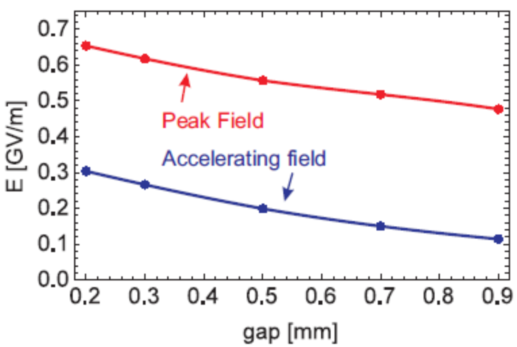
Synchronous frequency



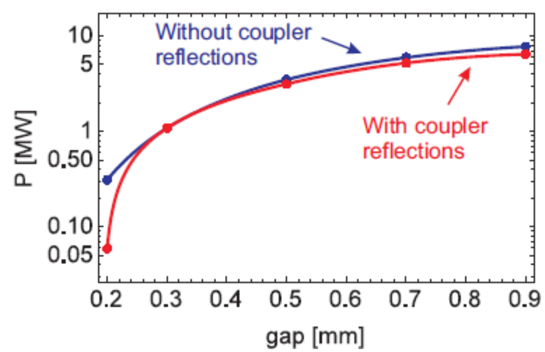
Decay length



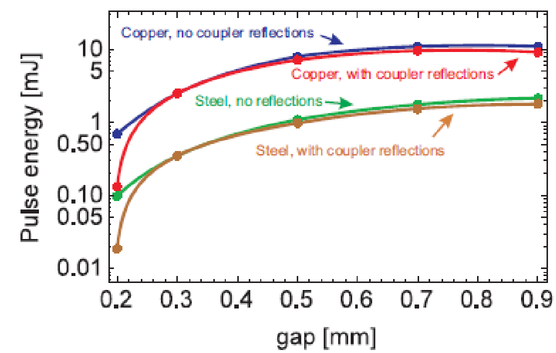
Group velocity



Peak electric field and accelerating electric field

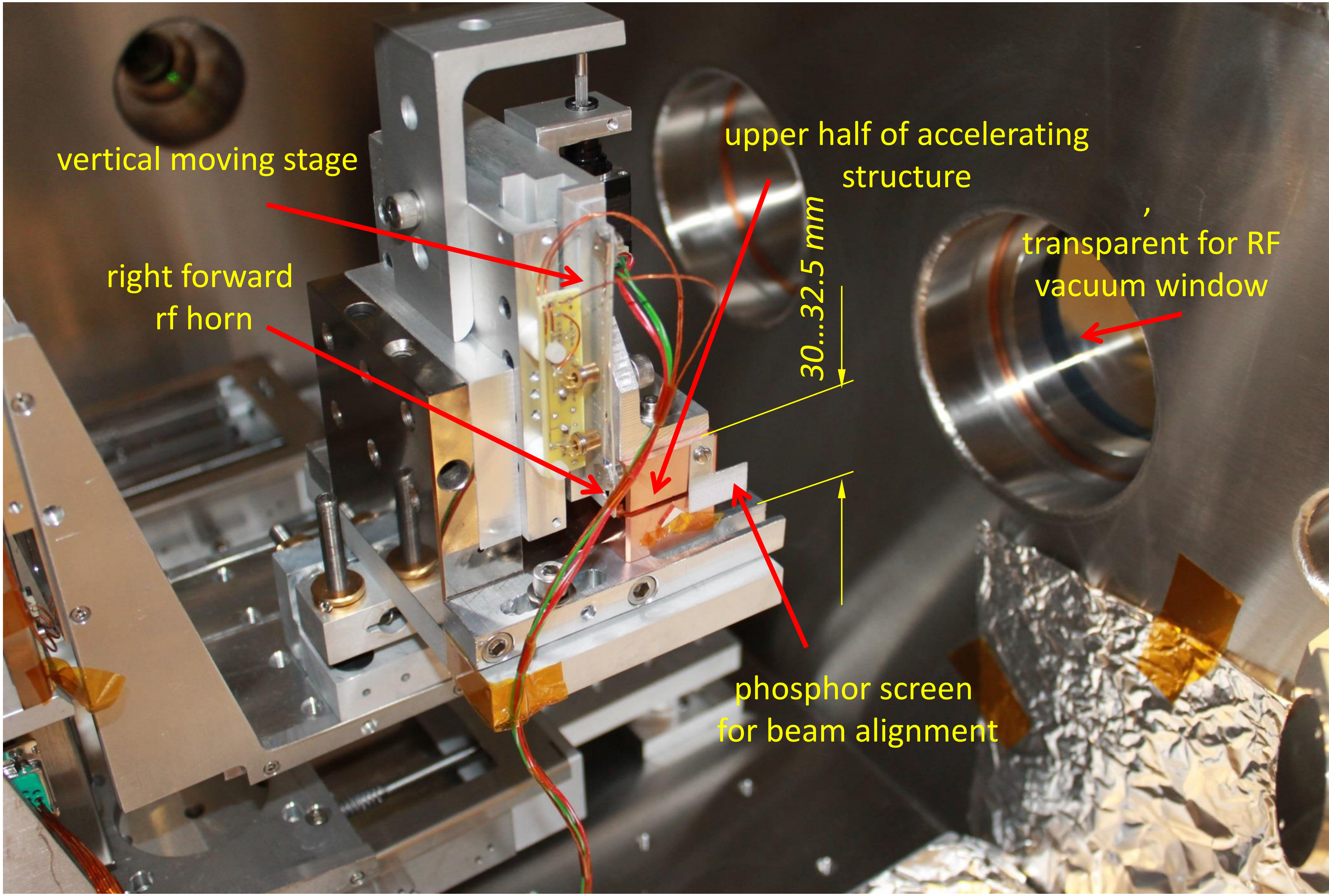


Peak power travelling along the cells, and power exiting from the waveguide considering the reflection



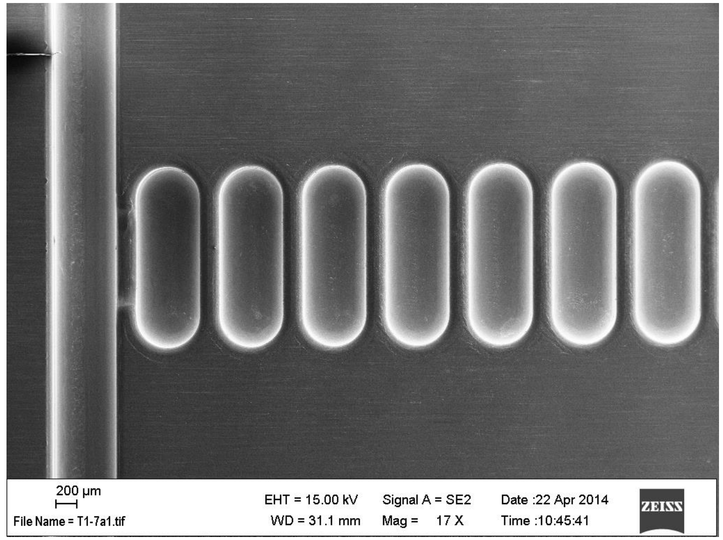
Pulse energy with and without considering the coupler reflection

FACET experiment with *copper structure* in vacuum chamber

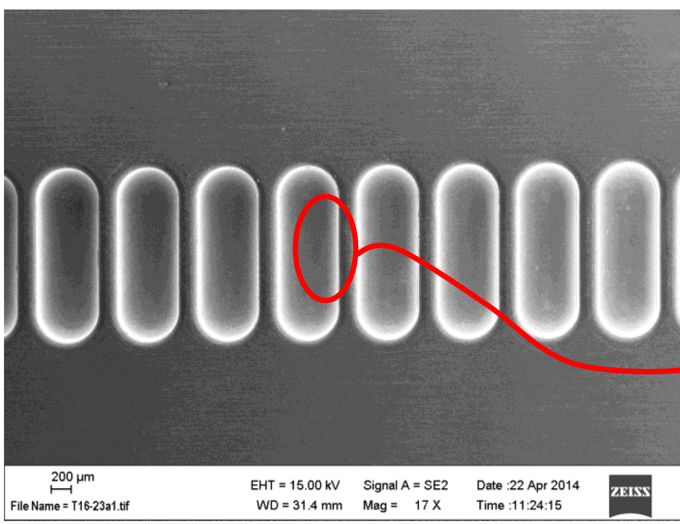


After test autopsy

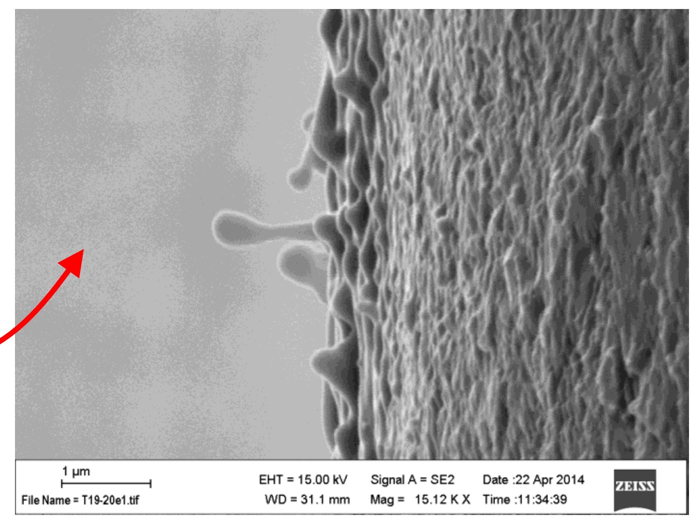
electron beam



Input coupler, cells 1-7, no damage



Cells 16-23, fist signs of damage



Iris 19-20, fist signs of damage

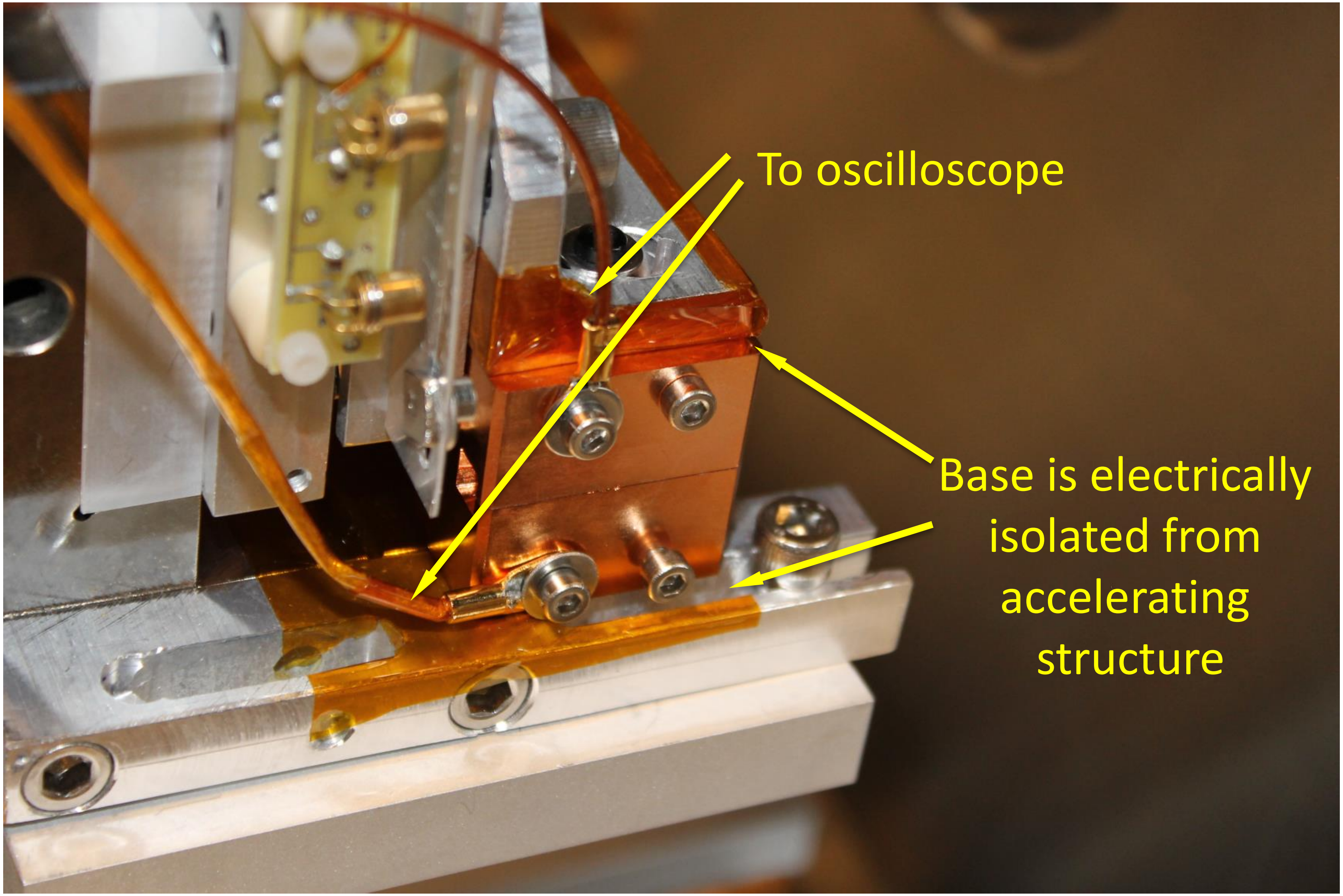
Summary of 1st traveling wave copper structure test

We see massive damage in all structure but first ~20 cells

- The smallest gap in this experiment was 0.2 mm, this gives us estimation for field levels at which the structure was not damaged: peak surface electric fields of 0.64 GV/m (fundamental mode), 1.2 GV/m (sum of all trapped modes) and accelerating gradient of 0.3 GV/m.

In this experiment we could not detect signals from RF breakdowns, so we had to invent new diagnostics.

Current monitor to detect rf breakdowns in open accelerating structures

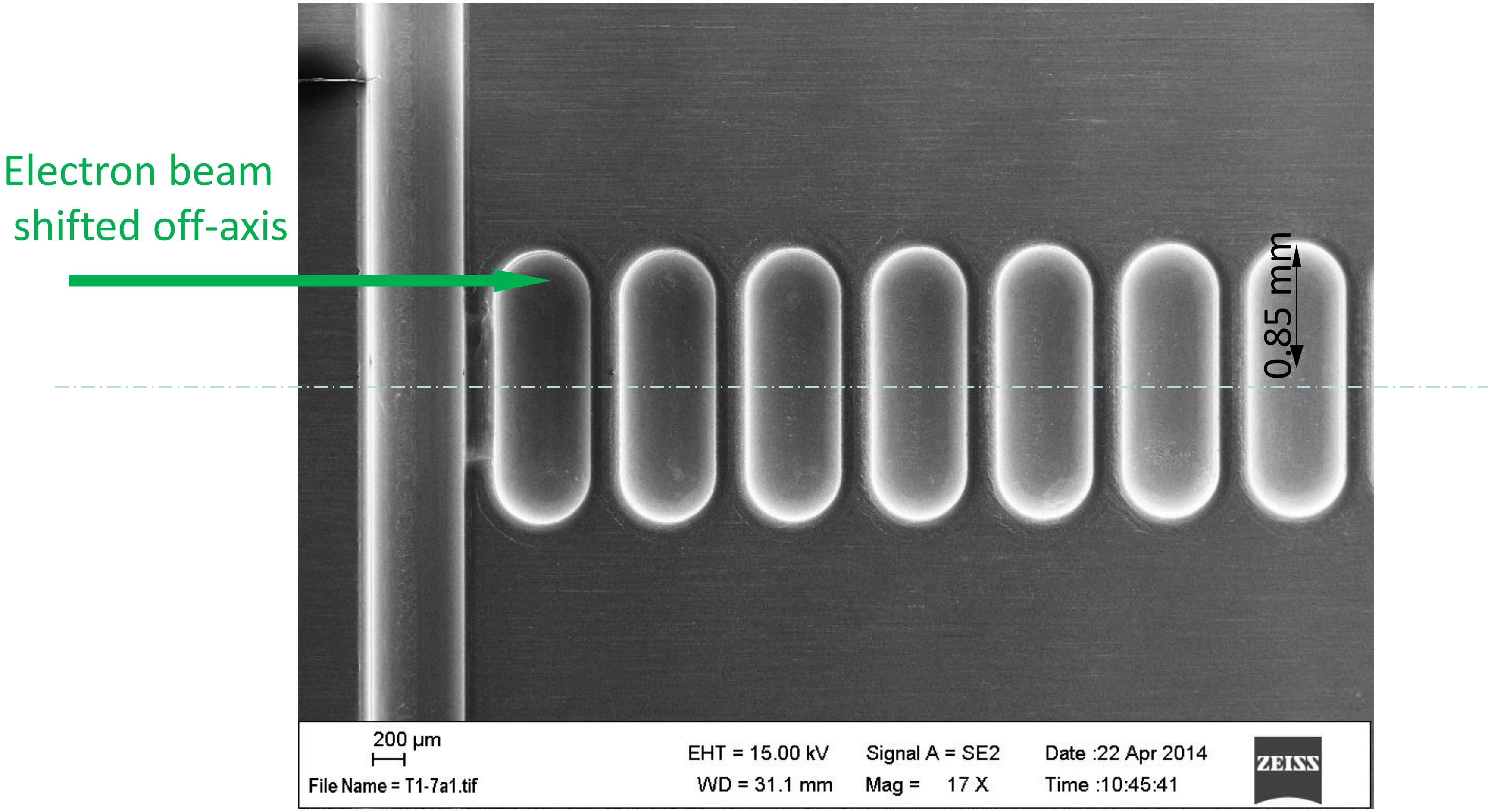


Very preliminary: 2nd copper TW structure, measurements of breakdown rate plus measurements of decelerating and deflecting fields

Some of these was presented in:

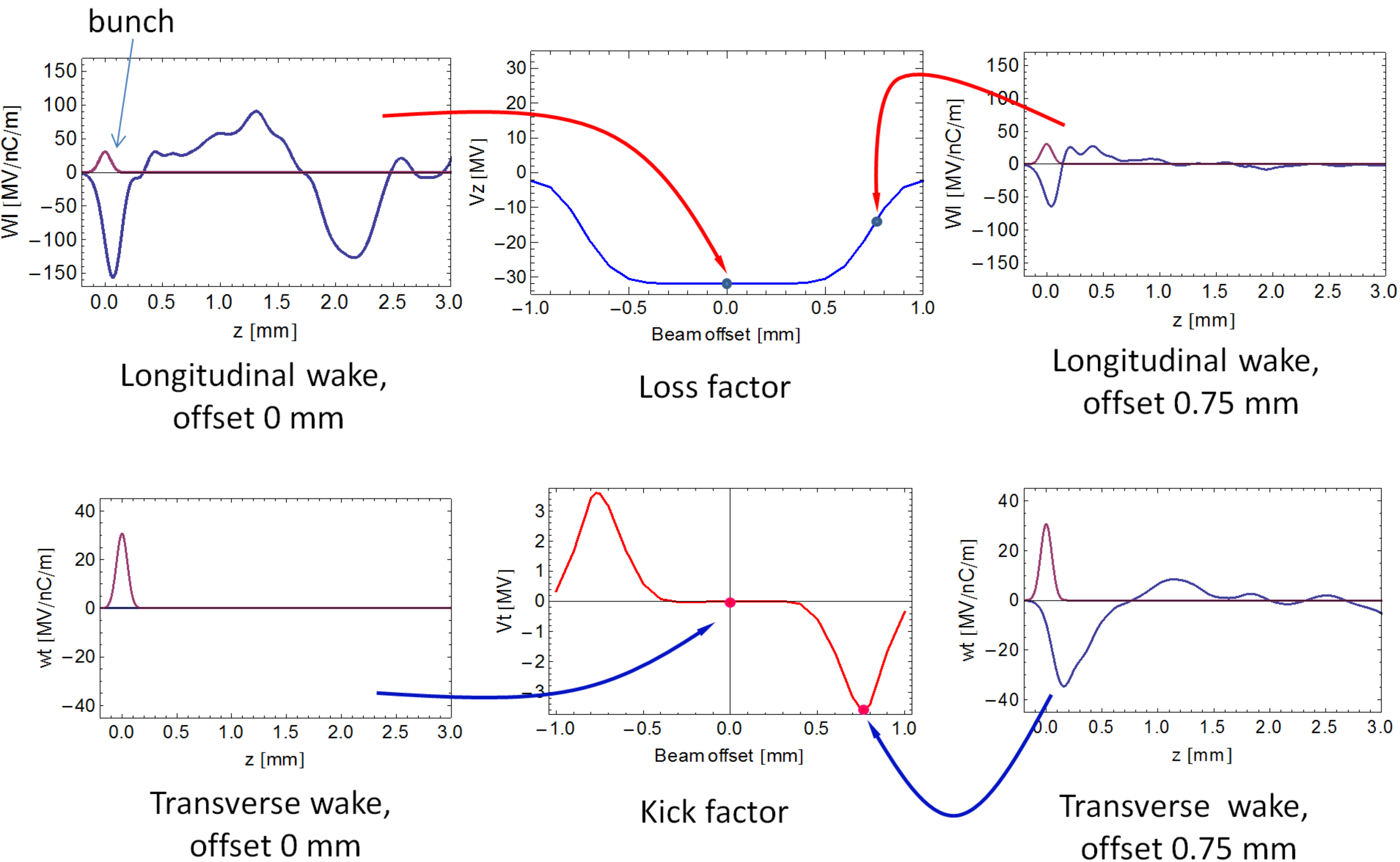
V.A. Dolgashev et al., *"Attosecond Diagnostics of Muti-GeV Electron Beams Using W-Band Deflectors,"* Femtosecond Electron Imaging and SpectroscopyFEIS-2, Lansing/East Lansing, Michigan, May 9th, 2015

Measurements of field inside the accelerating structure using wakefield-beam-deflection

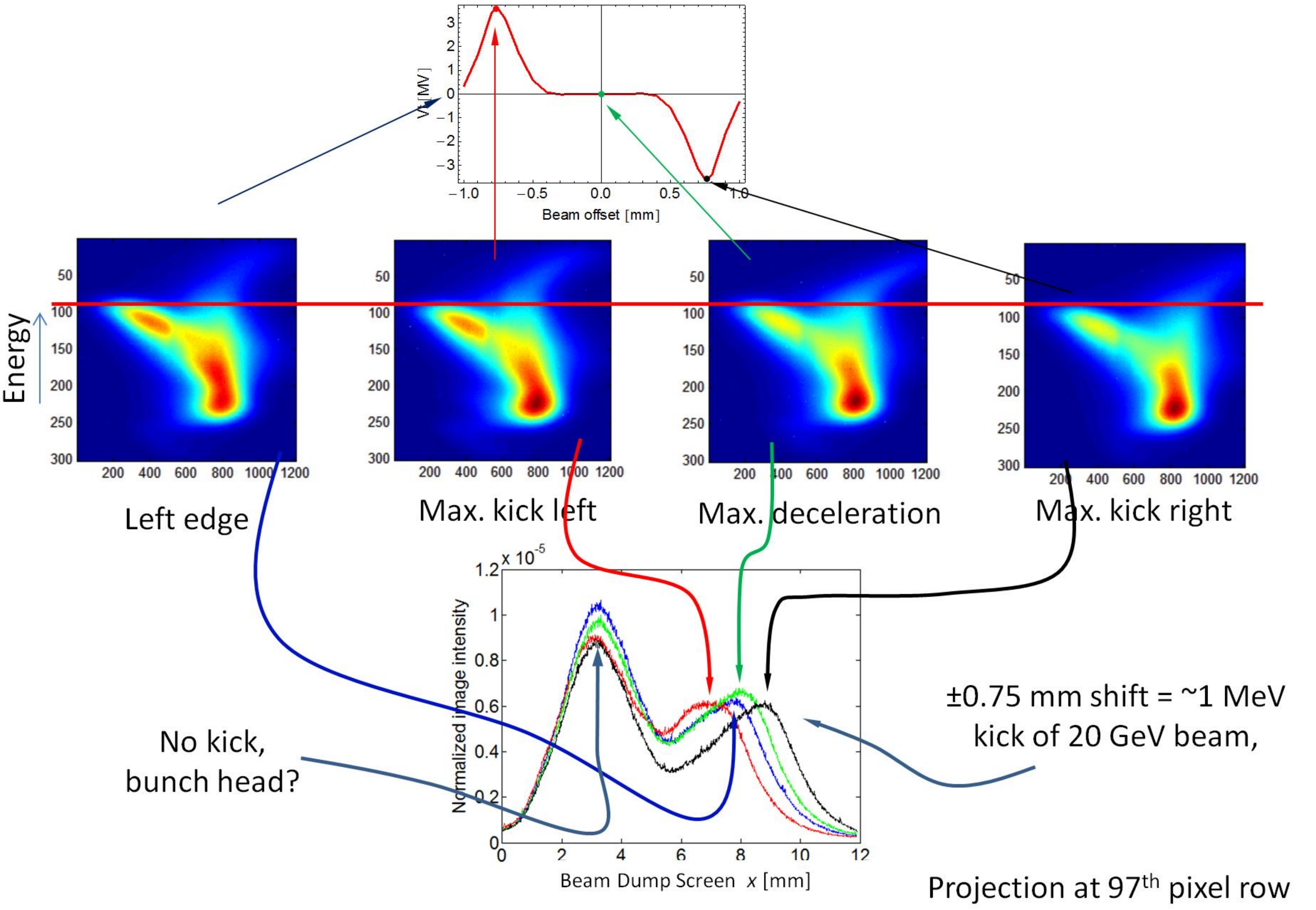


2nd 100 GHz traveling wave copper accelerating structure

Short range wakefields in 100 GHz accelerating structure, gap 0.3 mm, bunch length 50 μm



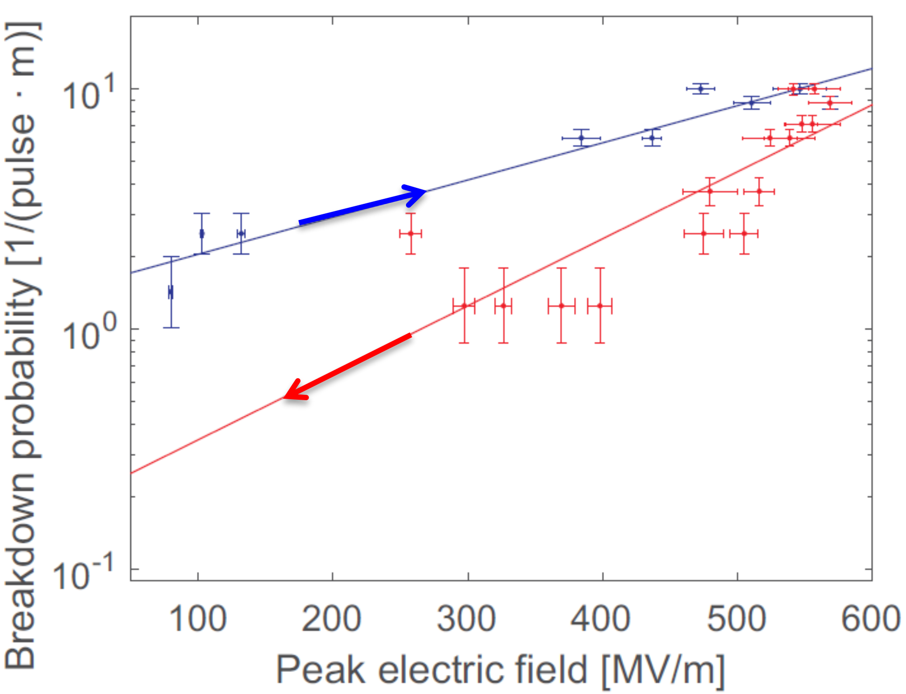
100 GHz accelerating structure, gap 0.9 mm, FACET shift 4 April 2015



Results of 120 GHz tests

- From SEM inspection of first three structures, we estimate "no damage" pulse parameters which allow as to determine the upper bound of the breakdown rate.
- With second copper TW structure we measured deflecting fields inside the structure using beam deflection and correspondent breakdown rate.
- We propose to use this structure as a mm-wave rf deflector for attosecond electron beam

Breakdown probability versus peak surface electric filed obtained in a horizontal scan of 100 GHz traveling wave accelerating structures, 0.9 mm gap.

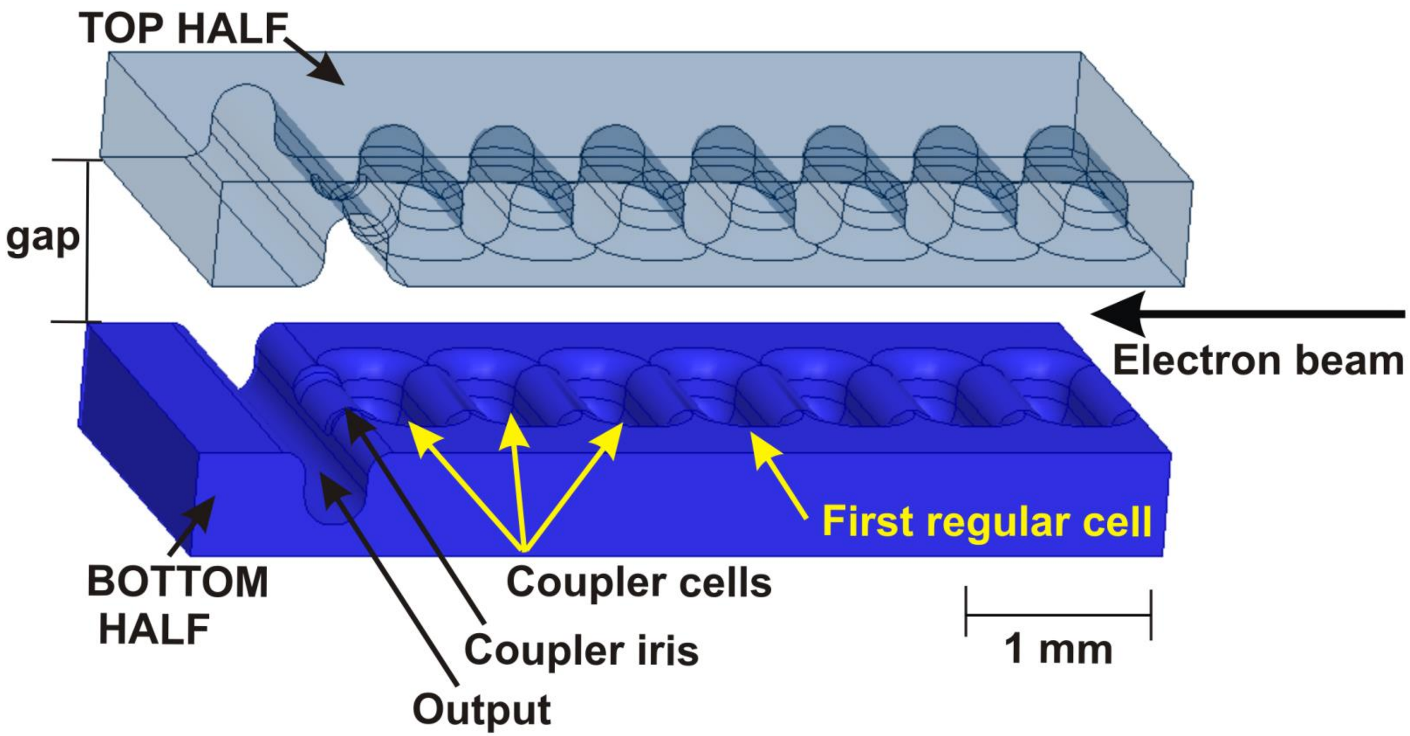


Basic Physics of RF Breakdown

Experiments on frequency scaling of RF breakdown probability

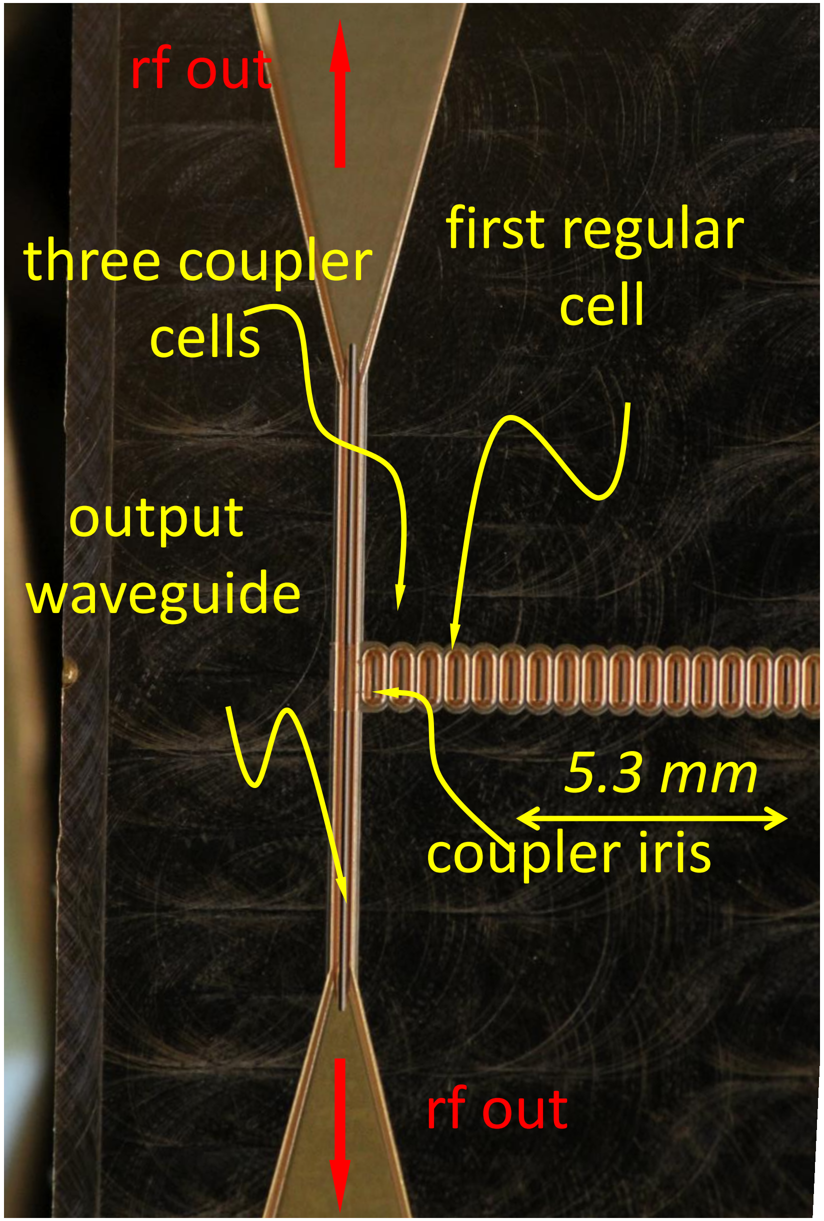
- 90 GHz (Argonne)
- 120 GHz (FACET –E204, SLAC-INFN)
- 235 GHz (FACET – E204, SLAC-INFN)

Output part of the *235 GHz open travelling wave accelerating structure*, including coupler and output waveguides.



SLAC-INFN

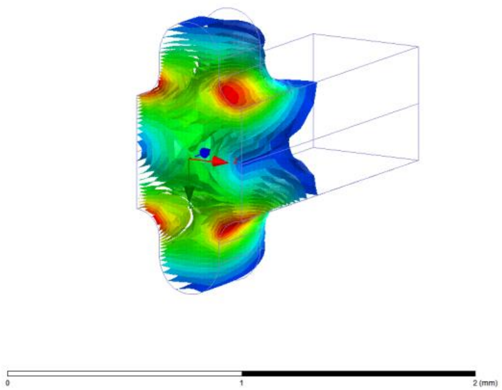
Output Part of the 235 GHz Open Copper Traveling Wave Accelerating Structure



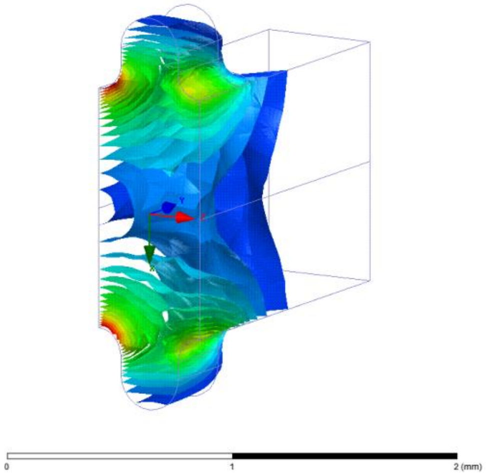
Electron beam

SLAC-INFN

Accelerating mode in 200 GHz open traveling wave accelerating structure



Gap 5 mm, a/λ = 0.185, 224 GHz, phase advance 142 deg. per cell

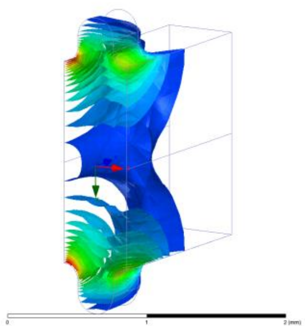


Gap 1.1 mm, a/λ = 0.376, 205 GHz, phase advance 132 deg. per cell

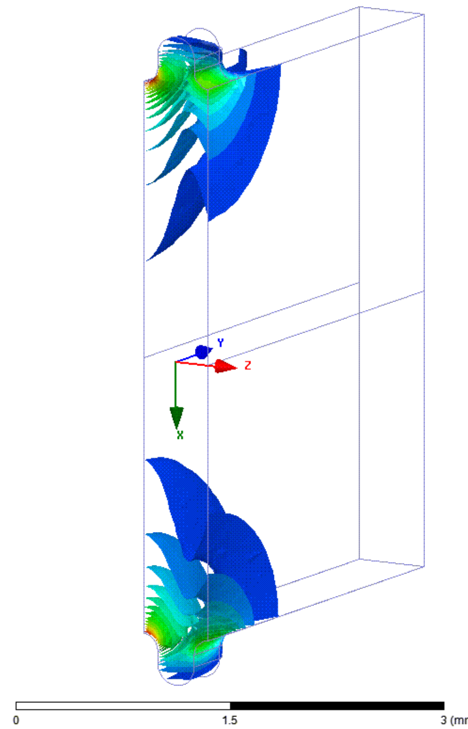
At this frequency and gap the mode is cut-off so it is expected to be trapped.

Accelerating mode is above cutoff, so it should leak toward outer wall, but looks trapped.

Change of Accelerating mode in 200 GHz open traveling wave accelerating structure with increasing beam aperture



Gap is 1.5 mm, $a/\lambda = 0.503$, 201 GHz, phase advance 130 deg.

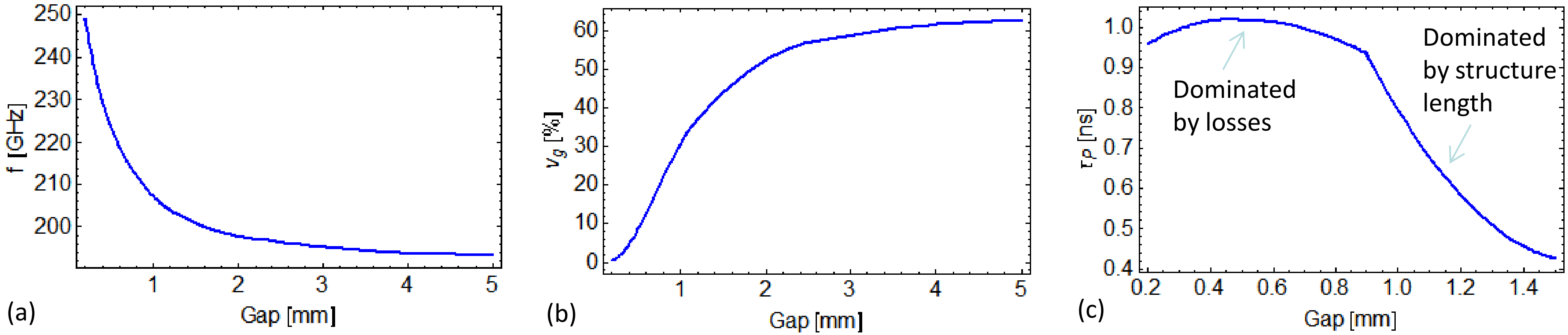


Gap is 4 mm, $a/\lambda = 1.3$, 194 GHz, phase advance 128 deg. per cell.

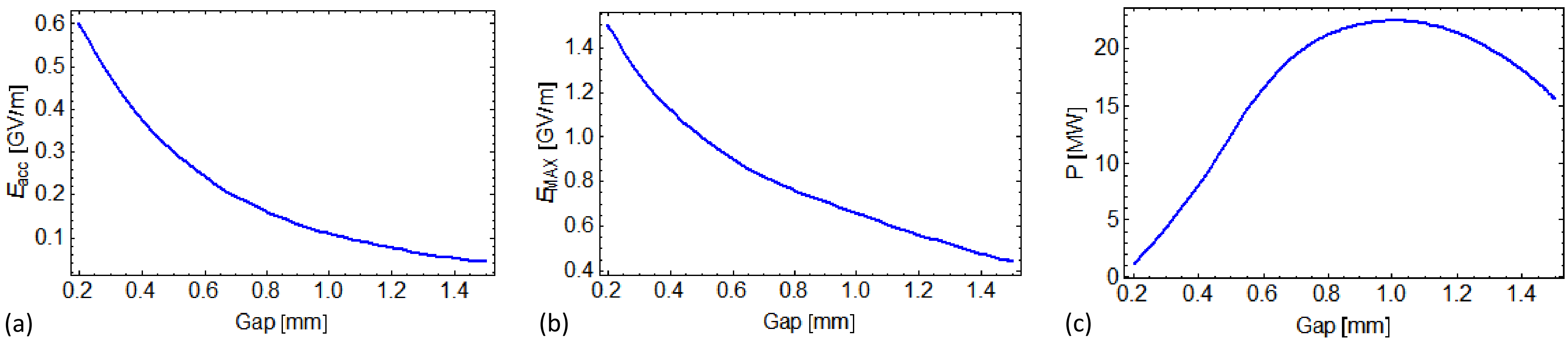
The mode wavelength is twice shorter then the gap cutoff, mode still trapped.

Gap is so large that removal of the one half of the structure completely does not effect the guided mode, we excited “surface mode”.

Rf parameters of open 235 GHz traveling wave acclerating structure *vs.* different gaps

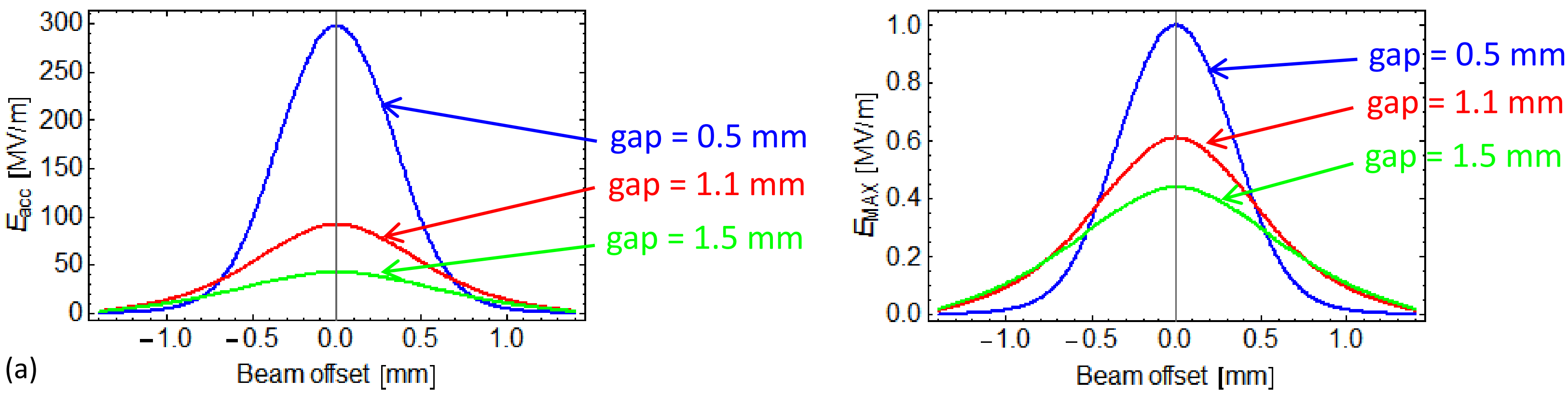


Synchronous frequency (a), group velocity (b) and pulse length as a function of the structure gap.

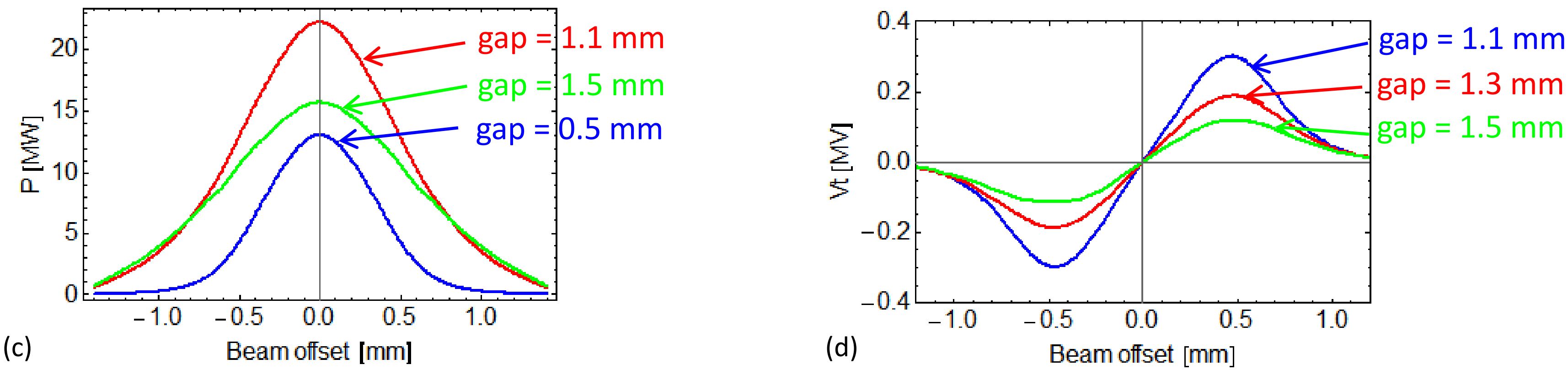


Deceleration gradient (a), Peak electric field (b) and Output power (c) of the fundamental mode as a function of the gap, with Q = 3.2 nC and σ_z = 50 µm.

Horizontal beam scans

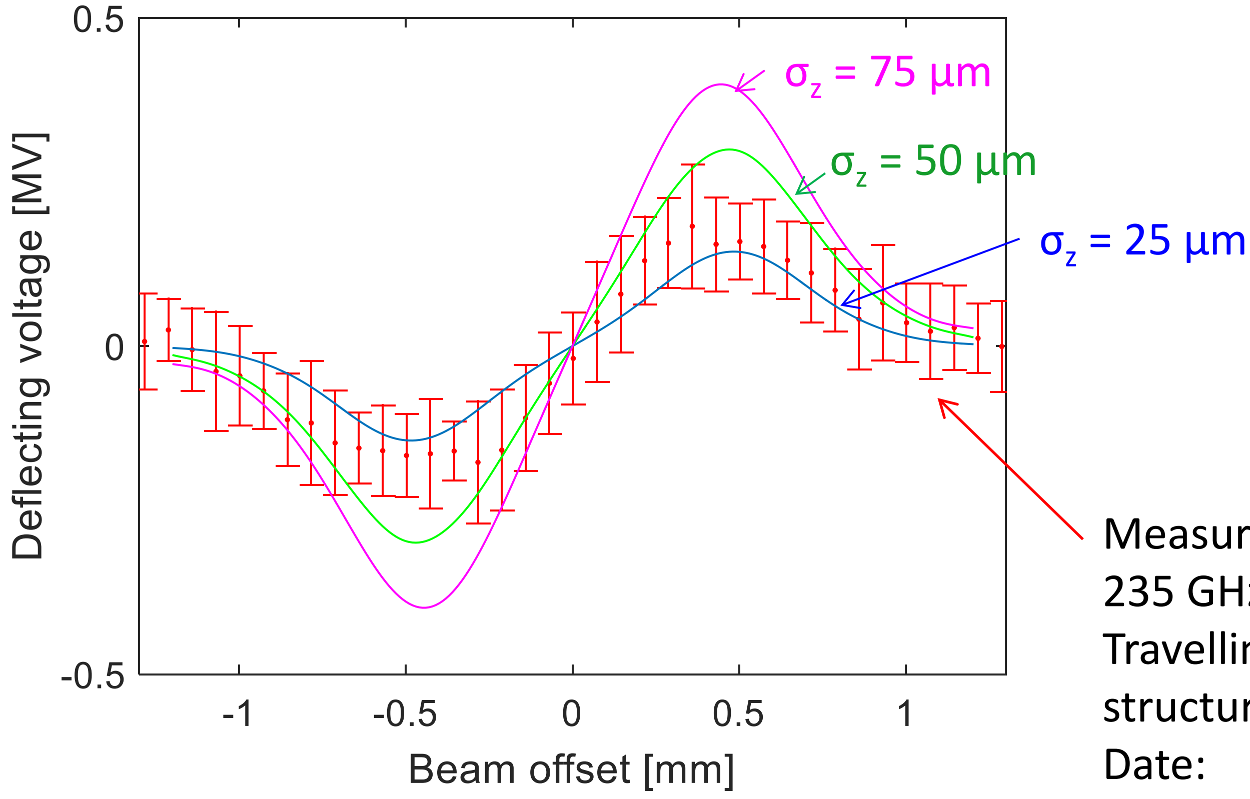


Deceleration gradient of fundamental mode (a), Peak electric field of fundamental mode (b) as a function of the horizontal beam-structure displacement, Q = 3.2 nC and σ_z = 50 µm.



Output power of fundamental mode (c), and deflecting voltage (d) as a function of the horizontal beam-structure displacement, Q = 3.2 nC and σ_z = 50 µm.

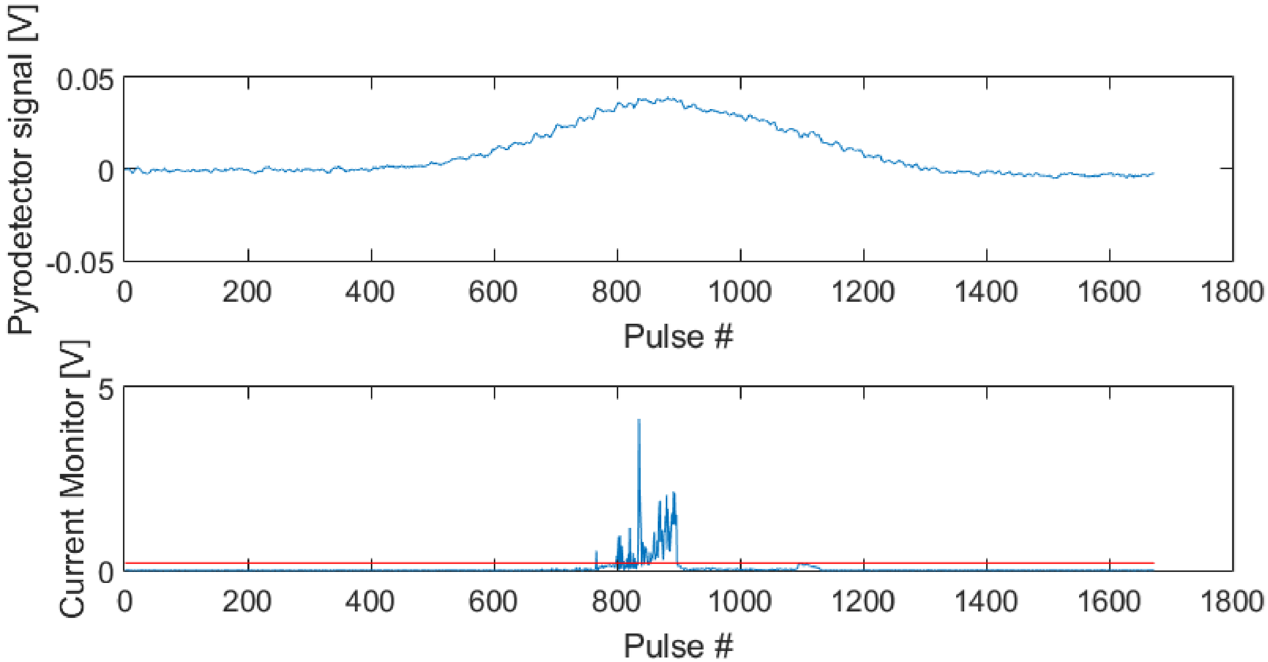
Measurement of beam deflection in a horizontal scan

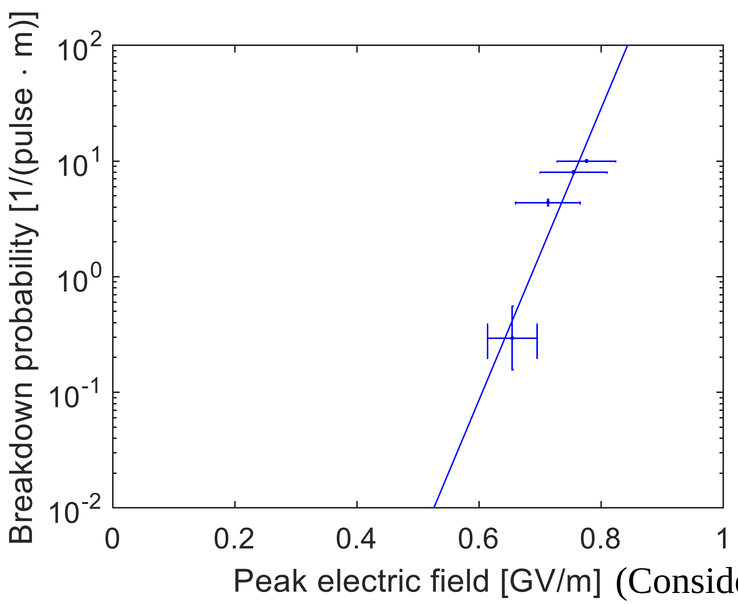


Measurement:
235 GHz Copper Travelling wave structure.
Date:
2015-04-25 (26)

Gap = 1.1 mm, q = 3.2 nC

Breakdown rate, scan# 11: gap = 1.1 mm, Q = 3.2 nC, σ_z = 50 µm





(Considering all modes)

235 GHz Copper Travelling wave structure.
Date:
2015-04-25 (26)

Results of 235 GHz tests

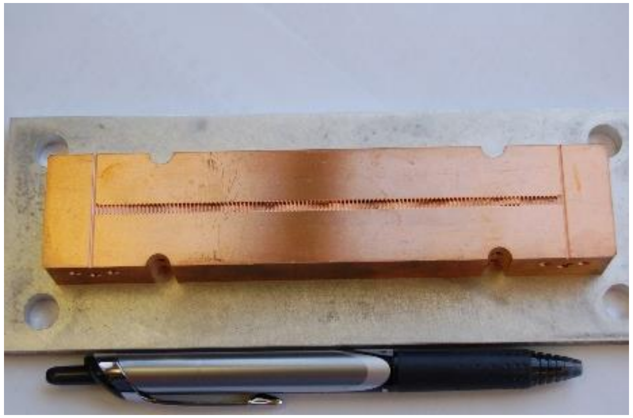
- We successfully measured deflecting fields inside the structure using beam deflection and correspondent breakdown rate.
- We found the the accelerating mode in our open accelerating structure belongs to class of so called surface modes that exist on one surface guided without diffraction losses along periodic corrugations.

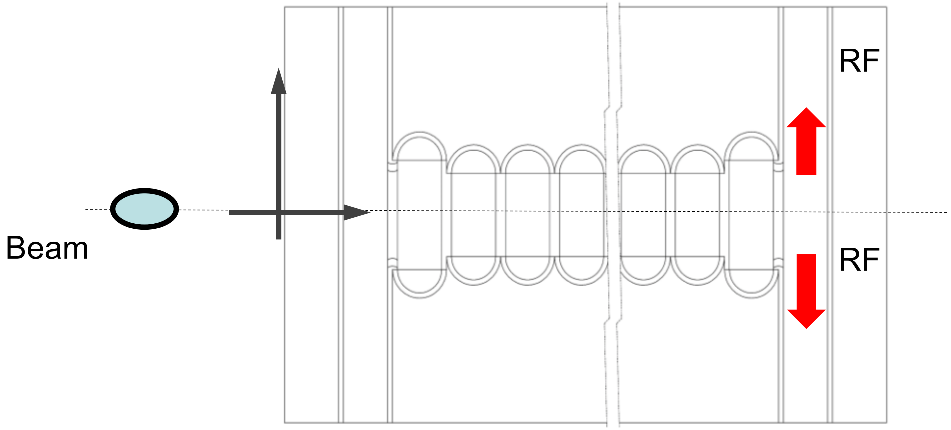
Basic Physics of RF Breakdown

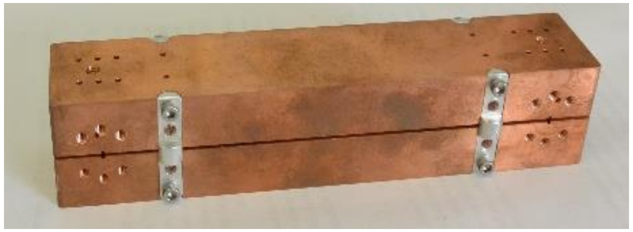
Experiments on frequency scaling of RF breakdown probability

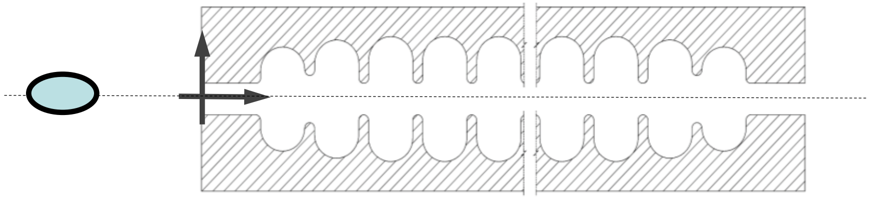
- 90 GHz (Argonne)
- 120 GHz (FACET –E204, SLAC-INFN)
- 235 GHz (FACET – E204, SLAC-INFN)

91 GHz Traveling Wave Accelerating structure at the Argonne Wakefield Accelerator







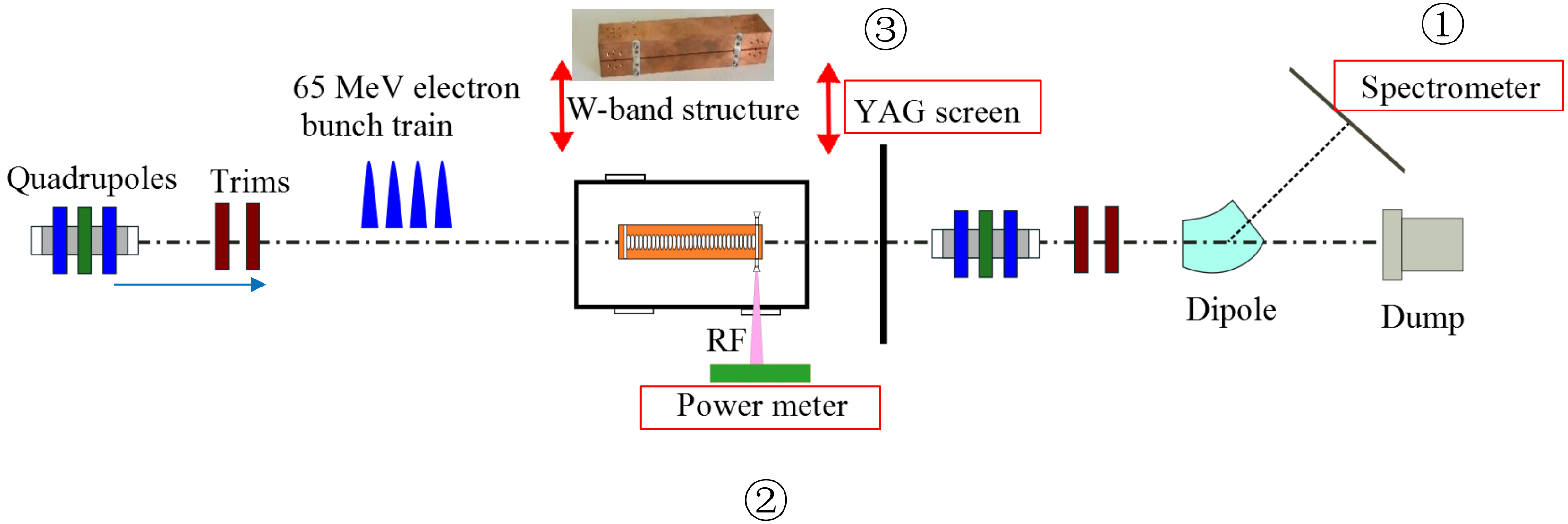


Wang Dan, Argonne National Laboratory

Experimental set up at the Argonne Wakefield Accelerator for testing 91 GHz traveling wave accelerating structure

Main detectors :

- 1. Spectrometer: energy loss of electron beam
- 2. Power meter : RF power
- 3. YAG screen: Beam profile effected by transverse wakefield



Wang Dan, Argonne National Laboratory

Measured longitudinal wakefield in 91 GHz TW Structure

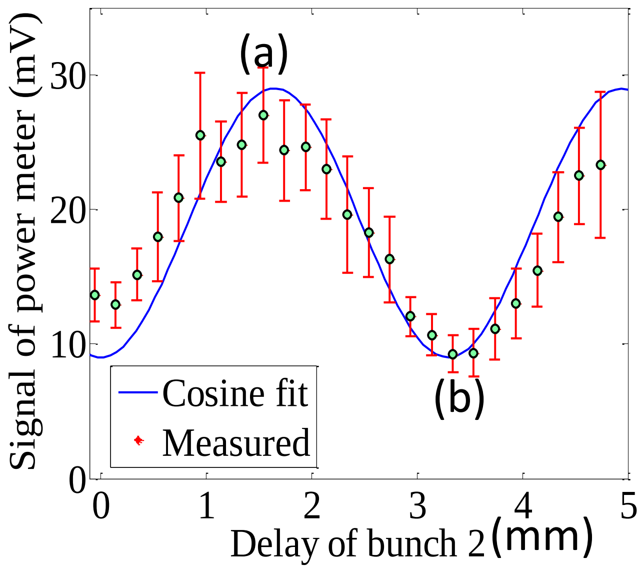
Bunch 1 and bunch 2

---- same charge of 2 nC for each bunch

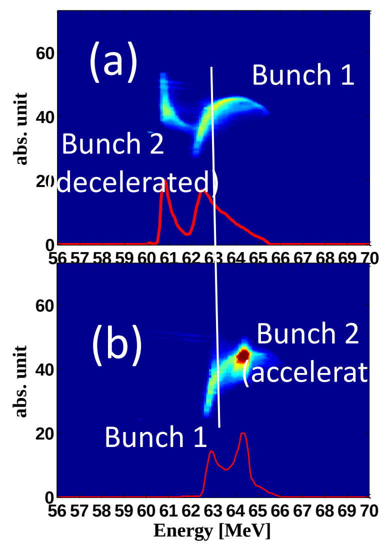
----- same distribution of initial energy distribution (mean energy is 65.5 MeV)

before the W-band structure

Take bunch 2 as a witness beam



Wavelength is of 91 GHz



(a) <- This case : bunch 2 is decelerate by wake from bunch 1

(b) <-- This case : bunch 2 is accelerate by wake from bunch 1 OR wakefield (RF) of bunch 1 convert to the bunch 2 energy

In case (a), wakefield excited by two bunches add up in phase

- Maximum RF power of 91 GHz is 2.7 MW, wakefield gradient inside the structure is 60 MV/m
- When driven with bunch train (valid 3 bunches , 2nC of each sub-bunch), we measured deceleration correspondent to maximum RF power of 5 MW, gradient is 85 MV/ m (no break drown observed)

Wang Dan, Argonne National Laboratory

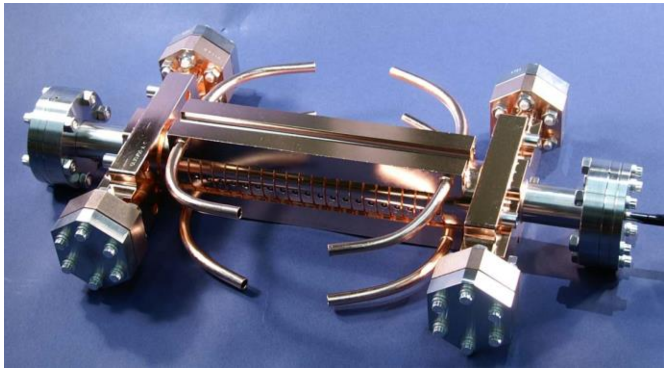
Tests of full scale traveling-wave structures

These tests study effects of complex, multi-cell interactions in rf breakdown physics and result in practical devices

CERN-SLAC-KEK-THU

Traveling Wave accelerator structures, CLIC prototypes

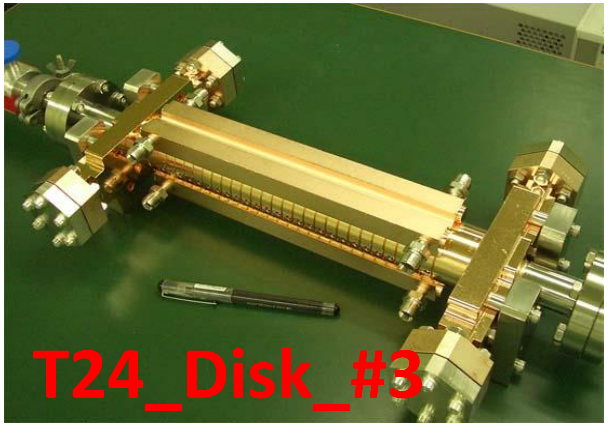
T18 →TD18→T24→TD24



T18_Disk_#2

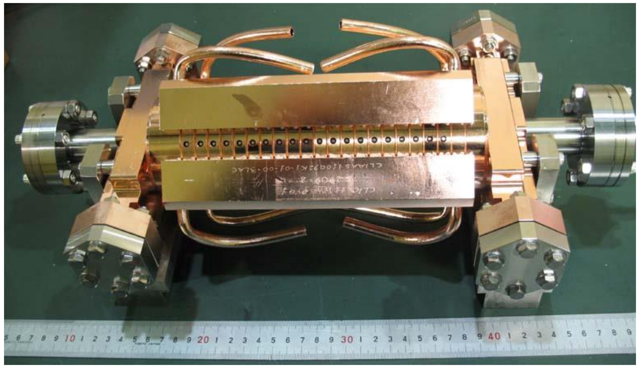
2009

undamped



2011

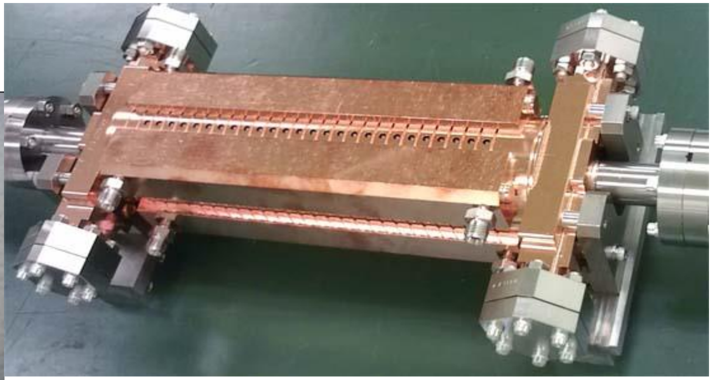
2010



TD18_Disk_#2

damped

2011~12

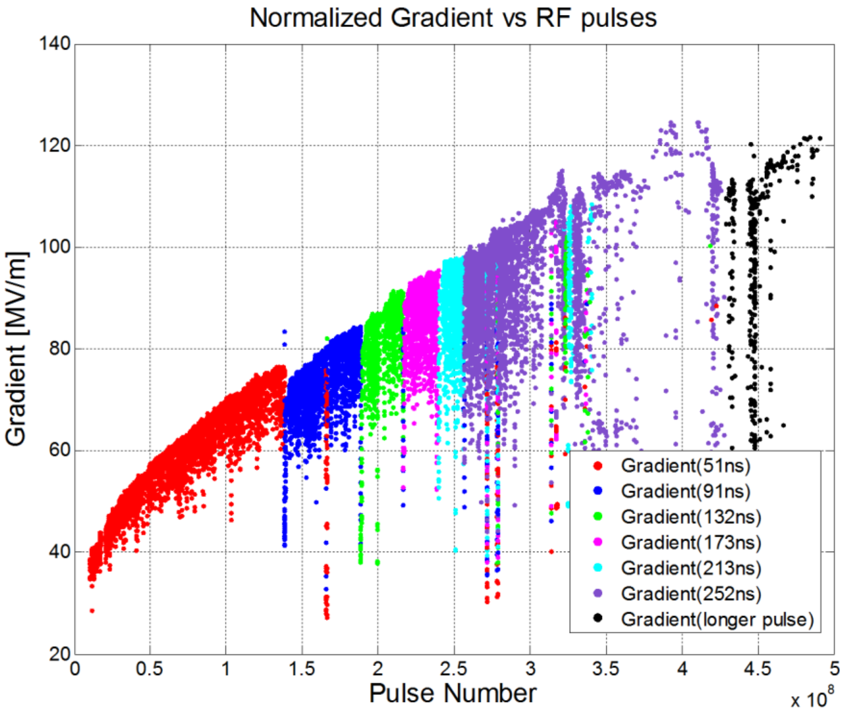


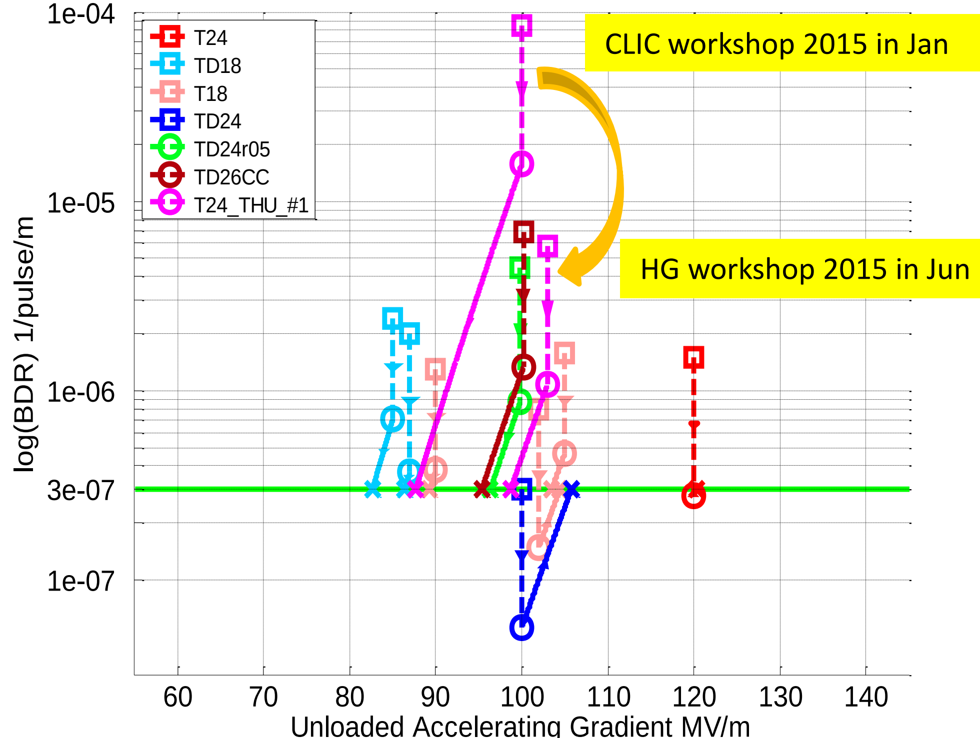
TD24_Disk_#4

CERN-SLAC-KEK-THU

History plot of CLIC Prototype T24_THU_#1 manufactured by *Tsinghua University* and tested at KEK

- Gradient in each pulse width operation increases smoothly
- BDR almost keeps at lower than 2e-5 bpp

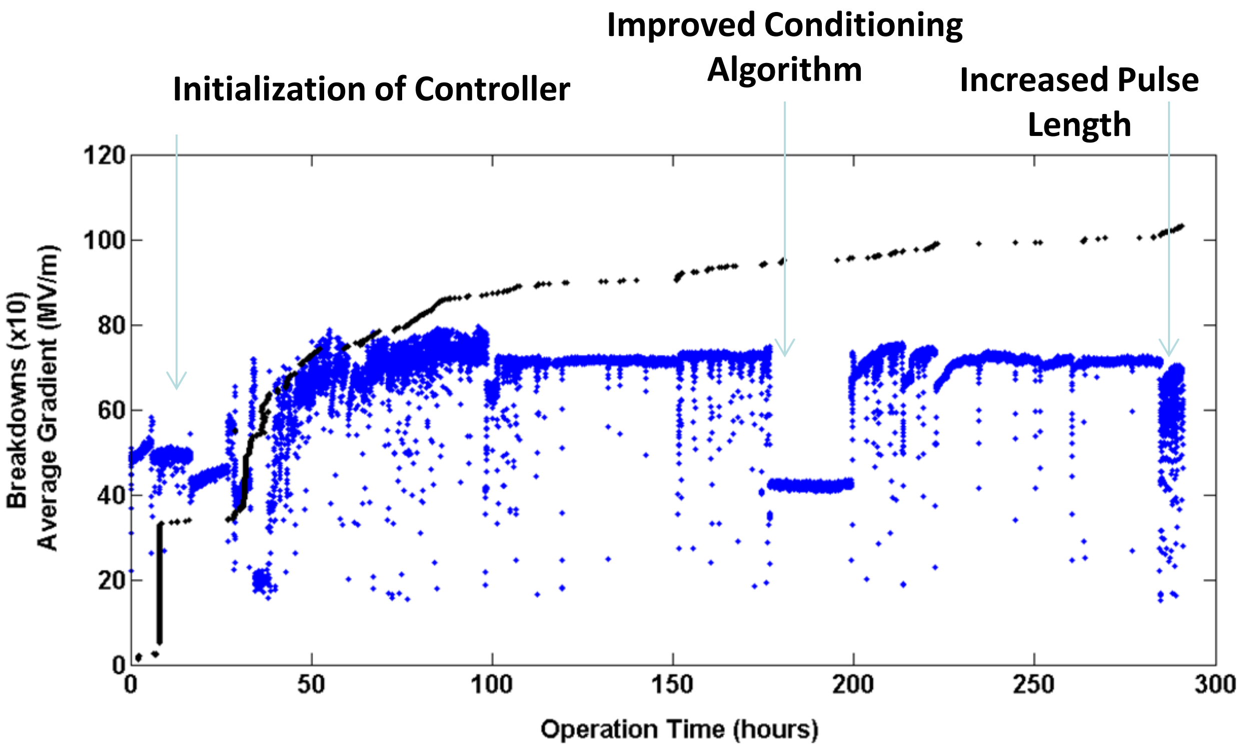




CERN-KEK-THU

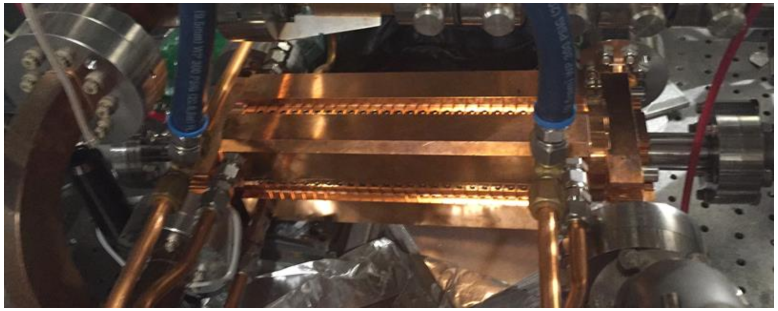
SLAC-ASTA: CLIC Structure High Power Test

Xbox II Architecture



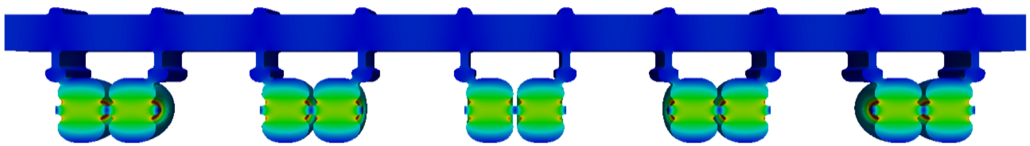
PXI Controller

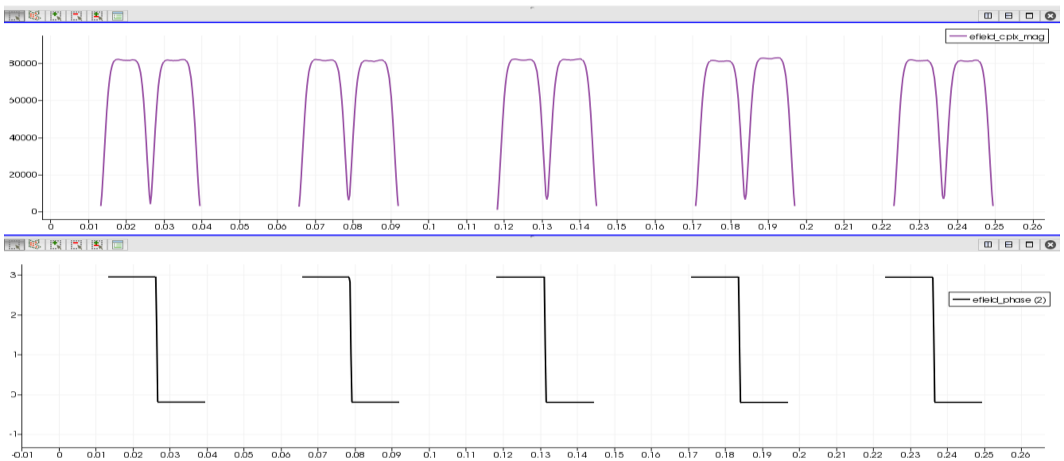
CLIC Accelerating Structure

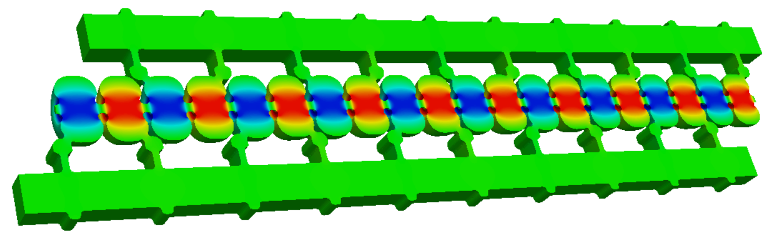


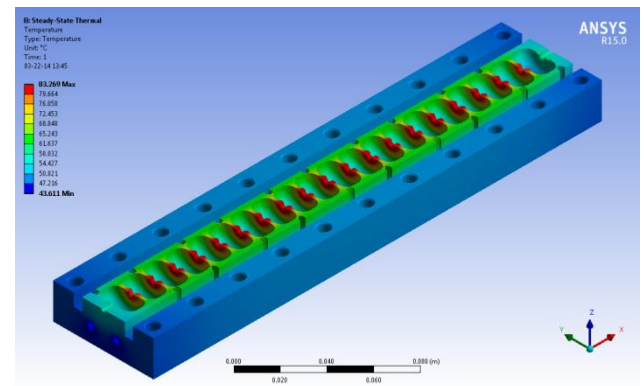
CERN-SLAC

Novel Distributed Coupling to Each Accelerator Cell Enables *Doubling* RF to Beam Efficiency and Ultra-High-Gradient Operation.





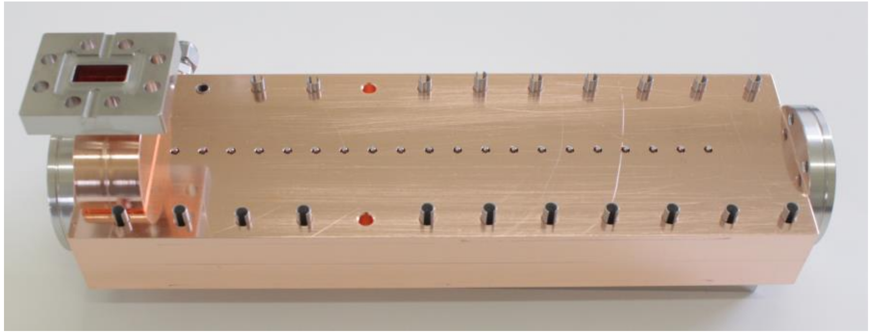


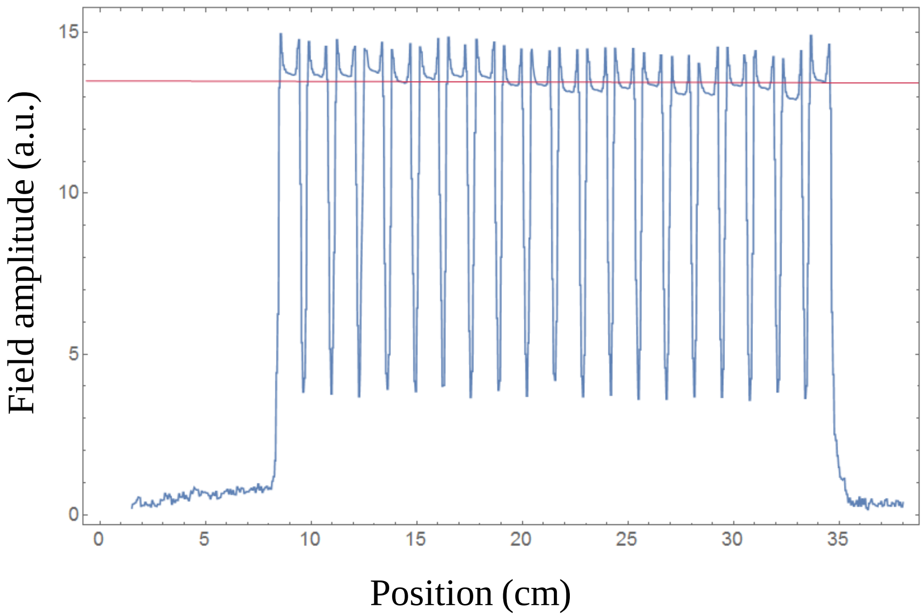


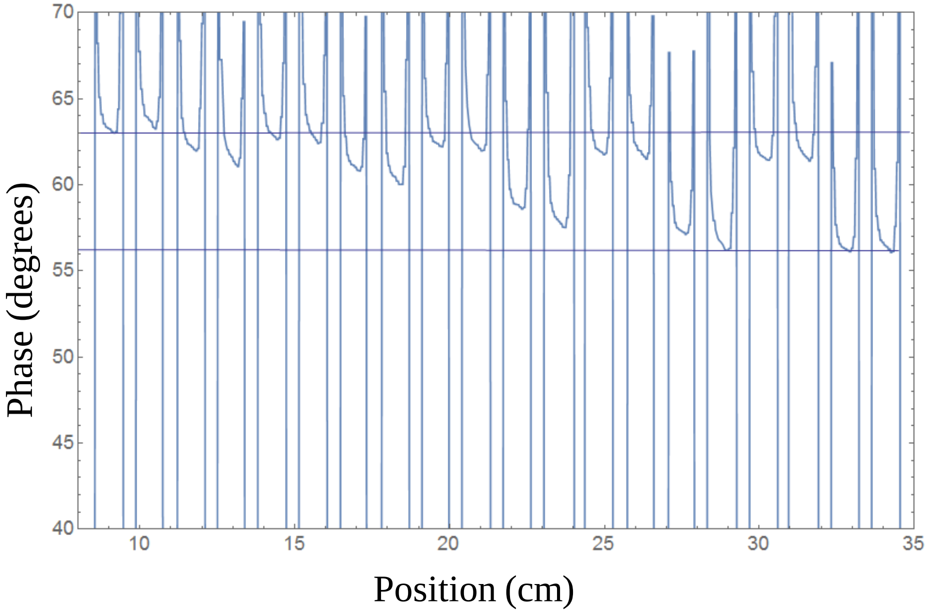
- Optimize individual cell shape for maximum gradient and shunt impedance without cell-to-cell coupling constraint
- Requires only 66 MW/m for 100 MV/m gradient compared to 200 MW/m for a typical X-band structure
- Inexpensive to manufacture
- Patent filed by Stanford
- 2015- First accelerator structure of this class is now under test at high power
- 2016-2017
  - Combine the structures into one monolithic super structure
  - Understand the Wakefield properties
  - Construct structures with engineered materials (alloys)
- Beyond 2017
  - Incorporate into an energy recovery system.
  - Fold into a realistic modular design for a future TeV collider

Sami Tantawi - SLAC-Stanford University

Cold test of the new structure







- First accelerator structure class is under test at high power
- Funded by grants to the Stanford School of Medicine and SLAC

Physical models

- Dislocation dynamics
- Near surface power flow

Realistic model of the breakdown trigger should include both electric and magnetic rf fields and behave similar to fatigue-faults induced in metals by pulsed mechanical stress.

For multi-cell structures, this model should also predict mysterious (but typical) behavior: along the length of such a structure the breakdown probability *depends weakly on local field parameters*.

See Walter Wuensch WG3 talk this afternoon

Dislocation dynamics

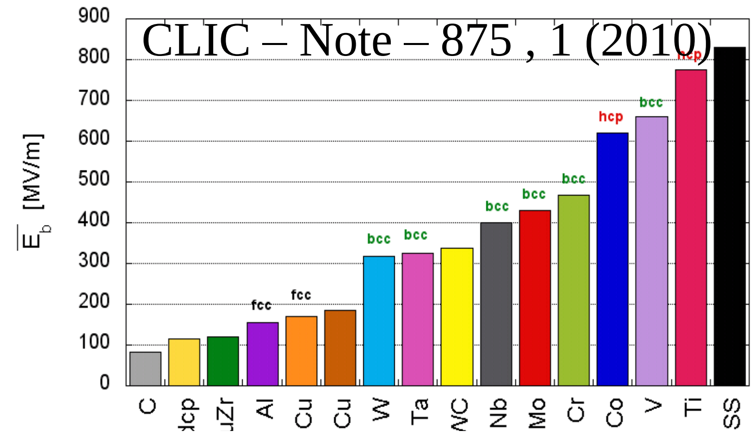
Current hypotheses which explain experimentally observed statistical properties of rf breakdown include processes which result in metal fatigue due to periodic mechanical stresses.

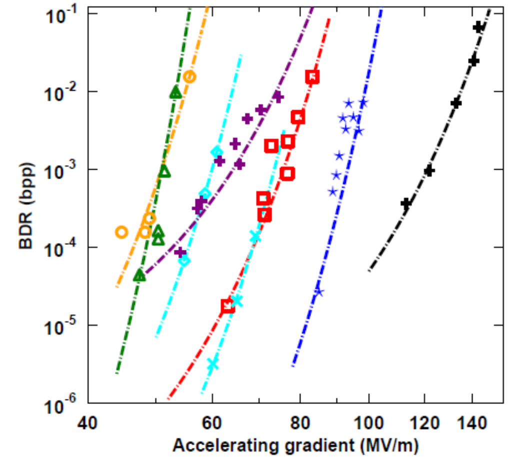
Experimental observation leading to studies of metal plasticity under periodic stress

Several observations such as :

- Correlation between lattice structure and maximal field.
- Dark current Fowler-Nordheim curves indicating large field emitters
- strong dependency of breakdown rates on pulse length and field - $\mathrm{BDR} \propto E^{30} t^{5}$

Led to the proposition (W. Wuensch, F. Djurabekva et. al.) that plastic surface response underlies the initial stages of BD evolution.

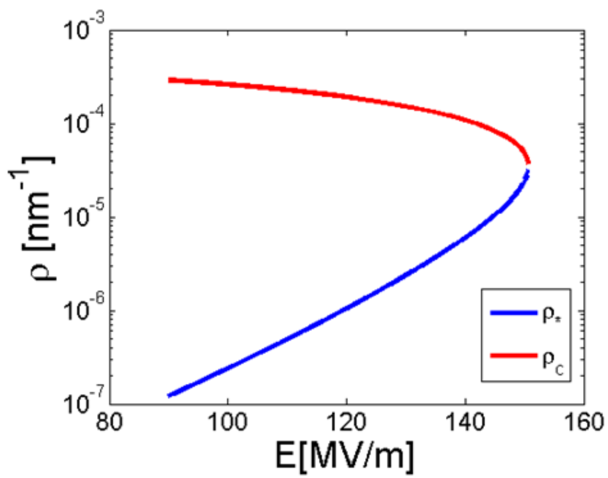




K. Nordlund and F. Djurabekova, Phys. Rev. ST-AB 15, 071002 (2012).

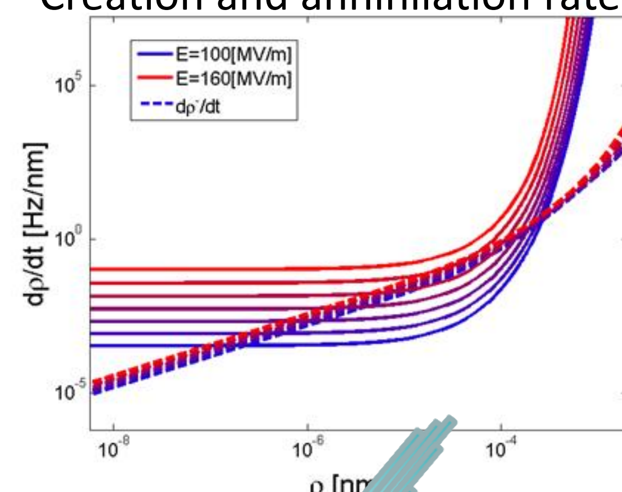
Vacuum initiation due to pre-BD plastic activity

- Assuming a plastic process leads to protrusion formation which have large aspect ratio - field enhancement and locally reduced work function
- Trying to calibrate a full stochastic model for surface evolution prior to breakdown formation – leading to the actual BD event.
- It is suggested that dark current fluctuations due to surface topography evolution is indicative of imminent breakdown
- Population of mobile dislocations kinetics is described using a stochastic model.
- The model shows a metastable region with a critical transition in a range of fields.



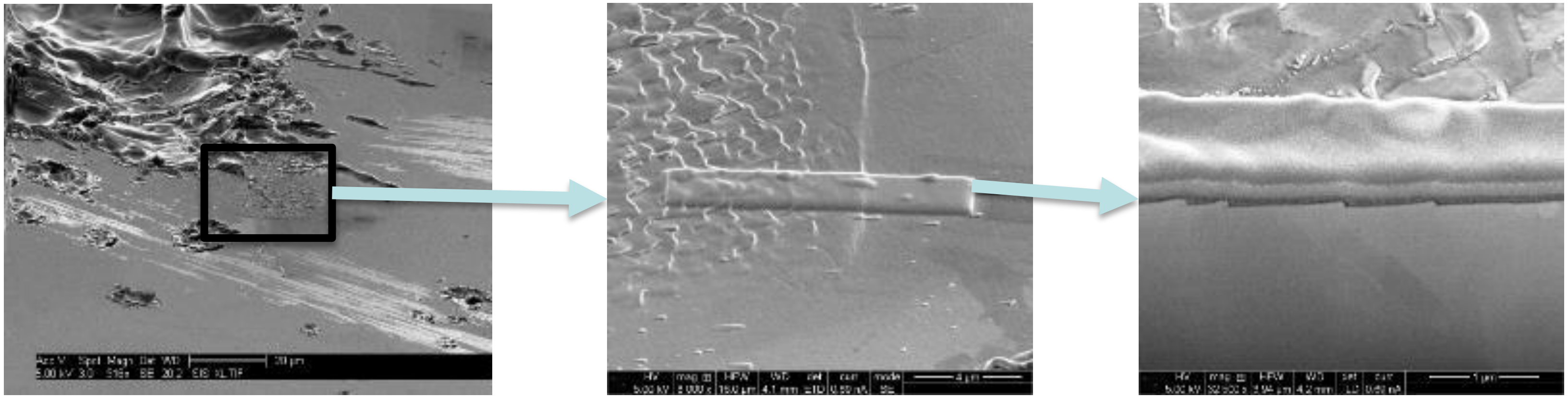
Critical (red) and metastable (clue) mobile dislcaoitons density

Creation and annihilation rates

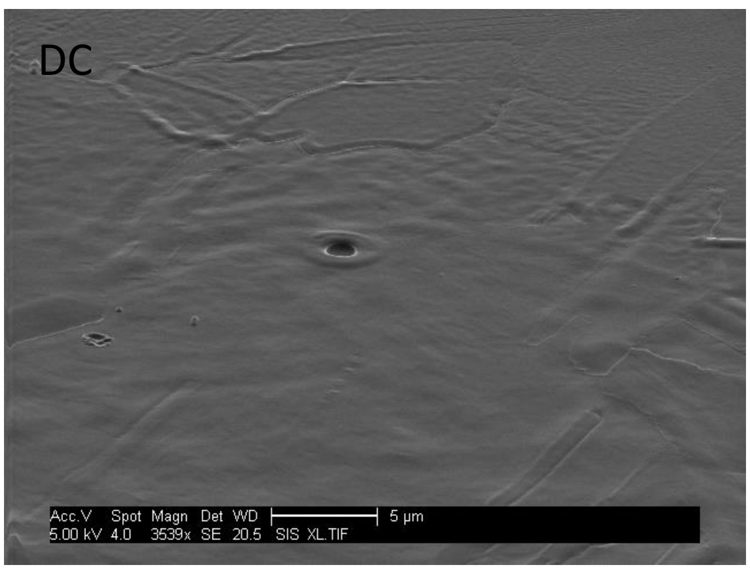


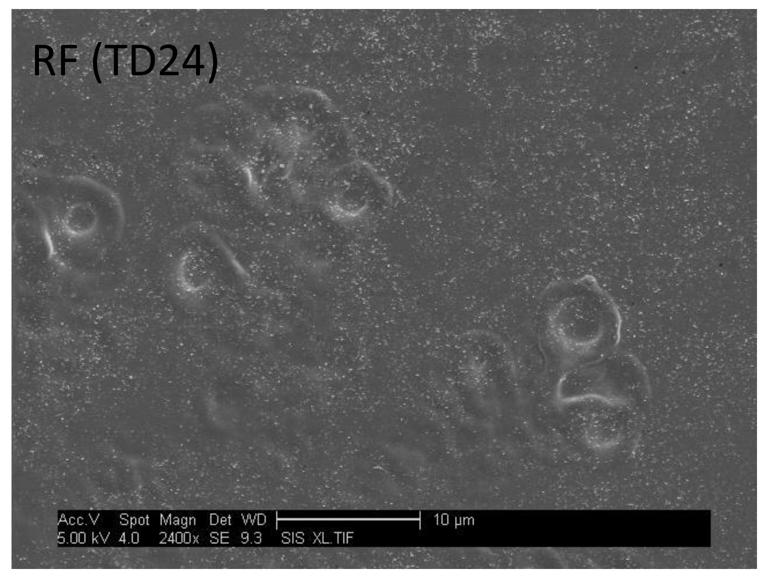
Y. Ashkenazy, Hebrew University of Jerusalem

Surface modifications affecting plastic activity



- SEM+FIB - Violently modified BD “craters” are surrounded by larger (gentle) surface modified regions
- Similarity between RF and DC “far from BD” regions
- Possible source for conditioning?

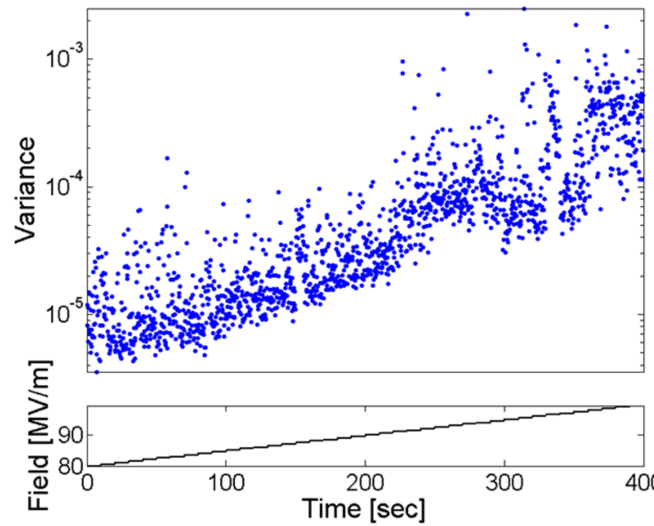




A. Yashar, Y. Ashkenazy, I. Popov, Hebrew University of Jerusalem

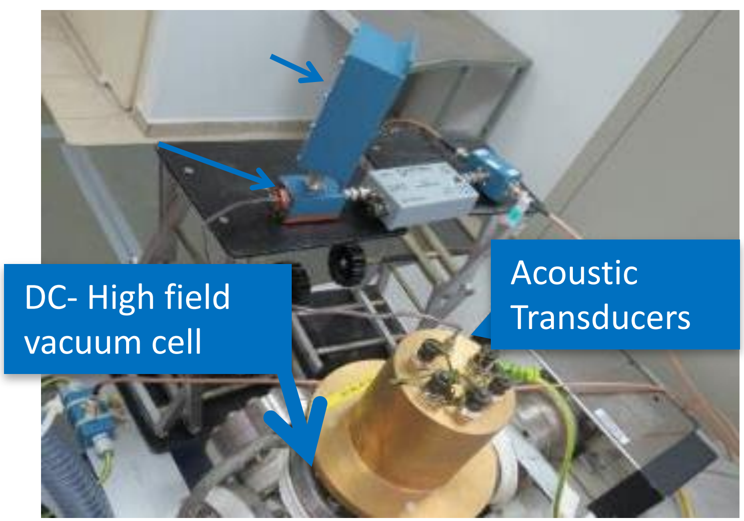
Pre-BD signals of plastic activity

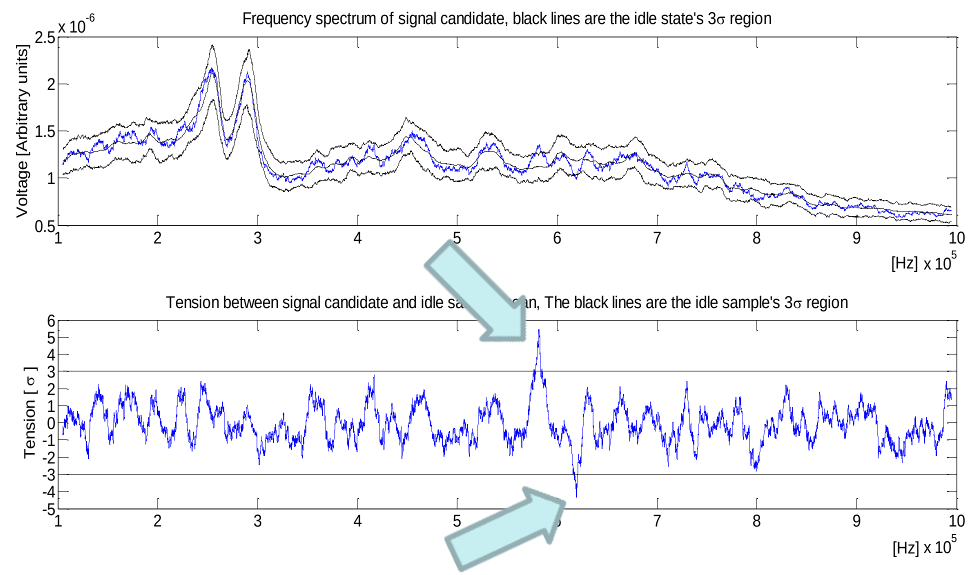
- As a critical plastic process – increase in pre-transition fluctuation is expected
- Initial indications to increase in dark current fluctuations as measured in CERN DC system



T. Muranaka & Y. Ashkenazy

- Using a new system that monitors acoustic emission in unison with DC-high field application initial indication of pre-BD plastic activity





I. Nachshon & Y. Ashkenazy, Hebrew university of Jerusalem

Summary

- This high gradient work is characterized by a strong national and international collaboration. This is the only way to gather the necessary resources.
- With the understanding of geometrical effects and material requirements, we systematically move toward full featured accelerating structures that work with extremely low breakdown rates and gradients well above 100 MV/m.
- New theoretical approaches being developed driven by extensive experimental results.