Progress on High Gradient Research

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Overview

* Experimental Program
  - Basic Physics studies using Single cell structures
  - Testing program at NLCTA
  - Pulsed heating experiments
  - Material studies
* Structure integration and wake field damping
* Future work/Open problems
* Summary

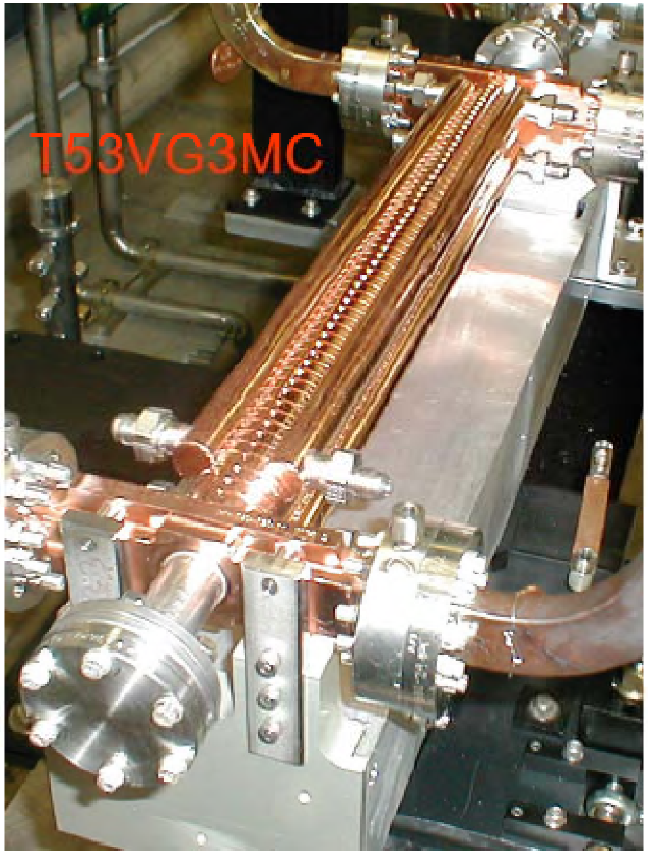
Methodology

* Traditionally linear collider programs dictated the performance of the accelerator structures. Here we would like to find the limitations of structures due to these choices and see if we can design the collider around an optimized structure design
* We have to address fundamentals early; these include, but are not limited to
  – Frequency scaling
  – Geometry dependence
  – Energy, power and pulse length
  – Materials
  – Surface processing technique (etching, baking, etc.)
  – Theory
  – …

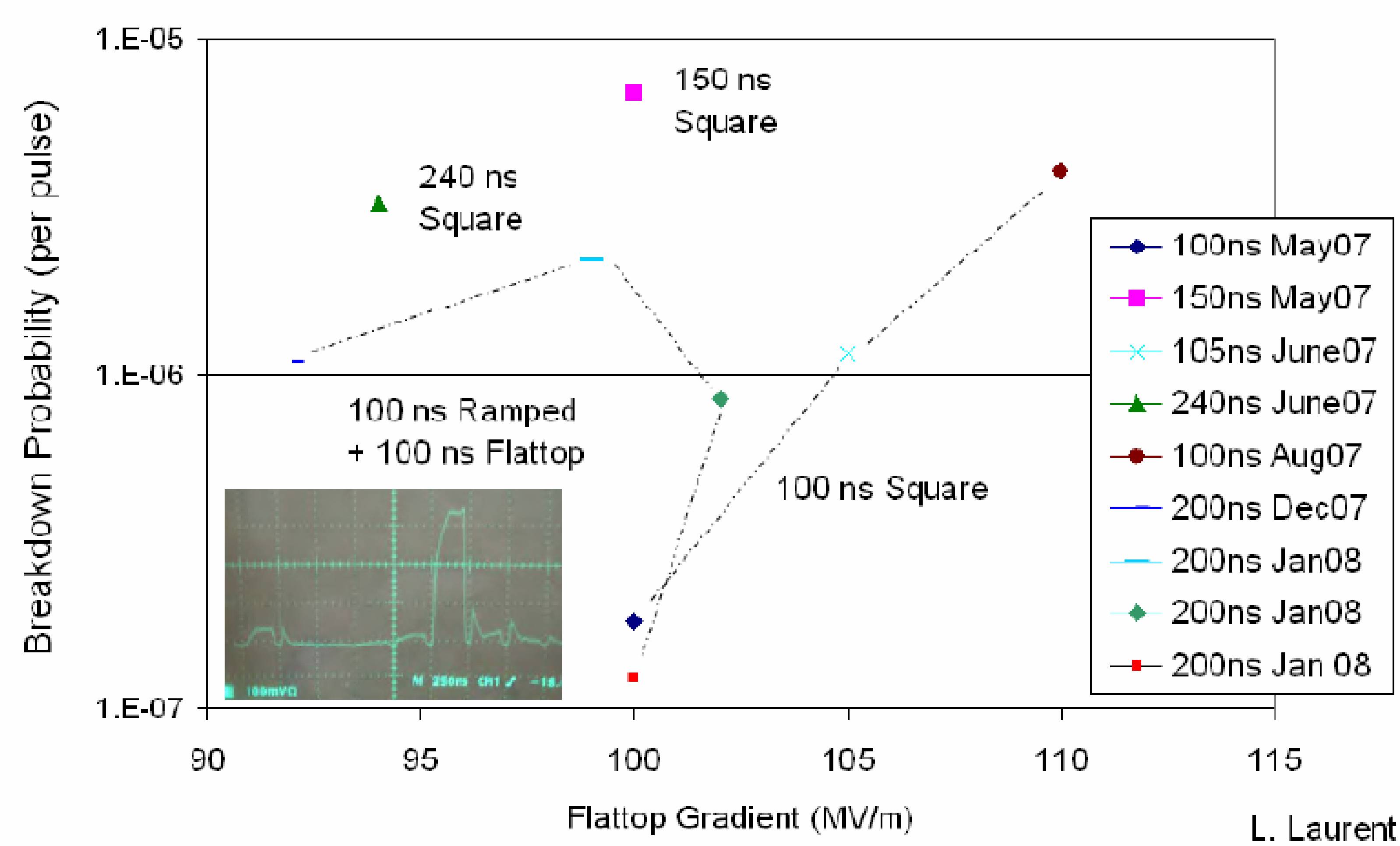
Early NLC/GLC Low Vg Test Structure

First with Mode Converter input coupler – performed exceptionally well in 2002

- 53 cm long, a/λ = 13%, initial vg = 3.3%, requires 98 MW for 100 MV/m operation
- In 2002, breakdown rate < 5e-7 at 90 MV/m with 400 ns square pulses
- Reinstalled in 4/07 and have since run 2300 hours with shorter pulses (includes two vents to SLED system)
- In following plot, most points based on 60 Hz operation for more than 50 hours



Short Pulse Operation of T53VG3MC



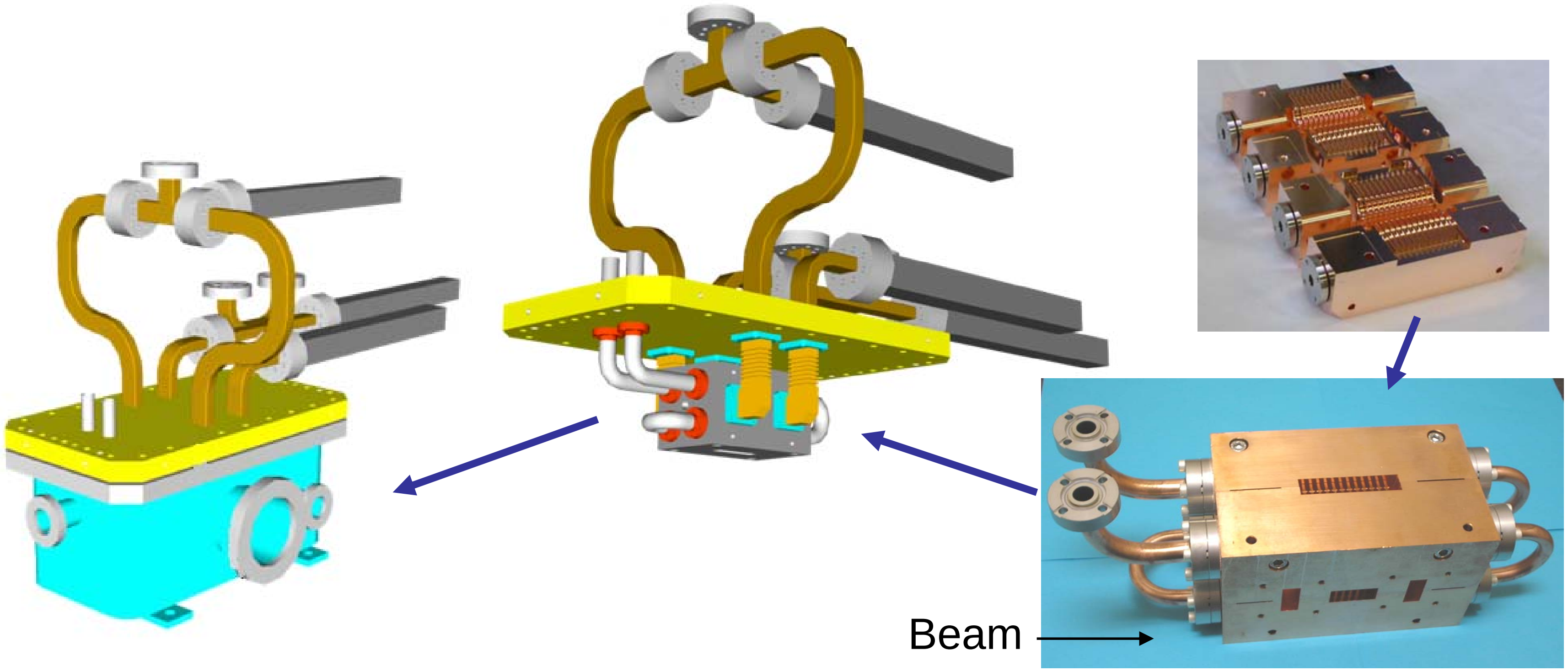
T26

- Based on the wonderful results of the T53 structure a new structure was proposed, the T26
- Basically a shorter version where every other cell is being used.
- It is currently under test
  - Bad cells or wrong geometry?

HDX11 11.424 GHz Structure

*L. Laurent, C. Adolphsen, G. Bowden, S. Döebert, A. Farvid,
R. Fondos, S. Tantawi, F. Wang, J. Wang*

- Fabricated at CERN and RF Tested at SLAC at NLCTA Station One
- Quadrant Clamped Structure (Low phase advance-60 deg, slotted iris)
- Reduction in Es/Ea (Es/Ea = 1.66)



HDX11 Conditioning Statistics

~ 600 hours total conditioning +experiment

~ 20,000 Breakdowns

‘Stable running’: 60 MV/m; at 70 ns

57 MV/m; at 150 ns

(Max Power: 200 MW at 40 ns; 150 MW at 70 ns)

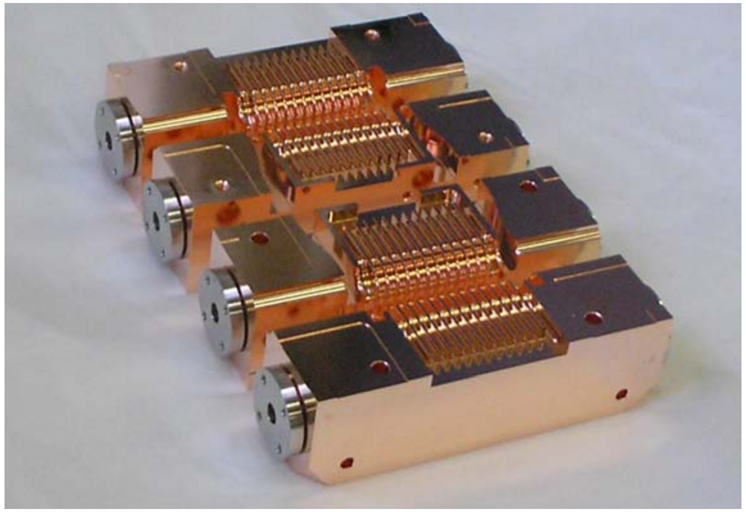
Recent testing of other structures for comparison:

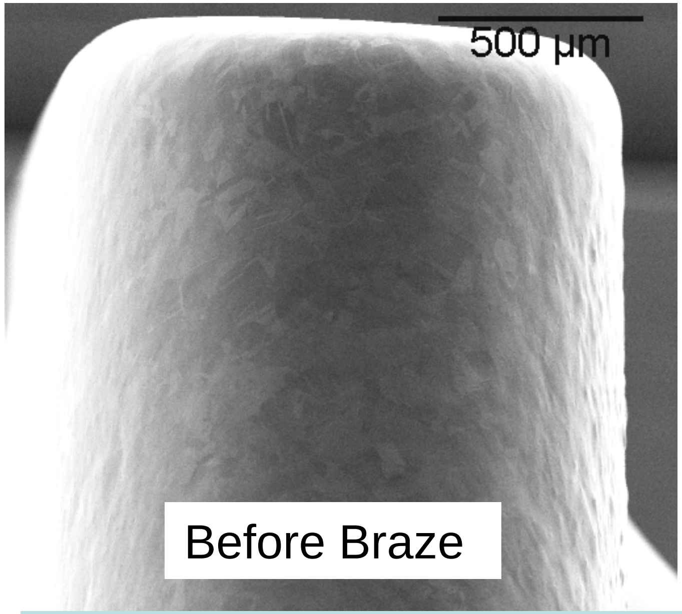
T53VG3MC 105 MV/m; at 105 ns

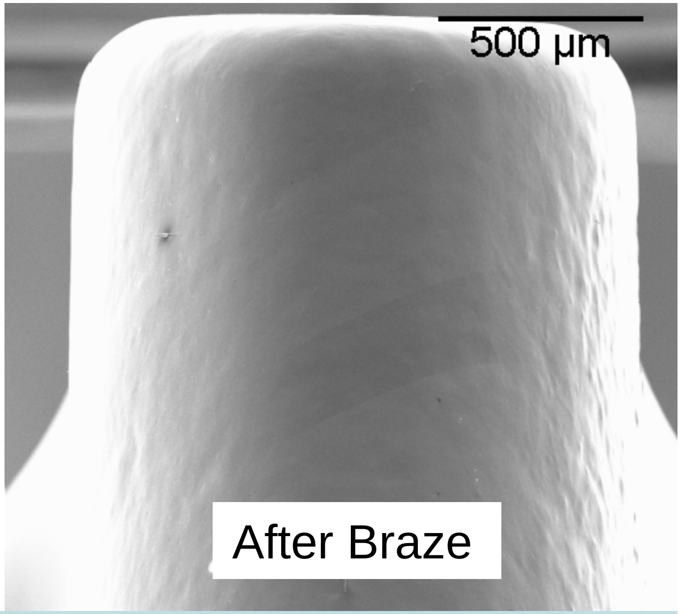
H75VG4S18 102 MV/m; at 150 ns

Performance of HDX11 significantly worse than NLC structures

HDX11 Redux: After brazing on new water fittings

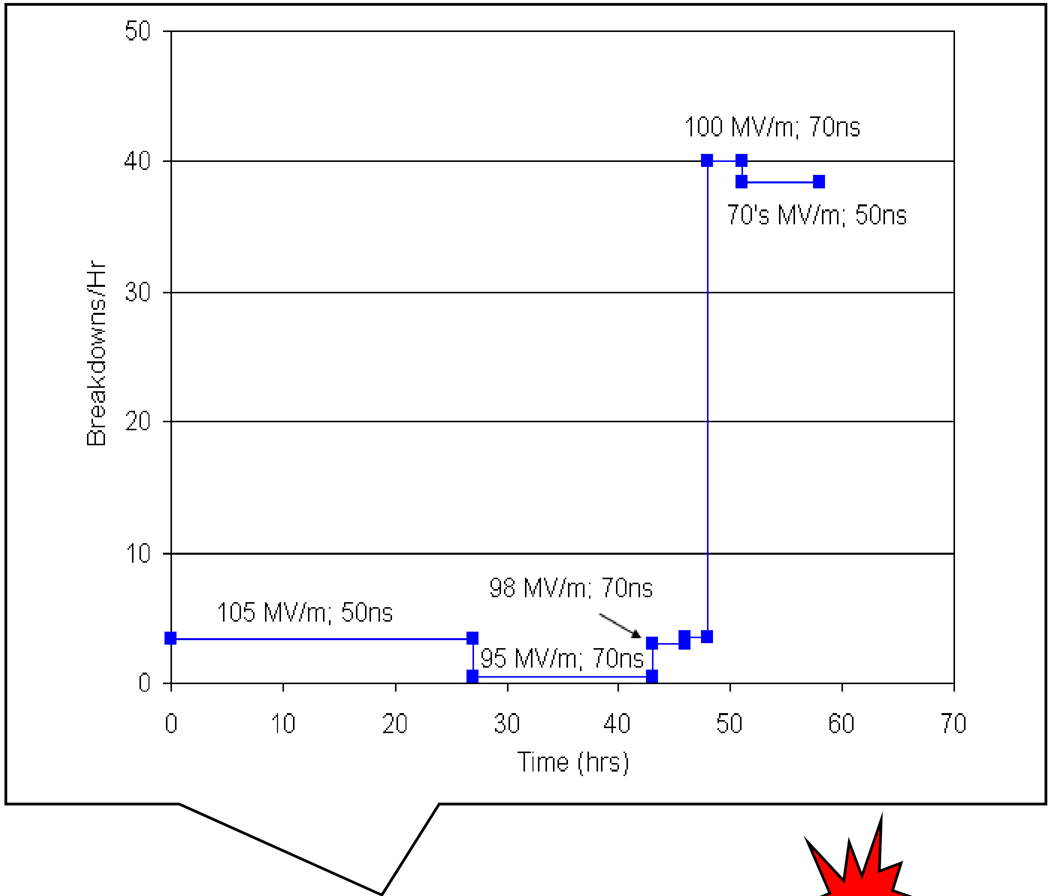






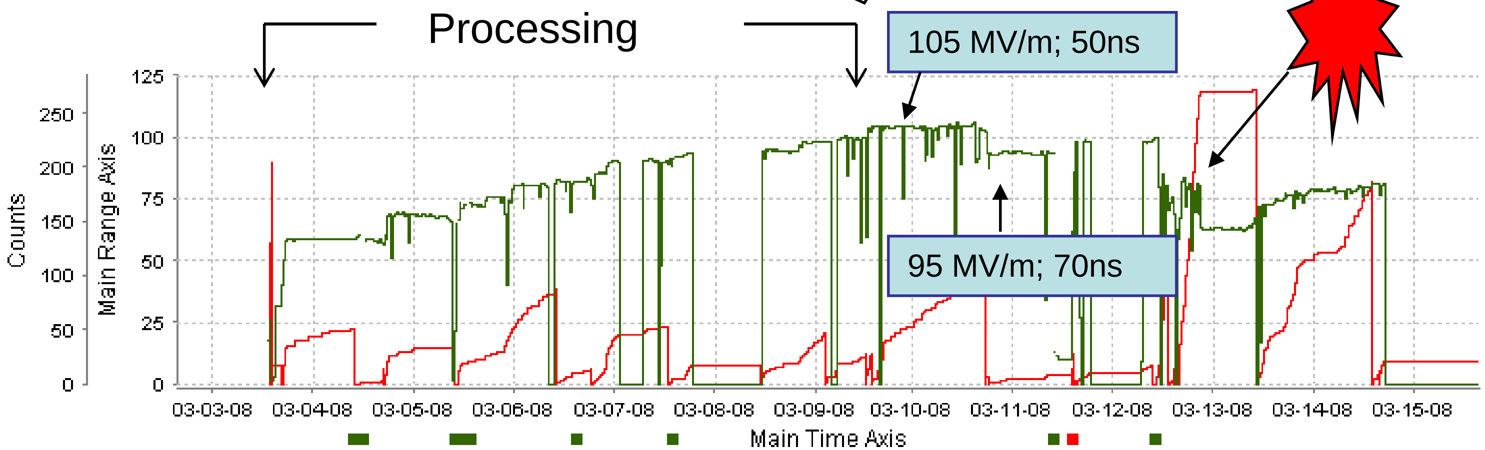
Quad 7-8: Iris 1. Grain growth significantly increased after braze cycle

HDX11 Redux Assembly: Orientation reversed so the ‘good’ end now sees the input power.



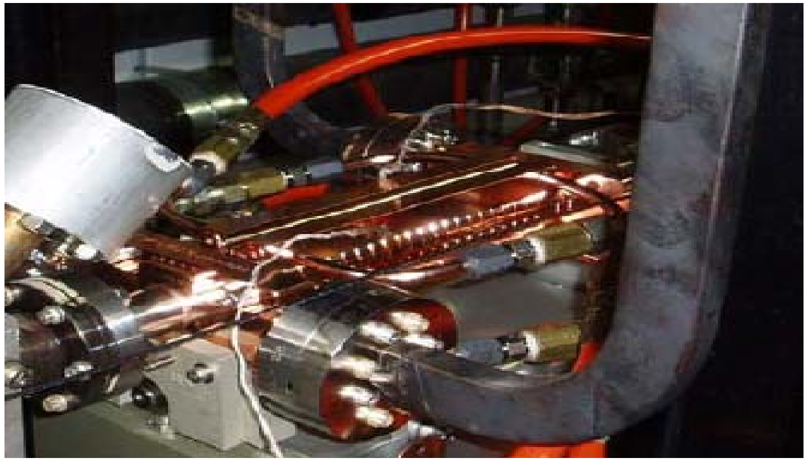
Green: E-Field (MV/m);

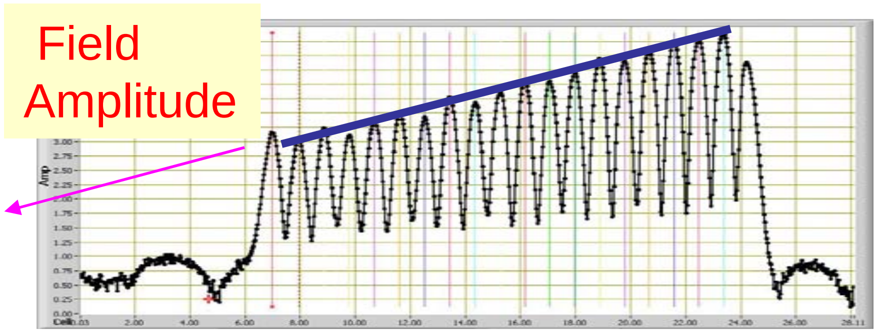
Red: Breakdown Counts



Full Accelerator structure testing (the T18 structure)

Frequency.	11.424GHz
Cells	18+input+output
Filling Time	36ns
a_in/a_out	4.06/2.66 mm
vg_in/vg_out	2.61/1.02 (%c)
S11	0.035
S21	0.8
Phase	120Deg
Average Unloaded Gradient over the full structure	55.5MW→100MV/m





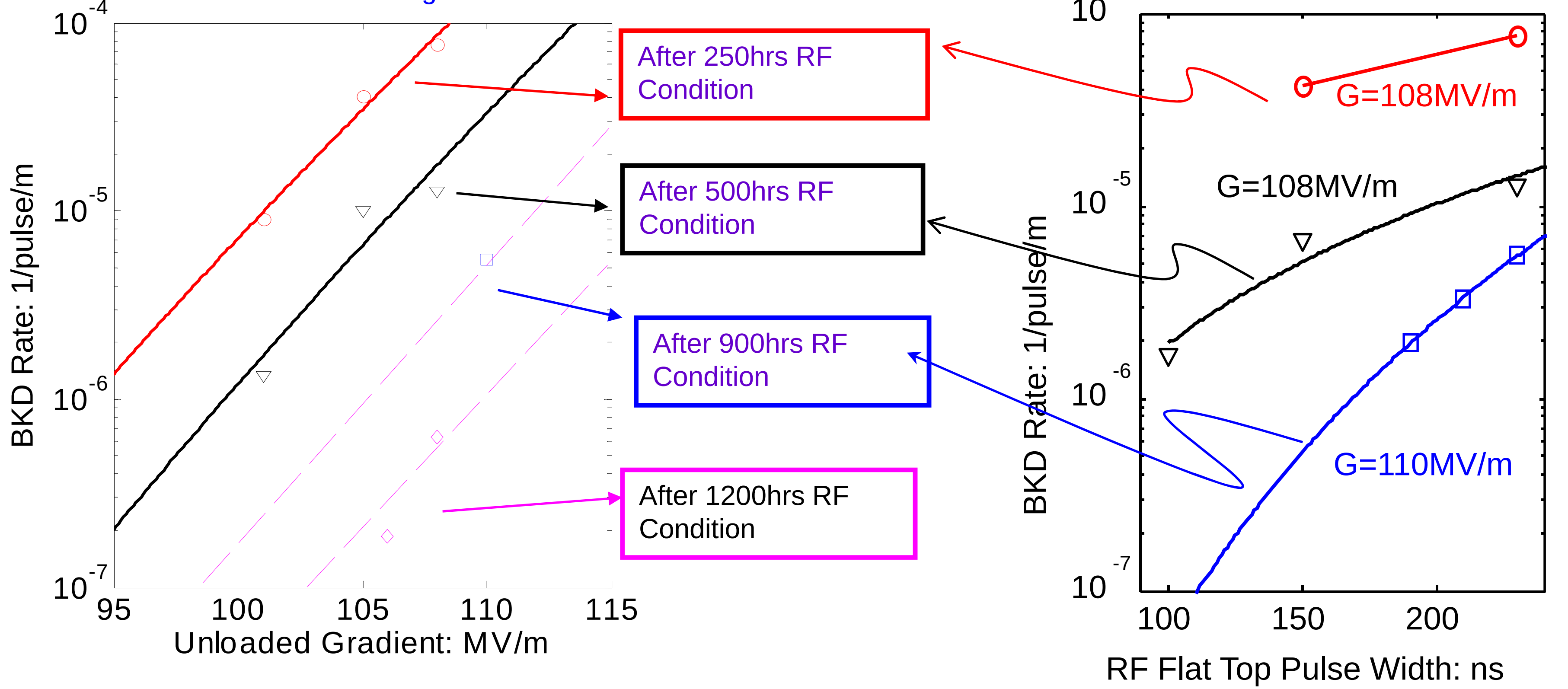
$$E_{acc\_out} / E_{acc\_in} \sim 1.5$$

- Structure designed by CERN based on all empirical laws developed experimentally through our previous work
- Cell Build at KEK
- Structure was bonded and processed at SLAC
- The structure is also tested at SLAC

RF Processing of the T18 Structure

RF BKD Rate Gradient Dependence for 230ns Pulse at Different Conditioning Time

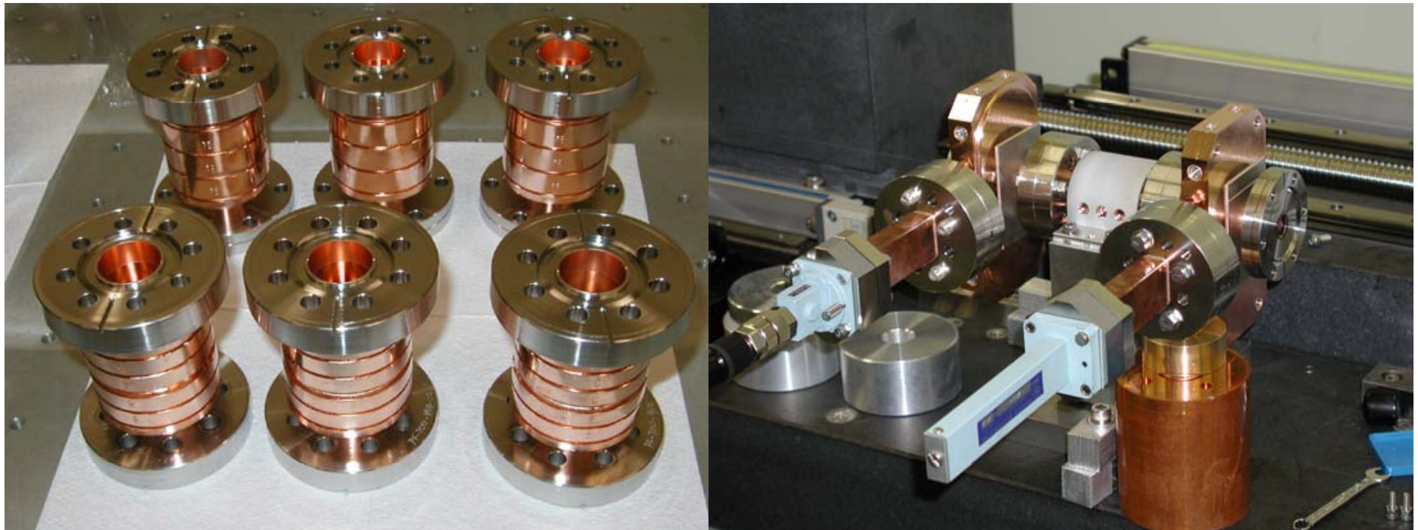
RF BKD Rate Pulse Width Dependence at Different Conditioning Time



This performance *maybe* good enough for 100MV/m structure for a warm collider, however, it does not yet contain all necessary features such as wake field damping. Future traveling wave structure designs will also have better efficiencies

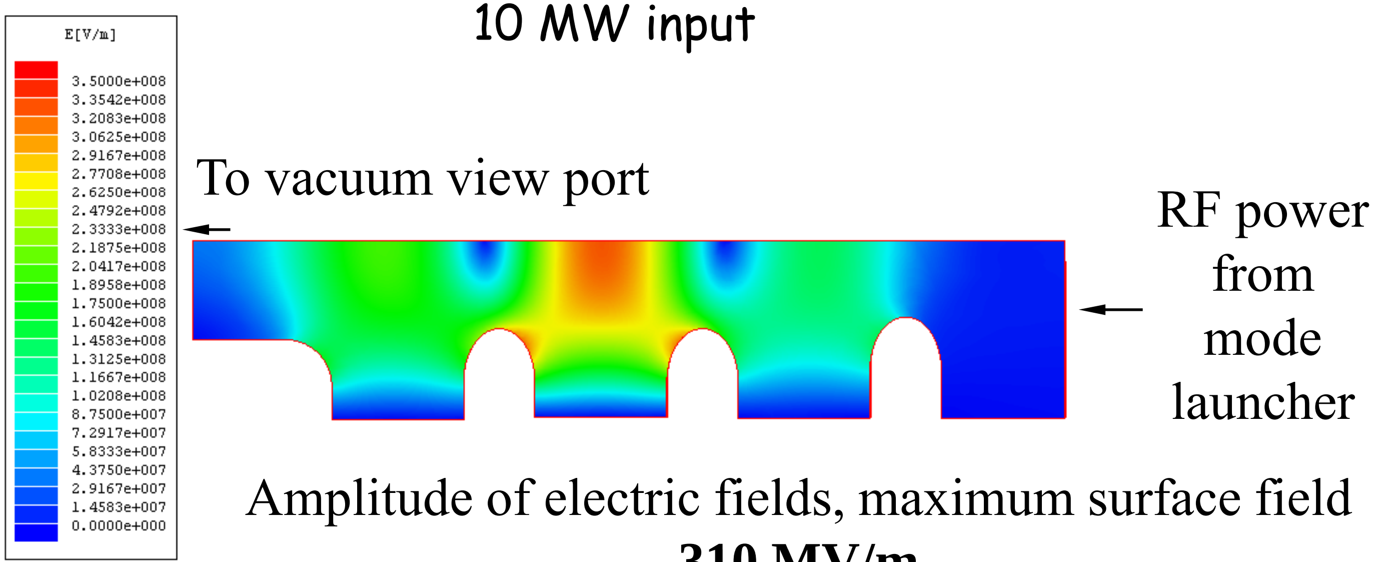
Experimental Studies

* Basic Physics Experimental Studies
  - Single and Multiple Cell Accelerator Structures (with major KEK and CERN contributions)
    - traveling- wave single cell accelerator structures (Needs ASTA)
    - single-cell standing-wave accelerator structures (Performed at Klystron Test Lab)
  - Waveguide structures (Needs ASTA)
  - Pulsed heating experiments (Performed at the klystron Test Lab, also with major KEK and CERN contributions)
* Full Accelerator Structure Testing (Performed at NLCTA, with CERN contributions)

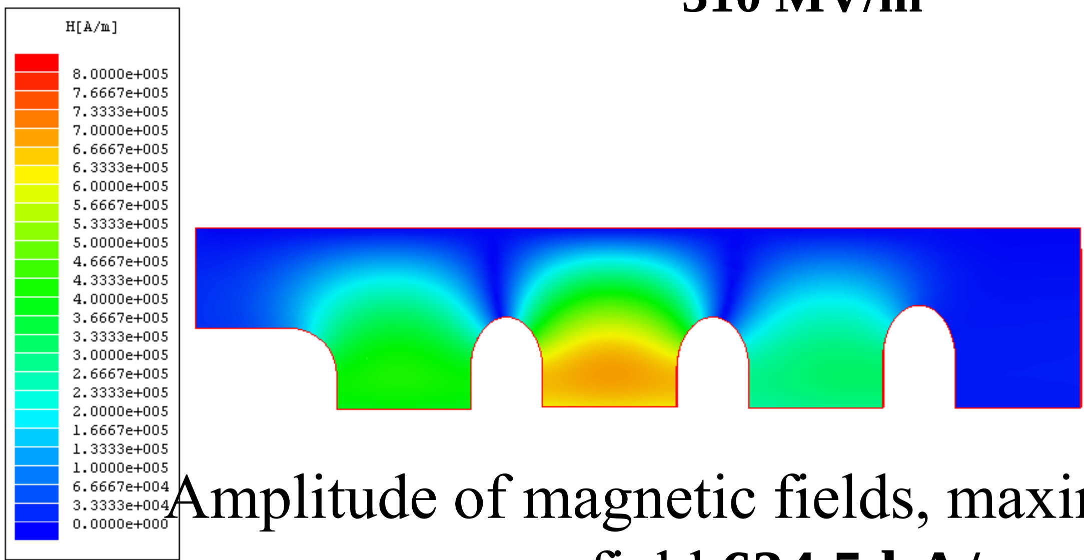


Single-Cell-SW-A5.65-T4.6-Cu

10 MW input



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



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

High Power Tests of Single Cell Standing Wave Structures

Tested

- Low shunt impedance, a/lambda = 0.215, *1C-SW-A5.65-T4.6-Cu*, 4 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 in high gradient cell, *1C-SW-A5.65-T4.6-Choke-Cu*, two tested
- Cu Zr Structure

Total of 12 tests completed

- Next test: Low shunt impedance, made of CuZr, *1C-SW-A5.65-T4.6-CuZr*

In manufacturing

- Photonic-Band-Gap in high gradient cell, *1C-SW-A5.65-T4.6-Cu-PBG*
- Highest shunt impedance, a/lambda = 0.105, *1C-SW-A2.75-T2.0-Cu*
- Three cells, WR90 coupling to power source, *3C-SW-A5.65-T4.6-Cu-WR90*
- High shunt impedance, made of CuZr, *1C-SW-A3.75-T2.6-CuZr*

…

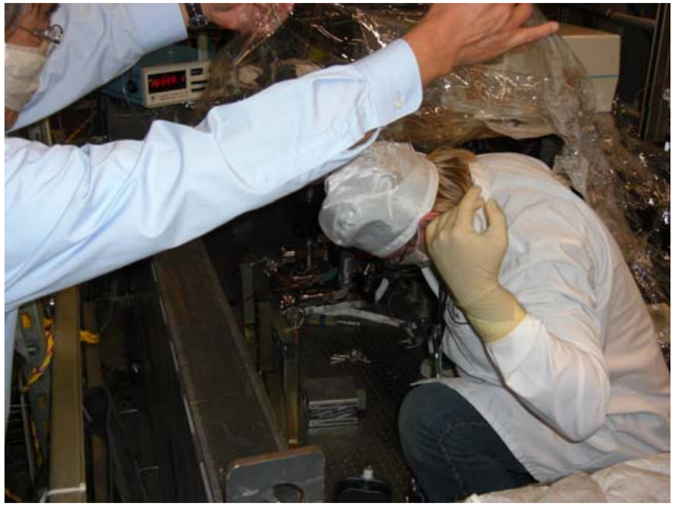
Parameters of periodic structures @ Eacc=100 MV/m

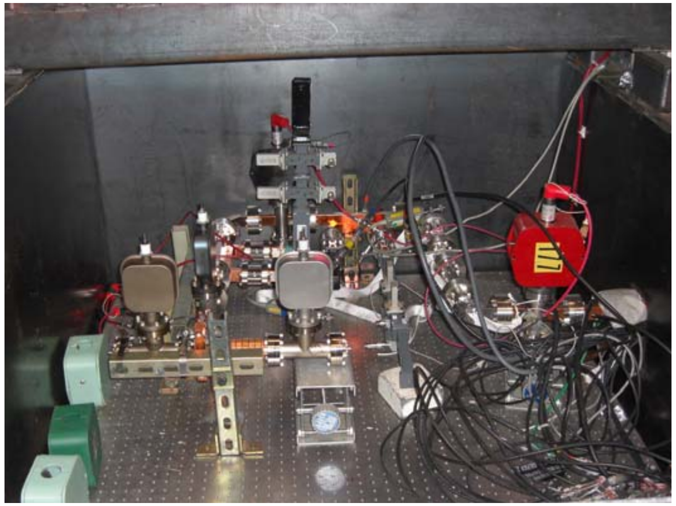
Name	A2.75-T2.0-Cu	A3.75-T1.66-Cu	A3.75-T2.6-Cu	A5.65-T4.6-Choke-Cu	A5.65-T4.6-Cu	*T53VG3*
Stored Energy [J]	0.153	0.189	0.189	0.333	0.298	*0.09*
Q-value	8.59E+03	8.82E+03	8.56E+03	7.53E+03	8.38E+03	*6.77E+03*
Shunt Impedance [MOhm/m]	102.891	85.189	82.598	41.34	51.359	*91.772*
Max. Mag. Field [A/m]	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*

Surface processing

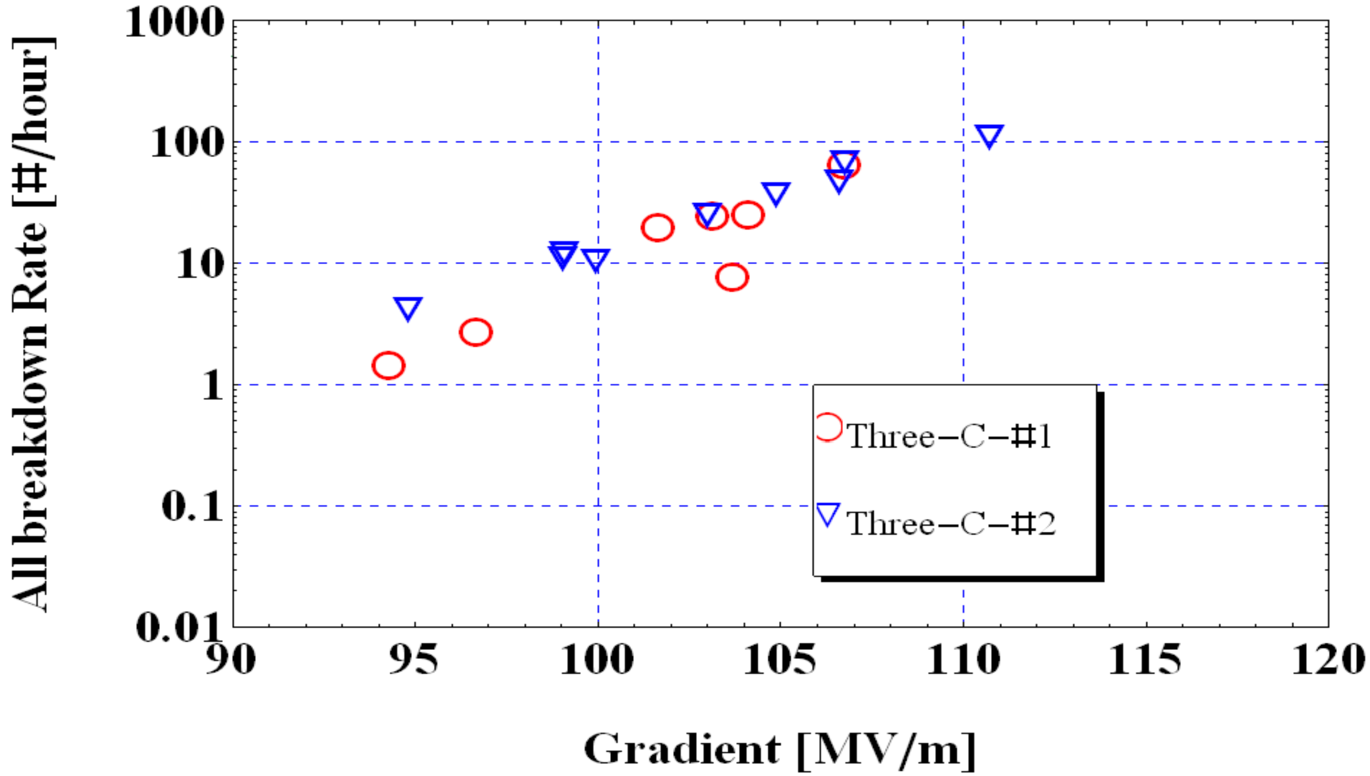
A special structure was built and processed (with best cleaning and surface processing we can master) at KEK and hermetically sealed, then assembled at SLAC at the best possible clean conditions

Dr. Yasuo Higashi and Richard Talley assembling Three-C-SW-A5.65-T4.6-Cu-KEK-#2





Two structured #1 processed normally and #2 processed similar to superconducting accelerator structures

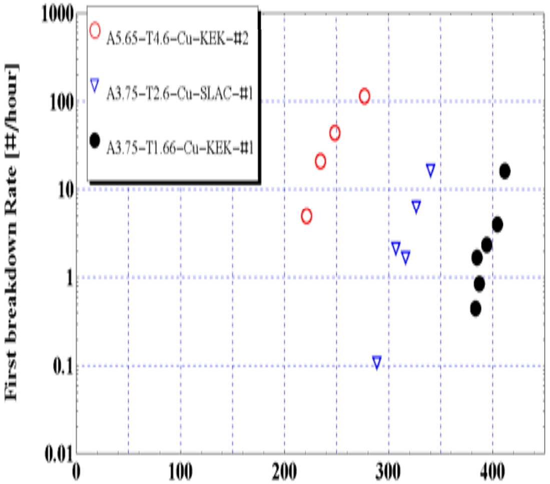


The near perfect surface processing affected only the processing time. The second structure processed to maximum gradient in a few minutes vs few hours for the normally processed structure.

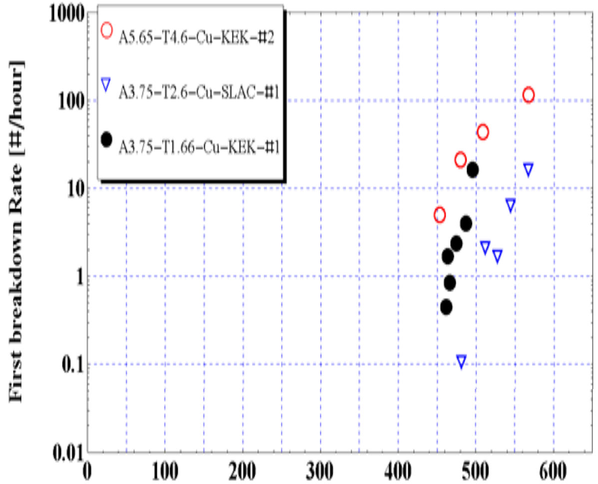
Geometrical Studies

3 different single cell structures: Standing wave structures with different iris diameters and shapes; a/λ=0.21, a/λ=0.14 and a/λ=0.14 and elliptical iris.

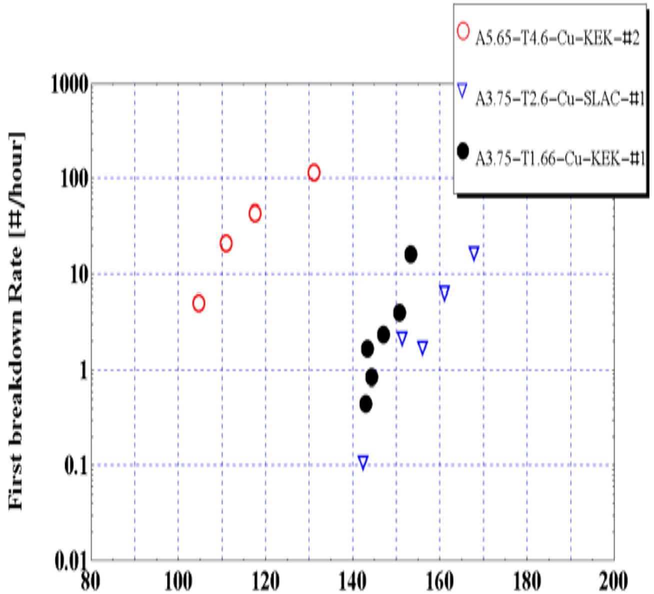
Global geometry plays a major role in determining the accelerating gradient, rather than the local electric field.



Maximum surface electric fields [MV/m]

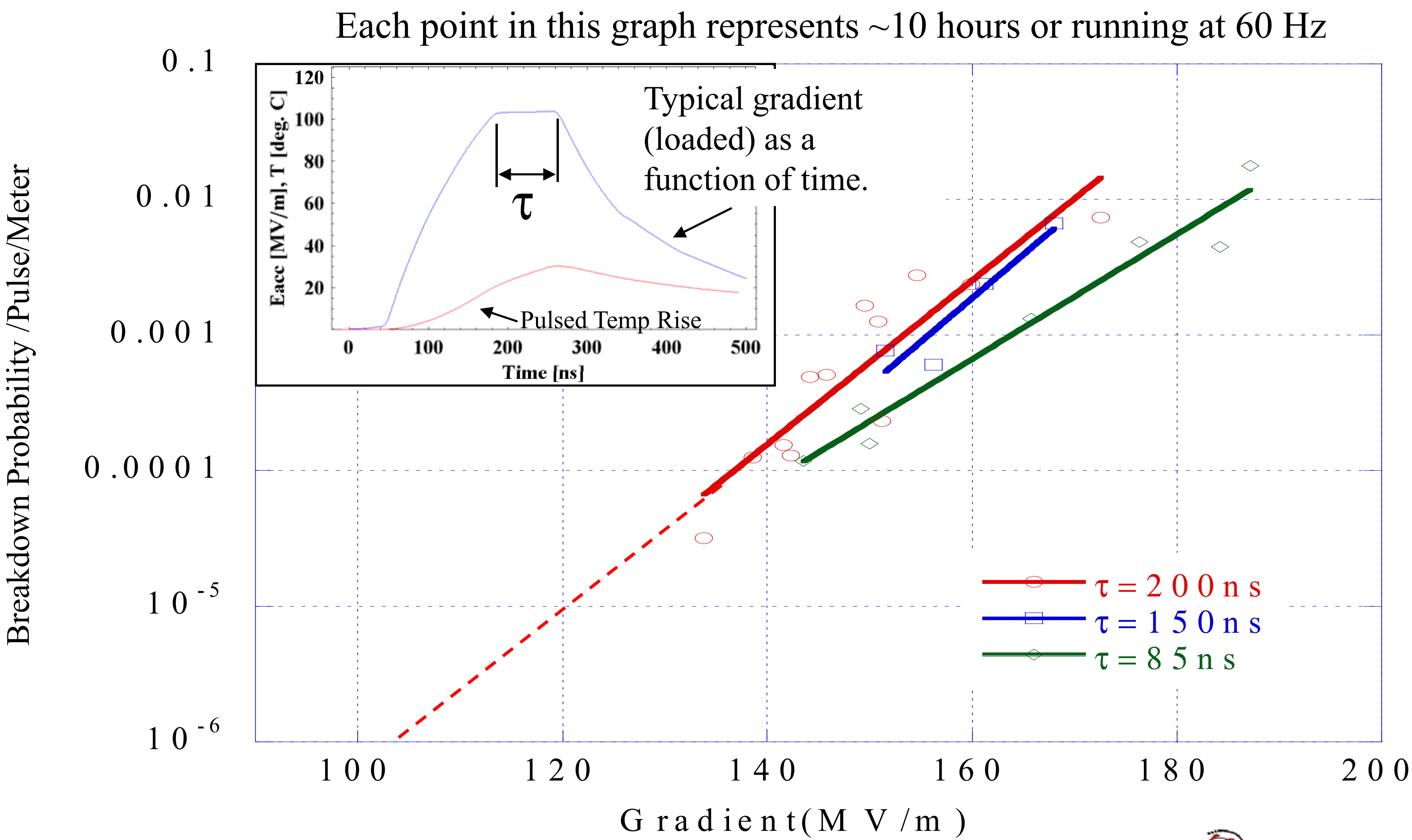


Maximum surface magnetic fields [kA/m]

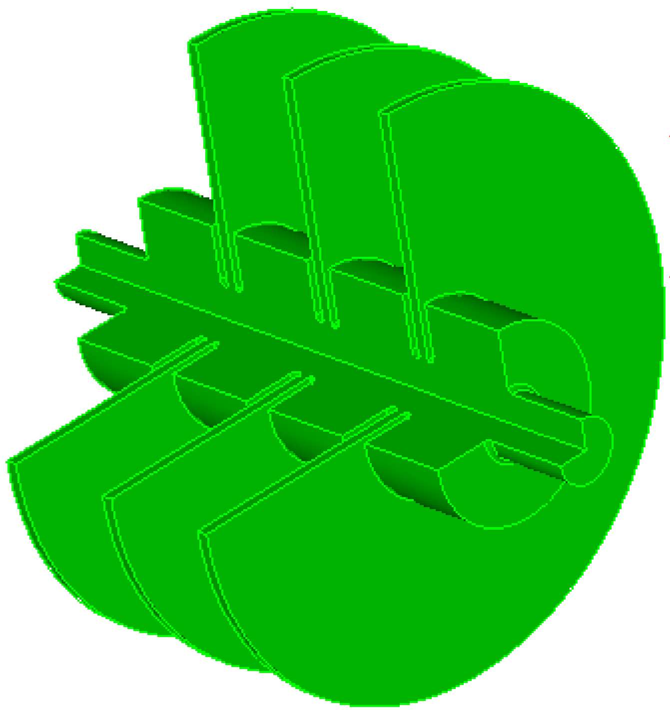


Accelerating fields [MV/m]

Standing-Wave Accelerator Structure Recent Results (a/λ~0.14)



“Iris slot” type structure



- The idea of this structure is to feed each cell directly from one of four feeds, which will hopefully increase the gradient based on single cell results.
- An slot is located in the center of each iris, which splits the iris into two parts.
- An HOM load made from a cylindrical absorber is located on the outer radius of the slot.

Effect on fundamental mode

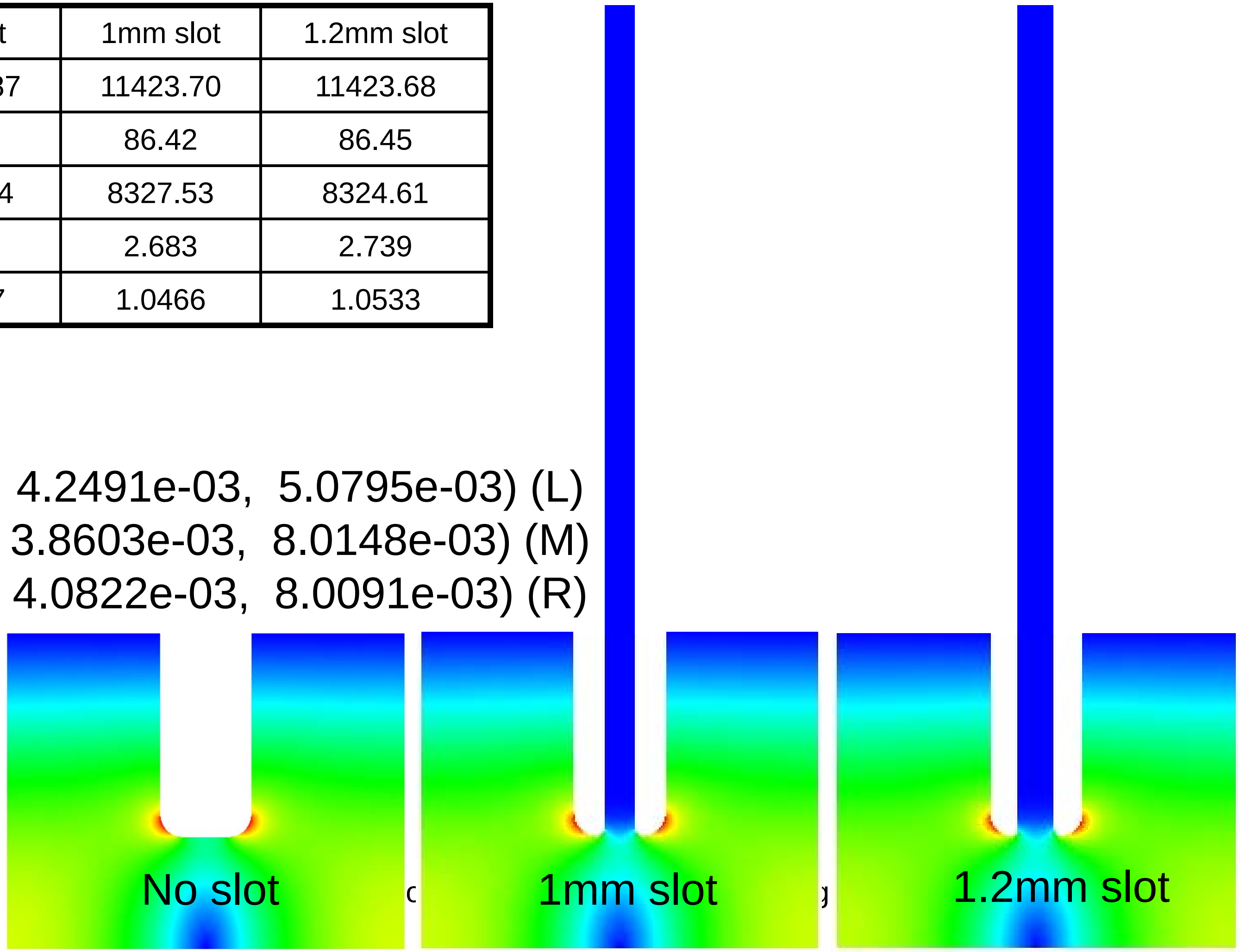
Iris thickness: 3mm
Length of 1 period: 13.12mm

	No slot	1mm slot	1.2mm slot
Freq / MHz	11423.87	11423.70	11423.68
R / Mohm/m	87.24	86.42	86.45
Q	8326.74	8327.53	8324.61
Es/Ea	2.665	2.683	2.739
k / %	0.9557	1.0466	1.0533

Regular Cell

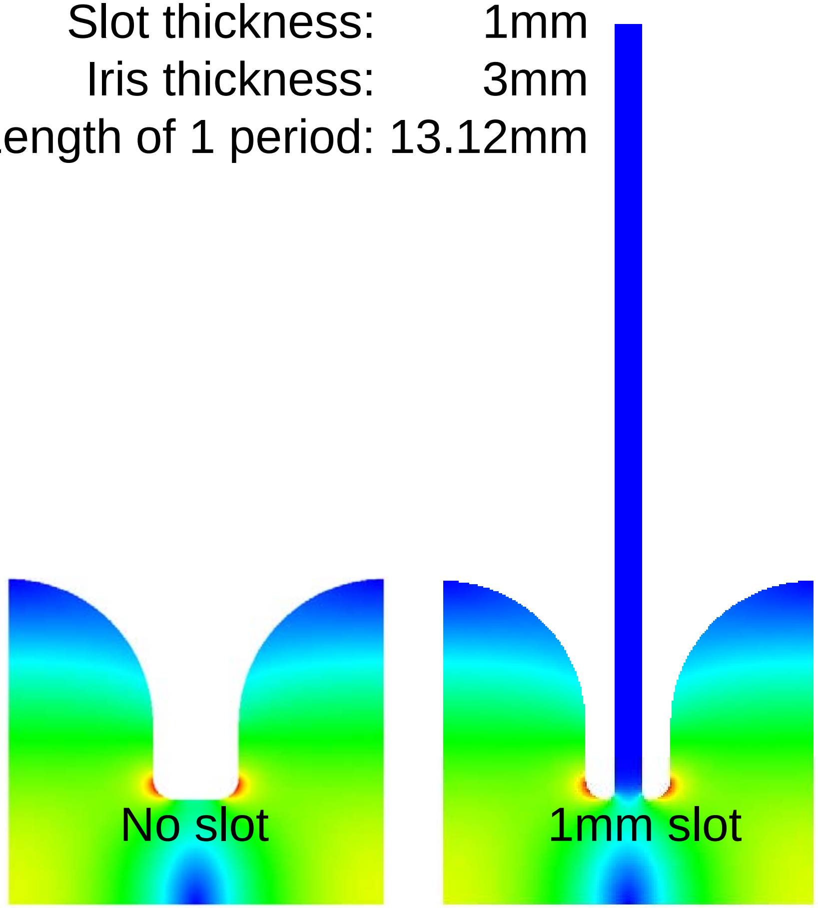
Slot has no big effect on FM mode.

Esmax @ (1.9819e-04, 4.2491e-03, 5.0795e-03) (L)
Esmax @ (1.5699e-03, 3.8603e-03, 8.0148e-03) (M)
Esmax @ (4.9067e-04, 4.0822e-03, 8.0091e-03) (R)



Cell shape optimization

Slot thickness: 1mm
Iris thickness: 3mm
Length of 1 period: 13.12mm



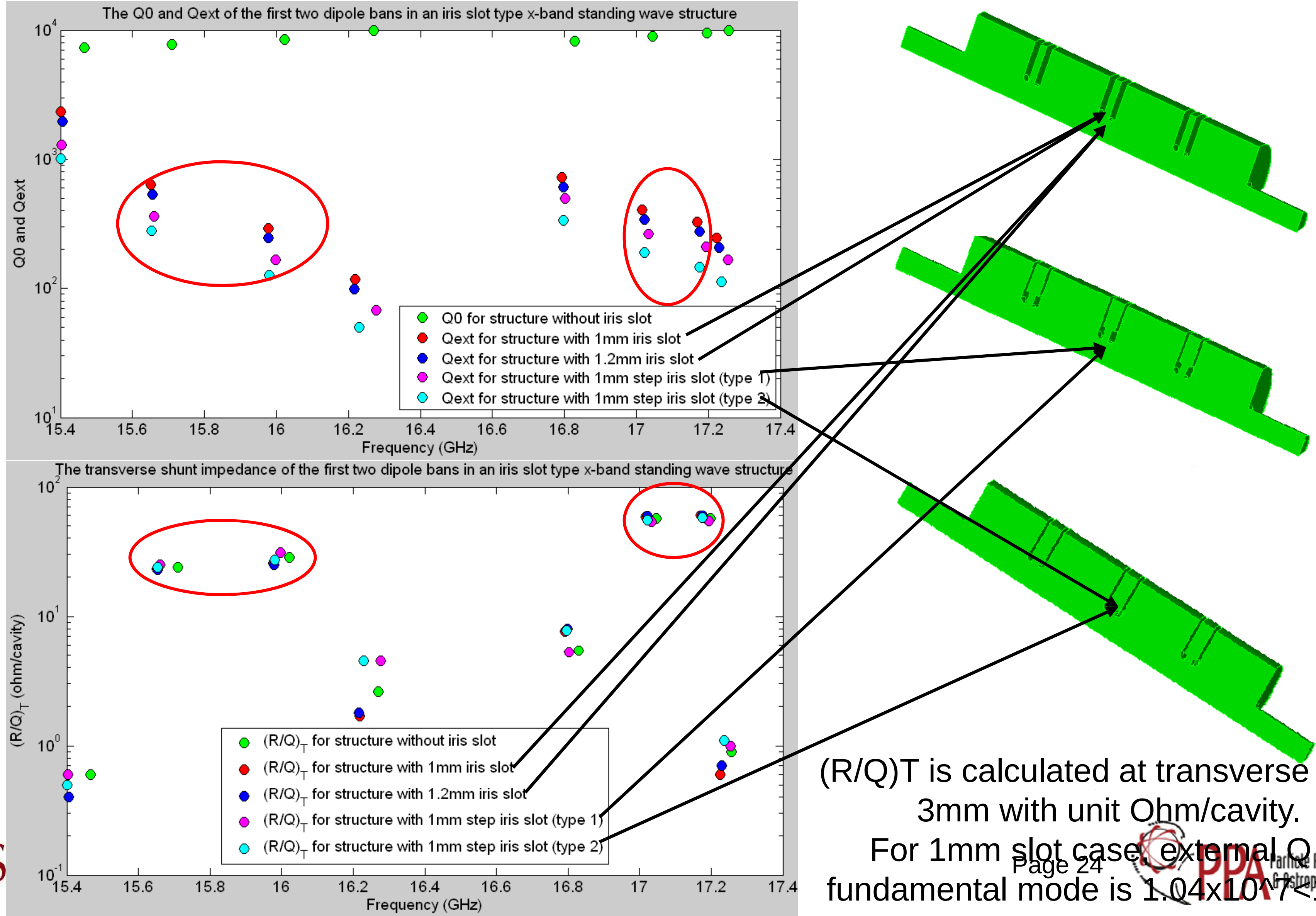
Regular Cell

One way to further increase impedance.

	No slot	With slot
Freq / MHz	11423.84	11423.74
R / Mohm/m	97.28	96.39
Q	9521.69	9523.13
Es/Ea	2.607	2.634
k / %	0.9142	1.0014

Esmax @ (1.9404e-04, 4.1523e-03, 8.0109e-03) (L)
Esmax @ (5.0545e-04, 4.0949e-03, 7.9984e-03) (R)

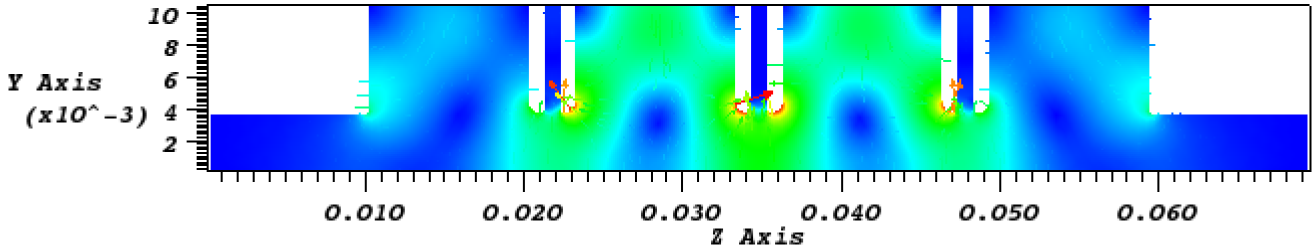
Effect on HOM damping



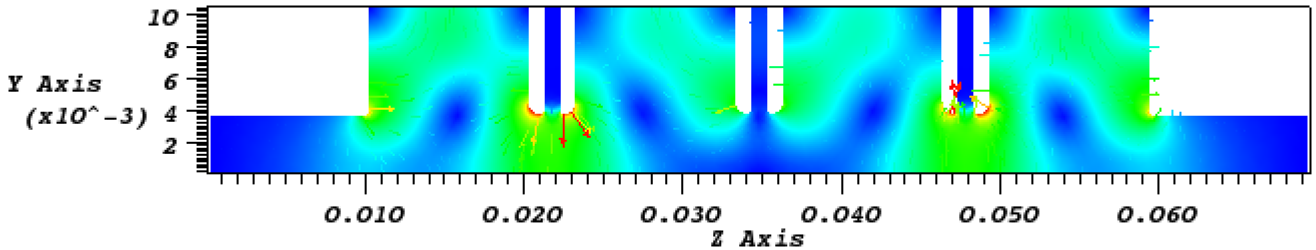
(R/Q)T is calculated at transverse offset 3mm with unit Ohm/cavity.
For 1mm slot case, external Q of fundamental mode is 1.04x10^7<10^8.

Effect on HOM damping

Dipole mode 3rd band TM111
With 1mm slots for 4-cell structure

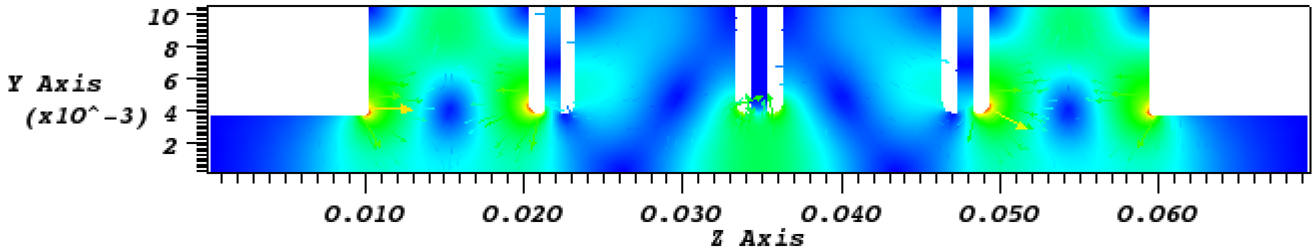


20945.63MHz
Q0: 6033.37
Qext: 9311.37
(R/Q)T=59.16

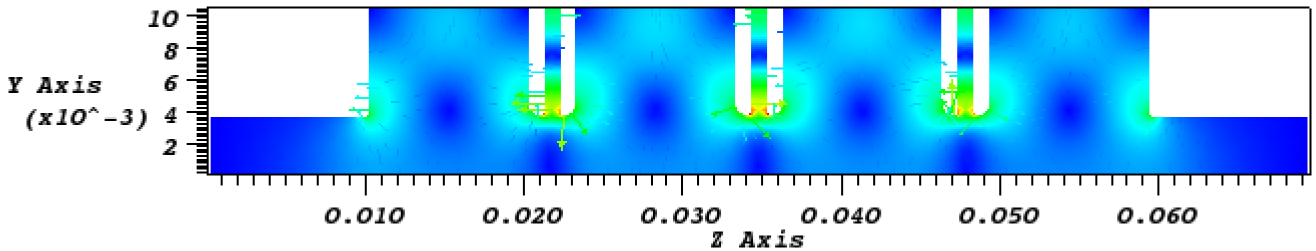


21194.28MHz
Q0: 6270.86
Qext: 1969.58
(R/Q)T=16.54

Not damped

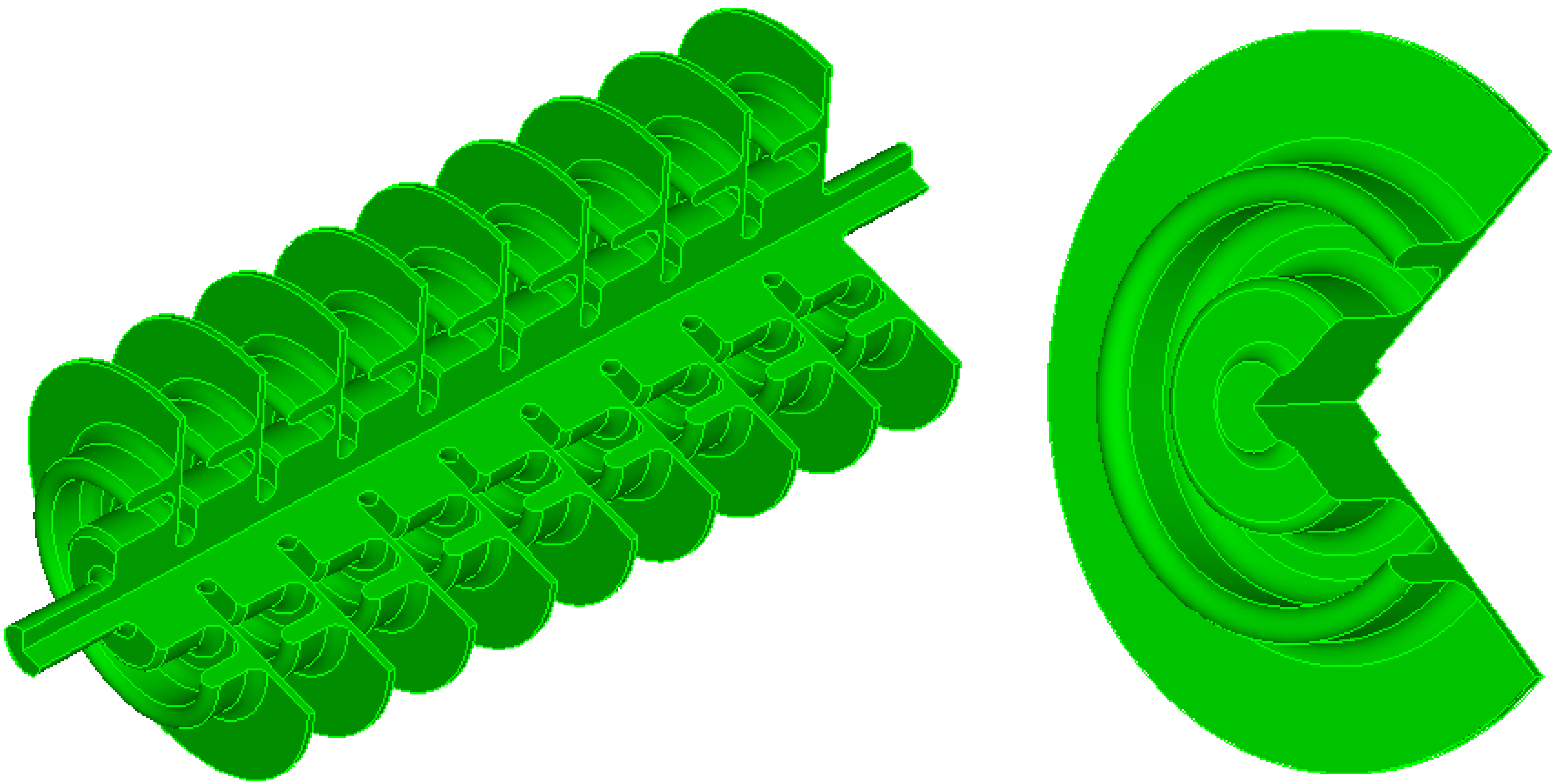


21582.90MHz
Q0: 6578.54
Qext: 604.94
(R/Q)T=7.37



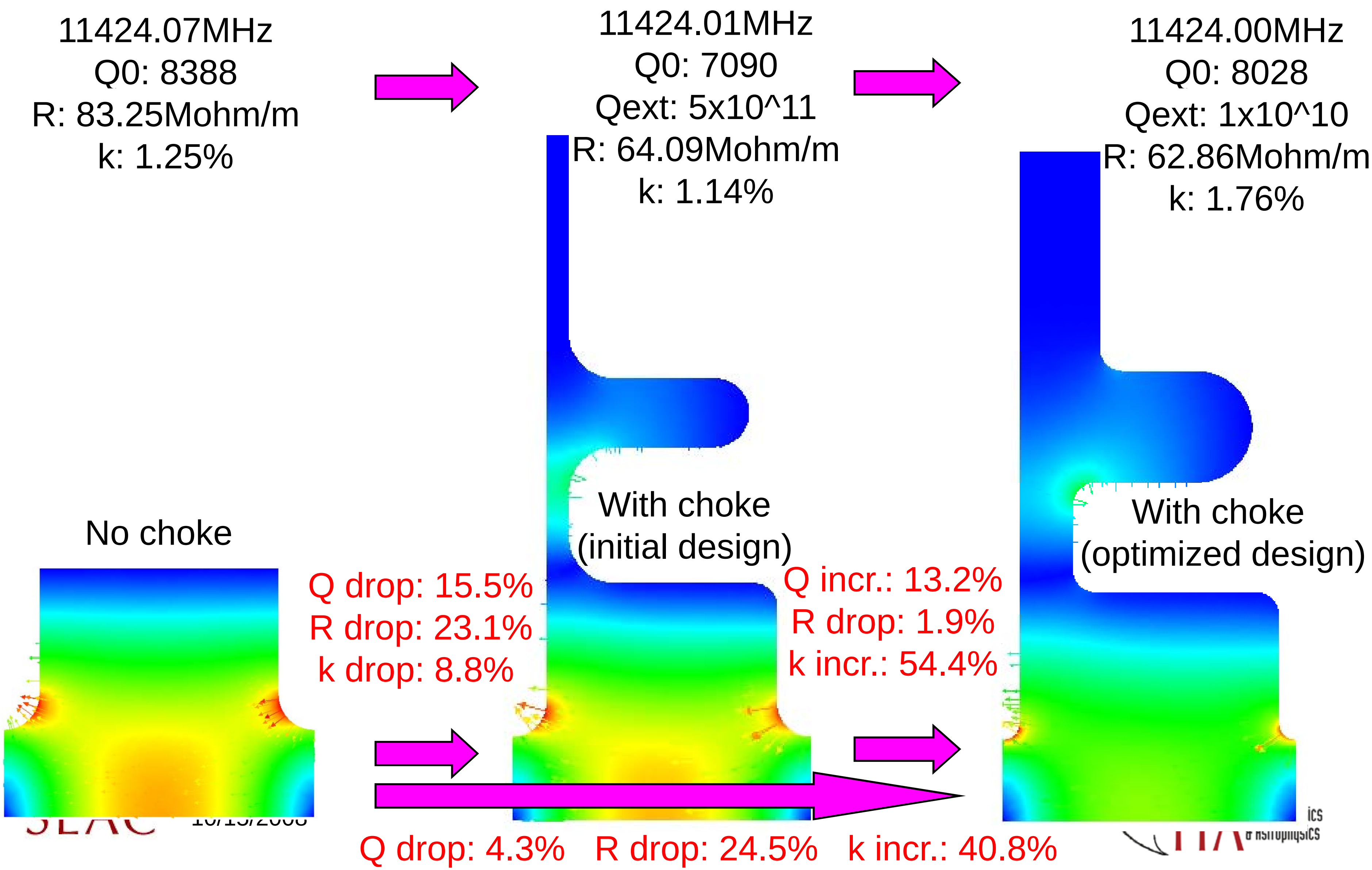
21969.83MHz
Q0: 7004.62
Qext: 214.60
(R/Q)T=0.54

"Choke mode" structure



We pick 9 cell structure for our study, the real case maybe different.

Effect on fundamental mode

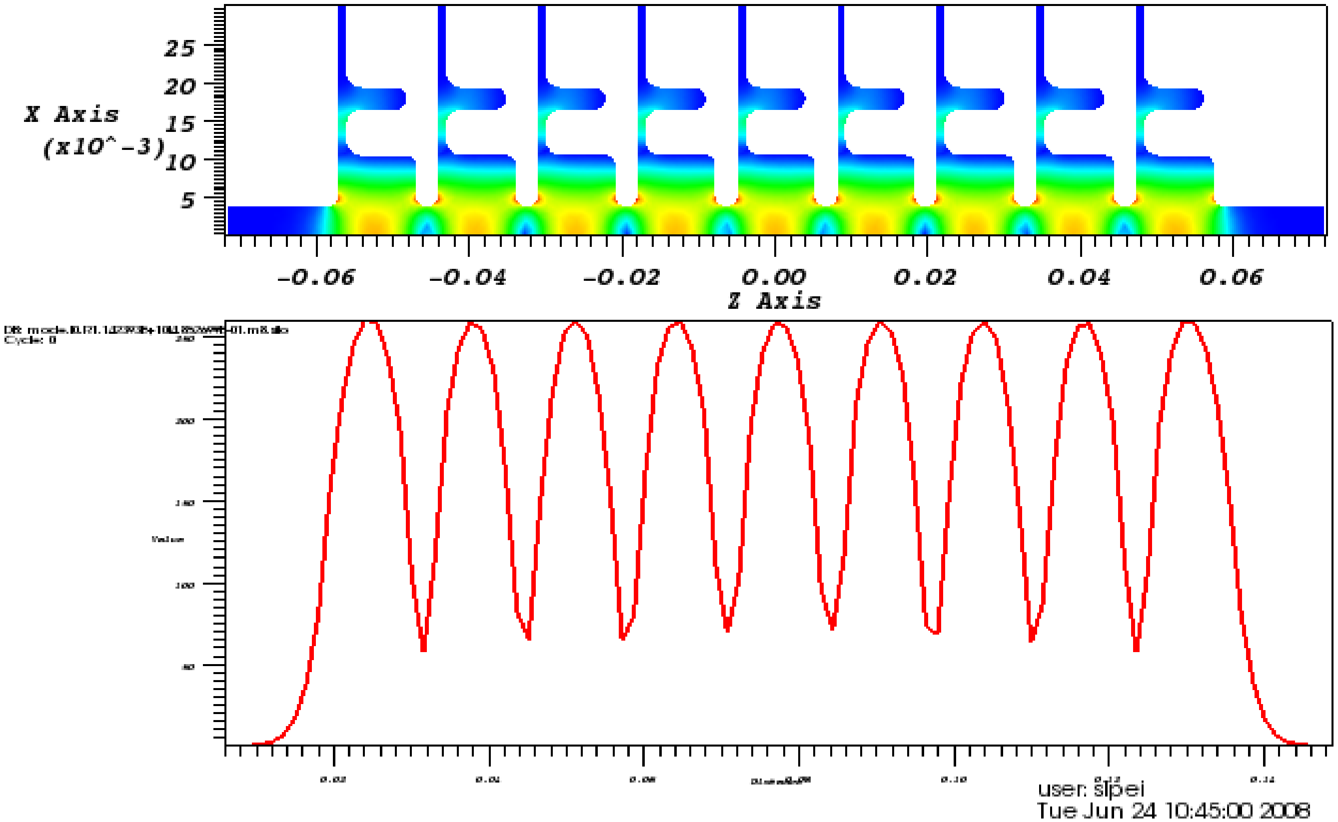


Effect on fundamental mode

Due to the nonsymmetrical feature of the choke mode structure, in order to get one flat axis electric field pattern, the left and right end cells need to have different dimensions, which will result in redundant modes.

11423.93MHz, Q0: 7081, Qext: 1.2x10^10, Reff: 64.14Mohm/m

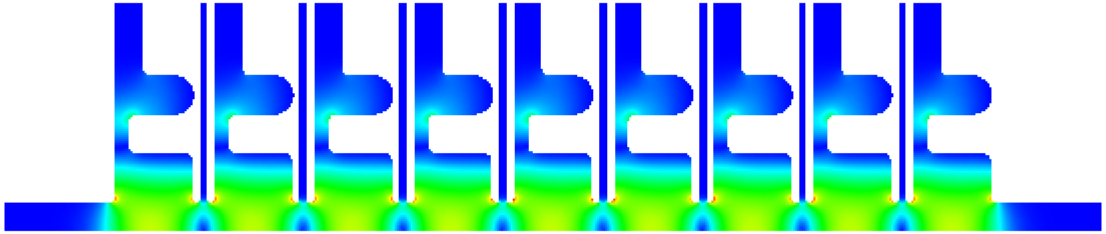
9cell choke mode structure (initial design)

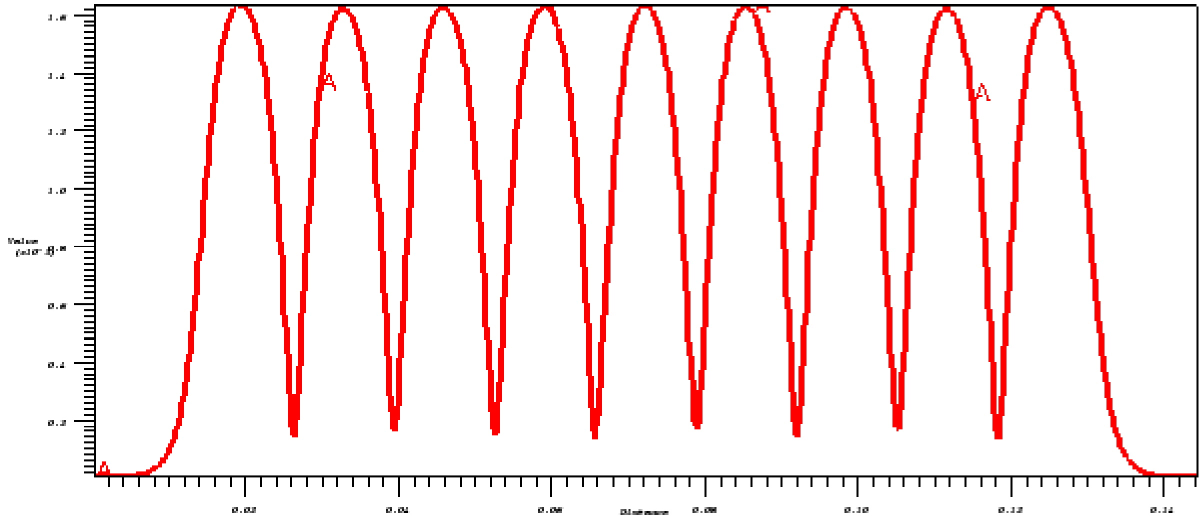


Hybrid structure

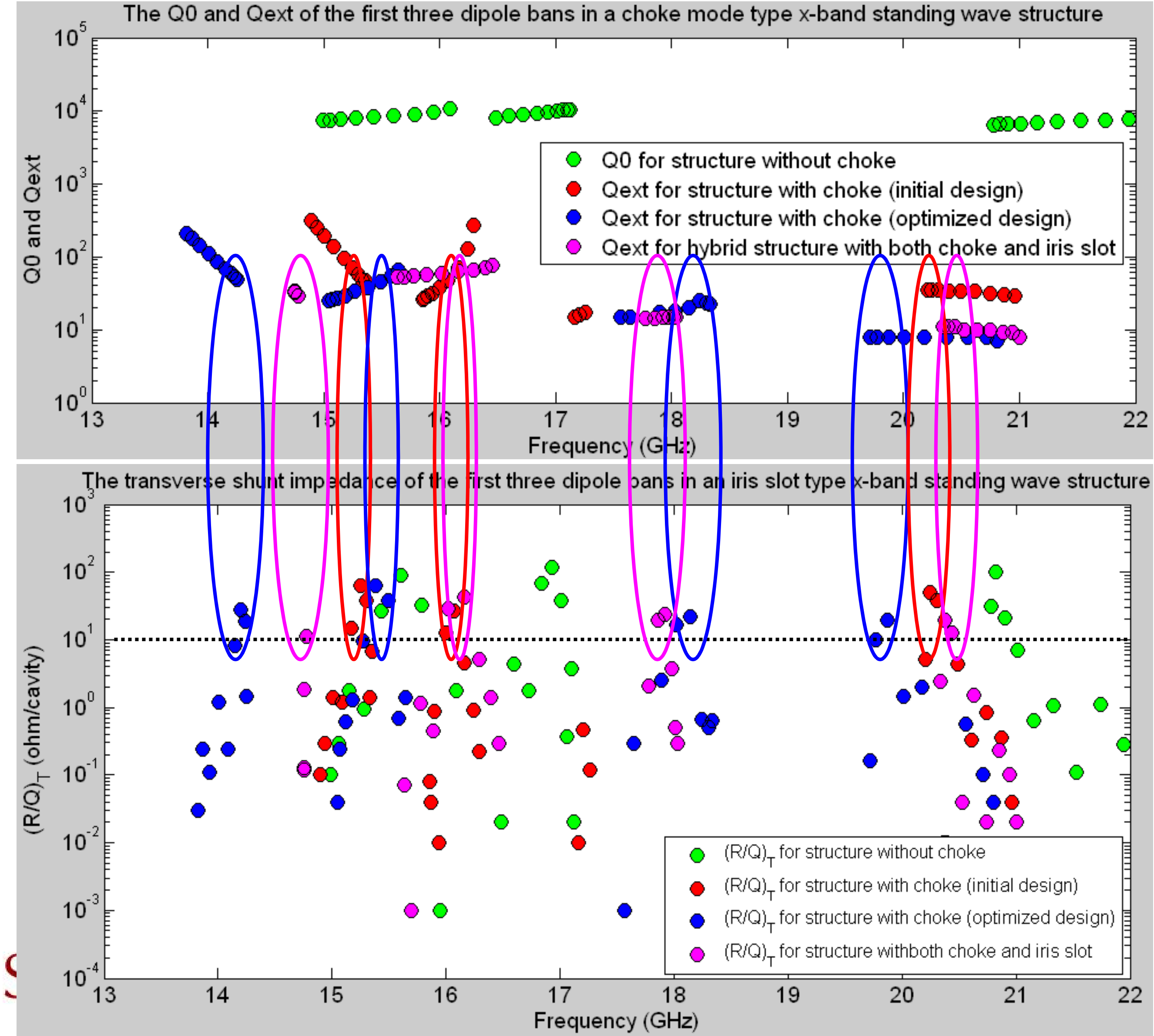
Besides the “iris slot” and “choke mode” structure, the hybrid structure with both “iris slot” and “choke” is also looked.

11423.60MHz, Q0: 7220, Qext: 1.4x10^6, Reff: 62.99Mohm/m





Effect on HOM damping



Modes in the first 3 dipole bans are shown, but the non-symmetric feature of the structure results in redundant modes, whose field pattern is difficult to identify.

In general, hybrid structure has lowest dipole modes' Qext. However, there is no much benefit, and the Qext of fundamental (FM) mode is also the lowest, which might be a problem.

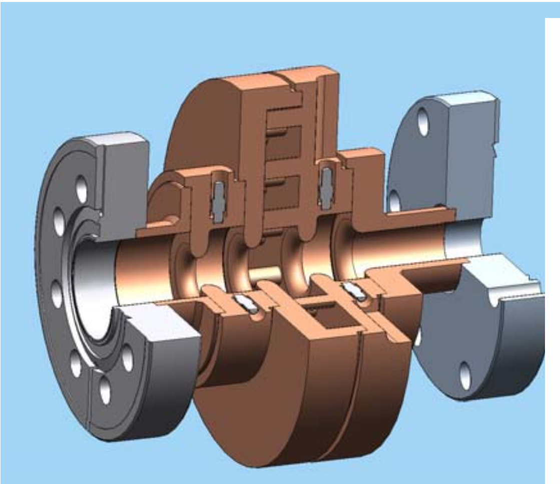
PPA Particle Physics & Astrophysics

Summary

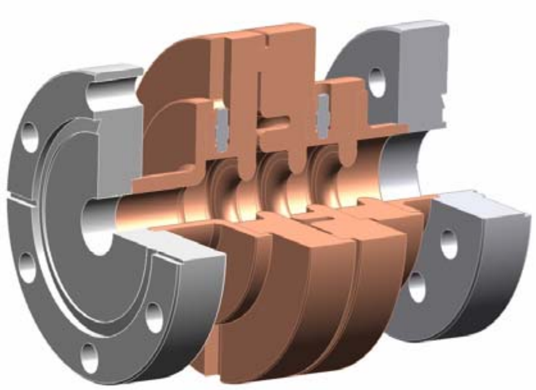
* For “iris slot” structure, slot has little effect on FM mode properties and the lowest Qext of dipole mode with high $(R/Q)_T$ is 100-300. Particular higher band modes (e.g. 1^{st} & 2^{nd} mode in 3^{rd} band) with high $(R/Q)_T$ are not damped.
* For “choke mode” structure, FM mode R and Q0 are lowed by 5-25% and Qext of dipole modes with high $(R/Q)_T$ is 10-70 (nearly all of the dipole modes can be damped). However, modes exist in the choke joint with high Q, which need to be considered.
* To further suppress the dipole modes, detuning needs to be used as well.

Structure modifications for wake field damping

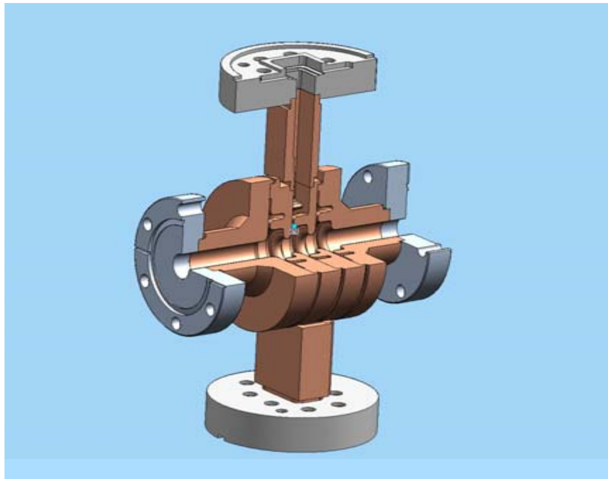
- CERN is pursuing side slotted structures (to be tested soon at NLCTA)
- MIT PBG Structure (Mechanical Design Done, submitted to shop)
- Choked structures has been manufactured and is currently under test.
- Side fed structures will pave the way to parallel fed structures with gradients above 140 MV/m (currently being manufactured)
- Other methods of damping are being studied theoretically.



PBG Structure



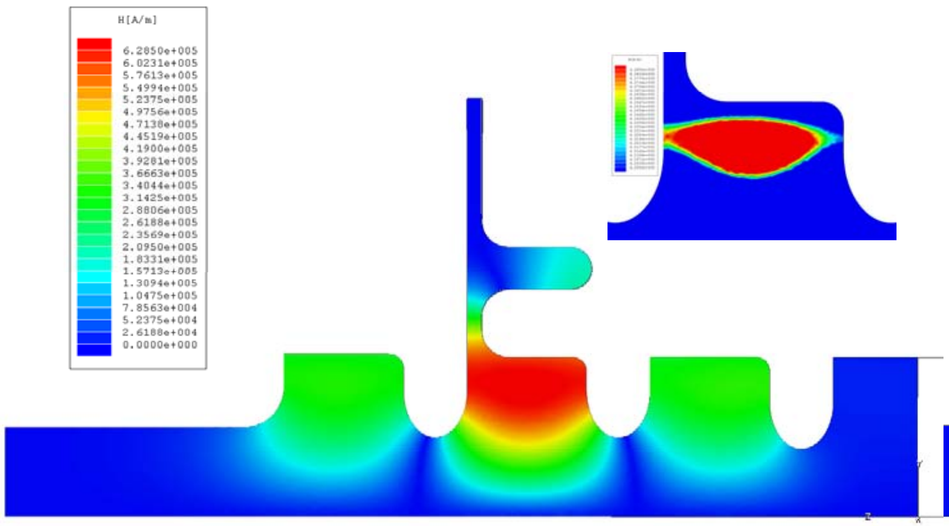
Choke Structure

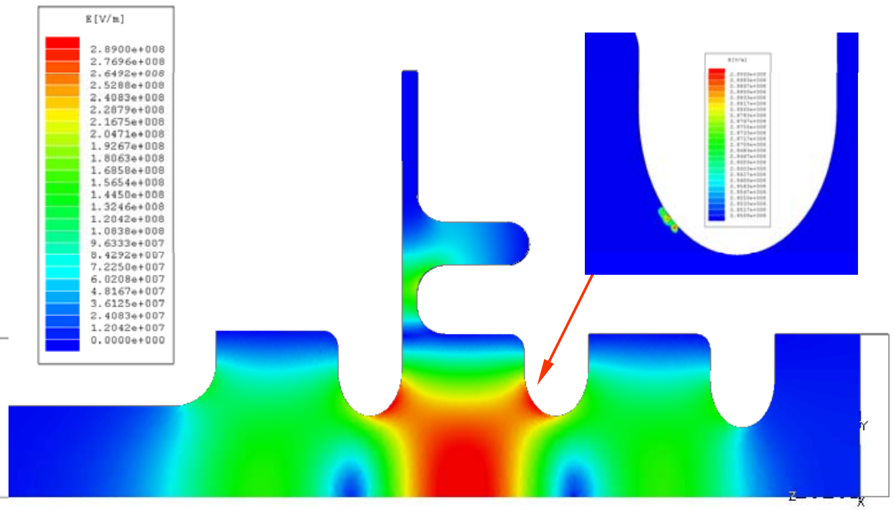


Choke structure with side feed

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

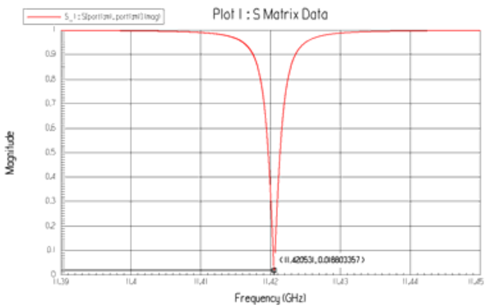
10 MW input

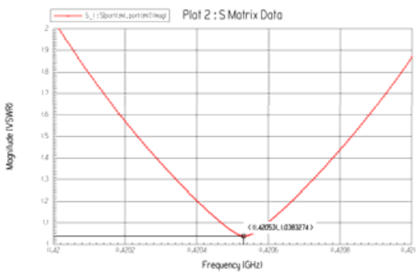


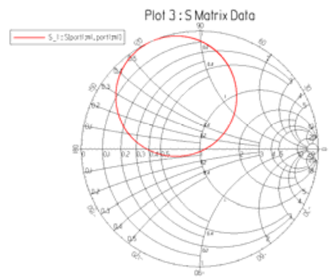


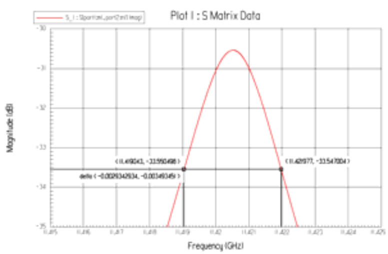
Maximum magnetic field 628.5 kA/m
(SLANS 627.5 kA/m)

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









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

Resonance at 11.42053 GHz (SLANS 11.424 GHz)

β = 1.03832 (SLANS 1.045)

Over-coupled loaded Q

Unloaded Q=7,933 (SLANS 7,933.5)

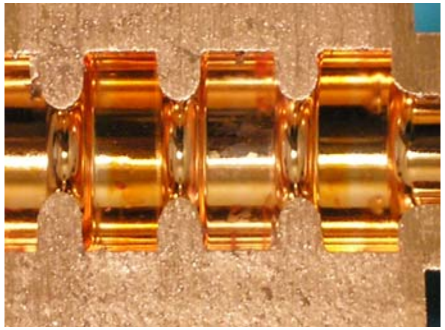
$$\frac{11.42053}{0.00293429}\cdot(1+1.03832) = 7{,}933\times 10^{3}$$

V.A. Dolgashev, 25 September 2007

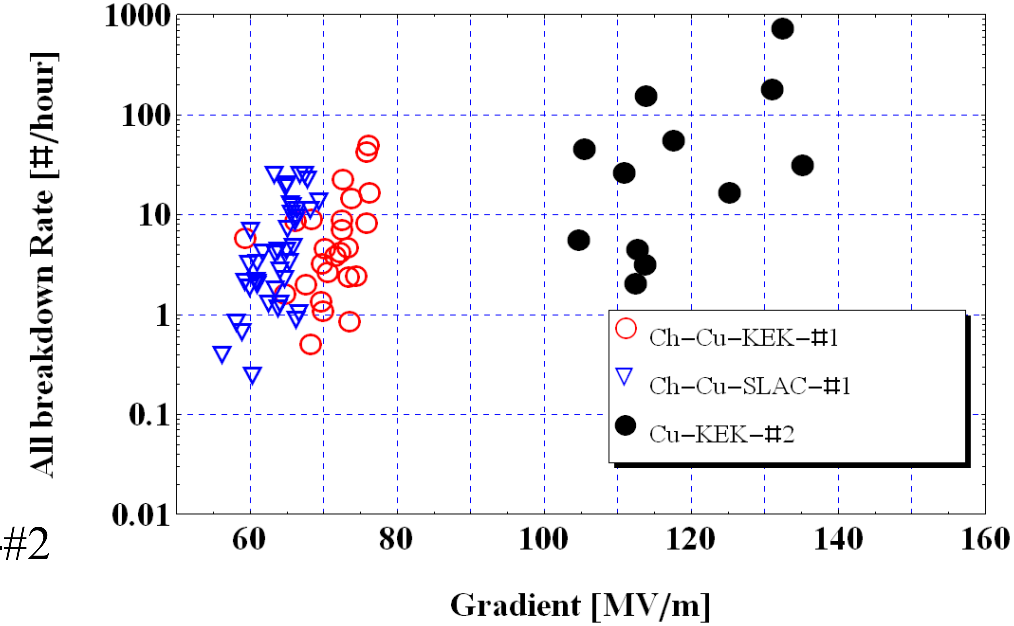
1C-SW-A5.65-T4.6-**Ch**-Cu-SLAC-#1

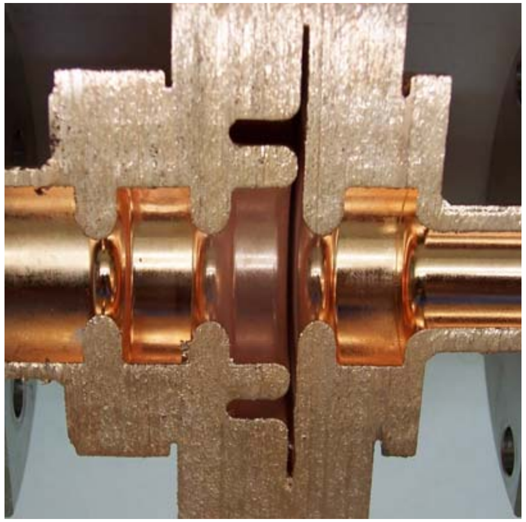
1C-SW-A5.65-T4.6-**Ch**-Cu-SLAC-#1

Choke *vs.* no Choke

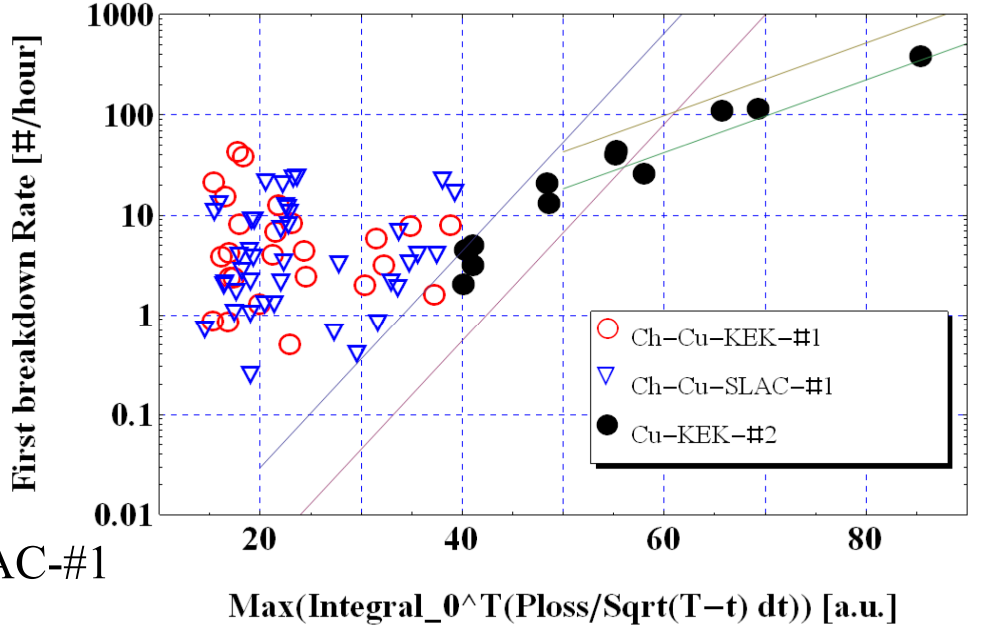


1C-SW-A5.65-T4.6-Cu-KEK-#2





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



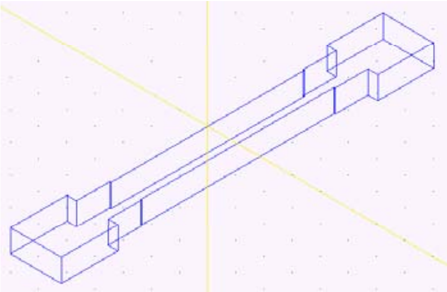
Waveguide high gradient study

Goals:

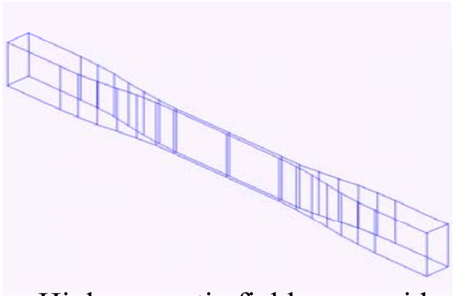
•***RF breakdown vs. geometry (low magnetic field waveguide vs. high magnetic field waveguide); same electric field for same peak power and surface area***

•Different materials: copper, gold , stainless steel, molybdenum

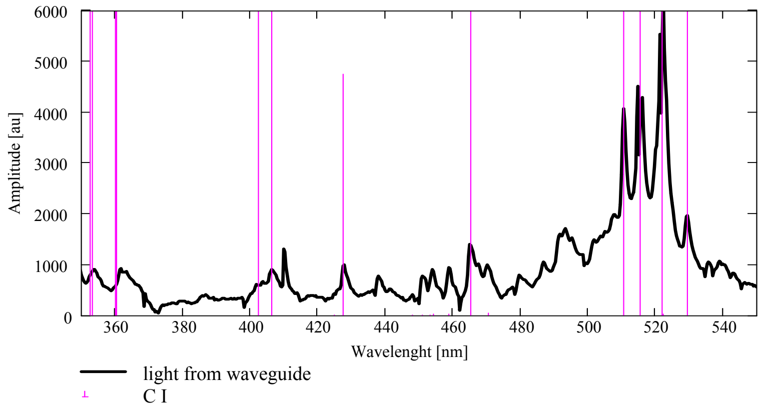
•3D Particle-In-Cell simulations of the breakdown dynamics



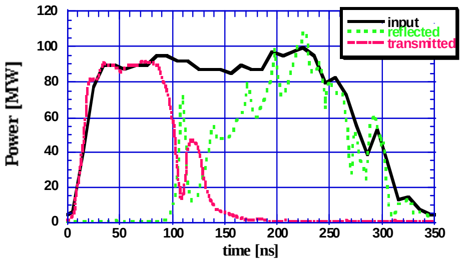
Low magnetic field waveguide, height 10 mm



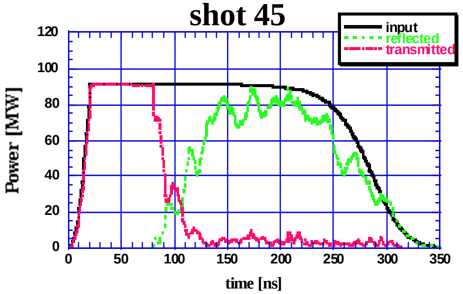
High magnetic field waveguide, height 1.3 mm



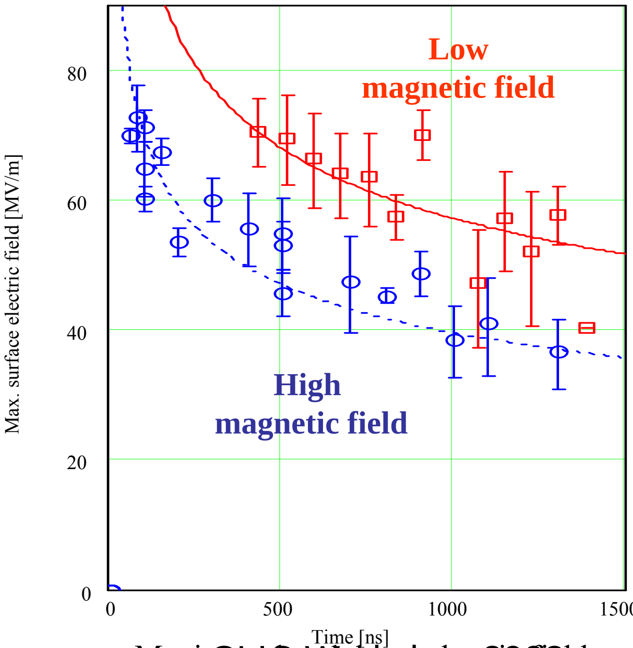
Light spectrum measured during breakdowns in copper waveguide



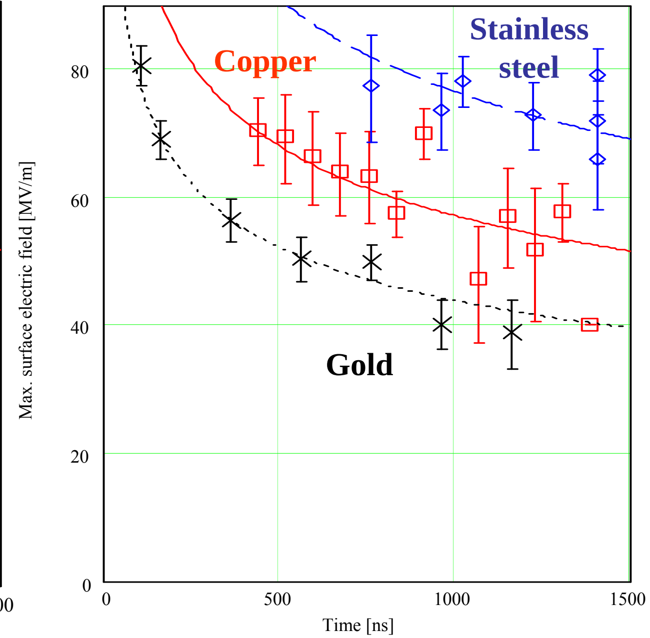
Measurements, 24 April 2001,18:13:40, shot 45



3D PIC simulations, 4x4 mm emitting spot, electron current 7kA, copper ion current 30A



Maximum breakdown electric fields copper waveguide of different geometries

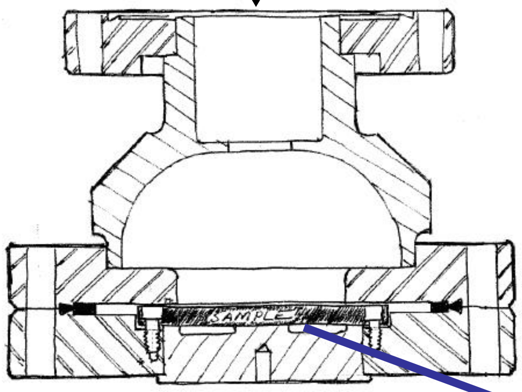


Maximum breakdown electric fields for different materials

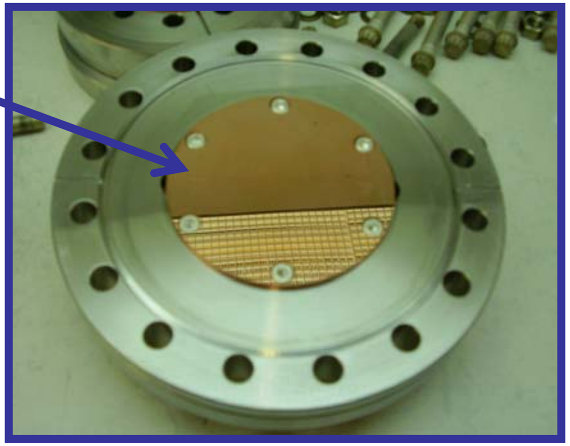
Pulse Heating Experimental Testing at SLAC

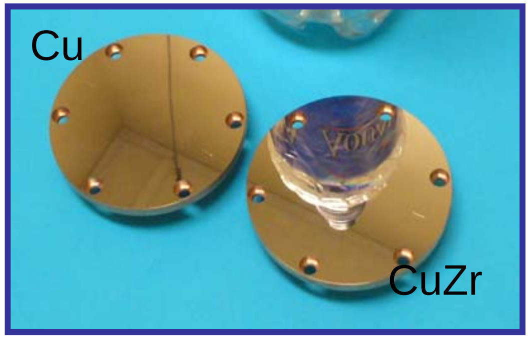
High Gradient Collaboration: SLAC, CERN, KEK

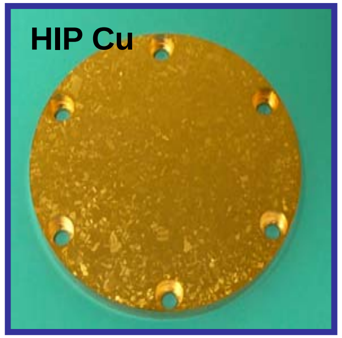
Pin



3-inch diam. pulse heating sample





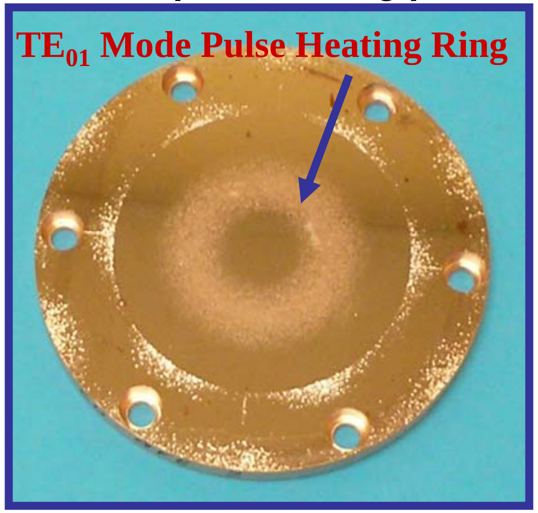


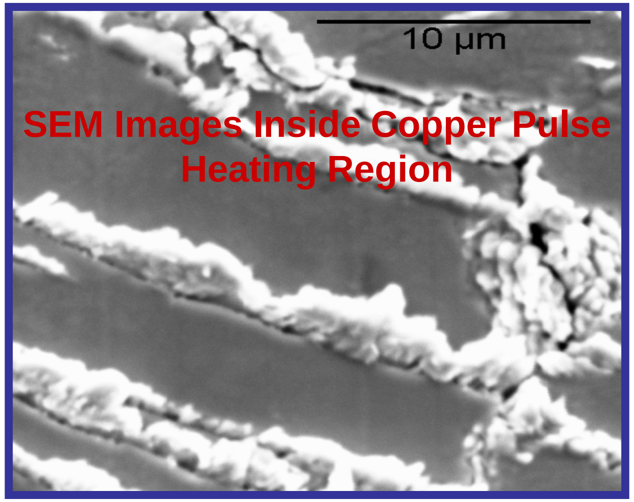
L. Laurent

Material Testing (Pulsed heating experiments)

Special cavity has been designed to focus the magnetic field into a flat plate that can be replaced.

Max Temp rise during pulse = 110°C





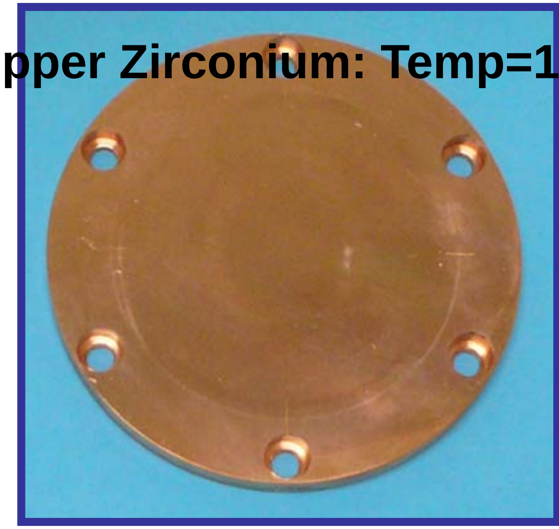
Metallography: Intergranular fractures 500X

* Economical material testing method
* Essential in terms of cavity structures for wake field damping
* Recent theoretical work also indicate that fatigue and pulsed heating might be also the root cause of the breakdown phenomenon

Results from Pulsed Heating Experiments

Copper: Temp=110ºC

Copper Zirconium: Temp=100ºC

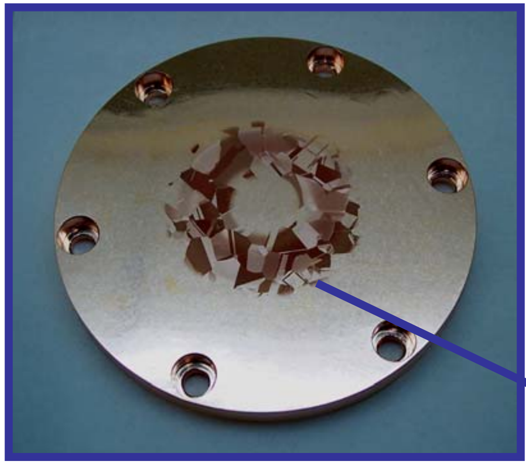


Ultra pure HIP Copper: Temp=100ºC

Ultra pure Copper: Temp=100ºC

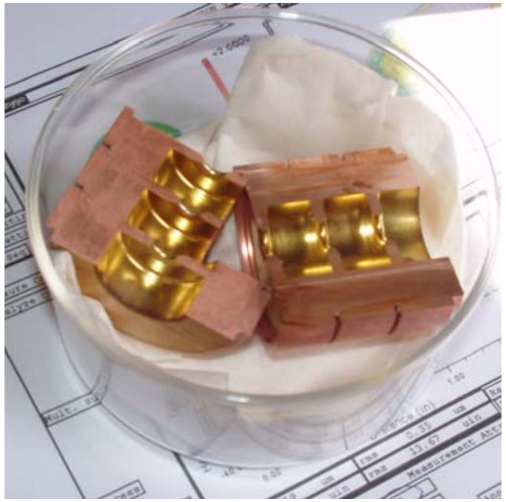
KEK3 (Etched & H2 Fired):

Pulse Heating Temp = 110^{o}C

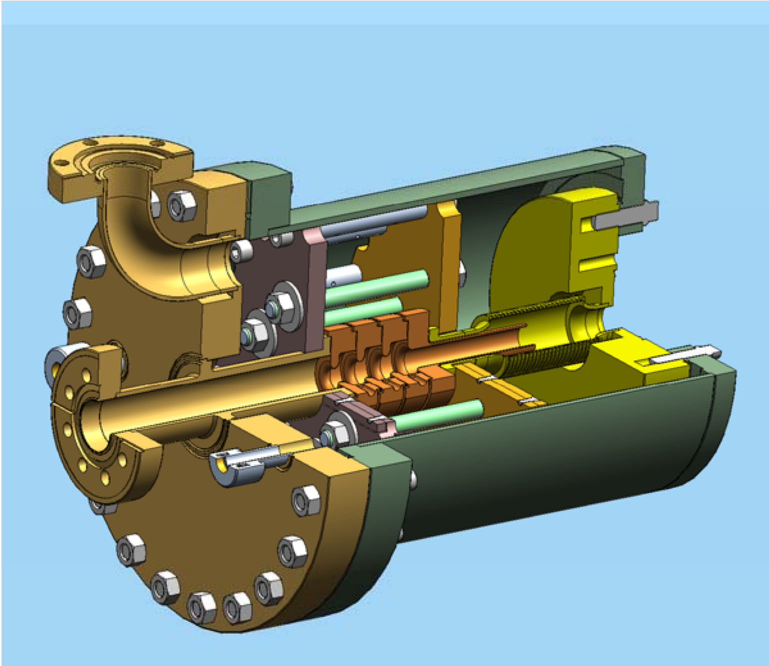


Material Studies

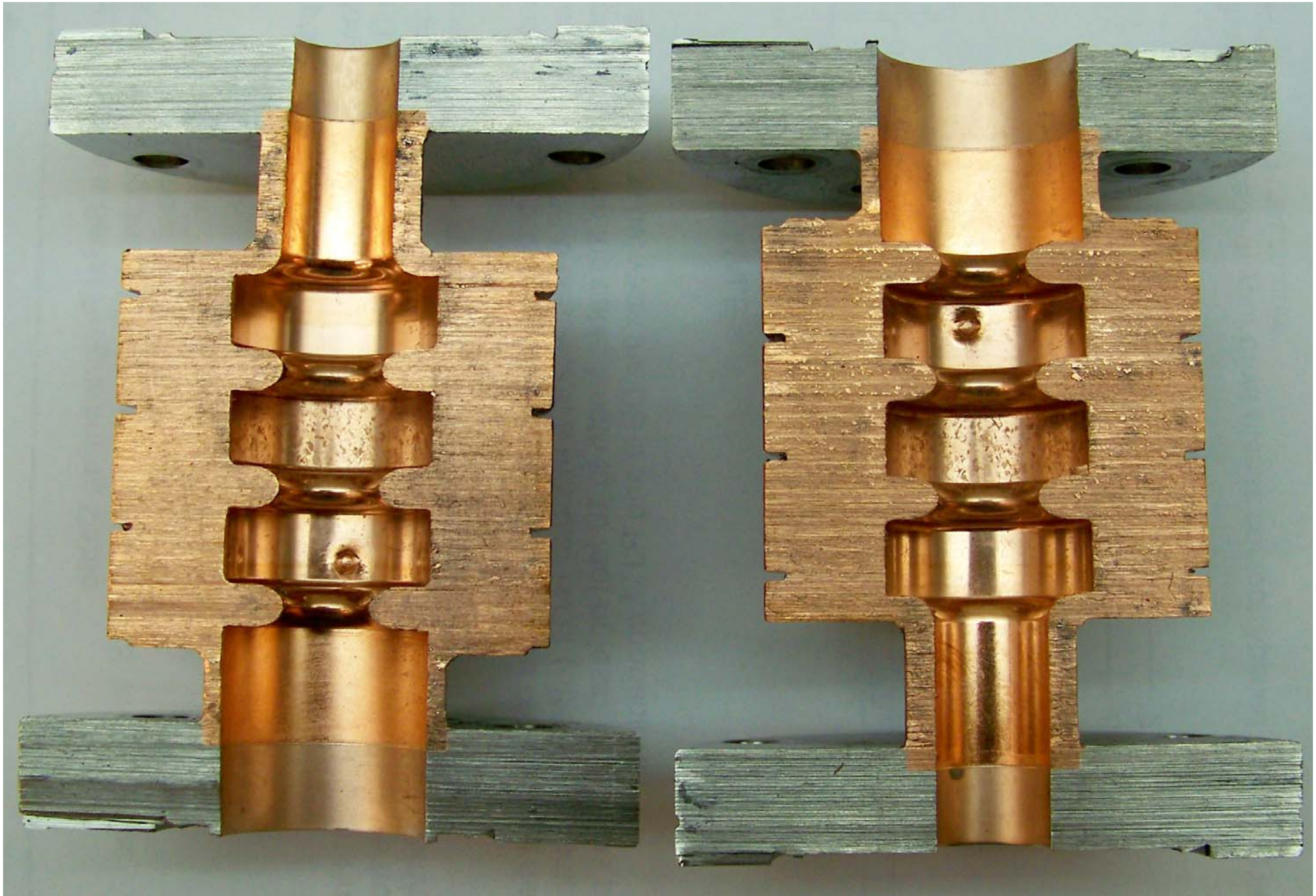
* Clamping Structure for testing copper alloys accelerator structure (Mechanical Design Done, submitted to shop)



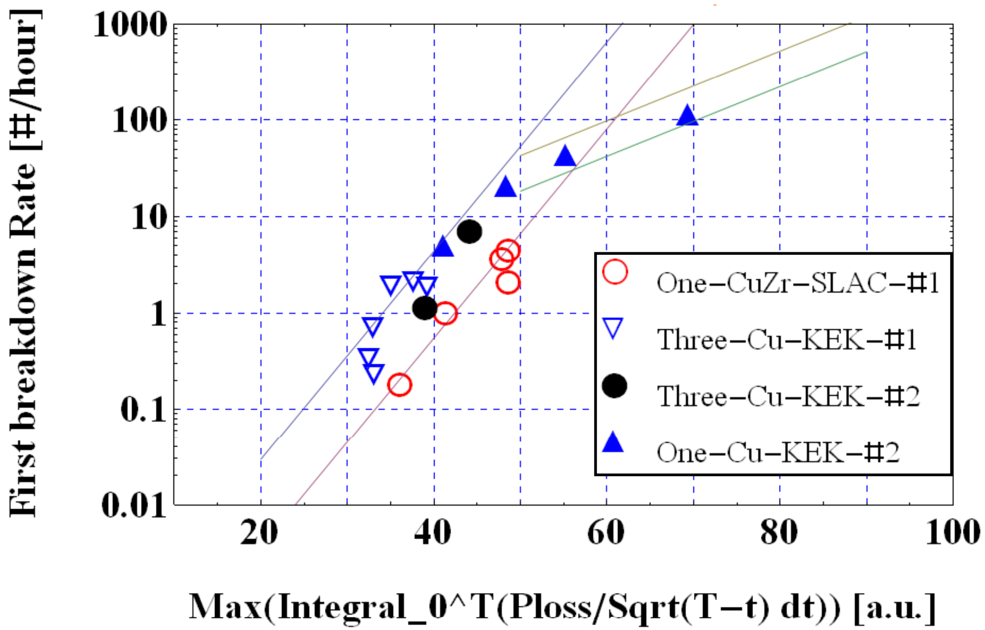
Diffusion bonding and brazing of copper zirconium are being researched at SLAC.

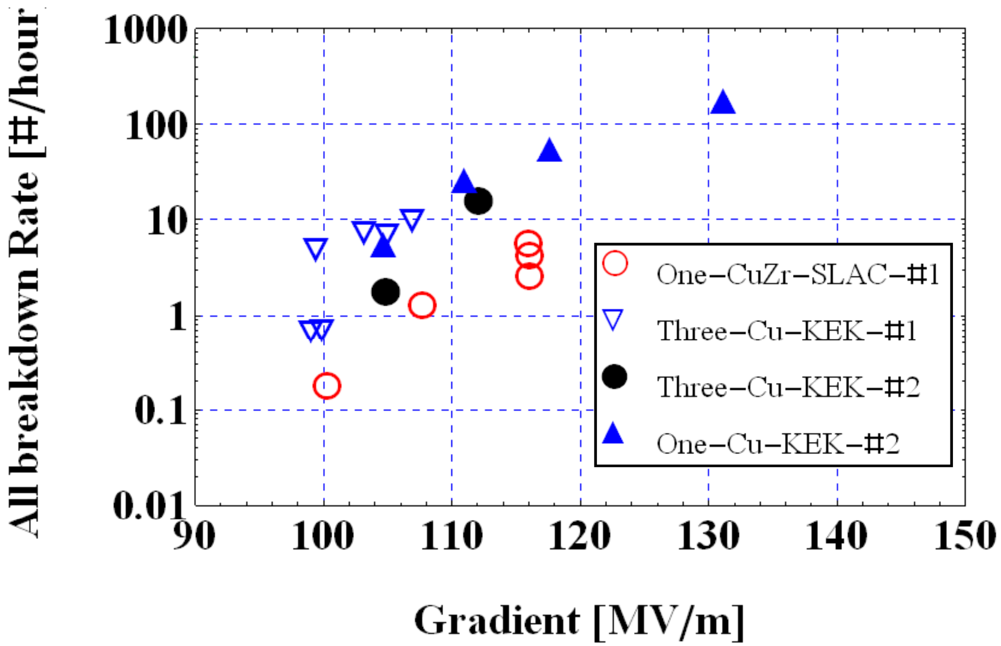


The clamped structure will provide a method for testing materials without the need to develop all the necessary technologies for bonding and brazing them. Once a material is identified, we can spend the effort in processing it.

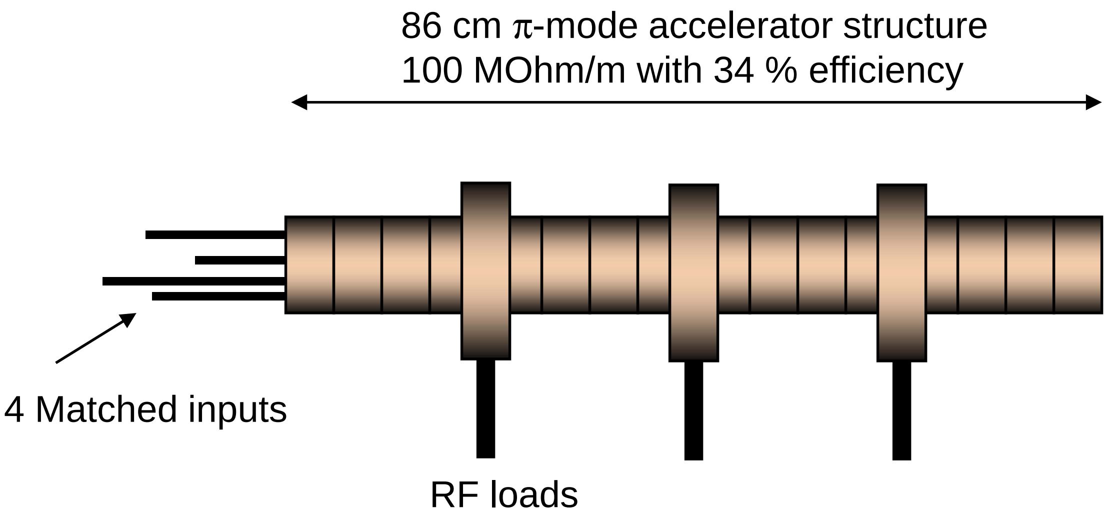


150 ns “shaped pulse”





Future Accelerator Structures



Best possible shunt impedance and efficiency @ a/λ~0.14

Future work/Open Problems

* Full length accelerator structures based on standing wave cells:
  – These are being theoretically designed and modeled. The structure will feature parallel coupling and would look matched like any other traveling wave structure from the outside.
  – we expect to build an 86 cm long structure and test it in 2009.
  – We hope to prove a structure capable of exceeding 140 MV/m gradient
* Wake field damping features are being studied theoretically and experimentally through out the collaboration. This work have just began
* Accelerator structure made of copper alloys are being studied and in 2009 we should start to see some fruits from this effort.
* The effect beam-loading on gradient need to be verified.
* The development of theoretical understanding and Modeling of the RF breakdown phenomena is starting to take shape however, this is still at its infancy and during 2009 we hope that this effort will take off with the help of our collaborator at university of Maryland.
* Ultra High Gradient accelerator structures will be useless without the developments of an efficient RF sources to drive them. The developments of these source has to be given attention in the near future

Summary

* The work being done is characterized by a strong national and international collaboration. This is the only way to gather the necessary resources to do this work.
* SLAC has developed and opened its test facilities for all collaborators
* The experimental program to date has paved the ground work for the theoretical developments.
* With the understanding of geometrical effects, we have demonstrated standing and traveling wave accelerator structures that work above 100 MV/m loaded gradient.
* Standing wave structures have shown the potential for gradients of 150 MV/m or higher
* Further understanding of materials properties may allow even greater improvements
* We still have not demonstrated a full featured accelerator structure including wake field damping. This is expected in the near future

Acknowledgment

* The work being presented is due to the efforts of
  - V. Dolgashev, Lisa Laurent, F. Wang, J. Wang, C. Adolphsen, D. Yeremian, J. Lewandowsky, C. Nantista, J. Eichner, C. Yoneda, C. Pearson, A. Hayes, D. Martin, R. Ruth, Shilun Pei, Zenghai Li SLAC
  - T. Higo and Y. Higashi, et. al., KEK
  - W. Wuensch et. al., CERN
  - R. Temkin, et. al., MIT
  - W. Gai, et. al, ANL
  - Gregory Nusinovich et. al., University of Maryland
  - S. Gold, NRL