Research and Development for Ultra High Gradient Accelerator Structures

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SLAC NATIONAL ACCELERATOR LABORATORY

LELAND STANFORD JUNIOR UNIVERSITY

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Outline

- Introduction
- Review of the on going Experimental work
  - Basic Physics experiments with geometry
  - Martial Studies
- Full featured accelerator structures
- On going developments of new types of structures
  - Standing-wave Accelerator structures
  - Photonic-band gap structures
  - Multi-frequency structures
- Applications
- Conclusions

Introduction

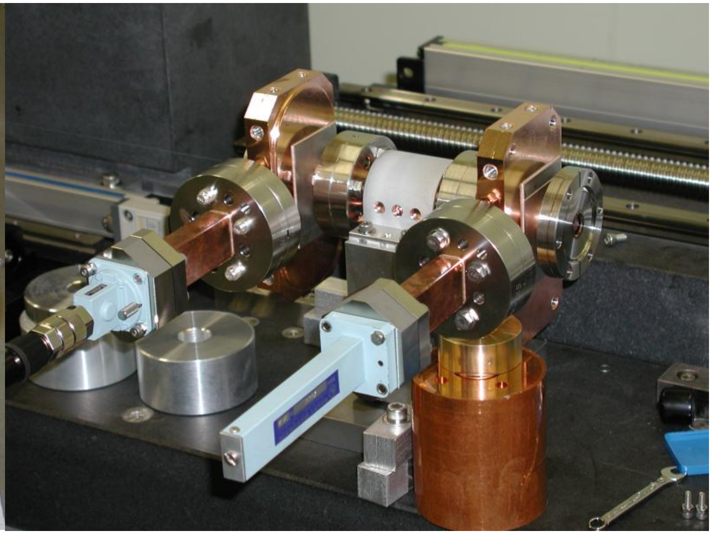
- This research was originally motivated by the desire for a compact accelerator for future collider applications.
- recently, research to study the basic physics associated with the limits of room temperature linacs has been vitalized by the national US Collaboration on High Gradient Research and associated international collaborations.
- This lead to new advances in the state of the art including:
  - a new optimization methodology for accelerator structure geometries,
  - An ongoing research on alternate and novel materials.
  - New types and novel structures.
  - Advances in the theoretical modeling of the breakdown phenomenon.
- In addition to colliders, other applications include compact Inverse Compton Scattering gamma ray sources for national security applications, and compact proton linacs for cancer therapy.
- High-frequency room temperature linacs can also be effectively used for low cost, high-repetition-rate X-ray FELs and for dynamic, short-period, large-aperture RF undulators.

Introduction (continued)

- Research on the basic physics of high-gradient, high frequency accelerator structures and the associated RF/microwave technology are essential for the future of discovery science, medicine and biology, energy and environment, and national security.
- We will review the state-of-the-art for the development of high gradient linear accelerators. We will present the research activities aimed at exploring the basic physics phenomenon of RF breakdown together with the development activities of linacs with special designs such as wake field damping features. We also will survey the current theoretical and modeling activities. Finally, we present a vision for the future research activities.

Experimental Studies

- Basic Physics Experimental Studies
  - Single and Multiple Cell Accelerator Structures (with major Frscati, KEK and CERN contributions)
    - single cell traveling-wave accelerator structures
    - single-cell standing-wave accelerator structures
  - Pulsed heating experiments
- Full Accelerator Structure Testing



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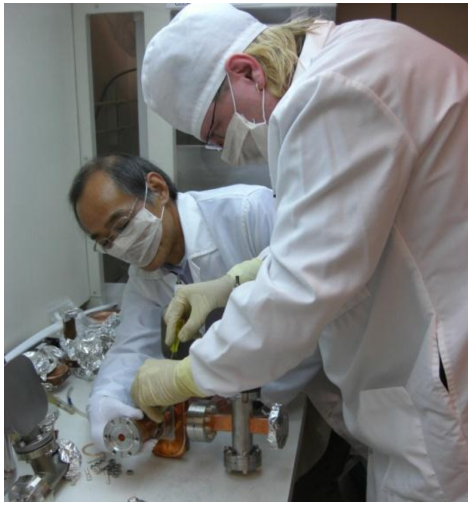
High Power Tests of Single Cell Standing Wave Structures

- Low shunt impedance, *a/lambda* = 0.215, *1C-SW-A5.65-T4.6-Cu*, 5 tested
  - *KEK=#1…KEK-#4*
  - *Frascati-#2*
- Low shunt impedance, TiN coated, *1C-SW-A5.65-T4.6-Cu-TiN-KEK-#1*, 1 tested
- Three high gradient cells, low shunt impedance, *3C-SW-A5.65-T4.6-Cu,* 2 tested
  - *KEK-#1…KEK-#2*
- High shunt impedance, elliptical iris, *a/lambda* **=** 0.143, *1C-SW-A3.75-T2.6-Cu-SLAC-#1*, 1 tested
- High shunt impedance, round iris, *a/lambda* **=** 0.143, *1C-SW-A3.75-T1.66-Cu-KEK-#1*, 1 tested
- Low shunt impedance, choke with 1mm gap, *1C-SW-A5.65-T4.6-Choke-Cu*, 2 tested
  - *SLAC-#1*
  - *KEK-#1*
- Low shunt impedance, made of CuZr, *1C-SW-A5.65-T4.6-CuZr-SLAC-#1,* 1 tested
- Low shunt impedance, made of CuCr, *1C-SW-A5.65-T4.6-CuCr-SLAC-#1,* 1 tested
- Highest shunt impedance copper structure *1C-SW-A2.75-T2.0-Cu-SLAC-#1***,** 1 tested
- Photonic-Band Gap, low shunt impedance, *1C-SW-A5.65-T4.6-PBG-Cu-SLAC-#1,* 1 tested
- Low shunt impedance, made of hard copper *1C-SW-A5.65-T4.6-Clamped-Cu-SLAC#1,* 1 tested
- Low shunt impedance, made of molybdenum *1C-SW-A5.65-T4.6-Mo-Frascati-#1,* 1 tested
- Low shunt impedance, hard copper electroformed *1C-SW-A5.65-T4.6-Electroformed-Cu-Frascati-#1,* 1 tested
- High shunt impedance, choke with 4mm gap, *1C-SW-A3.75-T2.6-4mm-Ch-Cu-,* 2 tested
  - SLAC-#1
  - KEK-#1
- High shunt impedance, elliptical iris, ultra pure Cu, *a/lambda* **=** 0.143, *1C-SW-A3.75-T2.6-6NCu-KEK-#1*, 1 tested
- High shunt impedance, elliptical iris, HIP treated, *a/lambda* = 0.143, *1C-SW-A3.75-T2.6-6N-HIP-Cu-KEK-#1*, 1 tested
- High shunt impedance, elliptical iris, ultra pure Cu,, *a/lambda* **=** 0.143, *1C-SW-A3.75-T2.6-7N-Cu-KEK-#1*, 1 tested
- Low shunt impedance, made of soft CuAg, *1C-SW-A5.65-T4.6-CuAg-SLAC-#1,* 1 tested
- High shunt impedance hard CuAg structure *1C-SW-A3.75-T2.6-LowTempBrazed-CuAg-KEK-#1,* 1 tested
- High shunt impedance soft CuAg, *1C-SW-A3.75-T2.6-CuAg-SLAC-#1*, 1 tested
- High shunt impedance hard CuZr, *1C-SW-A3.75-T2.6-Clamped-CuZr-SLAC-#1*, 1 tested
- High shunt impedance dual feed side coupled, *1C-SW-A3.75-T2.6-2WR90-Cu-SLAC-#1,* 1 tested

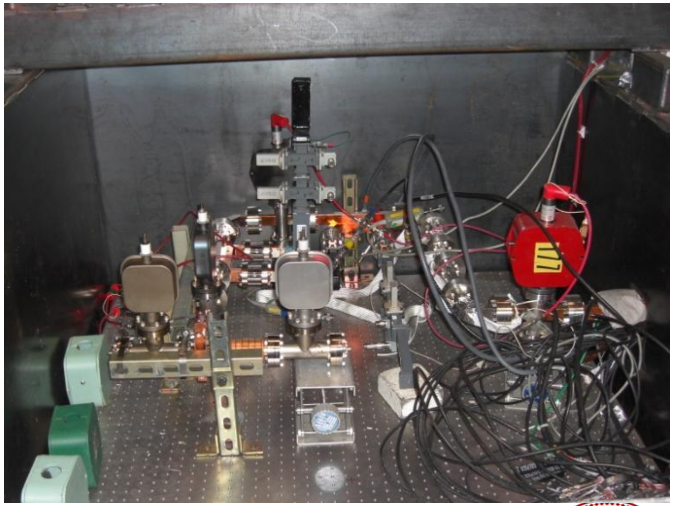
Now 30^{th} test is ongoing,
single feed side coupled
1C-SW-A3.75-T2.6-1WR90-Cu-SLAC-#1

Surface processing

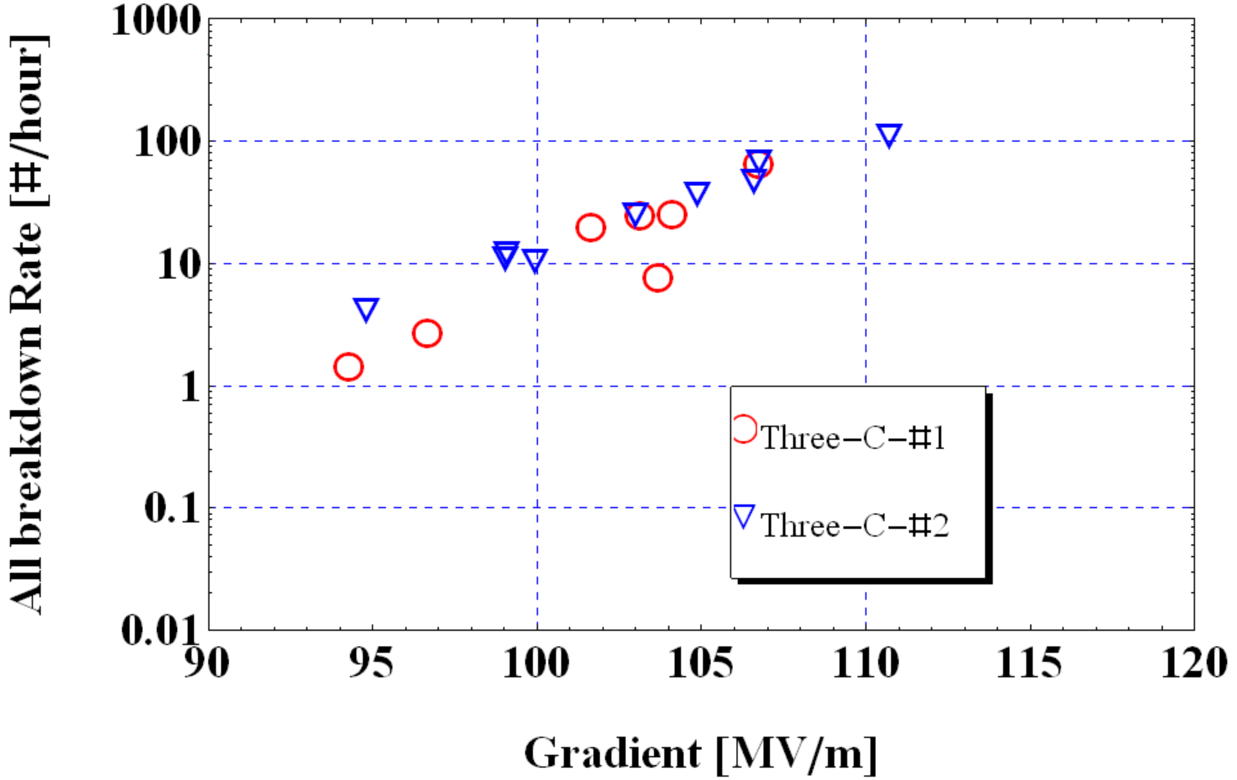
Dr. Yasuo Higashi and Richard Talley assembling Three-C-SW-A5.65-T4.6-Cu-KEK-#2



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



Two structures #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 a few hours for the normally processed structure.

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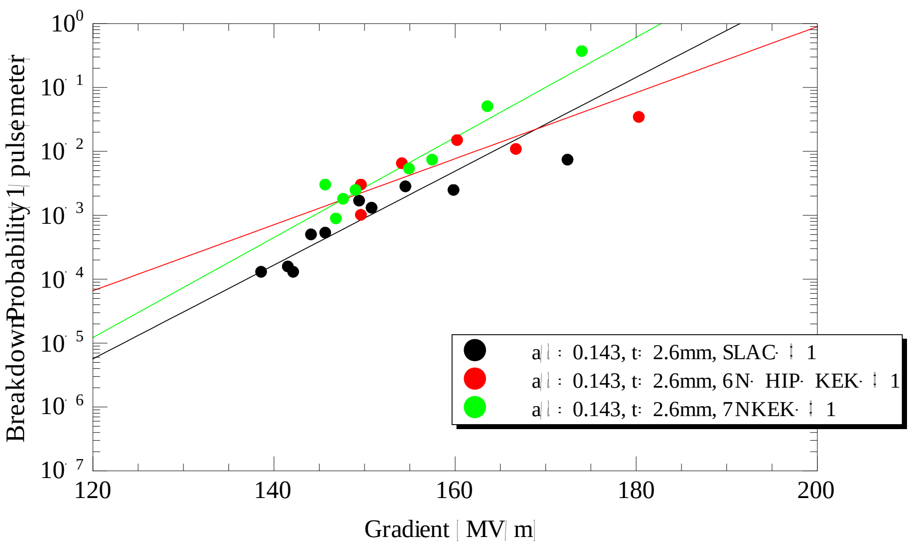
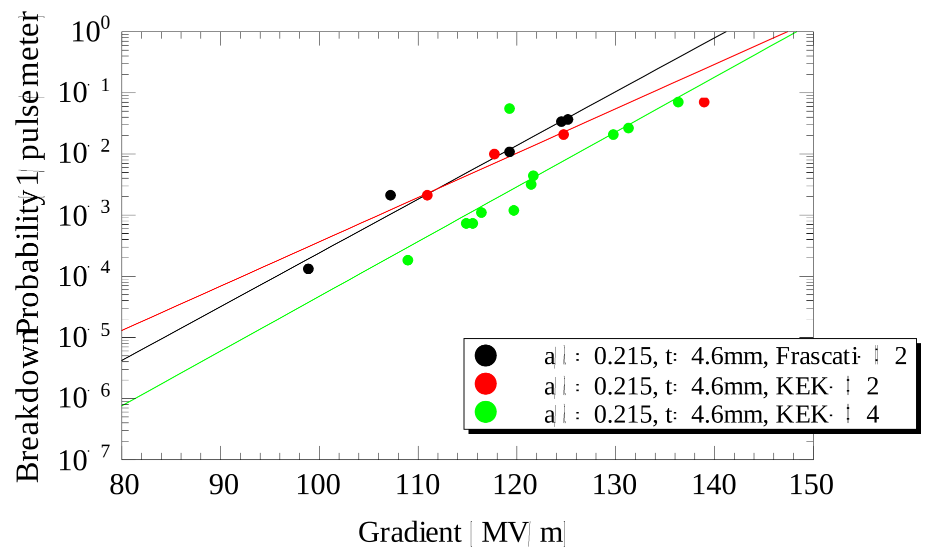
Pure Copper studies

Accelerator structures manufactured with different grades of copper purity



Accelerator structures manufactured by different laboratories



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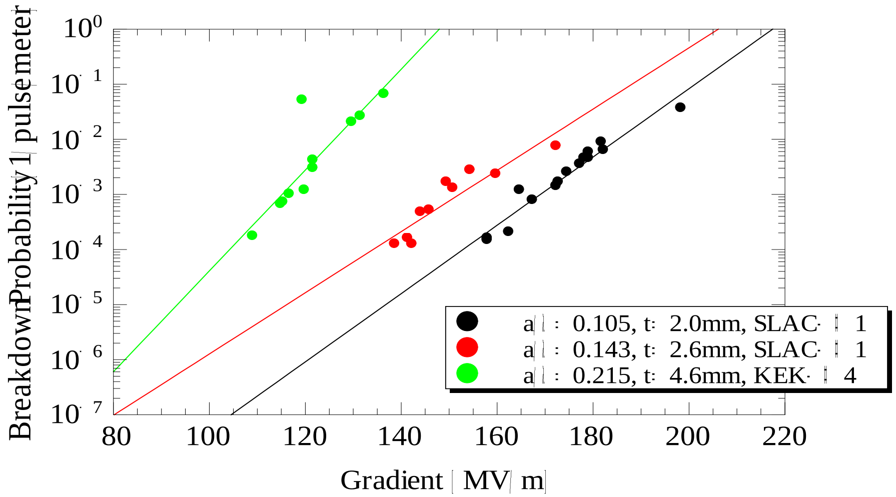
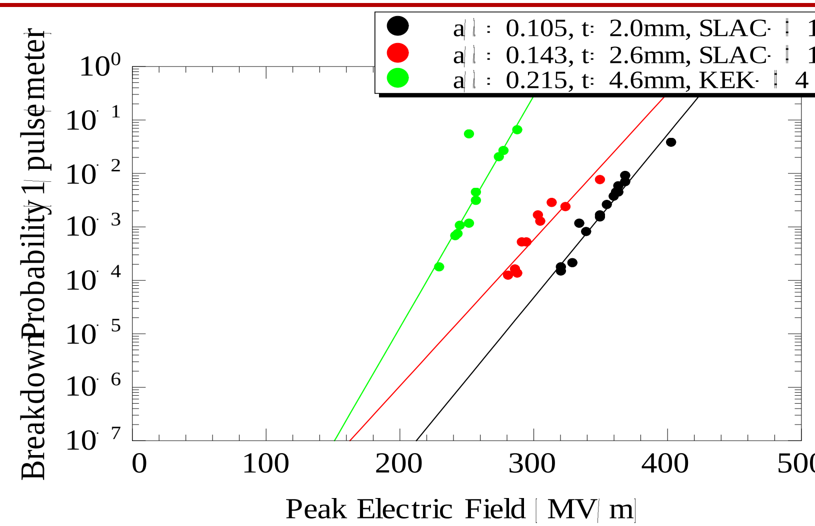
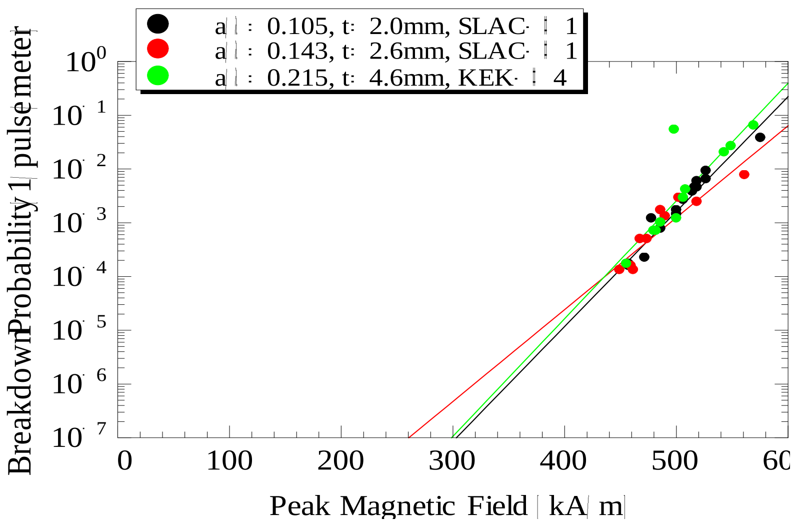
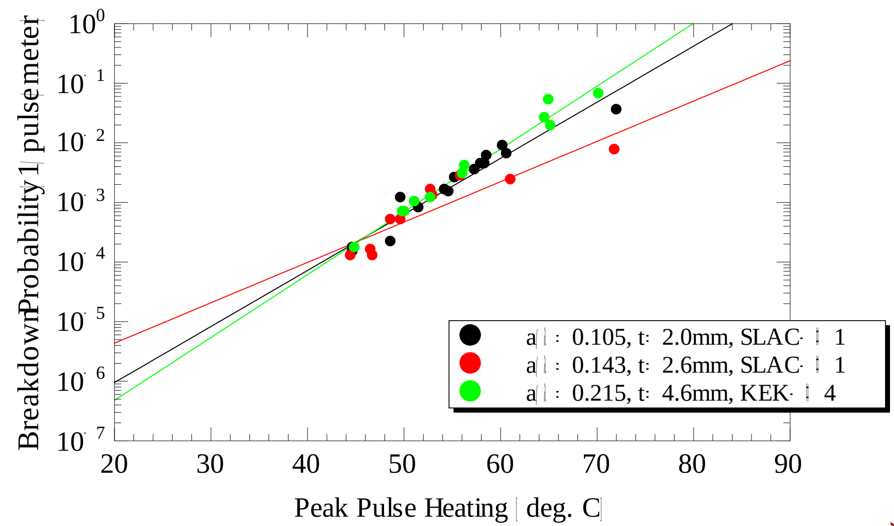
Geometrical Studies

Different single cell structures: Standing-wave structures with different iris diameters and shapes; $a/\lambda=0.215$, $a/\lambda=0.143$, and $a/\lambda=0.105$









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

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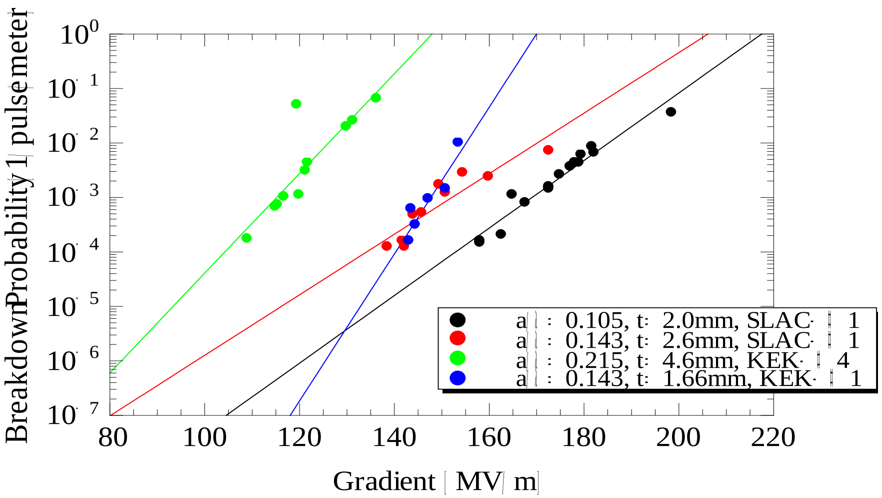
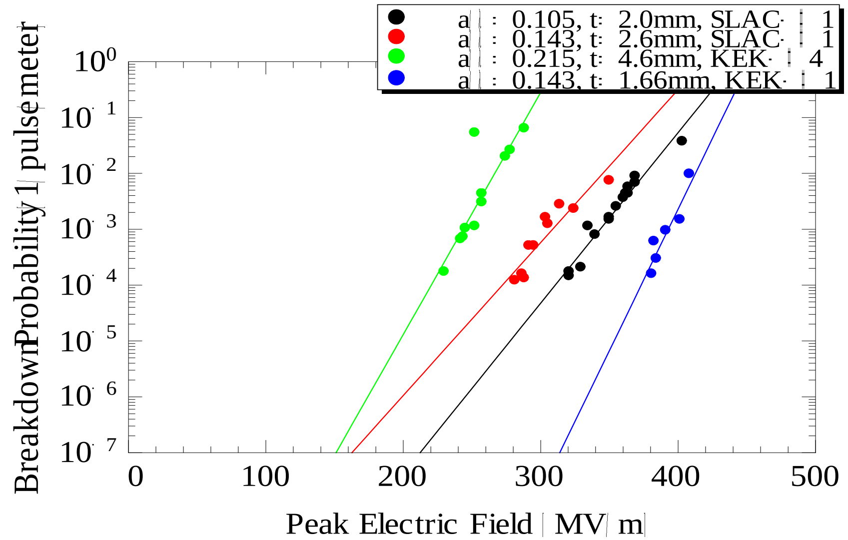
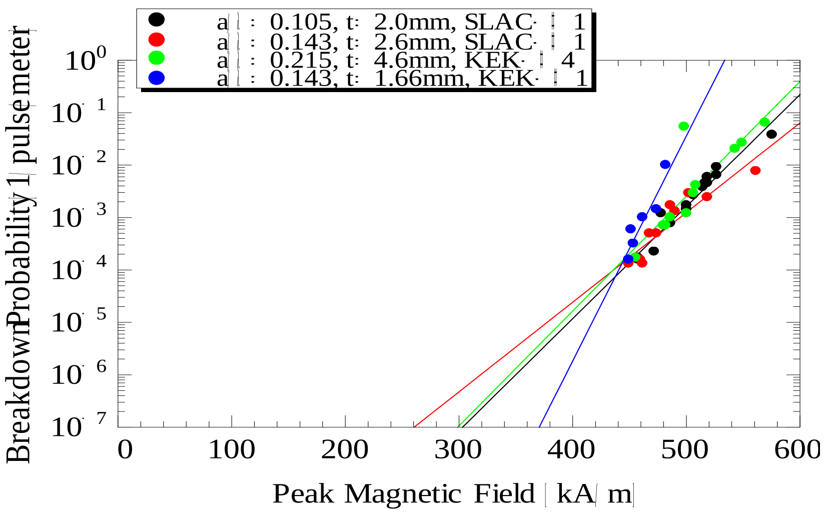
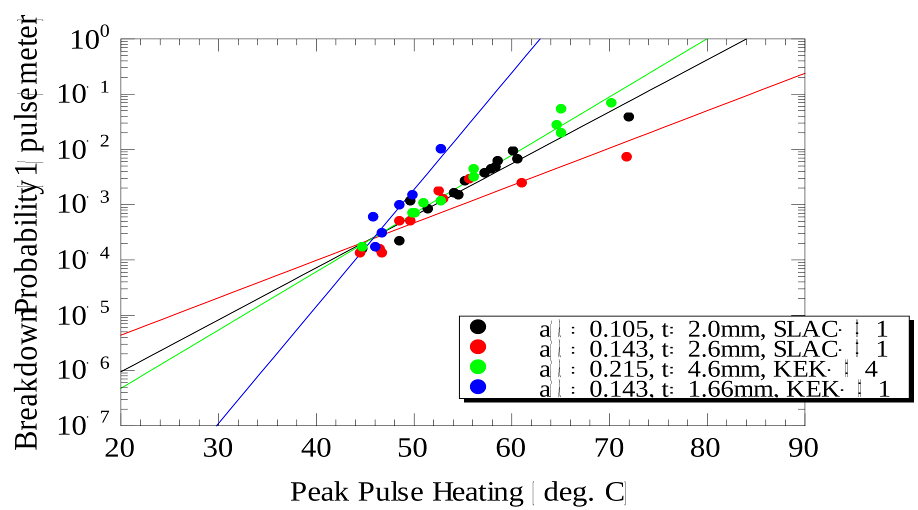
Geometrical Studies

Different single cell structures: Standing-wave structures with different iris diameters and shapes; a/λ=0.215, a/λ=0.143, and a/λ=0.105, and a/λ=0.143round iris









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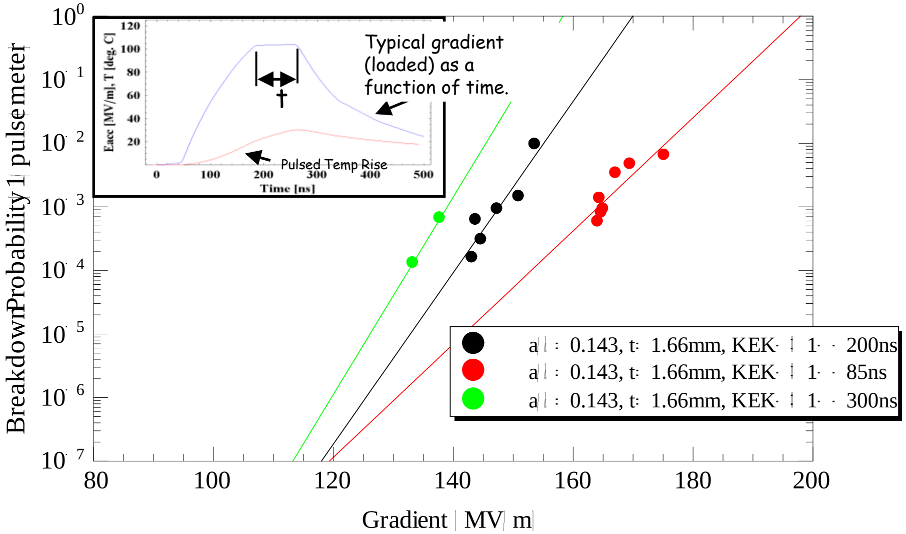
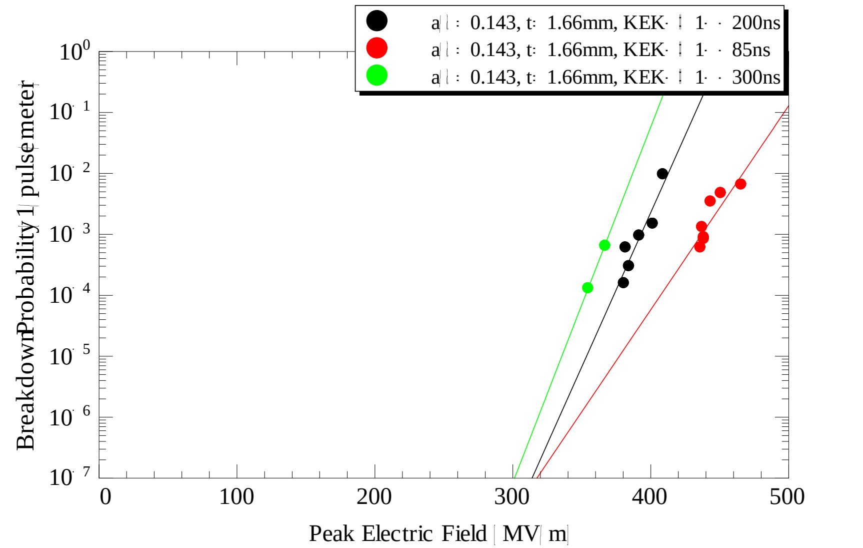
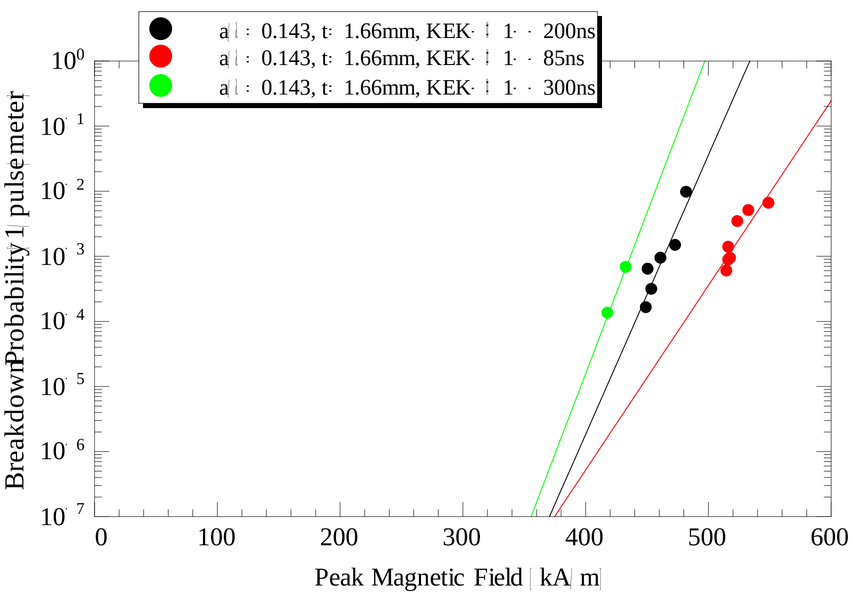
Global geometry plays a major role in determining the accelerating gradient, rather than the local electric field.

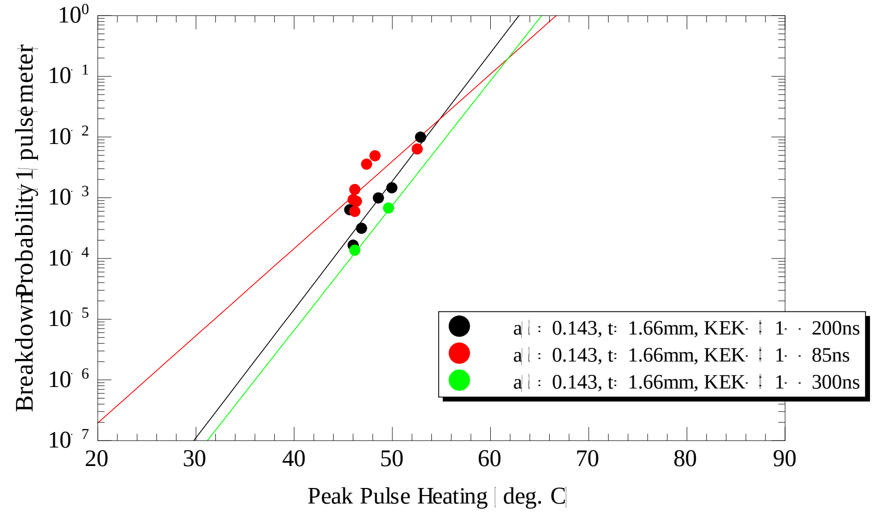
Pulse Length Dependence

Peak Pulse Heating correlate better than peak magnetic field



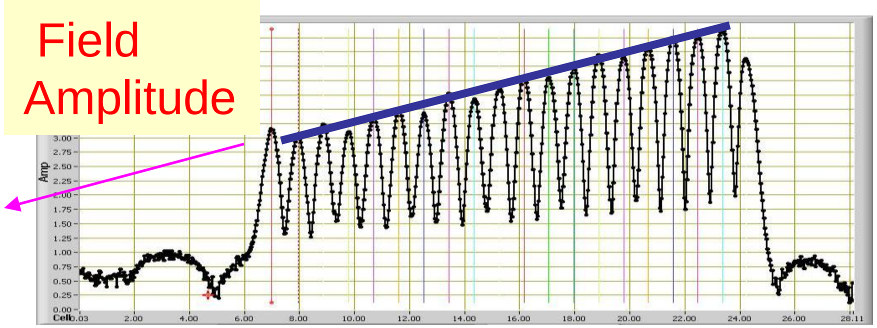




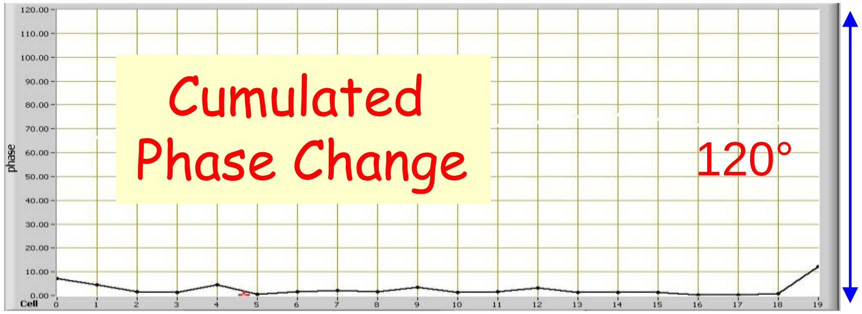


Full Accelerator structure testing (the T18 structure)

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

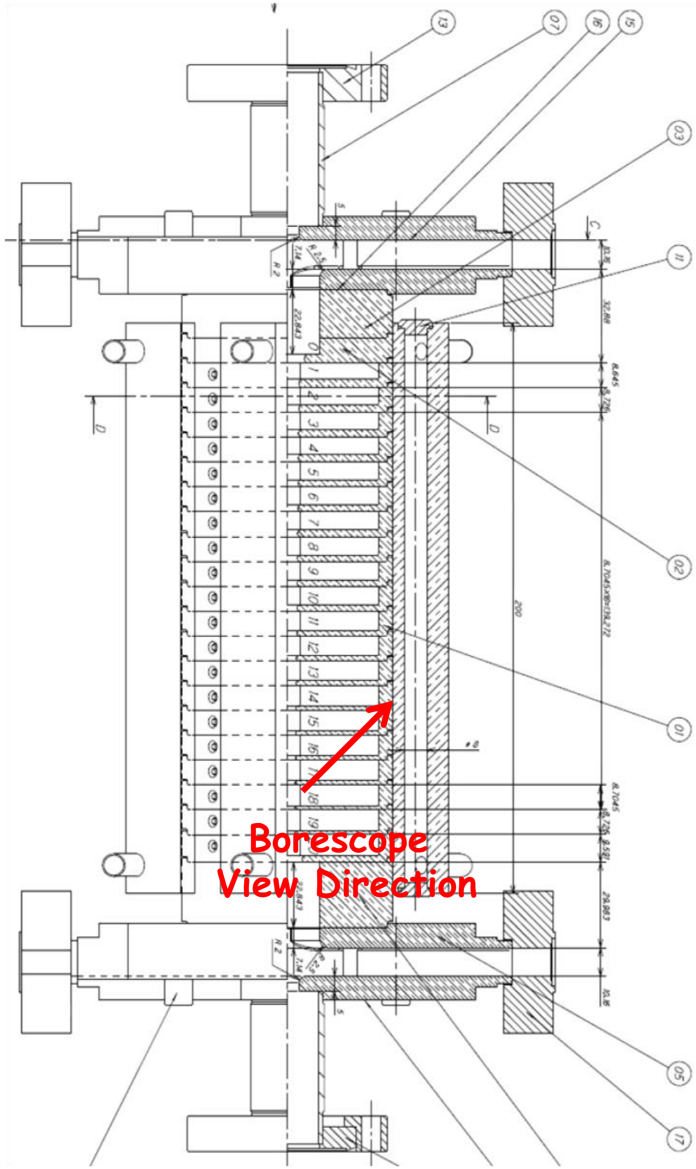


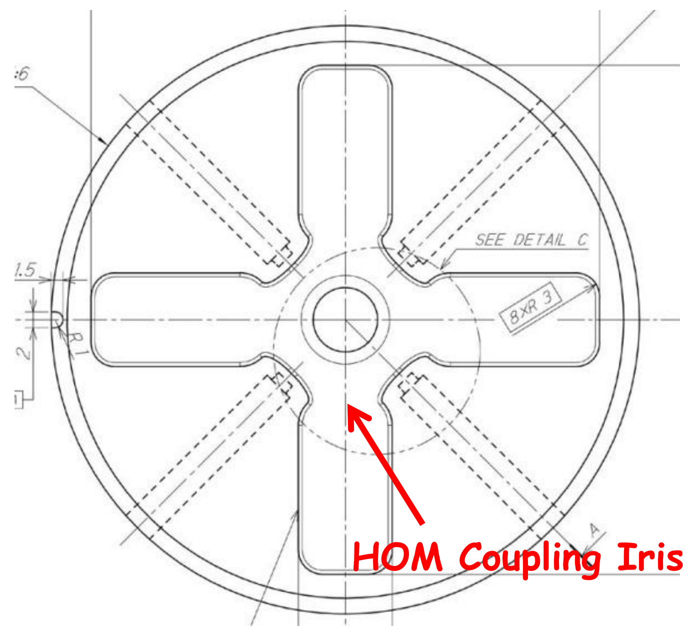
$$E_{acc\_out}/E_{acc\_in} \sim 1.5$$



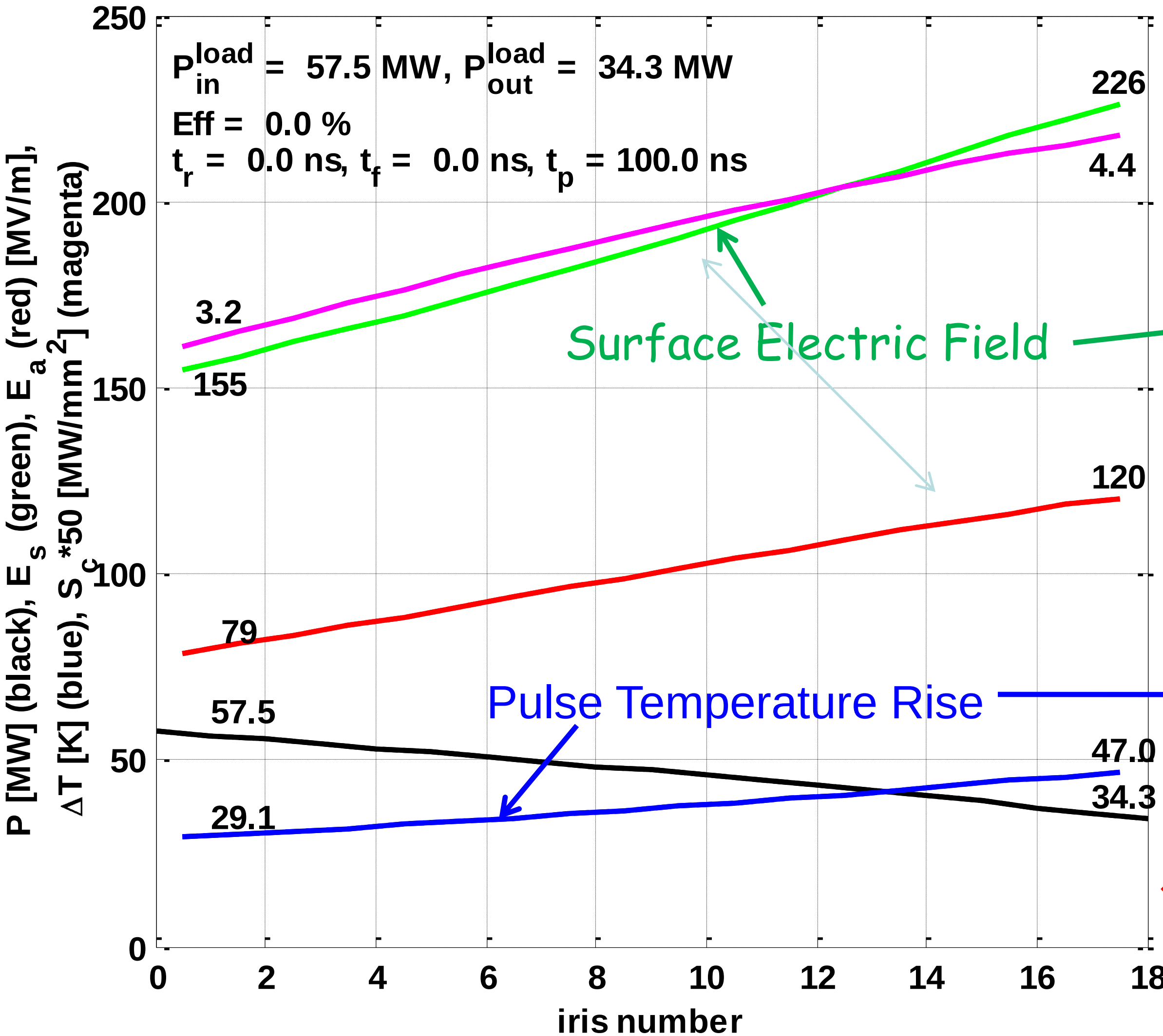
- Structure designed by CERN based on all empirical laws developed experimentally through our previous work
- Cells Built at KEK
- Structure was bonded and processed at SLAC
- Several versions were tested at SLAC and KEK with reasonably consistent results

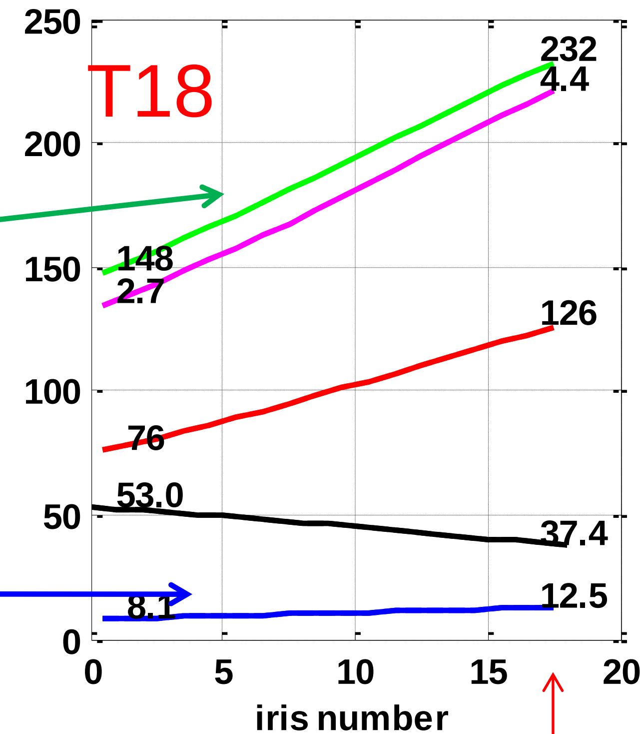
The TD18 version of the T18 structure contain HOM couplers in each cell





TD18 Parameter Plots for an Unloaded Gradient of 100 MV/m





High ΔT : 47 degC for 100 ns Pulse whereas T18 is only 12.5 degC

A. Grudiev (CERN)
C. Adolphsen (SLAC)

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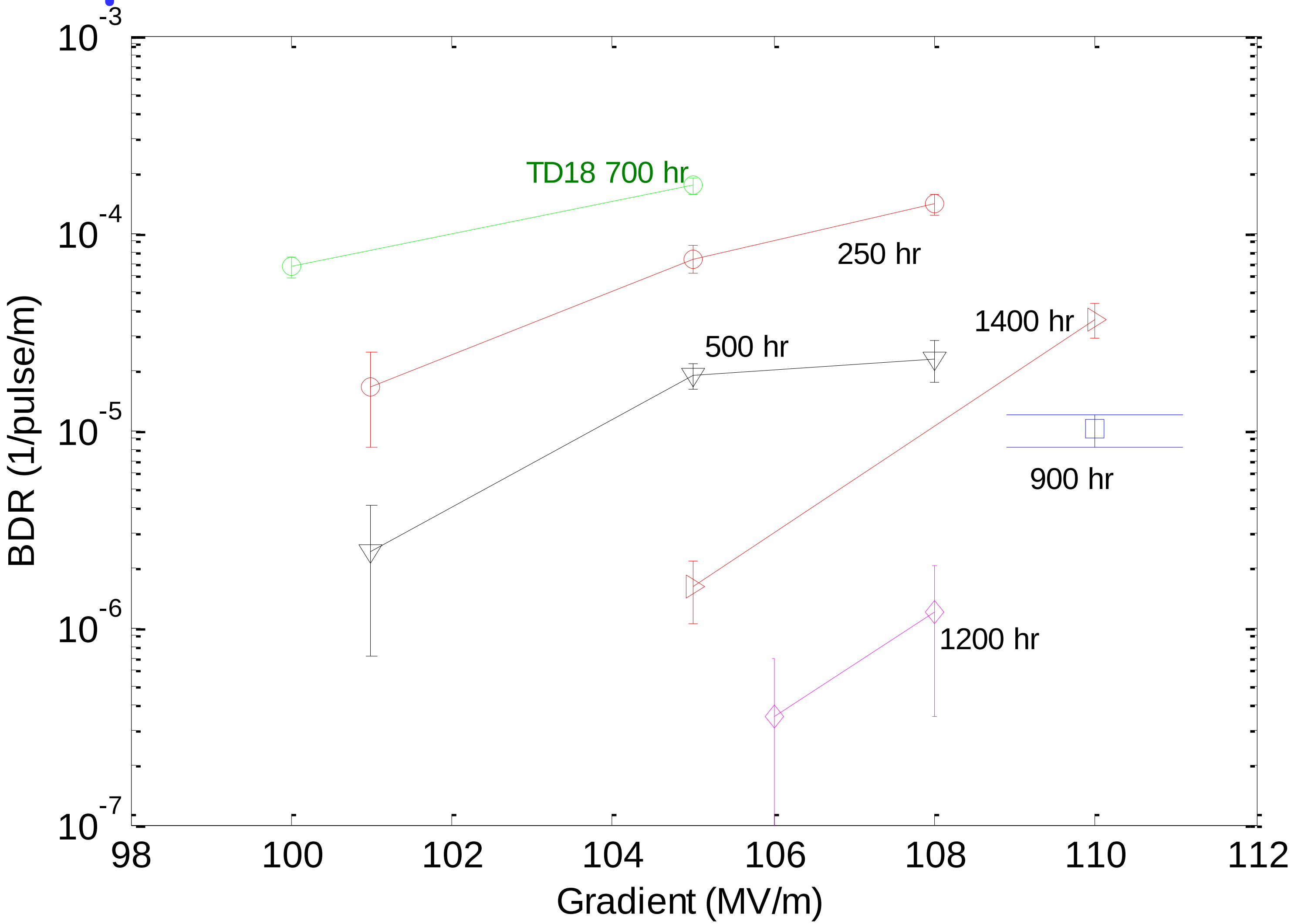
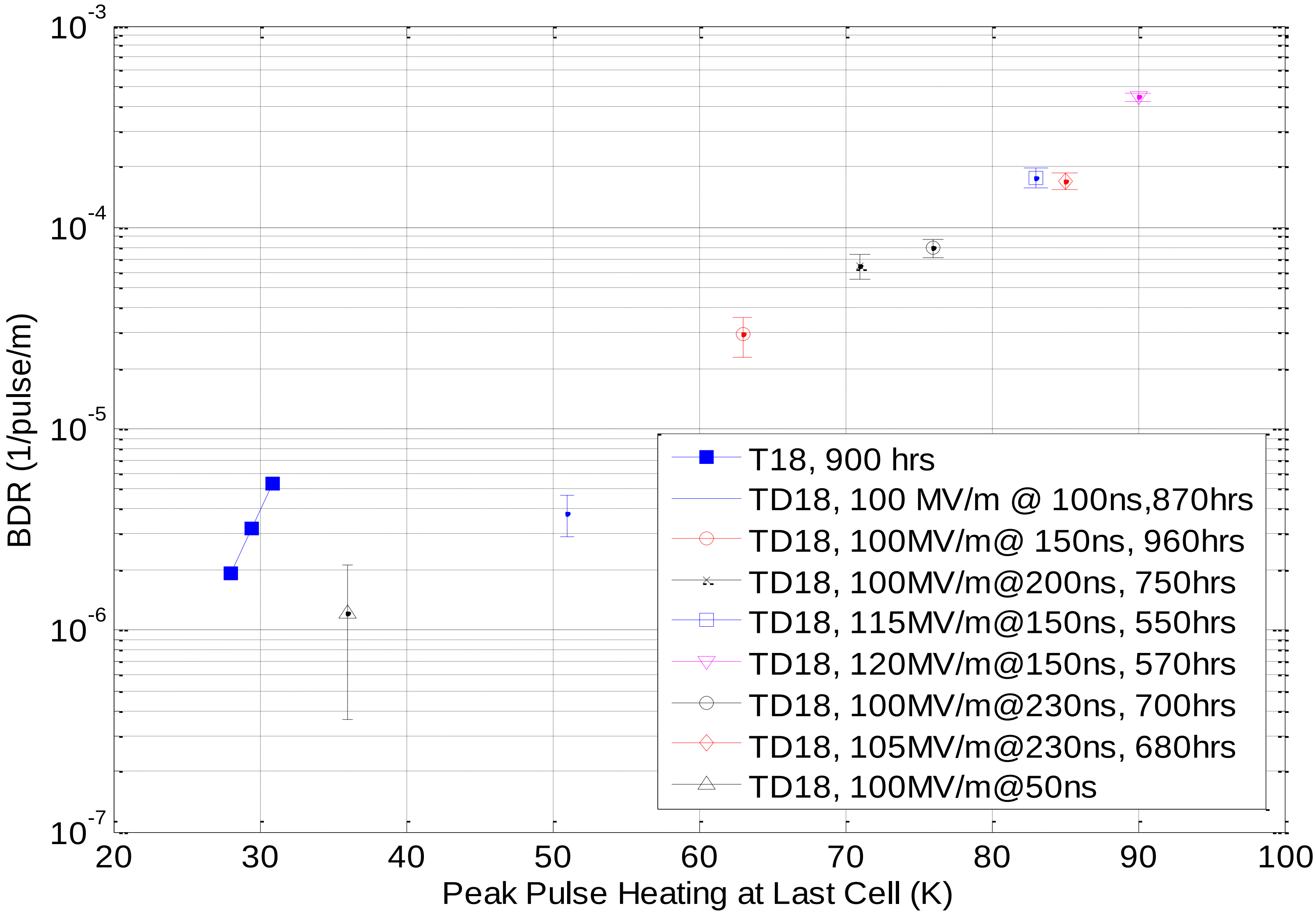
Comparison Between T18 and TD18



Pulse width 230ns: Green line for TD18, Others for T18

F. Wang, C. Adolphsen

Breakdown Rate Pulse Heating Dependence

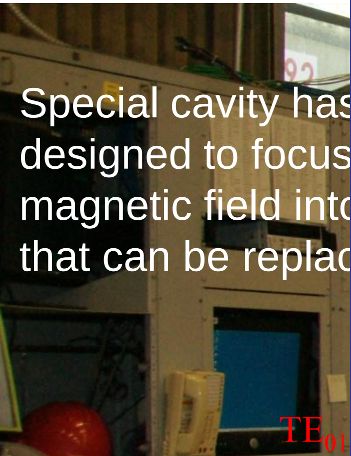


F. Wang, C. Adolphsen

Material Testing

- Experimental and theoretical evidence points to the magnetic field as an important factor in determining the ultimate gradient of a given structure.
  - Magnetic field can be responsible for:
    - Geometrical effects
    - Effective field enhancement
    - Secondary effects due to gas release at high magnetic field points.
  - Surface fatigue can explain the low statistics phenomena of breakdown; why a breakdown occurs every million pulses.
- Surface fatigue is particularly important in areas where peak magnetic field can cause damage such as wakefield damping areas.

Material Testing (Pulsed heating experiments)



Special cavity has
designed to focus
magnetic field into
that can be replac

method
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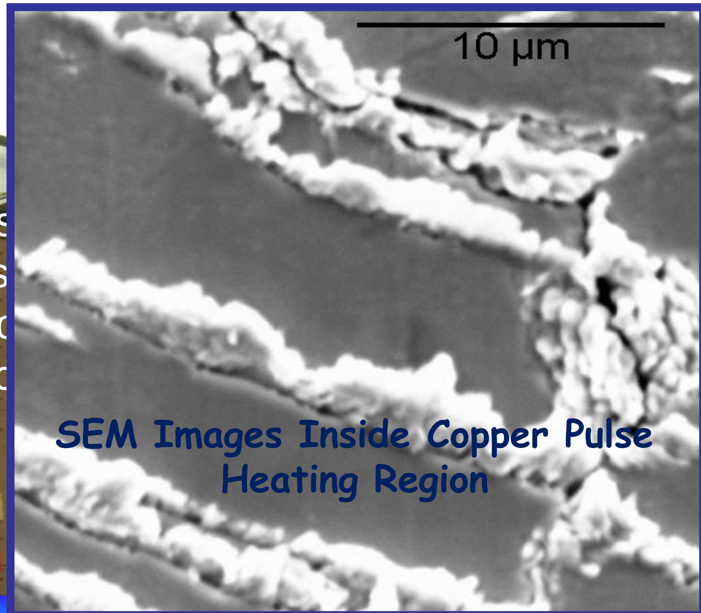
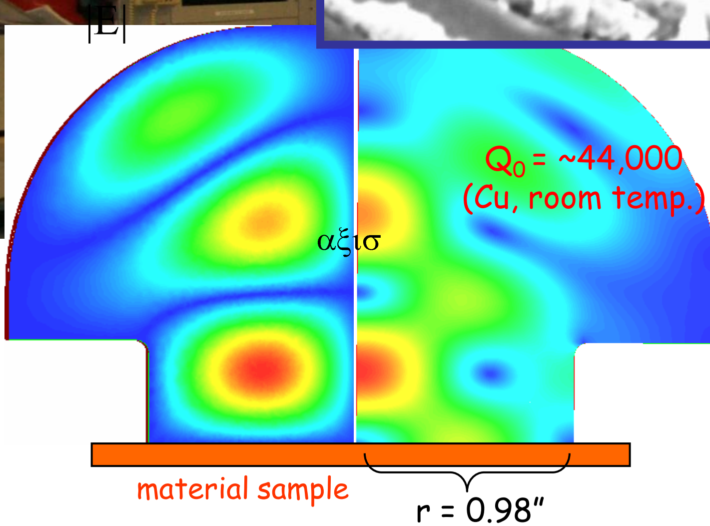
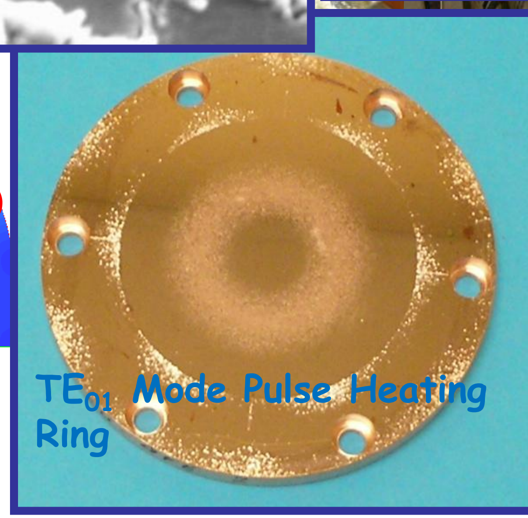


SEM Images Inside Copper Pulse Heating Region

Metallography: Intergranular fractures 500X





TE_{01} Mode Pulse Heating Ring

Max Temp rise during pulse = 110°C

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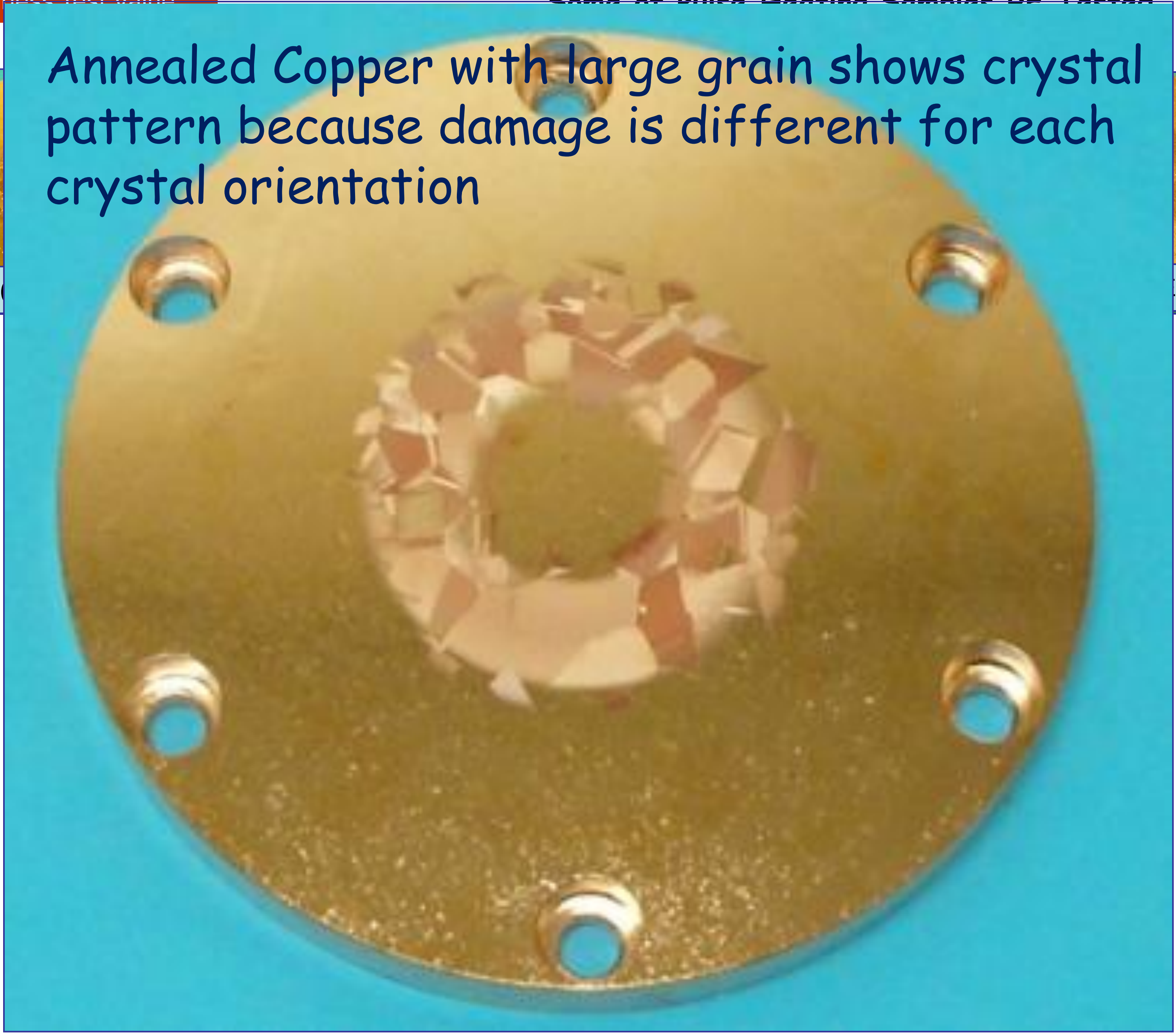
Hardness Test Value

Some of Pulse Heating Samples RF Tested

Cu101 (

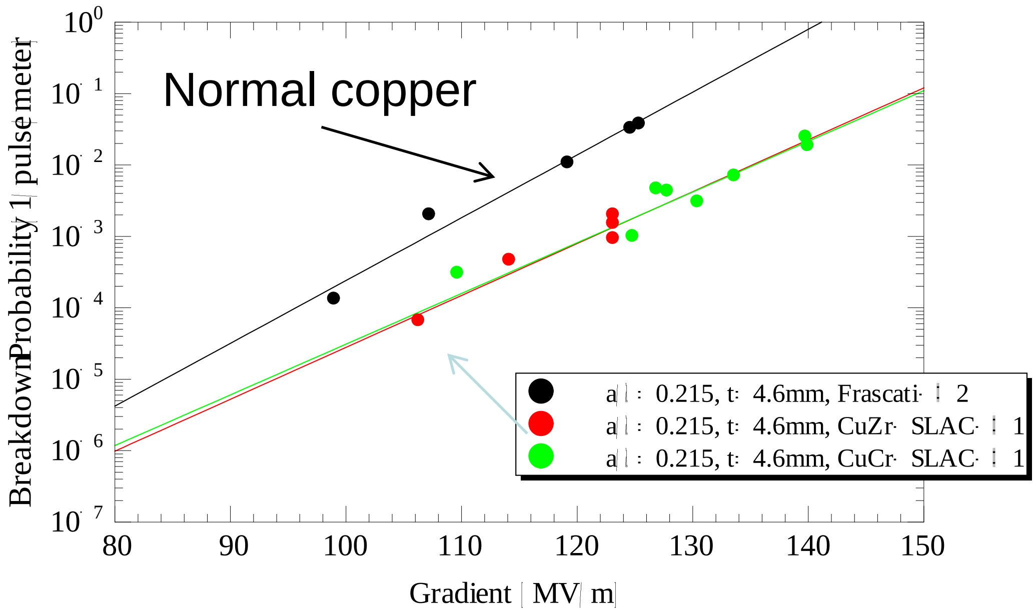


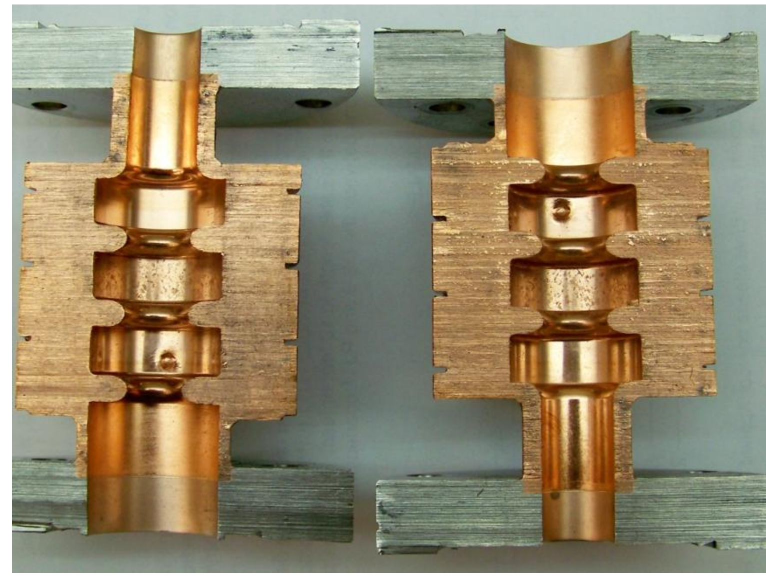
Annealed Copper with large grain shows crystal pattern because damage is different for each crystal orientation

RN)


Breakdown and pulsed heating
effects on an standing wave
accelerator structure iris
Photo John Van Pelt

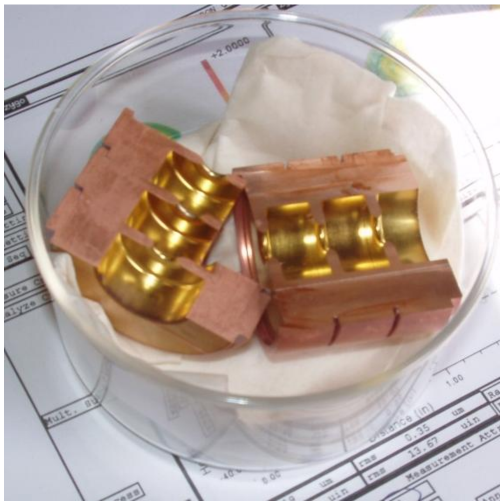
Test of a Vacuum Brazed CuZr and CuCr Structures



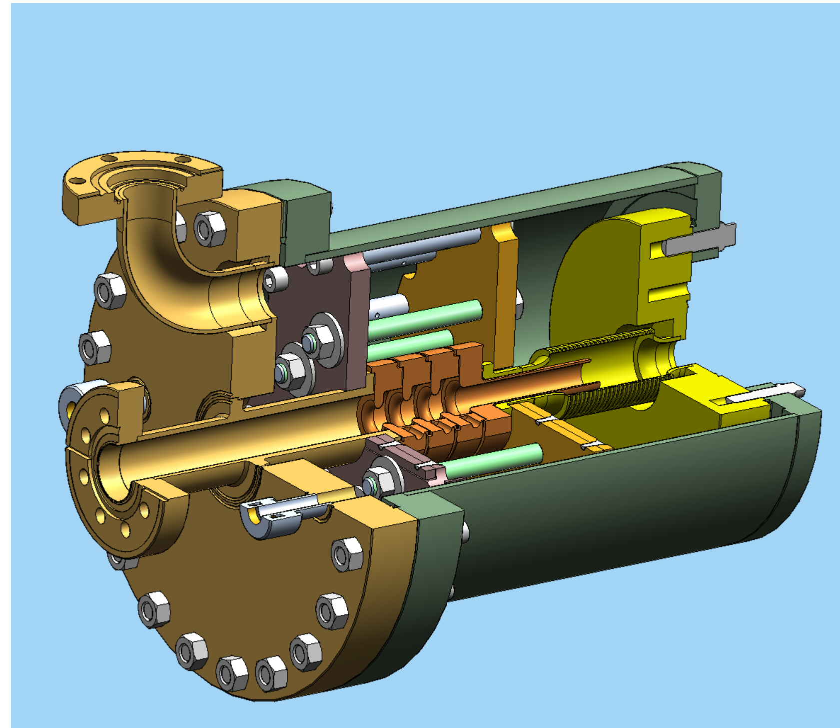


Clamped Structure

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



Clamping Structure for testing copper alloys accelerator structure

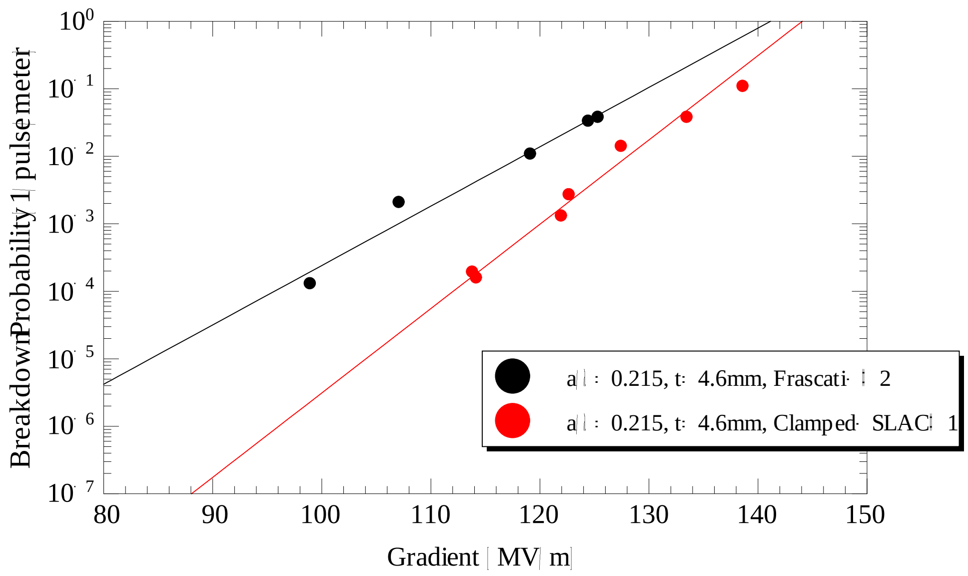


- The clamped structure will provide a method for testing materials without the need to develop all the necessary technologies for bonding and brazing them.
- Once a material is identified, we can spend the effort in processing it.
- Furthermore, it will provide us the opportunity to test hard materials without annealing which typically accompany the brazing process

Test of Hard Copper

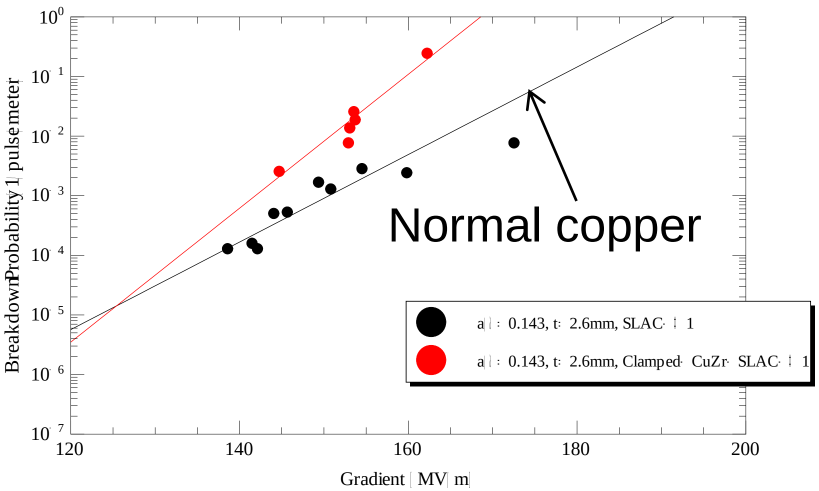
Hard Copper showed an observable improvements of annealed brazed

Clamped Structure with Hard Copper cells



Test of Hard CuZr

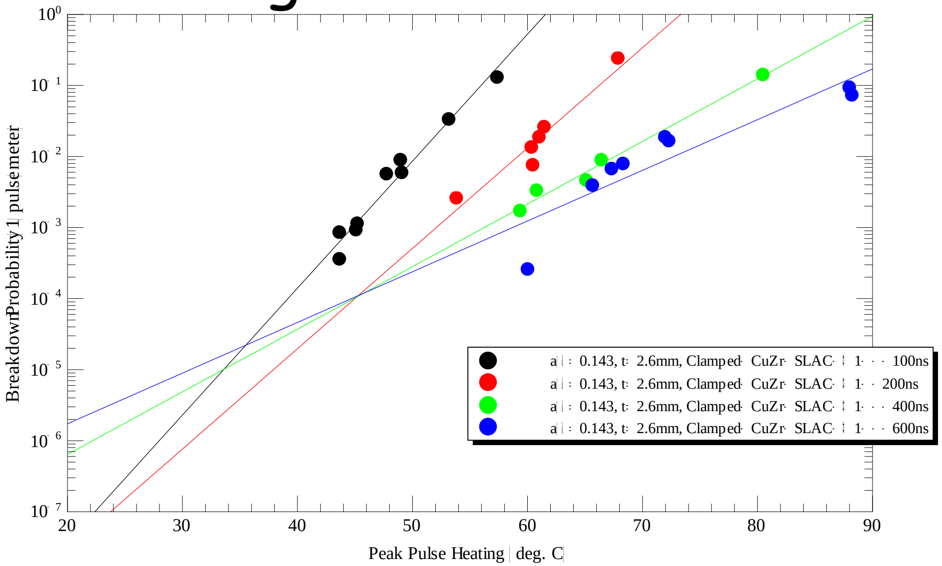
Hard Copper showed an observable improvements of annealed brazed structures



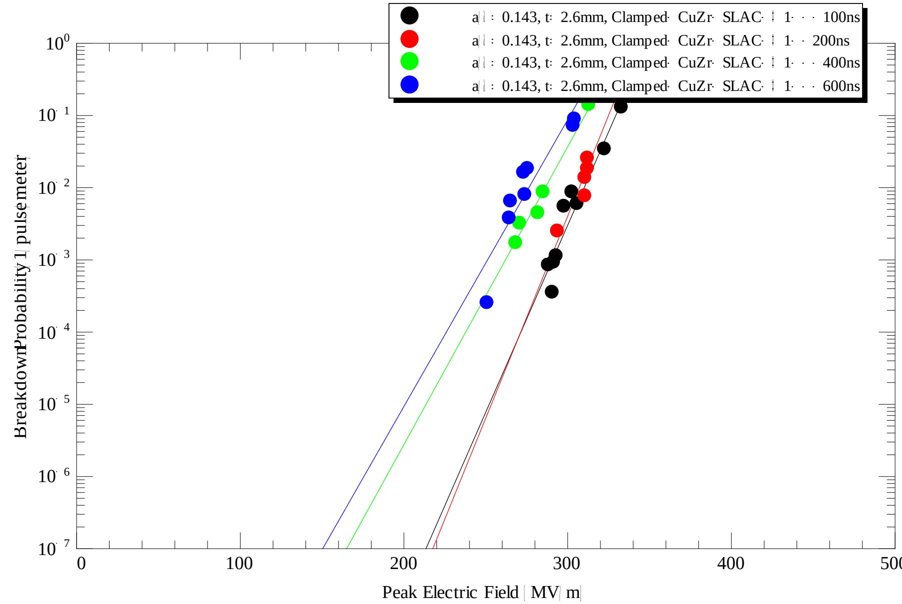
Clamped Structure with Hard Copper alloy cells

Test of Hard CuZr

It seems to follow peak electric field on surface rather than peak pulse heating



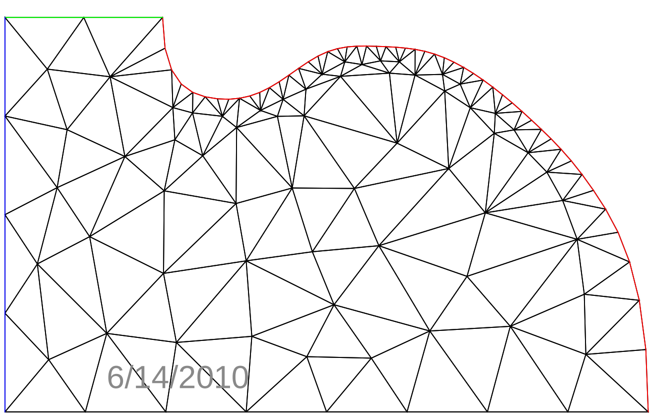
Weak pulse length dependence

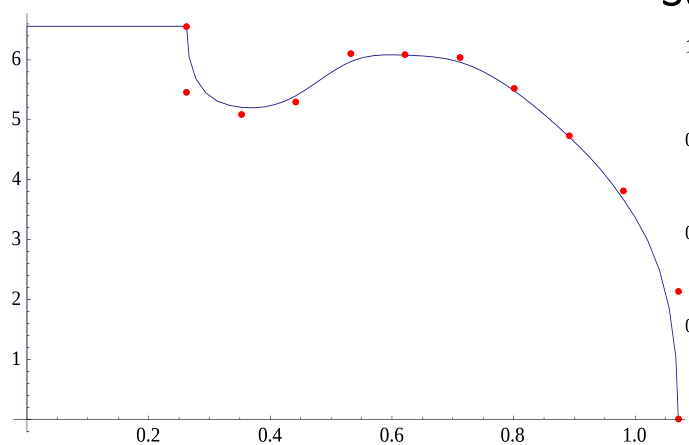


Yet Another Finite Element Code

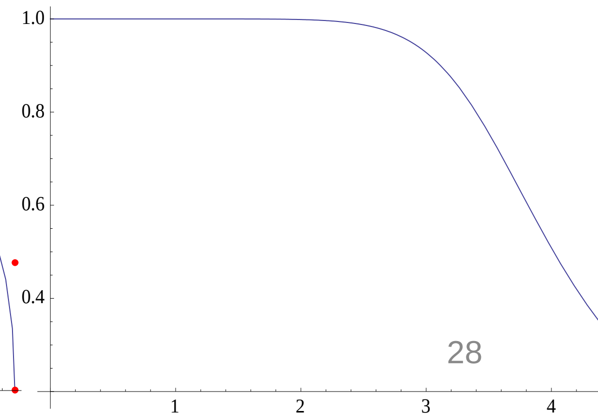
Motivated by the desire
•to design codes to perform *Large Signal Analysis* for microwave tubes (realistic analysis with short computational time for optimization)
•study surface fields for accelerators
•the need of a simple interface so that one could "play"

•A finite element code written completely in Mathematica (then translated to C++) was realized.
•To our surprise, it is running much faster than SuperFish or Superlance
•The code was used with a Genetic Global Optimization routine to optimize the cavity shape under surface field constraints



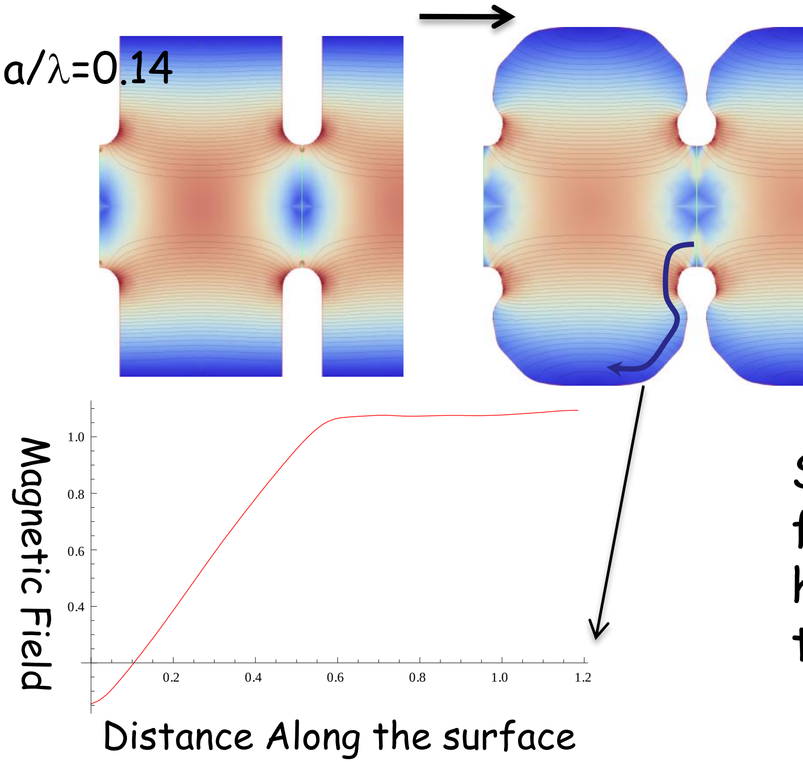


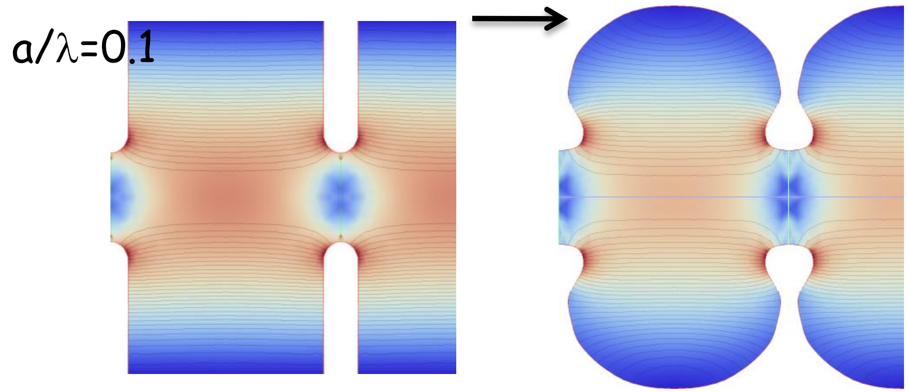
Surface field penalty function



Iris shaping for Standing-Wave π-mode structures

	Left (original)	Left (shaped)	Right (original)	Right (shaped)
Shunt Impedance	83 MΩ/m	104 MΩ/m	102 MΩ/m	128 MΩ/m
Quality Factor	8561	9778	8645	9655
Peak E_s/E_a	2.33	2.41	2.3	2.5
Peak Z_0H_s/E_a	1.23	1.12	1.09	1.04





Shape optimization reduces magnetic field on the surface, and hence, we hope to improve breakdown rate with the enhanced efficiency

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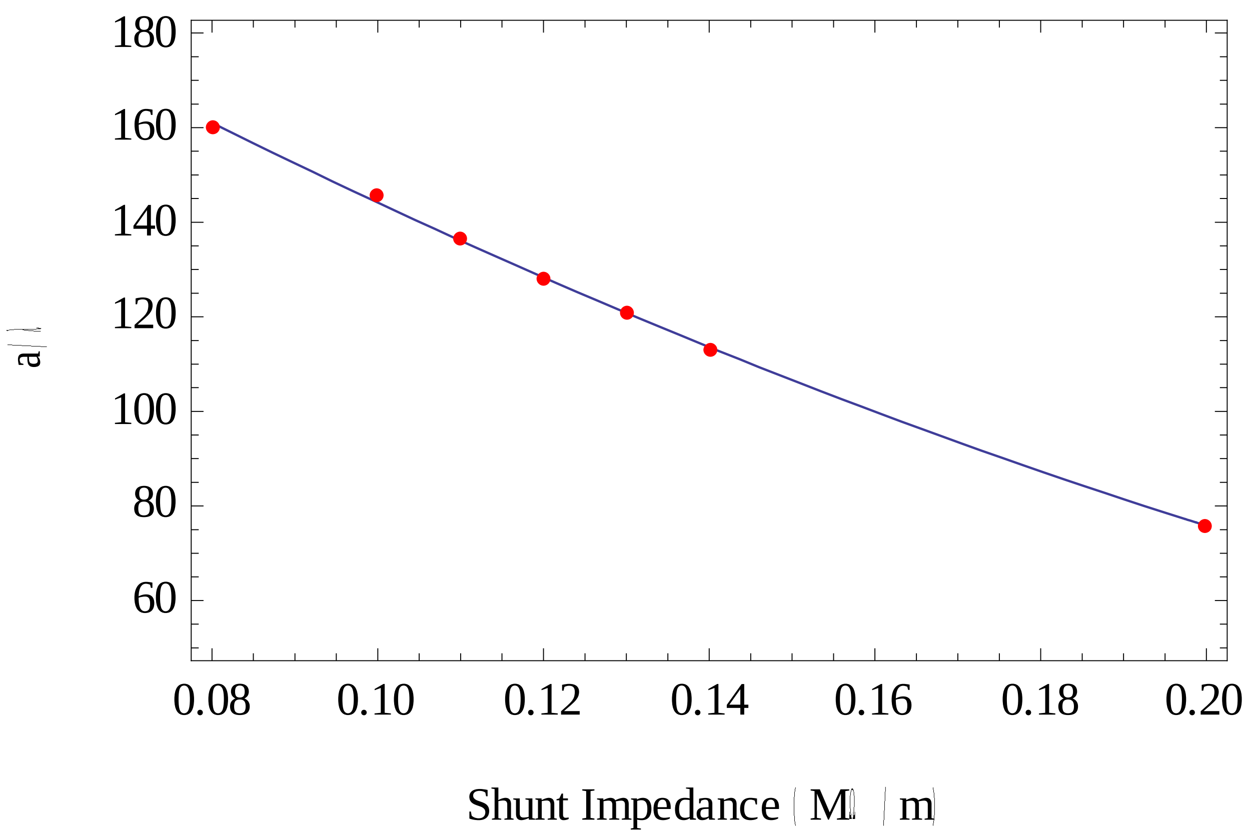
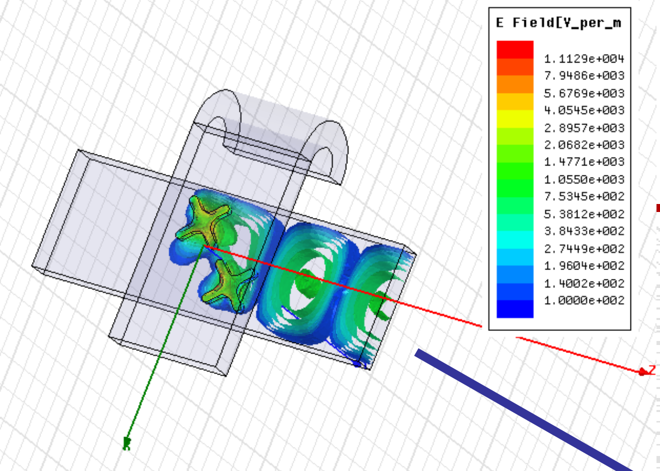
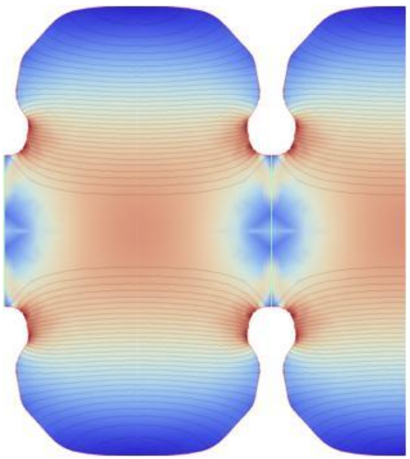
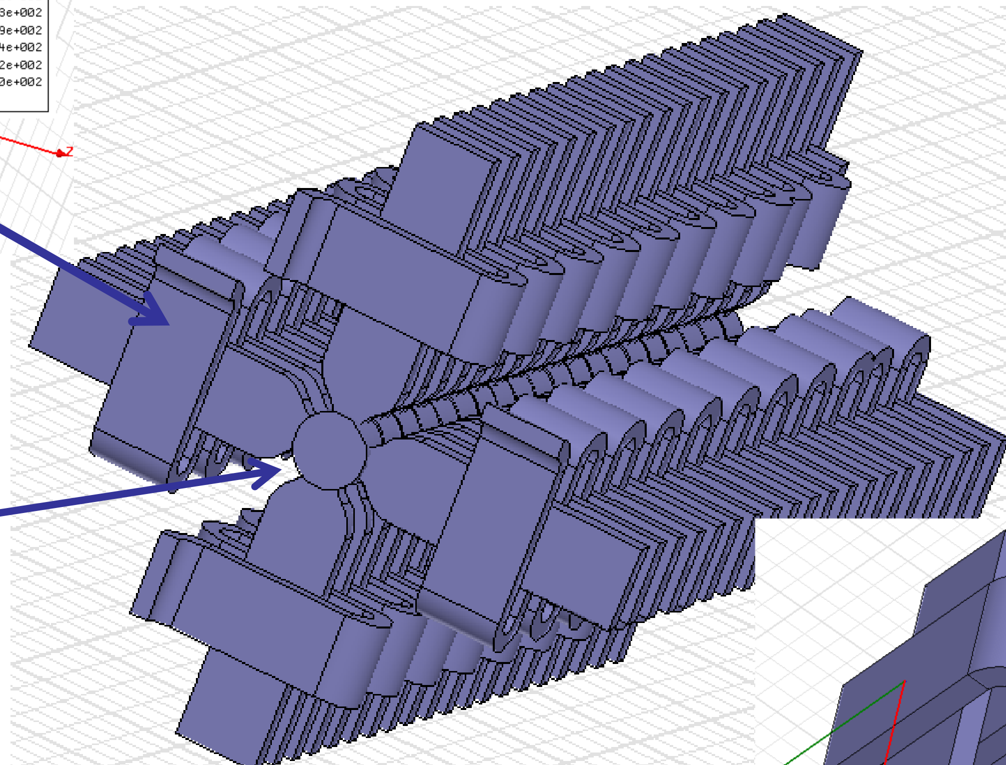
The effect of a/λ on optimized shunt impedance

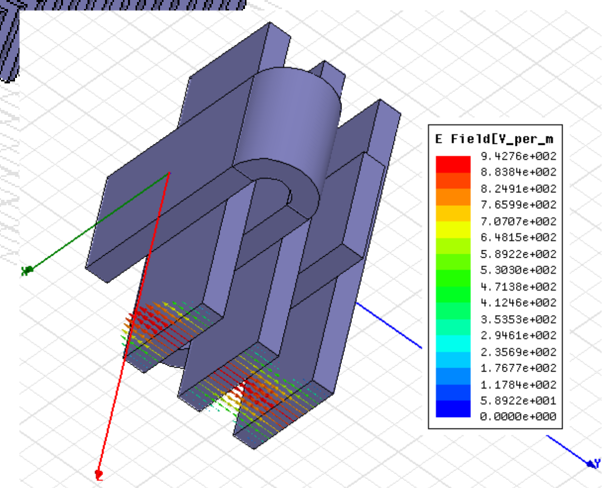


New Accelerator Architecture for Standing wave accelerator structures withy a combined damping and feeding.









- This is proposed for an efficient high gradient linac for application to a warm collider.
- If one let go of the restrictions imposed by wake fields, the RF distribution system and cell feeding could be done with much more simpler structure.

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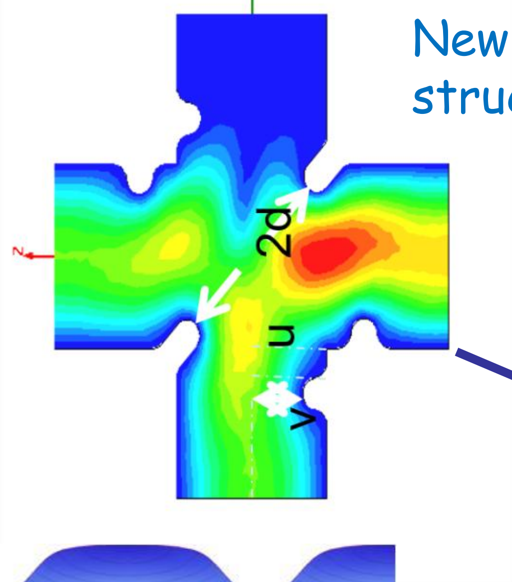
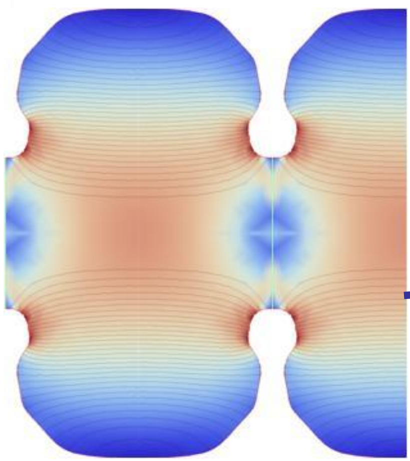
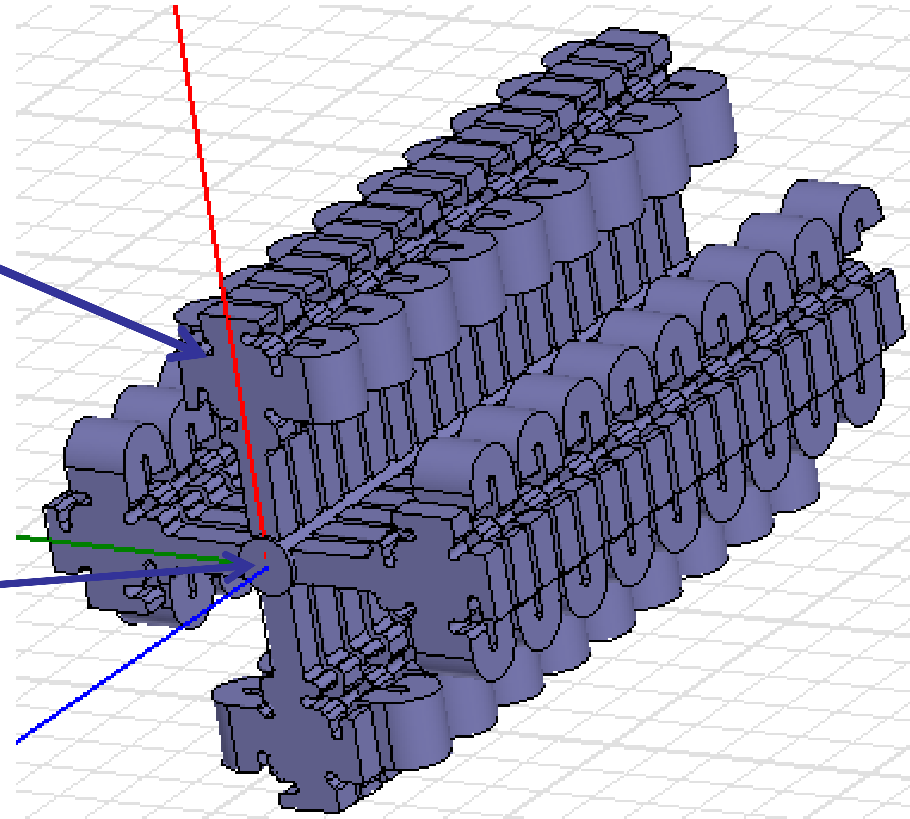
Jeff Neilson

New Accelerator Architecture for Standing wave accelerator structures withy a combined damping and feeding.







•With a "new" type of planner cross-guide coupler the structure could be made simpler

Jeff Neilson

HFSS PBG HOM Simulations

- Perfectly Matched Layer simulation results

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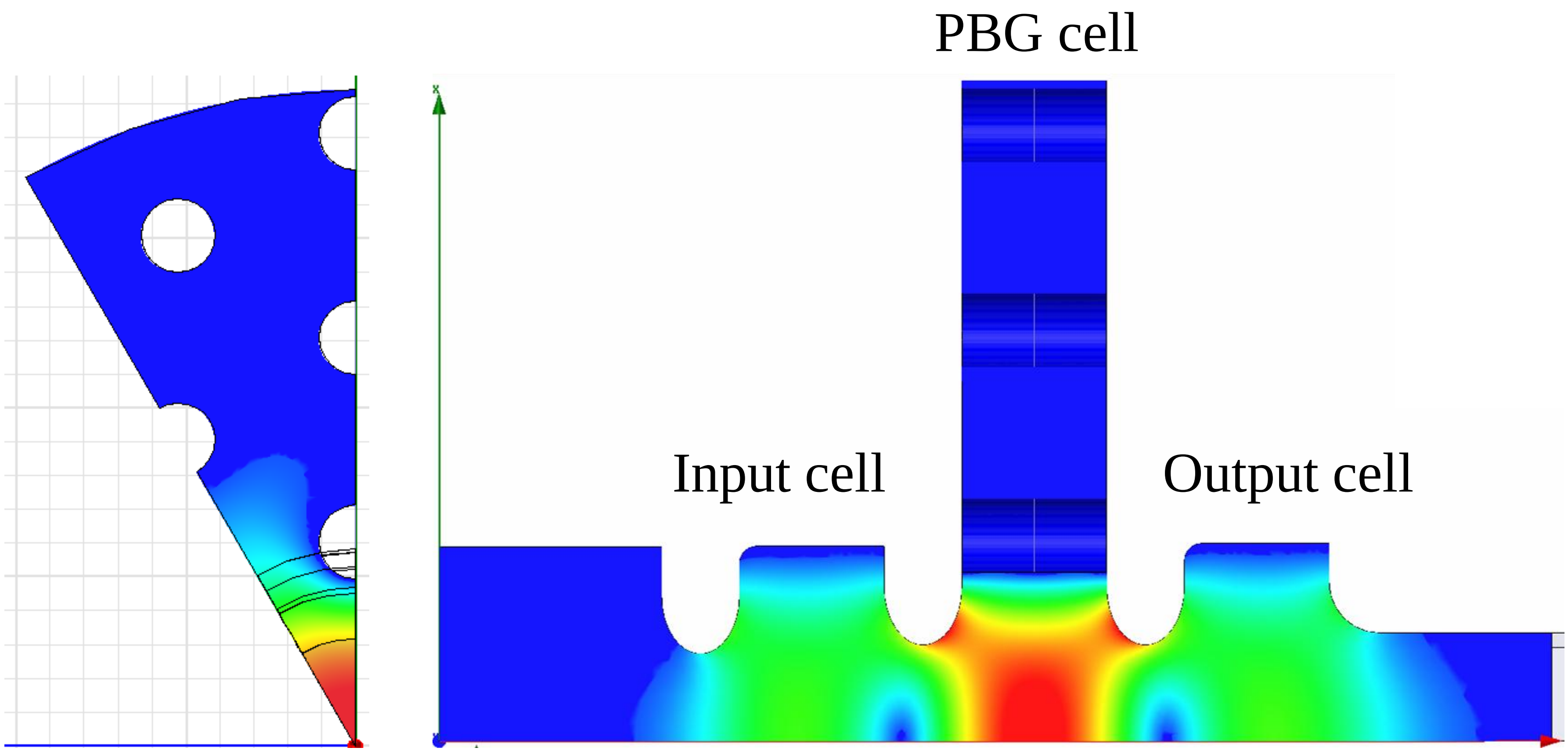
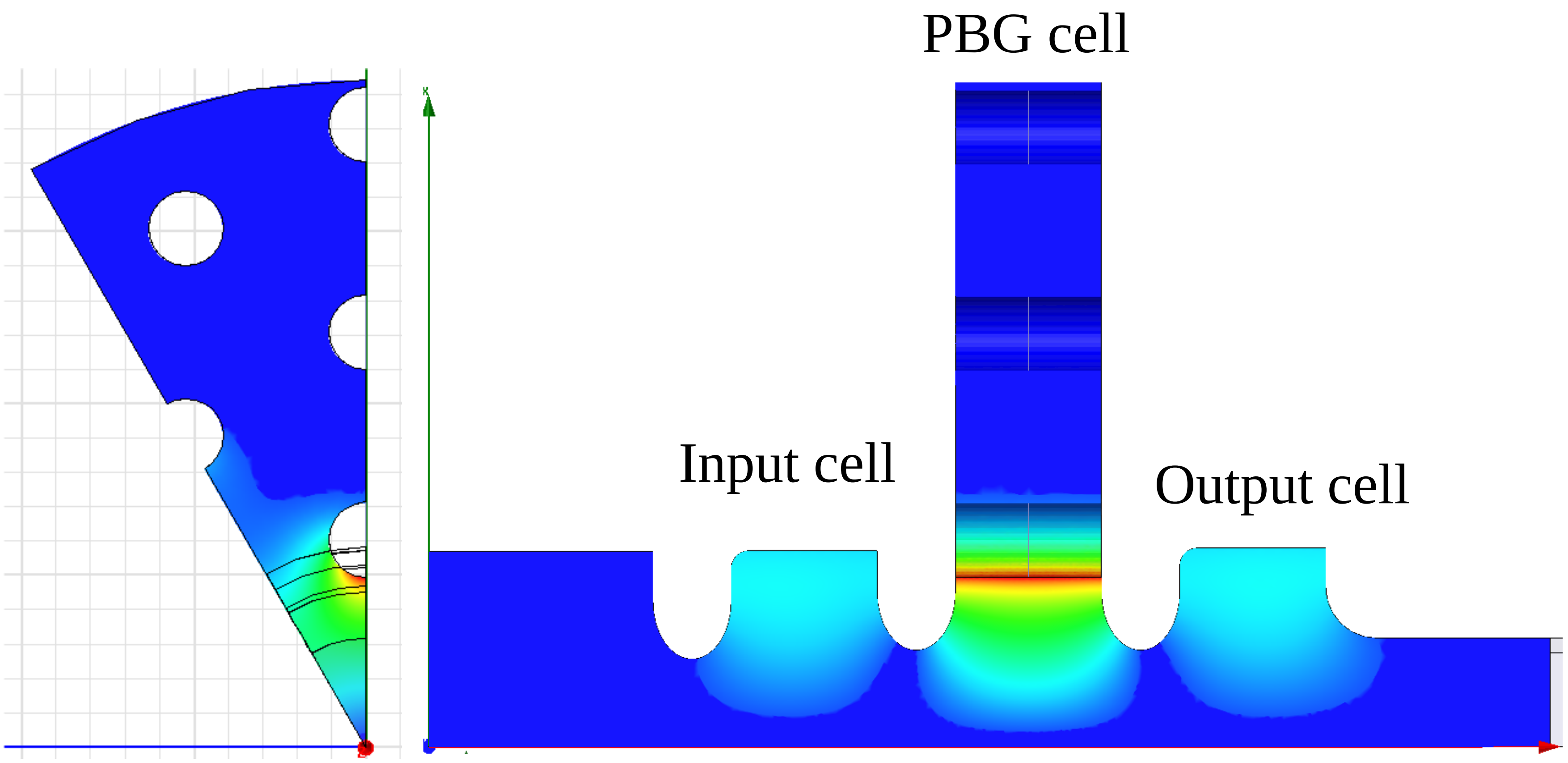
Electric Field

- For 5.9 MW of power, 100 MV/m gradient = 208 MV/m surface field on iris

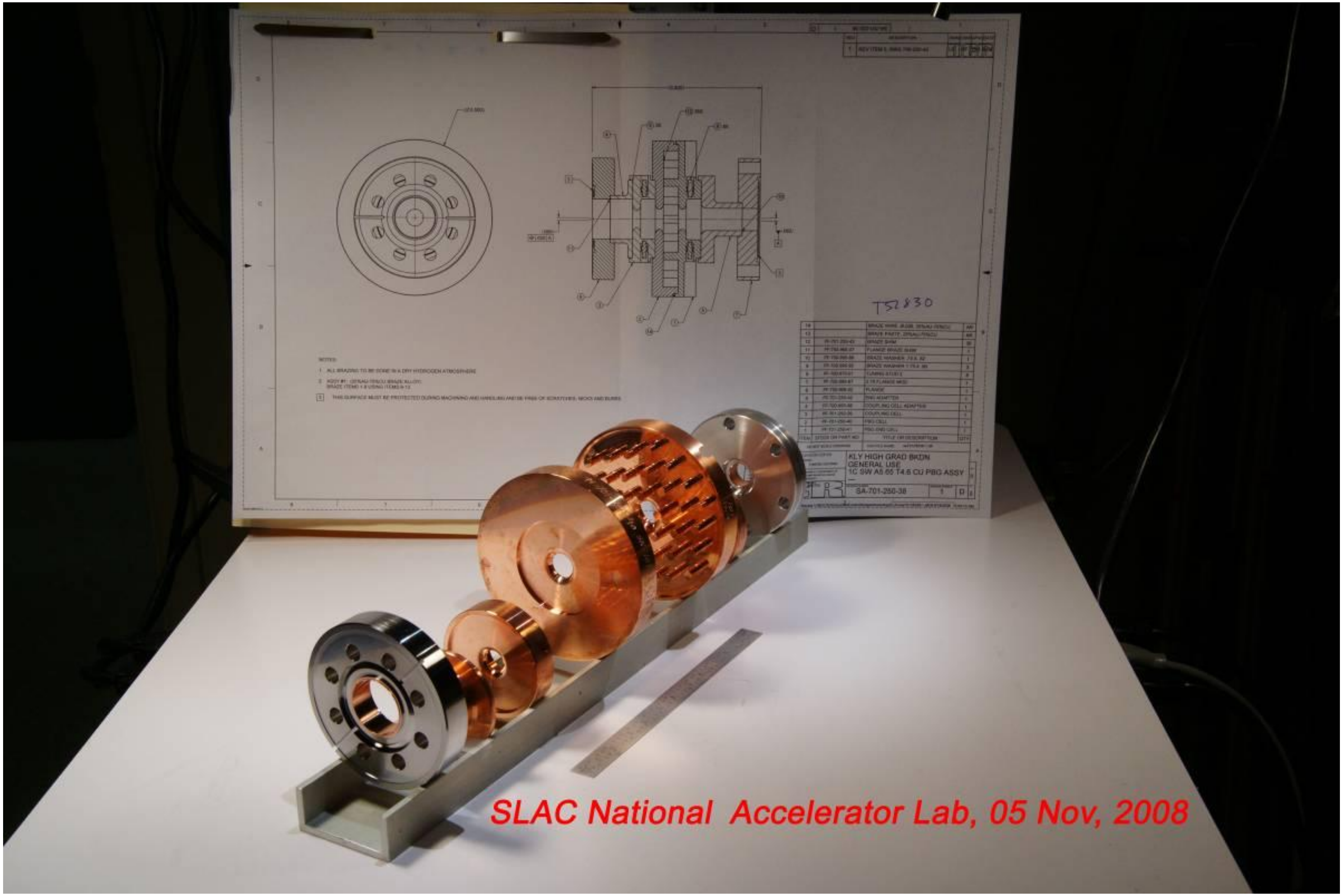


Magnetic Field

- For 5.9 MW of power, 100 MV/m gradient = 890 kA/m surface field on inner rod



PBG Structure Fabricated at SLAC



Breakdown Data

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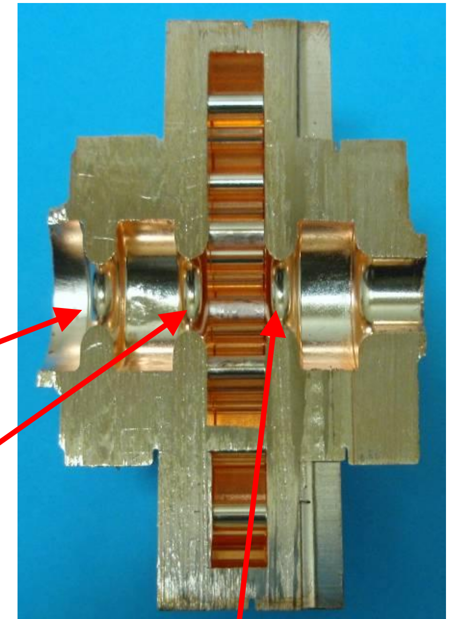
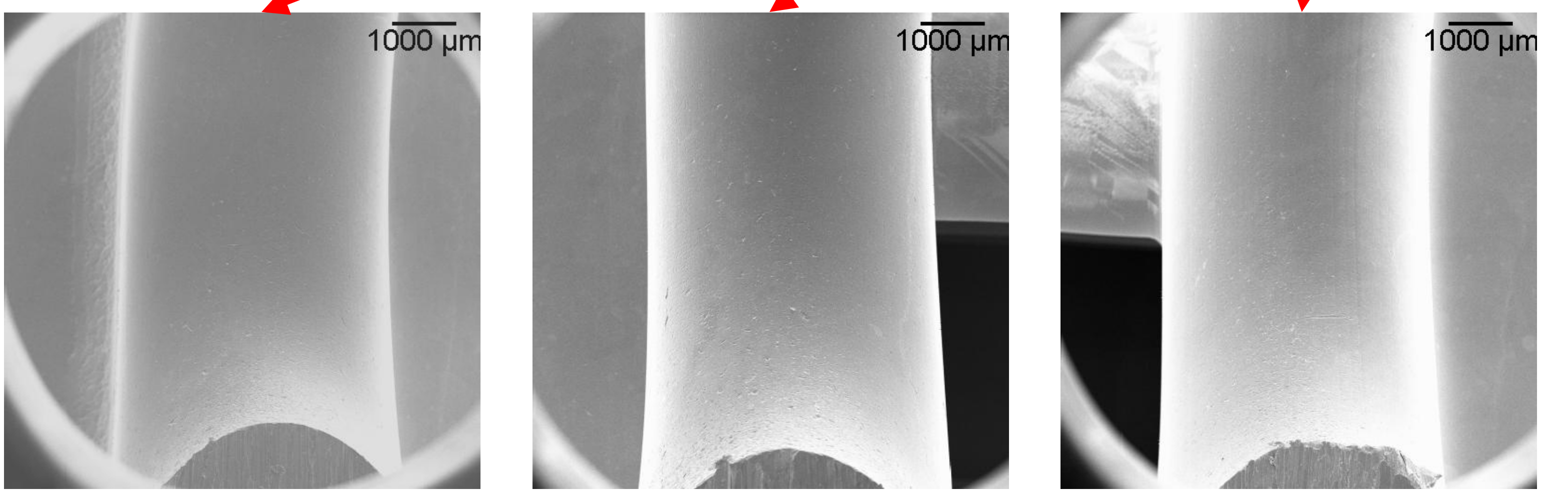
PBG SEM Damage

- After High Power testing
- Cut the structure in half
- Scanning Electron Microscopy

- Irises undamaged



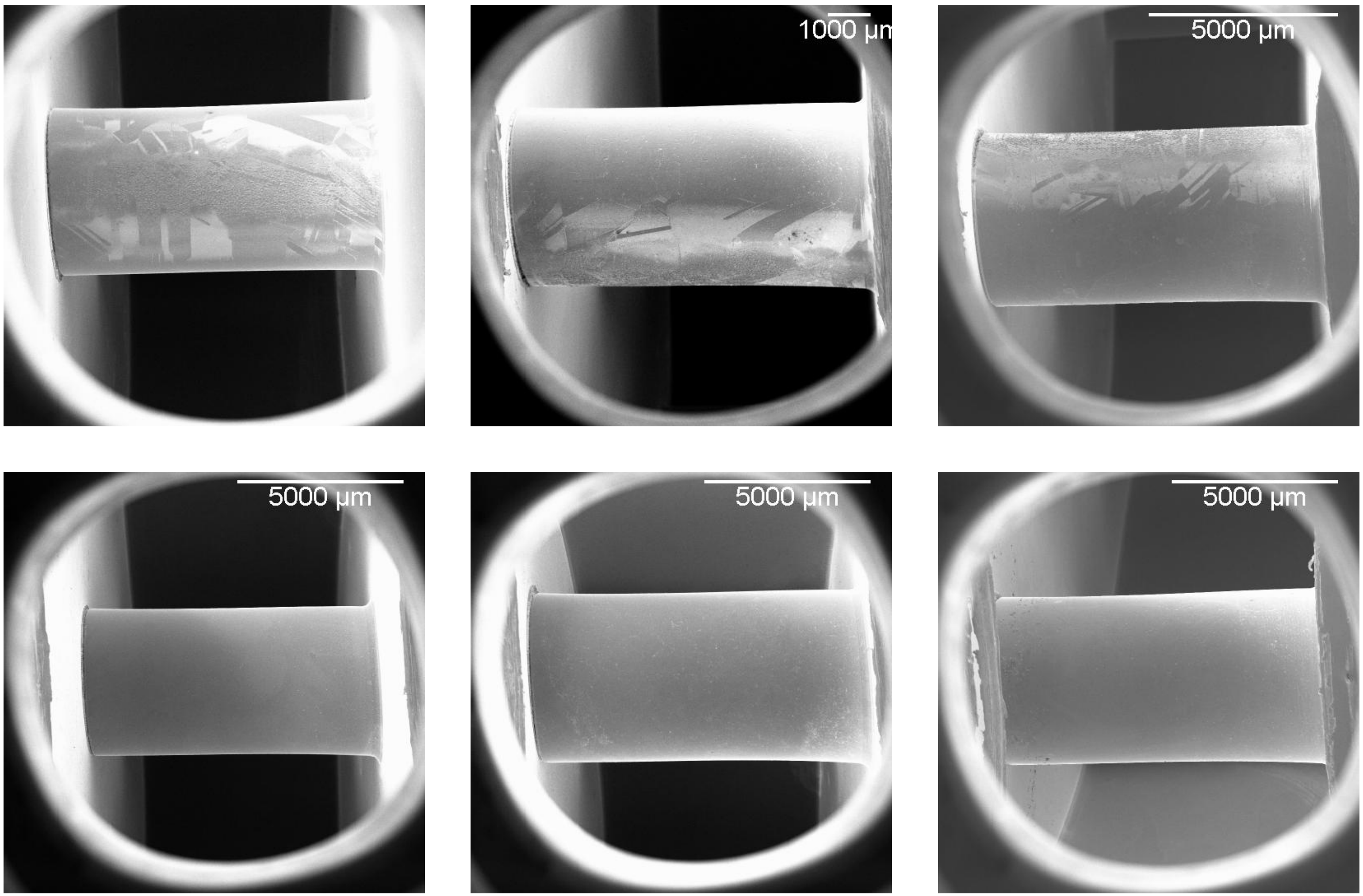


PBG SEM Damage

- Inner Rods damaged, Outer Rods undamaged

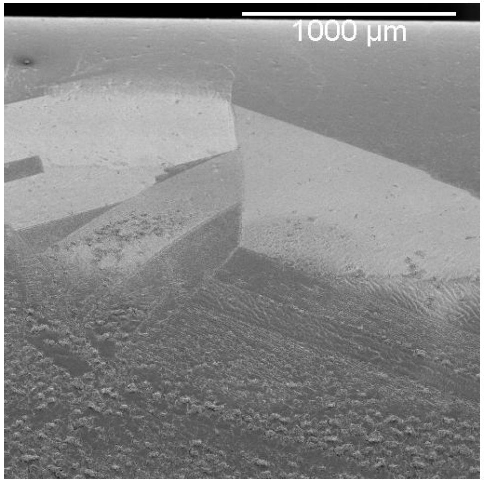
Inner Rods

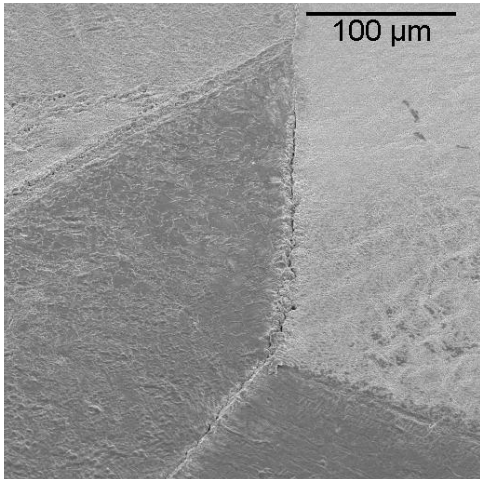
Outer Rods

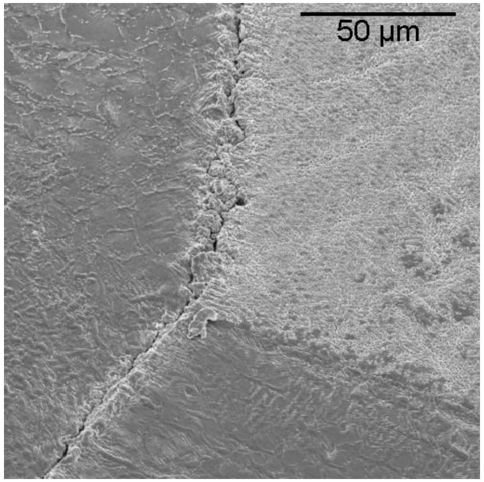


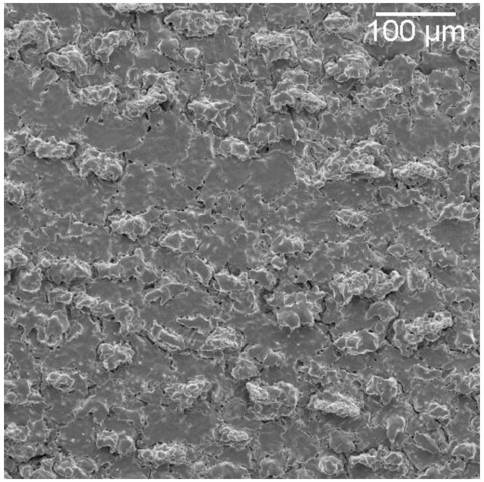
PBG SEM Damage

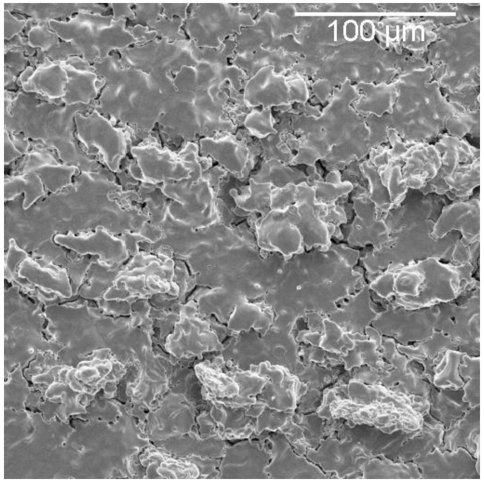
- Pulsed Heating damage on Rods, detail







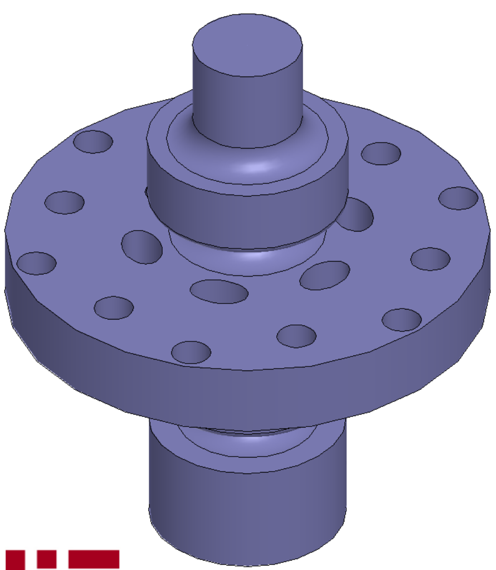


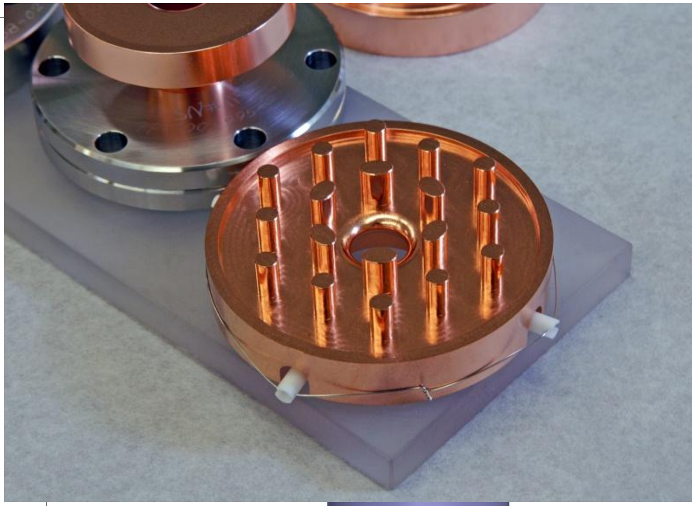


PBG Structures, *The Next Generation*

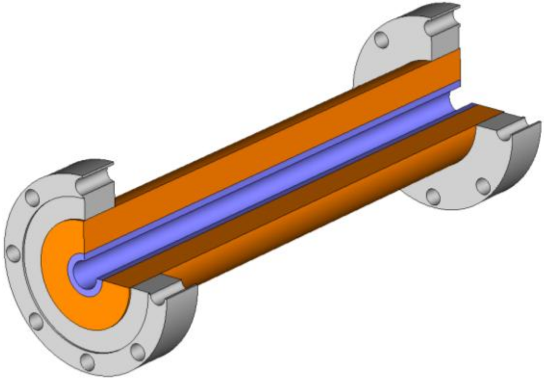
- Elliptical rod design with less pulsed heating
- 100 MV/m, 100 ns, 48 K temperature rise on rods, compared with 78 K for first PBG structure

Parameter	Value
Major Radius	3.399 mm
Minor radius	2.266 mm
Rod Spacing	12.588 mm
Outer Rod Radius	2.266 mm





Dielectric-Loaded Accelerators



DLA (Dielectric-Loaded Accelerator)

- Dielectric (instead of irises) is used to reduce v_{ph} to c.
- Ceramic is the material of choice
  - High ε, low $tan\ \delta$
  - High-vacuum compatible
  - Doesn't charge up

Advantages of DLA

- Simple geometry
- No field enhancements on irises
- High gradient potential
- Comparable shunt impedance
- Easy to damp HOM

Challenges of DLA

- Multipactor
- Broadband coupling

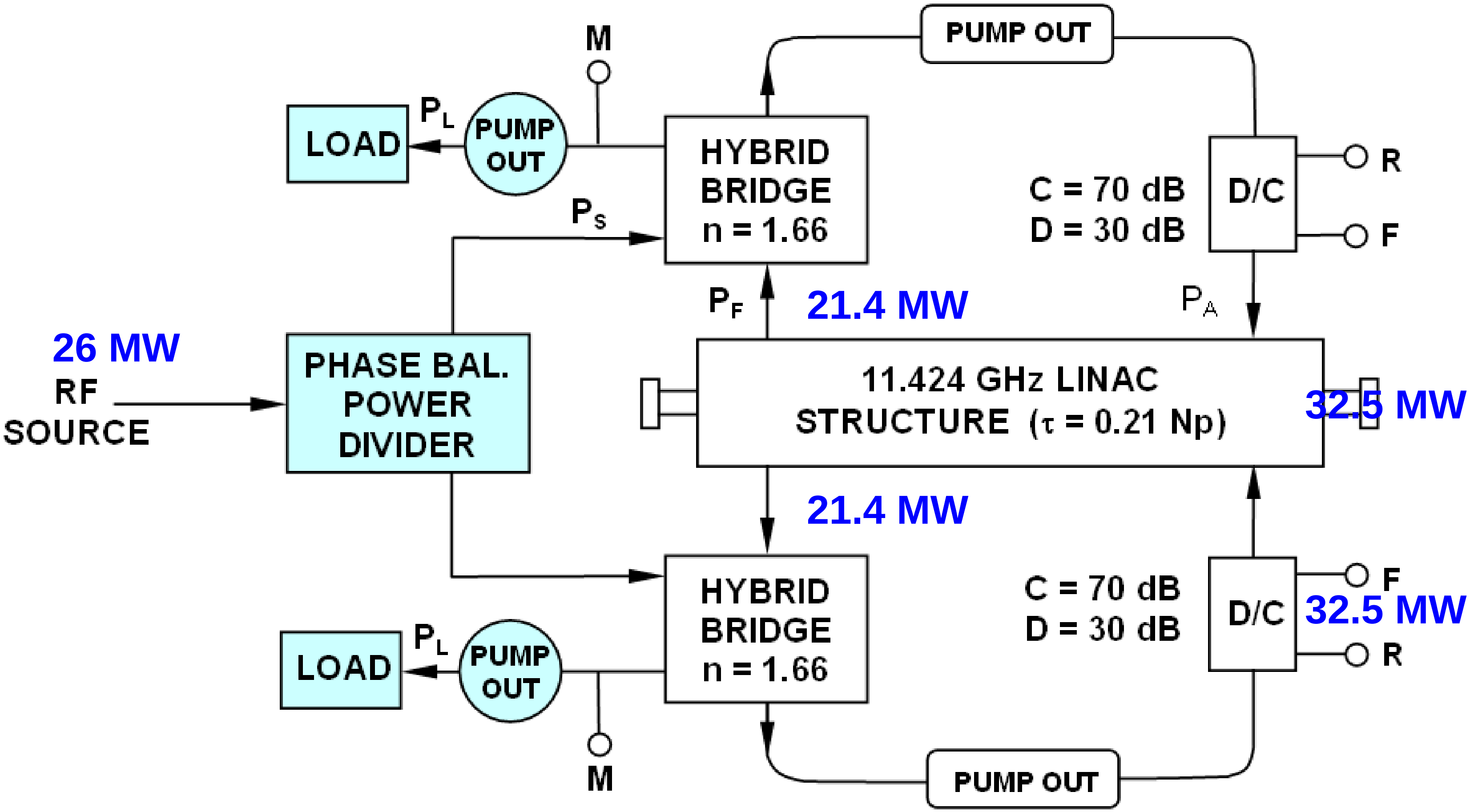
Selective Achievements @ ANL
(collaborated with Euclid, NRL, SLAC, etc.)

•Demonstration of the collinear and two-beam wakefield acceleration schemes in a DLA.
•100MV/m achieved in a wakefield DLA and 200ns, 15MV/m in an external DLA. No dielectric breakdown observed.
•Demonstration of 40MW high power rf generation in Dielectric based wakefield power extractors.
•Demonstration of a transverse wakefield damping technique in a DLA structure
•Demonstration of the enhanced transformer ratio in a collinear DLA.
•Development of a technique to tune the frequency of a DLA.

→ ***Goal: A cost effective, high-gradient dielectric-loaded accelerator.***

An 11.424 MHz Dual Resonant Ring System for High Gradient Testing CLIC/KEK/SLAC T18 Structures

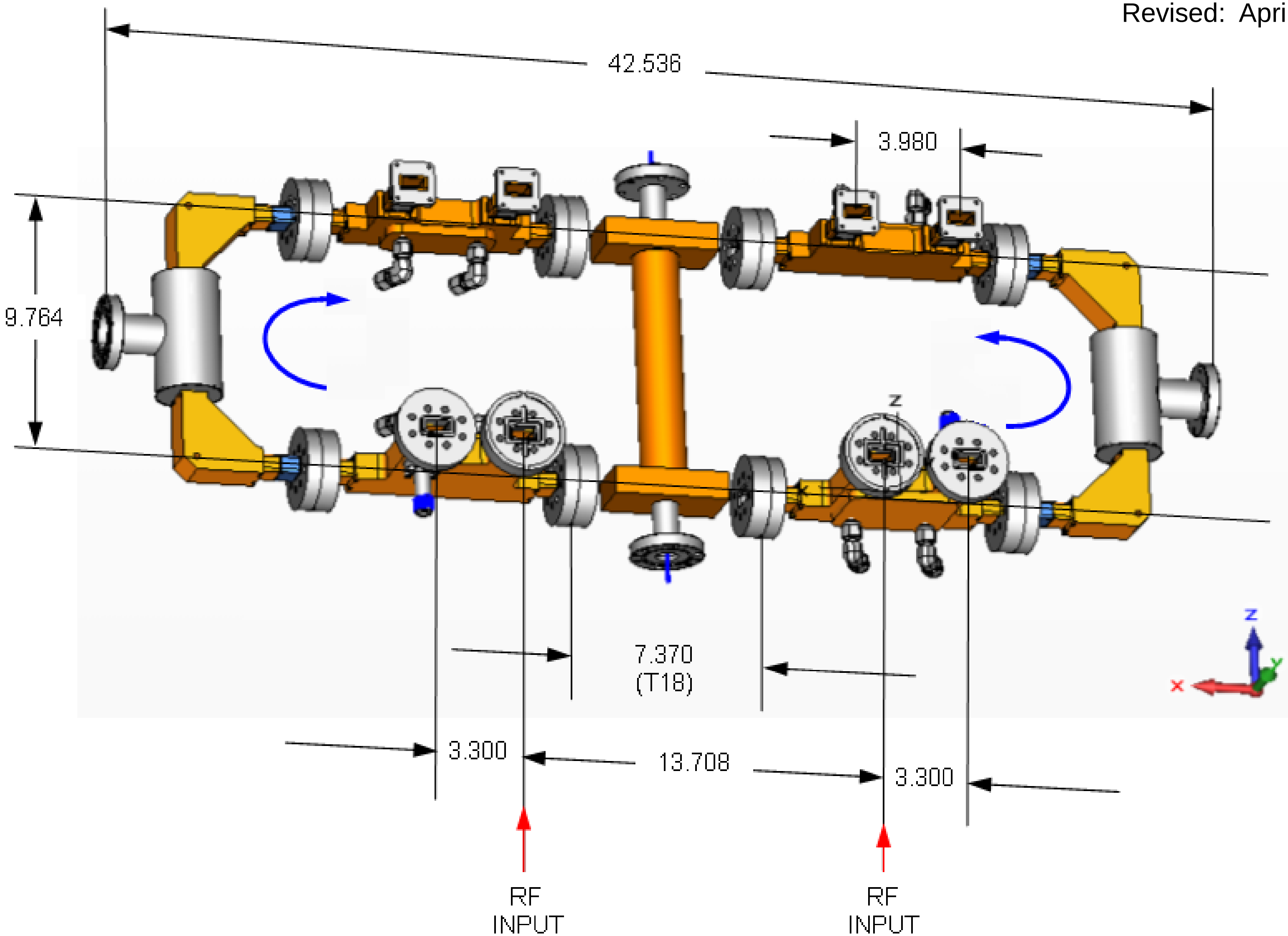
Power Distribution to Achieve an Unloaded Accelerating Gradient of 108 MV/m



Jake Haimson

Recirculation Implementation

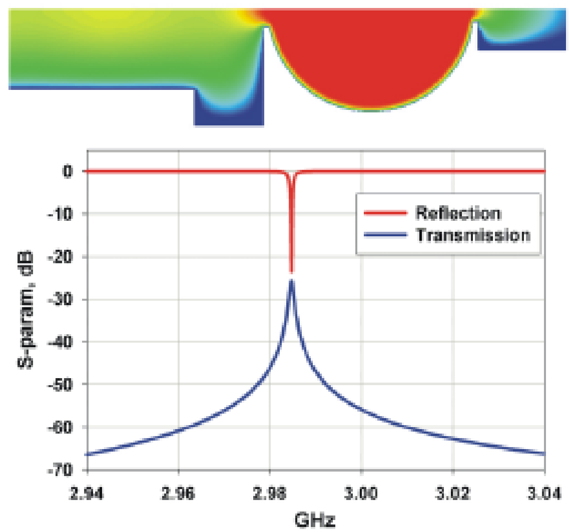
Revised: April 7, 2010



Jake Haimson

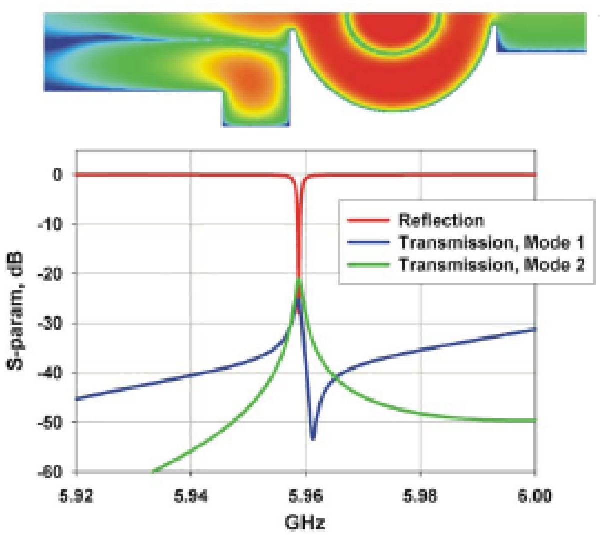
Coupling design for a bimodal cavity

3 GHz



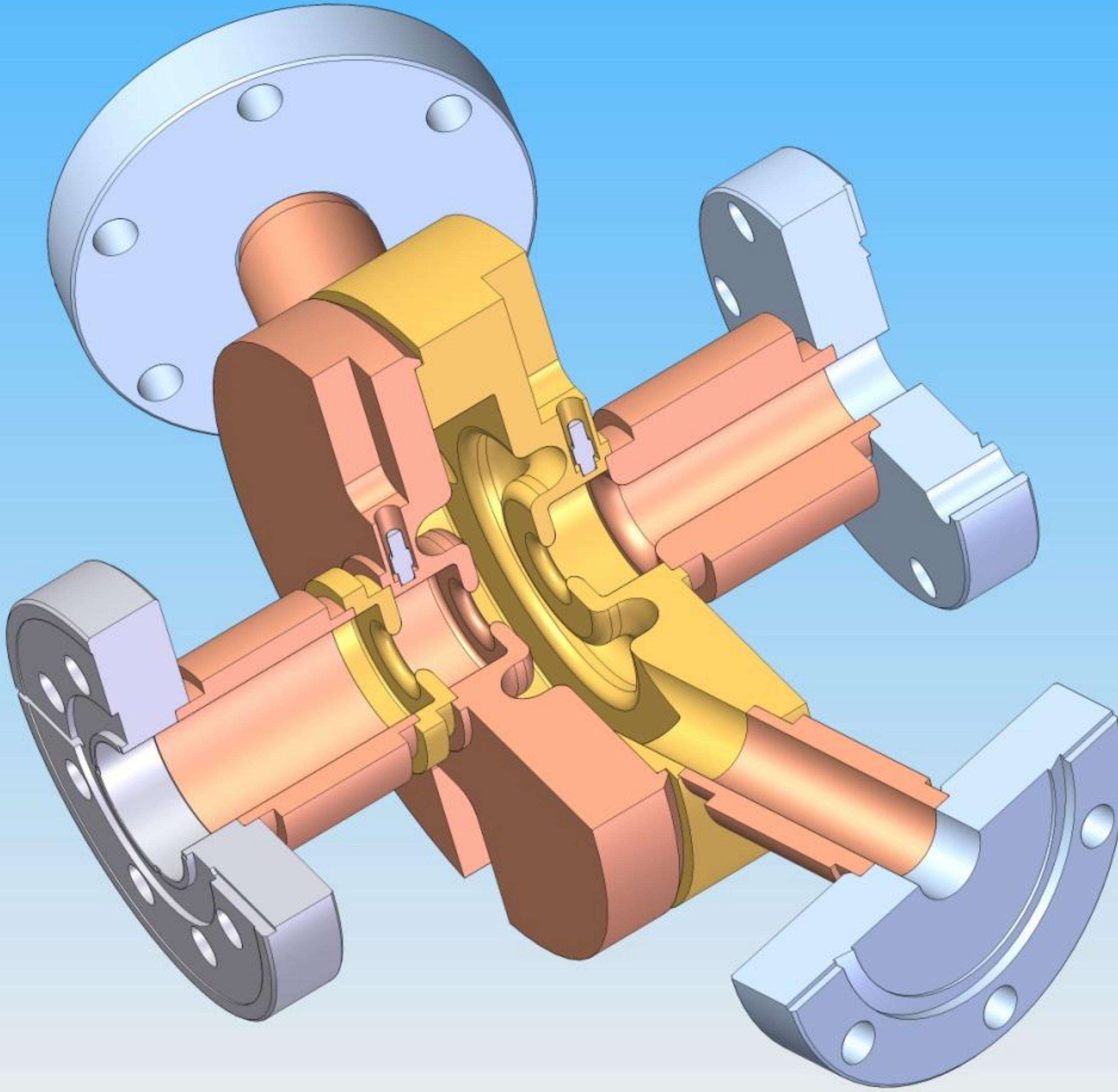
A coupling design using a high-frequency choke on the low-frequency input waveguide is used to couple power from two phase-locked high-power RF sources into cavities in an accelerator structure without the higher frequency component leaking through and being transmitted back to the lower frequency source.

6 GHz



Power coupling from waveguide at the left side into multimode cavity at 3.0 GHz and from waveguide at right into bimodal cavity at 6.0 GHz. Only slight penetration of 3.0 and 6.0 GHz radiation into the waveguide at the opposite side of cavity.

X Band Full Choke Structure 1C-SW-A3.75-T2.6 View Port-Cu

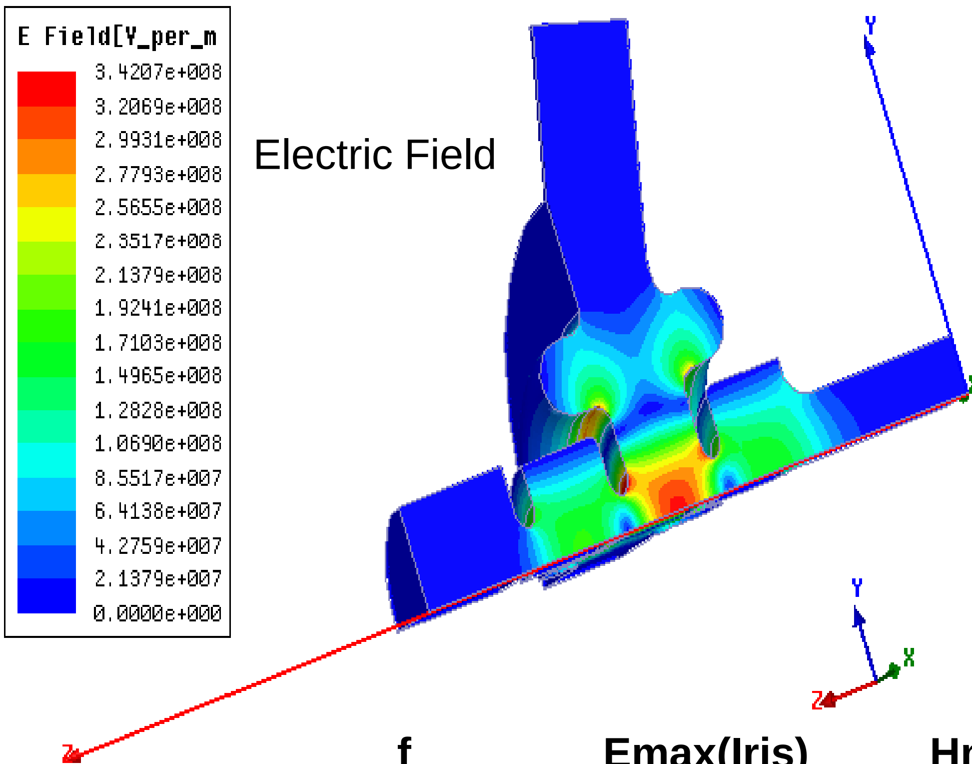


Solid model by David Martin

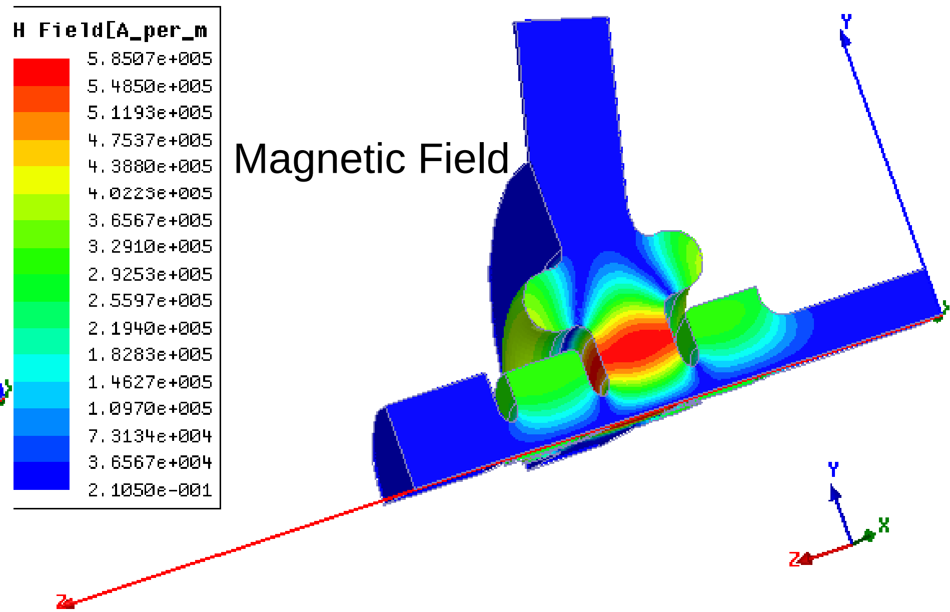
1C-SW-A3.75-T2.6-Full Choke View Port-Cu, Fields Normalized to 10MW RF Losses

Eigenmode	Frequency (GHz)
Mode 1	11.4228
Mode 2	12.4296

Electric Field



Magnetic Field

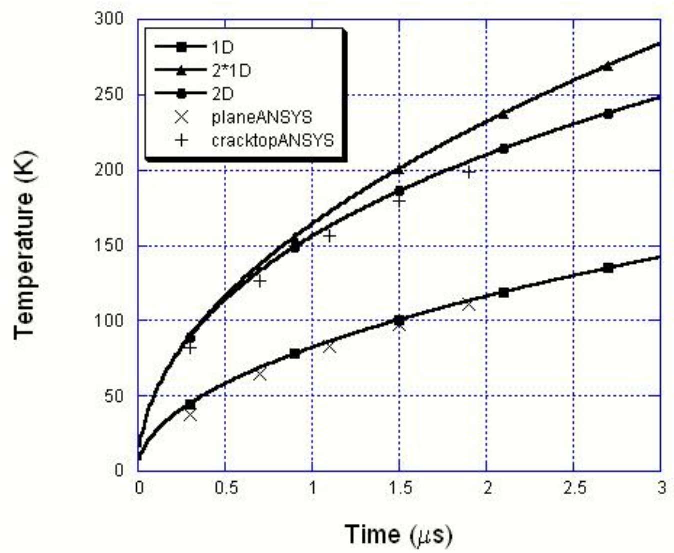


	f (GHz)	Emax(Iris) (MV/m)	Hmax(Iris) (kA/m)	Emax(ch) (KV/m)	Hmax(ch) (A/m)
At location		**Iris**	**Iris/cell**	**VPbase/@VP**	**VPbase/@VP**
	11.4228	350	200/580	50/28	300/200

A.D Yeremian, 3 May 2010

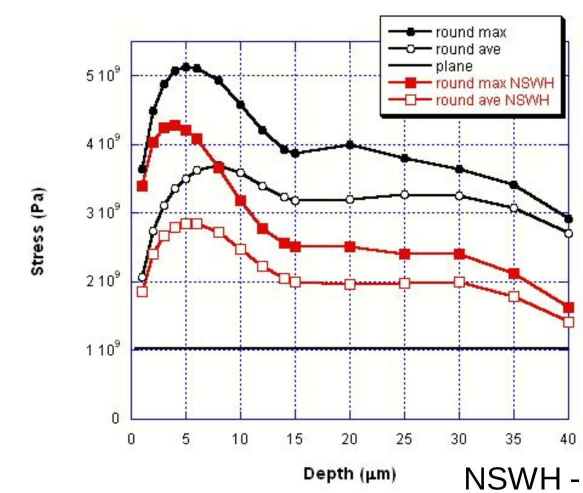
Temperature rise and stresses in cracks

(W. Zhu, J. Mizrahi, T. Antonsen and G. Nusinovich, AAC-2010, Tuesday, poster #18)

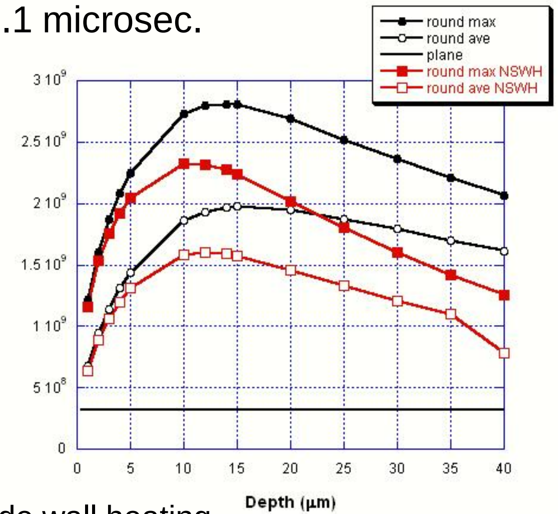


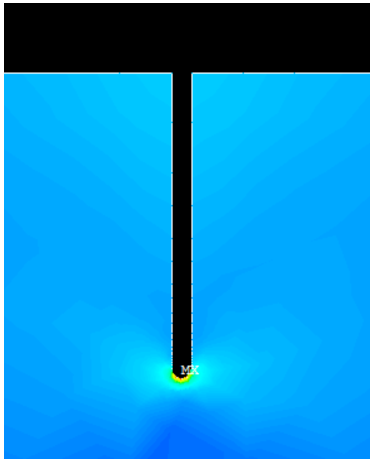
Stresses are maximal at the depth which corresponds to the heat propagation distance. So these stresses may result in the appearance of ‘wrinkles’ on structure surface, not in its complete deterioration.
But microprotrusions may appear on crack rims.

0.21 microsec.



2.1 microsec.





NSWH - no side wall heating

Point Charge Model

Dmytro Kashyn, Gregory Nusinovich, Thomas Antonsen, Jr. and Kevin Jensen

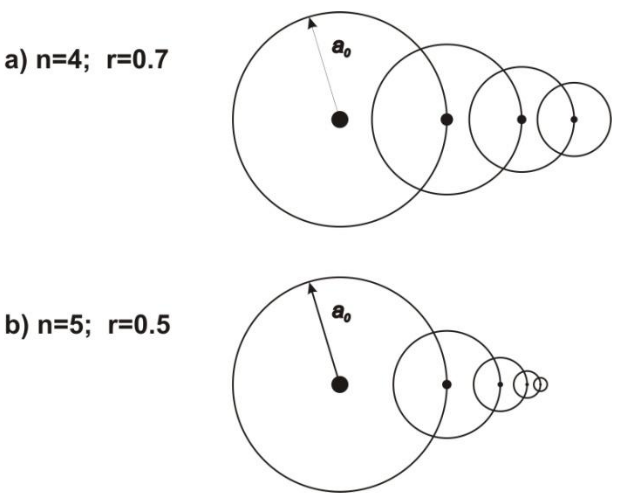
Point Charge Model (PCM) is a good way to describe the sharp protrusions. This model was originally developed to study field emitters.
Define the equipotential line for the *n*-th charge as a_n, then the magnitude of the charge can be related to the a_n.
Charges are assembled into the line such that the *n*-th charge is located on the apex of *n-1*-th sphere. This assembly approximates the protrusion. The field at the tip radius can be determined analytically if the ratio $a_{n+1}/a_n=r$ for all n.

If the ratio $a_{n+1}/a_n=r$ is constant, then an analytical expression for the potential, electric field and for the amplification factor β can be derived.

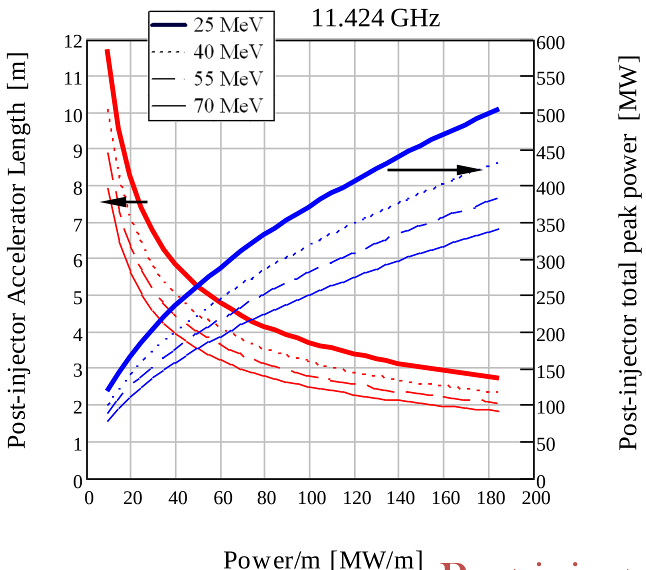
$$V_n(\rho,z)=F_0 a_0\left\{-\frac{z}{a_0}+a_0\sum_{j=0}^{n}\frac{\lambda_j}{\sqrt{\rho^2+(z-z_j)^2}}\right\}$$

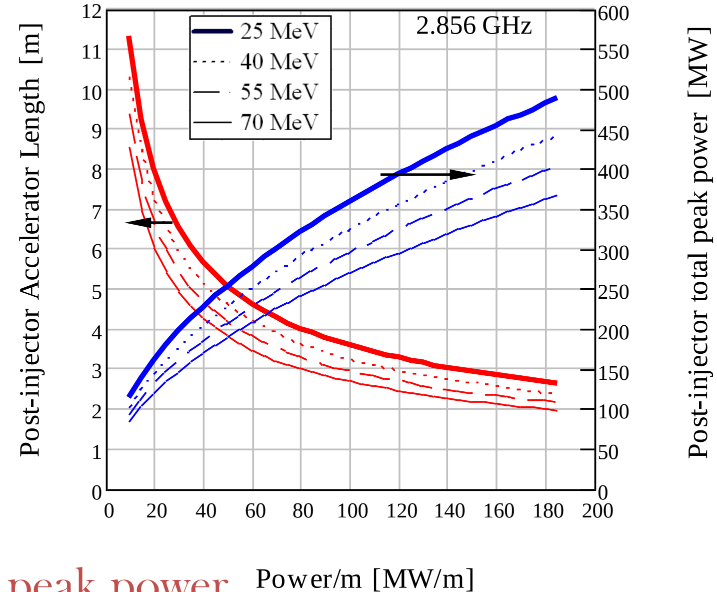
λ_j is the magnitude of the charge, determined from the boundary condition:

$$V_n(0,z_{n+1})=0$$

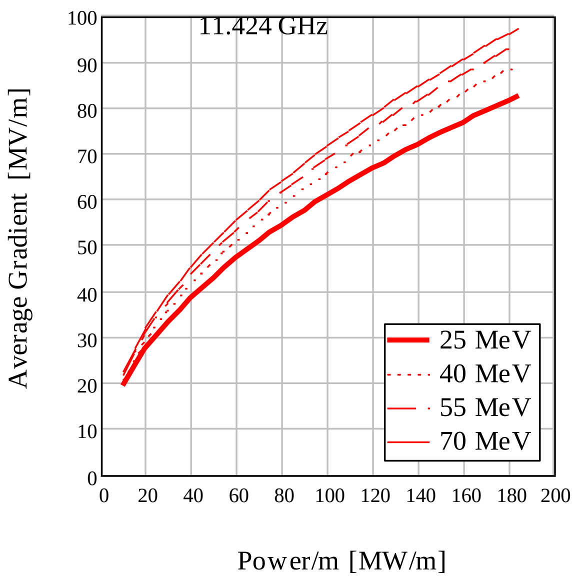


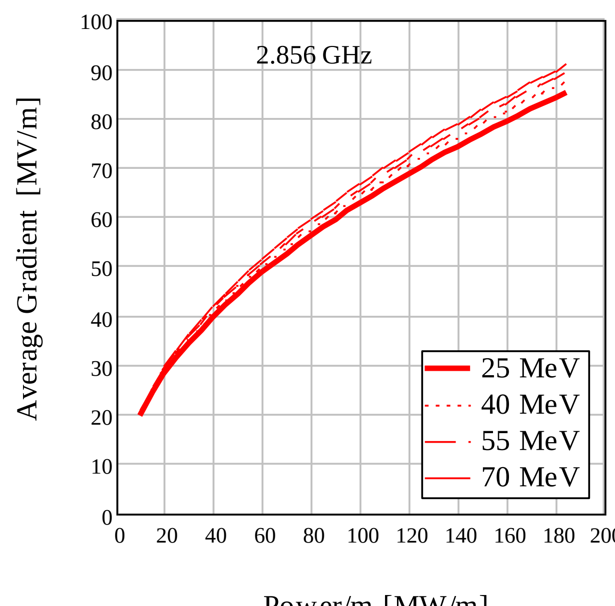
Length, Total Peak Power and average gradient of 11 GHz and 3 GHz for a 250 MeV proton linac for compact Therapy Machines





Post-injector length and total peak power

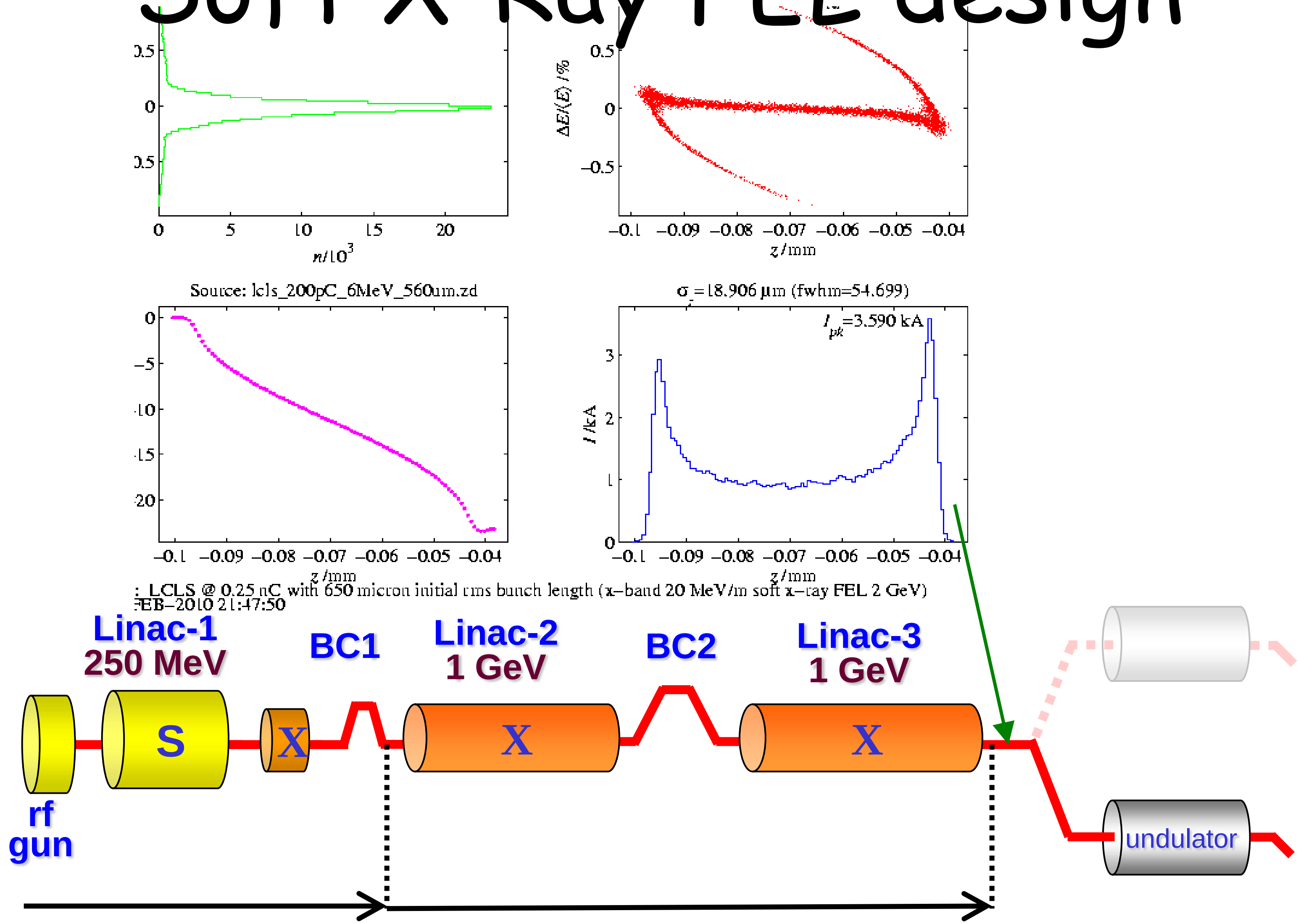




Average gradient of the post-injector accelerator

V.A. Dolgashev, 17:51, 6 April 2009

Soft X-Ray FEL design



LCLS-like injector

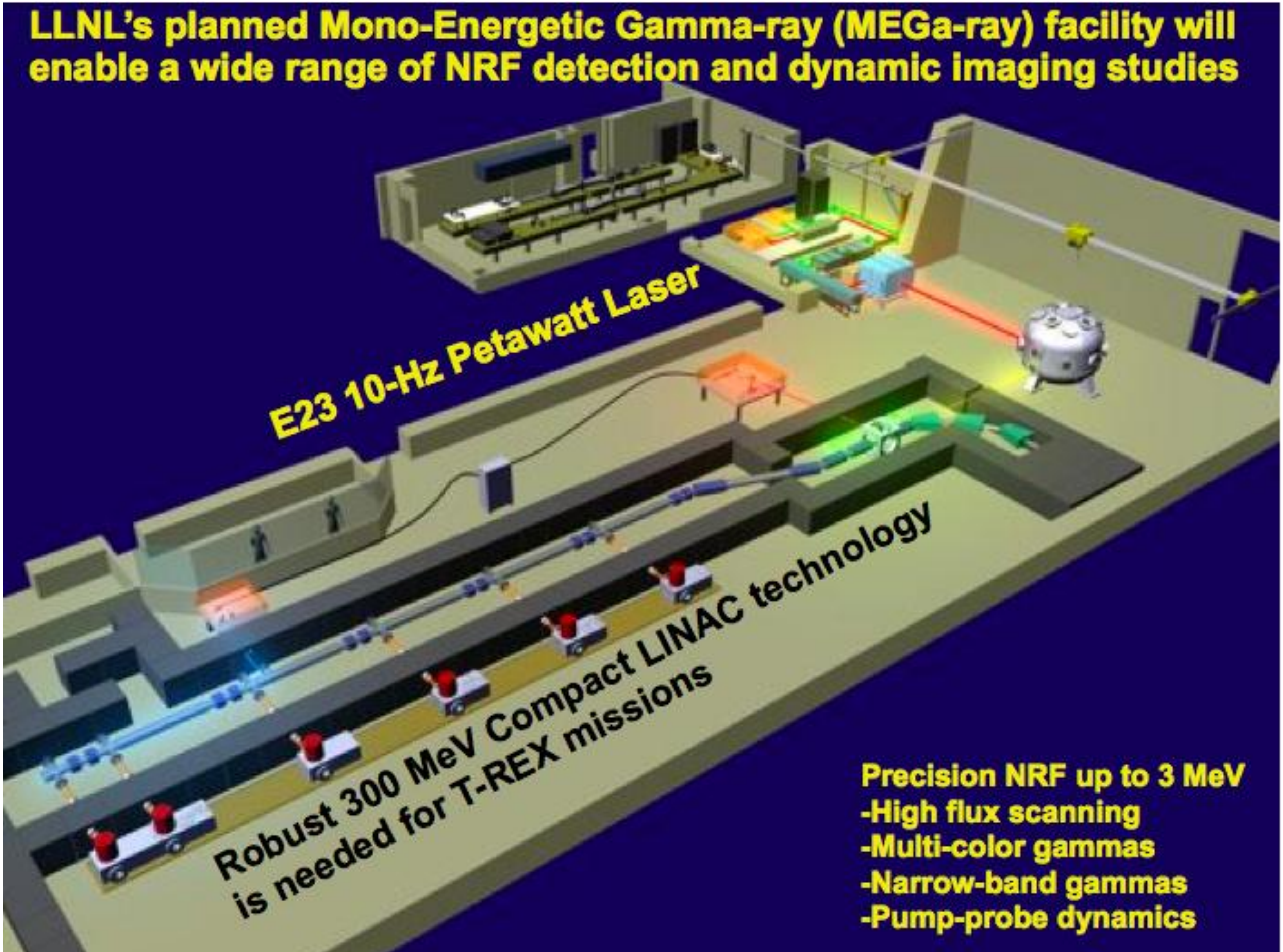
L~50 m

250 pC, $\gamma\varepsilon_{x,y} \approx 0.4\ \mu m$

X-band main linac+BC2

G~20 MV/m, L~100 m

Zhirong Huang


LLNL's planned Mono-Energetic Gamma-ray (MEGa-ray) facility will enable a wide range of NRF detection and dynamic imaging studies
E23 10-Hz Petawatt Laser
Robust 300 MeV Compact LINAC technology is needed for T-REX missions
Precision NRF up to 3 MeV
-High flux scanning
-Multi-color gammas
-Narrow-band gammas
-Pump-probe dynamics

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 hope to prove a structure capable of exceeding 140 MV/m gradient
- Wakefield damping features are being studied theoretically and experimentally.
- Accelerator structures made of copper alloys are being studied
- The effect of beam-loading on gradient needs 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.
- Ultra High Gradient accelerator structures will be useless without the development of efficient RF sources to drive them. The development of these sources 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.
- Magnetic field plays a very important role in determining the breakdown probability in a given structure
- 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 wakefield damping. This is expected in the near future.