Progress on High Gradient Research

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SLAC National Accelerator Laboratory

PAC09
May 6, 2009

Acknowledgment

* The work being presented is due to the efforts of
  - V. Dolgashev, L. Laurent, F. Wang, J. Wang, C. Adolphsen, D. Yeremian, J. Lewandowski, C. Nantista, J. Eichner, C. Yoneda, C. Pearson, A. Hayes, D. Martin, R. Ruth, S. Pei, Z. 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
  - J. Norem, ANL
  - G. Nusinovich et. al., University of Maryland
  - S. Gold, NRL
  - Bruno Spataro, INFN Frscati

Overview

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

Collaborations

* It was recognized early that such a study requires us to harness the national and international resources and infrastructures.

* Hence, we created a national collaboration which comprises:
  - SLAC, NRL, MIT, University of Maryland and ANL, University of Colorado, SBIR companies, and others.

* Also, we have an international collaboration which includes:
  - SLAC, CERN, KEK, and INFN, Frascati, Cockcroft Institute

* CTF3 Collaboration/CLIC, which is an international effort with great effect on high gradient research

* This effort which have a focus on the basic physiscs of high gradient accelerator is young. We have just started to get initial results from these efforts, we are just at the beginning.

Methodology

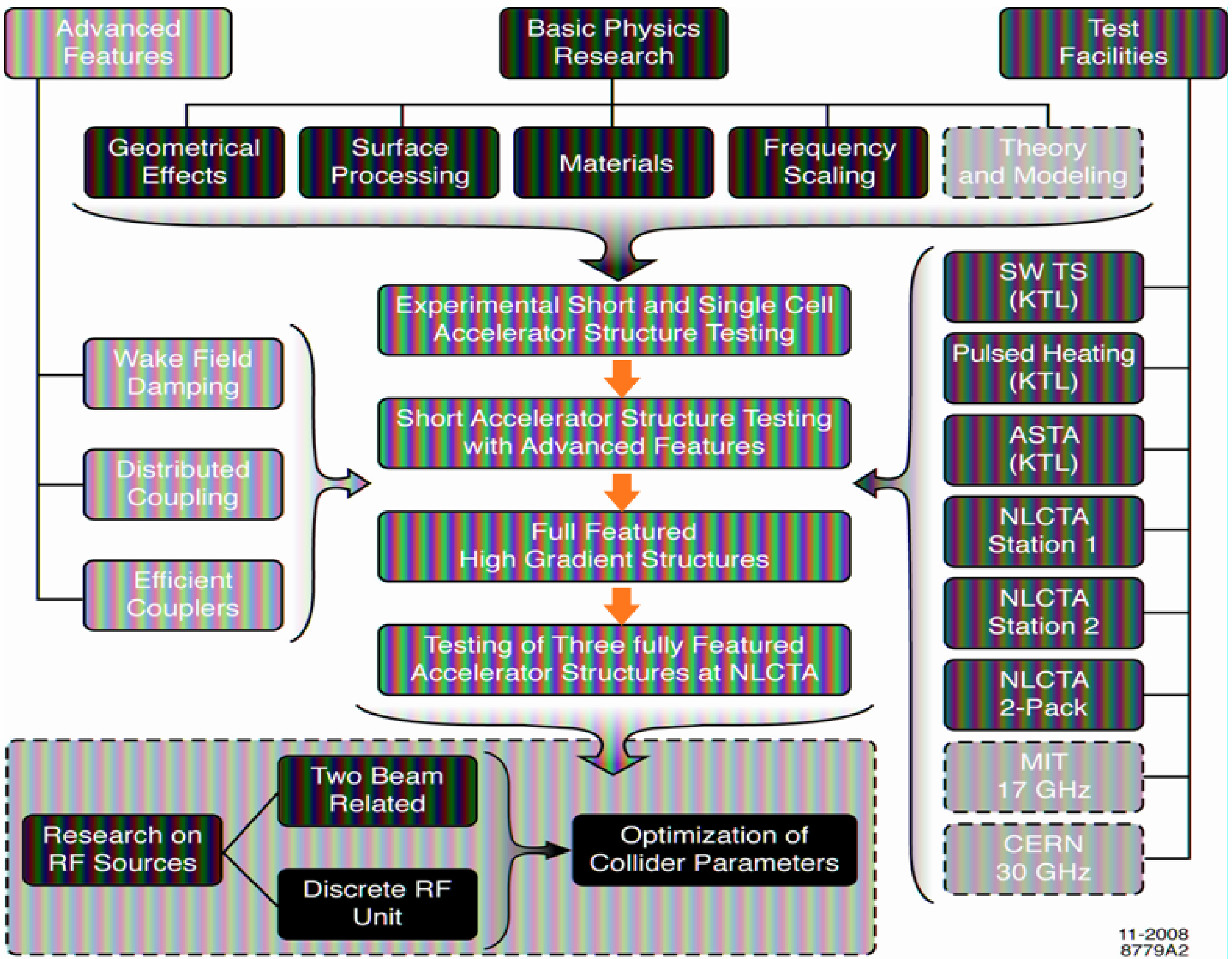
* Traditionally linear collider programs dictated the performance of accelerator structures. Here we would like to find the fundamental limitations on structures and design a collider around an optimized structure.

* we are trying to push the boundaries of the design to achieve:
  - Ultra-high-gradient; to open the door for a multi-TeV collider
  - High rf energy to beam energy efficacy, which leads to an economical, and hence feasible design
  - Heavily damped wakefield

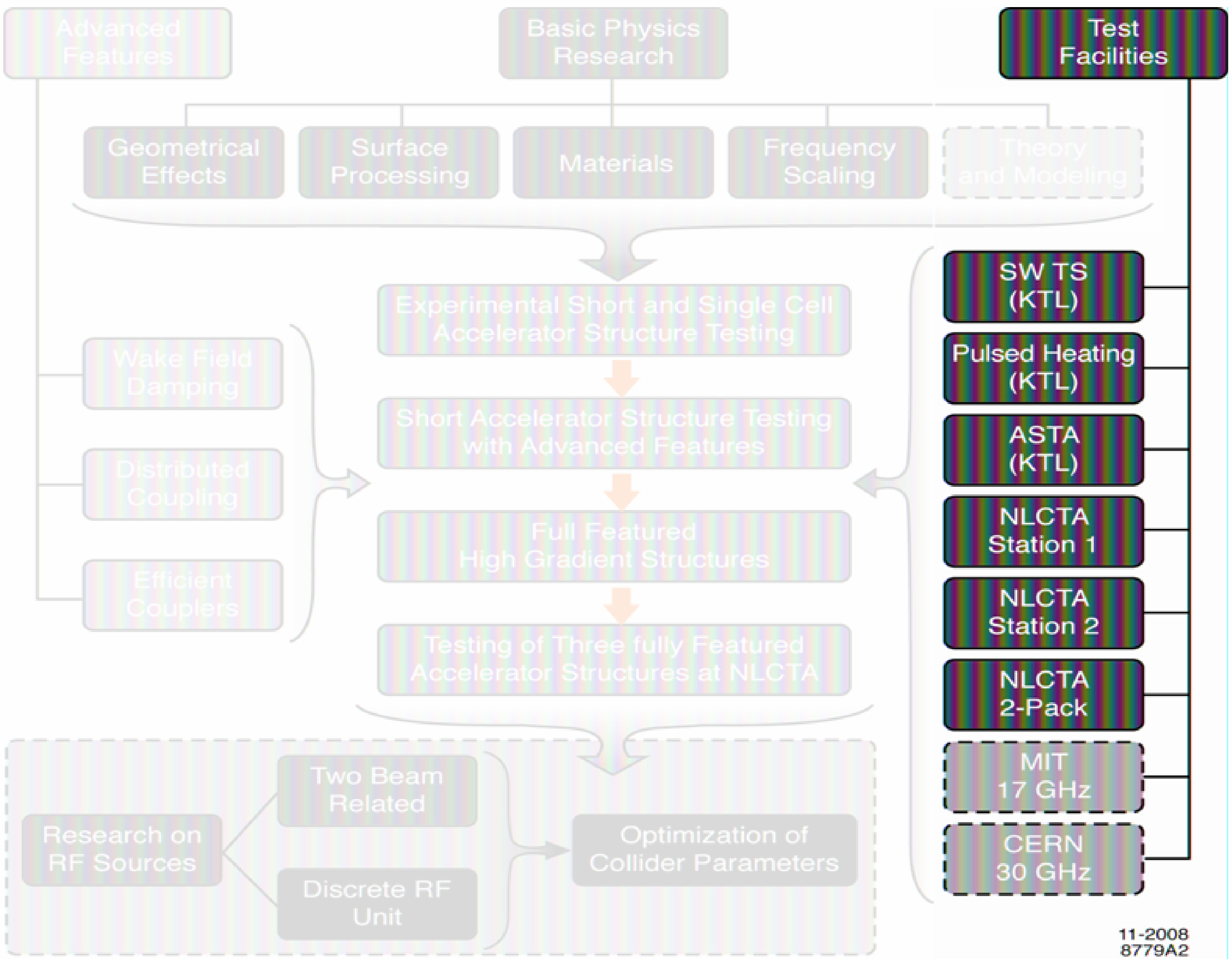
* We started from where the NLC/GLC efforts have ended; a 65 MV/m accelerator structure operating at X-band.

* We have to address fundamentals early; these include, but are not limited to:
  - Frequency scaling
  - Geometry dependence
  - Materials
  - Surface processing techniques (etching, baking, etc.)
  - Theory

Research and Development Plan



Research and Development Plan



Facilities

* At the beginning of the program we put an emphasis on test facilities internationally, within the US, and at SLAC.

* We helped the development of test facilities at MIT, and NRL

* SLAC facilities
  - Improved our infrastructure for rapid economical testing
  - Created new versatile test facilities: ASTA, Pulsed Heating Station, and the Two-Pack system.
  - Opened our facilities for users from the US and from around the world

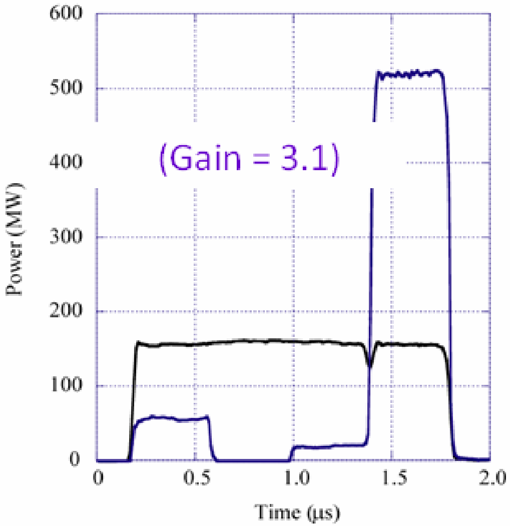
* We are planning with our CERN colleagues to use their test facility at 30 GHz.

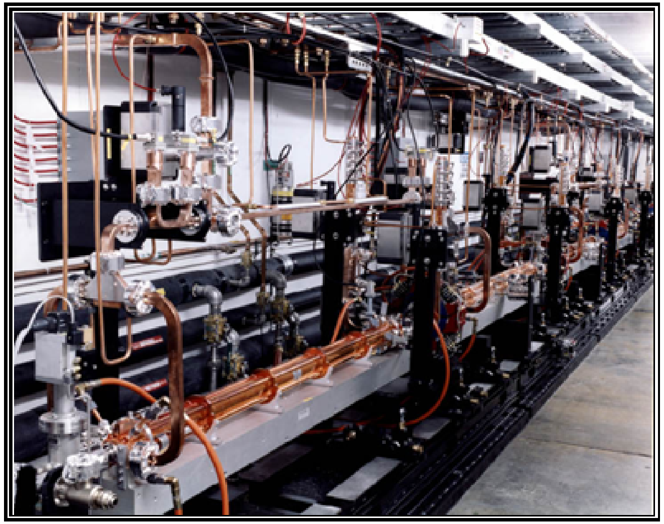
NLCTA - Layout

* 3 x RF stations
  - 2 x pulse compressors (240ns - 300MW max), driven each by 2 x 50MW X-band klystrons
  - 1 x pulse compressors (400ns – 300MW /200ns – 500MW variable), driven by 2 x 50MW X-band klystrons.
* 1 x Injector: 65MeV, ~0.3 nC / bunch

* In the accelerator housing:
  - 2 x 2.5m slots for structures
* Shielding Enclosure:

  suitable up to 1 GeV
* For operation:
  - Can run 24/7 using automated controls





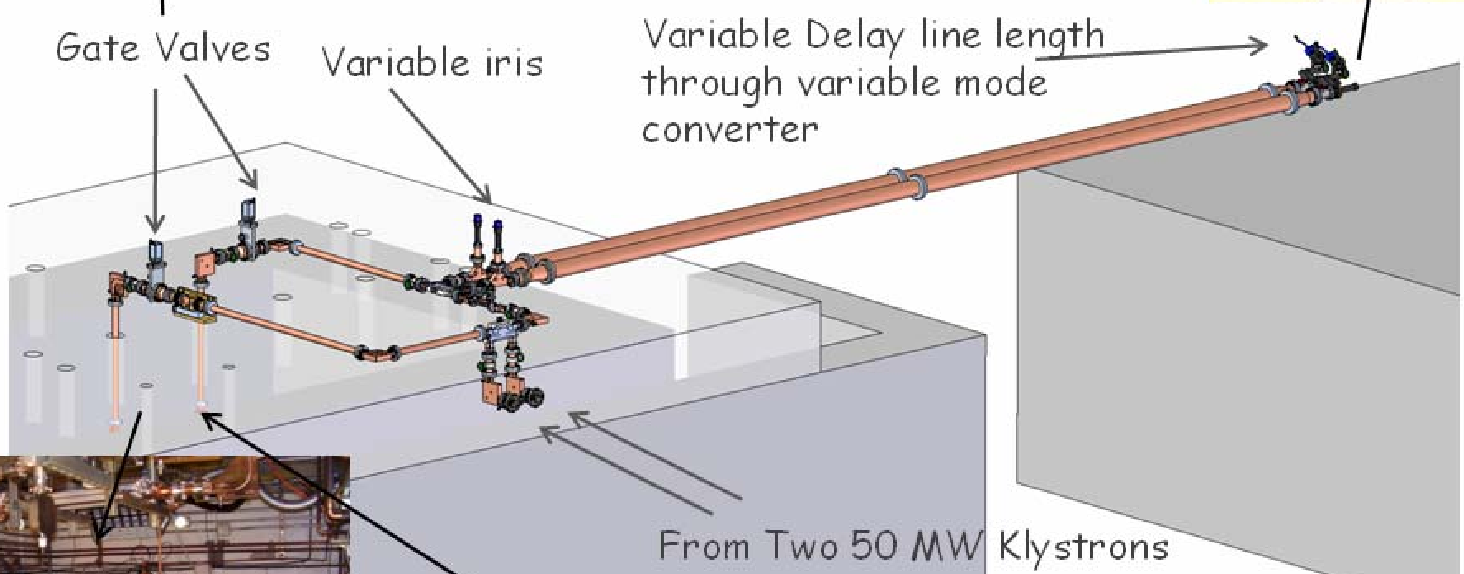
Klystron Test Lab - Elements

4 x RF Stations

- Stations #6 and # 8 = ASTA
  - 2 x 50MW 1.5 μs klystrons.
    - With a variable compressor (63ns / 132ns / 264 ns), or through a simple addition, they can produce:
      "100MW 1.5 μs" ~ "550MW 63 ns" and feed two experimental outputs in an enclosure.
    - Cost-effective testing due to new design of a gate valve (A.Gudiev)
- Station #4
  - 1 x 50MW 1.5 μs klystron
    - Dedicated to testing of standing-wave structures
    - Stand-alone shielding enclosure
- Stations #2
  - 1 x 50MW 1.5 μs klystron
    - Dedicated to pulsed-heating experiments
    - No shielding

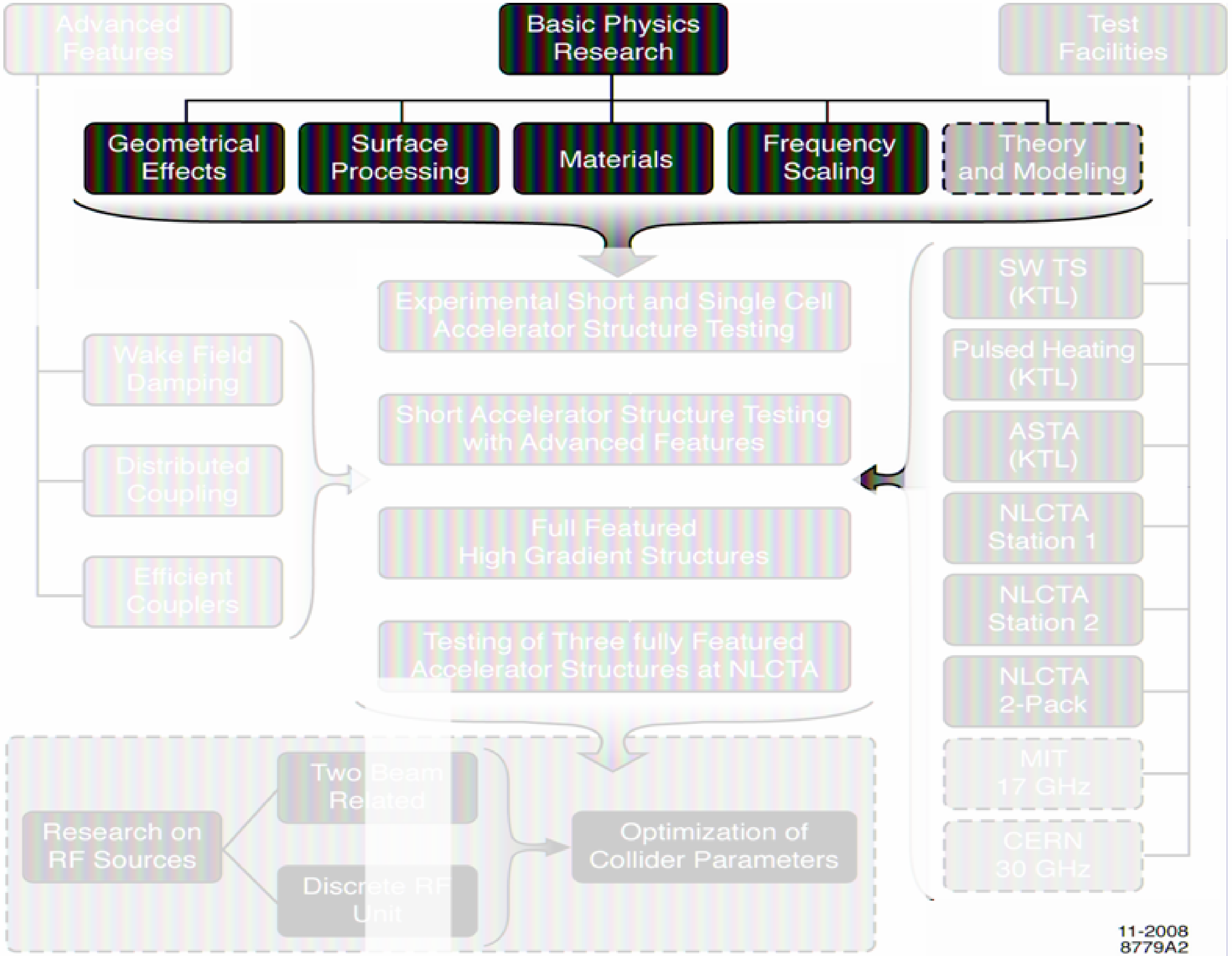
ASTA RF system

- Designed for economical testing of TW, SW accelerator structures, and waveguides.
- Add an electron gun to test gradients next year
- Versatile structure for future applications (beyond high gradient work)

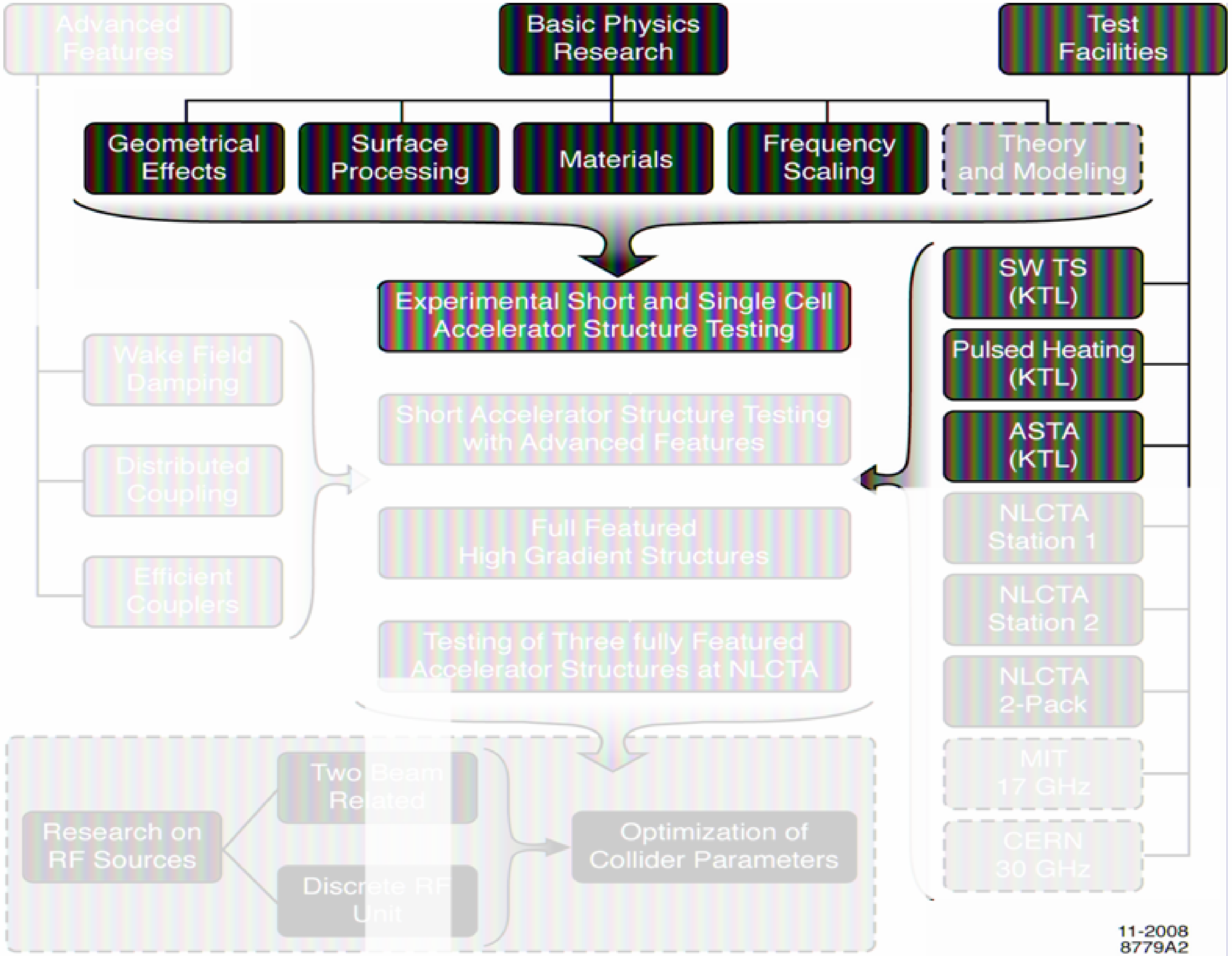


Two experimental stations inside the enclosure, one with compressed pulse and the other without the benefit of the pulse compressor.

Research and Development Plan

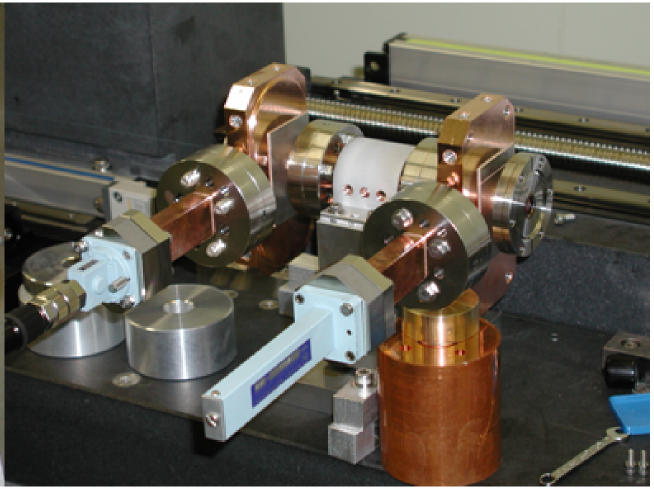


Research and Development Plan



Experimental Studies

* Basic Physics Experimental Studies
  – Single and Multiple Cell Accelerator Structures (with major KEK and CERN contributions)
    • single cell traveling-wave 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)
  Can only be done at NLCTA at SLAC



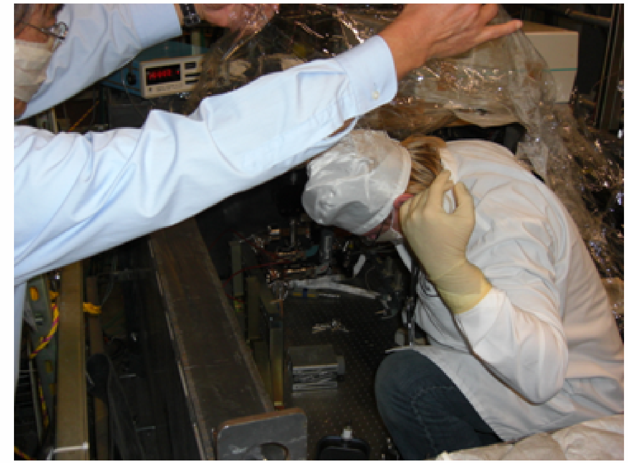
High Power Tests of Single Cell Standing Wave Structures

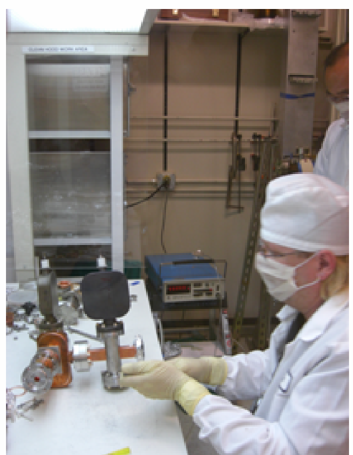
- Tested:
  - Low shunt impedance, a/lambda = 0.215, *1C-SW-A5.65-T4.6-Cu*, 4 tested
  - Low shunt impedance, TiN coated, *1C-SW-A5.65-T4.6-Cu-TiN*, 1 tested
  - Three high gradient cells, low shunt impedance, *3C-SW-A5.65-T4.6-Cu*, 2 tested
  - High shunt impedance, elliptical iris, a/lambda = 0.143, *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*, 2 tested
  - Cu Zr Structure 1 tested
  - CuCr Structure 1 tested
  - Cu Frascati Structure 1 tested
  - Photonic-Band-Gap in high gradient cell (in collaboration with MIT) 1 tested
  - Highest shunt impedance, a/λ = 0.105 1 tested
  - Clamped Structure (Under Test)
- Total of 18 tests completed (8 manufactured by KEK, Japan, and two by Frascati Italy)
- In manufacturing:
  - Three cells, WR90 coupling to power source,
  - High shunt impedance, made of CuCr
  - C10 structures (in collaboration with CERN, 4 structures being manufactured this year and 4 for next year)
  - Clamped Structures from CuCr, CuZr, CuAg, etc.

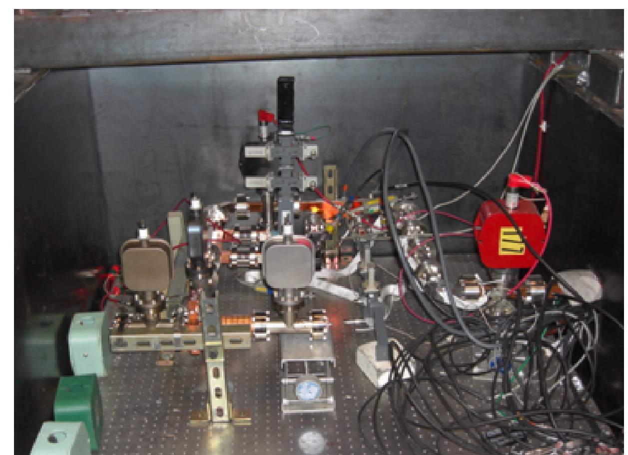
Surface processing

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

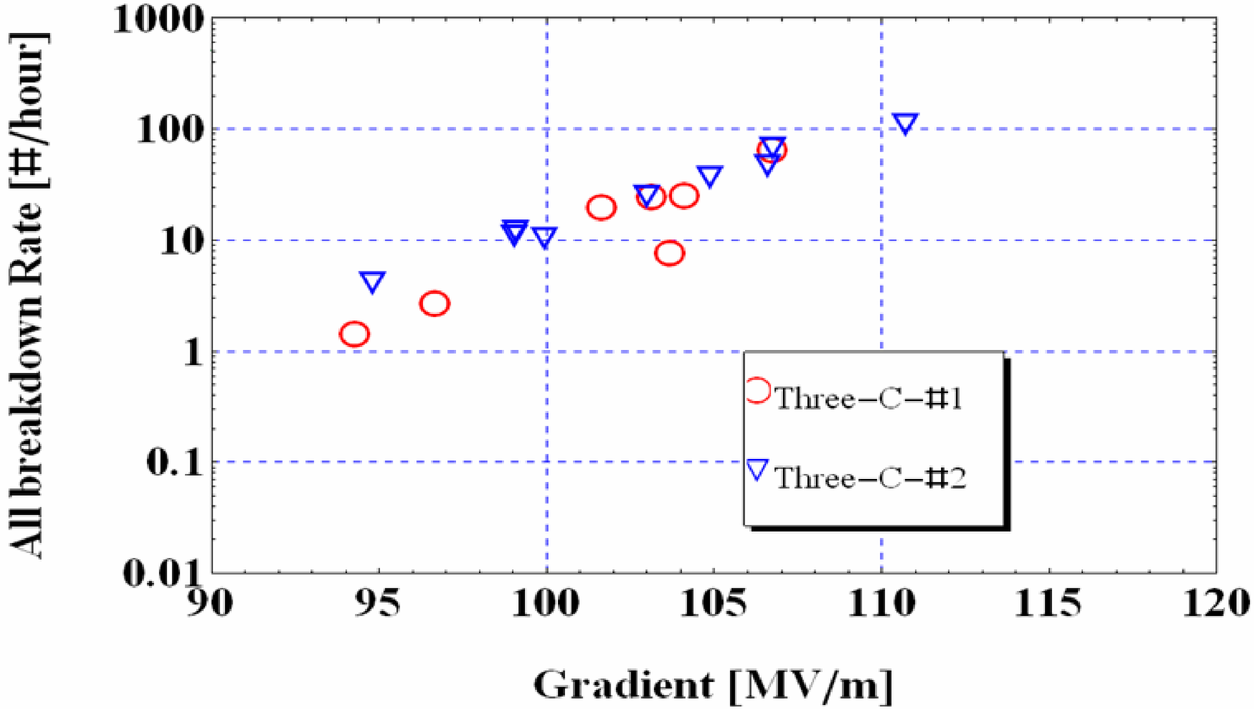
Δρ. Ψασυο Ηιγασηι ανδ Ριχηαρδ Ταλλεψ ασσεμβλινγ Τηρεε–Χ–ΣΩ–Α5.65–Τ4.6–Χυ–ΚΕΚ–#2







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

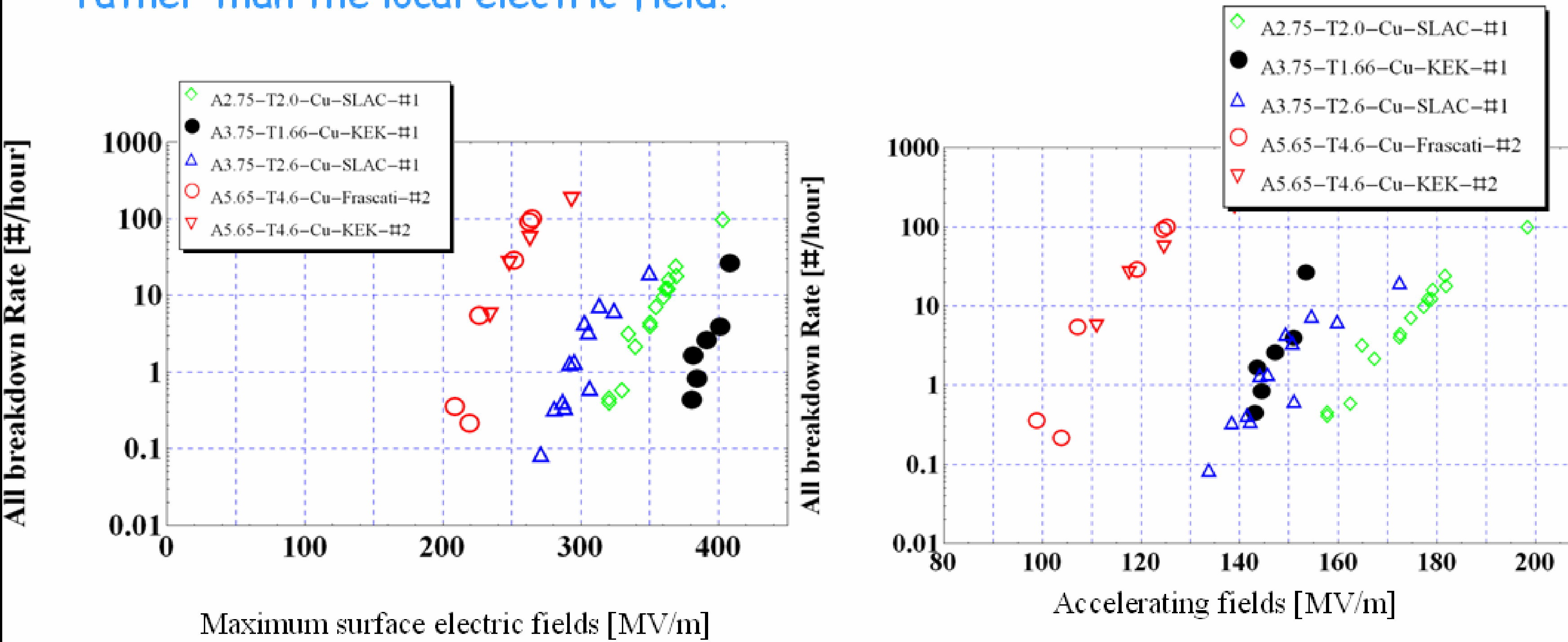


The near perfect surface processing affected only the processing time. The second structure processed to maximum gradient in a few minutes vs a few hours for the normally processed structure.

Geometrical Studies

3 different single cell structures: Standing-wave structures with different iris diameters and shapes; a/λ=0.21, a/λ=0.14, a/λ=0.14 (elliptical iris), and a/λ=0.105 and.

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



Geometrical Studies (Continued)

3 different single cell structures: Standing-wave structures with different iris diameters and shapes; a/λ=0.21, a/λ=0.14, a/λ=0.14 (elliptical iris), and a/λ=0.105 and.

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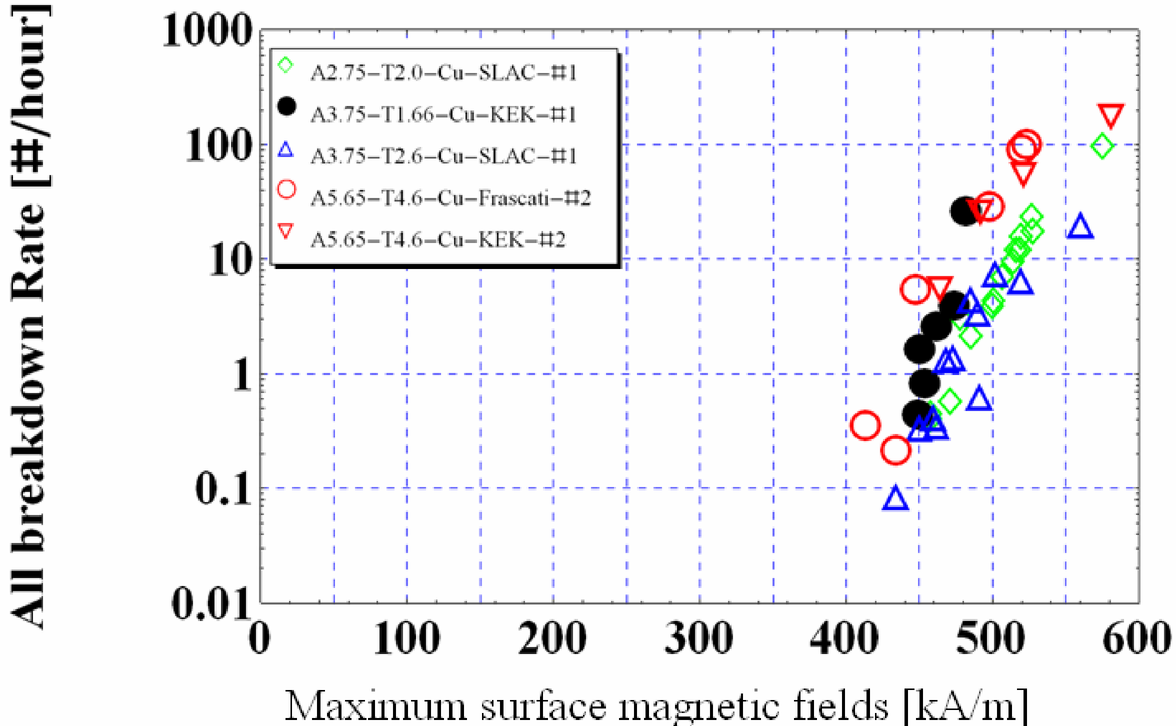
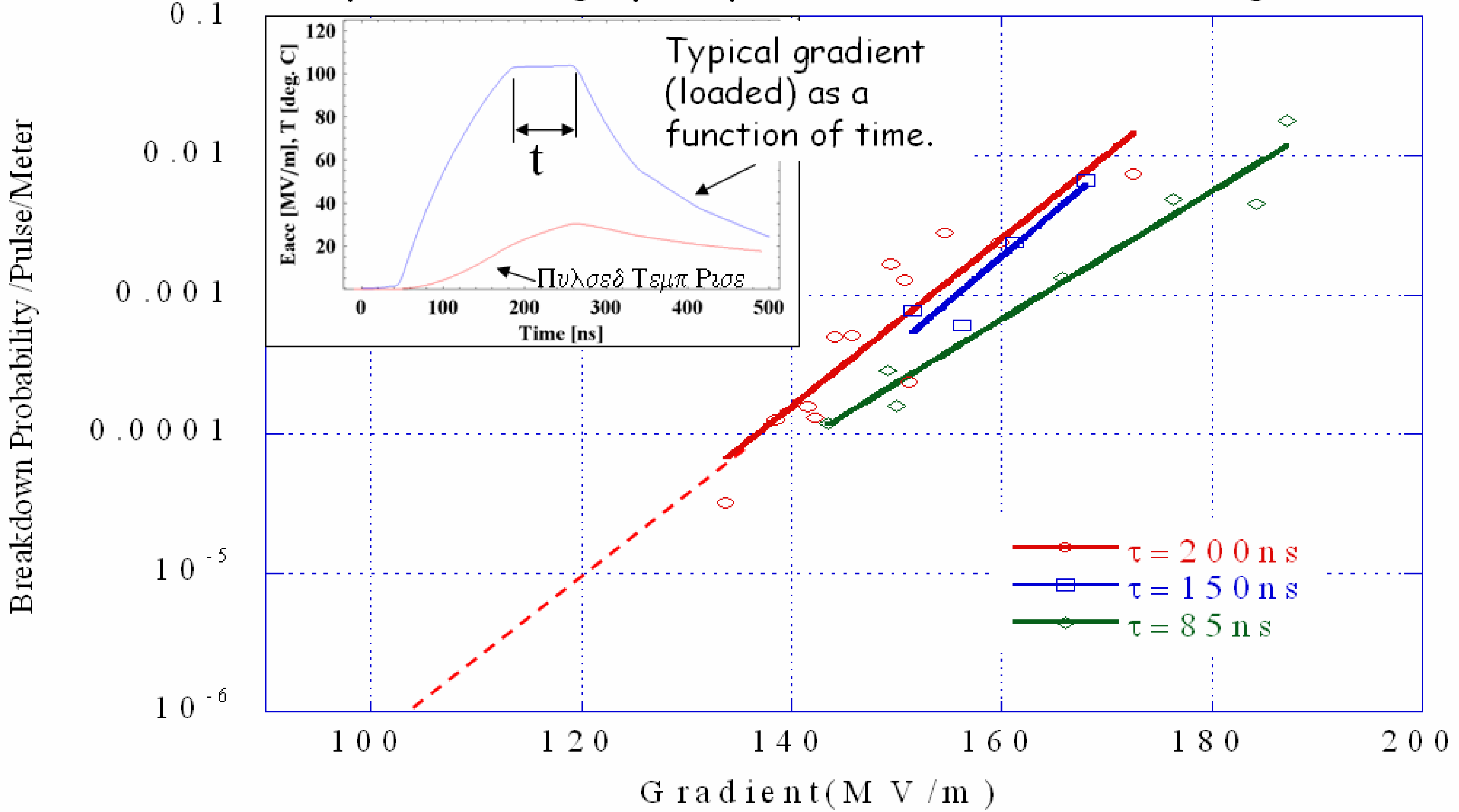
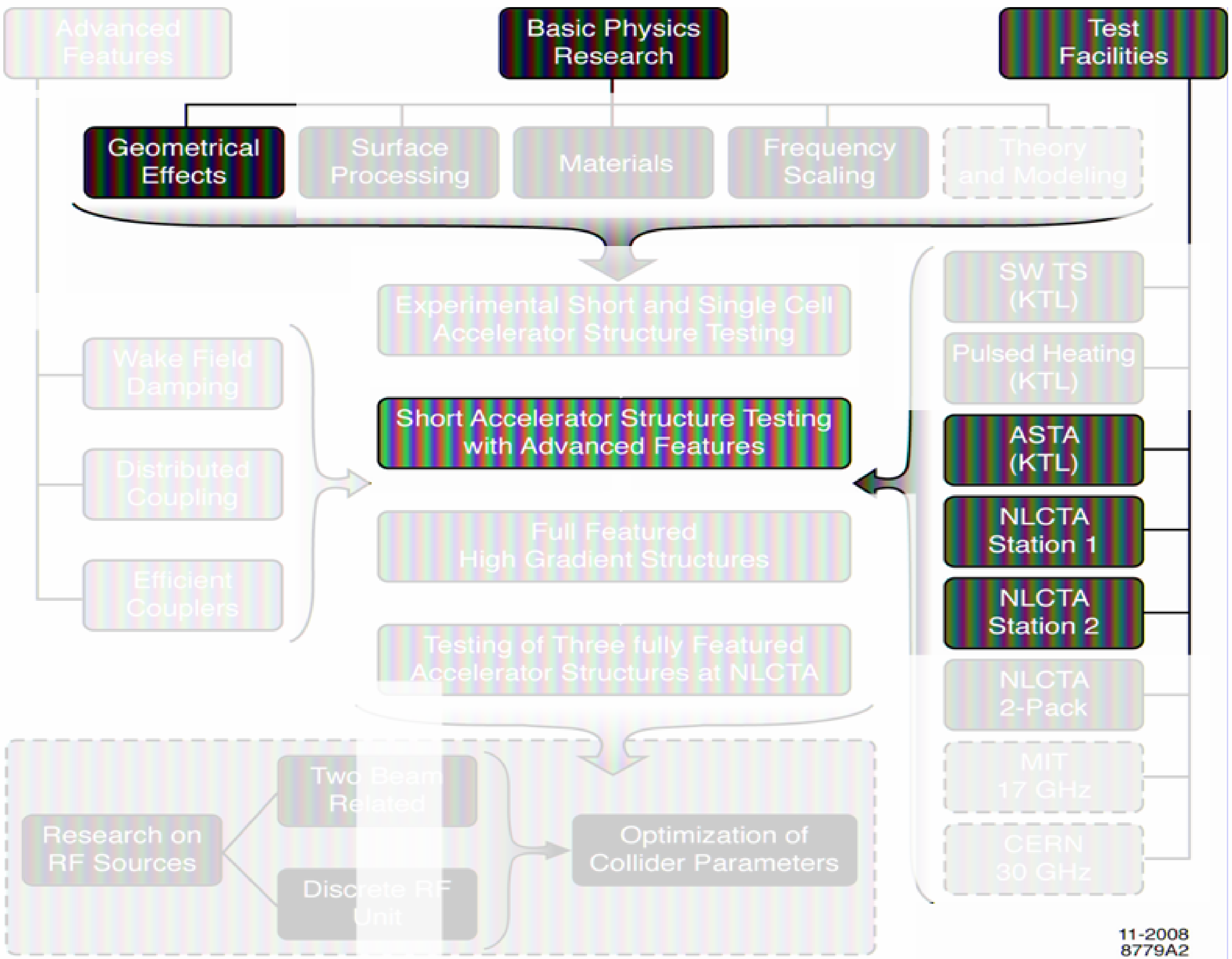


Standing-Wave Accelerator Structure
Recent Results (a/λ~0.14)

Each point in this graph represents ~10 hours or running at 60 Hz

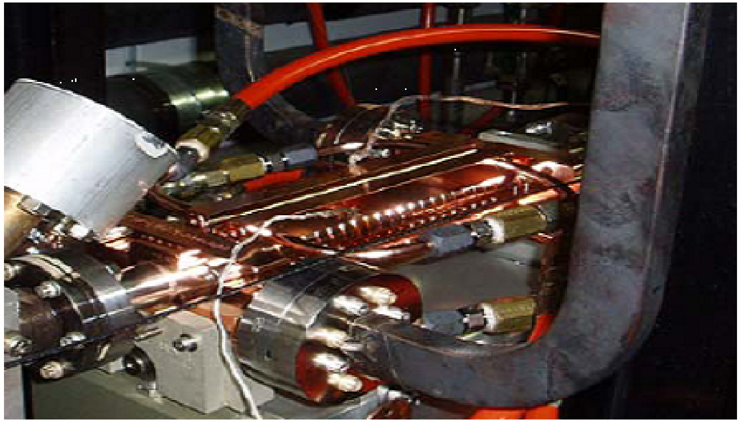


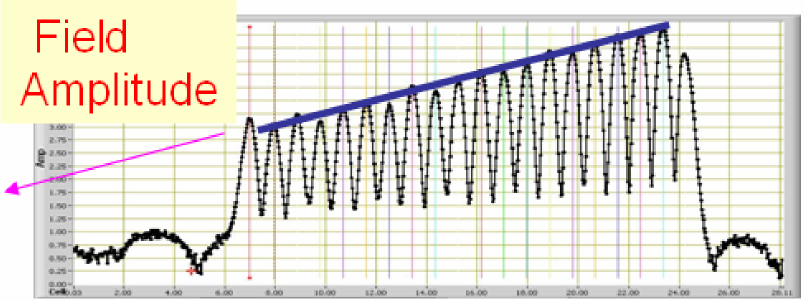
Research and Development Plan



Full Accelerator structure testing (the T18 structure)

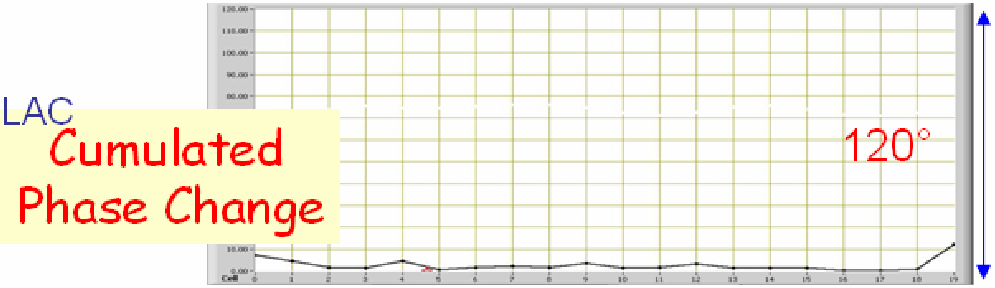
Frequency.	11.424GHz
Cells	18+input+output
Filling Time	36ns
a_in/a_out	4.06/2.66 mm
vg_in/vg_out	2.61/1.02 (%c)
S11	0.035
S21	0.8
Phase	120Deg
Average Unloaded Gradient over the full structure	55.5MW→100MV/m





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

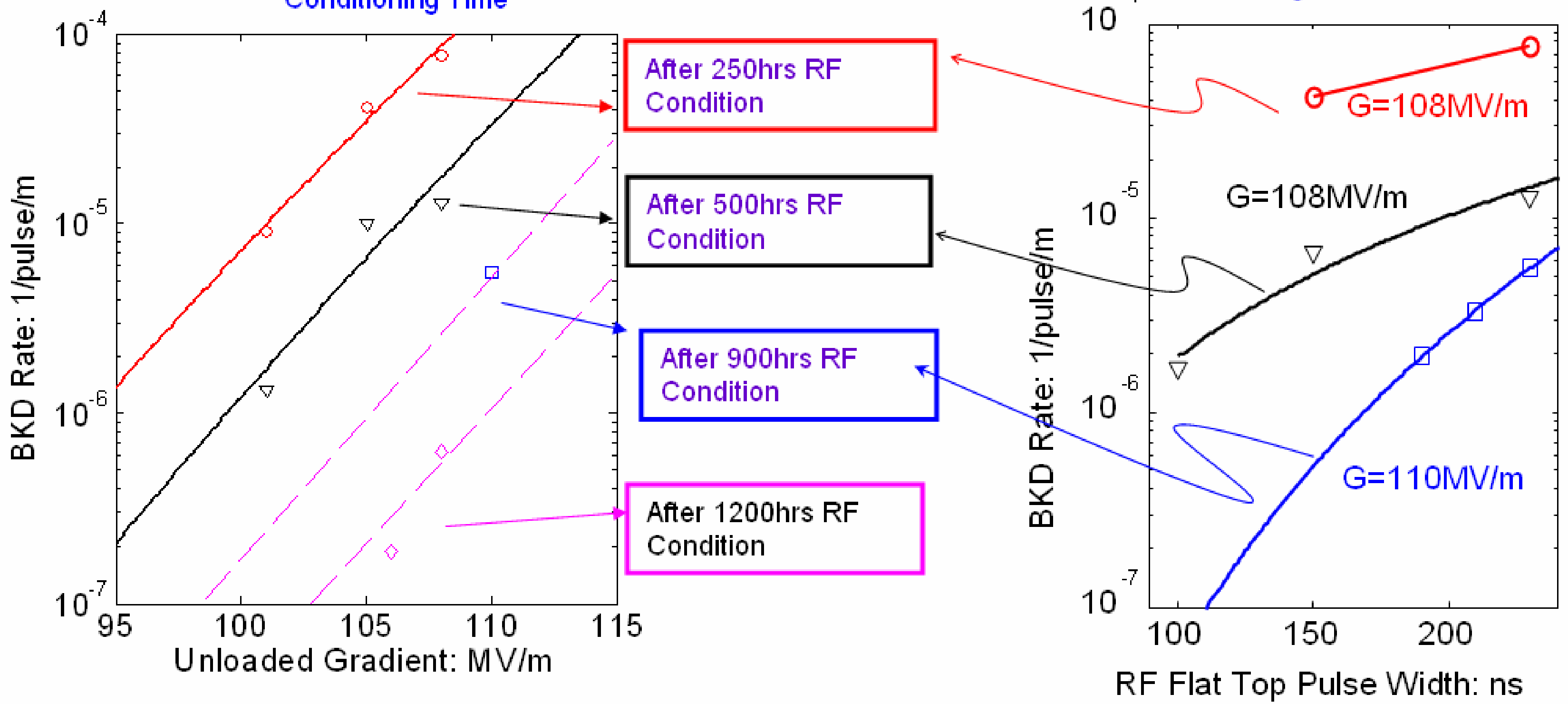
- Structure designed by CERN based on all empirical laws developed experimentally through our previous work
- Cells Built at KEK
- Structure was bonded and processed at SLAC
- Structure was also tested at SLAC



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



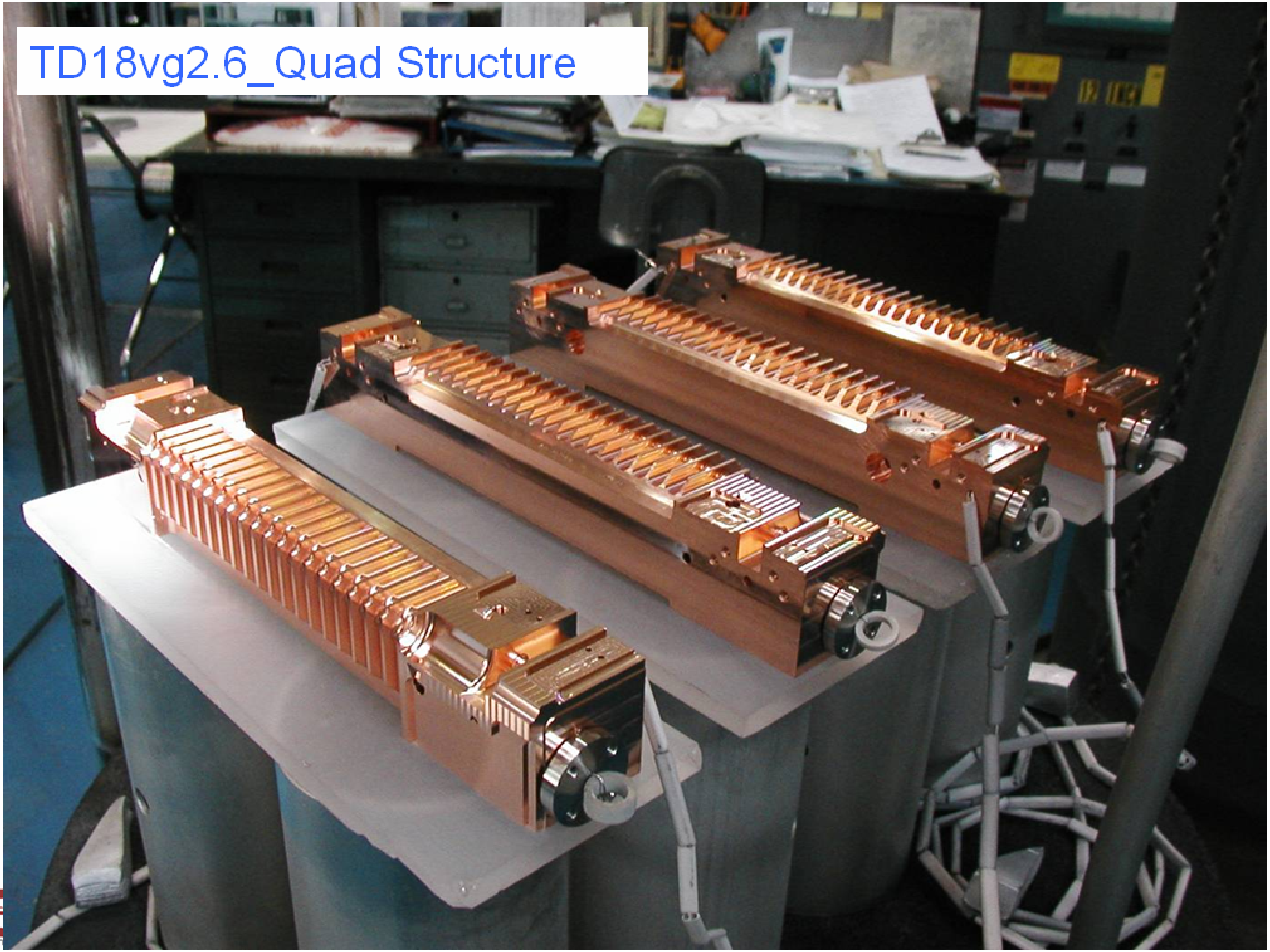
This performance *may be* good enough for 100MV/m structure for a warm collider, however, it does not yet contain all necessary features such as wakefield damping. Future traveling wave structure designs will also have better efficiency

2007-09 CERN/CLIC Design Structures Tested at NLCTA

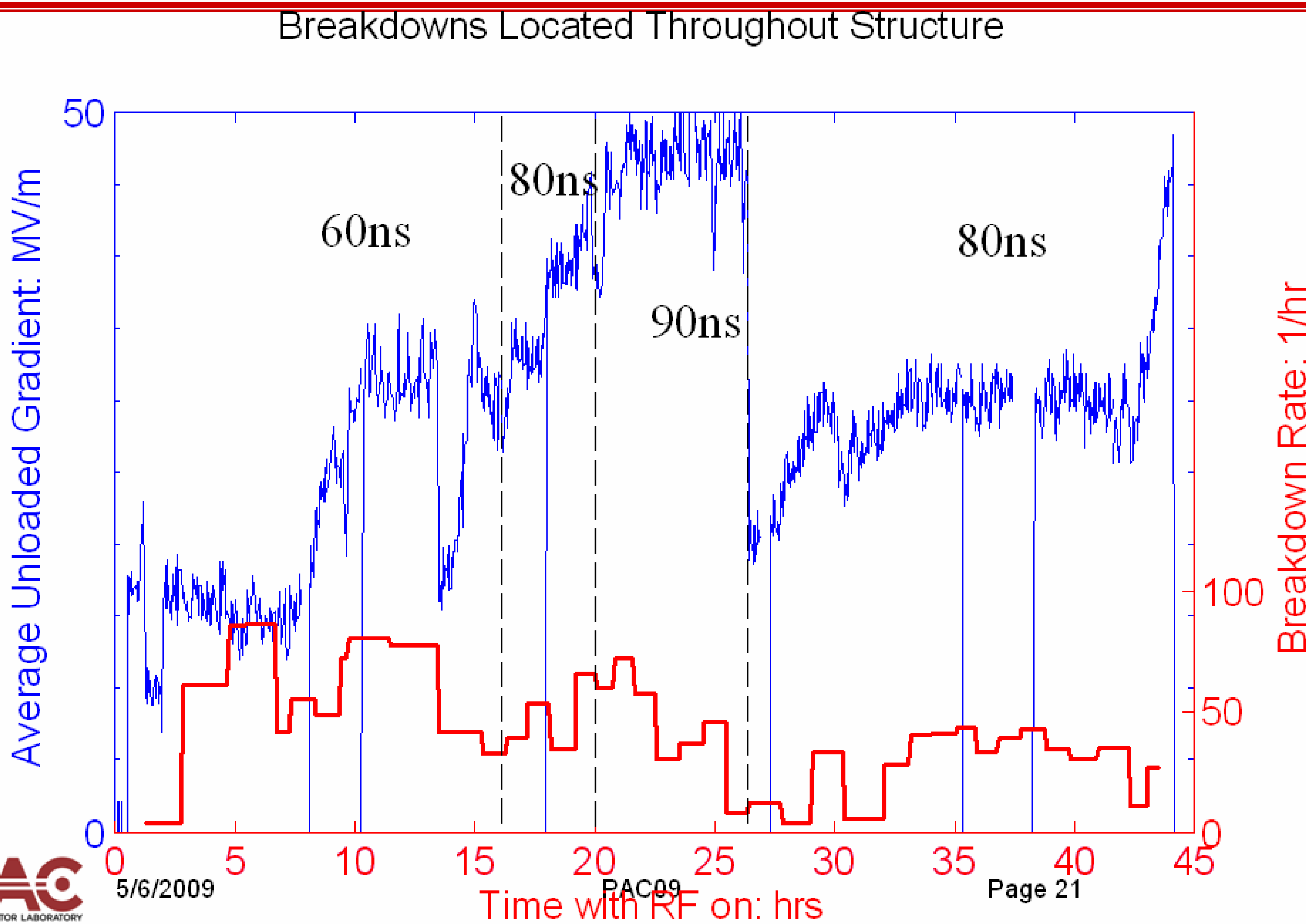
(Yellow = Quad Cell Geometry, Green = Disk Cell Geometry)

In Beamline	Structure	Note	Performance
11/06 - 2/07	C11vg5Q16	First X-band Quad - Irises Slotted	Poor: 57 MV/m, 150 ns, 2e-5 BDR - grew whiskers on cell walls
2/08 - 4/08	C11vg5Q16 Redux	Refurbished	Initially good (105 MV/m, 50 ns,1e-5 BDR) but one cell degraded
4/07 - 10/07	C11vg5Q16-Mo	Molybdenum Version of Above	Poor: 60 MV/m, 70 ns, 1e-6 BDR
10/08 - 12/08	TD18vg2.6_Quad	No Iris Slots but WG Damping	Very Poor: would not process above 50 MV/m, 90ns - gas spike after BD
4/08 - 7/08	T18vg2.6-Disk	Cells by KEK, Assembled at SLAC	Good: 105 MV/m, 230 ns at LC BDR spec of 5e-7/pulse/m but hot cell developed
7/08 - 10/08	T18vg2.6-Disk	Powered from Downstream End	Good: 163 MV/m, 80 ns, 2e-5 BDR in last cell, consistent with forward operation
12/08 - 2/09	T18vg2.6-Disk CERN	CERN Built, Operate in Vac Can	Very Poor: very gassy with soft breakdowns at 60 MV/m, 70 ns

TD18vg2.6_Quad Structure



TD18vg2.6_Quad Processing History

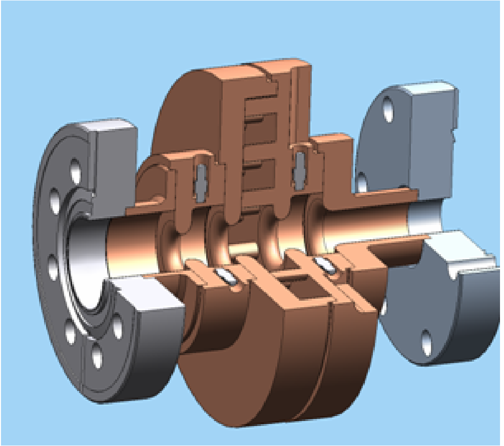


Summary for Structure testing

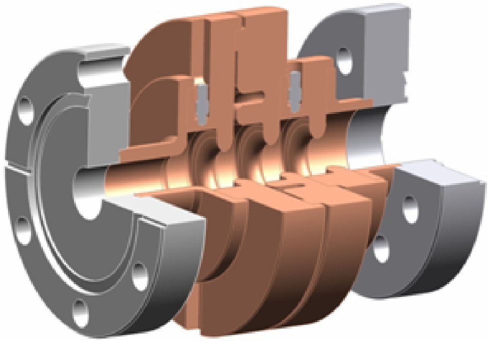
* Too many variables to evaluate gradient dependence on simple geometry (a,vg,phi) alone
* Quad approach
  - Fab may easier and the design allows thinner irises
  - But probably cannot allow irises to touch, and cannot have a low phase advance per cell (which lowers Es/Ea)
  - Need to improve quad 'z' alignment and reduce virtual leaks
  - KEK is building a 2p/3 version with 50 mm rounded iris edges, which may help (a 150 deg phase adv, slotted 30 GHz structure failed)
* T18 design is promising
  - Features: 2.6% initial vg, 13% ave a/l and 55% gradient ramp
  - CERN/KEK/SLAC version #1 ran with 230 ns pulses at 105 MV/m with a BDR of 5e-7/pulse/m (LC spec) but then developed a hot cell
  - CERN/KEK/SLAC version #2 ran well at KEK
  - CERN built version only reached 60 MV/m with 70 ns pulses and had hot cells - being autopsied

Structure modifications for wakefield damping

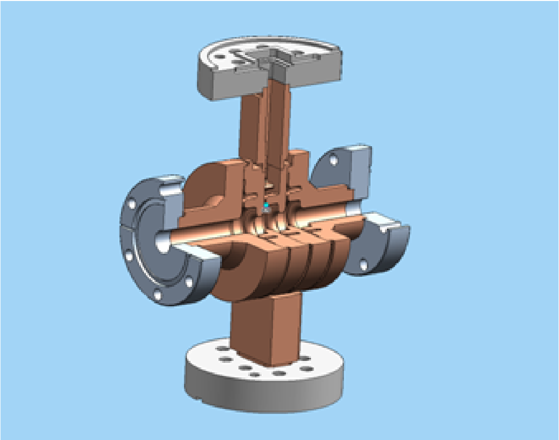
- CERN is pursuing side slotted structures (to be tested soon at NLCTA)
- MIT PBG Structure (already tested first version)
- Choked structure (already tested).
- Side fed structures will pave the way to parallel fed structures with gradients above 140 MV/m (currently being manufactured)
- Other methods of damping are being studied theoretically.



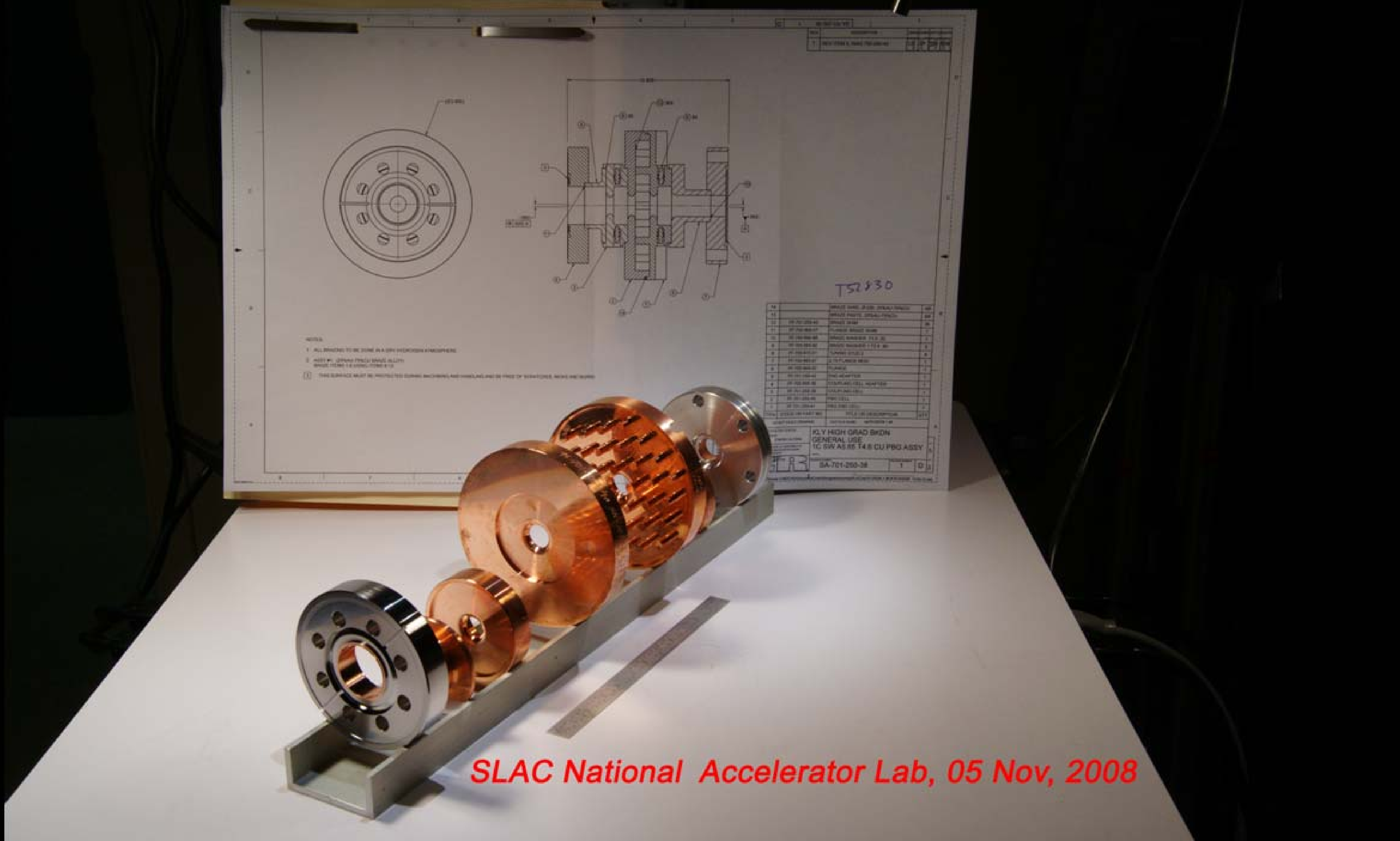
PBG Structure



Choke Structure

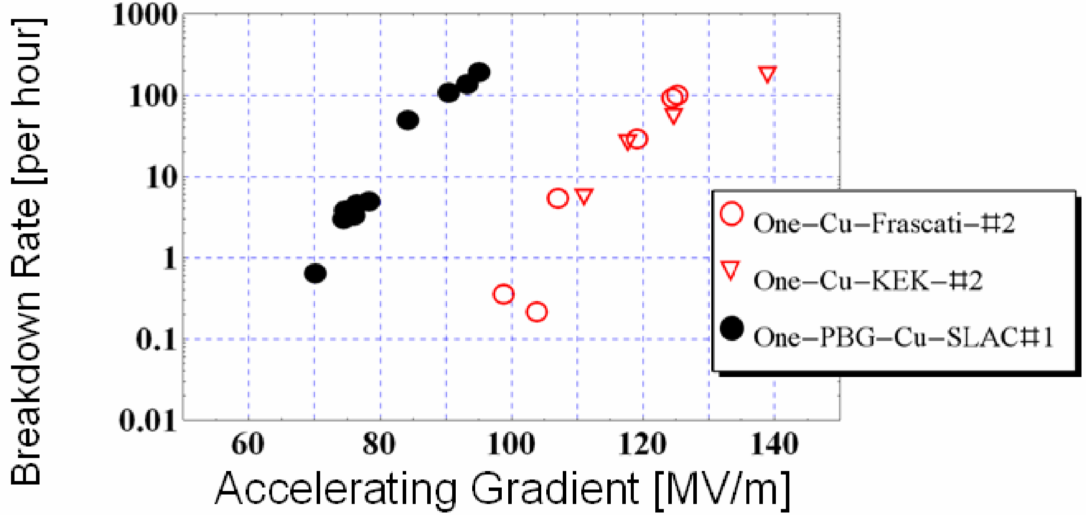


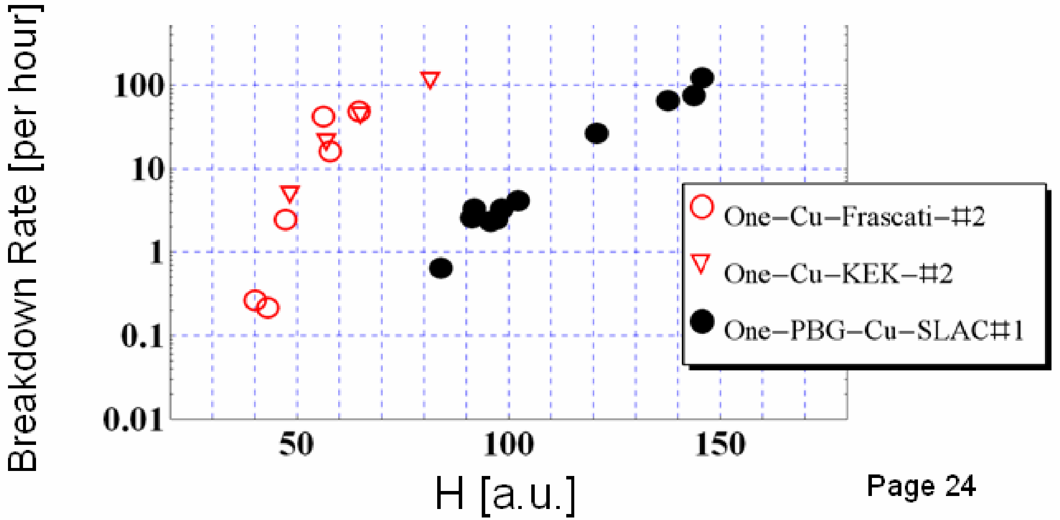
Choke structure with side feed

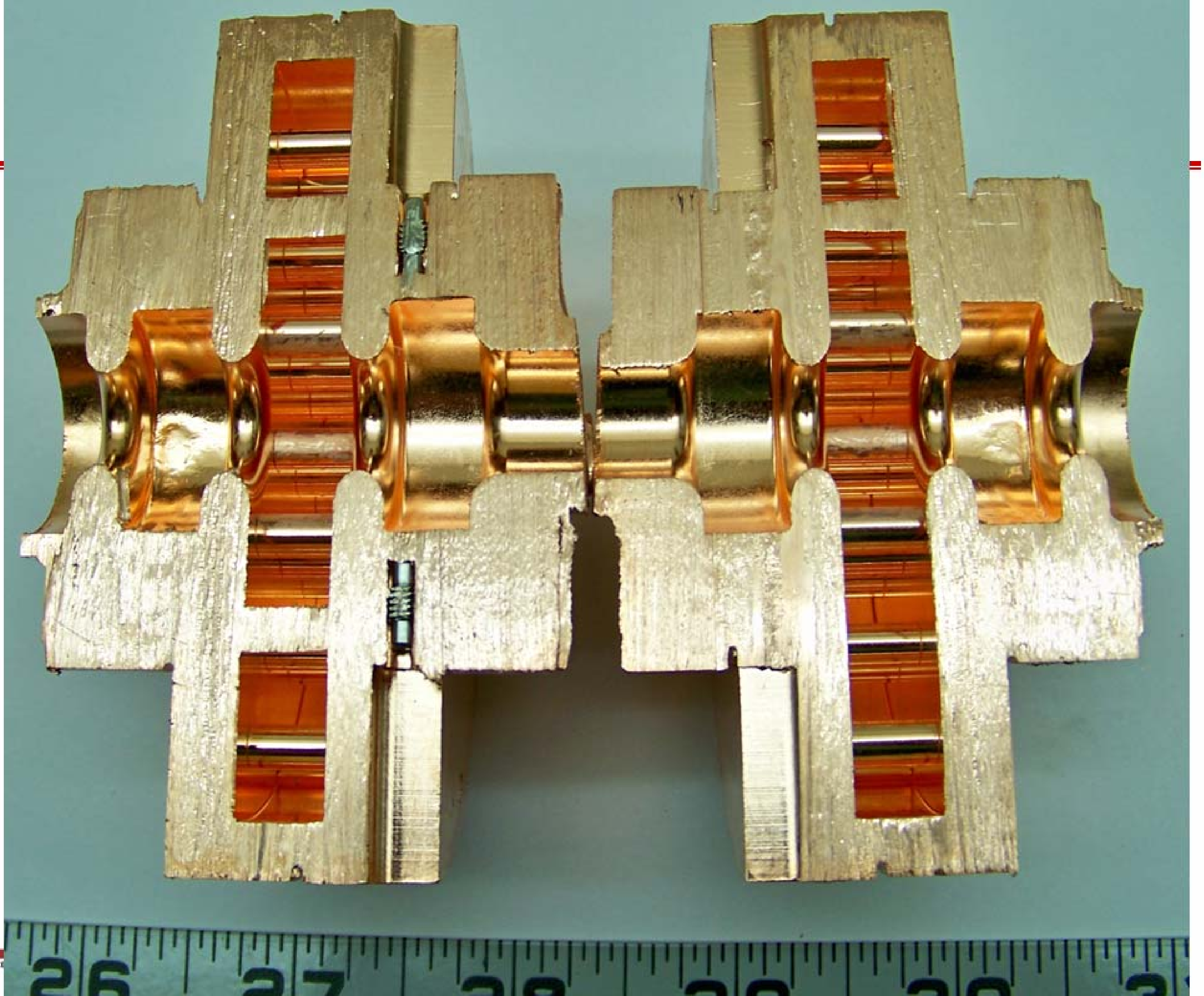

KLY HIGH GRAD BKDN
GENERAL USE
1C SW A5.65 T4.6 CU PBG ASSY
SA-701-250-38
SLAC National Accelerator Lab, 05 Nov, 2008

Accelerating Gradient and Surface Magnetic fields for 2 disc-loaded and one PBG single cell structures, *shaped* pulse

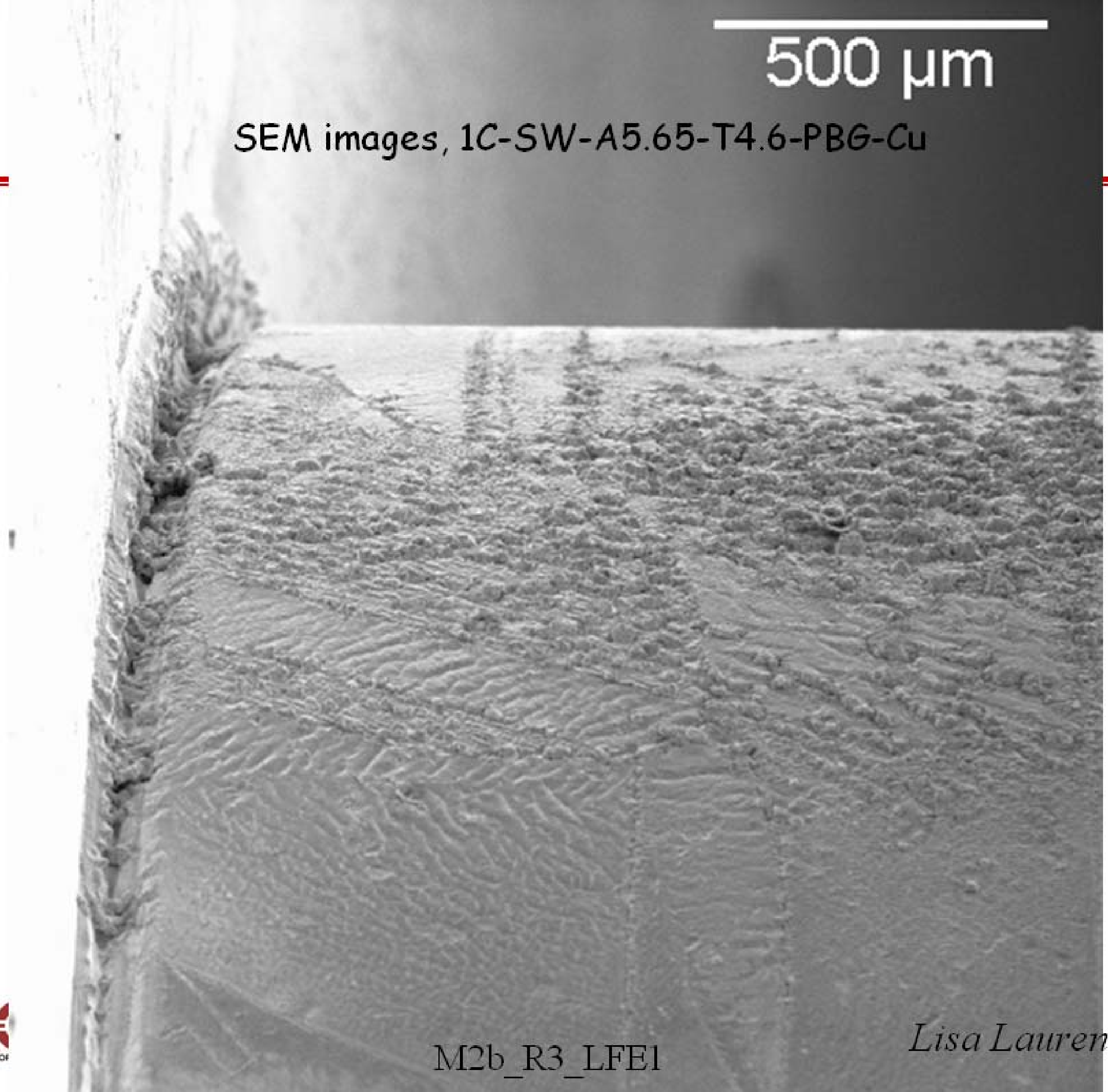
(*flat* part: A5.65-T4.6-KEK-#2- 150 ns, A5.65-T4.6-Frascati-#2- 150 ns, A5.65-T4.6-PBG-SLAC-#1- 150 ns)







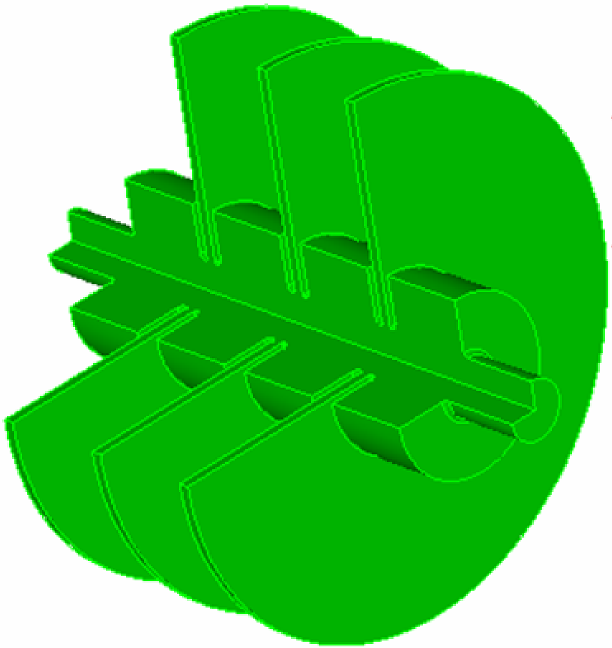
SEM images, 1C-SW-A5.65-T4.6-PBG-Cu



M2b_R3_LFE1

Lisa Laurent, SLAC

"Iris slot" type structure for π-Mode Standing wave Accelerator Structures



* 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

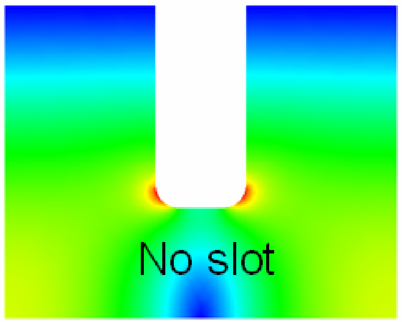
Iris thickness: 3mm
Length of 1 period: 13.12mm

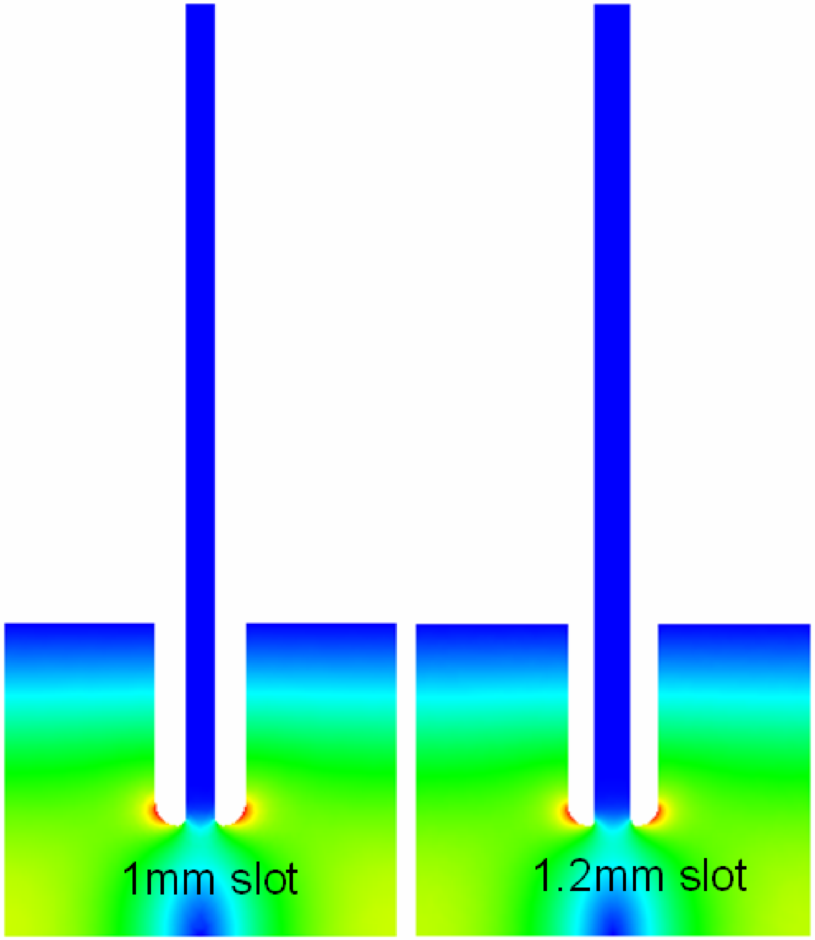
	No slot	1mm slot	1.2mm s
Freq / MHz	11423.87	11423.70	11423.6
R / Mohm/m	87.24	86.42	86.45
Q	8326.74	8327.53	8324.6
Es/Ea	2.665	2.683	2.739
k / %	0.9557	1.0466	1.0533

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

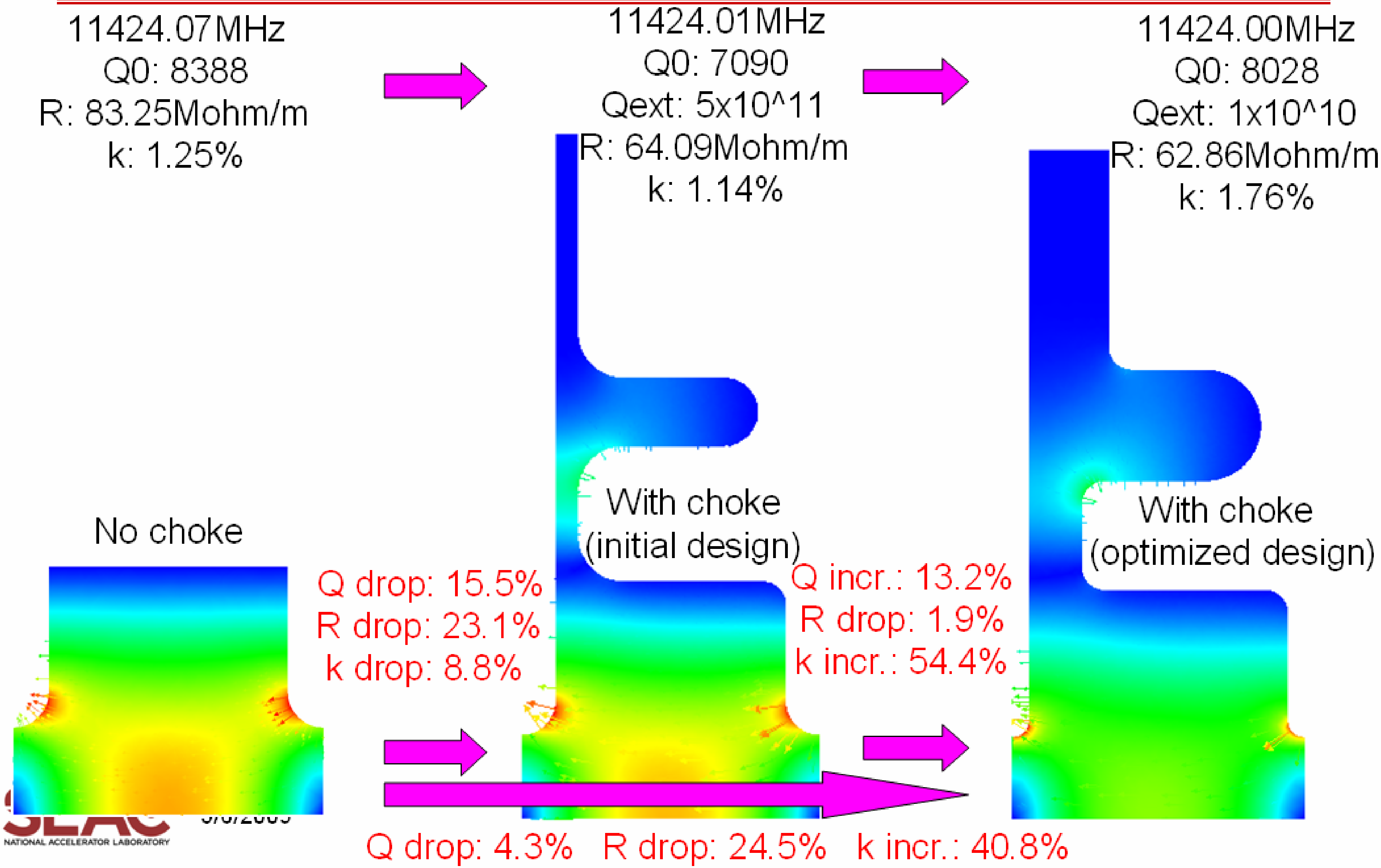
Regular Cell

Slot has no big effect on FM mode.

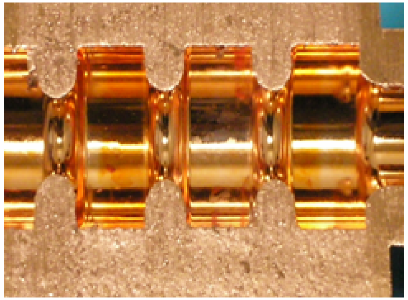




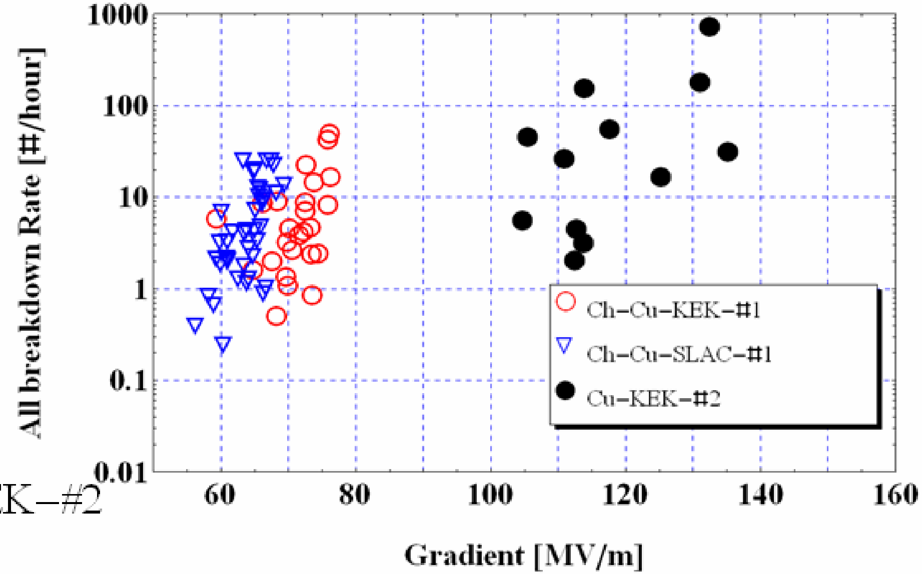
Effect on fundamental mode

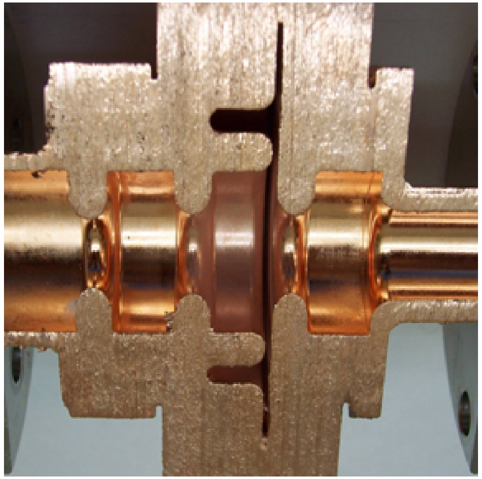


Choke *vs.* no Choke

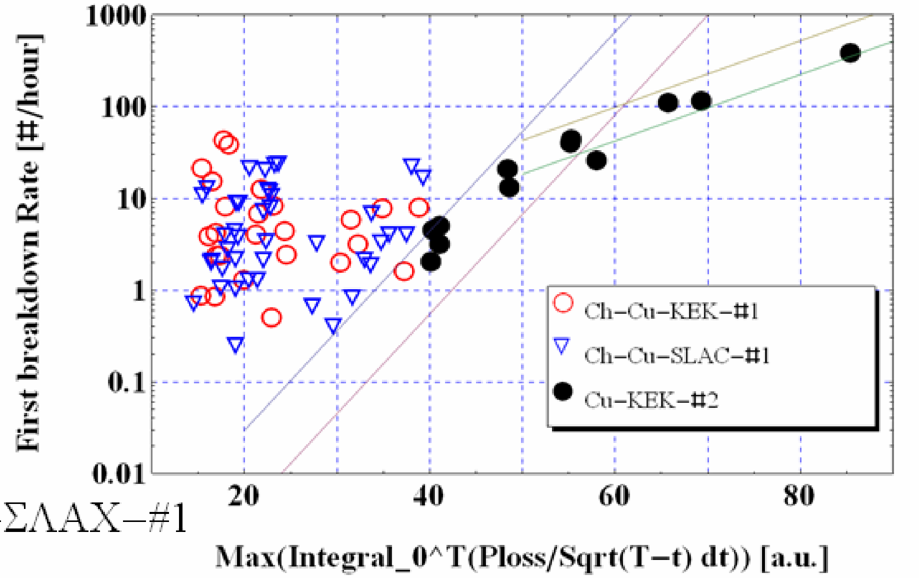


1X–ΣΩ–A5.65–T4.6–Xυ–KEK–#2





1X–ΣΩ–A5.65–T4.6–**Xη**–Xυ–ΣΛΑΧ–#1



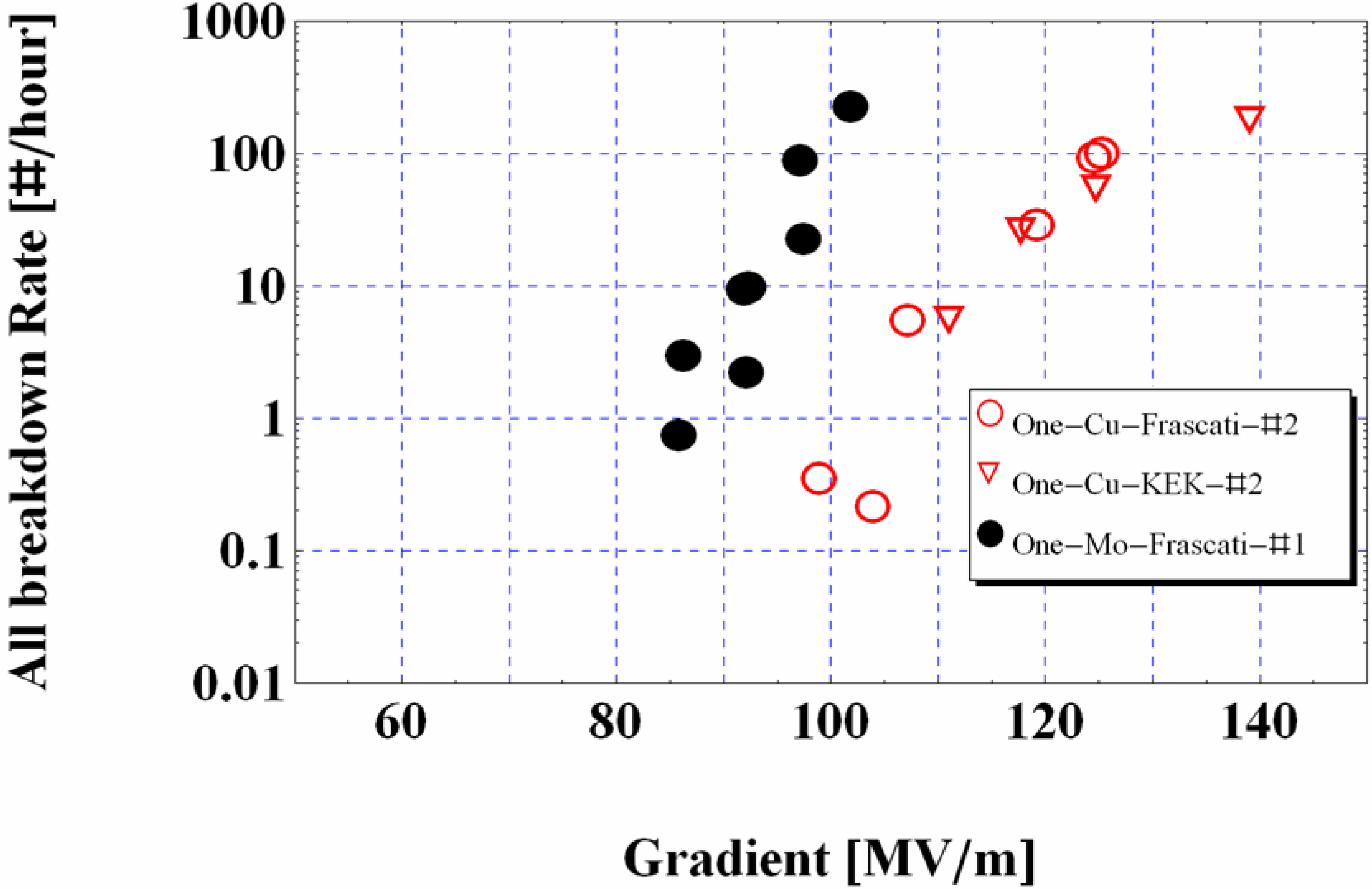
1X–Σ

1X–Σ

Material Testing

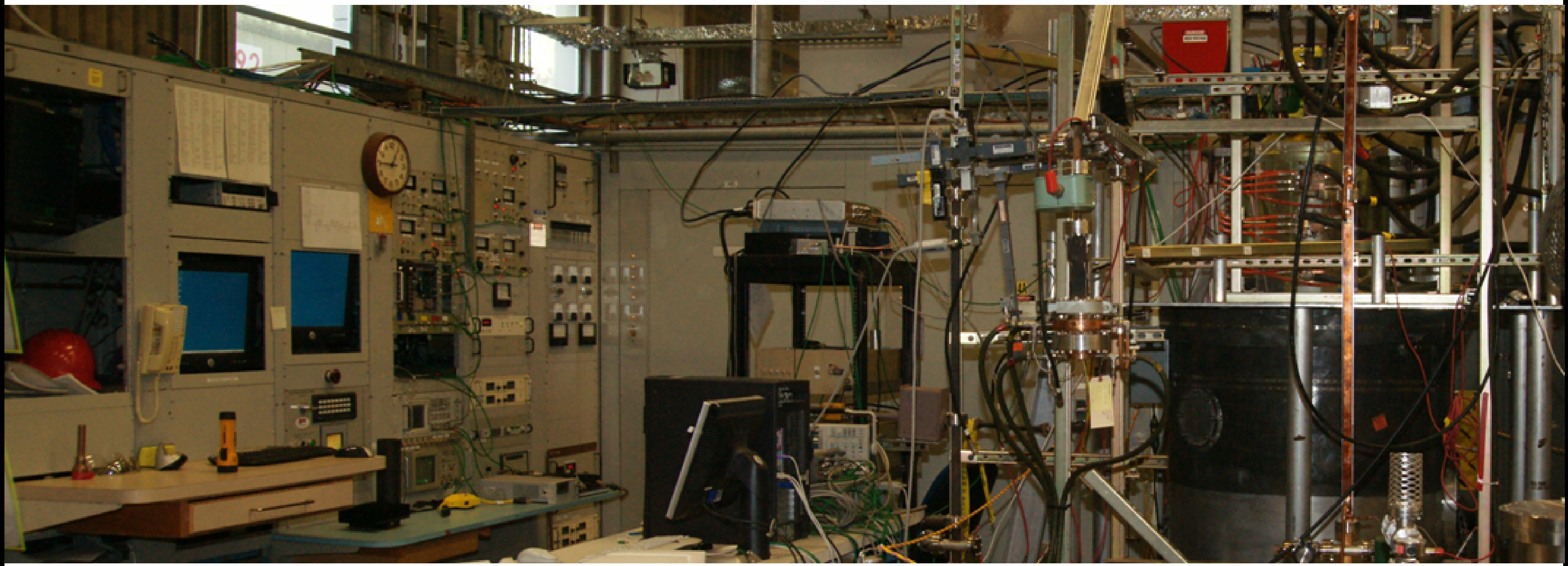
* Experimental and theoretical evidence points to the magnetic field as an important factor in determining the ultimate gradient of a given structure.
  - Magnetic field can be responsible for:
    - Geometrical effects
    - Effective field enhancement
    - Secondary effects due to gas release at high 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.

Comparison of peak pulse heating for two copper and one molybdenum 1C-SW- A5.65-T4.6-Cu structures, *shaped* pulse, flat part 150 ns



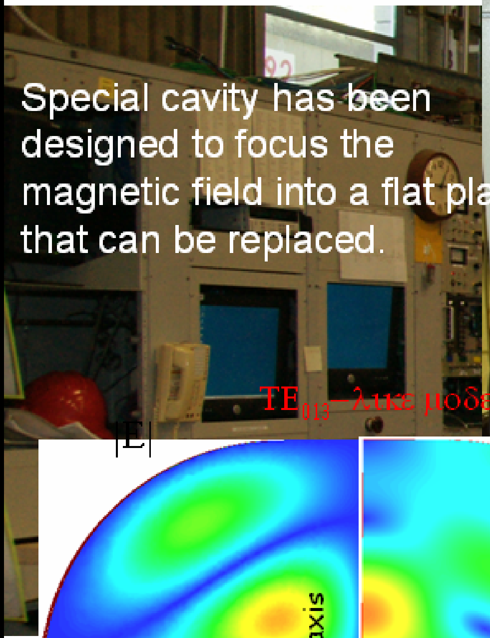
V.A. Dolgashev 4 May 2009

Material Testing (Pulsed heating experiments)

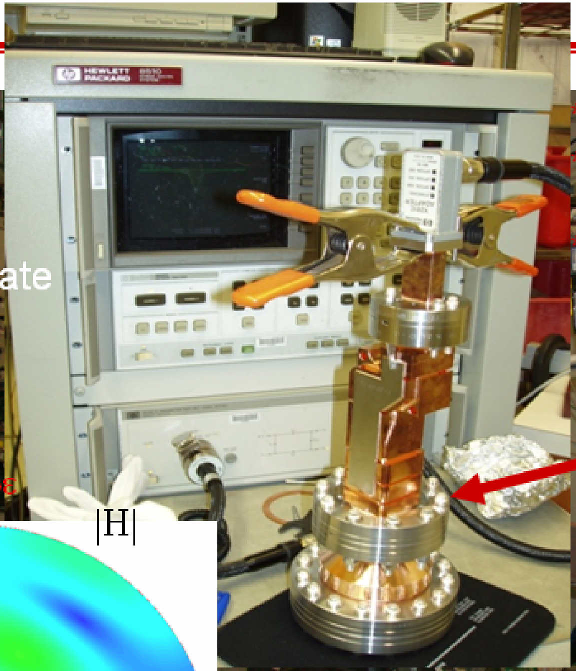


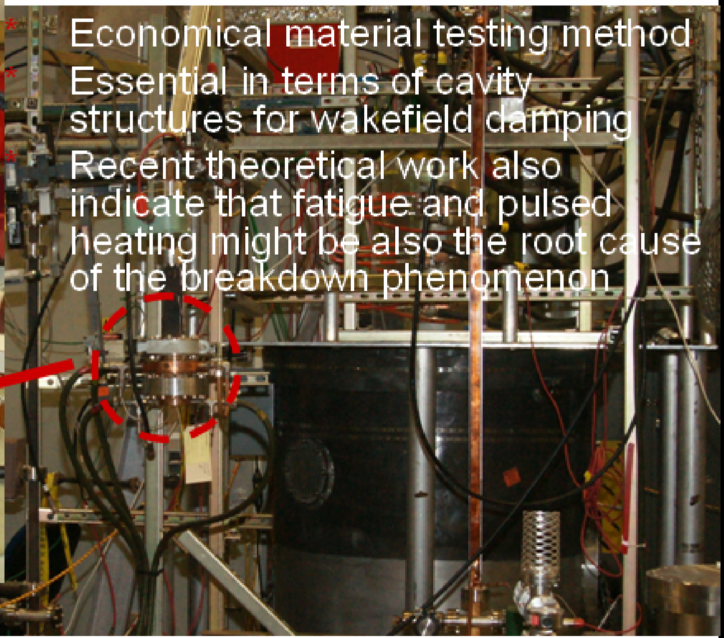
Max Temp rise during pulse = 110^{o}C

Material Testing (Pulsed heating experiments)

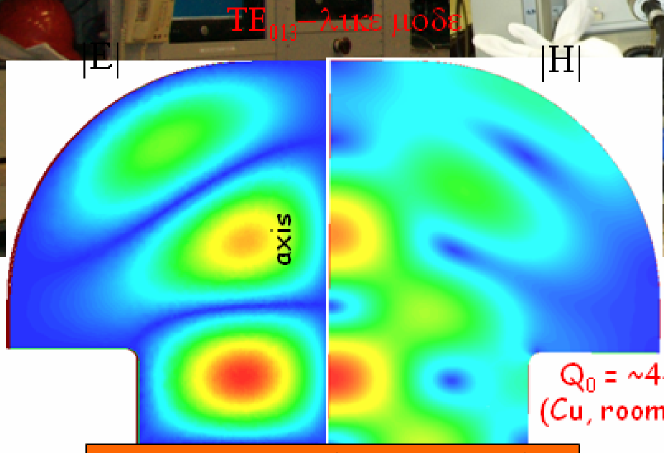


Special cavity has been designed to focus the magnetic field into a flat plate that can be replaced.





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



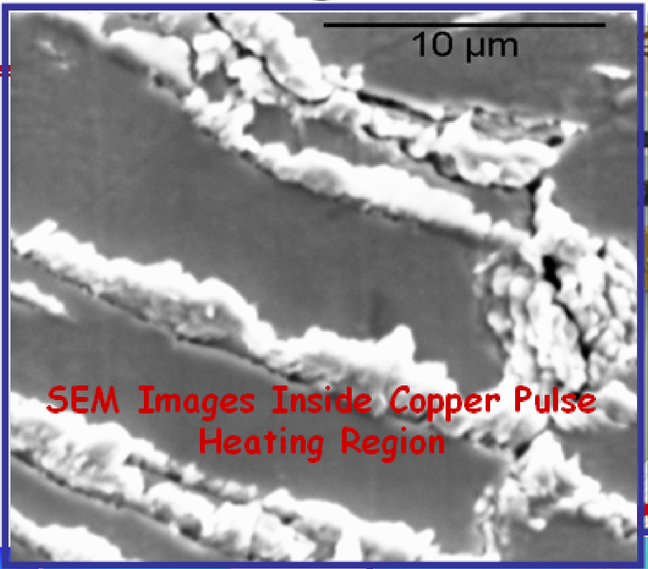
material sample

r = 0.98"

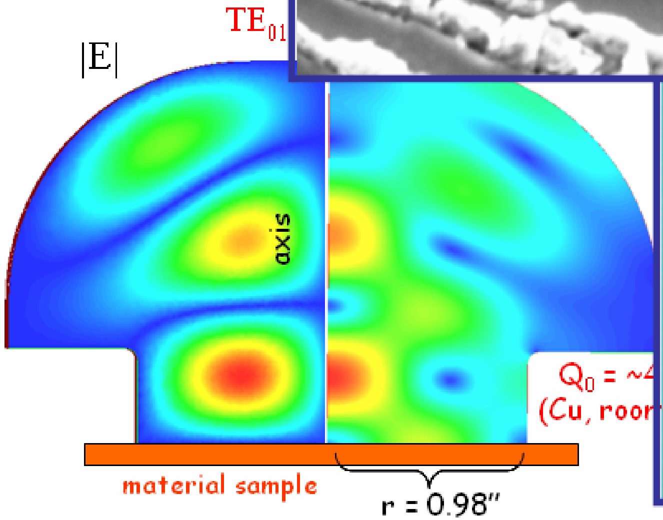
Q_0 = ~44,000
(Cu, room temp.)

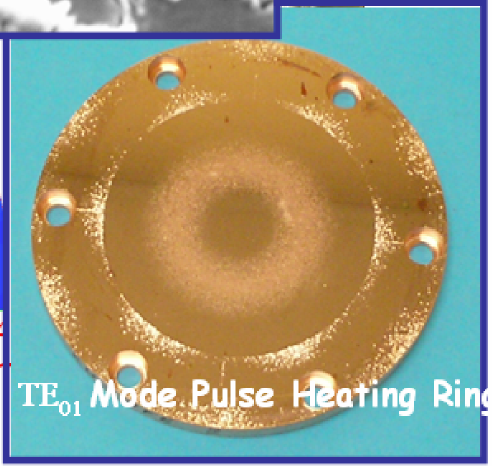
Max Temp rise during pulse = 110°C

Material Testing (Pulsed heating experiments)



Metallography: Intergranular fractures 500X





Max Temp rise during pulse = 110°C

Pulse Heating Sample Inventory and Status
(March 2009)

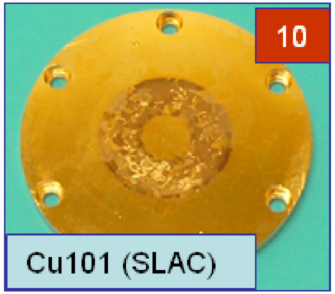
Pulse Heating Sample	Rf Tested	SEM	Reported
Cu1-1 (CERN)	✓	✓	KEK May08
Cu1-2 (CERN)	✓	✓	KEK May08
CuZr1-1 (CERN)	✓	✓	KEK May08
CuZr1-2 (CERN)	✓	✓	KEK May08
Cu2-1 (CERN)			
CuZr2-1 (CERN)			
CuZr2-2 (CERN)	✓		ANL Mar09
Cold Worked CuZr3-1 (CERN)	✓		ANL Mar09
Cold Worked CuZr3-2 (CERN)	✓	✓	ANL Mar09
Cold Worked CuZr3-3 (CERN)			
Glidcop4-1	✓		
Glidcop4-2	In Test		
HIP1 Cu (KEK)	✓		
HIP2 Cu (KEK)	✓	✓	CERN Oct08
E-Deposited Cu (KEK)	✓	✓	CERN Oct08
Single Crystal Cu (KEK)	✓	✓	CERN Oct08
KEK1 (KEK)			
KEK2 (KEK)			
KEK3 (KEK)	✓	✓	CERN Oct08
CuAg (KEK)	✓	✓	ANL Mar09
Silver Plated Cu (KEK)	✓	✓	ANL Mar09
Cu101 (SLAC)	✓		
Cu102 (SLAC)	✓		
CuCr_101 (SLAC)	✓		
CuCr_102 (SLAC)	✓	✓	CERN Oct08
CuAg4 (SLAC)			
CuAg5 (SLAC)	✓	✓	ANL Mar09
CuAg6 (SLAC)			
CuAg7 (SLAC)			

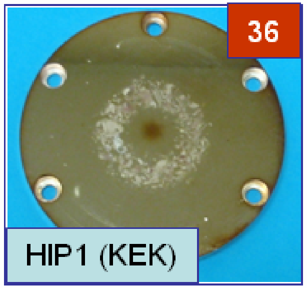
Total Number of Samples	29

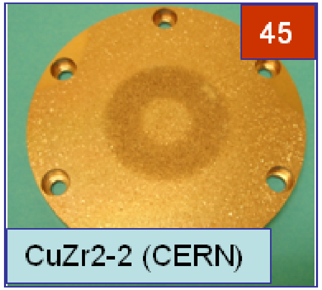
	Rf tested	SEM
Samples Not Complete =	9	6
Samples Completed =	20	13

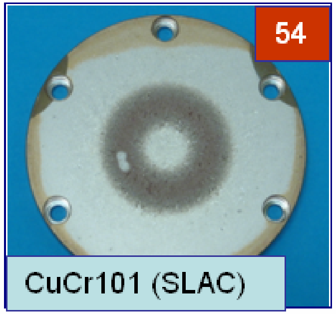
Hardness Test Value

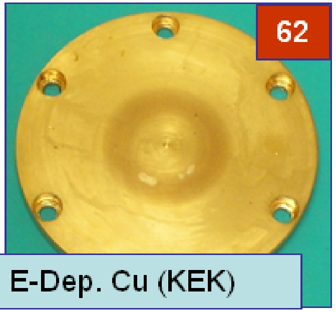
Pulse Heating Samples RF Tested as of March 2009

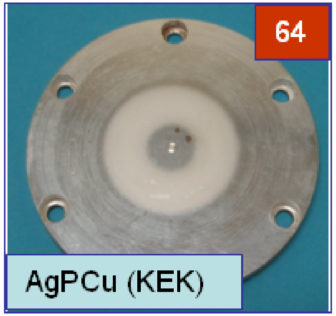


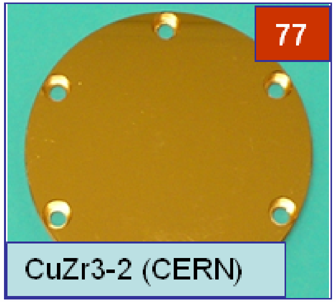


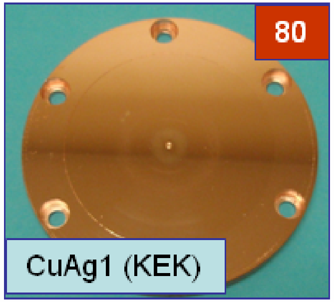






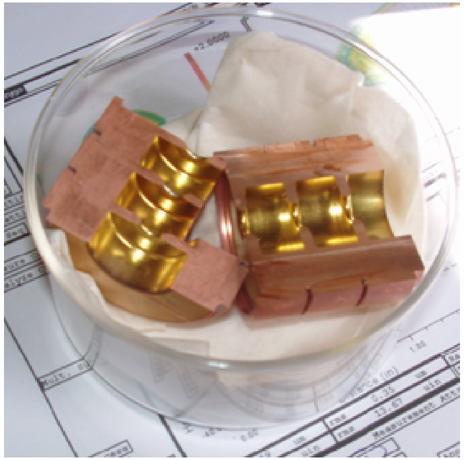




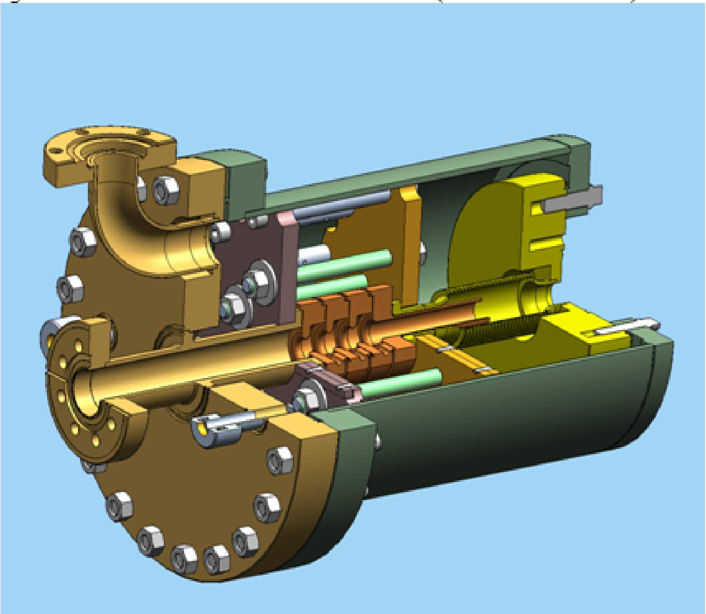


Material Studies

* Clamping Structure for testing copper alloys accelerator structure (under test)

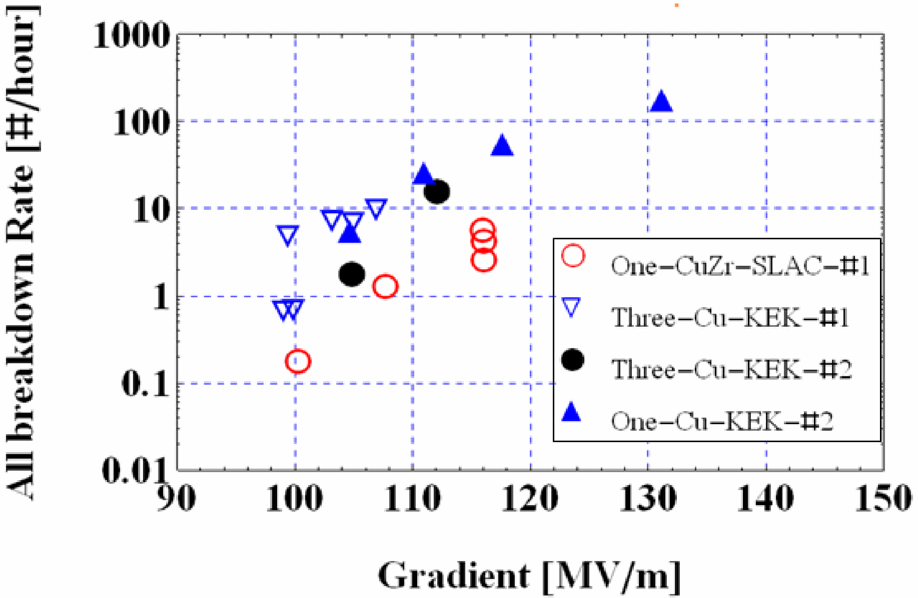


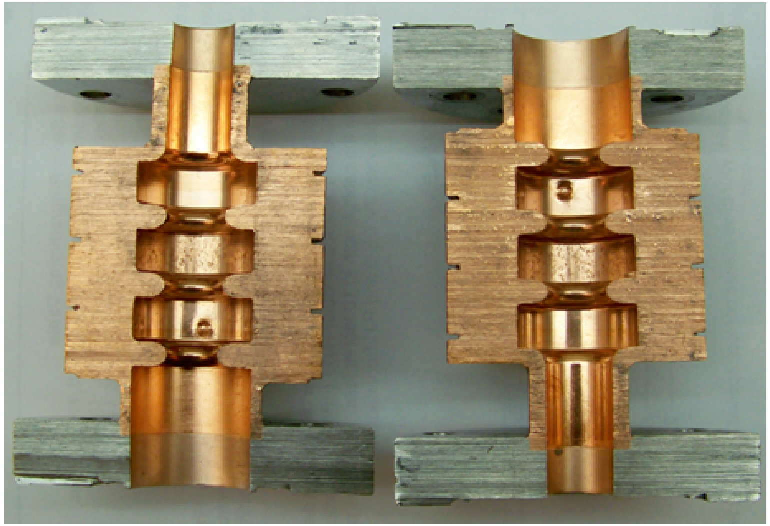
Diffusion bonding and brazing of copper zirconium are being researched at SLAC.



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.

First Test of a Vacuum Brazed CuZr Structure

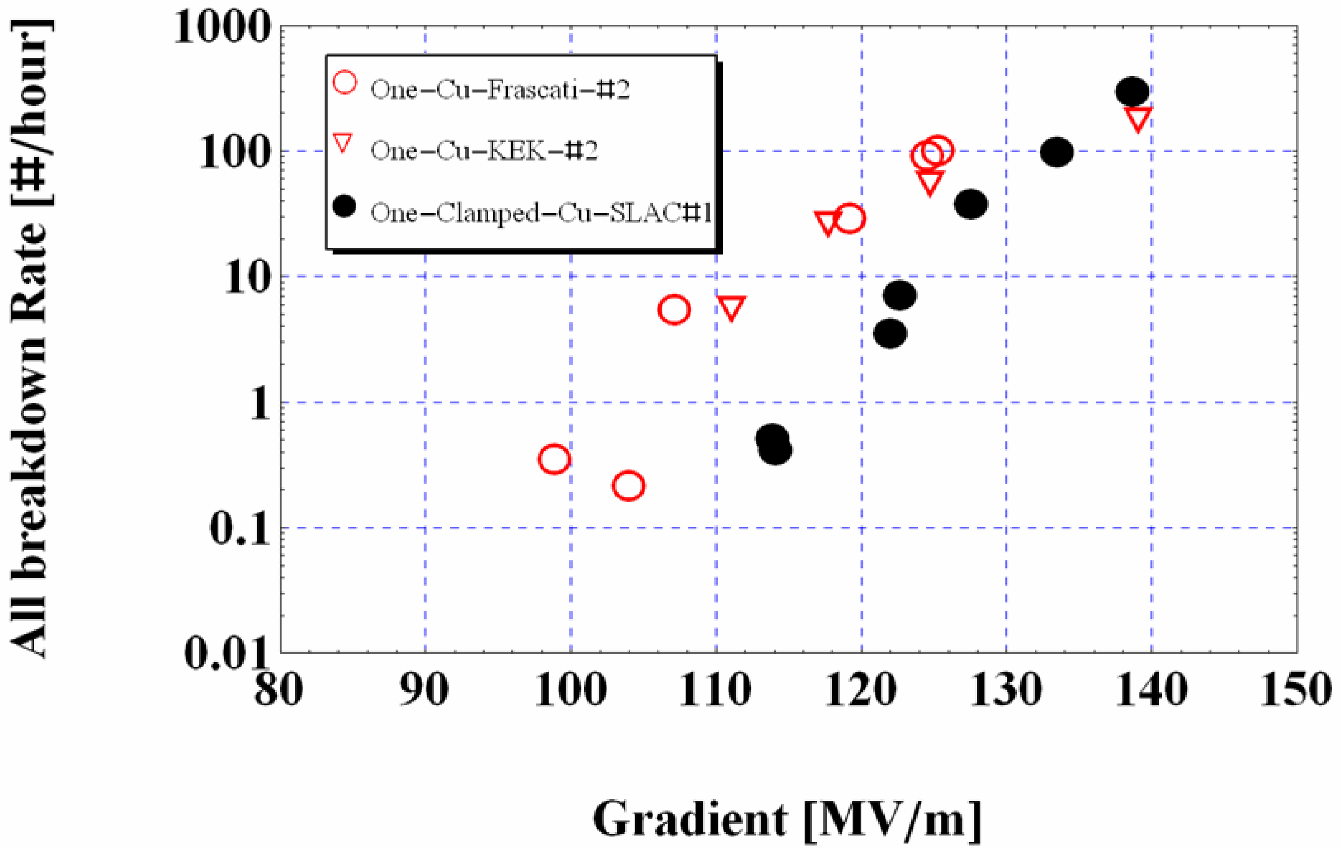




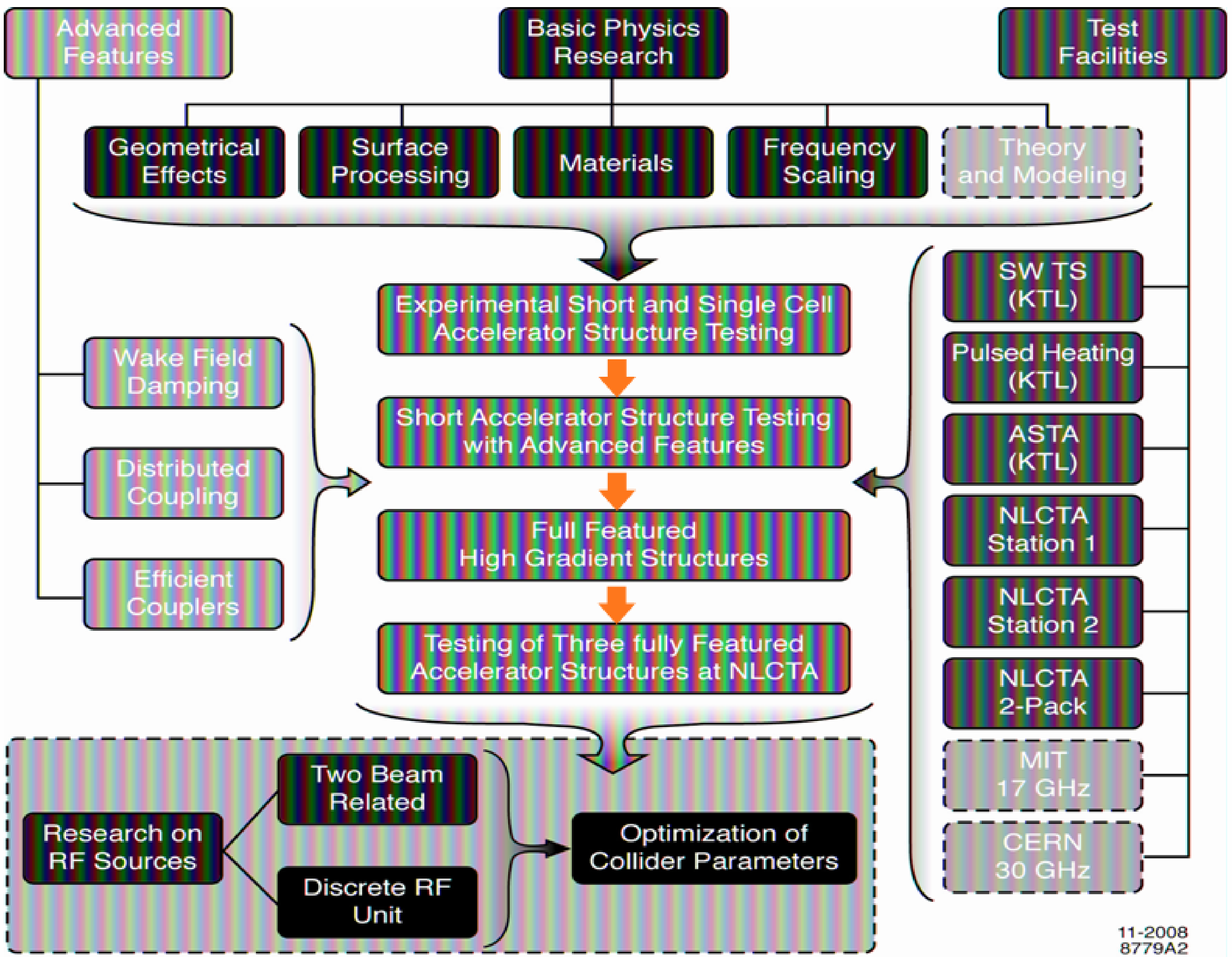

SLAC National Accelerator Lab, 19 Nov, 2008

SLAC National Accelerator Lab, 19 Nov, 2008

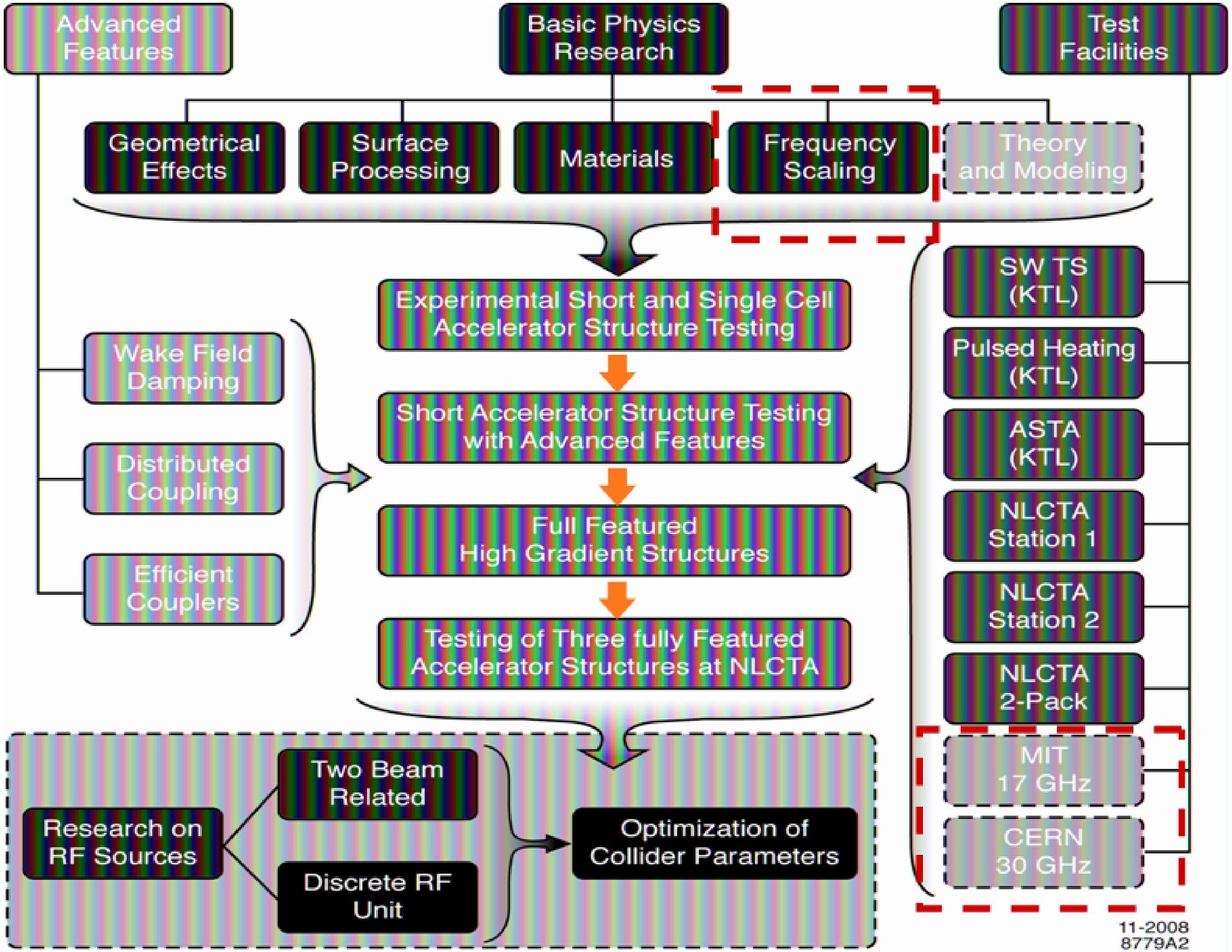
Comparison of two 1C-SW- A5.65-T4.6-Cu structures and 1C-SW- A5.65-T4.6-Clamped-Cu , *shaped* pulse, flat part 150 ns



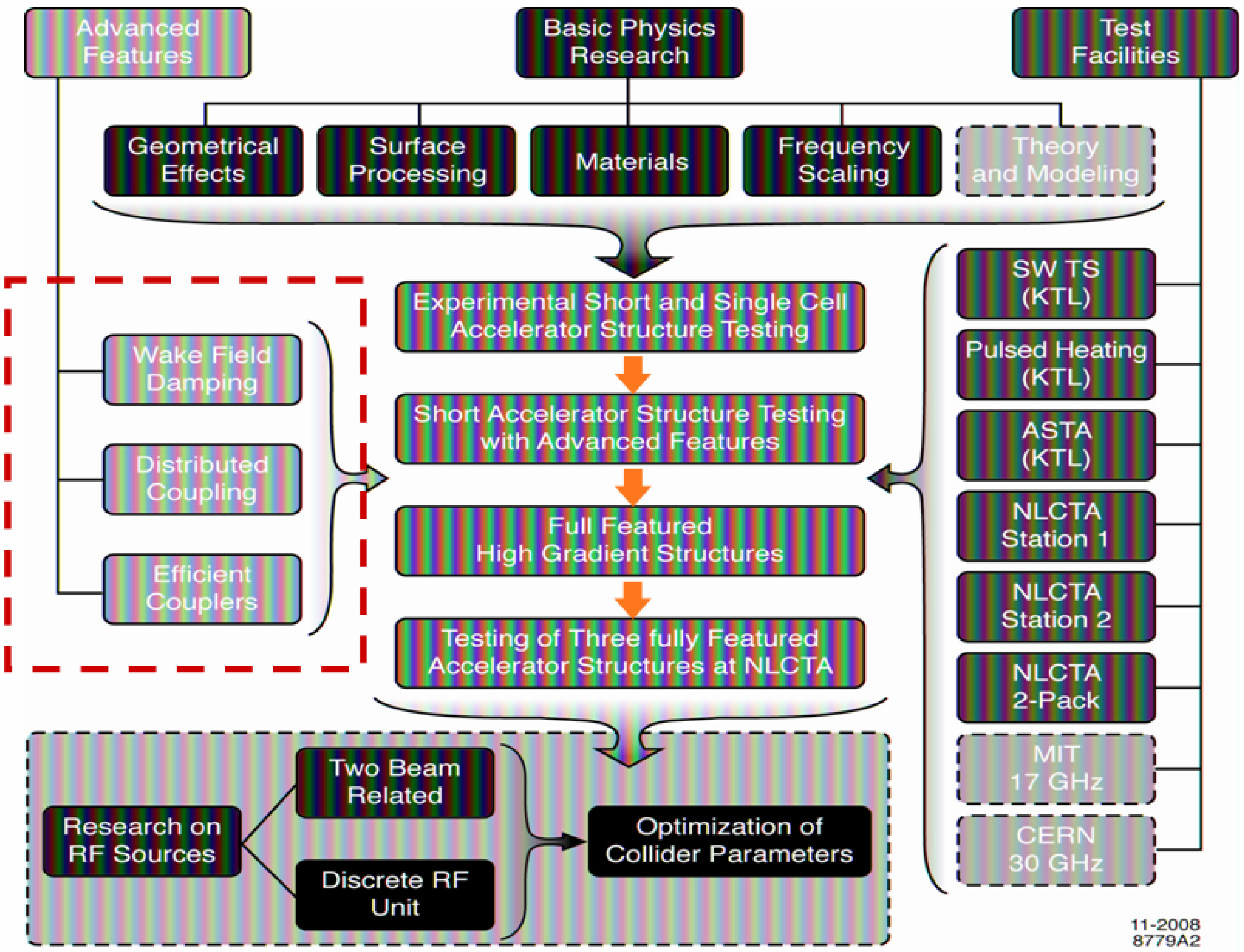
Research and Development Plan



2009 Research and Development Plan

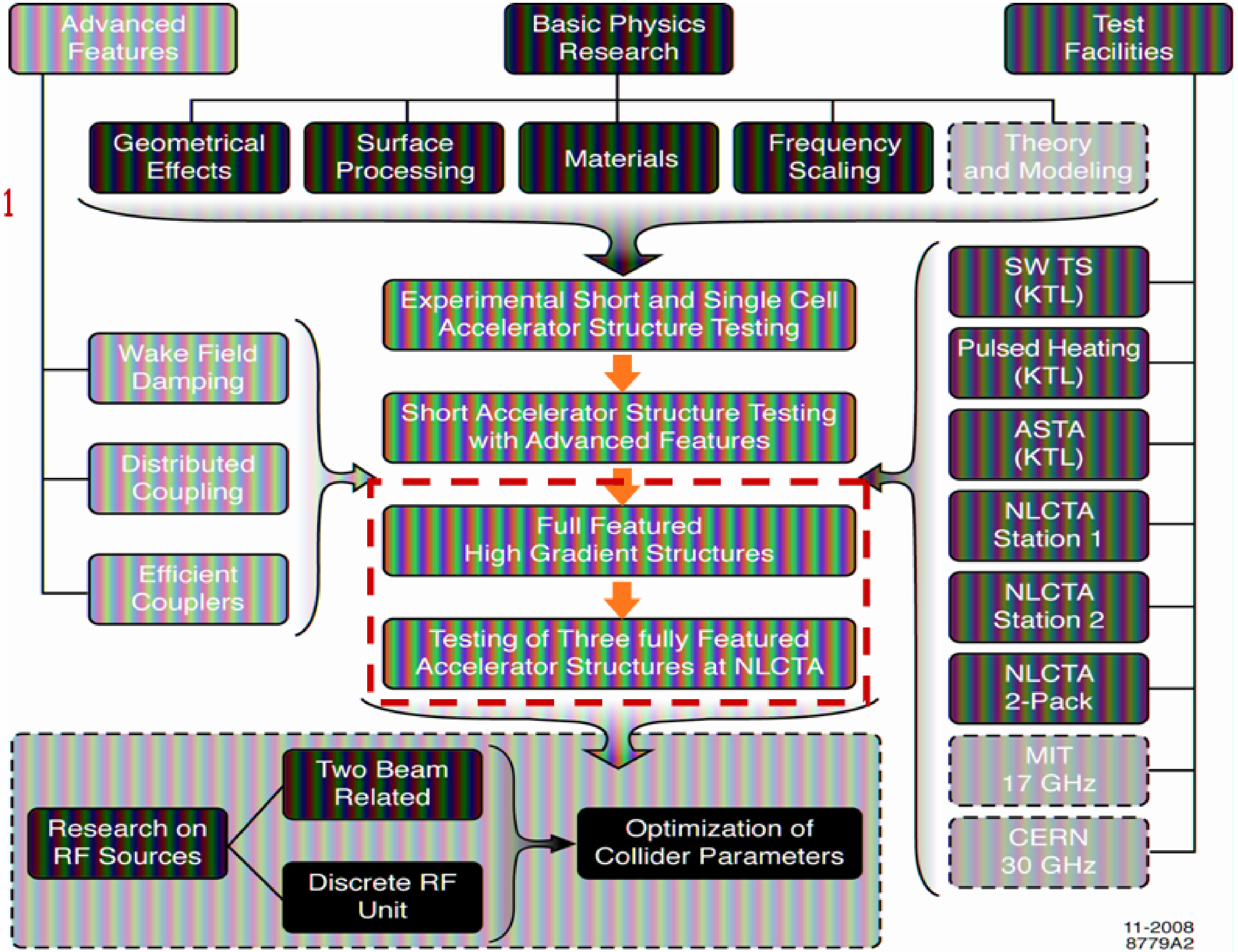


2009 Research and Development Plan



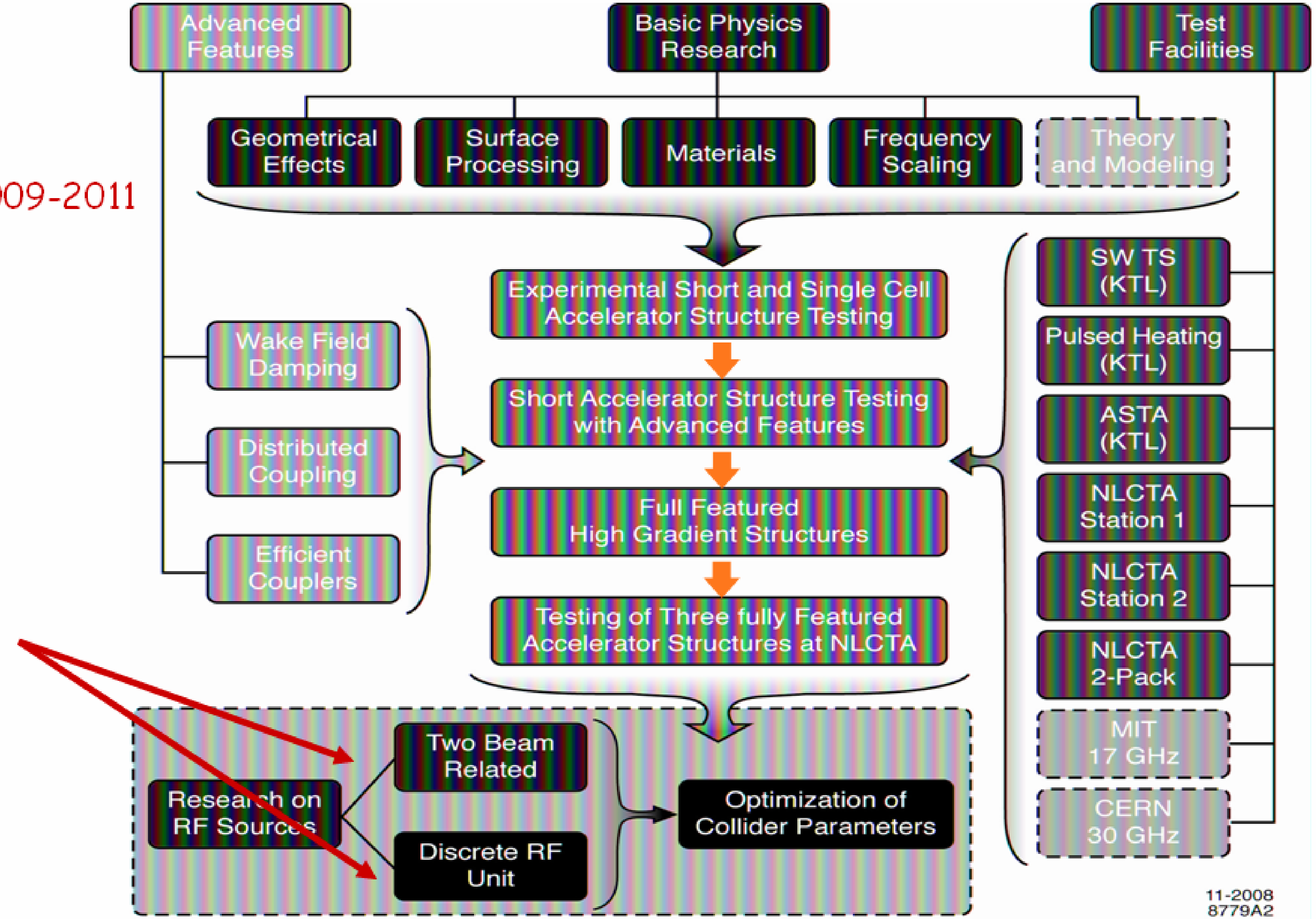
Research and Development Plan

2009-2011



Research and Development Plan

2009-2011



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
* Wakefield damping features are being studied theoretically and experimentally throughout the collaboration. This work has just begun
* Accelerator structures made of copper alloys are being studied with first results in 2009.
* 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 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 development of efficient RF sources to drive them. The development of these sources has to be given attention in the near future

Summary

* SLAC is leading the experimental work for the developments of high-gradient accelerator structures.
  - unique capabilities for designing, and fabricating RF accelerator structures
  - Unique expertise on ultra-high-power microwave technology
  - Unique facilities
  - Very strong theoretical and modeling groups.
* 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 wakefield damping. This is expected in the near future