The High Gradient Collaboration

Sami Tantawi, for the collaboration
SLAC

Outline

- The US High Gradient Collaboration for Multi TeV Linear Collider
  - Introduction
    - Collaboration structure and management
    - Proposed Work at University of Maryland
    - Proposed work at MIT
    - Collaborative work with ANL and NRL
    - Testing of CERN structures
  - SLAC's program on high gradient research
    - Budget and resources
    - Basic Physics Experimental Studies.
    - RF Sources
    - RF technology developments at 11.424 GHz and at 30 GHz
    - Pulsed heating experiments and superconducting material testing.

US Collaboration on High Gradient Research for a Multi-TeV Linear Collider

- Current Members:
  - Laboratories:
    - Argonne National Laboratory
    - Lawrence Berkeley National Laboratory
    - Naval Research Laboratory
    - Stanford Linear Accelerator Center (Also the host of the collaboration)
  - Universities :
    - University of Maryland
    - Massachusetts Institute of Technology
    - UCLA
    - University of Colorado

US Collaboration on High Gradient Research for a Multi-TeV Linear Collider

- Business Associates
  - Omega-P, Inc.
  - Calabazas Creek Research, Inc.
  - Haimson Research Corporation
  - Tech-X Corporation
  - Euclid
  - Communications and Power Industries

- Foreign Colleagues
  - CERN
  - KEK

US Collaboration on High Gradient Research for a Multi-TeV Linear Collider

- Governance Structure
  - Spokesman
    - Selected to lead this effort by the directors of SLAC and Fermilab at the request of the DOE, Prof. Ronald Ruth of SLAC
  - Advisory Council
    - Prof. Sami Tantawi of SLAC (11.4 GHz research/overall technical coordination);
    - Dr. Richard Temkin of MIT (high frequency research and RF source development);
    - Dr. Gregory Nusinovich of UMD (theory and code development)
    - Dr. Wei Gai of ANL (other experimental programs).
  - Scientific Secretary
    - Dr. Christopher Nantista of SLAC has been selected to be the current collaboration Scientific Secretary.

Goals

- The purpose of this collaboration is to perform research to determine the gradient potential of normal-conducting, rf-powered particle beam accelerators, and to develop the necessary accelerator technology to achieve those high gradients.
- Harnessing the momentum of the concluded NLC/JLC development programs and working in conjunction with the ongoing CLIC studies, the collaboration will explore the possibility of pushing the useable acceleration gradient from the 65 MV/m reliably achieved in NLC structures up towards 180 MV/m or higher.
- Advancing the state-of-the-art in this area is essential to the realization of a post-ILC, multi-TeV linear collider using two-beam rf power generation.

Scope

- This collaboration should not be viewed as an umbrella for general research into RF accelerator technology or other advanced accelerator techniques.
- For example, the general development of RF sources, modulators, and RF components are not included in this effort.
- Specific technology may be included, provided that it is required for achieving the goals expressed in the introduction.
- As our research proceeds, the collaboration may enhance or limit the scope of our work plan to include additional techniques or technologies which address the primary goal of the achievement of high acceleration gradient.

Methodology

- This research and development effort will include studying the rf breakdown phenomenon itself, theoretically and experimentally.
- It will aim to establish a better understanding of the frequency scaling of the limiting gradient, as well as its dependence on material, surface preparation, structure design, pulsed heating, etc.
- It will explore the high gradient barriers due to choices made in linear collider programs to date.
- The experimental side of this effort will entail the upgrade of test facilities and the development of new high-power rf sources specifically designed for high gradient testing.
- The final goal is to produce and successfully test at very high gradient an accelerator structure suitable for use in a multi-TeV two-beam linear collider.

Methodology: We must lay a technical and theoretical foundation

- Our research should be systematic and thorough, but it must be targeted due to limited resources.
- 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
  - …

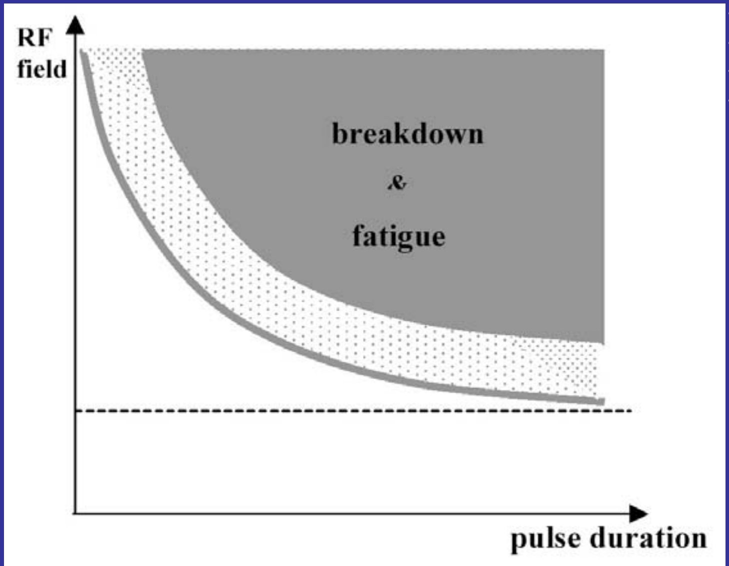
INSTITUTE FOR RESEARCH IN ELECTRONICS & APPLIED PHYSICS

University of Maryland program

Gregory Nusinovich et. al.

Theory and modeling of physical effects limiting reliable operation of high gradient accelerating structures

Goal: identification of the boundary between non-destructive (dotted) and destructive (dark grey) regions of operation in various structures



Nondestructive effects – dark current, multipactoring, Destructive – RF breakdown.

Multipactoring in metallic and dielectric-loaded structures: stationary and non-stationary theory

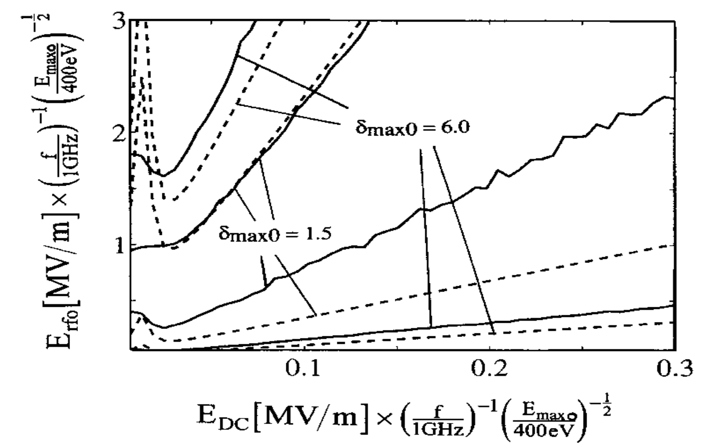
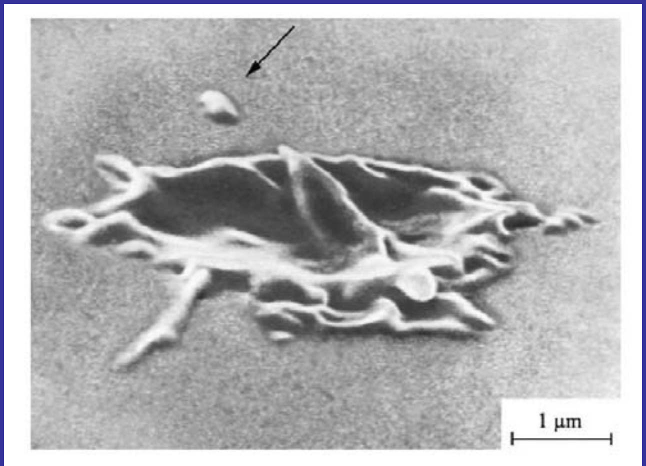


FIG. 5. Multipactor regions derived analytically (dashed) compared with the ones obtained through Monte Carlo simulations (solid) for $\delta_{max0} = 1.5$ and $\delta_{max0} = 6.0$. Here, $E_{0m}/E_{max0} = 0.005$.

The theory of dielectric-loaded structures will be developed in application to joint NRL-ANL X-band experiment.
Non-stationary theory + XOOPIC simulations

Analysis of the dark current will include studies of field emission from the irises of structures used at SLAC and CLIC, (thermal-field emission theory, geometric models of field enhancement, statistics of emission site non-uniformities and random profile models included).

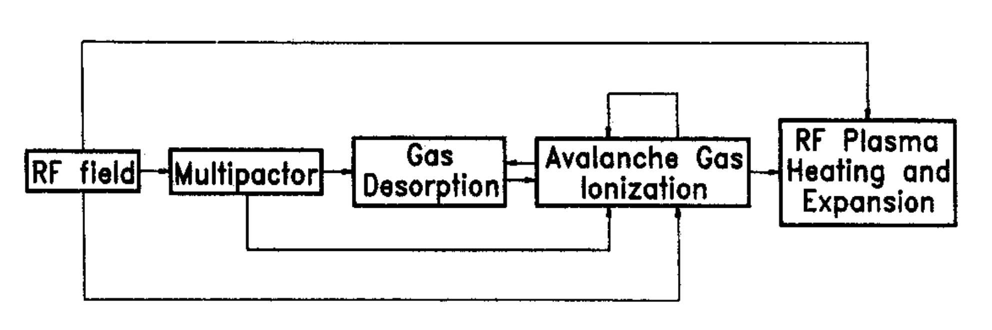
Destructive RF breakdown: formation of craters and their clusters (collaboration with SLAC)



Two scenarios of the RF breakdown:

a) Direct breakdown,

b) Breakdown via multipactoring

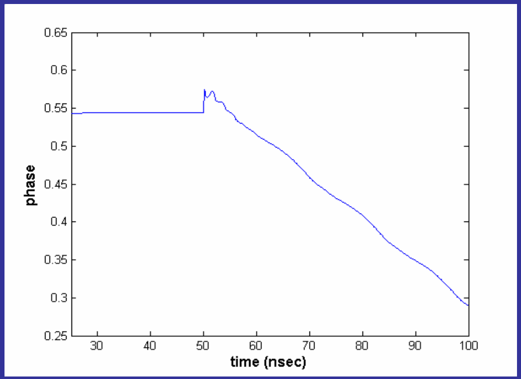


Novel structures: PBG and quasi-optical structures allow for stronger damping of wake fields – operation with shorter pulses.

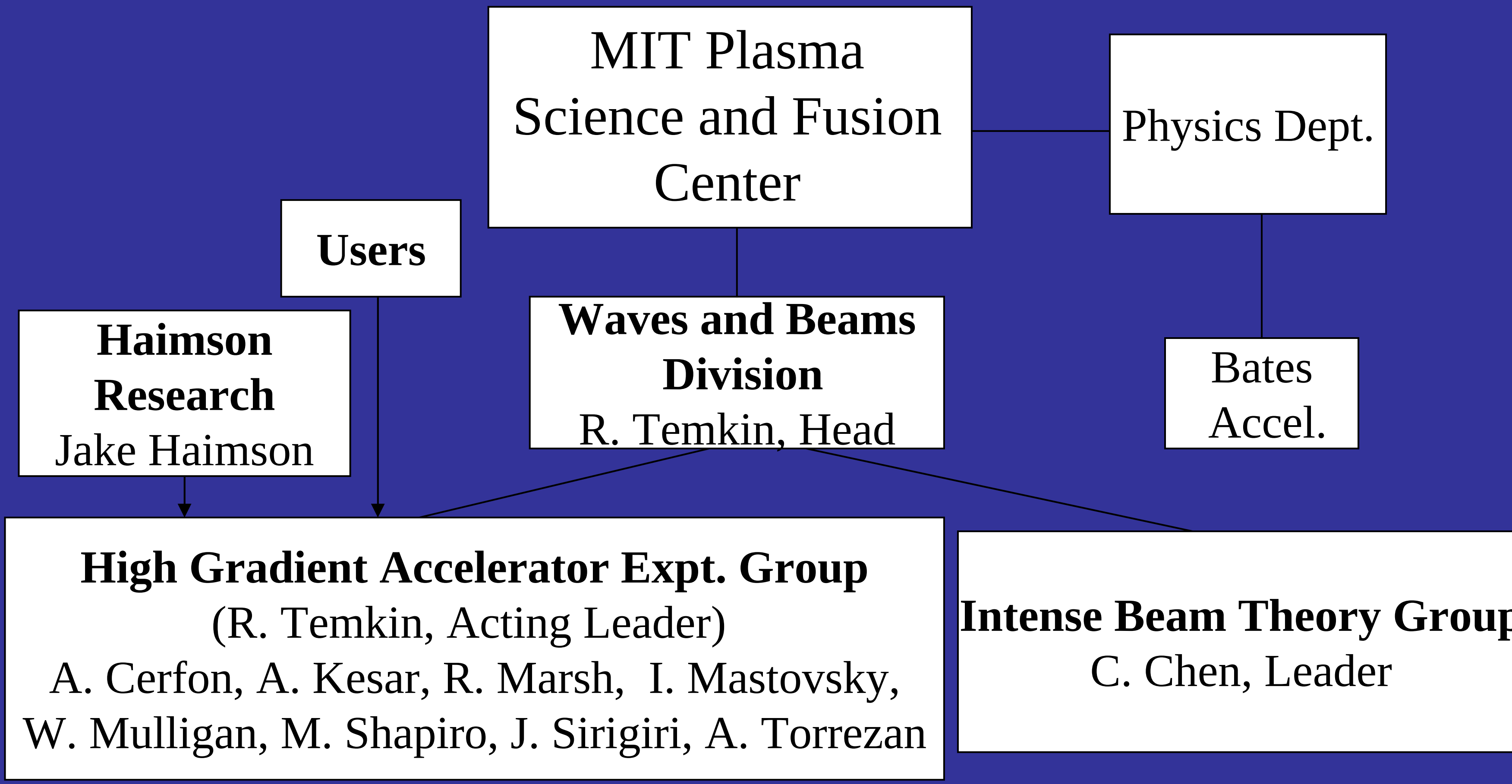
Pulse heating and RF breakdown issues to be addressed. (Collaboration with MIT and Omega-P)

Gyrotron oscillators for testing high-gradient structures (30 GHz - CLIC frequency) .

Phase sensitivity to voltage variations in free-running and phase-locked devices. (Collaboration with SLAC and MIT)



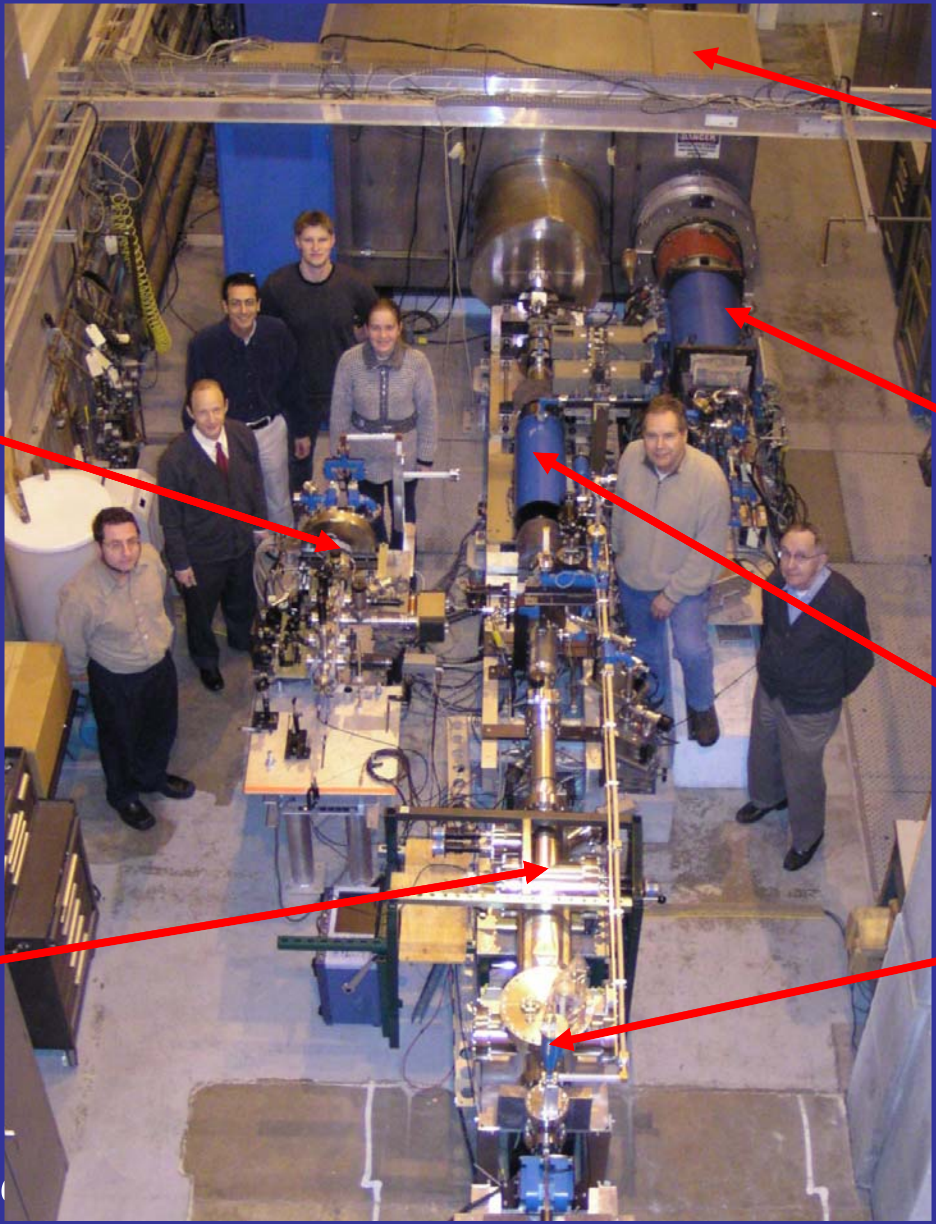
MIT Accelerator Research



17 GHz Accelerator Laboratory

RF Break-down / RF Gun Test Stand

THz Smith-Purcell Expt.



Modulator
700 kV, 780A
1 μs flattop

Klystron 25 MW
@ 17.14 GHz

25 MeV Linac
0.5 m, 94 cells

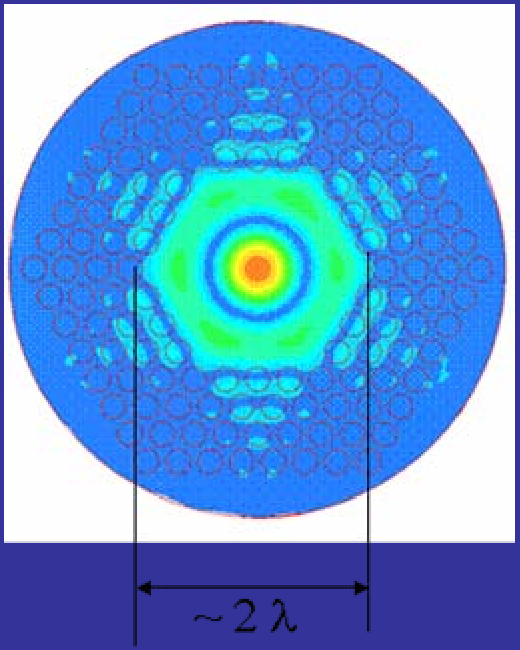
Novel High Gradient Structure / Photonic Bandgap Test Stand

Proposed Use of Existing 17 GHz Facility

- Test RF Breakdown in novel structures
  - Test at 17 GHz with up to 10 MW at > 200 ns.
- Already demonstrated to > 300 MeV/m
- Optical diagnostics.
- Electron Beam / Dark Current diagnostics.
- User Friendly

Examples of Proposed Novel Structure Research

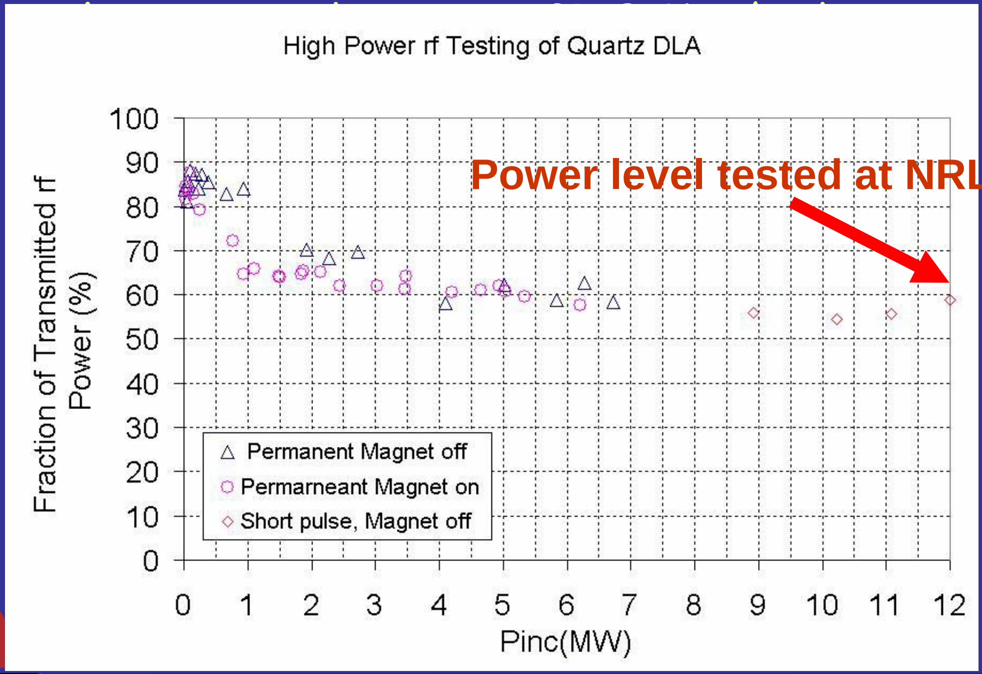
- Novel structures "outside of the box"
- MIT Examples:
  - Dielectric Photonic Bandgap Structures
  - High order mode accelerators
    - Shapiro et al., PAC03
  - Surface mode accelerators
    - Shapiro et al., PAC05
- New Ideas
  - Specific new proposals have been developed by MIT

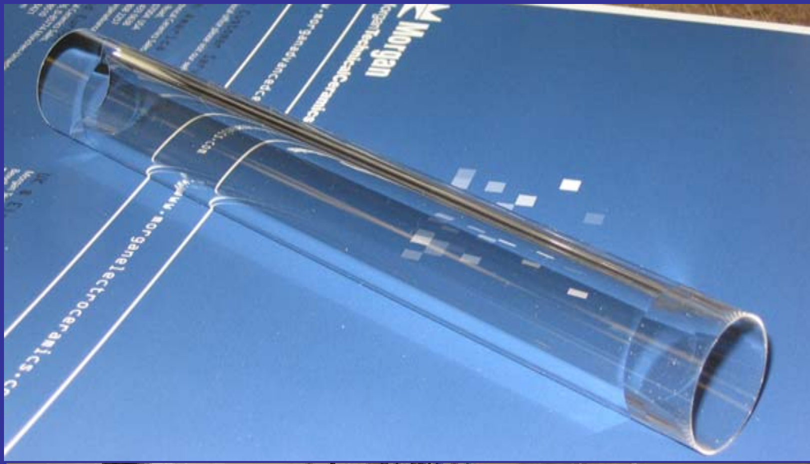


TM_{02}–like mode

A Quartz tube fabricated and tested at NRL, up 12 MW. More power needed. Higher power (10 – 50 MW) planned at SLAC this fall.

Parameters	Value
Material	Fused Silicon
Inner Radius	8.97mm
Outer Radius	12.08mm
Dielectric Const	3.78
Group Velocity	0.38c
R/Q	3.614kΩ/m





High Power RF-Technology

22.8-30 GHz RF Sources and related technologies

- Several RF sources have been proposed at these high frequencies, including, gyrotrons, gyroklysrons, sheet-beam klystrons, magnicons, Harmonic Converters, etc.

- The Gyrotron is our best bet for a workhorse device in a short period of time.
  - If we buy this device only CPI can do it and they will probably team with MIT and Maryland for theoretical support.
  - If we make it we will use the same people with the addition to SLAC's experience to make electron guns. In this case we will have all the world experts working on this at the same time. It will also force us to talk to each other and collaborate.
  - No mater what this is a research device and the risk is high.
  - All the first and second generation experts, within the US, on Gyro devices are in this collaboration

- We have been successful in getting the rest of the collaboration to follow our lead on this matter!

Budget and Facilities for the High Gradient Program (continued)

- NLCTA (3 RF stations, one Injector, one Radiation shielding)
  - Two 240ns pulse compressor, 300 MW peak, powered by two X-band 50 MW klystrons (used mainly for CERN and NLC type experiments)
  - One 400/200 ns pulse compressor, 500 MW peak, powered by 2 X-band 50 MW klystrons (Modulator is in final stage of construction)
  - 65 MeV injector with a 1 nC charge/bunch
  - Shielding enclosure suitable for up to 1 GeV
- Klystron Test Lab (2 RF stations, 2 modulators, 2 shielding enclosures)

  RF Stations
  - Stations 6 and 8, two 50 MW klystrons that can be combined and a variable length pulse compressor that can produce up to 500 MW (under construction).
  - Station 4, 50 MW klystron,

  Modulators
  - Station 2, ~500 kV, ~200 A modulator
  - Station 3, 500 kV, ~xxx A modulator

  Radiation Shielding
  - A shielding enclosure suitable for up to 100 MeV (ASTA Bunker)
  - A shielding enclosure suitable for up to 5 MeV

Most of the RF stations were not available this year because of either reconstruction or priority conflict with other lab programs such as LCLS. We have asked our management for a dedicated facilities for the High Gradient work. We will try to use both ASTA and the two-pack at NLCTA as the prime facilities for this research

2006-2007 ASTA TESTS:

In the summer of 2006 the LCLS Gun #1 tests will be tested with an S-band RF source in the structure in order to condition the gun, measure dark current and visualize possible breakdown with video.

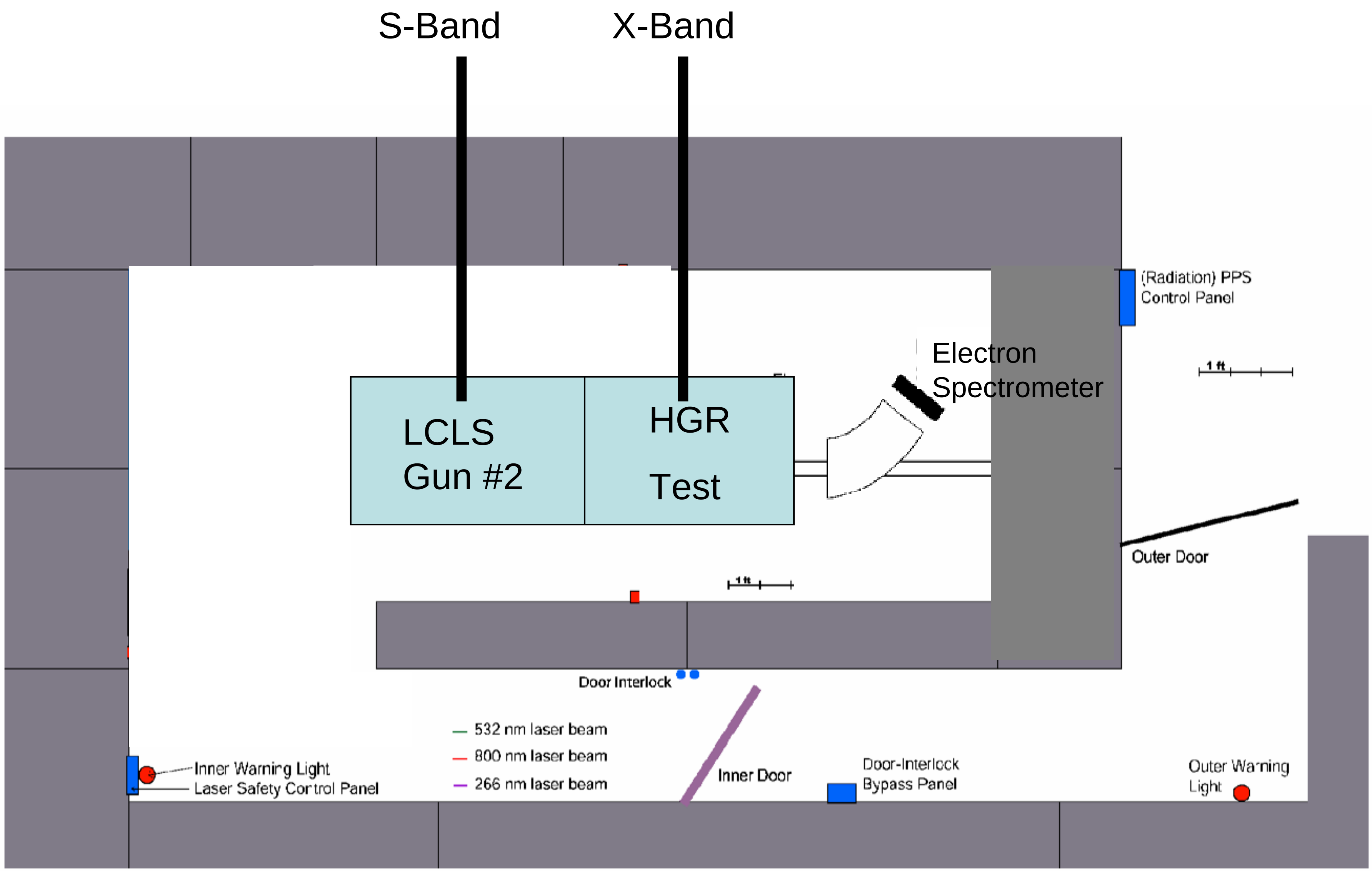
In the fall of 2006 the HGR program will test the SLAC/KEK cell and/or the ANL dielectric structure.
In January of 2007 LCLS gun #2 will be tested with a laser in ASTA.

2006-2007 ASTA Schedule:

June – September: S-band to test LCLS gun #1 under RF

October – December: X-band to test High Gradient structures

January – December 2007: Shared time between HGR test and test of LCLS gun #2, S & X band available



ASTA – Accelerator Structure Test Area – Fall 06

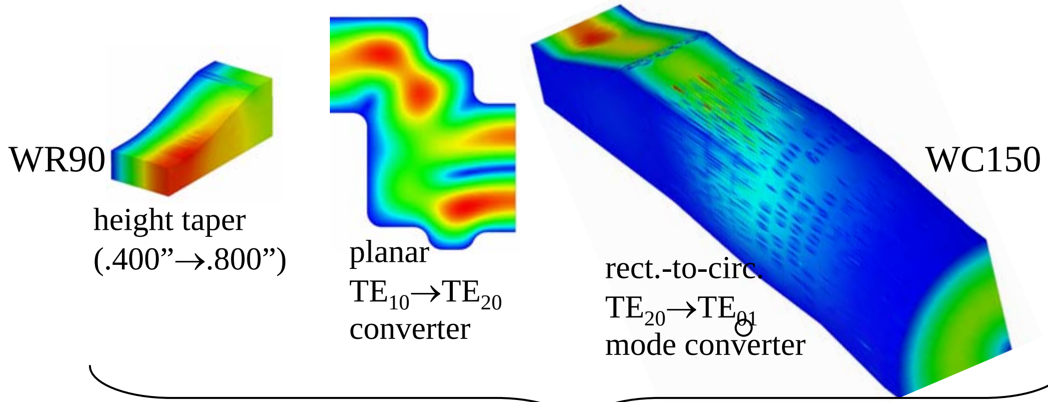
Stephen Williams

2006 SLAC program

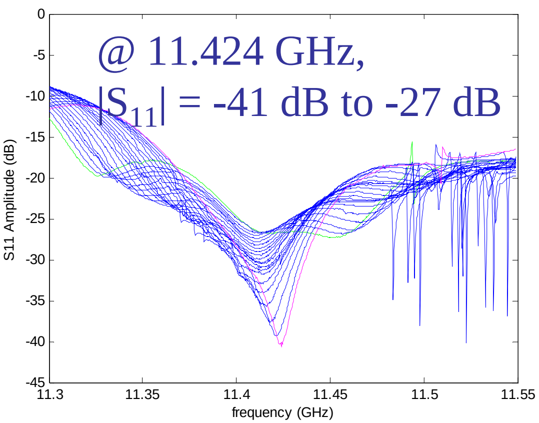
- Support for Other x-band facilities and experiments
- Rebuilding of X-band RF infrastructure at ASTA
- Reconfiguring the 2-pack facility
- Building a test setup for pulsed heating and superconducting material characterization
- Material characterization by electron beams (V. Dolgashev/KEK, funded by KEK)
- Testing waveguide and structures at NLCTA
  - Molybdenum waveguide
  - CERN structures
  - NLC structures
- Designing Active RF pulse compression switches at 30 GHz for use at CERN and later at SLAC

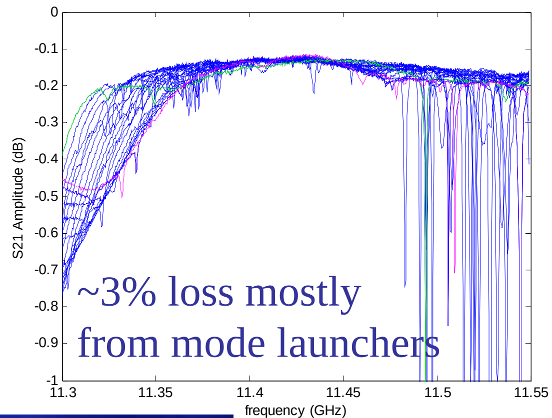
SLAC is not only supporting other labs in terms of SLAC's experimental facilities but also in terms of components and the developments of these components

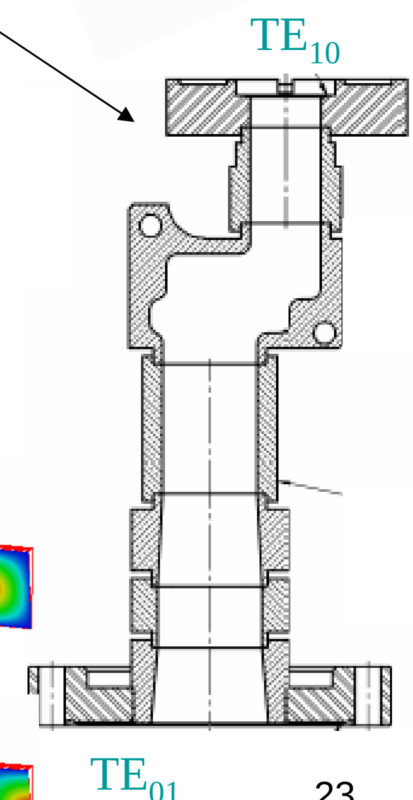
WR90-WC150 TE_{01} Mode Launcher

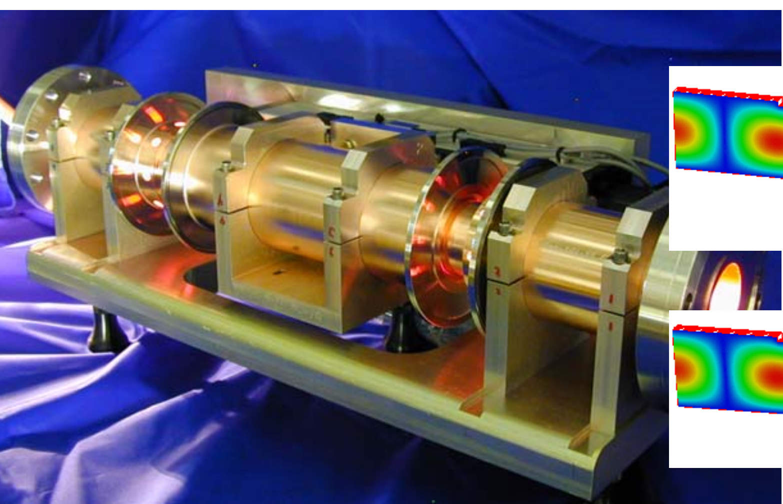


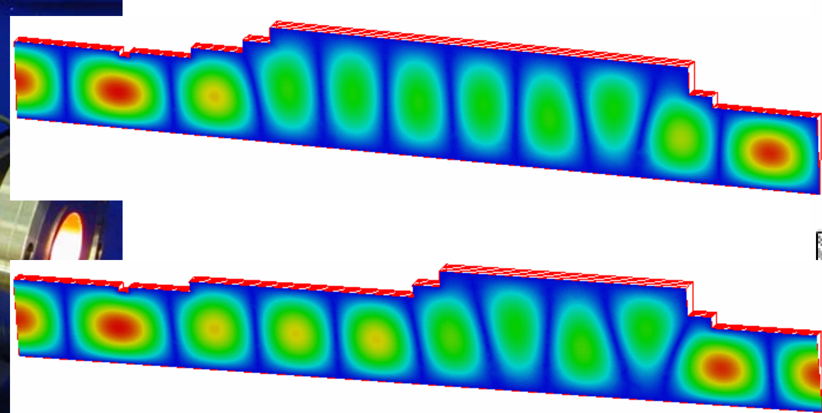
Circular TE_{01} Mode Slide Phase Shifter for NRL/ANL



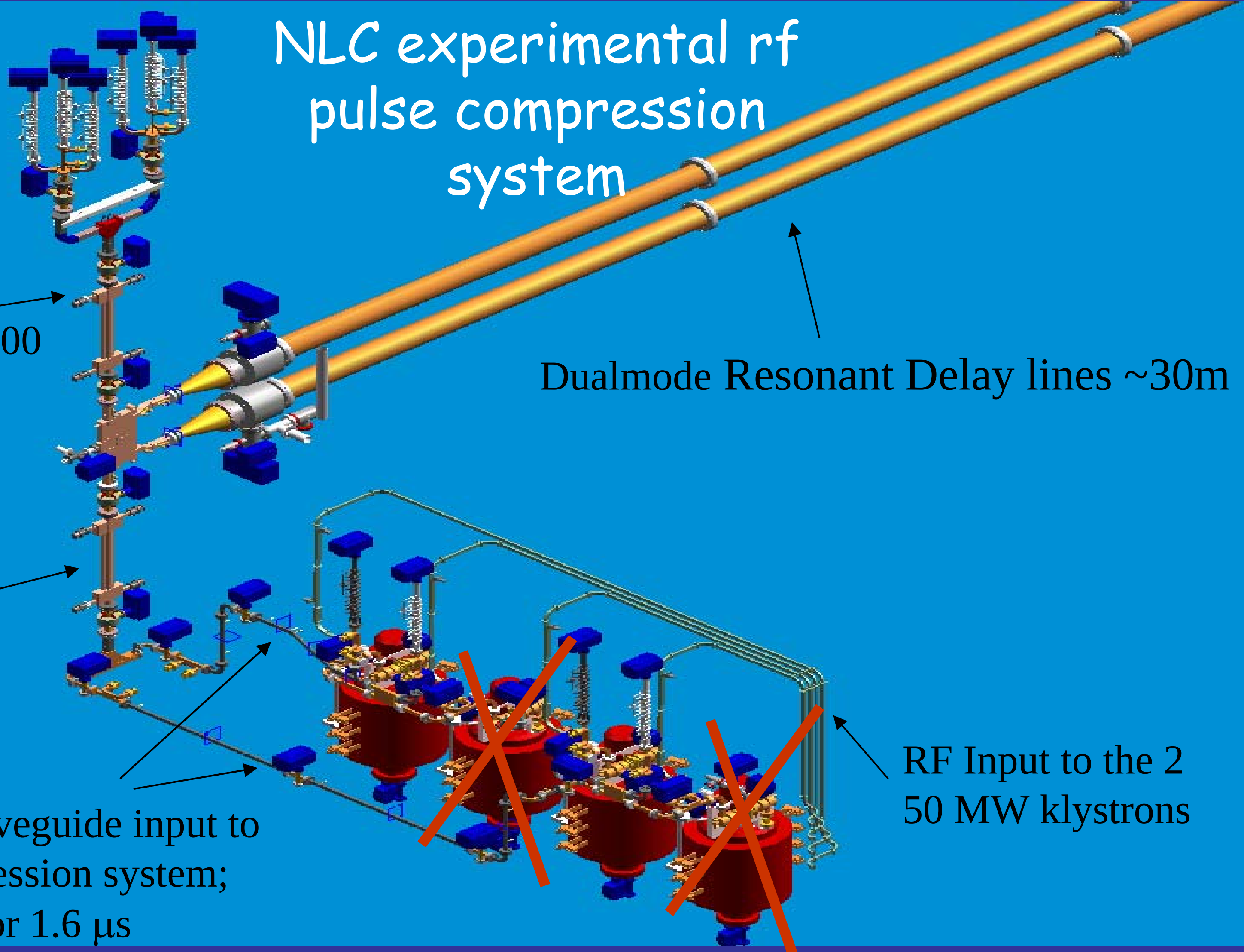




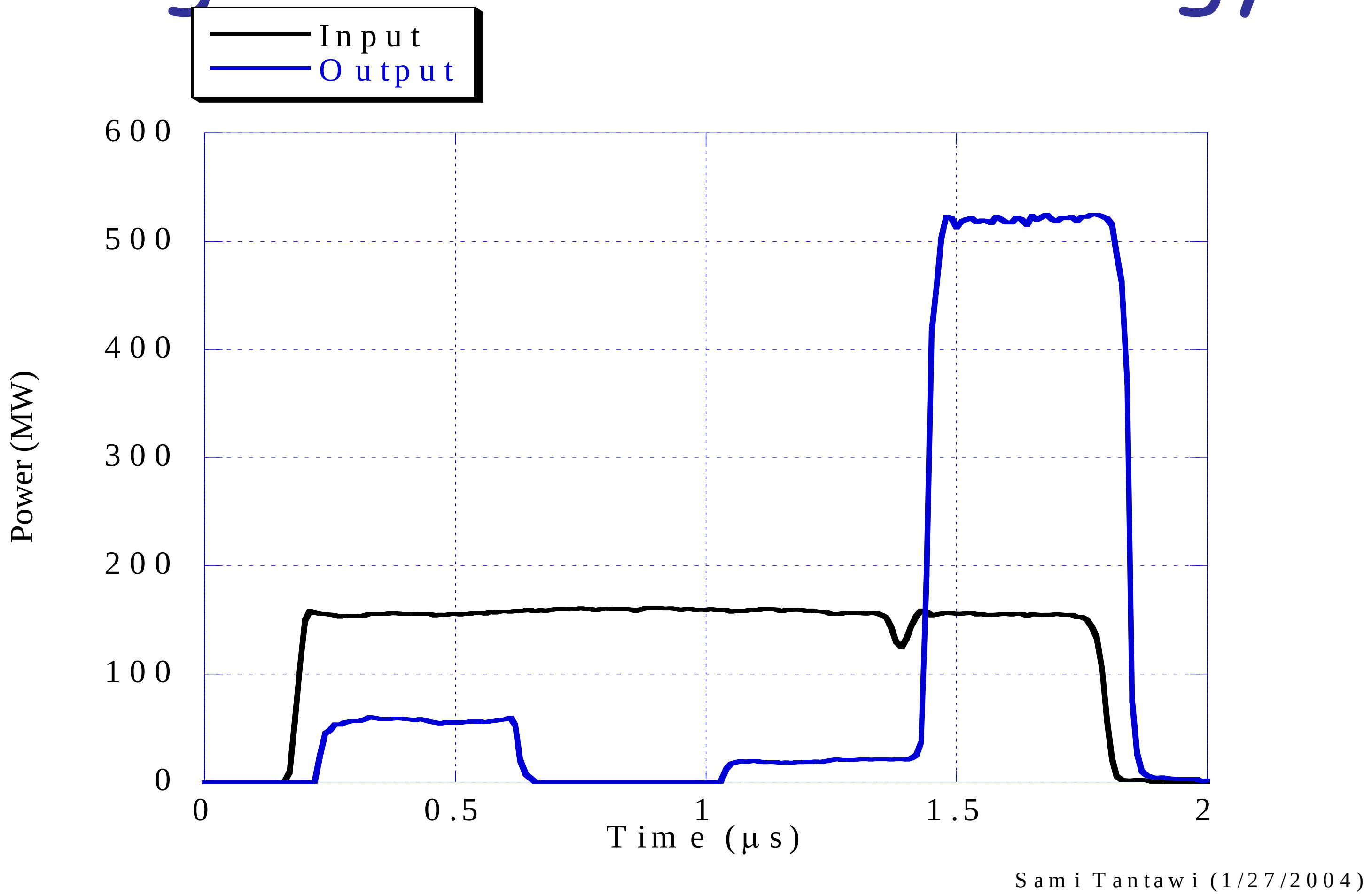




Ultra-High Power Multimoded Pulse Compression Systems Modified by removing two klystrons and using a new modulator



High Power RF-technology

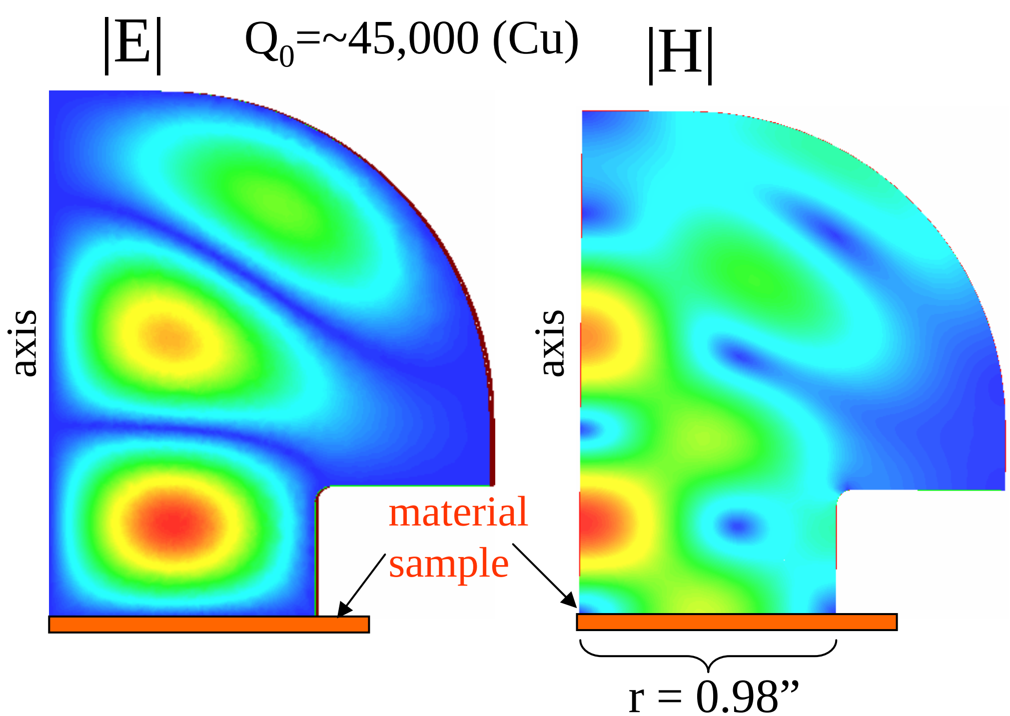


Output of the Experimental NLC Pulse Compression System

Superconducting Materials Test Cavity

TE$_{013}$-like mode

Q_0=~45,000 (Cu)

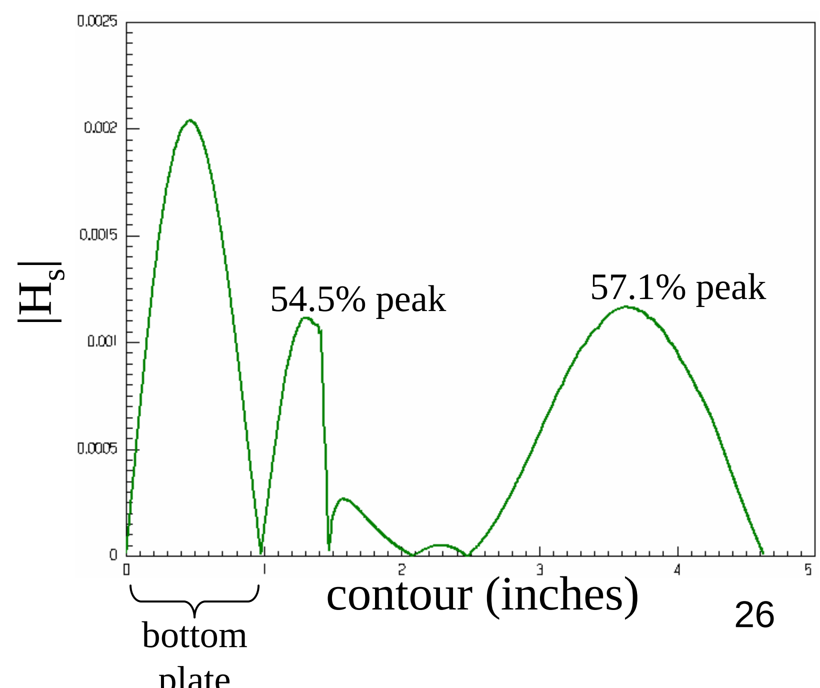


Features:

•No surface electric fields (no multipactor)

•Magnetic field concentrated on bottom (sample) face

•Purely azimuthal currents allow demountable bottom face (gap).



X-band (~11.424 GHz):

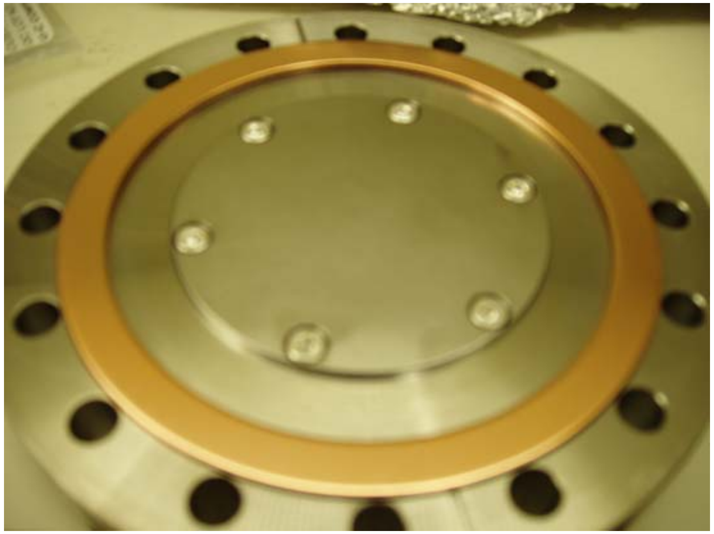
•high power available

•fits in cryogenic dewar

•small (3”) samples required

“Cold” Tests (Room Temperature)

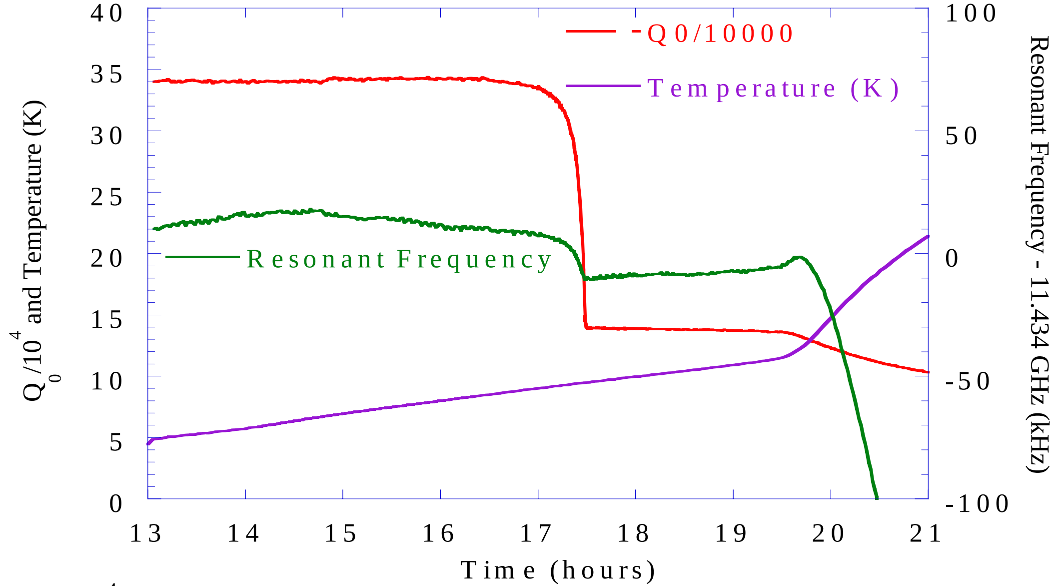
	HFSS (Cu)	Copper	Niobium
f_r	11.424	11.4072	11.4061
Q_L	30,991	29,961	20,128
β	0.4383	0.4611	0.2728
Q_0	44,575	43,775	25,619
Q_e	101,694	94,944	93,906



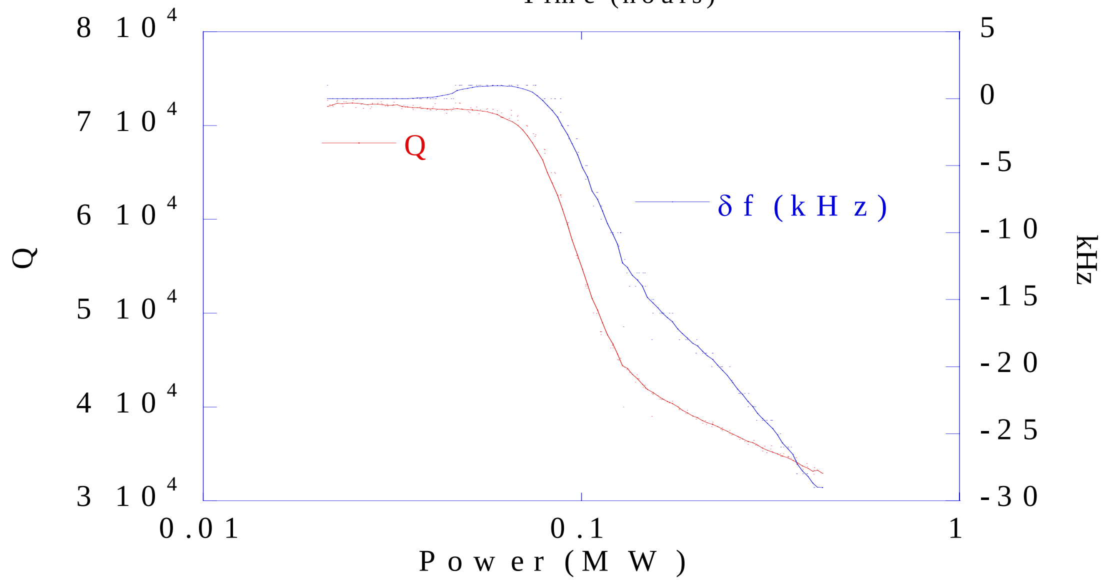
Nb sample mounted in bottom flange

HP 8510C Network Analyzer

Fundamental Research in RF Superconducting Materials



Low-power test



High-power test

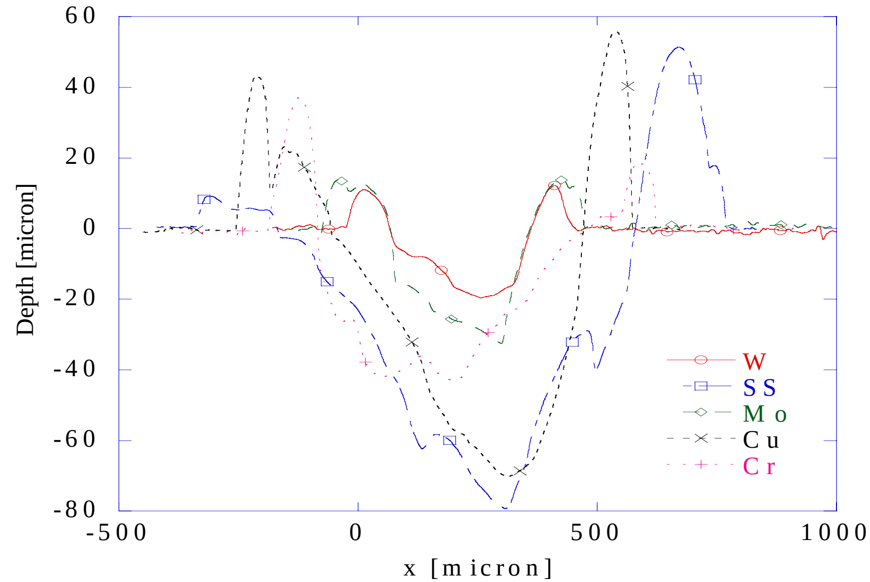
New test setup for inexpensive accurate characterization of high-field RF properties of materials and processing techniques

Sami Tantawi et. al.

Material Characterizations

(Funded by KEK)

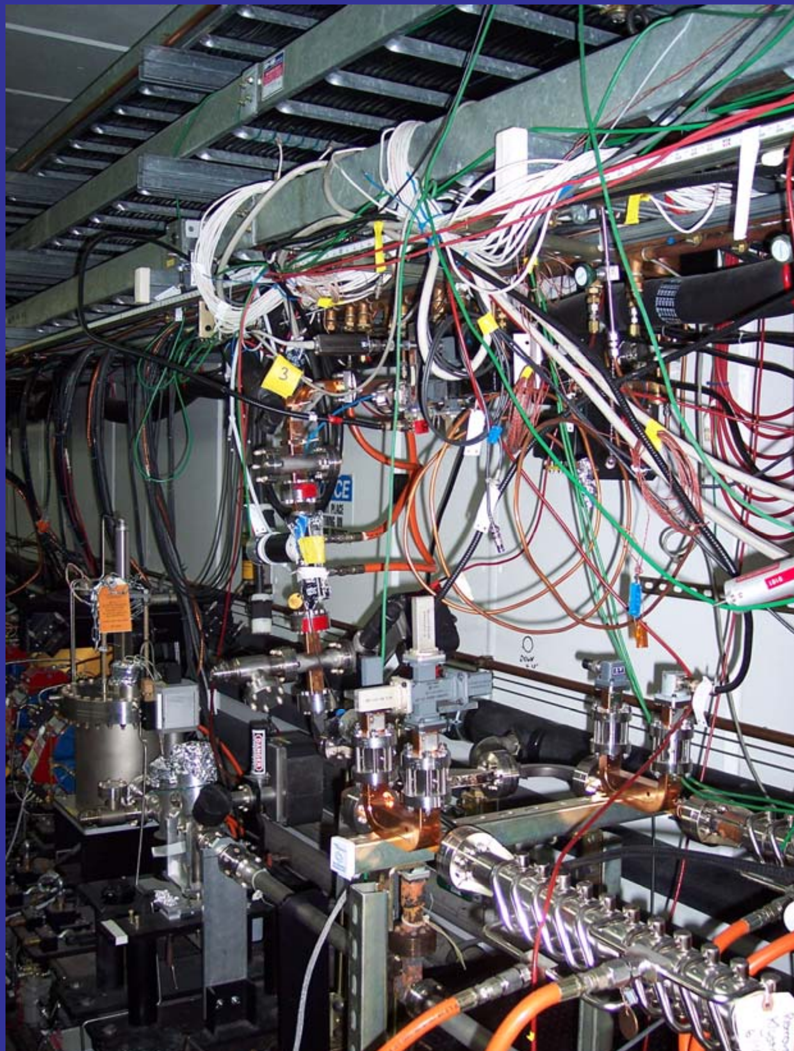
Profile of craters from 150 keV electron beam on 5 different metals: Tungsten, Molybdenum, Copper, Chromium, and Stainless Steel

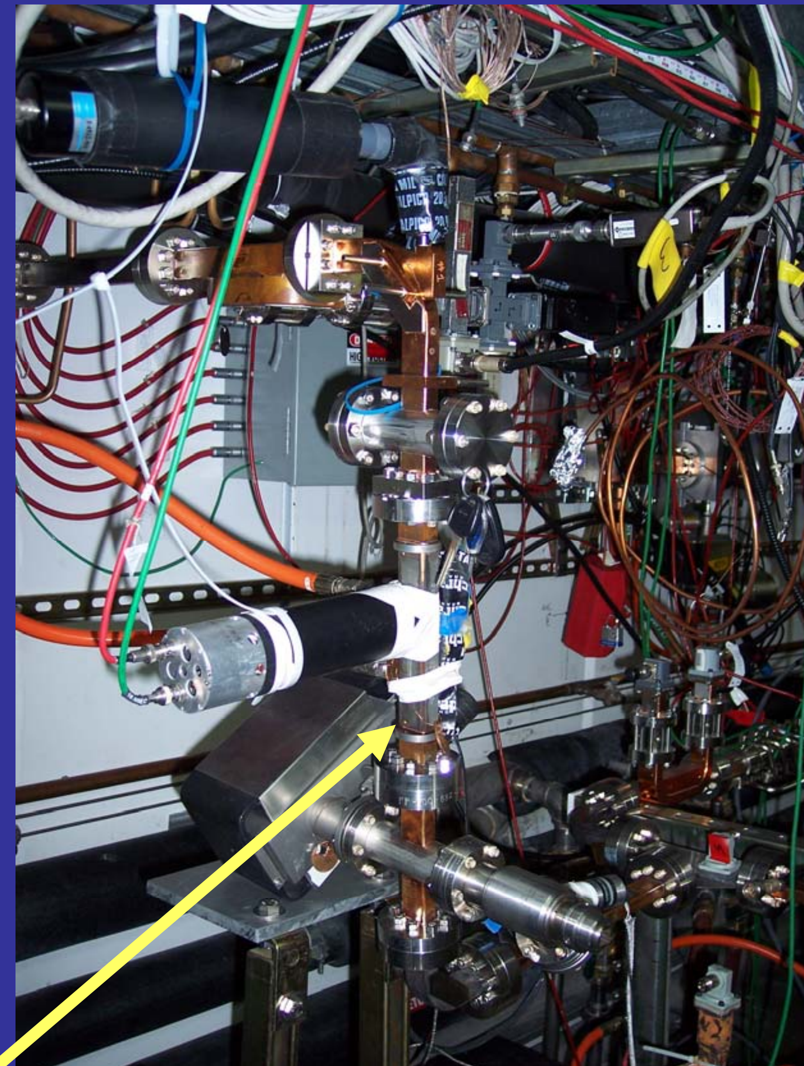


Understanding material electron bombardment interaction (Central to breakdown theory as developed by P. Wilson/V. Dolgashev)
SLAC/KEK collaboration: V. Dolgashev (SLAC), Y. Higashi (KEK), T. Higo (KEK)

Processing of molybdenum waveguide

- **Goal:** Study arc-resistant metals
- Preliminary data shows stainless steel and molybdenum have superior to copper breakdown performance (molybdenum is less lossy)
- Processing behavior is different from that of copper (also limited sampling)
- Further study limited by availability of rf sources

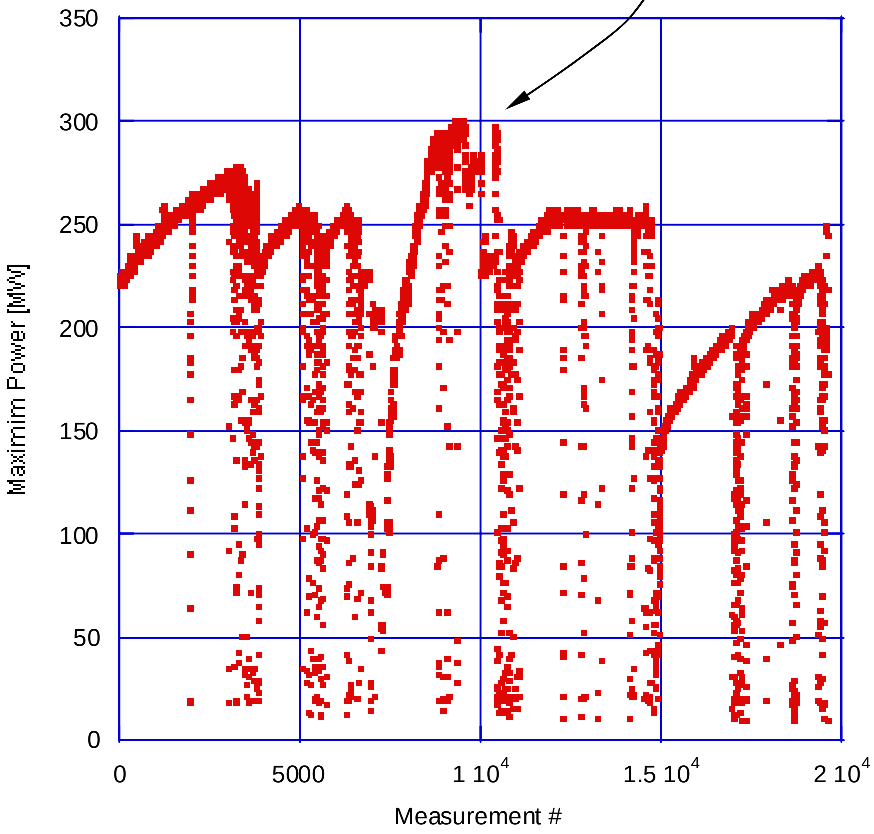


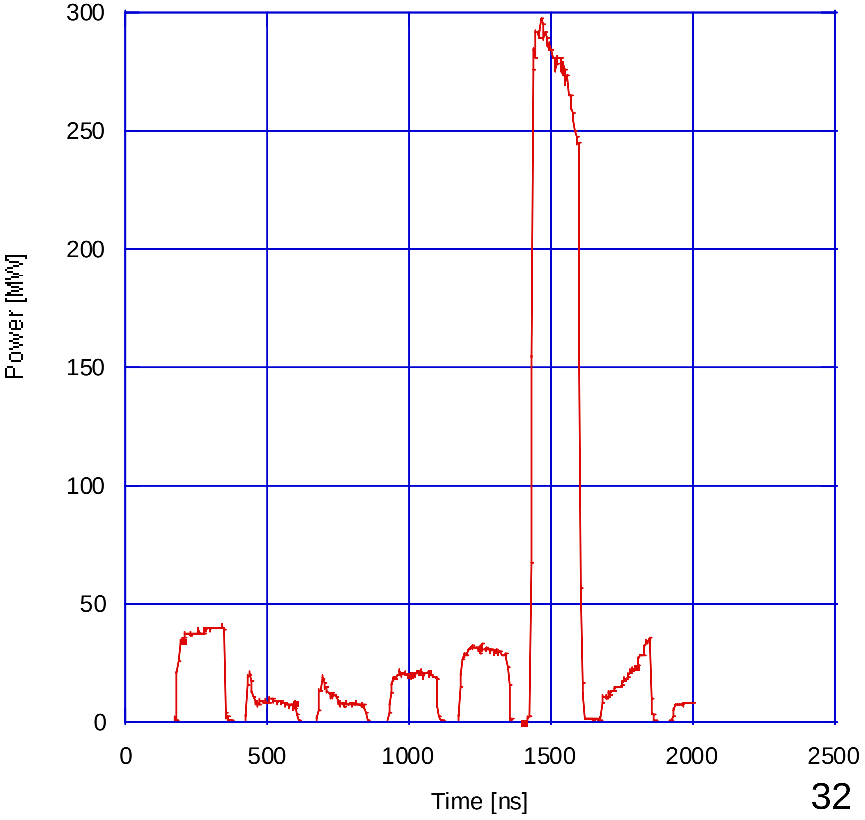


Molybdenum
Waveguide

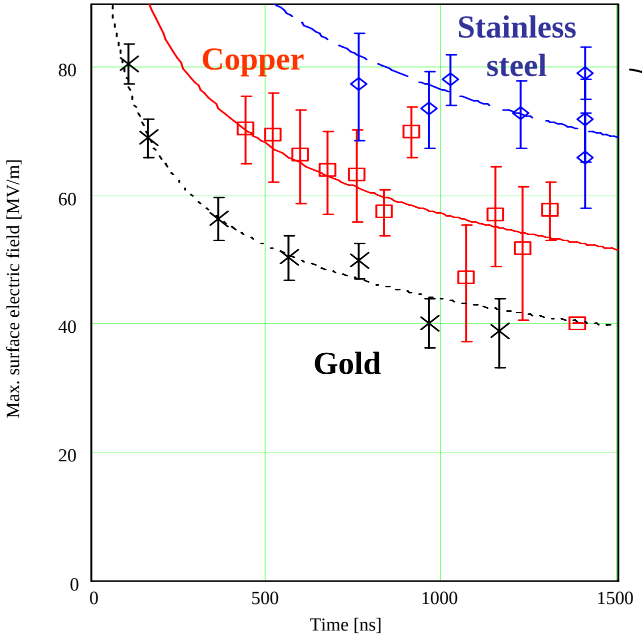
Processing of molybdenum waveguide

Measurement 9500, 1216_25jan06

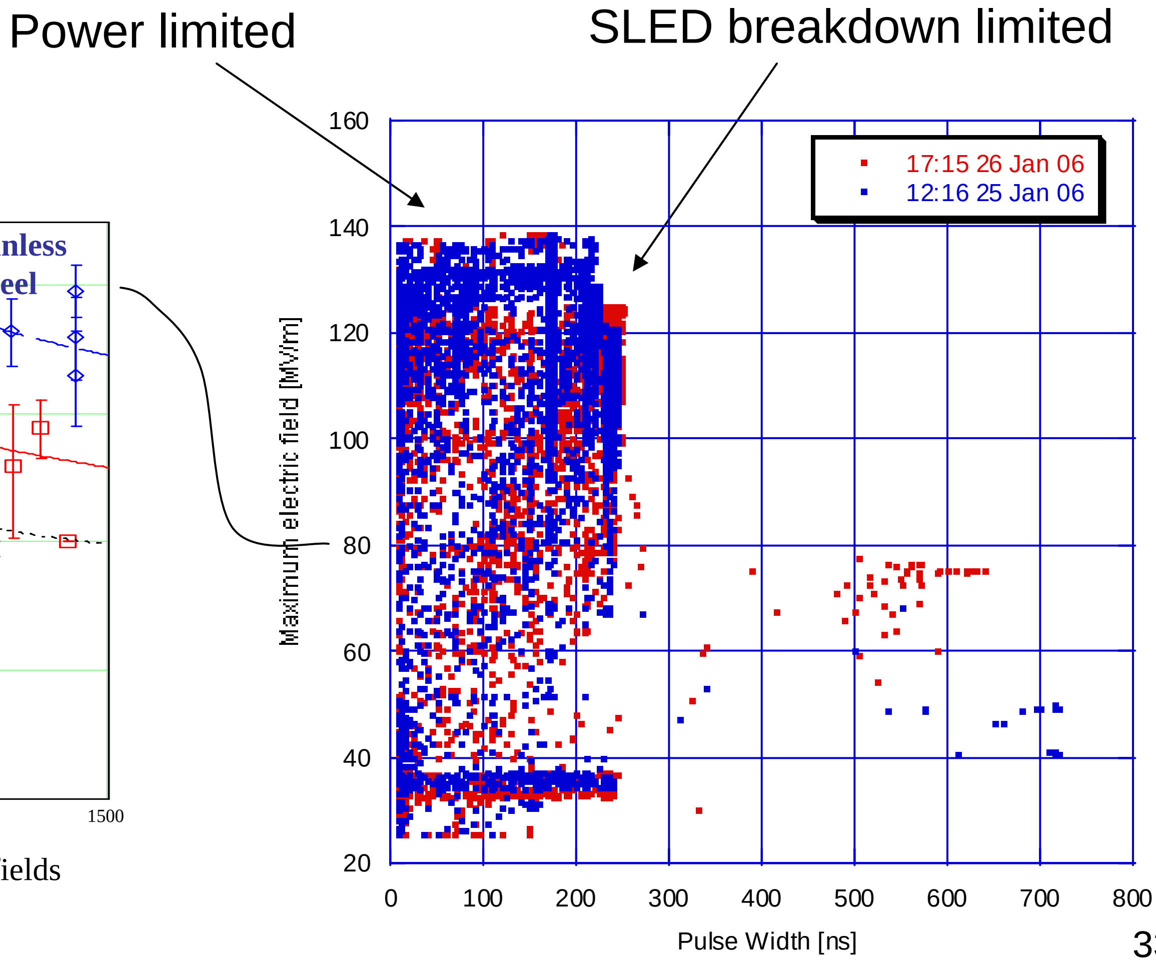




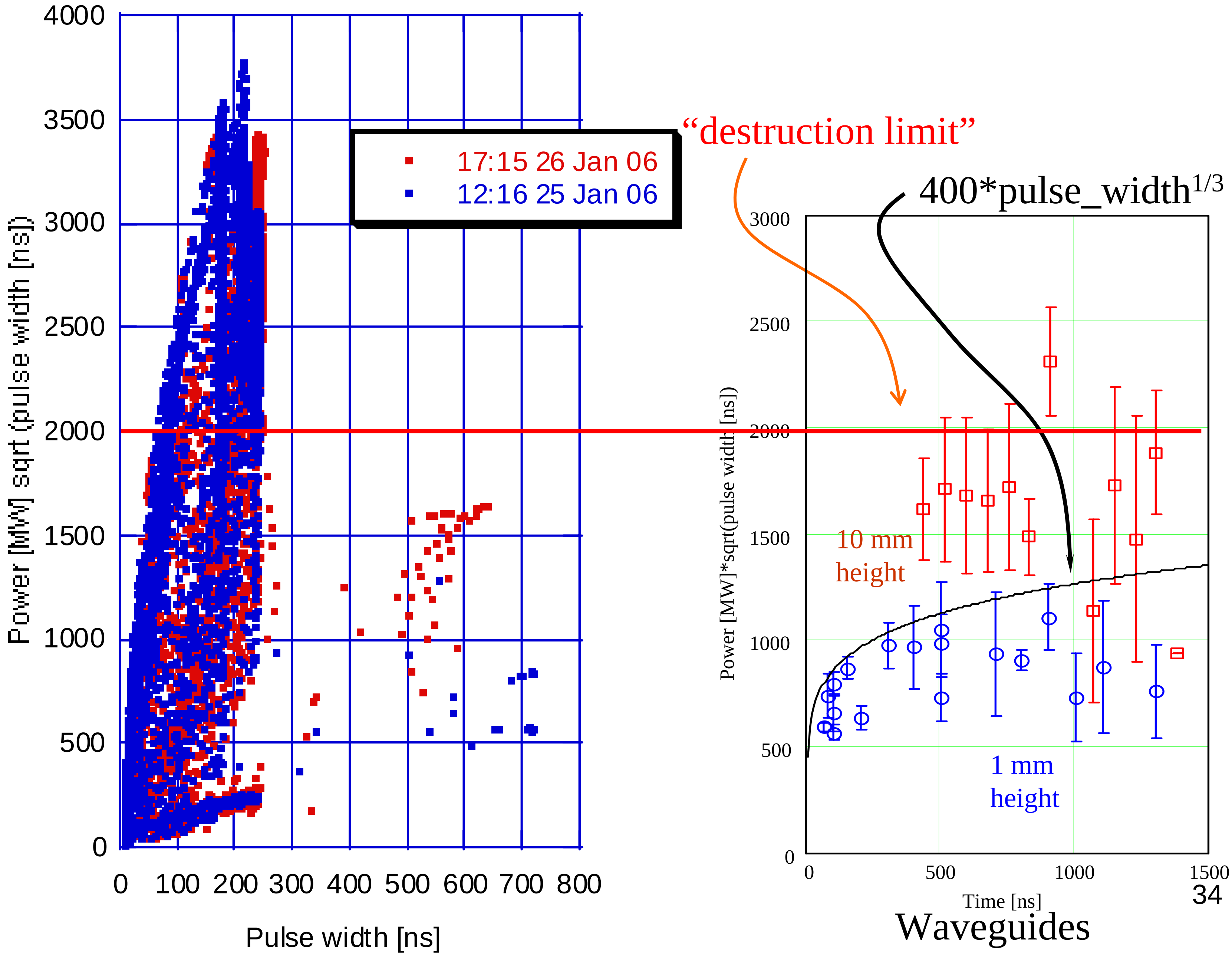
Processing of molybdenum waveguide



Maximum breakdown electric fields
for different materials



Processing of molybdenum waveguide



Waveguides

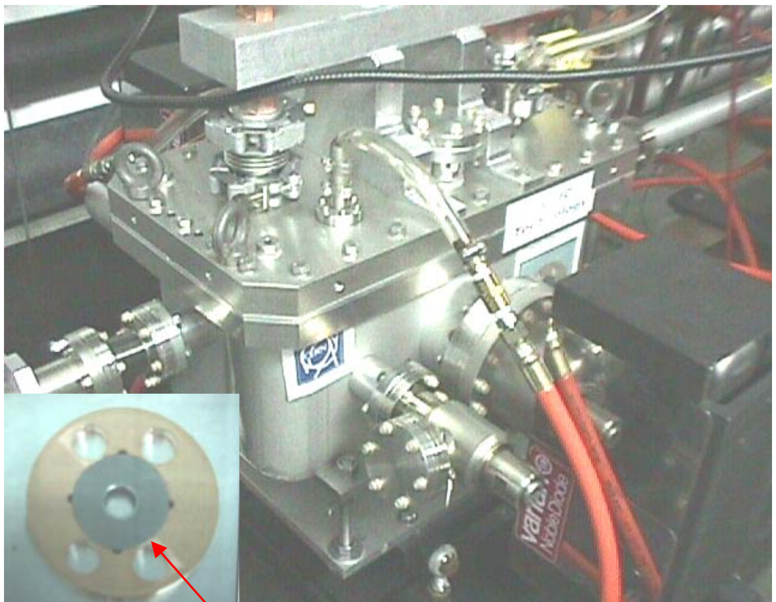
NLC and CLIC X-band Structure Program in FY06

- Evaluate CERN clamped Tungsten-iris structure
  - Completed: performed worse than Copper NLC structures
- Evaluate SLAC/KEK 75 cm NLC structure
  - Longer than the ‘standard’ 60 cm NLC prototypes
  - Tests at nominal temperature (45 degC) complete - performed better than expected – currently evaluating it at 10 degC
- Evaluate Cu and Mo CERN HDS structures
  - Structures being assembled
- Measure breakdown rate with double pulse -vs- pulse separation in an NLC structure – not yet started
- Test hermetically sealed NLC structure – parts acquired

L. Laurent, C. Adolphsen

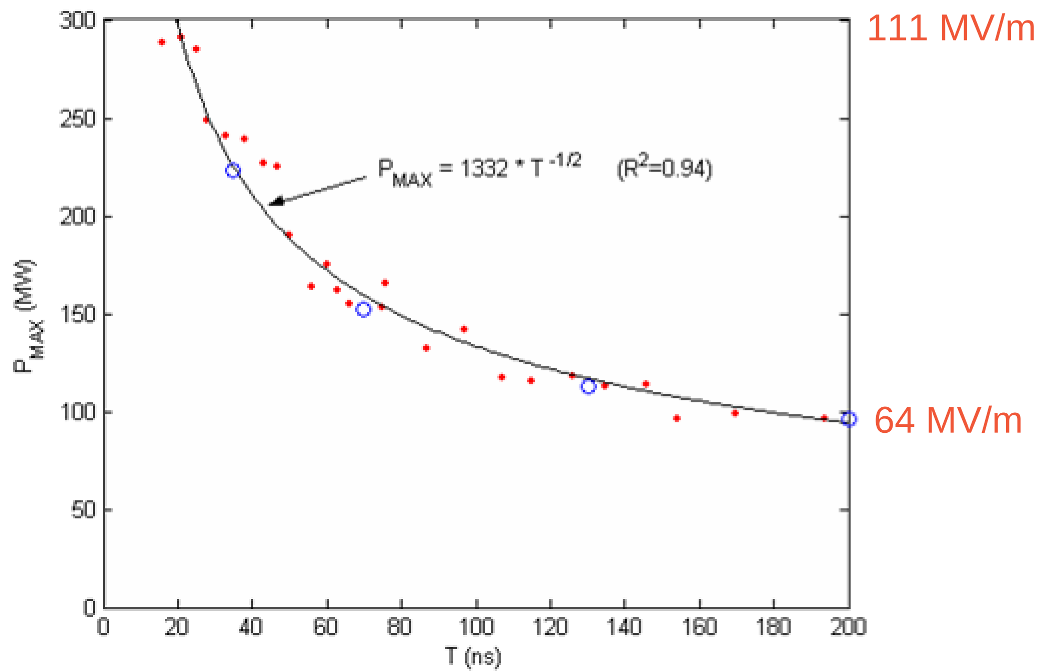
CERN X-Band Accelerator Structure with Tungsten Iris Inserts

Photo of Setup and Cell



Tungsten Insert

Power vs Pulse Length

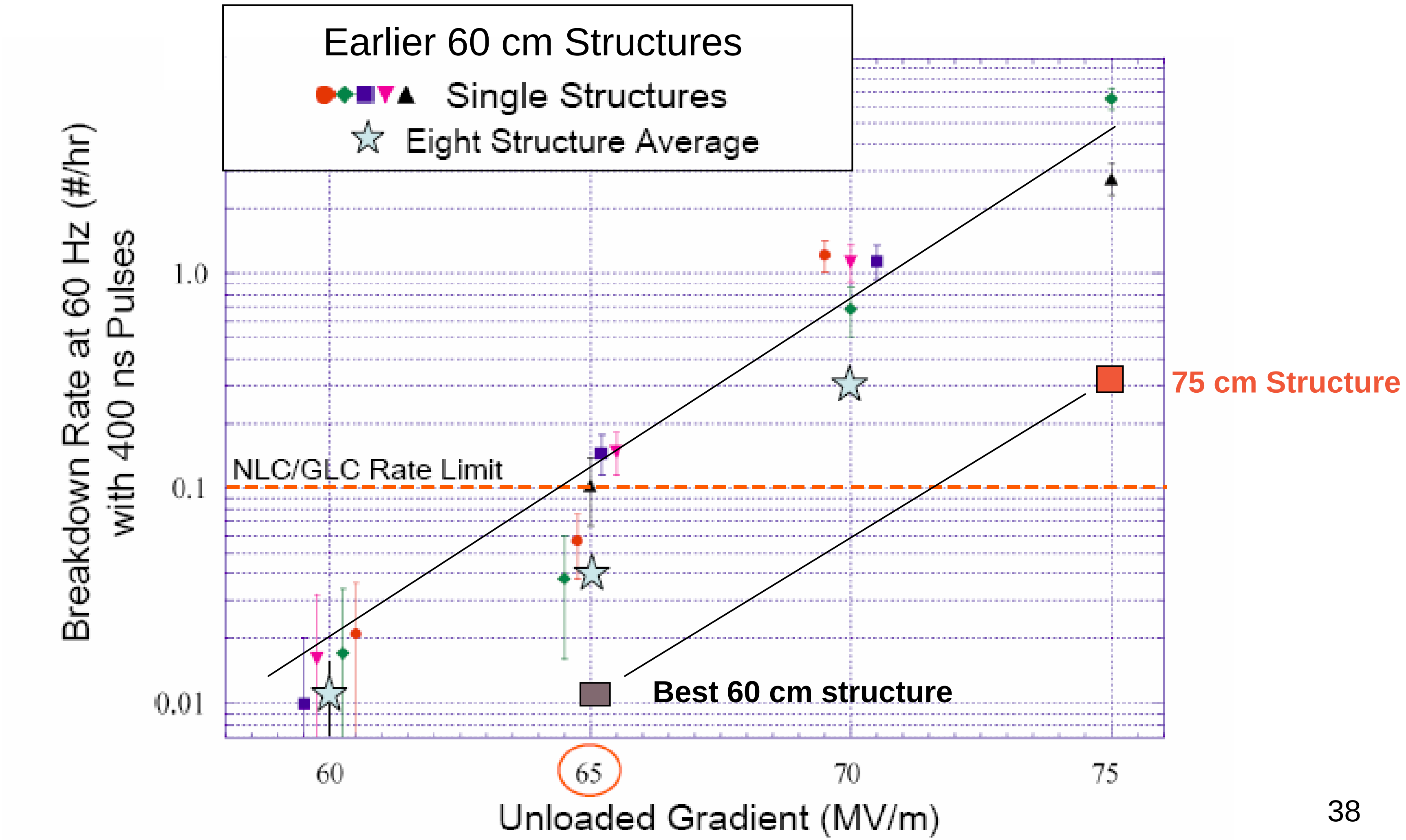


Dots = Achieved Initially with ~ 60 breakdowns / hr
Circles = After 1750 hrs of processing with 10-20 breakdowns / hr

W-Structure Conclusions

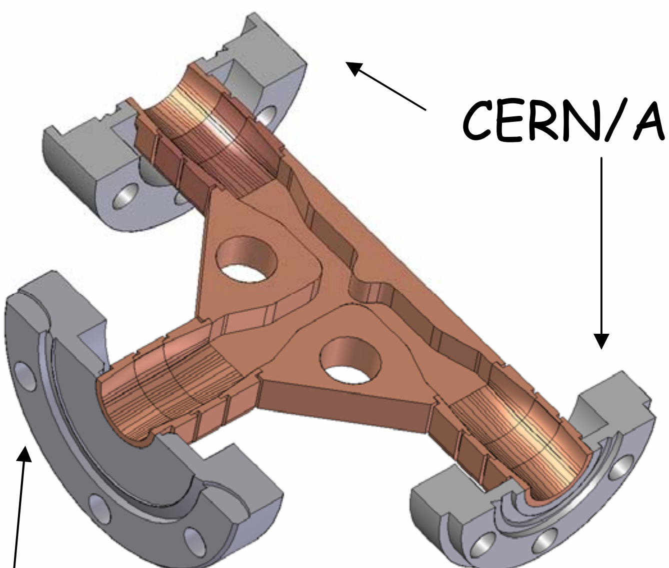
- No significant improvement with continued rf processing.
- Tungsten performed much worse than copper structures:
  - W-structure: 200ns, 63 MV/m (10-20 bds/hr)
  - Cu-structure: 250ns, 100MV/m (<10 bds/hr) in recent test.
- Reprocessing was necessary when returning to any given pulse length in order to reach previously achieved power levels.
- Observed characteristic breakdown "spitfests": One breakdown initiates multiple breakdown events.

Test of a Longer (75 cm -vs- 60 cm), Higher Input Power NLC Structure

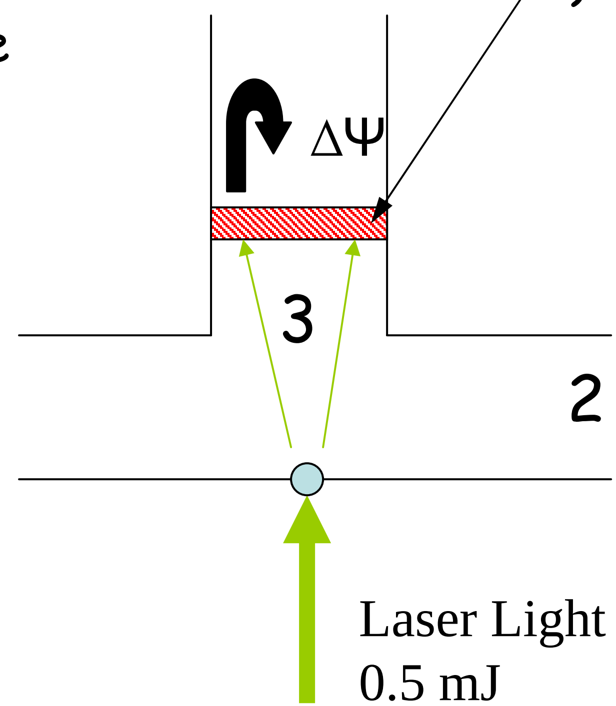


Design of the Switch Module

- Using an oscillator source requires an active pulse compression system.
- CERN also needs an active pulse compression system because of the difficulty of *fast* switching of the driving beam phase.
- Collaboratively we will developed this system based on our old ideas of optically controlled RF pulse compression system.



30 GHz TE_{01} Tee



SLAC's future program on high gradient research

- Novel Accelerator Structures.
  - Distributed coupling accelerator structure (to leverage as much as possible what we learned about geometrical effects)
  - Dielectric Accelerator structures at high frequency (we may be able to do experiments at 90 GHz if the CCR Inc 10 MW gyroklystron test is successful)
  - Heavily damped structures are being studied at CERN, MIT and University of Colorado.
- Basic Physics experimental studies
  - We have two vehicles for these studies
    - Waveguides
    - Single cell accelerator structures

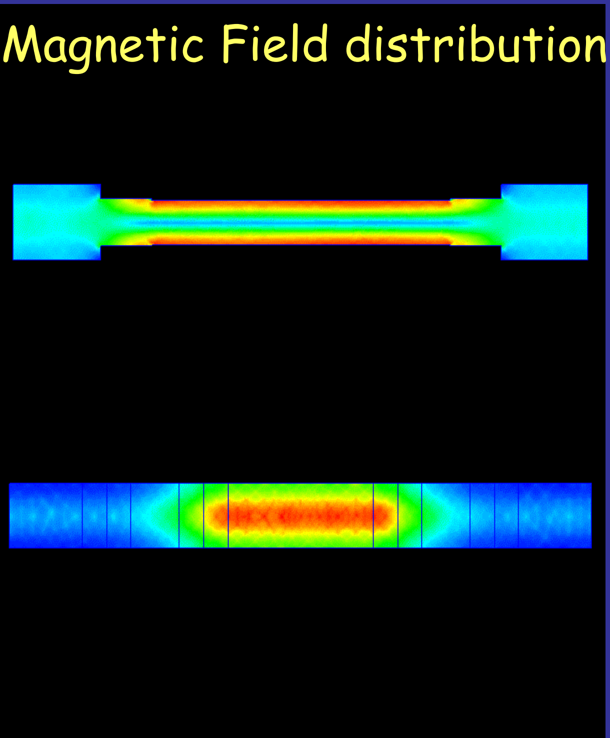
Future Work (2007)

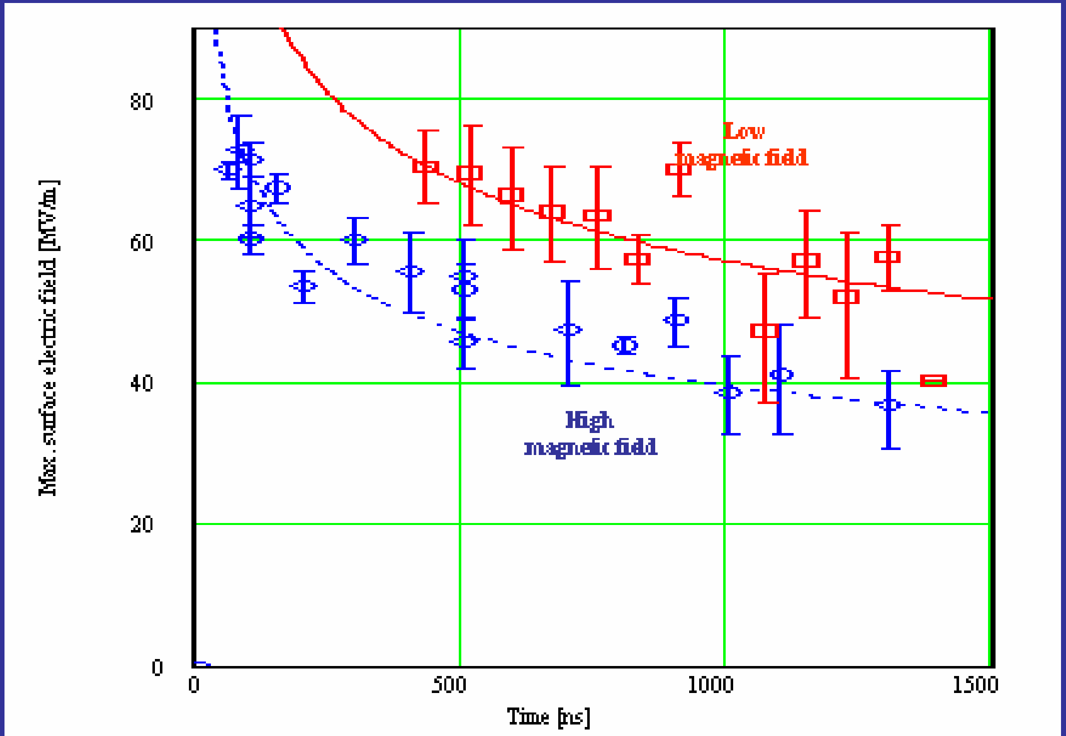
- Operation in two facilities (ASTA and the two-pack)
- Testing of single Cell Accelerator structures
- Testing of Waveguides with different materials
- Characterizing high magnetic field response of materials from SLAC, CERN, KEK, JLabs, SNS, and LANL
- Progress on 30 GHz RF source
- Realization of 30 GHz Active pulse compression system
- Progress on Breakdown theory
- Extended collaboration with MIT, U of Maryland, and ANL

SLAC's future program on high gradient research

Waveguides studies

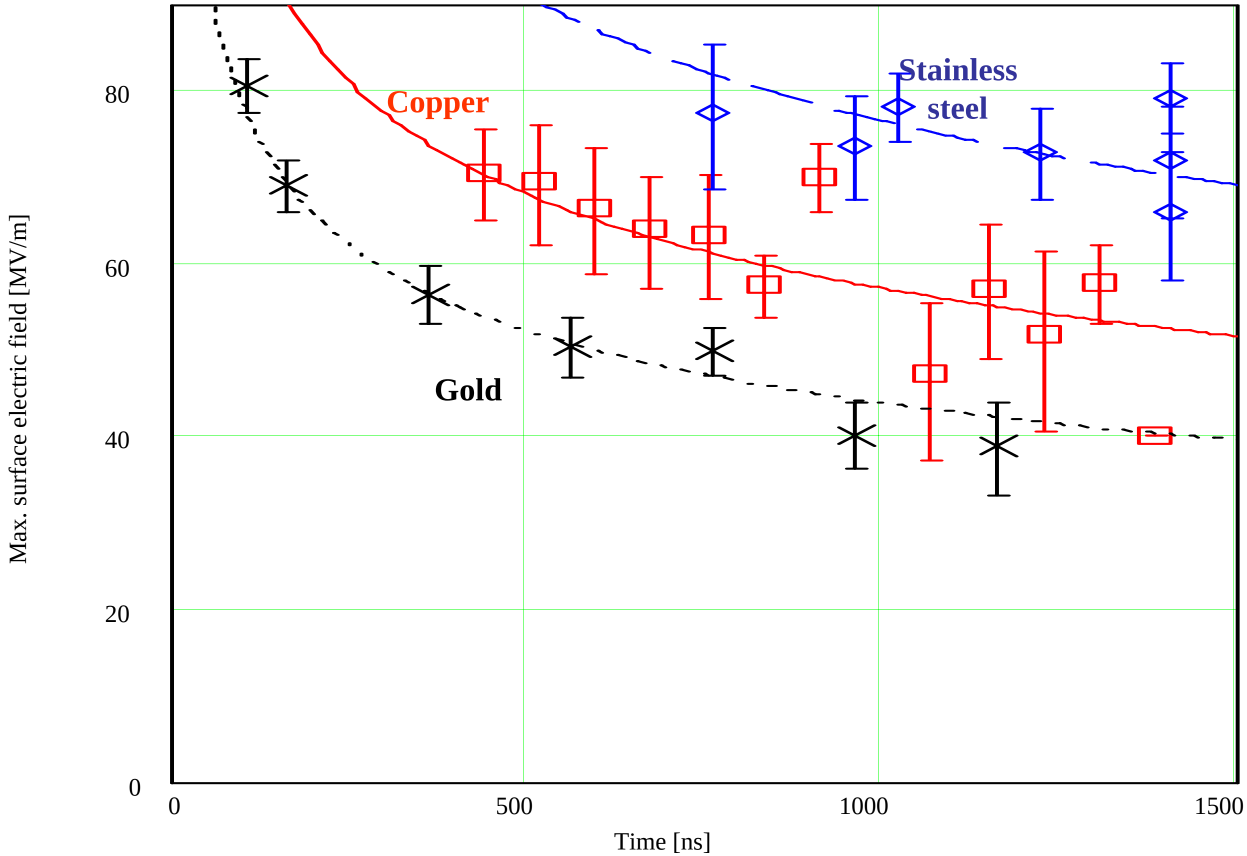
Two waveguide with identical electric field fro a given power distributed over the same area and completely different magnetic field distribution





Material Dependence

1. Planned waveguide tests
   Molybdenum waveguide
   Stainless steel high magnetic field waveguide
   Chromium waveguide



Waveguide High Gradient Study Maximum breakdown electric fields for different Materials

Single Cell Accelerator Structure Motivations Motivation

Goals

- Study rf breakdown in practical accelerating structures: dependence on circuit parameters, materials, cell shapes and surface processing techniques

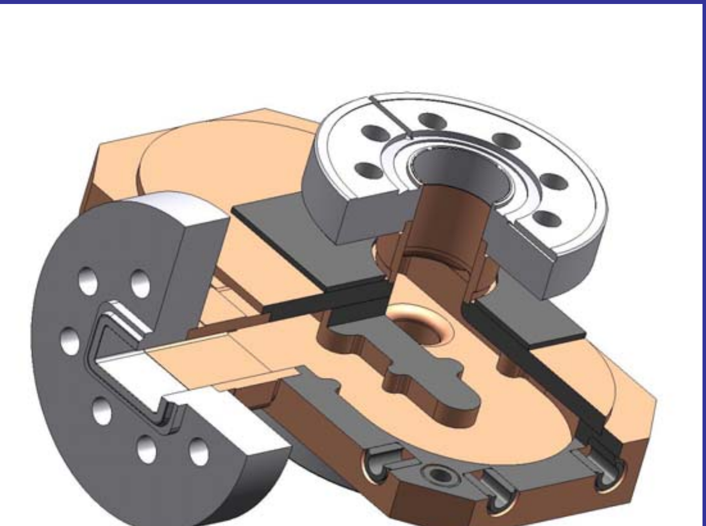
Difficulties

- Full scale structures are long, complex, and expensive

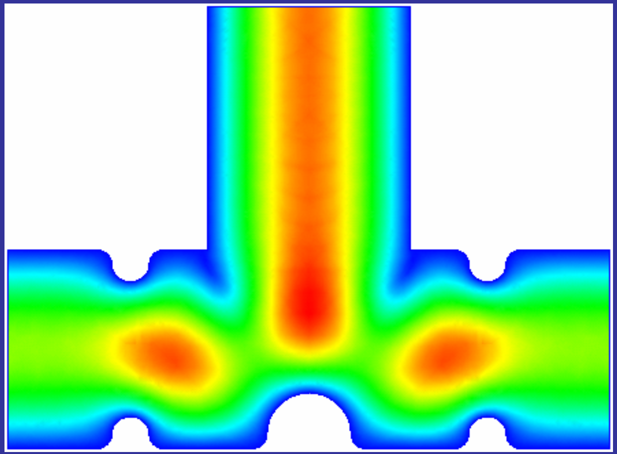
Solution

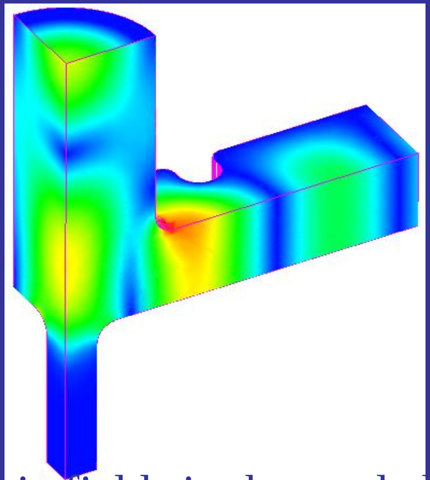
- *Single cell Traveling wave (TW)* and *single cell standing wave (SW)* structures with properties close to that of full scale structures
- Reusable couplers

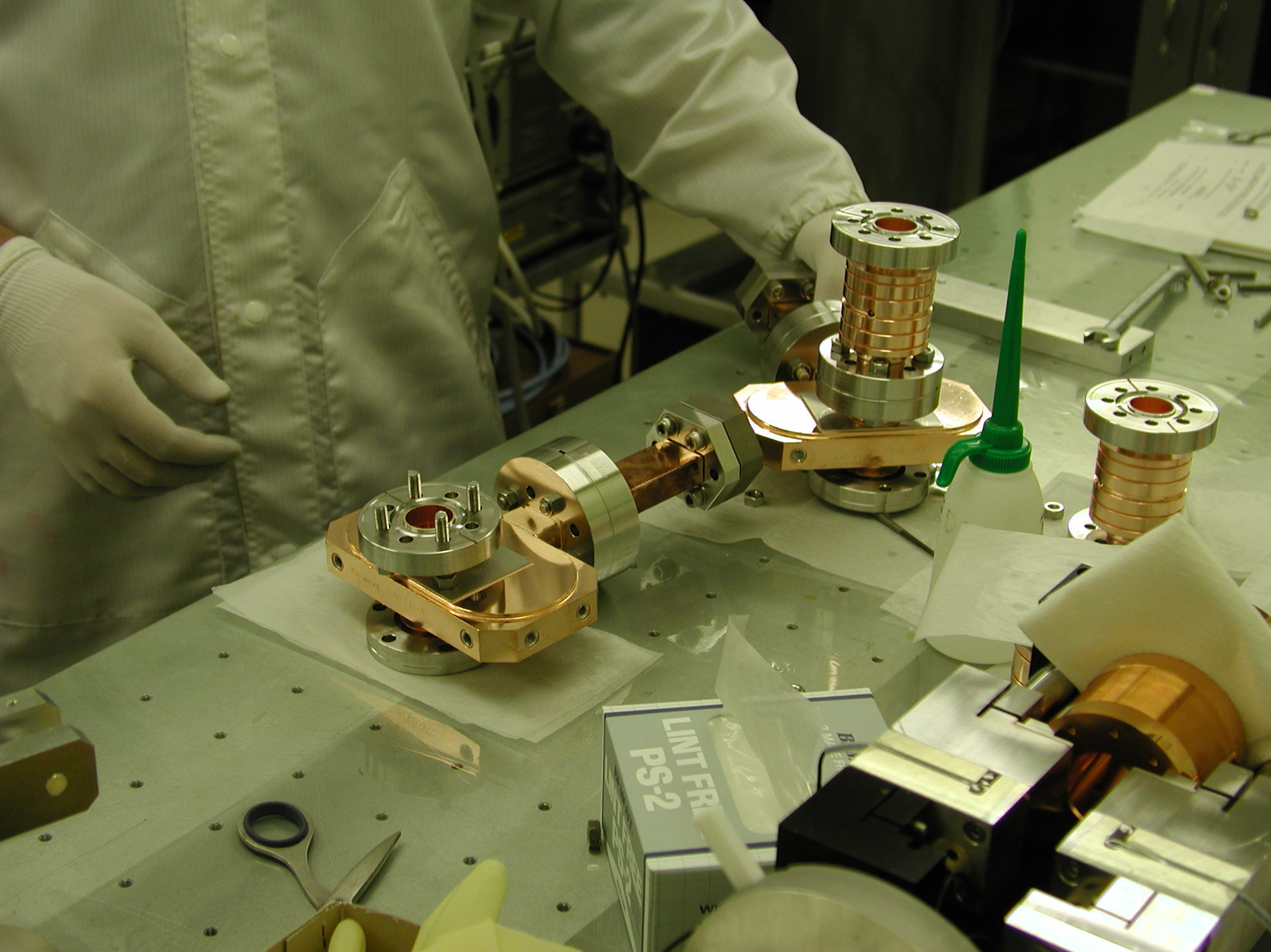
TM_{01} Mode Launcher



Cutaway view of the mode



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Structure Fabrication

- **SLAC**: Mode launchers and copper TW structures
- **KEK**: Copper, molybdenum-copper, molybdenum SW and TW structures

Planned Experiments

- RF breakdown *vs.* circuit parameters (SW *vs.* TW)
- RF breakdown *vs.* different surface processing technique (light etching, high pressure water rinsing, baking)
- RF breakdown *vs.* different materials: copper, molybdenum, molybdenum-copper

Conclusion

- A US collaboration for studying high gradient accelerator structures with application to muti-TeV colliders has been established.