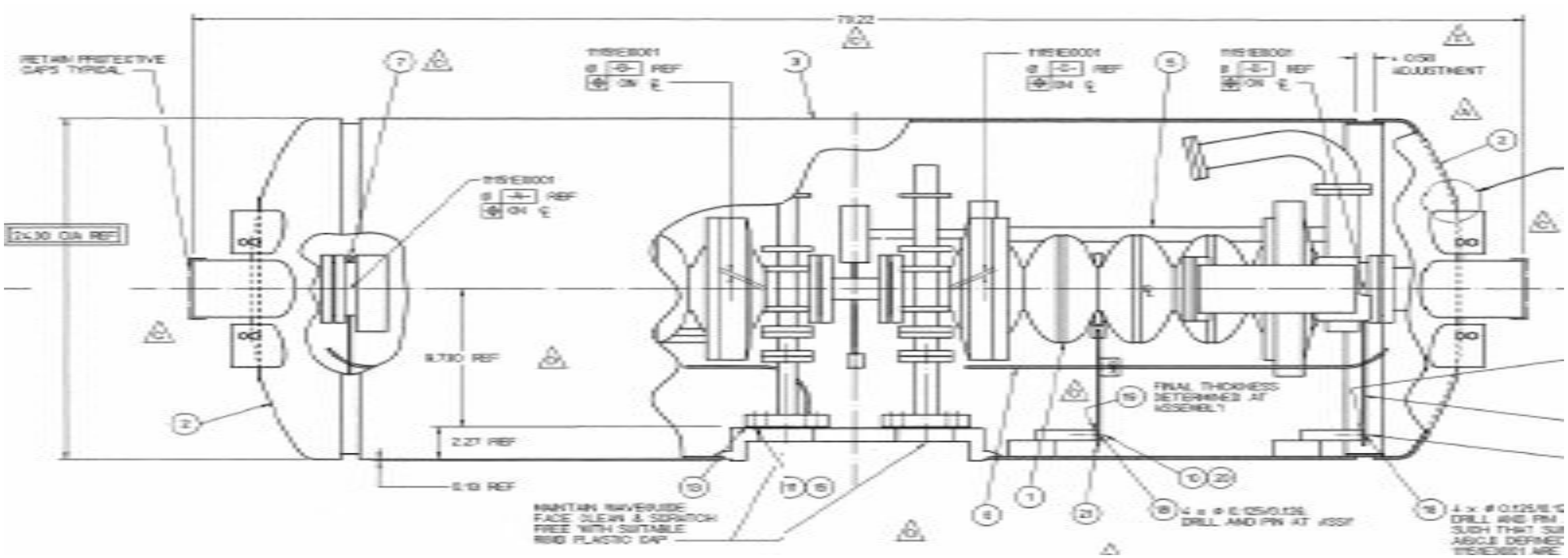
Absorber Materials at Room and Cryogenic Temperatures

F. Marhauser
Jefferson Lab, Newport News, Virginia 23606, USA

HOM-Damping Workshop in SRF Cavities
11-13. October 2010

Motivation

- **We aim to find a load material working at 2K as used in CEBAFs Original Cornell Cavities**
- **Such loads have been developed at JLab and Ceradyne, Inc. in the early 1990s**
  - → manufactured by Ceradyne, Inc. with lots of R&D at JLab
  - → at this time no lossy ceramics (e.g. SiC based) showed temperature-independent absorption
  - → CEBAF was designed for low beam current (200 μA), HOM power (mW range) is not an issue
- loads are sitting in waveguides fully immersed in Helium, **requirements:**
  - → temperature-independent properties down to 2K
  - → high thermal conductivity, brazeability, low outgassing rates
  - → return loss of about 10dB required within 1.9-10 GHz ($\varepsilon_r \sim$ 20-30, $\delta_\varepsilon \geq$ 0.1 up to 6 GHz)



1497 MHz Original Cornell Cavity-Pair Cryo-Unit (4 in each cryomodule)

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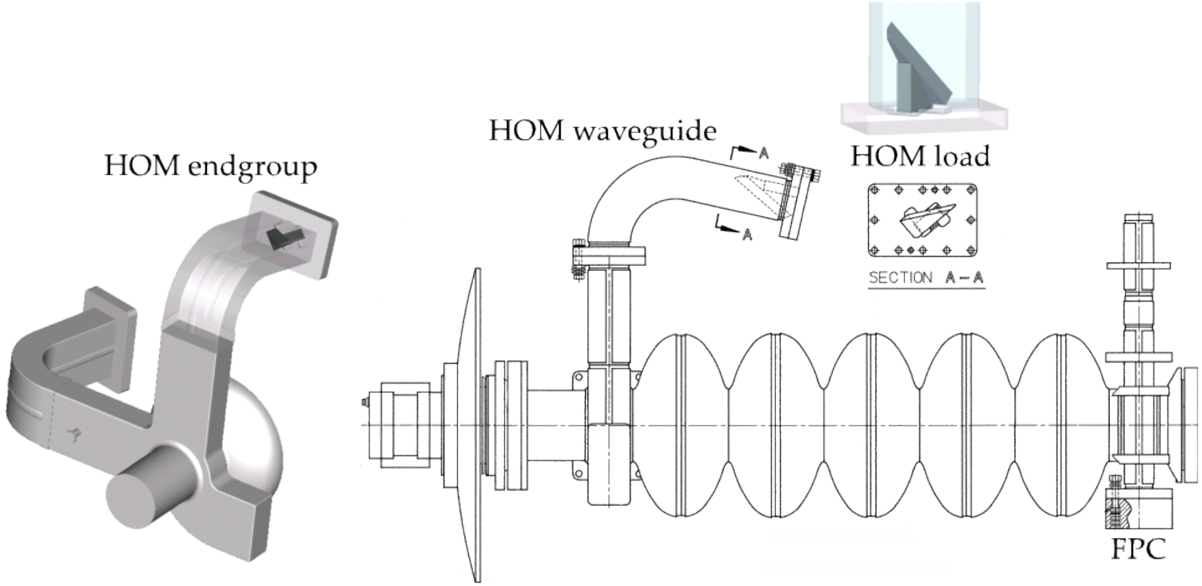

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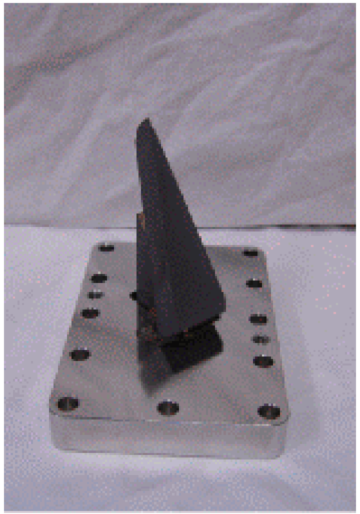
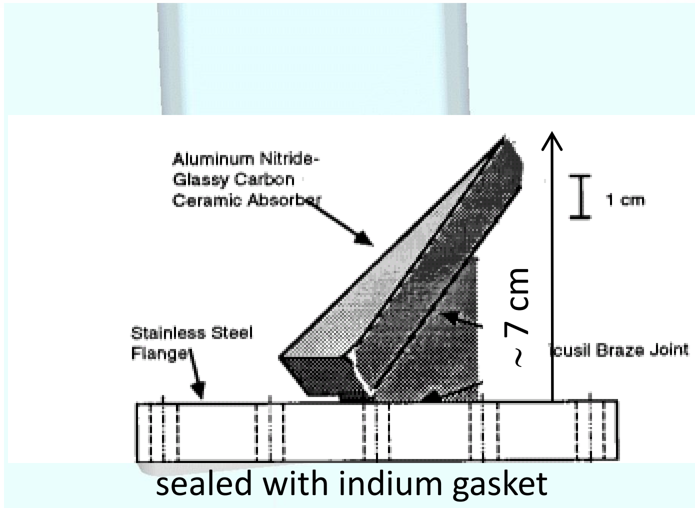
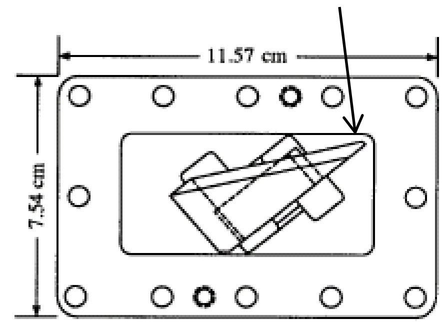
- material developed was **ceramic Aluminum-Nitride based composite**
  - → AlN alone has $\varepsilon_r \sim 8.5$, $\delta_\varepsilon \sim 10^{-4}$
  - → dissipation provided with **glassy carbon spheres** (3-12 μm, amorphous form of carbon)
  - → concentration must be below 15% in volume to avoid temperature dependence (7% chosen)
  - → hot pressed to achieve full density and vacuum compatibility
  - → material provides good mechanical strength and good thermal conductivity of 60-80 W/(m·K)

CEBAF 2K HOM waveguide absorber





peak placed as close as possible to corner
→E~0 for all TE waveguide modes
→ best matching to E-fields

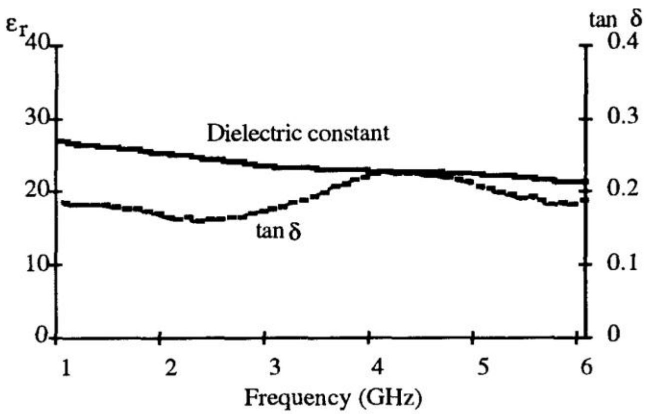


inner dimensions: 3.11 x 1.5”
TE10 cutoff 1.9 GHz

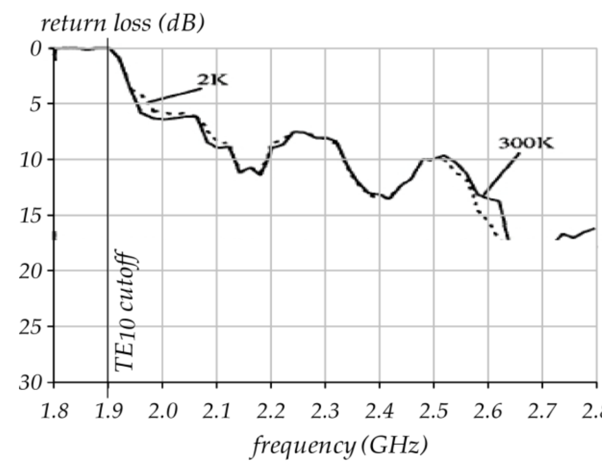
The Design and Production of the Higher-Order-Mode Loads for CEBAF*

Isidoro E. Campisi, Lynda K. Summers, Ben H. Branson, A. Michelle Johnson and Aldo Betto
Continuous Electron Beam Accelerator Facility
12000 Jefferson Avenue, Newport News, VA 23606-1909

1993



measurement range limited



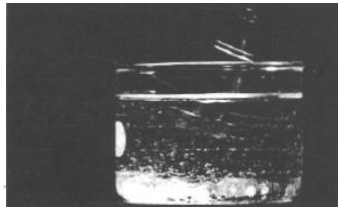
How were complex material measured at this time ?

- ❑ knowing material properties is essential to optimize the load shape
- ❑ complex electric and magnetic properties up to 20 GHz measured by W. Hartung at Cornell in an RF transmission line (could not find further documentation)
- ❑ at JLAB within 1-6 GHz (picture shown avove) a HP dielectric probe with Vector Network Analyzer used
  → measures complex properties in seconds from 200 MHz – 20 GHz
  → manual states: for liquids (and semi solids)

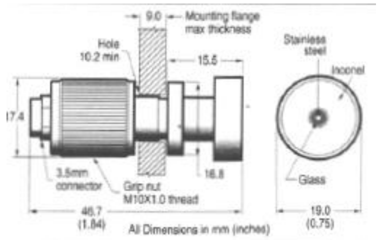
HP 85070M Dielectric Probe Measurement System

HP 85070B High-Temperature Dielectric Probe Kit

Technical Data

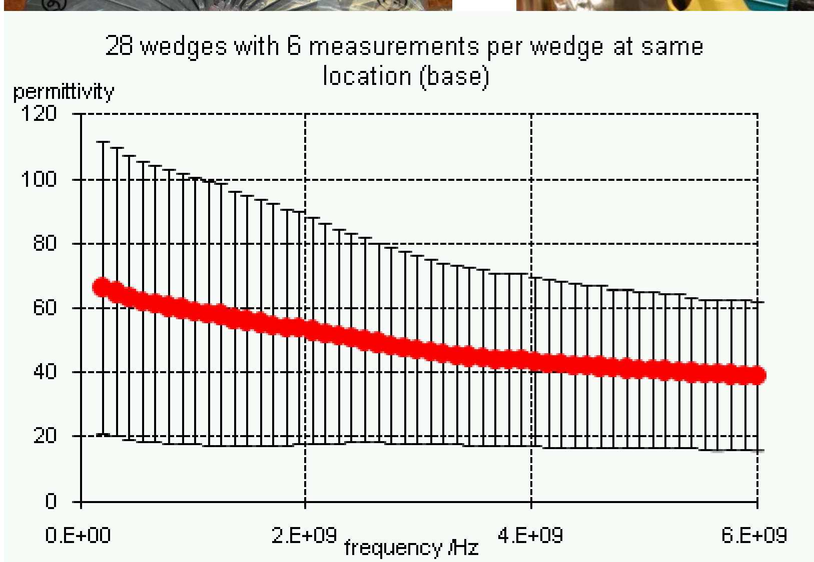


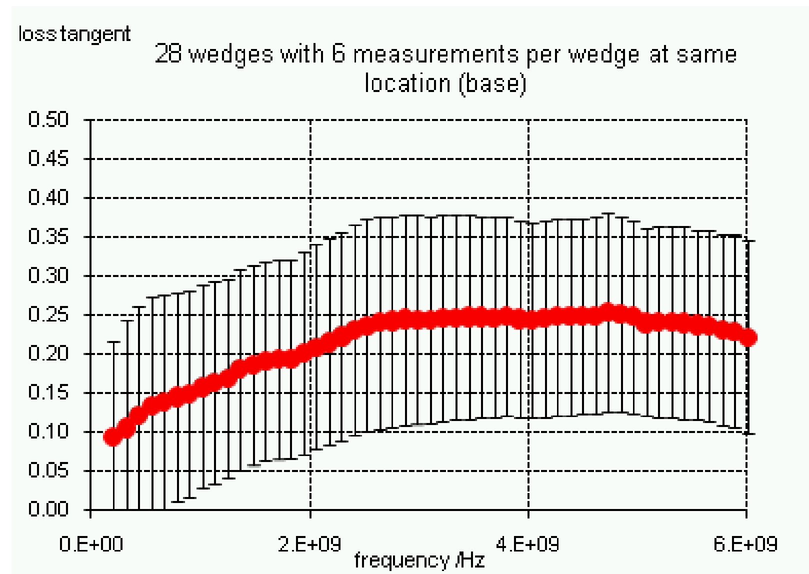
200 MHz to 20 GHz



Does HP Probe deliver accurate results ?

- we performed measurements in 2007 with same probe (M. Stirbet, F. Marhauser)
- 28 Silicon Carbid wedge absorbers from **same batch** measured
- each wedge measured 6 times at same location to determine broadband complex material properties
- results showed large data jitter/error both for same wedge at same location and from wedge-to-wedge
- **however, when using worst and best performing wedge pairs in waveguide RF results were similar (not shown here)**





NOT ACCURATE FOR SOLIDS

HP 85070M Dielectric Probe Measurement System

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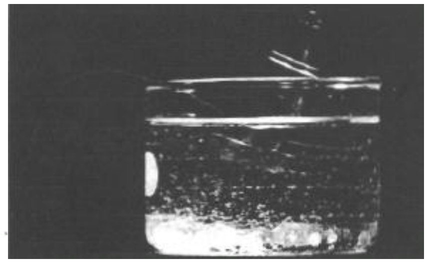
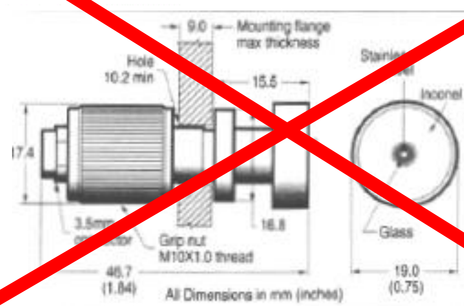


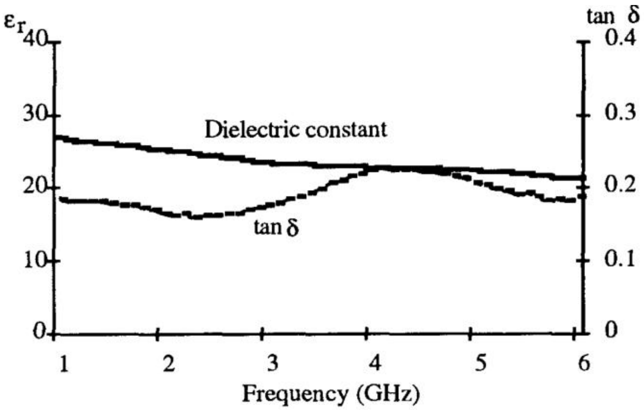
200 MHz to 20 GHz

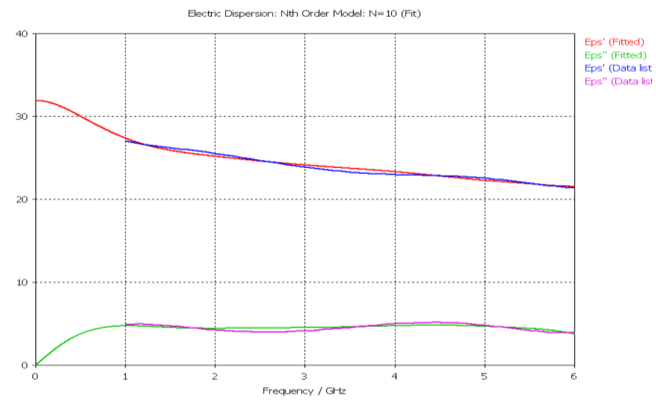


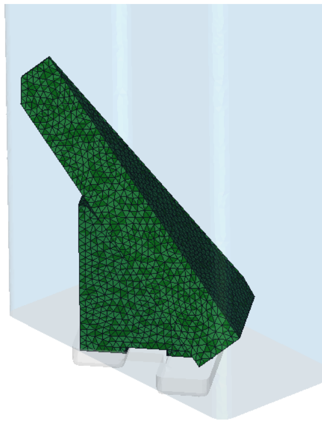
Simulation

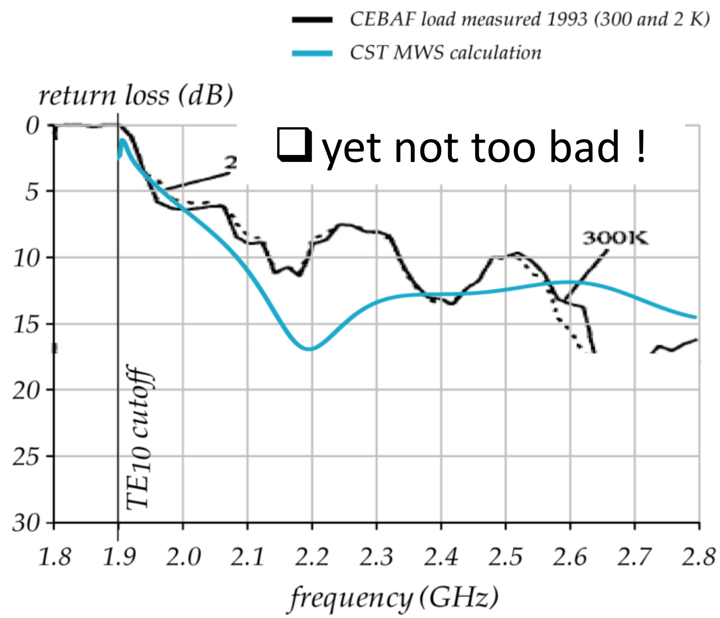
input material data in model (CST MWS) → complex material data model (eps', eps'' in CST MWS)

tetrahedron mesh representation









- yet not too bad !

Why do we search for new material ?

- CEBAF has successfully refurbished 10 weakest old cryomodules (~ doubling energy gain) to strenghten the 6 GeV operation (activity: 2006-2010)
  - → many loads cracked during disassmebly (or cracked before by thermal cycling in cryomodule?),
  - → required repair /rebraze as we ran out of spares
- Ceradyne, Inc. ceased to provide absorber material
- Several cryomodules are planned to be refurbished in the future again
  - → we want to develop a simpler load shape
  - → 1 or 2 wedge-concept
  - → simpler shape
  - → simpler/reliable braze concept

- what we do not intend to do
  - → R&D on materials, but rather survey commercially existing materials
  - → (as far as I know:) >1M$ have been spent in 1990s for the load development
  - → this time: almost no funds and resources

What's available with cold lossy properties ?

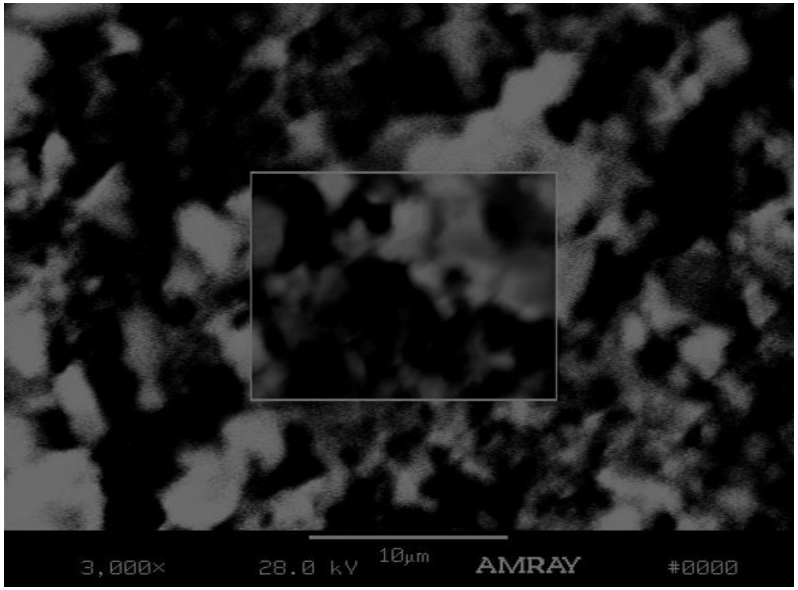
- main question: **what material is available commercially off-the-shelf ?**
  - → the only known composite to work at cryogenic temperatures still owned by Ceradyne
  - → **Ceralloy CA-137, claimed to have losses temperature-independent down to 3K**
  - → **with δ_ε =0.2 and ε_r = 18-28 within 1-10 GHz**
  - → they filed patent

ceradyne, inc.
ADVANCED TECHNICAL CERAMICS

* Patent Pending

Property	AIN Composite	
Grade	Ceralloy 137 CA*	Ceralloy 137 CD1*
Composition	AIN Composite	AIN Composite
Tailored Composition Available	Yes	Yes
Processing Route	Hot Pressing	Hot Pressing
Density (g/cm3)	2.99	2.99
Outgassing	No	No
Thermal Conductivity (W/mK)(RT)	85	95-105
Dielecric Constant		
@1.0GH	28	
@8.0GH	18	38
@10.0GH	18	31
@12.0GH		27
Loss Tangent		
@1.0GH	0.2	
@8.0GH	0.2	0.45
@10.0GH	0.2	0.4
@12.0GH		0.5
Thermal Expansion Coefficient x10^-6/C (RT - 1000C)	5.0	5.0
Flexural Strength (MPa)		190
Key Features	Dielectric Loss Independent of Temperature to 3K	Higher Thermal Conductivity than Ceralloy 2710 @ Temperatures >150C. Close Match in Electrical Properties
Applications	Terminations, Sever Wedges, Load Pellets, Absorbers, Cryogenic Environmental Applications	Replacement for Ceralloy 2710 BeO-SiC, Terminations, Sever Wedges, Load Pellets, Absorbers

- SEM imaging (Andy Wu/JLab): no glassy carbon spheres, but carbon is used as lossy particles



What has been tested so far (work in progress)

material	vendor	material ID	project	test temperature
AlN composite	JLAB R&D /Ceradyne Inc.	AlN/GC	CEBAF	293K- 2K
AlN composite	Ceradyne Inc.	Ceralloy 137 CA	CEBAF	293K- 2K
AlN composite	Sienna Technologies, Inc.	STL-100 HP-179	CEBAF	293K- 2K
AlN composite	Sienna Technologies, Inc.	STL-100C HP-193	CEBAF	293K- 2K
AlN composite	Sienna Technologies, Inc.	STL-100C HP-197	CEBAF	room temperature
AlN composite	Sienna Technologies, Inc.	STL-100C HP-199	CEBAF	room temperature
AlN composite	Sienna Technologies, Inc.	STL-150D HP-214	CEBAF	room temperature
SiC	CoorsTek	SC DS (SC-30)	High Current	293K- 2K
SiC Graphite loaded	CoorsTek	SC-DSG (SC-35)	High Current	293K- 2K

- ❑ CoorsTek SC DS (SC-30) Direct Sintered Silicon Carbide
- ❑ CoorsTek SC-DSG (SC-35) Graphite Loaded Sintered Silicon Carbide

Cryogenic RF material testing setup

- ❑ old CEBAF setup has been resurrected and refurbished

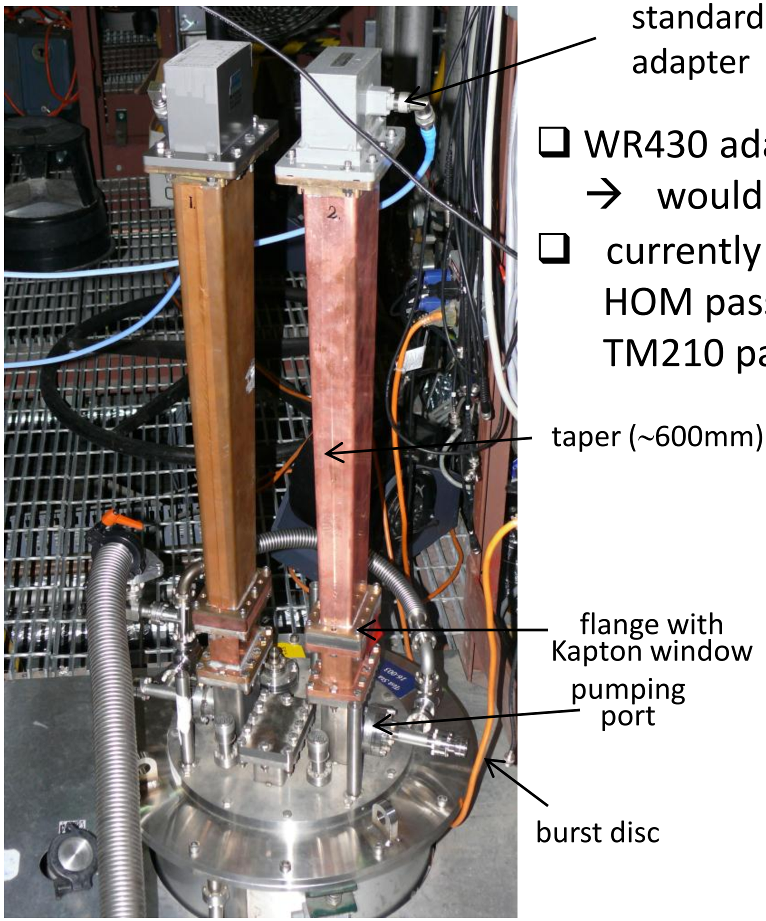
thin Kapton foil (0.005“) utilized
as RF window for broadband transmission

- ❑ Two new ~1.5 m long waveguides with CEBAF waveguide dimensions
  → measure two material candidates at a time
- ❑ integrity of braze (loads on SS or copper flanges) is verified before RF test by cold shocking/cycling load assembly from room temperture to LN_2 temperature

material
under test

new vertical test cage

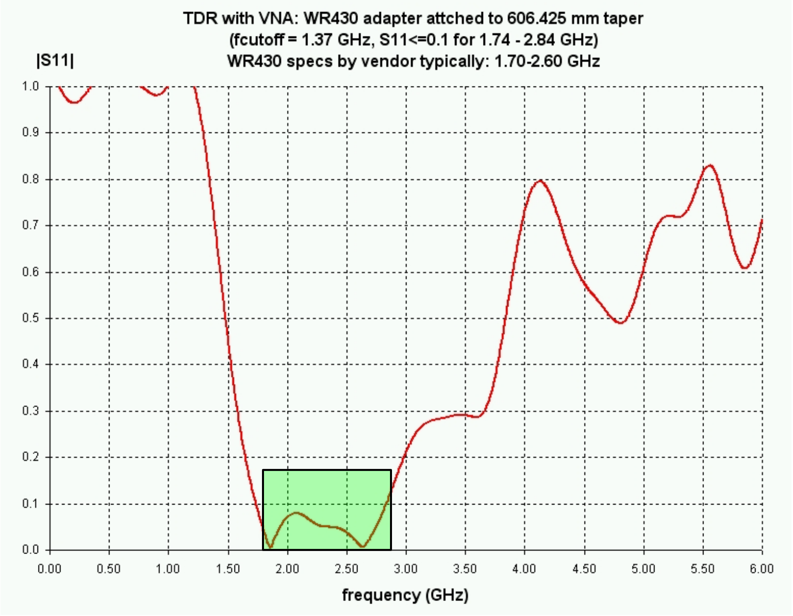
Frequency range is limited by adapter



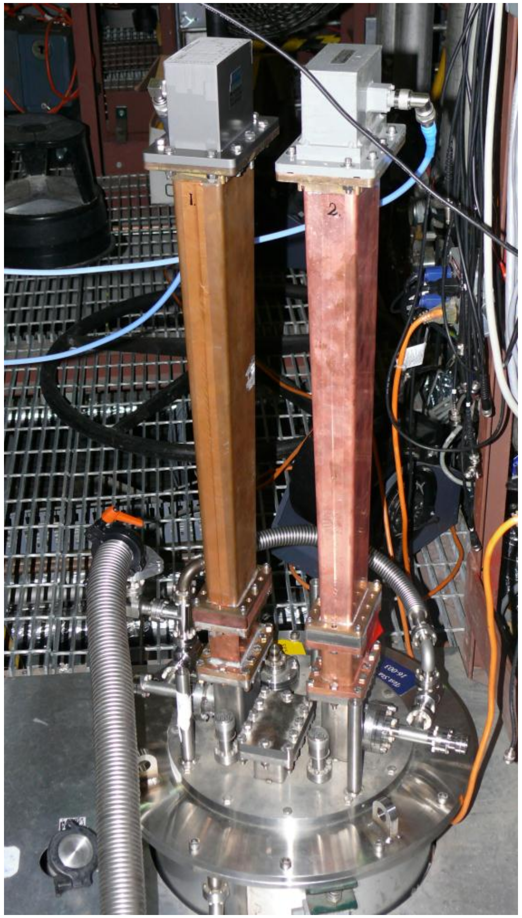
waveguide transition outside dewar

- ❑ WR430 adapter limits usable frequency range
  - → would require additional hardware to assess higher frequencies
- ❑ currently we cover the frequency range of both trapped dipole HOM passbands (TE111, TM110) and (less important) TE211, TE011, TM210 passband

WR430: 1.8-2.8 GHz

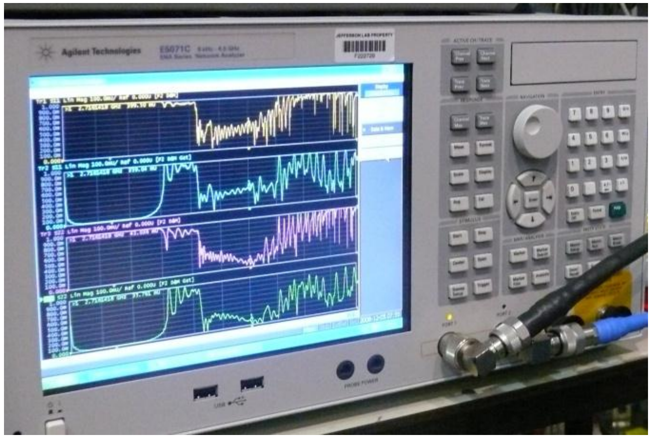


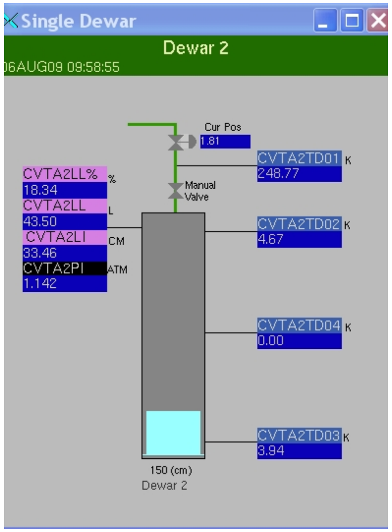
Measurement Technique



waveguide transition outside dewar

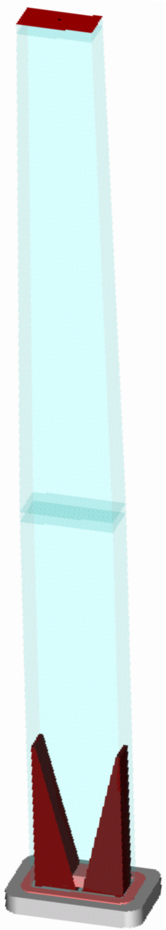
- **Use Time Domain Gating with Vector Network Analyzer to de-embed material at end of waveguide from its environment**
  - → gets rid of adapter and window contribution to losses
- Labview program developed for ENA 5071C (C. Grenoble, JLab) to automatically switch between ports and record data at user-defined time steps
- Dewar Helium pressure and related temperature is recorded for each measurement remotely from EPICS system (also various other temperature measured at different diode locations)



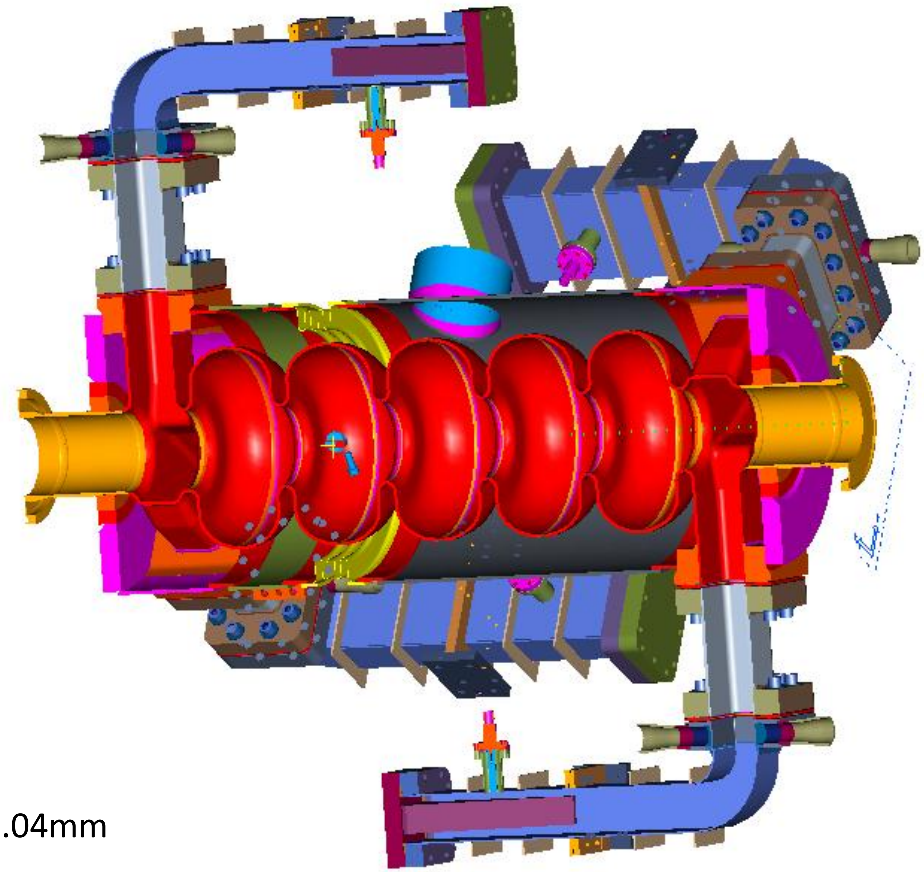


Additional Setup for Room Temperature Measurements
both for CEBAF and High Current (HC) Cavity Absorber Candidates

- motivation for HC project is to find suitable loads working effectively at room temperature
  → several Watt to kW power level range (10mA – Ampere level beams)



inner dimensions: 72.14 x 34.04mm
TE10 cutoff 2.08 GHz



Additional Setup for Room Temperature Measurements
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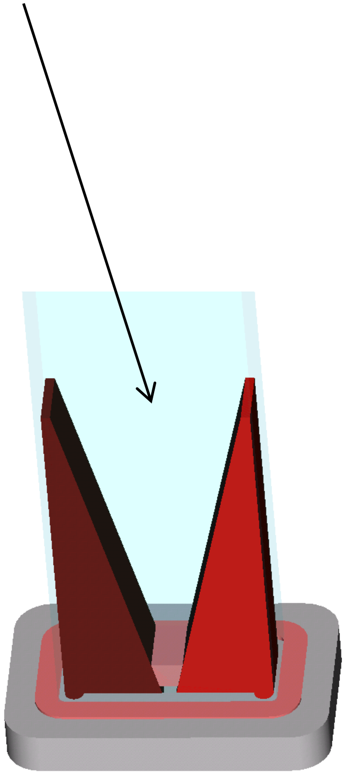
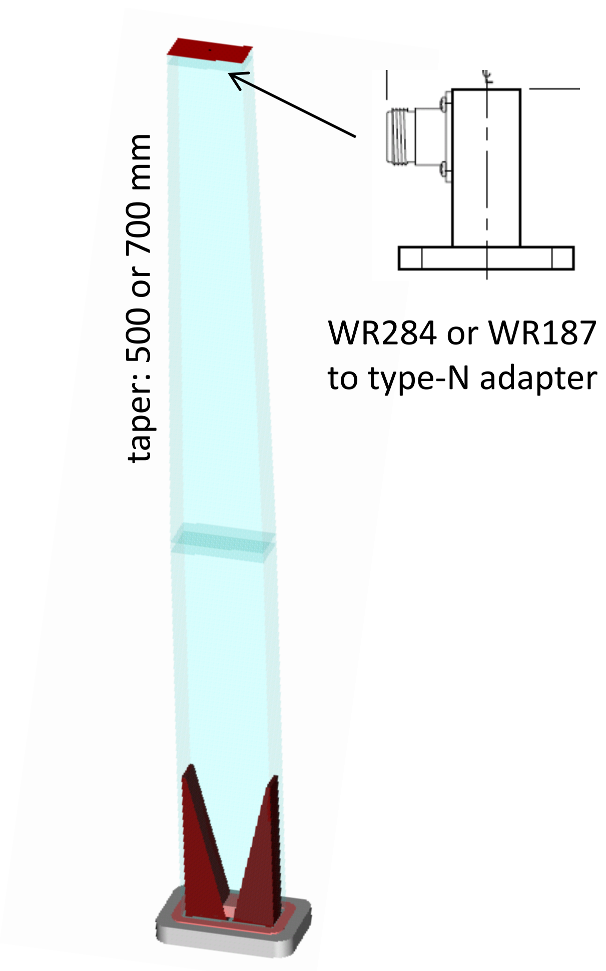
- ❑ mechanical fixture fabricated for "2-wedge design" to quickly exchange different absorber materials
  → groove in base plate, a copper block presses wedges in place

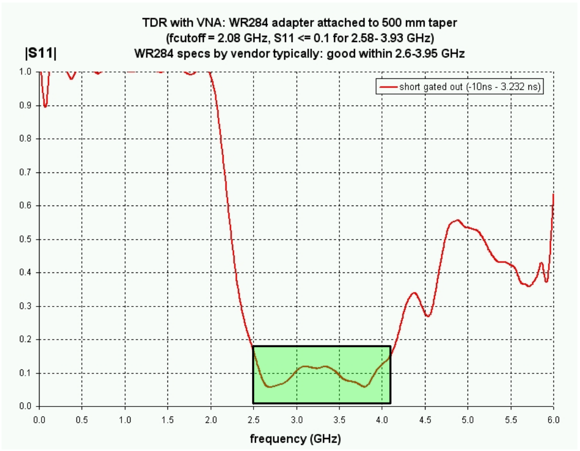


Also: room temperature measurements outside Dewar

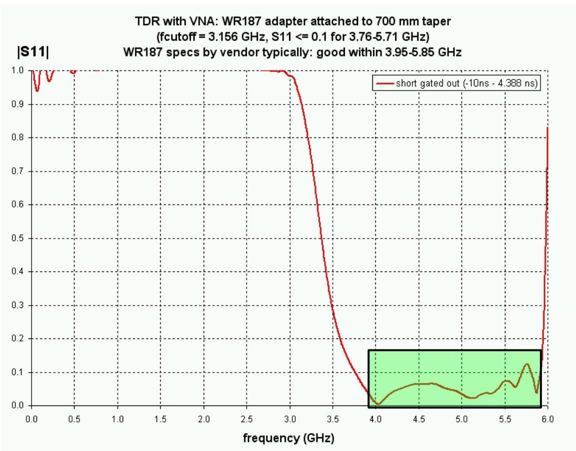
- again: adapter limit usable frequency range, but we have 2 different hardwate sets to cover range up to 6 GHz



WR284 (2.6-3.9 GHz)

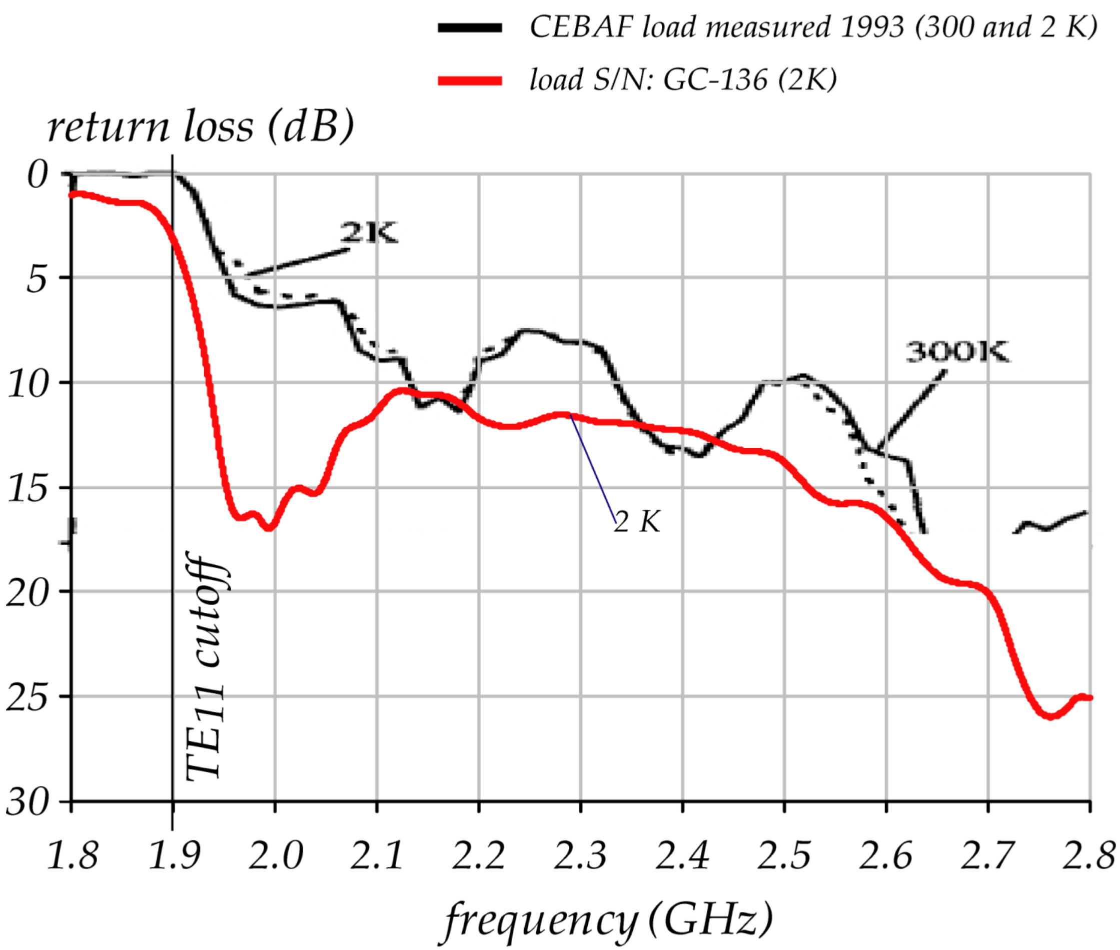


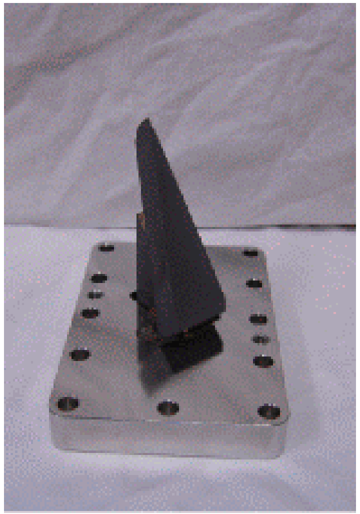
WR187 (3.9-5.9)



1) AlN Glassy Carbon (AlN-GC) at 2K

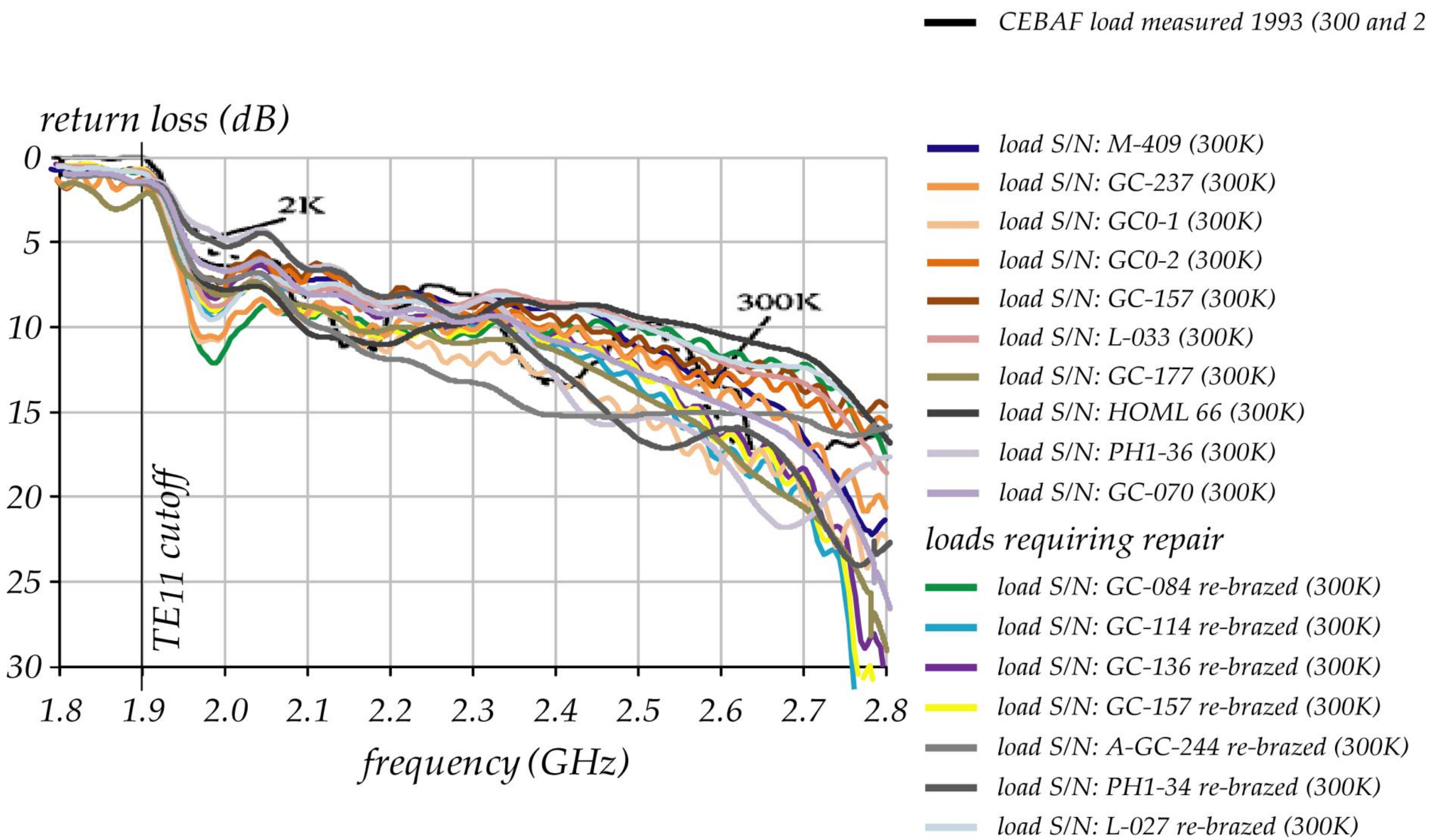
- ❑ required first: verification of results for CEBAF 2K absorber comparing old (1993) with new data
- ❑ **outcome: reasonable agreement**
  - → consider material properties might and measurement technique does differ





1) AlN-GC at room temperature only

- **Question: how reliable is performance of AlN-GC from lot-to-lot, batch-to-batch ?**
- Important when using several hundreds of loads requiring similar results
  → e.g. CEBAF has 338 OC cavities (18 in injector, 320 in north and south linac) = 676 loads
  → such RF results can be fed back to vendor to stabilze fabrication methods (e.g. sintering temperatures)



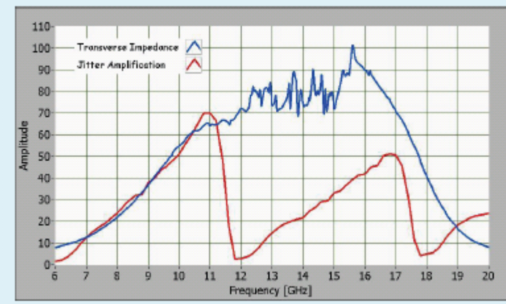
1) Example: reproducibilty requirement

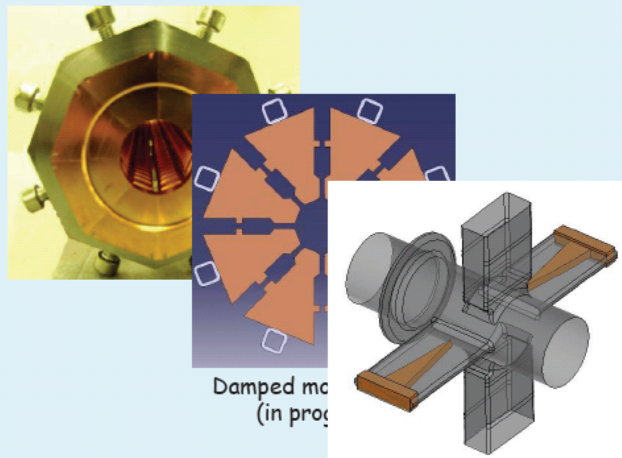
Absorbers Materials for HOM Damping in CLIC PETS and Accelerating Structures

Tatiana Pieloni, EPFL
Riccardo Zennaro, CERN

Short Term needs:
Power Extraction Structures PETS

Current design:

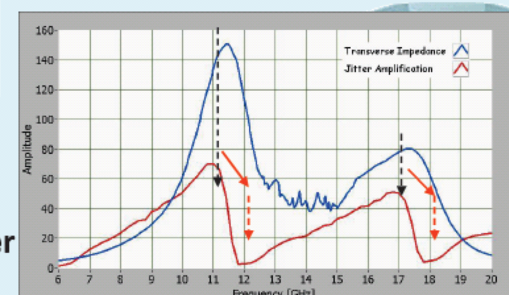




Damped mo
(in prog

Damped modification
(in progress)

Fast example of the spectrum modification with 4 loads being switched off:



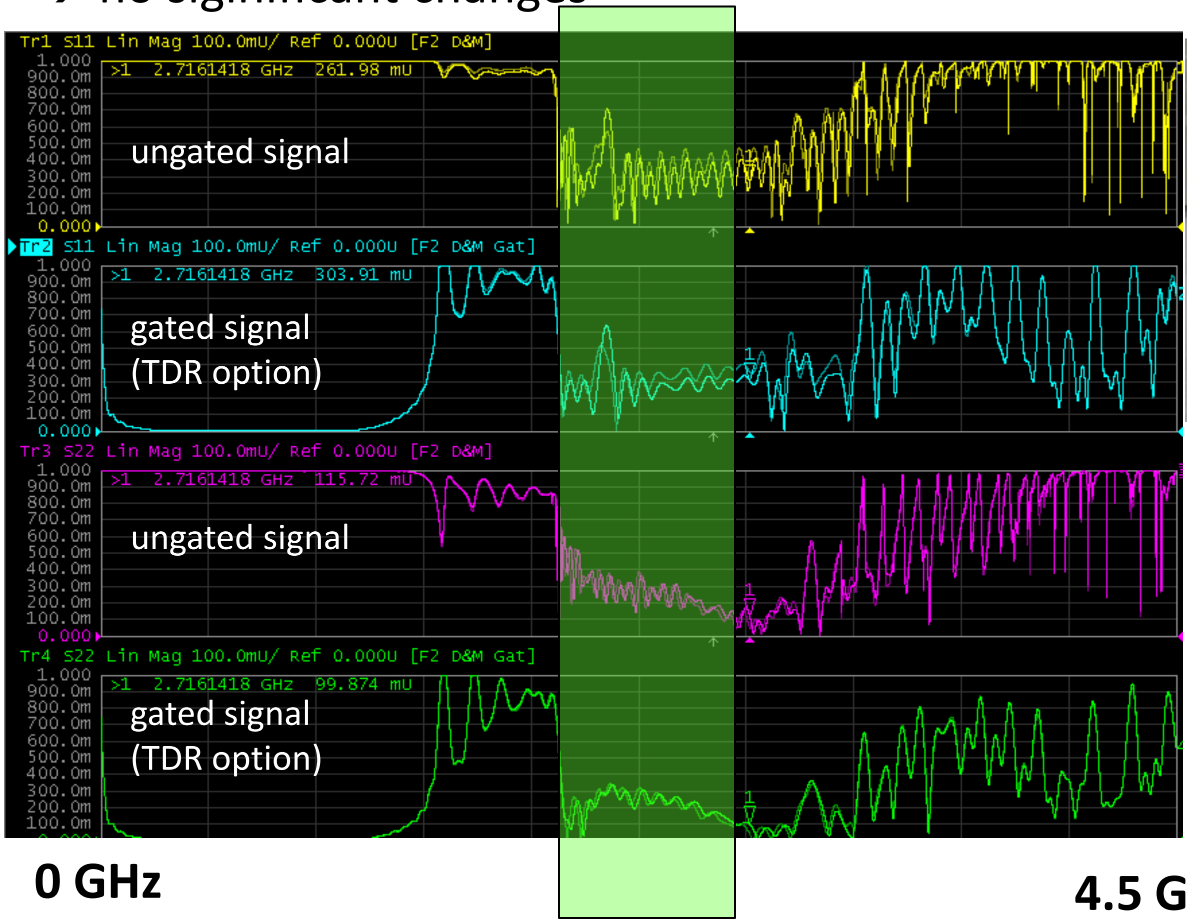
- **ε in the range of 20 to 30**
- **loss tangent of at least 0.3**
- **reproducibility of permittivity of the order of 10% is necessary**

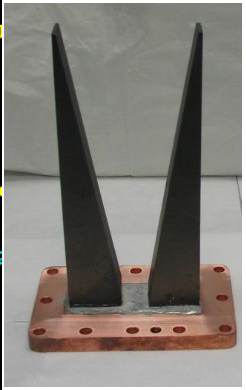
Cortesy of I. Syratchev

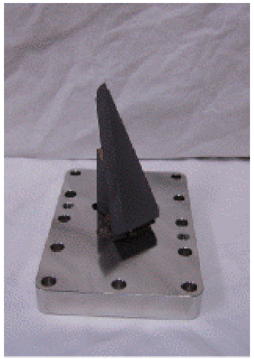
HOM FREQUENCY RANGE 10-20 GHz

2) Ceralloy 137 CA vs. AlN-GC vs. room temperature to 2K

- reflection coefficients stored at room temperature and at 2K
  → no siginificant changes



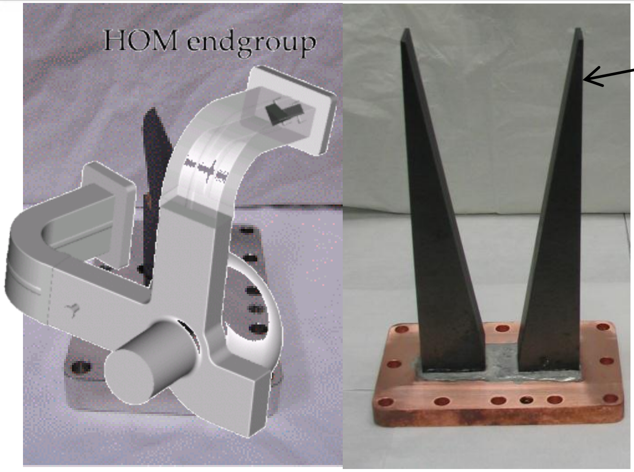




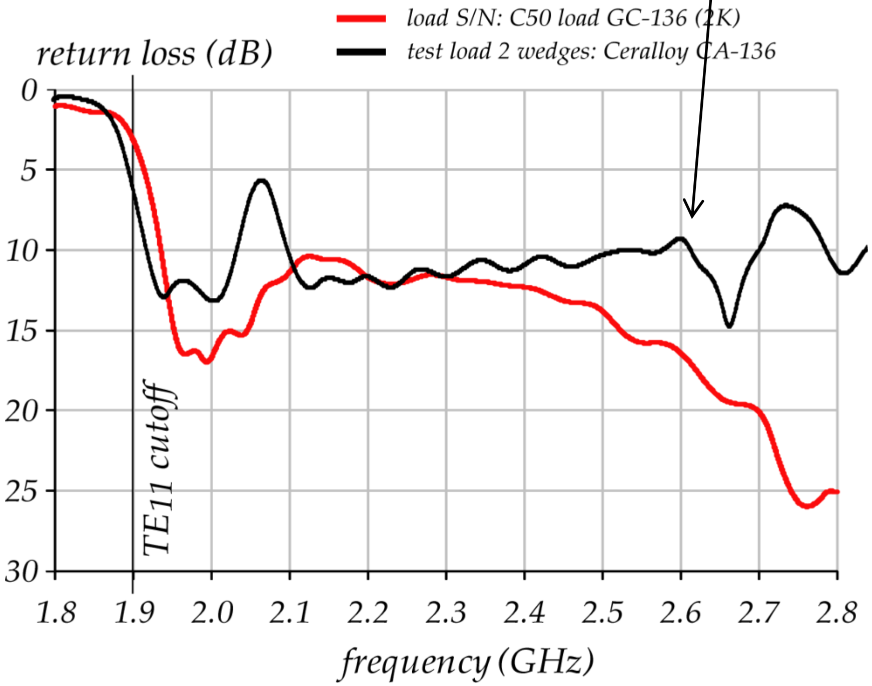
0 GHz **4.5 GHz**

valid window 1.8-2.8 GHz

2) AlN-GC vs. Ceralloy 137 CA
at 2K



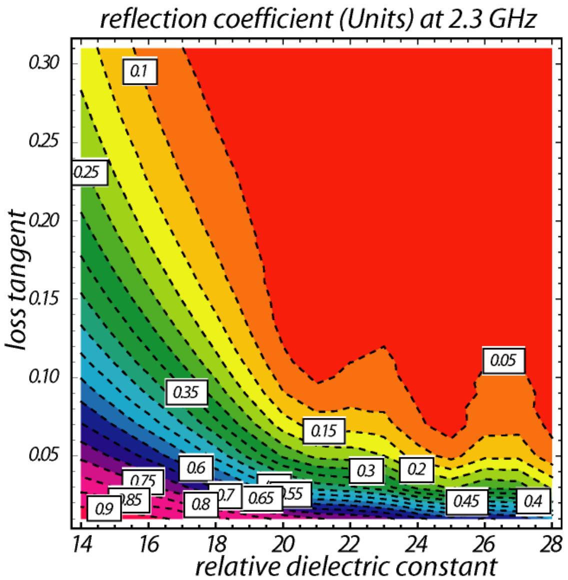
- current wedge shape too long for CEBAF cavity waveguide
- test wedge shape can be optimized numerically to perform better
  → complex material data required
- tried numerical approach to extract properties by scanning loss tangent and permittivity (exact at one frequceny) to fit measurement
  → is very tedious
  → may deliver ambiguous results
  → rather do measurements



INVESTIGATIONS ON ABSORBER MATERIALS AT CRYOGENIC TEMPERATURES*

PAC 09

F. Marhauser, T. Elliot, R. Rimmer, JLab, Newport News, VA 23606, U.S.A



Complex material property assessment

- ❑ JLAB currently cannot do this
  → but Cornell

Proceedings of 2005 Particle Accelerator Conference, Knoxville, Tennessee

MEASUREMENTS OF ε AND μ OF LOSSY MATERIALS FOR THE CRYOGENIC HOM LOAD

Valery Shemelin, Matthias Liepe, Hasan Padamsee
Laboratory for Elementary-Particle Physics, Cornell University, Ithaca, NY 14853

a) 1-12.4 GHz (washer)
b) 12.4-18 GHz Ku-band (slab)
c) 18-26.5 GHy K-band (slab)
d) 26.5-40 GHz Ka-band (slab)

Figure 1: Transmission lines for 4 frequency ranges.

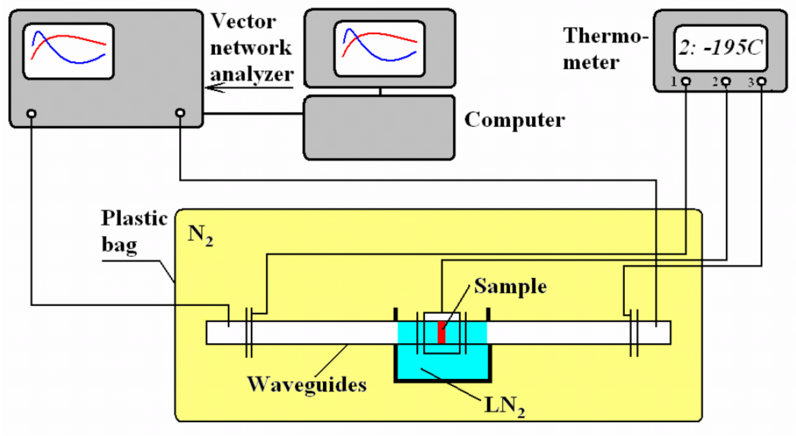
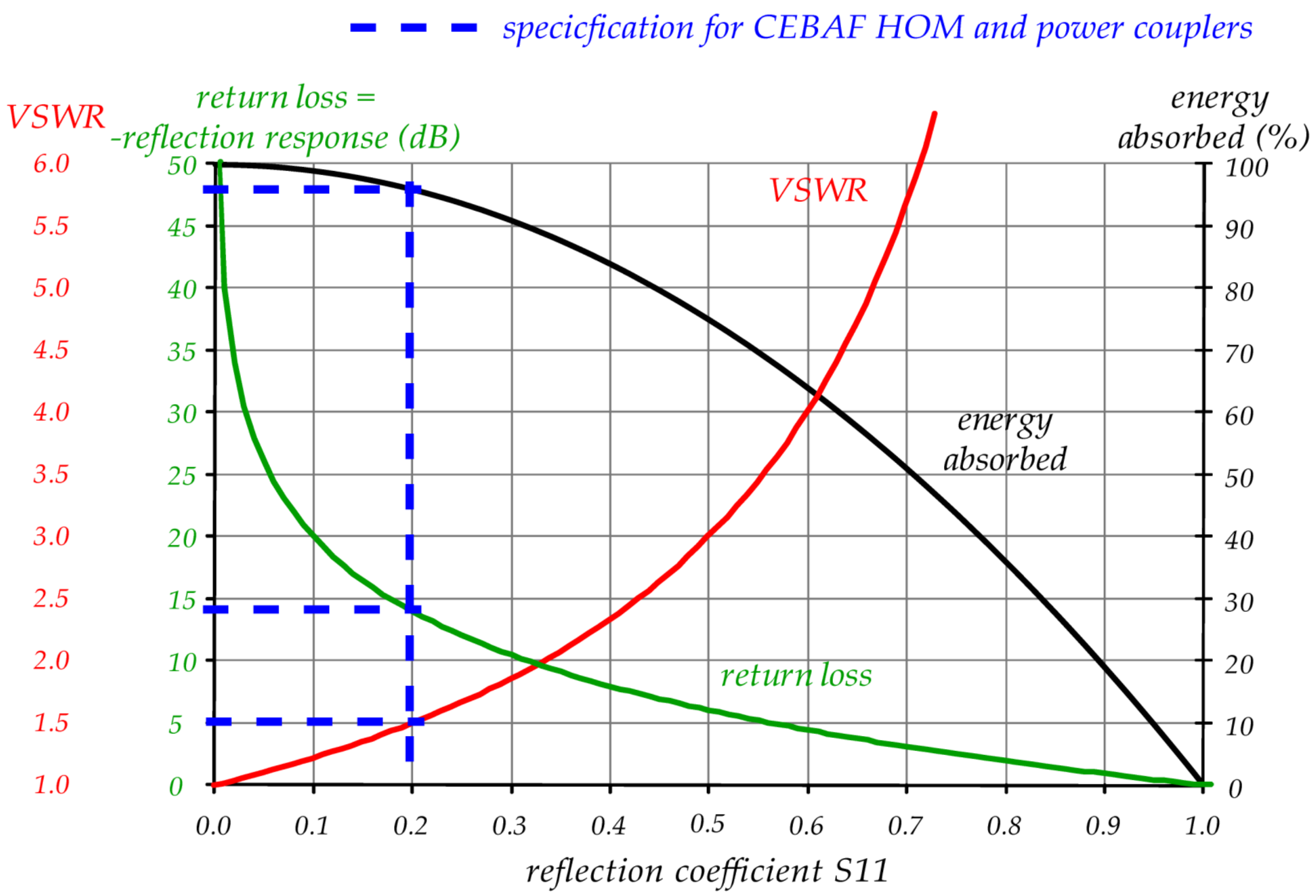


Figure 2: Schematic of test setup.

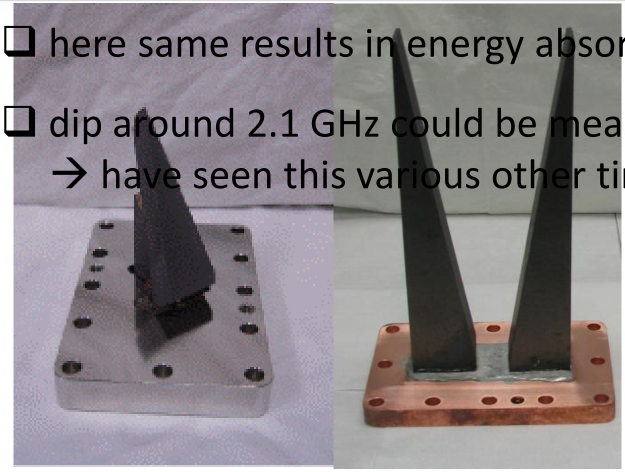
Alternative units

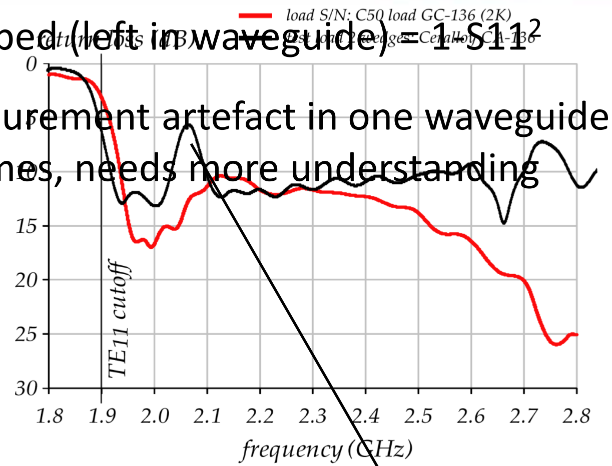
- ❑ there are more ways to look at data
- ❑ looking into absorbed energy may be more intuitive
- ❑ e.g. 95% energy absorption for CEBAF absorbers still delivers BBU threshold >> 1mA
  → far above old specification for CEBAF at maximum current of 200 µA and at 4 GeV/5 passes (800 kW)

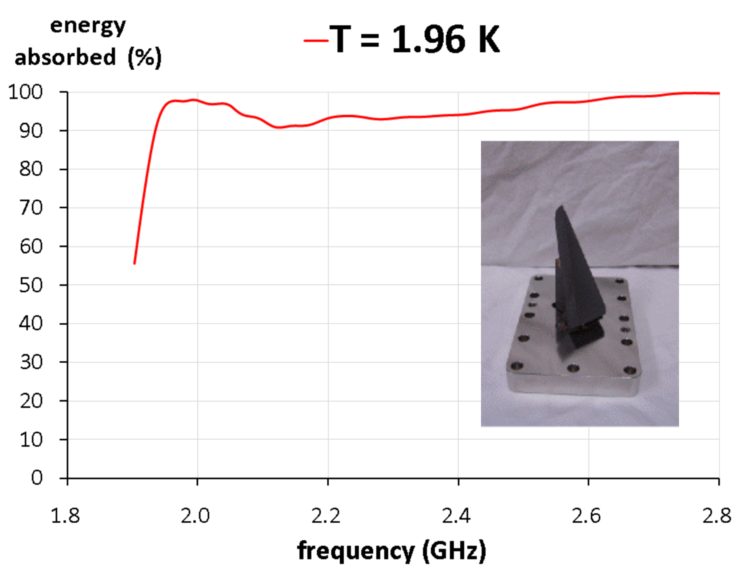


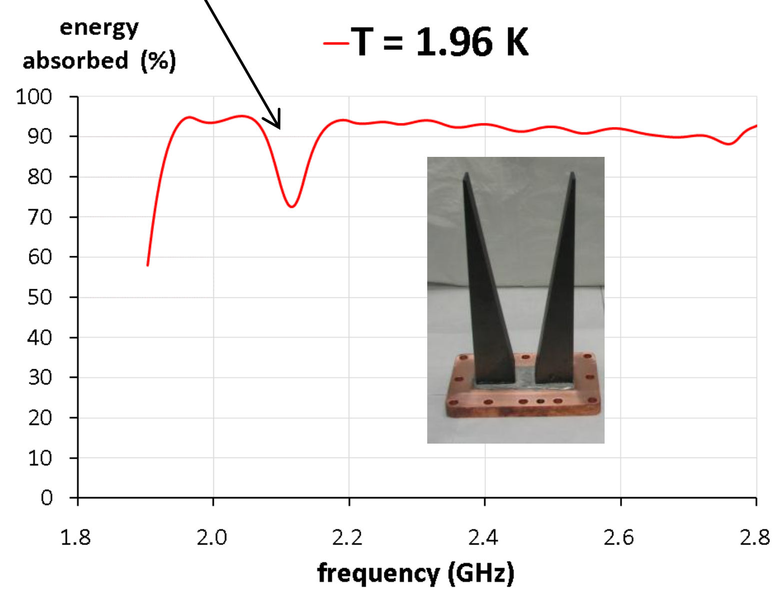
2) AlN-GC vs. Ceralloy 137 CA
at 2K

- ❑ here same results in energy absorbed (left in waveguide) = $1 - S11^2$
- ❑ dip around 2.1 GHz could be measurement artefact in one waveguide (!?)
  → have seen this various other times, needs more understanding

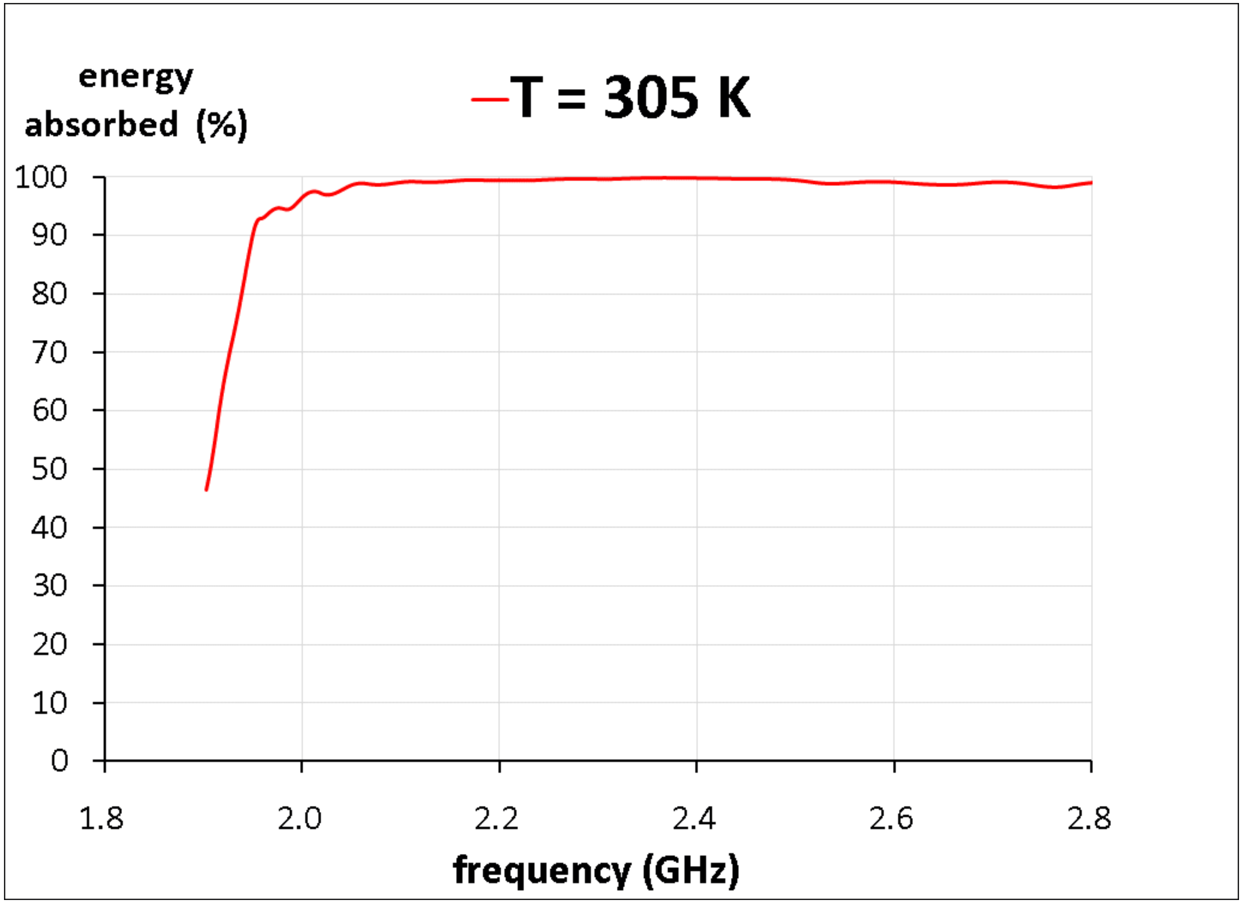


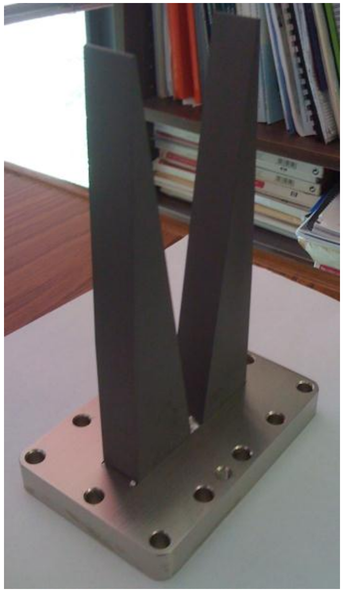






3) Sienna Technologies (STL-100 HP-179)
from room temperature to 2K

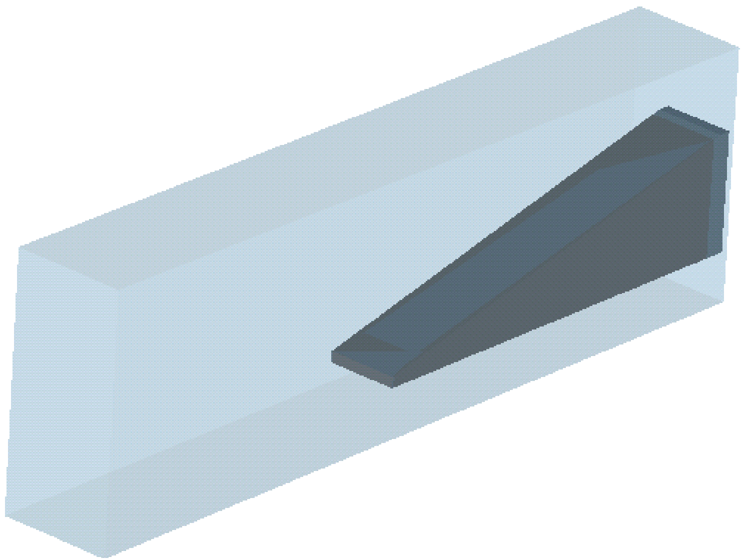




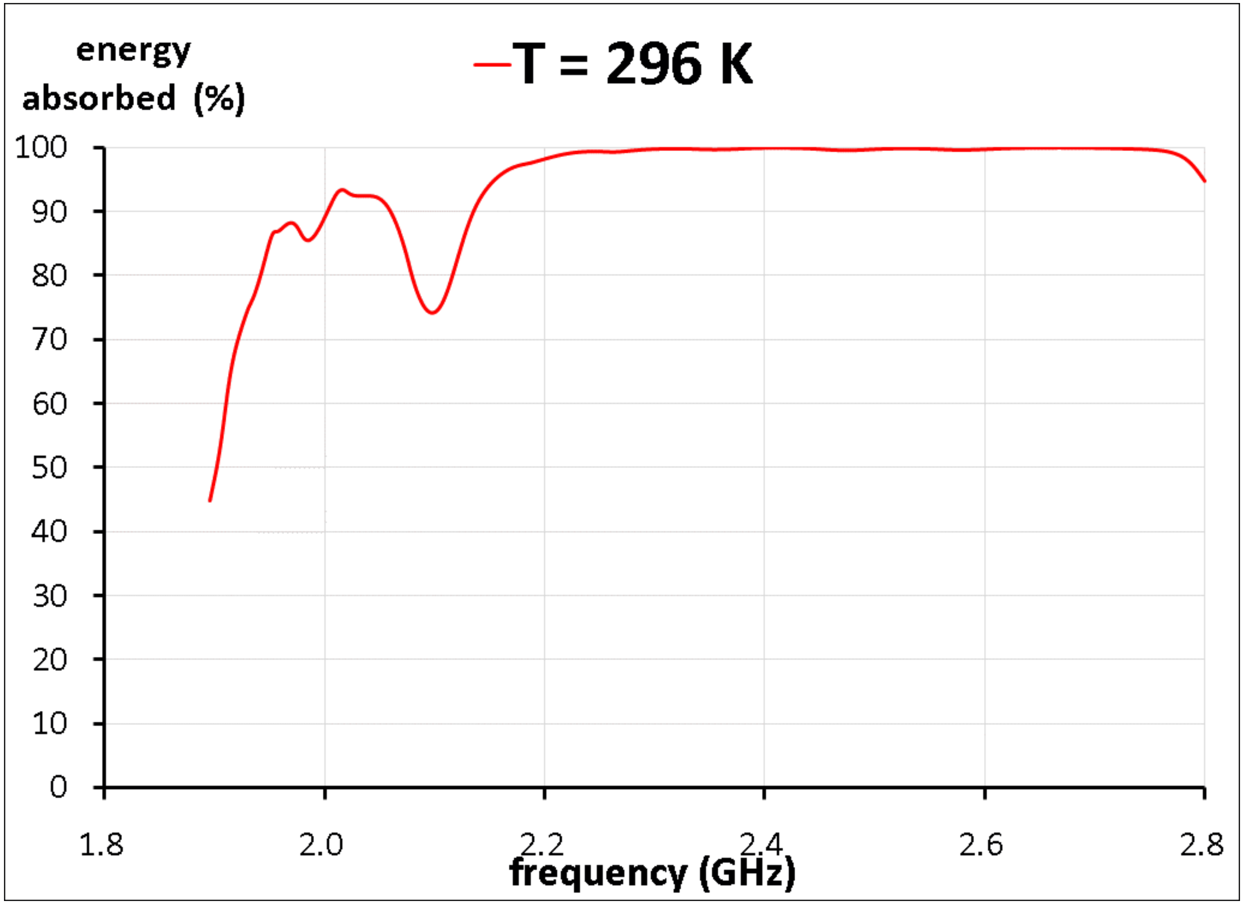
4) CoorsTeK SC-30 and SC-35

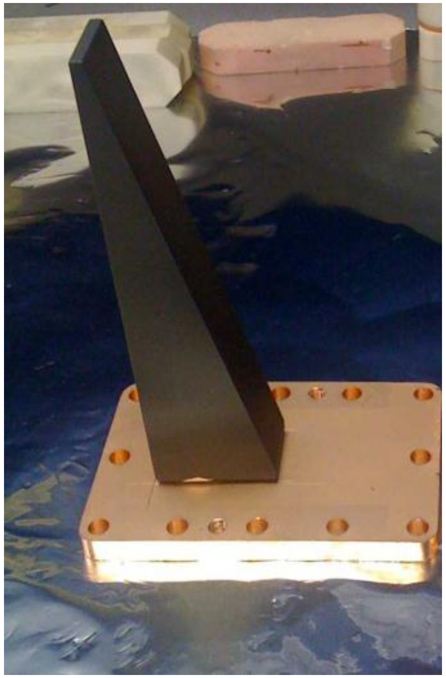
1 wedge in waveguide each only

- for HC cavity larger wedge have been produced
  - → only 1 wedge fits in CEBAF cavity HOM waveguide size for cold measurements
  - → some numerical optimization done regarding location of wedge



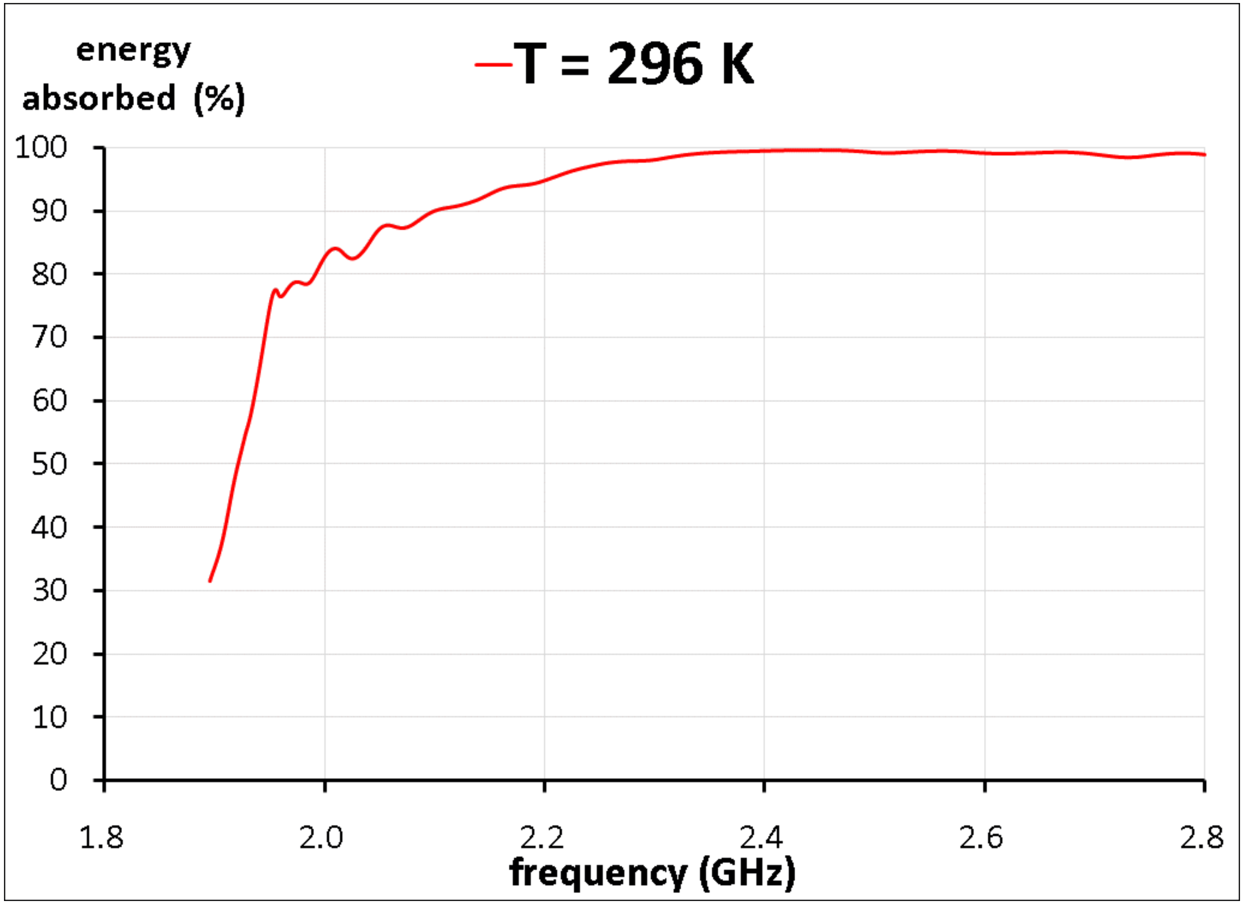
4a) CoorsTeK SC-30
from room temperature to 2K





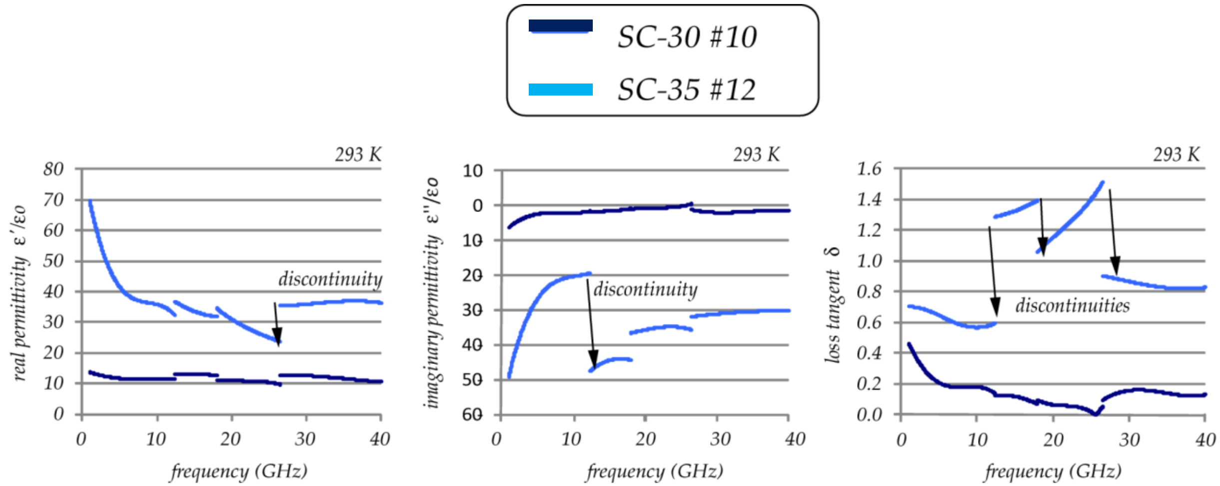
4b) CoorsTeK SC-35 Graphite Loaded
from room temperature to 2K

promising candidate for 2K absorber found!



4) Material properties of SC-30 and SC-35 composites

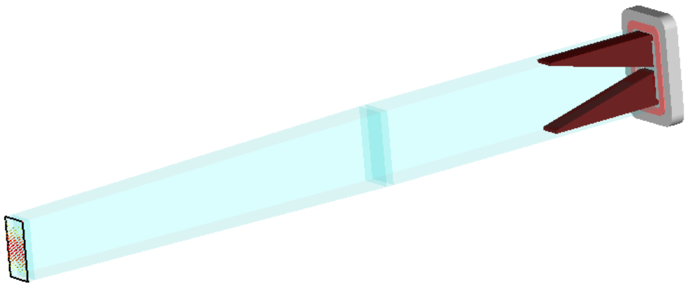
- big thanks to **Eric Chojnacki** (Cornell) for carrying out the RF measurements of dielectric properties up to 40 GHz
  → typically 30% error have to be considered
  → sometimes however no smooth behaviour (SC-30) among different measurement regimes

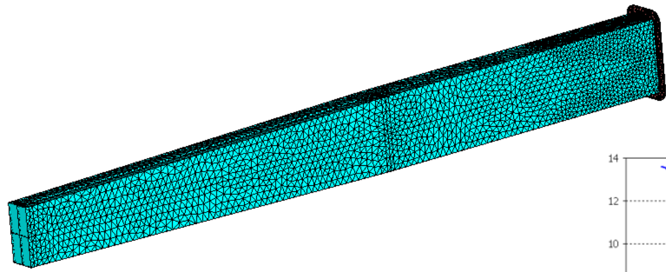


1) **SC-30**: Eric found low DC conductivity at 293K, which drops going down to 77K (would not be good for beamline absorber)
   → reasonable loss tangent
   → good real permittivity range (good for compact waveguide absorber)
2) **SC-35**: good DC conductivity both 293K and 77K (good for beam line absorber and 2K load)
   → discontinuities indicate systematic errors (deviation of washer disc shape from ideal?)
   → high real permittivity
   → high losses

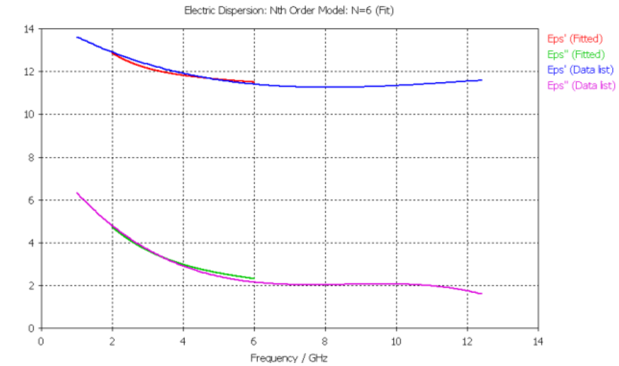
4a) CoorsTeK SC-30
at room temperature: 2 wedges in waveguide

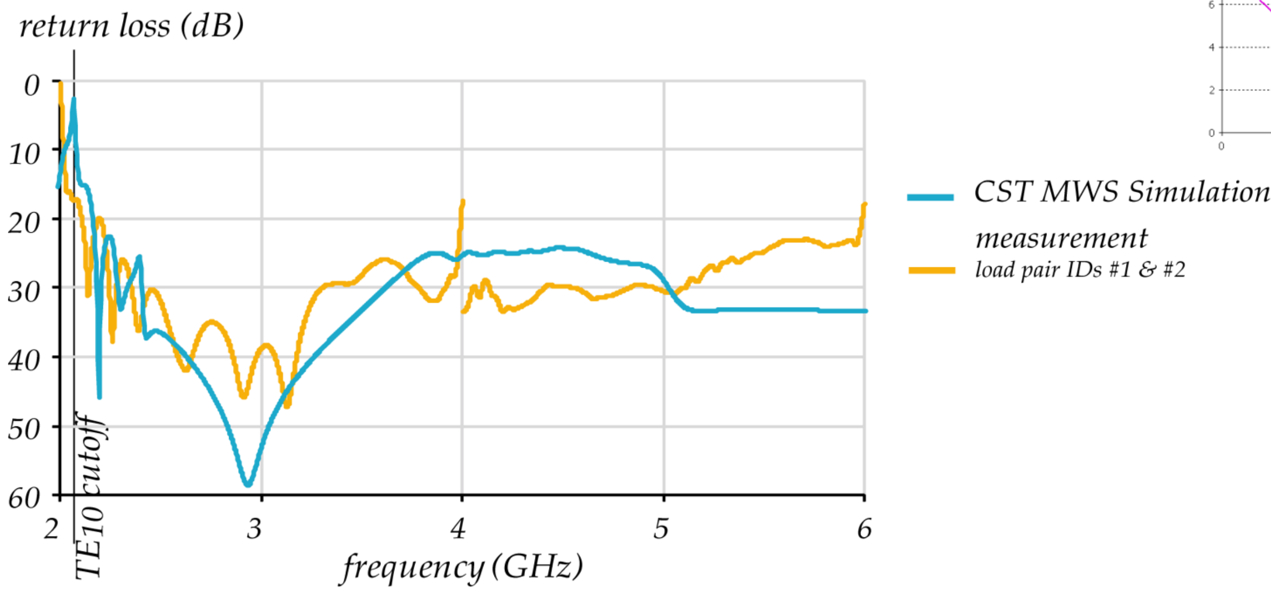
- ❑ measurement compared with numerical results utilizing measured material data

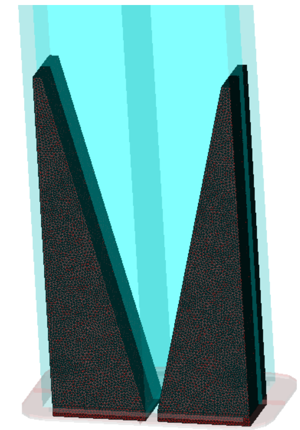




material data approximation
in CST MWS



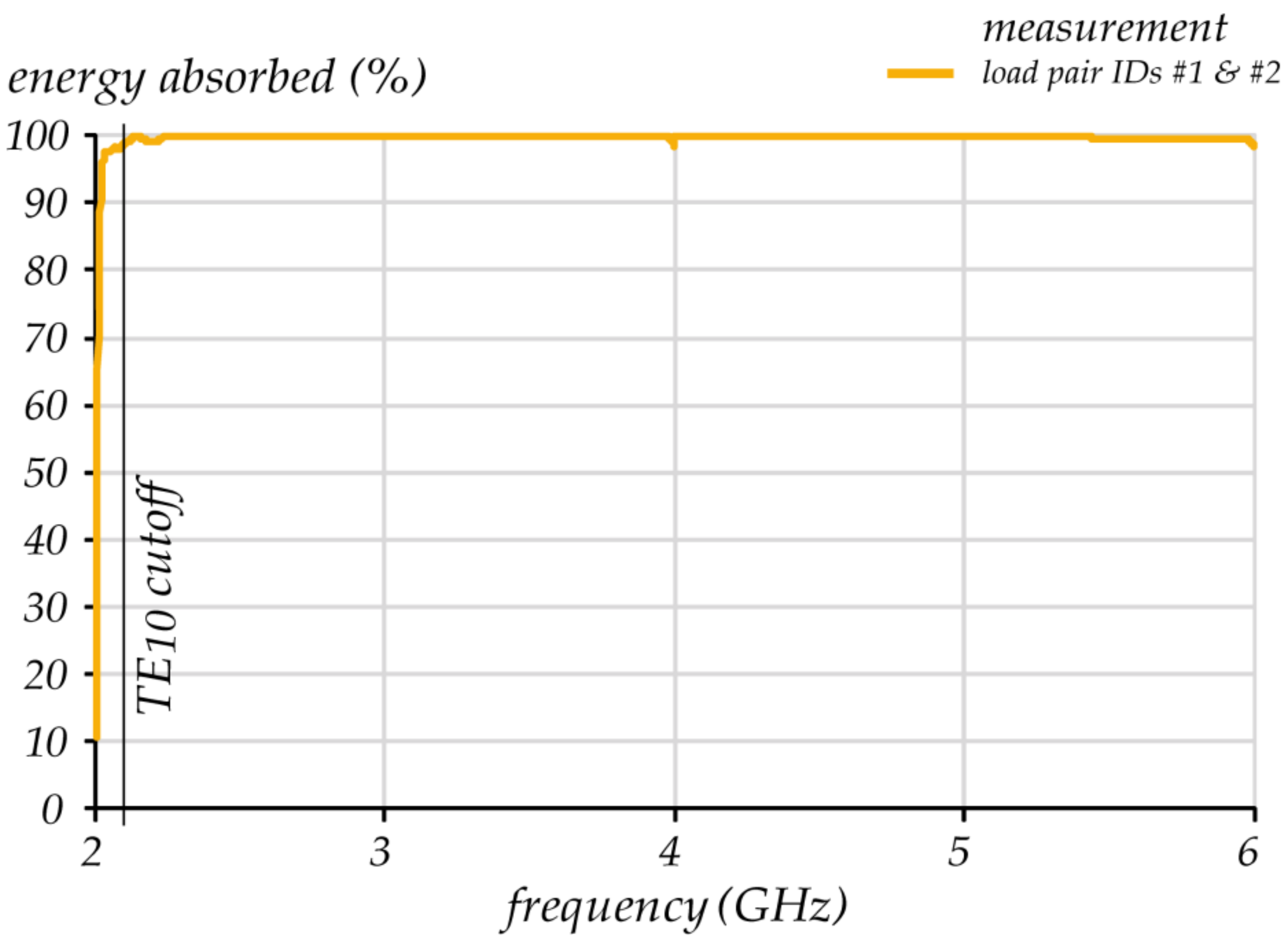


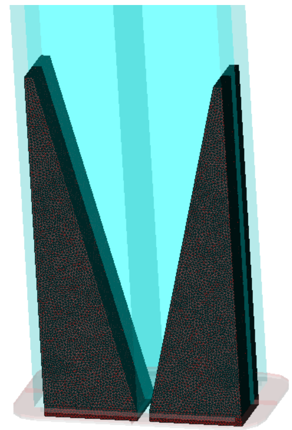


- ❑ **excellent room temperature load**

4a) CoorsTeK SC-30
at room temperature: 2 wedges in waveguide

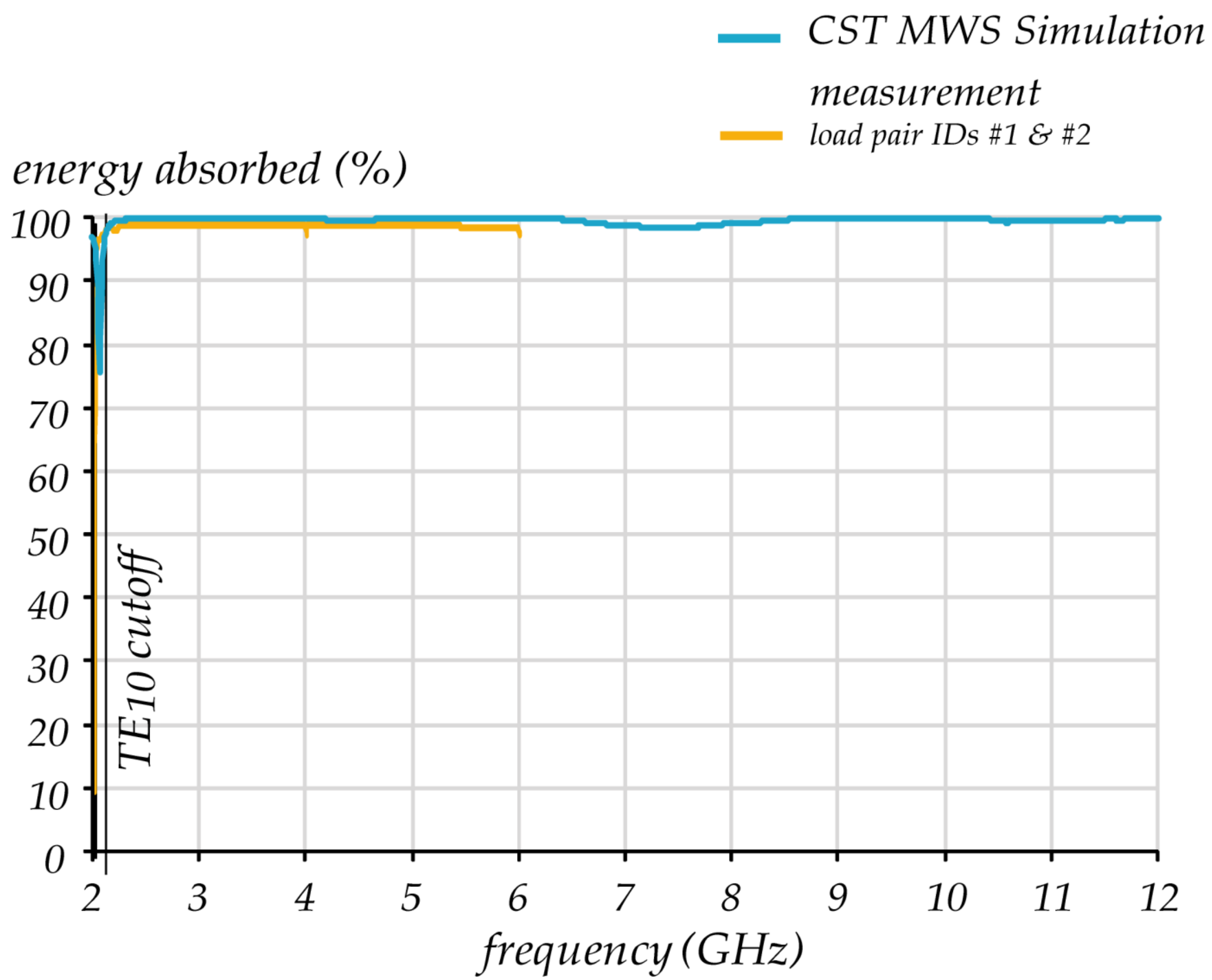
- ❑ same figure (measurement only) with energy absorbed

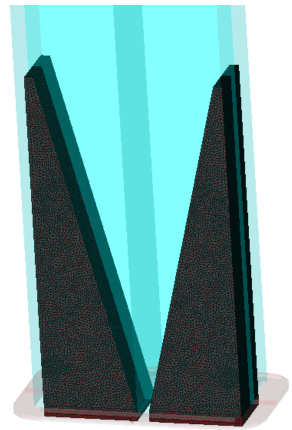




4a) CoorsTeK SC-30
at room temperature: 2 wedges in waveguide

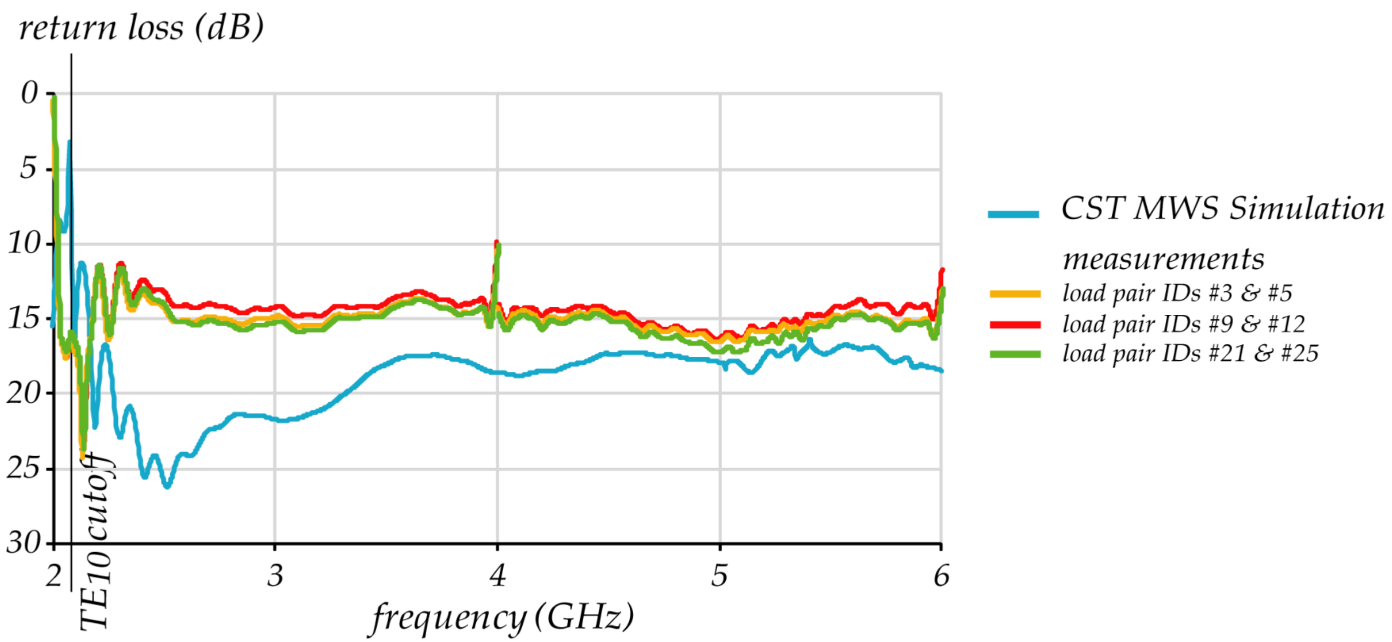
- measurement with numerical prediction up to 12 GHz

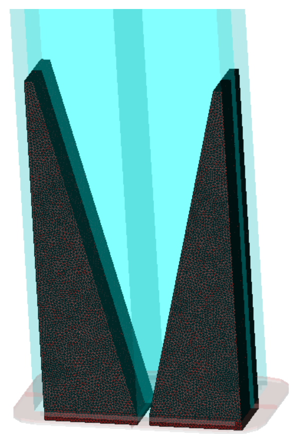




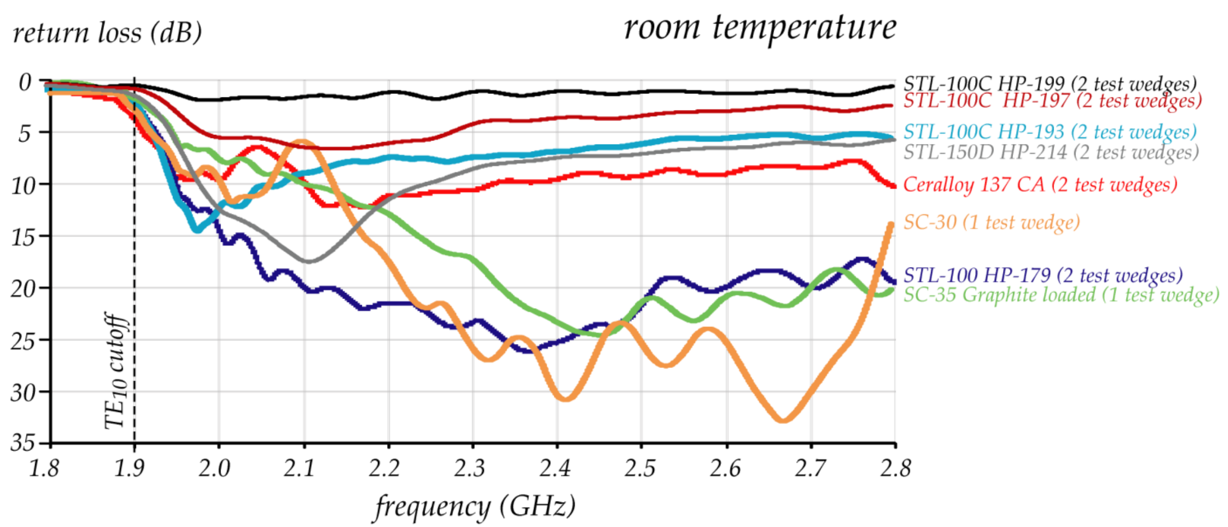
4a) CoorsTeK SC-35 Graphite Loaded
at room temperature: 2 wedges in waveguide

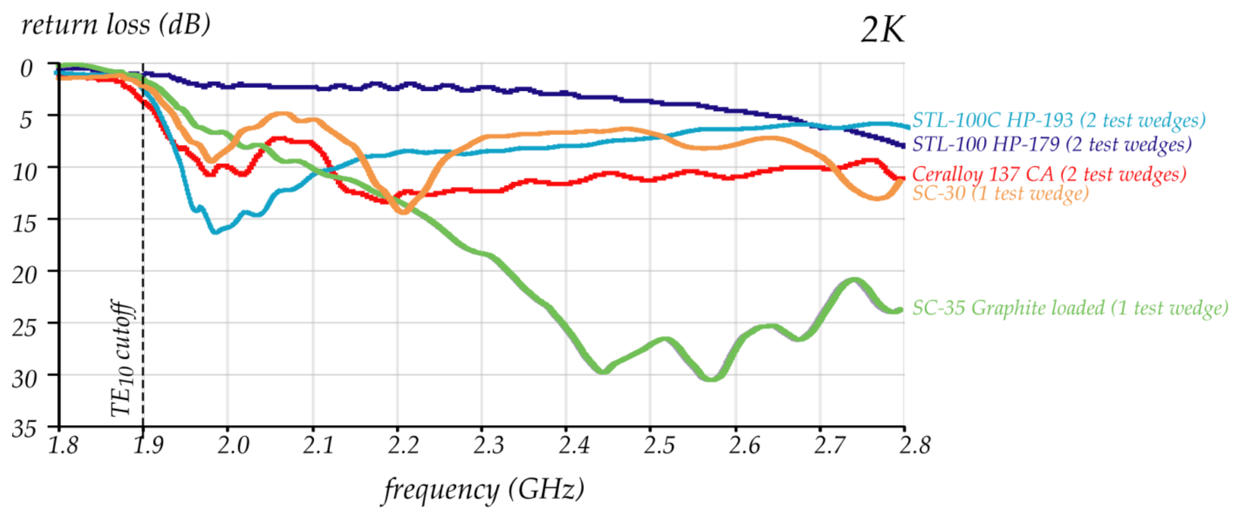
- similar studies carried out for SC-35
  - → simulation predicts better performance (material data errors at low frequency ?)
- **repeatability of performance studied with three different wedge pairs**
  - → **no huge difference**
  - → **bulk material seems to be stable**





5) Combined summary: data at room temperature and 2K

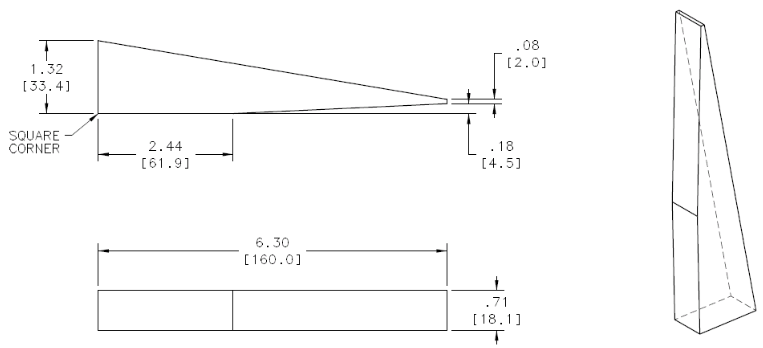


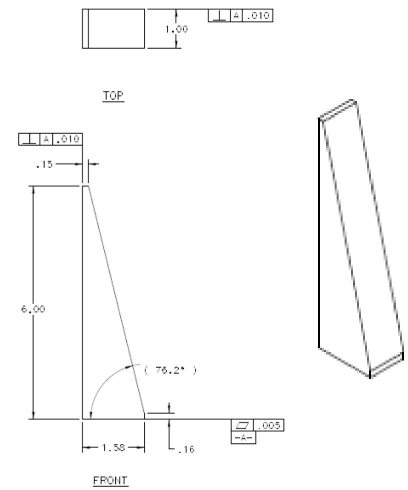


Conclusion

- various promising materials have been identified, which can be used as
  1) 2K loads (Ceralloy 137 CA, SC-35)
  2) Room temperature loads in waveguides (STL-100 HP179, SC-30, SC-30)
  3) cold beam line absorbers (SC-35)
- to optimize load shape, the complex material properties have to be measured as done at Cornell

- **if you may have any material that needs to be RF tested cold, we can do some work at JLAB**
- drawings available for wegdes or use own design which fits in our waveguides





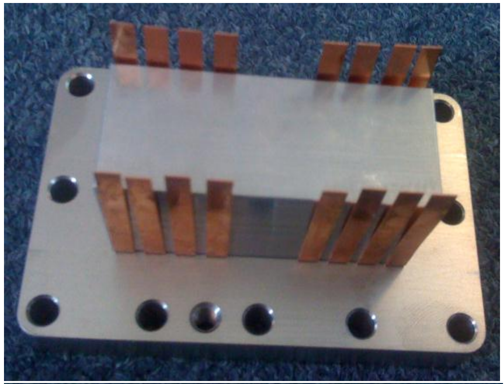
Thank You!

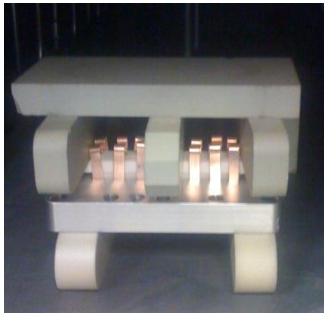
Backup Slides

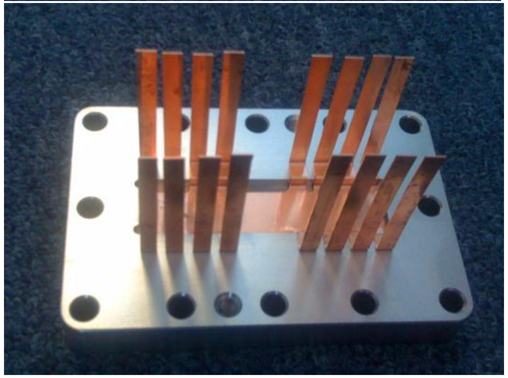
some brazing research

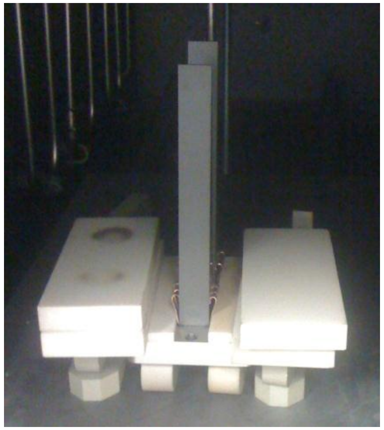
T. Elliot, F.M.

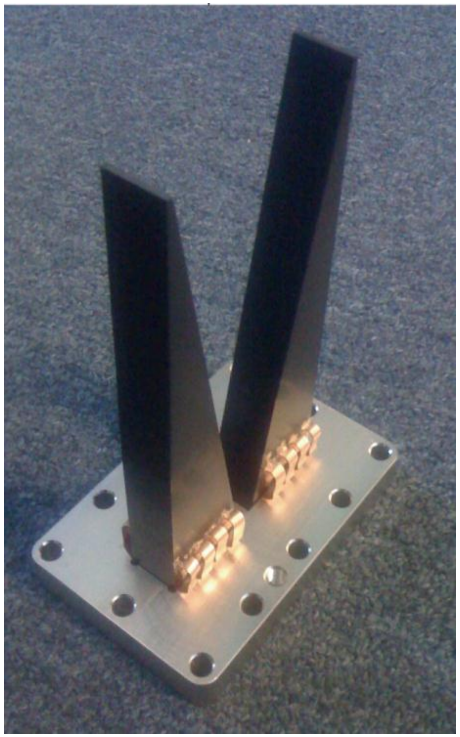
- copper brackets (15 mil thick) bent to shape with tool
- brazed to SS 316L flange with 50/50 % CoAu foil (3 mil thick) at 995 deg. C
- InCuSil Active Brazing Alloy (ABA) (no metallization needed) in form of paste or foil placed between wedges and copper fingers (brazing at 860 deg. C)



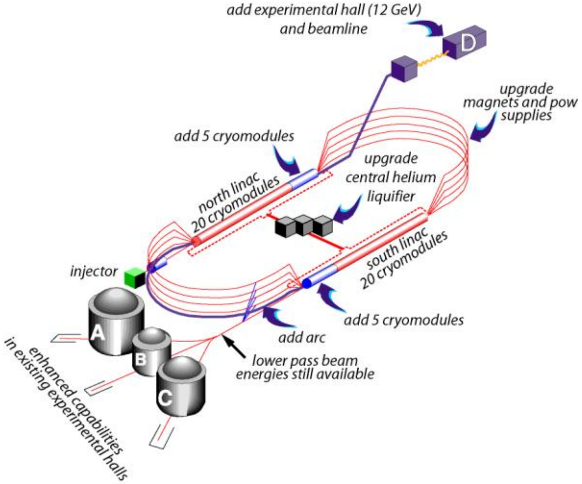




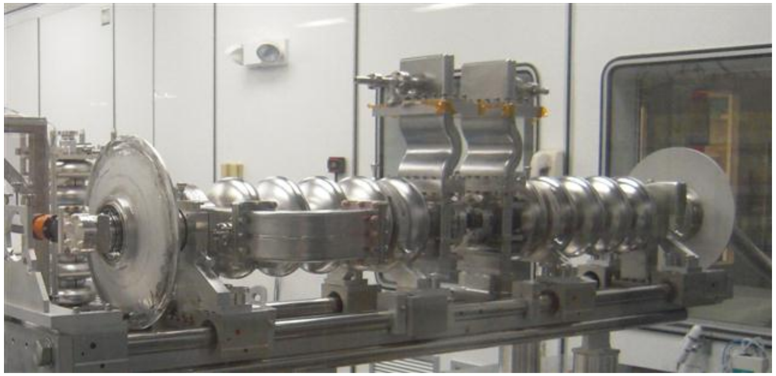




CEBAF



CEBAF at 6/12 GeV



1497 MHz Original Cornell Cavity-Pair Cryo-Unit