HOM Absorbers Using SiC Ceramics
(for KEKB Normal Conducting Cavity)

Oct 20th, 2011

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Outline of talk

- HOM dampers for KEKB ARES cavity.
- Effects of surface wave modes in absorbing materials.
- RF dielectric properties of the SiC ceramics and control of these properties.

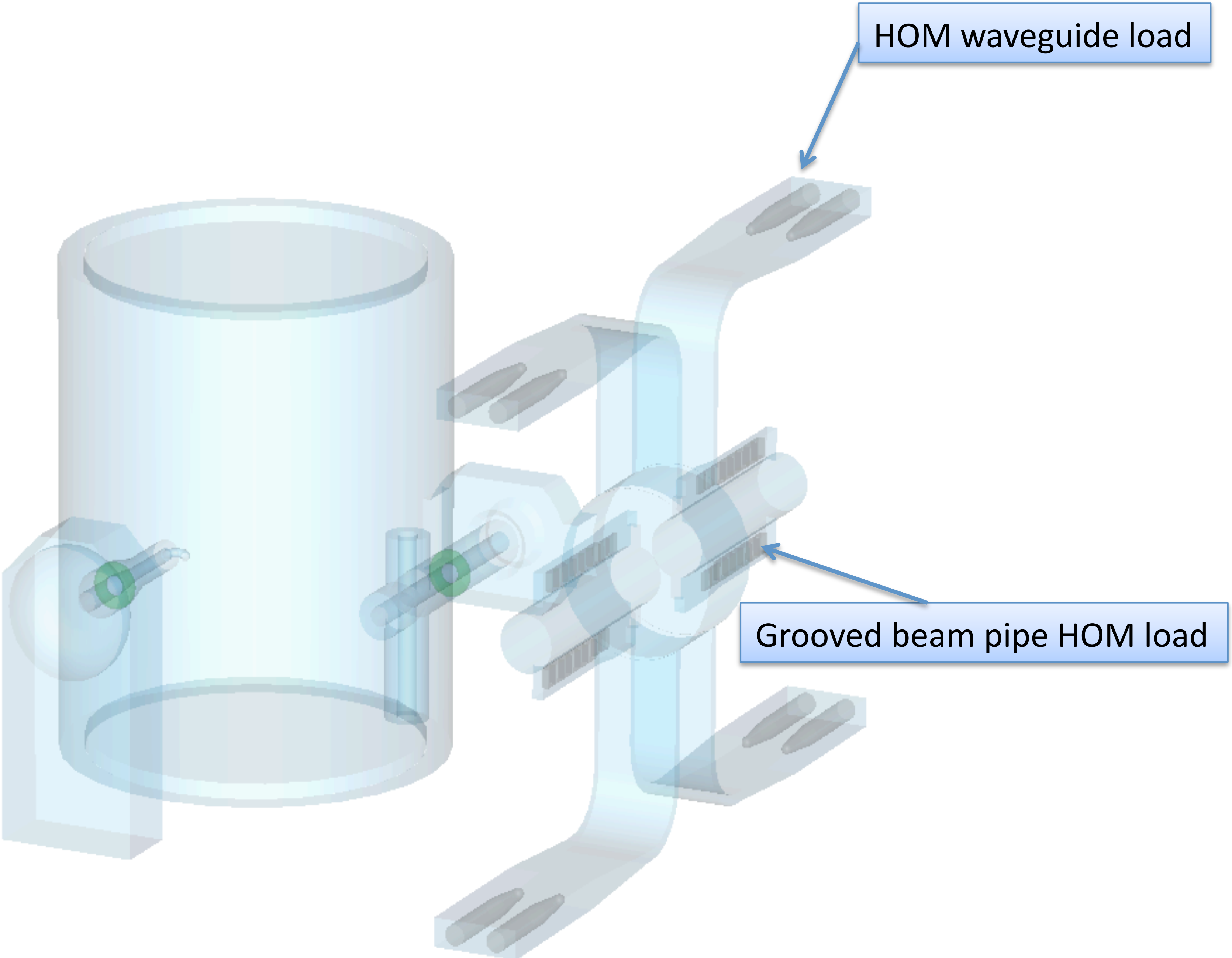
Why we chose SiC ceramics for HOM absorbers

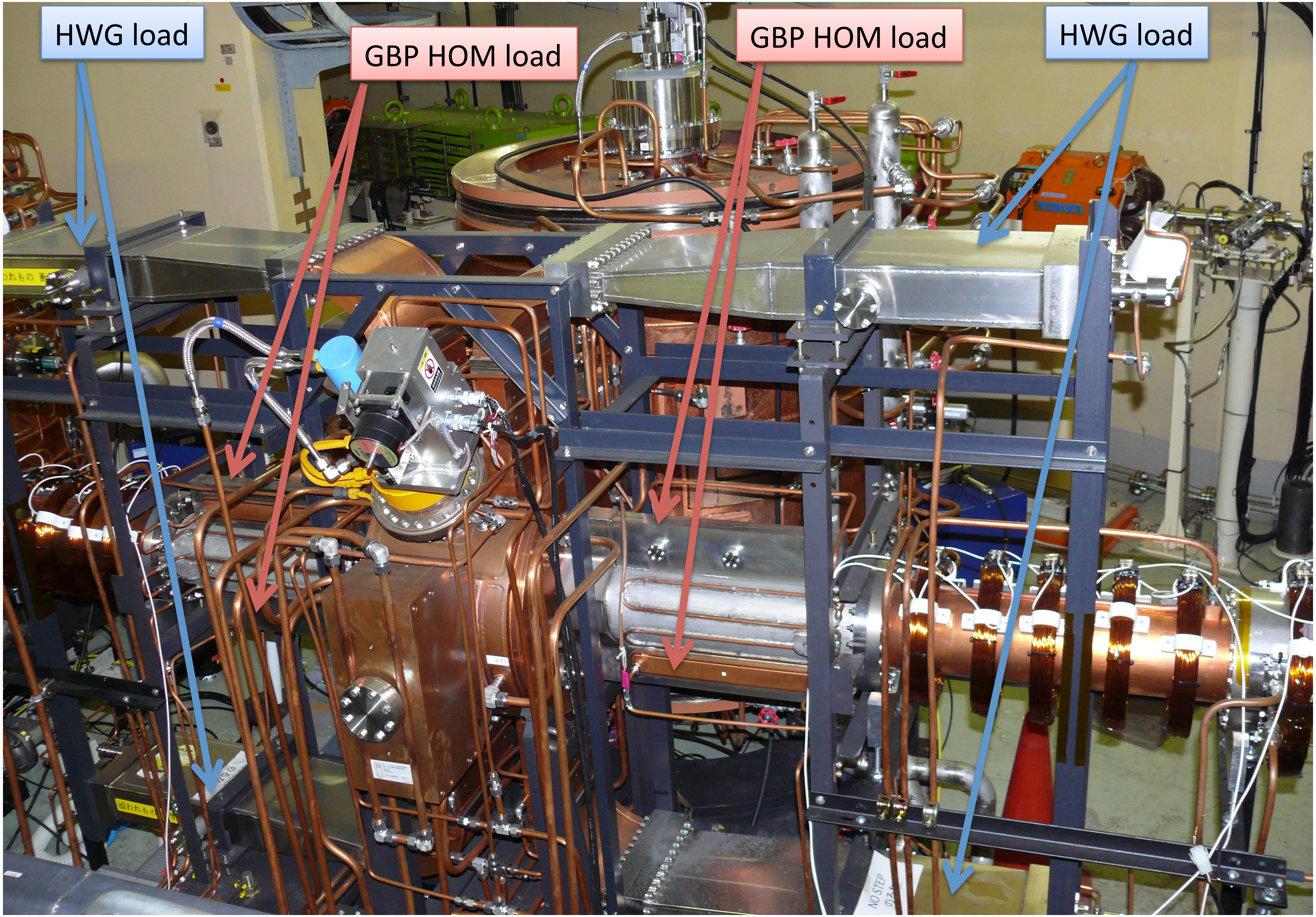
- Large values of ε' and ε" at microwave frequencies (at room temperature).
- Fine and dense, high mechanical strength, low outgassing rate, chemically inert.
- Relatively high thermal conductivity ~120W/mK, (half of aluminum; 230W/mK).
- Many SiC ceramics had been used for absorbers successfully in KEK when we started in 1994. *,**

*Ref : H.Matsumoto, et al., "Application of SiC Ceramics for Microwave Absorber", Proceedings of the 9th Linear Accelerator Meeting in Japan, Kyoto, 1984, pp. 124-126, (Japanese).

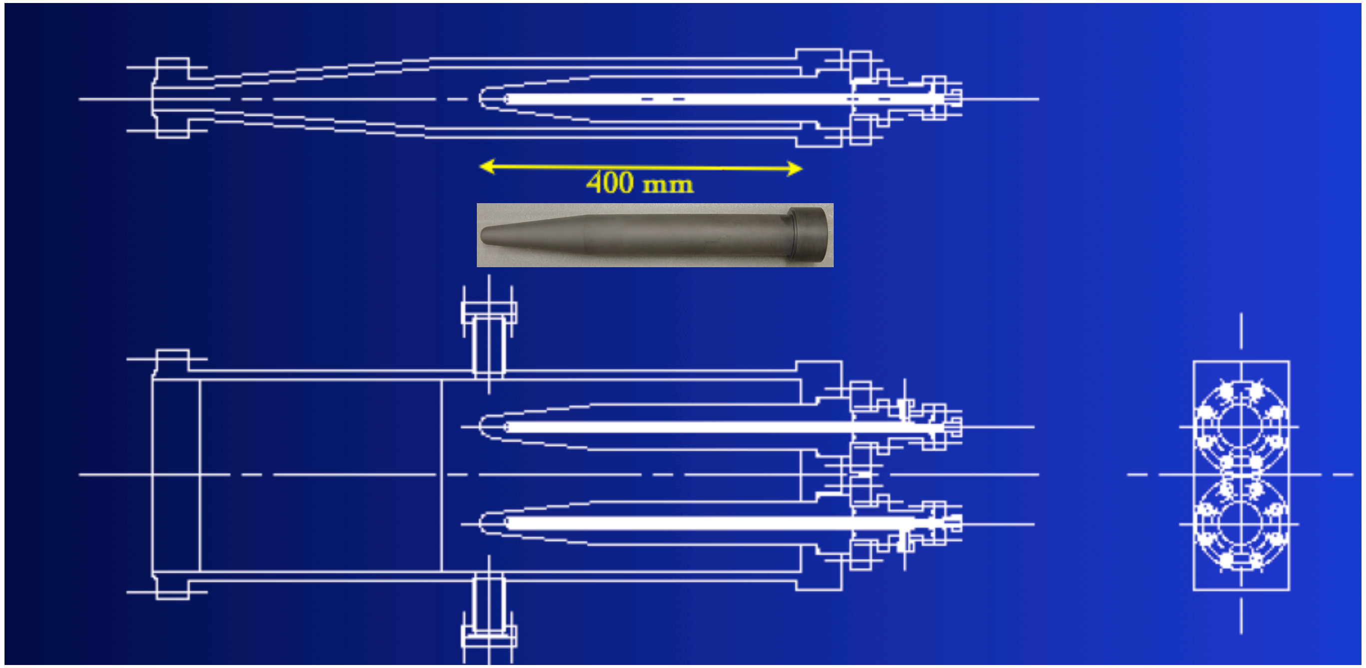
** Ref : M.Izawa et al., "Characteristics of a SiC microwave absorber for a damped cavity", Rev. Sci. Instrum. 66(2), Feb., 1995.

KEKB normal conducting cavity (ARES)




HWG load
GBP HOM load
GBP HOM load
HWG load

HWG LOAD



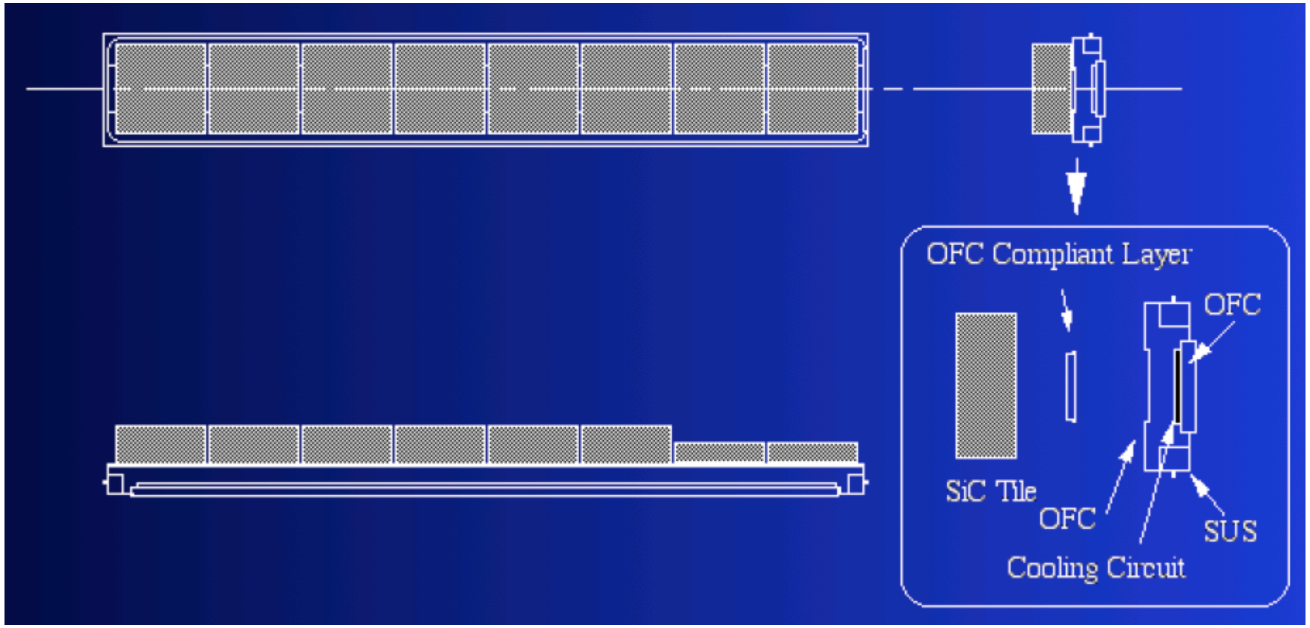
Bullet-shape SiC : diameter 55mm, effective length 400mm
(material, HEXOLOY®)

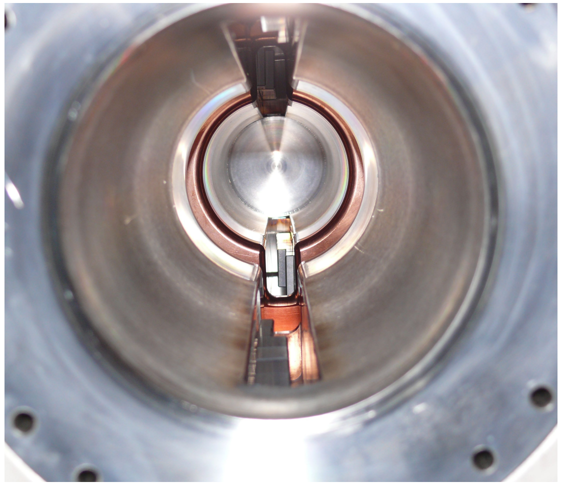
Spec. for KEKB (1996) : 2.5kW/WG, 1.25kW/SiC (0.8-2GHz)
Operation (1998-2010) : 1.05kW/WG, 0.53kW/SiC
(32xARES, 128xWG, 256xSiC)

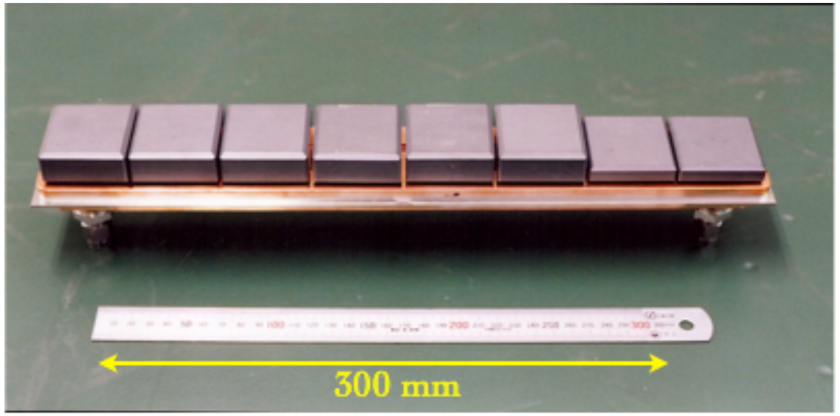
High power test : 20kW/WG, 10kW/SiC (@1.25GHz,CW)

Spec. for Super KEKB (2011) : 5kW/WG, 2.5kW/SiC (0.8-2GHz)

GBP LOAD







SiC tile : 48mmx48mmx20mm 6pieces/groove
48mmx48mmx10mm 2pieces/groove
(material, CERASIC-B®)

Spec. for KEKB (1996) : 0.5kW/groove (0.8-2GHz)
Operation (1998-2010) : 0.3kW/groove
(32xARES, 128xgroove, 1024xSiC)

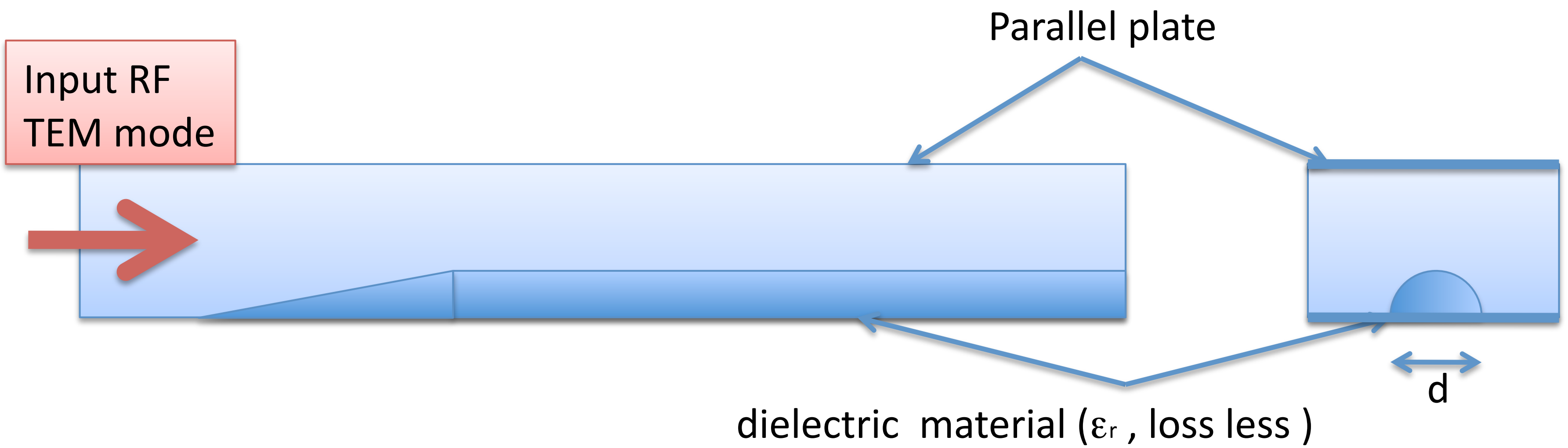
High power test : 1.2kW/groove(@1.25GHz,CW)

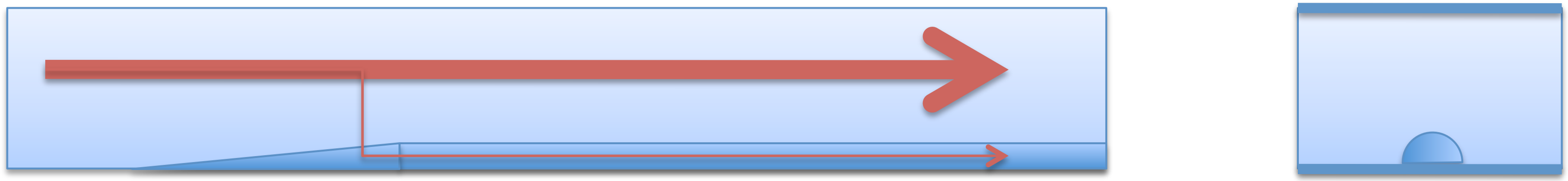
Spec. for Super KEKB (2011) : 1kW/groove
(0.8-2GHz)

Theses HOM loads can be considered as a waveguide partially filled with dielectric material.

->> Property of surface wave mode appear, which is like “cutoff ”.

Example: Half part of bullet shape dielectric material (loss less) in a parallel plate.



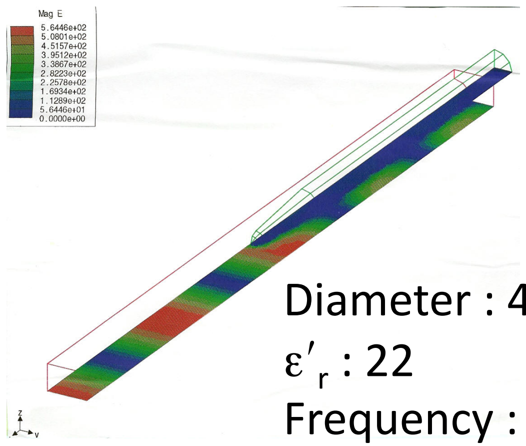


When $v_t < v_{critical}$ (some critical value) , almost RF waves travel outside of the dielectric material.
Where $v_t = \mu_0 \omega d \varepsilon_r^{1/2}$.

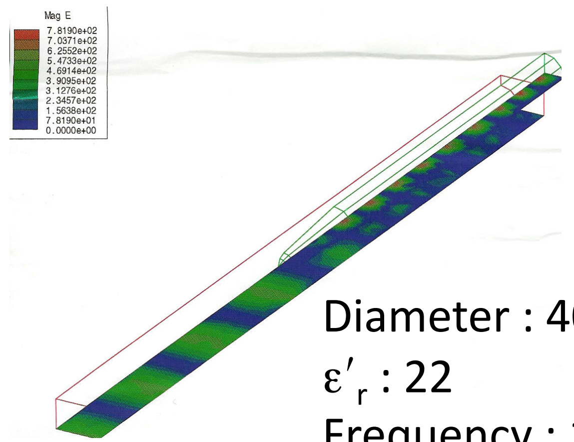
When $v_t > v_{critical}$ (some critical value) , almost RF waves travel in the dielectric material.
Where $v_t = \mu_0 \omega d \varepsilon_r^{1/2}$.

Last one is better for the load.

TEM → HE_{11} -like mode



Diameter : 40 mm
ε'_r : 22
Frequency : 0.7 GHz
f_c : ~0.9 GHz



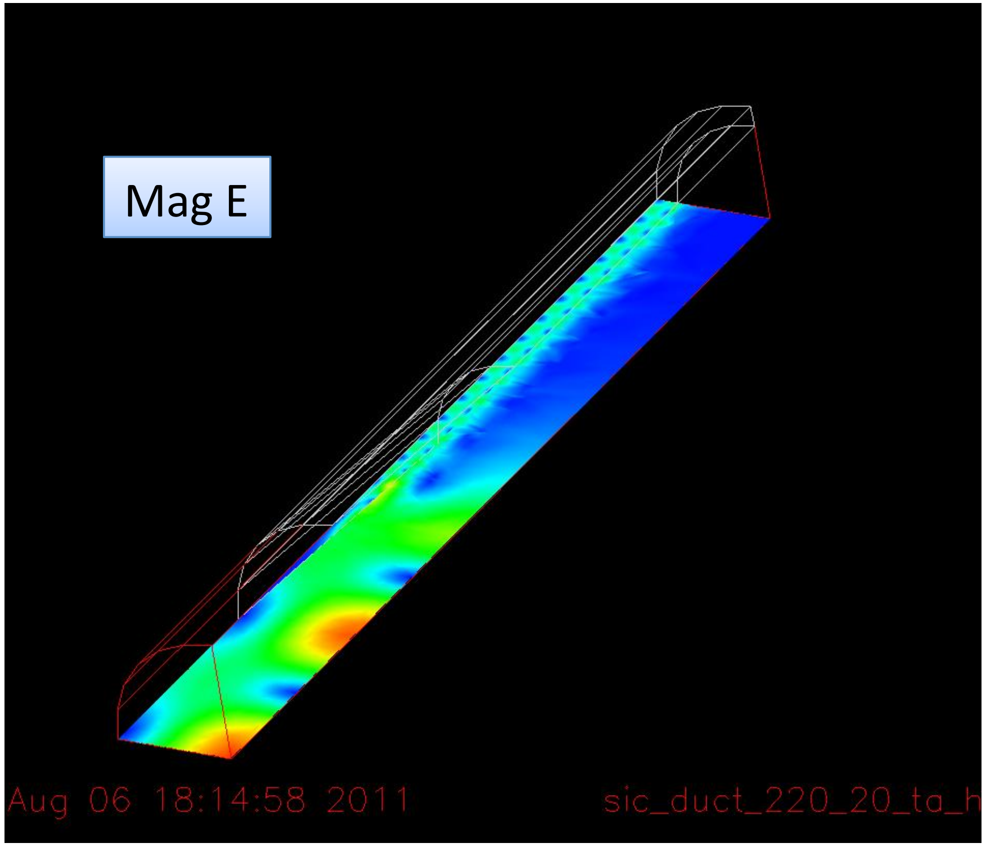
Diameter : 40 mm
ε'_r : 22
Frequency : 1.5 GHz
f_c : ~0.9 GHz

Dielectric rod in a parallel plate line.
Frequency < f_c : HE_{11} mode propagates outside the rod mainly.
Frequency > f_c : HE_{11} mode is propagates inside the rod.
Critical frequency (= f_c) is a function of ε' and diameter of the rod.

In the rectangular waveguide, similar properties appear clearly.
Analyzing these properties, we decided the diameter of the bullet shape SiC, d=55mm.

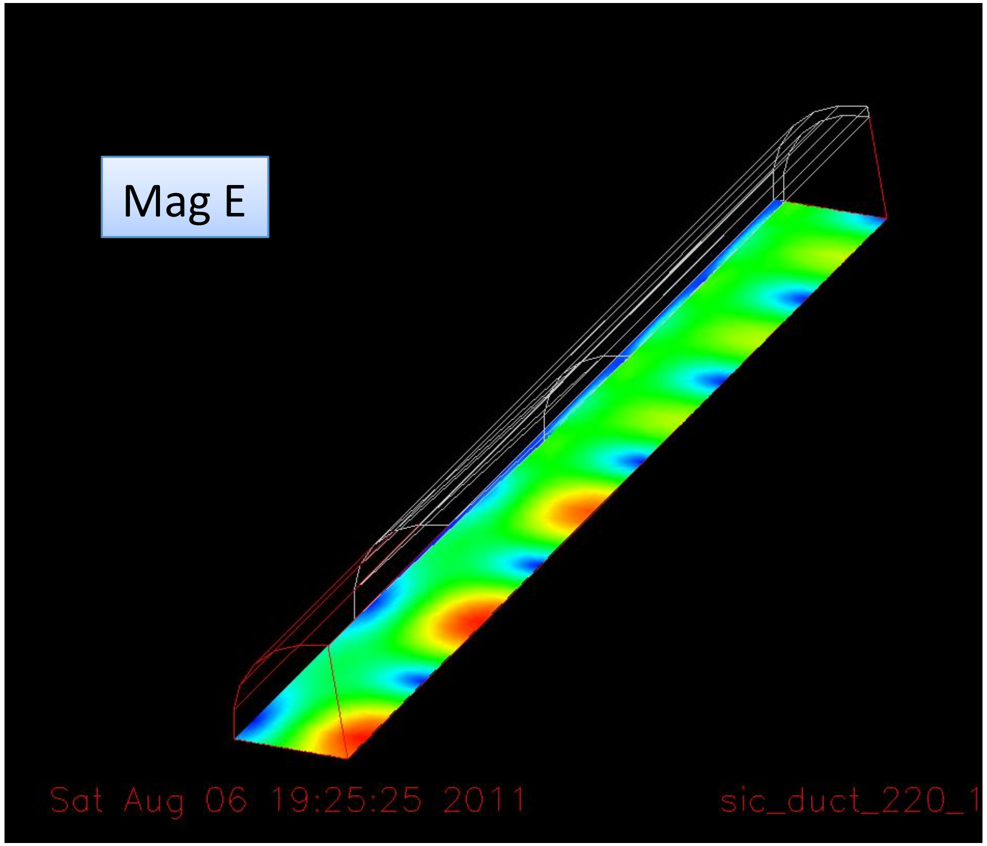
Ref: Y.Takeuchi et al. "The SiC Absorber for the KEKB ARES Cavity", EPAC 96, (kek preprint 96-59).

Surface wave mode in circular WG with dielectric duct



Surface wave mode propagates in the dielectric duct mainly.

Circular WG : diameter 220mm
Dielectric duct : thickness 20mm (with taper)
ε_r = 20.895 (loss less)
Abs(S_{21}) = 0.9999
Frequency : 1.3GHz
Input mode : TM_{01}



TM mode wave propagates outside of the dielectric duct mainly.

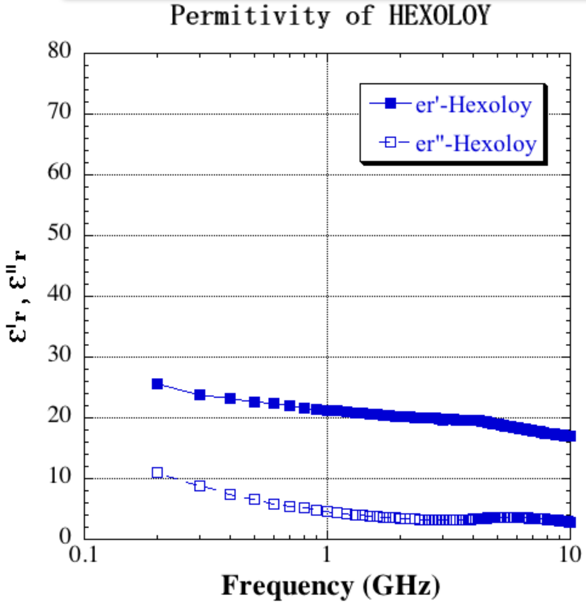
Circular WG : diameter 220mm
Dielectric duct : thickness 10mm (with taper)
ε_r = 20.895 (loss less)
Abs(S_{21}) = 0.9993
Frequency : 1.3GHz
Input mode : TM_{01}

Permittivity of SiC ceramics

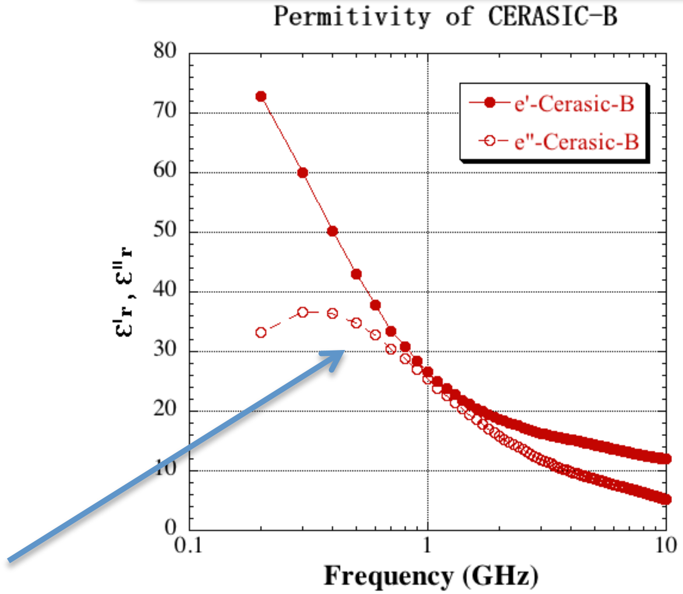
Since most of the SiC ceramic products are for mechanical parts,
the dielectric constant is not specified usually.

At the production of SiC tiles (over 1000 pieces),
we selected the raw material lot (SiC powder) which made better dielectric properties,
and fixed it. This procedure was successful in practice.

bullet shape SiC ceramics



SiC tiles for GBP HOM load



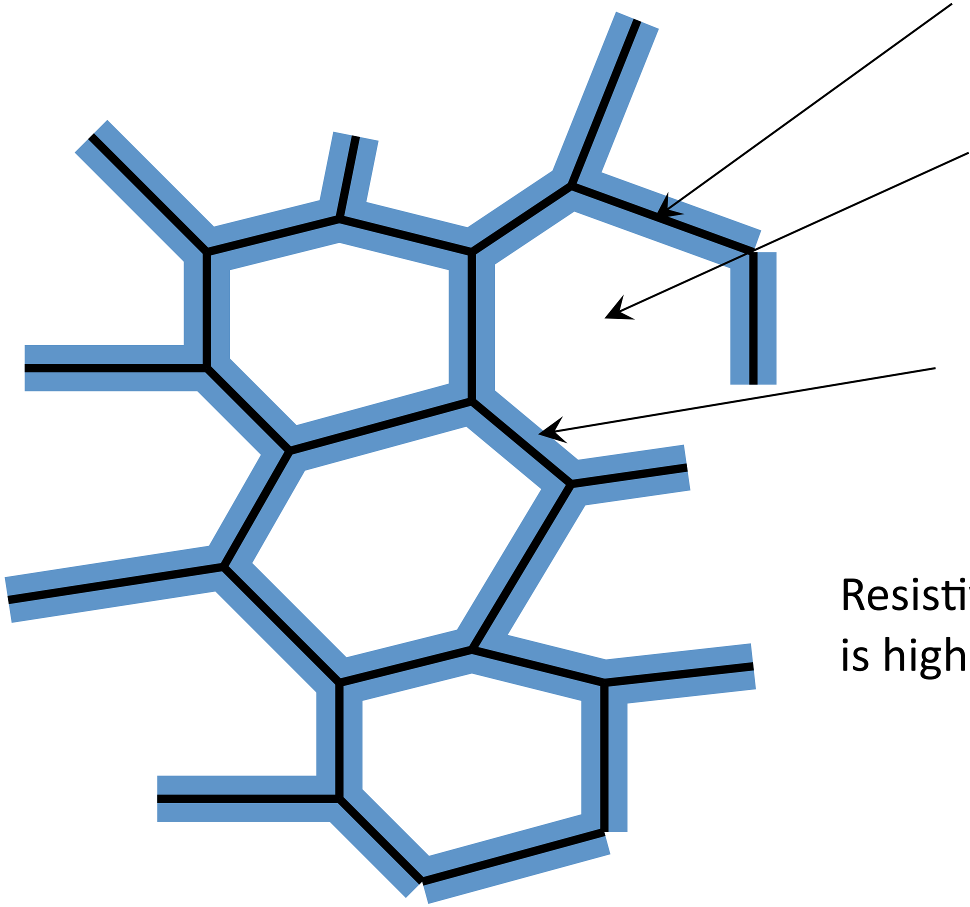
This curve behavior is like a Debye-type relaxation.

Single crystal of SiC is known as a semiconductor (ε_r : 6~10).
Where these dielectric properties come from?

→ These properties are explained by the structure of the grain and grain boundary.

Schematic Model of SiC Ceramics with BeO Addition*

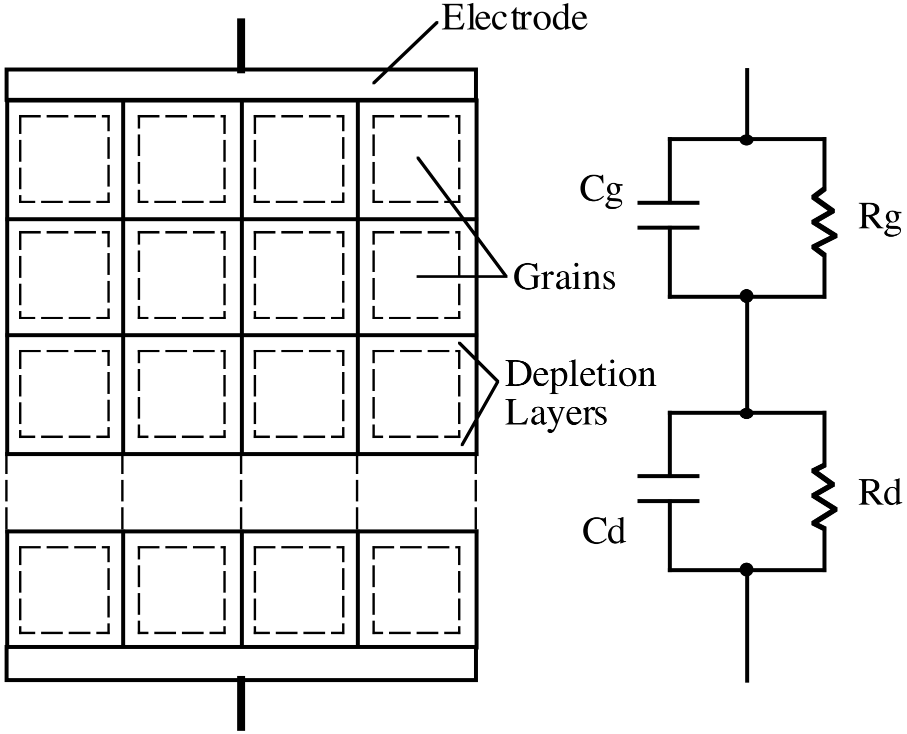
Electrical structure of the SiC ceramics was found by Maeda in 1984.



Resistivity of SiC Ceramics (BeO addition) is higher than 10^{13} Ω·cm.

*Ref: K.Maeda, et al., “Grain-boundary Effect in Highly Resistive SiC Ceramics with High Thermal Conductivity”, pp. 260-268 in Advances in Ceramics, Vol. 7, Additives and Interfaces in Electronic Ceramics, ed. M.F.Yan and A.H.Heuer, American Ceramics Society, Columbus, OH., 1984.

Two-layer Model and Equivalent Circuit



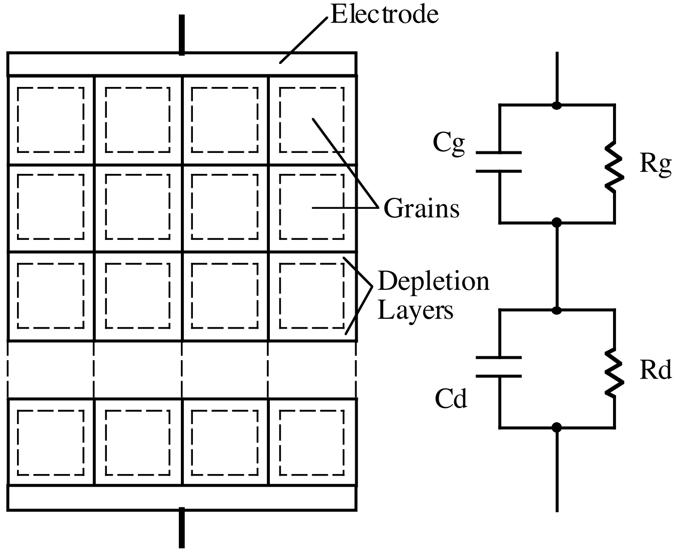
K. Maeda et al. (Hitachi co.) investigated the dielectric properties of SiC ceramics using this equivalent circuit in 1985.*

This model is known as "Maxwell-Wagner two-layer condenser", and described in a textbook.**

*Ref: K.Maeda, et al., "Dielectric Behavior of SiC Ceramics with BeO Addition", Extended Abstract of Electronics Div. 21-E-85, Annual Meeting, Am. Ceram. Soc., 1985.

**Ref: R. Von Hippel, "Dielectrics and Waves", pp. 228-234, John Wiley & Sons, Inc., New York, 1954.

Analysis using equivalent circuit : (CERASIC-B)



$$\varepsilon'_r = \varepsilon_{r\infty} + \frac{\varepsilon_{r0} - \varepsilon_{r\infty}}{1+\omega^2\tau^2} \qquad (1)$$

$$\varepsilon''_r = \frac{(\varepsilon_{r0} - \varepsilon_{r\infty})\omega\tau}{1+\omega^2\tau^2} + \frac{\sigma}{\varepsilon_0\omega} \qquad (2)$$

$$\tau \equiv \frac{(R_g\tau_d + R_d\tau_g)}{R_g + R_d} = \frac{R_g R_d (C_g + C_d)}{R_g + R_d} \qquad (3)$$

with $\tau_g = R_g C_g, \quad \tau_d = R_d C_d$

In this model $R_g << R_d, \quad C_g << C_d$

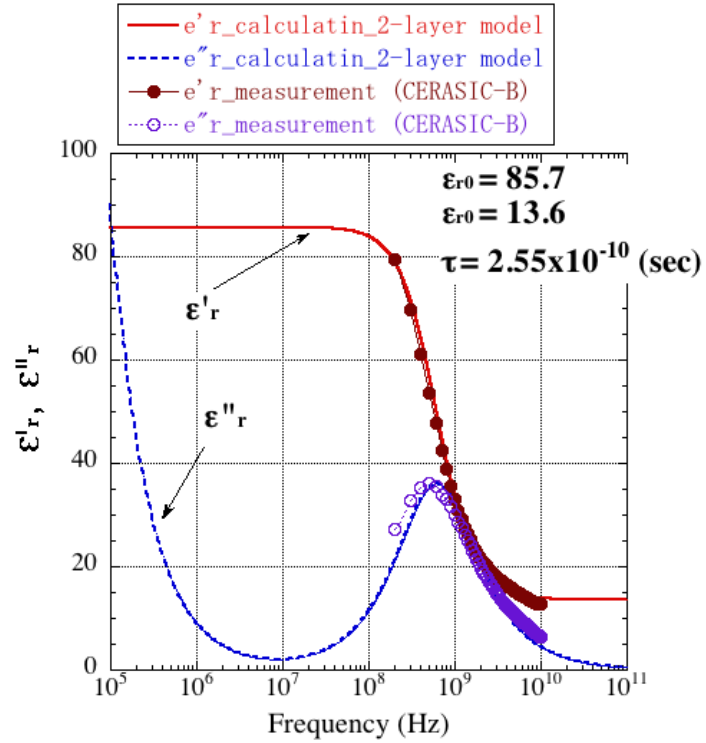
$\rightarrow \quad \tau \approx R_g C_d \qquad (4)$

CERASIC-B : σ=1/(2x10³) (1/(Ωm))

$\frac{\sigma}{\varepsilon_0\omega} < 0.05$ above 0.2GHz. ⇒ negligibly small

Then (1),(2) → Debye equation

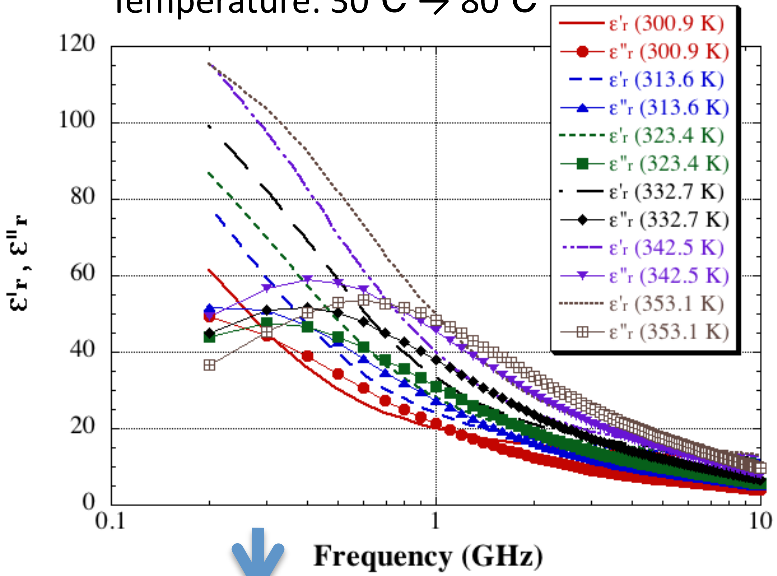
$$\varepsilon_r \approx \varepsilon_{r\infty} + \frac{\varepsilon_{r0} - \varepsilon_{r\infty}}{1+j\omega\tau} \qquad (5)$$

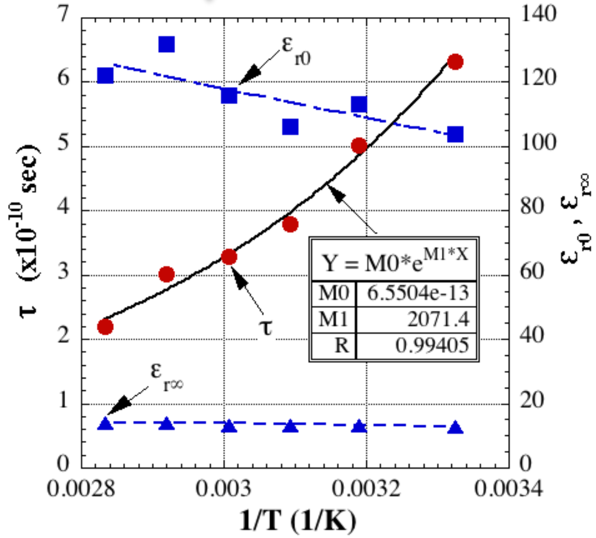


Measurement data are fitted to eqs (1),(2).
Curves (2-layer model fitting) show good agreement with the measurement data.

Temperature dependence of the relaxation curve (CERASIC-B)*

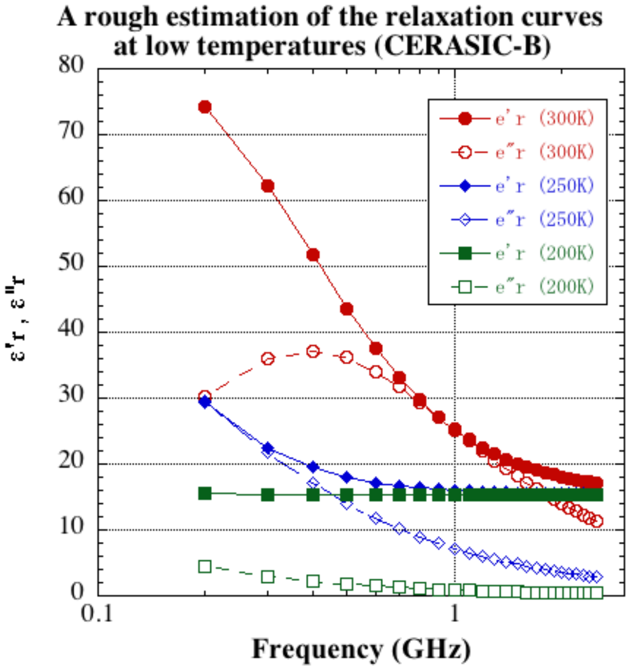
Measurement data (CERASIC-B)
Temperature: 30℃ → 80℃





ε_{r0}, $\varepsilon_{r\infty}$ and τ vs. temperature (CERASIC-B).
The relaxation time, τ decreases abruptly as temperature increases.

Extrapolating the curve of the relaxation time, we can estimate the dielectric properties at low temperatures.



Assumption: only τ changes with temperature.

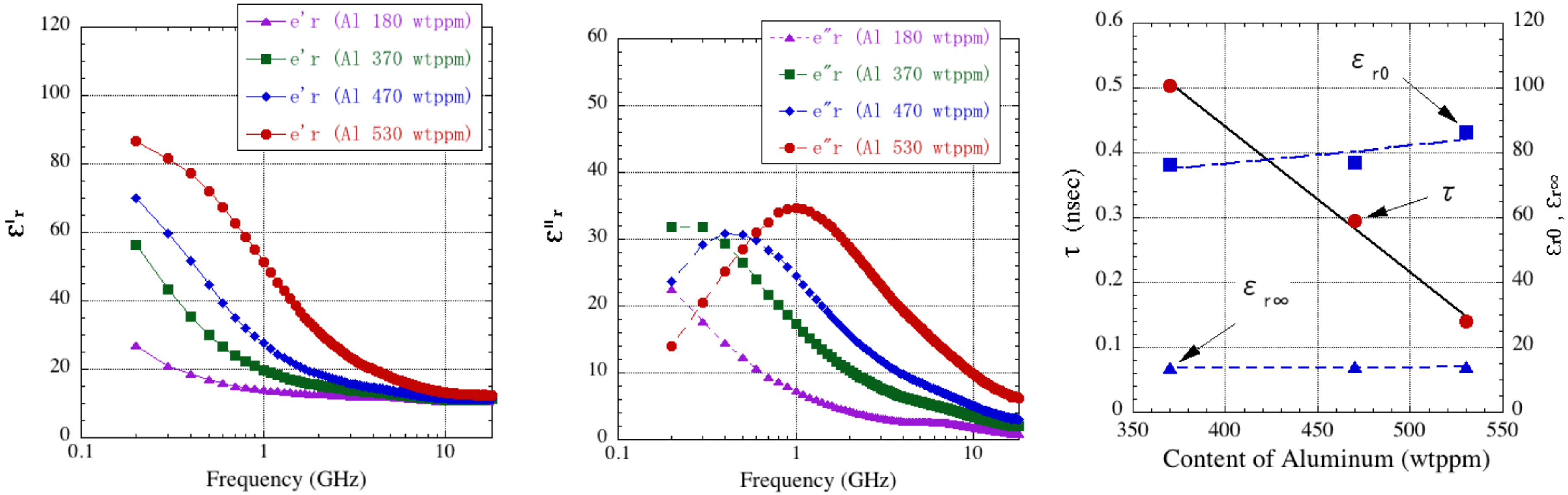
$\varepsilon''_r \approx 0$ above 1GHz at 200K.
I think this product would not be suitable for the HOM load application at low temperature.

•Ref: Y. Takeuchi, et al., "RF DIELCTRIC PROPERTIES OF SiC CERAMICS AND THEIR APPLICATION TO DESIGN HOM ABSORBERS", PAC2005, KEK Preprint 2005-53.

Control of the RF dielectric properties

τ≈ RgCd, and Rg depends on the carrier concentration in grain.
If we can change the carrier concentration, we can control the relaxation time.

→ We made samples of CERASIC-B with different carrier concentrations by adding aluminum compound.*



Content of Aluminum ; 180, 370, 470, 530 (wtppm)

The dielectric relaxation time decreases with increase in the doping aluminum amount.
Control of the RF dielectric properties of SiC ceramics is possible by using this method.

*Ref: Y.Takeuchi, et al. "Control of RF Dielectric Properties of SiC Ceramics for HOM Absorbers ", KEK Preprint 2011-17 (Japanese).

Summary

1) KEKB normal conducting cavities are equipped with 2 types of HOM absorbers using SiC ceramics and have been operated successfully over 10 years.

2) Properties of surface wave modes were analyzed to determine the diameter of the bullet shape SiC absorber.

3) RF dielectric properties of SiC ceramics can be explained by the polycrystal structure model with electrically conductive grains and non-conductive grain boundaries, and can be analyzed with the 2-layer model.

4) By extrapolating the curve of the relaxation time, the dielectric properties of CERASIC-B at low temperatures were roughly estimated. This product would not be suitable for low temperature applications.

5) We tried to control the relaxation time of CERSIC-B by increasing the carrier concentration in the grains, and had successful results. We are planning to apply this method to the HOM absorbers for the super KEKB.

Thank you .

HOM damper	absorber	Specification (1996)	Operation data	High power RF test	SiC ceramics	Cooling water
Waveguide type. 4xWG HOM damper / ARES.	2 bullet-shape SiC/WG.	10kW/ARES, 2.5kW/WG, 1.25kW/ bullet.	4.2kW/ARES	20kW/WG, 10kW/bullet (1.25GHz, CW)	HEXOLOY	Operation : 5L/min, High power test : 7L/min
Grooved beam pipe type. 4xgroove/ ARES.	8xSiC tile/ groove. SiC:6pieces, 48x48x20t. SiC:2pieces, 48x48x10t.	0.5kW/ groove, 2.0kW/ARES	0.3kW/ groove, 1.2kW/ARES	1.2kW/ groove, 4.8kW/ARES (1.25GHz, CW)	CERASIC-B	Operation : 4L/min, High power test : 6L/min
SiC duct type. 4xSiC duct/ LER, 2xSiC duct/ HER, 2xSiC duct/ Crab cavity.	ID:150mm OD:170mm L:240mm	10kW/SiC duct	15.1kW/SiC duct (@crab cavity, 1.6A beam)		CERASIC-B	10L/min (LER,HER), 15L/min (crab cavity).

Debye Model

Input : Step function

Output : $P_0(t)=P_0(1-e^{-t/\tau})$

Debye equation

$$\varepsilon_r(\omega) = \varepsilon_{r\infty} + \frac{\varepsilon_{r0} - \varepsilon_{r\infty}}{1 + j\omega\tau} \qquad (1)$$

where $\varepsilon_{r0}=\varepsilon_r'(\omega=0)$, $\varepsilon_{r\infty}=\varepsilon_r'(\omega=\infty)$

τ : relaxation time.

Debye model is characterized by the three parameters, ε_{r0}, $\varepsilon_{r\infty}$ and τ.