19 Oct 2023, 11:50 – 12:10

Developments of Dielectric-Assist Accelerating structure at C-band and beyond

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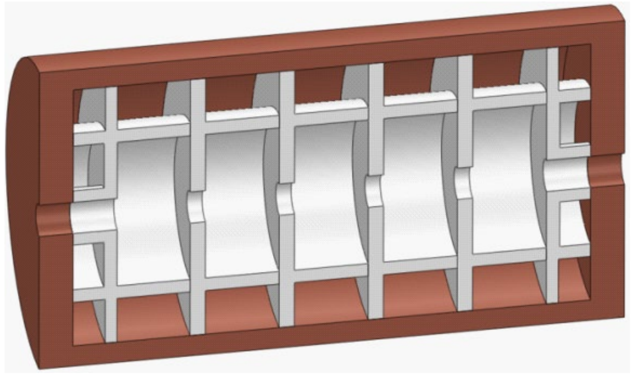
【Outline】

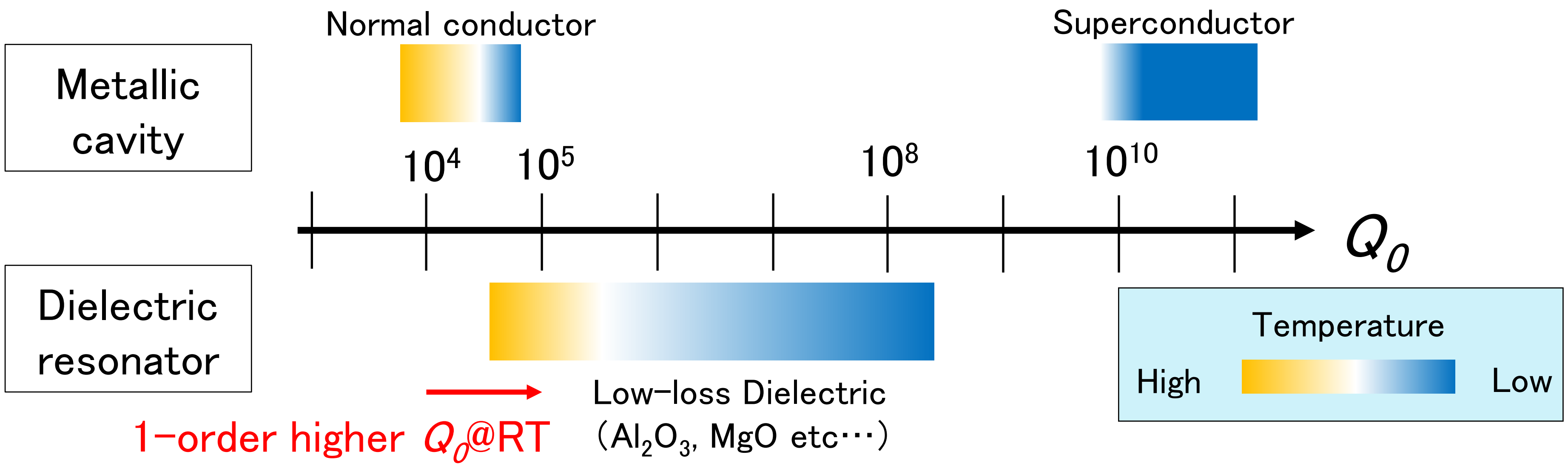
- **Motivation**
- **Operation principle of DAA structure**
- **Proof of principle study**
  - ✓Design and fabrication
  - ✓Low power test
  - ✓High power test
- **Toward improving DAA performance**
- **Research plan**

<u>D</u>ielectric <u>a</u>ssist <u>a</u>ccelerating structure, DAA



【Motivation】

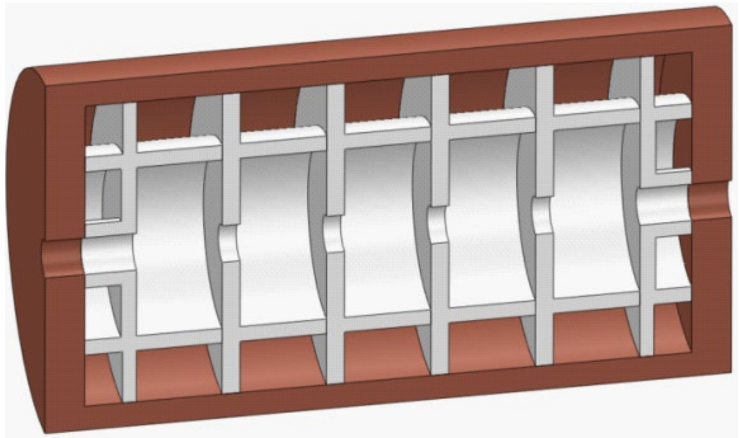
【Comparing the Q_0 of the metal cavity and the dielectric resonator】



N. McN Alford, et al., J Eur. Ceram. Soc. 21, 2605 (2001)

Dielectric loaded cavity has potential to become a high Q value and high Z_{sh}

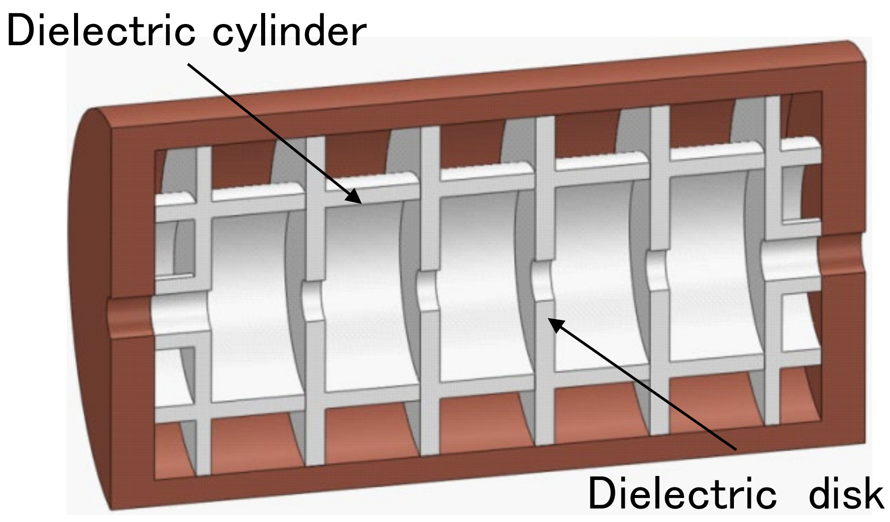
Started the development of a high power efficiency accelerating structure **focusing on the low RF loss characteristics of the dielectric.**



<u>D</u>ielectric <u>A</u>ssist <u>A</u>ccelerating (DAA) Structure

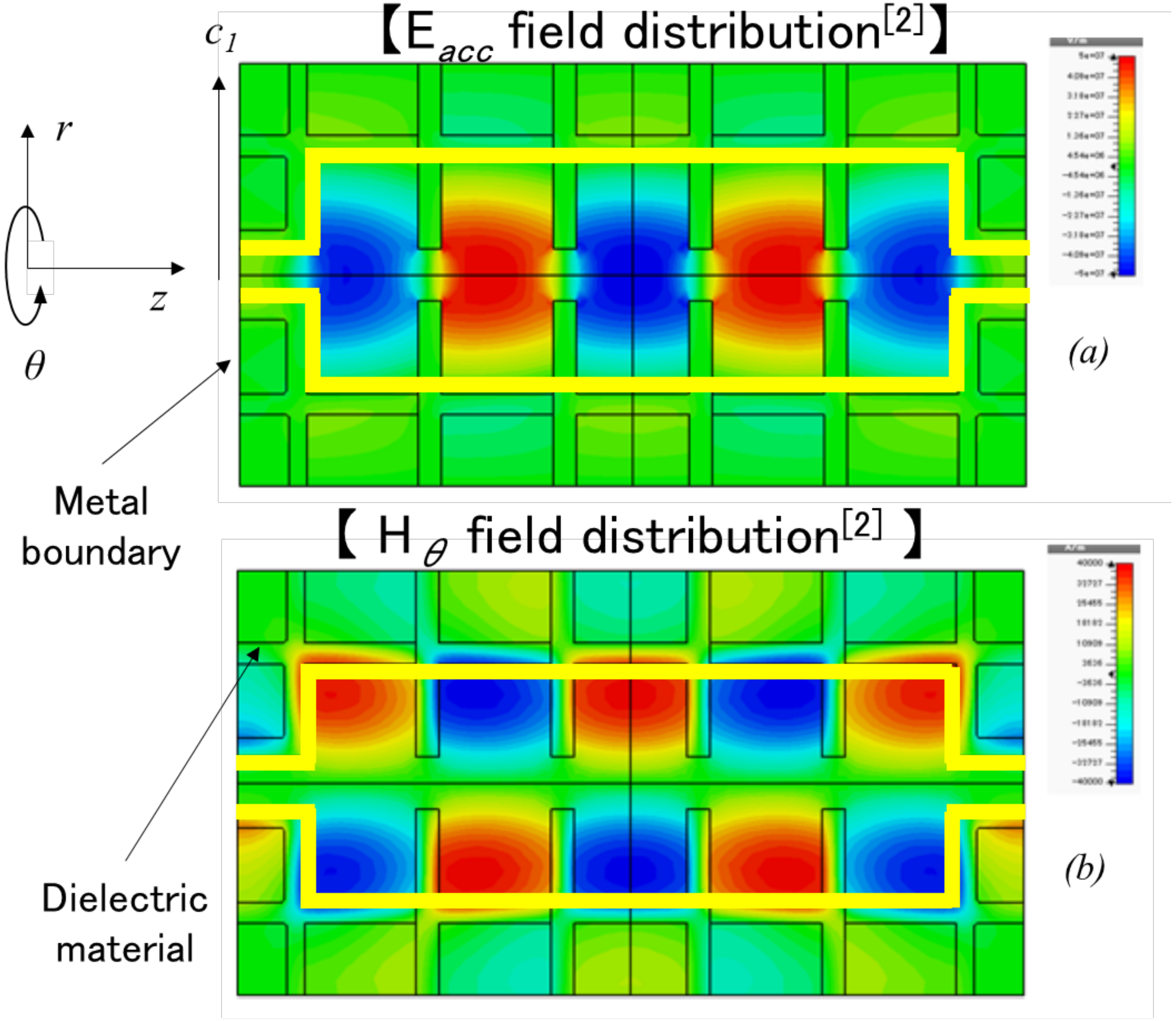
【 Operation principle of DAA structure】

【Conceptual diagram of DAA structure】



- DAA consists of dielectric cylinders and disks with irises which are periodically arranged in a metallic enclosure.
- Higher order TM_{02n} mode is used for beam acceleration.

→ Wall loss on conducting surface is drastically reduced in DAA structure



[1] D. Satoh, et al., PRAB 19, 011302 (2016)
[2] D. Satoh, et. al., PRAB 20, 091302 (2017)

Patent : PCT/JP2016/087683

$TM_{01} - \pi$ mode like

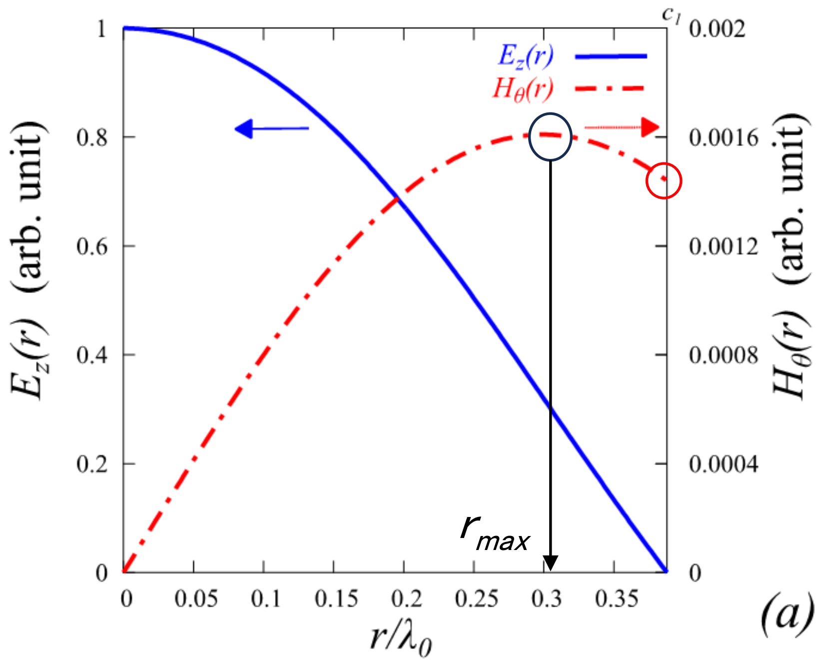
【 Mechanism of high-Q_0 】

<u>Wall loss on a conducting cylinder: P_{wall}</u>

$$P_{wall} \propto c_1 \times |H_\theta(c_1)|^2$$

* c_1: inner radius of conductive cylinder

【Pillbox cavity】



【Pillbox cavity】

$c_1 = 0.39\,\lambda_0$

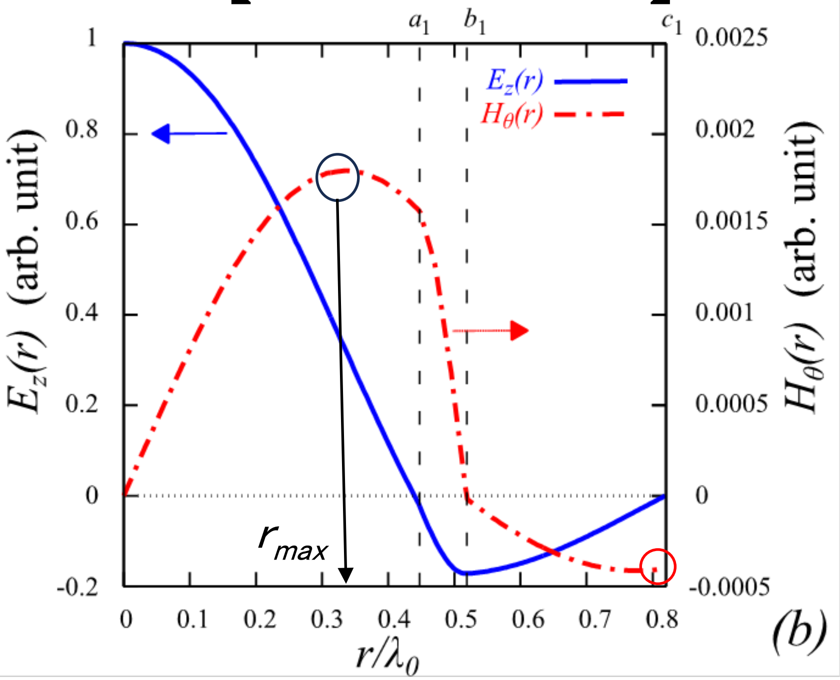
$$\frac{|H_\theta(c_1)|}{|H_\theta(r_{max})|} = 0.89$$

【DAA】

$c_1 = 0.82\,\lambda_0$

$$\frac{|H_\theta(c_1)|}{|H_\theta(r_{max})|} = 0.23$$

【DAA structure】

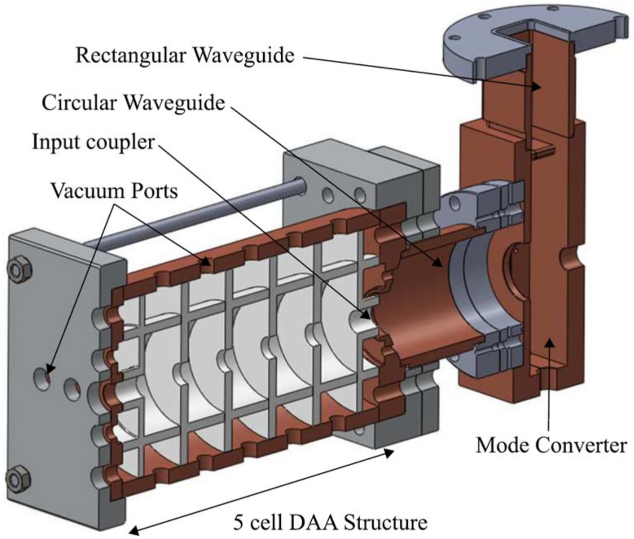


$|H_\theta(c_1)|$ in DAA structure is almost 1/4 that of pillbox cavity

→ The wall loss on conducting cylinder is drastically reduced !

【 Design and Fabrication of prototype 】

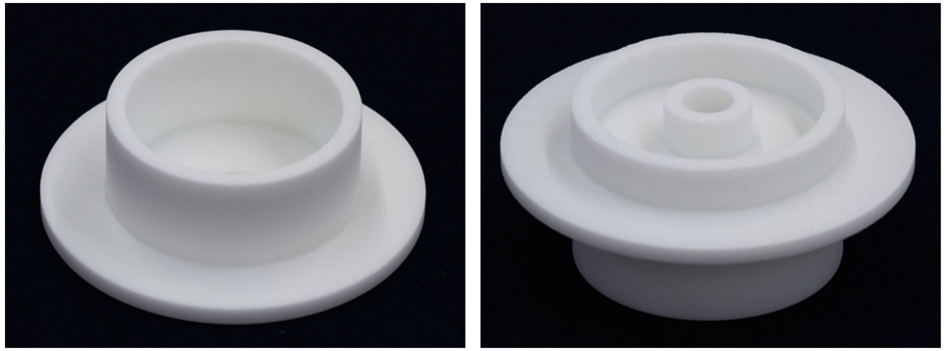
【5 cell DAA structure[2]】



【Cavity parameters[2]】

Parameter	Five-cell DAA structure
Dielectric material	Magnesia
ε_r	9.64
$\tan\delta$	6.0×10^{-6}
Accelerator type	Standing wave type
Accelerating mode	TM_{02}-π mode
Operation frequency	5.712 GHz
Number of accelerating cells	5
Total cavity length	157.5 mm
Q_0	126,400
Z_{sh}	630 MΩ/m
E_{max}/E_0	2.92
H_{max}/E_0	2.74 mA/V

【Dielectric cells[2]】



【DAA structure assembly[2]】

[2] D. Satoh, et. al., PRAB 20, 091302 (2017)

【 Low-power test of the prototype 】

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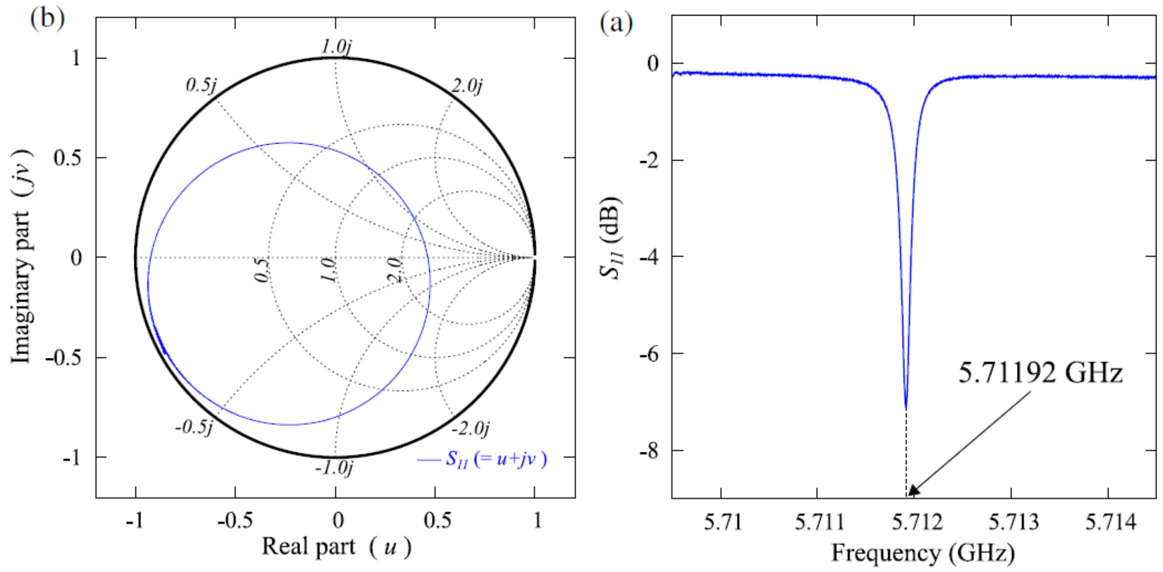
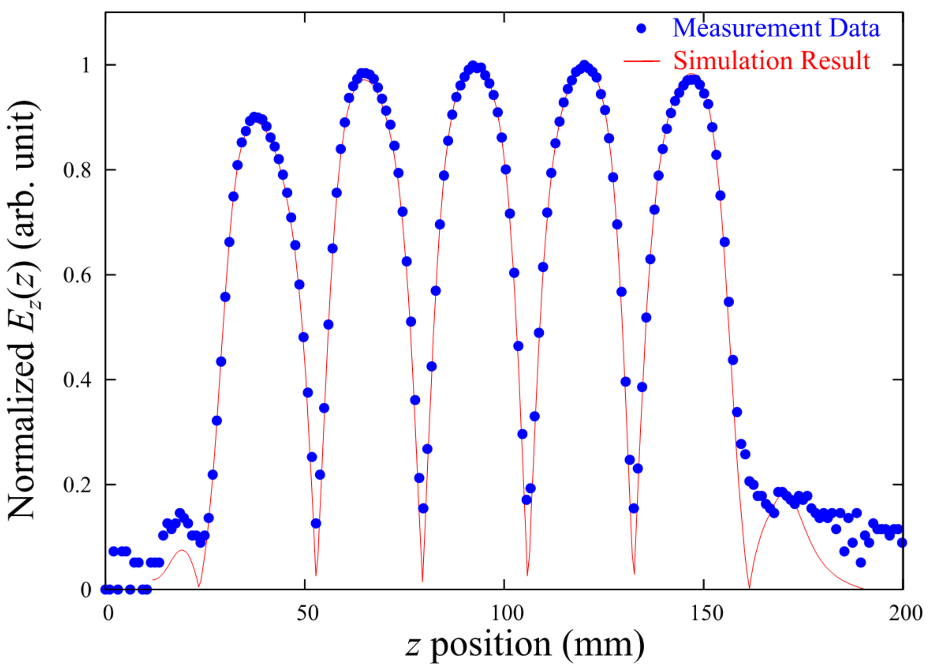
【Experimental Results[2]】



Parameters	Designed values	Measured values
f_0 (GHz)	5.7120	**5.71192**
Q_0	125,000	**119,314**
Q_{ext}	48,803	46,246
Q_L	35,112	33,328
β	2.56	2.58

【E_{acc} field along beam axis[2]】



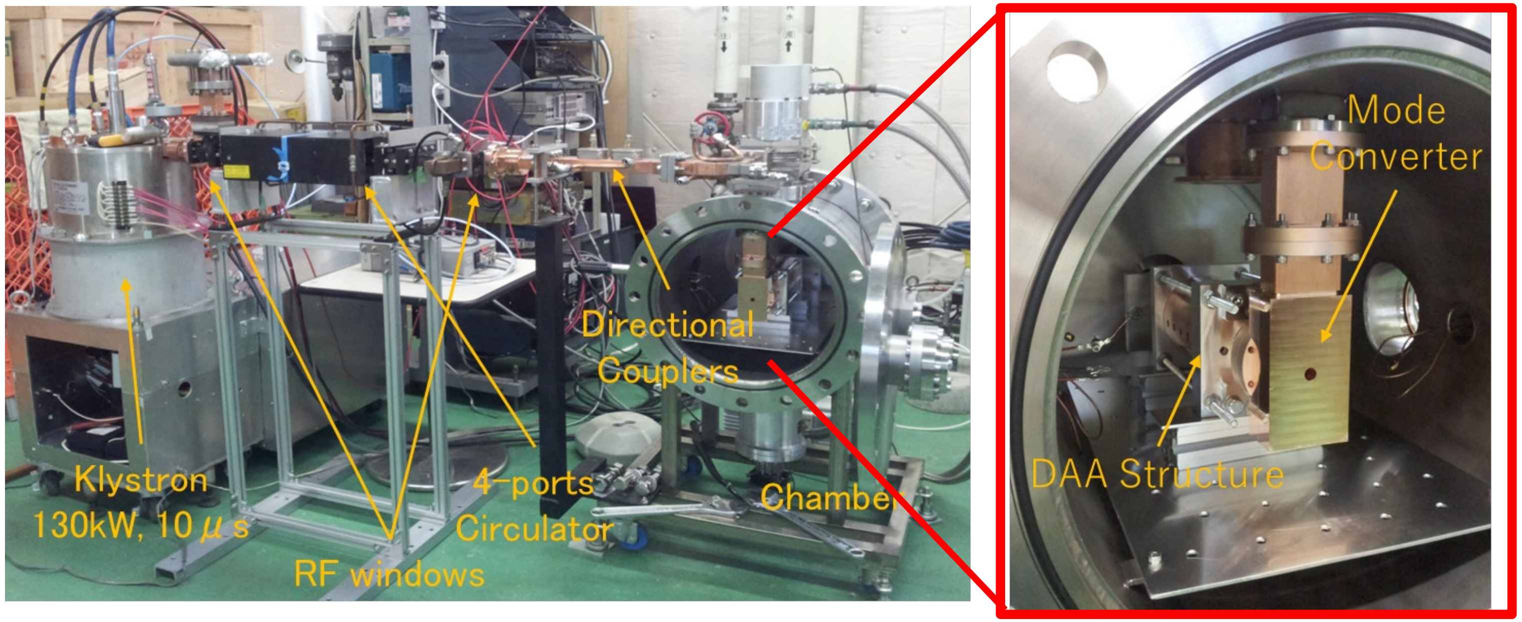
Z_{sh} = 617 MΩ/m

[2] D. Satoh, et. al., PRAB 20, 091302 (2017)

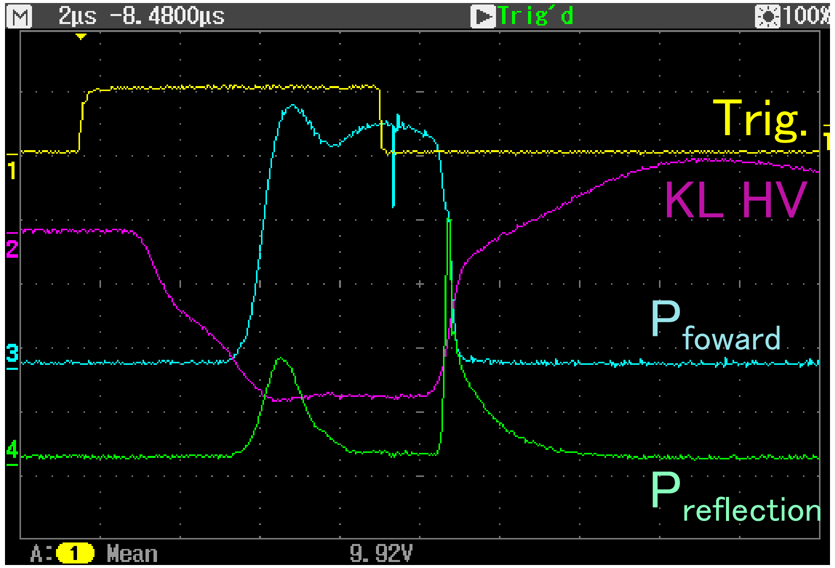
【 High power test of the prototype】

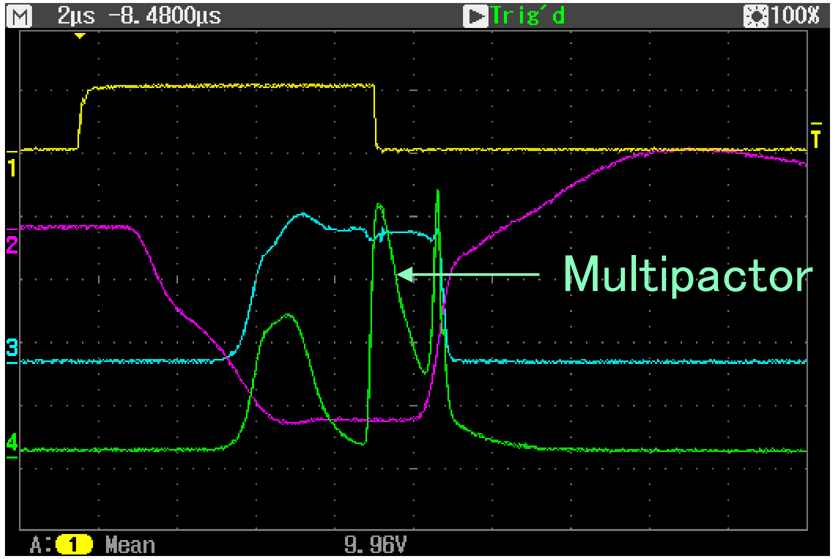
【Test stand @KEK】

High power tests were performed with pulse width of T_p = 2 – 7.5 μs.



【Results】





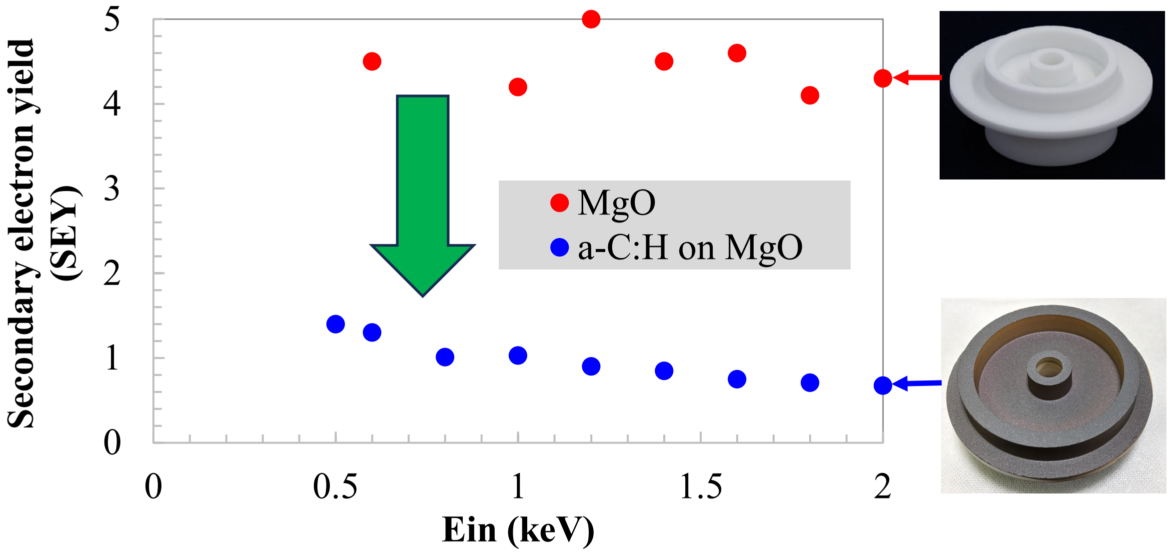
- $E_{acc,max}$ = 2 MV/m (@ T_p = 2 μs) achieved.
- But, it did not rise to any higher $E_{acc,max}$ after operating for more than 6×10^6 shots.
- The longer the pulse width, the slower the progress of cavity conditioning and the lower $E_{z,\ max}$ was.

【 Diamond like carbon coating on DAA】

DLC coating is known to reduce secondary electron yield while not increasing dielectric losses.

H. Xu et al., PRAB 22, 021002 (2019).

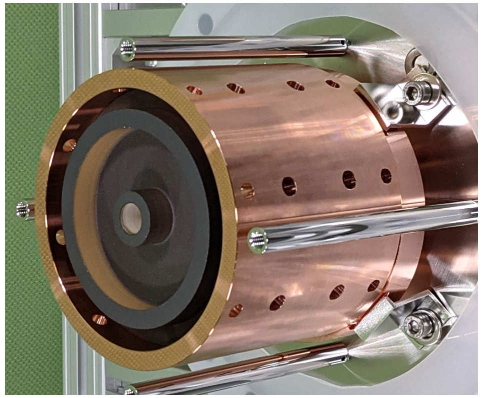
【Secondary electron yield of MgO and DLC surface】



Succeeded in significantly reducing SEY of MgO !

- $E_{acc,max}$ = 11 MV/m (@ T_p = 5.4 μs) achieved.[3]
- However, a large breakdown caused irreversible deterioration in accelerator performance.

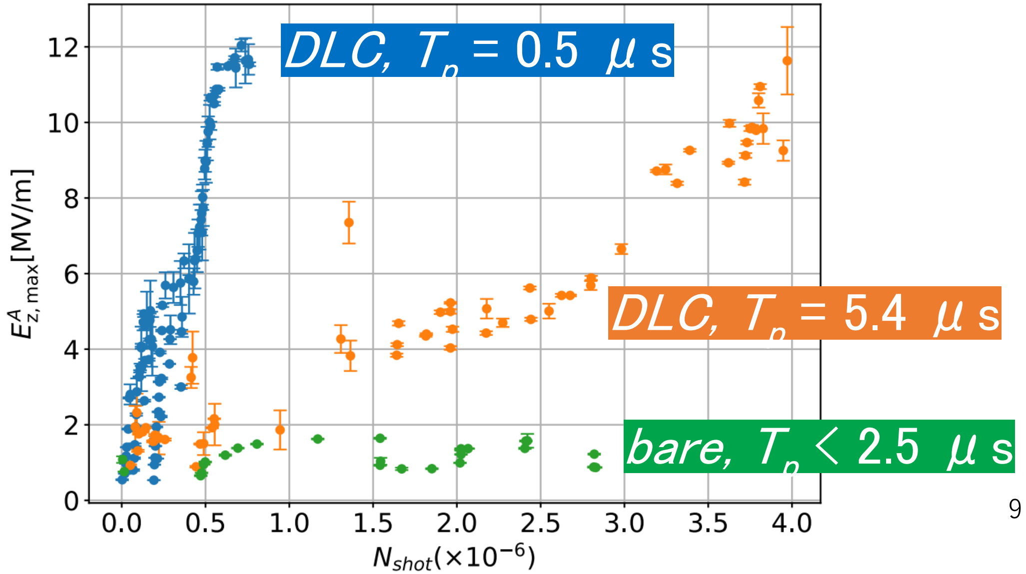
【DLC coated dielectric cell & DAA structure】



【Low power test[3]】
Q_0-uncoated : 112,000
Q_0-DLC(a-C:H) : 113,000

Maintaining a high Q_0 value !

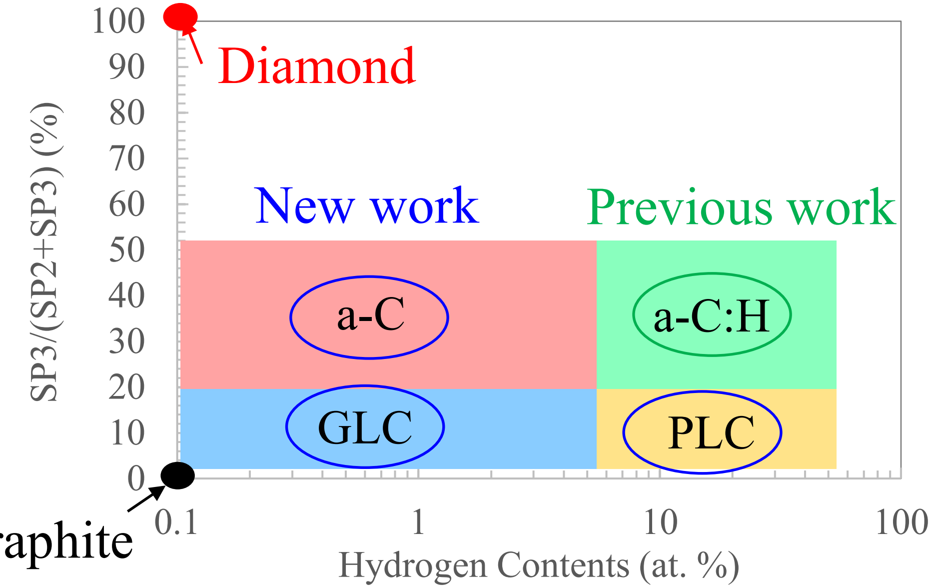
【High power test of DLC-DAA structures[3]】



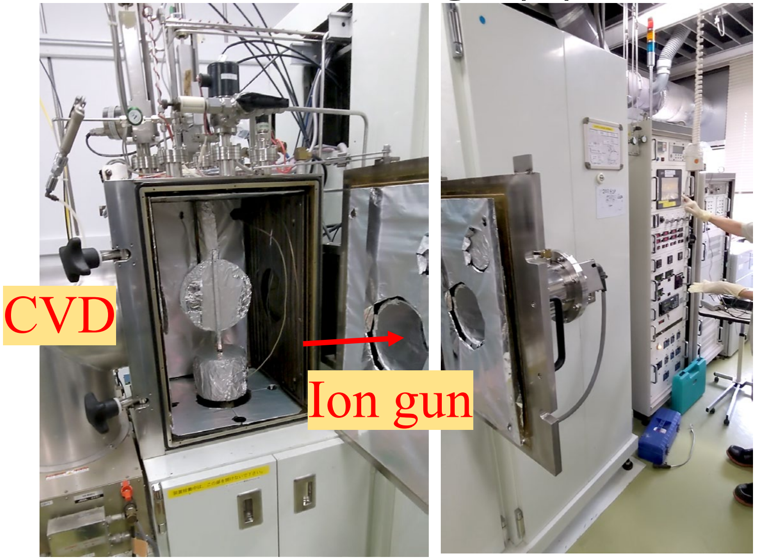
[3] S. Mori, M. Yoshida, D. Satoh, PRAB 24, 022001 (2021)

【Toward improving DAA performance】

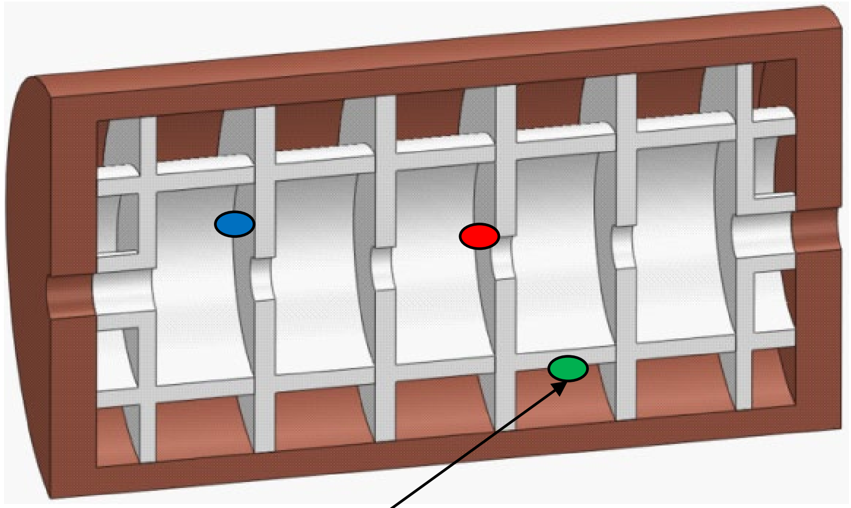
【Optimization of DLC coating】



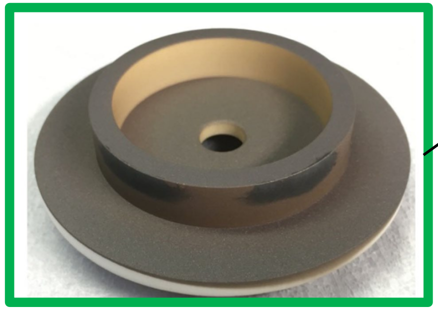
【DLC film forming equipment】



【Dielectric cells after high power tests】



Ref [3]



Discharge traces were observed on the edge and surface of the dielectric disk and on the outer wall surface of the dielectric coaxial structure.

A deep understanding of **discharge phenomena in these points of DAA structures** is important for higher gradient.

【X-band DAA @Nextef2】

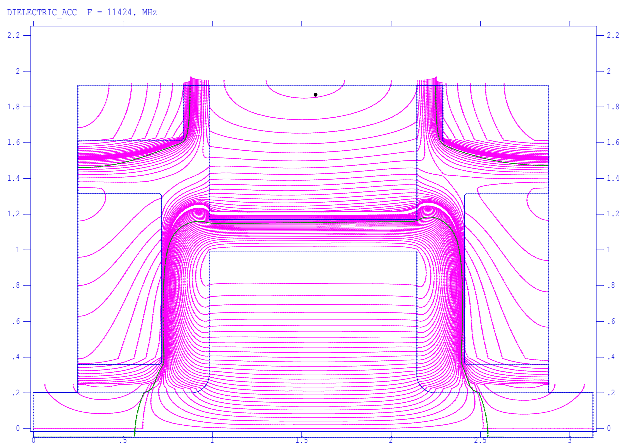
High gradient was realized by beam-driven and short pulse dielectric accelerators

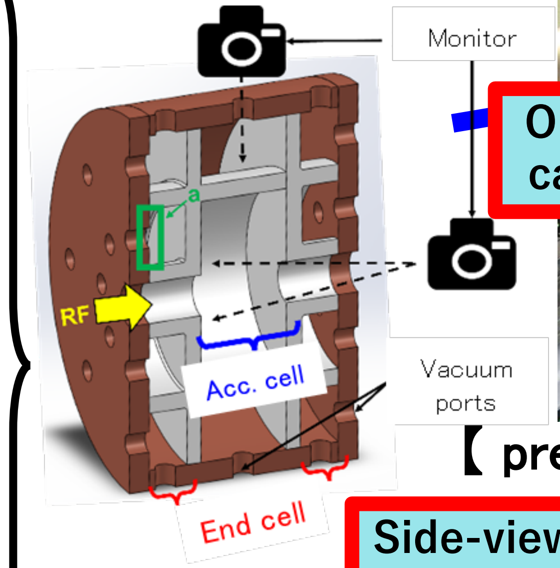
- ●320 MV/m@422GHz, – B.D. O' Shea et al., Nat. Comm. 7, 12763 (2016).
- ●102 MV/m@X-band, – B. Freemire et al., PHYS. REV. ACCEL. BEAMS 26, 071301 (2023).

⇐ **Very short pulse**

→ Short pulse excitation by X-band＋step pulse input → high Z_{sh} + high E_{acc}

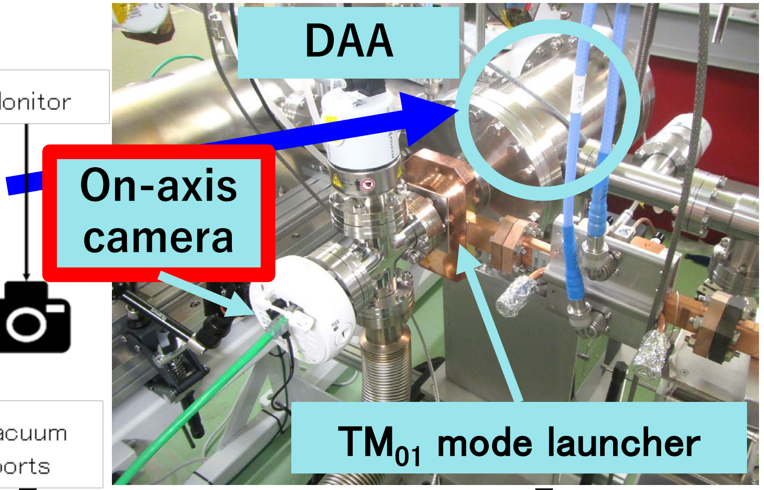
【 Single cell X-band DAA structure】



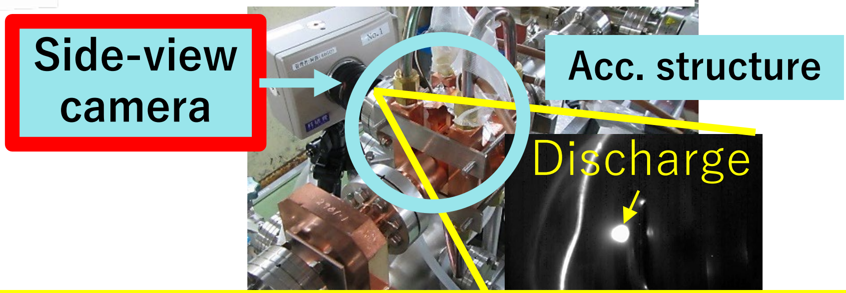


Parameters	MgO
ε_r	9.64
tan δ	6.0×10^{-6}
Frequency	11.424 GHz
Q_0	6.55×10^{5}
Z_{sh}	600 MΩ/m

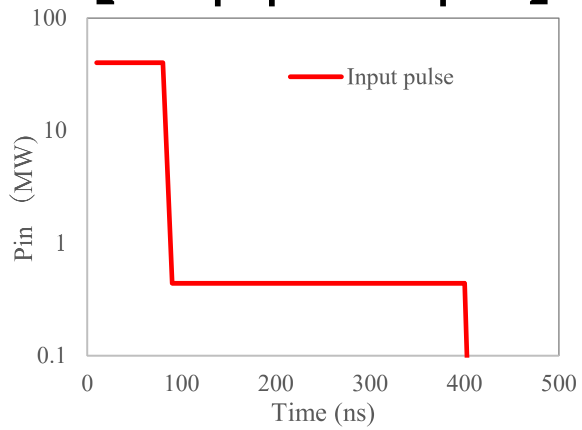
【 Nextef2/Shield-B@KEK】

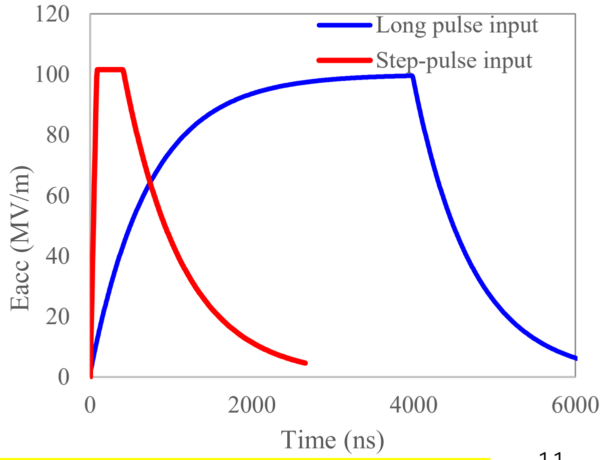


【 previous study @KEK】



【 Step-pulse input 】





- Observation of discharge occurring in DAA cavities from many point.
- Update of the internal structure based on the observation record to achieve higher gradient.

【 Summary】

- We proposed the DAA structure and have been performed a proof-of-principle study.
- The DLC coating lowerers the SEY of MgO cells while maintaining a low tanδ. → $E_{acc,max}$ = 11 MV/m (@ T_p = 5.4 μs)
- It is important to understand in detail where and what causes the discharge in the DAA structures in order to further increase the Eacc.
- A new research program is currently underway to develop an X-band DAA structures (2023); short pulse excitation of the DAA structures with step-pulse input and monitoring of the discharge inside the cavity is planned for April 2024.

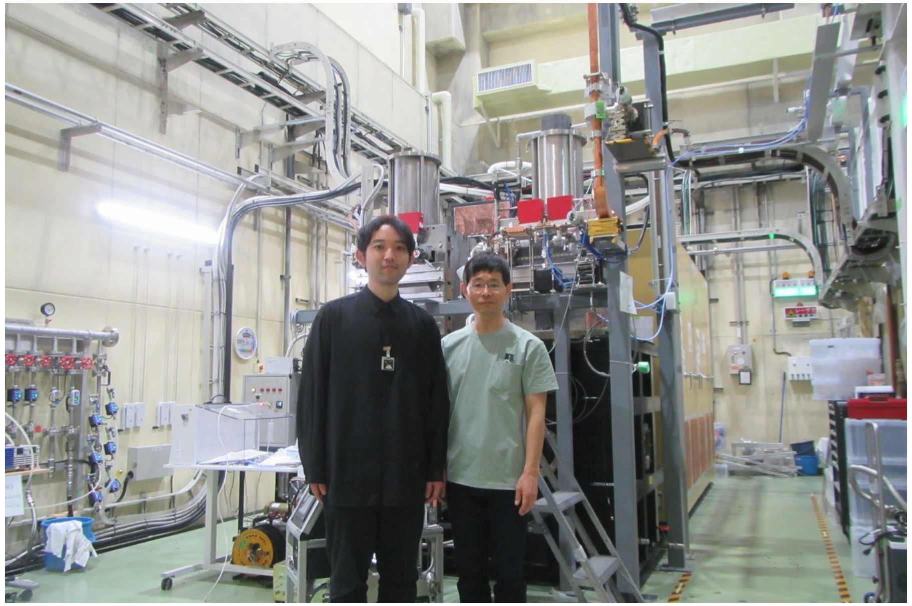
【Special Thanks】

N. Hayashizaki (Tokyo Thech.), S. Mori, Y. Yamamoto, M. Yoshida, T. Natsui, N. Toge (KEK), S. Miura, N. Shigeoka (MHI), H. Ogawa, Y. Hakuta, H. Mano(AIST)

【Acknowledgment】

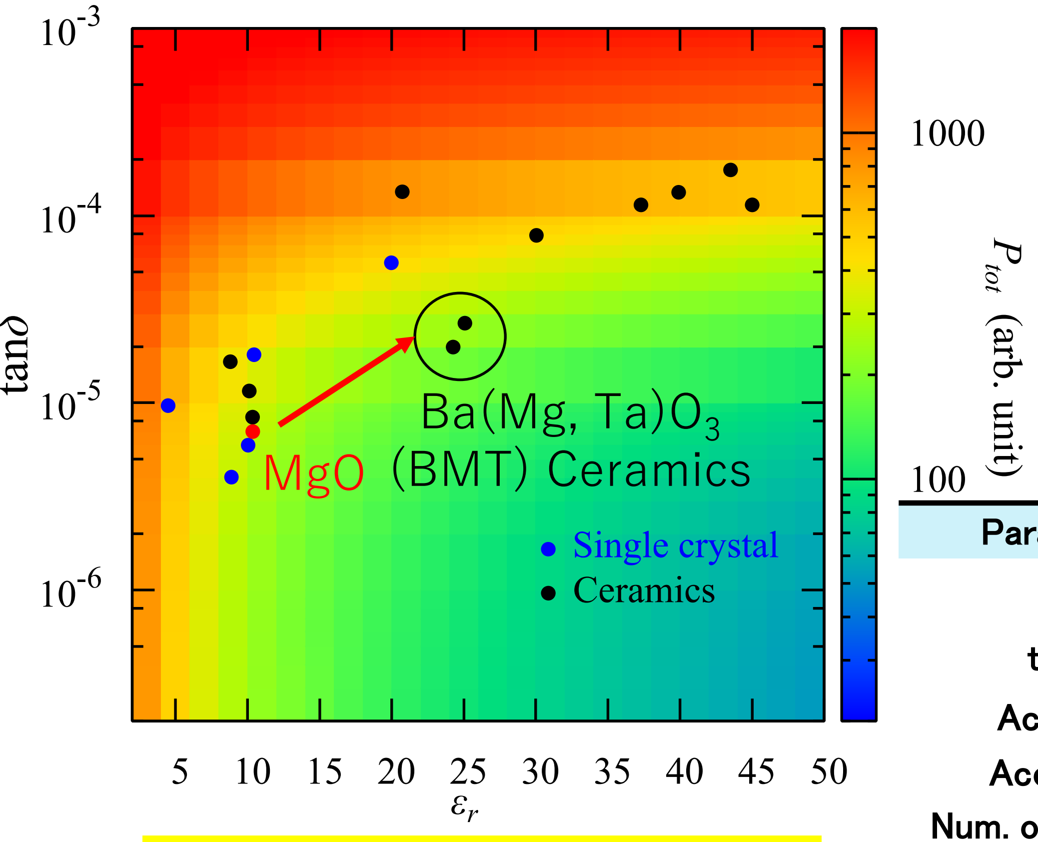
This work has been supported by【MEXT Development of key element technologies to improve the performance of future accelerators Program】Japan Grant Number JPMXP1423812204 and Grant in Aid for JSPS Fellows Grant No. 13J08681, 16H02134, 19K20609 and 22684010, .

Thank you for your attention.

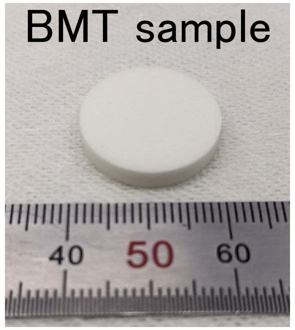


【 Improvement of the power efficiency】

【 Optimum dielectric material selection】



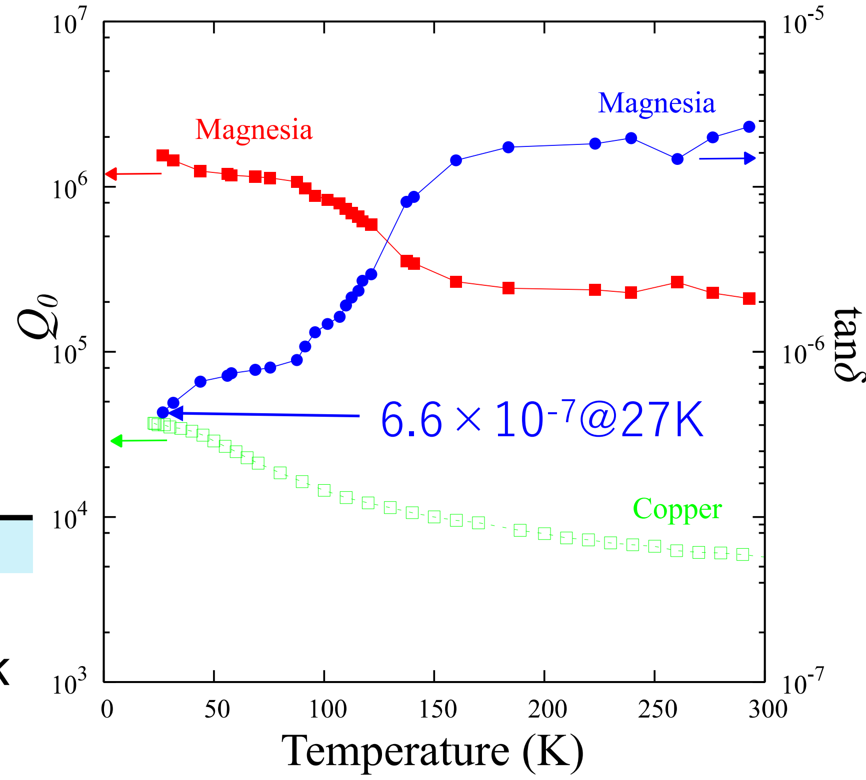
Shunt impedance can be improved by **38%** compared to the prototype.



Under development

Parameters	BMT	MgO
ε_r	24.2	9.64
tan δ	2.5×10^{-5}	6.6×10^{-7}@27K
Acc. type	Standing wave type	
Acc. Mode	$TM_{02}-\pi$ mode	
Num. of Acc. cells	5	
Frequency	5.712 GHz	5.712 GHz
Temperature	20 ℃	27 Kelvin
Q_0	121,200	7.65×10^6
Z_{sh}	870 MΩ/m	3.8 GΩ/m

【cooling】



The cryogenic temperature operating DAA structure is expected to have **6 times higher Q_0 and Z_{sh}** than that of RT operating DAA prototype.

[4] D. Satoh et al., Nucl. Instrum. Methods Phys. Res. B, 459, 148 (2019).