X-band dielectric assist accelerating structure

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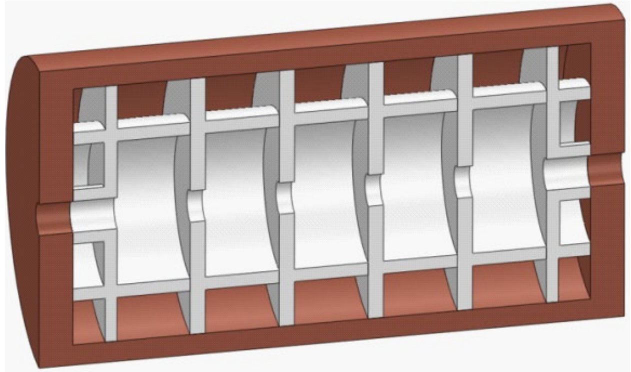
【Outline】

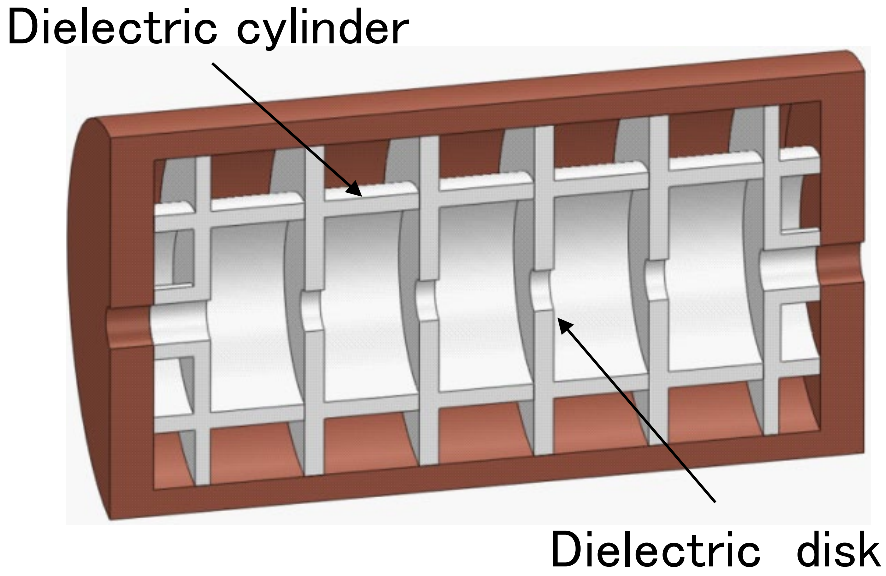
- Operation principle of DAA structure
- Current issues and initiatives
- Design, fabrication, and cold test of X-band DAA structure
- High power test (2024/6/25 ～)
- Summary & Research plan

Dielectric assist accelerating structure, DAA



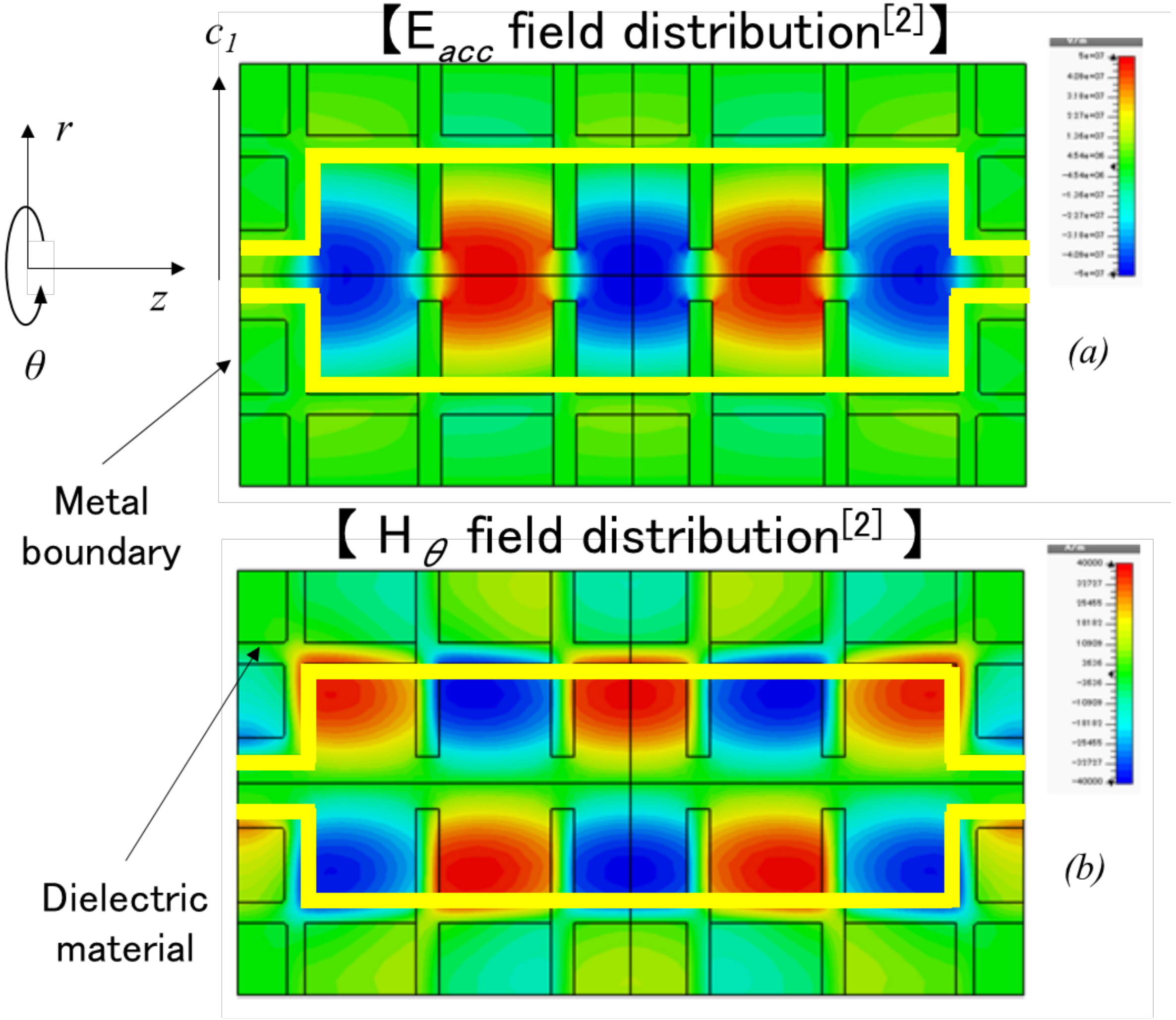
【 Dielectric assist accelerating (DAA) structure】

【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

【 Current issues and initiatives】

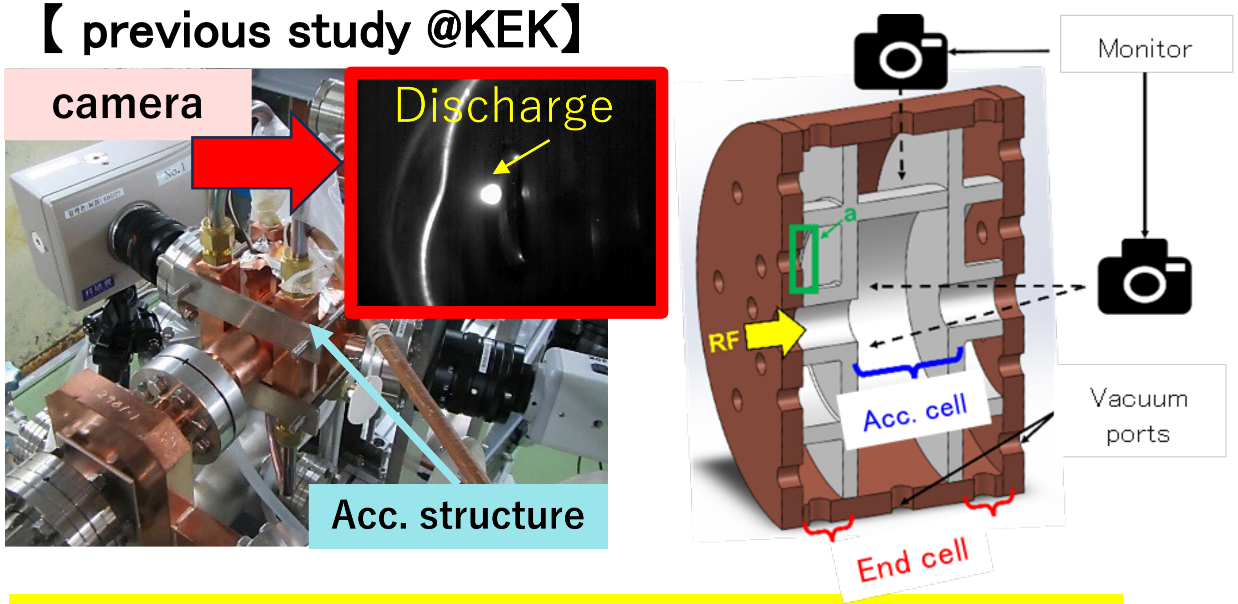
◎ High shunt impedance Z_{sh} ~ **600 MΩ/m**@5.712 GHz was realized.

× $E_{acc,max}$ ~ **11 MV/m** @DLC-coating MgO cells is limited by multipactor and discharge.

Toward higher gradient DAA structure

【 (i) Understanding discharge phenomena 】

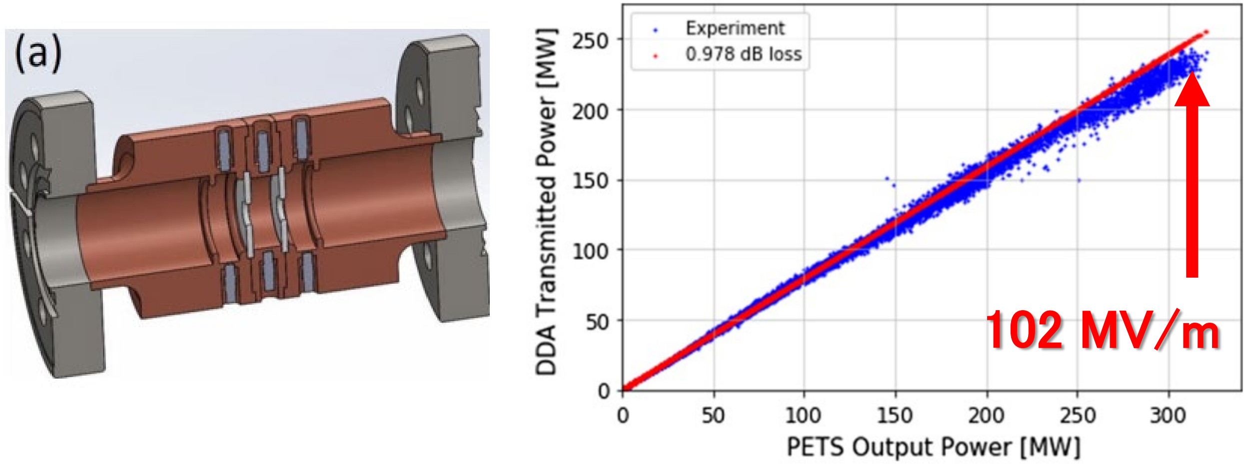
【 previous study @KEK】



- Observation of discharge phenomena in DAA structures using (high-speed and Hyperspectral) cameras.
- Update of the internal structure based on the estimation of discharge locations and causes to achieve higher gradient.

【(ii) Short pulse excitation 】

High gradient was realized by short pulse dielectric disk accelerating structure.



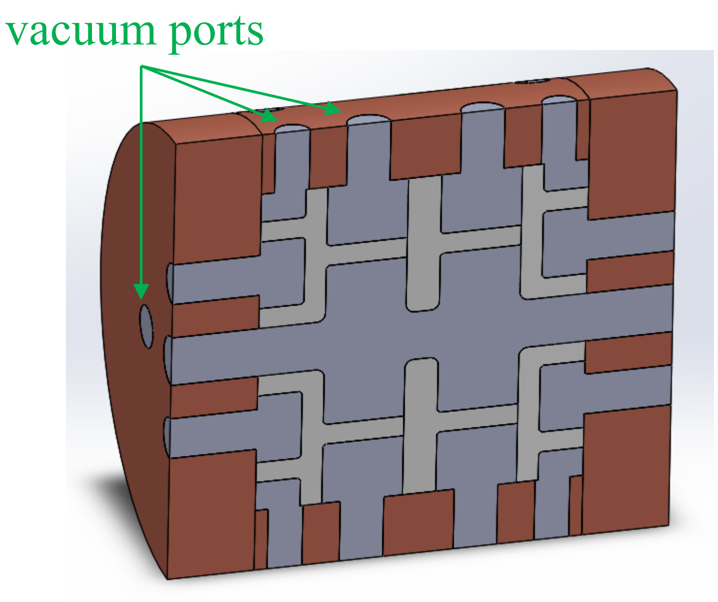
[3] B. Freemire et al., PHYS. REV. ACCEL. BEAMS 26, 071301 (2023)

Verify whether higher E_{acc} excitation is possible by inputting RF pulses shorter than the filling time.

【RF Design of X-band DAA structure】

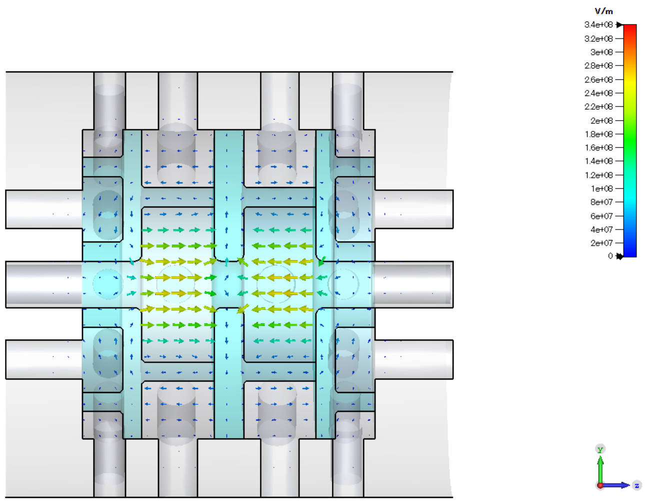
- Optimize the structure for high E_{acc} by deepening **the physical understanding of vacuum discharge** in DAA structures.
- We considered a DAA#X1 in which all closed regions within the DAA structure can be optically observed from the outside.

【Basic structure of DAA#X1】



- DAA#X1 is a 2-cell DAA structure.
- The DAA#x1 was designed to be introduced into the chamber.
- Many holes works as vacuum ports and observation ports

【Simulation results】



Dielectric material	SC - Sapphire
$\varepsilon_{\perp}$ / $\varepsilon_{//}$	9.395 / 11.586
$\tan\delta_{\perp}/\tan\delta_{//}$	1.6×10^{-5} / 3.0×10^{-5}
f_0	11.424 GHz
Q_0	59,000
Z_{sh}	400 MΩ/m

【 Fabrication and cold test of DAA#X1】

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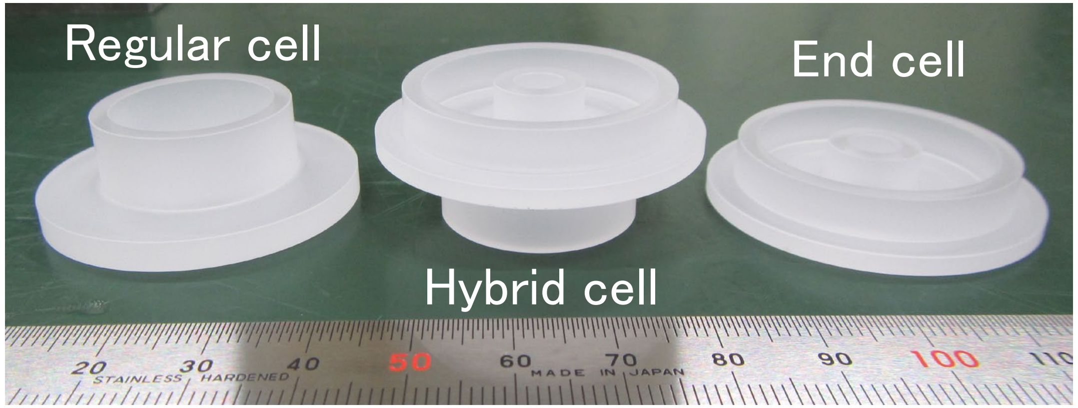
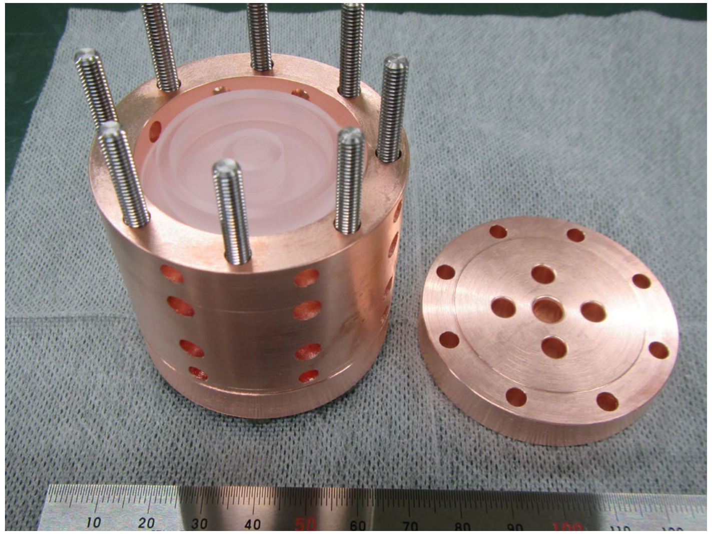
【Dielectric cells】

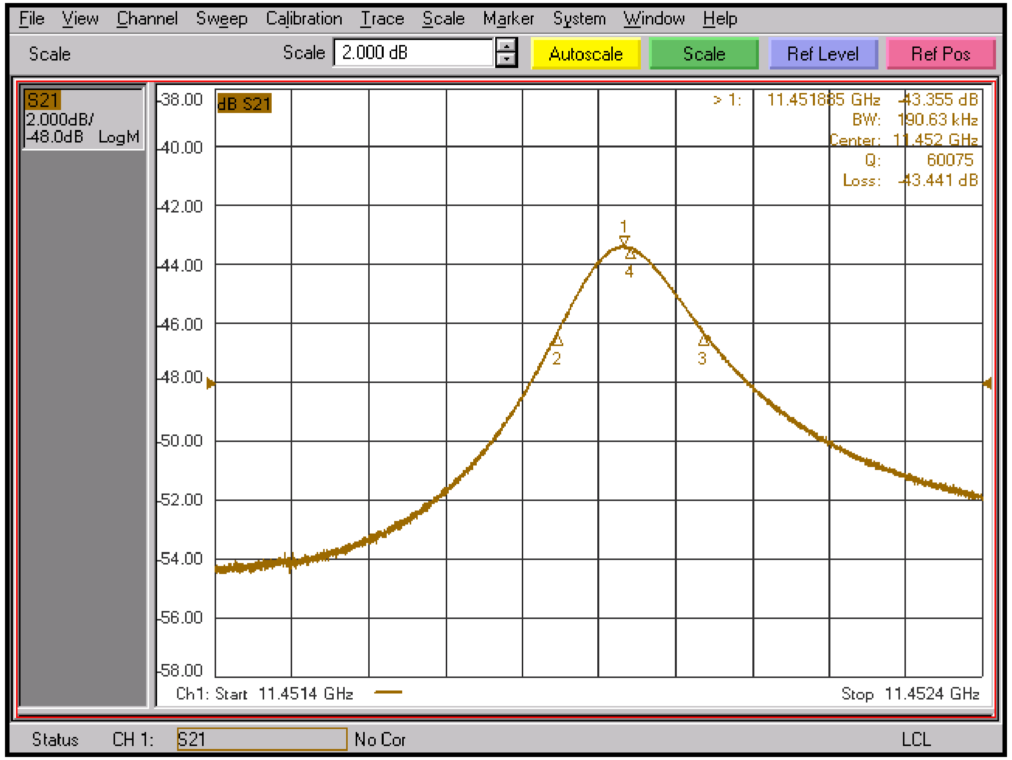


The tolerance of the dielectric cell was set to finish at a higher frequency than 11.424 GHz for frequency tuning.

【Assembled DAA#X1】



【Results of low power test @ DAA#X1】



Parameters	Simulation Results	Measured Results
f_0	11.4526 GHz	11.4519 GHz
Q_0	59,000	60,000

【 Fabrication and cold test of DAA#X1】

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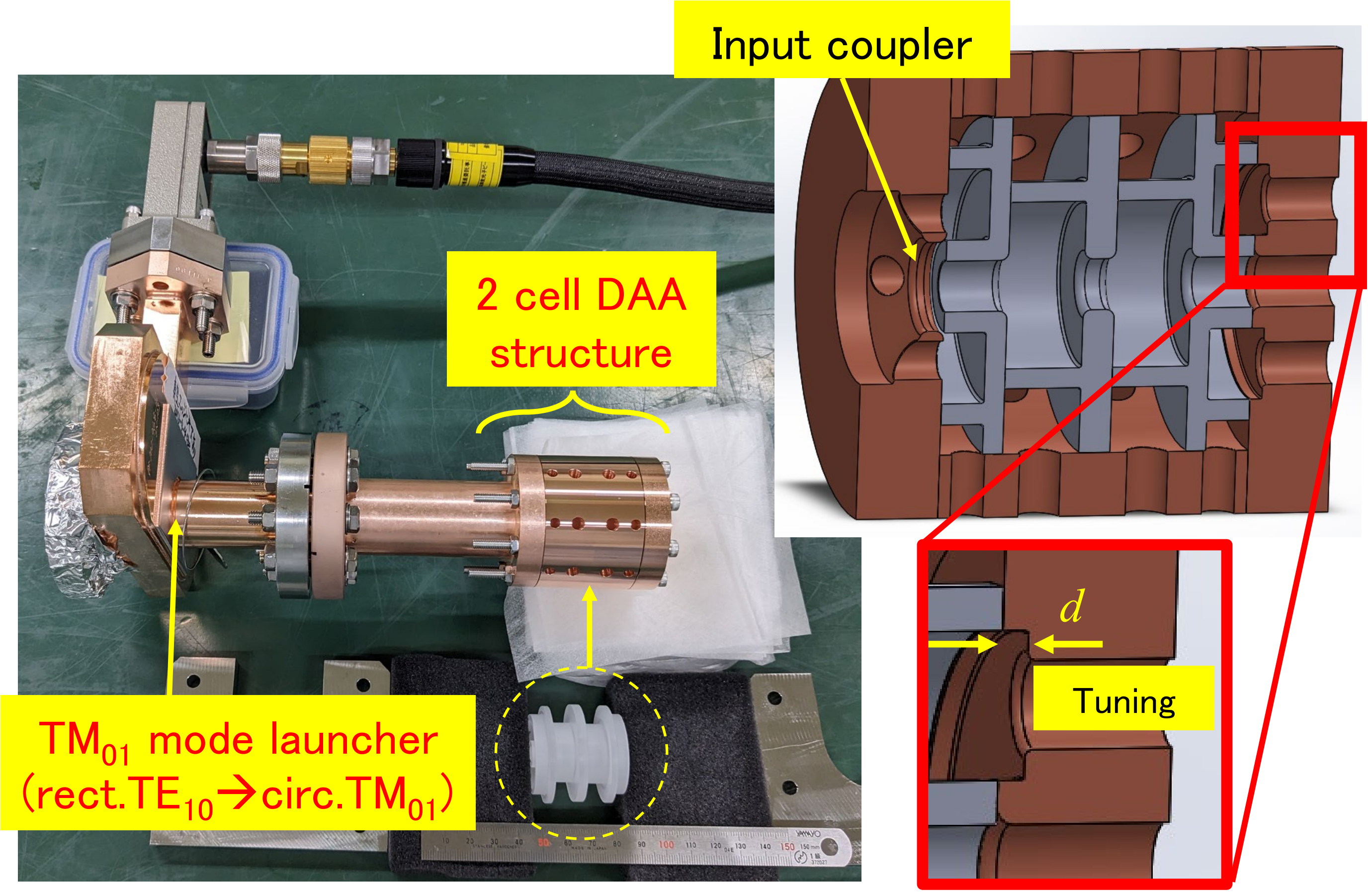
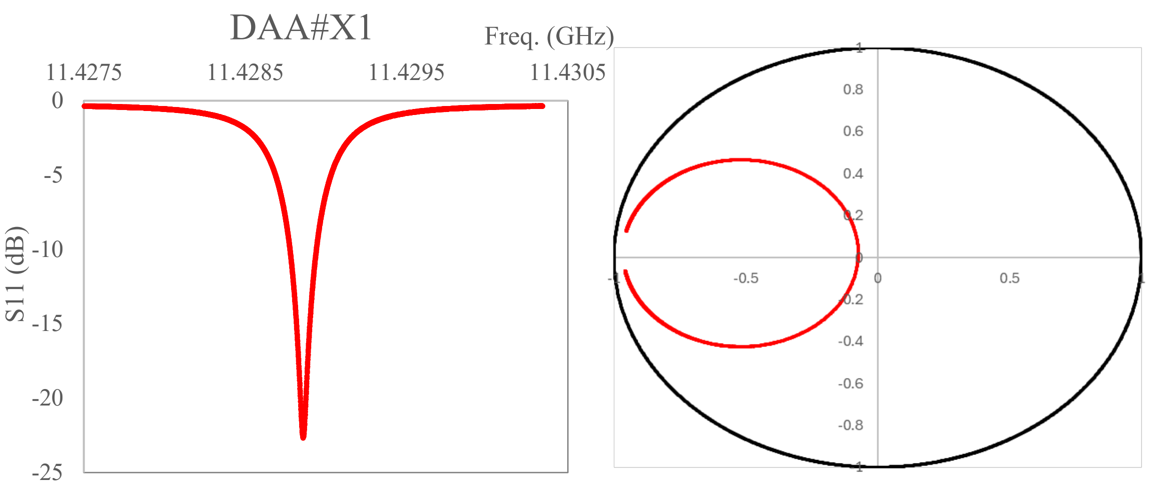
【Coupler feed Assembly】



【Results of low power test @ DAA#X1】



Parameters	Measured Results
f_0	11.4289 GHz
Q_0	**43,046**
Q_{ext}	50,971

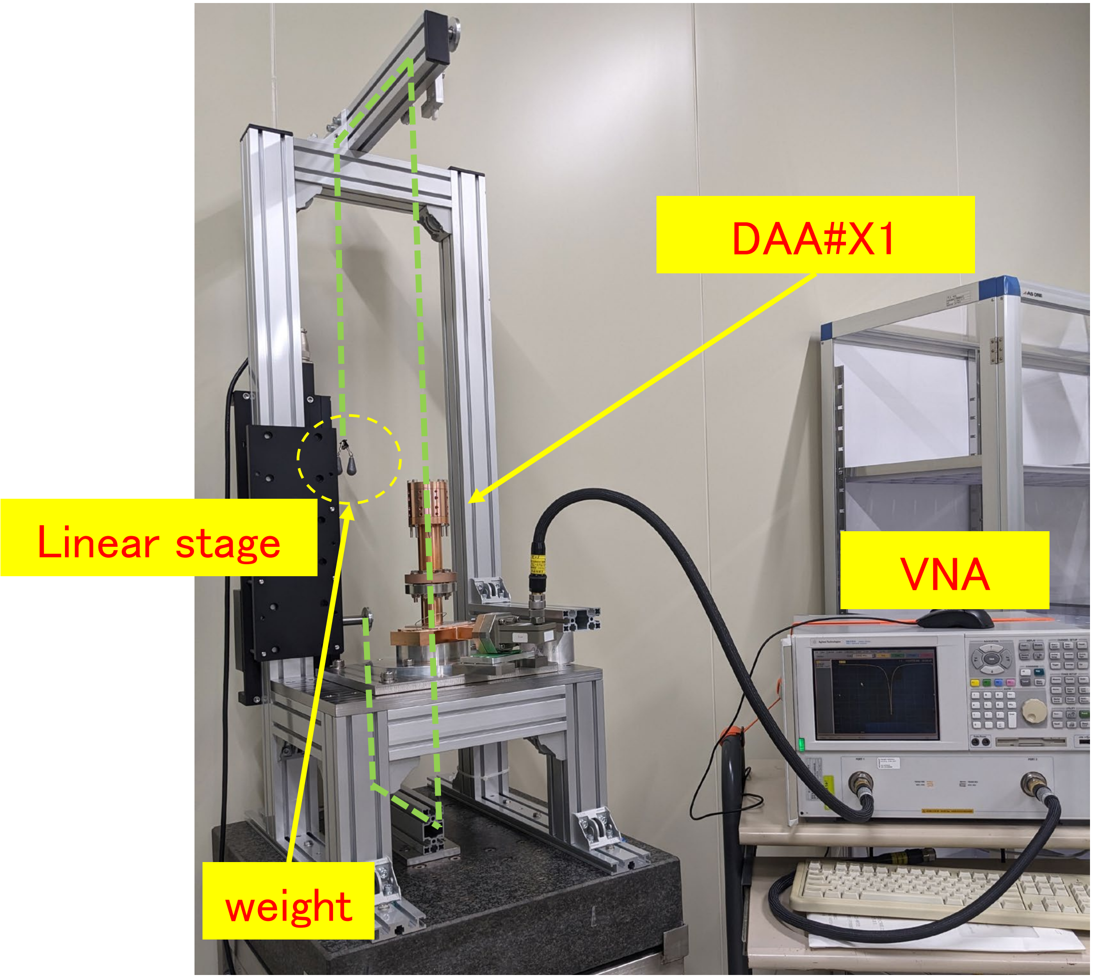
- DAA#X1 couples with the TM_{01} mode of the circular waveguide on the axis.
- The f_0 was tuned by removing a portion (d) of the copper end plate.

The distribution of the EM field changed due to the alteration of the end plate shape, leading to an increase in conductor loss and a decrease in Q_0.

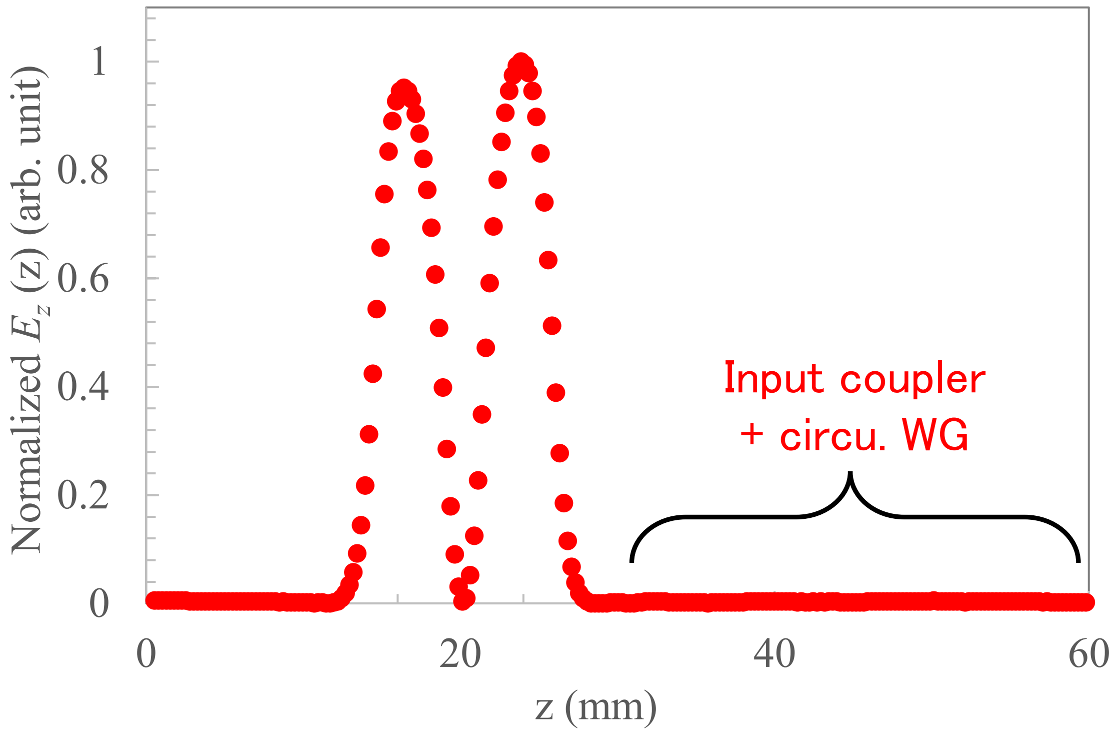
Under investigation

【 Bead pulling measurement of DAA#X1】

【Bead pulling measurement】



【E_{acc} field along beam axis】

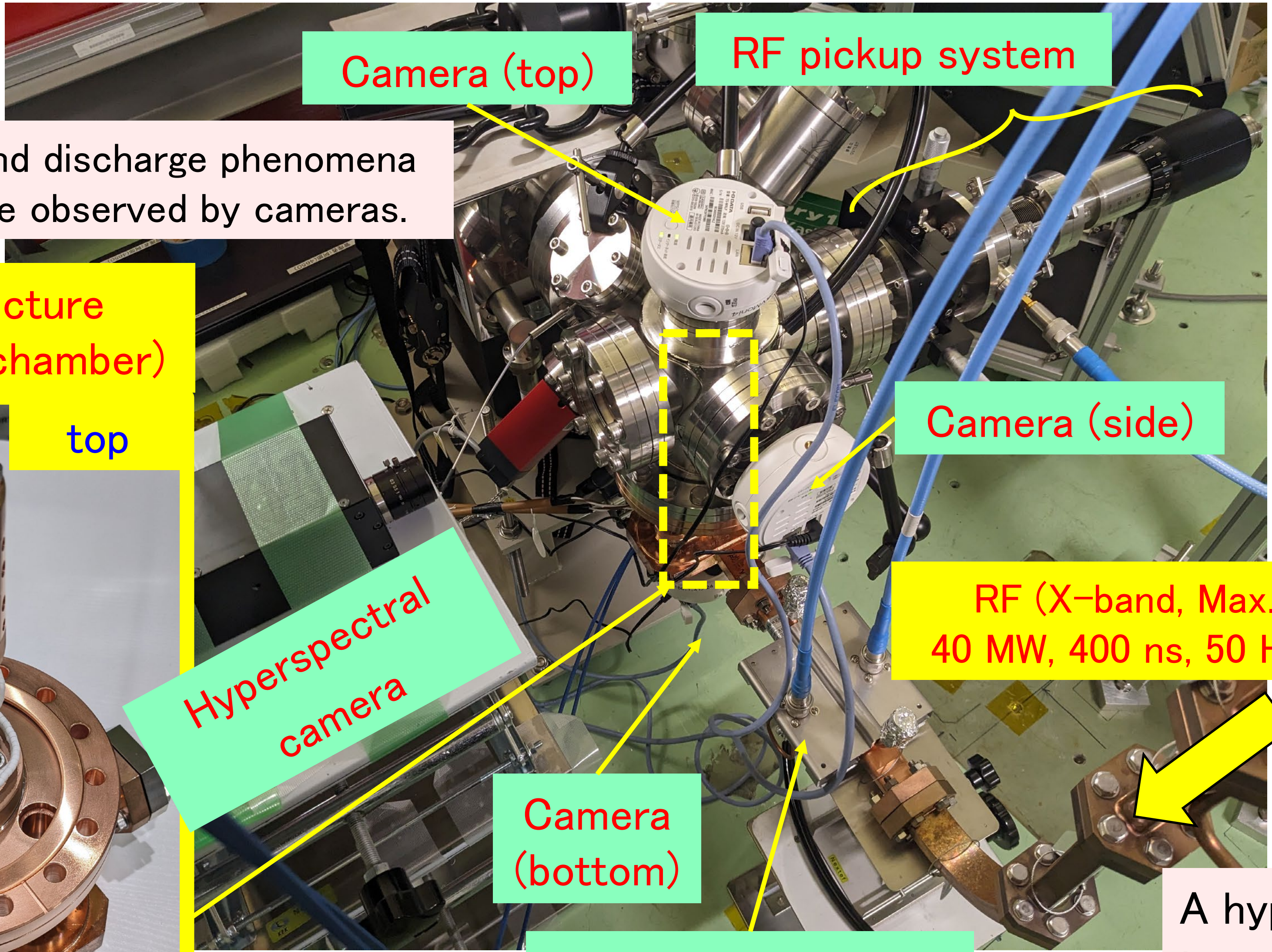


We confirmed that this particular resonance is in acceleration mode by employing bead-pulling measurement.

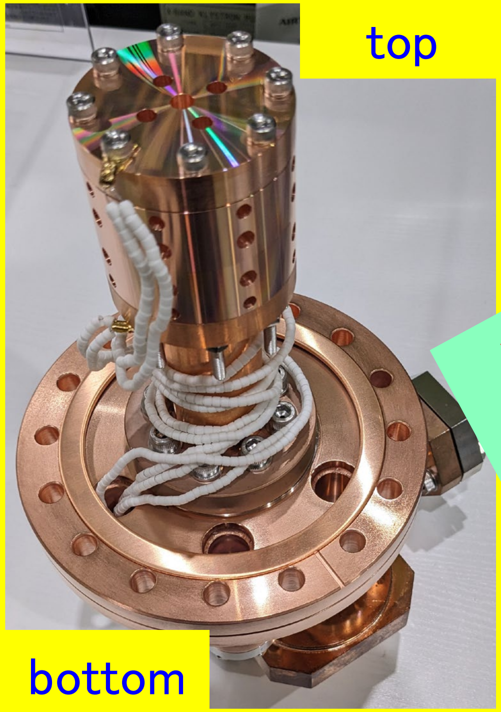
【 Setup for the high-power test in Nextef2/Shield-B】

【Setup in Nextef2/Shield-B 】

Multipactor and discharge phenomena in DAA#X1 are observed by cameras.

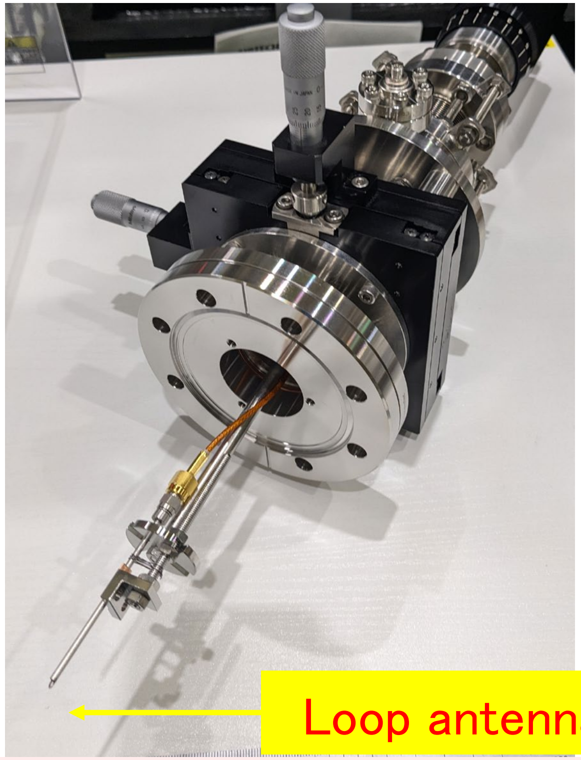


DAA structure (in vacuum chamber)



A hyperspectral camera are used to measure emission spectra.

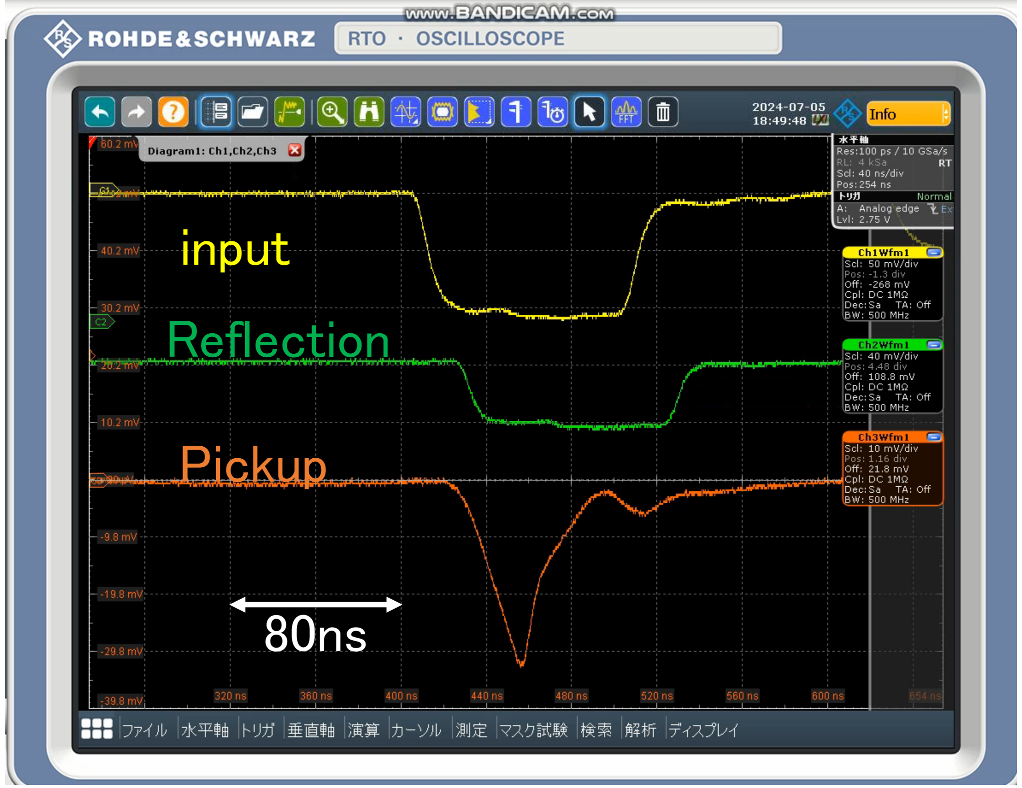
【RF pickup system】



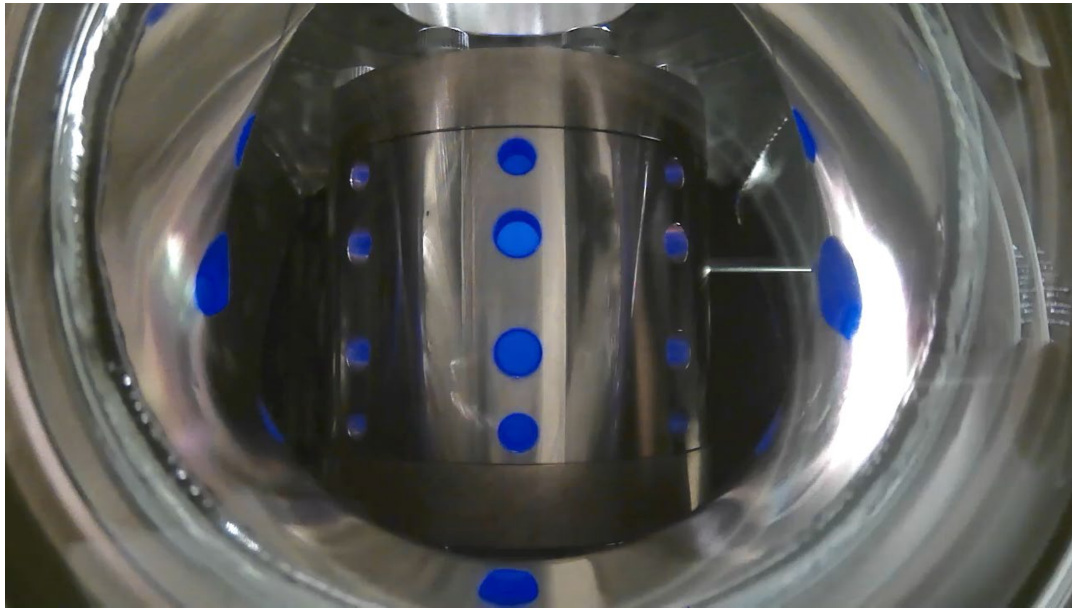
E_{acc} is measured using a loop antenna from the side holes.

【High-power (HP) test in Nextef2@KEK　:　6/25 ～】

【Result : Pin = 90 kW, 100 ns, 5 Hz】



【Side view of DAA#X1】

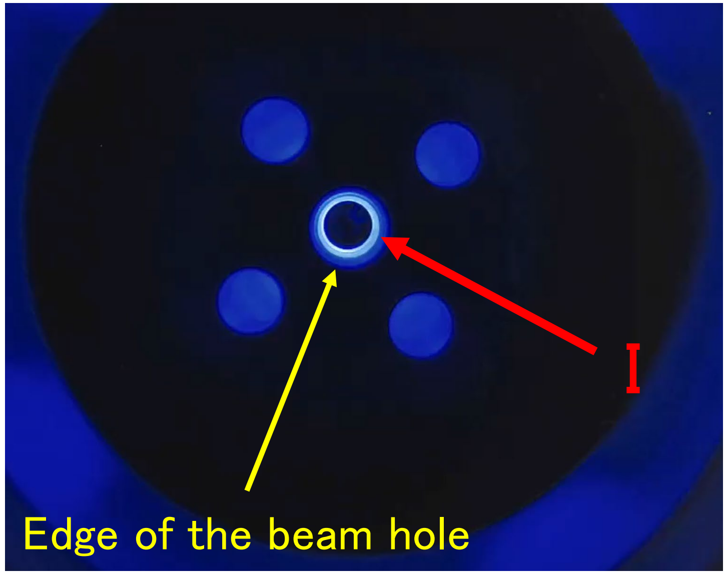


The color CMOS cameras detected blue luminescence.

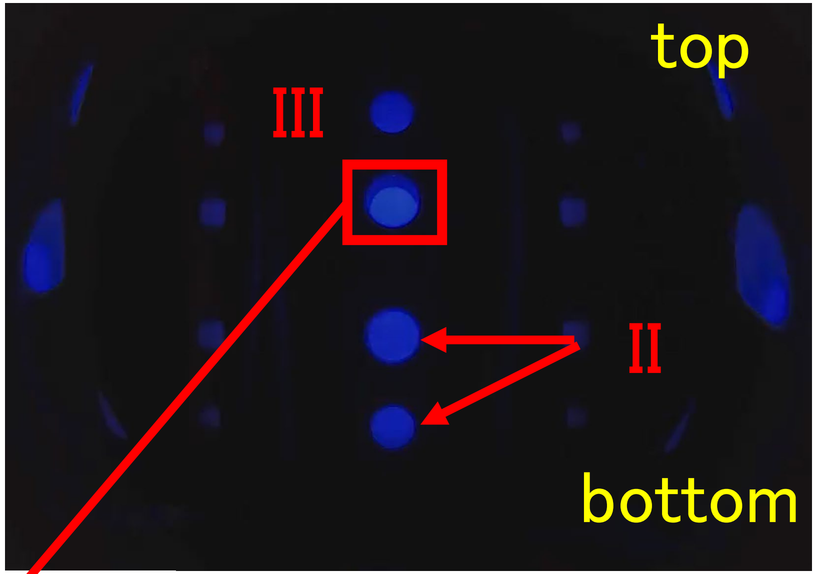
- The E_{acc} in DAA#X1 was unstable even with input power of a few kW.
- The time constant for E_{acc} bildup and decay are much shorter than the filling time of DAA#X1.
  → multipactor or discharge may be occurring in the DAA#X1.
- The E_{acc} is still limited at about a few MV/m (2024/07/07).
  * This trend is similar to the results for the prototype of DAA@C-band without DLC coating.

【Luminescence in DAA#X1 : 0.6 MW, 200 ns, 50 Hz】

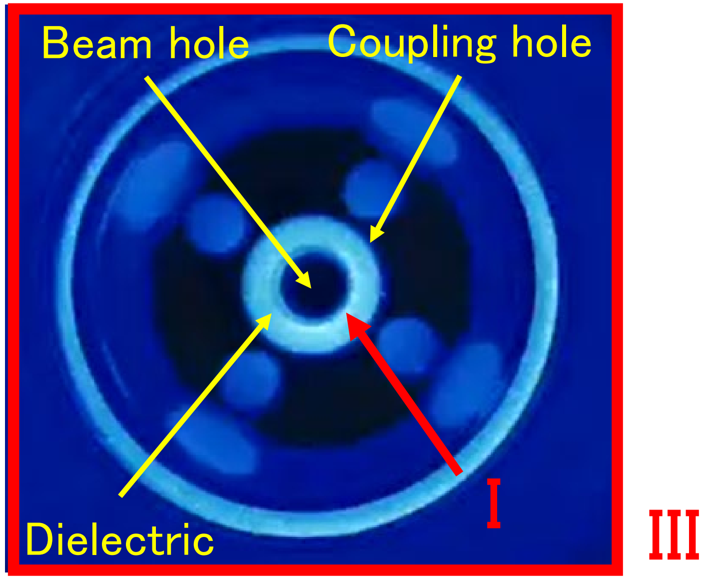
【top】



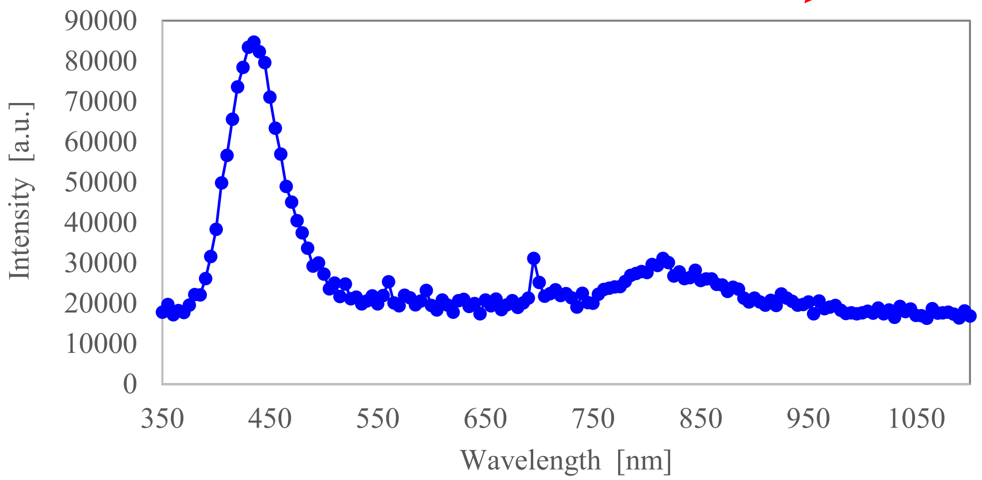
【side】



【bottom : coupler】



Spectrum (integrated in III)



I. **Significant luminescence** was observed **slightly inside the beam holes** as the input power increased.

II. The luminescence intensity observed from the side hole is much lower than that from the center area.

III. A hyperspectral camera measured the luminescence spectrum from the vacuum holes (side and bottom), confirming **a main peak at a wavelength of 435 nm**.

【Discussion : Luminescence in DAA#X1 】

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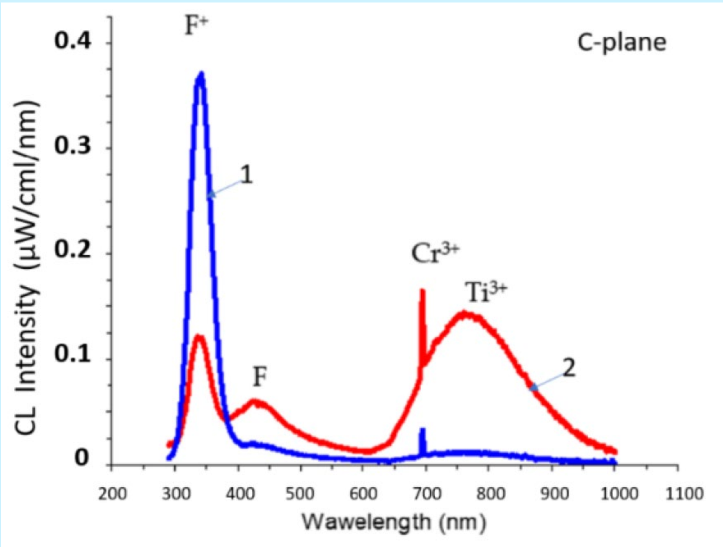
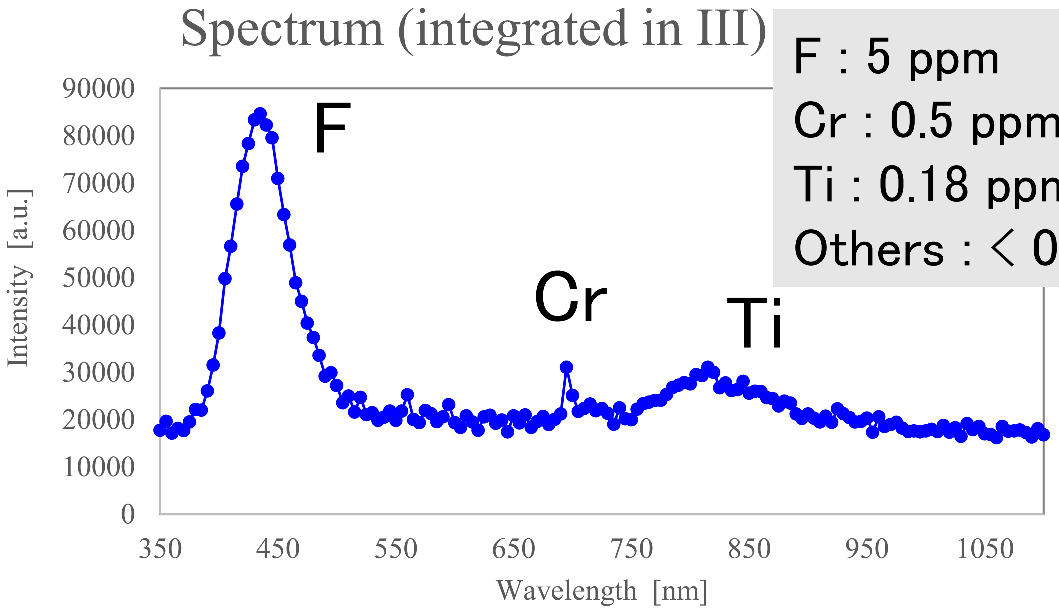
Cathodoluminescence spectrum of sapphire

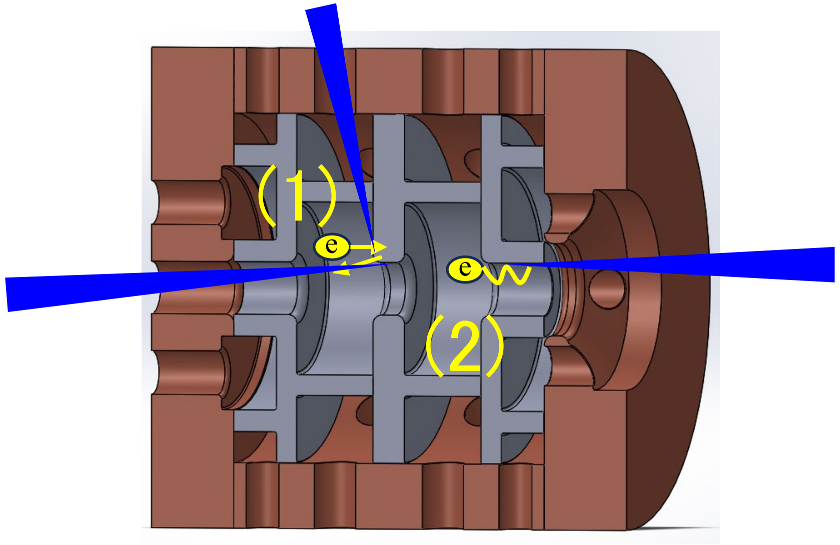


[4] A. Muslimov and V. Kanevsky, Materials 2022, 15, 1332

Impurities of DAA#X1 sapphire



F : 5 ppm
Cr : 0.5 ppm
Ti : 0.18 ppm
Others : < 0.1 ～0.05 ppm



- The representative peak wavelengths of the luminescence from the DAA#x1 was match to that of **the cathodoluminescence spectrum in sapphire.**
- It is most likely that the luminescence is caused by impurities in the sapphire due to **electron impact by multipactors**.
- Multipactors may be occurring (1) between dielectric disks near the beam axis and (2) inner cylinder surface of end cell, etc… considering the luminescence intensity.

【 Summary 】

- To achieve a higher gradient in the DAA structure, high-power tests were initiated on June 25, 2024, to deepen our understanding of the physical phenomena within the DAA structure.
- During the high-power test, blue luminescence was detected by the color CMOS cameras. → **It is highly likely that this luminescence is caused by impurities in the sapphire due to electron impacts from multipactors.**
- Multipactors may be occurring between the dielectric disks near the beam axis and the inner cylinder surface of the end cell.

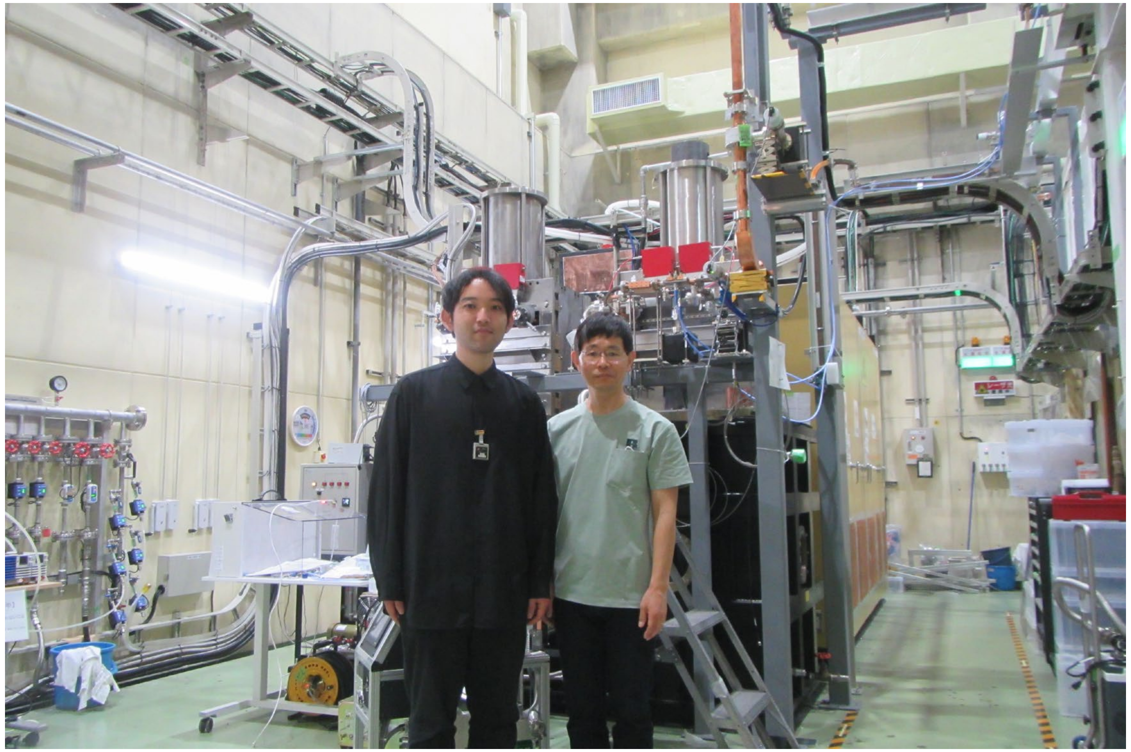
【 Research plan】

- High-power tests will continue to verify the conditioning effects of DAA structures and to measure temporal changes in discharge and multipactor phenomena.
- The locations of multipactors will be estimated in detail **by observing it from various angles**.
- Updates to the internal structure will be made based on these identified locations and causes of multipactor, with the aim of achieving a higher gradient.

【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.

Thank you for your attention.



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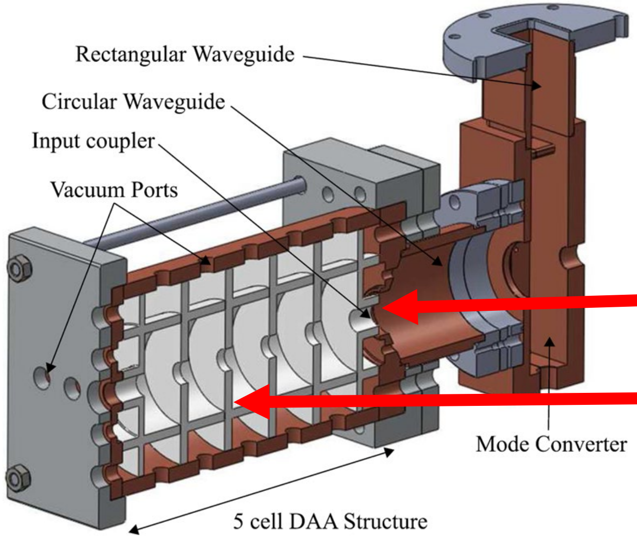
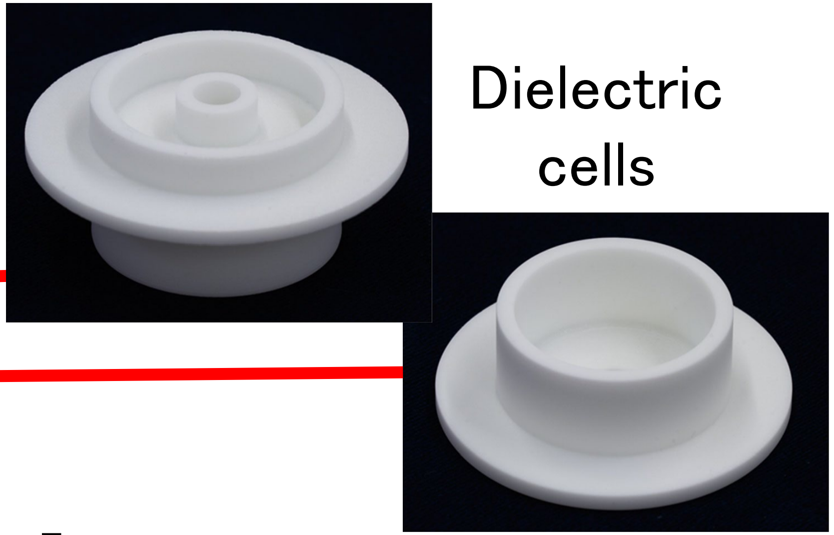
Additional slides

【 Accelerator performance of DAA structure[2]】

【Prototype : 5 cell C–band DAA structure】





Dielectric cells

【DAA structure assembly】

【Cavity parameters】

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

- **$Q_{0,\,proto} > 10^5$** @RT, C-band[2]
- **$Z_{sh,\,proto} > 600$ MΩ/m** @RT, C-band[2]

- $Z_{sh,\,proto}$ is **four times** higher than that of a NC accelerating structures !
- DAA structures have the potential to significantly increase the **electrical efficiency** of NC linacs, including LCs.

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

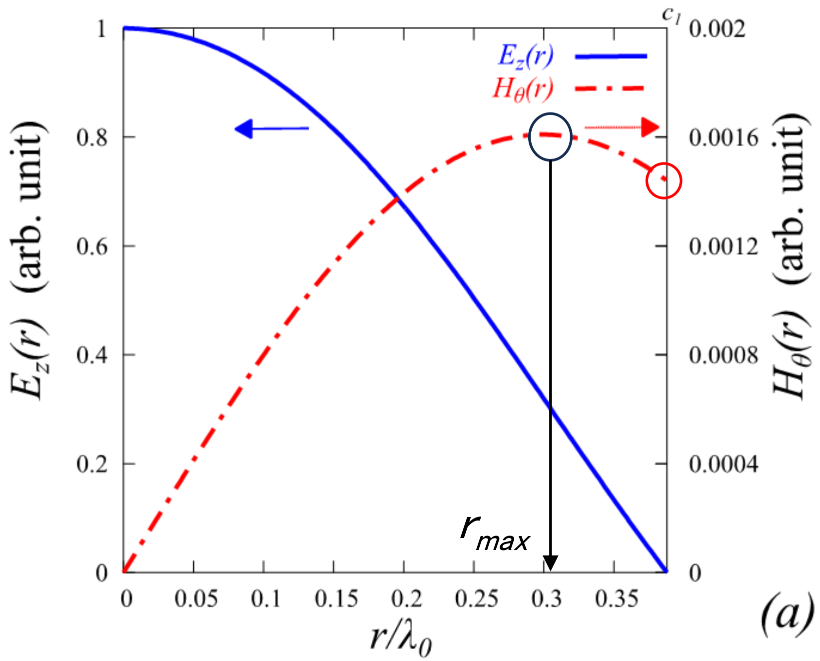
【 Mechanism of high−Q_0 】

Wall loss on a conducting cylinder: P_{wall}

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

* c_1: inner radius of conductive cylinder

【Pillbox cavity】



【Pillbox cavity】

$c_1 = 0.39\,\lambda_0$

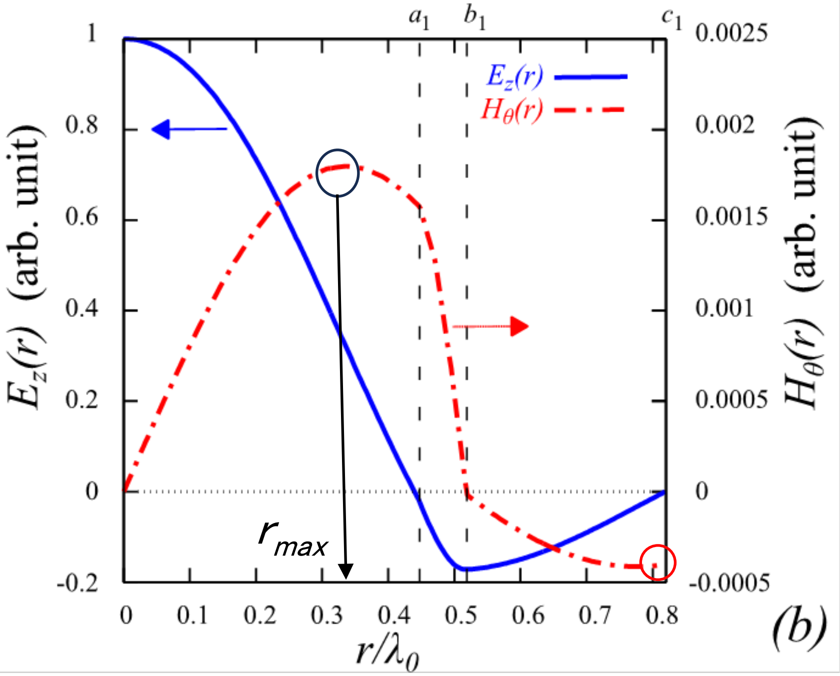
$$\frac{|H_\theta(c_1)|}{|H_\theta(r_{max})|} = 0.89$$

【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

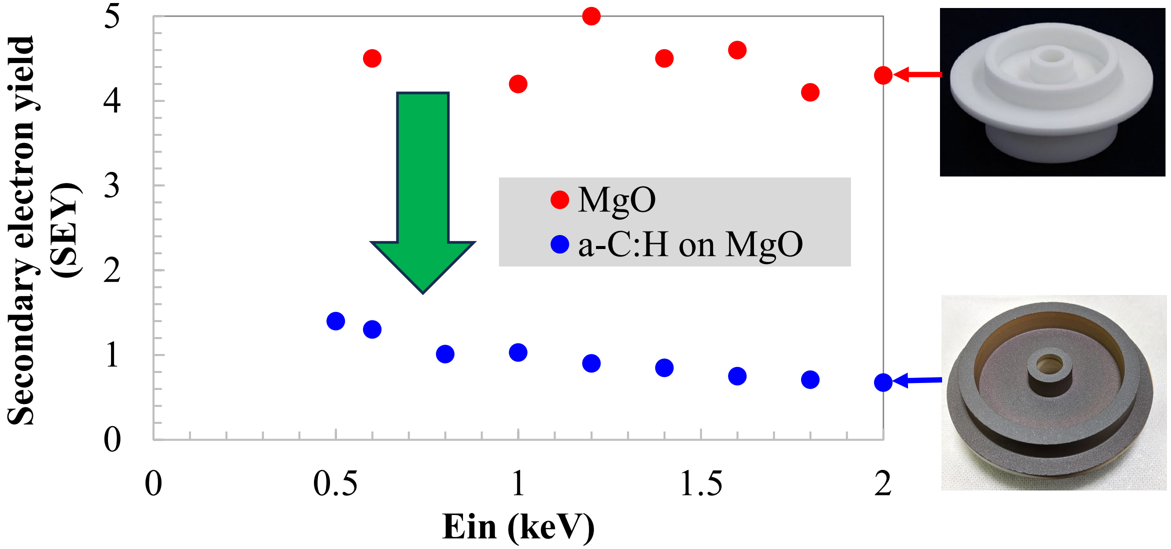
→ The wall loss on conducting cylinder is drastically reduced !

【 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).

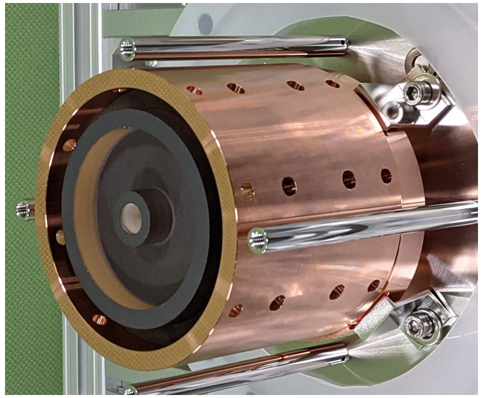
【Secondary electron yield of MgO and DLC surface】



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.

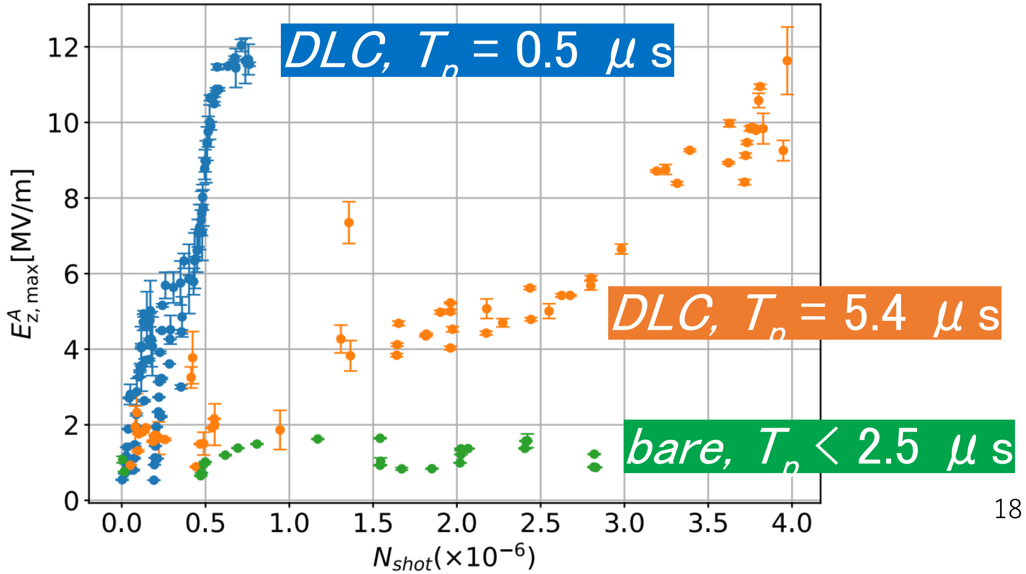
【DLC coated dielectric cell & DAA structure】



【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)