

LiteBIRD Polarization Modulator

Yuki Sakurai and LiteBIRD HWP team

Kavli IPMU

B-mode from space workshop @ Berkeley



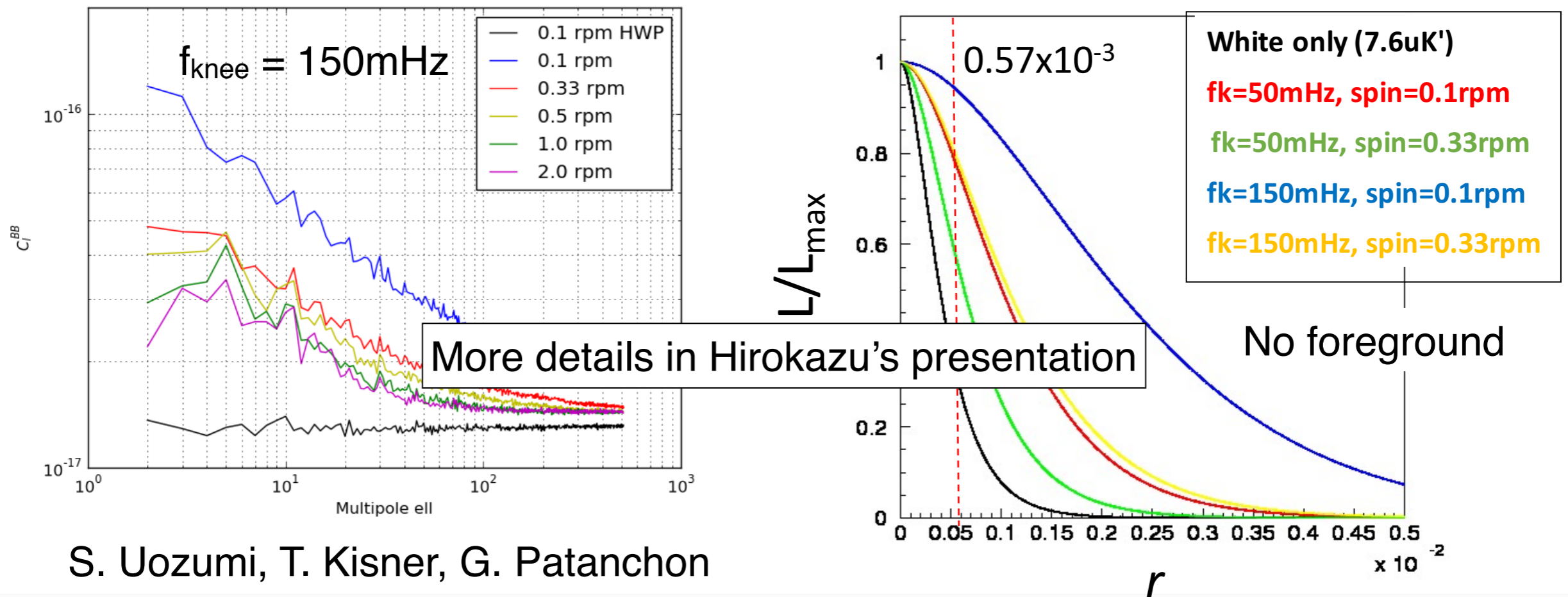
研究拠点形成事業
Core-to-Core Program

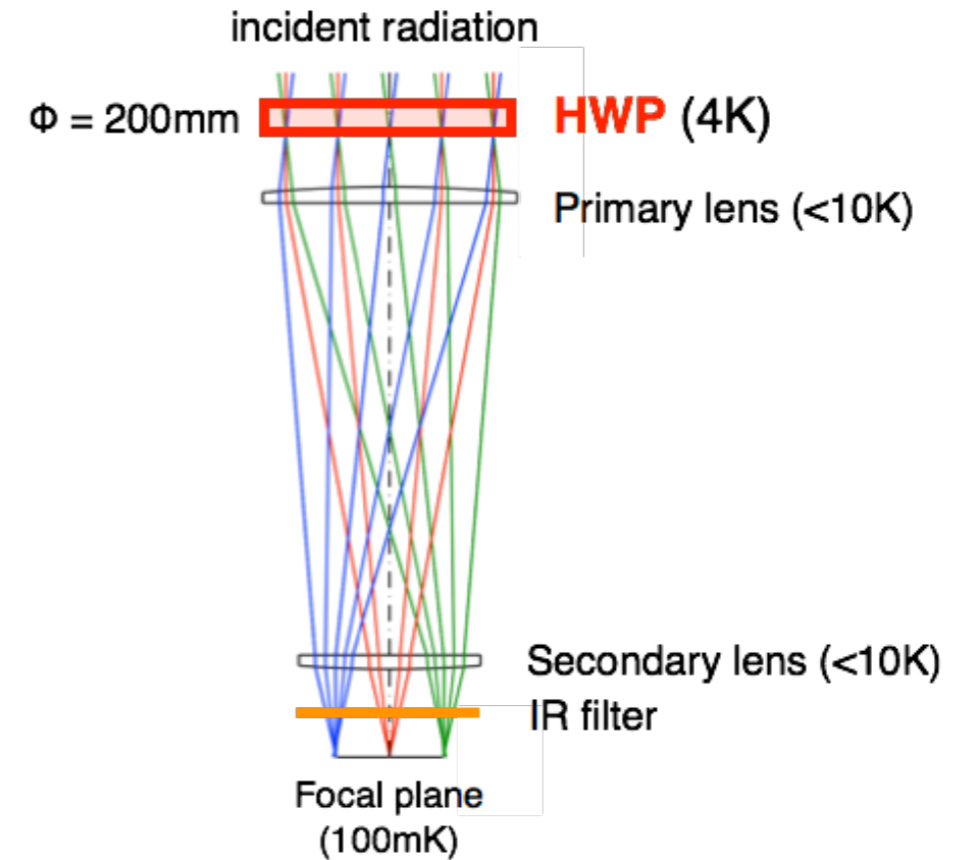
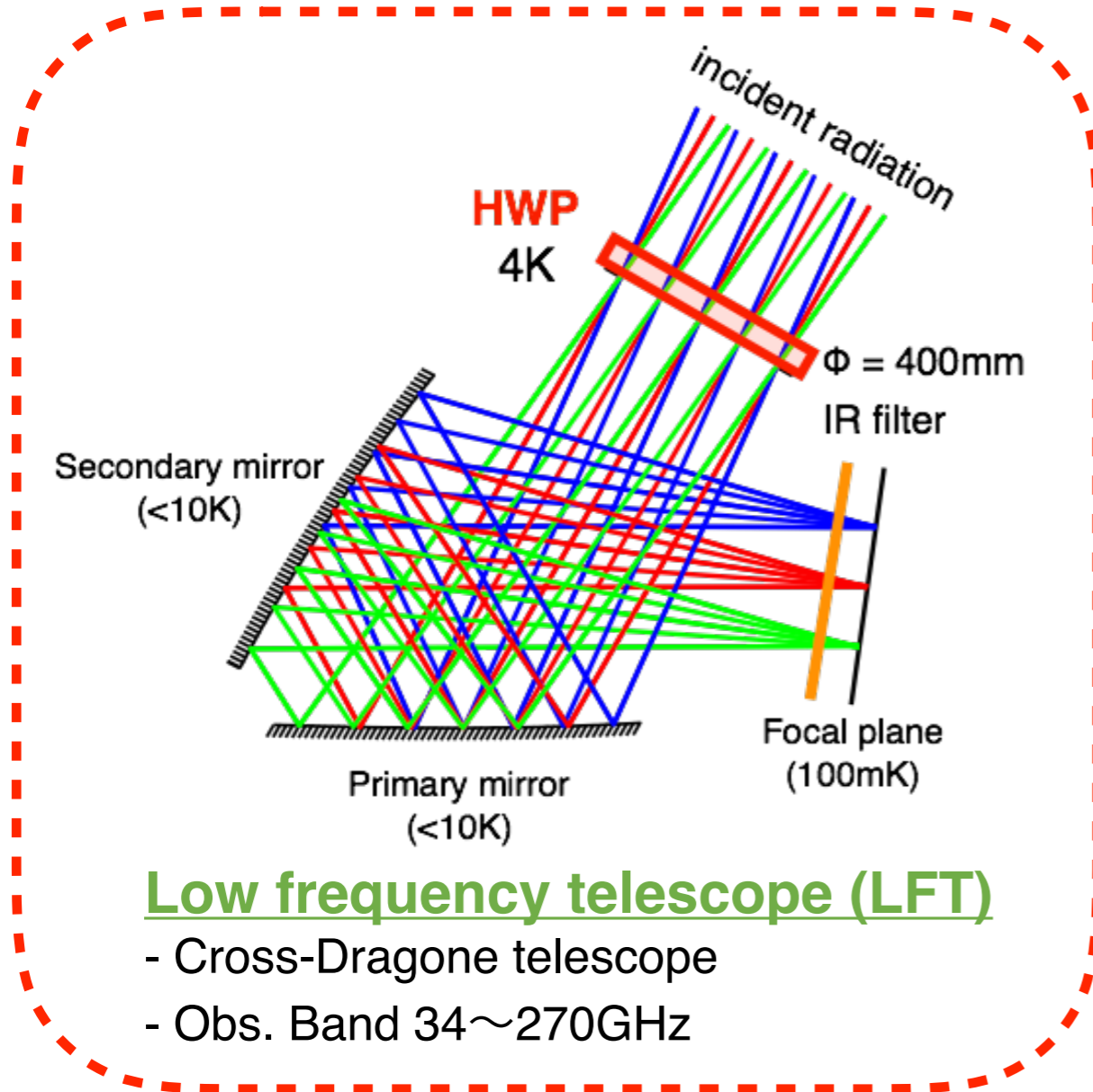




- ✓ The continuous rotating HWP mitigates the low frequency detector noise and the differential systematics. Great benefit to achieve $\delta r < 10^{-3}$!!
- ✓ The $1/f$ noise power spectrum is estimated for various spin rate w/ and w/o HWP.
- ✓ In case the spin rate of 0.33 rpm (maximum spin rate), the increase in the power spectrum is a factor of 4 for $f_{\text{knee}} = 150\text{mHz}$.

The LiteBIRD baseline design employs continuous rotating HWP





Baseline of the LiteBIRD Polarization Modulator:
**Refractive Achromatic Half-wave Plate (Sapphire) +
 Cryogenic continuous rotation mechanism**



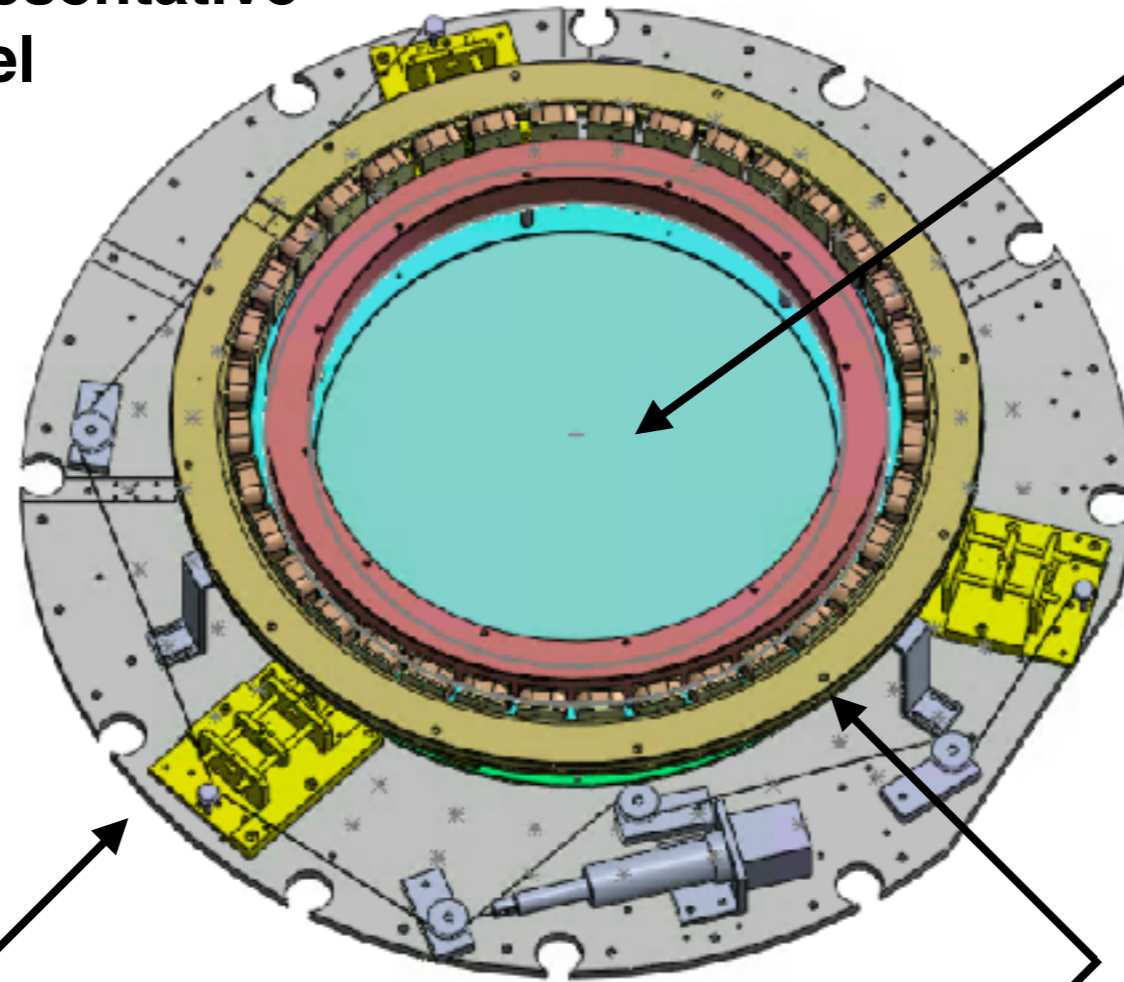
| Items | Requirement (LFT) |
|---------------------------|-------------------------------------|
| HWP Transmittance | > 90% in 34GHz - 270GHz |
| HWP Modulation Efficiency | > 98% in 34GHz - 270GHz |
| HWP diameter | ~ 450 mm |
| HWP temperature | < 10 K in 24hour (ADR recycle time) |
| Total heat dissipation | < ~ 3.5 mW |
| Rotation frequency | 1.2Hz (88RPM) |
| Encoder specification | < 0.001 degs |

Broadband HWP
4K stable continuous rotation
Minimum heat Dissipation

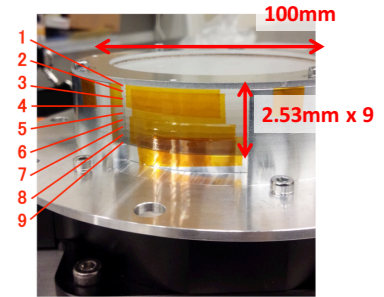
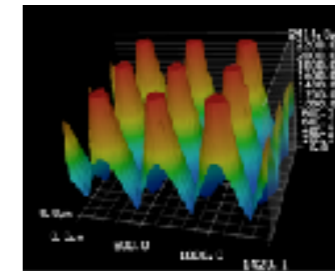
Developing items



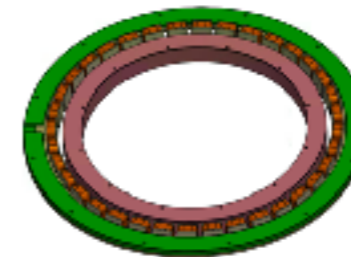
ϕ 400mm flight representative demonstration model



Anti-Reflection (AR)
Achromatic HWP (AHWP)

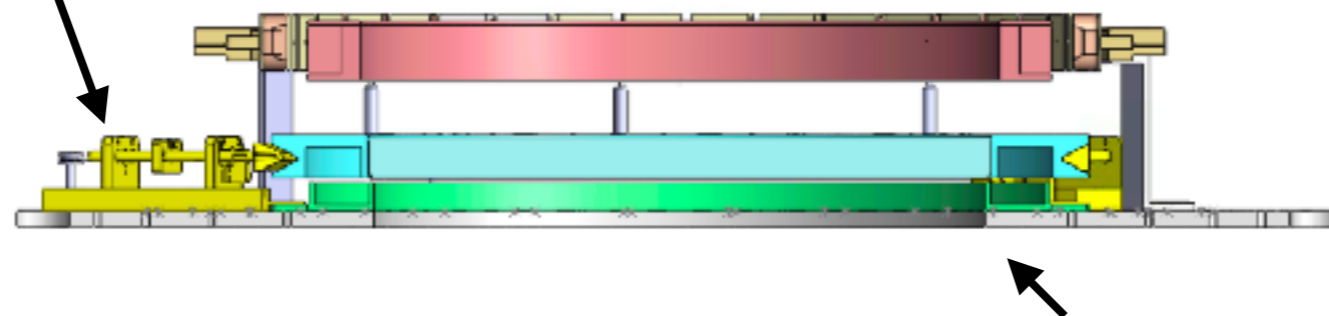
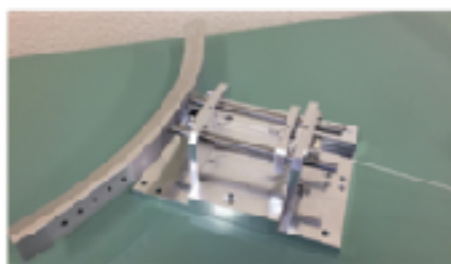


$\phi \sim 1\text{m}$ 4K cryostat

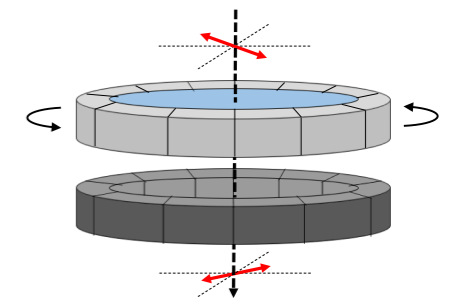


Cryogenic Synchronous Motor
Encoding System

Gripper Mechanism



Superconducting Magnetic Bearing





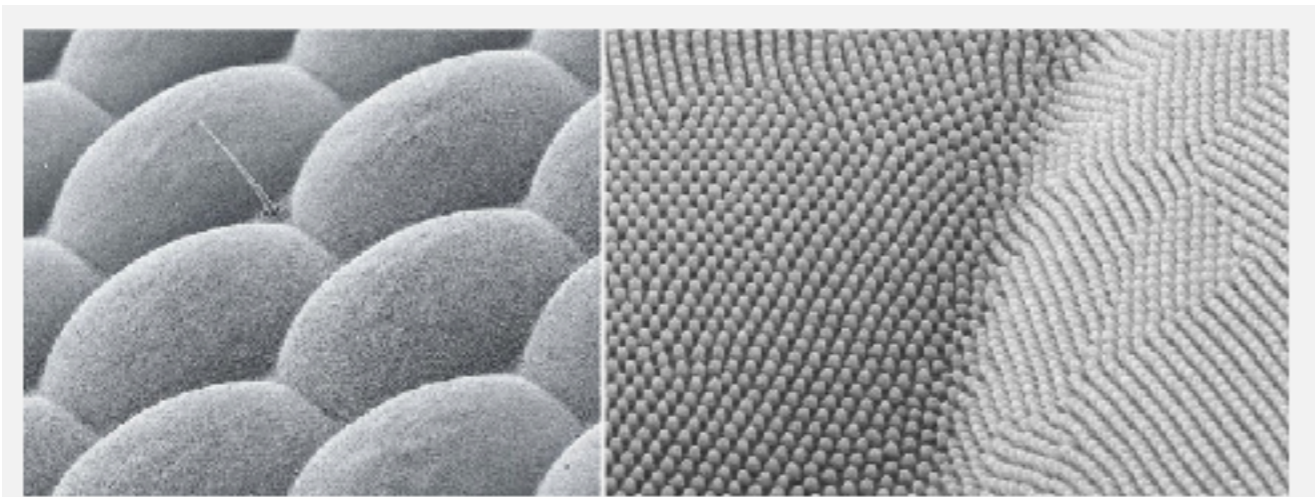
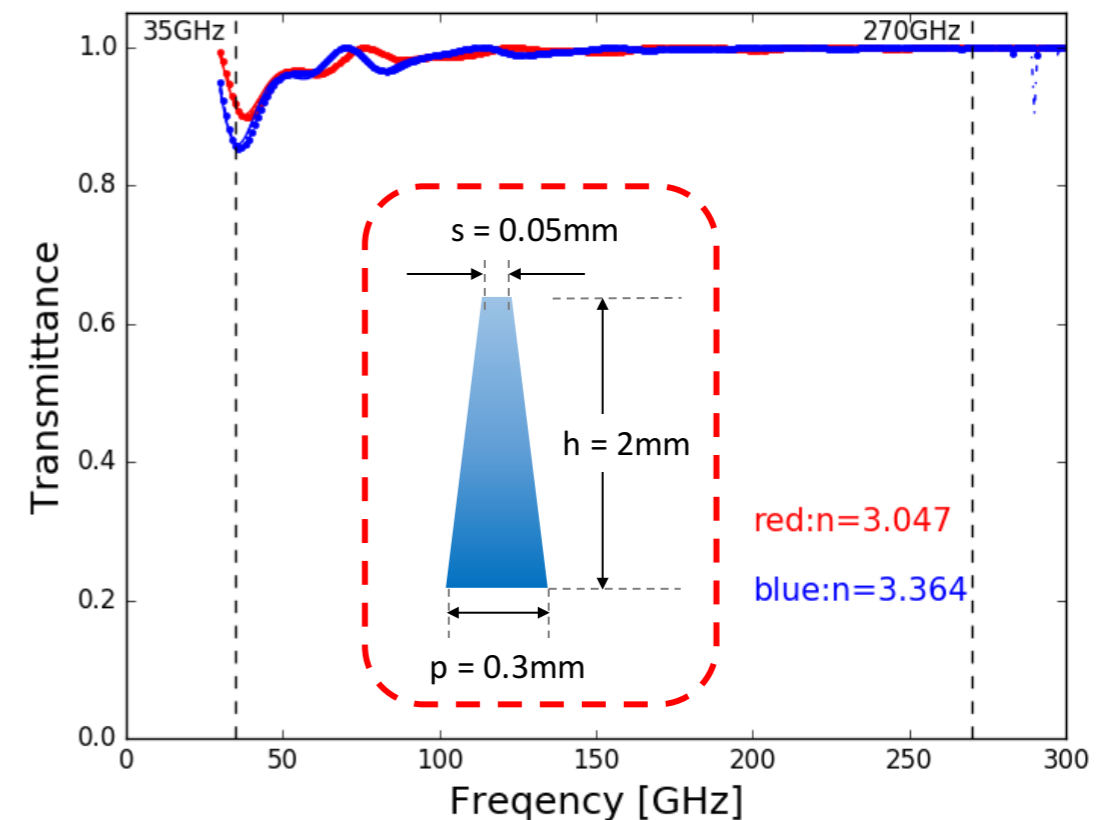
- ✓ The AR structure is introducing an extra-layer to match the impedance mismatch.
- ✓ We are developing **moth-eye based sub-wavelength structure** to cover 34 - 270GHz.
- ✓ We started with the simplest pyramid design.
- ✓ The requirement ($T > 90\%$) is almost satisfied even with the simplest pyramid design.
- ✓ There is a room for improvements by the detailed design: bell shape etc.

AR Structure



AR Structure

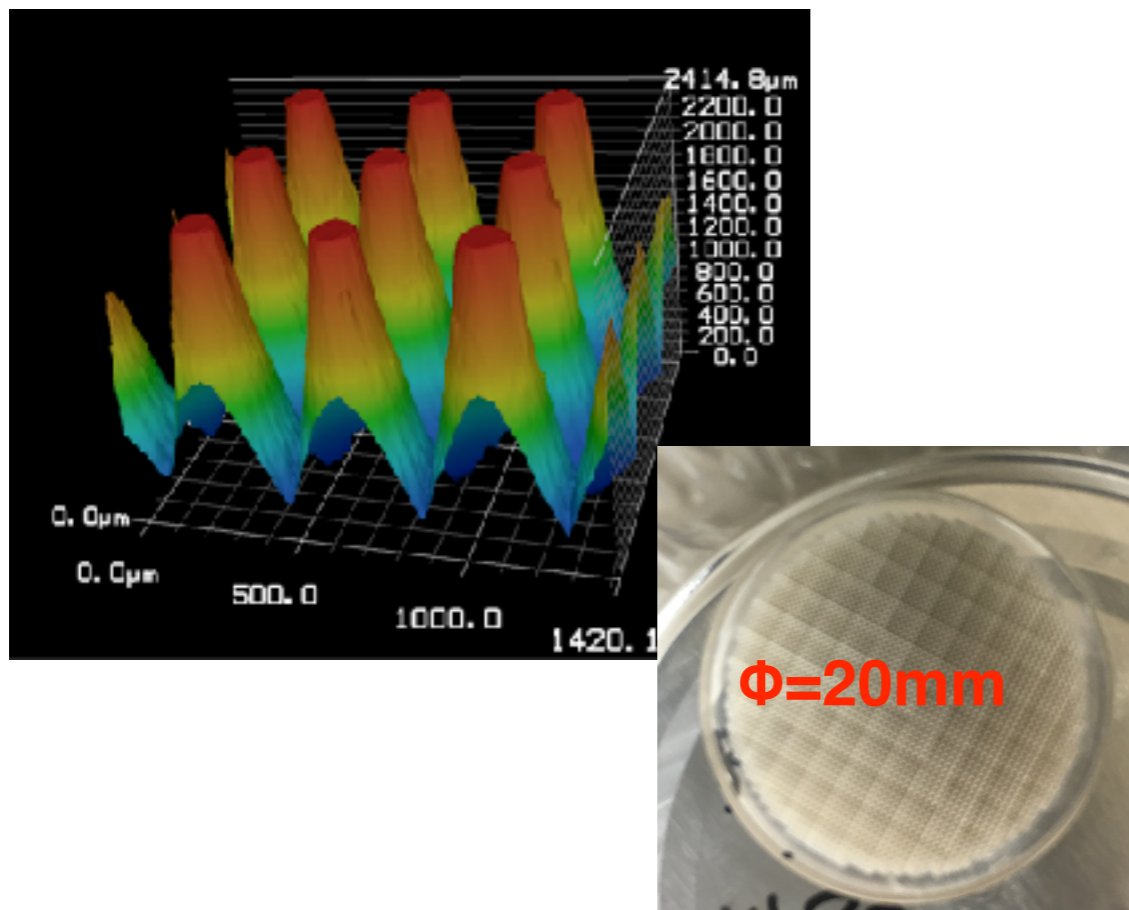
performance with designed pyramid shape



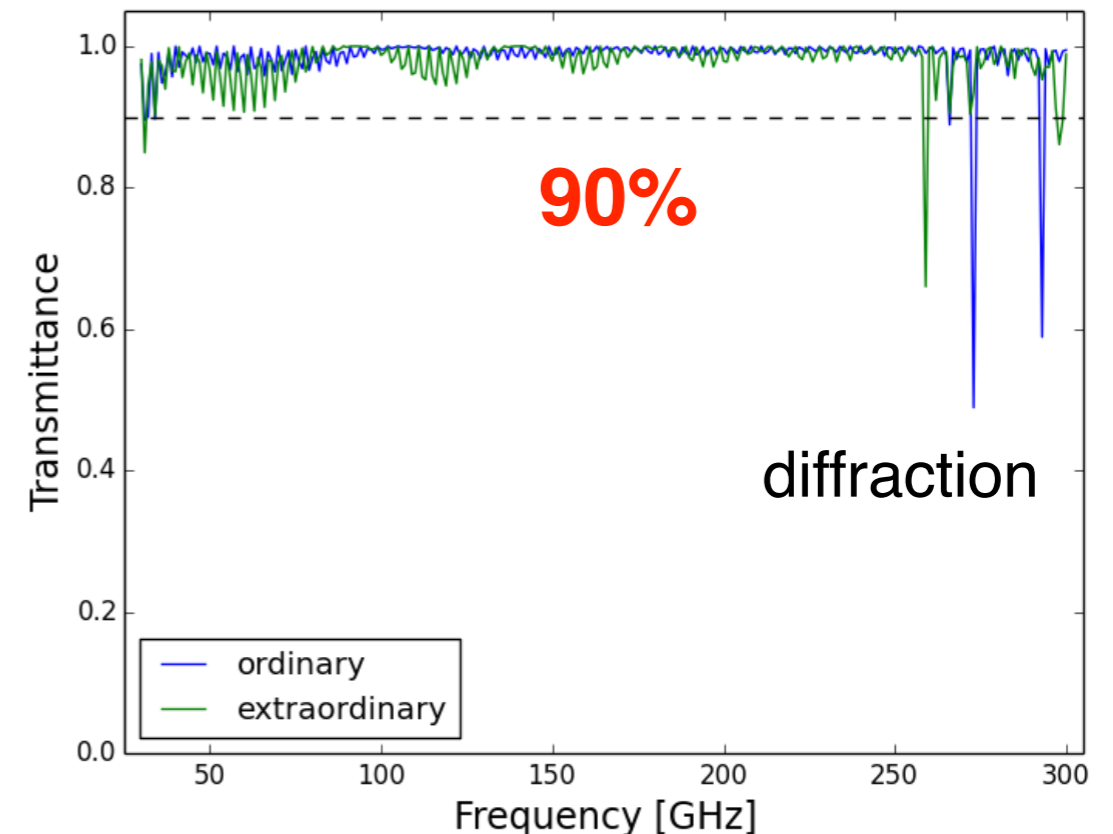
<https://asknature.org/idea/moth-eye-antireflective-coatings/#.Wh0XWLaKUdU>



- ✓ Moth-eye structure is fabricated on the sapphire using a **laser machining**.
- ✓ Current best fabricated sample is with **$p = 400\mu\text{m}$, $h = 2.3\text{mm}$** , $s = 100\mu\text{m}$.
- ✓ The simulated performance using fabricated shape is satisfied the requirement except for diffraction effect (=pitch).
- ✓ Several developments are on-going in parallel:
pico, nano, femto sec laser? IR, UV ,Green? shape? high power laser?



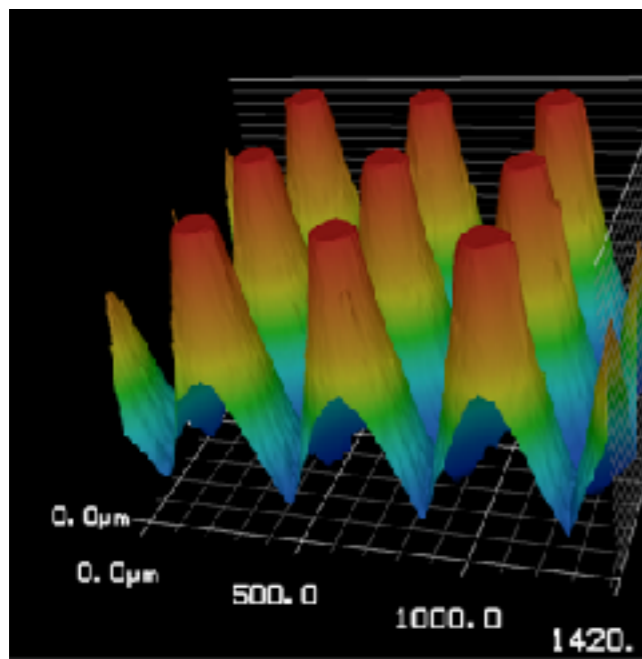
Simulated performance with fabricated structure



Broadband AR structure

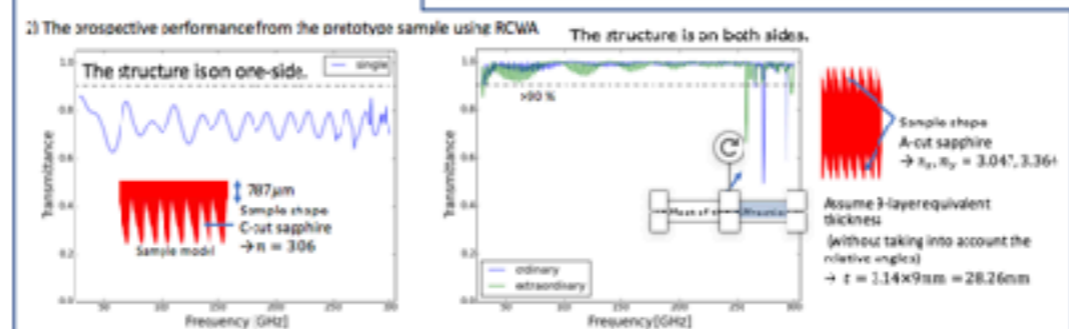
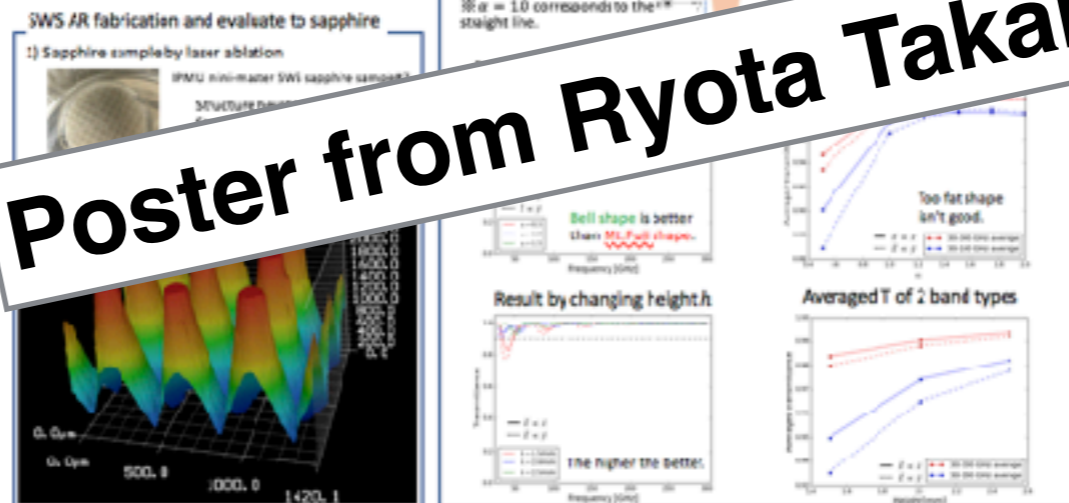
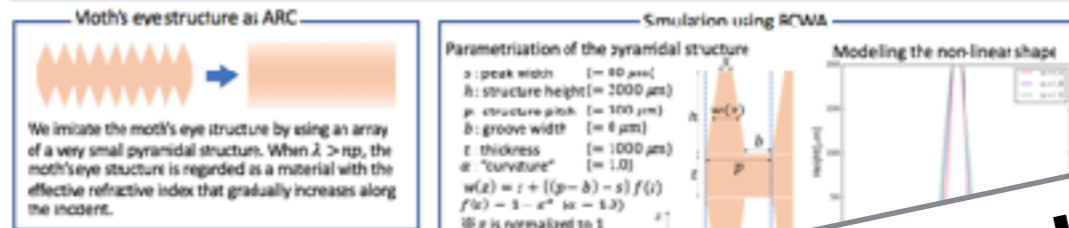
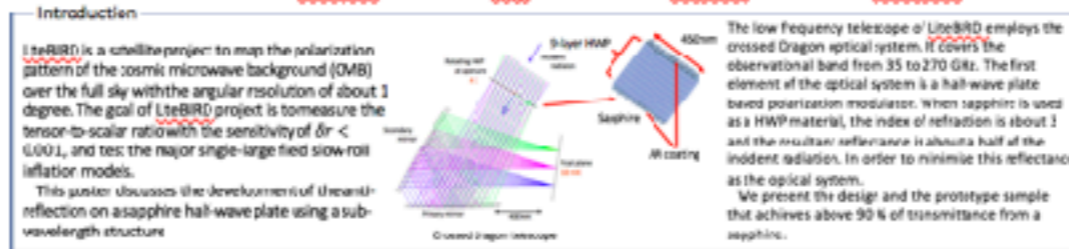


- ✓ Moth-eye structure is
- ✓ Current best fabrication
- ✓ The simulated performance except for diffraction
- ✓ Several development methods: pico, nano, femto s



Anti-reflection coating using moth's eye structure

R. Takaku^a, H. Imada^a, T. Matsumura^c, Y. Sakurai^c, N. Katayama^c, K. Komatsu^c, S. Itanari^d, K. Yung^e, Q. Wen^f
^aYokohama National University, ^bJAXA/ISAS, ^cKavi IPMJ, ^dOlayarra University, ^eUniversity of Minnesota



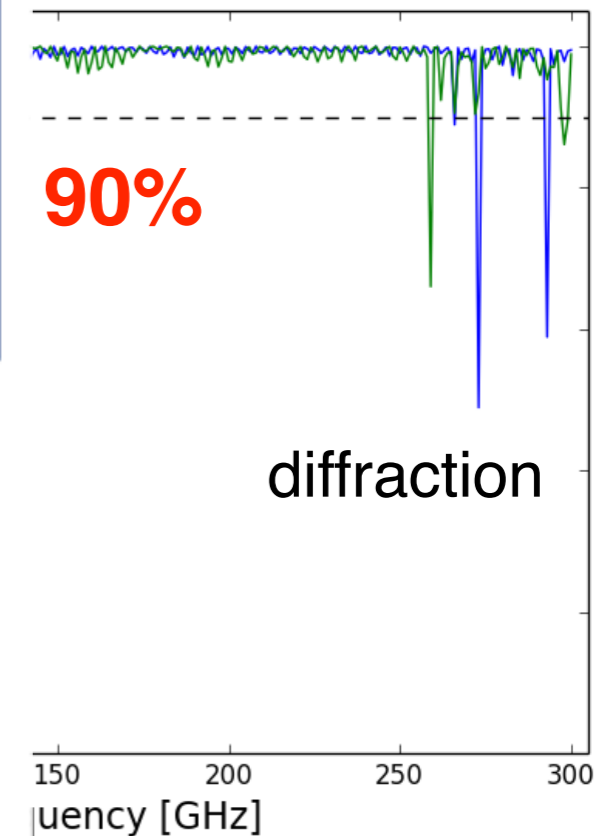
Summary

- We conducted the design optimization and the prototype fabrications.
- The structure shape is desired to be a bell shape rather than a MT-Full shape to achieve high transmittance. The optimal range of the parameter is broad.
- We fabricated the prototype sample and simulate the result. We achieved above 90% transmittance using the SWS AR over the 1-FT measuring band.

laser machining.
 100 μm, s = 100 μm.
 specified the requirement

Poster from Ryota Takaku

power laser?
 ice with fabricated structure

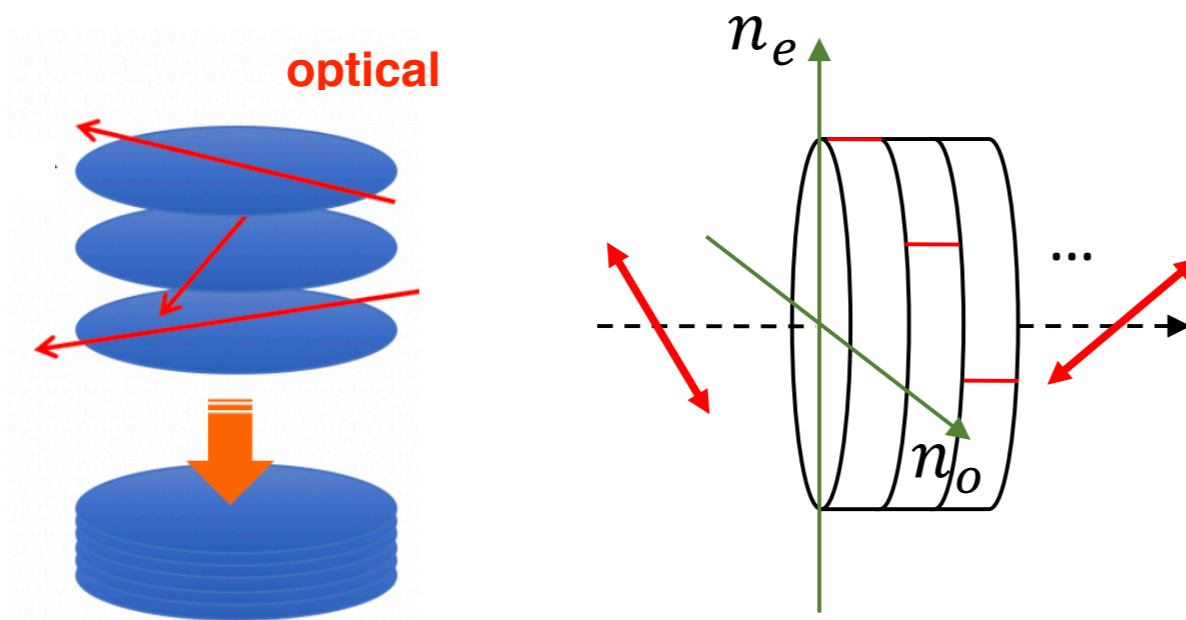
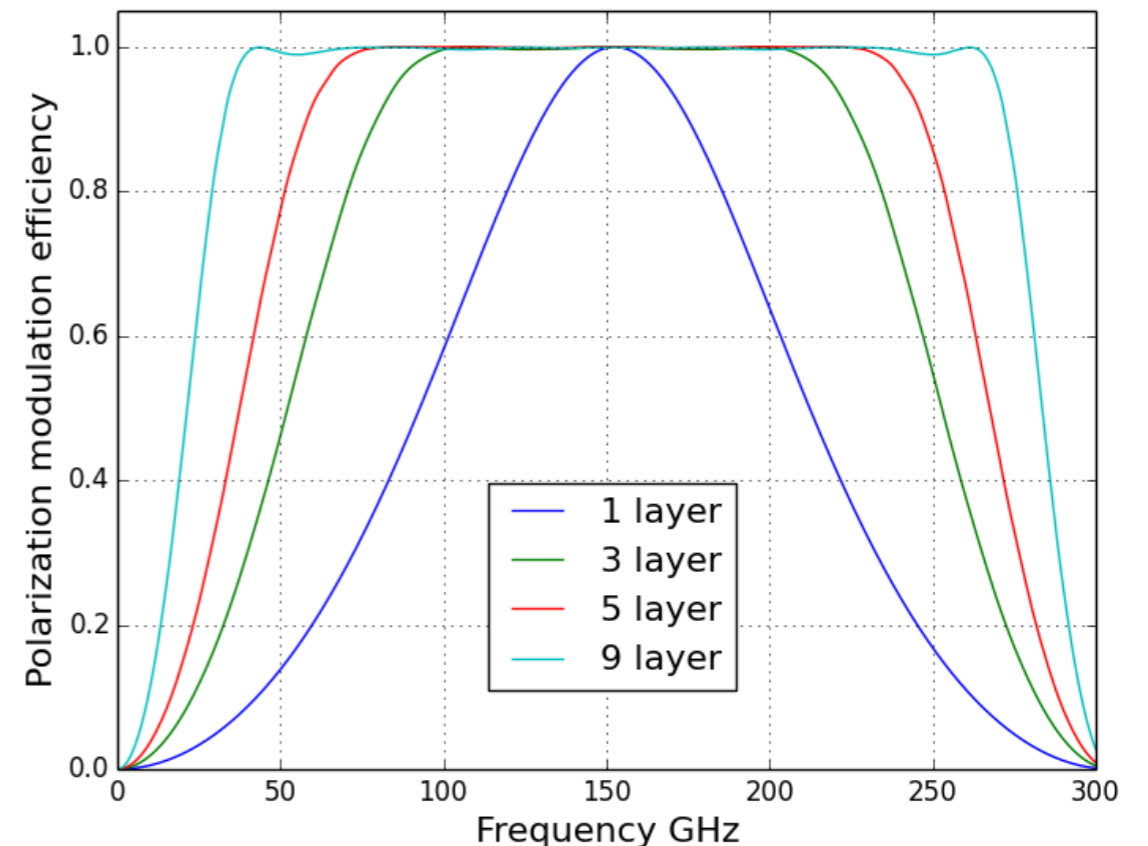




- ✓ A single layer sapphire becomes a HWP at only single frequency.
- ✓ We can obtain a broader bandwidth with a Pancharatanam achromatic HWP (AHWP).
- ✓ AHWP consists of multiple plates stacked with offset angles with respect to each other. We design the 9-layer AHWP to cover 34 - 270 GHz.

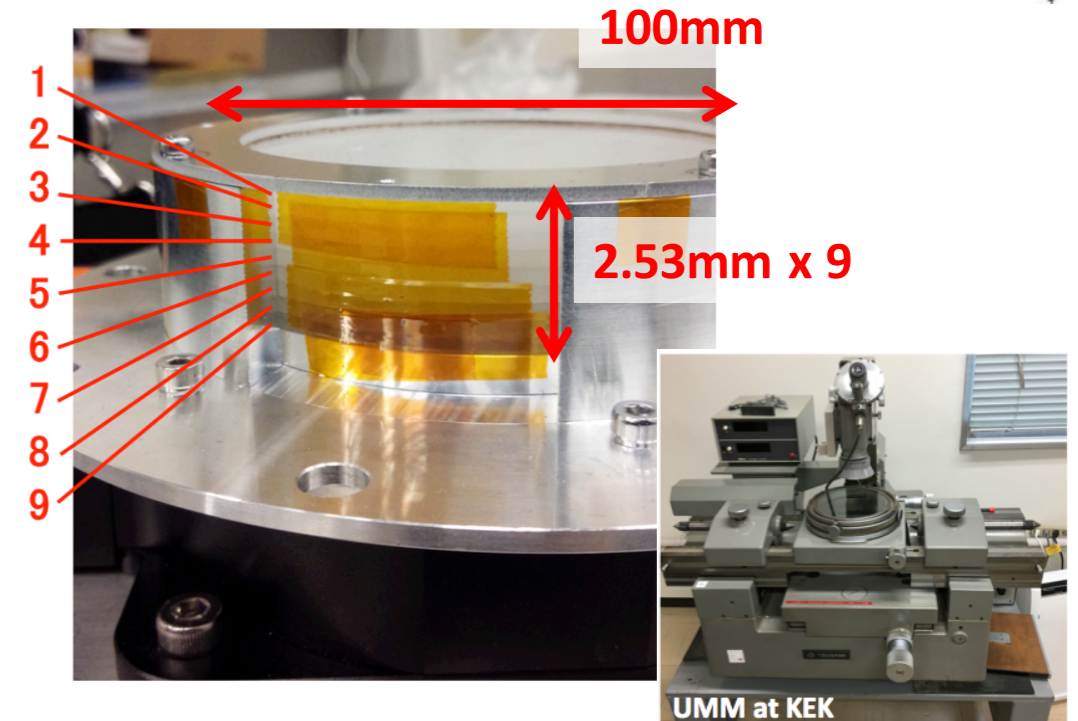


performance with ideal case

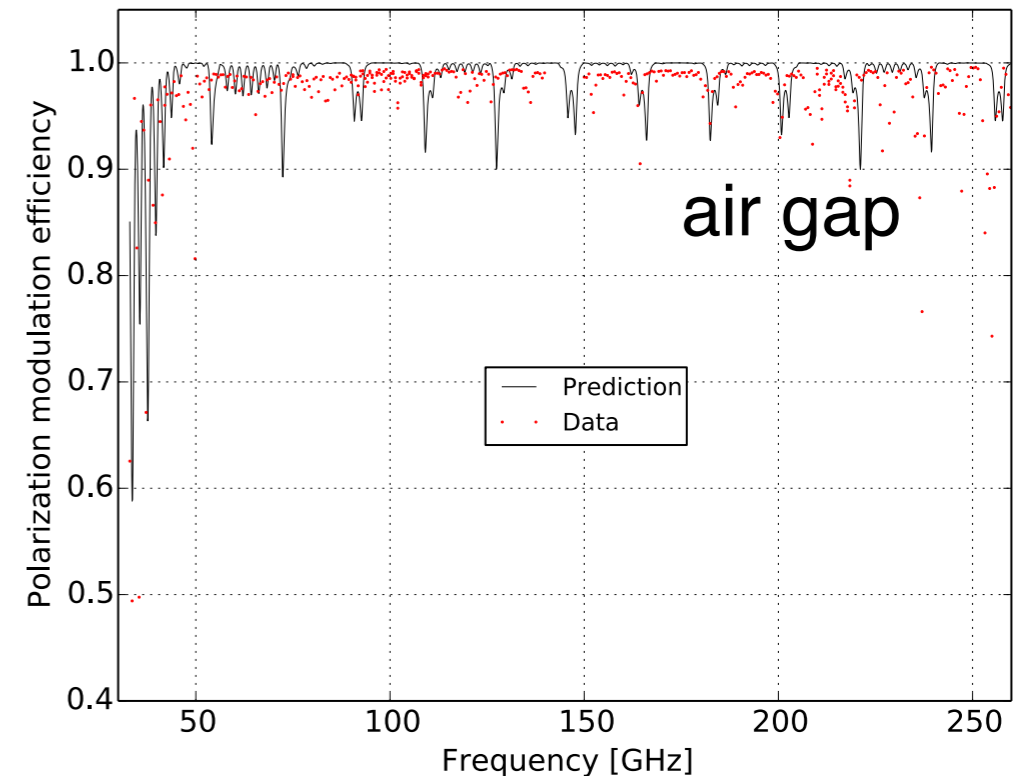




- ✓ 9 layer sapphire AHWP with $\phi=100\text{mm}$ is assembled using a universal measurement machine (UMM) at KEK. The assembled accuracy in a relative angle is <10 arcmin.
- ✓ We measure modulation efficiency of the fabricated AHWP using the optical system @ Kavli IPMU
- ✓ The result is consistent with the prediction except for the air gap effect.
- ✓ Next step is to fabricate $\phi=400\text{mm}$ model.
- ✓ In parallel, We are devising a design with reduced number of layer.



9 layer AHWP Data v.s Prediction





Development of Pancharatnam achromatic half-wave plate for polarization modulator of LiteBIRD

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M. Hazumi^C, N. Katayama^A, and other LiteBIRD Phase-A1 team
Okayama University, Kavli IPMU^A, ISAS/JAXA^B, High Energy Accelerator Research Organization^C

Introduction

Inflation is one of the theories giving rise to the initial condition of the hot big bang of our universe. The rapid space expansion which occurred immediately after the universe was born expanded the quantum fluctuation of the space-time generating the primordial gravitational waves. The primordial gravitational waves created the B mode polarization in large scales of Cosmic Microwave Background (CMB). The strength of the gravitational waves is represented as a tensor-to-scalar ratio. Most of the inflation models with a single scalar field predict a value of r to be greater than 0.01. The value of r can be measured from B mode polarization.

LiteBIRD is a satellite project to measure the polarization of CMB with an unprecedented accuracy by observing all the sky for three years at the sun-earth Lagrange point 2. The goal of LiteBIRD is to detect the B-mode polarization in a large angular scale and to measure the value r with an accuracy of $\delta r < 0.001$. In order to mitigate some of the systematics, LiteBIRD plans to mount the continuous rotating half-wave plates (HWPs) to modulate polarization of the incoming light. We report our development status of the HWP.

Polarization modulator

- The continuous rotating HWP can modulate the polarization angle of the incoming light electric field with a frequency twice of the rotation rate. When we use the detectors sensitive to the single polarization, the observed signal has a frequency of four times of the HWP rotation rate.
- The advantages of using the polarization modulators are as follows:
 - The polarization can be measured using a single detector \rightarrow Remove systematics arising from the difference in multi detector characteristics.
 - Mitigate 1/f noise by shifting the signal frequency above the knee frequency.
- The requirements to the HWP specification for the low frequency telescope of LiteBIRD.

| Frequency range | Lif. time | Diameter | PME* | Transmission | Temperature |
|-----------------|-----------|----------|--------|--------------|-------------|
| 34-270 GHz | > 1 year | 40 cm | > 0.98 | > 0.99 | < 10 K |

* Polarization Modulation Efficiency (PME) is ratio of the polarization intensity of the outgoing light to the incident light. In ideal HWP case, PME is equal to one.

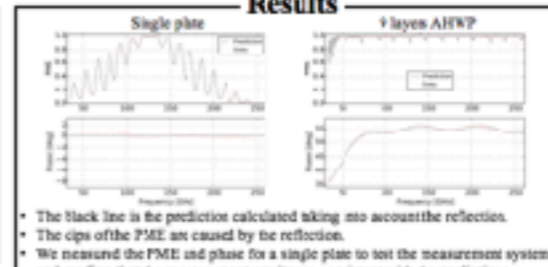
Achromatic half wave plate

- A single layer HWP cannot cover all the frequency range from 34 to 270 GHz.
- To cover the targeted frequency range, we make use of Pancharatnam achromatic half-wave plate (AHWP).
- AHWP consist of a stack of nine layers.
- The relative optic axis are staggered.
- The material used is sapphire.

Poster from Kunimoto Komatsu

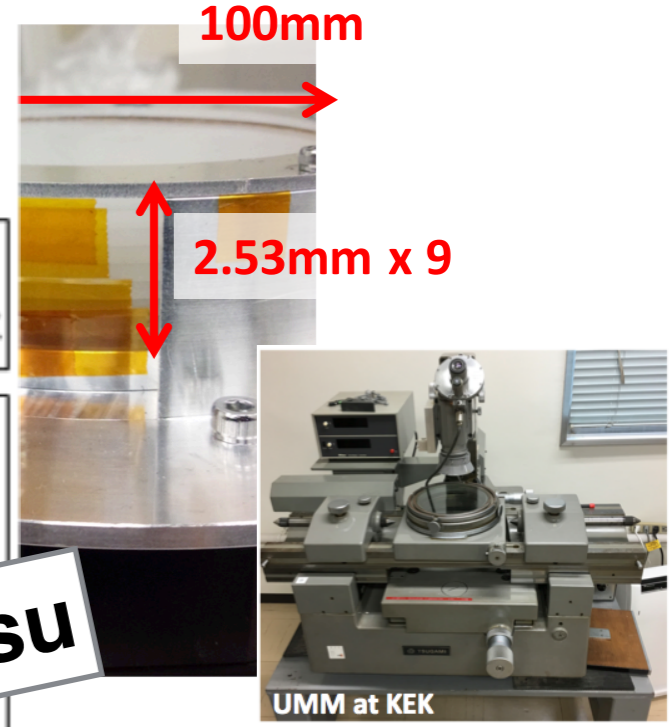
Measurement

- This system can measure the transmitted power of the specimen with the frequency range of 33 to 260 GHz.
- The injected waves are polarized larger than 99%.
- The plane wave is formed with the first parabolic mirror.
- We set the nine layer AHWP in the system and rotate it continuously.
- We measure the single polarization power of the light passing through the plate as a function of the rotation angle.
- We fit the angle dependency using the function $D(\theta)$ to obtain PME which is defined as the ratio of a_1 / a_0 , and a phase of the modulation with a frequency four times of the rotation rate.

$$D(\theta) = a_0 + \sum_{n=1}^{\infty} c_n \cos\{n(\omega t + \phi_n)\}$$


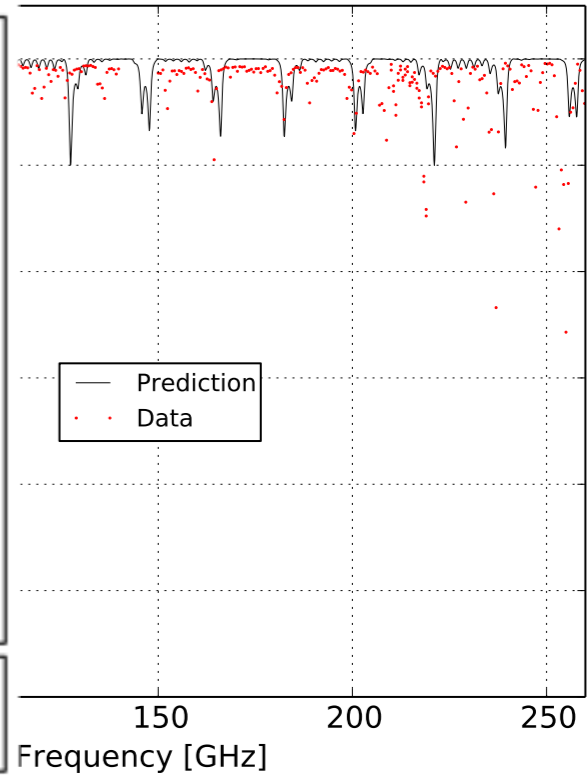
Summary

- We have measured the PME and phase for the AHWP and found that those are consistent with the expectations with the wide frequency range.
- We have a plan to measure the transmittance, to implement the Moiré-eye anti-reflection structure and to evaluate the performance with the designed modulator size of 40cm diameter.



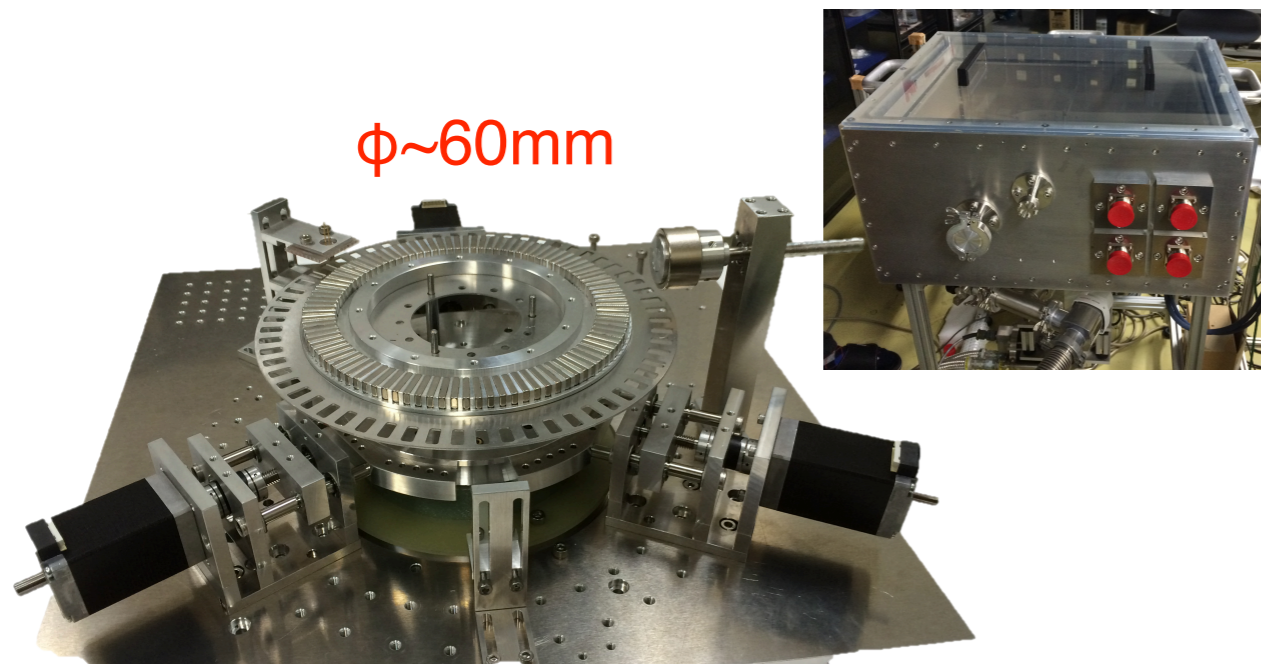
- ✓ 9 layer sapphire AHW assembled using a universal measurement machine. The assembled accuracy angle is <10 arcmin.
- ✓ We measure modulation efficiency of fabricated AHWP using a universal measurement machine @ Kavli IPMU
- ✓ The result is consistent with prediction except for the air gap
- ✓ Next step is to fabricate a larger size
- ✓ In parallel, We are developing a reduced number of layers

Data v.s Prediction

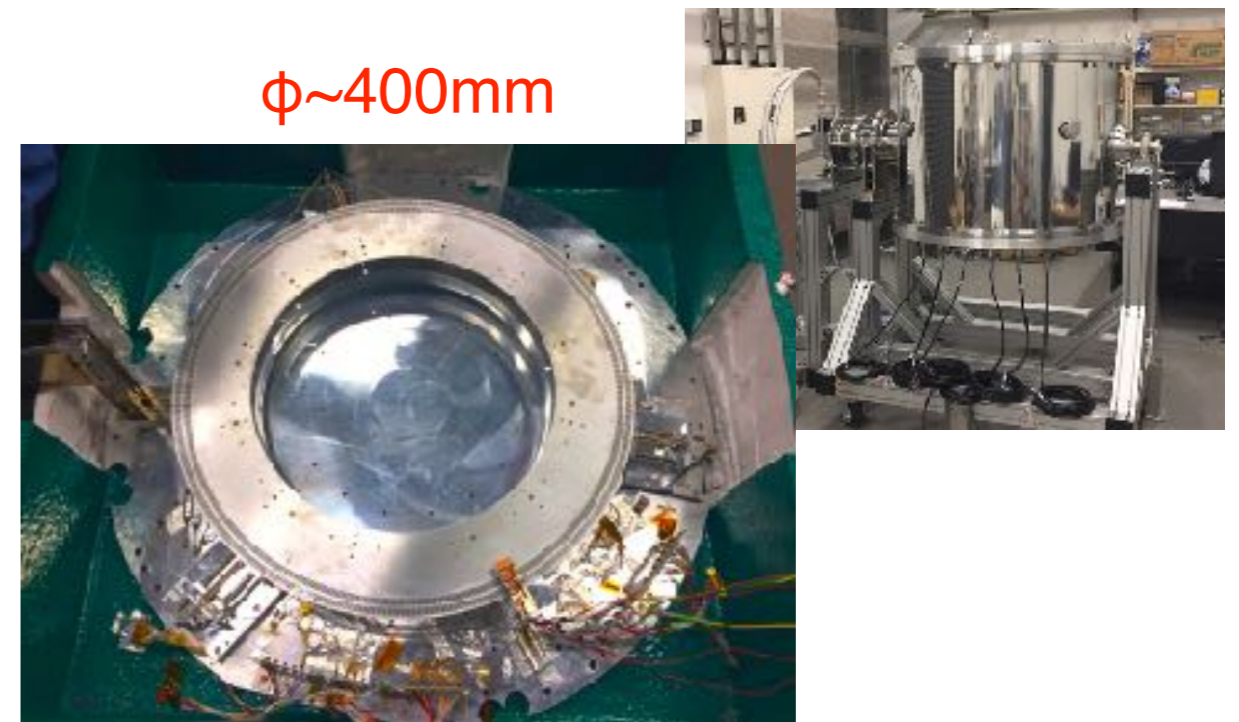




- ✓ The feasibility study of cryogenic rotation in 4K environment is almost done using $\phi \sim 60\text{mm}$ small prototype
- ✓ We constructed a flight representative demonstration model with $\phi 400\text{mm}$ inside a large 4K cryostat at Kavli IPMU.
- ✓ The rotation mechanism consists of superconducting magnetic bearing, synchronous motor, holding mechanism and encoder system.
- ✓ The current focused development point is to minimize heat dissipation of each component.



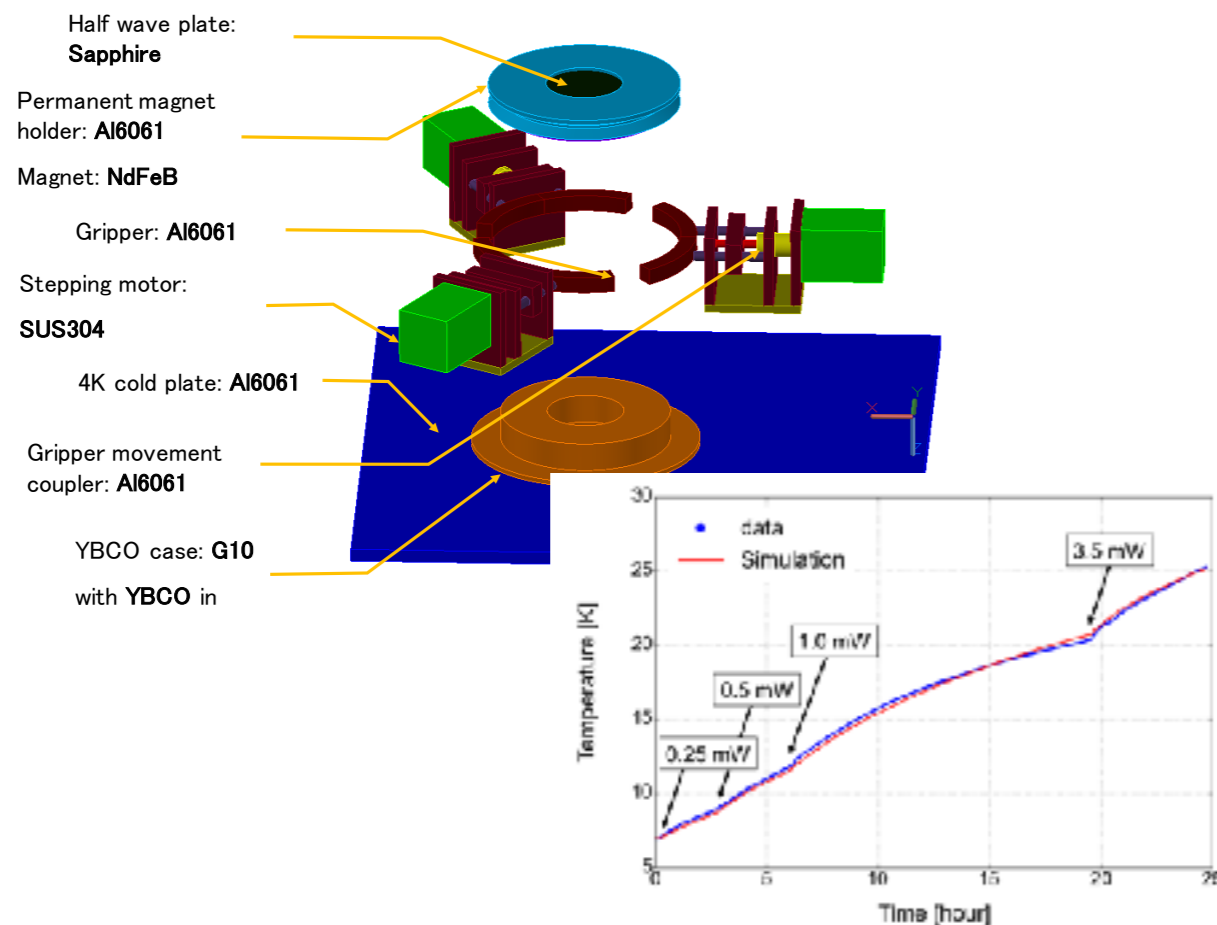
Small prototype



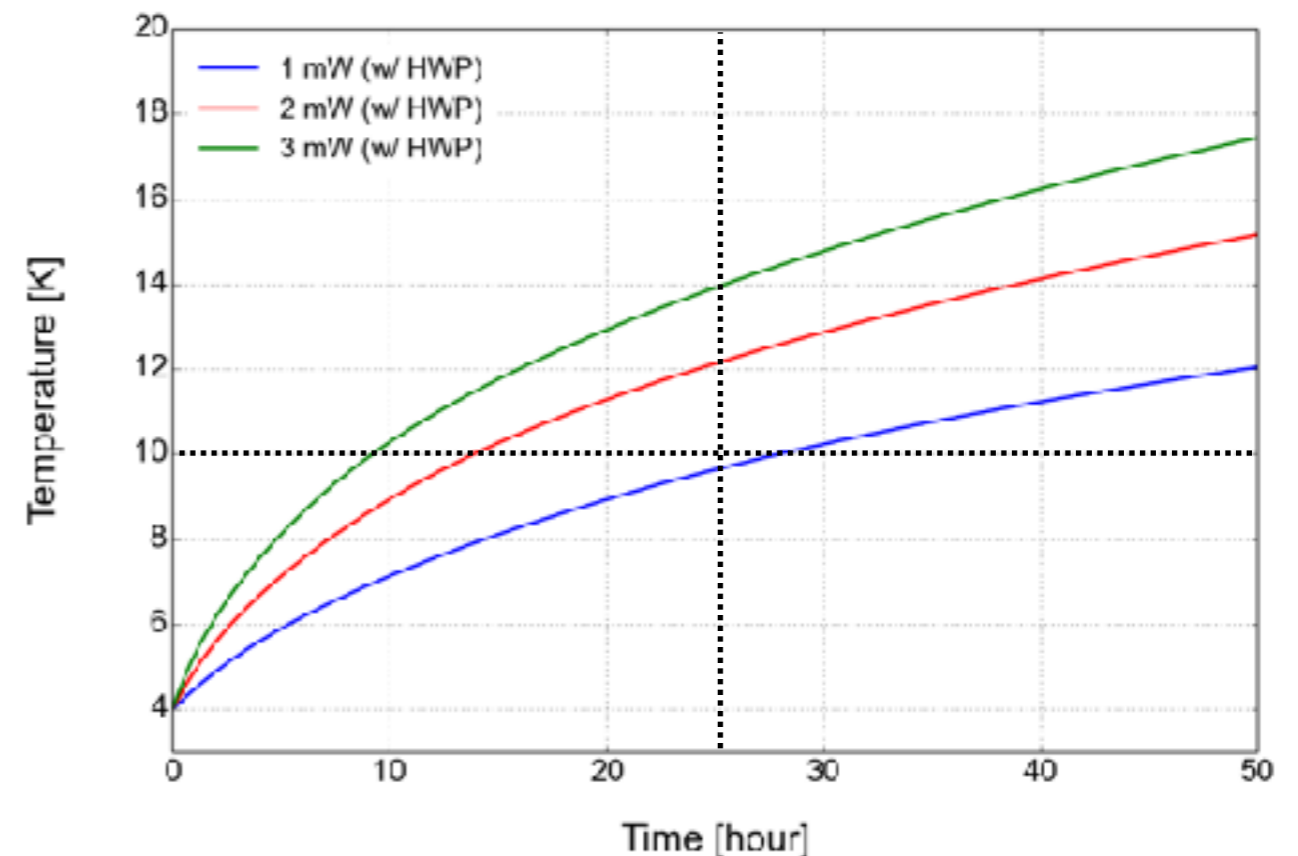
Demonstration model

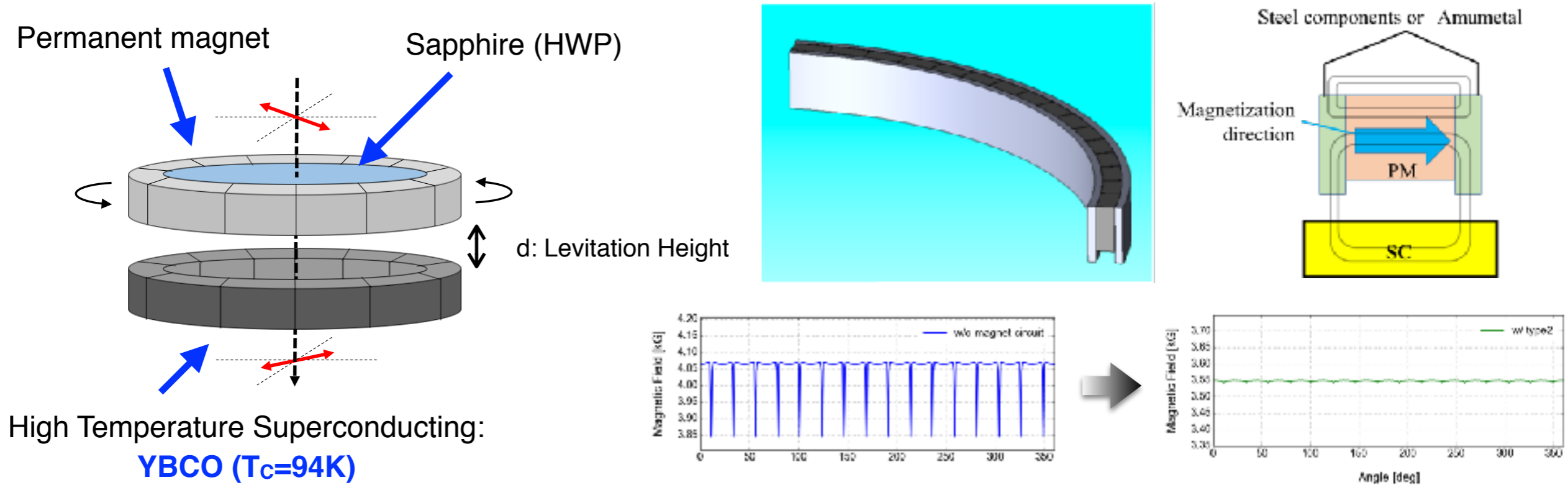


- ✓ Using small diameter prototype, the data from a levitating rotor with a heater and a temperature sensor are compared with a thermal model by ThermalDesktop Simulation.
- ✓ The model is agree within a few degrees by fitting unknown parameter: heat capacity of permanent magnet at cryogenic temperature.
- ✓ The model is expanded to the demonstration model with sapphire HWP
- ✓ The HWP temperature exceeds 10 K in 24 hours (ADR recycle time) with **1 mW** heat input or more according to the simulation result. → Need to minimize heat dissipation!



Thermal performance of levitating rotor w/ HWP



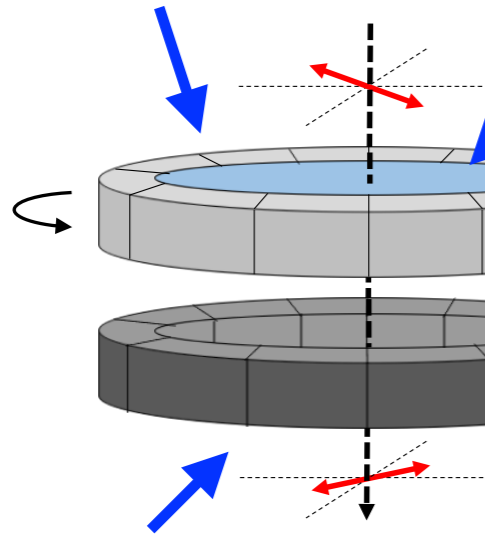


$$\Delta B/B : 7\% \rightarrow 1\%, \quad |B| : 4kG \rightarrow 3.5kG$$

- ✓ Contactless bearing using a coupling of a superconductor and a permanent magnet to minimize heat dissipation.
- ✓ Remaining heat sources are magnetic friction and eddy current
 - **Magnetic field homogeneity** is critical point
- ✓ We designed magnetic to be compatible with homogeneity and stiffness.
- ✓ New magnet is under fabrication and delivered at Feb. 2018.



Permanent magnet



High Temperature Superconductor
YBCO ($T_c=94K$)

- ✓ Contactless levitation
- ✓ permanent magnet
- ✓ Remaining heat → Magnet
- ✓ We designed
- ✓ New magnet

Estimating the rotational energy loss of a superconducting magnetic bearing for LiteBIRD

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¹Yokohama National University, ²Kavli IPMU, ³ISAS, ⁴The University of Tokyo

Introduction

- The inflation signal in the B-mode power spectrum appears at low ℓ , i.e. large angular scale, and thus it is essential to be able to make a distinction between the signal and the $1/f$ noise from the observational system including the detector and readout.
- Introducing a polarization modulator is one of the standard techniques to overcome this problem. The baseline design of LiteBIRD employs a continuously rotating half-wave plate (HWP) based polarization modulator. LiteBIRD is in Phase A1, and we focus on some of the key development items.
- We present the dynamical characteristics of the rotational mechanism using our prototype system.

Overview of Polarization Modulator for Low Frequency Telescope

We focus the development that is specifically for the polarization modulator of the low frequency telescope (LFT) of LiteBIRD.

- A HWP is placed at the aperture and as a first optical element.
- The HWP is cooled below 10 K.
- The frequency coverage of the LFT is 34-270 GHz (edge-to-edge).
- The aperture diameter is 400 mm, and correspondingly the HWP diameter is 400 mm.
- The HWP is 400 mm in diameter.

Dynamical characteristics using

Poster from Hiroaki Kanai



B : 4kG → 3.5kG

SMB spring model

In space, there is no gravity. In order to understand the dynamical characteristics of the SMB, the experimental results on the ground have to be extrapolated. We conducted the measurement of a spring constant with 4 different rotor masses when the rotor is levitating. Correspondingly, the levitation height varies due to the extra mass after the field cooling.

The spring constant given each mass is estimated from the resonance frequency. The spring constant of the SMB is purely determined by the magnetic field configurations, and thus the spring constant is different with and without the presence of the gravity. Due to the non-linear nature in the estimation of the spring constant, the spring constant with no gravity has to be estimated by the simulation, and it's in progress.

| Levitation height | rotor mass [kg] | ω_0 [1/s] | ω_1 [1/s] | A_0 [1/s ² cm ²] | A_1 [1/gcm ²] | f_r [Hz] | f_0 [Hz] | k_s [N/m] | k_t [N/m] | Δx [mm] |
|-------------------|-----------------|------------------------|------------------------|---|-----------------------------|------------|------------|---------------------|---------------------|-----------------|
| 5 mm @ 10-16 K | 0.783 | -1.3×10^{-5} | -2.2×10^{-4} | -3.31 | -5.58 | | | | | |
| 6 mm @ 10 K | 0.783 | -6.60×10^{-6} | -1.98×10^{-4} | -1.68×10 | -5.03 | 12.00 | 19.80 | 4.451×10^3 | 1.212×10^4 | 0.633 |
| 6 mm @ 10 K | 0.835 | -4.85×10^{-6} | -1.74×10^{-4} | -1.24×10 | -4.45 | 11.44 | 19.67 | 4.314×10^3 | 1.275×10^4 | 0.642 |
| 6 mm @ 10 K | 0.888 | -1.43×10^{-6} | -1.05×10^{-4} | -3.69×10^2 | -2.72 | 10.98 | 19.62 | 4.226×10^3 | 1.350×10^4 | 0.645 |
| 6 mm @ 10 K | 0.951 | -1.16×10^{-6} | -9.75×10^{-5} | -3.02×10^2 | -2.53 | 10.19 | 19.48 | 3.898×10^3 | 1.425×10^4 | 0.654 |

Summary

We measure the stiffness and the energy loss of the SMB with various rotor masses. These properties depend on the rotor mass due to the distance between the rotor permanent magnet and the YBCO. From these data set, we can simulate the SMB dynamics under no gravity. The modeling and its extrapolation is in progress.

factor and a

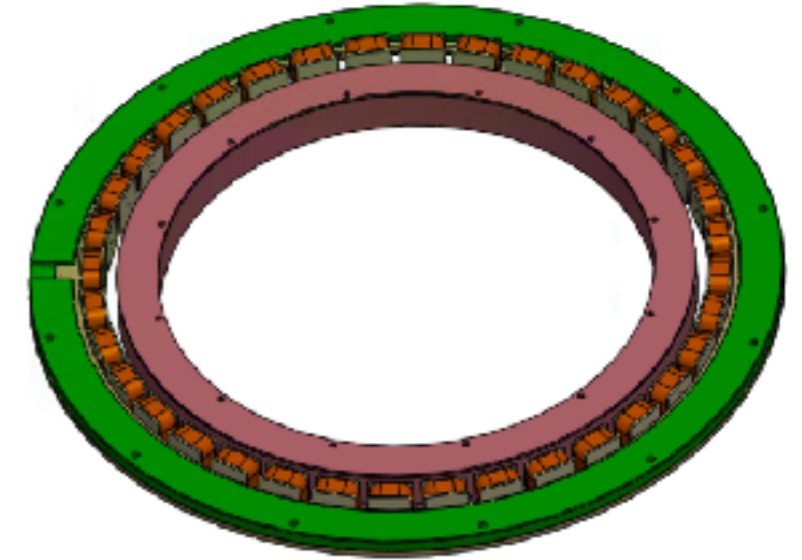
ddy current

energy and stiffness.

o. 2018.



- ✓ Contactless synchronous motor for no frictional wear and for minimum heat dissipation.
- ✓ The feasibility study is done and we are fabricating for demonstration model of $\phi=400\text{mm}$.
- ✓ Remaining R&D: “minimize joule heat from coil” = “resistance of Cu coil in cryogenic temperature”
- ✓ The Cu purity get worse due to the stress during coil forming, but it can be restored by annealing.
- ✓ We are performing feasibility test using LHe cryostat.



7N Cu wire



RRR ~ 1000

Formed into a coil



RRR ~ 100

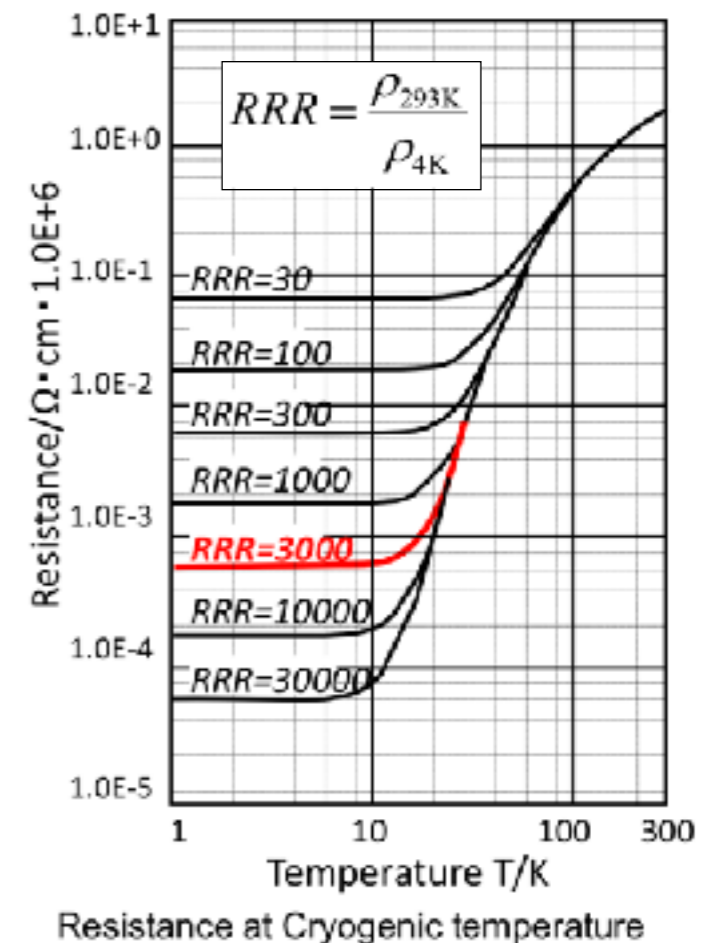
Annealing



RRR ~ 350

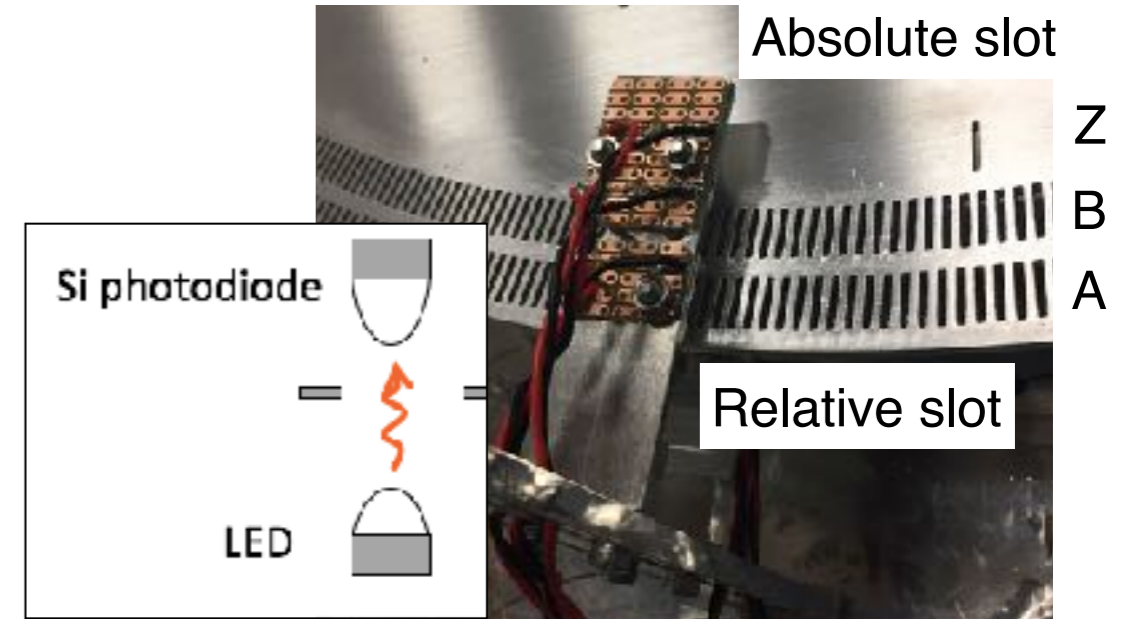


LHe cryostat

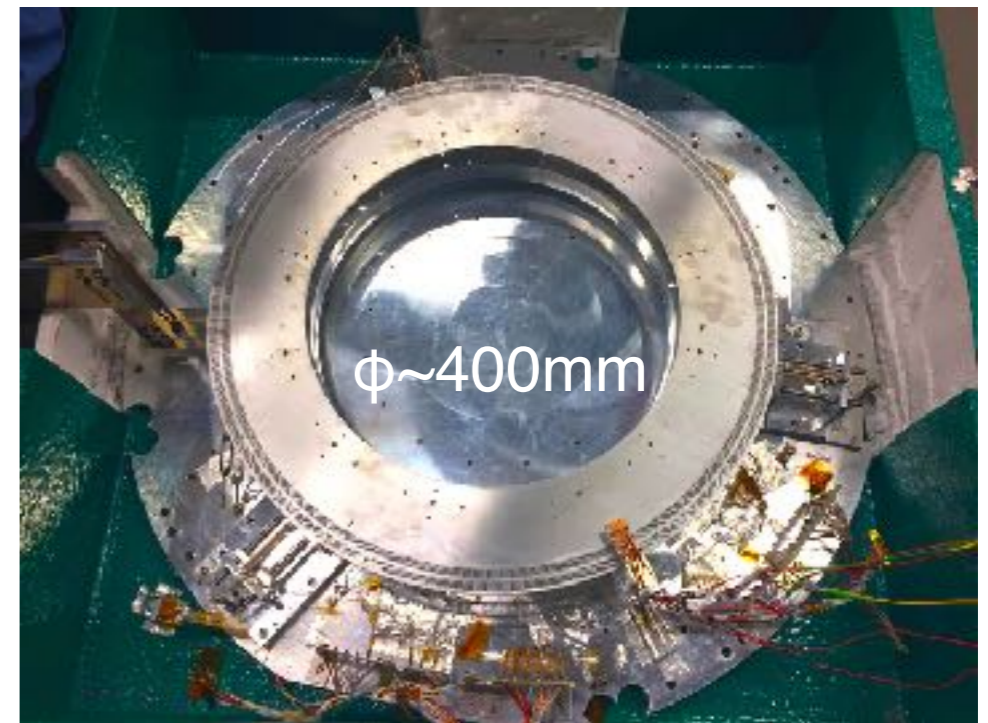
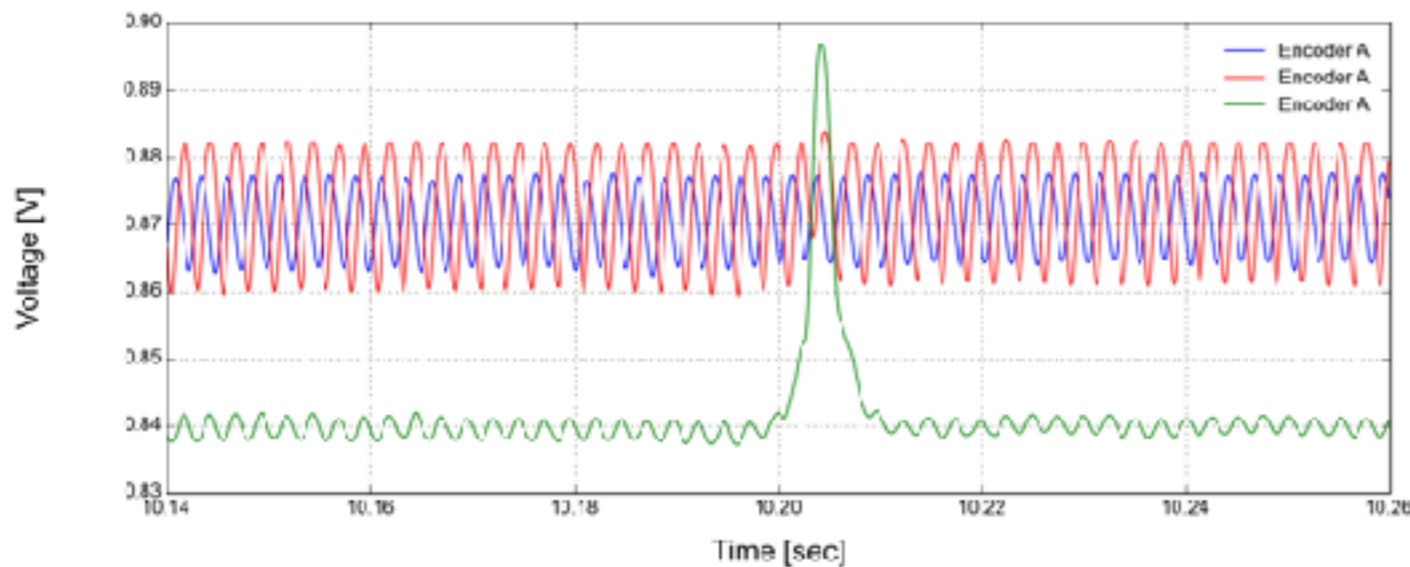




- ✓ Incremental optical encoder (absolute) is employed to reconstruct HWP angle.
- ✓ The encoder consists of LED and Silicon photodiode from Akari satellite heritage. Akari uses them as optical scale in FTS.
- ✓ The heat dissipation from LED $< 40\mu\text{W}$.
- ✓ The reconstruction accuracy $\Delta\theta < 0.001\text{deg}$ considering the rotation speed variation $\Delta f < 0.01\text{Hz}$



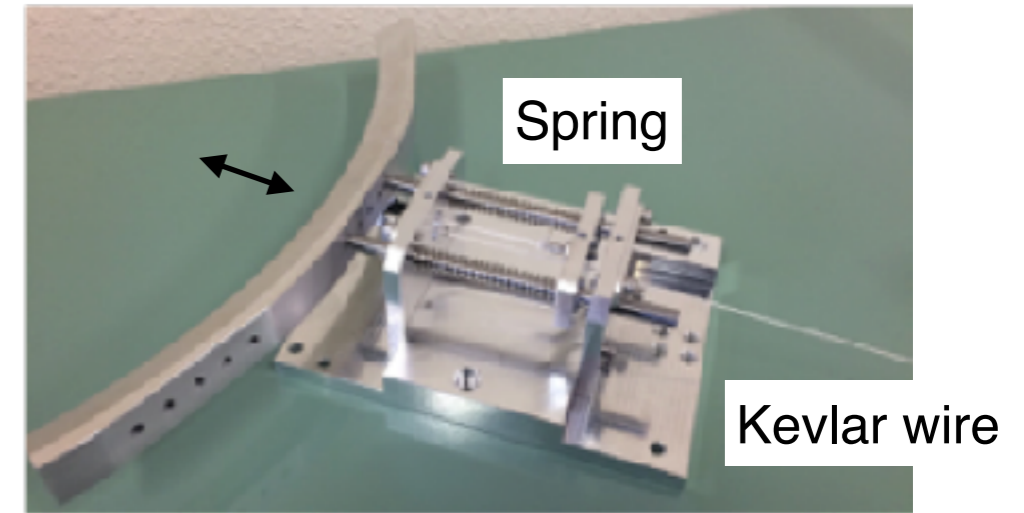
SiPD output



Holder Mechanism

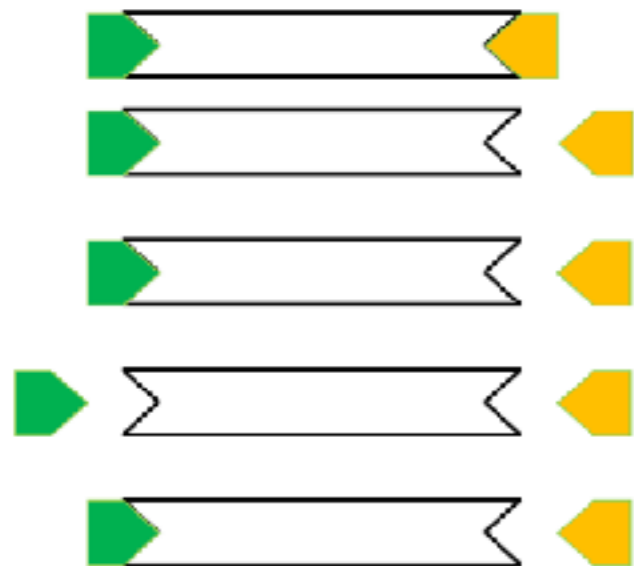


- ✓ The holder mechanism is employed to hold the rotor before levitation and temperature control of the HWP.
- ✓ The mechanism consists of linear actuator + wiring system + cryogenic stepping motor.
- ✓ The stepping motor can be placed at 20K stage to reduce 4K stage heat dissipation.
- ✓ Launch lock system is built separately.



Holder mech.

Launch lock

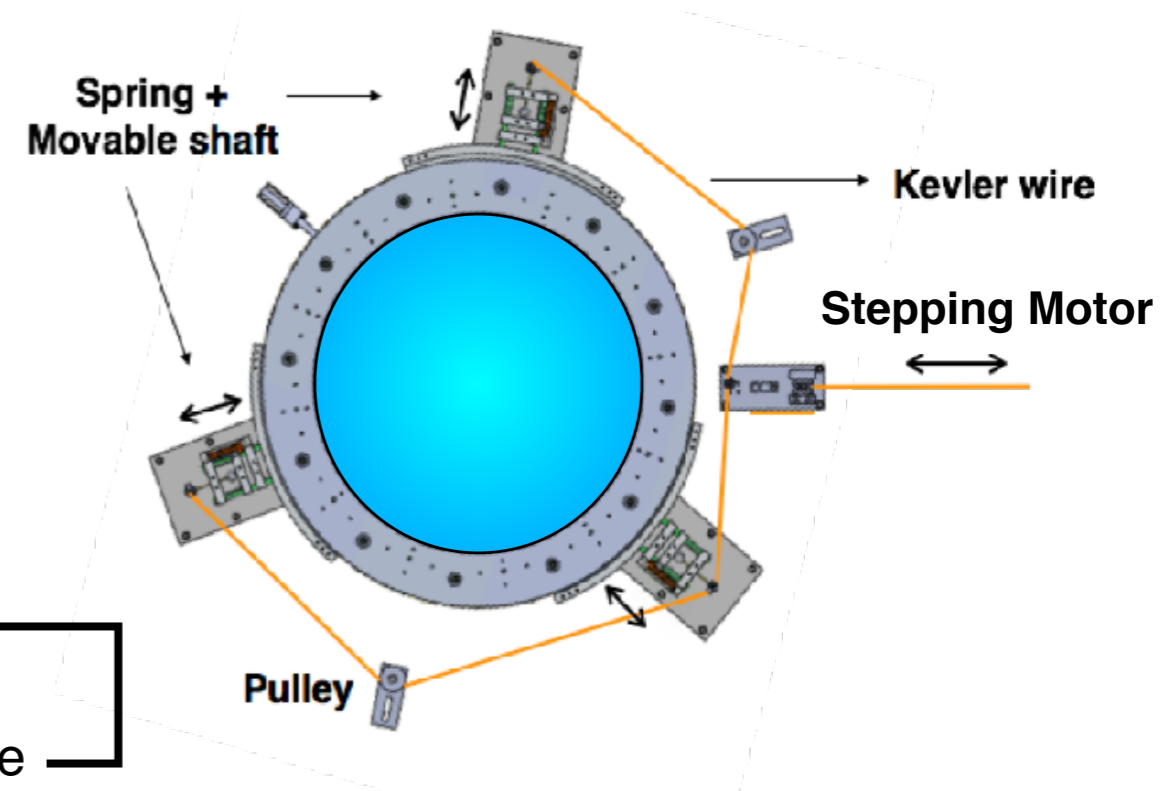


Launch

Release launch lock
Cooldown to 4K

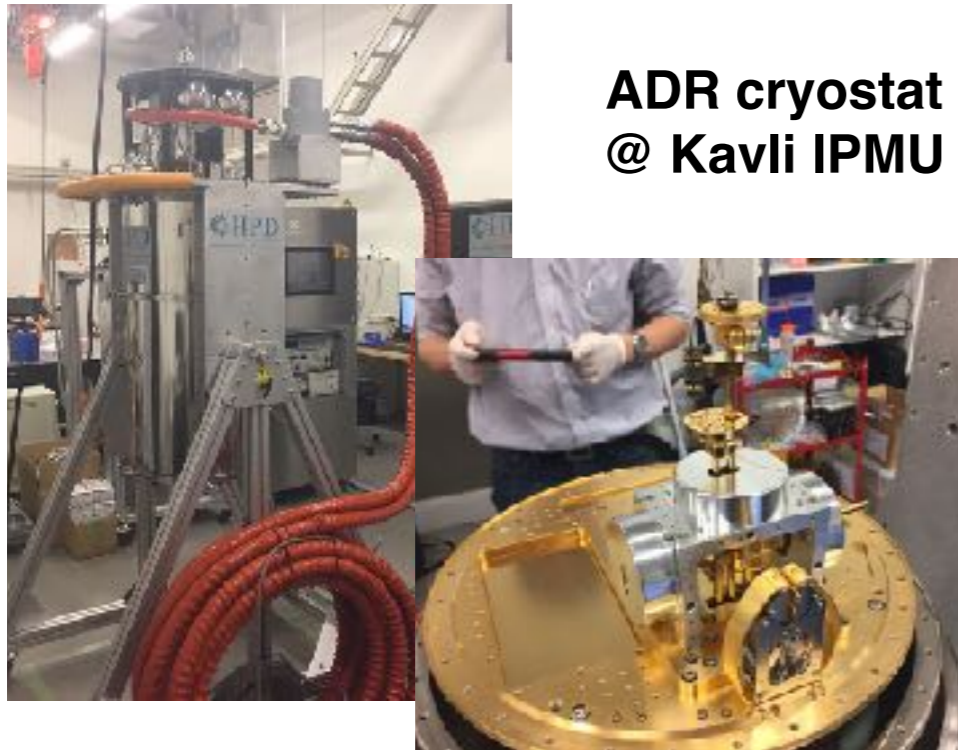
Levitation and observation

HWP cooling during ADR recycle





- ✓ Construction of optical measurement system
- ✓ Modulator controller with FPGA
- ✓ Construction of integrated test system of TES and modulator
- ✓ Cryogenic properties for sapphire, magnet, etc
- ✓ Cosmic ray test of sapphire, magnet, YBCO, etc
- ✓ Remote monitoring system to measure HWP temperature

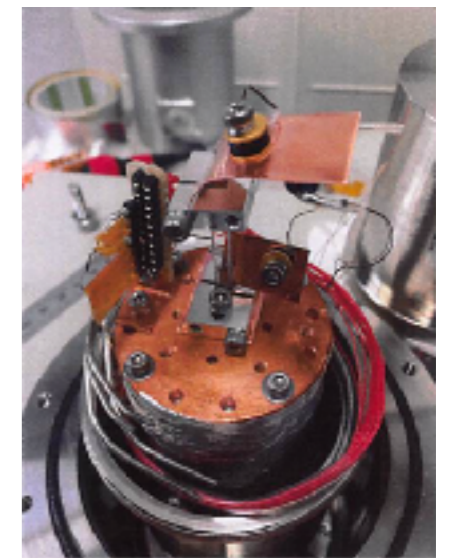


**ADR cryostat
@ Kavli IPMU**

Cosmic ray test @ HIMAC



**Cryogenic property
@ Kitasato Univ.**





- We are developing the polarization modulator for LiteBIRD: broadband HWP and cryogenic (4K) rotation mechanism
- The feasibility of broadband AR and AHWP are demonstrated with small diameter samples.
- ϕ 400mm flight representative demonstration model of cryogenic rotation mechanism is constructed.
- Developments that minimize heat dissipation are progressing: magnetic circuit, high purity Cu coil, wiring system, etc
- We plan to conduct modulator integration test including whole system by Aug. 2018 (the end of JAXA PhaseA-1).

Thank you!

BONUS



- ✓ The inhomogeneity of the magnetic field along the circumference of the rotor magnet causes the rotational frequency variation.
- ✓ Decompose it from total Δf in order to estimate angle accuracy ($\Delta\theta$).
- ✓ Measure Δf from spin down measurement.

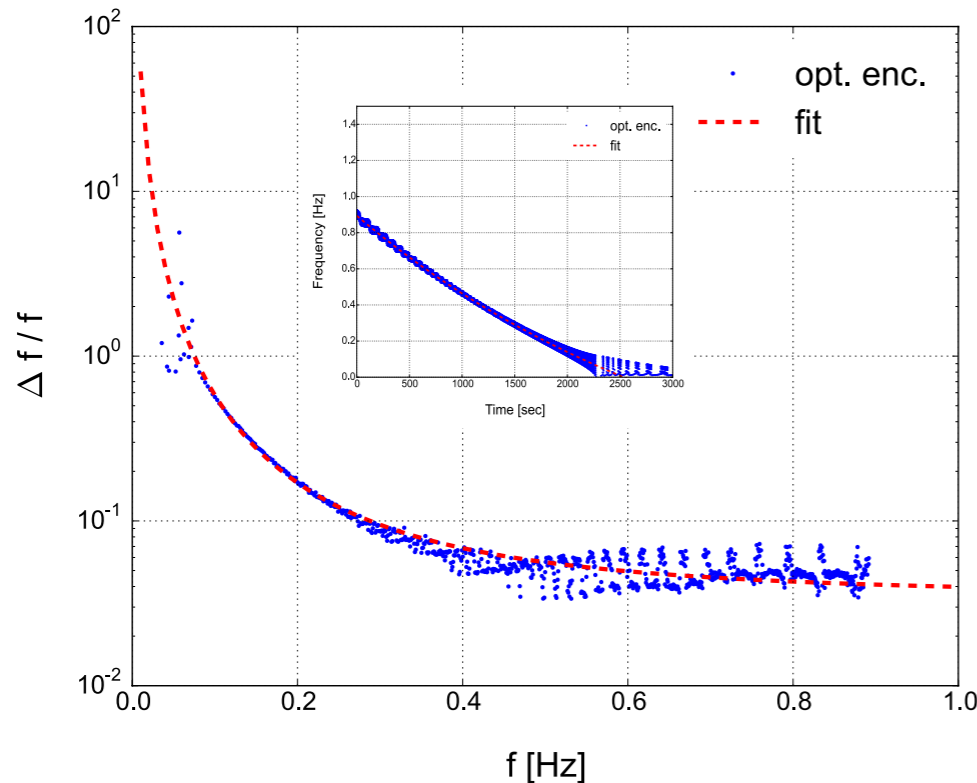
$$\frac{\Delta f}{f} = c_0 + \frac{c_1}{f^2}$$

Δf : frequency variation

f : frequency of one rotation

c_0 : encoder noise component

$\frac{c_1}{f^2}$: inhomogeneity component



$\Delta\theta$ is estimated by c_0 term :

$$\Delta\theta < 0.072\text{deg}$$

Improvement is in progress.

- Increase number of slot
- Noise reduction