LiteBIRD Polarization Modulator

Yuki Sakurai and LiteBIRD HWP team

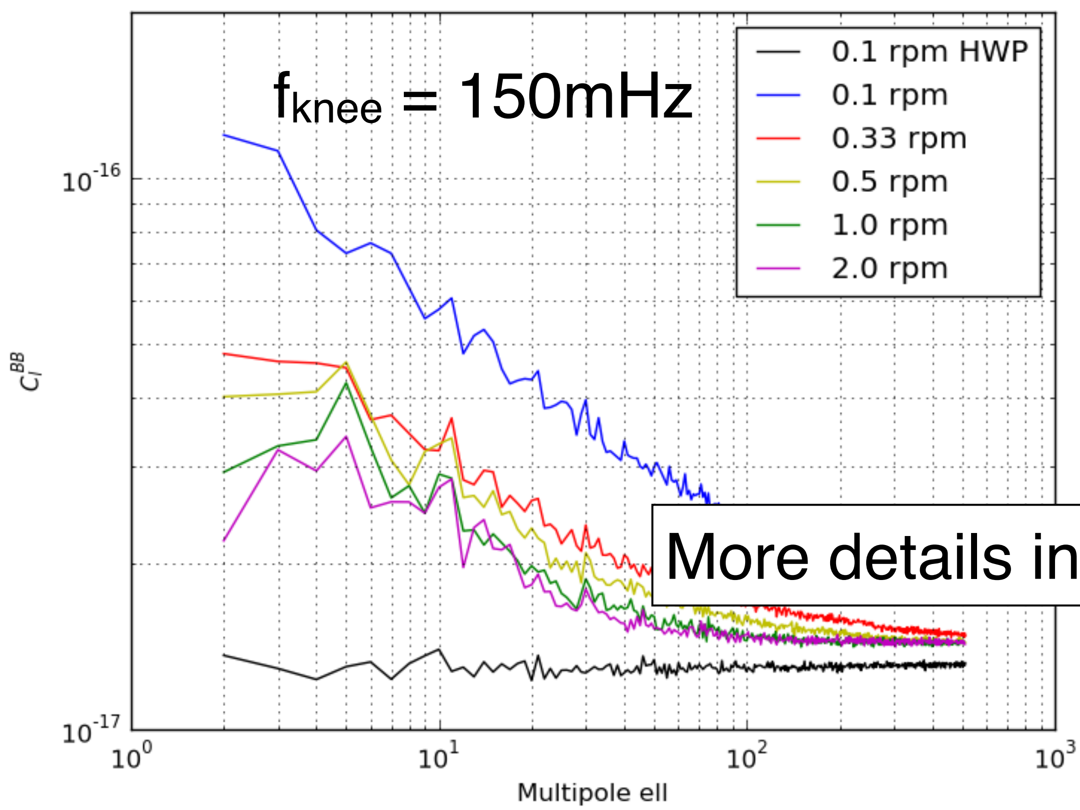
Kavli IPMU

B-mode from space workshop @ Berkeley

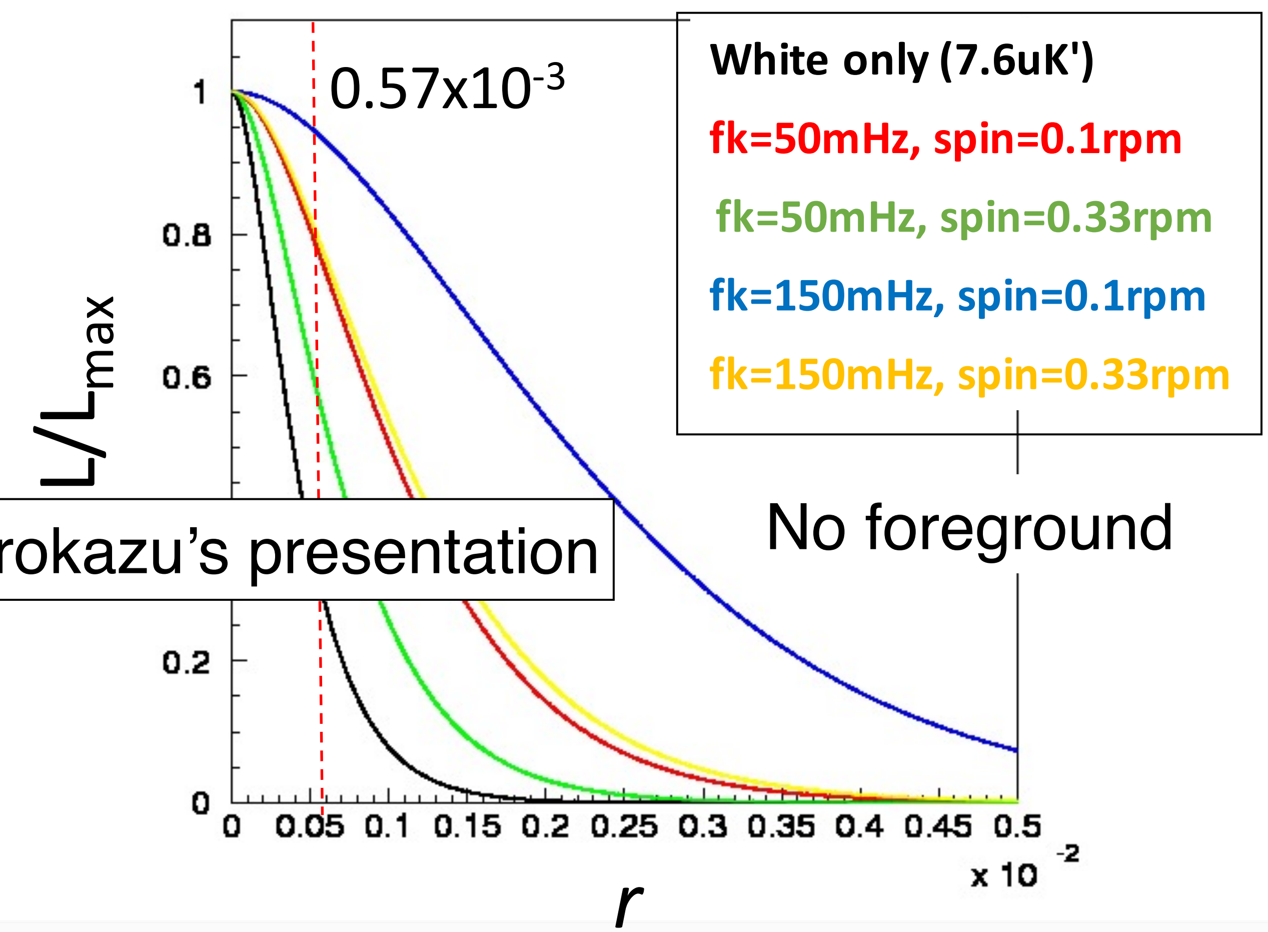
Why do we need modulator for LiteBIRD?

- ✓ 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_{knee} = 150mHz.

The LiteBIRD baseline design employs continuous rotating HWP

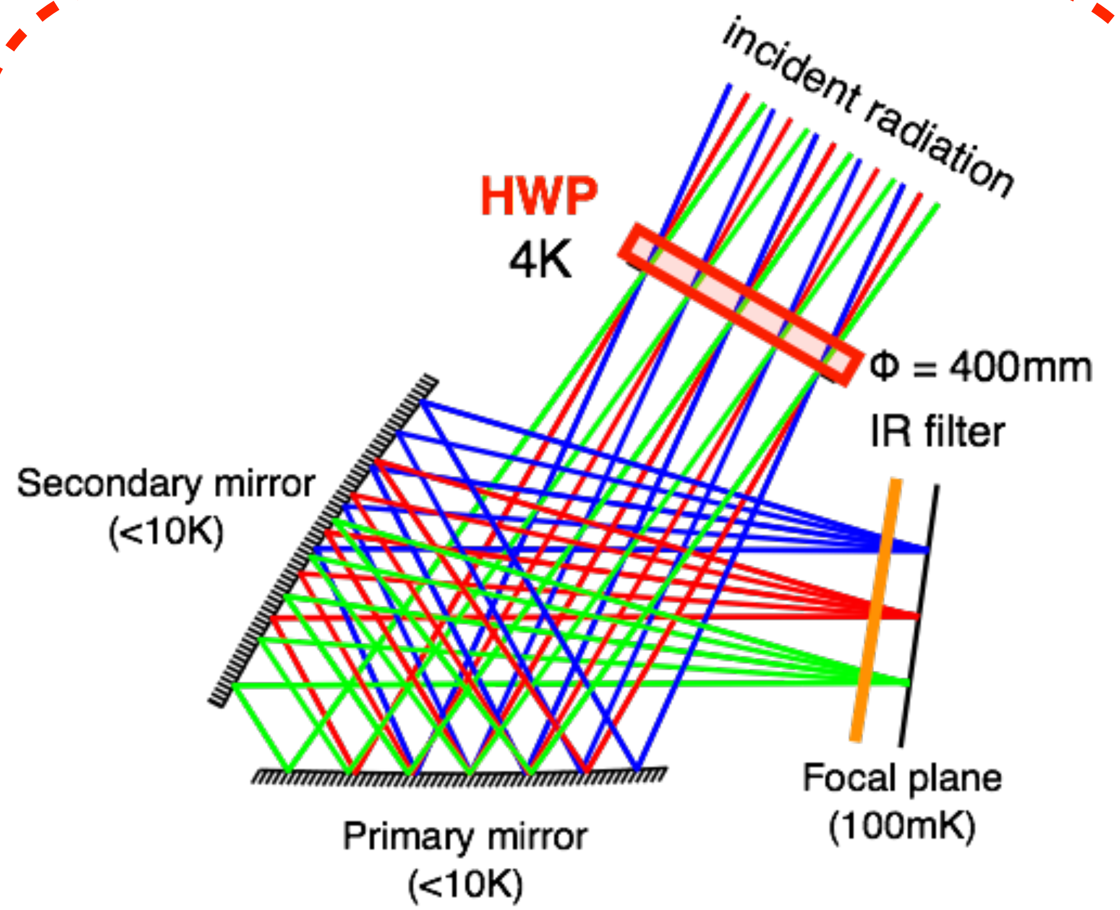


S. Uozumi, T. Kisner, G. Patanchon

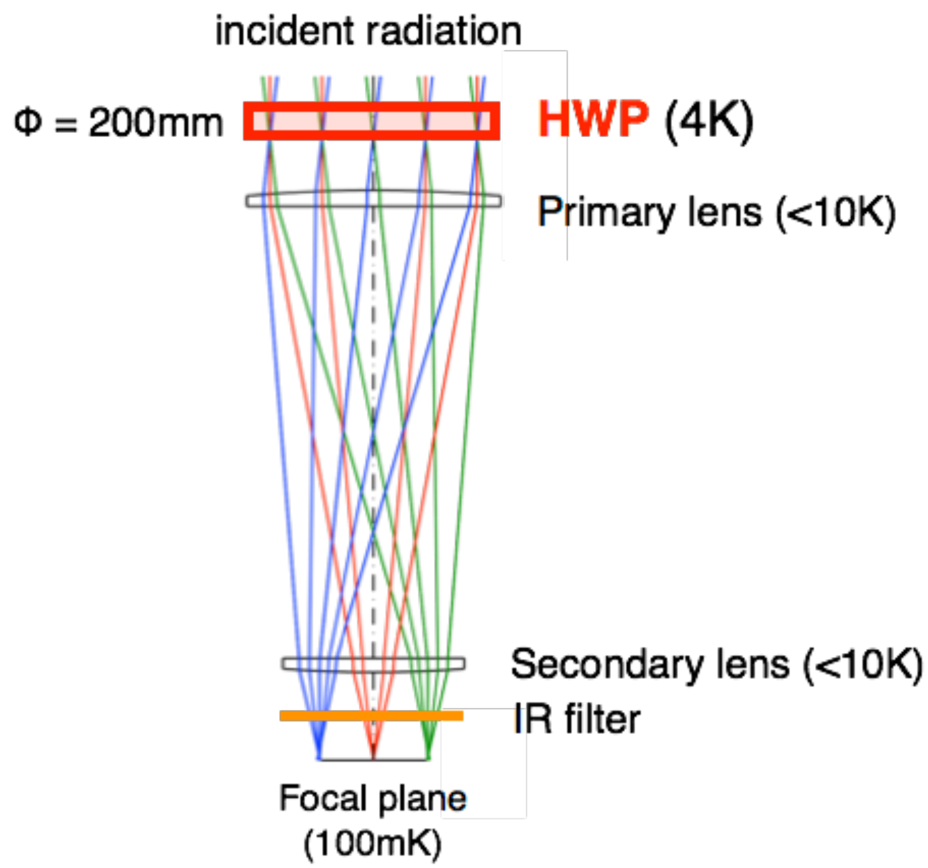


More details in Hirokazu's presentation

LiteBIRD telescopes



Low frequency telescope (LFT)
- Cross-Dragone telescope
- Obs. Band 34～270GHz



High frequency telescope (HFT)
- Refractive telescope
- Obs. Band 238～448 GHz

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

Representative Requirements

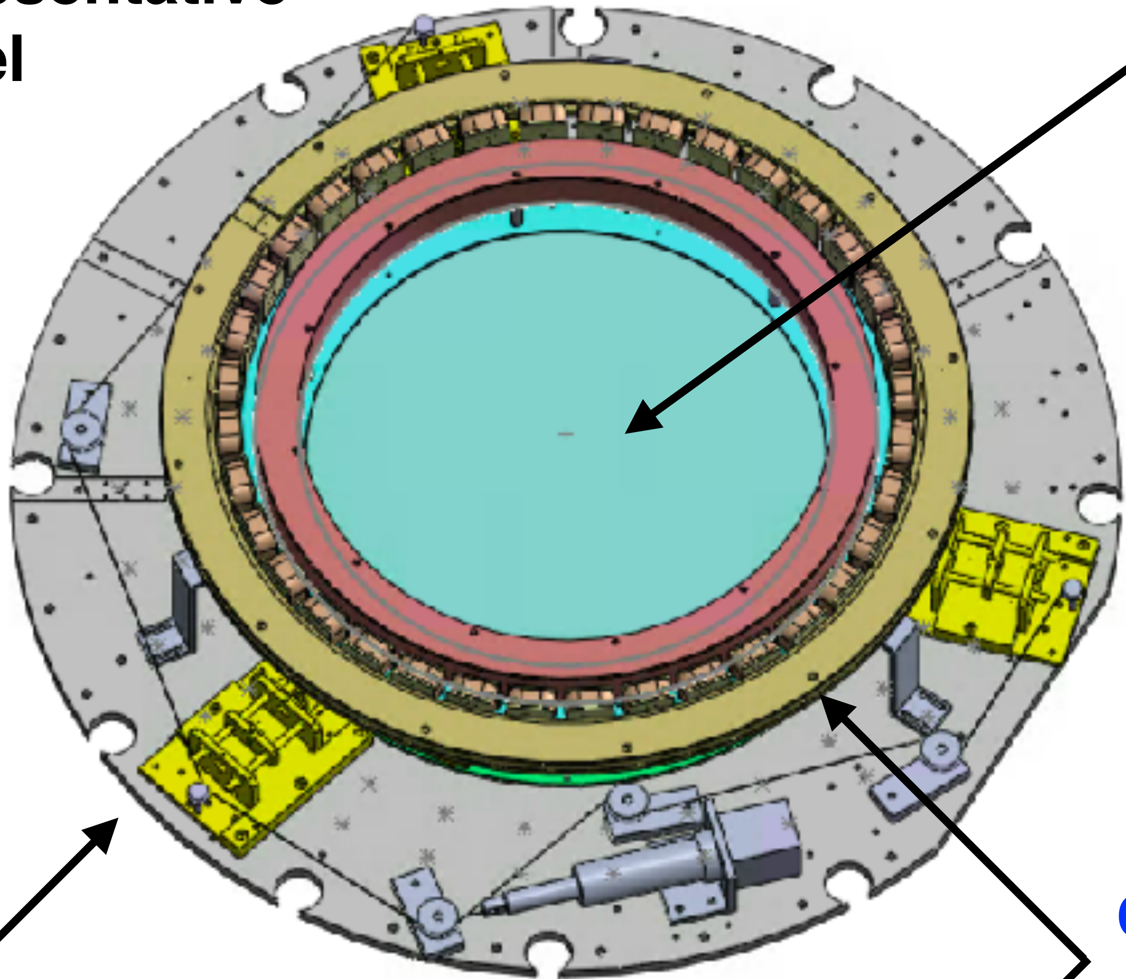
Items	Requirement (LFT)
HWP Transmittaince	> 90% in 34GHz - 270GHz
HWP Modulation Efficiency	> 98% in 34GHz - 270GHz
HWP diameter	~ 450 mm
HWP temperature	< 10 K in 24hour (ADR recycle time)
Total heat dissipation	< ~ 3.5 mW
Rotation frequency	1.2Hz (88RPM)
Encoder specification	< 0.001 degs

Broadband HWP
4K stable continuous rotation
Minimum heat Dissipation

Developing items

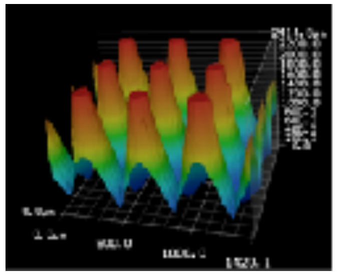
ϕ 400mm flight representative demonstration model

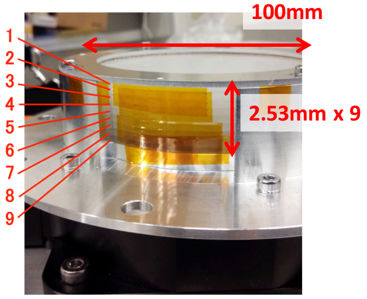
ϕ~1m 4K cryostat

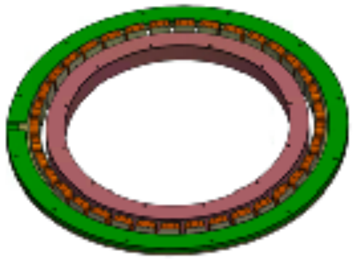


Anti-Reflection (AR)

Achromatic HWP (AHWP)



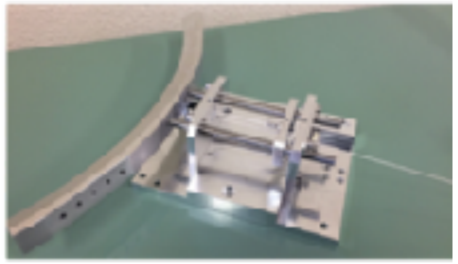


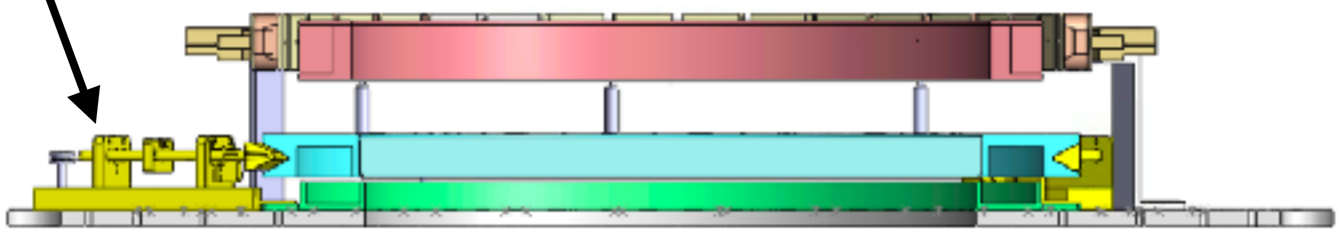


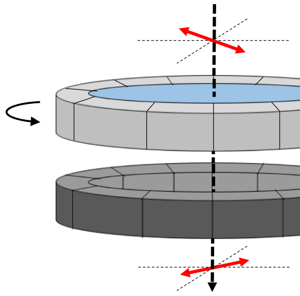
Cryogenic Synchronous Motor

Encoding System

Gripper Mechanism



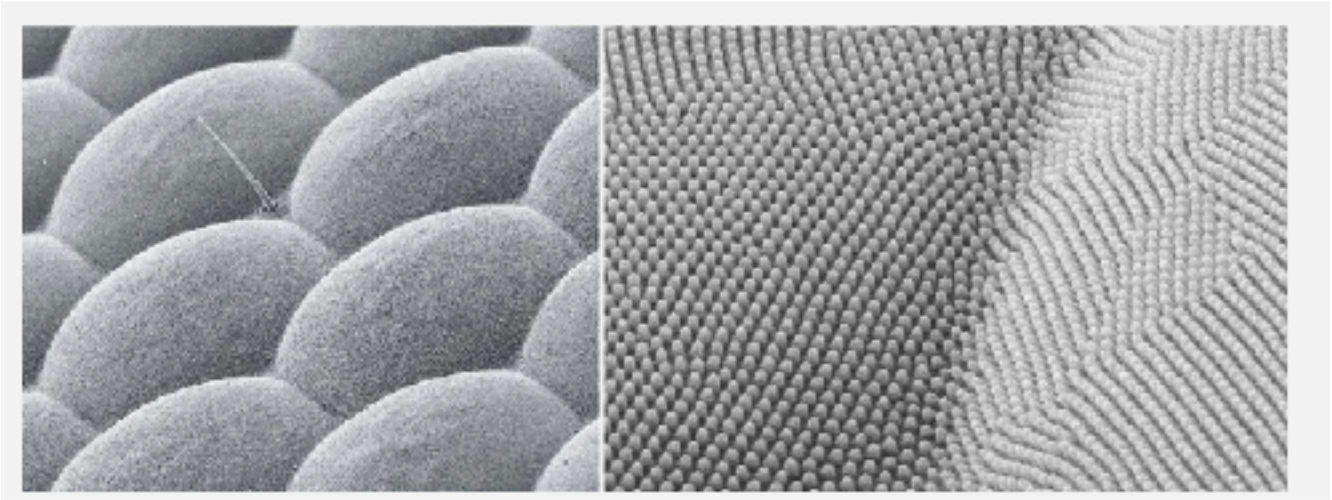




Superconducting Magnetic Bearing

Broadband AR structure

- ✓ 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.

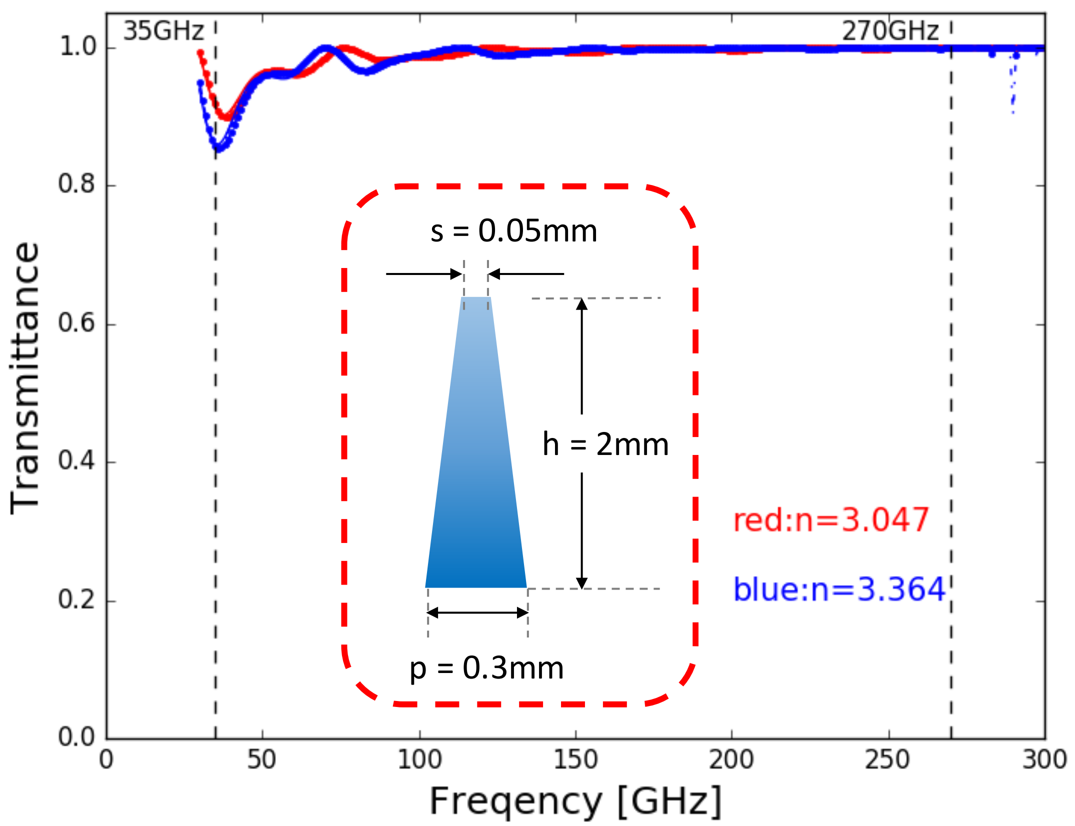


https://asknature.org/idea/moth-eye-antireflective-coatings/#.Wh0XWLaKUdU

AR Structure

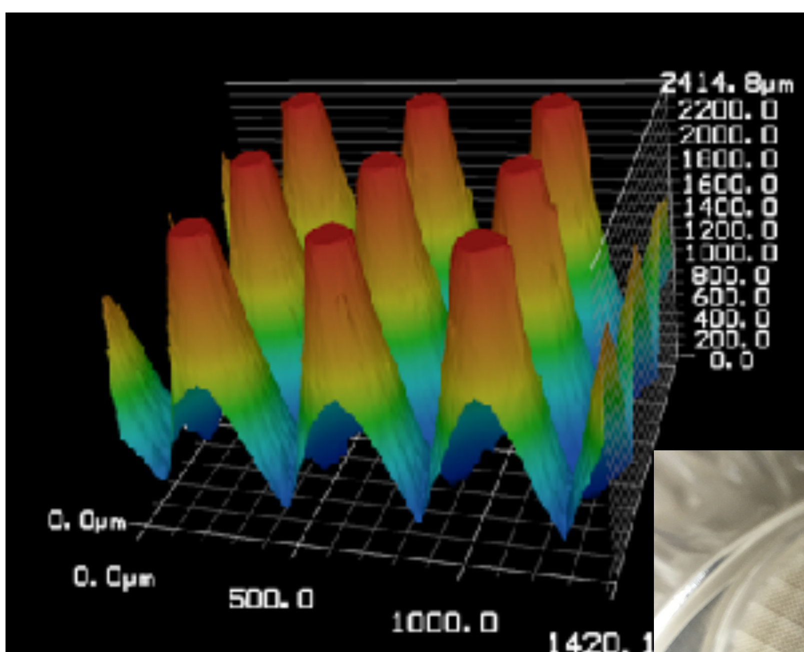
AR Structure

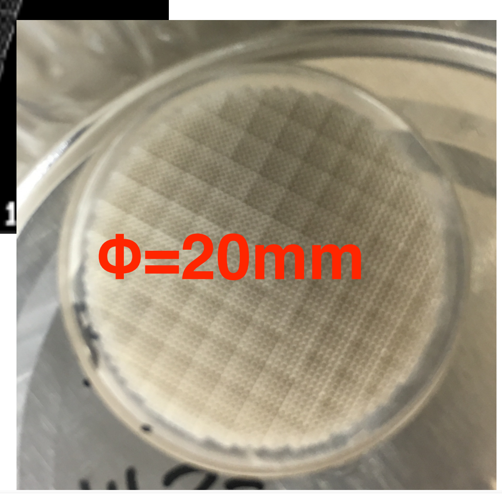
performance with designed pyramid shape



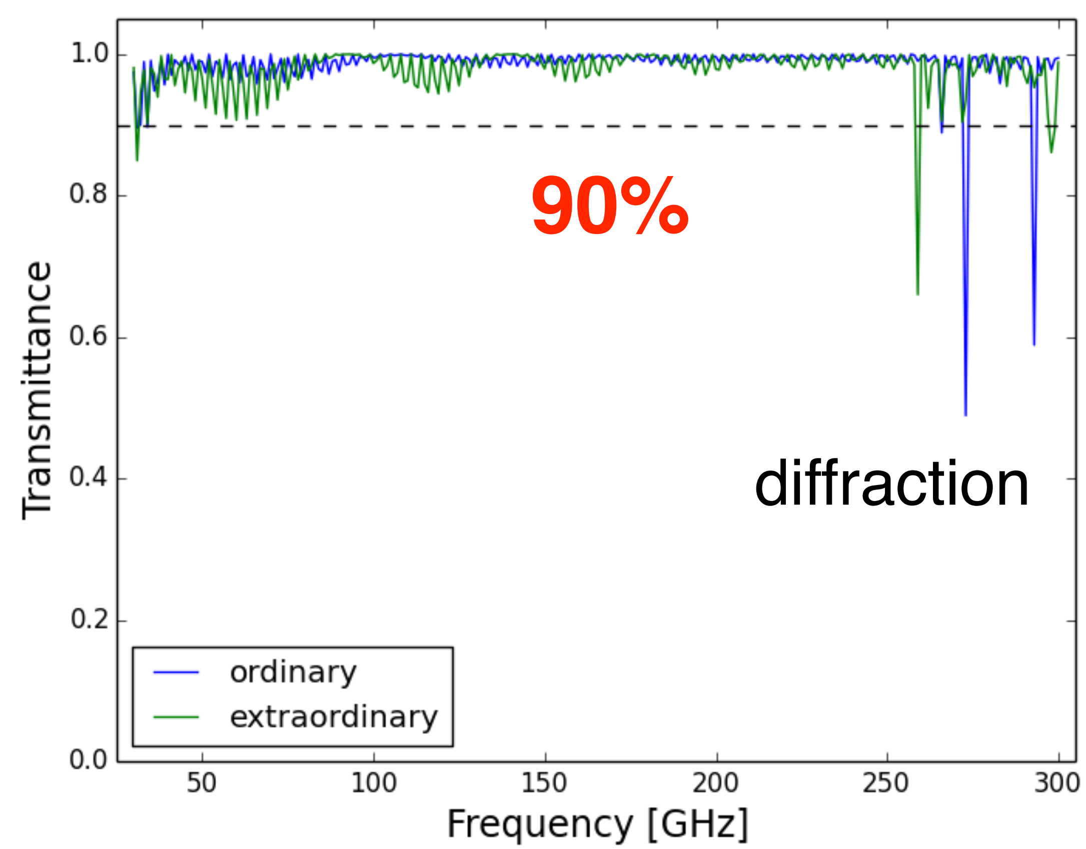
Broadband AR structure

- ✓ Moth-eye structure is fabricated on the sapphire using a **laser machining**.
- ✓ Current best fabricated sample is with **p = 400µm, h = 2.3mm**, s = 100µm.
- ✓ 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?



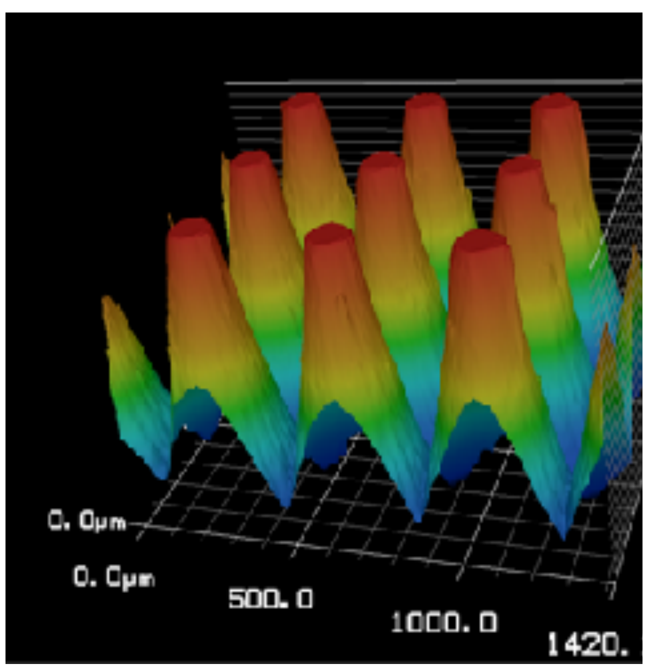


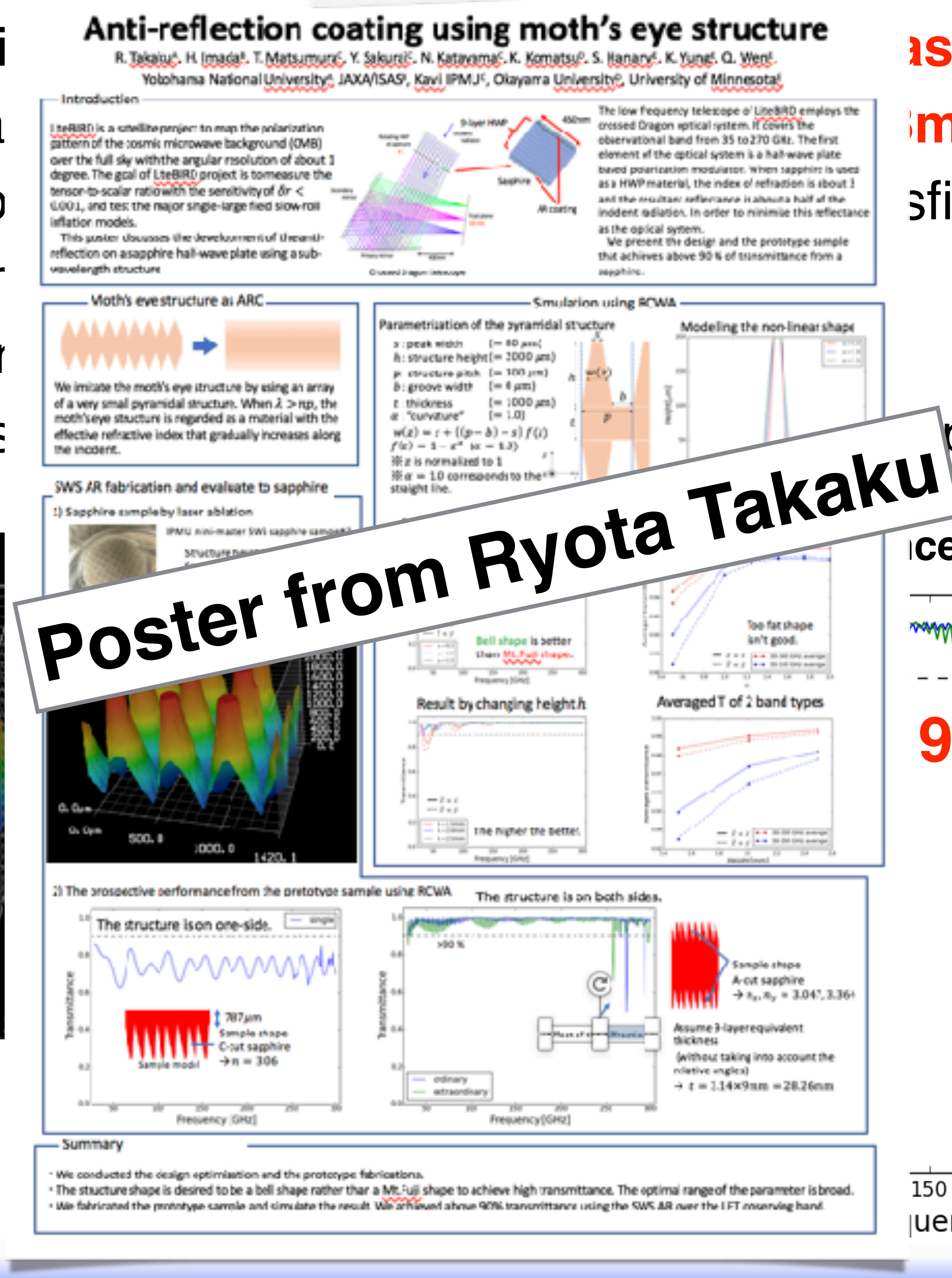
Simulated performance with fabricated structure

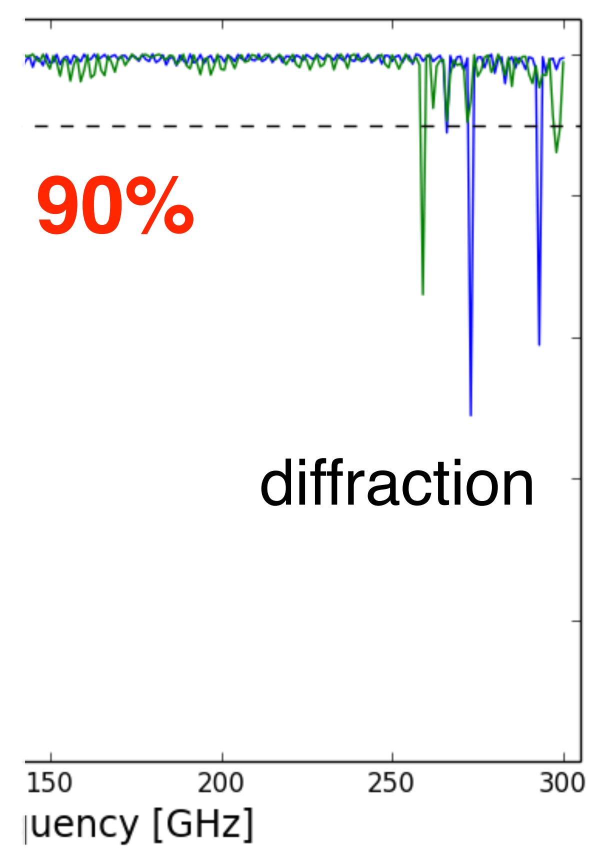


Broadband AR structure

- ✓ Moth-eye structure i ... aser machining.
- ✓ Current best fabrica ... mm, s = 100µm.
- ✓ The simulated perfo ... sfied the requirement except for diffractior
- ✓ Several developmer ... pico, nano, femto s ... power laser?

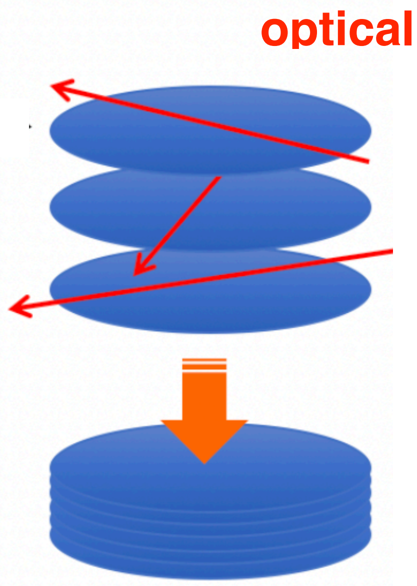


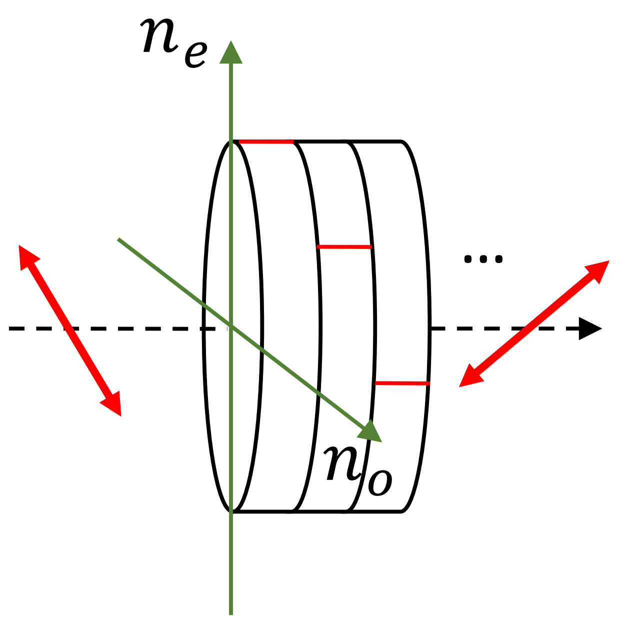




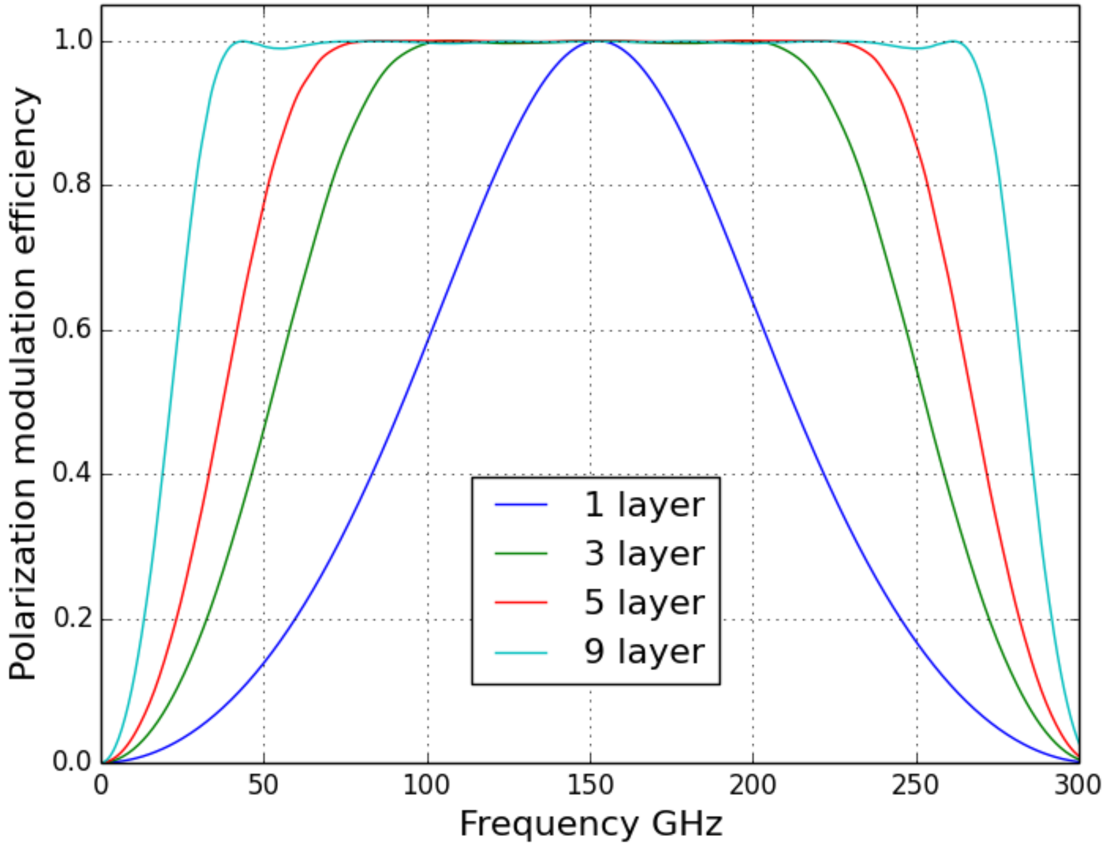
Broadband Achromatic HWP

- ✓ 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.



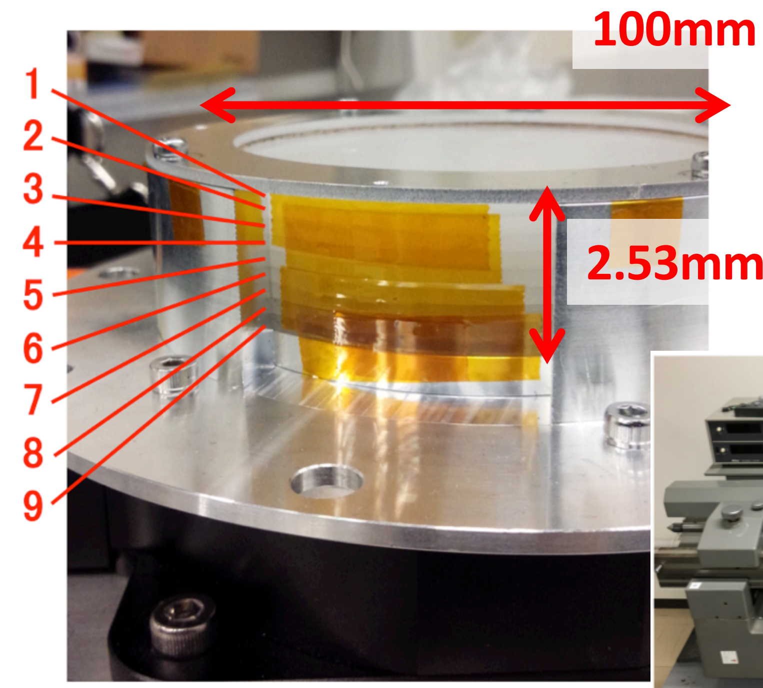


performance with ideal case

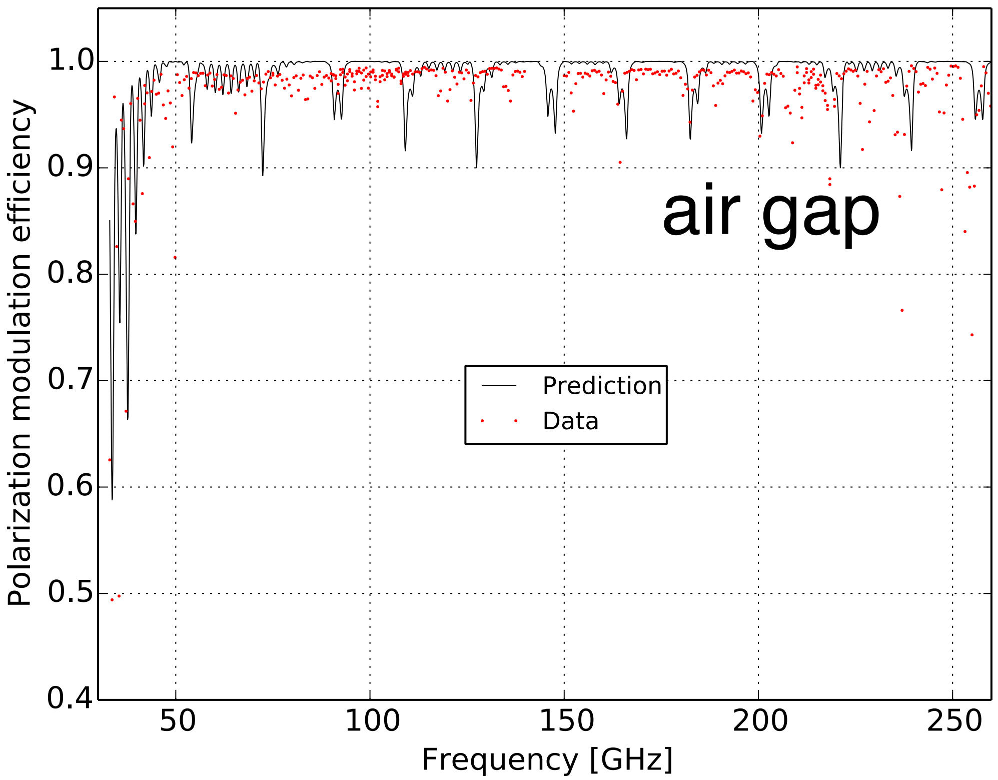


Broadband Achromatic HWP

- ✓ 9 layer sapphire AHWP with ϕ=100mm 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 ϕ=400mm model.
- ✓ In parallel, We are devising a design with reduced number of layer.

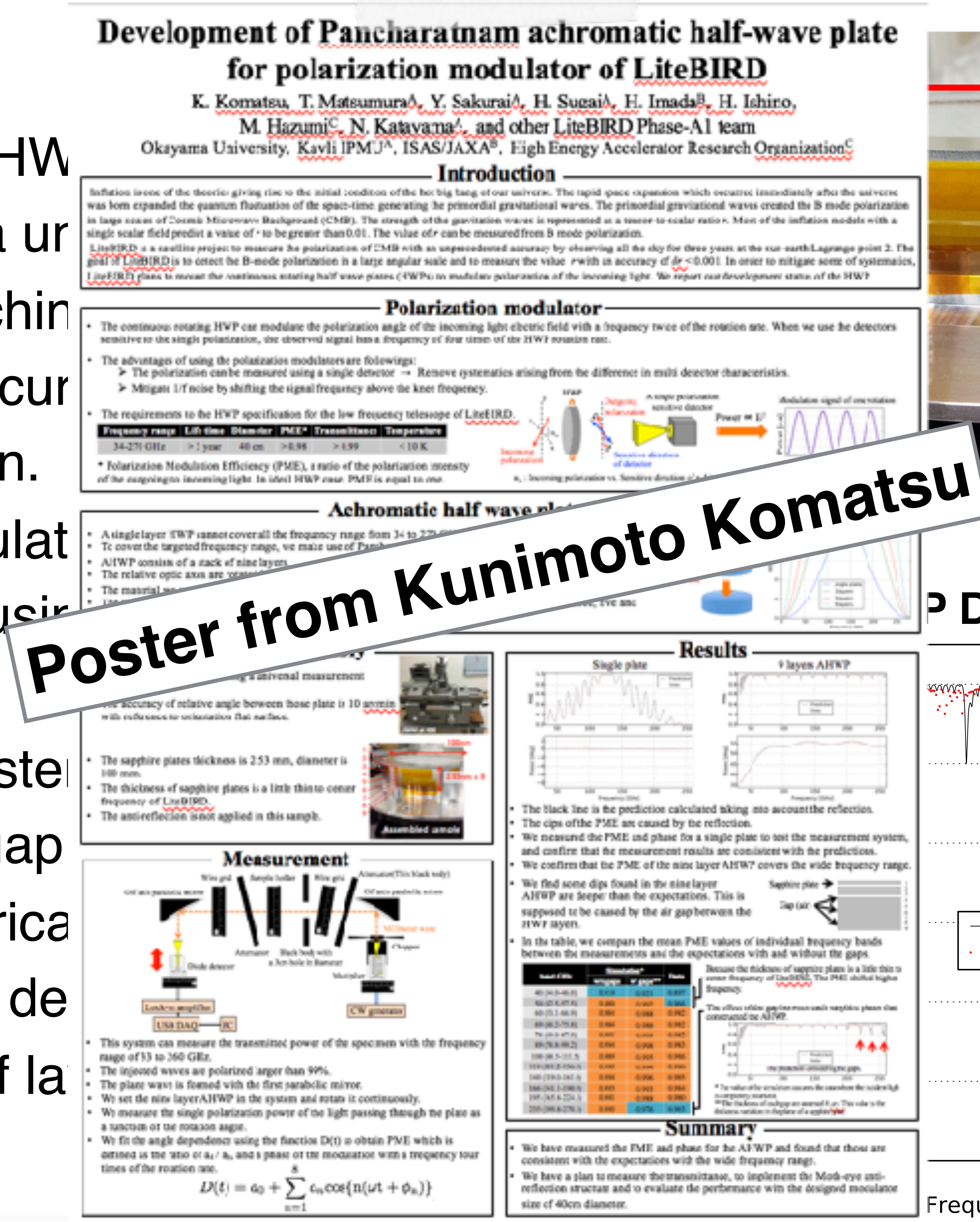


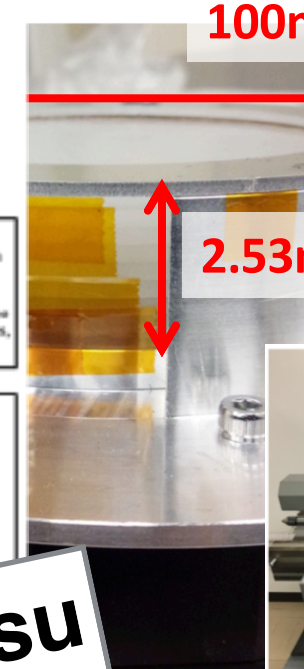
9 layer AHWP Data v.s Prediction

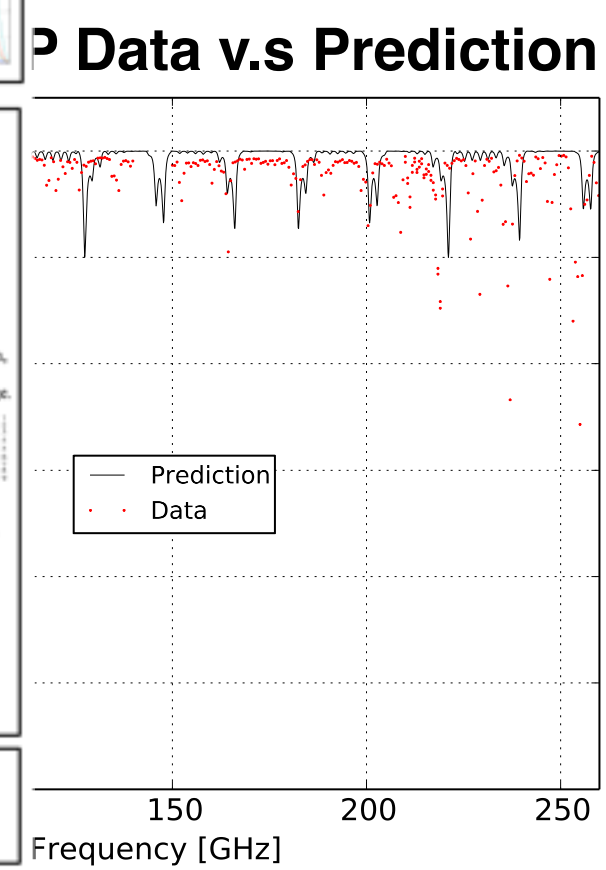


Broadband Achromatic HWP

- ✓ 9 layer sapphire AHW
  assembled using a ur
  measurement machin
  The assembled accur
  angle is <10 arcmin.
- ✓ We measure modulat
  fabricated AHWP usir
  @ Kavli IPMU
- ✓ The result is consiste
  except for the air gap
- ✓ Next step is to fabrica
- ✓ In parallel, We are de
  reduced number of la

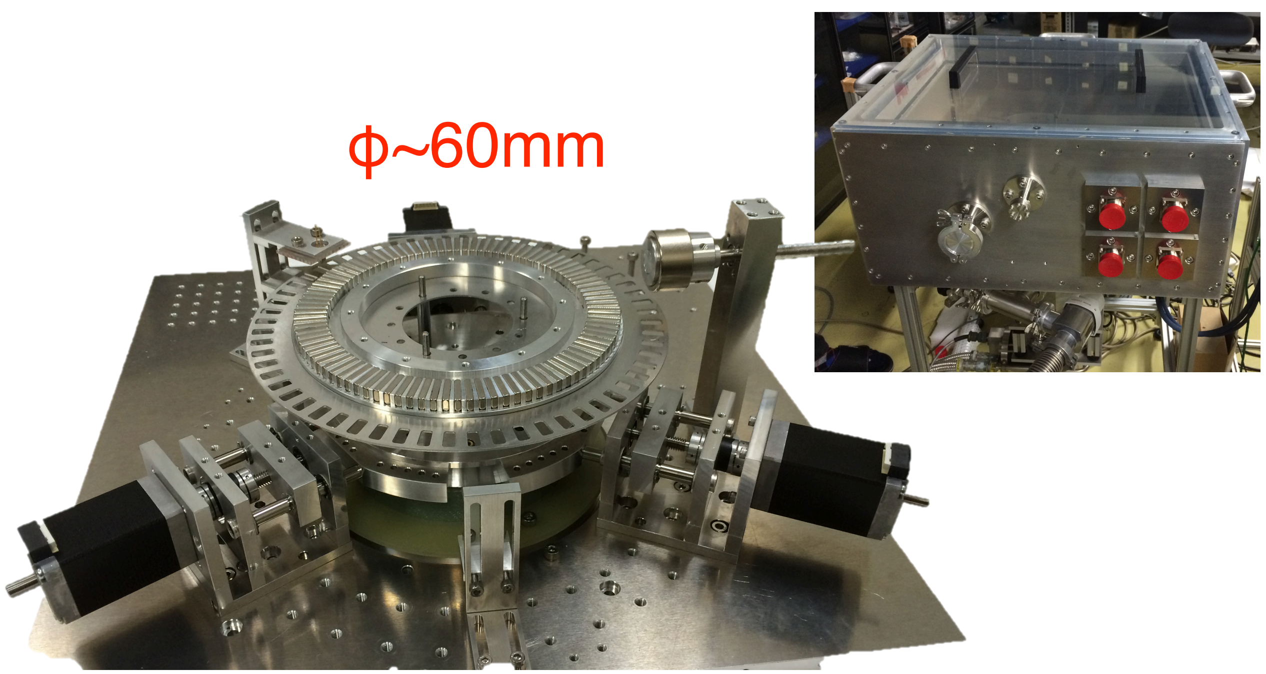




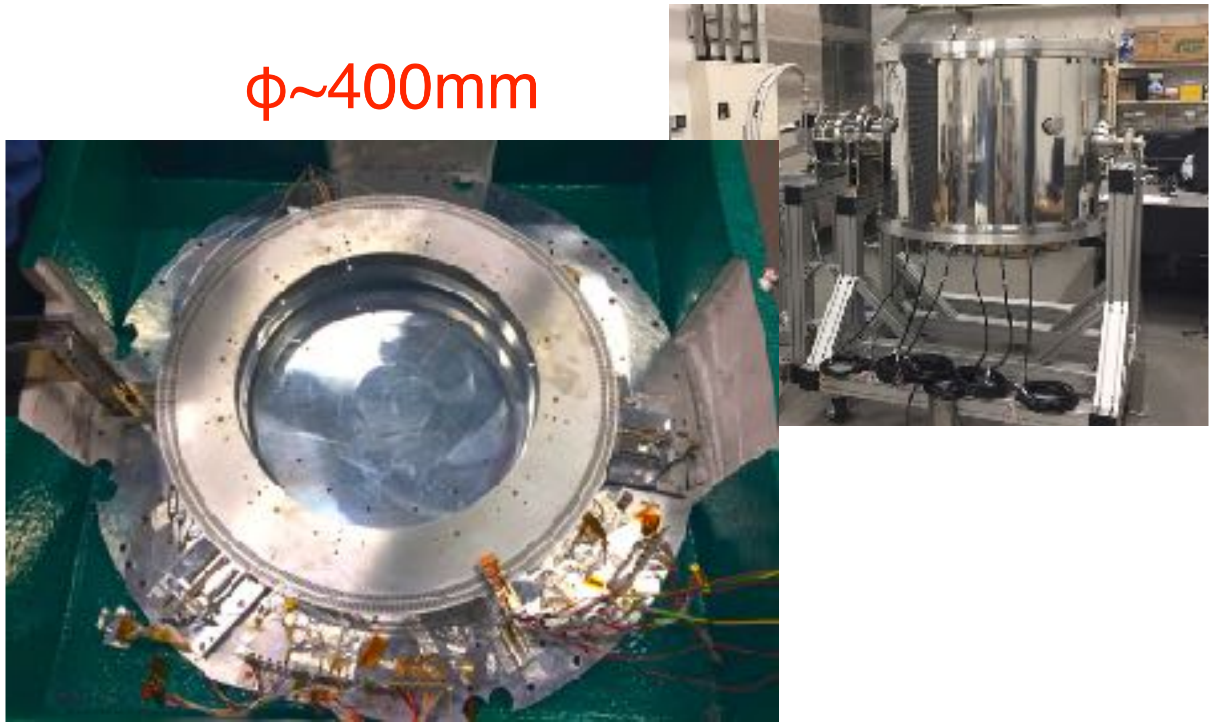


Cryogenic Rotation Mechanism

- ✓ The feasibility study of cryogenic rotation in 4K environment is almost done using ϕ~60mm small prototype
- ✓ We constructed a flight representative demonstration model with ϕ400mm 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.



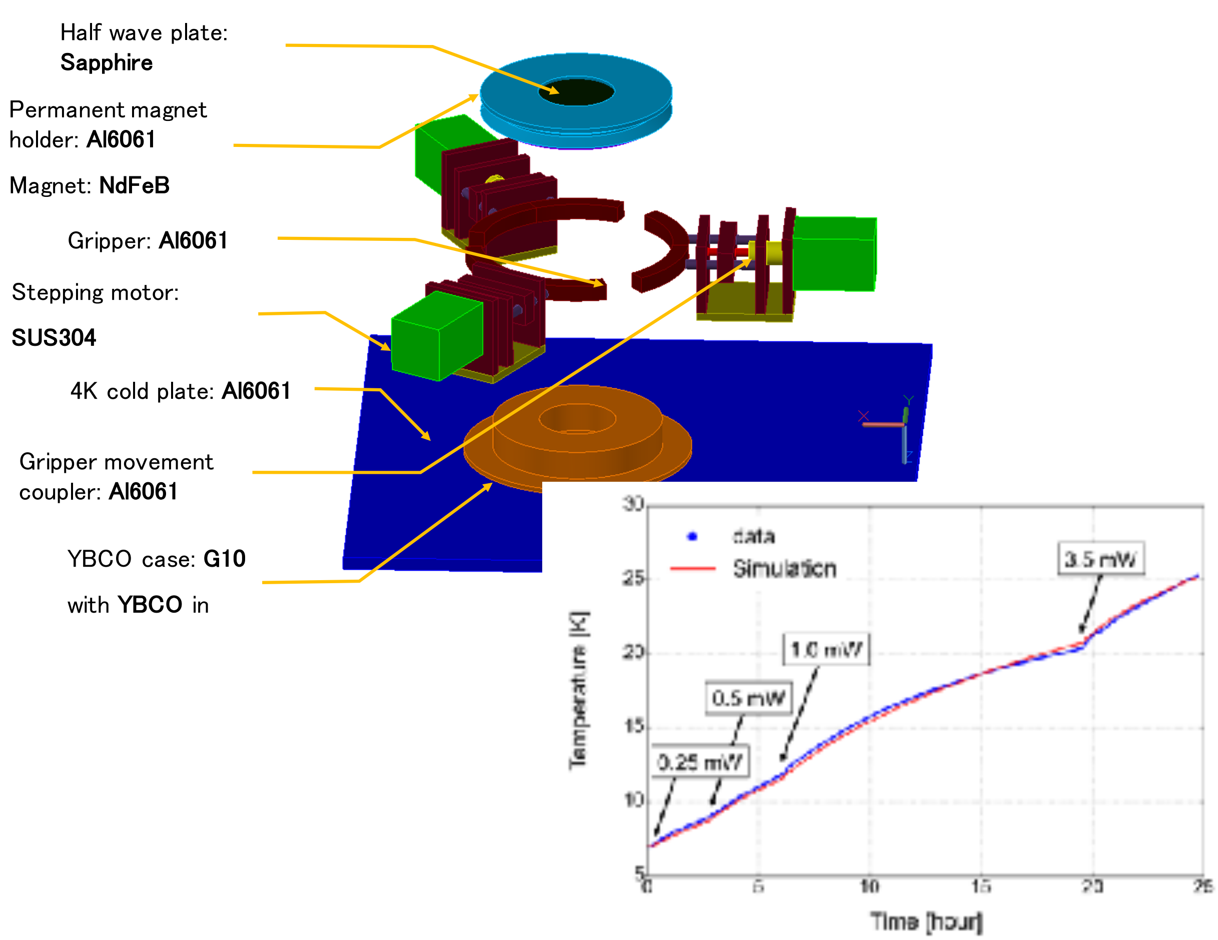
Small prototype



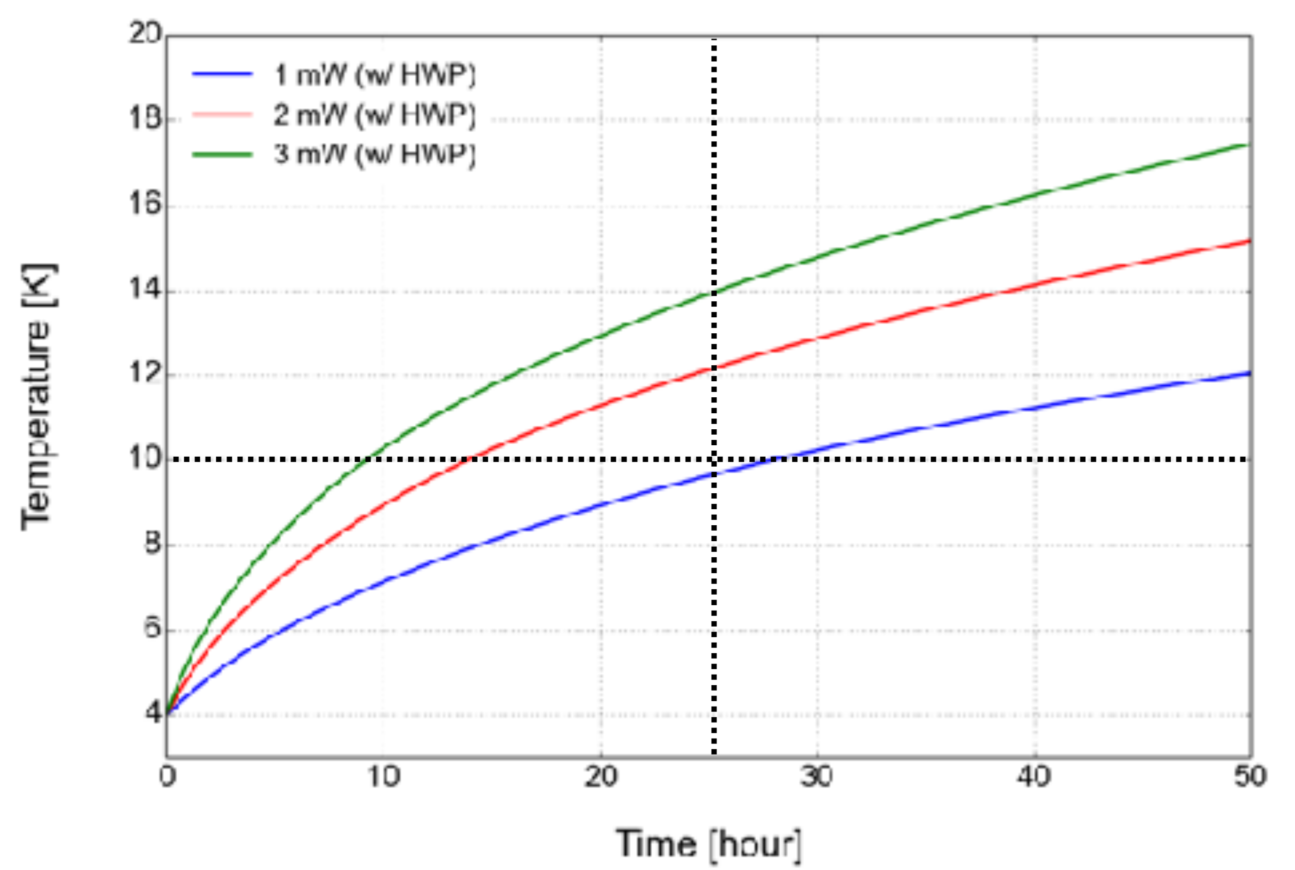
Demonstration model

Thermal Modeling

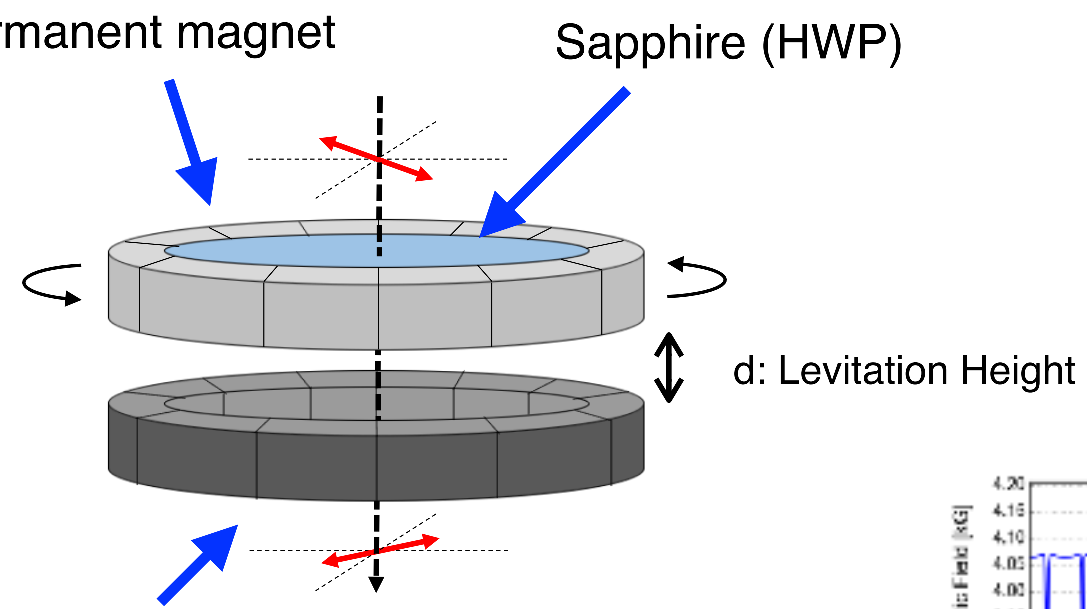
- ✓ Using small diameter prototype, the data from a levitating rotor with a heater and a temperature sensor are compared with a thermal model by ThermalDesktop Simulation.
- ✓ The model is agree within a few degrees by fitting unknown parameter: heat capacity of permanent magnet at cryogenic temperature.
- ✓ 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!



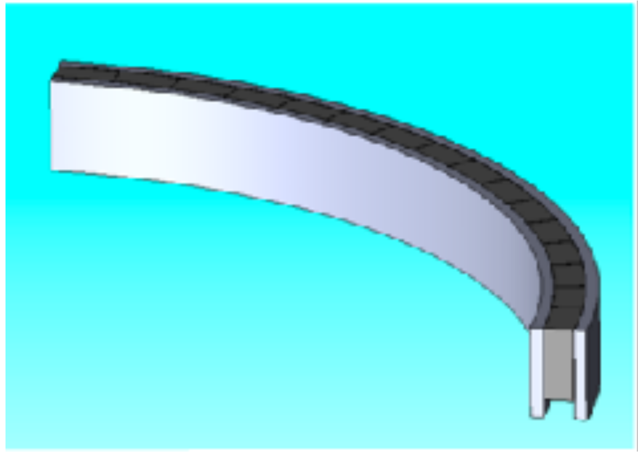
Thermal performance of levitating rotor w/ HWP

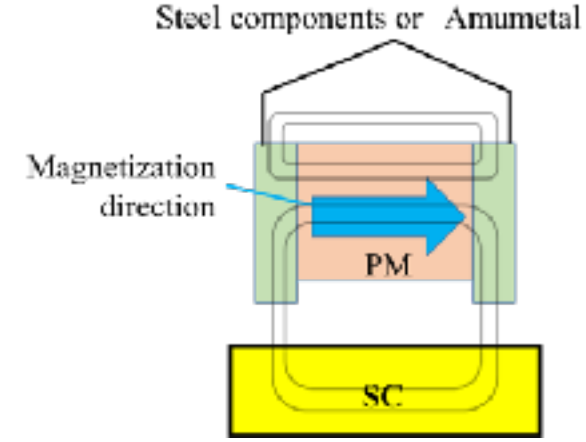


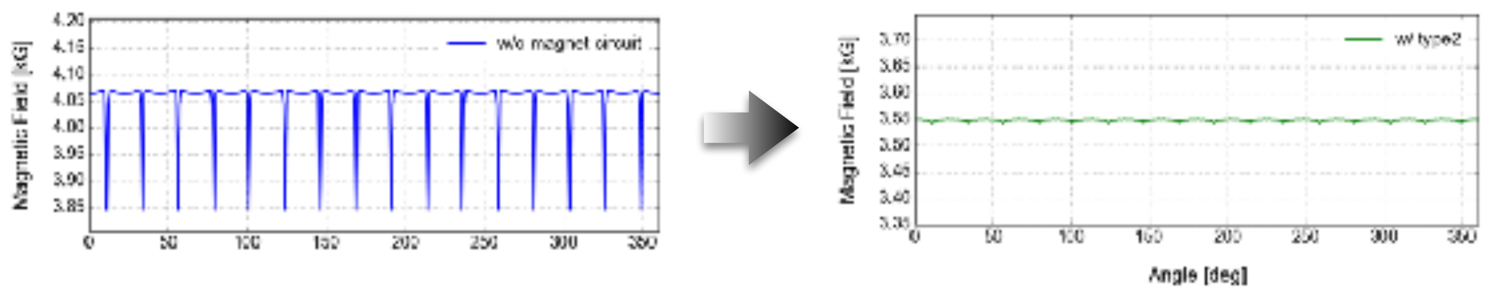
Superconducting Magnetic Bearing



High Temperature Superconducting:
YBCO (T_C=94K)



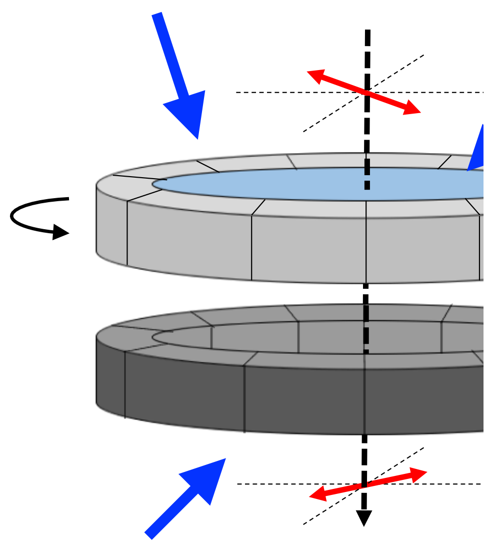


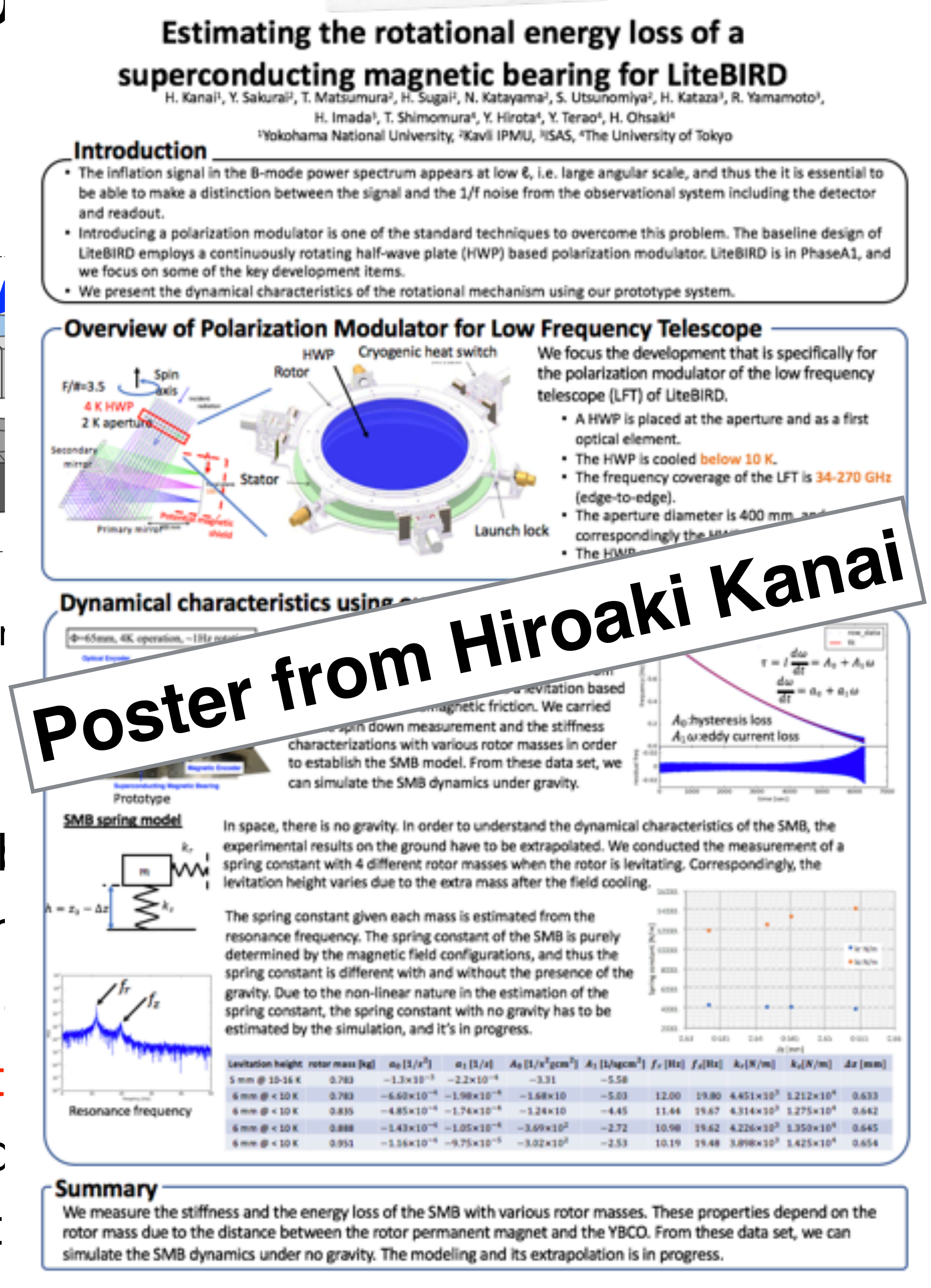


ΔB/B : 7%→ 1%, |B| : 4kG → 3.5kG

- ✓ 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.

Sup… Bearing





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

H. Kanai[1], Y. Sakurai[2], T. Matsumura[2], H. Sugai[2], N. Katayama[2], S. Utsunomiya[2], H. Kataza[3], R. Yamamoto[3], H. Imada[3], T. Shimomura[1], Y. Hirota[4], Y. Terao[4], H. Ohsaki[4]

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

Introduction

- The inflation signal in the B-mode power spectrum appears at low ℓ, i.e. large angular scale, and thus the 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 PhaseA1, 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 … corresponding the …
- The HWP …

Dynamical characteristics using …

…levitation based …magnetic friction. We carried … spin down measurement and the stiffness characterizations with various rotor masses in order to establish the SMB model. From these data set, we can simulate the SMB dynamics under gravity.

Prototype

$\tau = I\frac{d\omega}{dt} = A_0 + A_1\omega$

$\frac{d\omega}{dt} = a_0 + a_1\omega$

A_0: hysteresis loss

$A_1\omega$: eddy current loss

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.

$h = z_0 - \Delta z$

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.

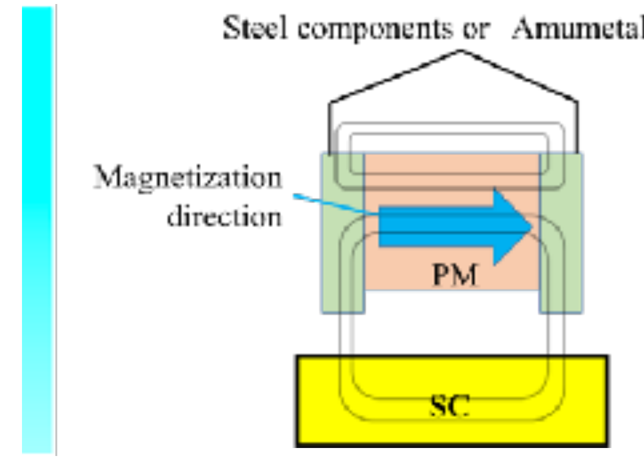
Resonance frequency

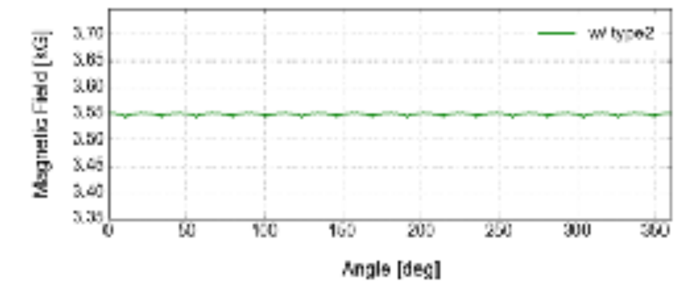
Levitation height	rotor mass [kg]	a_0 [1/s²]	a_1 [1/s]	A_0 [1/s²gcm²]	A_1 [1/sgcm²]	f_z [Hz]	f_r [Hz]	k_z [N/m]	k_r [N/m]	Δz [mm]
5 mm @ 10-16 K	0.783	-1.3×10^{-3}	-2.2×10^{-4}	−3.31	−5.58					
6 mm @ < 10 K	0.783	-6.60×10^{-4}	-1.98×10^{-4}	-1.68×10	−5.03	12.00	19.80	4.451×10^{3}	1.212×10^{4}	0.633
6 mm @ < 10 K	0.835	-4.85×10^{-4}	-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^{-4}	-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^{-4}	-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.

Poster from Hiroaki Kanai



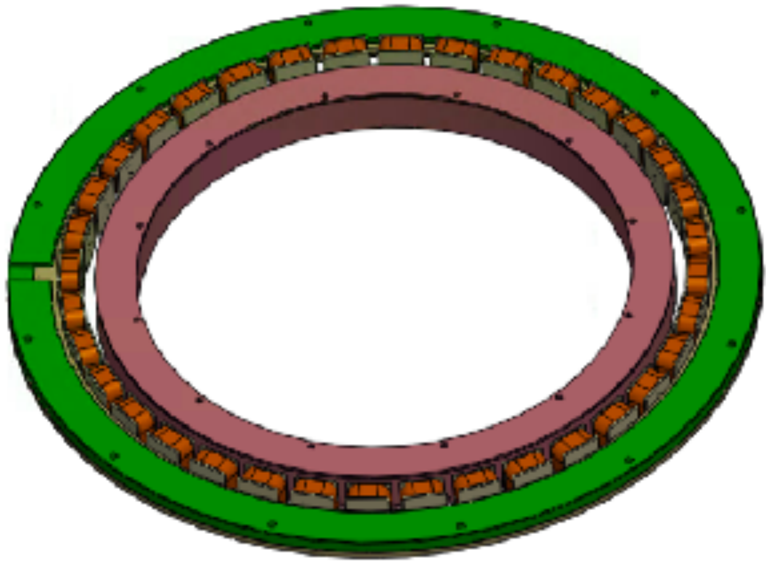


…l : 4kG → 3.5kG

- ✓ Contactless l… …uctor and a permanent m…
- ✓ Remaining h… …dy current
  - → Magnet…
- ✓ We designec… …eneity and stiffness.
- ✓ New magnet… …o. 2018.

Cryogenic Synchronous Motor

- ✓ 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 ϕ=400mm.
- ✓ 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

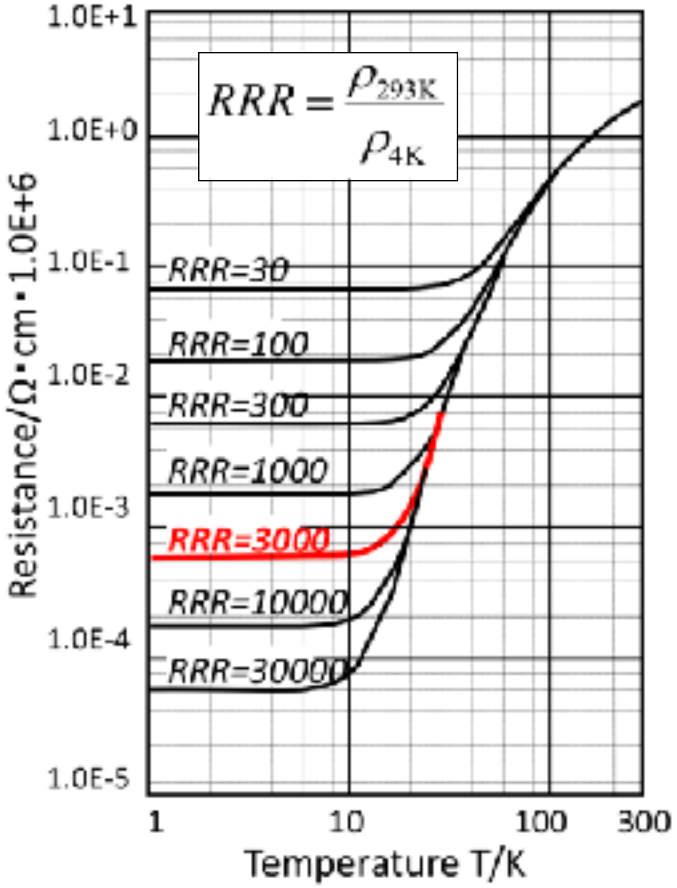
Formed into a coil

RRR ~ 100

Annealing

RRR ~ 350

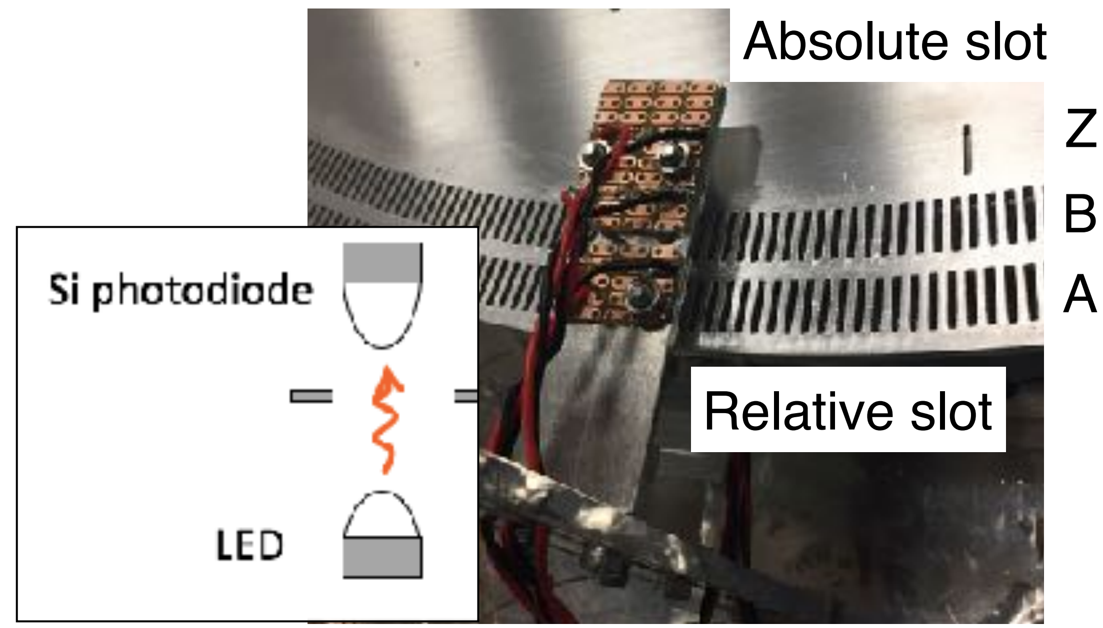
LHe cryostat



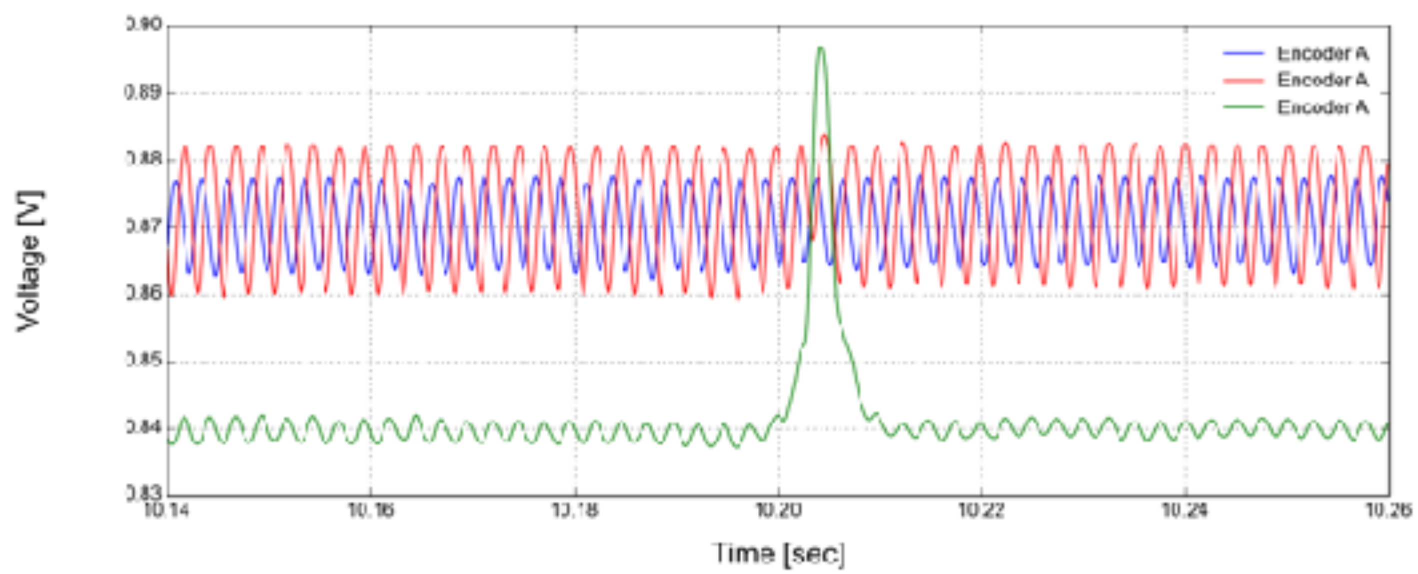
Resistance at Cryogenic temperature

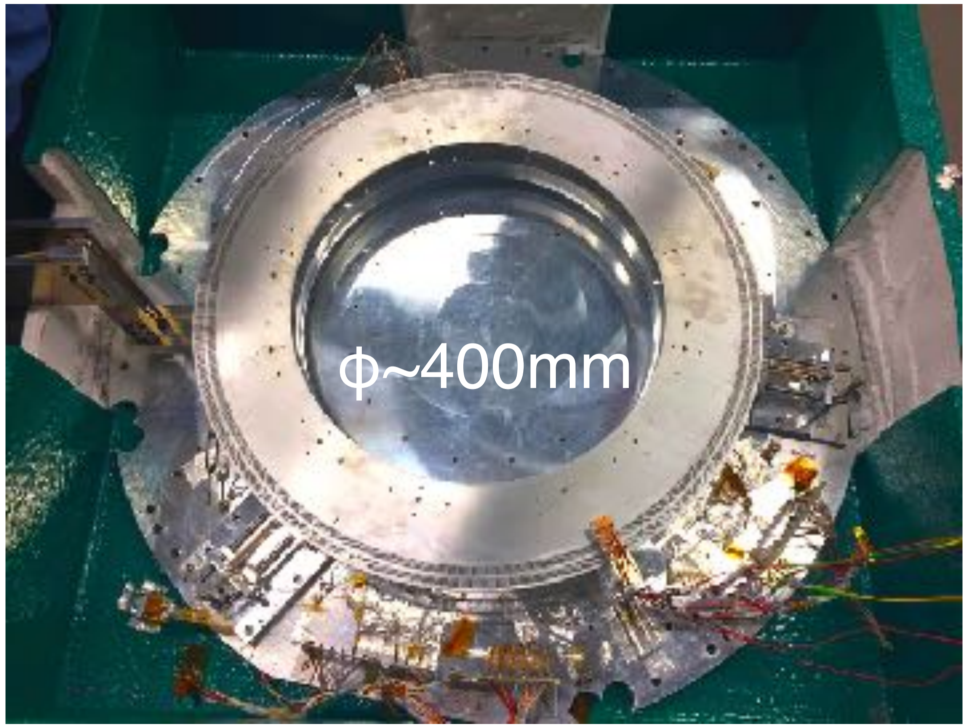
Encoding System

- ✓ 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 < 40μW.
- ✓ The reconstruction accuracy Δθ < 0.001deg considering the rotation speed variation Δf < 0.01Hz



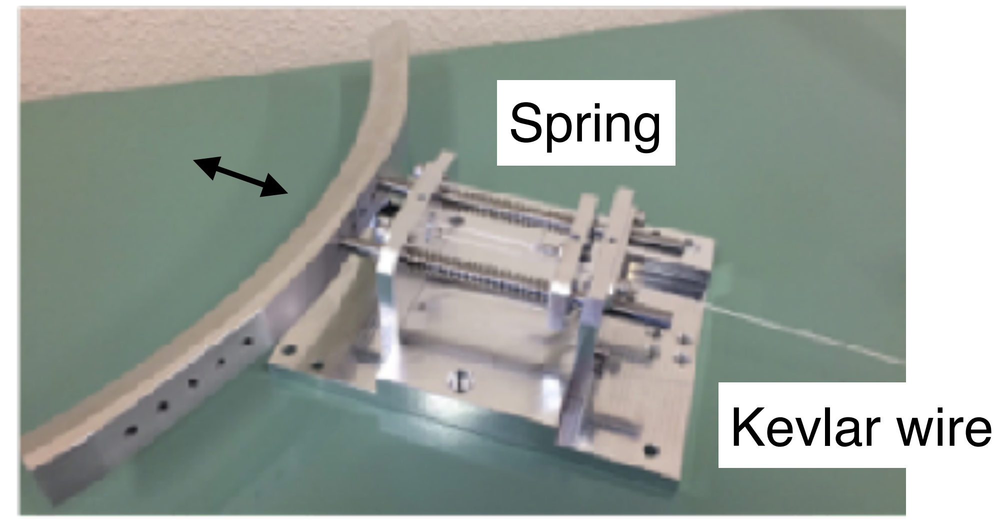
SiPD output



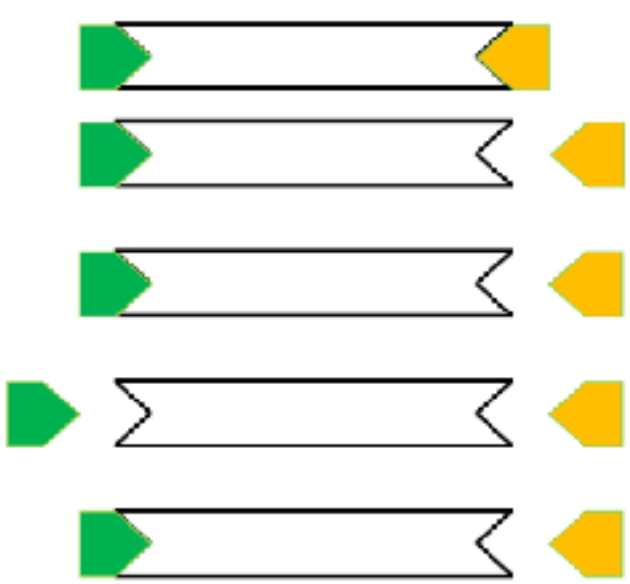


Holder Mechanism

- ✓ 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.



Hoder mech. Launch lock

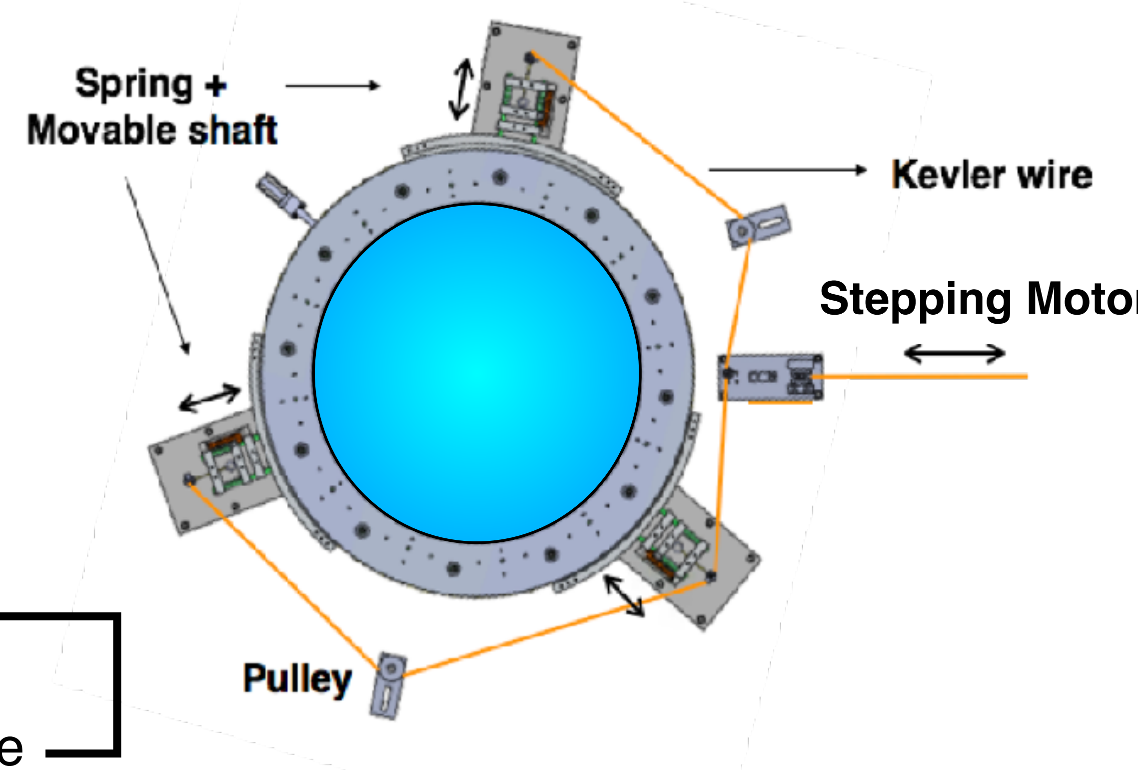


Launch

Release launch lock
Cooldown to 4K

Levitation and observation

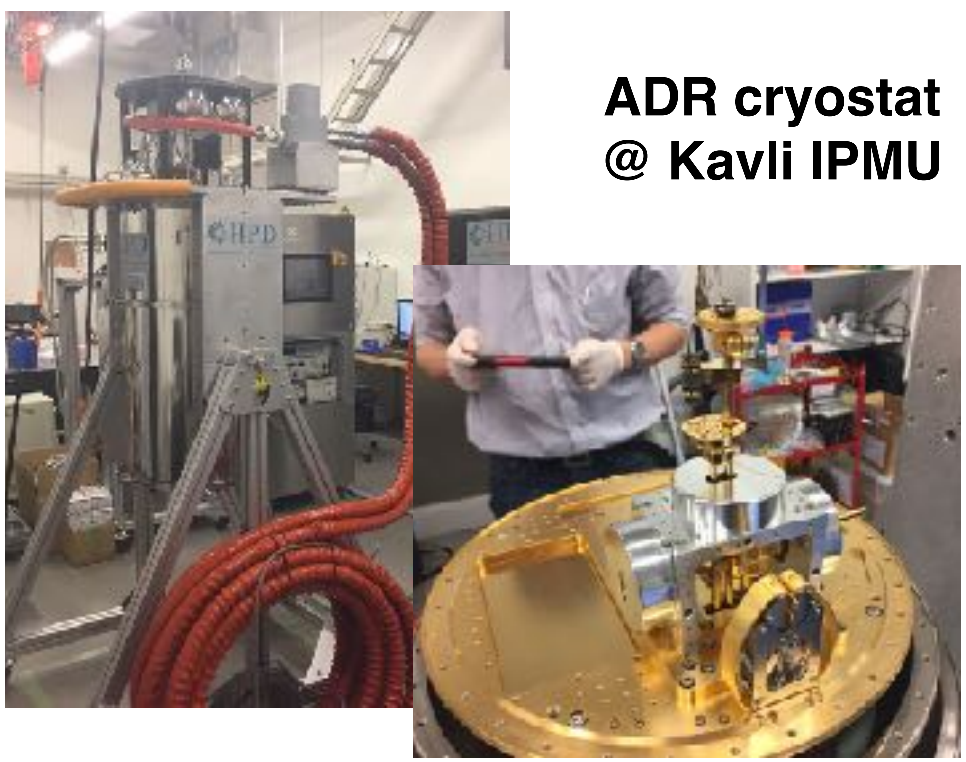
HWP cooling during ADR recycle



Other topics

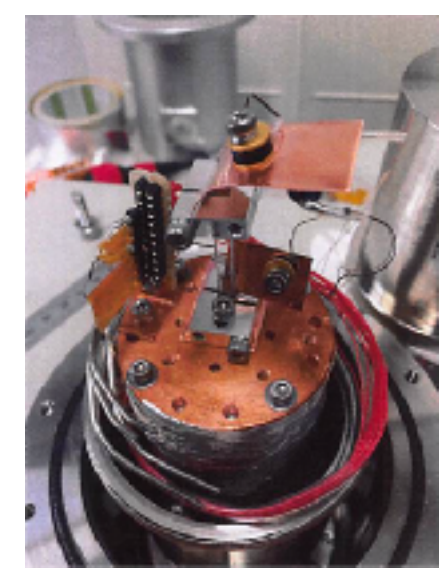
- ✓ Construction of optical measurement system
- ✓ Modulator controller with FPGA
- ✓ Construction of integrated test system of TES and modulator
- ✓ Cryogenic properties for sapphire, magnet, etc
- ✓ Cosmic ray test of sapphire, magnet, YBCO, etc
- ✓ Remote monitoring system to measure HWP temperature

ADR cryostat @ Kavli IPMU



Cosmic ray test @ HIMAC

Cryogenic property @ Kitasato Univ.



Summary

- 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

Encoder

- ✓ 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 (Δθ).
- ✓ Measure Δf from spin down measurement.

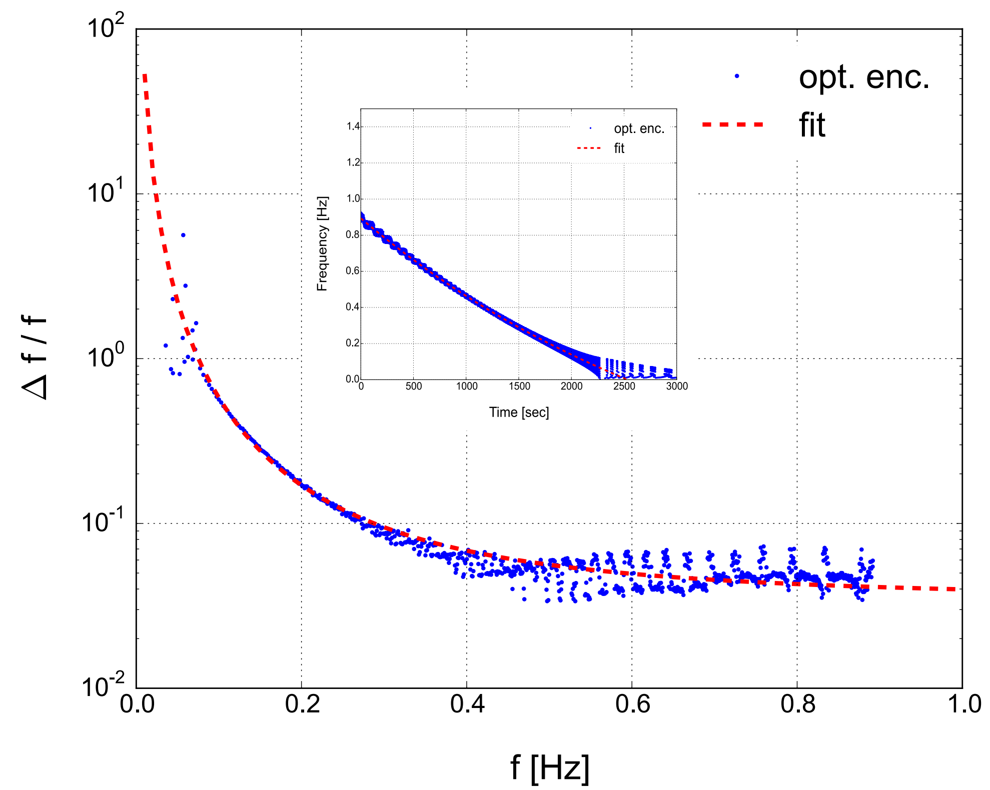
$$\frac{\Delta f}{f} = c_0 + \frac{c_1}{f^2}$$

Δf : frequency variation

f : frequency of one rotation

(red box) : encoder noise component

(green box) : inhomogeneity component



Δθ is estimated by c_0 term :

Δθ < 0.072deg

Improvement is in progress.

- Increase number of slot
- Noise reduction