Development of Polarization Modulator for Litebird

Yuki Sakurai (Kavli IPMU, The University of Tokyo)
and LiteBIRD PMU development team

Cosmic Acceleration Feb. 17-19, 2020

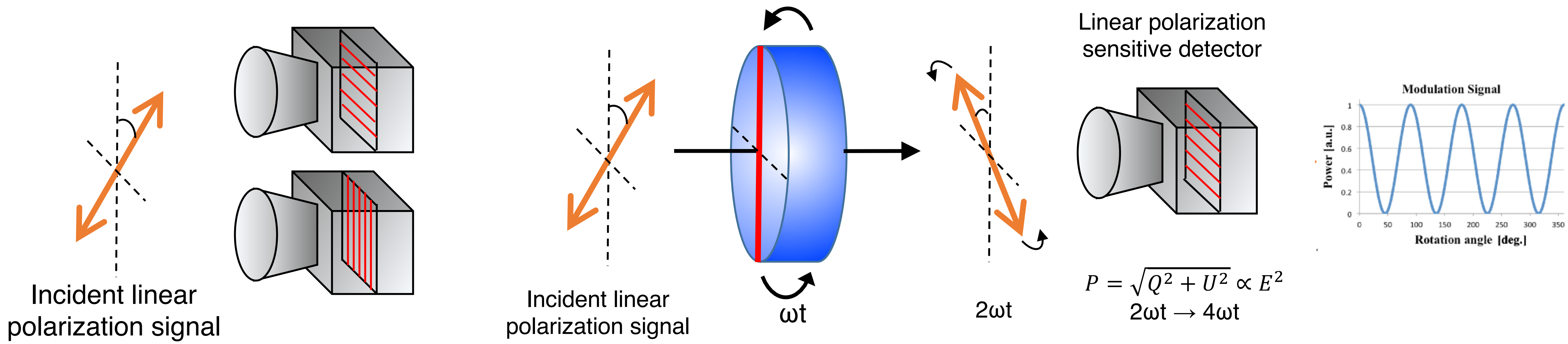
東京大学
THE UNIVERSITY OF TOKYO

wpi World Premier International Research Center Initiative

KAVLI IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

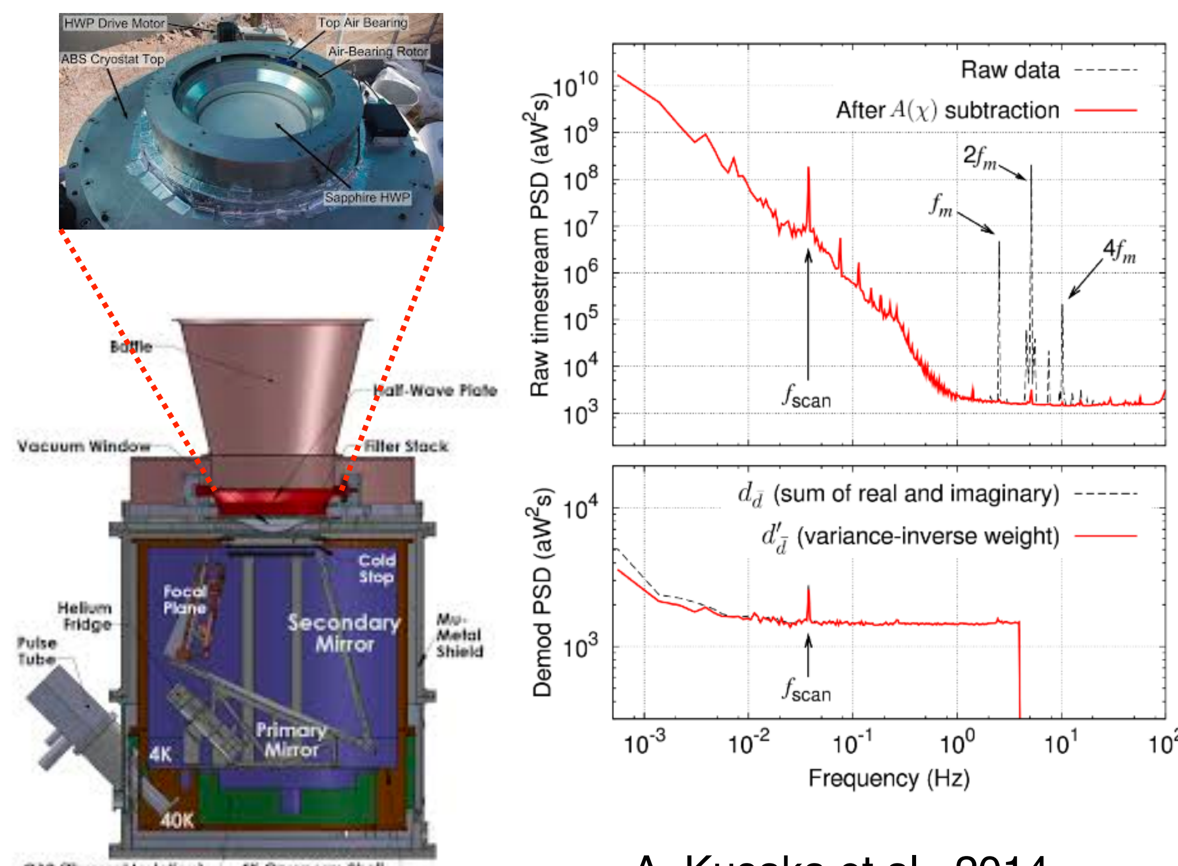
研究拠点形成事業
Core-to-Core Program

What is polarization modulator?



1. **1/f noise rejection**
   - ✓ Atmospheric noise, ground pickup
   - ✓ Detector / electrical noise
   - ✓ Long term instabilities
2. **Systematics mitigation**
   - ✓ Differential beam pointing, ellipticity
   - ✓ Differential gain

LiteBIRD full success is guaranteed with polarization modulator.



A. Kusaka et al., 2014

History of polarization modulator

MAXIPOL (balloon, 1999)

- First CMB experiment using rotating HWP

EBEX (balloon, 2012)

- First experiment using cold rotating HWP with superconducting magnetic bearing

ABS (ground, 2012)

- First ground experiment with warm rotating HWP

Simons Array, Simons Observatory SAT (ground)

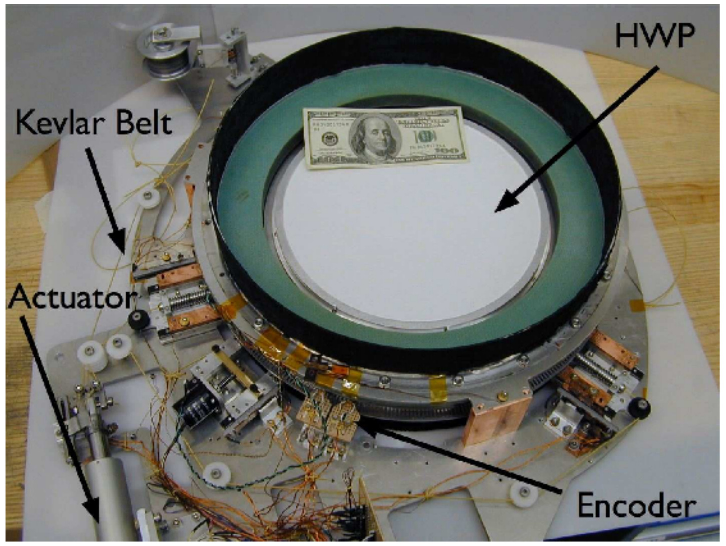
- First ground experiment with cold rotating HWP

LSPE/SWIPE (balloon)

- Balloon experiment with cold rotating HWP

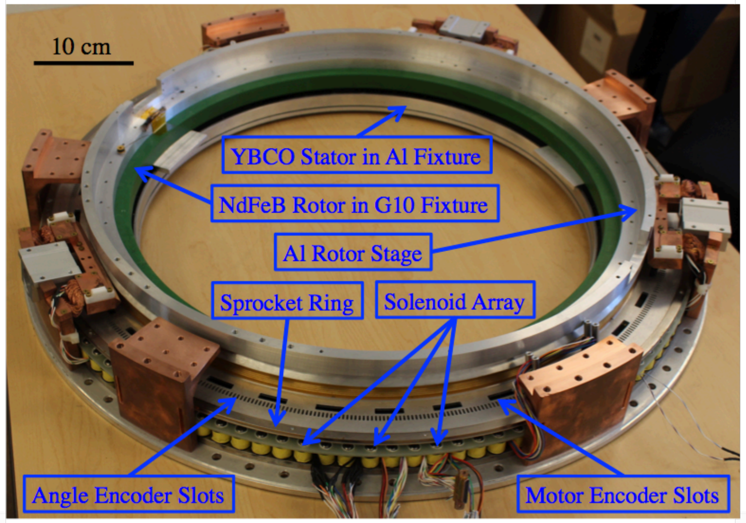
LiteBIRD (satellite)

- Satellite mission with cold rotating HWP

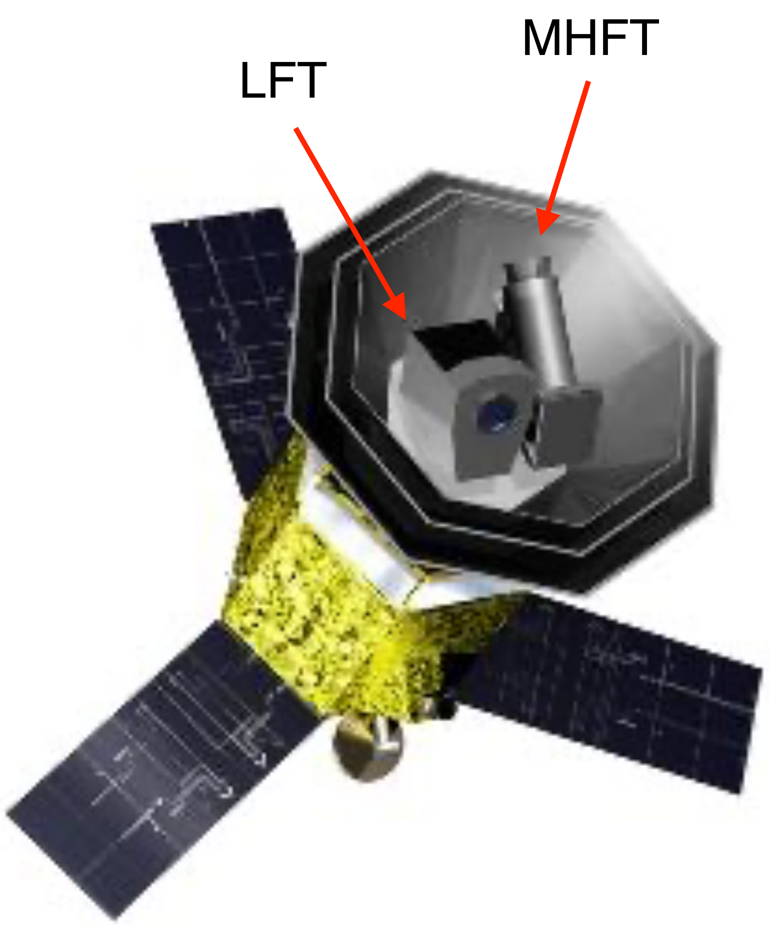


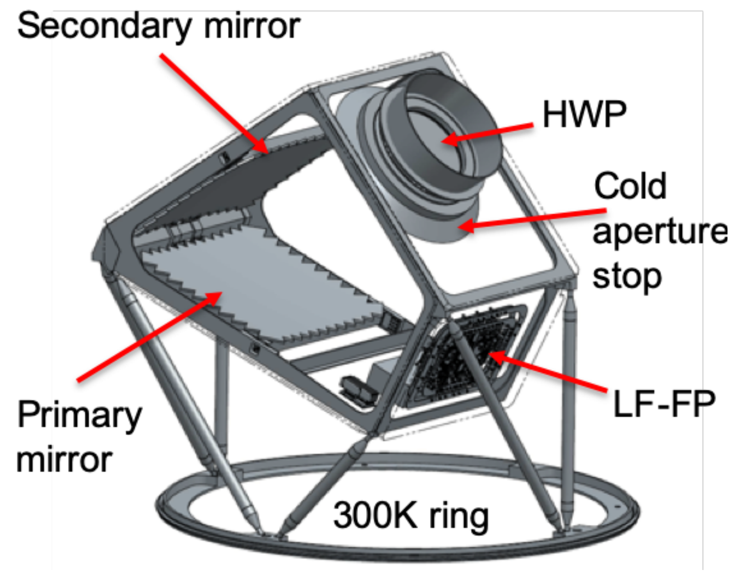
J. Klein et. al. Proc. SPIE 8150 (2011)

A. Kusaka et. al.(2013)

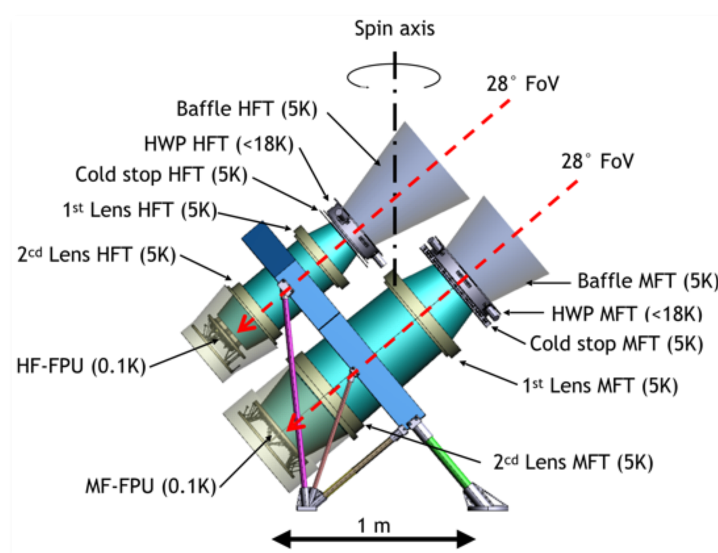


LiteBIRD polarization modulator





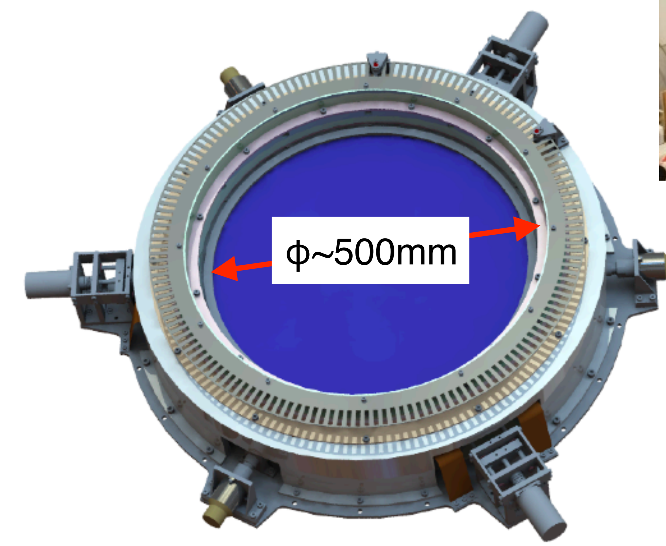
Low Frequency Telescope
34–161 GHz

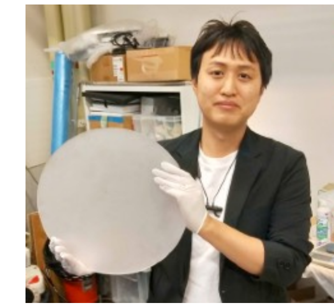


Middle & High Frequency Telescope

89-224 GHz & 166-488 GHz

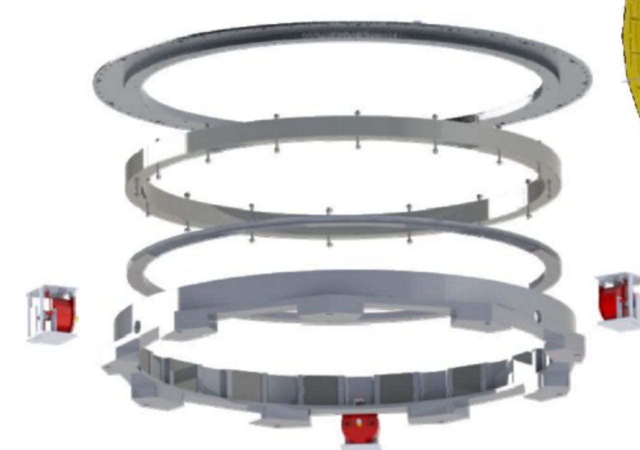
5K stage

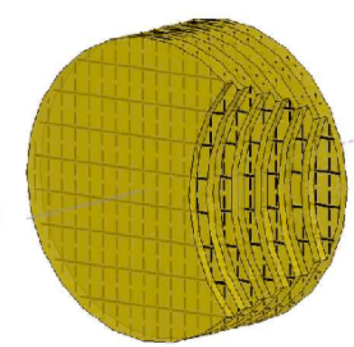




Kavli IPMU, U. Tokyo

5K stage





University of Rome Sapienza
Cardiff University

Technical difficulties for LiteBIRD

Higher science goal
- Broadband observation
- Lower HWP temperature
- Reducing HWP imperfections

Resource limitation
- Cooling power
- Mass
- Volume …

Space specific environment
- Launch tolerance
- Cosmic ray
- No gravity

System reliability
- Risk management
- Redundancy
- Emergency operation

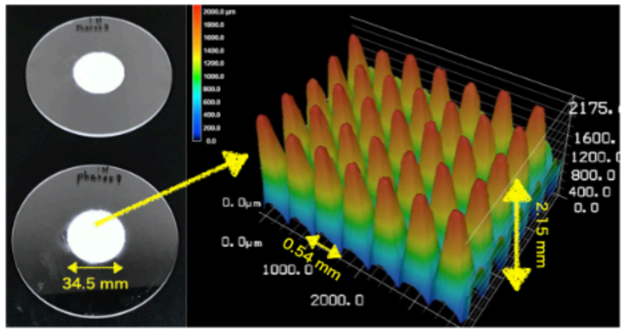
For example…)

1~3 frequency bands in 1 telescope (ground) vs. 15 bands (LiteBIRD)

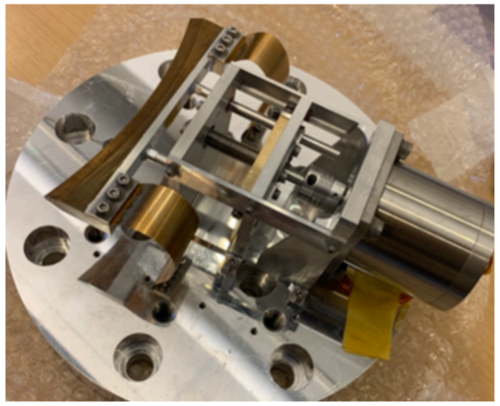
HWP temperature: 50K~300K (ground) vs. 20K (LiteBIRD)

Cooling power: ~1W (ground) vs. ~4 mW (LiteBIRD)

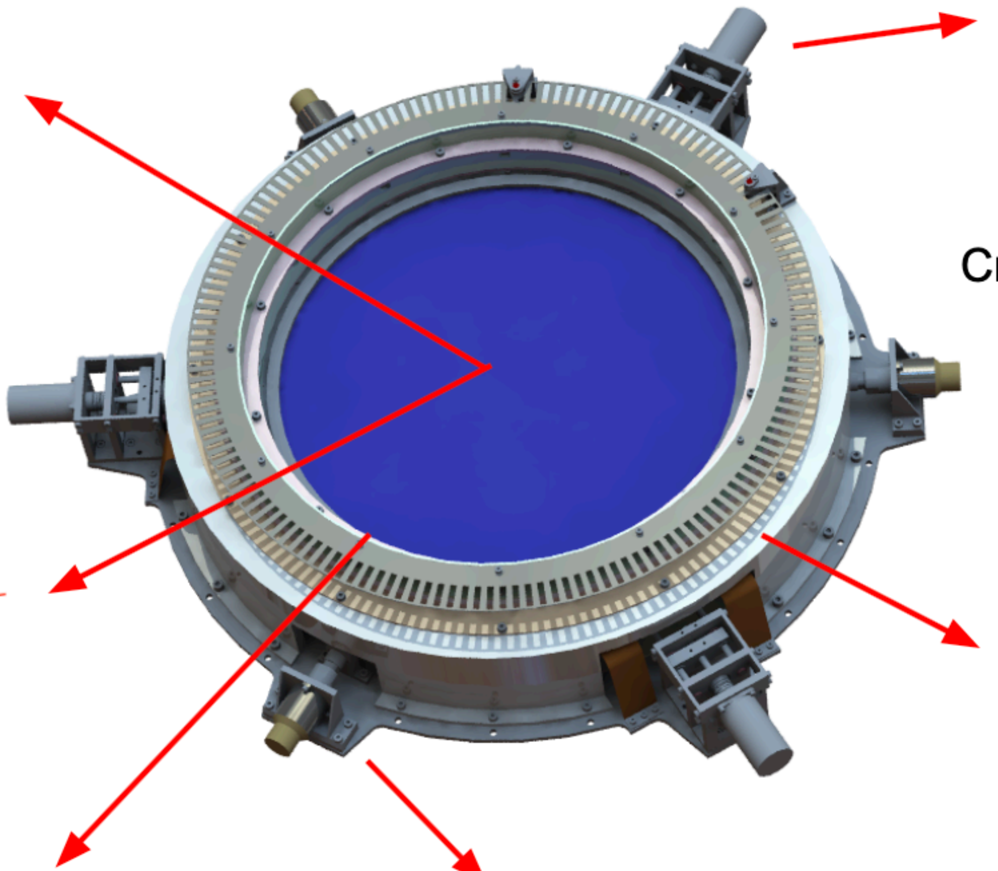
Current design of LiteBIRD LFT PMU

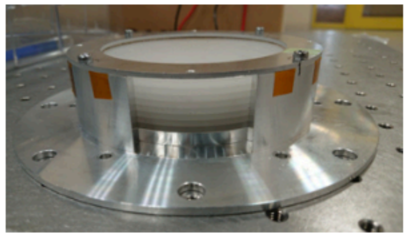


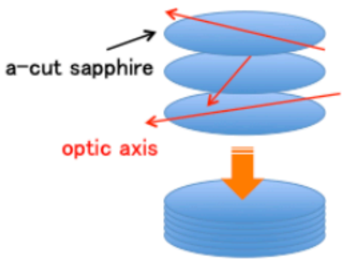
Anti-reflection structure



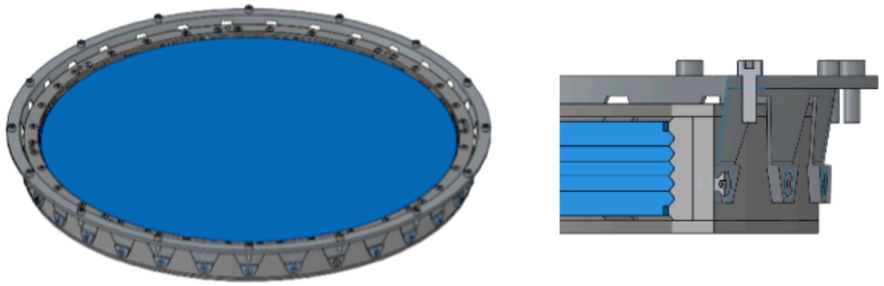
Cryogenic holder mechanism

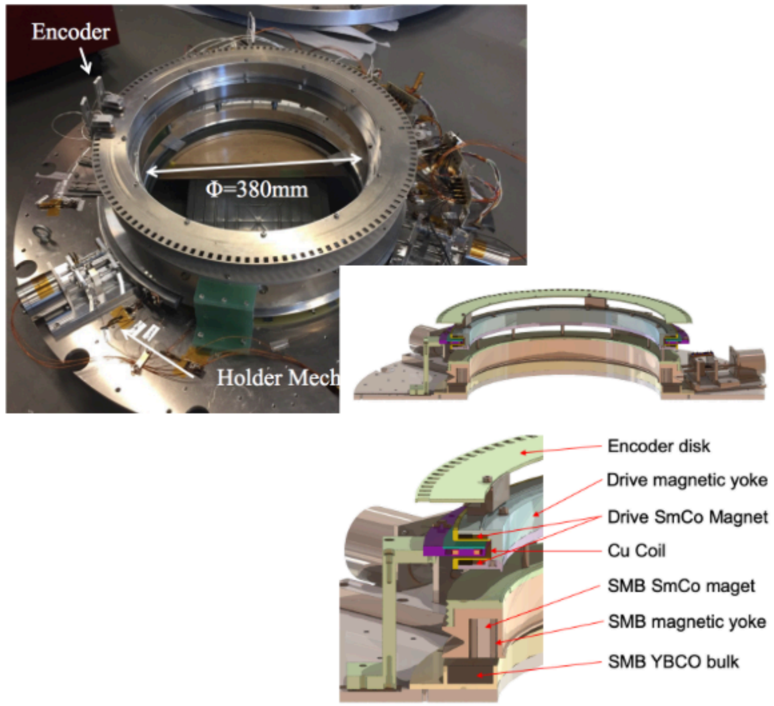


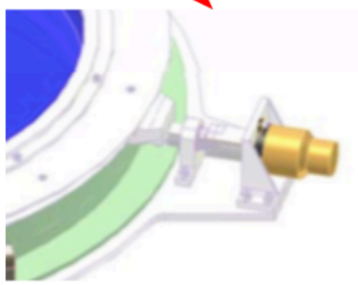




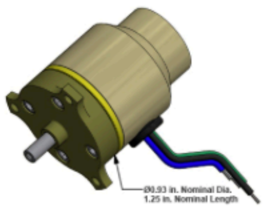
Sapphire stacked
Achromatic HWP







HWP holder

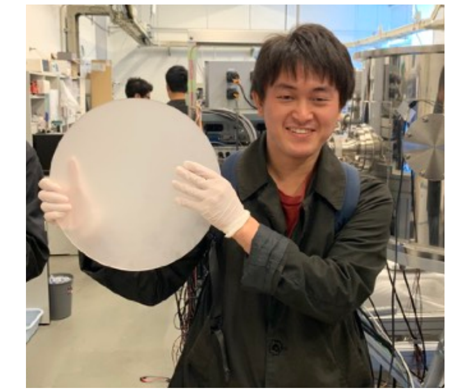


Launch lock mechanism

Rotation mechanism

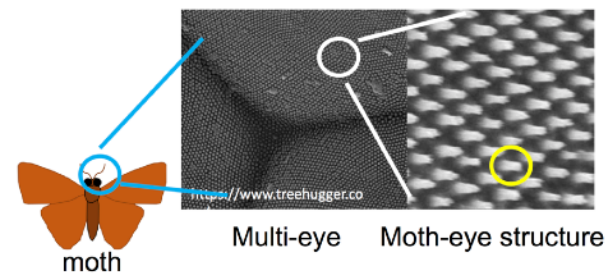
in Kavli IPMU laboratory!!

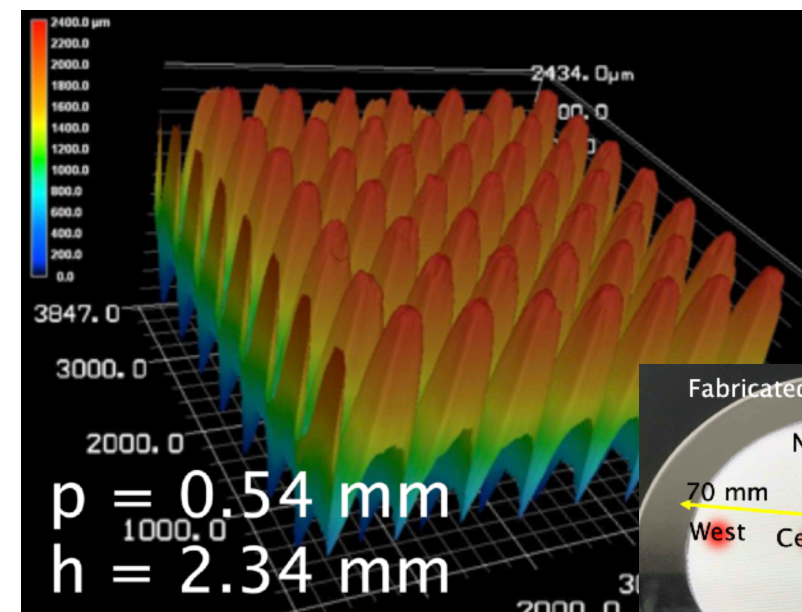
Broadband anti-reflection structure

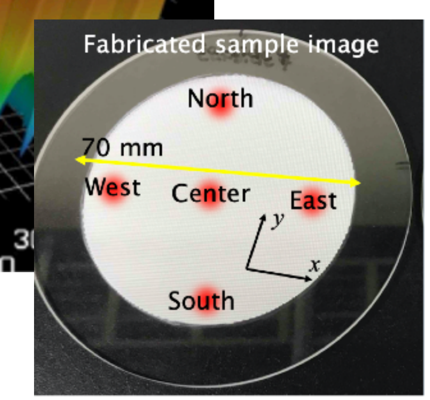


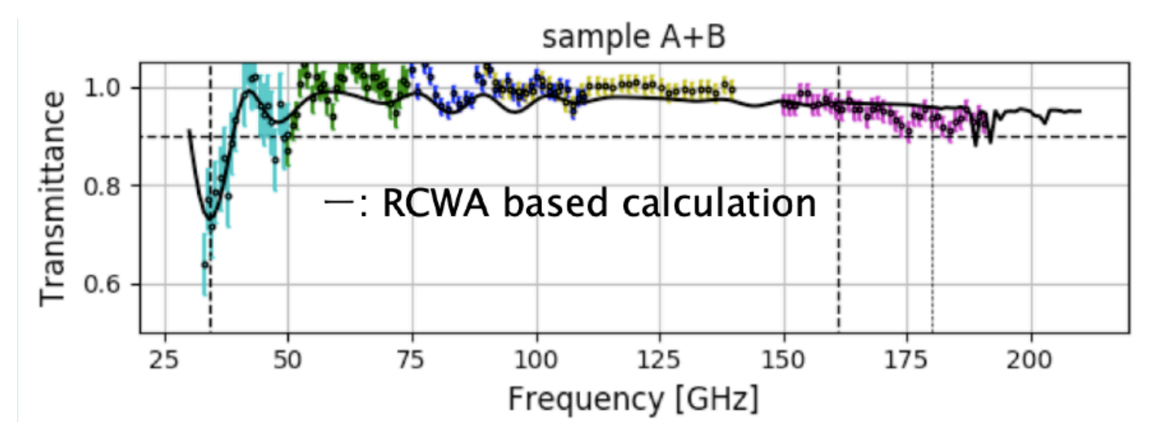
Ryota Takaku (U. Tokyo)

- Anti-reflection coating method: plastic sheet, epoxy layer, thermal spray…
- Broadband AR (34-161GHz): moth-eye based sub-wavelength structure by laser machining
- Demonstrated by Φ=70mm small sample with height 2.34mm, pitch 0.54mm (~4:1)
- > 90% transmittance with good agreement between data and simulation
- The expected processing time for Φ=450mm is < 1 month using 40W femto-second pulsed laser

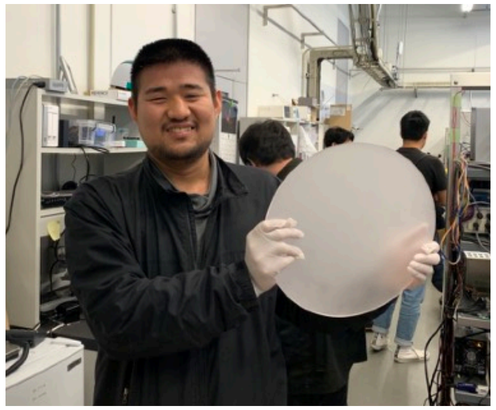






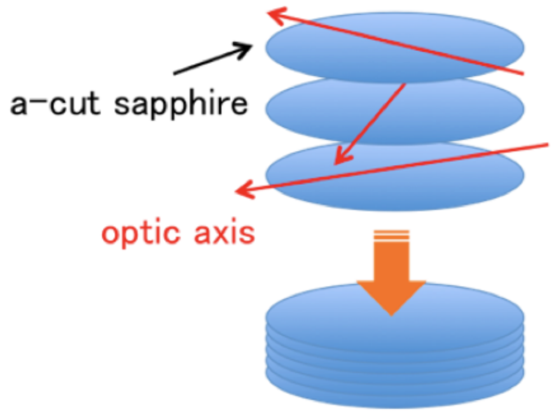


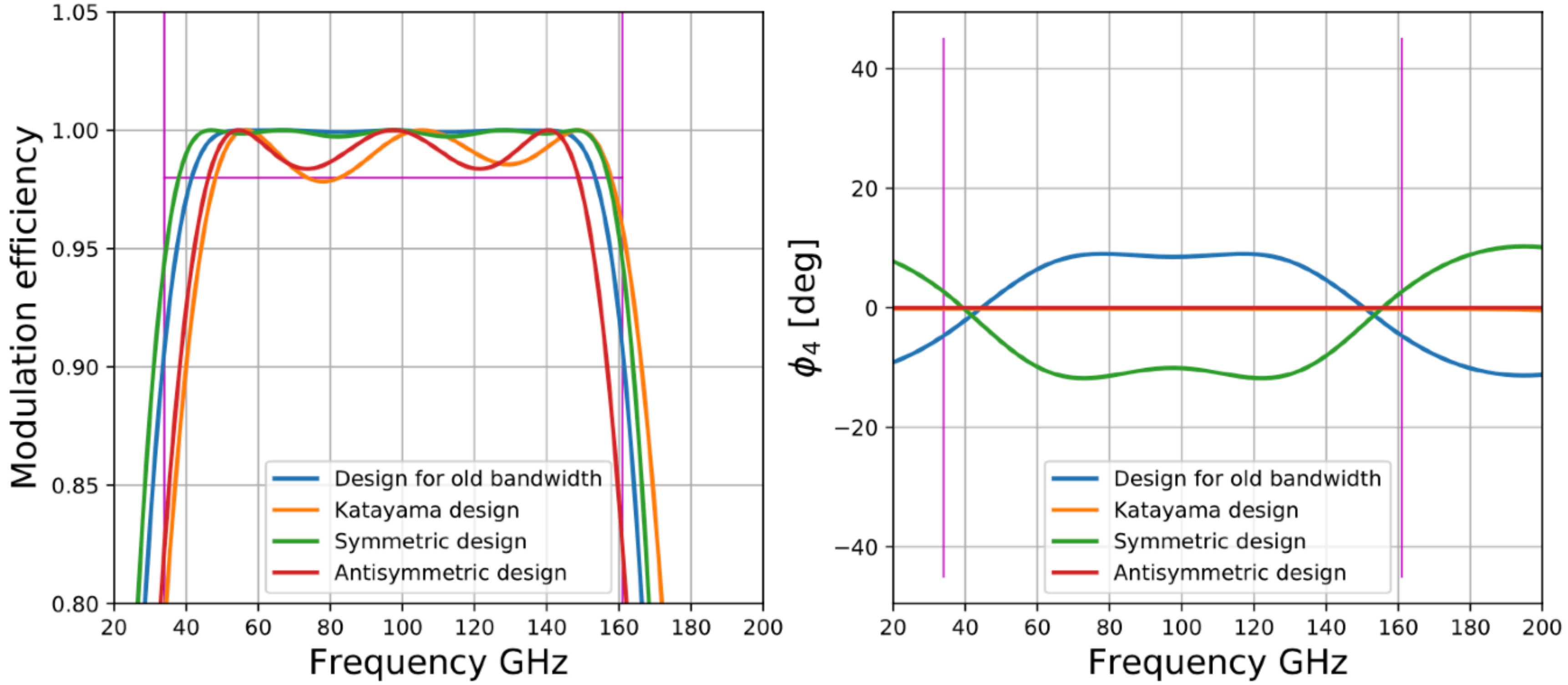
Sapphire AHWP development

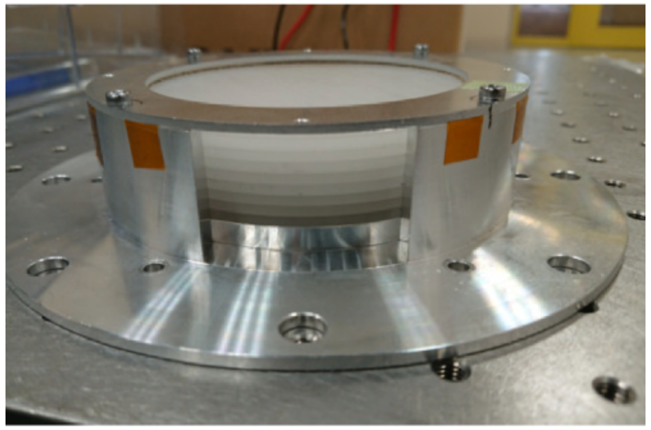


Kunimoto Komatsu (Okayama U.)

- ✓ Single sapphire plate has pol. eff. ε = 1 for the only single frequency.
- ✓ We adopt Achromatic HWP (AHWP) consists of multi-stacked sapphire with the different optic axis for each HWP.
- ✓ We optimize the AHWP design with 5 layer to cover 34-161GHz. (ground experiments use only 1~3 layers without a phase flat design)







K. Komatsu et al. (2019)

Rotation mechanism

- All components at 5 K stage
- Heat dissipation < 4 mW due to cooling power
- Rotor (HWP) must be operated < 20 K to reduce thermal emission

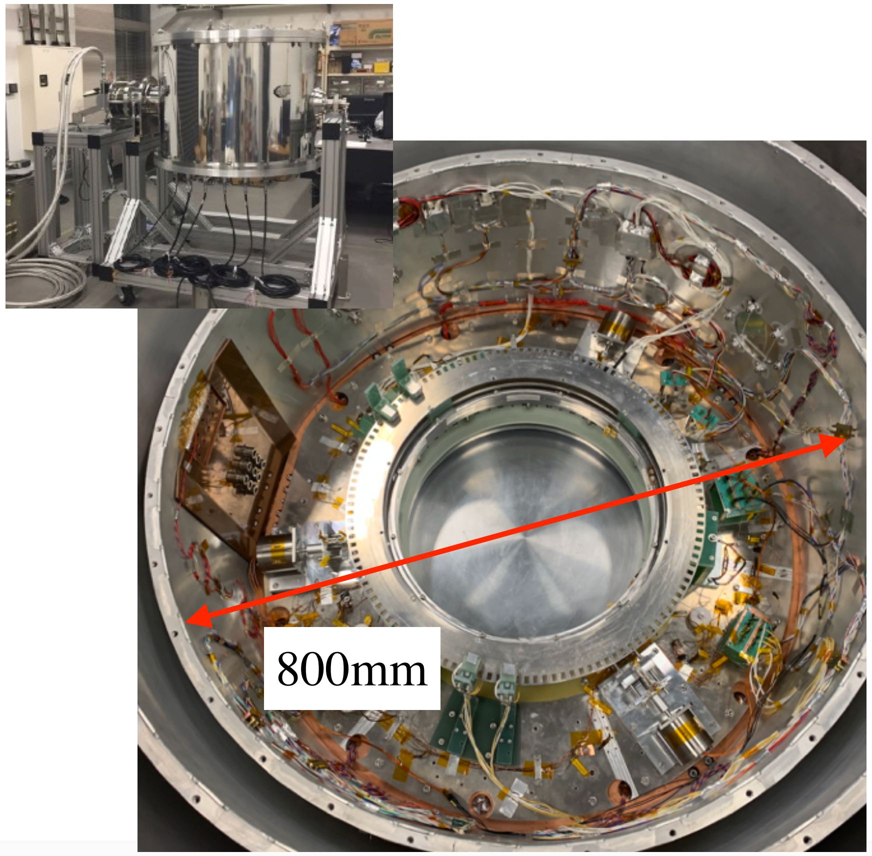
Stable continuous rotation at cryogenic temperature with small heat dissipation

Breadboard model (Φ=380mm)

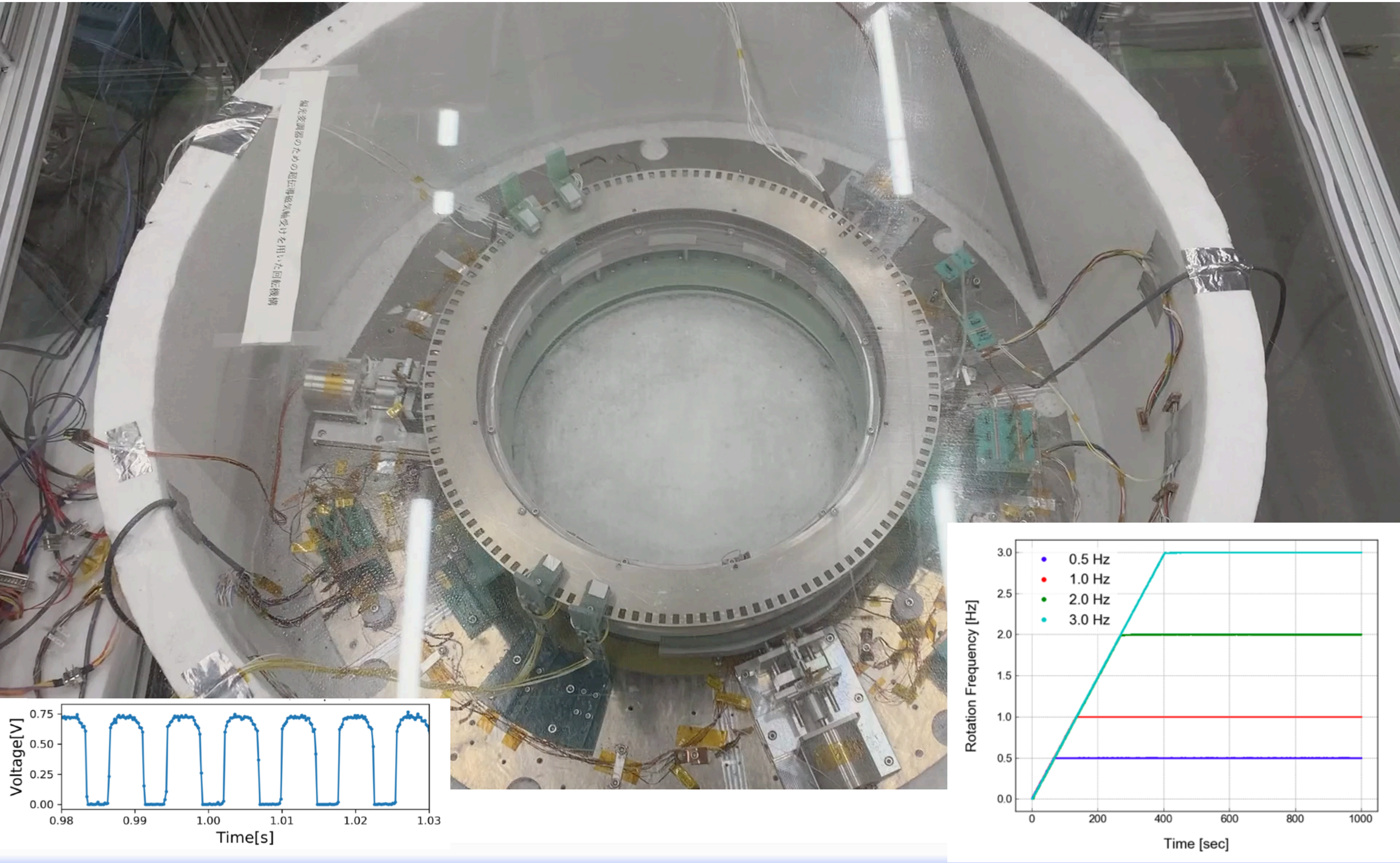
- Superconducting magnetic bearing

  Rotor: SmCo magnets + yoke for uniformity

  Stator: YBCO (Tc < 95 K)
- DC brushless motor with speed feedback control measured by optical encoder
- 3 grippers actuated by linear actuators (stepping motors)



Rotation mechanism



Thermal characteristics

- Perform thermal simulation to clarify heat input vs. HWP temperature.
- Heat sources are hysteresis loss, eddy current due to magnet inhomogeneity ΔB

Hysteresis

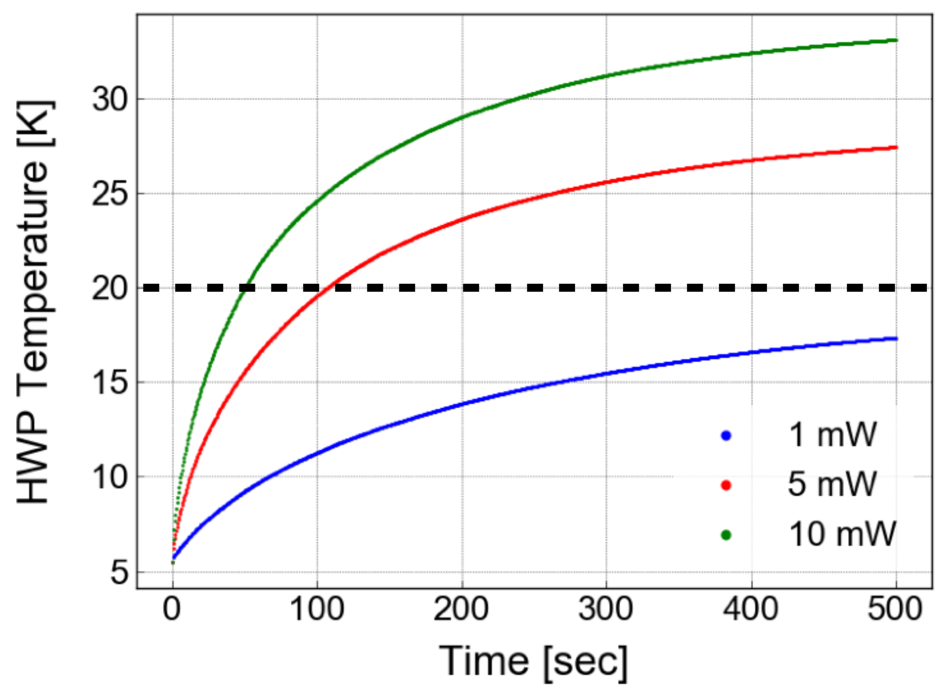
$$P_h \propto k_h f \frac{\Delta B^3}{J_c}$$

Eddy current

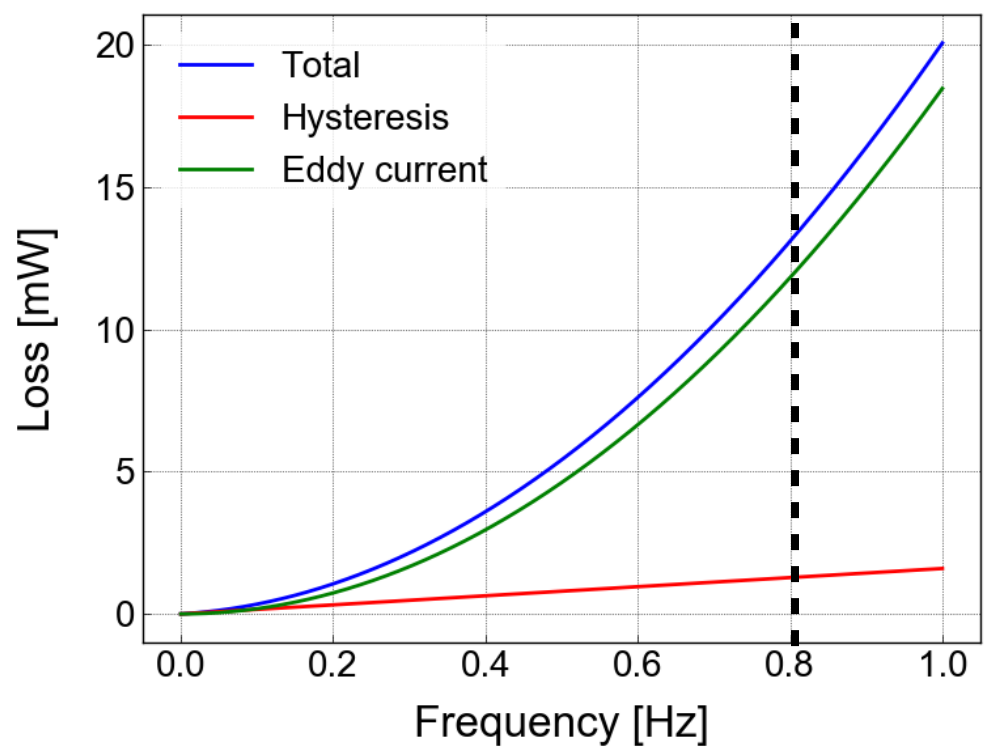
$$P_e \propto k_e f^2 \Delta B^2$$

- Total loss at nominal rotation speed (46 rpm) is ~10 mW, dominated by eddy current loss
- There is much room for improvement.
  - de-metallization and reduce weight
  - Uniform magnetic field for bearing
  - Improvement of drive motor

HWP temperature simulation



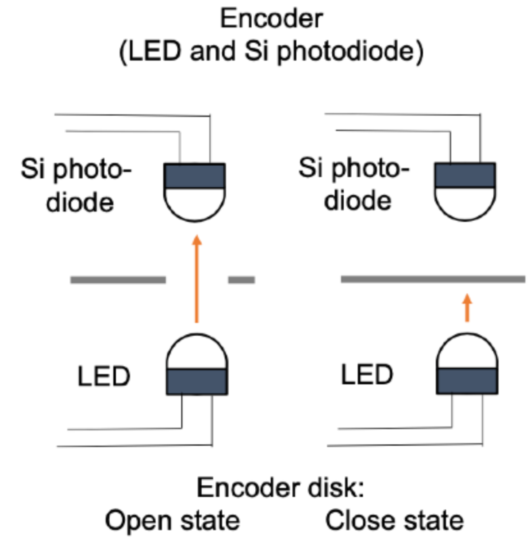
Calculated total loss from measurement

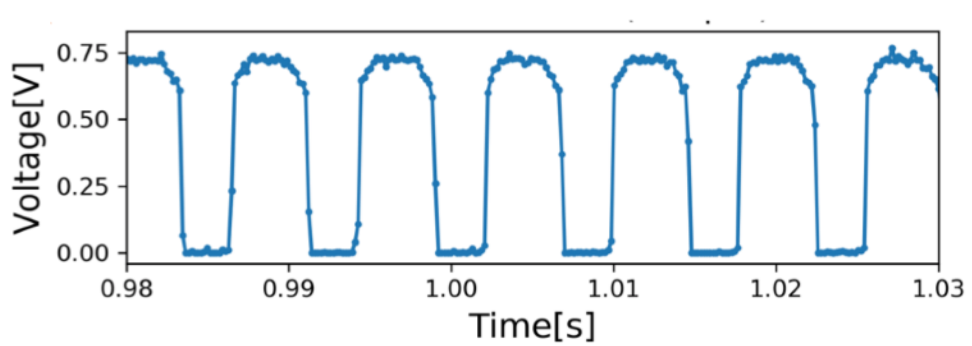


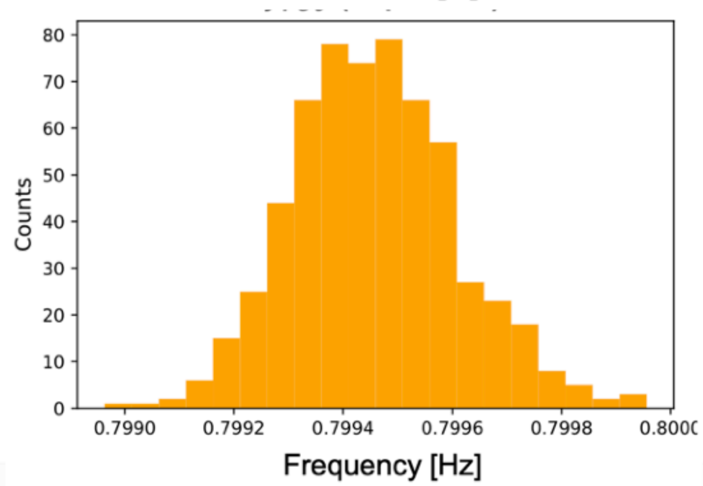
Angular encoding

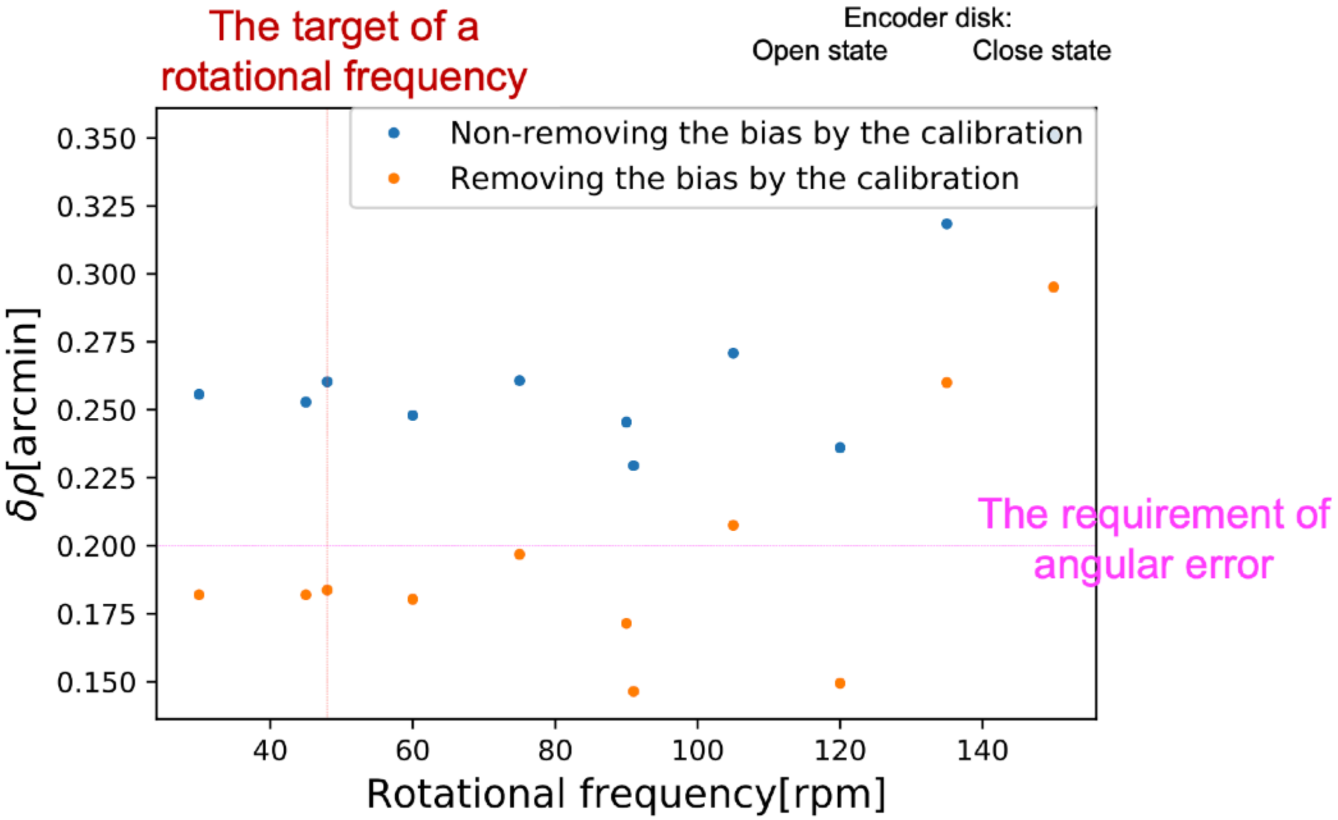
- Angle reconstruction is critically important for analysis, demodulating the signal.
- HWP angle reconstructed by a cryogenic optical encoder consists of LED and Si photodiode
- Bias components that appears constantly are calibrated (motor cogging, slot non-uniformity)
- The angle reconstruction error after the calibration is calculated as < 0.2 arcmin, which is sufficiently small for the angle requirement.

Shinya Sugiyama (Saitama U.)



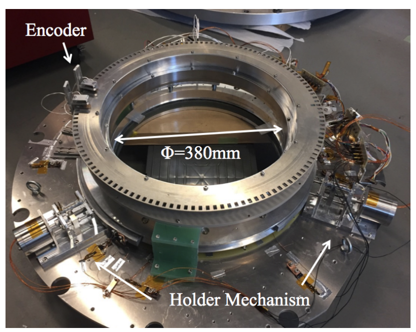


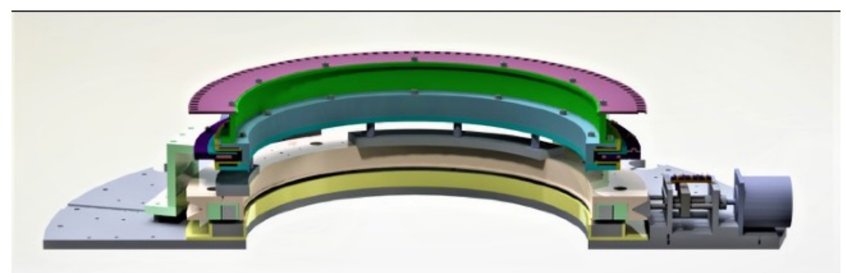


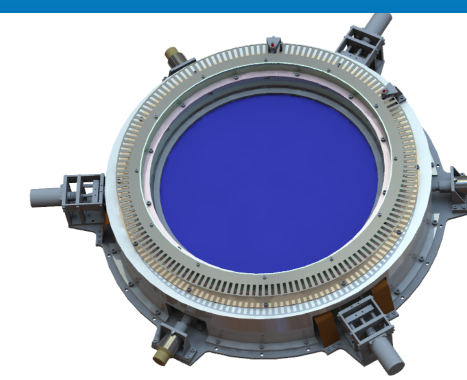


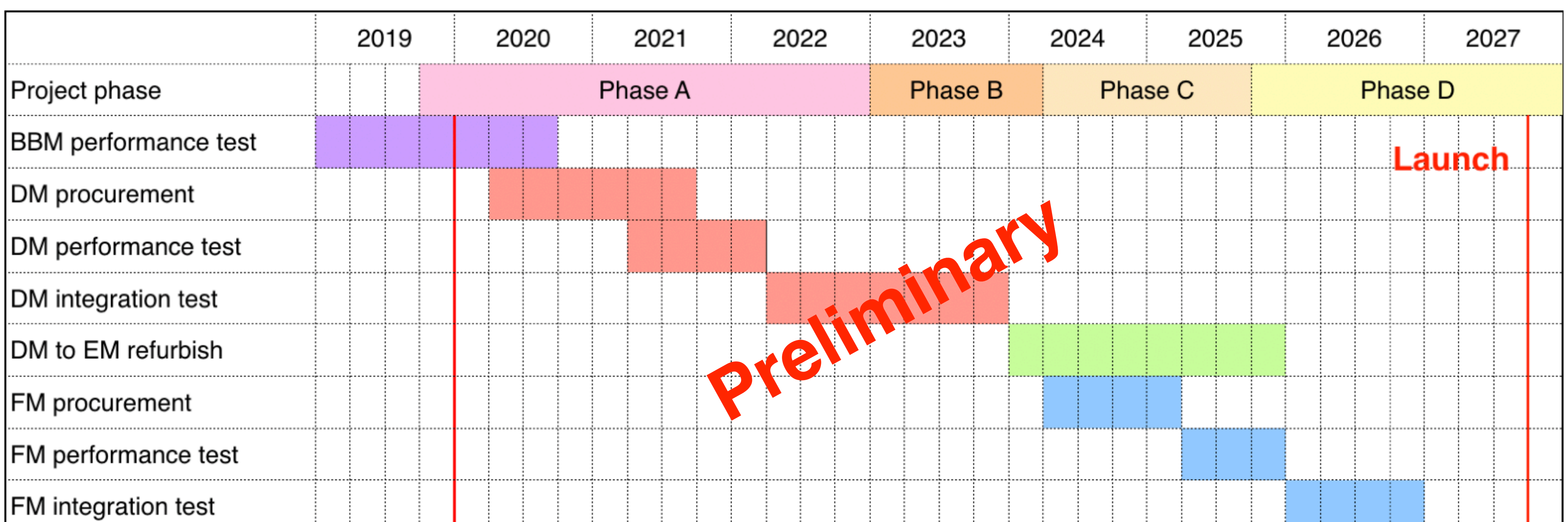
Development roadmap

~2020	2020~2024	2024~launch!
BBM **Φ=380mm**	**DM/EM** **Φ=500mm**	**FM** **Φ=500mm**









Achievements in Cosmic Acceleration

Total 6 Reviewed Papers

1. Design and thermal characteristics of a 400mm diameter levitating rotor in a superconducting magnetic bearing operating below at 10K for a CMB polarization experiment, IEEE Transaction on Applied Superconductivity, Vol. 28, Issue: 4, pp. 1-4, 2018
2. Design and development of a polarization modulator unit based on a continuous rotating half-wave plate for LiteBIRD, Proc. SPIE 10708, Millimeter, Submillimeter, and Far-Infrared Detectors and Instrumentation for Astronomy IX, 107080E, 2018
3. Vibrational characteristics of a superconducting magnetic bearing employed for a prototype polarization modulator, J. Phys.: Conf. Ser. 871, 012091, 2017
4. Thermal analysis of a prototype cryogenic polarization modulator for use in a space-borne CMB polarization experiment, IOP Conference Series: Materials Science and Engineering, Vol. 278, No. 1, p.012011, 2017
5. Estimation of the heat dissipation and the rotor temperature of superconducting magnetic bearing below 10K, IEEE Trans- actions on Applied Superconductivity, Volume: 27, Issue: 4, 2017
6. Demonstration of the broadband half-wave plate using the nine-layer sapphire for the CMB polarization experiment, Journal of Astronomical Telescope, Instruments, and Systems 5(4), 044008 (2019) pp.1-14,

Total 8 Oral Presentations & multiple posters (international conference)

ISS2016, 2017, 2018, B-mode from space 2017, 2018, 2019, SPIE2018, PASREG2017
RMMW-THz 2019, ISSTT2018, EUCAS2017, ASC2016 …

Summary

- ✓ Polarization modulator helps to reject 1/f noise and systematics.
- ✓ Continuously rotating HWP is employed to LiteBIRD with the main driver as 1/f noise.
- ✓ We presented the development status of LiteBIRD LFT PMU.
- ✓ Optical performance of AR and AHWP is successfully demonstrated using small samples.
- ✓ Cryogenic performance test of BBM rotation mechanism is in progress toward flight model.

Modulation techniques

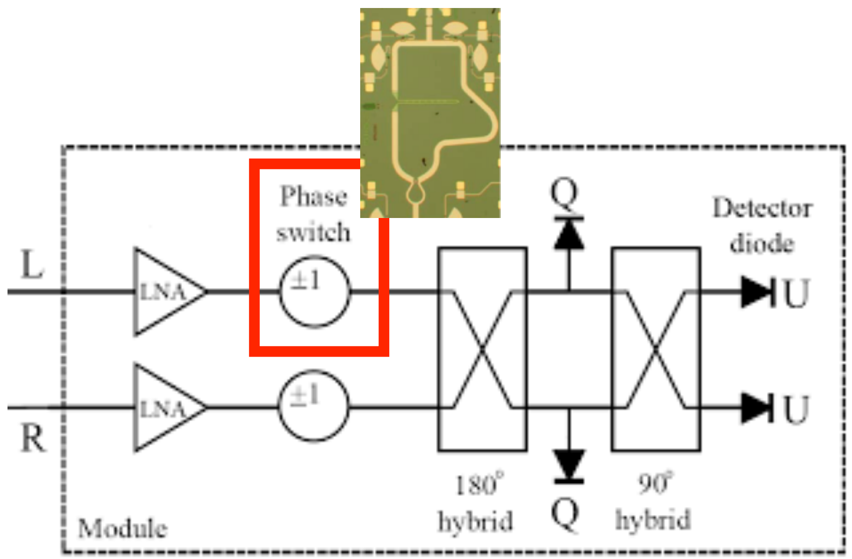
There are various polarization modulation techniques:

1. **Phase switch:** WMAP, CAPMAP, QUIET…
   - Modulation by switching the path length half-phase shifted
2. **Faraday rotation modulator (FRM):** BICEP1
   - Modulation using ferrite and coil by Faraday effect

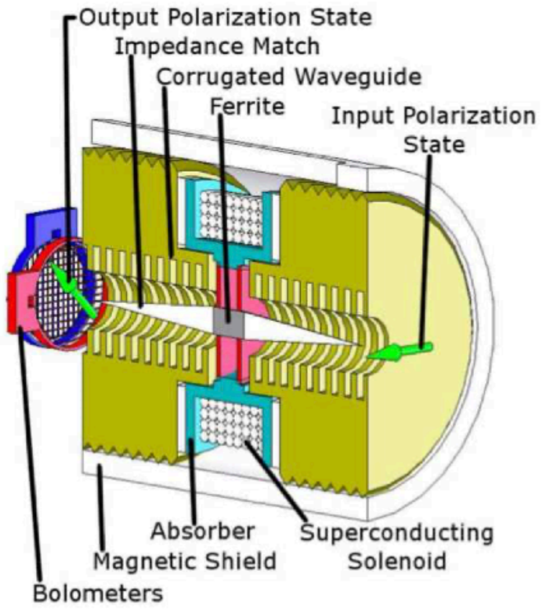
→ Install at front or rear of focal plane
Each pixel

3. **Half-wave plate (HWP):** MAXIPOL, EBEX, SA, SO, ACTPol, NIKA, LSPE/SWIPE, LiteBIRD…
   - Modulation by rotating HWP
4. **Variable-delay polarization modulator:** PIPER, CLASS

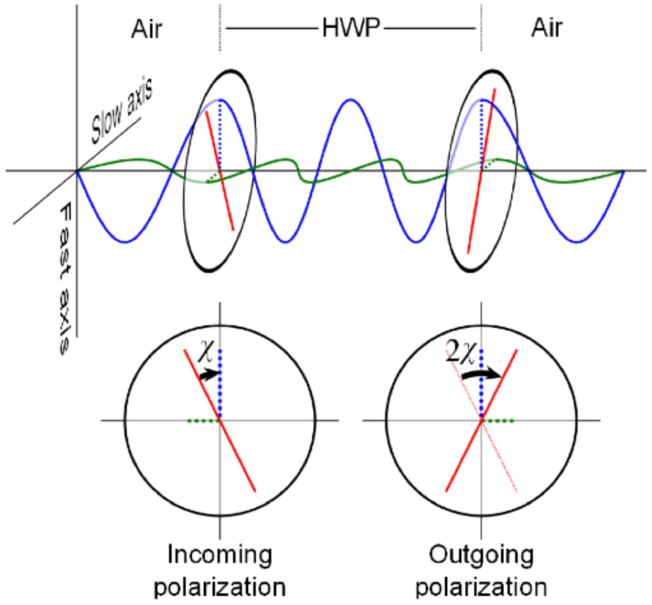
→ Install at aperture or within optical system
Entire focal plane



QUIET Collaboration et al. (2011)



S. Moyerman et. al. (2013)



A. Kusaka et. al. (2014)

Do we need polarization modulator for LiteBIRD?

Pros	Cons
1/f noise rejection Systematics mitigation	HWP systematics Sensitivity effect System risk

- LiteBIRD f_{scan} = 0.05 - 0.1rpm
- Do we have any guarantee for 1/f noise?
- 1/f is the main driver → continuously rotating HWP
- ABS, POLARBEAR successfully demonstrated f_{knee} ~2mHz.
- Concerns depend on hardware and calibration.

HWP systematics

Hardware development directly connects to systematics due to HWP imperfection

- HWP non-uniformity → AR and AHWP development
- Multiple reflections → AR development
- HWP phase freq. dependence → AHWP design optimization
- Beam effect through HWP → AR and AHWP development
- HWP temperature stability → rot. mech. thermal characteristics
- HWP wobbling → rot. mech. misalignment
- Angle reconstruction accuracy → encoder
- …

HWP hardware development is key to achieve LiteBIRD full success

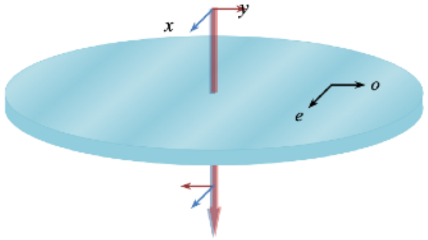
Representative requirements

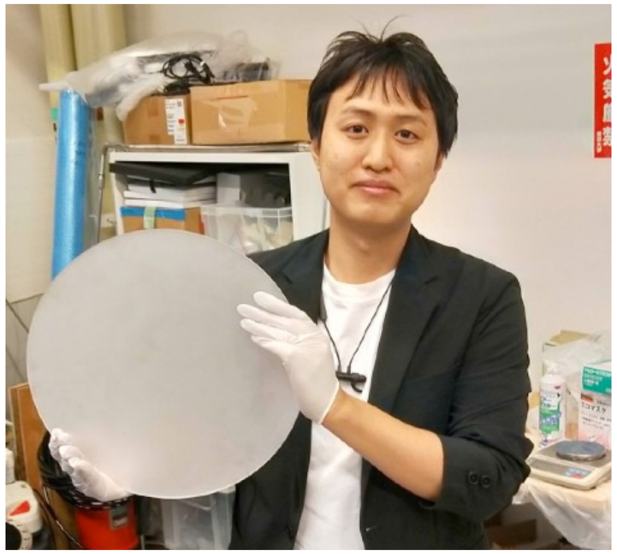
Items	Requirement (LFT)
Frequency band	34 GHz - 161 GHz
Transmittance	> 98% (depend on freq.)
Polarization efficiency	> 98% (depend on freq.)
Rotation frequency	0.8 Hz (48 RPM)
HWP diameter	> ~ 480 mm
HWP temperature	< 20 K
Total heat dissipation	< 4 mW
Mass	< 30 kg
Encoder specification	< 0.2 arcmin

- ✓ The requirement values are not yet fixed because the detail system design and the trade-off study are in progress.
- ✓ Main development items are broadband achromatic HWP and a cryogenic rotation mechanism.

HWP materials

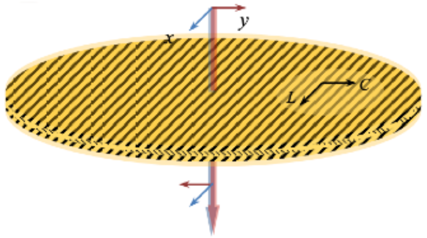
Sapphire

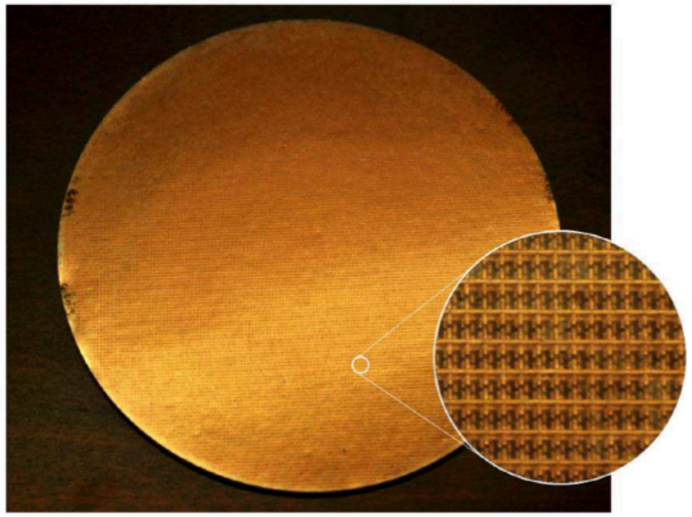




- Birefringence single crystal material
- Maximum diameter ≤ 500mm
- Need anti-reflection (AR) due to refractive index ~3.3
- Broadband of pol. eff. and phase difference are proportional to number of layer ≈ mass
- MAXIPOL, EBEX, SPIDER, ABS, SA, SO, LiteBIRD LFT

Metal-mesh HWP



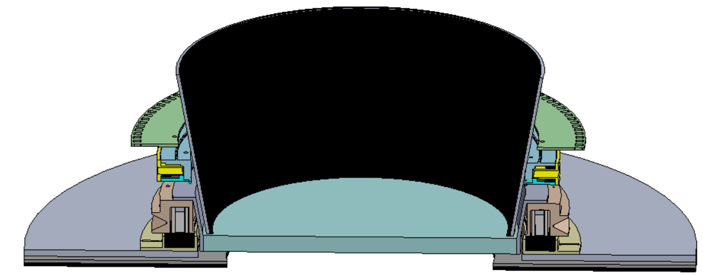


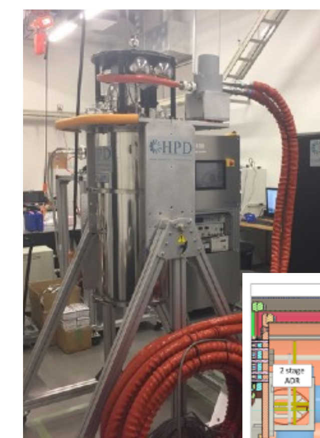
G. Pisano et al. in press in PIER M (2012)

- Based on metal-mesh filter technology
- Stack capacitive and inductive structure
- Bandwidth 3:1
- NIKA, ASTE, LSPE/SWIPE, LiteBIRD MHFT
- Reflective metal-mesh HWP is considered as backup solution.

Other activities toward flight model

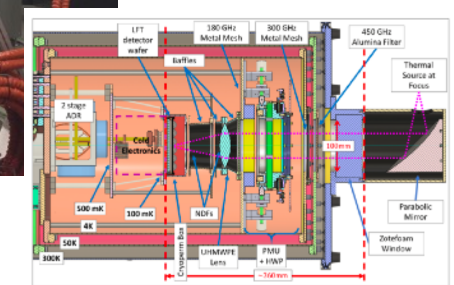
- Cosmic ray effect: radiation damage, heat input, charging
- AHWP gluing and holder design for launch tolerance.
- System optimization including baffle and stop
- Fault tree analysis (FTA) to identify critical risks and components required redundancy.
- Development of low loss cryogenic motor
- Cryogenic optical measurement system
- Small integrated test system of TES and HWP



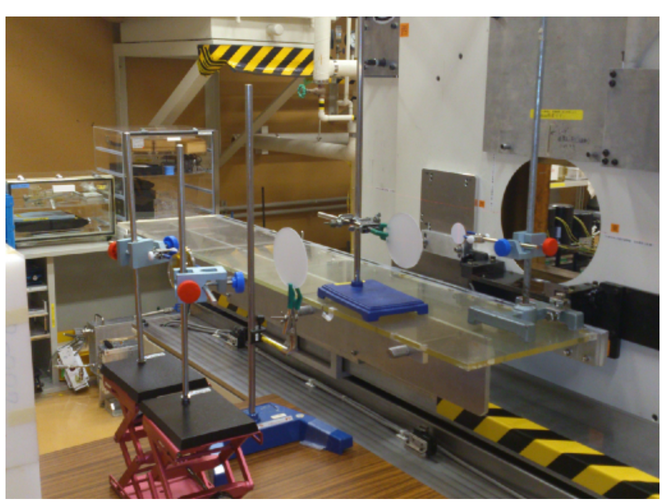


ADR testbed

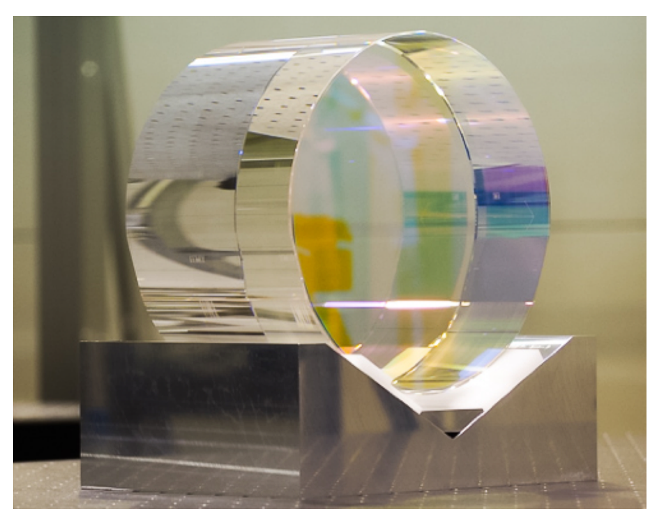
T. Ghigna et al (2019)



Cosmic ray test @ HIMAC



Sapphire Gluing (KAGURA)



4K CM cryostat @ Kavli IPMU