Development of space compatible Polarization Modulator

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

B-mode from space 2019 at Munich

Dec. 19, 2019

東京大学 THE UNIVERSITY OF TOKYO

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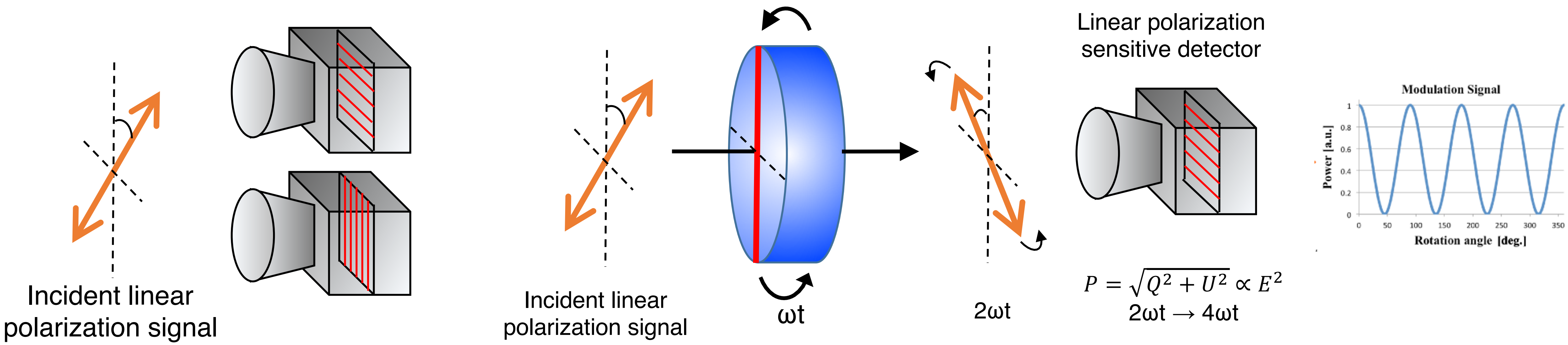
研究拠点形成事業 Core-to-Core Program

What is polarization modulator?

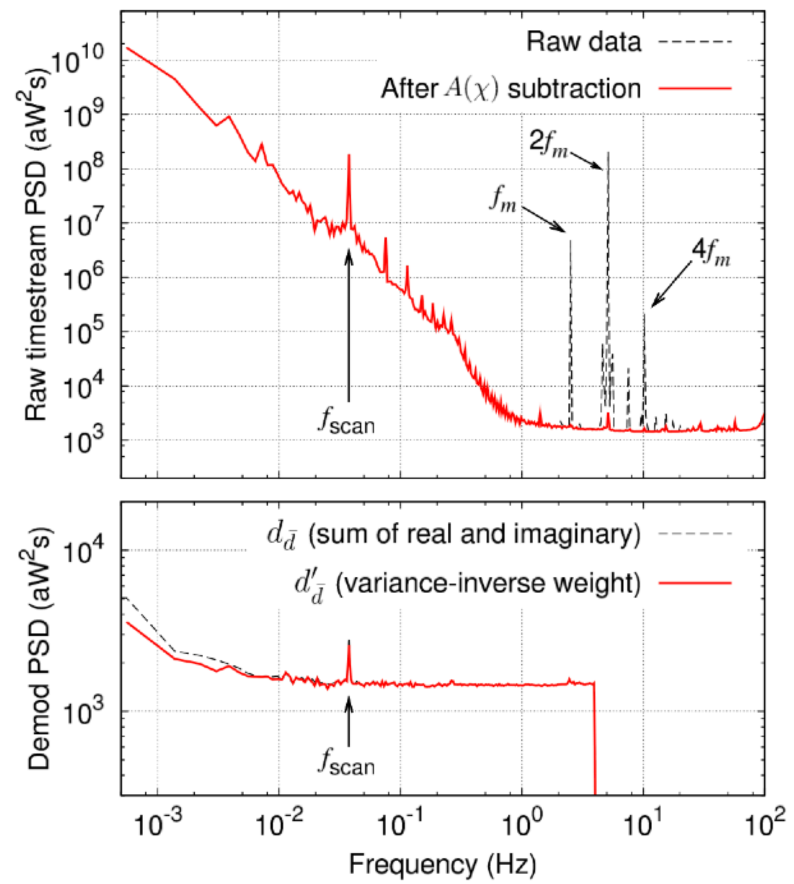


1. 1/f noise rejection

- ✓ Atmospheric noise, ground pickup
- ✓ Detector / electrical noise
- ✓ Long term instabilities

2. Systematics mitigation

- ✓ Differential beam pointing, ellipticity
- ✓ Differential gain



A. Kusaka et al., 2014

Modulation techniques

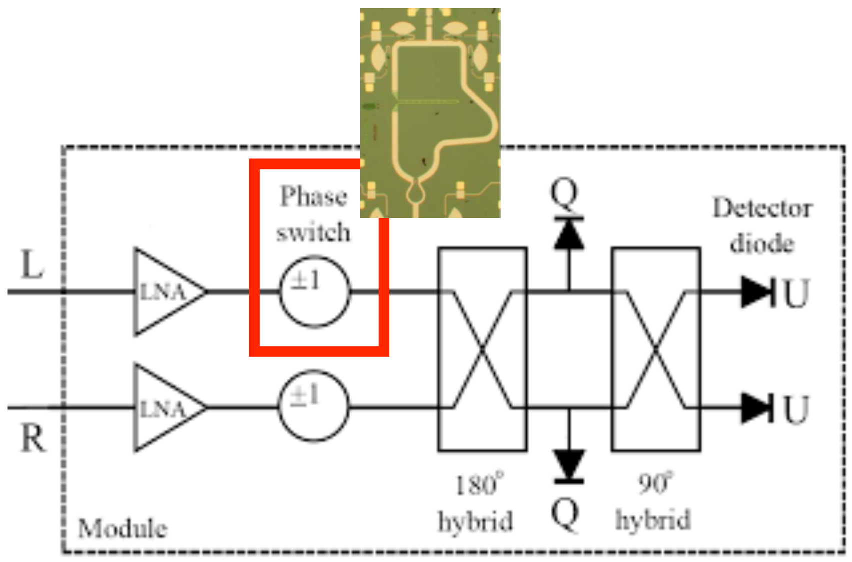
There are various polarization modulation techniques:

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

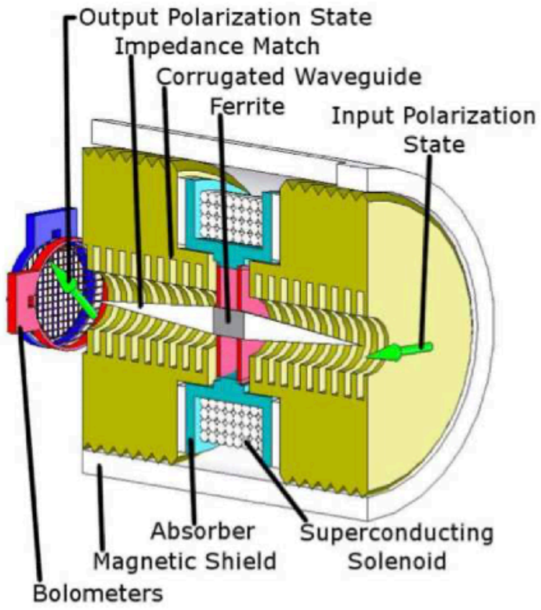
→ Install at front or rear of focal plane
Each pixel

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

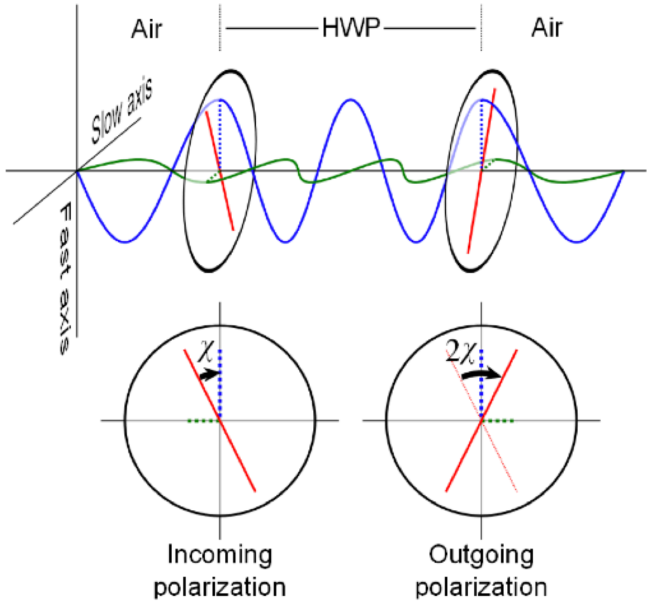
→ Install at aperture or within optical system
Entire focal plane



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

Continuously rotating HWP history

MAXIPOL (balloon)

- First CMB experiment using rotating HWP

EBEX (balloon)

- First experiment using cold rotating HWP with superconducting magnetic bearing

ABS (ground)

- First ground experiment with warm rotating HWP

Simons Array, Simons Observatory SAT (ground)

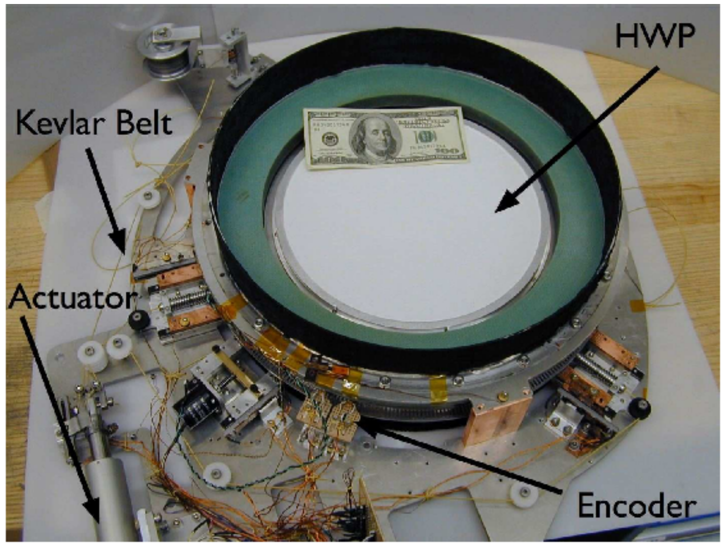
- First ground experiment with cold rotating HWP

LSPE/SWIPE (balloon)

- Balloon experiment with cold rotating HWP

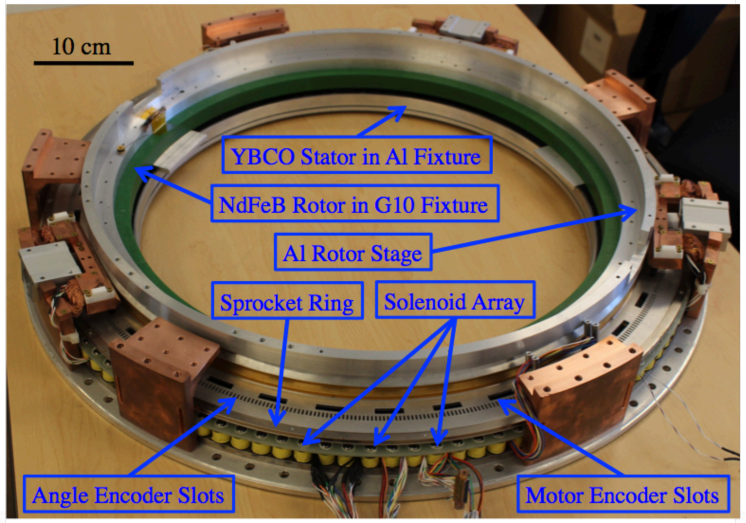
LiteBIRD (satellite)

- Satellite mission with cold rotating HWP



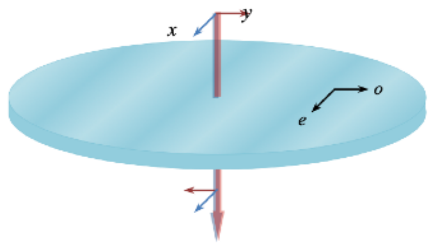
J. Klein et. al. Proc. SPIE 8150 (2011)

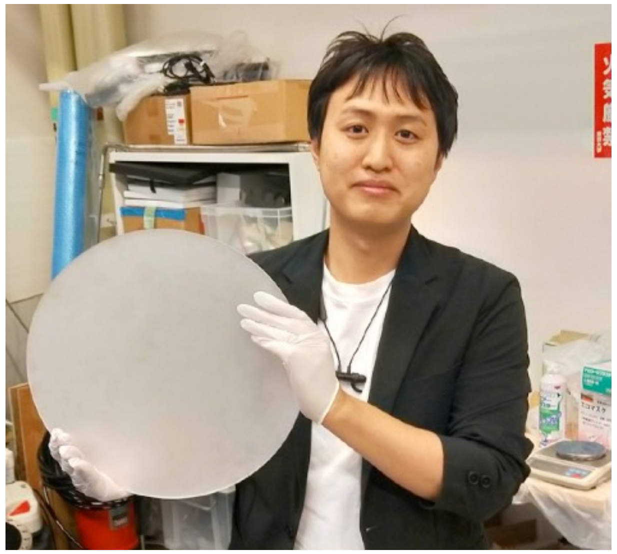
A. Kusaka et. al.(2013)



HWP materials

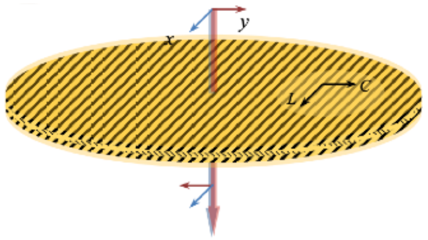
Sapphire



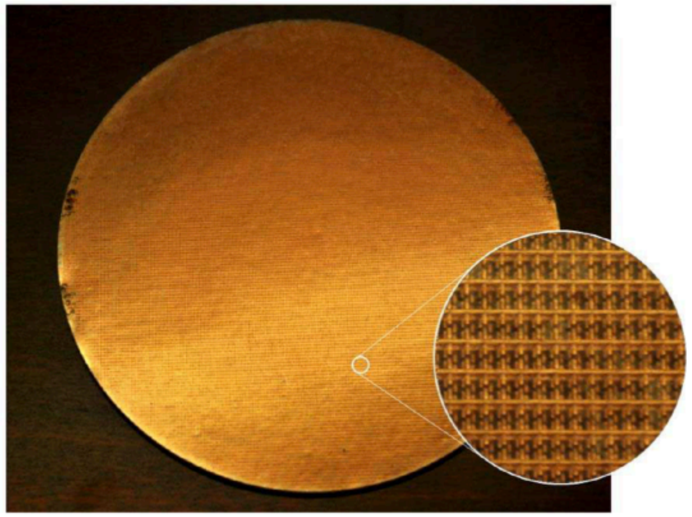


- Birefringence single crystal material
- Maximum diameter ≤ 500mm
- Need anti-reflection (AR) due to refractive index ~3.3
- Broadband of pol. eff. and phase difference are proportional to number of layer ≈ mass
- MAXIPOL, EBEX, SPIDER, ABS, SA, SO, LiteBIRD LFT

Metal-mesh HWP



- 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.



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

Toward satellite application

Higher science goal

- Wider frequency band
- Lower HWP temperature
- Reducing HWP imperfection

Resource limitation

- Cooling power
- Mass
- Volume …

Space specific environment

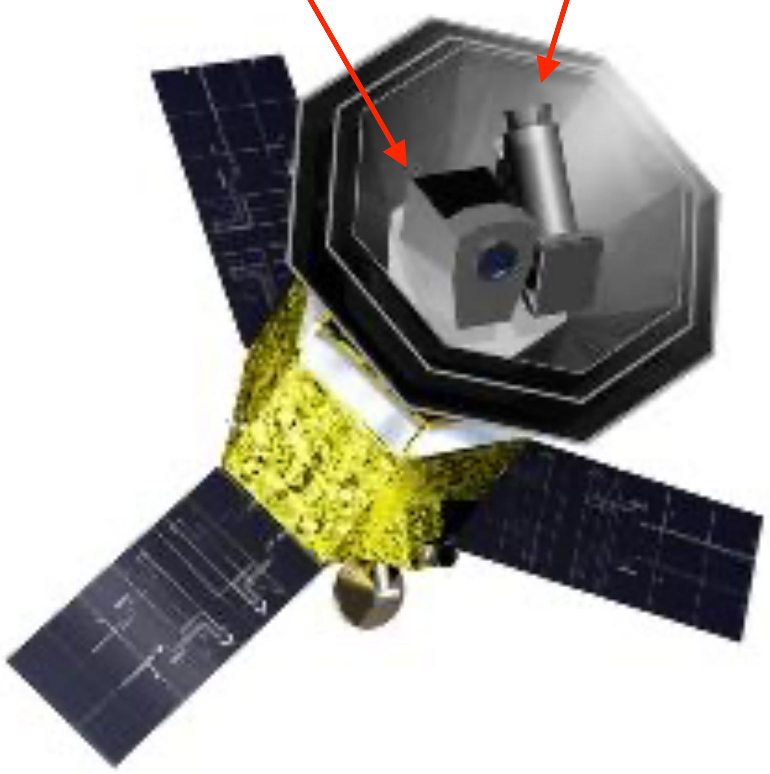
- Launch tolerance
- Cosmic ray
- No gravity

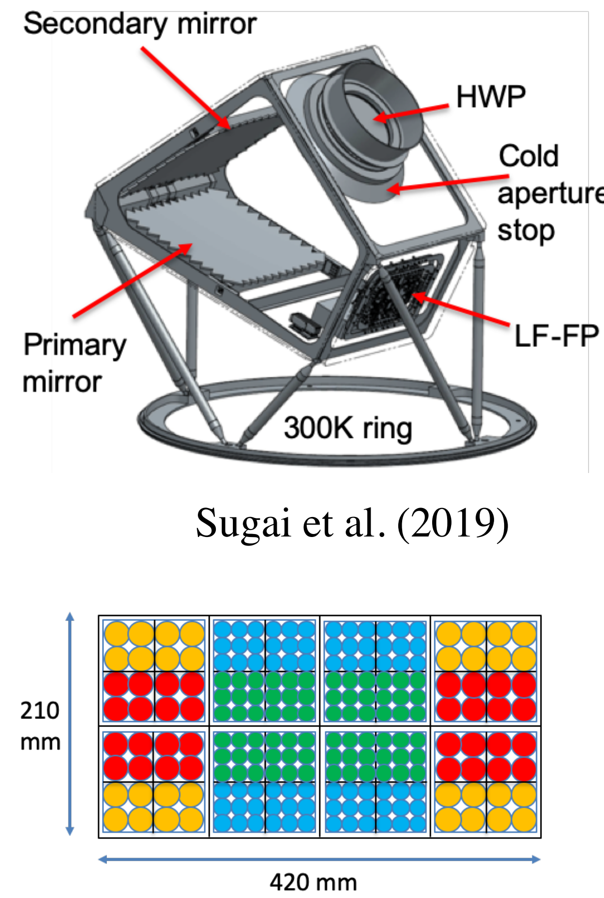
System reliability

- Risk management
- Redundancy
- Emergency operation

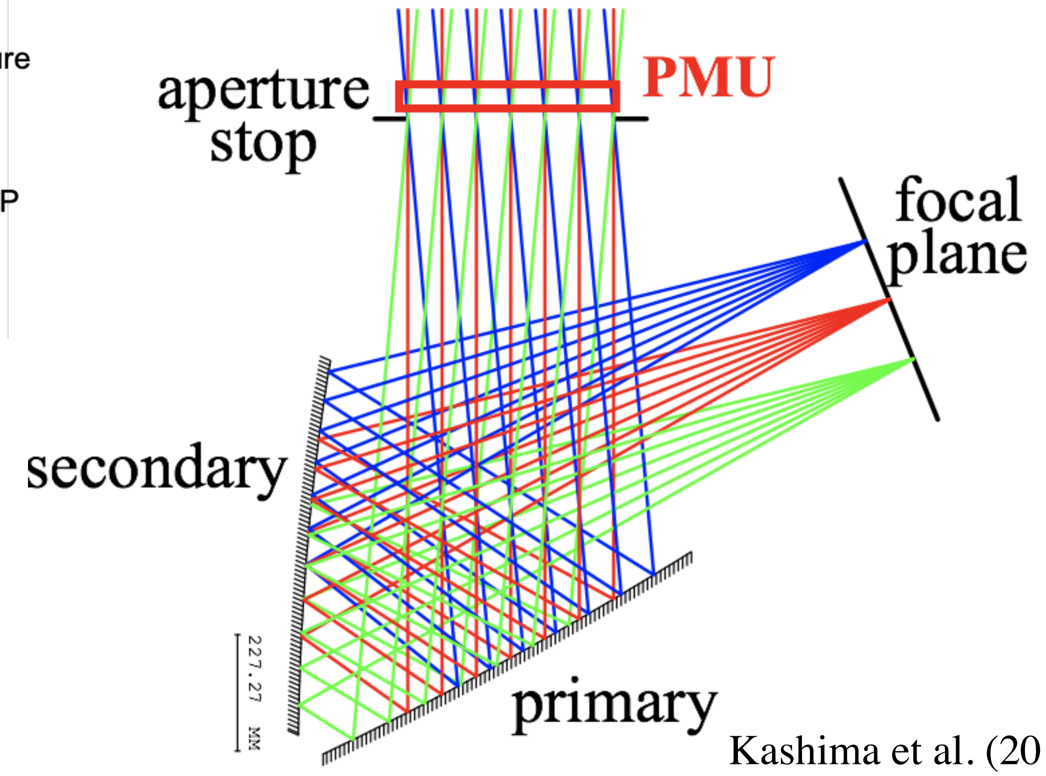
Polarization modulation unit (PMU) for LiteBIRD low frequency telescope (LFT)

LiteBIRD overview





Sugai et al. (2019)



Kashima et al. (2018)

Two telescopes : LFT (34 - 161GHz), MHFT (89 - 448GHz)

Focal plane unit : >4000 superconducting detector (TES) array

Scan strategy : L2 precession 45 deg. (10^{-2}-10^{-3} rpm), spin 50 deg. (0.05-0.1 rpm)

Cooling chain : V-groove → 20K-2ST → 4.8K-JT → 1.75K ADR → 300/100mK ADR

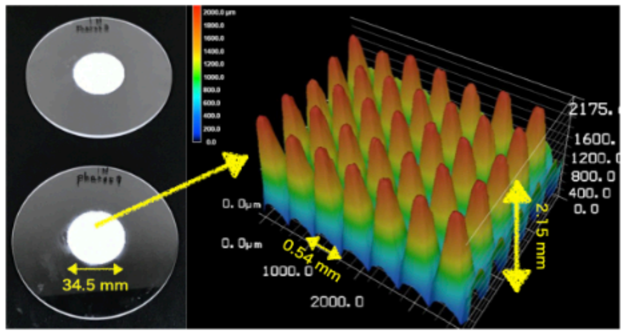
Continuous rotating half-wave plate at the aperture of LFT and MHFT

Representative requirements

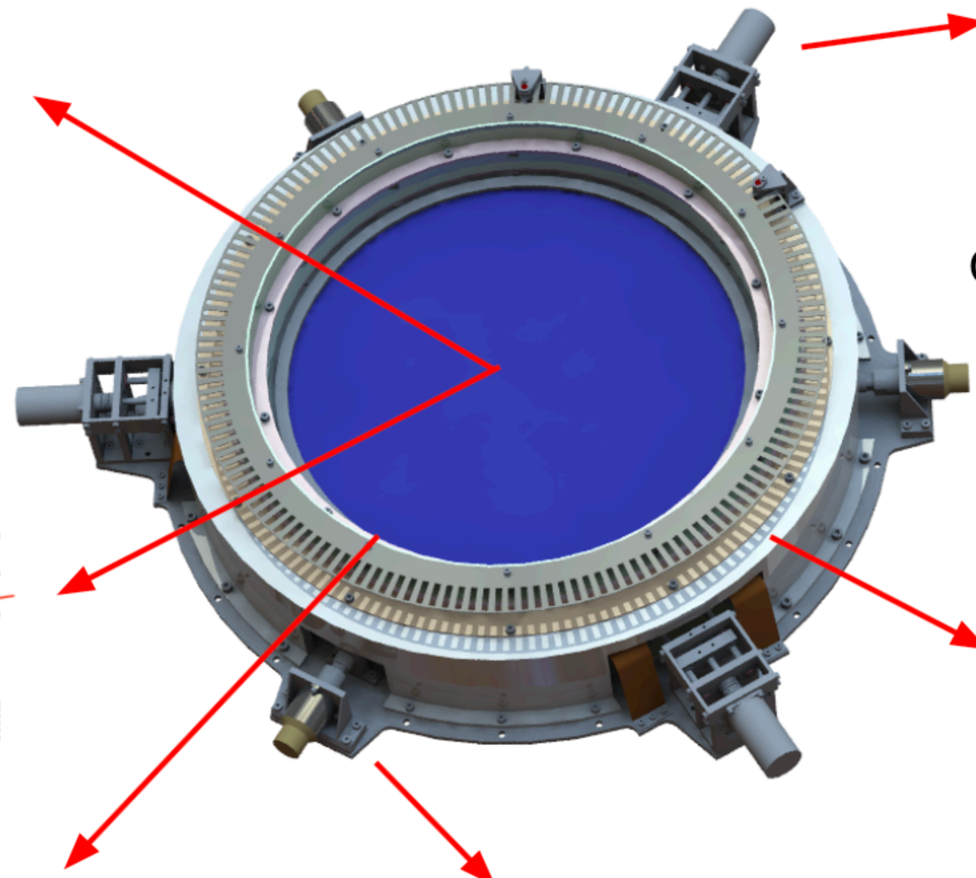
Items	Requirement (LFT)
Frequency band	34 GHz - 161 GHz
Transmittance	> 98% (depend on freq.)
Polarization efficiency	> 98% (depend on freq.)
Rotation frequency	0.8 Hz (48 RPM)
HWP diameter	> ~ 480 mm
HWP temperature	< 20 K
Total heat dissipation	< 4 mW
Mass	< 30 kg
Encoder specification	< 0.2 arcmin

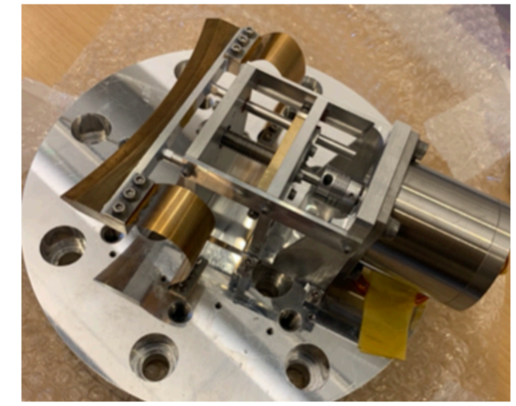
- ✓ The requirement values are not yet fixed because the detail system design and the trade-off study are in progress.
- ✓ Main development items are broadband achromatic HWP and a cryogenic rotation mechanism.

Current design of LiteBIRD LFT PMU

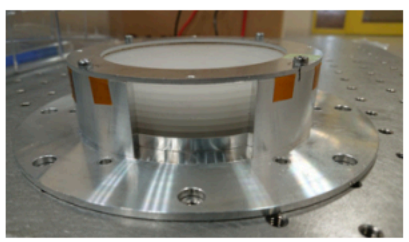


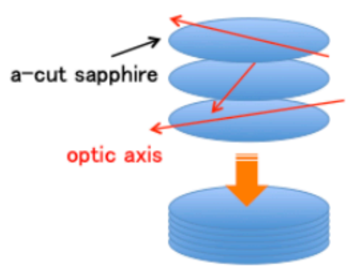
Anti-reflection structure



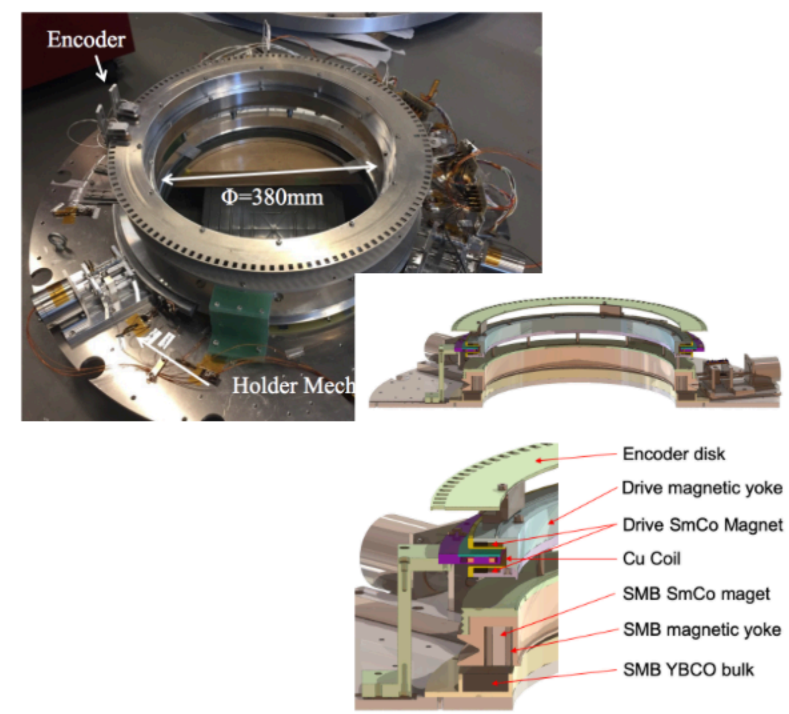


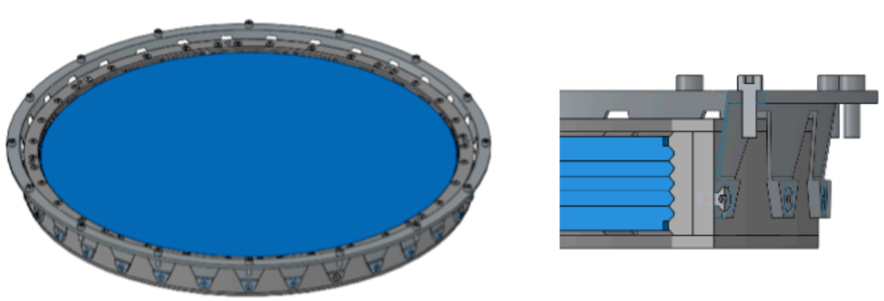
Cryogenic holder mechanism



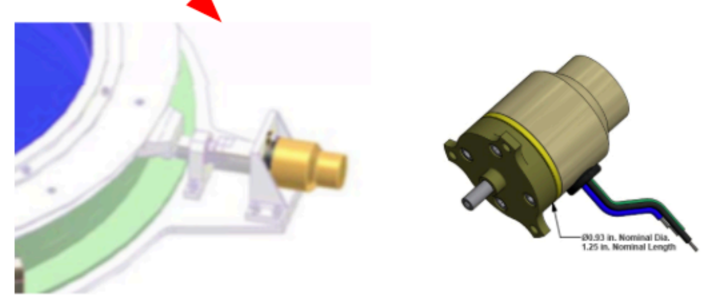


Sapphire stacked
Achromatic HWP





HWP holder

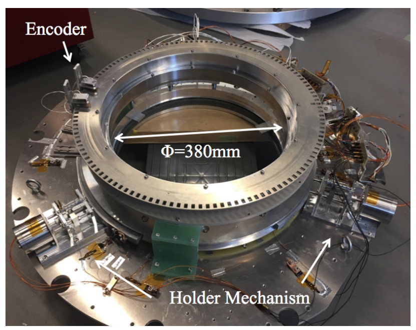


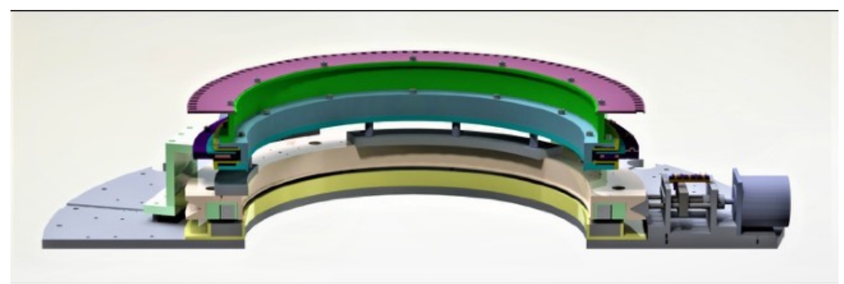
Launch lock mechanism

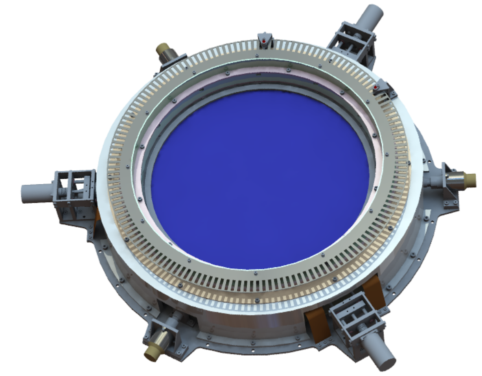
Rotation mechanism

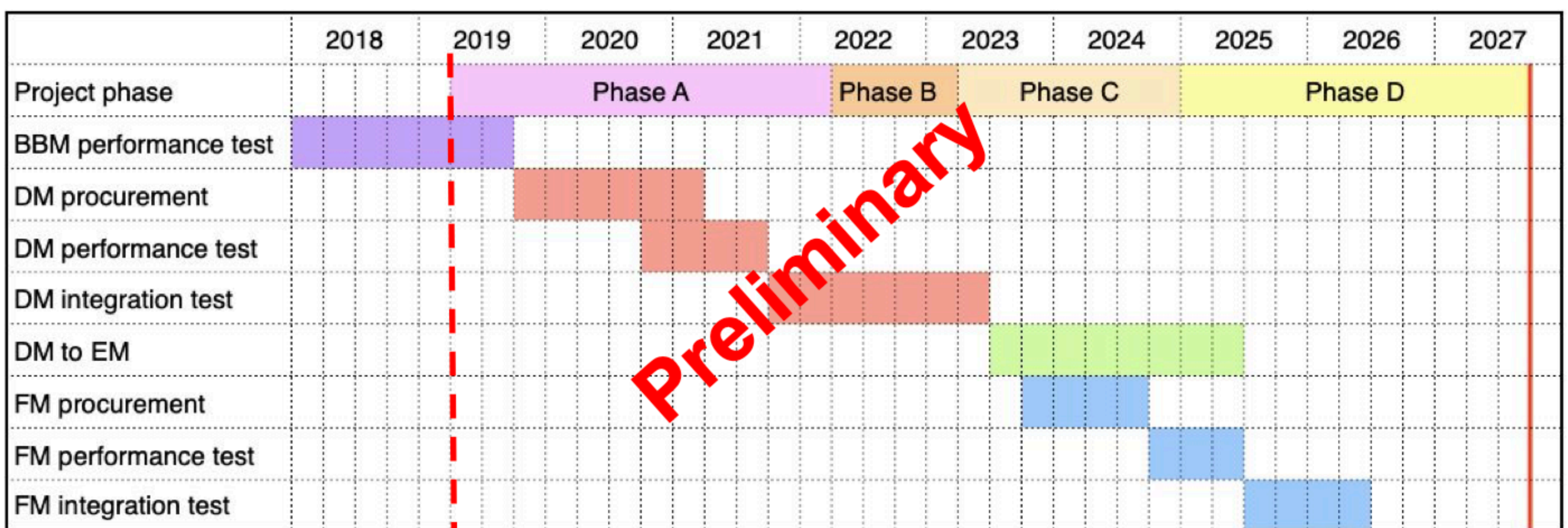
Development roadmap

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

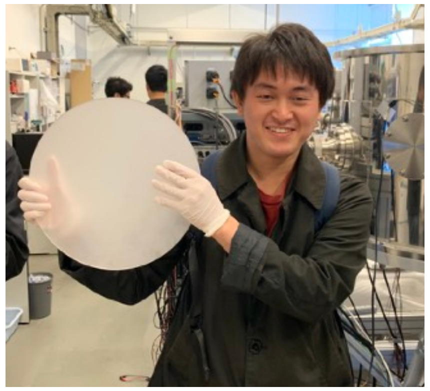




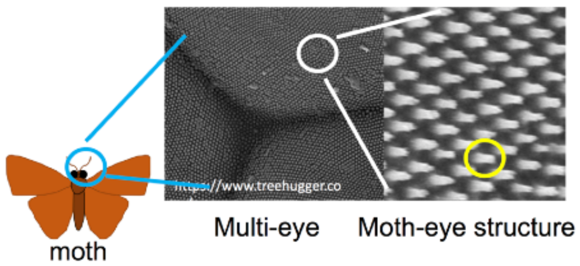




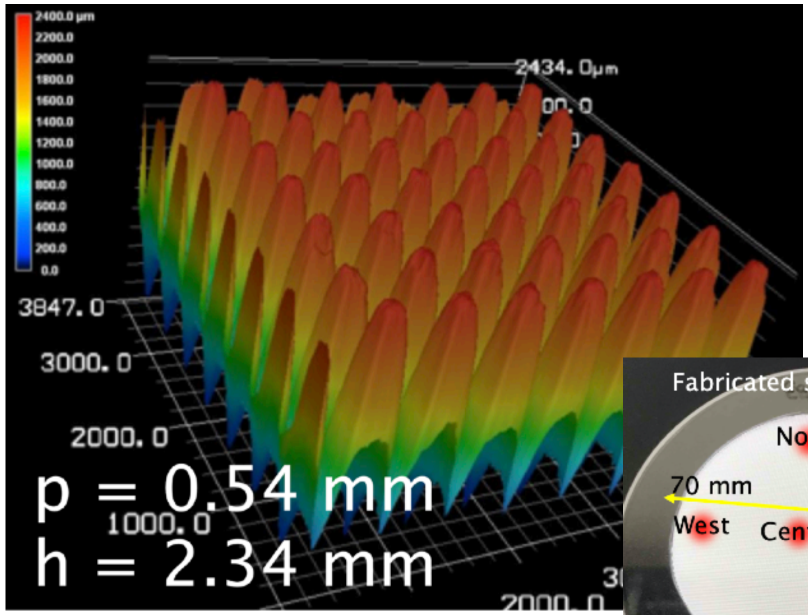
Broadband anti-reflection structure

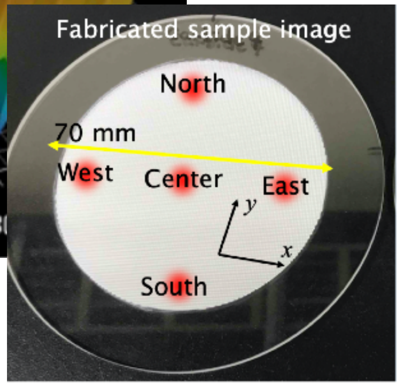


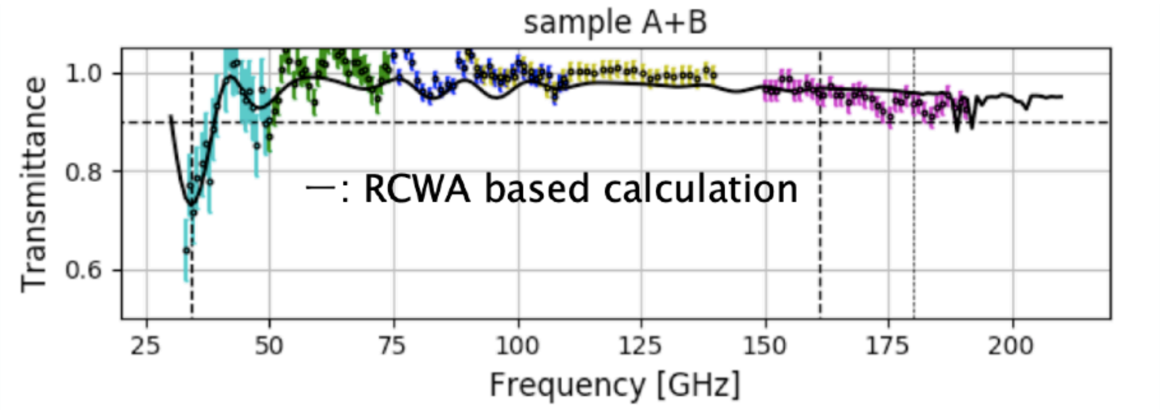
Ryota Takaku (U. Tokyo)



- Broadband antireflection (34-161GHz): moth-eye based sub-wavelength structure by laser machining
- Fabricated Φ70mm 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

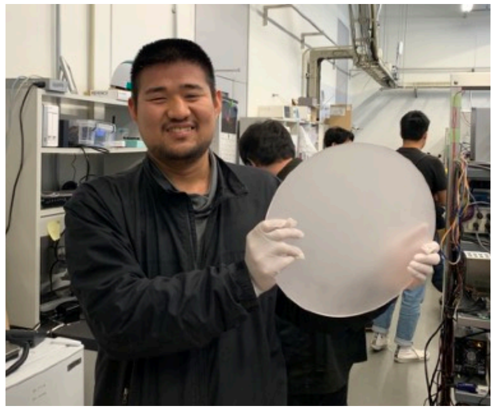




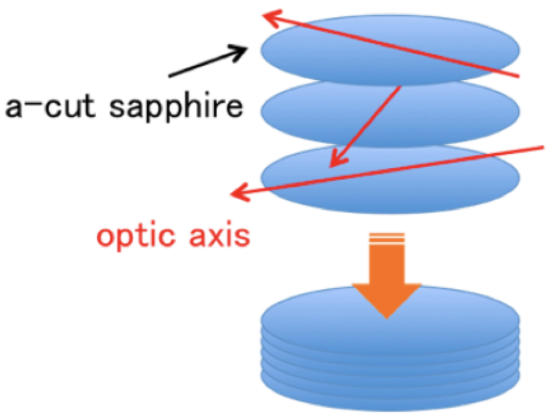


Sapphire AHWP development

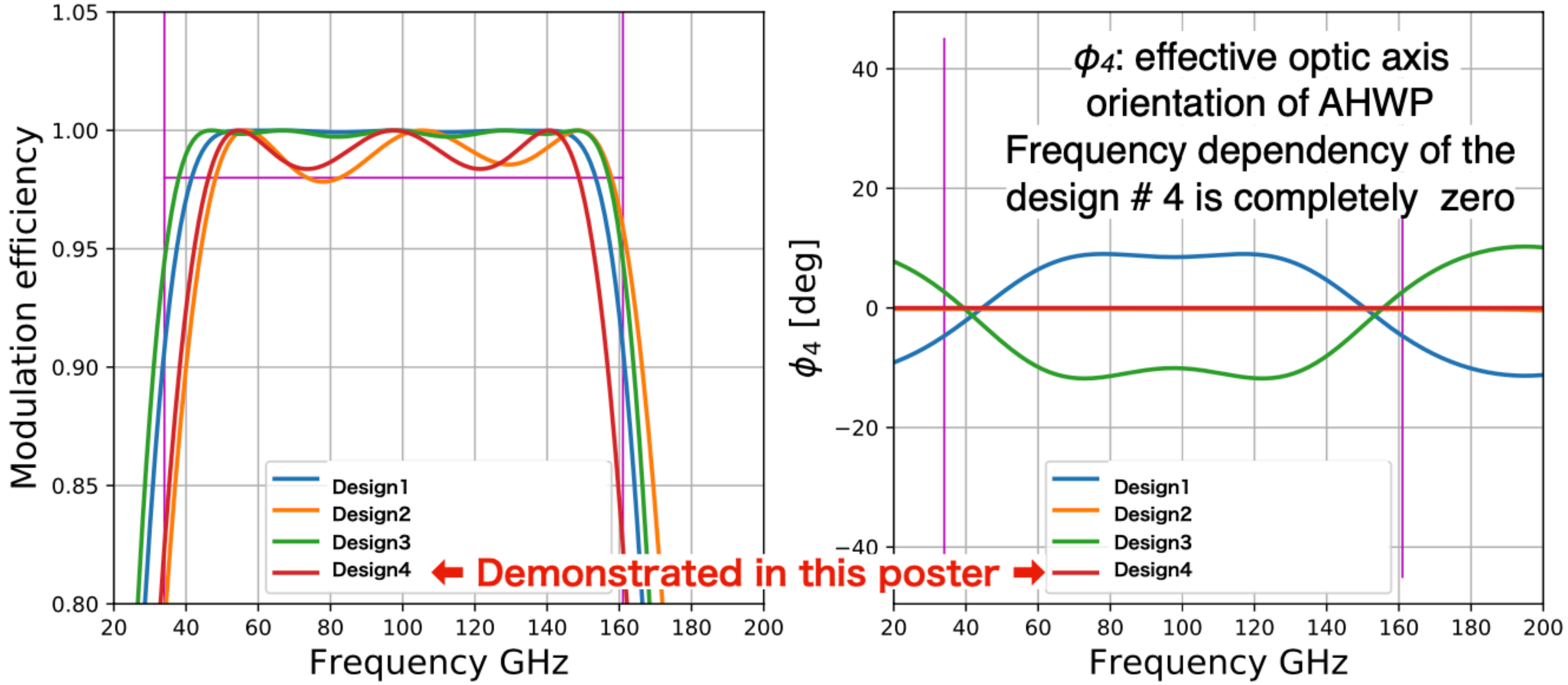
- ✓ Single sapphire plate has pol. eff. ε = 1 for the only single frequency.
- ✓ We adopt Achromatic HWP (AHWP) consists of multi-stacked sapphire with the different optic axis for each HWP.
- ✓ We optimize the AHWP design with 5 layer to cover 34-161GHz.

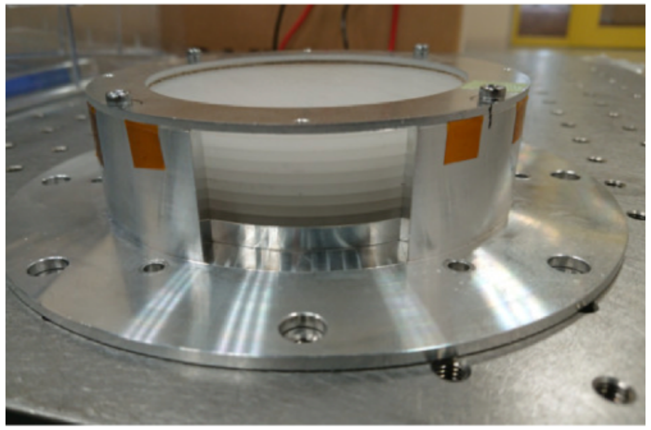


Kunimoto Komatsu (Okayama U.)



Prediction of each five-layer design (w/o reflection effect)





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

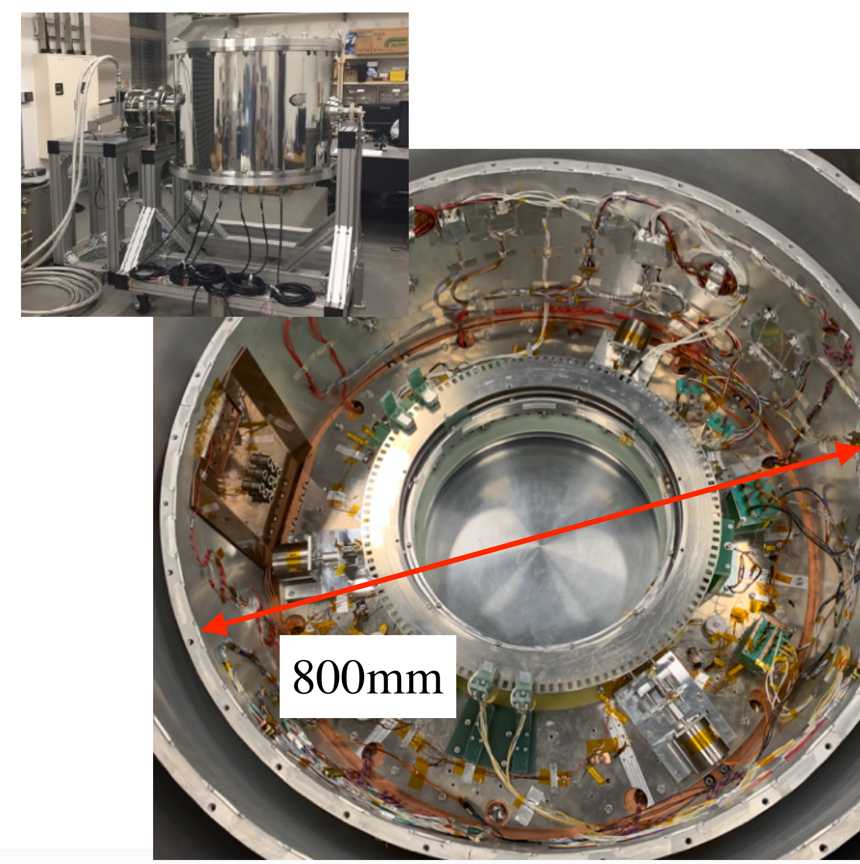
Stable continuous rotation at cryogenic temperature with small heat dissipation

Breadboard model (Φ=380mm)

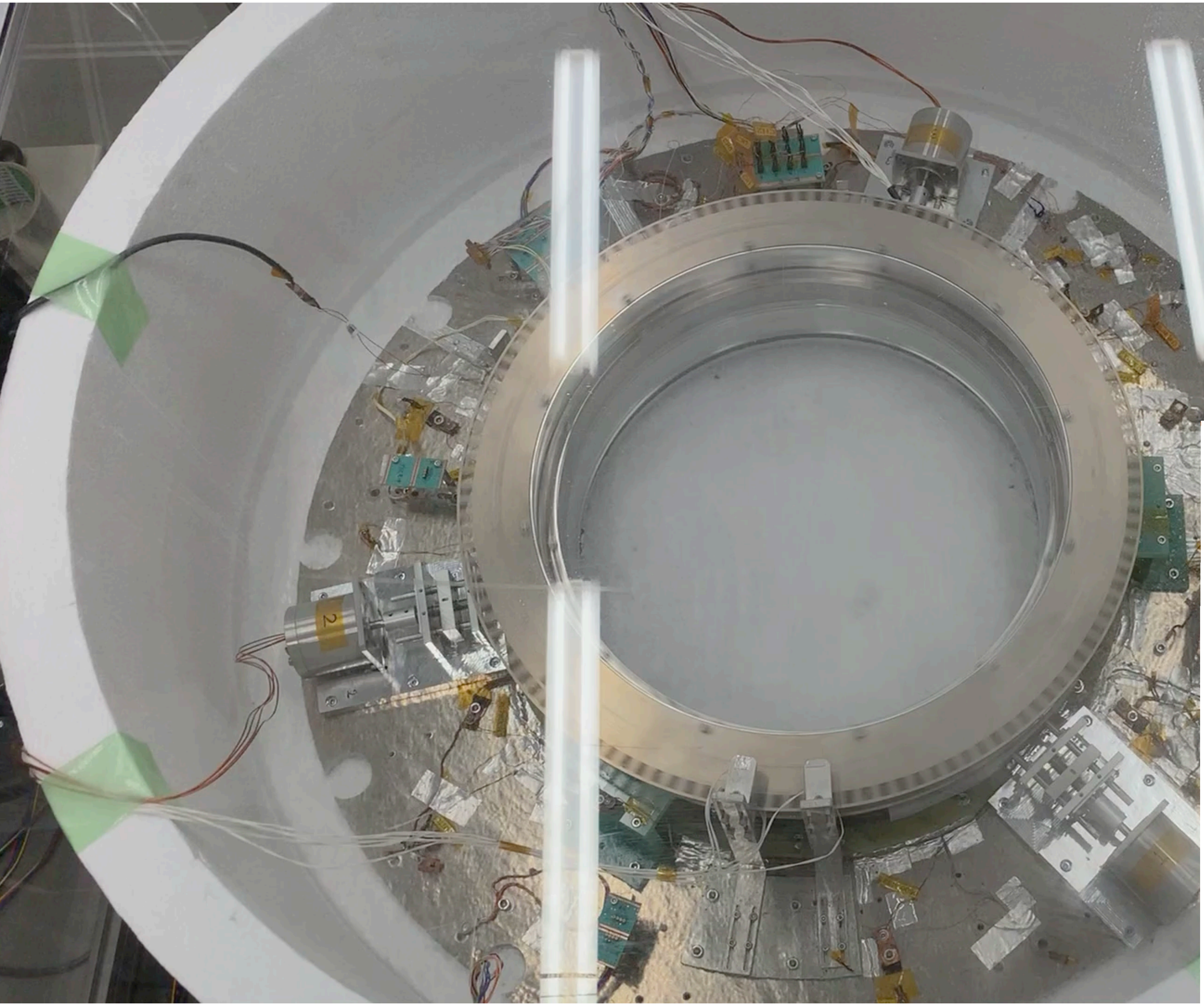
- Superconducting magnetic bearing

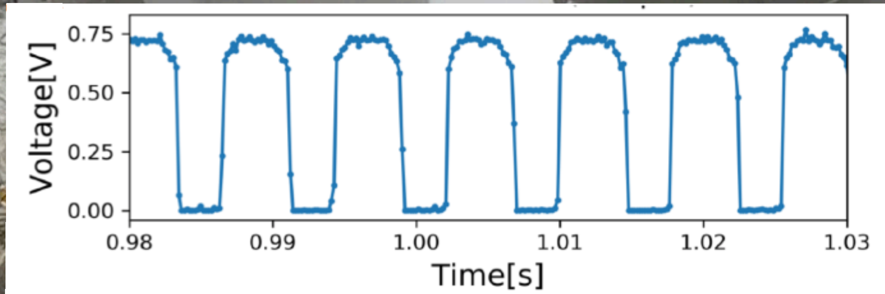
  Rotor: SmCo magnets + yoke for uniformity

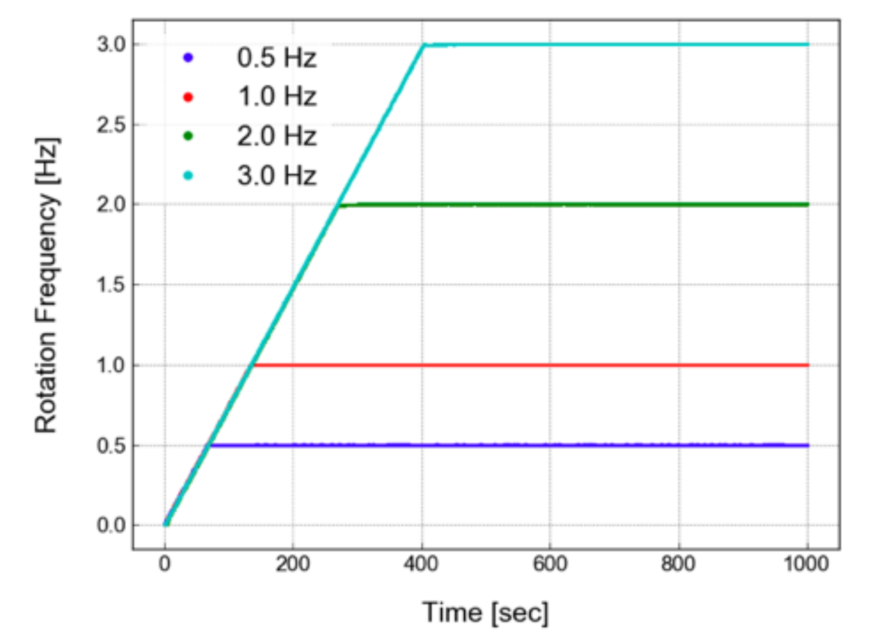
  Stator: YBCO (Tc < 95 K)
- DC brushless motor with speed feedback control measured by optical encoder
- 3 grippers actuated by linear actuators (stepping motors)



Rotation mechanism





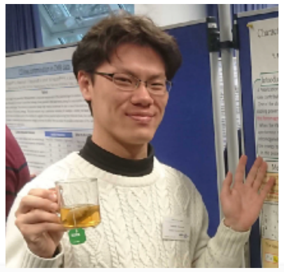


Thermal characteristics

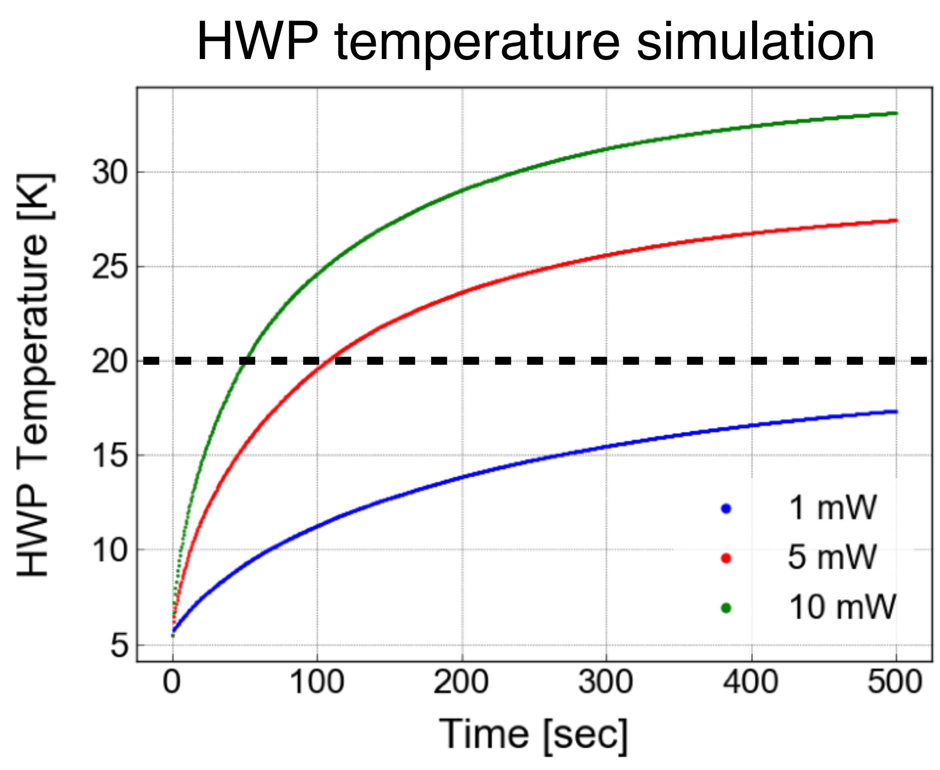
- Total heat dissipation ≤ 4.0 mW
- Rotor heat dissipation ≤ 1.0 mW from thermal simulation
- Heat sources are hysteresis loss, eddy current due to magnet inhomogeneity ΔB

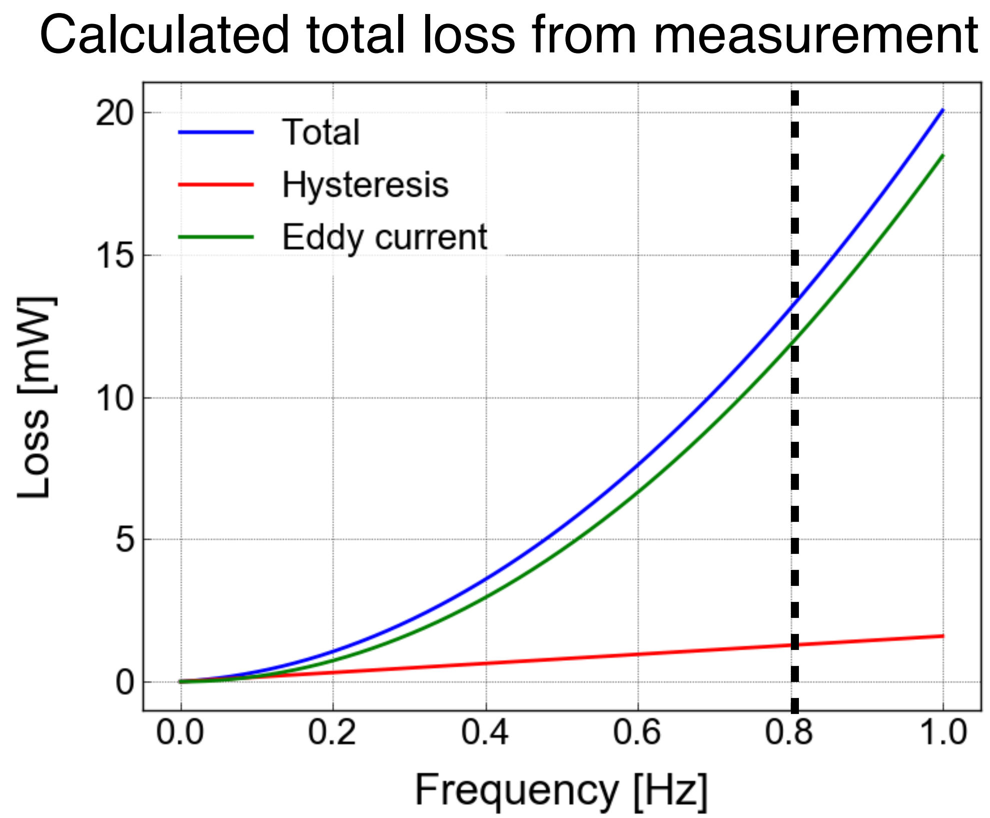
$$P_h \propto k_h f \frac{\Delta B^3}{J_c}, P_e \propto k_e f^2 \Delta B^2$$

- Total loss at nominal rotation speed (46 rpm) is ~10 mW, dominated by eddy current loss
- There is much room for improvement.
  - de-metallization, reduce weight …
  - Uniform magnet with yoke



Yoshiki Nomura (Saitama U.)

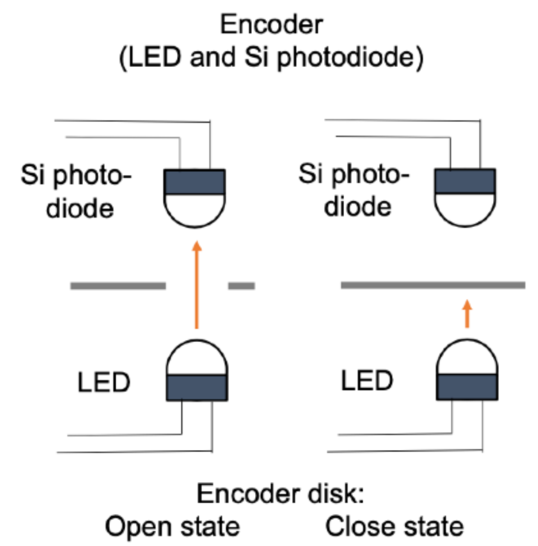


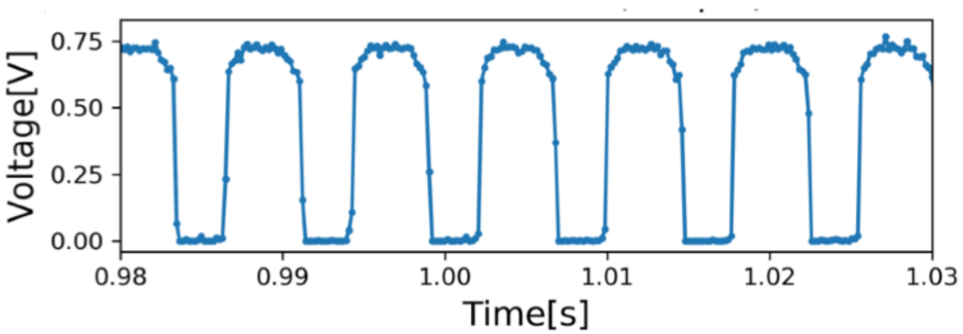


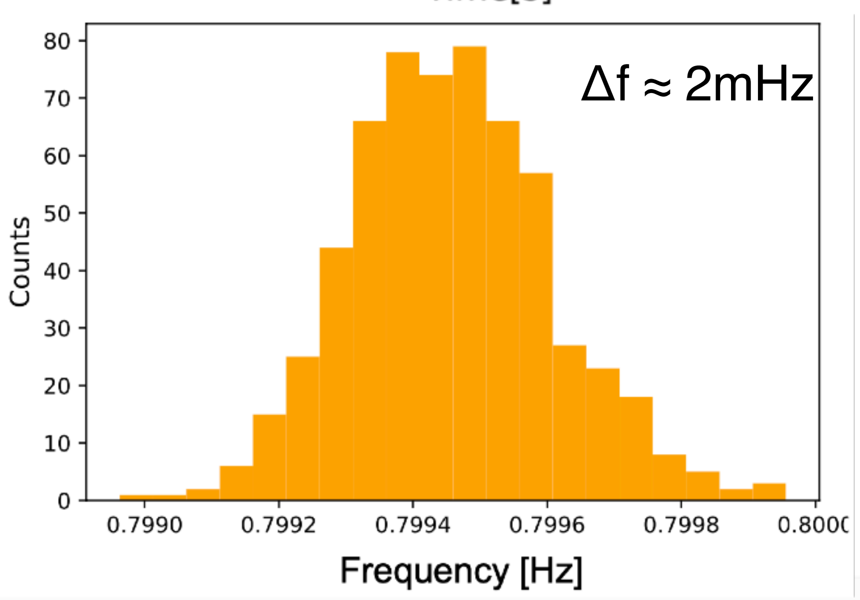
Angular encoding

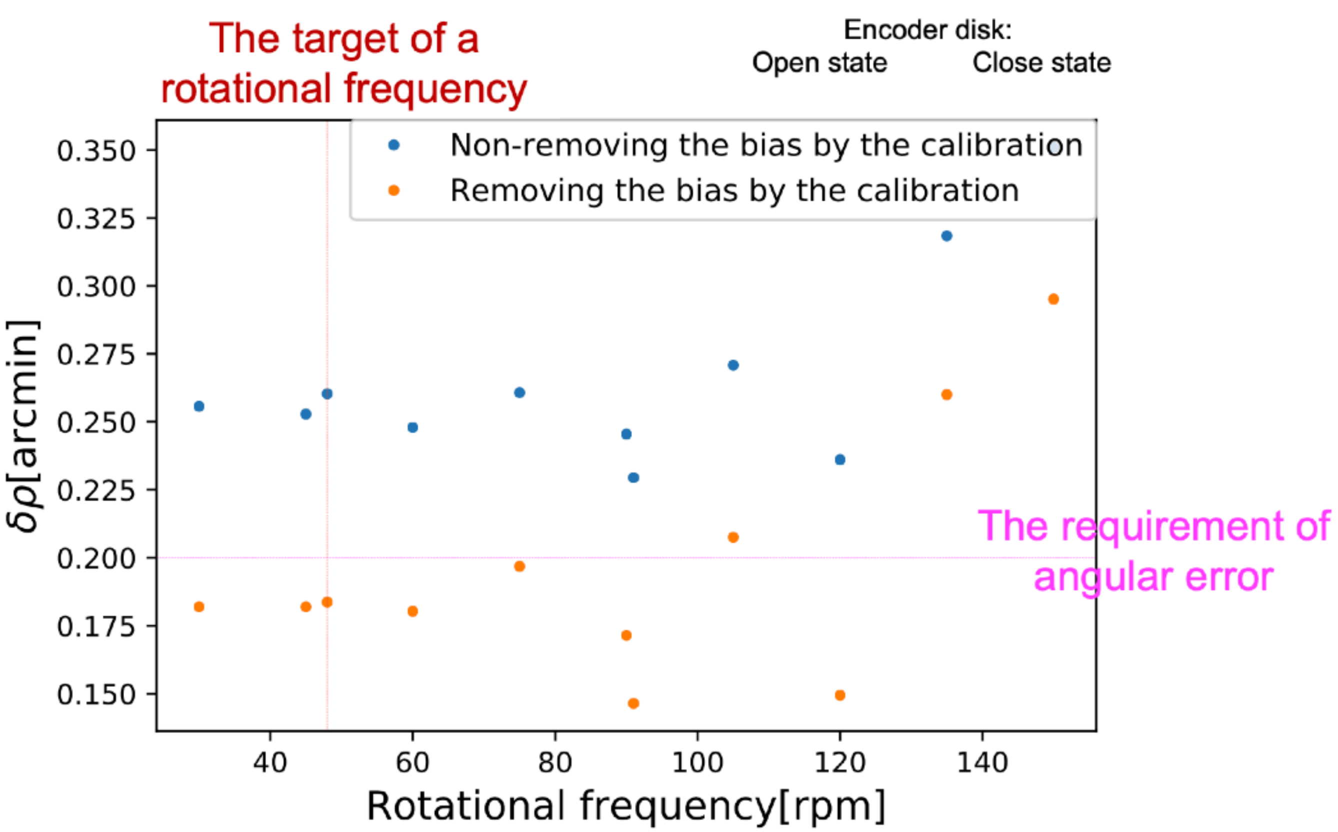
- HWP angle reconstructed by incremental encoder consists of LED and Si photodiode
- Calibrate bias component (not change with each rotation).
- The angular error (random component changed per rotation) is calculated as < 0.2 arcmin.

Shinya Sugiyama (Saitama U.)



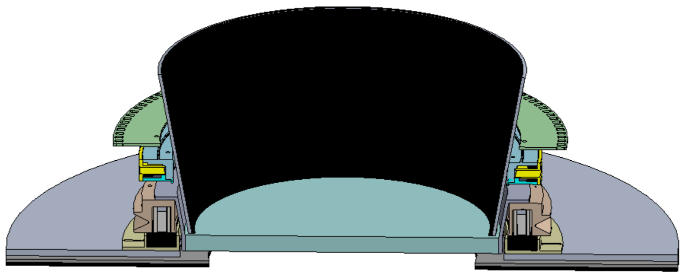


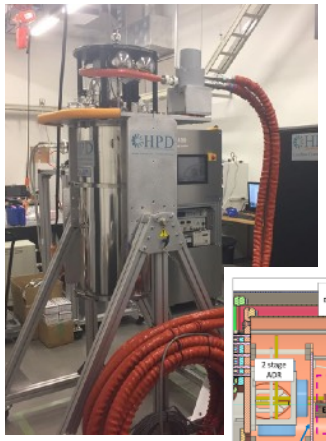




Other activities toward flight model

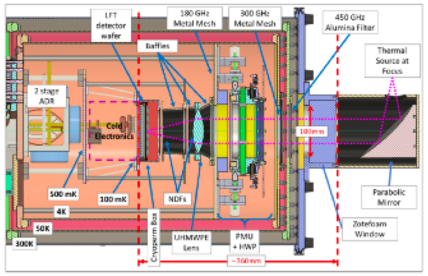
- Cosmic ray effect: radiation damage, heat input, charging
- AHWP gluing and holder design for launch tolerance.
- System optimization including baffle and stop
- Fault tree analysis (FTA) to identify critical risks and components required redundancy.
- Development of low loss cryogenic motor
- Cryogenic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



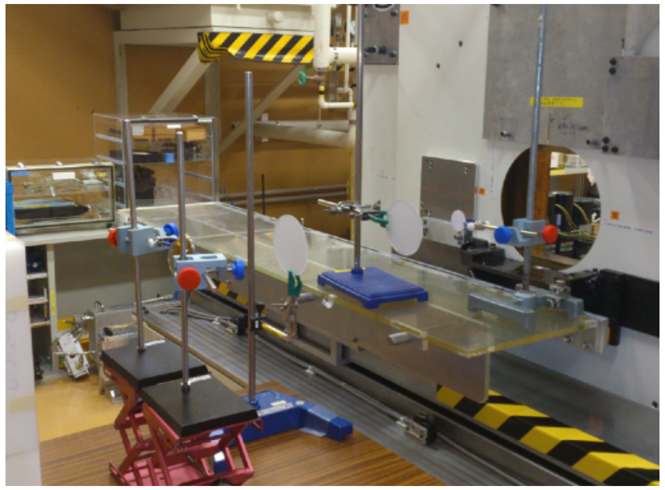


ADR testbed

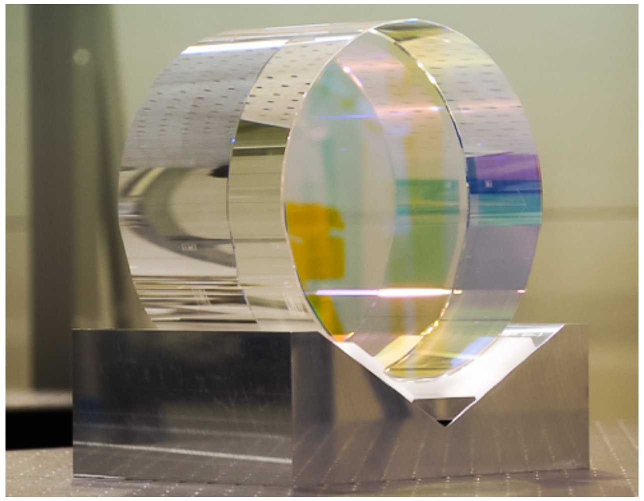
T. Ghigna et al (2019)



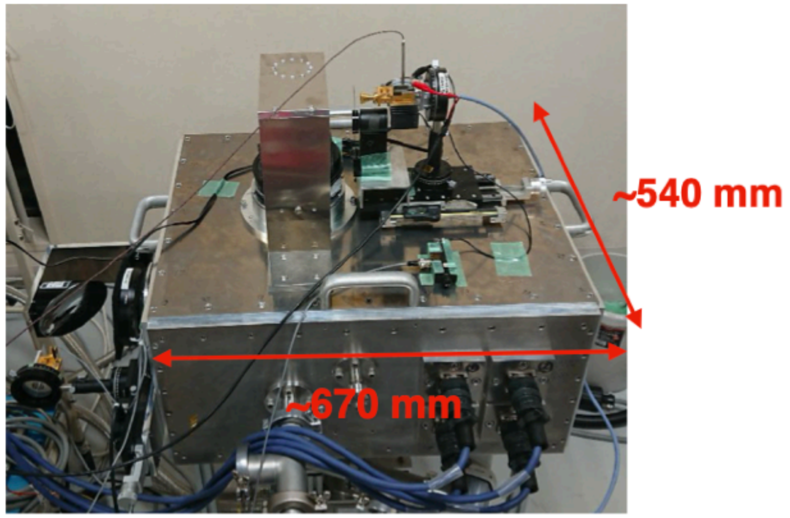
Cosmic ray test @ HIMAC



Sapphire Gluing (KAGURA)



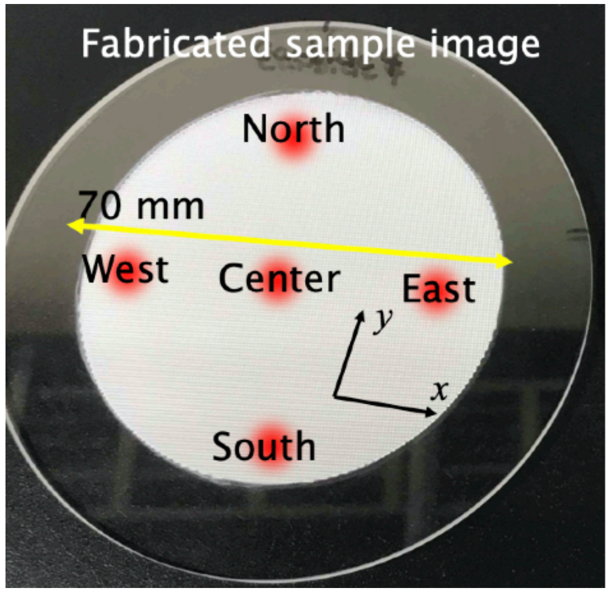
4K CM cryostat @ Kavli IPMU

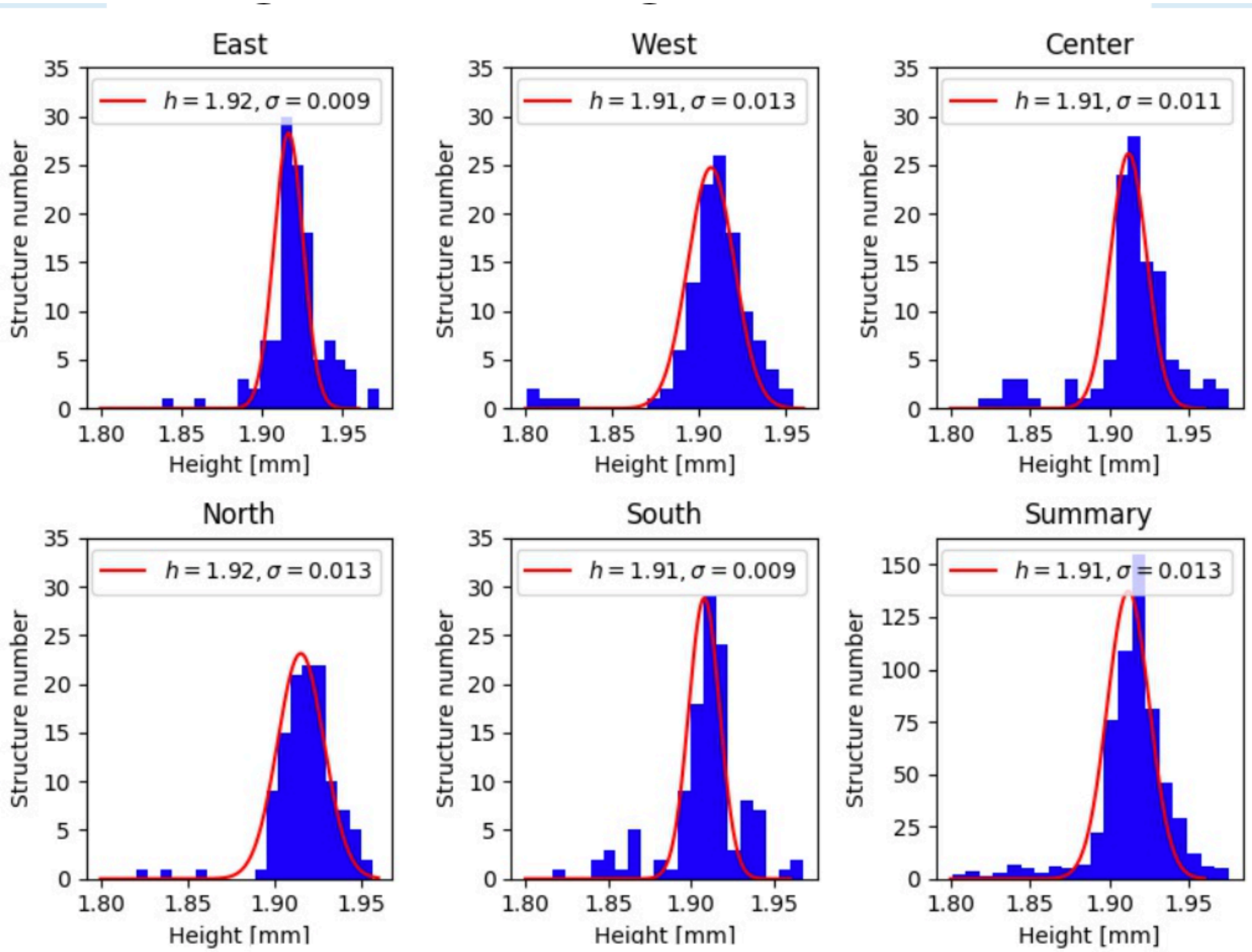


Summary

- ✓ 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 by small samples.
- ✓ Cryogenic performance test of BBM rotation mechanism is in progress toward flight model.

Otsukare!


Fabricated sample image
North
70 mm
West
Center
East
y
x
South


East
$h = 1.92, \sigma = 0.009$
West
$h = 1.91, \sigma = 0.013$
Center
$h = 1.91, \sigma = 0.011$
North
$h = 1.92, \sigma = 0.013$
South
$h = 1.91, \sigma = 0.009$
Summary
$h = 1.91, \sigma = 0.013$
Structure number
Height [mm]