

FINER: Far-Infrared Nebular Emission Receiver for LMT/GTM

Revision history

Date	Author(s)	Revision
2023-June-15	Yoichi Tamura	Version A

EXECUTIVE SUMMARY

When massive galaxies emerge and how common they are in the epoch of reionization and beyond (i.e., the age of the universe less than 600 million years, or the pre-reionization era, hereafter) is one of the most fundamental questions in astronomy. Recent progress in finding the excessive population of massive galaxies suggests an extremely high efficiency of galaxy assembly in the pre-reionization era, while it is still unclear what physical properties drive their rapid growth. Millimeter and submillimeter-wave spectroscopic observations of redshifted far-infrared spectral lines should be a key to address the question. For this sake we develop a dual-polarization sideband-separating superconductor-insulator-superconductor (SIS) mixer receiver, FINER, for the Large Millimeter Telescope (LMT) in Mexico. FINER covers a wide range in radio frequencies from 120–350 GHz, with an instantaneous intermediate frequency (IF) of 3–21 GHz per sideband per polarization, providing 40% of ALMA’s light-collecting area, a similar atmospheric transmittance to ALMA, and a 5× wider bandwidth than ALMA, which offers the highest spectral scanning capability in the northern hemisphere.

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1. INVESTIGATORS AND DEVELOPMENT TEAM

Yoichi Tamura	Nagoya	Principal investigator (PI)
Takeshi Sakai	UEC	Co-PI, receiver development
Development		
Takafumi Kojima	NAOJ	SIS mixer
Wenlei Shan	NAOJ	SIS mixer
Haoran Kang	NAOJ	Receiver development
Tatsuya Takekoshi*	Kitami Tech	Optics
Kunihiko Tanaka*	Keio	Software, LMT interface, commissioning
Akio Taniguchi*	Nagoya	Software, data handling, commissioning
Masato Hagimoto*	Nagoya	Spectrometer, commissioning
Norika Okauchi	Nagoya	Spectrometer
Tac Nakajima	Nagoya	LO waveguide filter
Ryohei Kawabe*	NAOJ/Nagoya	Systems, B4R PI

Tai Oshima	NAOJ	Systems
Commissioning		
Kotomi Taniguchi	NAOJ	Commissioning, astrochemistry
Teppei Yonetsu	Osaka Metropolitan U	Commissioning, star formation
Taichi Kitamura	Osaka Metropolitan U	Commissioning, star formation
Kotaro Kohno	UTokyo	Commissioning (lead), galaxy formation
Akiyoshi Tsujita	UTokyo	Commissioning, galaxy formation
(people with * also members of the commissioning team)		
Yoichi Tamura, Takeshi Sakai, Kunihiro Tanaka, Akio Taniguchi, and Masato Hagimoto are also members of the commissioning team.		
Science		
Akio K. Inoue	Waseda	Galaxy formation, spectral modeling
Takuya Hashimoto	Tsukuba	Galaxy formation, sample selection
Yuichi Harikane	UTokyo	Galaxy formation, luminosity function
Ken Mawatari	NAOJ	Galaxy formation, spectral modeling
Yoshinobu Fudamoto	Chiba	Galaxy formation, sample selection
Tom Bakx	Chalmers	Galaxy formation, submm data
Hideki Umehata	Nagoya	Galaxy formation, submm data
Bunyo Hatsukade	NAOJ	Galaxy formation, submm data
Yuichi Matsuda	NAOJ	Galaxy formation, infrared data
Hirofumi Maezawa	Osaka Metropolitan U	Solar system
Hideo Sagawa	Kyoto Sangyo U	Solar system
Takahiro Iino	UTokyo	Solar system
Shigeru Takahashi	UTokyo	Solar system

2. SCIENTIFIC RATIONALE

2.1. Scientific background

How and when first stars and galaxies form is one of the most fundamental questions in modern astronomy. The pristine materials in the early universe cooled down to form neutral hydrogen at redshift $z \sim 1000$ or 380k years after the Big Bang. Once first stars and galaxies are born, however, the hydrogen gas in the intergalactic space is ‘reionized’ by hydrogen-ionizing photons from the hot, massive stars. This so-called cosmic reionization is indirect evidence for the birth of the first luminous objects. In recent years, *Planck* satellite has reported that cosmic reionization occurred in the period centered at redshift $z = 7.8$ (660 million years after the Big Bang, [Planck Collaboration 2018](#)), whereas hundreds of galaxy candidates have been identified with *Hubble* and *James Webb Space Telescopes* (*HST* and *JWST*) even before the period (e.g.,

[Naidu et al. 2022](#); [Donnan et al. 2022](#); [Finkelstein et al. 2022](#); [Harikane et al. 2022](#), [Bouwens et al. 2023](#)), meaning that we are likely witnessing the birth of the earliest galaxies in the universe (**Figure 1**).

In particular, finding *massive* galaxies in the era is difficult but is expected to offer unique information on galaxy formation, because the probability of finding them (i.e., volume density or luminosity function) depends on cosmic structure formation models. Recent discoveries of the excessive massive galaxy candidates at $z > 8$ made by *HST* and *JWST* (**Figure 2**) suggest an extremely high efficiency of galaxy assembly in the earliest Universe, while it is still unclear what drives the rapid growth of the massive population. Then, the key questions we are trying to address in this research include

- when massive galaxies emerge,
- how common they are in the pre-reionization era,
- what controls their growth.

It is, however, difficult to confirm galaxy "candidates" in the era; in general, identifying an object as a galaxy and determining its physical properties begin with spectroscopy of atomic or molecular spectral lines. But, the combination of bright spectral lines and a sensitive instrument that are sufficient for detection of a galaxy even in the furthest universe was very limited.

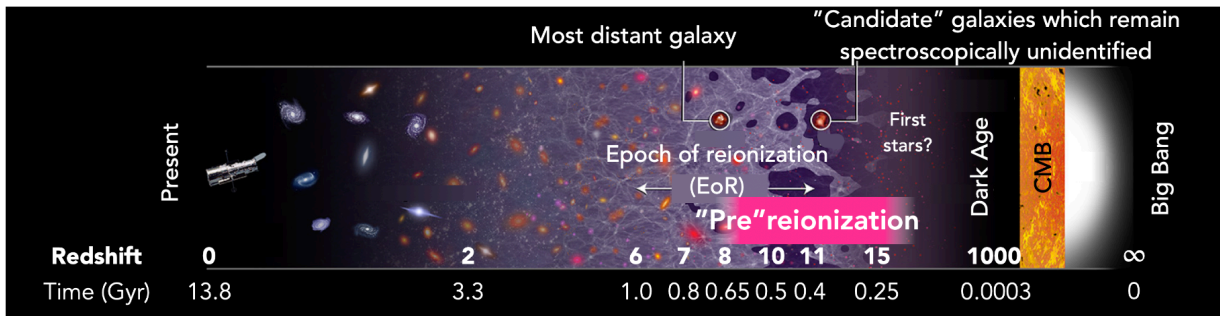


Figure 1. Galaxy formation at the epoch of reionization and beyond (pre-EoR) in the history of the Universe.

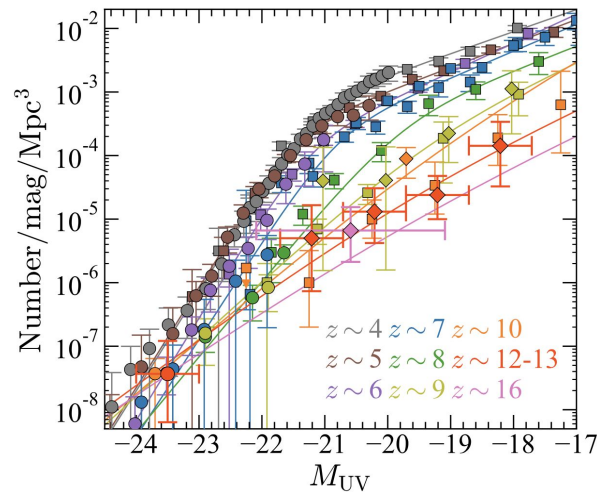


Figure 2. Evolution of the UV luminosity function from $z = 4$ to 16 (Harikane et al. 2022). The bright-end ($M_{\text{UV}} < -22$) number densities at $z > 8$ seem to exceed those expected from the lower- z evolution.

2.2. Key science goal

In this study, we aim for a sensitive spectroscopic survey of galaxies in the pre-reionization era using the far-infrared fine-structure lines, the $^3\text{P}_1 \rightarrow ^3\text{P}_0$ transition of doubly-ionized oxygen [O III] 88.3 μm (3393.01 GHz) and the $^2\text{P}_{1/2} \rightarrow ^2\text{P}_{3/2}$ transition of ionized carbon [C II] 157.7 μm (1900.54 GHz), based on our novel mm and submm-wave receiver, FINER, for the Large Millimeter Telescope (LMT, [Hughes et al. 2010, 2020](#)). The [OIII] line is demonstrated to be bright in ultraviolet-selected galaxies ([Inoue et al. 2016, Science](#)) and now becomes a useful tracer in identifying their spectroscopic redshifts (e.g., [Hashimoto et al. 2018, Nature](#); [Tamura et al. 2019, Figure 3](#)) even compared with *JWST* ([Figure 4](#)). We also aim to elucidate their physical properties, such as gas-phase metallicity, ionizing photon and gas densities, and multi-phase gas structure, such as a covering fraction of neutral gas in photodissociation regions. Those physics are the key to unveil the origins of the extraordinary efficiency of star formation in the earliest massive galaxies *JWST* has found.

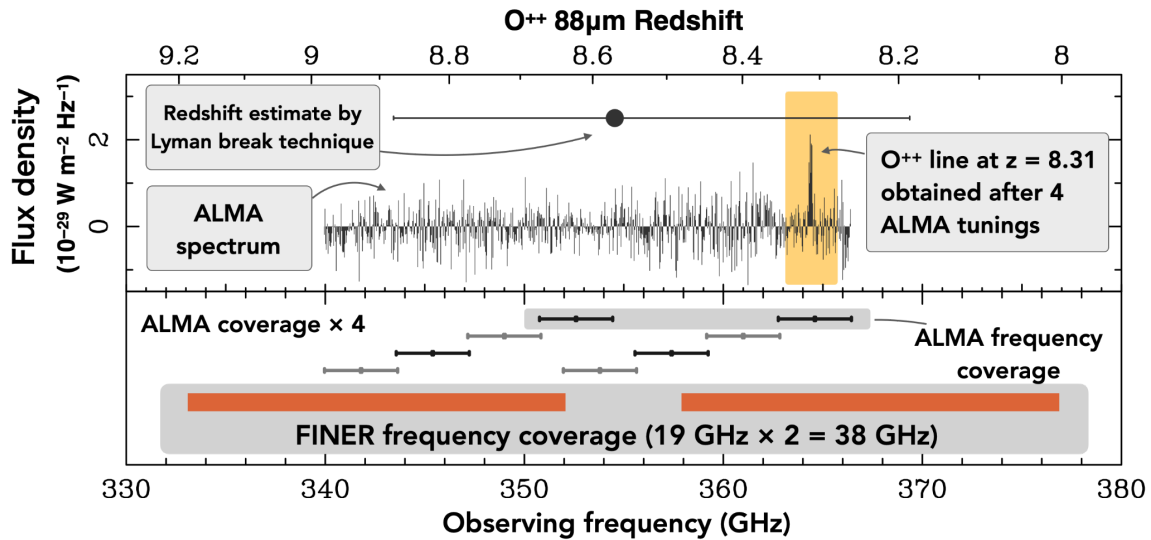


Figure 4. The [O III] 88 μm line detected a $z = 8.31$ Lyman break galaxy, MACS0416_Y1 (Tamura et al. 2019). The spectrum was obtained by four tunings of ALMA. Redshift uncertainty of a typical galaxy candidate at $z \sim 10$ is $\Delta z \sim 1 \frac{z}{10}$, requiring a > 30 GHz spectral coverage. ALMA requires 4 to 6 tunings, whereas FINER only needs a single tuning to cover > 30 GHz.

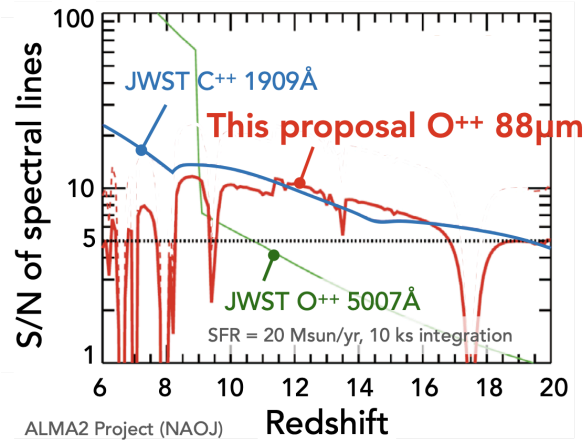


Figure 4. The expected signal-to-noise ratio of redshifted spectral lines in the rest-frame far-infrared and the UV to optical with *JWST*/NIRSpec, MIRI (Inoue, ALMA2 Science Book). The line intensities are calculated by assuming a young star-forming galaxy with star-formation rate (SFR) of $20 M_{\odot} \text{ yr}^{-1}$. At redshifts > 9 it is expected that LMT/FINER is competitive to the *JWST* NIRSpec spectroscopy of CIII] 1909Å.

2.3. Broad impact and complementary role of FINER

Figure 5 shows how FINER complements the capabilities of LMT’s existing receivers. FINER fully covers the same frequency bands as ToITEC but with broad, high-dispersion spectroscopic capabilities. Although FINER is a single-beam receiver, it offers the imaging spectroscopic capability, which complements SEQUOIA and allows one to seamlessly cover the mm to submm bands. As shown in the right panel of **Figure 5**, FINER is the unique instrument offering the highest spectral-resolving power $R \equiv f/\Delta f$ over the frequency range from 125 to 210 GHz, which is useful for planetary, Galactic, and extragalactic spectroscopic studies and thus will benefit the LMT user community. It also offers the widest instantaneous frequency coverage with a modest spectral resolving power $R = 10,500\text{--}17,500$ among the LMT receivers operating at 125–350 GHz (the bottom edge of the ‘FINER’ rectangle in **Figure 5** left).

With these capabilities, FINER offers broader science cases in addition to the EoR galaxy science (see **Table 1**), such as

- solar system
- interstellar medium and astrochemistry
- star formation
- nearby galaxies
- distant submillimeter-bright galaxies

In addition, FINER will offer a better continuum sensitivity for telescope calibration, such as relative pointing, focusing, astigmatism correction, and beam efficiency measurements. In what follows, we describe the science cases in astrochemistry and dust-obscured galaxy evolution that FINER will offer. We also mention the impact on telescope calibration.

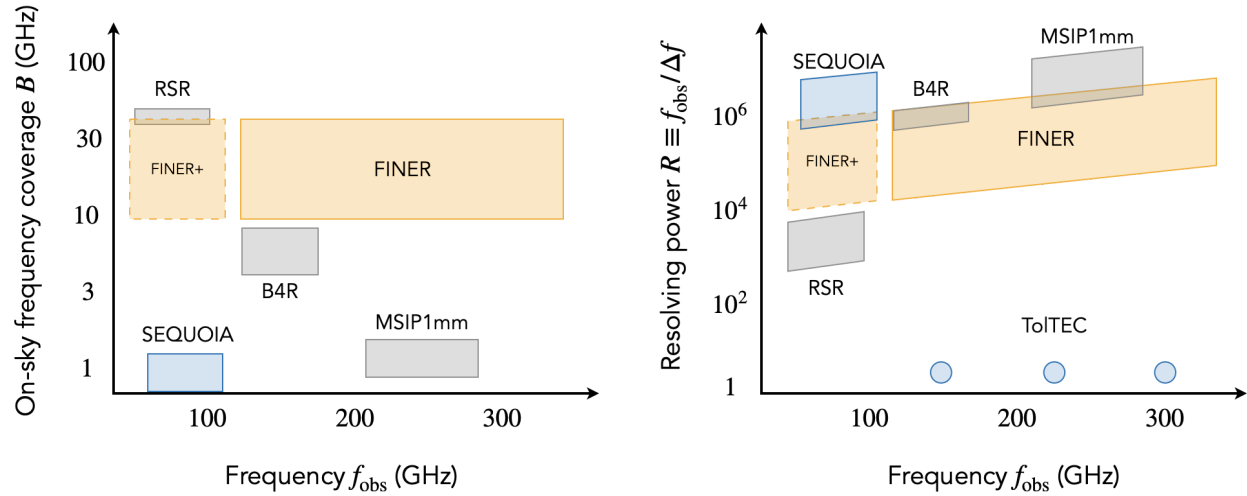


Figure 5. Instantaneous on-sky frequency coverage and resolving power of LMT receivers as a function of frequency. The gray and blue rectangles represent the capabilities of existing single and multi-beam receivers/camera, respectively. FINER and its potential 3-mm extension (denoted as FINER+, see also §5.3) are represented by the orange rectangles.

Table 1. A summary of potential science cases afforded by LMT-FINER.

Scientific field	Use cases	Complementarity to existing receivers
Solar system	• High resolution spectral-line mapping of planetary atmosphere • Molecular line survey • ToO/monitoring observations	• Venus cloud layer with ToI TEC. • Spectral-line mapping capability complementing SEQUOIA, MSIP, and ToI TEC.
Star-formation and astrochemistry	• Molecular line survey • High angular resolution spectral-line mapping	• Spectral-line mapping capability complementing SEQUOIA, MSIP and ToI TEC.
Dusty star-forming galaxies (DSFGs)	• Redshift identification in CO, [CI], and [CII] • CO spectral energy distribution • Physical and chemical properties of ISM	• Spectroscopic follow-ups of ToI TEC-detected DSFGs. • High-J CO, [CI], and [CII] follow-ups of DSFGs with RSR spectroscopic redshifts.
Galaxy formation	• Redshift identification in [OIII] and [CII] • Physical and chemical diagnostics of ISM	• Dust continuum search with ToI TEC.

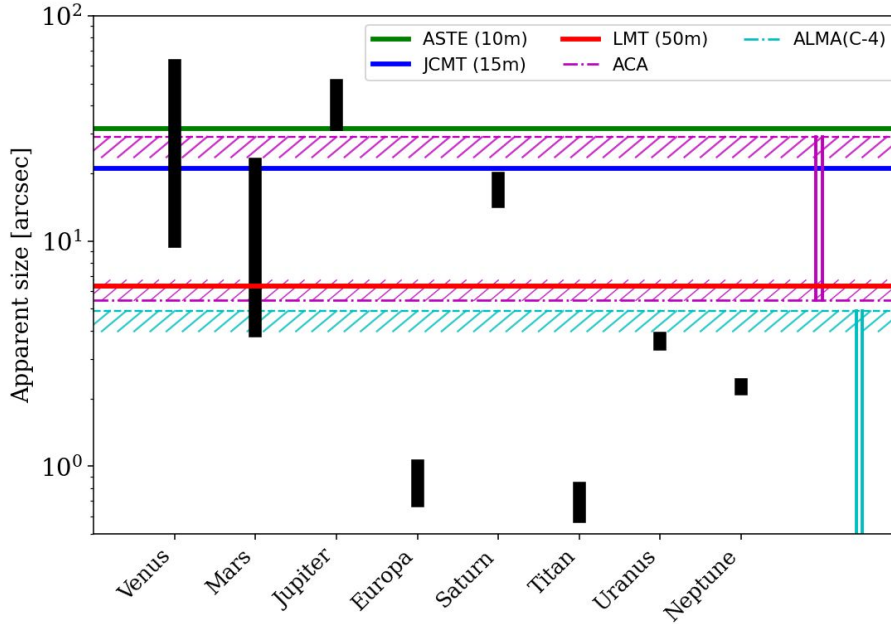


Figure 6. The apparent size of the planets in our solar system and the 230 GHz angular scales probed by LMT-FINER (red solid line), ALMA baseline array and ACA (dash-dotted), and other single-dish telescopes, ASTE (green) and JCMT (blue). For the interferometers (ALMA and ACA), the upper and lower boundary represents the maximum recoverable scale and the angular resolution, respectively. Thus, any objects larger than these upper boundaries are inevitably subject to spatial frequency filtering.

2.3.1. Solar system

The wideband and high spectral resolution capability of LMT/FINER enables us to observe multiple transitions of various molecular species in solar system objects such as planetary atmospheres and comets. It allows for the understanding of their chemical composition, chemical reaction processes, isotopic ratios, physical properties, and their evolution. The advent of ALMA has brought innovation to such observational studies, but due to the discrete sampling of spatial frequencies (uv coverage) of ALMA, only images modified by spatial frequency filters can be obtained. Furthermore, these filters change with diurnal motion during the observations. Further inconveniences intervene in the observations of Venus, Mars, and Jupiter; they possess apparent diameters beyond the spatial scales that can reliably be reproduced by ALMA, depending on the timing (**Figure 6**). Moreover, monitoring observations, which is an important perspective for solar system sciences, with ALMA are difficult due to operational constraints. Therefore, as shown in **Figure 6** LMT/FINER with high sensitivity and high spatial resolution while ensuring the reliability of the observed quantity and the scientifically desired spatial resolution is a powerful instrument for understanding temporal variations in planetary atmospheres, sometimes associated with solar activity, and transient phenomena such as cometary outbursts.

One of the essential quantities in planetary sciences is the vertical temperature distribution of the planetary atmosphere. The temperature distribution of Venus and Mars is usually estimated by CO, a trace gas that is relatively abundant in their atmosphere while the line profiles are sometimes broader than a spectrometer bandwidth. FINER allows for complete scans of CO $J = 2-1$ and $3-2$ lines and its isotopologues (^{13}CO , C^{18}O). As the optical depths vary among those lines, they probe the temperature at different altitudes of the atmosphere. The vertical temperature profile is also useful to characterize the atmospheric chemistry traced by minor species, such as HOx and SOx, which will also be another important target of FINER. On top of that, 1–2 mm continuum observations of Venus with ToI TEC enables one to probe inside of the thick sulfuric acid cloud layer at an altitude of 50–70 km, which is only doable in this 1–2 mm band. ToI TEC will also map the surface temperature of Mars during dust storm events, allowing the detailed comparison of atmospheric physics afforded by FINER spectroscopy.

Another key quantity is the trace gas abundance in planetary atmospheres and its time variation. FINER enables one to obtain the broad spectral feature of the tropospheric volatiles such as CO and PH_3 in Jupiter and Saturn. The high sensitivity of LMT/FINER is also useful to investigate those of distant planets and satellites, such as Uranus, Neptune, Pluto, Enceladus, Titan, Triton and TNOs. Neptune's tropospheric CO is the key to understanding vertical atmospheric dynamics while exhibiting an absorption feature as broad as ~ 10 GHz, which is beyond a typical bandwidth of conventional heterodyne spectrometers while doable with FINER.

Cometary sciences are also intriguing cases enabled by LMT/FINER. Comets hold the ancient information of the primordial solar system environment, which can be derived by comparing the trace constituent abundances and isotopic ratios with those of ISM in the solar neighborhood. A molecular line survey with FINER will provide the key trace molecular compositions of HC_3N , NH_2CHO , HCOOH and HCOOCH_3 , which are useful to constrain the primordial condition of our solar system but have only been obtained from the C/1995 O1 (Hale-Bopp) so far. Transient events are another interesting aspect of cometary science. Some comets sporadically eject its inner gas and enhance the column density dynamically, which may allow one to understand volatiles and isotopic ratios. Also, the small icy bodies such as satellites, Centaurs, and TNOs are suitable targets of LMT/FINER because some of them exhibit a CO coma, providing a clue to understanding their internal structure.

2.3.2. Astrochemistry

To take advantage of a wide radio frequency coverage and a wide IF range, one of the most prospective astrochemical studies is line survey observations. In the radio frequency band of FINER, there are several important molecular lines that are useful to trace components around star-forming cores in Galactic molecular clouds; HCN (DCN) and DCO^+ trace dense cores, HC_3N traces warm cores, CH_3CN traces hot cores and is a useful temperature probe, CCH traces the cavity wall, SiO traces shocked regions. **Figure 7** shows a simulated LMT-FINER spectrum of those molecular lines which have been frequently detected in star-forming cores and are expected to be detected by FINER within a short (less than 2 hours) observing time.

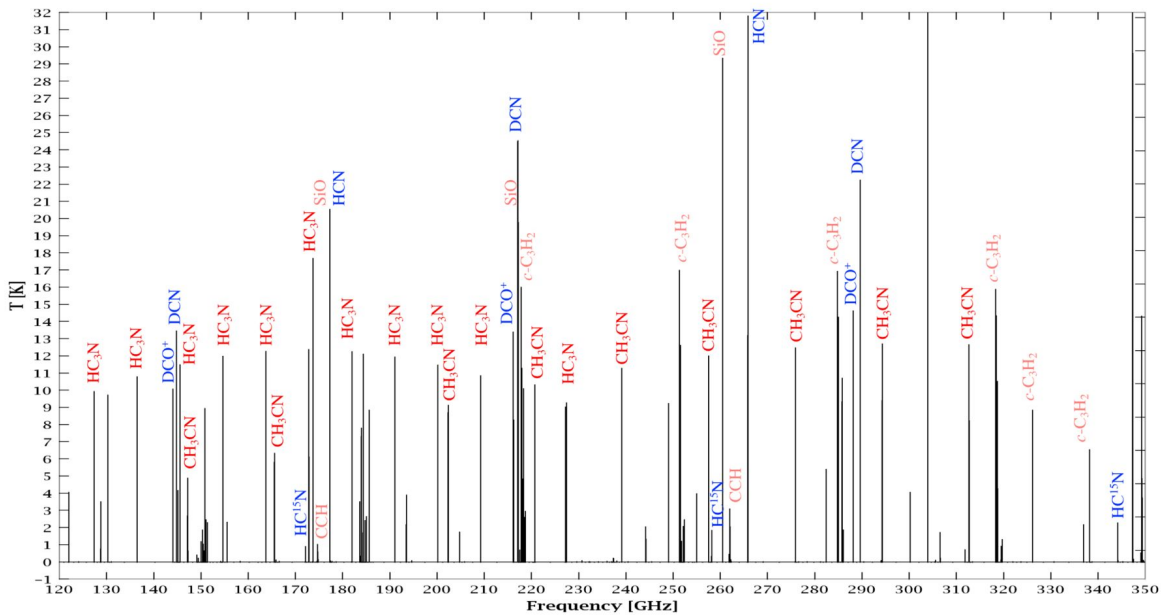


Figure 7. A stick diagram of molecular lines which are easily detected in star-forming cores (HCN, HC^{15}N , DCN, DCO^+ , CCH, HC_3N , CH_3CN , $c\text{-C}_3\text{H}_2$, SiO).

In addition, there are many transitions of various complex organic molecules (COMs) in the FINER frequency bands. COMs are one of the key tracers of physical conditions where molecular ISM has been placed in the past including the molecular cloud stage.

Another astrochemical study with FINER is the interstellar physics probed by deuterium fractionation of H_2O and COMs (e.g., $\text{CH}_2\text{DOH}/\text{CH}_3\text{OH}$, $\text{CH}_2\text{DCN}/\text{CH}_3\text{CN}$). The deuterium fractionation is sensitive to the physical conditions, such as temperature, and the molecular D/H ratios reflect the environment where the molecules formed on the surface of dust grains during the starless or prestellar core phases. The D/H ratios of molecules tell us their formation processes in ice mantles, allowing us to infer when they formed (e.g., [Caselli & Ceccarelli, 2012](#)). When characterizing the D/H ratio of water, the H_2^{18}O isotopologue is often employed with reasonable assumption of a $^{16}\text{O}/^{18}\text{O}$ elemental abundance ratio instead of directly using H_2^{16}O , because H_2^{16}O is not accessible from ground-based facilities. This method is called the “double isotope method.” FINER covers the H_2^{18}O ($3_{1,3}-2_{2,0}$) and HDO ($3_{2,1}-4_{0,4}$) lines at 203.40752 GHz and 207.1108522 GHz, respectively, which enables us to derive a more accurate D/H ratio. FINER can also cover other strong HDO lines of the $2_{1,1}-2_{1,2}$ and $2_{2,0}-3_{1,3}$ transitions at 241.56155 and 266.16107 GHz, respectively. The double isotope method is also important when lines of the main isotopologue are optically thick. Several deuterium species and other isotopologues of COMs (e.g., methanol; CH_2DOH , $^{13}\text{CH}_3\text{OH}$, $\text{CH}_3^{18}\text{OH}$) can also be observed simultaneously. In summary, FINER will provide unique opportunities to pioneer a lot of samples (both sources and molecular lines), which will be revolutionized in the ALMA WSU era.

2.3.3. Dusty star-forming galaxies

Another case enabled by the wide-band capability of FINER is redshift confirmation and multi- J CO line observations of the dusty star-forming galaxies (DSFGs) discovered with TolTEC and RSR. In the past decade, the 250 to 500 μm imaging with *Herschel Space Observatory*'s SPIRE instrument has revealed that the dust-obscured galaxies dominate the cosmic star formation out to $z \sim 4$. However, the relative contribution of the dusty population at higher redshifts is unknown ([Casey et al. 2021](#)). In particular, far-IR color selection with *Herschel*/SPIRE tends to find a population with higher dust temperatures at higher redshifts, which may potentially bias against the massive dust masses at $z > 4$. In order to overcome the bias and to precisely evaluate the dust-obscured part of cosmic star formation, exploration at longer wavelengths is necessary.

With this in mind, TolTEC will allow us to select a statistically-large sample of those $z > 4$ galaxies. TolTEC is the MKID-based continuum camera with three frequency bands at central wavelengths of 1.1, 1.4, and 2.0 mm ([Wilson et al. 2020](#)). With its superb sensitivity combined with the LMT, the planned large-scale structure survey will produce a sample of thousands of DSFGs over a total of > 40 sq-deg with moderate sensitivity ($S_{1.1\text{mm}} \sim 0.2$ mJy). As demonstrated by a recent ALMA 2-mm continuum imaging survey ([Casey et al. 2021](#)), the 1 to 2 mm color allows for efficient selection of high-redshift DSFGs ($z > 3$).

One of the important deep fields TolTEC will map is the North Ecliptic Pole (NEP) field, which will be targeted with near-IR imaging surveyors, such as *Euclid* and *Roman Space Telescopes*, but is not accessible with ALMA due to a high declination. This means that a

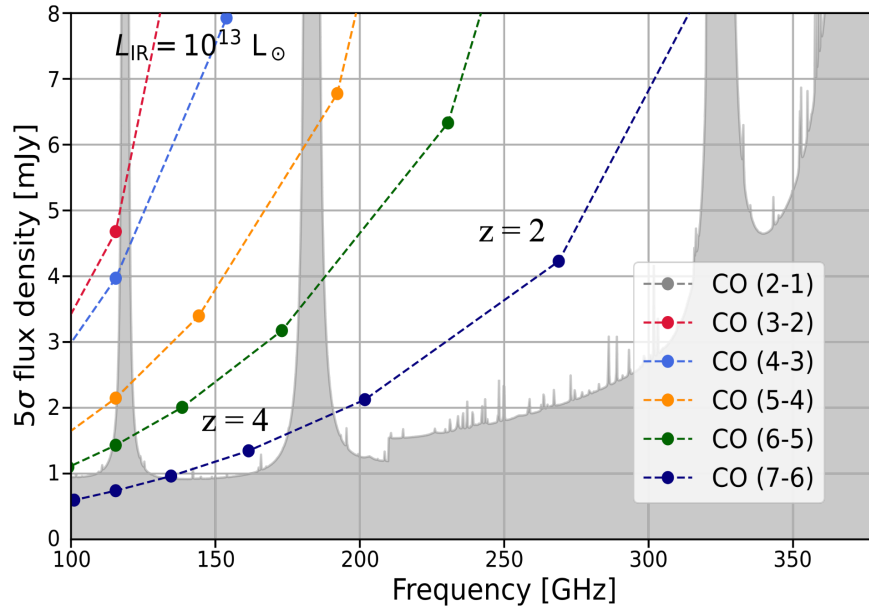


Figure 8. The CO line intensities and 5σ sensitivity of LMT-FINER, predicted for an ultraluminous infrared galaxy (ULIRG) with an apparent infrared luminosity of $L_{\text{IR}} = 1 \times 10^{13} L_{\odot}$. The line width is assumed to be 500 km/s in FWHM. We assume the similar CO excitation to that of lensed submillimeter galaxies with ALMA detections of CO ([Hagimoto et al. 2023](#)). The dots connected with a dashed line represent the peak CO flux densities at $z = 1, 2, 3, \dots$ from right to left.

high-sensitivity wide-band spectrometer for follow-ups for those sources is highly demanded and is possible with LMT-FINER.

The wide RF/IF capability of FINER enables us to simultaneously observe a luminous DSFG in two or more CO transitions at once at these redshifts (**Figures 8 and 9**). For instance, for a $z \sim 5$ DSFG with an IR luminosity of $L_{\text{IR}} = 1 \times 10^{13} L_{\odot}$, only two adjacent tunings of FINER at 150 GHz will cover an instantaneous bandwidth of 58 GHz on the sky with no frequency gap, providing redshift coverage of $\Delta z = 2.3$. In this case, always three (and sometimes four) CO transitions (from rotational quantum numbers from $J \sim 7$ to 10) are obtained. These middle to high J transitions of CO, as well as the atomic carbon lines [C I] $^3P_1 \rightarrow ^3P_0$ and $^3P_2 \rightarrow ^3P_1$ or the bright H₂O lines, will complement the CO lines covered by a 3-mm spectrum obtained with RSR. A spectral line energy distribution (SLED) of CO provides valuable information not only about the accurate molecular gas mass, but also their physical properties. FINER in combination with RSR will depict the rise and fall of the CO SLED, which is the most important part of a SLED to determine the CO excitation state, enabling us to characterize the physical properties of molecular gas more accurately than ever. As FINER covers the high- J transitions of CO, which are frequently observed to be bright for powerful AGN hosts such as quasars at high- z , it is more sensitive to the presence of molecular gas in X-ray dominated regions (XDRs, [Meijerink & Spaans 2005](#)).

2.3.4. Impact on telescope calibration

The improved continuum sensitivity offered by FINER's wide frequency coverage will have a positive impact on telescope calibration measurements, such as relative pointing, focusing, astigmatism and beam efficiency measurements. The instantaneous IF bandwidth covered by the DRS4 spectrometers is 33 GHz per polarization, which is ~ 20 times wider than the current per-polarization bandwidth of MSIP1mm. This wideband capability will increase the continuum sensitivity by a factor of ~ 4.5 , contributing not only to the improvement in the calibration accuracy but also to a substantial decrease in the overhead time for telescope calibration. Accurate measurements of telescope performances with a single receiver system will reduce potential systematics of the measurements and will allow us to more precisely understand the thermal, mechanical, and optical performances of the telescope across a wide frequency range from 120 to 350 GHz. This can also be verified and cross-checked by ToITEC, providing reliable results for the telescope parameters that benefit every type of science observation with the LMT.

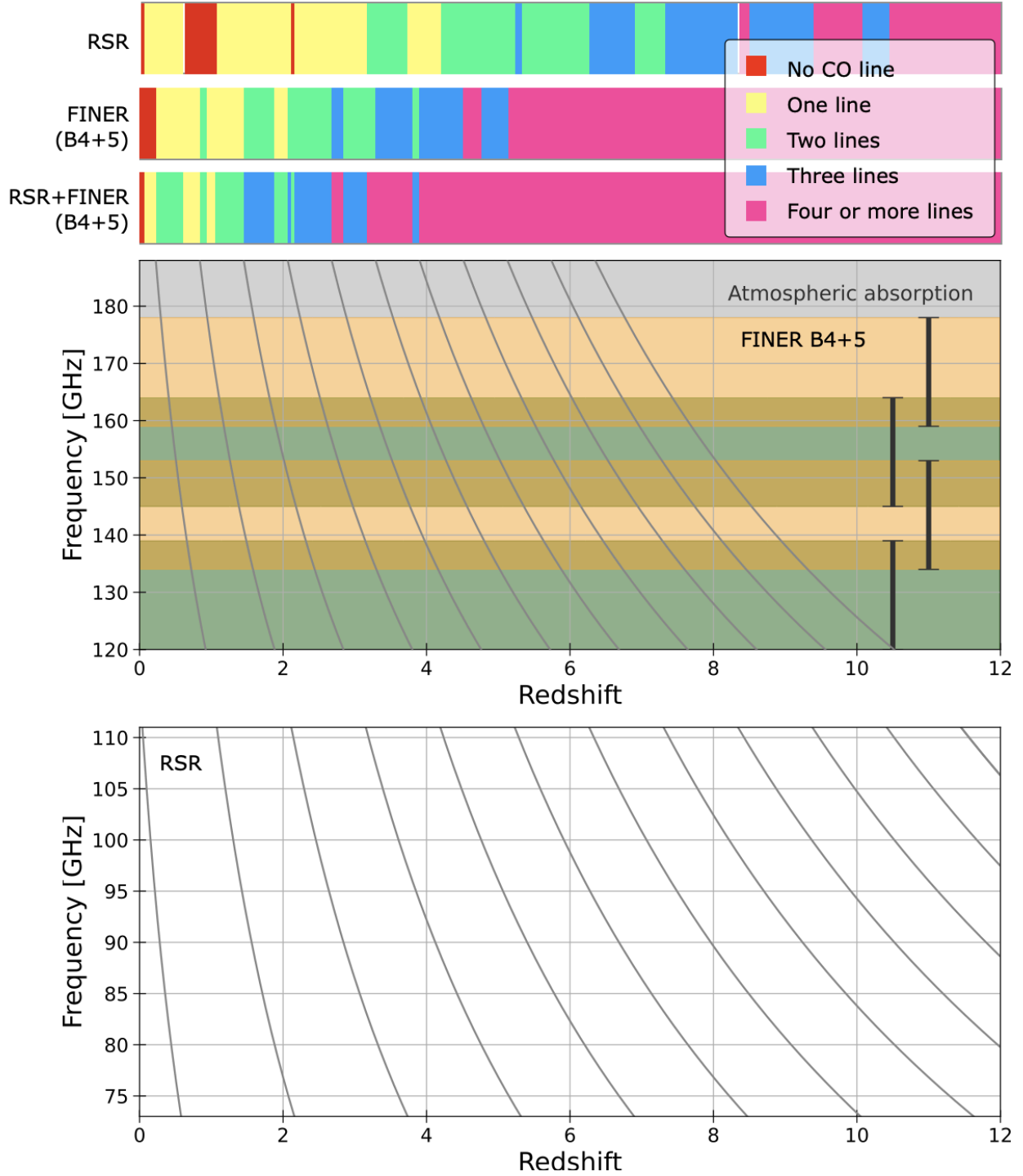


Figure 9. The observed frequencies of CO lines versus redshift, which can be covered by two tunings of FINER's low-frequency band (orange and green bands denoted as B4+5, middle panel) and RSR (bottom panel). The gray curves show the CO transitions from $J = 2-1$ to $12-11$ for FINER and from $J = 2-1$ to $12-11$ for RSR (from left to right).

3. INSTRUMENT

3.1. Overview

FINER is a dual-polarization sideband-separating superconductor-insulator-superconductor (SIS) heterodyne receiver system which comprises two frequency bands covering 120–210 GHz (Band 4+5) and 210–350 GHz (Band 6+7), each of which has an intermediate frequency (IF) bandwidth of 3–21 GHz per sideband. The feeds of the two frequency bands are placed on the focal plane separately, allowing simultaneous dual-band observations with an on-sky beam separation of 60 arcsec (TBD). FINER employs novel SIS mixers with a high critical current density (J_c) circuit to increase the IF bandwidth ([Kojima et al. 2017](#), [2020](#)). It is also equipped with an array of FPGA-based digital spectrometers with the total bandwidth of 163.84 GHz (16×10.24 GHz).

This offers an instantaneous bandwidth 5 times wider than ALMA, while achieving the same sensitivity as ALMA (**Figure 4**). LMT-FINER will provide 40% of ALMA's light-collecting area, a similar atmospheric transmittance to ALMA, and a 5x wider bandwidth than ALMA. This offers the most sensitive spectral-scanning capability among mm/submm telescopes in the northern hemisphere (**Figure 10**).

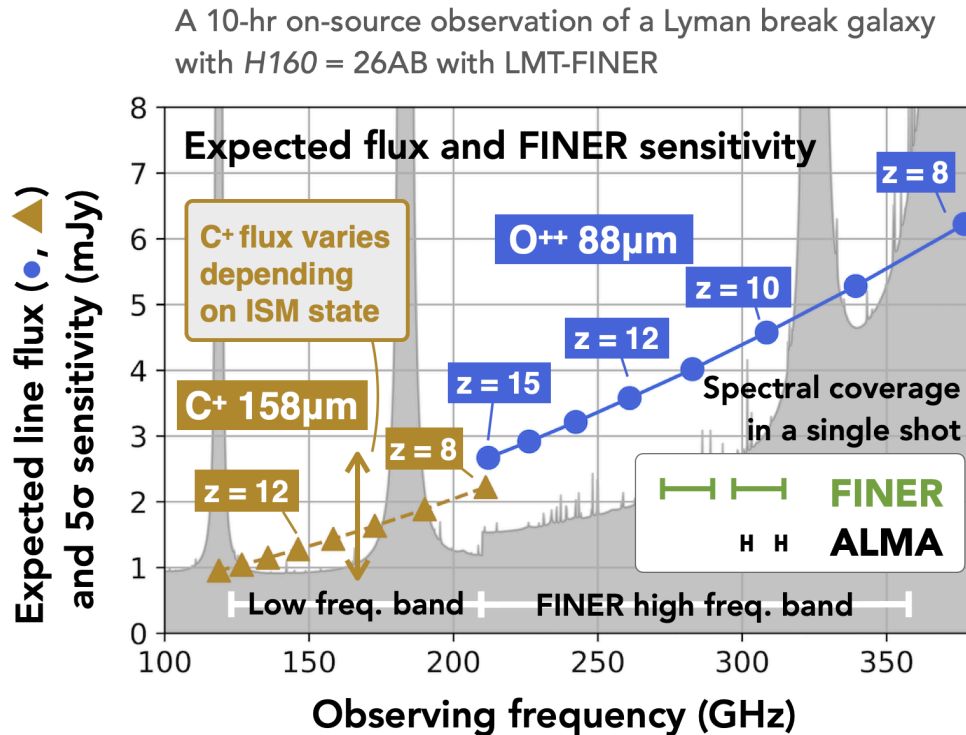


Figure 10. The expected intensities of the [O III] and [C II] lines and the 5σ limiting sensitivity of LMT-FINER as a function of observing frequency.

3.2. Science requirements and specifications

The science requirements are as follows.

- A single Lyman break galaxy with $H = 25.0$ AB and $\Delta z/(1+z) = 0.1$ needs to be detected in [O III] 88 μm at a S/N = 5 or higher within a single night (8 hr) observation.
- The redshifted [O III] and [C II] at $z = 9$ to 15 need to be observed by a tunable receiver.
- The expected peak flux density of [OIII] 88 μm is 5 mJy at $z = 10$.

The level 1 requirements are broken down to the technical specifications as listed in the science traceability matrix (**Table 2**). **Table 3** summarizes the specifications of FINER. **Figure 10** shows how the specified capabilities meet the science requirements.

Table 2. Science traceability matrix

Level	Requirements	
Level 1: Science objectives	• To measure the bright-end ultraviolet luminosity function ($M_{\text{UV}} < -22$) of galaxies at redshifts $z = 8.7$ to 11. • To constrain the bright-end ultraviolet luminosity function ($M_{\text{UV}} < -22.5$) of galaxies at redshifts $z = 12$ to 15. • To constrain a covering fraction of neutral medium surrounding the ionized regions of bright-end galaxies.	
Level 2: Science requirements	Science observables	• Spectroscopic redshift of a candidate galaxy selected by the Lyman break technique. • [C II] 158 μm to [O III] 88 μm luminosity ratio. • The number of spectroscopically-identified galaxies.
	Measurement requirements	• To detect [O III] 88 μm of a candidate $z \sim 10$ galaxy in 24 hours, with a peak flux density $S_{\text{peak}} = 4$ mJy, a velocity width of 150 km/s, and a prior photometric-redshift uncertainty of $\Delta z = 1$. • To detect [C II] 158 μm or put a meaningful constraint on its flux in 24 hours. • Forty (20) spectroscopically-identified galaxies for goal (for baseline).
Level 3: Instrument requirements	Technical parameters	• Tunable frequency range. • Instantaneous on-sky frequency coverage. • Spectral resolution. • Sensitivity.
	Technical requirements	• Tunable frequency range: 120–350 GHz with no gap (except for frequency bands of the telluric water vapor lines at 183 and 325 GHz). • Instantaneous on-sky frequency coverage: > 30 GHz ($\Delta z > 1$ for [O III] at $z = 10$) with as small a gap as possible. • Spectral resolution: 20 MHz ($\Delta V = 50$ km/s at 120

	GHz, 17 km/s at 350 GHz). • Sensitivity: Receiver noise temperature (single sideband) of 45 K for 120–210 GHz and 75 K for 210–350 K, yielding system noise temperature of $T_{\text{sys}} \leq 100$ K at 120 GHz, ≤ 200 K at 300 GHz, ≤ 300 K at 350 GHz.[†] [†] Precipitable water vapor (PWV) of 2 mm.
Level 4: Mission requirements	• PWV ≤ 2 mm (270–350 GHz), ≤ 3 mm (120–270 GHz). • Surface error ≤ 75 μm r.m.s. (> 270 GHz), ≤ 90 μm r.m.s. (< 270 GHz) • 10 hours per source (including overheads) times 40 (20) nights.

Table 3. FINER specifications.

Item	Baseline	Goal	Note
Frequency (Band 4+5)	125–210 GHz	120–210 GHz	
Frequency (Band 6+7)	210–350 GHz	210–360 GHz	
Beam size	7 (Frequency/200 GHz) ⁻¹ arcsec		
No. of polarizations	2		
Trx (B45)	45 K	45 K	>95% of IF band
Trx (B67)	75 K	75 K	>95% of IF band
IF	4–20.5 GHz	3–20.5 GHz	
Sideband separation	2SB, > 10 dB	2SB, > 25 dB	
No. of basebands	8	16	
Bandwidth	81.92 GHz (8 $\times$ 10.24 GHz)	163.84 GHz (16 $\times$ 10.24 GHz)	Wide mode (DRS4)
Spectral resolution	20 MHz		Wide mode (DRS4)
Bandwidth per pol.	15 GHz (6 $\times$ 2.5 GHz)	20 GHz (8 $\times$ 2.5 GHz)	Highres mode (XFFTS)
Spectral resolution	88 kHz		Highres mode (XFFTS)
Data dumping rate	100 ms		

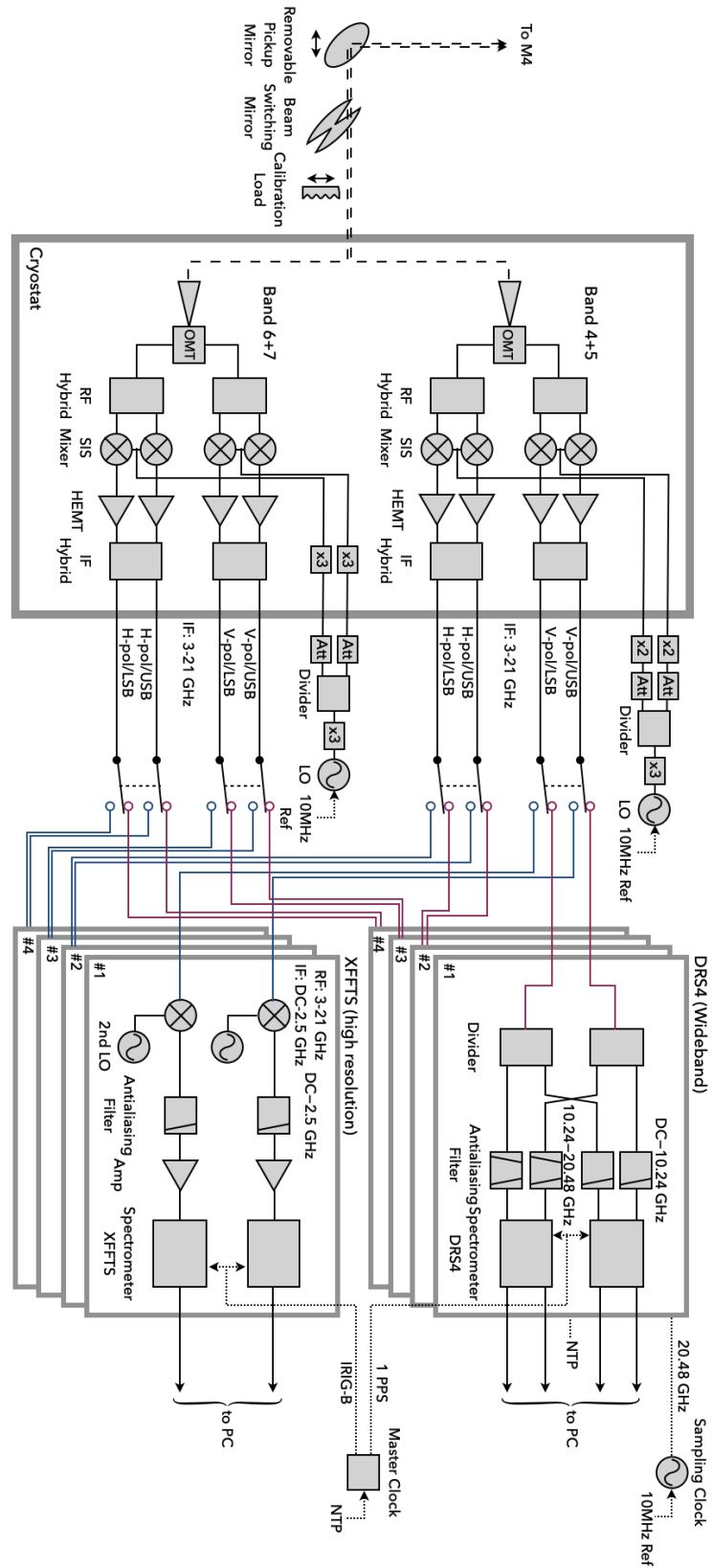


Figure 11. The system block diagram of FINER.

3.3. System

The system block diagram is shown in **Figure 11**. The system comprises the following subsystems; optics, frontend receiver, backend spectrometer, computers and software.

3.3.1. Optics subsystem

Warm optics include a pickup mirror (M5) and following elliptical focusing mirror(s), a beam switching mechanism (“fast sky chopper”, optional), and a load calibration device. The detailed optical parameters and layout are to be fixed (as of the time of writing). The pickup mirror is placed on a motorized linear slider and can be controlled remotely.

The fast sky chopper is a set of removable mirrors to change the optical path slightly and to throw the on-sky beam position by 120 arcsec (TBD) at a frequency of $\sim 1\text{--}2$ Hz, which allows fast beam-switching observations. The number of available bands is limited to 1 when using the fast sky chopper due to the limitation of optical configuration.

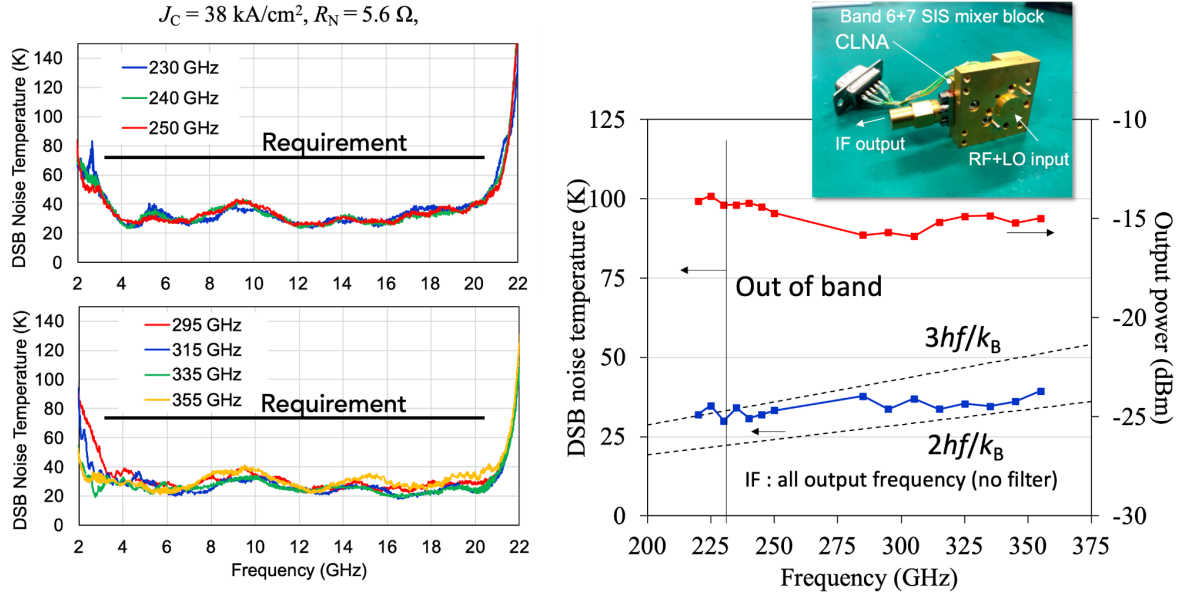


Figure 12. The performance of the Band 6+7 mixer (Kojima et al. 2023, in preparation). (Left) The double sideband (DSB) noise temperatures across the IF band, which are all below the requirement (75 K). (Right) The DSB noise temperatures and output power as a function of RF. The inset shows a photo of a mixer block.

3.3.2. Frontend receiver subsystem

The receiver is coupled with the optics through corrugated feed horns. FINER uses the SIS receiver technology with wide RF and IF (Figure 12, Kojima et al. 2017, 2020), which has been developed for ALMA Wideband Sensitivity Upgrade (WSU, Carpenter et al. 2022). Band 4+5 and 6+7 components are accommodated by a single cryostat, which is cooled with a two-staged GM 4-K cryocooler (RDK-415DP, Sumitomo Heavy Industry Inc.). Both bands are available simultaneously with the on-sky beam separation of 60 arcsec (TBD). The observed frequencies

of both bands are set independently. The receiver detects two polarizations in both upper and lower sidebands (USB and LSB) separately, yielding 4 IF outputs in each band. Note that it does not offer Stokes parameters other than intensity (i.e., Stokes-*I*).

3.3.3. Backend spectrometer subsystem

The IF signals are sent to the spectrometers. FINER offers two types of spectrometers; wideband and high-resolution modes realized with DRS4 (Elecs Inc., **Figure 13**) and XFFTS (RPG Inc., [Klein et al. 2012](#)), respectively. Users can select one of the spectrometer modes.

DRS4 directly samples the signal at 20.48 GSps with a good analog transmission up to 20.48 GHz. This offers the capability of spectroscopy in the 10.24–20.48 GHz band with no secondary downconverters, in addition to the baseband (DC–10.24 GHz). DRS4 is an FX-type spectrometer with an optional output of cross-correlation for detailed calibration such as digital sideband separation correction. The input signal is digitized with a 3-bit 20.48 GSps analog-to-digital converter and is Fourier-transformed with one of window functions, rectangular, Hann, and Hamming, and then is squared and integrated to produce a 512 channel power spectrum at a dumping rate of 100 ms, while it does not offer a polyphase filterbank capability due to a limitation of the computational resource. It also offers a digital sideband separation capability ([Finger et al. 2015](#); [Rodriguez, et al. 2018](#)), to compensate for the imbalance of complex gain (i.e., amplitude and phase) between the sidebands and to remove the image sideband signal digitally (under development).

XFFTS is an off-the-shelf spectrometer with high spectral resolution (88 kHz, corresponding to ~ 0.13 km/s at 200 GHz) and a 2.5-GHz bandwidth. See [Klein et al. \(2012\)](#) for details. Six boards of XFFTS are operational for B4R, and we will use them for FINER.

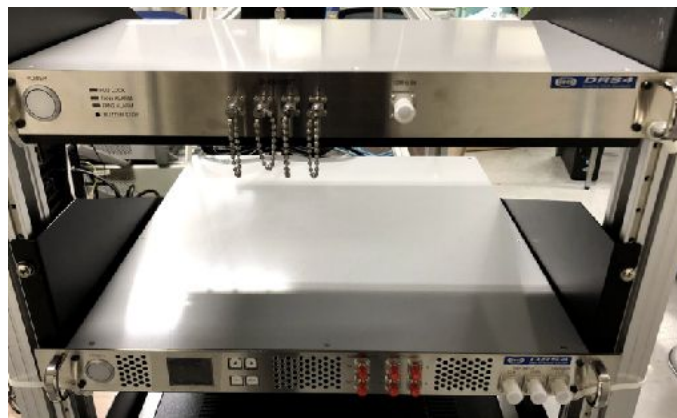


Figure 13. The digital spectrometer DRS4 with four 20.48 GSps samplers (bottom) and the 20.48 GHz reference signal generator (top).

3.3.4. Computer and software subsystem

A control computer at the LMT backend cabin controls receiver tuning including LO frequency setup and LO power optimization, spectrometer mode selection, pickup mirror drive, beam switching, and load calibration. The spectrometer outputs are recorded with NTP-synced

timestamps on a data acquisition computer in the LMT backend cabin at a dumping rate of 100 ms. FINER is synchronized with the TCS through TCP/IP or UDP connection and does not require any hardware reference clocks from the TCS.

3.4. Hardware configuration

The proposed optics layout is shown in **Figure 14**. As we intend to replace the existing B4R receiver¹ (PI: Kawabe, **Figure 15**) with FINER, the layout is almost the same as B4R; The ray from M4 to M5 (yellow beam toward SEQUOIA) is bent by a removable pickup mirror. The bent ray is directly led into the FINER cryostat and is coupled with the two feed horns of Band 4+5 and 6+7. FINER has a beam-switching mechanism in between the pickup mirror and the cryostat, as well as a chopper wheel for the standard single-load calibration.

The cryostat is placed at the position of B4R in the LMT receiver cabin. We will replace B4R's cryostat and cryocooler with new ones, while the helium hoses and chiller of B4R will be used for FINER. The LO system and digitizers are placed alongside. The IF signal is sent to the spectrometers in the backend cabin downstairs.

3.5. Data analysis software

The observed data will be provided in the *MeasurementSet* (MS) format of CASA ([CASA Team et al. 2022](#)), in which time series spectra taken on- and off-source and for load calibration are contained along with telescope boresight positions, ancillary environmental records and metadata.

Users will receive MSs as initial datasets and will use CASA for fundamental data reduction including intensity and bandpass calibration, flagging, velocity correction, spectrum making, and map/cube making. Further analysis such as spectral fit can also be made with the single-dish tasks by CASA.

A new data-scientific noise-removal method demonstrated using the B4R receiver ([Taniguchi et al. 2021](#)), which reduces the baseline ripples and improves the observed sensitivity by a factor of $\sqrt{2}$, will also be provided by the development team.

¹ The B4R (band 4 receiver) is the 2-mm receiver system which consists of a single-beam two-polarization SIS receiver operating at 125–163 GHz and four XFFTS spectrometers. B4R is based on the ALMA band-4 2SB mixer technology ([Asayama et al. 2014](#)). See <http://lmtgtm.org/telescope/instrumentation/instruments/b4r/?lang=en> for details.

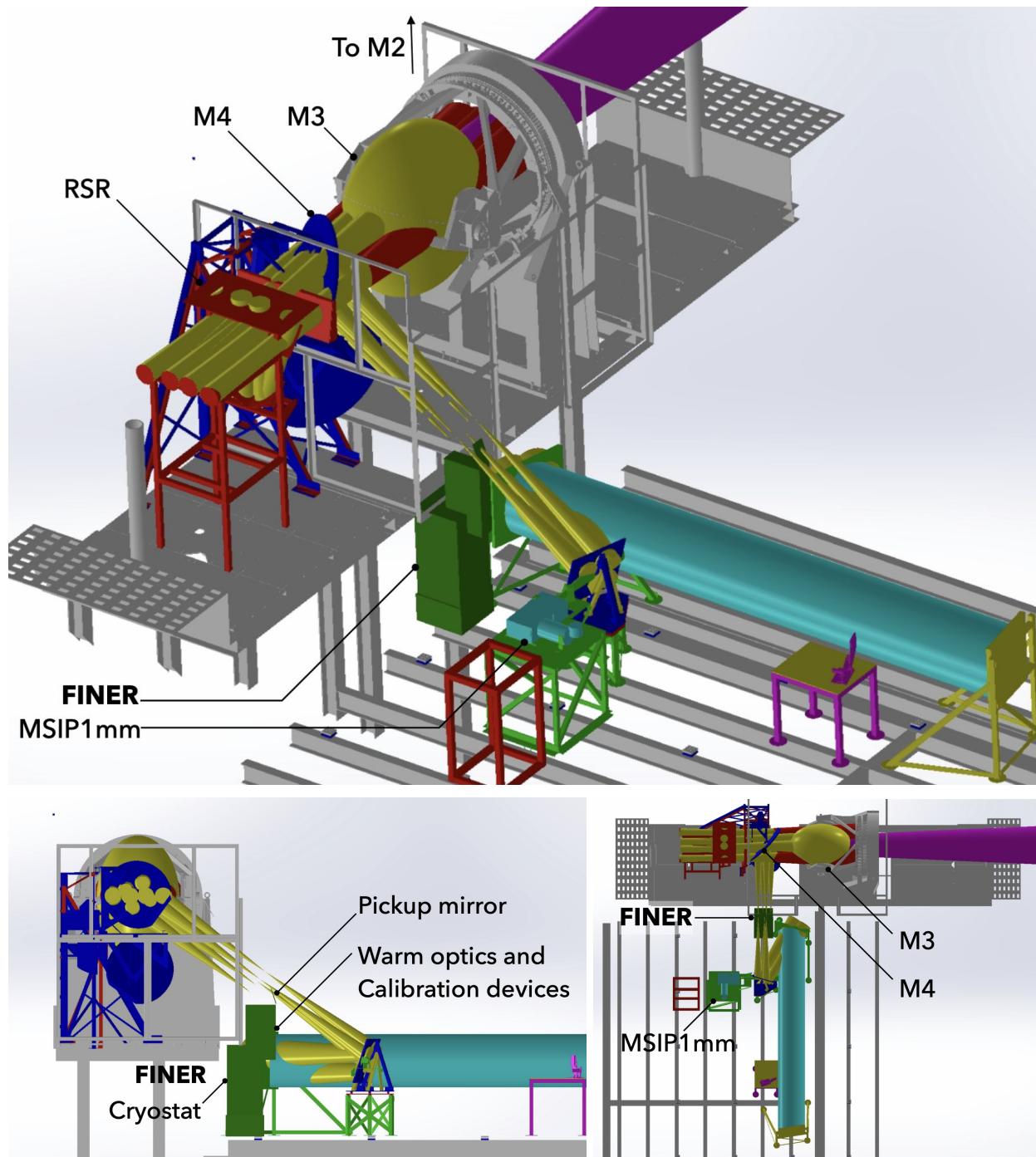


Figure 14. The configuration of the FINER receiver and warm optics in the LMT receiver cabin. Top, bottom-left, and bottom-right panels show the CAD layout in bird's eye view, from the direction parallel to the elevation axis, and from the top, respectively. FINER is indicated by a green box. The beam ray from M4 to M5 is represented as the yellow bars, part of which is picked off by the FINER warm optics. The location of FINER is similar to that of B4R.

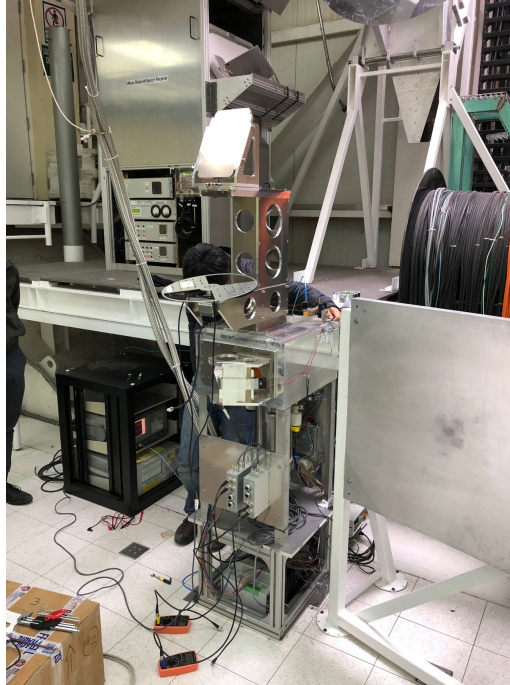


Figure 15. The B4R receiver system.

3.6. Interface to LMT

The interfaces to LMT are listed below, which are almost the same as those of B4R.

- Physical interface
 - 1 m² on the floor of the receiver cabin, fixed with bolts / receiver
 - 19' rack at the receiver cabin / LO, DC power supply, spectrometers
 - 19' rack at the backend cabin / spectrometers, control PC
- Cryogenic interface
 - Compressor the same as the one we are using for B4R. No update is necessary.
- Electric interface
 - 120 VAC, < 1.5 kW / UPS 100 VAC, receiver cabin
 - 120 VAC, < 1.5 kW / UPS 100 VAC, backend cabin
 - 200 VAC, 7 kW / Compressor
- Logical interface
 - NTP synchronization on the telescope control system (TCS) network / master clock, wideband spectrometers (DRS4)
 - LAN connection to the TCS and the internet / control PC
- RF and IF signal interface
 - Optical path from M4 to M5 / Motorized removable pickup mirror
 - IF power (analog DC signal) fed into the LMT's calibration if necessary. (currently B4R does not provide it due to a low time resolution of B4R's power meter. Instead we just use the total power output from the B4R backend (XFFTS) for calibration.)

4. DEVELOPMENT PLAN

4.1. Overview

The development is led by Nagoya University in collaboration with the University of Electro-Communications (UEC), Advanced Technology Center (ATC) at NAOJ, the University of Tokyo, Keio University, and Kitami Institute of Technology. A total of 150M JPY (~1.1M USD) is awarded for development, commissioning, and operations of FINER in 2022–2026 (for 5 years) by Japan Society of the Promotion of Science (JSPS) grant-in-aid ([No. 22H04939](#)). We will spend the first 3 years for development, deliver the instrument to LMT in late 2024 to early 2025, and start commissioning and science operations in 2025.

4.2. Work breakdown structure

The work breakdown structure is shown in **Figure 16**, in which work packages are listed. NAOJ ATC is responsible for fabrication of SIS mixers. The assembly and evaluation of the front-end receivers are led by UEC with NAOJ ATC. Kitami Institute of Technology is responsible for design and fabrication of the optics. The spectrometer evaluation is done by Nagoya University, while the end-to-end test will be done at NAOJ ATC at the final stage of development. Keio University and Nagoya University will be in charge of control and reduction software development.

We expect the installation and commissioning of the FINER instrument in late 2024 to early 2025, which is led by UTokyo, Nagoya, UEC, and Keio.

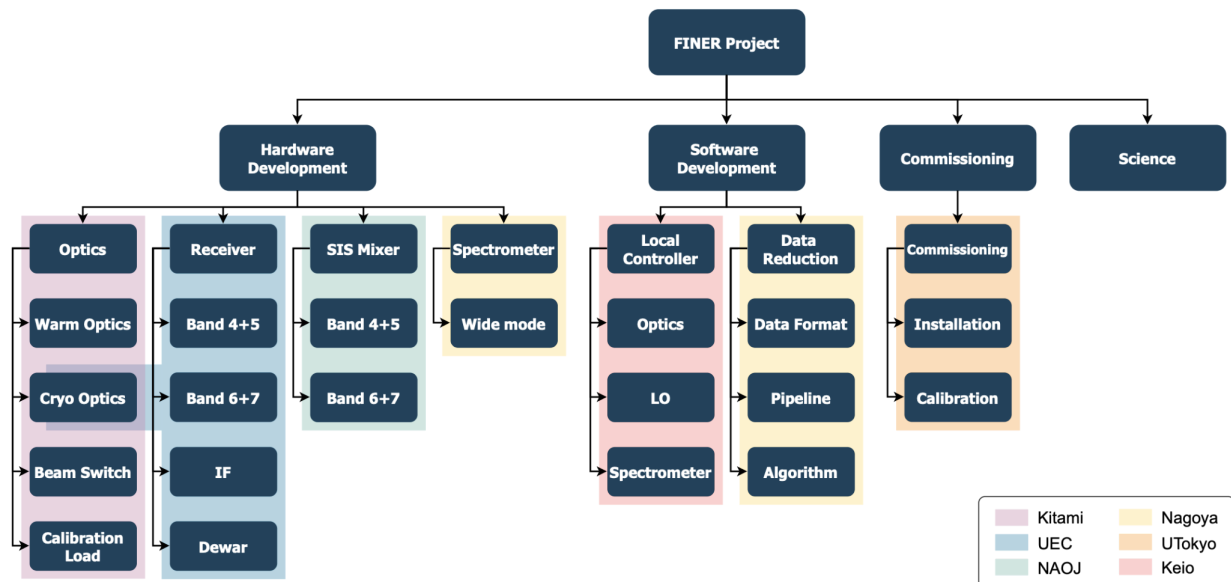


Figure 16. Work breakdown structure of the FINER project.

4.3. Schedule

The schedule as of 2022 December is shown in **Table 4**. In 2024 Q4, the receiver is ready for commissioning at LMT.

Table 4. Schedule of development toward science operations.

WP	Level1	Level2	2022	2023				2024				2025			
			Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
SIS mixer	Band 6+7	Mixer chip													
		Assembly													
	Band 4+5	Engineering													
		Science grade													
Receiver	Band 6+7	2SB unit & OMT													
		LO													
		Horn													
	Band 4+5	LO													
		Horn													
	IF														
	Dewar														
	Testing														
Optics	Design														
	Fabrication	Feed horn													
		Mirrors													
	Mechanical component														
	Testing														
Spectrometer	Prototyping	Programming													
		Testing													
	Mass production														
	Testing														
Lab testing															
Installation and commissioning	Logistics														
	Installation														
	Commissioning														

4.4. Milestones and risk analysis

Major milestones are twofold; decision on conceptual design and warm optics layout (2023 January to February) and delivery of the instrument (2025 January to March). We need to complete the detailed warm optics design by the end of 2023 Q2 (June) to move on to the detailed design and fabrication of the cryogenic components, such as the dewar and the feed horns, which limits the later development schedule. The completion of receiver development is expected at the end of 2024 Q4 and is followed by shipping to the LMT site in 2025 Q1.

Band 4+5 mixer production could be a potential risk in this development plan. The Band 6+7 mixer is built in a mixer block and has been demonstrated in the lab ([Kojima et al. 2020](#)) and on-site ([Masui et al. 2021](#)). Unlike Band 6+7, however, a Band 4+5 mixer design needs to be established, which is why the Band 4+5 mixer production will take longer time than Band 6+7

(Table 4). To hedge the risk we are taking two options; (i) a planar integrated circuit for Band 4 (Shan et al. 2018, 2019) and (ii) a similar mixer block scaled from Band 6+7. Figure 17 shows an integrated SIS circuit developed at NAOJ ATC. The integrated circuit approach is being developed with the aim to enhance the capability in forming multi-beam focal plane arrays with SIS mixers. The proof-of-concept single-beam chip with $f_{\text{RF}} = 125\text{--}163\text{ GHz}$ and $f_{\text{IF}} = 4\text{--}8\text{ GHz}$ exhibits a good performance and has been shown to meet the current ALMA specifications, while the RF and IF coverages need to be extended to meet the FINER specifications.

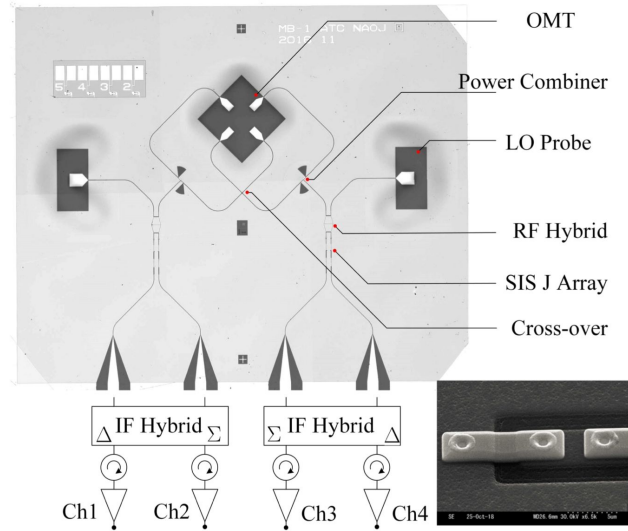


Figure 17. The superconducting integrated circuit for the 2-mm band developed at NAOJ ATC (Shan et al. 2019). The chip is 13 mm × 10 mm in size. The inset shows an SEM image of the 3-junction series array.

5. OPERATIONS PLAN

5.1. Overview

Here we describe the operations plan after the commissioning in early 2025.

5.2. Concept and scope

For the LMT users community, opportunities of scientific observations using FINER are provided through the Call for Proposals.² Science deliverables of FINER include raw and calibration data in the CASA's *MeasurementSet* format, which will be provided according to the LMT's common use framework.³ The FINER development team is in charge of development and maintenance of the reduction pipeline based on CASA and an original pipeline script,⁴ and observers can use

² <http://lmtgtm.org/for-lmt-users/call-for-proposals/>

³ <http://lmtgtm.org/for-lmt-users/data-reduction-and-retrieval/>

⁴ <https://github.com/b4r-dev/b4rpipe>

the pipeline to reduce their own data. Currently we have no concrete plan for quality assurance of the common-use data, which needs to be discussed with the LMT observatory.

For the science operations, the FINER development team is responsible for an operations manual and knowledge transfer to the LMT observatory, so that the observatory staff can perform commissioning and daily operations of the instrument. In the initial phase of operations (e.g., first 2–3 years), the FINER development team will be responsible for the commissioning, start-up, and shut-down of the instrument. We propose to handover the entire receiver system to the observatory at some point after the initial phase, although how to handover the FINER system is yet to be discussed with the observatory.

We note that the FINER project complies with the trilateral agreement (in preparation at the time of writing) between NAOJ, THERS, and UEC that the SIS mixers of FINER are properties of NAOJ and must be returned back to NAOJ after FINER is fully decommissioned.

5.2. Maintenance

In this section, we briefly mention regular and irregular maintenance. The regular maintenance includes that of the cryocooler and compressor, which will typically be performed once every 2–3 years. The recommended run time before the maintenance is 10,000 hours for the cryocooler and 30,000 hours for the compressor. For the maintenance, the cryocooler should be removed from the dewar and sent to Sumitomo North America.

The irregular maintenance includes repairs and replacement of broken or malfunctional items. If the SIS mixers are broken, new SIS mixers will be provided by NAOJ. If other equipment fails, a replacement will be sent from Japan. However, this depends on the budgetary situation and may be delayed.

5.3. Mid to long term upgrades

At the initial phase FINER will begin with the ‘Baseline’ specifications (**Table 3**) and will aim for the ‘Goal’ specifications when technologies and resources are ready. As the SIS mixer technology is likely being improved after FINER gets operational, we may upgrade the SIS mixer device if this is the case. The backend spectrometers are also added to enhance the capability. The data reduction pipeline will be improved by implementing a new algorithm for noise removal ([Taniguchi et al. 2021](#)).

The FINER cryostat and warm optics are designed so that another additional single-beam SIS receiver, such as a 3–4 mm band receiver, may be accommodated in the future, without any conflict with the 120–360 GHz band (see the FINER+ parameter space in **Figure 5**). We will consider this upgrade depending on the user demand.

Appendix A. Abbreviations

ALMA	Atacama Large Millimeter/submillimeter Array
B4R	Band 4 Receiver
CASA	Common Astronomy Software Applications
DRS4	Direct RF Sampler 4th generation
DSFG	Dusty star-forming galaxy
FINER	Far-Infrared Nebular Emission Receiver
GSps	Giga-samples per second
IF	Intermediate frequency
LMT	Large Millimeter Telescope
LO	Local oscillator
MS	MeasurementSet
OMT	Ortho-mode transducer
RF	Radio frequency
SEM	Scanning electron microscope
SIS	Superconductor-insulator-superconductor
TCS	Telescope control system
WSU	Wideband sensitivity upgrades
XFFTS	Extended bandwidth Fast Fourier Transform Spectrometer

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