ALMA Band 2 Cold Cartridge Assembly Design

ALMA Band 2 Cold Cartridge Assembly Design

Belitsky V.[1], Lapkin I.[1], Fredrixon M.[1], Lopez C.[1], Ferm S.-E.[1], Pavolotsky A.[1], Strandberg M.[1], Sundin E.[1], Desmaris V.[1], Hesper R.[2], Adema J.[2], Barkhof J.[2], Baryshev A.[2], Bekema M.[2], Realini S.[2], Koops A.[2], de Haan, R. [2], Rodenhuis M.[2], Cuttaia F.[3], Nesti R.[4], Ricciardi S.[3], Terenzi L.[3], Villa F.[3], Gonzalez A.[5], Kaneko K.[5], Sakai R.[5], Imada H.[5], Kojima T.[5], Phillips N.[6],Yagoubov P.[6]

***Abstract*— As part of the ALMA development, we present the design of the ALMA Band 2 Cold Cartridge Assembly (CCA). The Band 2 is the last band that completes the suit of the 10 receiver channels of ALMA. The originally planned ALMA Band 2 receiver cartridge should cover the RF band of 67 - -90 GHz. The recent progress in technology, optics, OMT design and mm-wave amplifiers, however allowed to implement receiver that has an extended RF band up to 116 GHz. Furthermore, the Band 2 receiver pursues 2SB layout and provides 4-18 GHz IF band for two sidebands in a dual-polarization configuration. Here, we describe the design of the Band 2 CCA that includes optics, amplifier assembly, internal RF transport, mechanics and cryogenics. The downconverter part and performances are described elsewhere.**

***Index Terms*— ALMA receiver, cold cartridge assembly, amplifiers, RF transport, vacuum, cryogenics.**

I. INTRODUCTION

ALMA Observatory is the most advanced and modern radio astronomy observatory. Yet, the development and expanding ALMA capacity observing different frequencies is not completed and the last remaining receiver band, ALMA Band 2, covering 67-90 GHz is under progress. Recent advances in the low-noise amplifier (LNA) technology [1, 2, 3, 4] and optics components [5, 6] allow building ultra-wideband low-noise systems, e.g. 67-116 GHz RF band, with state-of-the-art performance. In such receiver that follows ALMA receiver layout, the CCA provides low-noise gain and is operated inside ALMA Front End (FE) cryostat at cryogenic temperatures while in the Warm Cartridge Assembly (WCA), the 2SB mixer and IF amplifiers provide signal conditioning and down-conversion to deliver it to ALMA Correlator. ALMA Band 2 receiver with it outstanding IF bandwidth 4-18 GHz belongs to a new generation of receivers demanded for new prospective science in the ALMA Roadmap 2030 [7].

II. ALMA BAND 2 CCA DESIGN

A very significant effort in developing technology and making ALMA Band 2 pre-prototype was done during several preceding years [8] within the study led by the European Southern Observatory (ESO) with participation from GARD[1], INAF[3], NAOJ[5], University of Chile, University of Manchester, RPG-Radiometer Physics GmbH, LNF-Low Noise Factory, MPIfR in collaboration with IAF, and other institutions. Building up on these results, we have developed all-new design for ALMA Band 2 CCA with extended RF band and covering 67 - 116 GHz and with interfaces fully in compliance with the ALMA FE cryostat and ALMA antenna.

The CCA employs optics [9] that consists of a short-focus UHMWPE lens placed at room temperature, also acting as a vacuum window, and a corrugated horn. The optics provides frequency independent illumination of the secondary. The design of the lens is optimized based on available ALMA FE cryostat window opening for Band 2, spillover loss, dielectric loss in the lens (the shorter the focal length, the thicker the lens) and position of the corrugated horn inside the cryostat. In the ALMA Band 2, the corrugated horn is placed in the space between the 110K and 15K thermal shields, Fig. 1.

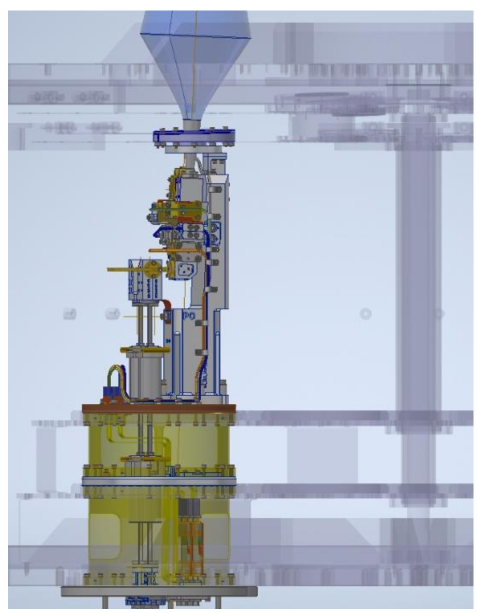

Fig. 1. 3D model. ALMA Band 2 CCA inside the ALMA FE cryostat. The lens and its support are not shown. The simulated antenna

This manuscript was submitted on April 20, 2023. This work was supported by European Sothern Observatory (ESO) under the Agreement #87603/ESO/18/88584/ASP. NAOJ contribution was supported by the national funds of Japan. *(Corresponding author: Victor Belitsky, victor.belitsky@chalmers.se).*

The authors' current affiliations according to the footnotes: [1]GARD, Chalmers University, Gothenburg, 41296, Sweden; [2]Kapteyn Astronomical Institute, University of Groningen, 9747 AV Groningen, the Netherlands; [3]INAF-OAS Via Gobetti, 101, 40129, Bologna, [4]INAF-OAA, Largo Enrico Fermi 5, I - 50125 Firenze, Italy; [5]National Astronomical Observatory of Japan (NAOJ), 181-8588, Mitaka, Japan; [6]ESO, Karl-Schwarzschild-Strasse 2, D-85748, Garching, Germany.

beam clearly shows the lens position and the horn placed in space between 110K and 15K thermal shields.

The original ALMA FE IR filter at 15K thermal shield has to be removed to allow the horn taking the desired position between the 110K and 15K thermal shields of the ALMA FE cryostat. To preclude the leak of the IR radiation into the 15K environment, we have introduced a baffle that blocks the IR radiation yet provides the necessary clearance for the horn during CCA-FE integration procedure. In turn, the clearance space is sealed against IR radiation leaks by introducing an additional reflector placed around the horn but below the 15K shield level and thermally terminated at 15K via the support pillar, see Fig. 2 for details.

The thermal design of the ALMA Band 2 CCA is largely defined by the optics. Because of the optics layout, the horn, OMT and amplifiers are placed at substantial distance from 15K thermal plate. The cooling of the passive components (the horn, OMT, waveguides) and active components (CLNAs) is extremely important for achieving ultimate noise performance. In order to cool down all the components, we used a massive pillar made of Aluminum AW-6082 alloy. The pillar also provides a mechanical reference for the optics and support for all receiver components.

The polarization split occurs in the OMT [8, 9] that is directly attached to the corrugated horn. In each polarization, two wideband low-noise cryogenic amplifiers (CLNA) are used connected in series with an isolator in between to control the ripples. With the total gain of the amplifiers over ~45 dB and the loss in the internal RF transport chain less than 6 dB, the contribution of the warm downconverter electronics of the WCA to the noise temperature is less than 2%.

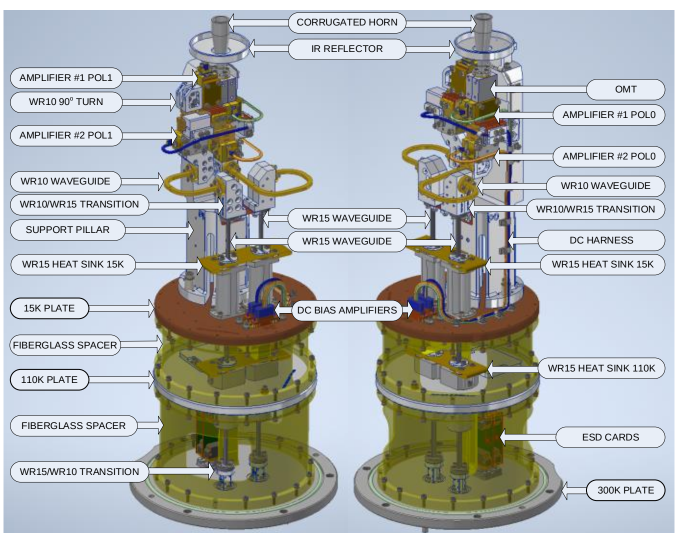

Fig. 2. Annotated picture shows ALMA Band 2 CCA 3D model.

ALMA Band 2 CCA allows to accommodate different types of the available CLNAs, [2, 3, 4]. Together with the amplifier vendors, all the amplifiers were harmonized in their WR10 interfaces, lengths and DC connectors. However, the material used for the amplifier blocks were Aluminum alloy and Tellurium copper. In order to accommodate the difference in materials that causes significant mechanical stress during the cooling because of the thermal contraction, the design uses "adapter approach". Depending on the particular amplifier and material used, the cooling bracket was used as an adapter, which shape, material and design were adjusted to provide sufficient cooling via mechanical contact to the pillar playing the role of the cooling buss while the adapters' material with theirs shapes were chosen to compensate for the difference in the thermal contraction. When possible, with CLNAs with Aluminum bodies, we used all-Aluminum alloy solid thermal adapters and/or semi-rigid links when CLNAs with Tellurium copper bodies were used.

The internal RF transport system employs combination of the WR10 and the oversized WR15 waveguides and is designed to allow controlling the RF insertion loss, ensuring minimum mechanical stress while cooling to cryogenic temperatures. The shape of the RF transport system waveguides was chosen to fit in the tight space within the CCA body while controlling the RF signal insertion loss. The oversized WR15 waveguides ensure low RF insertion loss and were made straight to avoid generation of high-order modes and trapped modes at the turns. All necessary turns were made either by bent copper WR10 waveguides or using milled split-blocks of an Aluminum alloy, Fig. 2. The copper WR10 waveguides are bended in one plane; this facilitates manufacturing and provides required flexibility to absorb/relax the stress caused by thermal contraction of the cartridge body and the pillar supporting the optics and amplifiers. The WR10-to-WR15 transitions and split-block turns were simulated in Ansys HFSS to achieve a better than -20 dB return loss at any frequency within the RF band 67-116 GHz. As example here, Fig. 3 demonstrates the design and performance of the 90 – degree corner WR10 adapter used in the Pol1 RF transport chain right after the CLNA. The option to have the 90-deg corner before the CLNA was studied but abandoned. In the implemented design of the CCA, the corner is just after the CLNA. In this respect the important parameter is the return loss and not the insertion loss.

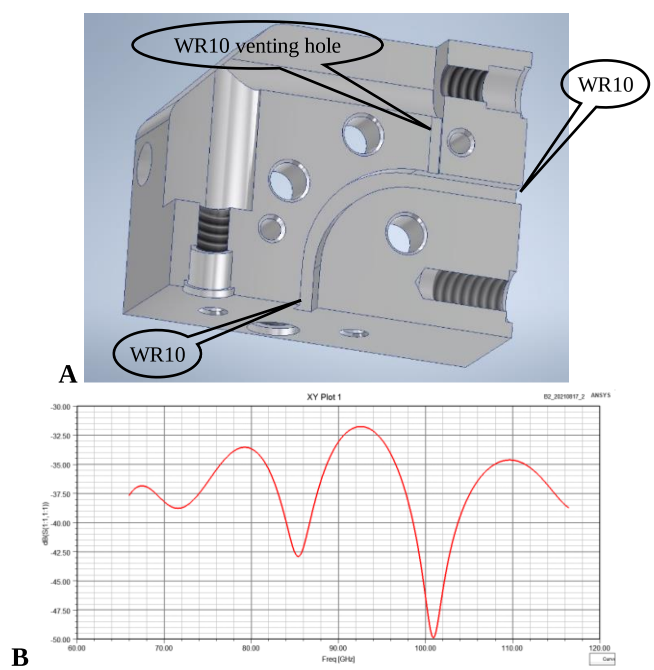

Fig. 3. A) 90 – degree corner WR10 adapter made in split block and

used in the Pol1 RF transport chain. **B**) The HFSS simulated S_{11}/S_{22} of the adapter.

The vacuum WR10 RF feedthroughs were designed and optimized for the entire RF band to provide less than 0.5 dB insertion loss and S_{11}/S_{22} better than -20dB, see reference [10] for the details.

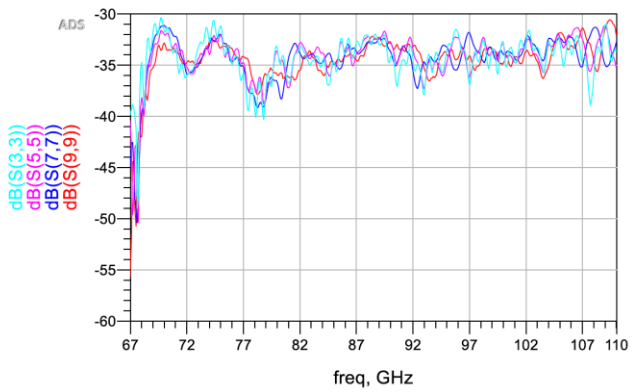

Fig. 3. C) Measured magnitude of the return loss of 4 fabricated 90 – degree WR10 corner adapters; better than -30dB in the RF band of 67-116 GHz.

The stainless steel WR15 thin-wall waveguides ensure necessary thermal isolation between the different temperature stages inside the CCA because of the low thermal conductivity of the material thus providing minimum thermal load to the 15K cryogenic stage with the amplifiers and the intermediate 110 K stage of the ALMA cryostat. The oversized waveguide dimensions ensure reduced insertion RF loss for the signal as compared to WR10 waveguide. Flexible thermal links, Fig. 2, connect the WR15 waveguides to the cartridge thermal plates via additional "chimneys" that allow us to choose the required length of the waveguide separating different temperature levels. By choosing the appropriate length, we could control the heat influx at the specified levels for the CCA 110K and 15K temperature plates.

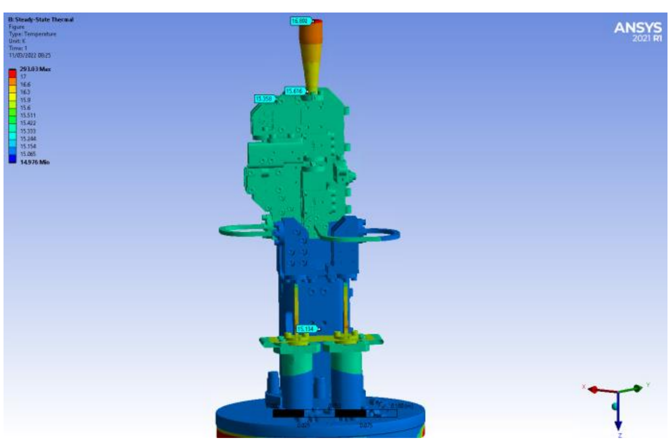

Fig. 4. ALMA Band 2 CCA cooling simulated with ANSYS™ Mechanical® software. For better scale resolution, only components mounted at the ALMA Band 2 CCA cartridge 15K plate are shown. In the simulation, all LNAs have 22.5mW power dissipation and 100mW of the IR radiation power were added at the corrugated horn to simulate IR radiation thermal influx from 110K environment.

The thermal simulations using Ansys have shown that the chosen cooling structure fulfills its purpose by keeping the passive components and the amplifiers close to the 15K temperature provided by the ALMA FE cryostat. The laboratory measurement results in the ALMA Cartridge Test Cryostat for a single cartridge have shown the temperature at the CLNAs are very close to the simulated levels of the temperature. The simulations results are presented in Fig. 4.

Table 1 below shows *calculated and specified heat loads* at different temperature stages of the CCA. The differences between the passive and total thermal loads give the margin for the heat produced by active components, e.g., 107 mW is available for CLNAs. During the simulations, we assumed that the horn that is exposed to the IR radiation of the 110K environment picks up 100 mW of power.

Table 1. Passive Heat Loading

FE Cryostat Stage	WR15 Heat Load	Harness Heat Load	Total Heat Load (spec)
15 K Stage	64 mW	14 mW	78 (185) mW
110 K Stage	243 mW	18 mW	261 (600) mW

At this stage of the ALMA Band 2 project, the two prototype ALMA B2 CCAs were built and tested, in the extended 67-116 GHz bandwidth, covering both the ALMA Band 2 and Band 3 frequency range, Fig 5. The measurements of the physical temperature of the critical components confirmed the simulations (Fig.4) with inaccuracy of the measured temperature $\pm$0.5 K at the CLNAs bodies. The prototype CCA simulated Eigen frequency for the lowest mode was 147,75 Hz. The CCA was run through the shaking test to confirm the Eigen frequencies are above the specified 75 Hz, the observed lowest resonance was at about 125 Hz.

Fig. 5. Assembled pre-production ALMA B2 CCA.

The CCA was complemented with the Warm Cartridge Assembly [9] and fully characterized including optics. The details on the test setup could be found in [12].

Fig. 6 demonstrate measured noise performance of one of the pre-production ALMA Band 2 receiver cartridges.

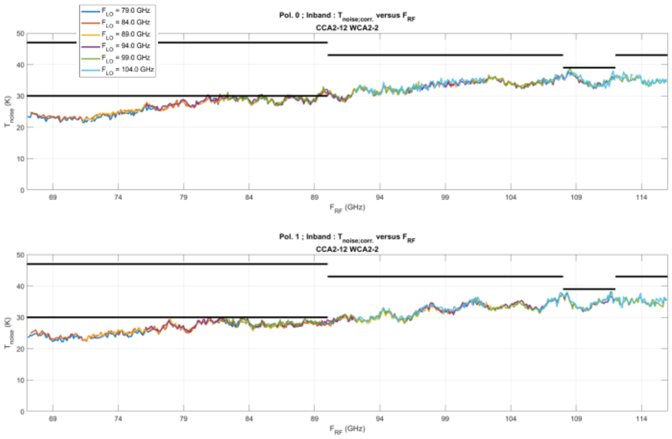

Fig. 5. ALMA Band 2 CCA 2SB-corrected receiver noise temperature vs. RF frequency at 100 MHz resolution, including specification markers (solid black lines).

III. Conclusion

A new generation receiver for ALMA, Band 2 covering 67-116 GHz, dual polarization, 2SB with the IF bandwidth 4-18 GHz has been designed, built and tested. The receiver complies with the ALMA specifications for Band 2 and Band 3 and produces total 56 GHz wide IF band from the two polarization channels and upper and low sidebands of each polarization. The receiver has an excellent noise temperature and fulfill expectations for next-generation ALMA receivers [7] with the extended IF bandwidth. At the time of writing this manuscript, the first ALMA Band 2 receiver was undergoing commissioning at the ALMA Observatory.

References

[1] Chau-Ching Chiong, Yunshan Wang, Kai-Chun Chang, and Huei Wang, “Low-Noise Amplifier for Next-Generation Radio Astronomy Telescopes”, IEEE Microwave magazine, Volume 23, Number 1, January 2022, ISSN 1527-3342.

[2] Y. Tang et al., “Cryogenic W-band LNA for ALMA band 2+3 with average noise temperature of 24 K,” in Proc. IEEE MTT-S Int. Microw. Symp. (IMS), 2017, pp. 176–179. doi: 10.1109/MWSYM. 2017.8058981. Custom model, https://lownoisefactory.com/product/lnf-lnc65_115wb-2/

[3] F. Thome, F. Schäfer, S. Türk, P. Yagoubov and A. Leuther, "A 67–116-GHz Cryogenic Low-Noise Amplifier in a 50-nm InGaAs Metamorphic HEMT Technology," in IEEE Microwave and Wireless Components Letters, vol. 32, no. 5, pp. 430-433, May 2022, doi: 10.1109/LMWC.2021.3134462.

[4] David Cuadrado-Calle, Danielle George, Gary A. Fuller, Kieran Cleary, Lorene Samoska, Pekka Kangaslahti, Jacob W. Kooi, Mary Soria, Mikko Varonen, Richard Lai, and Xiaobing Mei, “Broadband MMIC LNAs for ALMA band 2+3 with noise temperature below 28 K,” IEEE Trans. Microw. Theory Techn., vol. 65, no. 5, pp. 1589–1597, May 2017. doi: 10.1109/ TMTT.2016.2639018.

[5] P. Yagoubov et al, “67-116 GHz optics development for ALMA band 2-3 receivers”, 2016 41st International Conference on Infrared, Millimeter, and Terahertz waves (IRMMW-THz), https://doi.org/10.1109/IRMMW-THz.2016.7758971 .

[6] Gonzalez, A. et al., ALMA band 2+3 (67-116 GHz) optics: Design and first measurements, IEEE International Symposium on Antennas and Propagation 2016, https://doi.org/10.1109/APS.2016.7696305 .

[7] The ALMA Development Roadmap, AKA ALMA 2030, http://www.eso.org/sci/facilities/alma/announcements/20180712-alma-development-roadmap.pdf

[8] Yagoubov P., et.al, “Wideband 67-116 GHz receiver development for ALMA Band 2,” A&A, vol. 634, p. A46, 2020. https://doi.org/10.1051/0004-6361/201936777

[9] Álvaro González, et.al., "Development of receiver optics for ALMA bands 1 and 2, and possible synergies with ngVLA," Proc. SPIE 11453, Mm, Submm, and Far-Infrared Detectors and Instrumentation for Astronomy X, 114533S (December 2020), https://doi.org/10.1117/12.2561595

[10] Igor Lapkin, Cristian López, Mathias Fredrixon, Alexey Pavolotsky, Sven-Erik Ferm, Vincent Desmaris and Victor Belitsky, “Vacuum-seal Waveguide Feedthrough for Extended W band 67-116 GHz”, submitted to IEEE Journal of Microwaves, March 2023.

[11] Bertrand Thomas, “A 67-116 GHz MMIC-based dual-polarized 2SB down-converter for the ALMA Band 2 Warm Cartridge Assembly prototype development”, ISSTT2022.

[12] J. Barkhof et.al., “ALMA Band 2 Receiver Automated Test System”, ISSTT2022.