4GREAT: A Multiband Extension of GREAT from 490 GHz to 2.7 THz

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Abstract— The German REceiver for Astronomy at Terahertz frequencies (GREAT) has been in successful service onboard SOFIA since 2011. GREAT, with its modular approach, is composed of a group of cryostats containing detectors for different frequency bands (until now, between 1.25 and 4.7 THz). At any time, GREAT can carry two cryostats.

4GREAT (4G), a new member of the GREAT constellation, is a 4-color single-pixel module. Two channels, 4G-1 and 4G-2, are implemented using spare flight mixers developed for Herschel's *Heterodyne Instrument for the Far-Infrared,* namely HIFI band 1 and band 4. The third channel, 4G-3, makes use of the current GREAT L1 detector (1.2–1.5 THz), while 4G-4 covers the frequency range of GREAT $M_{a,b}$ (2.5-2.7 THz), using a newly developed mixer, (similar in design to the upGREAT HFA mixers). The four channels, co-aligned on sky, are operated in a single closed-cycle cooled cryostat.

4GREAT, scheduled for commissioning in July 2017, will be used simultaneously with the upGREAT-HFA (an array of 7 pixels working at 4.745 THz), allowing multiple frequency observations of astrophysically important species including among many others, the ground-state transitions of many hydrides (HDO, HCl, CH, ammonia NH_3, isotopic water $H_2{}^{18}O$, hydroxyl OH), as well as mid-J transitions of carbon monoxide.

INTRODUCTION

With the successful addition of the upGREAT LFA [2] and HFA [3] to the highly modular GREAT instrument [1], greatly enhanced scientific opportunities have been offered to the interested SOFIA communities. However, while these instruments increase the scientific yield of SOFIA by spatial multiplexing (14+7 pixels operating at the same time), there is also a strong demand for a complementary instrument that does span a wider range in sky frequencies. 4GREAT has been developed in response to these needs. The instrument will operate simultaneously four state-of-the-art detectors at science-defined frequencies between 0.5 and 2.7 THz.

Since Herschel ceased operations in 2012 [7], astronomers are lacking access to those parts of the sub-Terahertz spectrum that are not visible from ground-based observatories. In 4GREAT, we make use of the spare mixers developed for HIFI band 1 (4GREAT channel 4G-1) and for band 4 (4G-2). Much of their frequency ranges are blocked by Earth's atmosphere, even at high dry sites like the Chajnantor Plateau in Chile, the sites of APEX and ALMA [4,5].

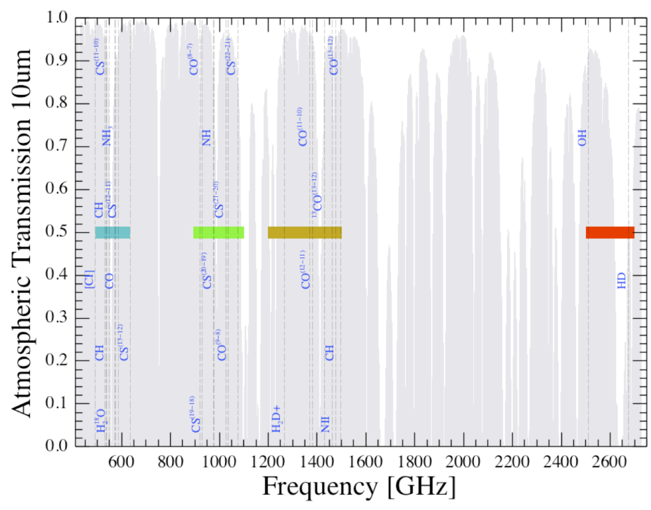

Fig. 1. The atmospheric transmission at PWV of 10 μm, for a SOFIA flight altitude of 43.000 ft. Astrophysical lines of interest and the frequency bands of the 4GREAT channels are marked.

4GREAT channel 3 reuses the existing GREAT-L1 (1.25 – 1.5 THz) mixer, while the channel 4 mixer (2.5 – 2.7 THz) is a newly developed detector, similar in design to the upGREAT-HFA mixers.

Fig. 1 shows the frequency coverages of the different channels plotted along with some scientific lines of interest and the atmospheric transmission for a high-altitude flight of SOFIA [6].

The use of closed-cycle cooled cryostats instead of cryogenics LHe/LN2 (wet) cryostats is a step forward in terms of operation and reliability of the GREAT receivers, as they do not require daily (cryo) services.

Design Description

The main requirement on the 4GREAT design is to allocate 4 different frequency detectors inside its closed-cycle cooled cryostat. The detectors shall operate simultaneously, and their beams must co-align on the sky. With this in mind and with tight constraints on the available volume for the mixers and cold optics inside the cryostat, a maximum weight budget for the overall system, the 4GREAT opto-mechanical design was optimized. The design is modular again. Special attention was paid to good maintainability.

TABLE I
4GREAT Main Components and Subcomponents Characteristics

Channel	CH1	CH2	CH3	CH4
RF Bandwidth (GHz)	492 - 630	892 - 1100	1200-1500	2490 - 2700
IF Bandwidth (GHz)	4 - 8	4 - 8	0 - 4	0 - 4
Mixer	SIS - Herschel HIFI - 1 (LERMA)	SIS-Herschel HIFI - 4 (SRON)	HEB - GREAT - L1 (KOSMA)	HEB - GREAT - M-HD (KOSMA)
LNA / Warm Amplifier	LNF-LNC4_8C (LNF)	LNF-LNC4_8C (LNF)	CITLF4 (CMT)	CITLF4 (CMT)
	AFS3-00100800 (Miteq)	AFS3-00100800 (Miteq)	AFS3-00100800 (Miteq)	AFS3-00100800 (Miteq)
Local Oscillator	S.S.Chain AMC563@LO-U (200uW)	S.S. Chain AMC581@LO-U (150uW)	S.S. Chain AMC627@LO-D (30uW)	S.S. Chain AMC616@LO-D (3.5 uW)
LO Coupling	Wiregrid Splitter	Wiregrid Splitter	Wiregrid Splitter	Diplexer
Optics	Common optics plate + Cold Tower + LO-U Optics	Common optics plate + Cold Tower + LO-U Optics	Common optics plate + Cold Tower + LO-D Optics	Common optics plate + Cold Tower + LO-D Optics
Trec (K) - DSB	100	300	800	1500
IF Processor	IFX x 1. High Order BPF 4-8 GHz	IFX x 1. High Order BPF 4-8 GHz	IFX x 1. High Order BPF 0-4 GHz	IFX x 1. High Order BPF 0-4 GHz
Backend	FFTS4G. Nyquist Band 4-8	FFTS4G. Nyquist Band 4-8	dFFTS4G x 1ch	dFFTS4G x 1ch
Taper (dB)	11.86 - 16.54	12.25 - 16.09	13.29 - 14.78	14.35 - 13.68

A. Mixers

The mixers for 4GREAT originate from different technologies and sources (Tables I, II). The 4G-1 and -2 mixers use Superconducting Insulator Superconducting (SIS) junctions developed by LERMA and SRON [7] for HIFI-Herschel. 4G-3 and -4 operate Hot Electron Bolometers (HEB), designed and built by KOSMA.

TABLE II
4GREAT Mixer Specifications

Band	Technology	Manufacturer	Remark
CH1	SIS	LERMA	HIFI-1 Flight Spare Mixer
CH2	SIS	SRON	HIFI-4 Special Qualification Model Mixer
CH3	HEB (NbTiN)	KOSMA	GREAT L1 Spare Mixer
CH4	HEB (NbN)	KOSMA	GREAT M-HD Mixer

B. Local Oscillators

4GREAT utilizes four solid-state local oscillator units or "LO chains", built by Virginia Diodes Inc. [13]. They consist of a reference oscillator and several multiplication stages along with high power amplifiers. Given the large response widths of the 4GREAT mixers (Q > 20%), three of the LO chains consist of two sub-chains each, which are combined to drive the last multiplier stages. Table I summarizes the band coverage and average output power over each band.

Space for the local oscillator units is very limited and thus LO chains were grouped in couples and split into two modules (Fig. 2): the lower LO unit (LO-D) houses the LO chains for the channels 4G-3 and -4 and uses one of the standard GREAT LO compartments, while the upper LO unit (LO-U) for 4G-1 and -2 attaches to the flange for the auxiliary calibration unit [1].

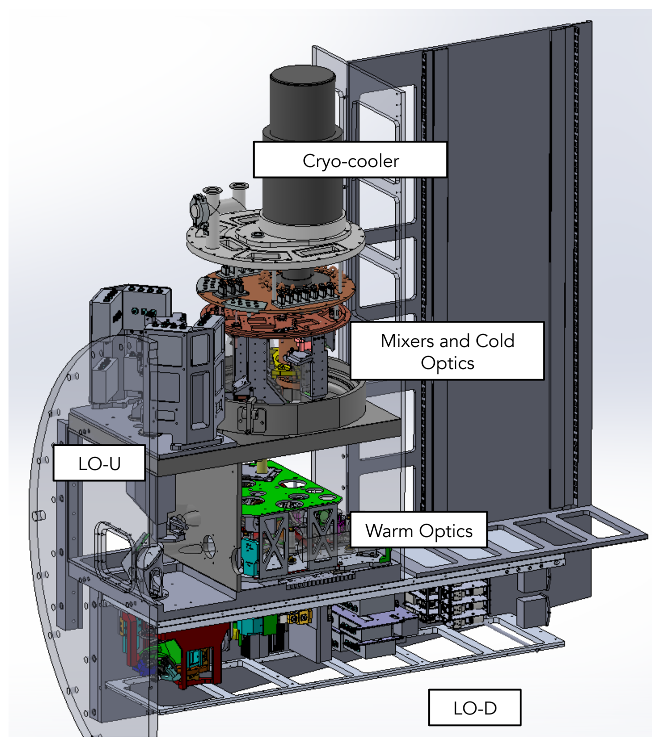

Fig. 2. 4GREAT subcomponents mounted on the GREAT SI structure: The cryostat (mixers, cooler and cold optics), the lower local oscillator unit (LO-D), the upper local oscillator unit (LO-U) and the warm optics are shown.

C. Optics

The 4GREAT optics consist of *Cold Optics* inside the cryostat, the *Optics Plate* where the splitting of the telescope beam into the 4 signal beams and superposition with the LO beams is done, and dedicated *LO Optics* for each of the LO chains. In general, a multiple *Gaussian telescope* approach was taken to make the system as frequency independent as possible, with the only exception of the LO for 4G-3. For every mirror and optical component, a 5*w* beam criterion was used, with a designed edge-taper of 14dB at the central frequency of each band. RF windows for the cryostat were manufactured by QMC [11] for 4G-1 and -2 (Quartz with A/R coating). Tydex [12] provided the windows (Silicon coated with A/R) for 4G-3 and 4G-4.

1) The Cold Optics

Each of the 4 mixers is mounted on a block that also contains part of the channel optics and the low noise amplifiers (LNA). Each of these blocks (*cold towers*) contains a paraboloidal mirror, located in front of each mixer horn, a flat mirror and an ellipsoidal mirror. The ellipsoidal mirror M1 then forms a Gaussian telescope with the first active mirror (M2) mounted outside the cryostat, on the optics plate, just in front of each window (Fig. 4).

Fig. 3 shows the four *cold towers* installed. Because of the low frequency and hence large beam size of 4G-1, the *cold tower* for this channel is much larger than the others.

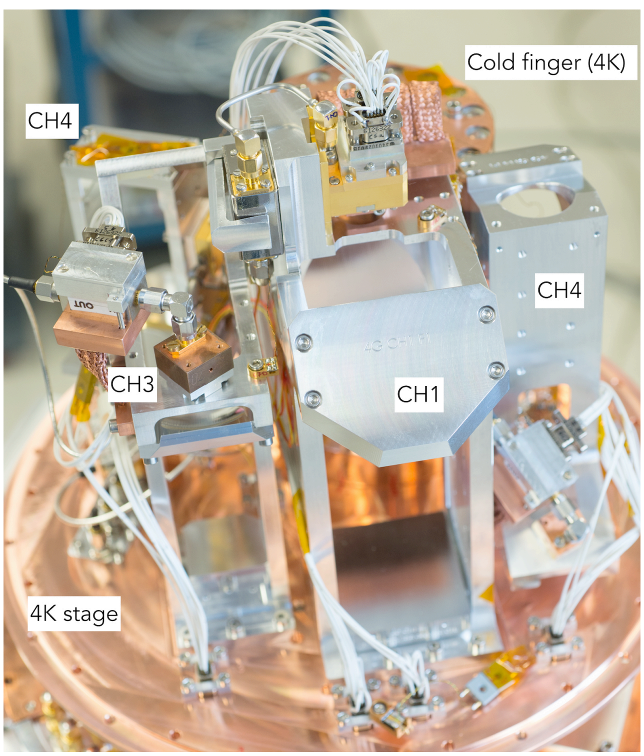

Fig. 3. Each *cold tower* mounts a paraboloidal (M0), a flat and an ellipsoidal mirror (M1), along with the corresponding mixer and cold LNA amplifier.

2) The Optics Plate

The optics plate or "*warm optics*" is placed just below the cryostat (Fig. 2). Fig. 4 shows the schematic of the optics for a single channel. Splitting the telescope beam into four separate signal beams is done using a wire grid and two dichroic filters. The wire grid is placed after the active mirror M4 that is common to all channels. Each of the transmitted (combined signal beams of 4G-2 and 4G-4) and reflected beams (combined signal beam of 4G-1 and 4G-3) is directed to a low-pass dichroic filter positioned between the next two active mirrors (M3-13 / M3-24 and M2n, n=1-4). Consequently, there are two M3 and four M2 mirrors on the optics plate. Between each M2 and before entering the cryostat, the signal beams of channels 1, 2 and 3 are superimposed with the corresponding LO beams by a wire grid (LO in reflection). Because of the relatively weak LO source (Table I) channel 4 uses a Martin-Puplett-Diplexer.

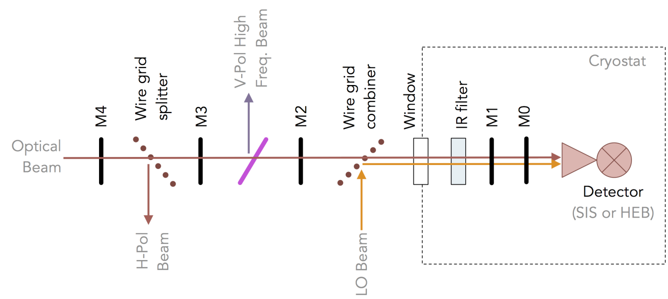

Fig. 4. Diagram showing the main optics components. 4G-4 uses a diplexer instead of a wire grid as combiner. The beam optics comprises two Gaussian telescopes: M4-M3 (at the Optics Plate) and M2 (Optics Plate) with M1 (Cold Tower).

On the optics plate, optical elements are positioned on two levels, spaced by 50mm. The lower level consists mainly of signal beam-related elements while the upper one is mostly used for the LO signal (Fig. 5).

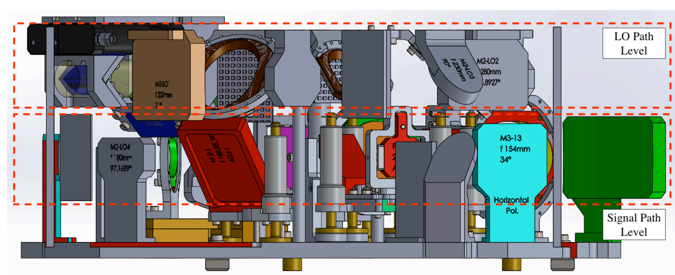

Fig. 5. Side view of the optics plate. Red dashed lines frame the two planes. Some non-critical elements have been omitted in the figure for better visualization.

3) The Optics of the upper LO Unit (LO-U)

The LO-U optics has a very particular design as it hosts the two "*low*" frequency channels, which require larger optical elements. Because of the location of the LO-U, its components are placed on an extension that sticks into the SI frame and then couples to the upper level of the optics plate (Figs. 5, 6). Each of the LO output beams is mapped to its respective mixer input beam by two Gaussian telescopes (4 active mirrors). The first Gaussian telescope is located inside/at the LO-U. The second Gaussian telescope is formed by an active mirror on the upper optics plate level and with M1 inside the cryostat.

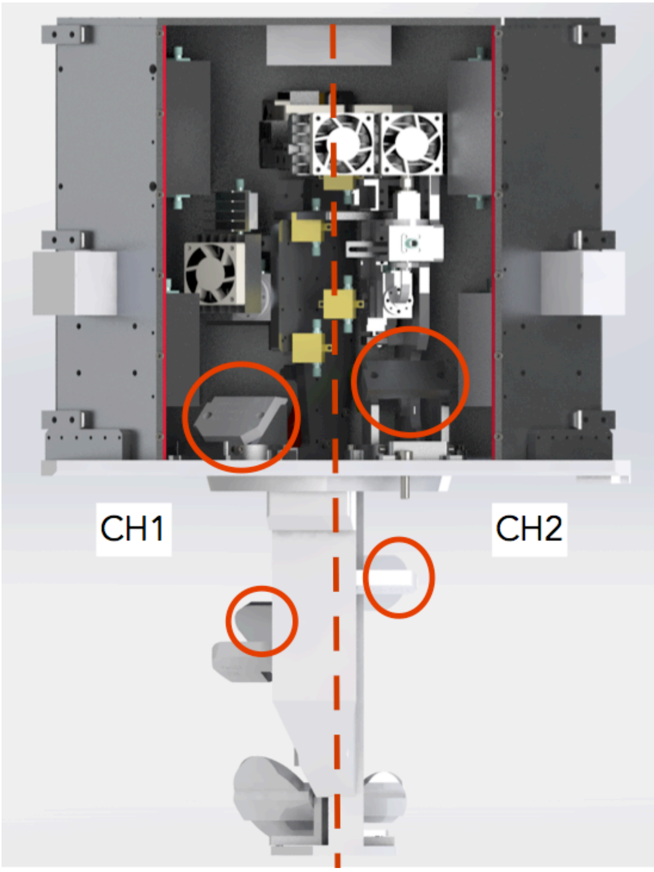

Fig. 6. The upper LO unit (serving 4G-1 and4G-2). The LO chains and optics components are visible in the image. The two active mirrors for each LO are encircled. The dashed line indicates marks the optical and electrical separation between the two channels.

4) *The Optics of the lower LO Unit (LO-D)*

For the upGREAT-LFA [2] the requirement of fitting two LO chains in the LO compartment was solved by tilting one of the LO beams. The design of 4GREAT LO-D with the LOs for 4G-3 and 4G-4 follows the same approach and uses some of the optical components already installed in the SI structure. This constraint requires that for the optics of the 4G-3 LO three active mirrors have to be used, which introduces a minor frequency dependence of the approach. The LO optics for 4G-4 uses four mirrors again as for the lower frequency channels, with a coupling wire grid, which is part of the diplexer optics on the optics plate, in between two of the active mirrors (M2 and M1).

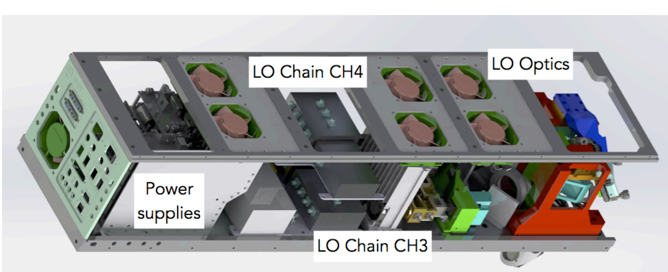

Fig. 7. The lower LO unit (serving 4G3 and 4G-4) is a very compact unit that includes its power supplies, the LO chains and the LO fore-optics.

5) *Cryostat and Closed Cycle Cooler*

As for the upGREAT LFA and HFA, 4GREAT uses a Pulse Tube closed-cycle cooler PTD-406C from Transmit GmbH [9] in a cryostat manufactured by Cryovac GmbH [10]. The cooler load map is shown in Fig. 8.

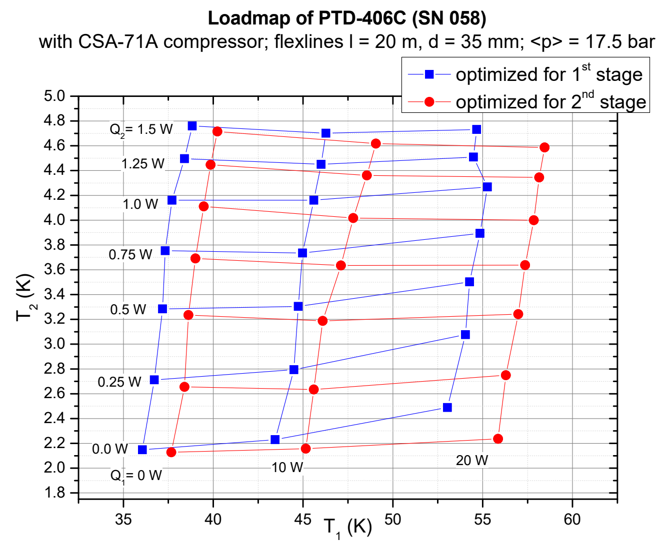

Fig. 8. Thermal load map for the Pulse Tube cooler used by 4GREAT. The operation temperatures are 3K (second stage) and 55K (fist stage).

6) *Intermediate Frequency Unit and Backend*

The Intermediate Frequency (IF) units for 4G-3 and 4G-4 make use of the 0 - 4 GHz IF processor modules already in use for the upGREAT LFA and HFA, while for 4G-1 and -2 new IF processor modules were developed to accommodate the 4 to 8 GHz range (given by the SIS IF bands).

A new version of the high-resolution digital back-end has been recently introduced to GREAT/upGREAT. dFFTS4G [8] is a dual 0-4 GHz bandwidth 32k channels spectrometer. A single card then serves the signals from both 4G-3 and -4 chains, while for 4G-1 and 4G-2 one card each of the FFTS4G spectrometer is employed. The latter operates directly in the 2nd Nyquist band (4-8 GHz).

LABORATORY RESULTS AND COMMISSIONING

4GREAT has been integrated at MPIfR during the months of April and May 2017. The preliminary results presented here have been derived from tests performed with the final aircraft configuration in the AFRC laboratories in Palmdale during May - June. Instrument commissioning is scheduled to take place during the New Zealand SOFIA deployment in July 2017.

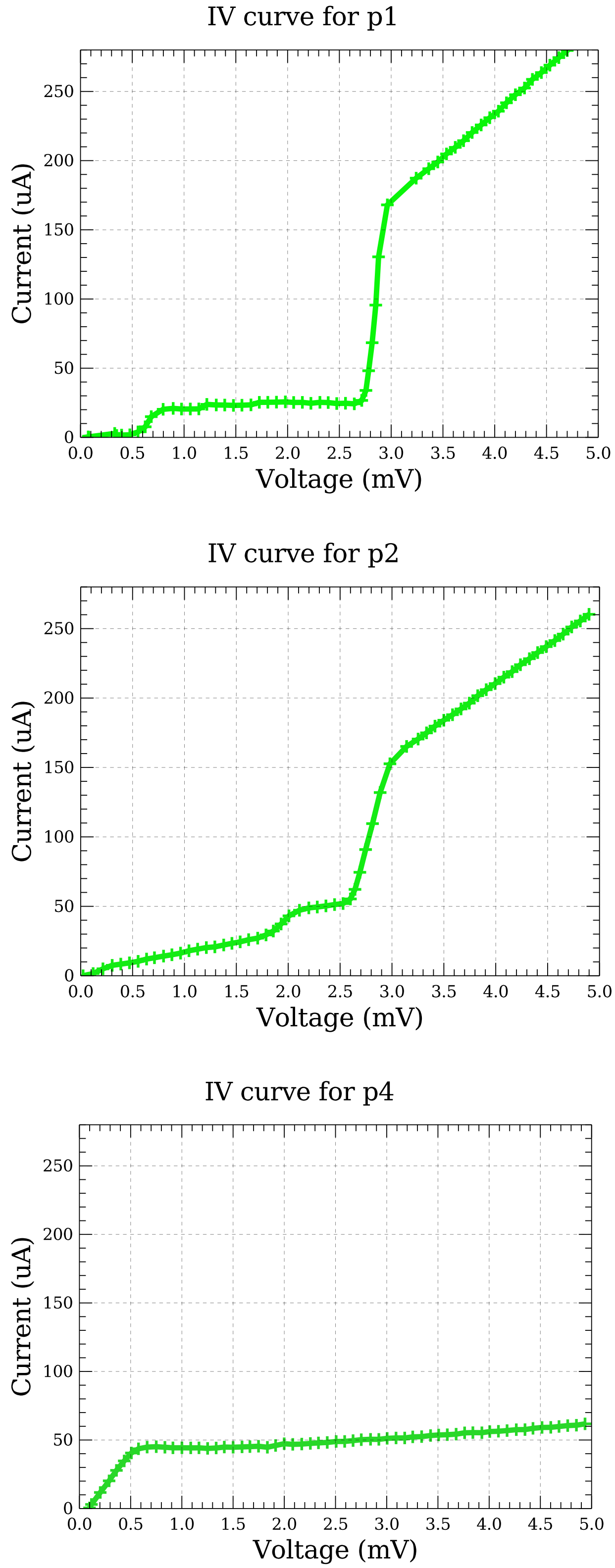

Fig. 9. Pumped I-V curves of the channels 4G-1, 4G-2 and 4G-4 mixers at 3.5 K. Curves for channels 1 and 2 were obtained with magnetic field applied.

CONCLUSIONS

The frequency-multiplexing of 4GREAT will bring new scientific opportunities to the SOFIA communities. The instrument will allow making more efficient use of the limited observing time by performing simultaneous observations at 4 different frequencies.

Though with extended science capabilities, the number of instrument configurations is now limited to two (LFA & HFA, 4GREAT & HFA) which will reduce significantly the technical overheads. All-closed-cycle operation does eliminate the need for daily cryogen service before flight and makes system operation more robust.

ACKNOWLEDGMENT

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