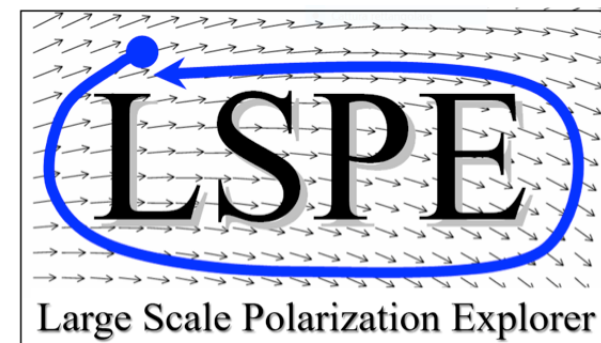




SAPIENZA
UNIVERSITÀ DI ROMA



SWIPE multi-mode pixel assembly

-

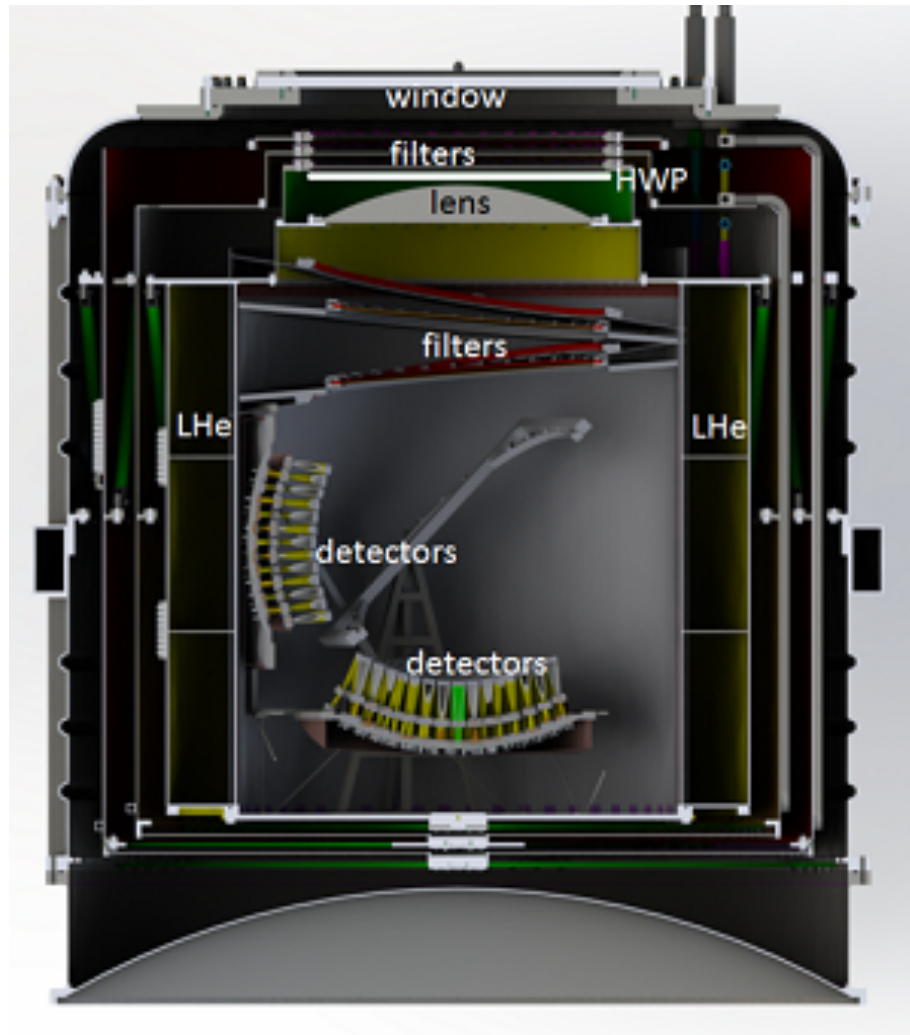
Beam pattern measurement

Fabio Columbro

on behalf of SWIPE detector team

Sapienza - University of Roma

LSPE - SWIPE



POSTER 165 - L. Lamagna The Large Scale Polarization Explorer

The Large Scale Polarization Explorer

ASI Agenzia Spaziale Italiana, INFN Istituto Nazionale di Fisica Nucleare, Sapienza Università di Roma, Università degli Studi di Milano, Università degli Studi di Genova, Università degli Studi di Padova, Università degli Studi di Trieste, INFN, INGV, CARDIFF, MANCHESTER, UNIVERSITY OF OXFORD, and others.

L. Lamagna, G. Addamo, P.A. Adde, C. Bacigalupi, A.M. Baldini, P.M. Battaglia, E. Battistelli, A. Bal, M. Bersanelli, M. Biscotti, C. Boragno, A. Boscaleri, B. Caccianiga, S. Caprioli, F. Cavaliere, F. Cel, K.A. Cleary, F. Columbro, G. Coppi, A. Coppolecchia, D. Corsini, F. Cuttala, G. D'Alessandro, P. de Bernardi, G. De Gasperi, M. De Petris, F. Del Torto, V. Falone, Z. Farooqui, F. Farsian, F. Fontanelli, C. Franceschet, T.C. Gaier, Gatti, R. Genova-Santos, M. Gervasi, T. Ghigna, R. Grosso, F. Incardona, M. Jones, P. Kangaslahti, N. Krachmalnicoff, R. Mainini, D. Maino, S. Mandelli, M. Maris, S. Masi, A. May, P. Mena, A. Mennella, R. Molina, D. Molinari, G. Morgante, F. Nati, P. Natoli, L. Pagano, A. Paiella, A. Passerini, M. Perez-de-Torres, O.A. Peverini, F. Pezzotta, F. Piacentini, L. Piccirilli, G. Pisano, L. Polastri, G. Polenta, D. Poletti, G. Presta, S. Realini, N. Reyes, A. Rocchi, J.A. Rubio-Martin, M. Sandri, S. Santor, A. Schillaci, G. Signorelli, M. Soria, F. Spinella, V. Tappia, L. Terenzi, M. Tomasi, E. Tommasi, C. Tucker, D. Vaccaro, D.M. Vignano, F. Villa, G. Virone, N. Vittorio, A. Volpe, B. Watkins, A. Zachari, M. Zannoni.

Context and Science Case

Measurements of the Cosmic Microwave Background (CMB) polarization anisotropies offer strong probes of the standard cosmological model. **Linear polarization of the CMB** is known to emerge from Thomson scattering off electrons at the last scattering surface in the presence of local quadrupole anisotropies in the scattered radiation field. The polarization pattern observed in the sky is commonly decomposed in a curl-free "E-mode" and a divergence-free "B-mode". E-modes alone emerge in the presence of the velocity fields around peaks in the baryon-photon fluid at last scattering, and thus exhibit a tight correlation with the temperature anisotropies of the CMB. As such, the TE angular cross-power spectrum and the EE power spectrum can be usefully combined with the TT power spectrum to break degeneracies among cosmological parameters, and to constrain specific parameters (e.g. the reionization optical depth) otherwise intrinsically degenerate with respect to temperature anisotropies. On the other hand, B-modes at small angular scales are observed as a result of E-to-B leakage due to gravitational lensing, and as such observed in correlation to the line-of-sight integrated lensing potential due to the presence of large scale structure across the light path to last scattering surface.

In addition, a large (degrees and above) scale contribution to the **B-mode angular power spectrum** is predicted to emerge from a stochastic background of tensor (metric) perturbations, i.e. **gravitational waves, generated during the inflationary expansion history of the early universe**. The amplitude of the gravitational wave background can be effectively used to constrain the inflationary paradigm: the B-mode power yields a direct measurement of the so-called **tensor-to-scalar ratio r** , i.e. the power ratio between the tensor and scalar perturbations at the end of the inflation. **A detection of large scale B-modes, if any at all, would thus represent the ultimate constraining probe for the physics of inflation**. The best current upper limits on r from the joint BICEP2 and Planck analysis, yields $r < 0.07$ at 95% c.l (Phys. Rev. Lett., 114, 101301, 2015).

Observationally, not only the **inflationary signal is tiny** (at most a fraction of percent of the total polarized CMB power), but **no region of the microwave sky can be safely considered free from foreground contamination** to allow a direct measurement down to the level required for primordial B-mode detection. A large scale B-mode measurement demands very clever and careful strategies, both in instrument design and signal conditioning to mitigate the hardware systematics but also accurate modeling and treatment of the foregrounds through component separation techniques, with systematics understood and traced across the analysis pipeline down to a fraction of the sensitivity level allowed by observations.

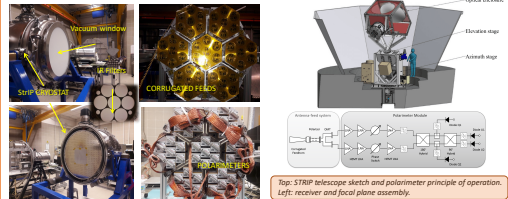
The CMB community is currently devoting a huge effort towards large scale polarization measurements. A number of ongoing and upcoming projects, including the recently JAXA-approved LiteBIRD satellite, have been designed to shed light on the so-far elusive B-mode signal from inflationary gravitational waves.

Project Description

LSPE is a program funded by the Italian Space Agency and INFN with the threefold aim to:

- **perform a large coverage survey** of the microwave polarized sky in 5 spectral bands, with the scope to understand the galactic foregrounds at degree scales;
- **test and validate** hardware solutions, observing strategies, and data processing techniques for the observational challenge of the inflationary B-modes, in view of even more ambitious ground-based and space-borne programs devoted to CMB polarization in the next decade (including LiteBIRD);
- **constrain r at the level of 0.01**.

LSPE will observe a 25% fraction of the sky in the Northern hemisphere by means of two instruments, complementary for frequency coverage and technology.



SWIPE (Short Wavelength Instrument of the Polarization Explorer) is a **Stokes polarimeter** based on a **50 cm refractive telescope** with a dual polarization focal plane hosting two arrays, one per polarization, totaling **330 large throughput multimode 300 mK TES bolometers**, with passbands centered at **145, 210 and 240 GHz**. SWIPE will survey the Northern Sky from a **spinning long duration stratospheric balloon**, launched from **Svalbard or from Kiruna during the Arctic Winter**. Its main features are summarized in table.

The key unique features of SWIPE are the use of a large aperture **Half-Wave Plate (HWP)**, acting as a **broadband polarization modulator** at the telescope foci, and the optimization of collection efficiency through the **multi-moded coupling of the single detectors to the system optics**.

The HWP rotation mechanism is based on a superconducting magnetic suspension system allowing continuous rotation at 60 rpm, corresponding to 4 Hz modulation of the polarized signal.

The multi-moded detectors for SWIPE trade system resolution for optical efficiency, coupling few tens of modes per detector across the covered bands, so that the effective photon noise limited sensitivity equals that of a few thousands single-moded detectors in both polarizations.

The limited number of physical detectors and the comparatively small number of wires required for the implementation of the readout allow the SWIPE receiver to comply with the strong constraints on power supply applying to a stratospheric night flight, while still achieving a sensitivity scaling like the root of the total number of coupled modes.

The readout electronics is based on a **Frequency Domain Multiplexing (FDM)** scheme with a factor 16:1. The cold part of the electronics is based on IC filter boards (including the bias resistor) next to the focal planes, at 300 mK, while the SQUID is at 1.6 K, in a shielded box. The warm readout custom board is based on an Altera Cyclone V SoC, and it features mezzanine DAC and ADC boards.

STRIP Status

At present, most of the STRIP hardware has been developed and tested. Q-band and W-band sub-systems, including passive components (feedhorns, polarizers, OMT's) and HEMT-based coherent receivers, have been successfully characterized at unit-level. Integration and system-level testing of the focal plane arrays inside the instrument cryostat is planned to be performed within the next months. Electronics and ancillary systems, such as the internal calibrator and the star tracker, are being finalized and verified as well. Verifications of the telescope parts are in progress. The preparation of the site and the construction of the sliding roof will be finalized between 2019 and 2020. STRIP is scheduled to be fully integrated at the observation site in Spring 2021.

SWIPE Status

Modulation system: The clamp/release system for the rotor, allowing to keep it in place before the superconducting transition of the support magnets, has been prototyped and successfully tested at cryogenic temperatures. The rest of the individual components (i.e. superconducting magnets, rotor permanent magnet, control coils and control electronics) have been built and individually tested in Rome. The full system will be assembled and cryogenically tested in the next months. Most of the issues involved with system design and the relevant systematics at 4-times the rotation frequency have been assessed. They need to be characterized and understood prior to system operation. These will be the target of the extensive calibration plan which will be performed at receiver level during the pre-integration campaign.

Multi-moded pixels: recent tests of the single-pixel prototypes for the SWIPE focal plane with a coherent source at 128 GHz prove a good consistency of the pixel response with the modeled multi-moded performance. Anyway, more extensive, broadband testing at the system-level is advised by the large size of the focal plane and by the frequency dependent positioning of the pixel units across the focal plane.

Readout: The first functional tests (e.g., tone generation) on the prototype flight model have been performed.

Gondola construction and flight cryostat assembly are underway. The pre-integration campaign and subsystem compliance review for SWIPE is scheduled at the end of 2019.

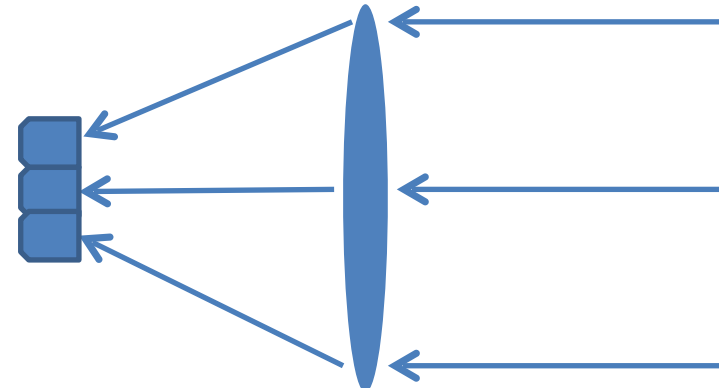
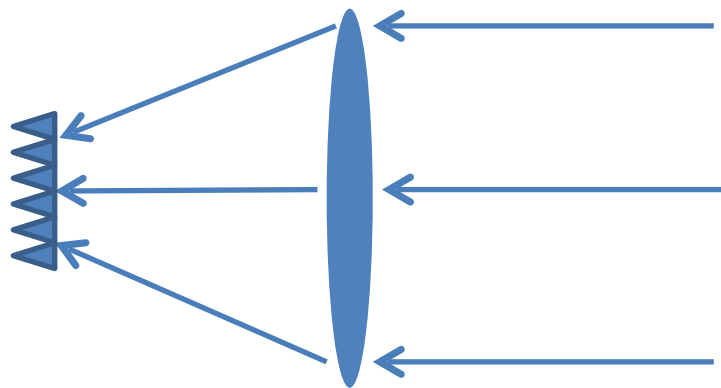
SWIPE-related contributions at LTD18:
F. Columbro et al., "SWIPE multi-mode pixel assembly design and beam pattern measurements at cryogenic temperature", Orals LM003 (Tuesday, 12.00)
B. Siri et al., "Bismuth-Gold absorber for large area TES spiderweb bolometers", Poster no. 400 (poster session Jul 25)
A. Tartari et al., "Development and testing of the FDM readout of the TES arrays aboard the LSPE/SWIPE balloon-borne experiment", Poster no. 267 (poster session Jul 25)



- Stratospheric balloon which will be launched from the Longyearbyen airport in Svalbard Islands
- Goal $r = 0.01$
- Stokes Polarimeter with 500 mm aperture refractive telescope
- Cryogenic HWP polarization modulator
- 2 large focal planes, filled with multimode bolometers at 140, 220, 240 GHz cooled by a ^3He refrigerator at 0.3K

Single-mode vs multi-mode design

- Diffraction- and photon-noise limited operation over quite a broad band demonstrated
- Solid modeling techniques
- Reliable methods for assessing real-life performance.
- Instrument design is complicated but huge experience accumulated by community over the last few years.
- Large numbers of detectors needed to break photon noise limit
- Reduce the number of individual sensitive elements each hitting the photon noise limit more easily
- Sensitivity per individual device scales like $N_{\text{modes}}^{1/2}$
- Comparatively larger detector units and coarser angular resolution.
- Viable and cost-effective when sensitivity is a stronger requirement than diffraction-limited operation (e.g. Planck 545 and 857 GHz)
- CMB spectral distortion and large scale B-mode searches can fully take advantage of mm design (PIXIE, LSPE)



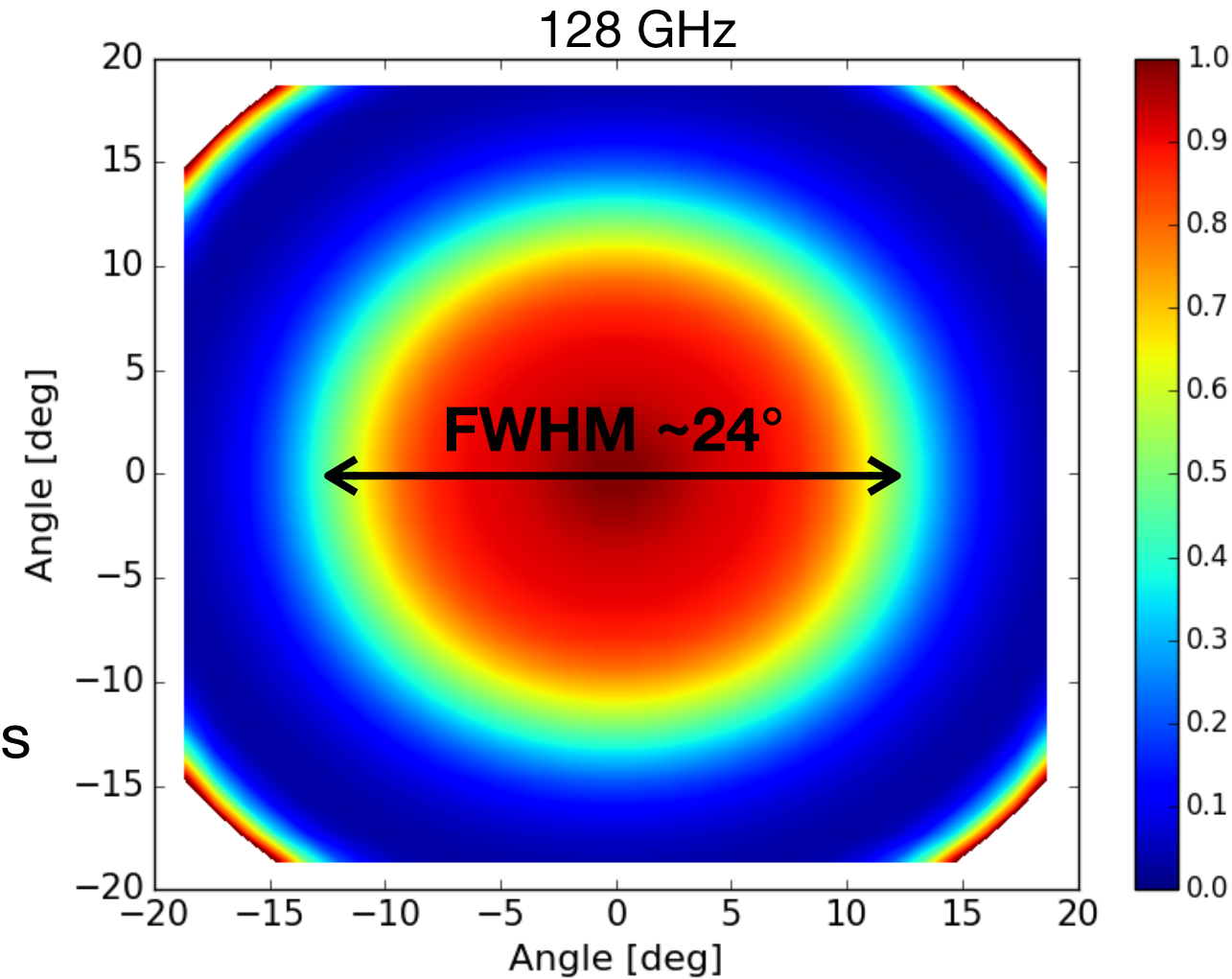
Testing the pixel angular response is essential

The SWIPE pixel assembly

- 326 detectors divided in the 3 frequency bands:
140 GHz, 220 GHz, 240 GHz
- ~8800 modes collected



Same sensitivity of ~9k pixels

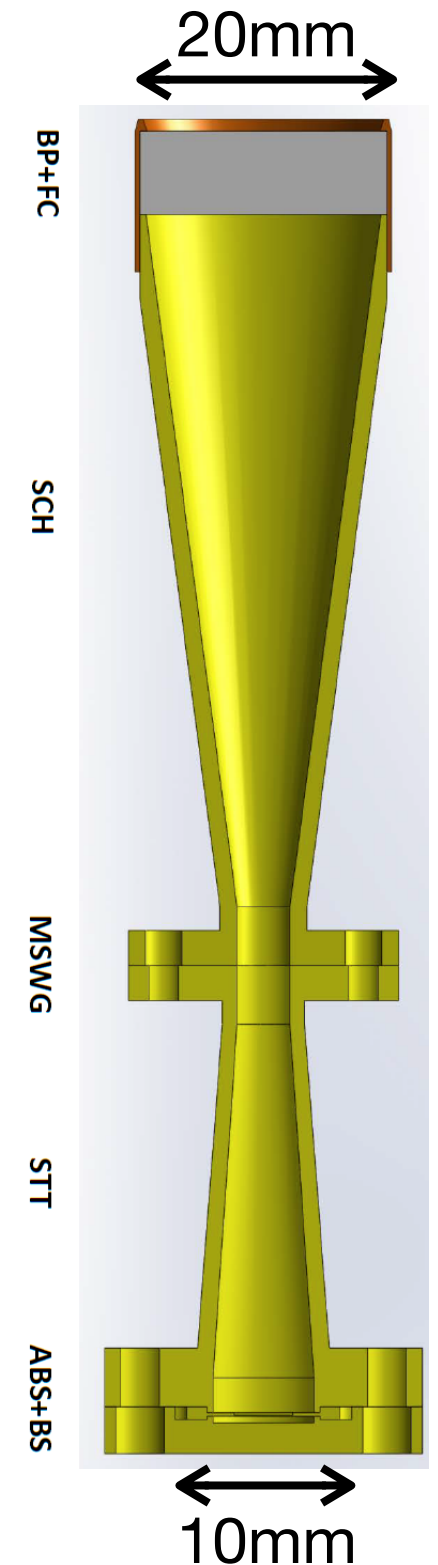


Nominal freq (GHz)	Bandwidth	Min freq (GHz)	Max freq (GHz)
140	30%	119	161
220	5%	214.5	225.5
240	5%	234	246

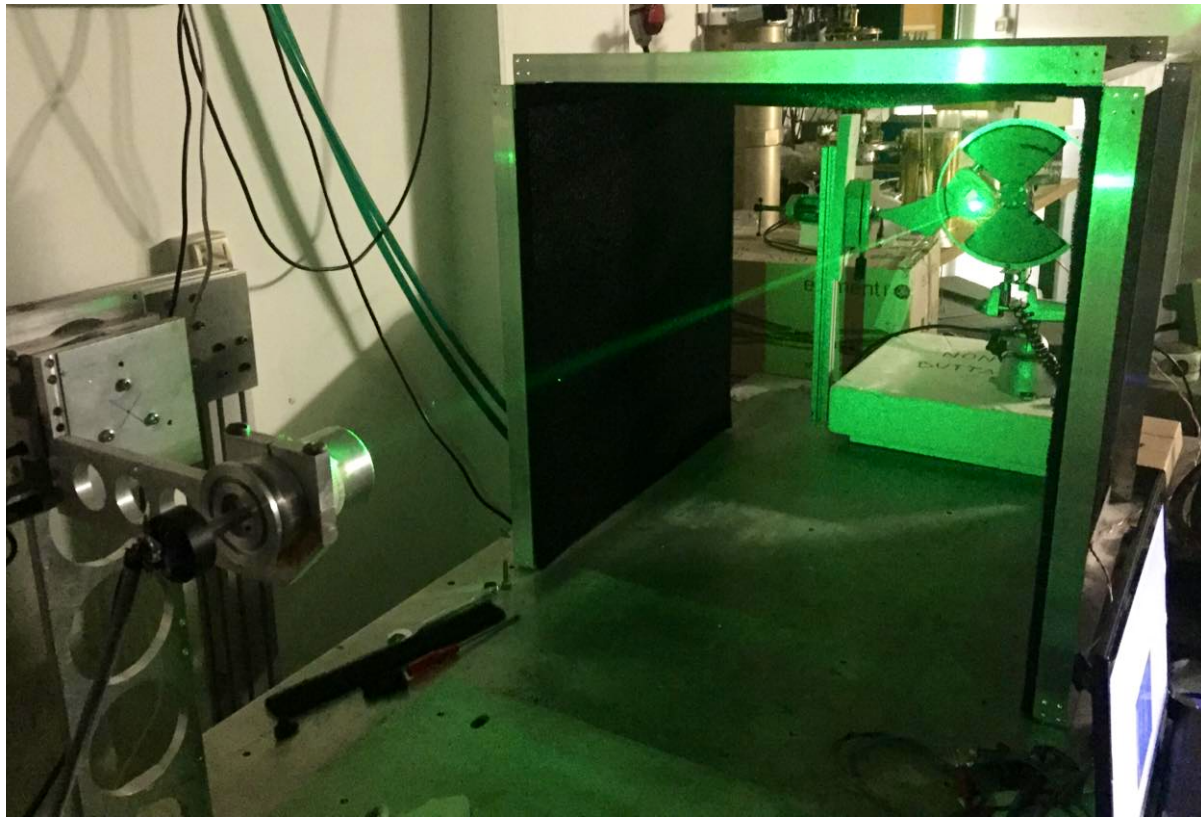
Table 1 – main features of the SWIPE bandpasses (source: C. Tucker, Cardiff Univ.)

Channel	ν_{\min} (GHz)	$N_{\text{modes}}(\nu_{\min})$	ν_{\max} (GHz)	$N_{\text{modes}}(\nu_{\max})$	ν_{eff} (GHz)	$N_{\text{modes}}(\nu_{\text{eff}})$
140	119	10	161	17	140	12
220	214	28	226	31	220	30
240	234	32	246	35	240	34

Table 2 – number of coupled modes N_{modes} at the center and at the edges of each SWIPE band. The total optical throughput at frequency ν is $N_{\text{modes}}c^2/\nu^2$.

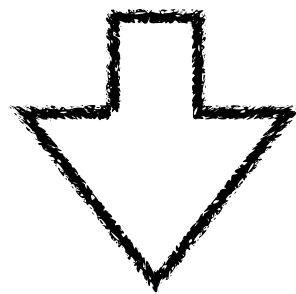


Room temperature measurements

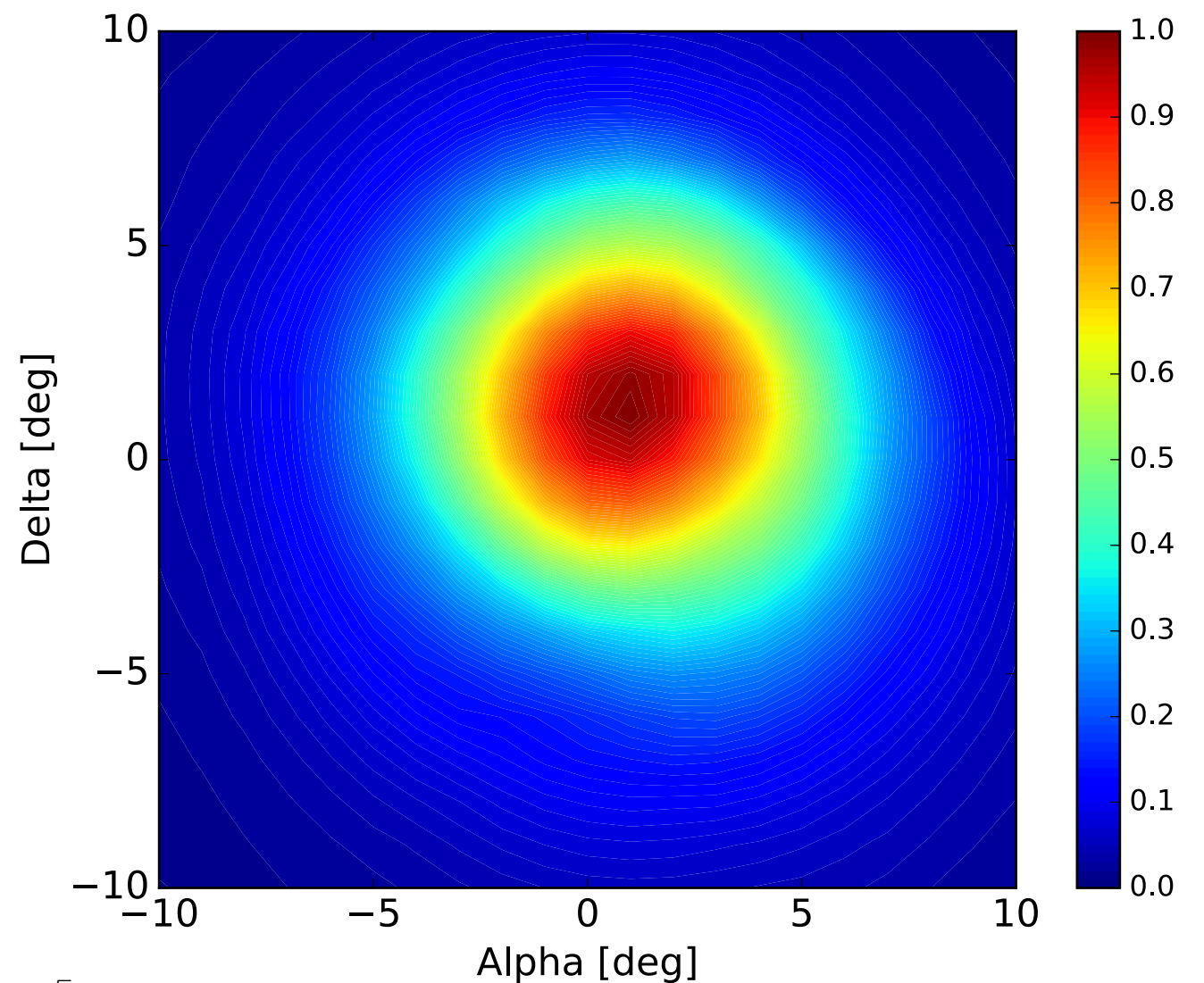


Bolometer replaced with a white paper diffuser and a custom holder. SWIPE horn coupled with a visible light photodiode.

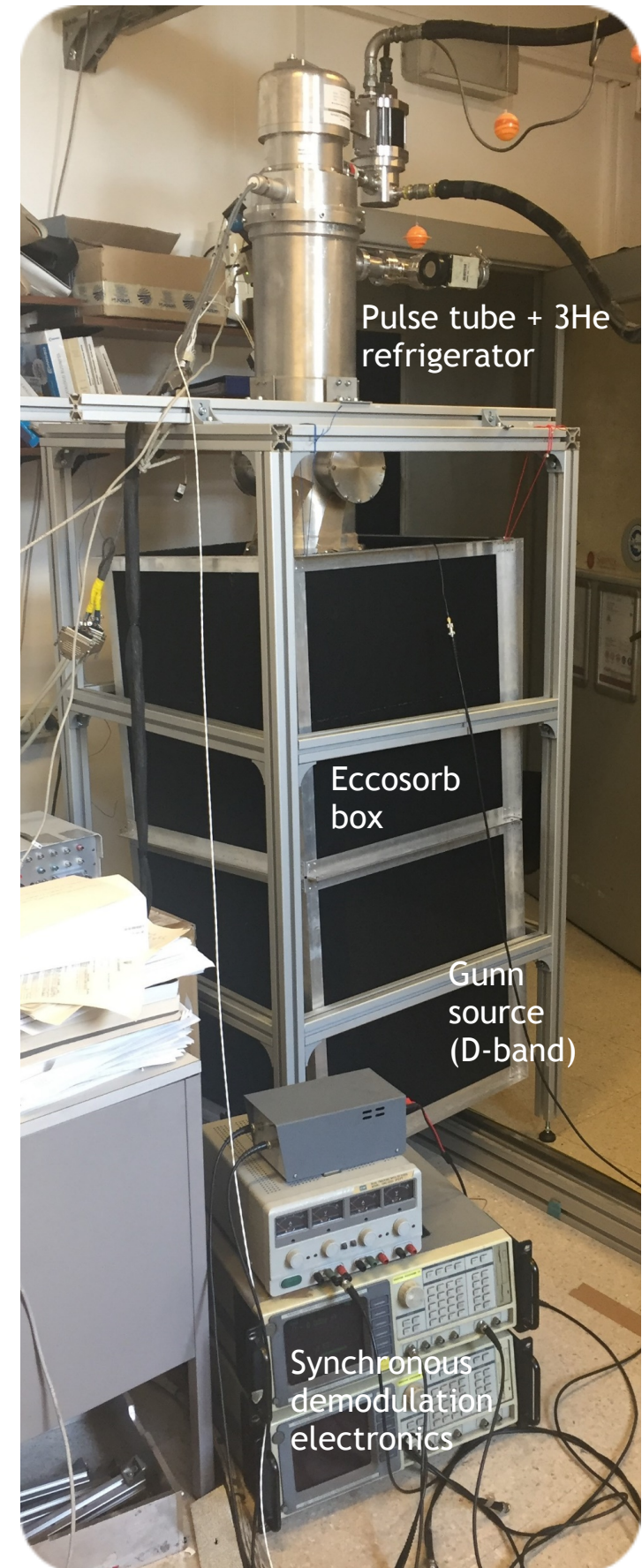
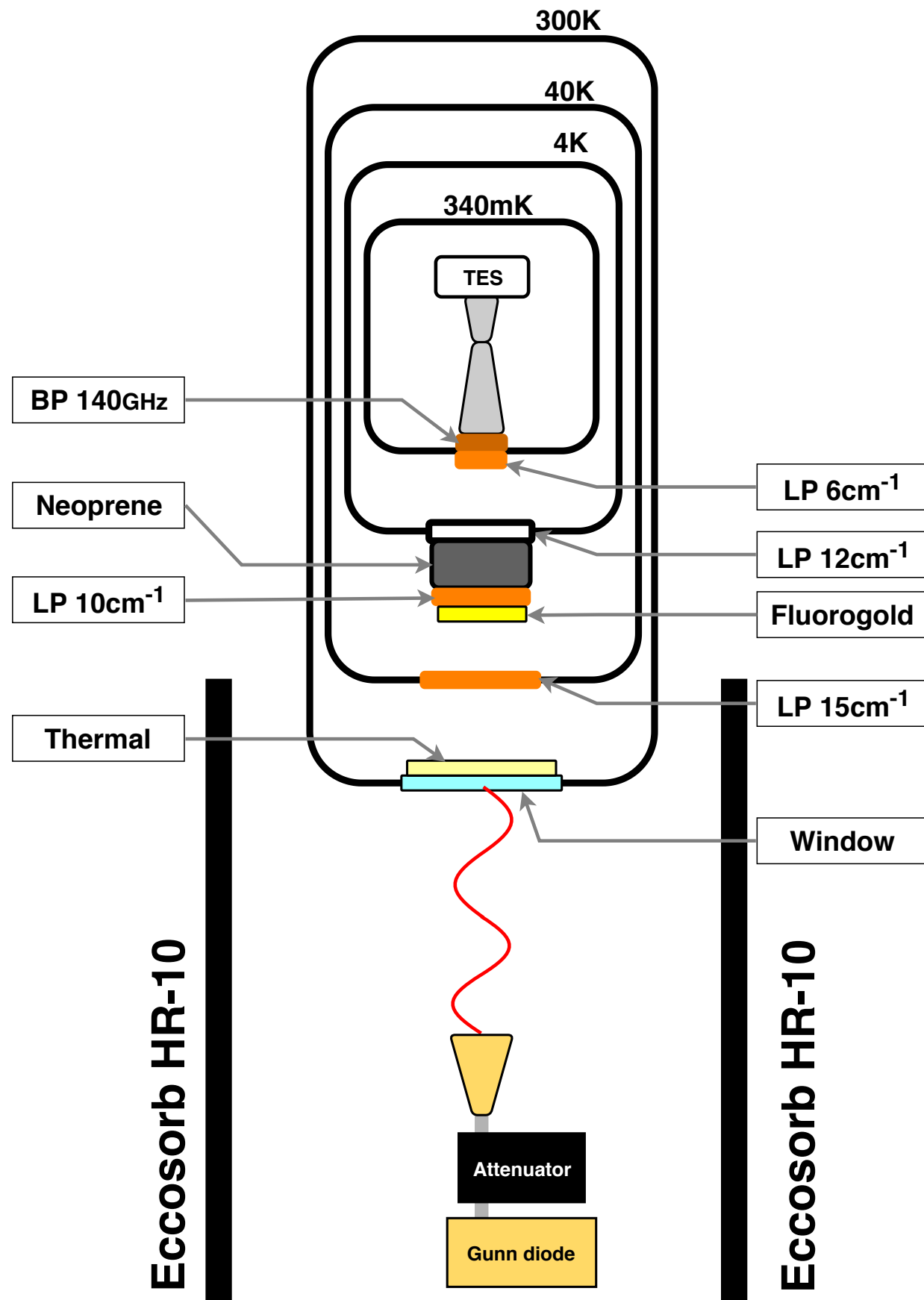
Expected circular beam



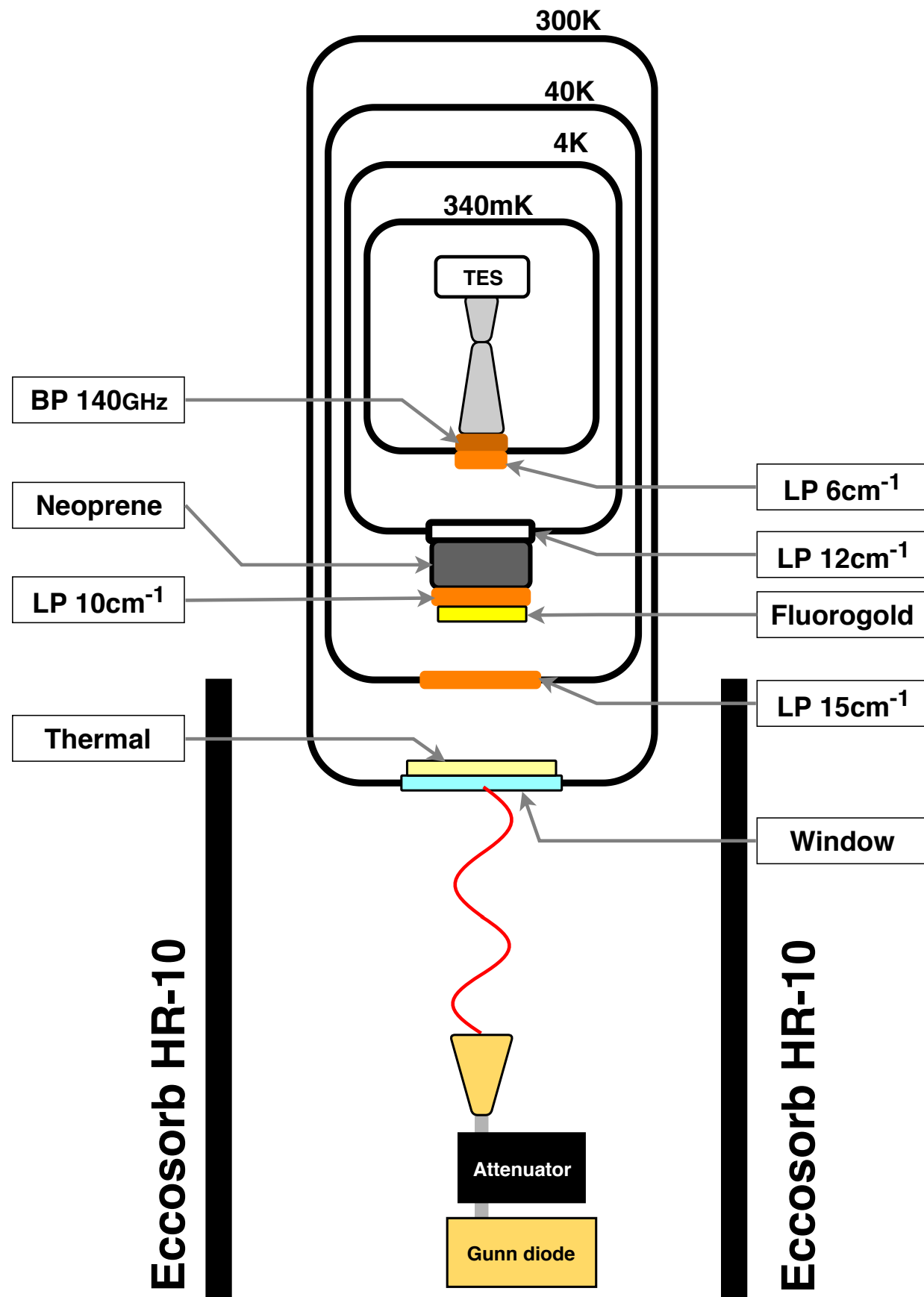
Symmetric pattern



Testbed



Testbed

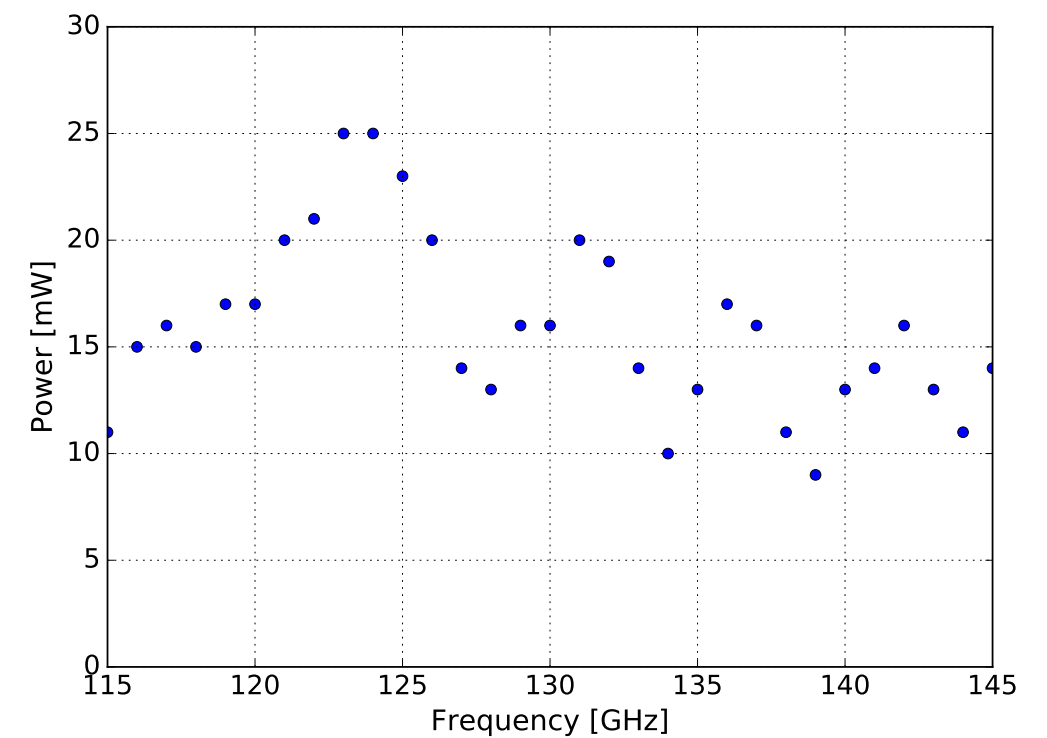
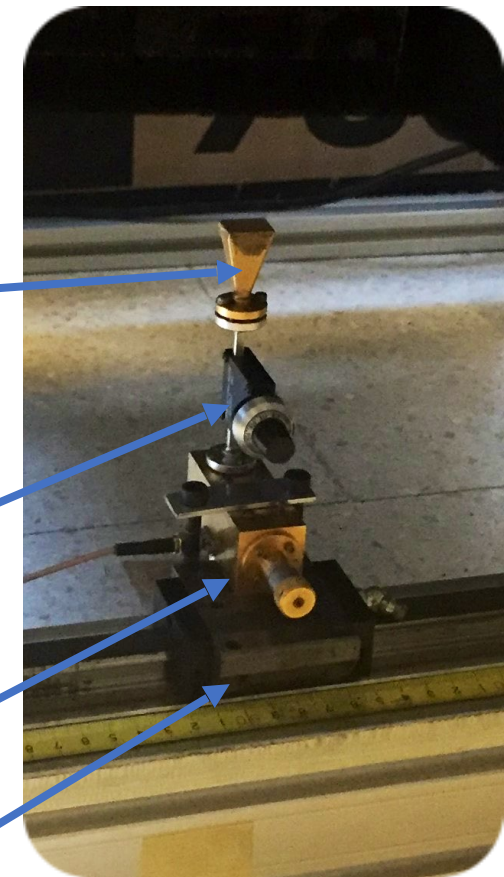


Pyramidal
horn 25 dB
WR08

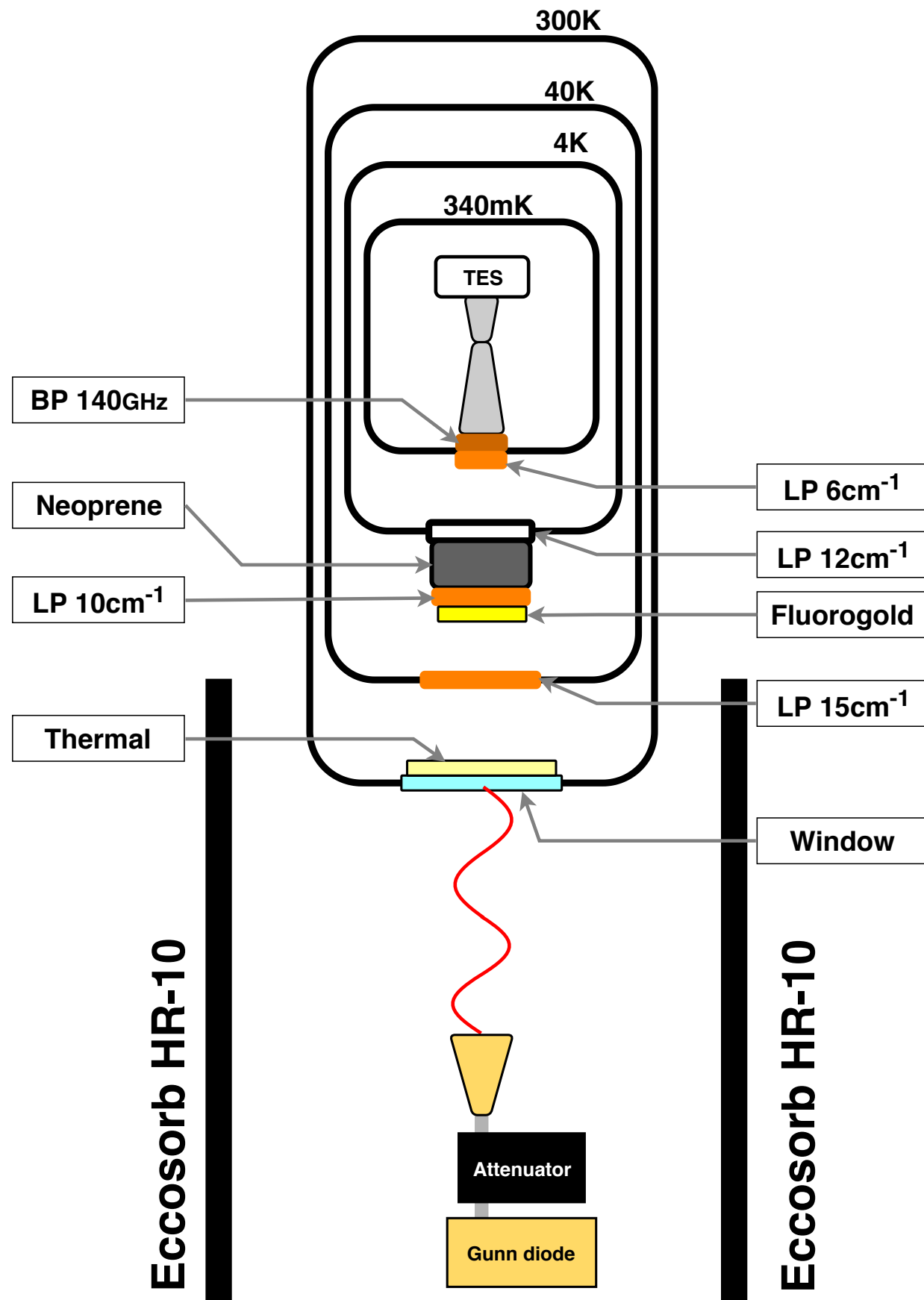
Variable
attenuator
WR08

Gunn oscillator
110-145 GHz

Linear stage



Testbed



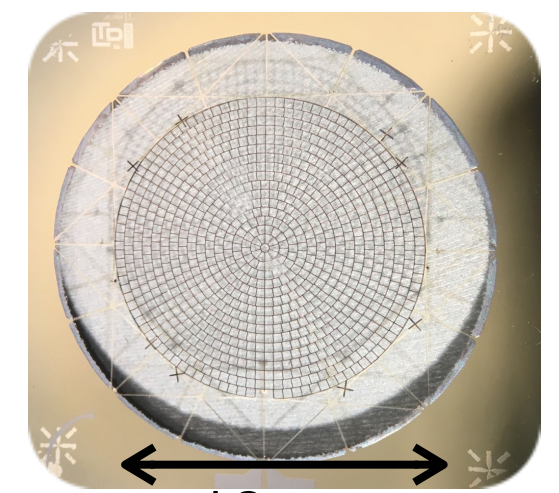
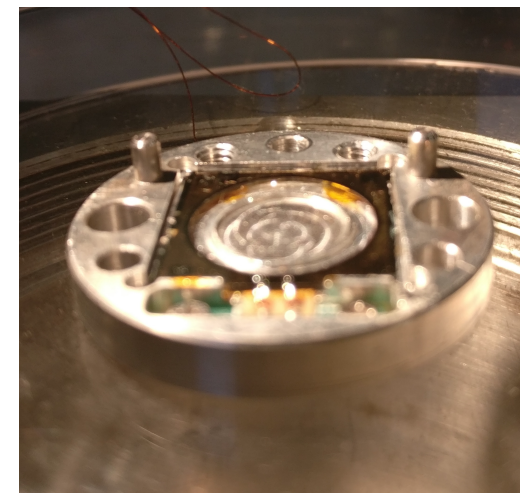
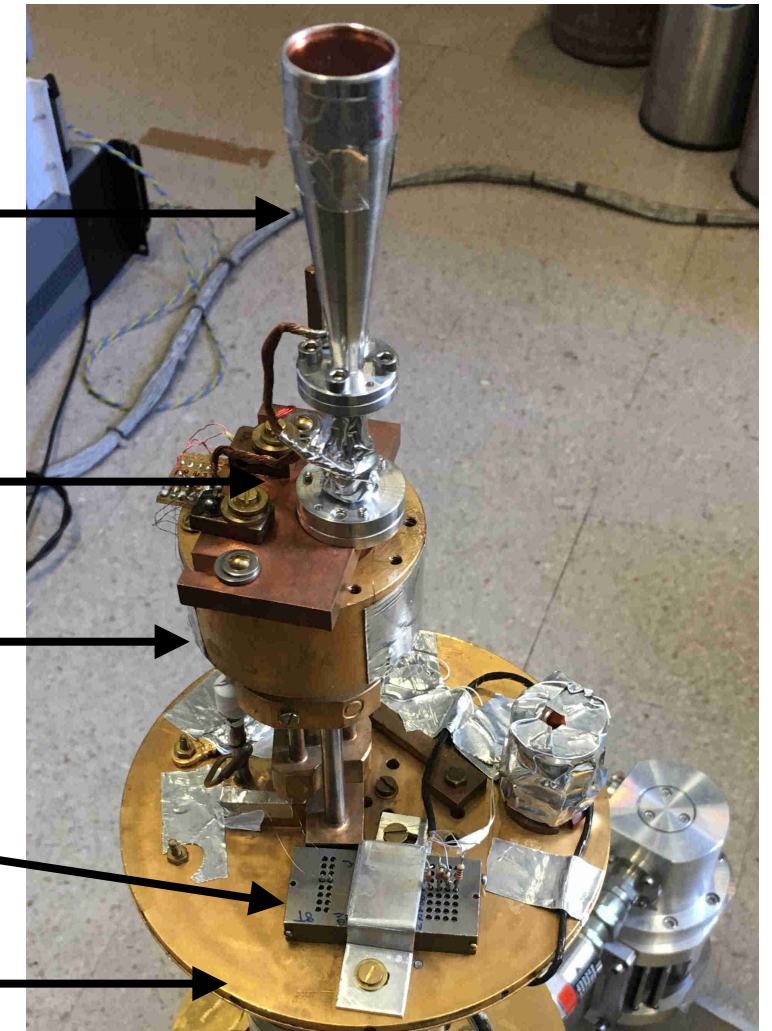
Feed structure & filter under test

bolometer

³He (0.3K) refrigerator

SQUID array

pulse-tube 2nd stage (4K)



POSTER 400 - B. Siri

Bismuth-Gold absorber for large area TES spiderweb bolometers

NDFs configuration

	Temperature [K]	Trasmissivity	Emissivity	Load [pW]
BP 4.7cm-1	0,3	0,9	0,01	<0,1
LP 6cm-1	0,3	0,9	0,01	<0,1
NDF	7,5	0,003	<0,01	~1,2
LP 12cm-1	7,5	0,9	0,01	<0,1
NDF	40	0,01	<0,01	<0,1
LP 15cm-1	40	0,95	0,01	<0,1
Thermal	300	0,99	<0,01	<0,1
Window	300	0,7	0,008	<0,1

**Stratospheric
background
~ 10pW**

**Total detector
background
~ 2pW**

Optical chain

Window
Thermal filter

↕ 300K

LP 15cm-1
NDF

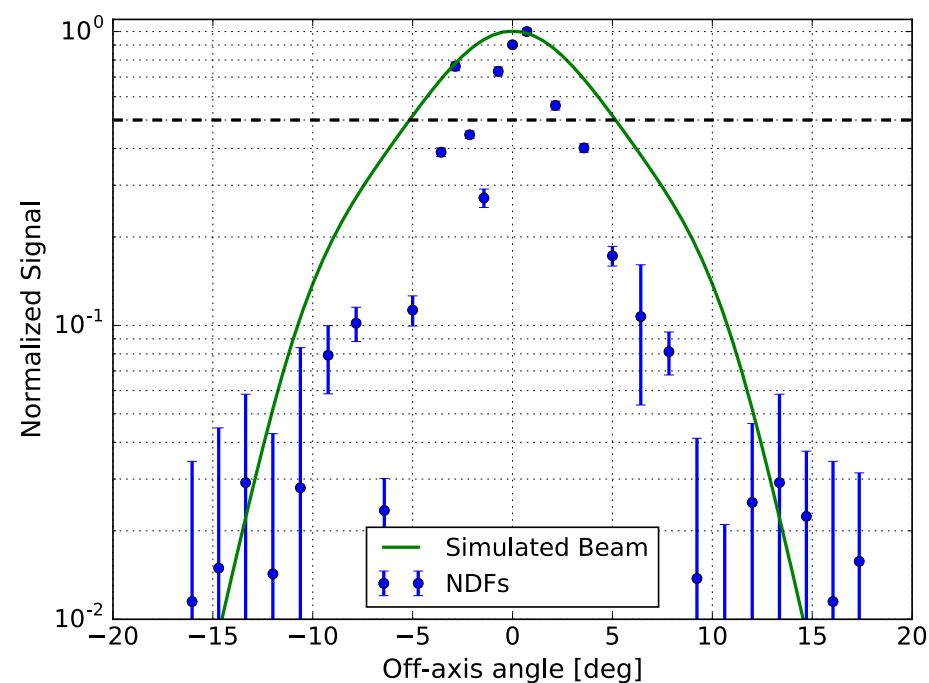
↕ 40K

LP 12cm-1
NDF

↕ 4K

LP 6cm-1
BP 5cm-1

↕ 0.3K



NDFs configuration

	Temperature [K]	Trasmissivity	Emissivity	Load [pW]
BP 4.7cm-1	0,3	0,9	0,01	<0,1
LP 6cm-1	0,3	0,9	0,01	<0,1
NDF	7,5	0,003	<0,01	~1,2
LP 12cm-1	7,5	0,9	0,01	<0,1
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Thermal	300	0,99	<0,01	<0,1
Window	300	0,7	0,008	<0,1

Stratospheric background
~ 10pW

Total detector background
~ 2pW

Optical chain

Window
Thermal filter

↕ 300K

LP 15cm-1
NDF

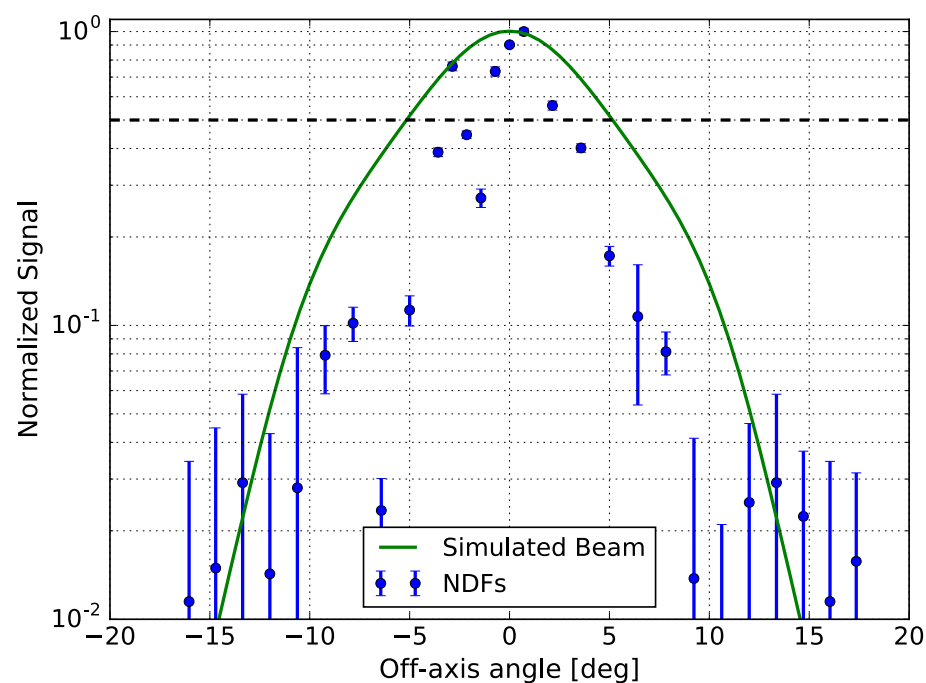
↕ 40K

LP 12cm-1
NDF

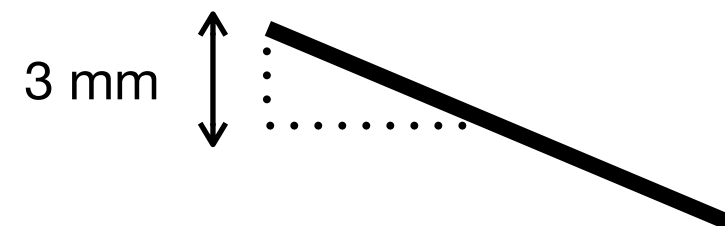
↕ 4K

LP 6cm-1
BP 5cm-1

↕ 0.3K



140 GHz → ~ 2 mm



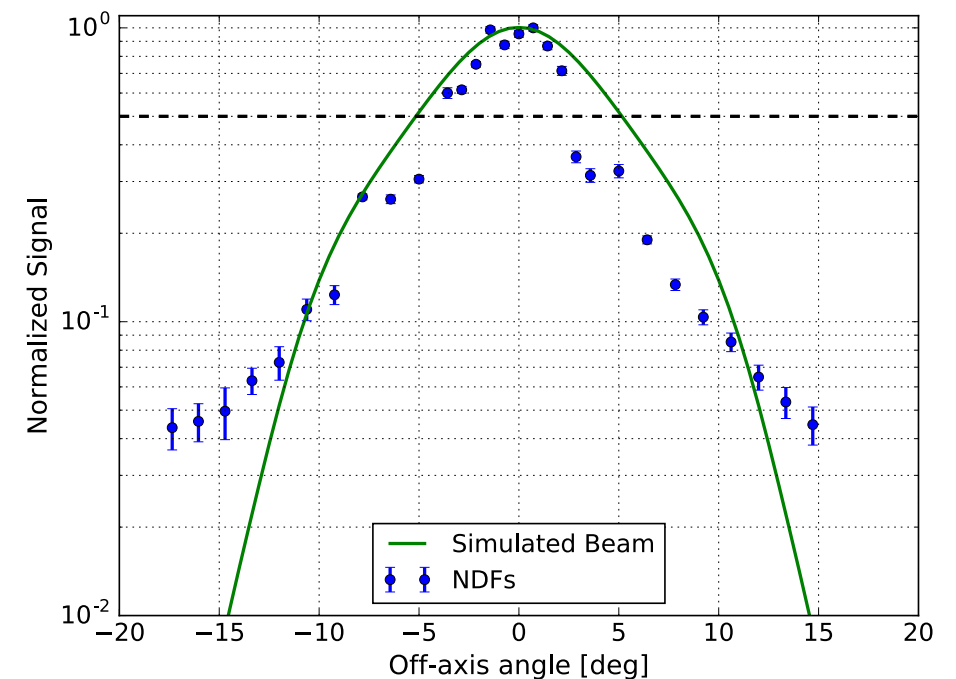
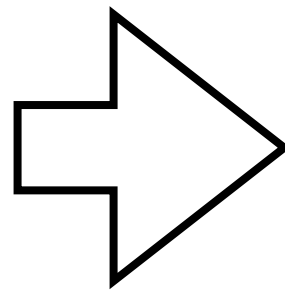
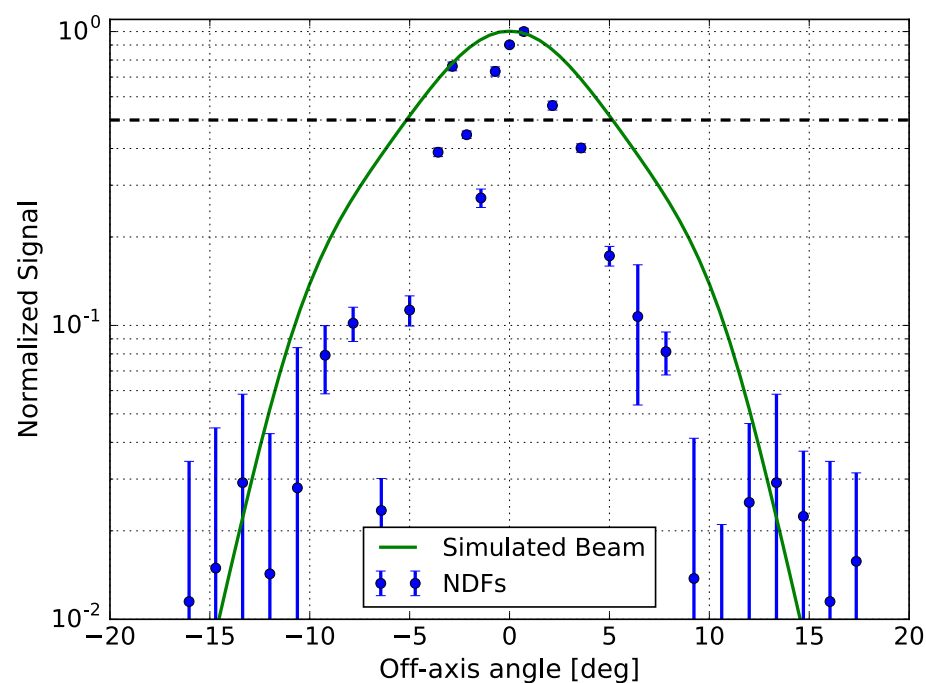
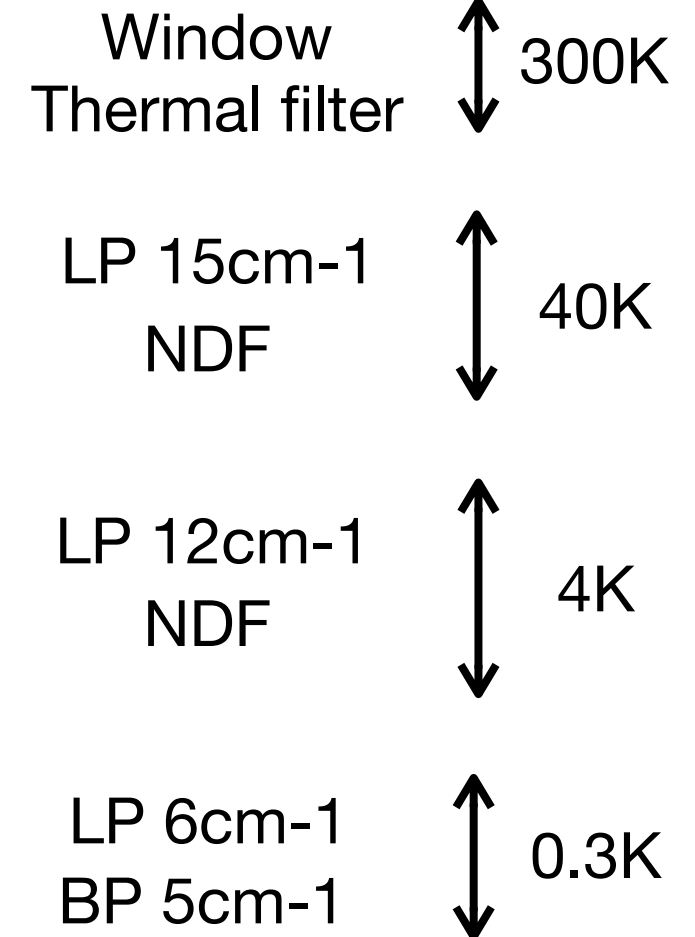
NDFs configuration

	Temperature [K]	Trasmissivity	Emissivity	Load [pW]
BP 4.7cm-1	0,3	0,9	0,01	<0,1
LP 6cm-1	0,3	0,9	0,01	<0,1
NDF	7,5	0,003	<0,01	~1,2
LP 12cm-1	7,5	0,9	0,01	<0,1
NDF	40	0,01	<0,01	<0,1
LP 15cm-1	40	0,95	0,01	<0,1
Thermal	300	0,99	<0,01	<0,1
Window	300	0,7	0,008	<0,1

Stratospheric background
~ 10pW

Total detector background
~ 2pW

Optical chain



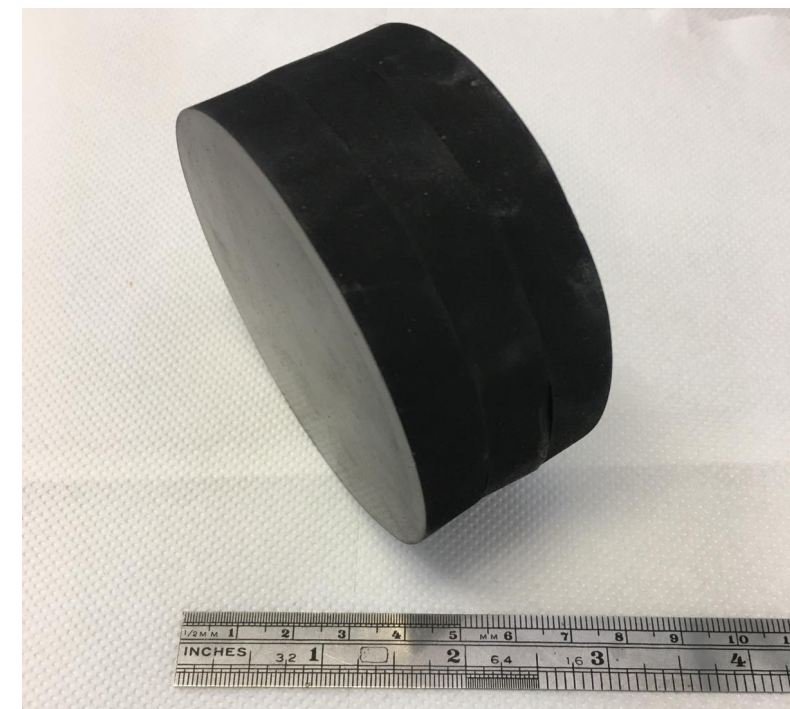
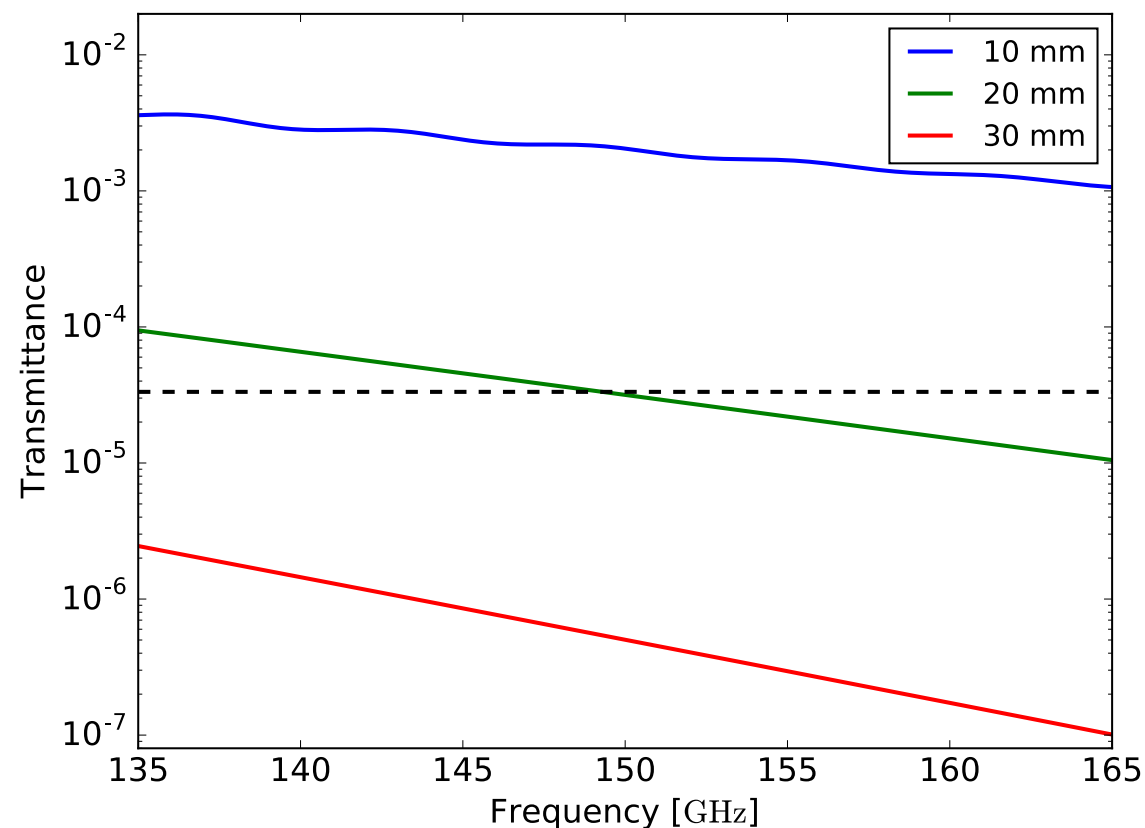
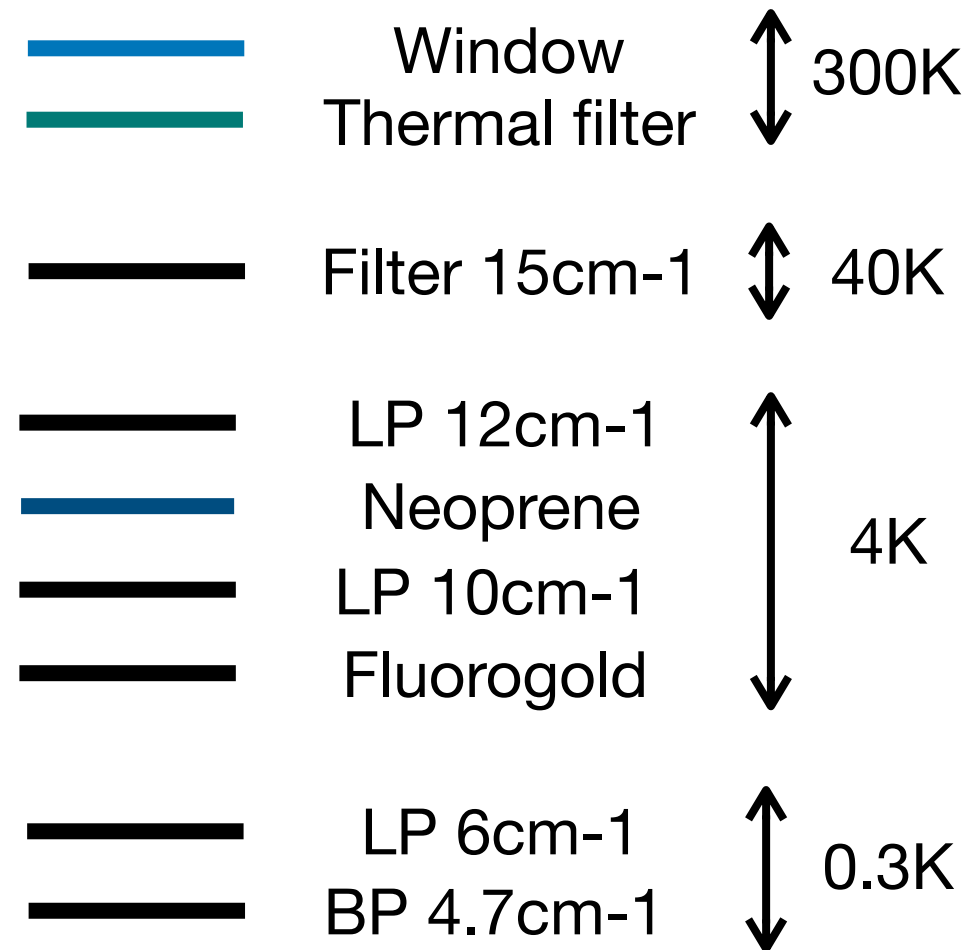
Neoprene configuration

	Temperature [K]	Trasmissivity	Emissivity	Load [pW]
BP 4.7cm-1	0,3	0,9	0,01	<0,1
LP 6cm-1	0,3	0,9	0,01	<0,1
LP 12cm-1	7,5	0,9	0,01	1,2
Neoprene	7,5	$\sim 10^{-6}$	0,13	14
Fluorogold	7,5	0,85	0,02	<0,1
LP 10cm-1	7,5	0,95	0,01	<0,1
LP 15cm-1	40	0,95	0,01	<0,1
Thermal	300	0,99	<0,01	<0,1
Window	300	0,7	0,008	<0,1

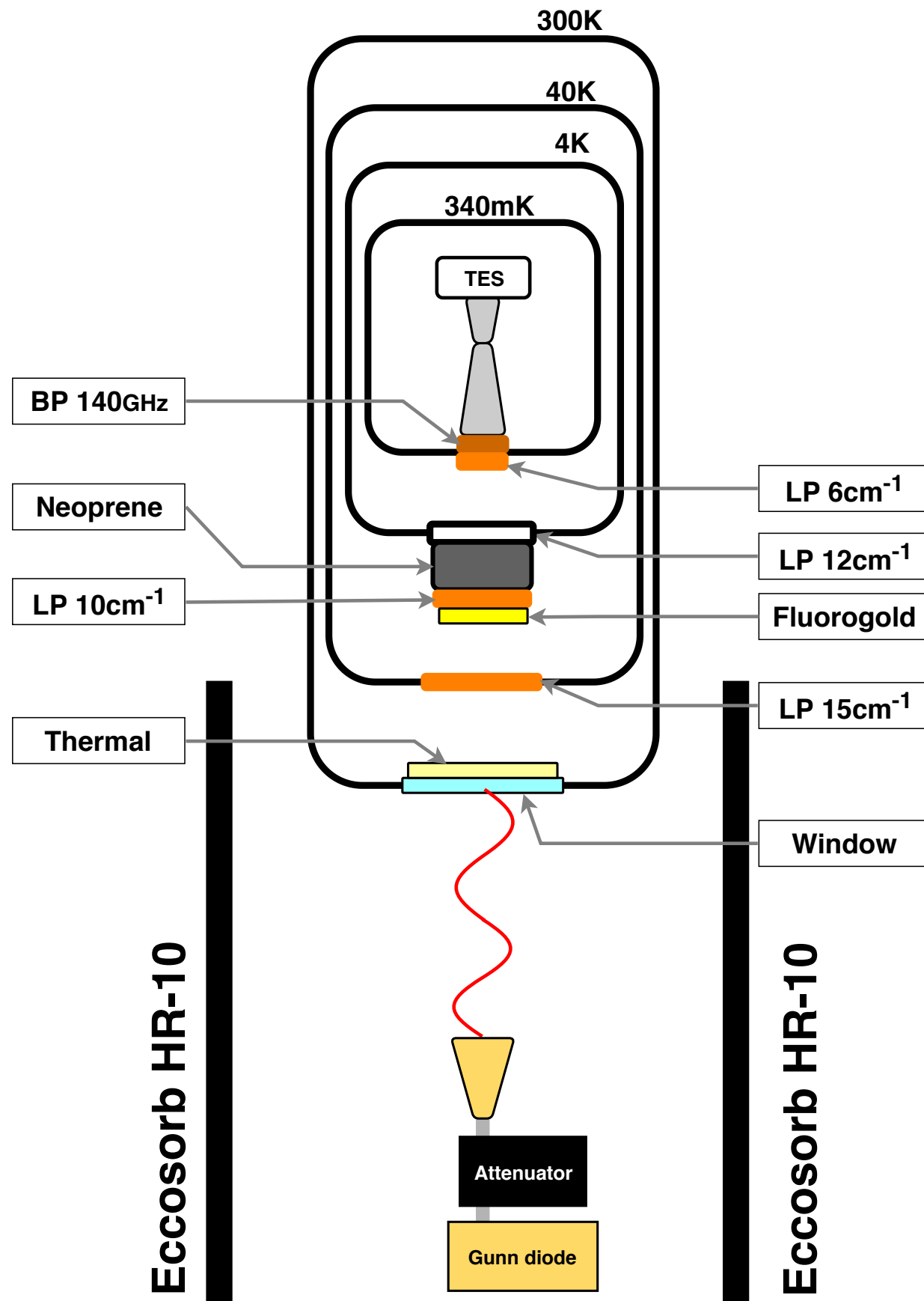
Stratospheric background
~ 10pW

Total detector background
~ 16pW

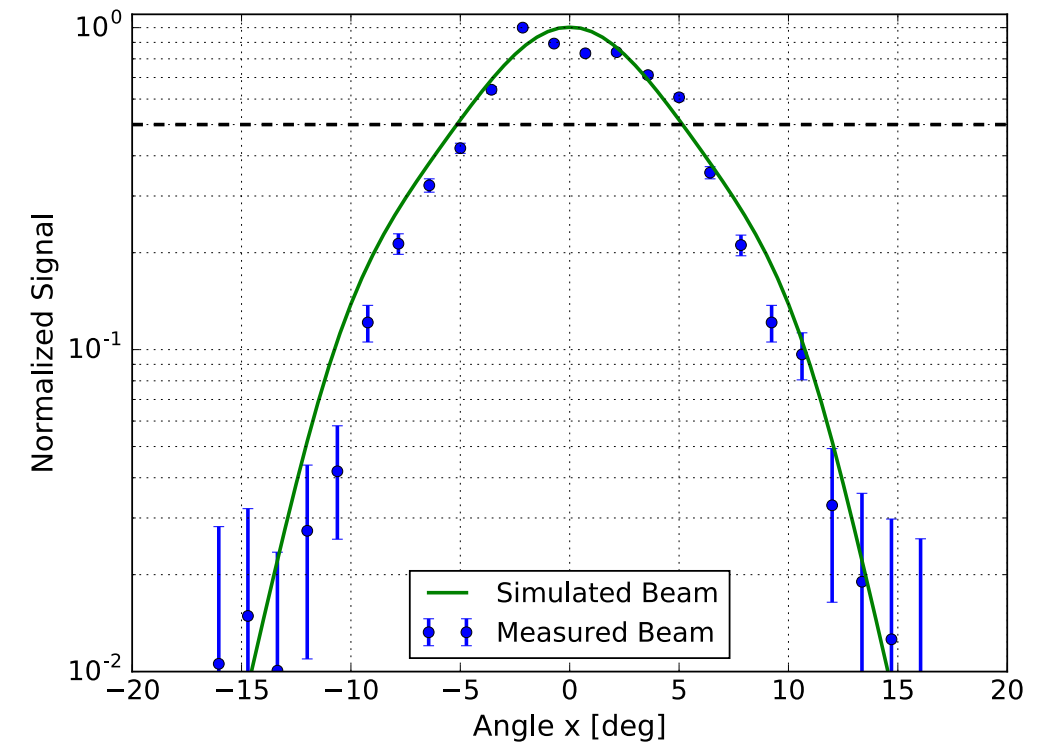
Optical chain



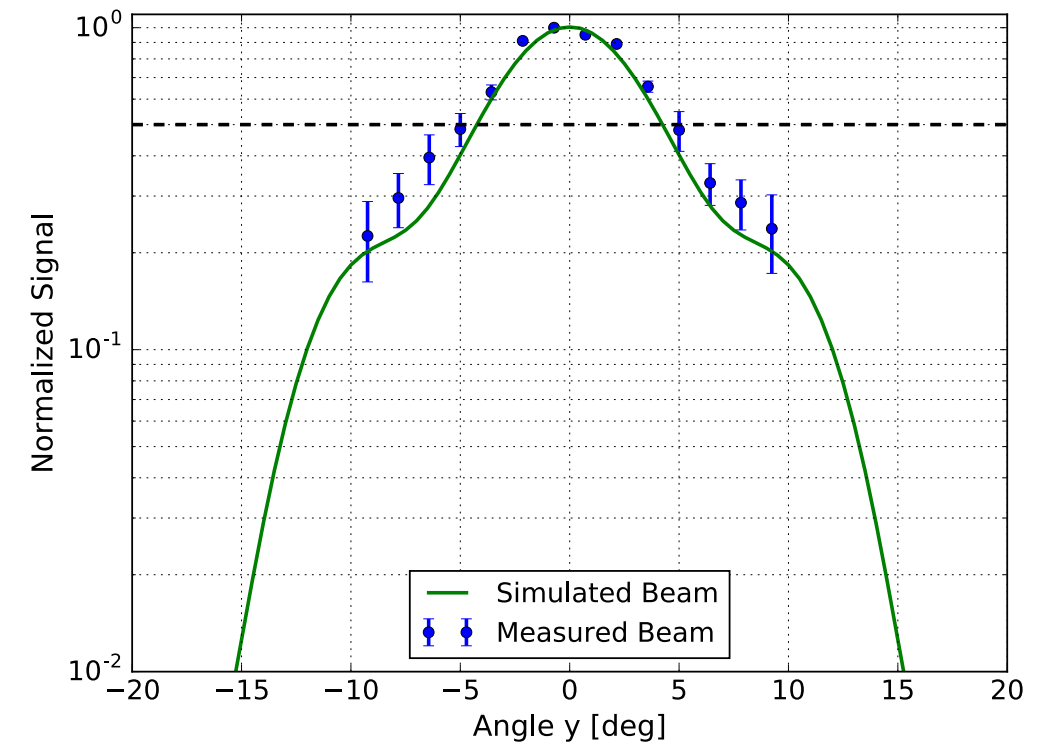
Neoprene configuration



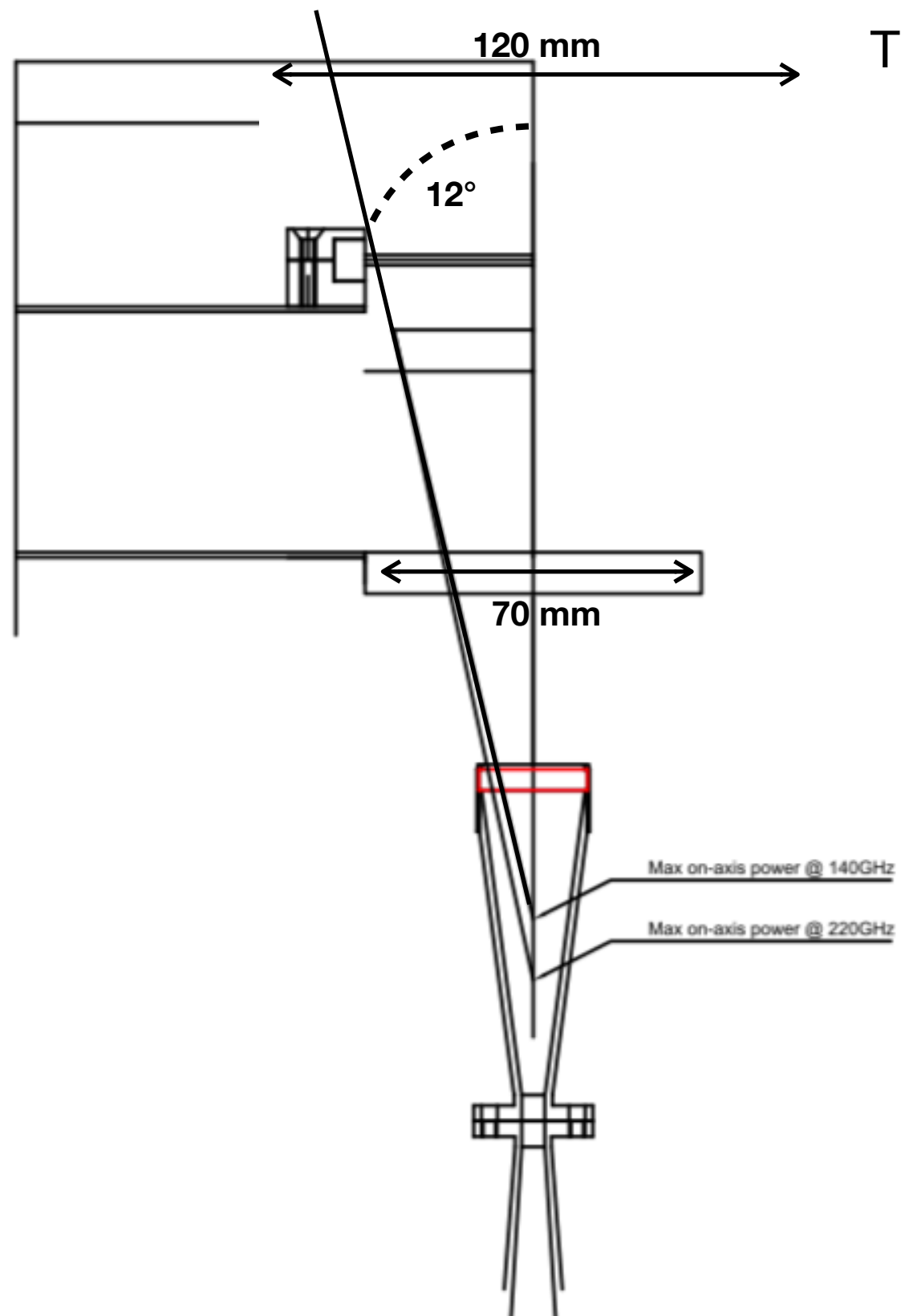
Cross-polar



Co-polar



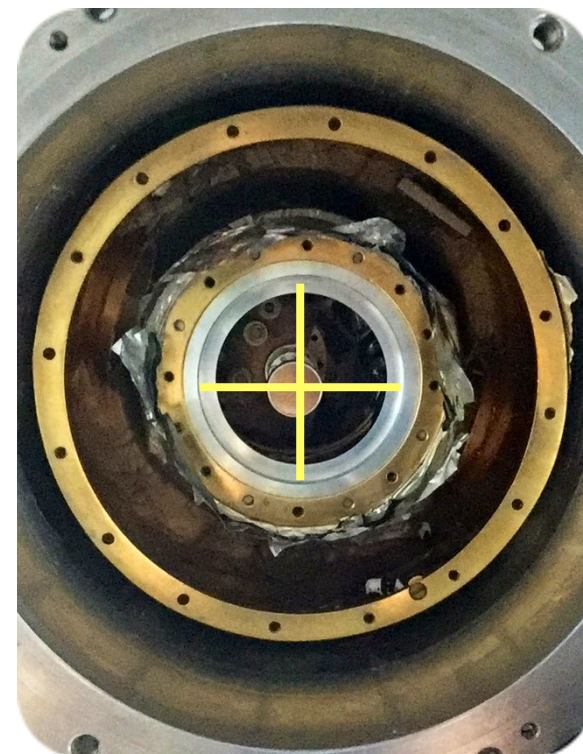
Beam measurements



The criticality of this system is represented by its free optical throughput.

- Beam truncation
- Different power distribution

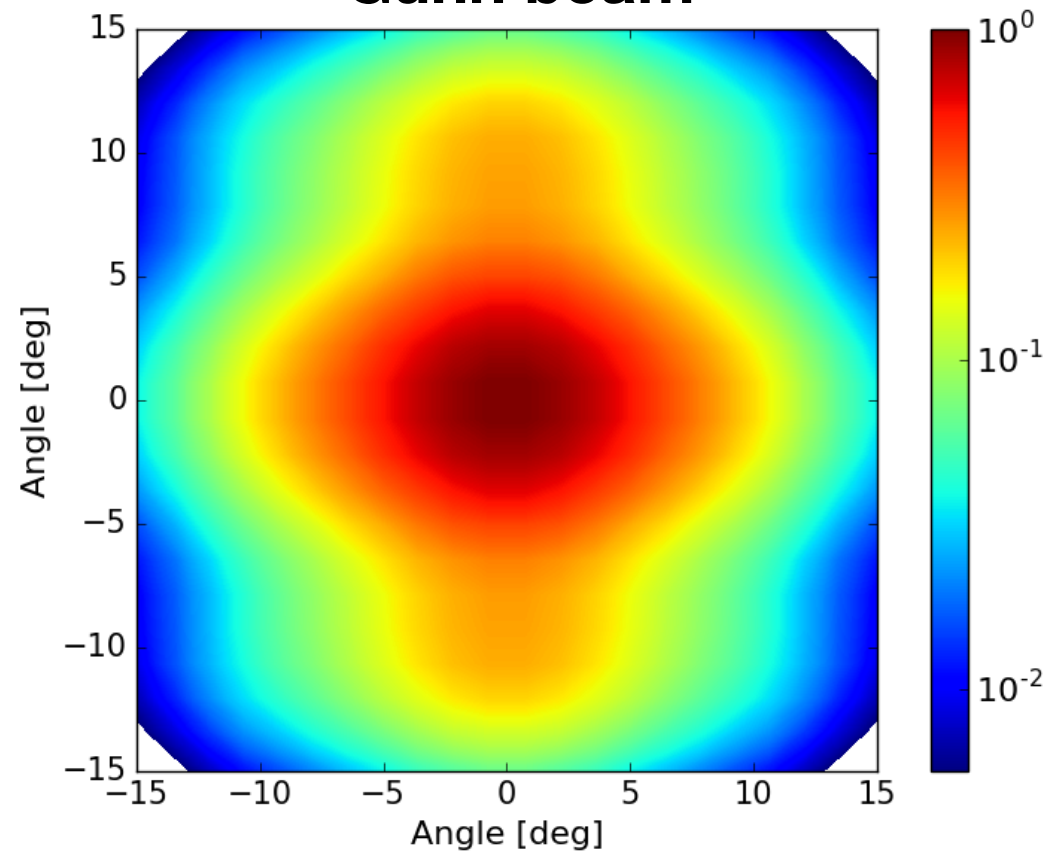
Main beam — —> Yes
Side lobes — —> Impossible!



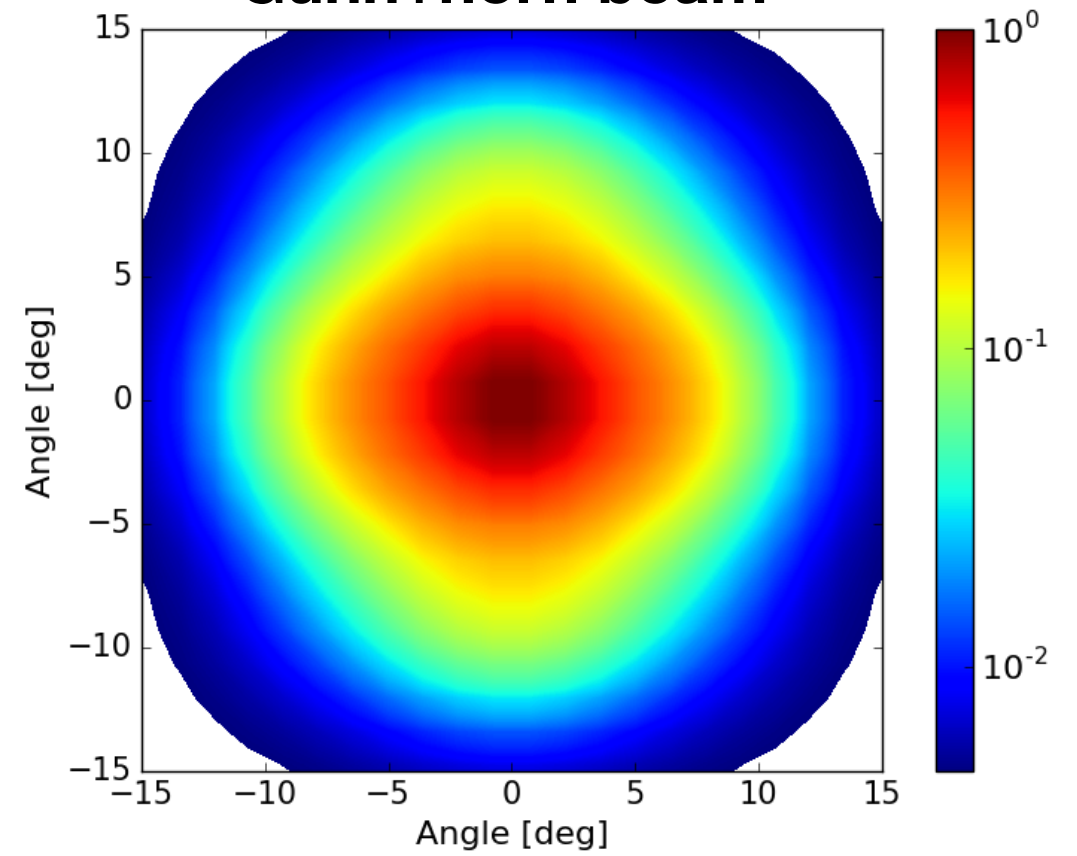
Asymmetry
in vignetting

2D beam map

Gunn beam

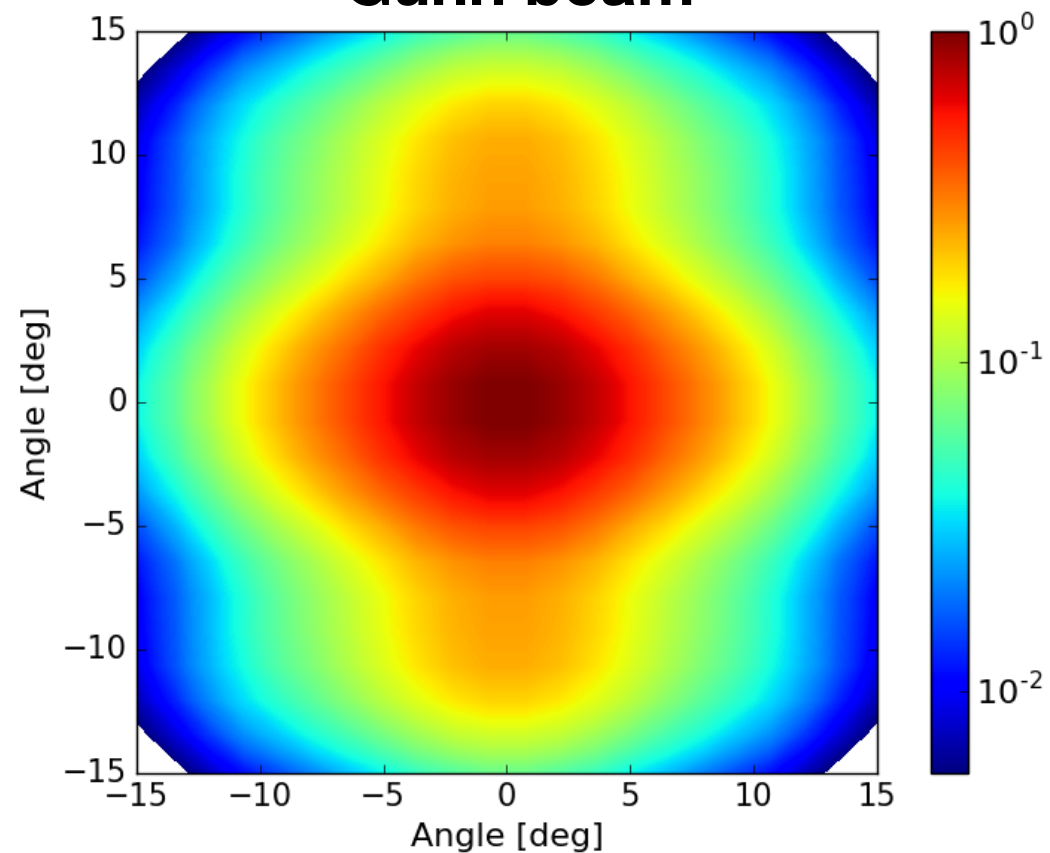


Gunn+horn beam

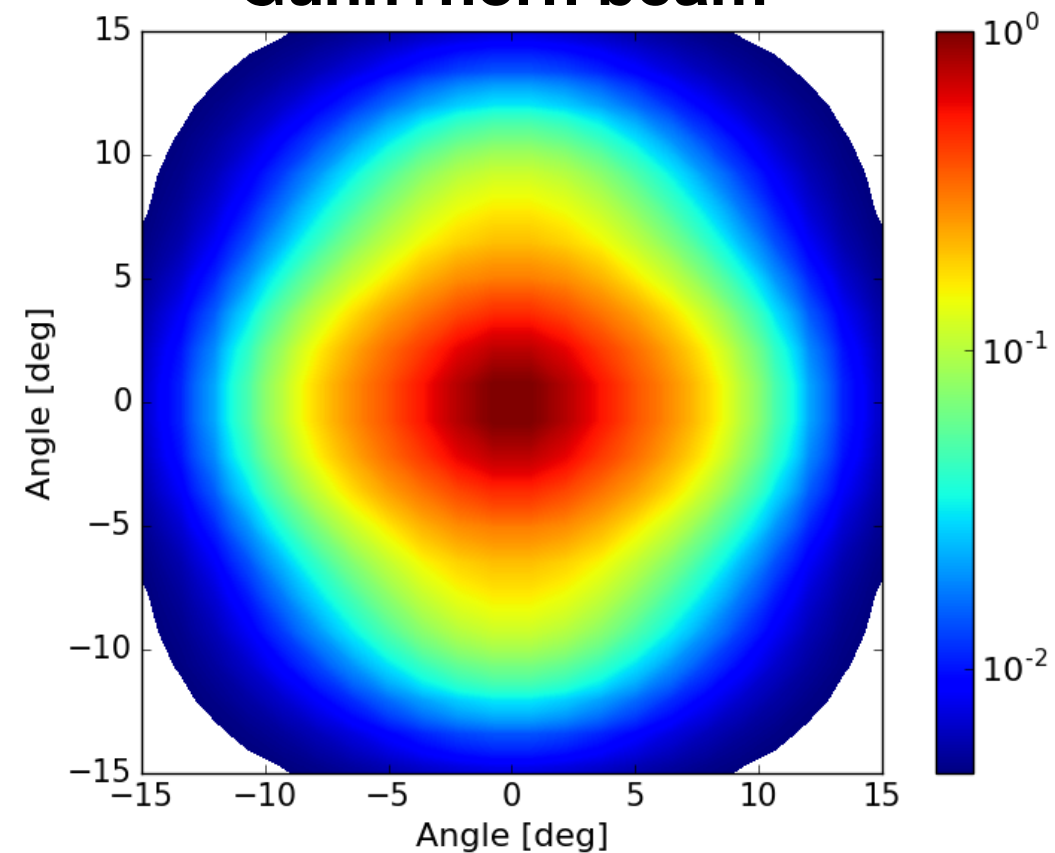


2D beam map

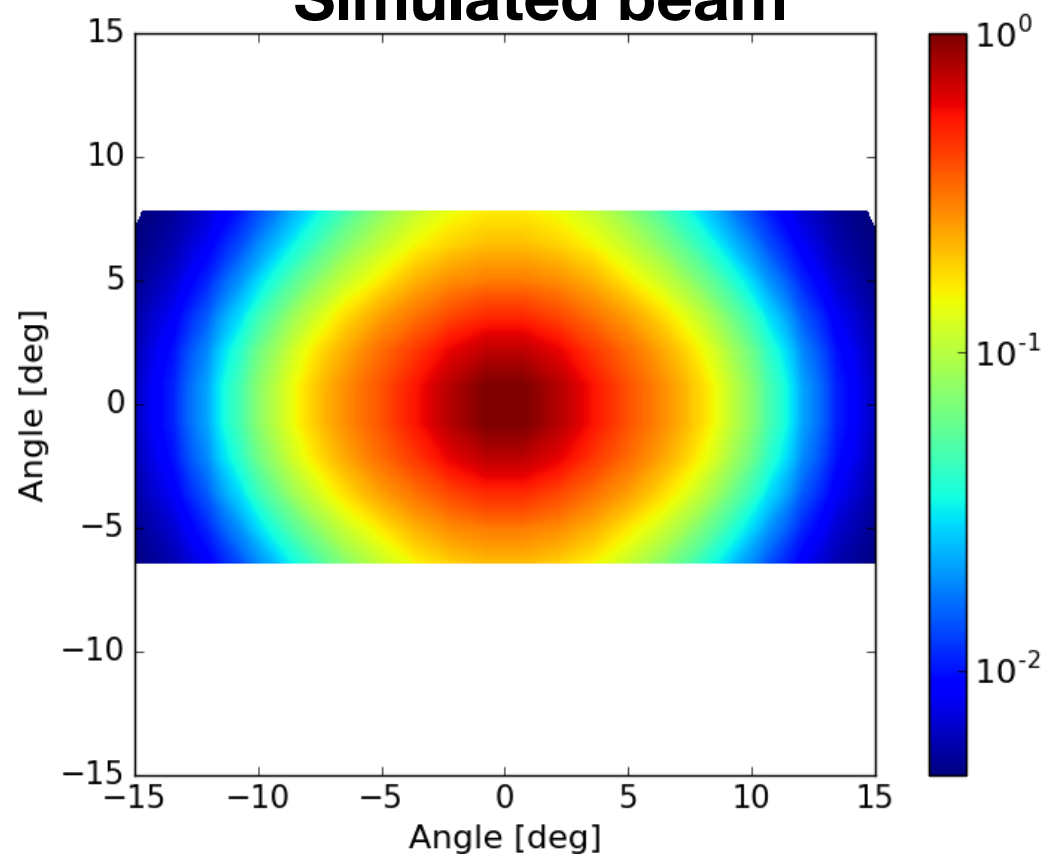
Gunn beam



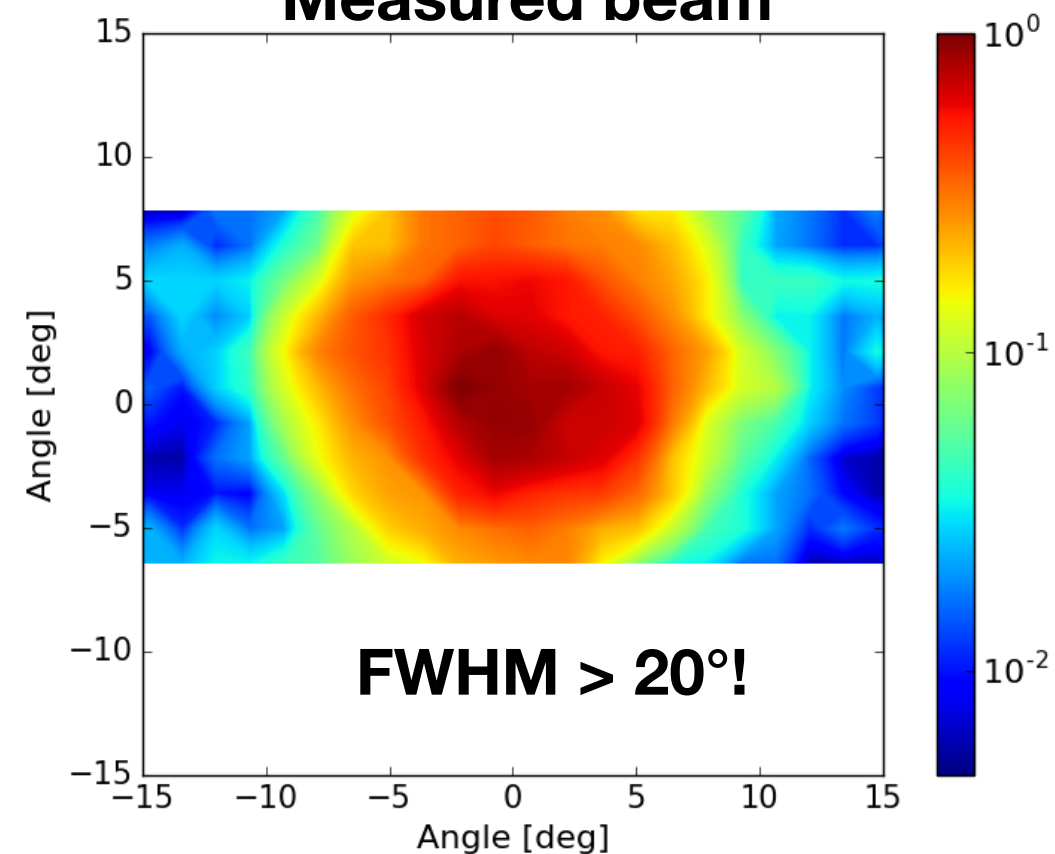
Gunn+horn beam



Simulated beam



Measured beam



Conclusions

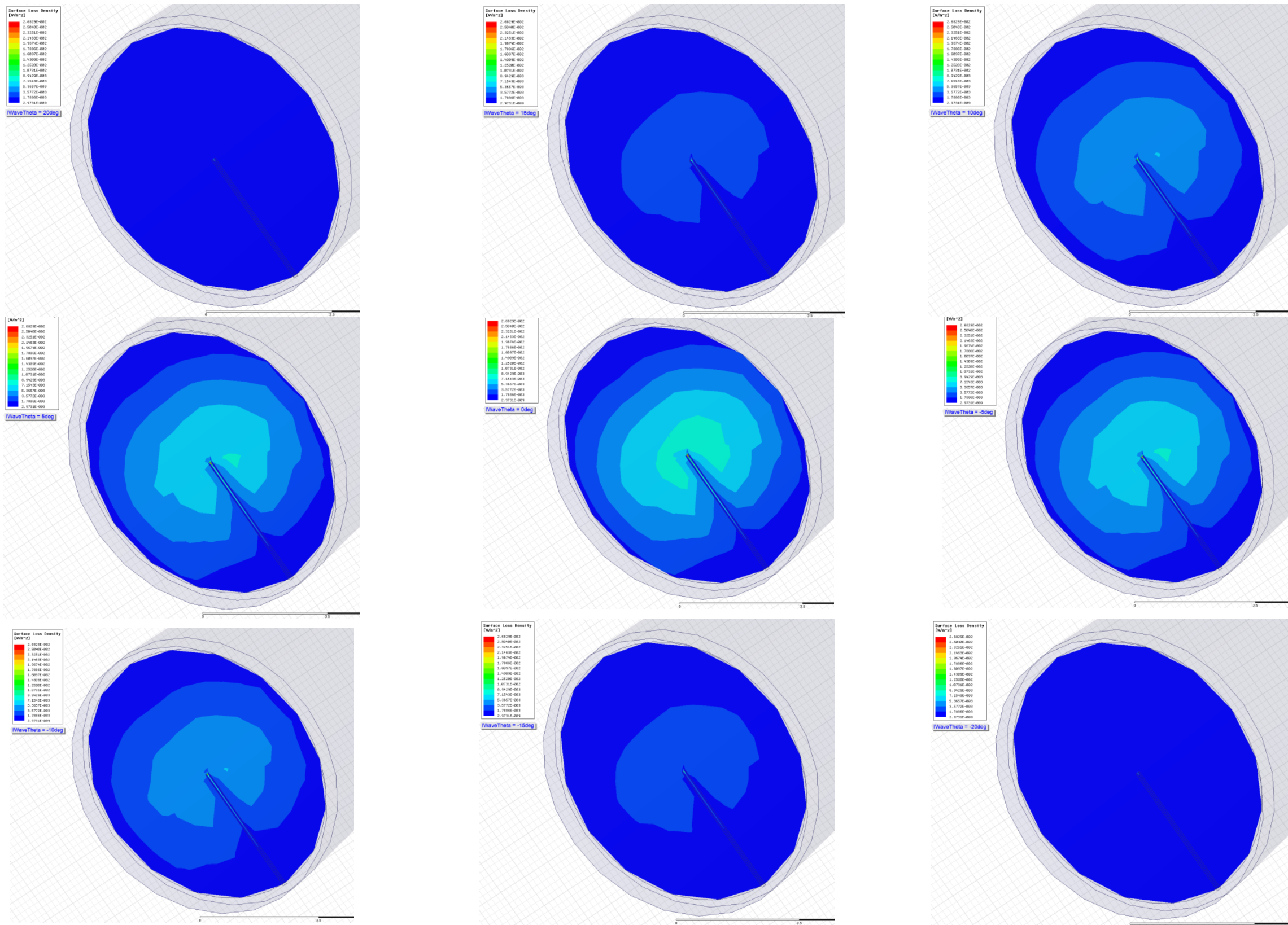
- The feedhorn assembly has reproduced the expected circular symmetry at room temperature.
- The facilities developed produces repeatable results in controlled conditions.
- Many systematic effects have been understood and controlled.
- Good beam shape measured in a cryogenic environment. Vignetting from the filters.
- Measurements will be repeated in the SWIPE cryostat which has a very large optical window and filters set

Feedback from simulations

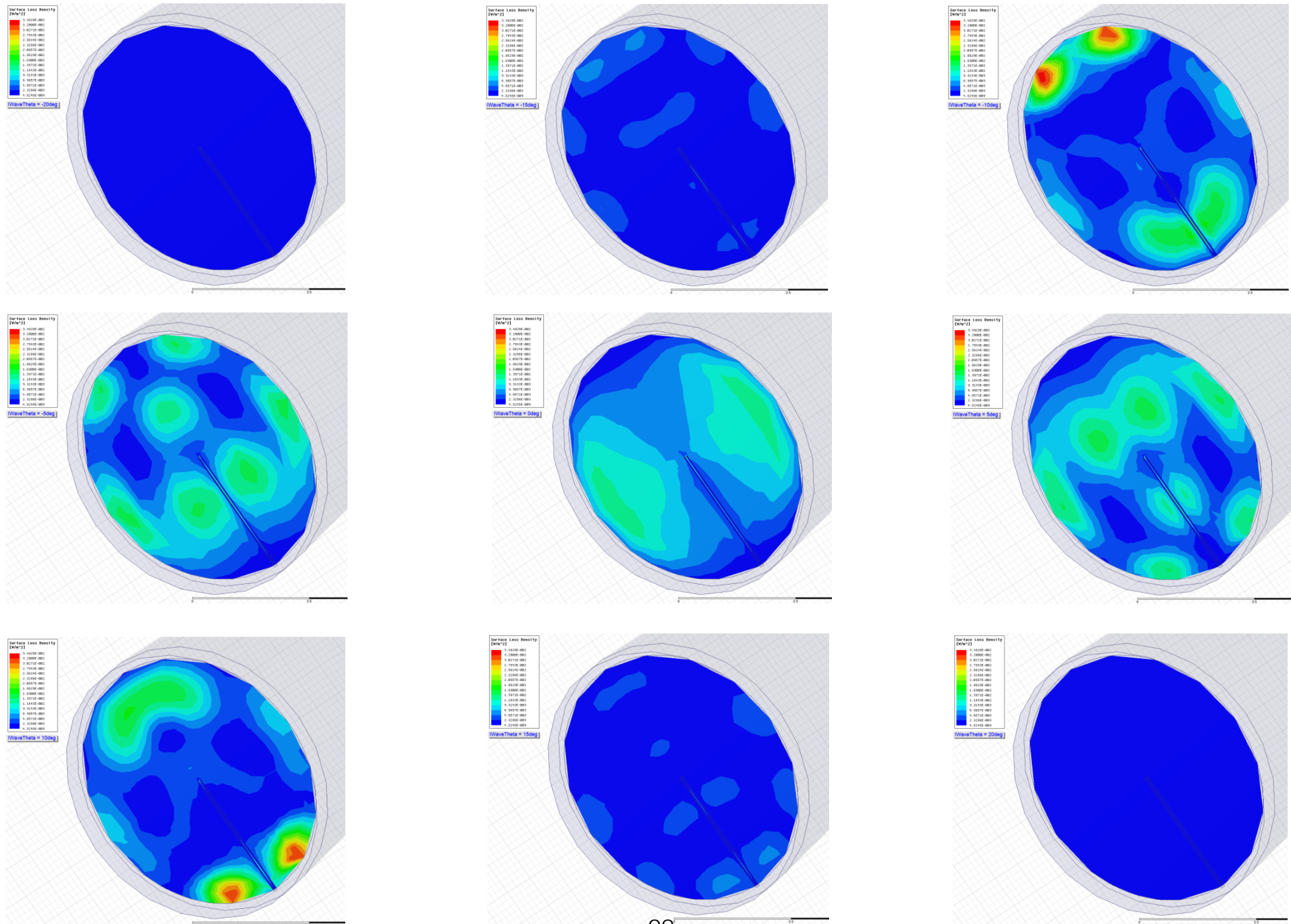
New simulation setup featuring:

- Direct illumination of horn aperture from far field (i.e. linear polarized, incident plane wave excitation with sweeps over θ and ϕ) – old setup was reverse path from the waveguide and made large use of symmetry assumptions to speed-up calculations.
- Full field propagation through horn, waveguide, flare, cavity, to evaluate flux distribution over the absorber with proper phase delays between the modes (determined by incidence angle at the aperture)
- Absorber still modeled as a planar, position-dependent impedance with conductive tracks from thermistor to readout
- Possibility to evaluate power leakage from the border
- Needs significant additional processing power, implying a few tradeoffs in numerical accuracy and parameter resolution

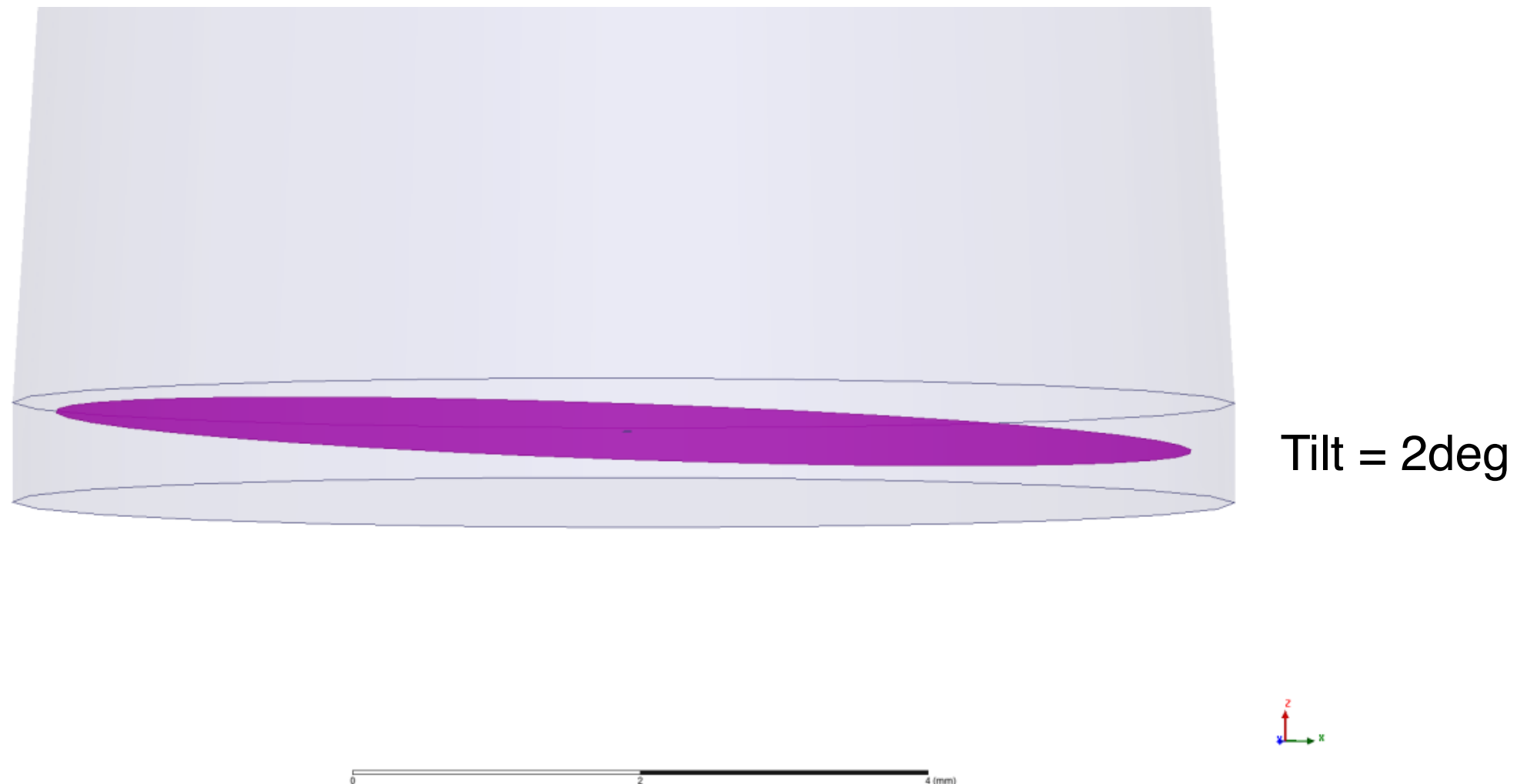
Absorber illumination vs incidence angle – single mode



Absorber illumination vs incidence angle – multi-mode



Test #1 – Absorber position



- Seems unlikely given the positioning method employed by manufacturer
- Needs macroscopic tilt/deformation to generate even the smallest observable feature in the beam.
- Basically ruled out as the dominant form of non-ideality.