SPIDER, BICEP, Keck Optics: Lessons for Space Missions

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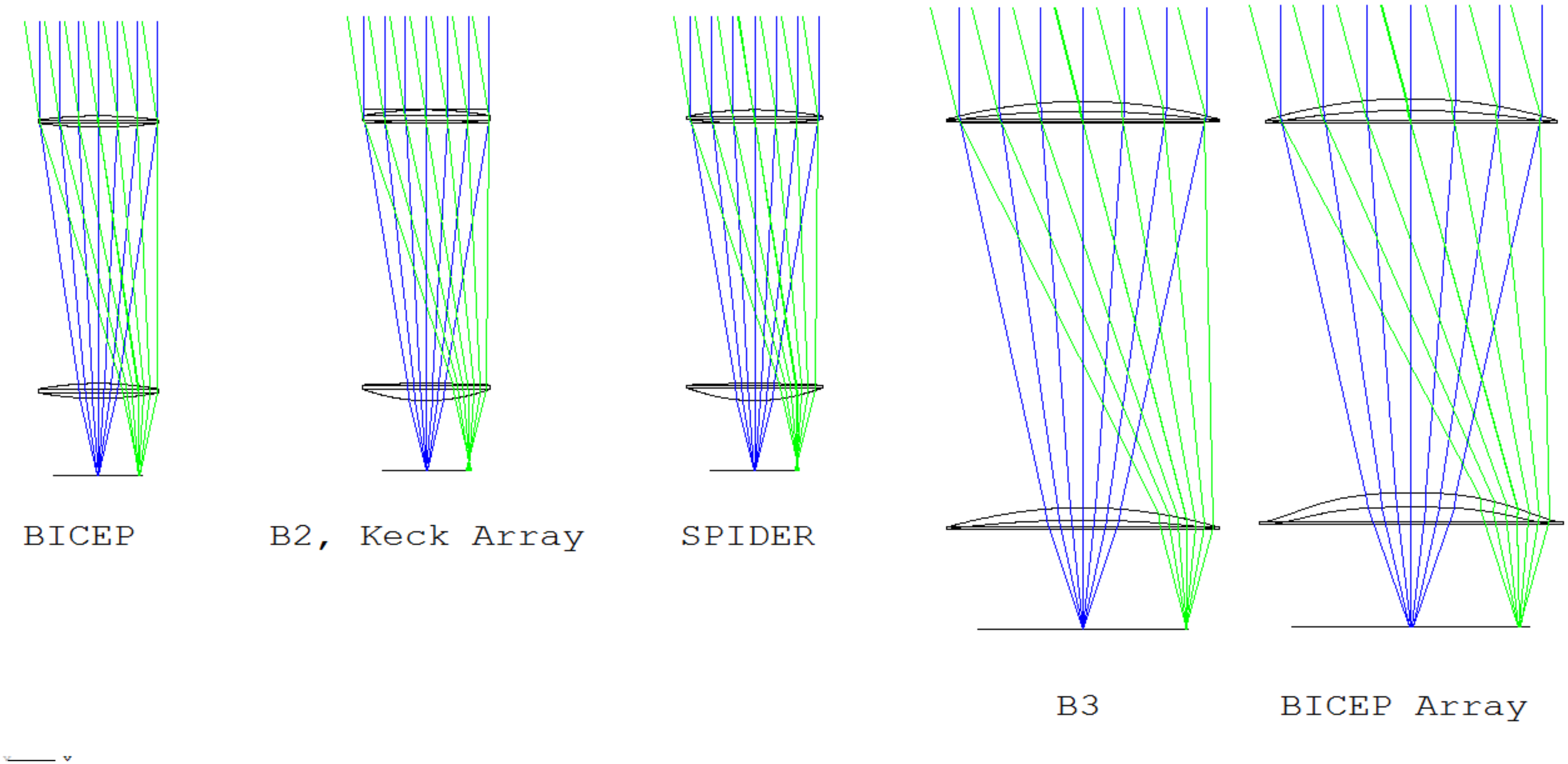
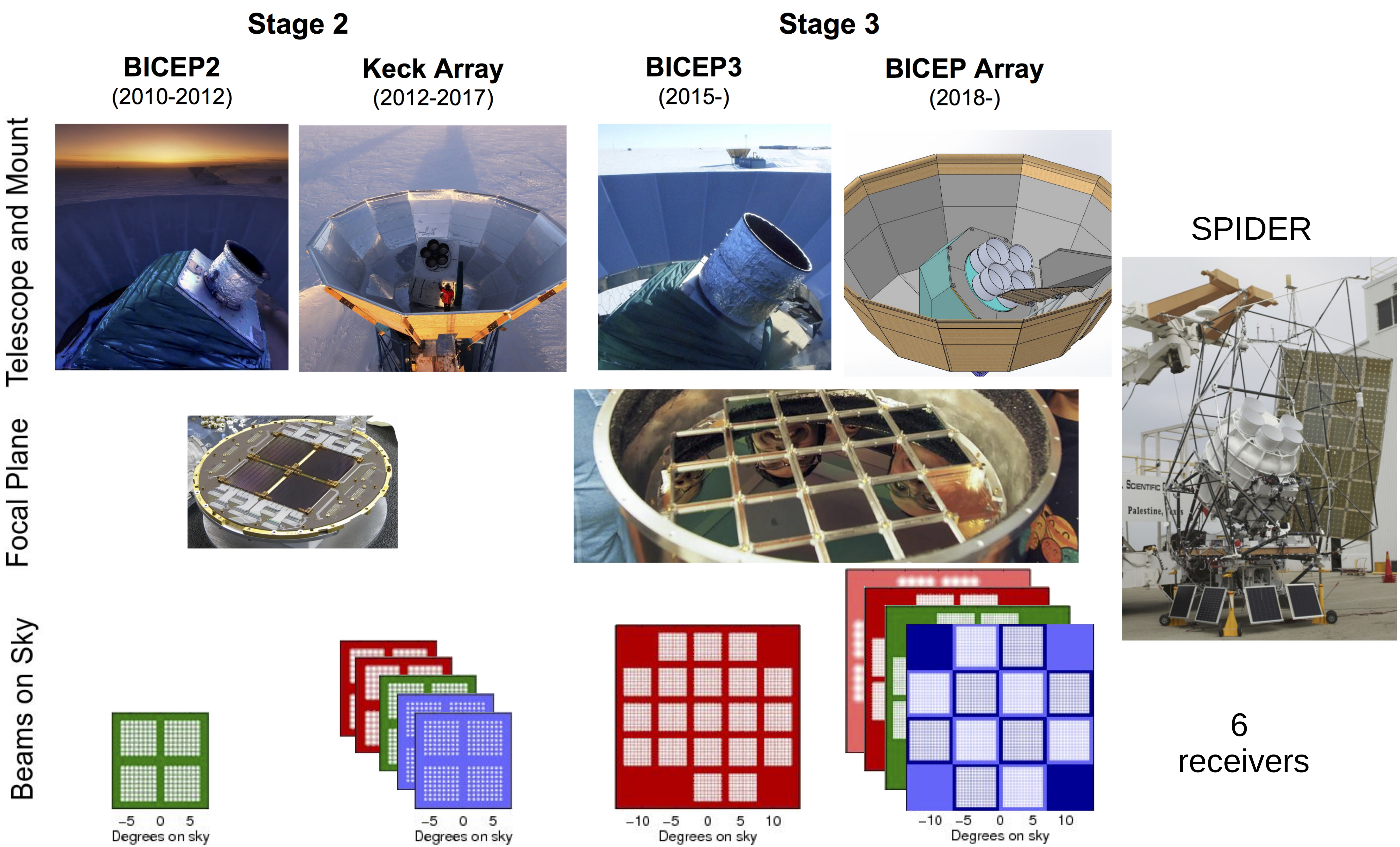
B-Modes from Space
Berkeley

BICEP/Keck/SPIDER: Ground and Sub-orbital Cryogenic Refractors



Filters and forebaffles not shown


Stage 2
Stage 3
BICEP2
(2010-2012)
Keck Array
(2012-2017)
BICEP3
(2015-)
BICEP Array
(2018-)
SPIDER
Telescope and Mount
Focal Plane
Beams on Sky
–5 0 5
Degrees on sky
–5 0 5
Degrees on sky
–10 –5 0 5 10
Degrees on sky
–10 –5 0 5 10
Degrees on sky
6
receivers

B/K/S Optics Summary

	BICEP	BICEP2	SPIDER	Keck Array	BICEP3	BICEP Arr.
Aperture	25cm	26.4cm	27cm	26.4cm	52cm	55cm
f-ratio, cent	2.28	2.32	2.16	2.3	1.60	1.52
window	Zotefoam PPA-30	Zotefoam PPA-30	thin UHMWPE	Zotefoam HD-30	thick HDPE	TBD (thin)
lens mat'l	HDPE	HDPE	HDPE	HDPE	alumina	alumina
Filts, 50+K	PTFE, Nylon	PTFE, Nylon	Ade shaders; 30K hot pressed	PTFE, Nylon	HD-30, alumina	HD-30, alumina
Filts, 4-K	Nylon	Nylon	hot pressed (4 and 1.6K), Nylon	Nylon	Nylon	Nylon
Forebaffle	absorptive	absorptive	reflective	absorptive	absorptive	absorptive
Notes	stop, baffles, lenses ~4K	stop, baffles, lenses ~4K	stop, baffles 1.6K, lenses ~4K	stop, baffles, lenses ~4K	stop, baffles, lenses ~4K	stop, baffles, lenses ~4K

Optics Issues for Refractors (a few examples)

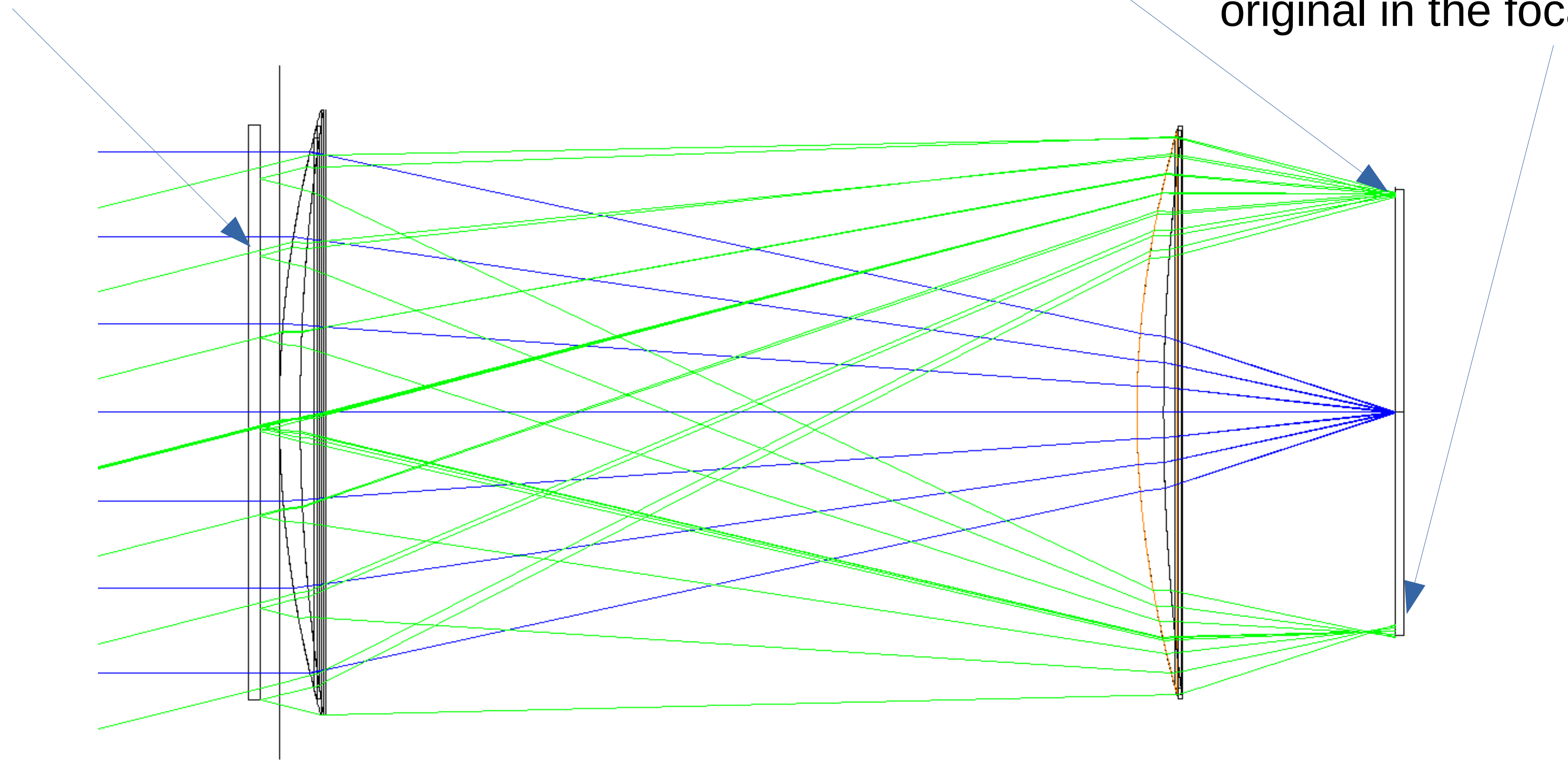
- Reflection off optical surfaces
  - ghost images both in focus and out of focus
  - extended wings on beam profiles
  - increased semi-uniform loading
- Scattering off optical surfaces and absorbers
  - test at zenith: decreased loading with forebaffle removed
  - excess power in far wings of beam profiles
- Birefringence and other undesired asymmetries
  - mesh filter fab issues: bridges between islands systematically in one direction
  - plastic dielectric
- Optical element fragility: *ordinary, mundane engineering but still important*
  - alumina is strong but brittle
  - mesh filters on 3.5µm film are fragile
  - many AR coatings are susceptible to damage, or their bond is

In-focus ghosts

some radiation reflects off detector plane, perhaps a few percent

then some percent of that gets reflected back off planar filters upstream of objective

and generates a ghost image opposite the original in the focal plane

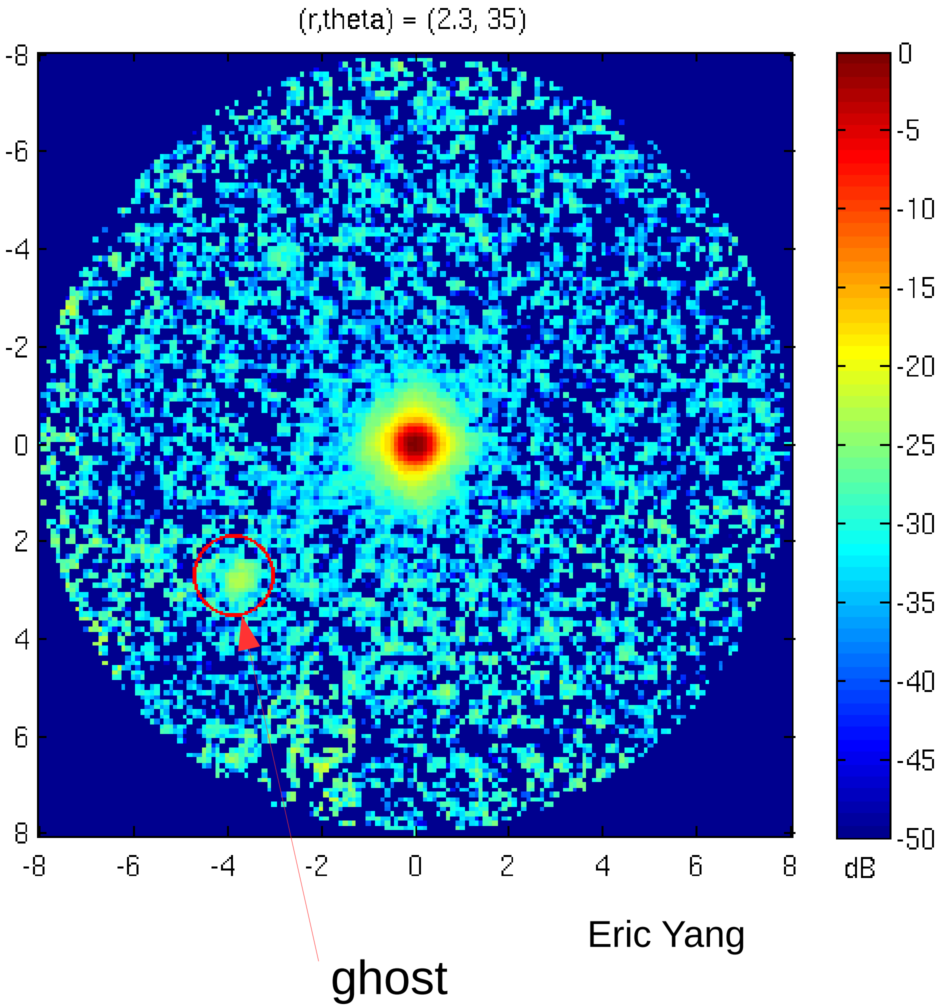


standard trick of tilting the filter(s) not always practical:

- space constraints, esp. with wide-field telescopes
- shifting of bandpass with tilt

BICEP3 Mesh Filters: Reflectivity

2016 beam map, 1 detector



Eric Yang

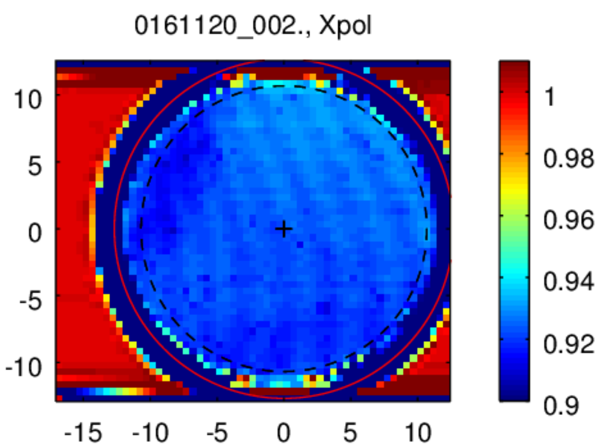
Seasons 2015/16: IR filters included 10 “mesh” filters: each few*0.1% in-band reflection (Ahmed, et al 2014) and some scattering

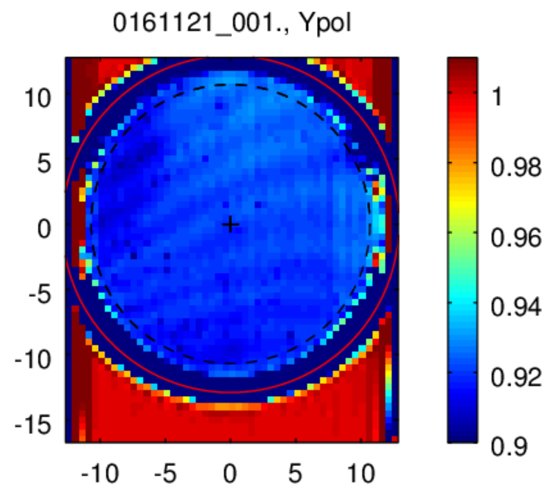
Season 2017+: Replaced mesh filters with stack of 0.125in Zotefoam HD-30 filters in manner of Choi, et al 2013

- Zotefoam great at scattering high-frequencies
- Nitrogen filling cells conducts heat, reducing the efficiency of a solid block for reducing IR loading
- Splitting foam into many thin layers avoids this problem
- Zotefoam almost perfectly transparent at the longer wavelengths, n~1.015 so surface reflections tiny
- bonus: better thermal performance

BICEP3 still has an AR-coated alumina filter and one mesh filter left.
Ghost analysis of 2017 season beam maps yet to be completed.

Mesh Filters: Transmission, Asymmetries and Quality Control



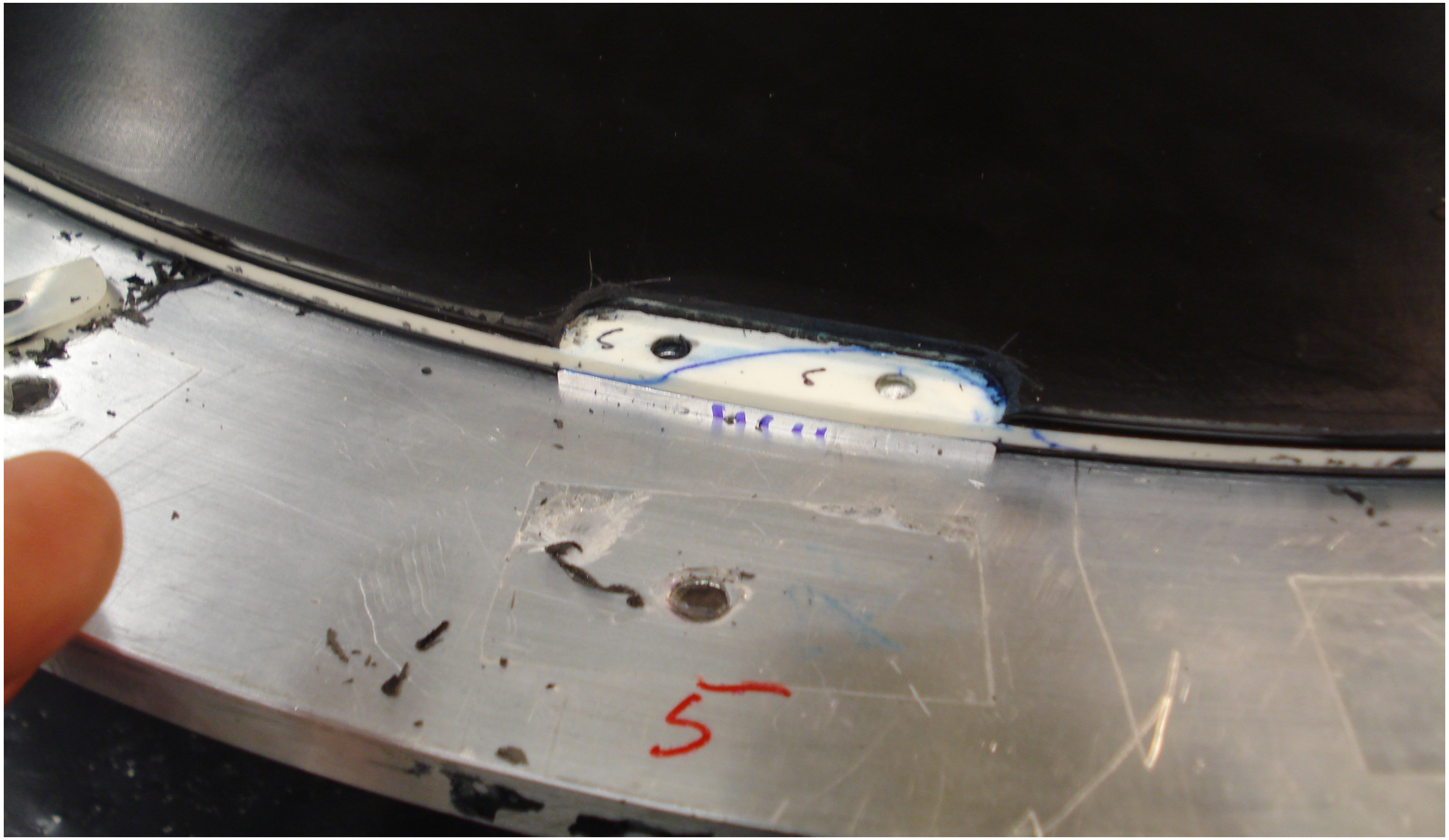


B3 2016 season 10-filter stack: mean transmission ~92%, one bad filter has low-transmission patch (loss of an extra ~1% in one area)

Mesh Filter Development:

- Current designs: best filters reflect a few tenths of percent in 95 GHz band, consistent with HFSS simulations
  - Some level of residual scattering, seen in forebaffle on/off tests brings loss per filter closer to 1%, *likely polarized, so particularly concerning*
- Yield not 100%, rejects' transmission not uniform, need full-aperture scans of every filter
- Some quality control problems in 2015 season batch, ***solved now***
  - polarization dependent transmission: aluminum bridges had preferred direction
- Multi-layer Zotefoam is superior for IR blocking at this point, but large-aperture filters constructed by laser ablation of aluminized film has great potential for other purposes

Damage during fab: alumina is hard and strong but concentrated tensile and shear stresses can cause cracks



Best explanation: differential expansion of aluminum mounting jig vs. alumina lens from mild heat generated during epoxy AR cure, causing positive radial stresses on the #8 mounting holes.

Lest you think they are too much trouble, there are some...

Advantages of Refractors

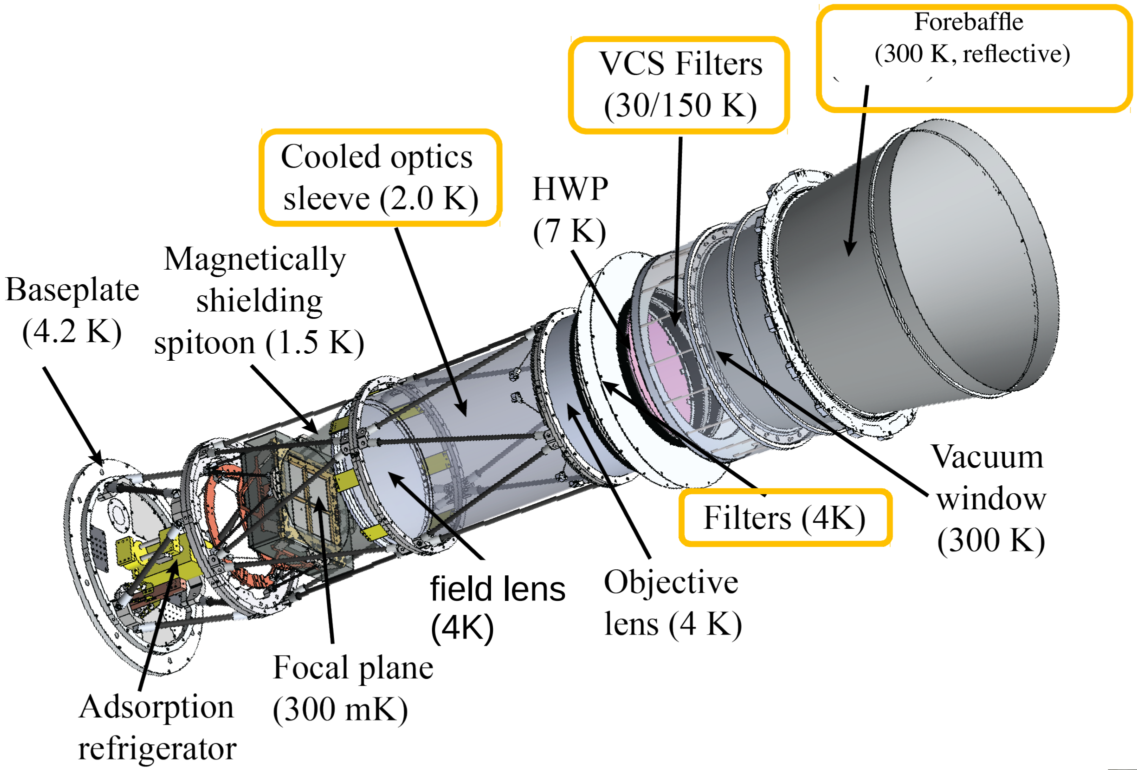
- Optical Design
  - Design Limits:
    - f-ratios below 1.5: compact, high detector count per wafer
    - good performance to high frequencies with ~1m apertures
  - Comparisons:
    - throughput competitive with crossed Dragone reflectors
    - volume smaller than most reflector designs
  - *Paper in preparation.*
- SPIDER demonstrates cryo refractor can be very low background experiment (also, hear Ed Young's talk)

SPIDER: Lessons from Near-Space

Very low **internal loads** (*detected power emitted by instrument*) are achievable with multi-element refractive fore-optics

	Pcmb	Patm	Pabsorb (*est.*)
95 GHz	~0.13 pW	*<0.1 pW*	≲ **0.25 pW**
150 GHz	~0.09 pW	*<0.1 pW*	≲ **0.35 pW**

Lower than BOOMERanG (0.5 pW)
Comparable to HFI @L2!



Key components (*monochromatic*)

- Reflective filter stack
- Cold stepped HWP
  All 6 turned well in flight!
- 4K HDPE lenses
- <2K internal baffling and Lyot stop
- Reflective warm forebaffle
- Thin UHMWPE window
  Tough, low insertion loss

slide from Jeff Fillippini