Detector Parallel Summary

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Brenna Flaugher, L2 Scientist (interim)
John Joseph CAM

Goal: identify issues and interfaces that need to be settled for CMB-S4 wafer designs

Detailed, constructive discussions and active chat

Very useful to have representatives from readout, modules, fab sites, SAT’s and LAT’s involved

Made a lot of progress in identifying the issues and potential solutions

We needed more time! Will plan to have focused workshop(s) in next few months to continue progress and reach conclusions prior to June Conceptual design review

Had three presentations:

Lorenzo - Dark Squids and TESs

John Ruhl - Options and open questions for Detectors specifications

Toki - Hex vs Rhombus Wafer layout analysis and options

Dark Squids and Dark TESs

- dark SQUIDs are used to monitor drifts in readout (mostly for magnetic pickup and occasionally crosstalk)
- 3 types of dark TESs depend on location:
  - on-chip “cut feedline” [not-really dark]
    - sensitive to on-TES island pickup or optical cross-talk above waveguide cutoff
  - off to the side “no resistor” [really dark]
    - less sensitive to on-TES island pickup or optical cross-talk
    - but still sensitive to thermal, microphonics, electrical cross-talk
  - optically-sensitive area: “taped horns” [not-really dark] can be temporary
    - sensitive to stray photons above waveguide cutoff that can bounce around behind the horn array

General agreement that we should have them but we need to decide on details: number, location, biasing

Dark Squids and Dark TES Recommendations

Dark SQUID soft recommendation: 1 per mux column (this is probably too many could be ½, ⅓)

- dark SQUIDs can inform how much of ground-subtracted component is due to mag pickup
- implementation could be “shorted” as in BICEP3, “open” as in BICEP2, or resistive (as mentioned in chat)

Dark TES recommendations include a few of each type per wafer (~4-10?) with good spatial coverage over the array and make them a combination of

- cut feedline with adjusted Psat (<Popt)
- no resistor with adjusted Psat (<Popt)
- tape-over horn use thes only during development

Prefered Biasing option : dark Psat< Popt but more discussion needed - active chat on this

Need to work with RO and on wafer layout to see what fits on each wafer type, (number and biasing)

Detector Options and Decisions (Ruhl)

- Progress! 11 different wafer types as of DSR, 8 different wafer types as of PBD, plus reduction in differences in Psats (SAT MF 1 and MF2 are now same Psat)

- Q1: only one type of SAT MF wafer with mixed bands?
  - Cons seemed to outweigh Pros.
- Q2: three high-density wafers (SAT UHF, LAT MF, LAT UHF), should they (can they) be the same?
  - Pros seemed to be winning, at least for the two UHF bands (LAT MF needs different horn/coupling wafers) but Hex Rhombus issue needs resolution
- Q3: can SATs adopt LAT frequency bands at 30/40 and 220/270?
  - Would make Detector fab easier, would need to validate SAT foregrounds (Bands based on experience) - interesting point: the crossover point is what is different, not the total band width, and it seems like having the same bands for the SATs and the delensing telescope would be important
  - Needs more work to decide
- Q4: are low density wafers wired out using only one (or two) side (s)?
  - Saves 100mk RO modules, needs more work

- From Discussion
  - We will want to “flash” detectors to unlatch. Zeesh says it can be designed in. This would put a requirement on readout: we want this.

pBD has all Rhombus (except SAT HF), this is not well matched to Fab. site expertise

More hex layouts would improve flexibility to optimize based on cost, schedule, demonstrated yield and risk - This is really critical as the project moves forward

What are the impacts of shifting some of the wafer designs from Rhombus to Hex?

Toki showed Hex layouts for wafers to see what actually fits

NOTE: Here "Horn diameter" means pixel pitch vs. the horn aperture size, which will include some sidewall thickness

Rhombus layout pixel count possibilities

Number of Rings	Pixels/wafer	Horn diameter (mm)	Horn diameter (mm)	Used in
Active wafer area diameter		130.00	134.00	
2	12	30.20	31.10	SAT 30/40GHz
3	27	20.70	21.10	LAT 20GHz
4	48	15.70	16.10	LAT 30/40GHz
5	75	12.70	13.0	
6	108	10.60	10.90	
7	147	9.10	9.40	SAT 85/145, 95/155
8	192	8.00	8.20	
9	243	7.10	7.30	
10	300	6.40	6.60	
11	363	5.80	6.0	
12	432	5.30	5.50	LAT 90/150, 220/280
13	507	4.95	5.10	
14	588	4.60	4.70	
15	675	4.30	4.40	
16	768	4.00	4.15	
17	867	3.80	3.90	
18	972	3.60	3.70	
19	1083	3.40	3.50	
20	1200	3.20	3.30	
21	1323	3.05	3.15	

HCP layout pixel count possibilities

Pixels on side of hex	Pixels across diameter	Pixels/wafer	Horn diameter (mm)	Horn diameter (mm)	Used in
			130.00	134.00	
1	1	1	130.00	134.00	
2	3	7	43.33	44.67	
3	5	19	26.00	26.80	
4	7	37	18.57	19.14	
5	9	61	14.44	14.89	
6	11	91	11.82	12.18	
7	13	127	10.00	10.31	
8	15	169	8.67	8.93	
9	17	217	7.65	7.88	
10	19	271	6.84	7.05	
11	21	331	6.19	6.38	
12	23	397	5.65	5.83	
13	25	469	5.20	5.36	SAT 220/280
14	27	547	4.81	4.96	
15	29	631	4.48	4.62	
16	31	721	4.19	4.32	
17	33	817	3.94	4.06	
18	35	919	3.71	3.83	
19	37	1027	3.51	3.62	
20	39	1141	3.33	3.44	

Details are important

Toki presented analysis for hex layouts of

- Pitch/detector counts
- Included room for wiring
- Space for bondpads along pixel edges (see module session)
- Internal detector components

Rhombus could be a hex layout if get rid of the “raceways” between the three sections.

Homework: detailed analysis of Rhombus layouts, for example make higher density by squeezing pixels, look into Hex layout with rhombus shaped pixels

Next few slides are from Toki's talk

Hex and Rhombus both have nice features

Hexagon	**Rhombus**	**Square**

• All site's equipment is naturally compatible
• Use direct write for non-contact lithography for wiring layer
• Wiring on single Nb layer, no cross-over
• TES bolometers for different frequencies are routed to same sides, repeated pattern
	• All features can be printed with stepper
	• Works well with steppers with rotation capability
	  • Requires x3 masks and x3 litho steps for steppers without rotation
	  • Direct write is possible, litho time?
	• Crossovers for wiring layers
	• TES bolometers from single frequency is mapped to one side
		• All site's equipment is naturally compatible
		• All features can be printed with stepper
		• Array size per wafer and pixel packing density is lower than hex/rhombus design
		• Wiring/cable routing can be done as hexagon or rhombus design

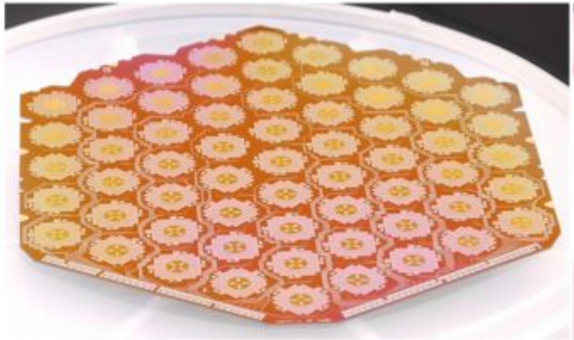
	Stepper with rotation	Direct write
ANL	No	Yes
JPL	No	Yes
LBNL-Seeqc	No	Yes (procuring)
NIST	Yes	Yes
SLAC	Yes (procuring)	Yes (procuring)
UCB	No	Yes

3

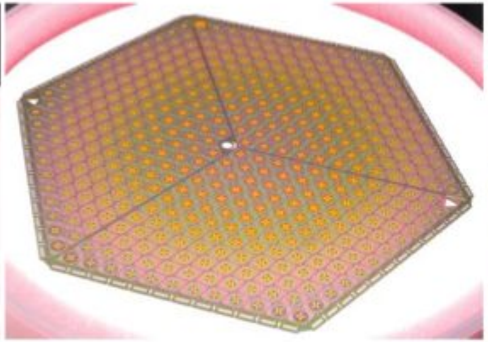
Detector layout

Layout Options

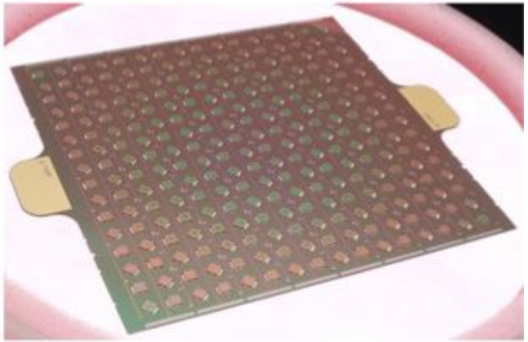
Detector arrays from NIST



Hexagon



Rhombus



Square

	Hexagon	Rhombus	Square
ANL	SPT3G	CDFG	
JPL			BICEP2, Keck Array, BICEP3, Spider
LBNL-Seeqc	PB2 layout, SO layout, CDFG		
NIST	ACTpol, SPTpol	AdvACT, SO, AliCPT, LiteBIRD	Spider
SLAC			
UCB	APEXSZ, EBEX, PB1, PB2, SO, CDFG		LiteBIRD

Pixel Pitch and Detector Count

Hexagonal layout

Type	Pixel Pitch [mm]	Pixel Count
LAT HF	5.200	469
SAT HF	5.200	469
LAT MF	5.200	469
SAT MF	8.930	169
LAT LF	14.900	61
SAT LF	26.800 or 30.000	19
LAT 20 GHz	19.150	37

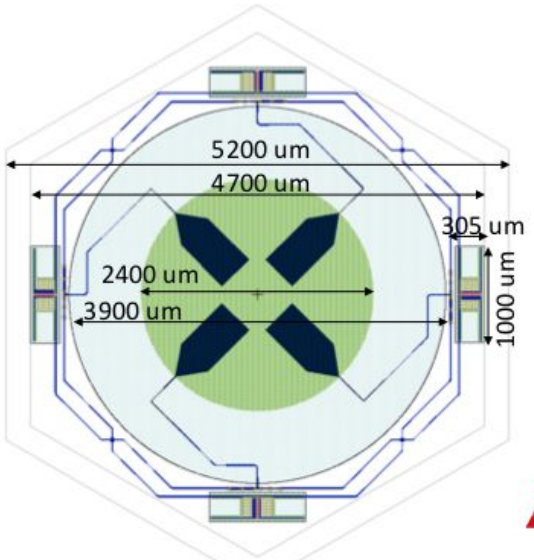
Rhombus layout

Type	Pixel Pitch [mm]	Pixel Count
LAT HF	5.300	432
SAT HF	5.300	432
LAT MF	5.300	432
SAT MF	9.400	147
LAT LF	15.700	48
SAT LF	31.100	12
LAT 20 GHz	21.100	27

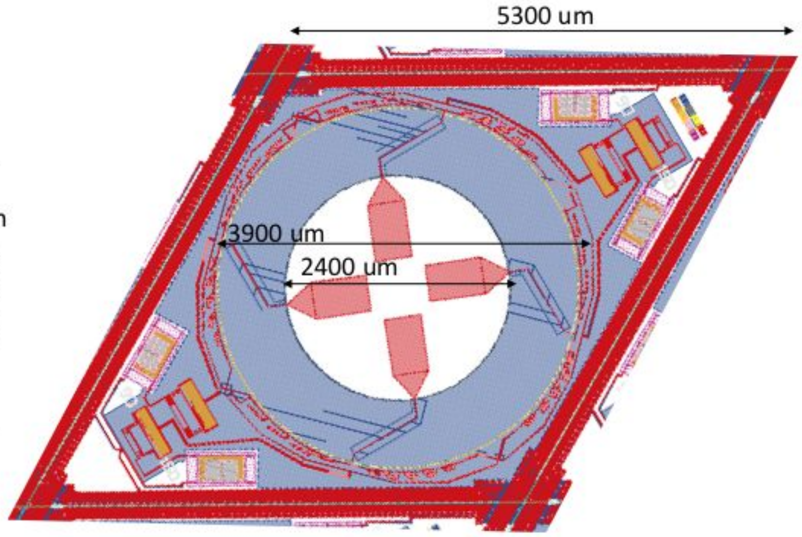
- **Pixel pitch and pixel count is quantized for fixed wafer size**
  - Assumed CDFG wafer size
  - For hexagonal design, I selected a design with higher pixel count, but lower count with larger pixel is possible
- **Next step is to verify pixel pitch and count works**
  - Quick layout study in back up slide suggest this works
  - Make sure detector structures for each site fit within detector area
- **Then study mapping speed, beam truncation point and beam shape for given pixel size**
  - Flow up/across WBS to make sure this is okay

6

Internal Pixel layouts differ - tightest is LAT MF



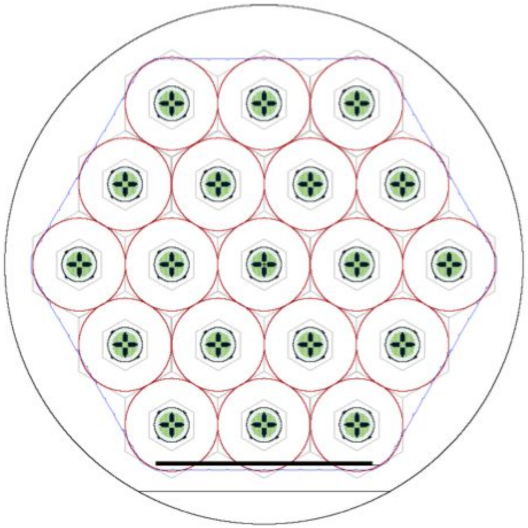
Hexagonal layout



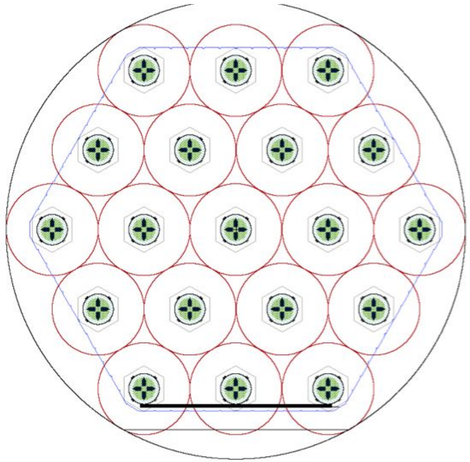
Rhombus layout

Need detailed wafer layouts to determine density and pitch. Preliminary analysis: Hex works for all wafer types, with interesting options for SAT LF

SAT LF Hex layout option 19 pixels (pDB has 12 pixels at 31.3mm pitch, Rhombus)



26.8 mm pitch has plenty of room



30mm pitch: Horn array would be bigger, with coupling wafer still in normal 6-inch wafer. Might not fit in FP though SATs are interested! Many interfaces to resolve

Next Steps

Continue analysis of Hex and Rhombus layouts, interfaces to modules and RO

CDFG meetings (Wed. Noon Central) , R&D meetings (Thursdays 11 central)

Focused workshops: One in late April, one in late May to resolve questions and/or document remaining open issues prior to June Detector review.

For each wafer type we need at least two Fab sites to have the same:

- Wafer Size and thickness
- Pixel location: pitch, shape, pixel count
- Wire bond pad location, and assignment to frequencies and darks (TES and Squids), material on the pads
- Performance Specifications (Rn, Tc, Time Constant, bandpasses, yield)
- Interfaces to modules and readout

Extras

Path to potentially deployable wafers and pre-production

- We need to resolve a few issues before we can make production layouts (will be discussed in parallel sessions):
  - Number of darks (and what are they)
  - Hex vs rhombus
  - Internal pixel layouts (documentation)
  - Bondpad locations, materials and frequency mapping
  - RF coupling design and interfaces to detectors
  - Readout and module design and interfaces
  - Anything else?

LATs and SATs both expressed preference for MF first, but if it is easier to settle all these issues for other types we should think about getting them started

Preproduction	FY22A	FY22B
Site 1 = ANL	LAT MF	LAT MF
Site 2 = JPL	SAT MF	SAT HF
Site 3 = SEEQC	SAT MF	SAT LF
Site 4 = NIST	LAT MF	LAT HF
Site 5 = SLAC		
Site 6 = Marvell	SAT LF	LAT LF

Detector Fabrication Plan cont.

- Each detector type will be fabricated by at least 2 sites
- Build on existing experience (NIST - SO, LAT MF, JPL - SATs, LBL and UCB support each other, SLAC will start production in FY25, etc)
- Assignment of detector types to fab sites allows focused R&D

Pixels/ wafer		Number Wafers	Site 1 = ANL	Site 2 = JPL	Site 3 = SEEQC	Site 4 = NIST	Site 5 = SLAC	Site 6 = Marvell
12	SAT 30/40GHz	28		6	10			12
27	LAT 20GHz	4						4
48	LAT 30/40GHz	25			8			17
147	SAT 85/145, 95/155	168		84	84			
432	LAT 90/150	162	66			64	32	
432	LAT HF	64	20			44		
469	SAT 220/280	52		16			36	
		503	**86**	**106**	**102**	**108**	**68**	**33**

Draft Production Fabrication plan (v5)

- Rates and detector types discussed with each site and iterated.
- Production rates require minimum ramp-up in capabilities at all sites
- Additional capacity is possible at most sites, with appropriate warning
- Plan to reoptimize based on performance, cost and schedule at least annually

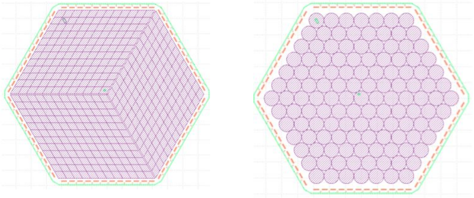
PRODUCTION		Split years into part A and B for transition to new detector type									
	FY23A	**FY23B**	**FY24A**	**FY24B**	**FY25A**	**FY25B**	**FY26A**	**FY26B**	**FY27A**	**FY27B**	**Total**
Site 1 = ANL	2	8	8	10	10	10	10	8	10	10	**86**
Site 2 = JPL	2	8	8	8	14	16	16	16	12	6	**106**
Site 3 = SEEQC	2	8	10	10	16	16	16	16	4	4	**102**
Site 4 = NIST	2	8	8	8	10	12	14	16	16	14	**108**
Site 5 = SLAC					8	12	16	11	11	10	**68**
Site 6 = Marvell	1	3	4	5	4	4	4	4	4		**33**
Total Science Grade	**9**	**35**	**38**	**41**	**62**	**70**	**76**	**71**	**57**	**44**	**503**
~ Number of wafer modules to test (inc. 12% overage and 67% yield)	**15**	**59**	**64**	**69**	**104**	**117**	**127**	**119**	**95**	**74**	**841**

Recent challenges: Matching wafer layouts to Fab. site expertise

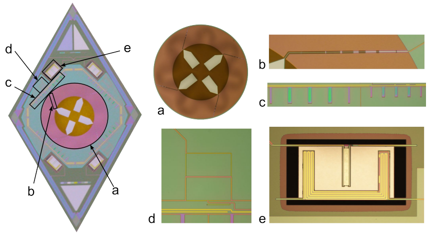
Fab sites have different equipment, experience and expertise

- Hex vs Rhombus layout
  - All sites could make Hex wafers (or square or rectangle)
  - Rhombus layout requires x3 more masks and lithography steps and stitching if sites do not have a stepper that can rotate
  - NIST, SLAC have equipment to do Rhombus, ANL is doing R&D for Rhombus layout with their existing equipment
  - LBL/Seeqc, Marvel and JPL prefer no crossovers and Hex layout
- Wiring Crossover/under and Mapping Freq. to bond pads:
  - Hex: bondpad pairs alternate frequencies, does not require crossovers: see Toki's talk (slide)
  - Rhombus: one freq per side, layout as implemented by NIST has lots of crossovers: see Shannon's talk (slides)
- RF structures internal to the pixel differ
  - Will need to document what was included in RF simulations (2D or 3D, coupling and horns) and what has been demonstrated for upcoming reviews
  - Size matters - some features may be too large for dense layouts
- Discussed with DSAC: supported allowing mix of approaches based on fab. site experience, but don't mix Hex and Rhombus in same wafer types. Different layouts for different bands seems fine.

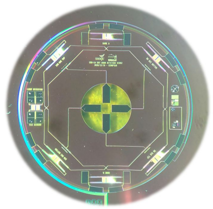
CDFG wafer layouts



NIST



LBL (Seeqc and UCB)



Detector Fabrication Plan Assumptions

- It is preferable to finish off detectors in integral units of cryostats (SAT and LAT)
  - integration and testing in the US
  - deployment after testing fully loaded cryostats
  - Preproduction modules could be used for some tests
- Plan (next page)
  - 1st SAT finished in FY24
  - SPLATR finished in first half of FY25
  - Assumes “sufficient” funding
- Many other distributions possible, this is just a start

Wafer type	Total Science Wafers	number per tube or cryostat
SAT 30/40GHz	28	14
SAT 85/145, 95/	168	28
SAT 220/280	52	13
SPLATR		
LAT 20GHz	4	4
LAT 30/40GHz	9	9
LAT 90/150	54	54
LAT HF	18	18
CHLATR		
LAT 30/40GHz	16	8
LAT 90/150	108	54
LAT HF	46	23

CMB-S4