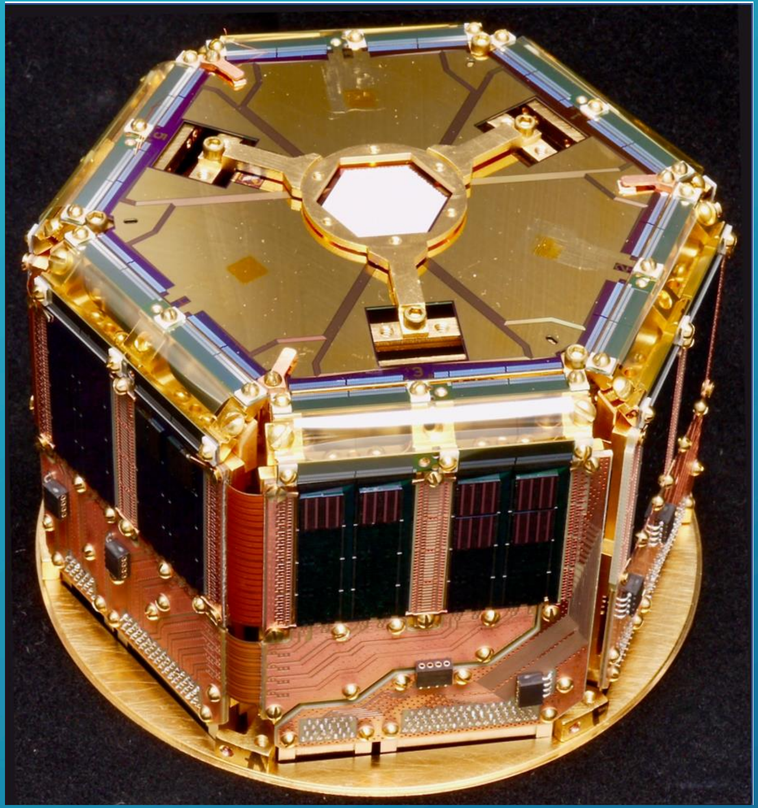
X-IFU

ATHENA X-ray Integral Field Unit

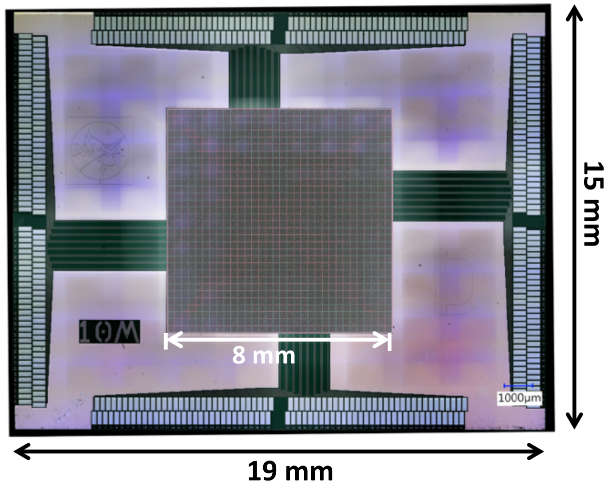
Update on developments towards the ATHENA X-ray Integral Field Unit Instrument (X-IFU)



Simon Bandler NASA/GSFC

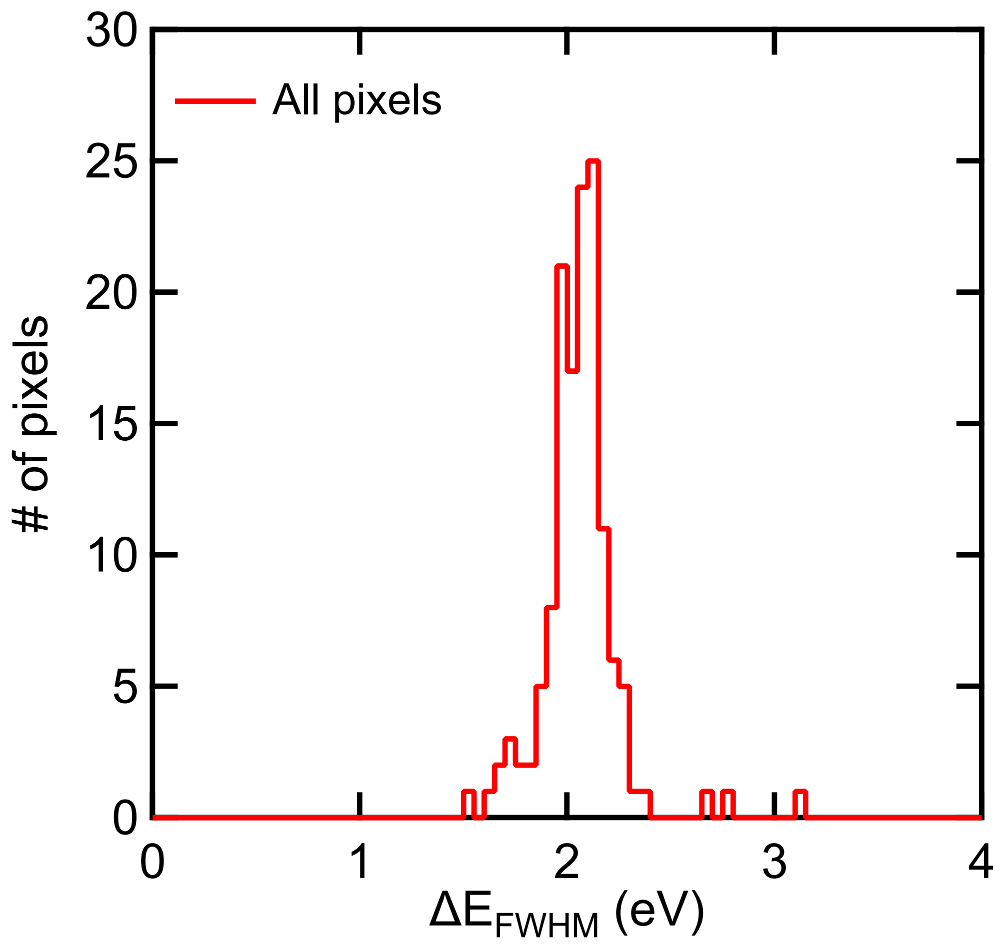
- On behalf of the team developing X-IFU microcalorimeter arrays & TDM MUX readout
- *NAST meeting, Feb. 12th 2021*

Intrinsic resolution of pixels



- Intrinsic $\Delta E_{FWHM} \approx 2.01$ eV (for infinite record length and no white noise).
- Measured in kilo-pixel arrays.

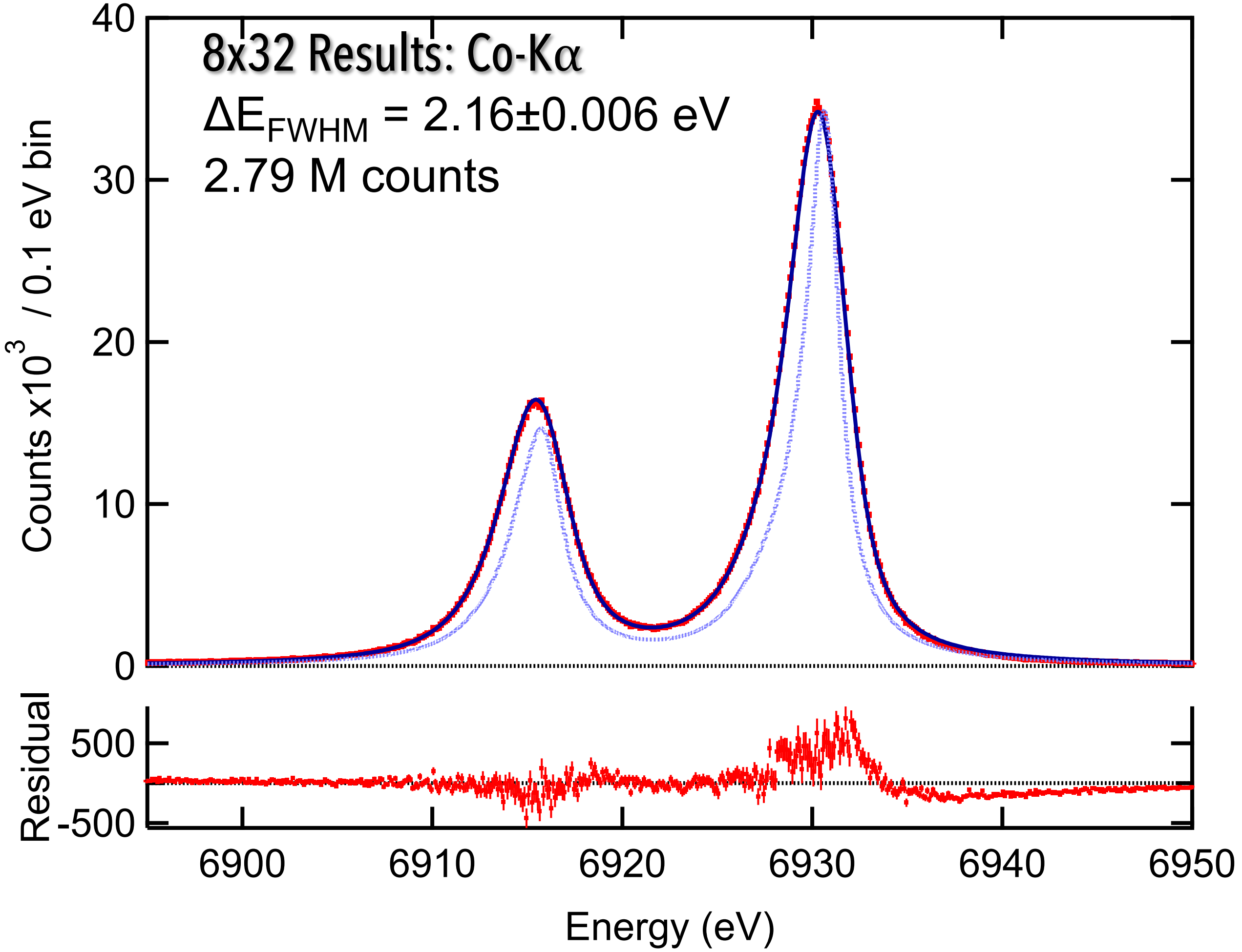
Detector energy resolution only:

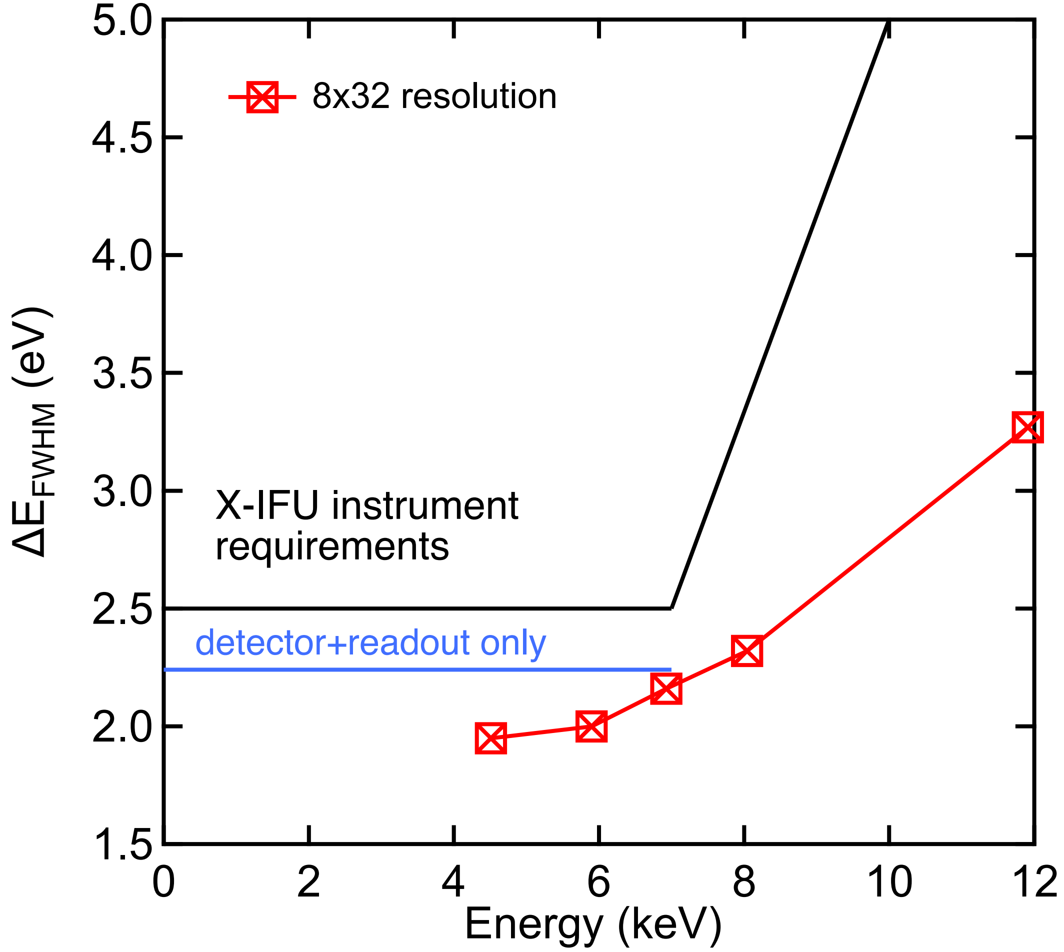


Contributor to energy resolution budget	Energy resolution
TES pixel	2.070 eV
TES R_{sh}	0.150 eV
TDM readout: broadband	0.704 eV
readout: other	0.151 eV
record length	1%
"readout level" sub-total	**2.243 eV**
other terms	0.810 eV
margin	0.750 eV
TOTAL	**2.500 eV**

Multiplexed performance at 7 keV

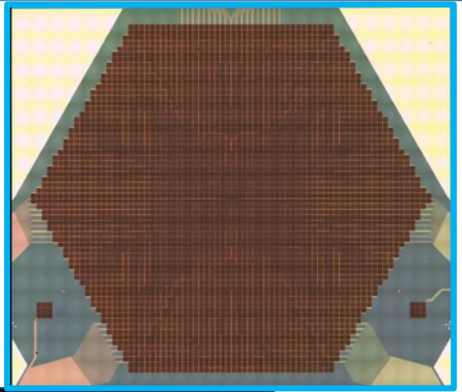
Improved MUXed result demonstrated at 7 keV

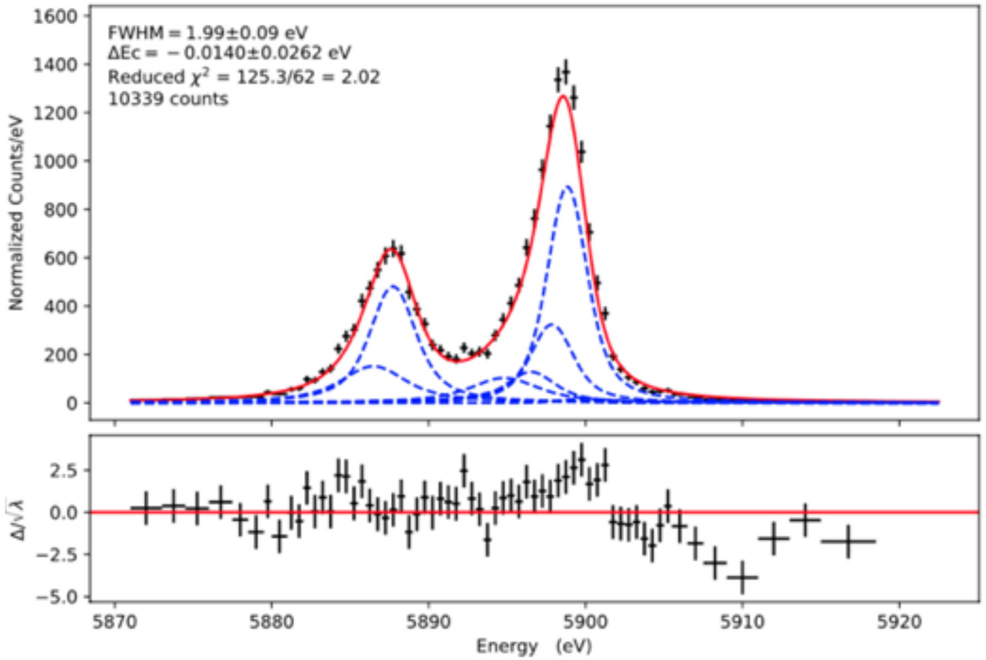


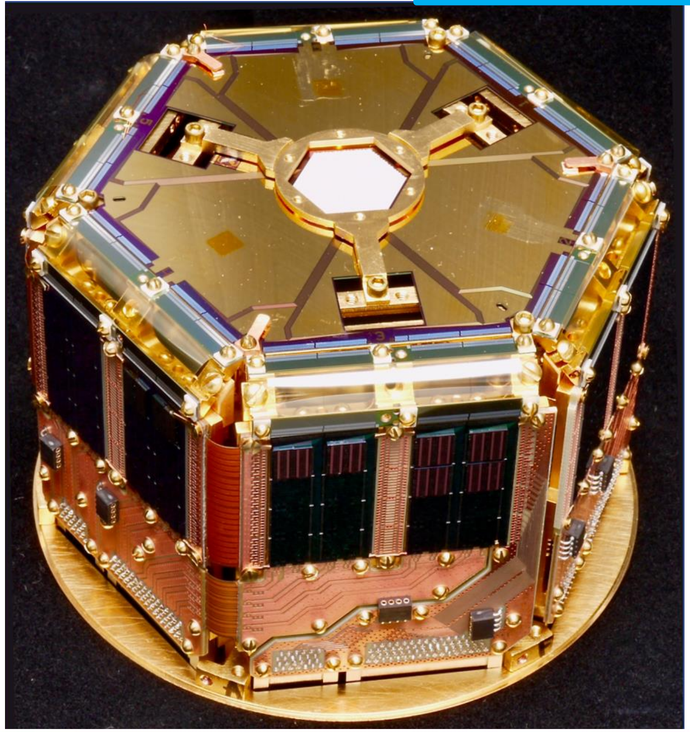


ATHENA-scale array development

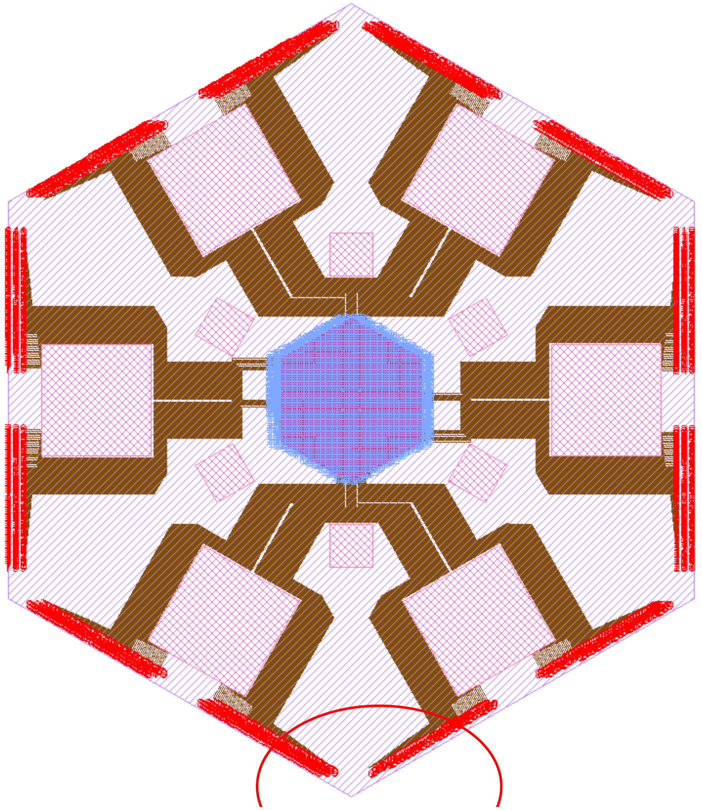
- Latest ATHENA-3B are full size arrays of pixels with LPA2.5a TESs on 275 um pitch, ~ 5 um gaps between pixels.
- Energy resolution < 2 eV at 6 keV was observed in pixel from full-scale Athena–X-IFU style array for the first time.
  - Pixels tested very close to desired specification & showed good uniformity of sensors.
  - First verification of performance in new set-up designed to accommodate full-size X-IFU arrays.
  - Tests showed that the desired level of temperature control & magnetic environment stability & vibration environment from the cryocooler does not affect performance.



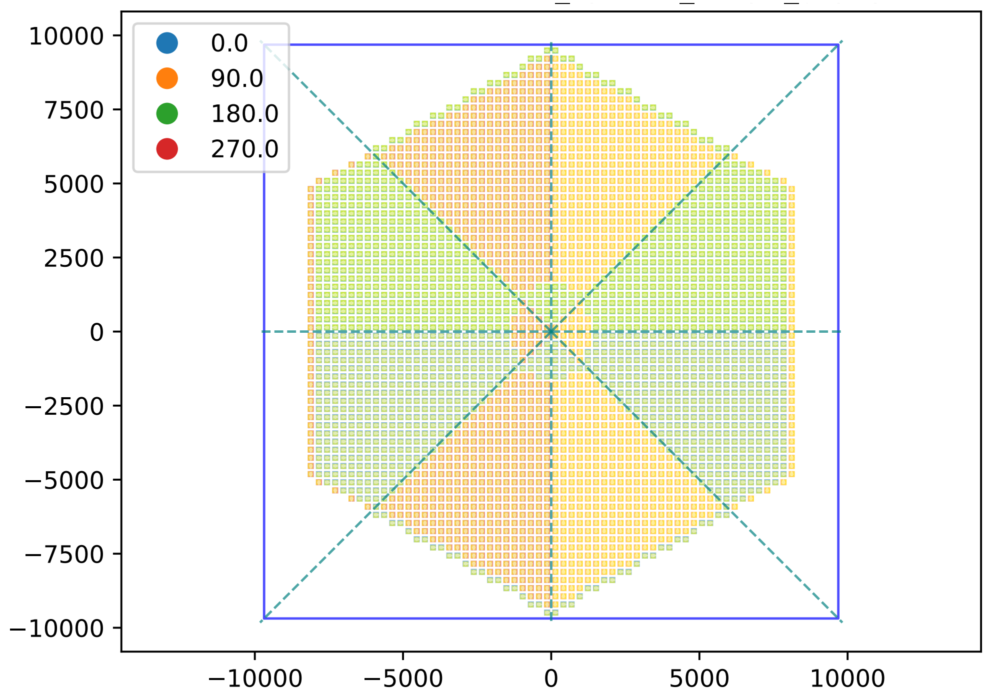




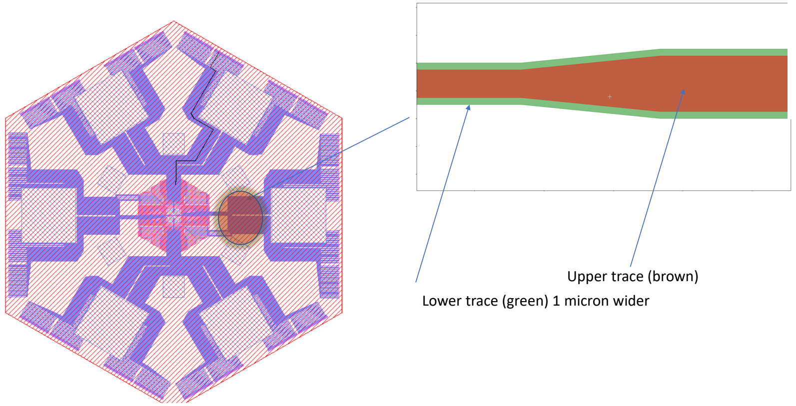
- Automated wire-routing implemented
  - Can now adjust pitch of pixels / size of muntins fairly easily.
  - All pixels wired within array.



- Pixel orientation and mapped for use in data analysis chosen:

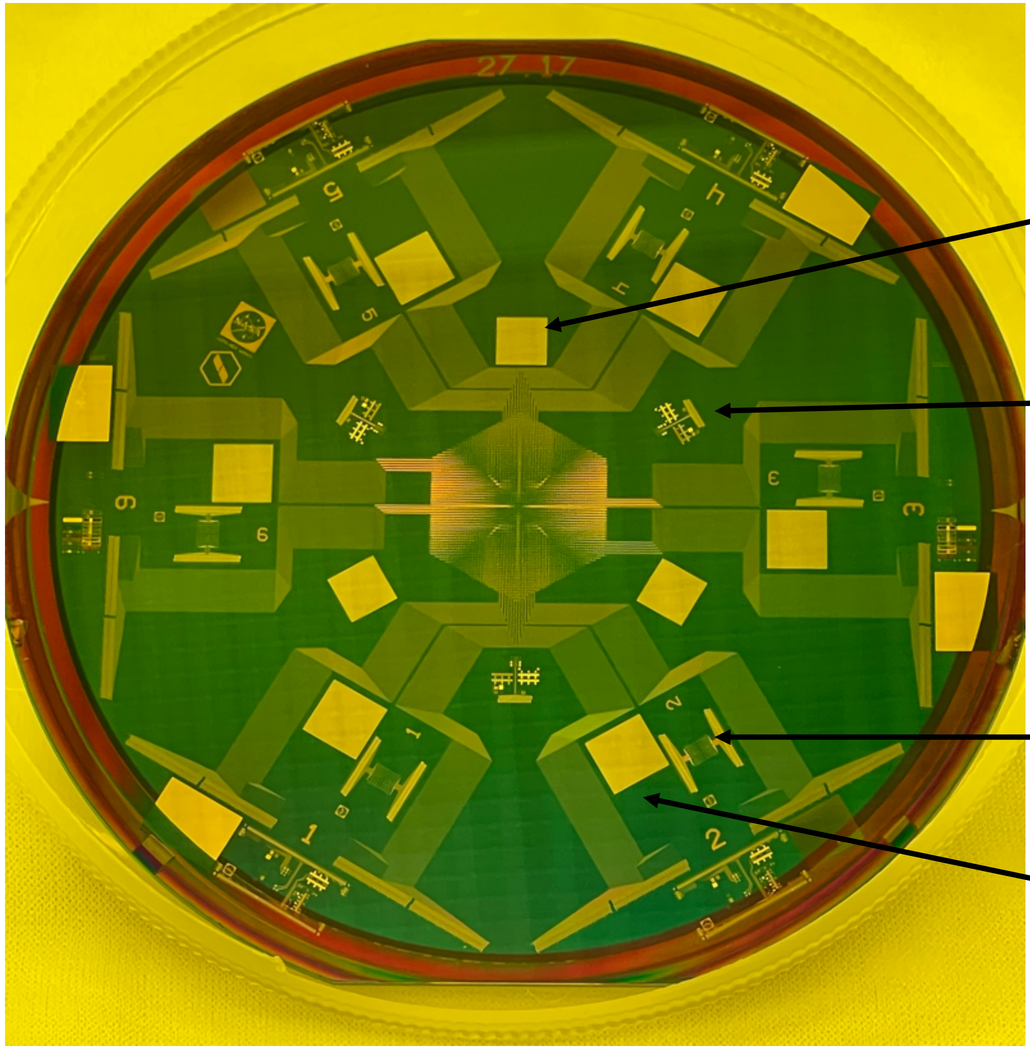


Transitions from thin trace to thick trace



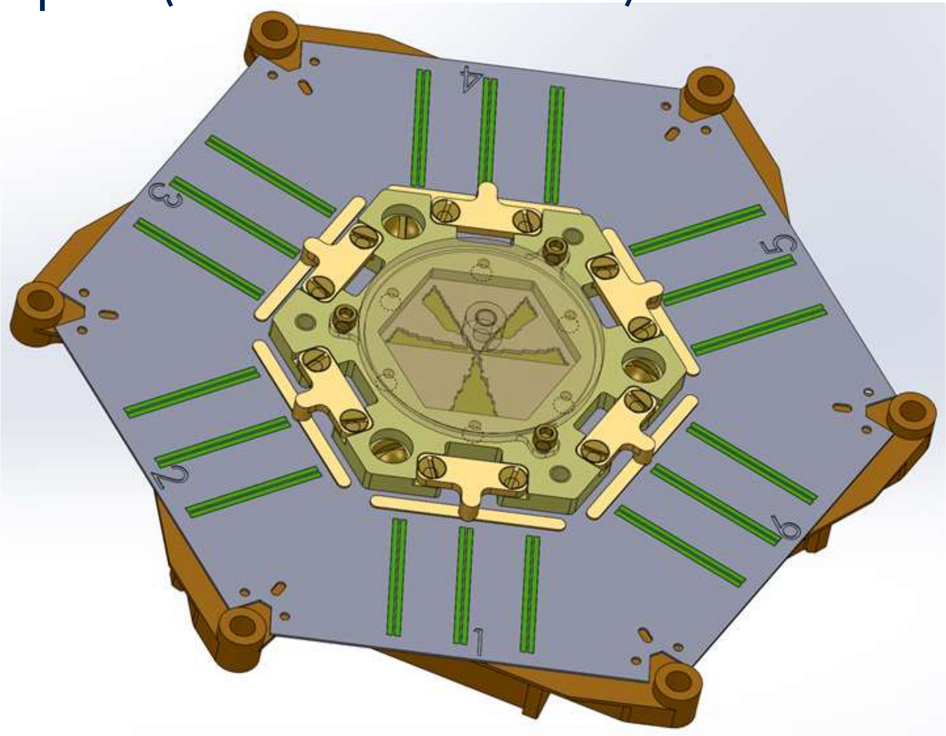
Next generation: "Athena-3D" array development

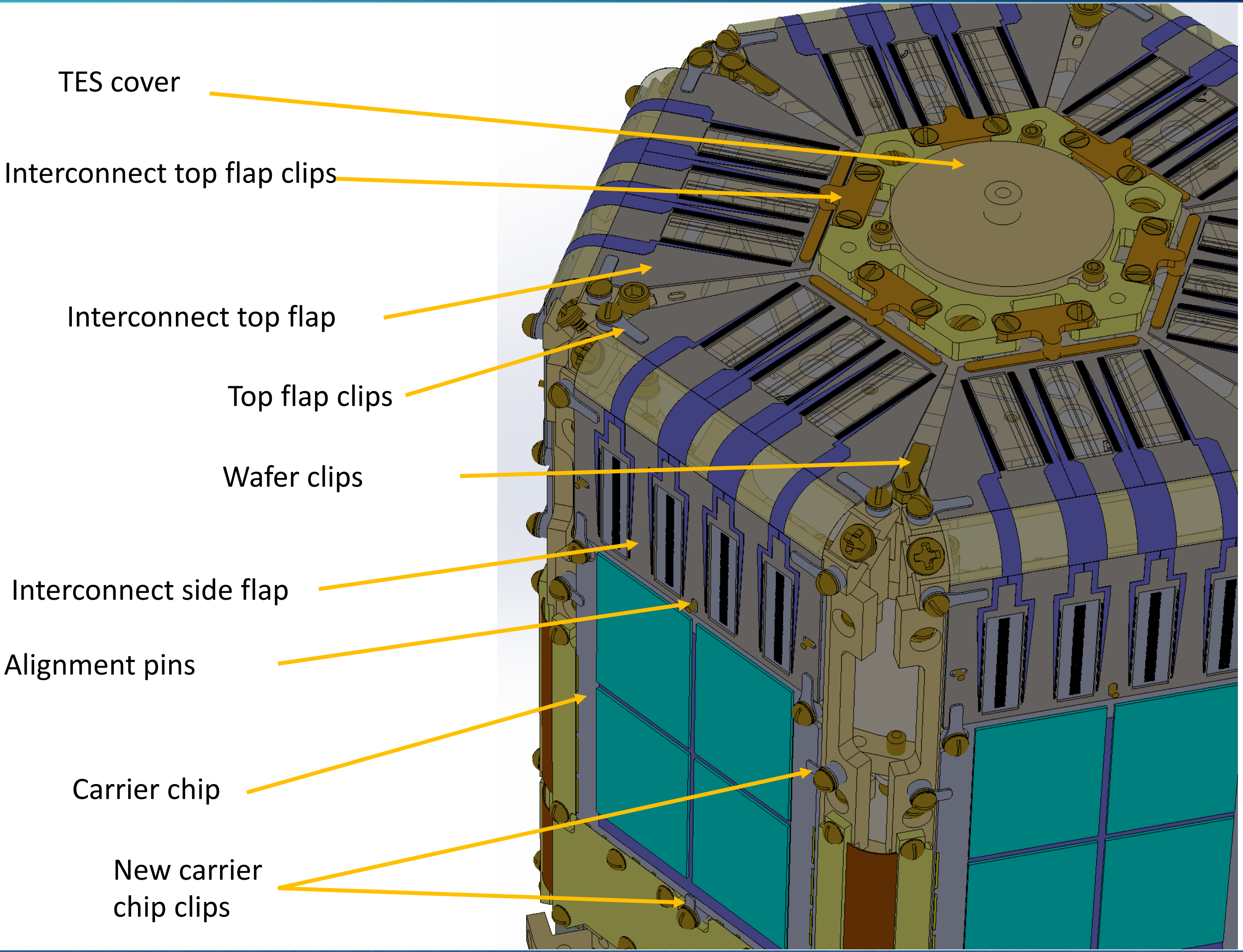
- First batch being fabricated.
- Test wafers needed to test that arrays can survive vibration verification (with flight-like etched holes).



Designing new GSE for EM/QM/FM/FS program

- FPA design almost complete that will allow us to test all pixels.
- Integrated interconnect separate from side panel to allow more arrays tests per single side-panel (~25-36 instead of 5-6)





Yield

- Previously overall yield assumed for detection chain (not considering throughput of IR-blocking filters) was 98%, with >99% yield expected for detectors.
- Have been working on yield "trade-off" bottom-up study to determine likely range of expected yields extrapolating from yields observed in kilo-pixel arrays to date.
- Proposed an initial functional yield requirement of 93% (221 "dead" pixels) for the detector array
  - at a confidence level of 92% will be able to produce >9 wafers that meet yield requirement for F.M.
- Further improvement could increase yield numbers towards 97% (95 "dead" pixels) through more enhanced post-process defect mitigation

Post-process mitigation level	Proposed yield requirement	Total wafers produced in QM/FM/FS period	Number of wafers expected to meet yield requirement	Probability of at least 9 wafers meeting yield requirement
None	**92%**	**24**	**12**	**92%**
Low	**93%**	**24**	**12**	**92%**
Medium	**94%**	**18**	**12**	**96%**
High	**97%**	**10**	**10**	**91%**

Table 6. Summary of proposed yield requirement for each level of mitigation, and consequence for the expected number of wafers that meet that requirement.

Yield

Following study, X-IFU PI proposed new yield requirement for dead pixels of 95% (TBC).

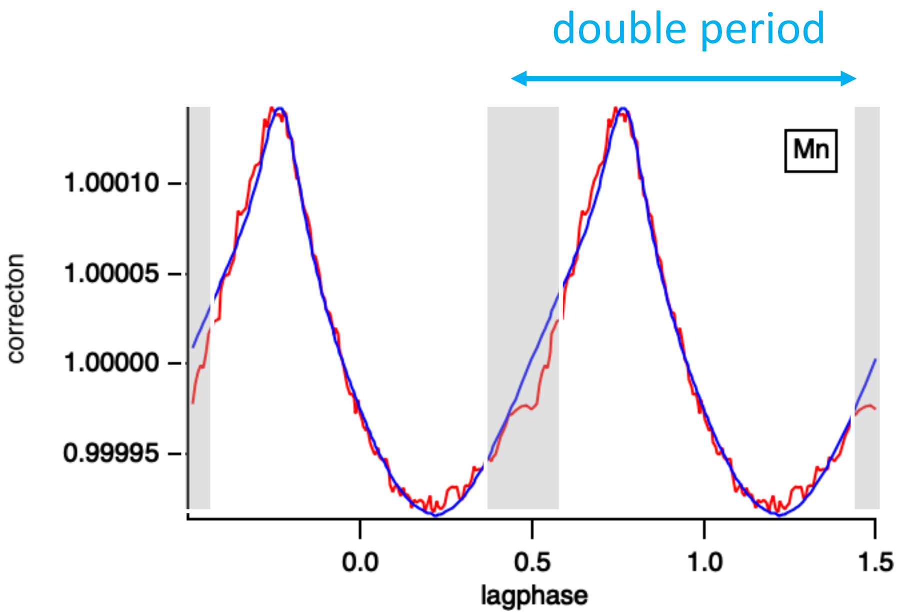
- The X-IFU instrument will be holding an additional 2% of system level margin on the overall instrument yield (for all contributions).
- One of two highest risks from GSFC detector program now retired.
- Loss of some assumed area for instrument, in addition to that from the X-ray optic.

	Suggested requirement	Current best estimate	Goal	Comments
FPA wire bonds (side-panel carriers to TES array)	99.8 %	99.5%	99.8%	Values based on a mature technology
MUX chip	98%	98.5%	99%	Assumptions: 32 best chips for FM out of 250 chips fabricated and screened, 96% average, overall pixel yield
MUX chip carrier	99%	99%	99%	MUX chip to TES array connection with strip lines
Bump bonds (TDM chips to side-panel carrier)	99.8%	99%(TBC)	99.8%	Values based on a mature technology
Main sensor array	95%	93%	97%	For FM : 92% confidence to produce 9 wafers with CBE yield
Total	91.6%	89%	94.6%	

Calibration

ATHENA IFU X-ray Integral Field Unit

- Test plan has been developed to address how to characterize and calibrate the energy scale and assess whether the energy scale instrument requirements can be met.
  - 1) Understanding how the energy scale evolves as environmental parameters are changed.
  - 2) How well behaved the fitting function is between calibration points.
  - 3) How well arrival time can be corrected and calibrated as a function of energy and environment.
  - 4) How well gain can be corrected in the presence of various environmental drifts.
  - 5) TDM read-out calibration accuracy has also been under study.



Parameterized function is a skewed Lorentzian plus a cosine

$$f(x) = 1 + B + A\left[\bar{L}(x) + \cos(2\pi x)\right]$$

fixed period of 1

where

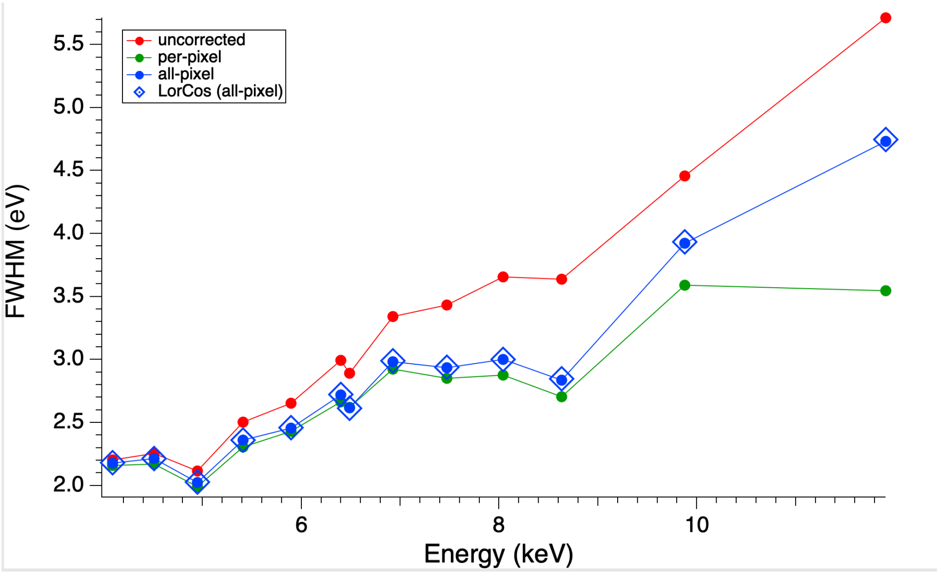
$$\bar{L}(x) = \frac{1}{1 + \frac{x}{\gamma}\left(\frac{x}{\gamma} - q\right)}$$

asymmetry parameter

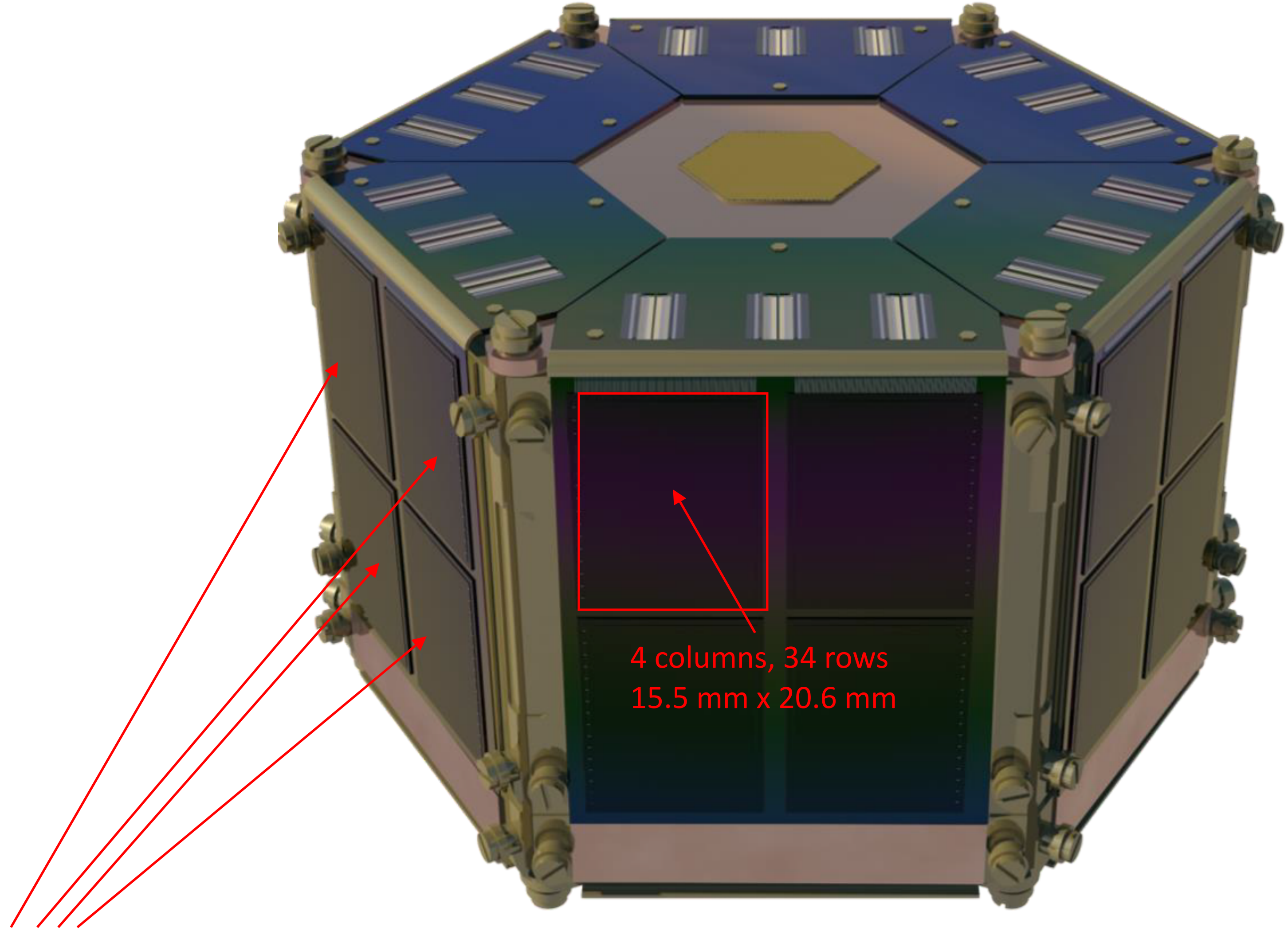
We fit for $f(x - x_s)$

There are 5 parameters: $A, B, x_s, q, 1/\gamma$

fit for 1/γ since f(x) → cos() as 1/γ → 0



ATHENA X-IFU time-division multiplexers – SQUID-based read-out chips



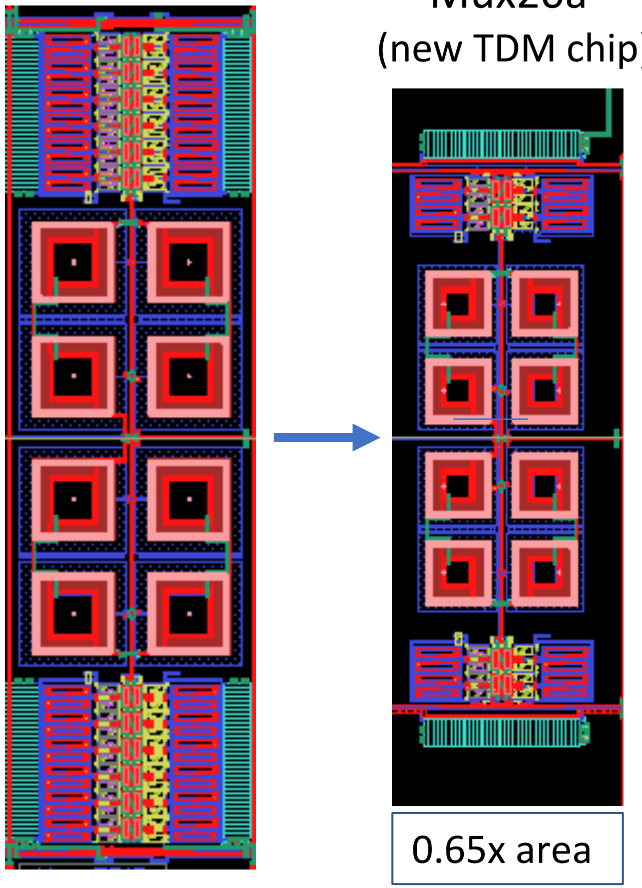
Each side panel has 4 TDM chips
Each TDM chip has readout circuitry for 4 columns of 34 rows
The TDM chips are indium bumped to the side panel carriers

TDM unit cell development

Unit Cell Redesign

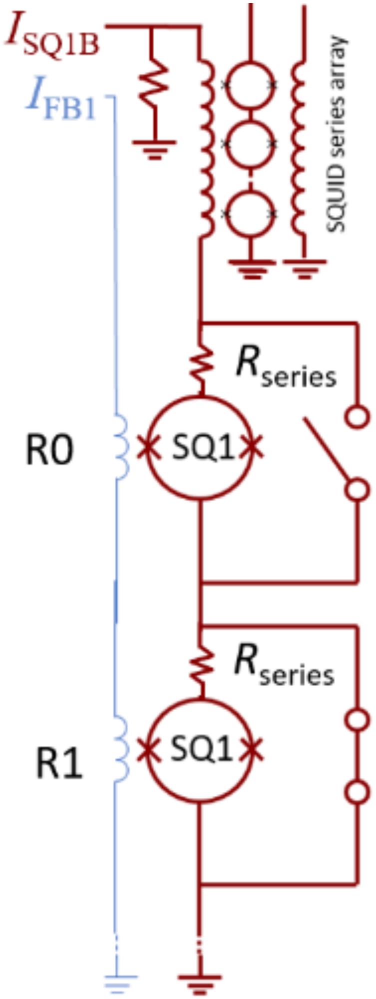
Mux19a
(used 8x32 TDM demos)

Mux20a
(new TDM chip)



0.65x area

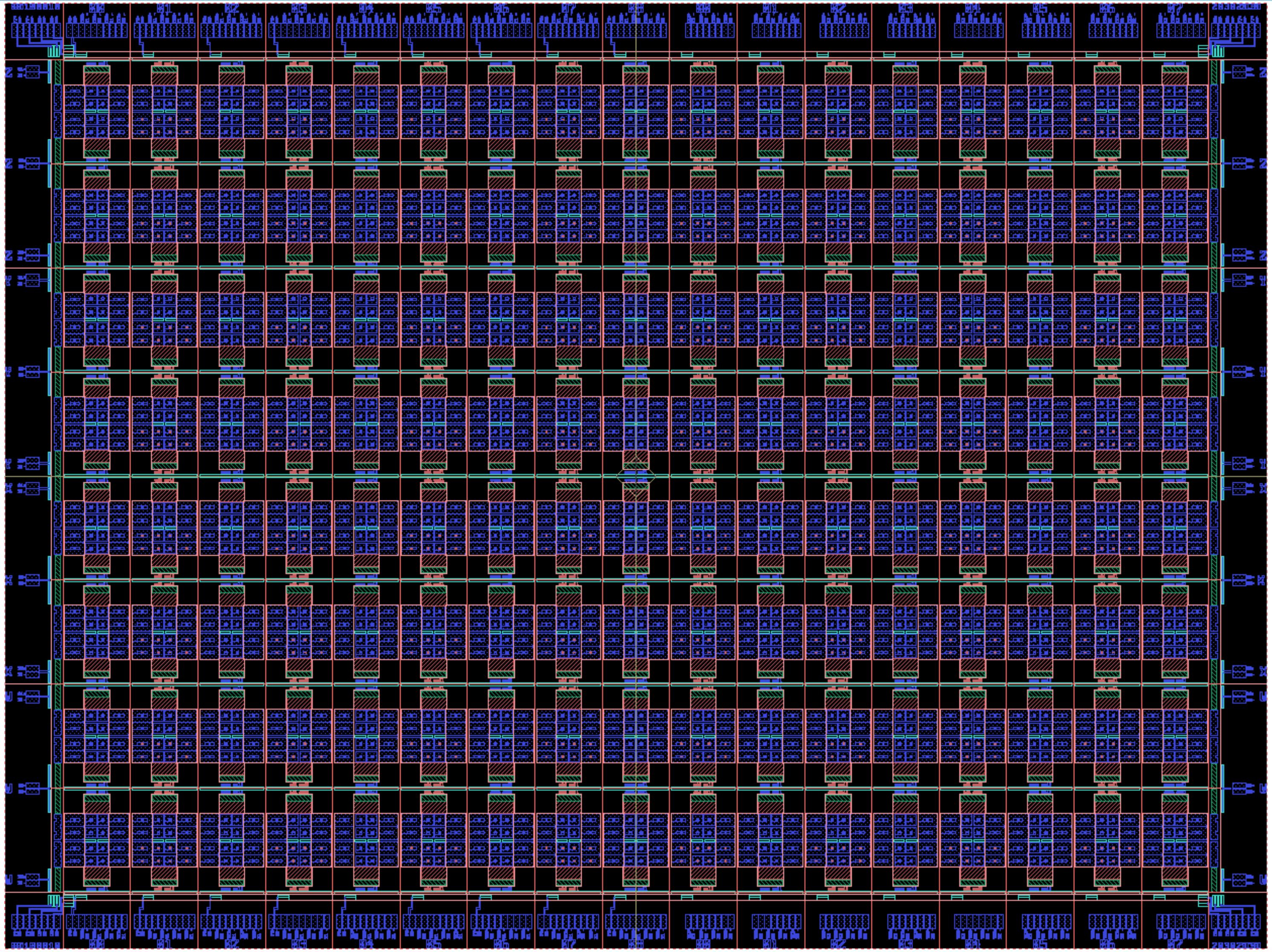
(Both chips shown on same scale)



NIST have successfully demonstrated new lower power, smaller chip area multiplexer unit cell.

- New footprint is 0.65 x area compared with previous designs and meets design requirements of X-IFU side-panels.
- Power dissipation of multiplexers (at 50 mK) is 60% lower than the previous generation.
- Broad band SQUID noise is also significantly lower than the previous generation.

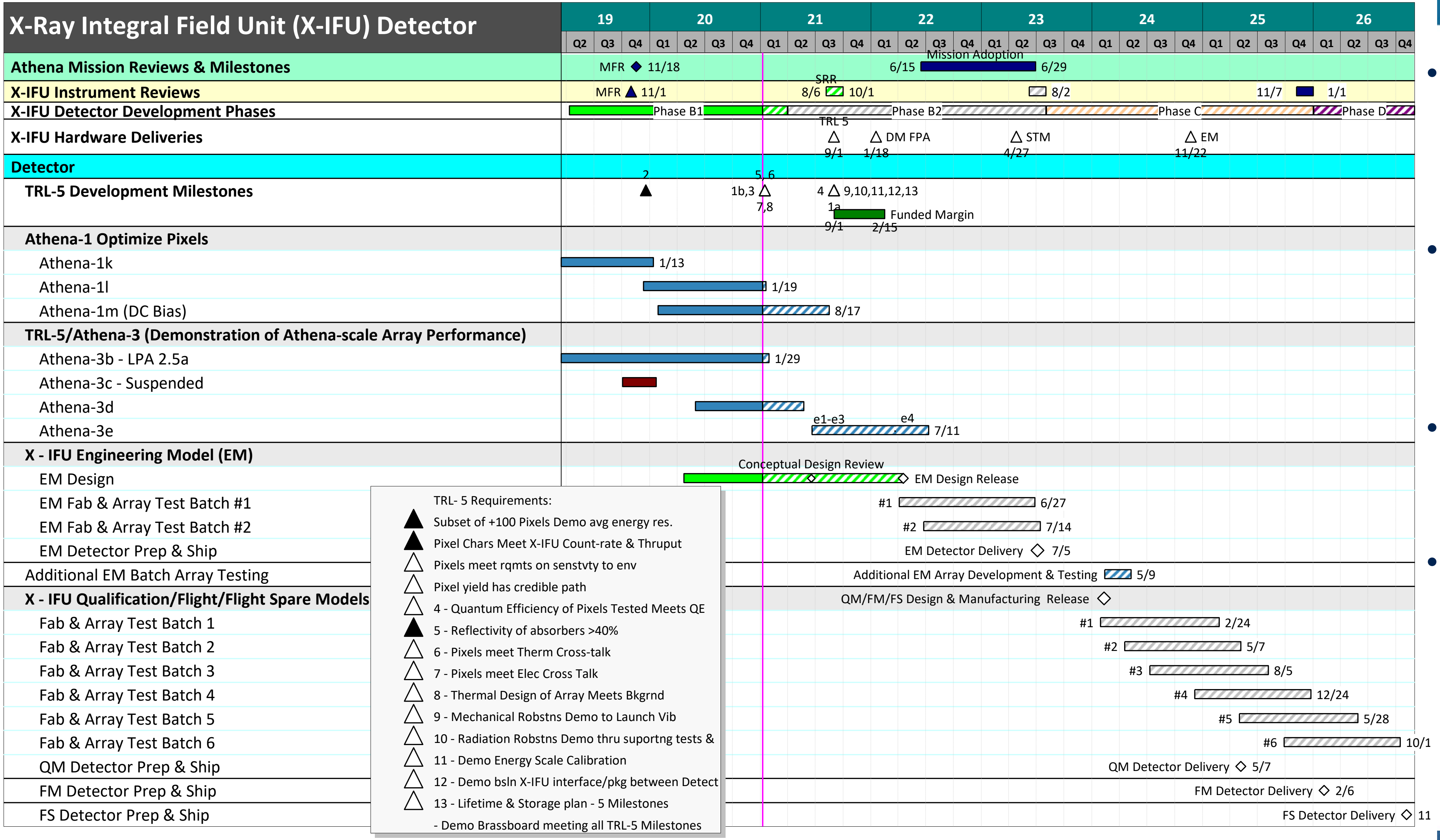
4x34 Chip dimensions and bump count



Prototype 2-dimentional TDM chip now designed:

- Chip size is 20.6 mm x 15.5 mm.
- There are 5,263 total In bumps.

Schedule



- Does not yet include effects of recent delays in M.A. and SRR review.
- Realistic schedule to still complete all required activities.
- Challenging schedule to meet E.M. delivery.
- Lot of work still needs to be done to fully establish TRL-5 prior to mission adoption & beginning of E.M. program.

Other updates/comments

- Project office arranged a detailed technical readiness level and programmatic review with an external review board.
  - The X-IFU detector and MUX read-out teams submitted their extensive review packages that described the TRL's for these technologies and the plans to reach TRL-6 from a technical standpoint, and programmatically in terms budget, schedule and risk.
  - Review generally agreed with internal assessment of the current TRL-levels.
  - Several very useful suggestions technically and programmatically for both detector and read-out development.
- COVID
  - Lots of critical design & planning work has taken place within U.S. team contributing to the X-IFU during period in which team was teleworking due to COVID.
  - Fabrication and testing has started again (Sept. 2020) and now proceeding at the ~ 75% level compared to normal operation.
- Our budget now consists predominantly of our "marching army" workforce.
  - Delays in schedule correspond almost almost proportionally to increase in cost of NASA contribution.
- Demonstration/test detection systems incorporating TDM read-out are almost ready to ship - will be delivered to IRAP and SRON in the next couple of months.

Acknowledgements - **Key contributors from the U.S.:**

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