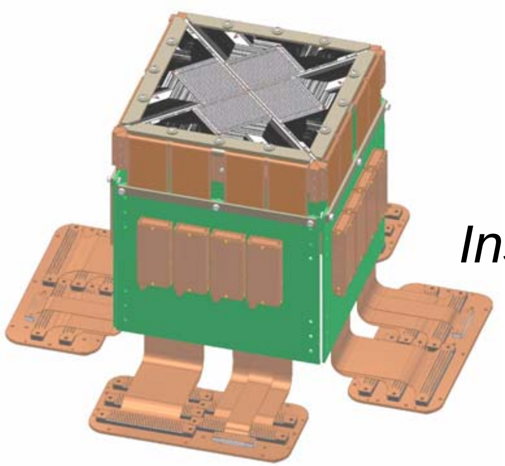
Detectors for the 10 000 pixel SCUBA-2 superconducting sub-mm camera for astronomy

Talk given at 2006 IRMMW-THz conference, Shanghai, China, 19th September 2006



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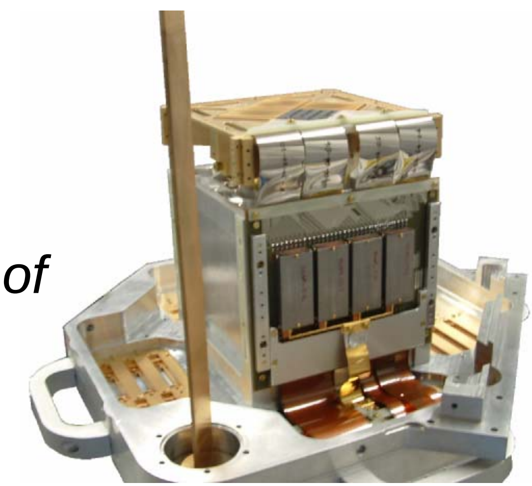

Sub-mm astronomy

- Sub-mm astronomy: wavelengths of a few hundred μm
  - Typically in "windows" around 450 and 850 μm (670 and 350 GHz)
- Lets us see cold things: peak in 10-K blackbody around 300μm
  - e.g. objects in formation (stars, planets…)
  - Also lets us see far away (red shifted) warmer objects: peak in 40 K blackbody at red shift Z=3 is at 300 μm
  - Sub-mm emission usually "optically thin"; so we see the interior rather than just the surface of objects

Example: Eagle Nebula in visible light (Hubble Space Telescope):

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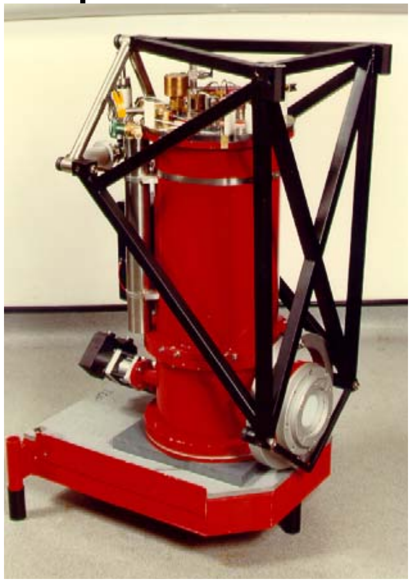
Example: sub-mm (850 μm) contours overlaid (SCUBA)

Instruments

- Instruments limited by small number of pixels
    - Gone from 1 pixel to 100s in a decade
    - Need more pixels!
    - But: can't compromise on noise performance
    - Aim is "BLIP" – background limited performance
        - Noise limit set by photon (shot) noise from sky

JCMT, Mauna Kea, Hawaii

UKT14
1986-1996
1 pixel

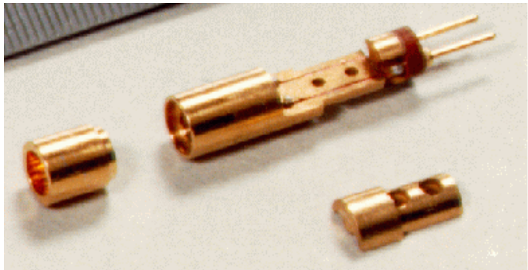


SCUBA
1997-2006
128 pixels

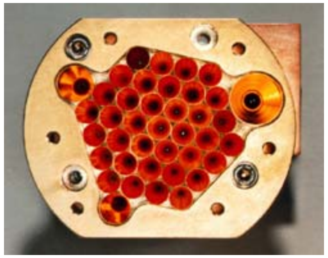
Detectors

- Most sensitive detection method is to use bolometers
  - Measure temperature rise due to absorbed radiation
  - Respond to wide wavelength range – define with filters
- Traditionally use NTD germanium thermistors
  - BUT: not background limited for best telescopes
  - Hard to make large arrays:
    - Ge chips have to be individually mounted on each pixel
    - Can't multiplex without prohibitive noise penalty
    - Separate wiring and read-out electronics for each pixel required

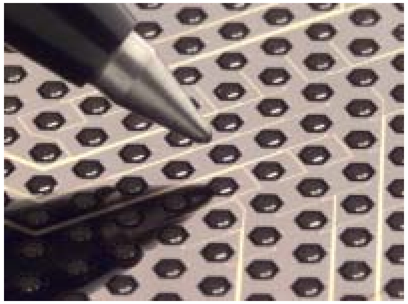
SCUBA individual pixel



SCUBA focal plane



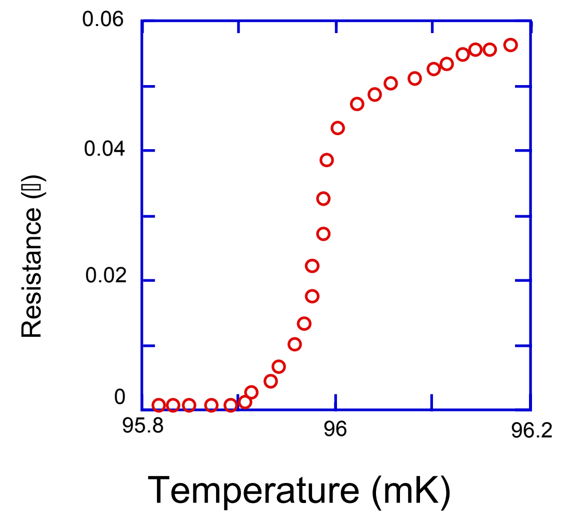
SPIRE array – multiple pixels on one silicon wafer



Solution

- Sensitive bolometer requires large dR/dT

- Very large dR/dT through superconducting transition
- Basis of TES (transition edge sensor), operated in superconducting transition

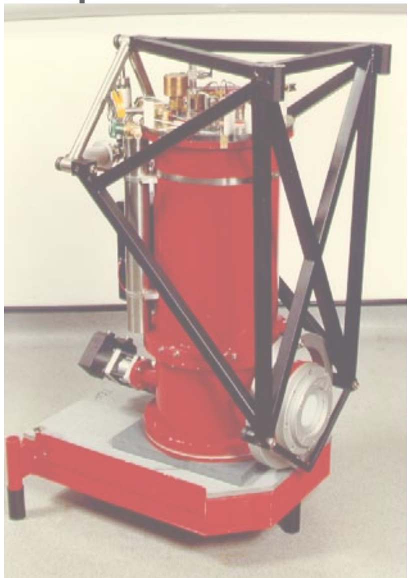


- Other advantages:
  - TES sensors can be deposited on silicon wafer:
    - Entire array can be constructed with no operations at the level of a single pixel
  - Detectors can be multiplexed with acceptable performance

SCUBA-2

- Wide field TES imaging camera with up to 1000 x mapping speed of predecessor (SCUBA)
- Sensitivity limited by sky background (photon noise)
- Capable of carrying out large scale surveys
    - So far only area of about size of moon mapped to any depth in sub-mm

UKT14
1986-1996
1 pixel



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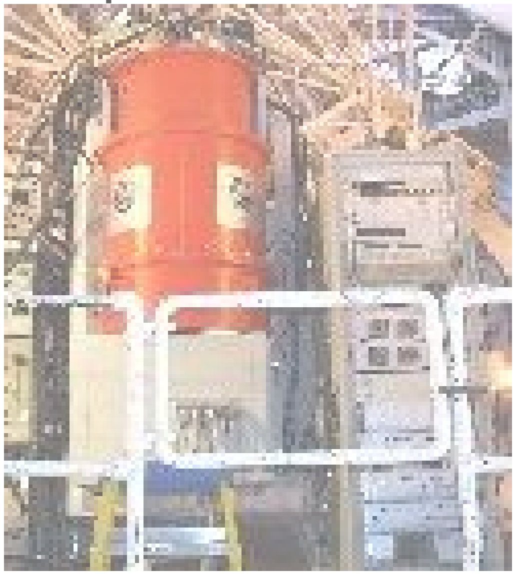


SCUBA-2
2006+
10240 pixels

Institutions

Instrument design, construction, testing, commissioning: *ATC, Edinburgh*

Multiplexer and TES devices: *NIST, Boulder*

Detector micromachining: *University of Edinburgh*

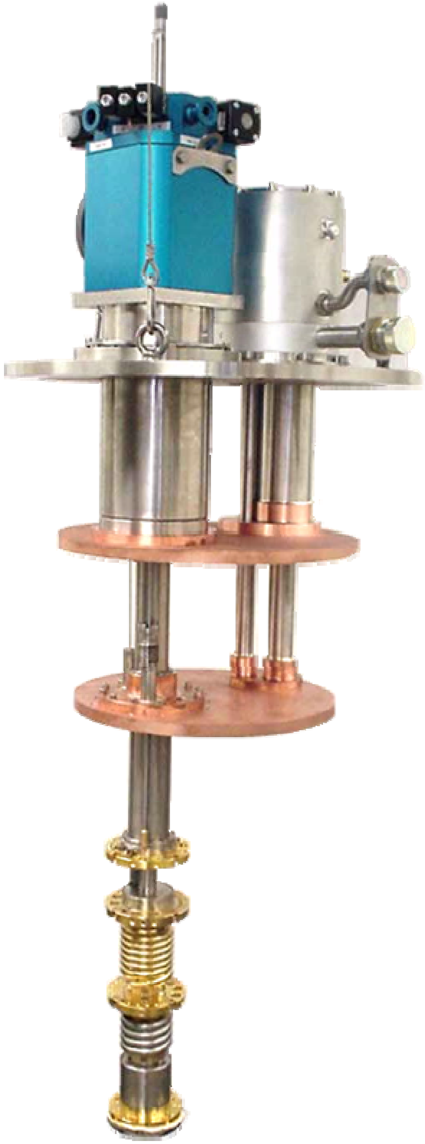
“1-K box” design and construction, detector test programme, filters/dichroic: *Cardiff University*

Warm electronics: *University of British Columbia*, MUX testing, *University of Waterloo*

Telescope infrastructure: *Joint Astronomy Centre, Hawaii*

Cryogenics

- Arrays must be operated from heat sink at 0.06 K
  - Cooling provided by dilution refrigerator (Leiden Cryogenics)
  - Operates from temperature of 4 K
    - Traditionally provided by bath of liquid helium
    - Instead use mechanical (pulse tube) cooler to reduce running costs
    - First commercial “dry” dilution refrigerator(?)
- Two more pulse tube coolers used for rest of instrument

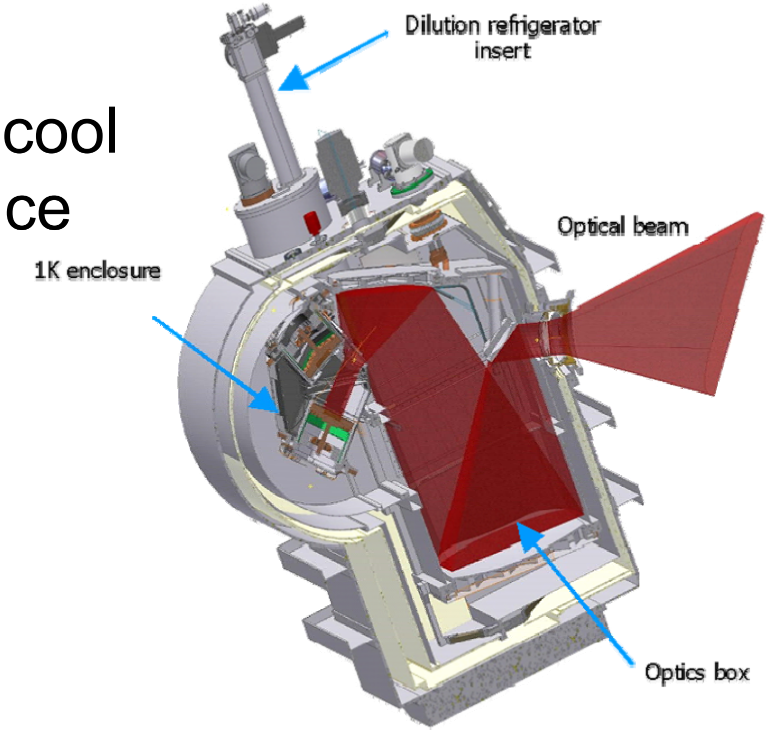


Dilution refrigerator insert

Leiden Cryogenics BV
Leader in LT Techniques

Size

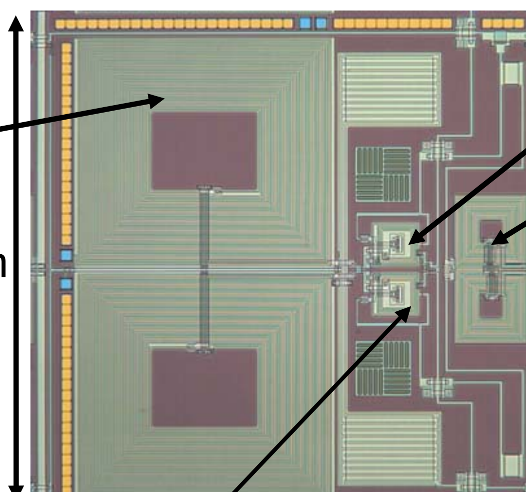
• Instrument size driven by need to cool large mirrors to below 10 K (to reduce thermal background on arrays)

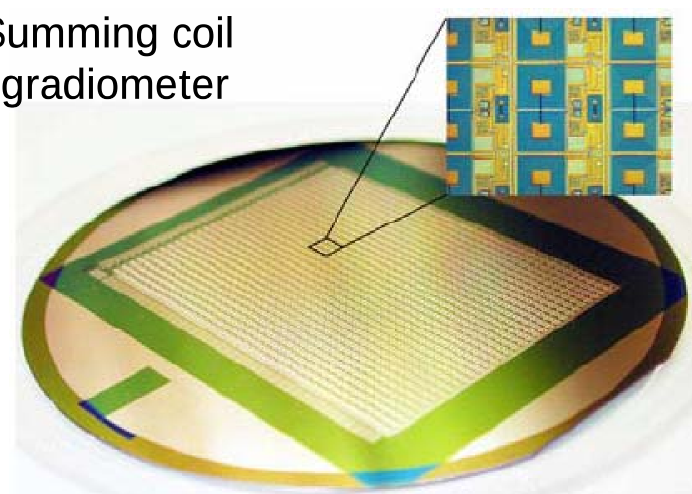


UK
Astronomy Technology Centre

Multiplexing

- Previous (much smaller) TES arrays have had separate detector and SQUID multiplexer chips
- For arrays of this size, number of wires would be impractical
- Instead, use new configuration: in-focal-plane multiplexer
    - MUX wafer is bonded to detector wafer
    - Indium bump bonds provide electrical connections



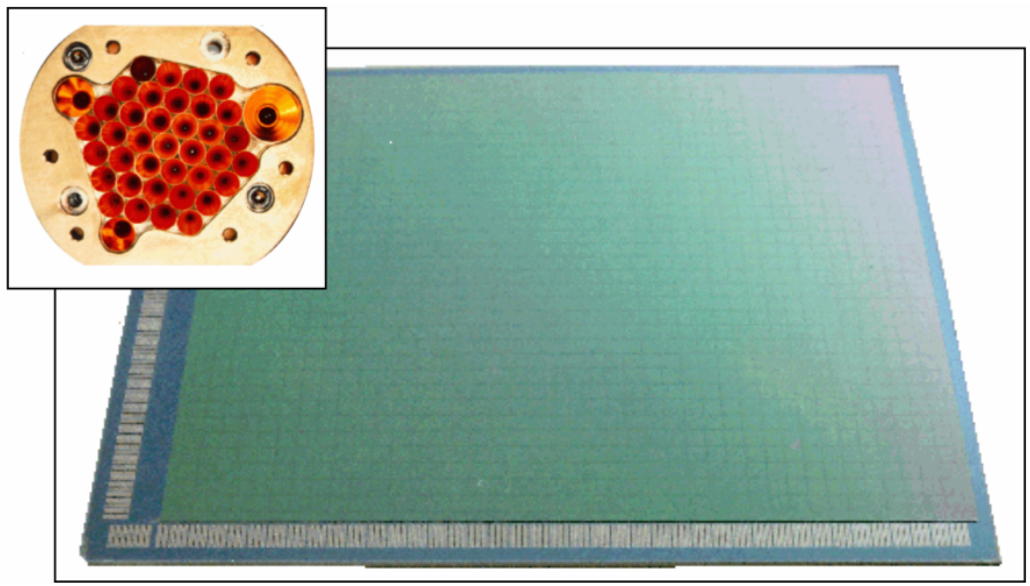


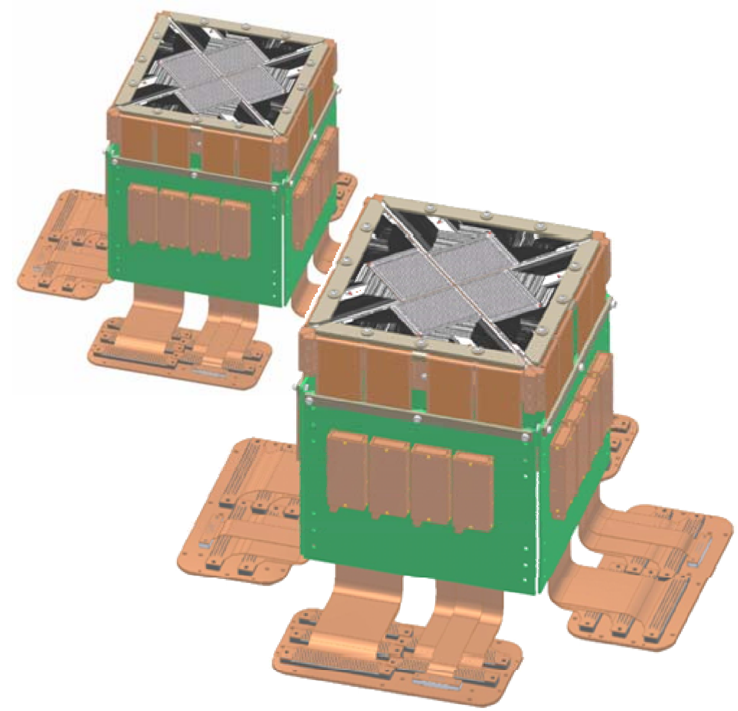
A full-sized (40 × 32 pixel) multiplexer wafer

Detectors

- Simultaneous dual colour imaging (450 and 850 μm)
- Each focal plane made up of four 1280 pixel sub-arrays

SCUBA-2 sub-array (SCUBA array inset)





SCUBA-2 detector units

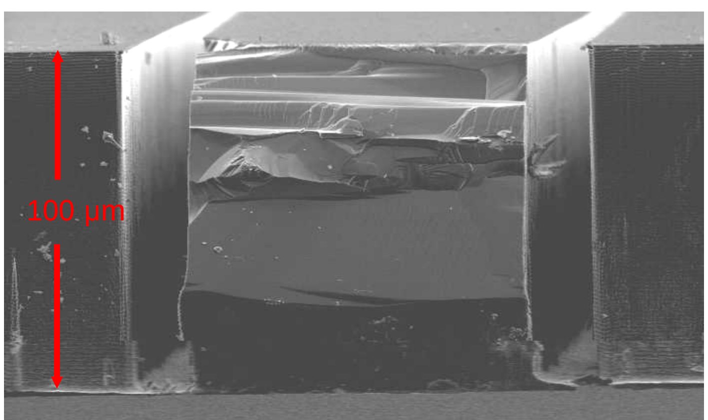
SMC SCOTTISH MICROELECTRONICS CENTRE

NIST National Institute of Standards and Technology

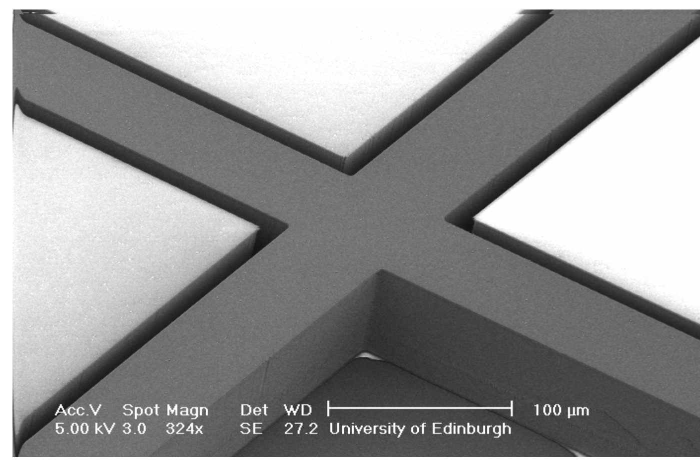
UK Astronomy Technology Centre

Detectors

- Time division multiplexing scheme
  - Separate readout box for each sub-array
- Pixels use Mo/Cu bi-layer superconductors
  - Weak thermal link provided by silicon nitride membrane
  - Pixel heaters used for sky background compensation

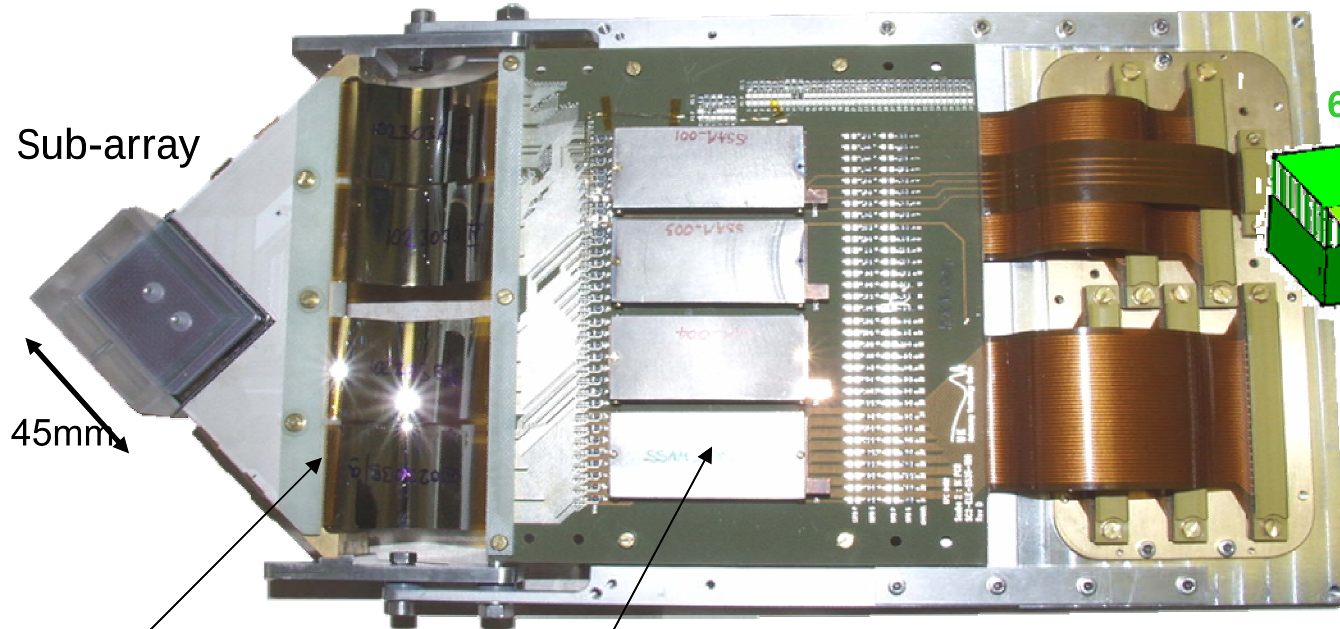


SMC
SCOTTISH MICROELECTRONICS CENTRE



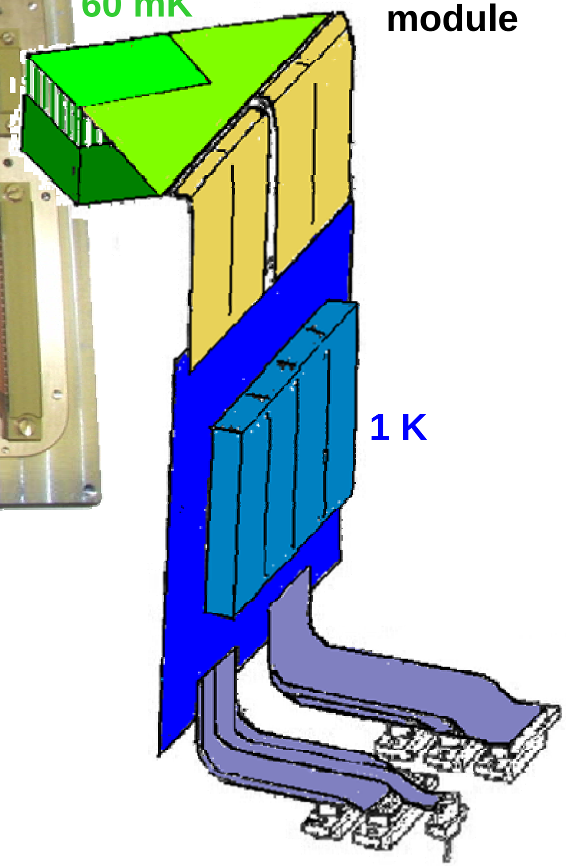
Sub-array module

Sub-array

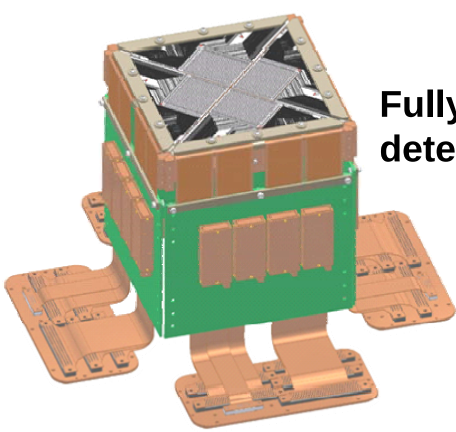


Niobium flex cables

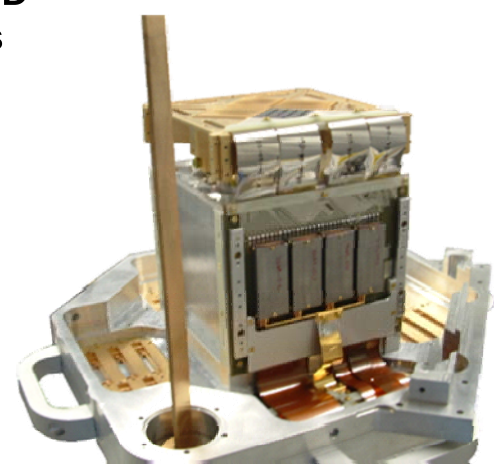
Shielded SQUID Series arrays



Folded sub-array module



Fully populated detector unit



Detector unit with one prototype array installed

Detector testing

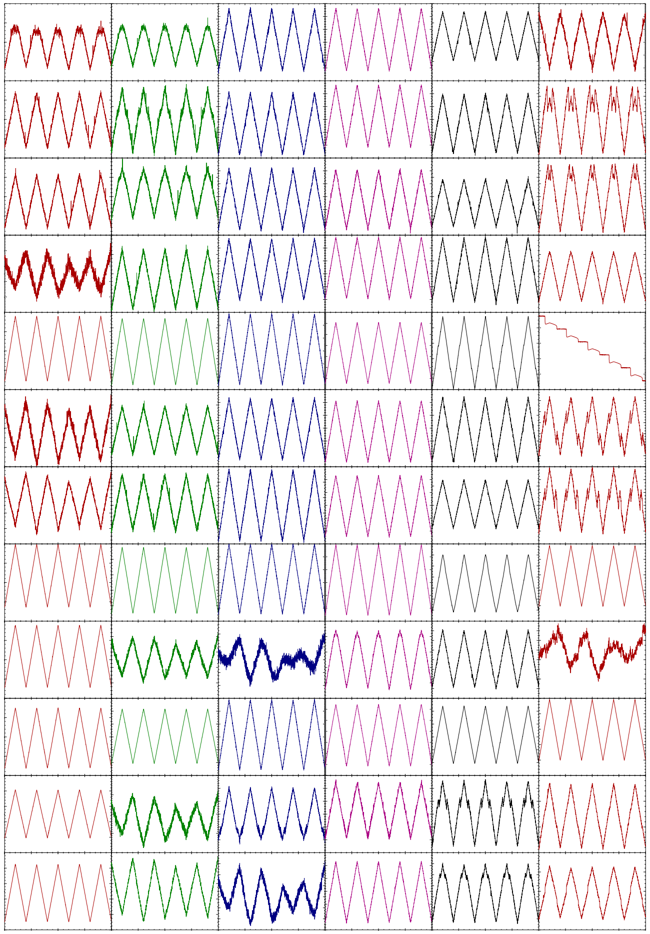
- Tests carried out on prototype 450 and 850 μm arrays
  - First tests of in-focal-plane MUX detector
  - First tests of arrayed SCUBA-2 style pixels
    - (Previous tests on single pixels only)
- Tests validate in-focal-plane concept as well as this implementation

- Tests carried out:
  - In dedicated testbed (Cardiff University)
    - Contains calibrated illuminator for optical measurements
  - In SCUBA-2 instrument (ATC, Edinburgh)

  - With test readout electronics
  - With prototype of final electronics

Multiplexing

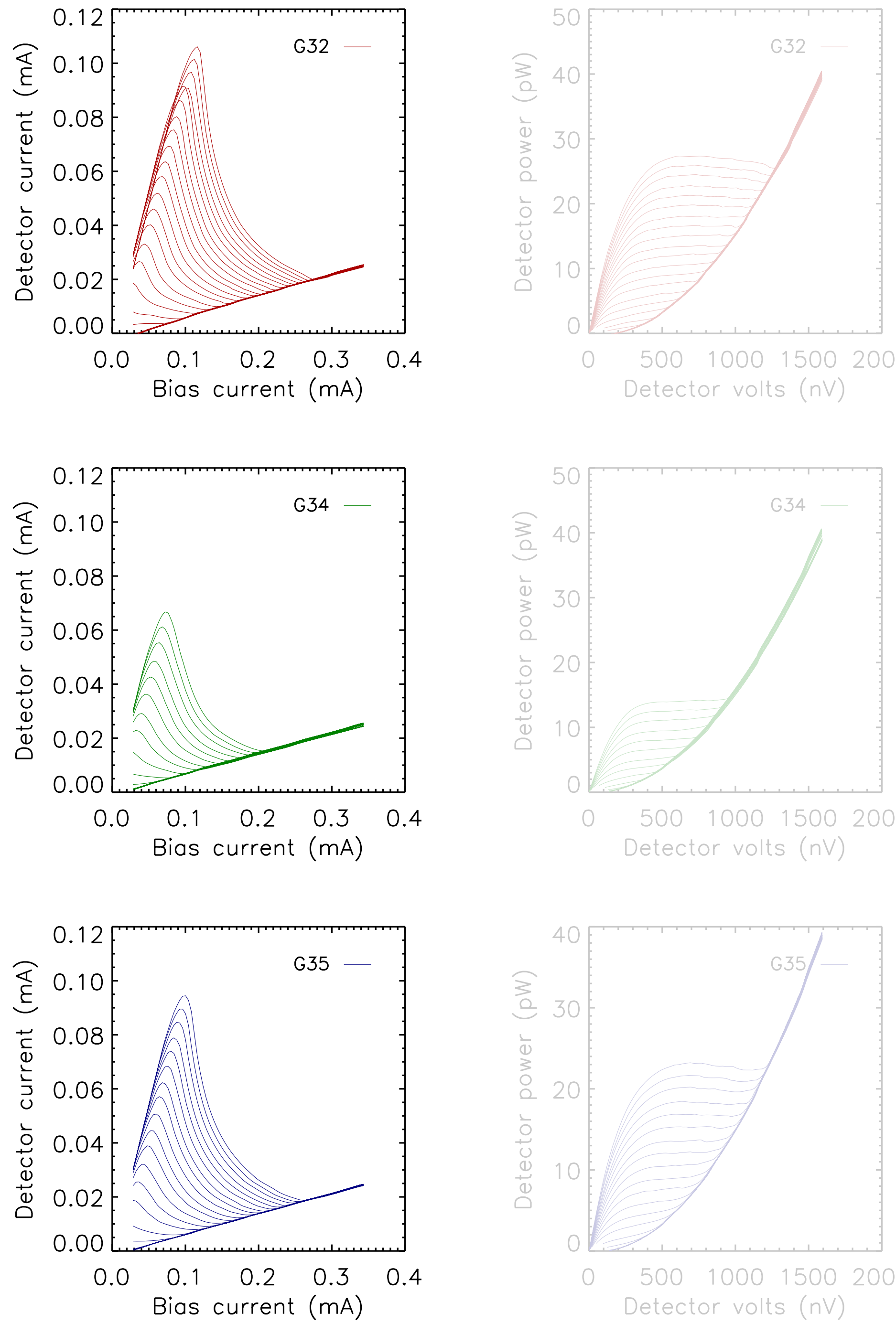
- Readout chain (through three series of SQUID) is complex, and requires tuning of several parameters
    - Automatic tuning not available yet



- Worked on small blocks of up to 72 pixels
    - All pixels read out simultaneously using multiplexer
    - Shown here responding to modulation of detector bias (6 columns, 12 pixels in each row

Load curves

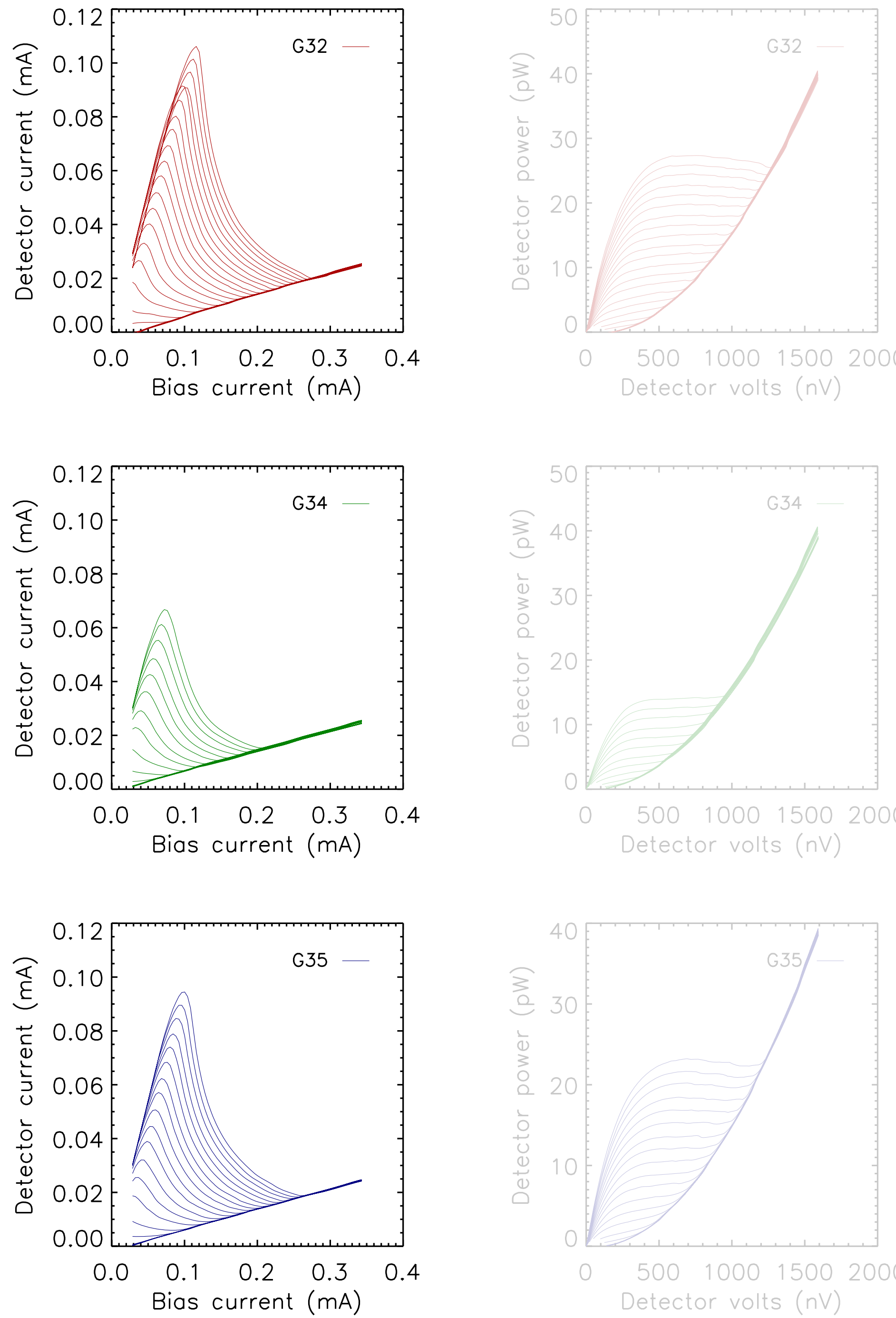
- Measure detector current as a function of bias current in multiplexed mode
- Basic characterization method
- Curves have expected shape
- Good agreement between two readout systems



Load curves

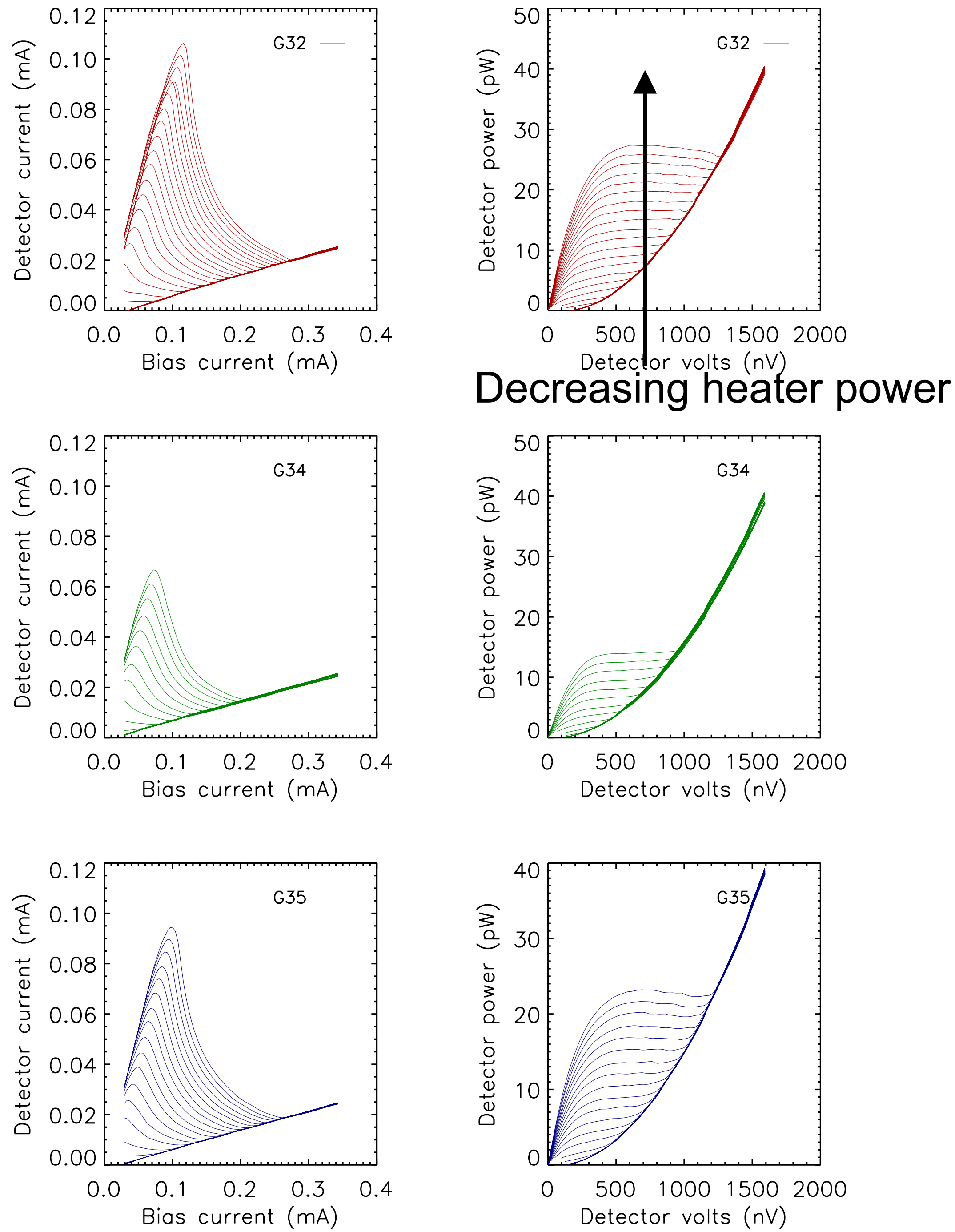
• Take set of load curves at different pixel heater settings

• Normal state resistance in agreement with design values √



Load curves

- Also plot as power in detector vs voltage
- Power constant in superconducting transition √
- Power proportional to V^2 in normal state √
- Responsivity (S) in transition proportional to 1/V √
- S = 5e5 to 8e6 A/W. Values agree with those from modulating bias



Power measurements

- Three ways of applying power to a pixel:
  - Bias
  - Pixel heater
  - Optical signal
    - Calculate power using calibration for illuminator power and measured filter profiles

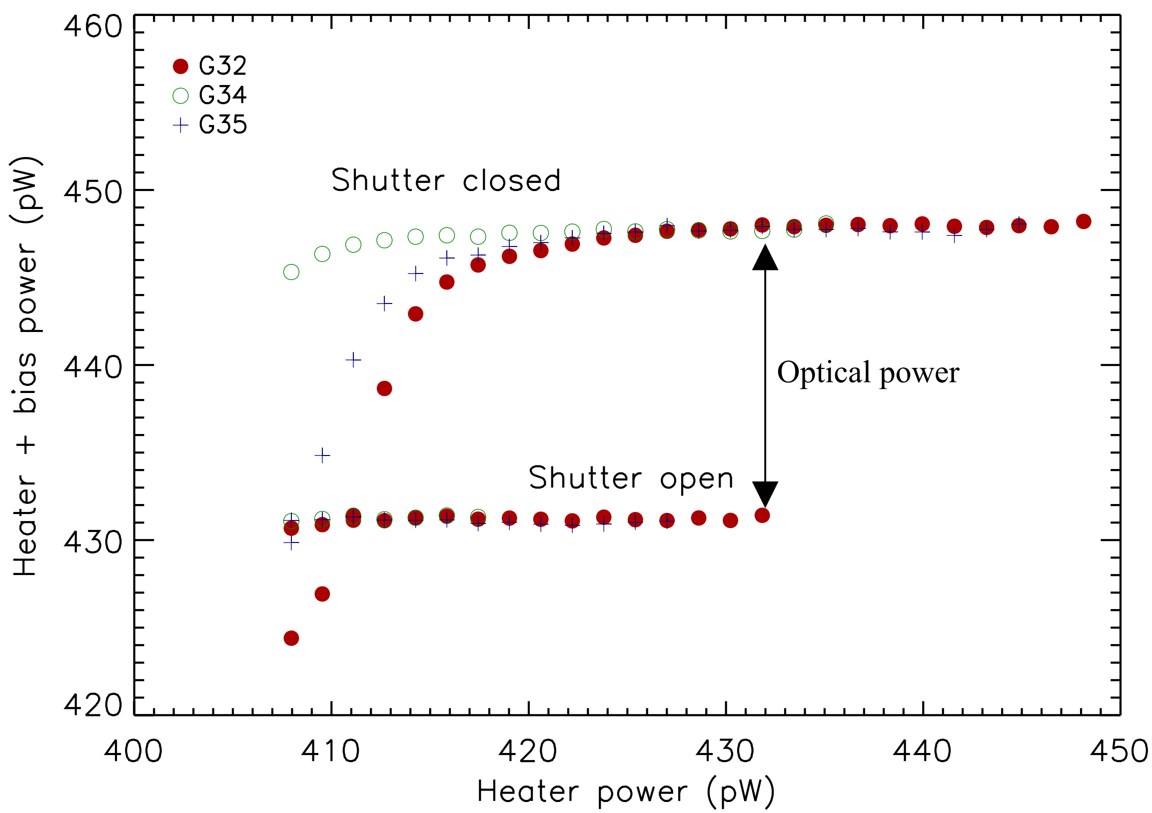
- Good agreement when power is applied all three ways
  - Calibration is well understood
    - We can have confidence in Noise Equivalent Power (NEP) values

Example

- For each load curve, plot electrical (heater+bias) power in transition

- Electrical power constant as heater power varies √

- Difference in power for shutter open and closed same for different pixels (NO calibration factor!) √



Performance

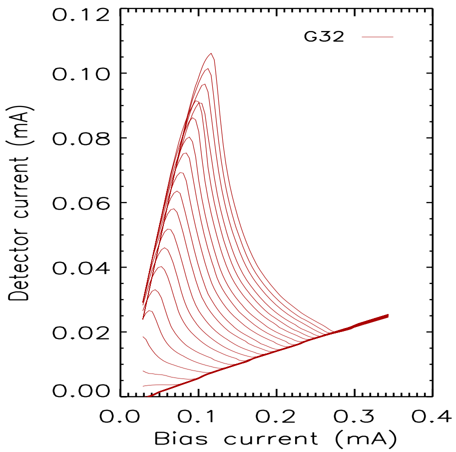
Parameter	**450μm**			**850μm**		
	Spec	**Single pixel**	**Proto array testing**	**Spec**	**Single pixel**	**Proto array testing**
T_c (mK)	150 – 170	193	175	120 – 140	133	130
Total power (pW)	200 – 250	267	460	40 – 60	57	60
G (nW/K)	~5	5.2	9.0	~1.5	1.6	2.0
Optical NEP (W/√Hz)	**$<29 \times 10^{-17}$**	**9.7×10^{-17}**	**14×10^{-17}**	**$<7 \times 10^{-17}$**	**3.5×10^{-17}**	**2.5×10^{-17}**
τ_e (msec)	<1.5	0.2	0.6	<2.8	0.6	1.0

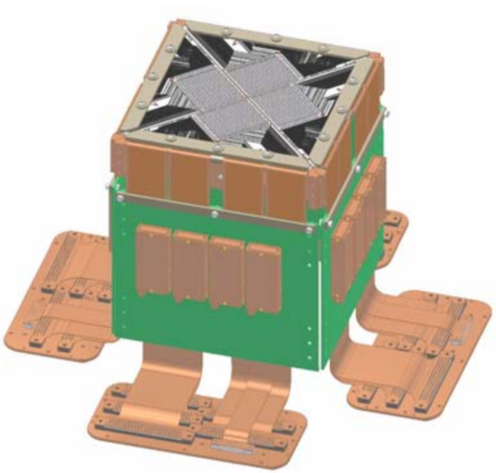
Conclusions

• Detectors and read-outs operate in a stable and reproducible fashion

• Basic concept of in-focal-plane multiplexer works

• Array design has been proven with performance parameters met





• *Instrument* performance has been verified using prototype array

• Results have enabled us to go ahead with science grade array production