First tests of prototype SCUBA-2 array

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Techniques and Instrumentation in Low Temperature Physics meeting

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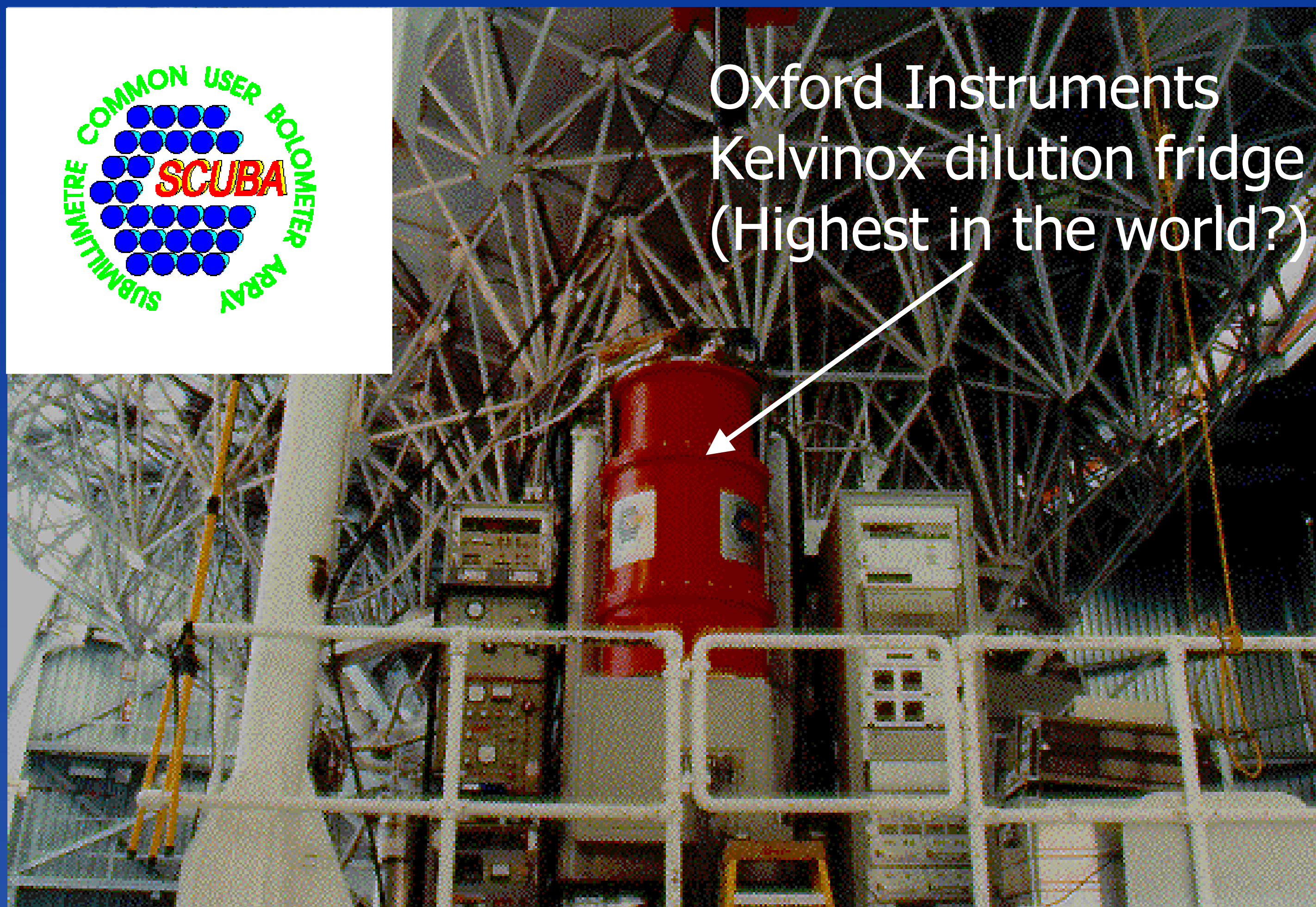
Sub-mm astronomy

- Wavelengths of a few hundred µm
- Use mix of optical (e.g. lenses) and radio (e.g. waveguides) techniques
- Atmosphere largely opaque at these wavelengths
- Need to observe from high and dry sites (e.g. Mauna Kea in Hawai'i or South Pole)
- Field still very immature; few applications outside astronomy for sub-mm detectors (this is changing though)

SCUBA (1)

- Huge revolution over the past decade
- Largely down to one instrument - SCUBA on the JCMT in Hawaii
- Development lead by ROE, Edinburgh
- Citation rate rivals Hubble
- Only instrument better known than the telecsope it’s on?
- Cryogenically challenging: mK operation at telescope, large wire counts

SCUBA on the JCMT



COMMON-USER SUBMILLIMETRE BOLOMETER ARRAY - 2

SCUBA2

Context

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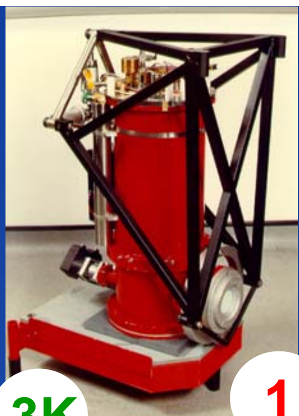
JCMT-UKT14
350μm-2mm



.3K 1

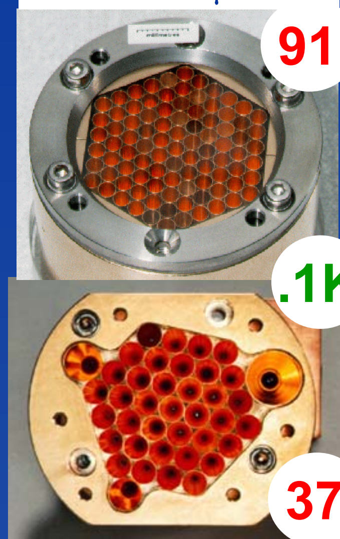
1986-1996

CSO-SHARC
350 μm array

.3K 20

1996-

JCMT-SCUBA
350/450 &
750/850μm

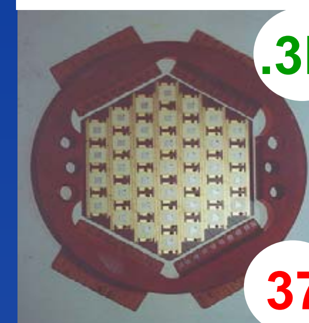


91 .1K 37

1997-

Also 19 pixel 2 mm array at 0.1 K

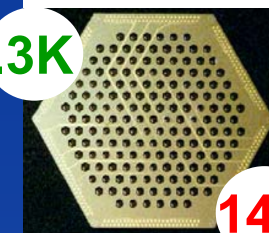
IRAM- MPIfR
1.3mm array



.3K 37

1998-

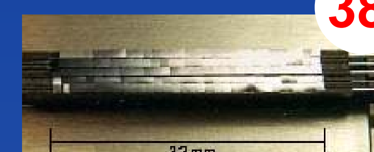
LMT-BOLOCAM
1.1mm



.3K 144

2001-

.3K 384



CSO-SHARC-II
350/450

2004-

91 Number of pixels

.3K Operating temperature

(300 mK much easier than 100 mK - can use sorption fridge)

Multiplex Advantage

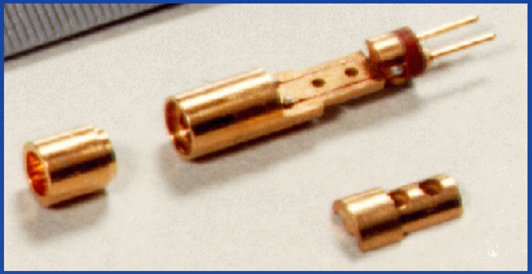
OECD Working Group on Large Future Facilities in Astronomy:

“The far-IR/submm is one of the few areas where massive advantages can still be made by increasing the multiplex gain (pixel count)”
R. Genzel

Instrument	Telescope	Year	No. of pixels
UKT14	UKIRT/JCMT	1986-1996	1
SHARC	CSO	1996	24
SCUBA	JCMT	1997	131
MAMBO	IRAM	2000	117
SHARC-II	CSO	2004	384
HAWC	SOFIA	2005	384
Laboca	APEX	2005	295
SCUBA-2	JCMT	2006	10000
SPIRE	Herschel	2007	280

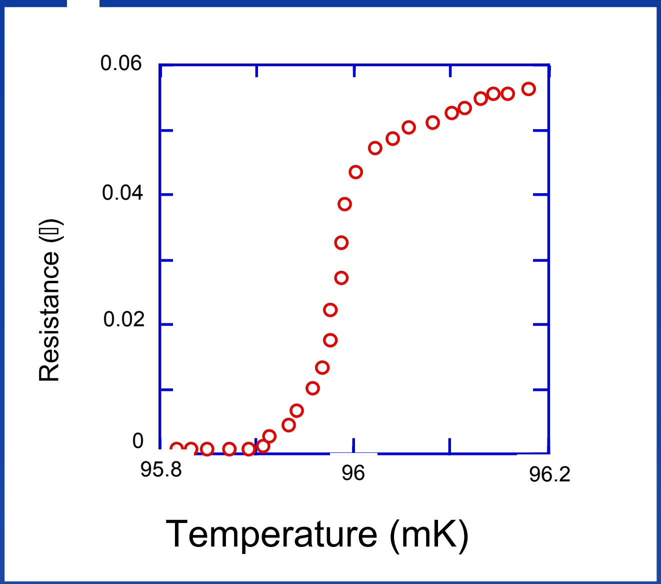
SCUBA-2

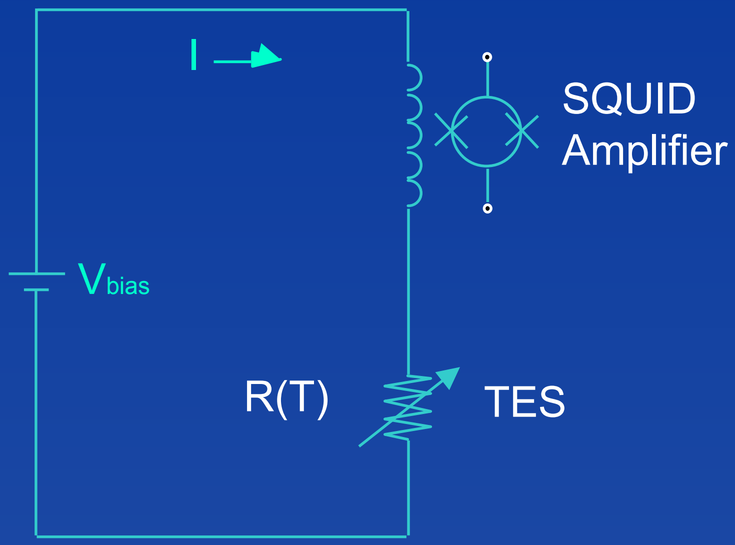
- Large step forward
- >5000 pixels at 450 and 850 μm.
- SCUBA-2 will bring CCD-style imaging to the sub-mm for the first time
- Need a change in technology - SCUBA uses semiconductor bolometers, each individually assembled.



- Need to multiplex to keep wire count reasonable. Not practical with semiconductors for SCUBA-2
- Use TES detectors:

Voltage biased TES



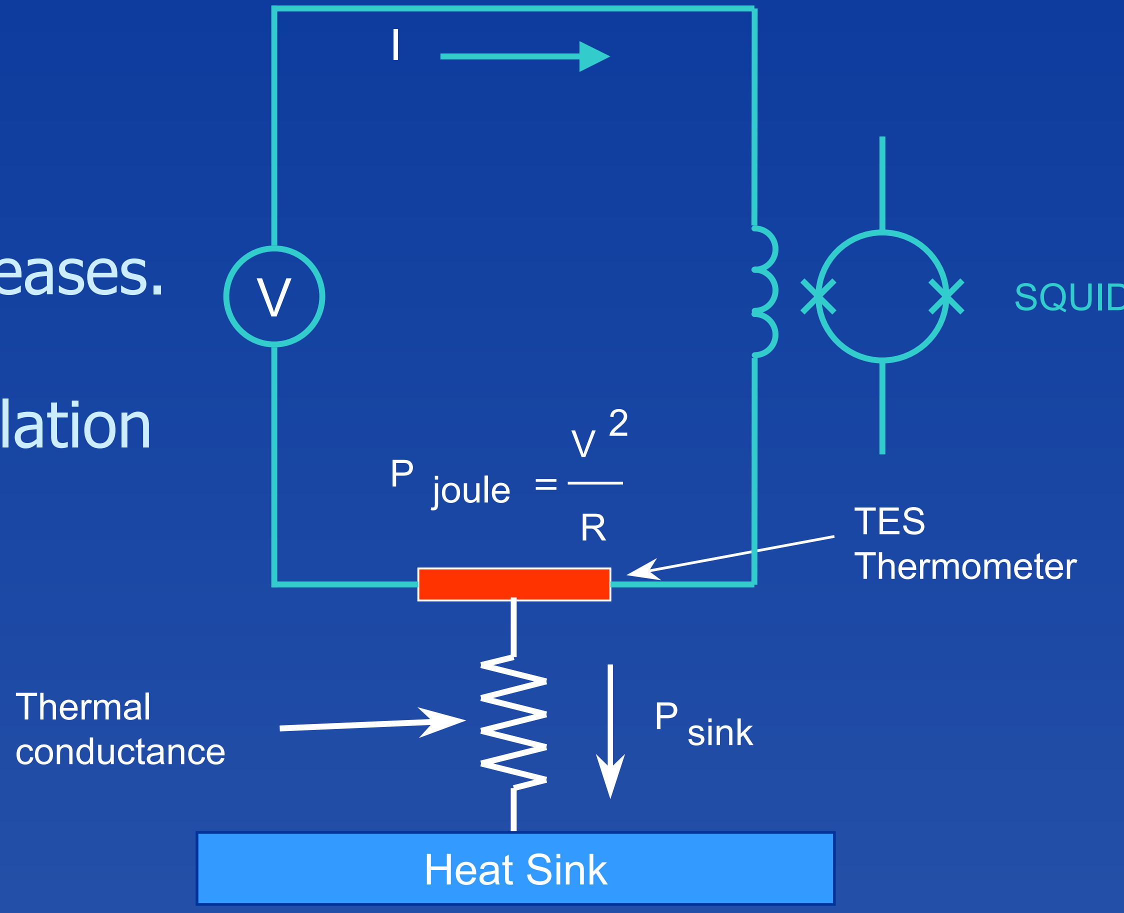


Superconducting Transition-Edge Sensor (TES)

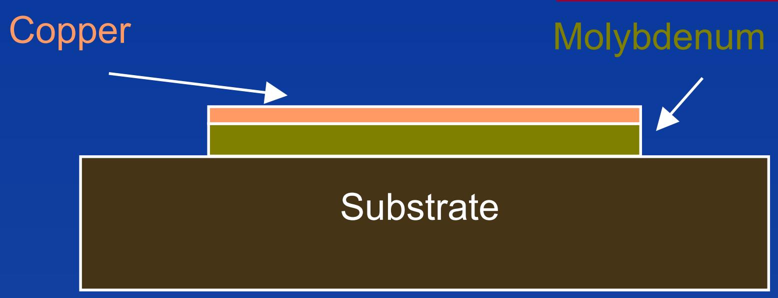
Self-biasing

As the film cools, R decreases
and Joule heating increases.

Temperature self-regulation
in stable equilibrium

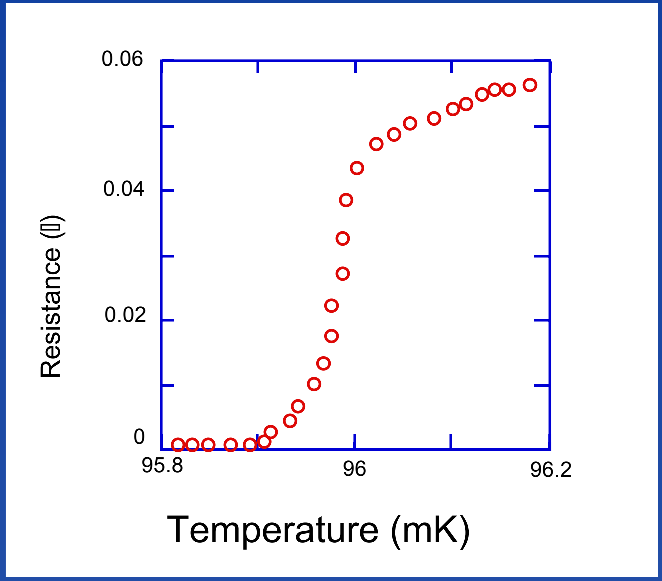


Mo/Cu bi-layer



Bilayer of thin superconducting and normal metal films acts as single superconductor with tunable T_c (proximity effect)

Molybdenum/copper:
Robust.
Transition is:
- sharp (<~5 mK)
- stable
- reproducible



COMMON-USER SUBMILLIMETRE BOLOMETER ARRAY - 2 SCUBA2

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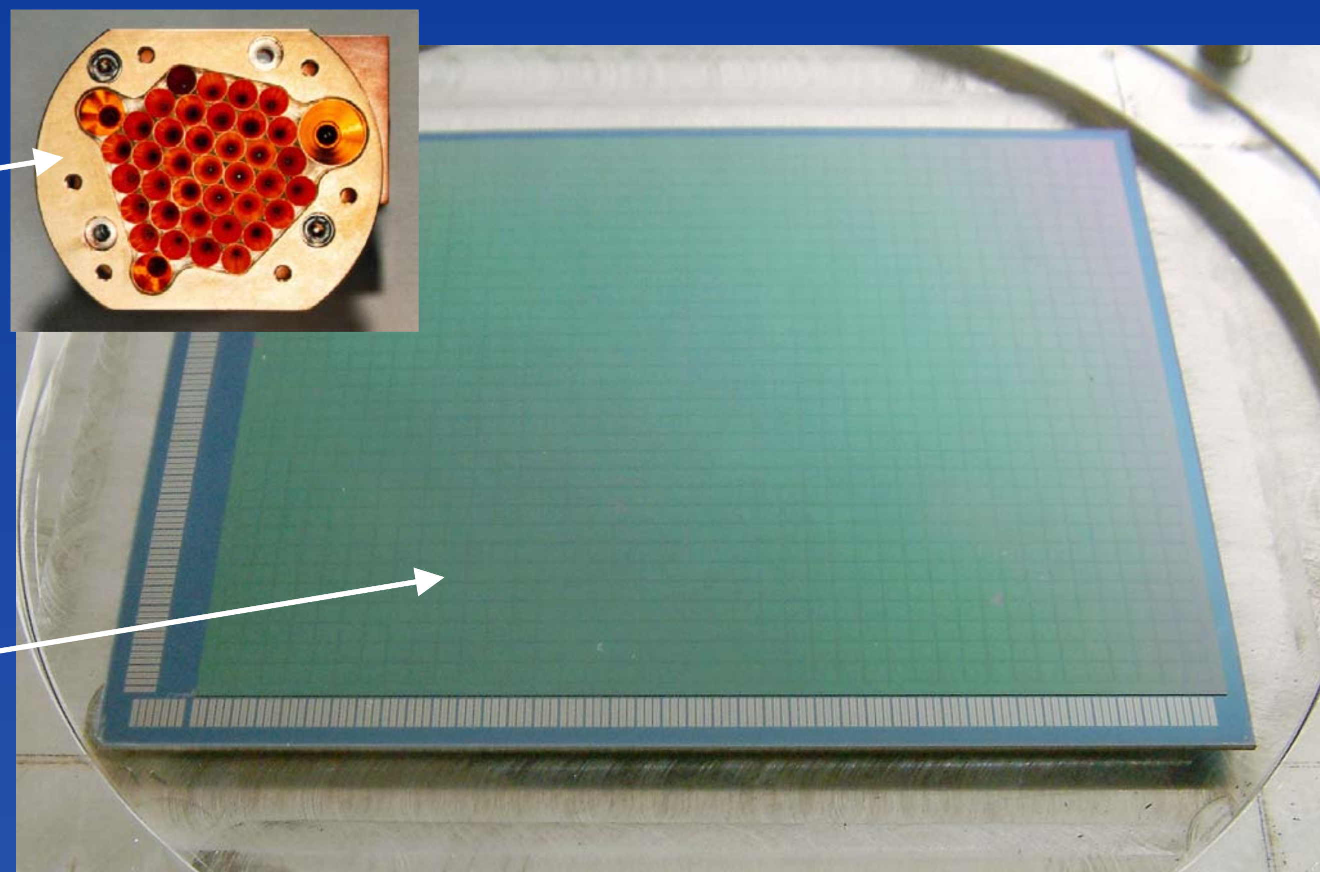
NIST Boulder Colorado

Arrays

Possible to fabricate array with large number of TES pixels

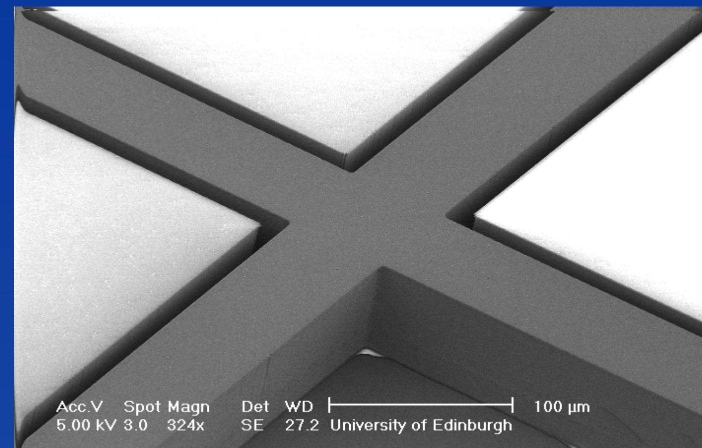
SCUBA 850μm array



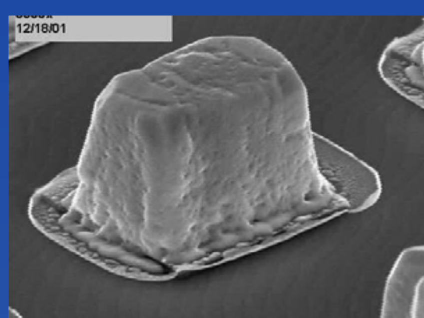
Completed 40 × 32 (1280) pixel prototype SCUBA-2 array

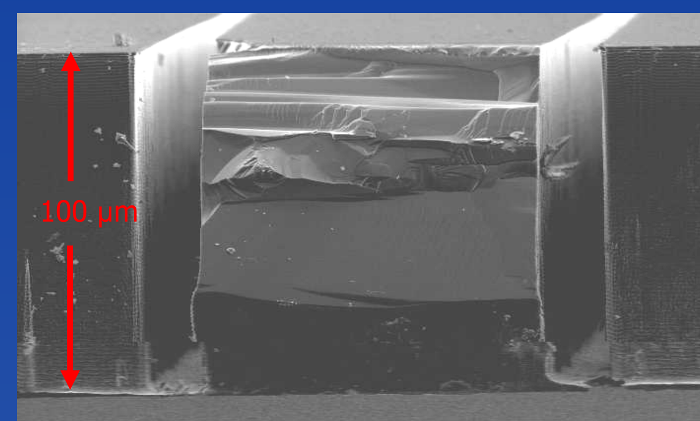
Array Production

Bump bonding
MUX to detector



Raytheon
Vision Systems



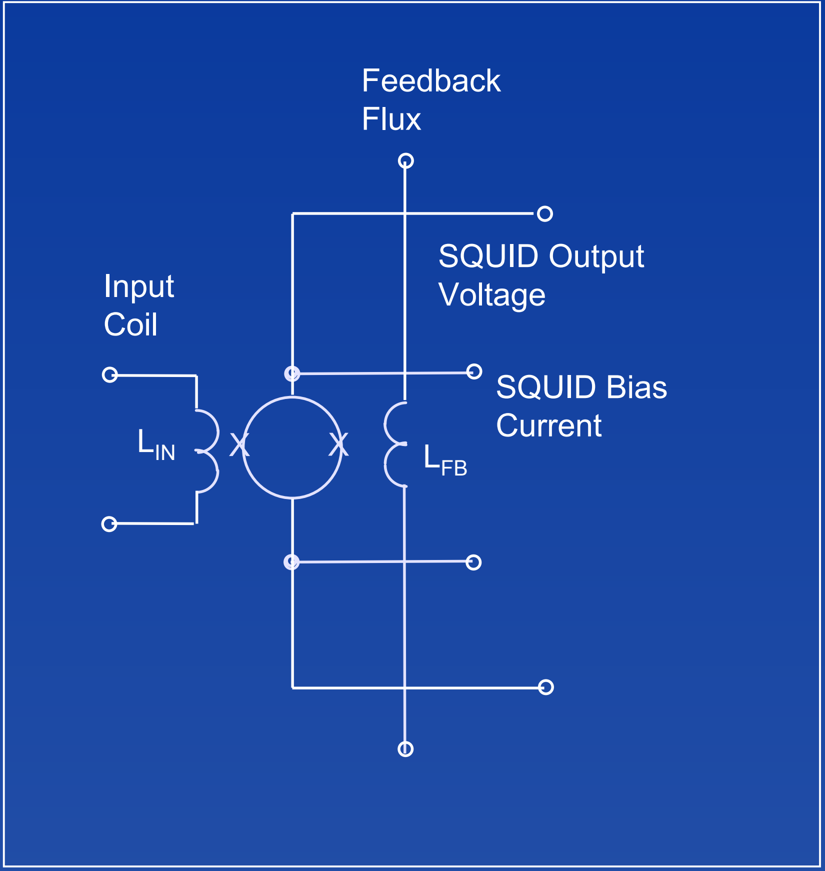


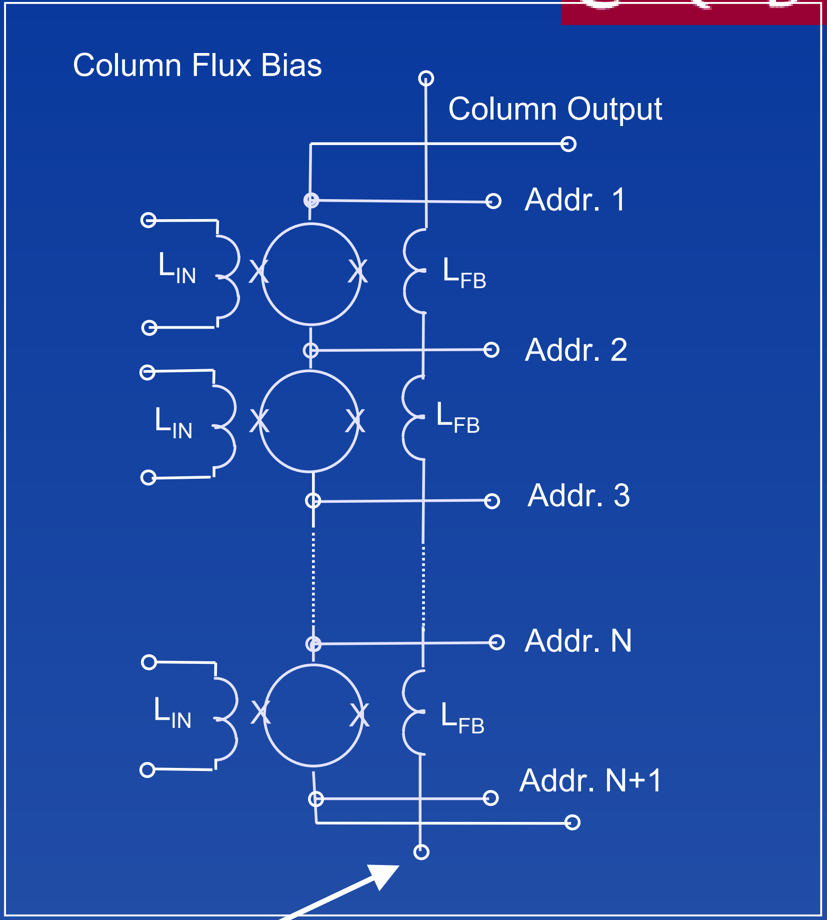
Deep etching to isolate detector pixels

Read-out

- So we have an array. But:
- Can't read each pixel individually - too many wires!
- Need to be able to multiplex
- This is another advantage of using TES detectors
- SQUID based multiplexing system has been developed at NIST
- Uses TDM (time division multiplexing)

Multiplexer

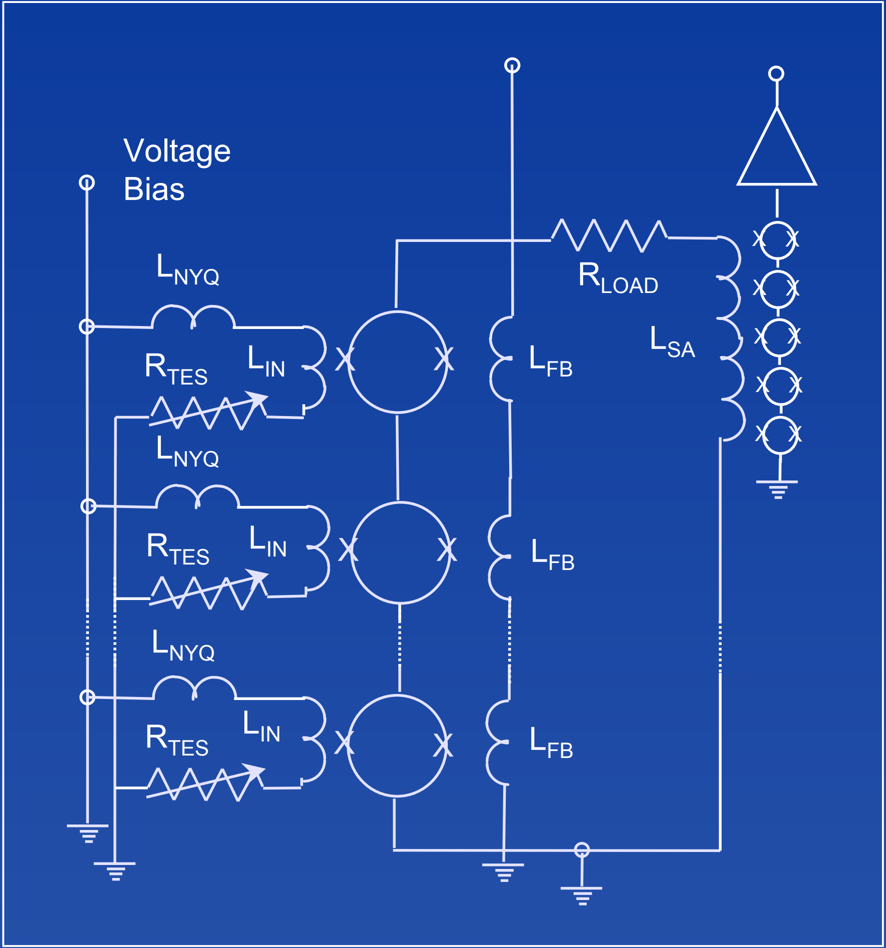




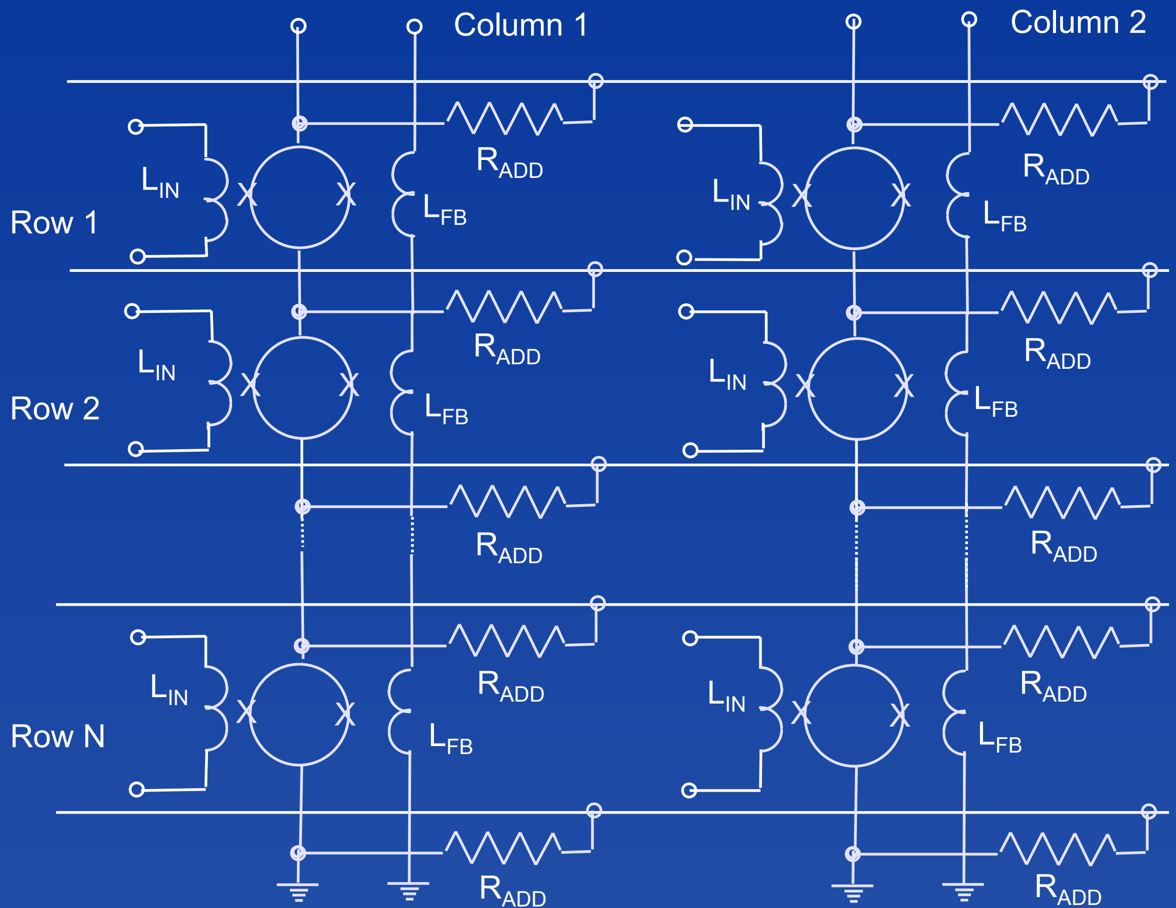
Price of TDM with SQUIDs: must use smart digital feedback which remembers last feedback setting to zero flux

Multiplexer

- Must use series-array SQUID *(invented at NIST)* to couple to room-temperature amplifiers.
- Required for high bandwidth and high dynamic range for switching feedback operation.
- Conventional SQUIDs: impedance is too low.



2-d multiplexer



In-plane multiplexer

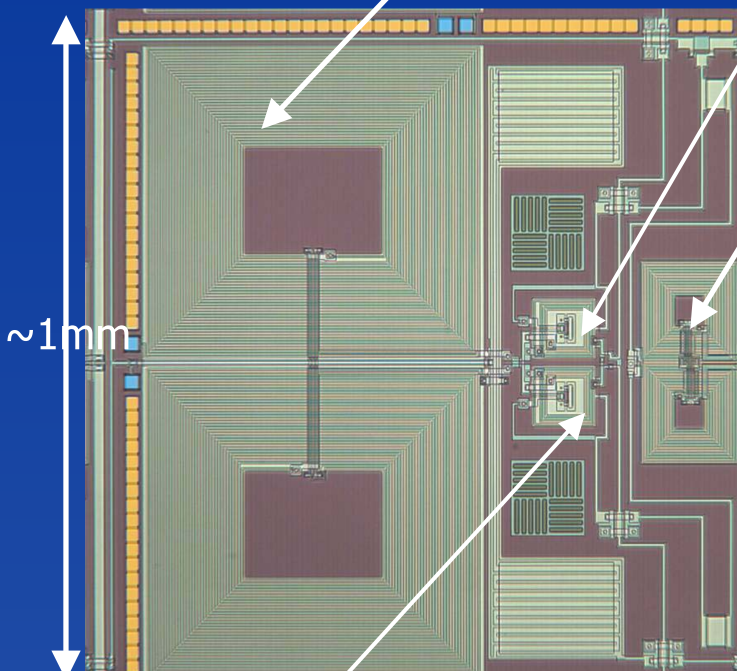
- Not practical to have separate multiplexer for SCUBA-2
- Not enough space
- Wiring the multiplexer to the detectors would be a nightmare
- Solution: position multiplexer below focal plane (never been done before)
- Use indium bump bonds to carry electrical signals and to bond the two wafers together

In-plane multiplexer

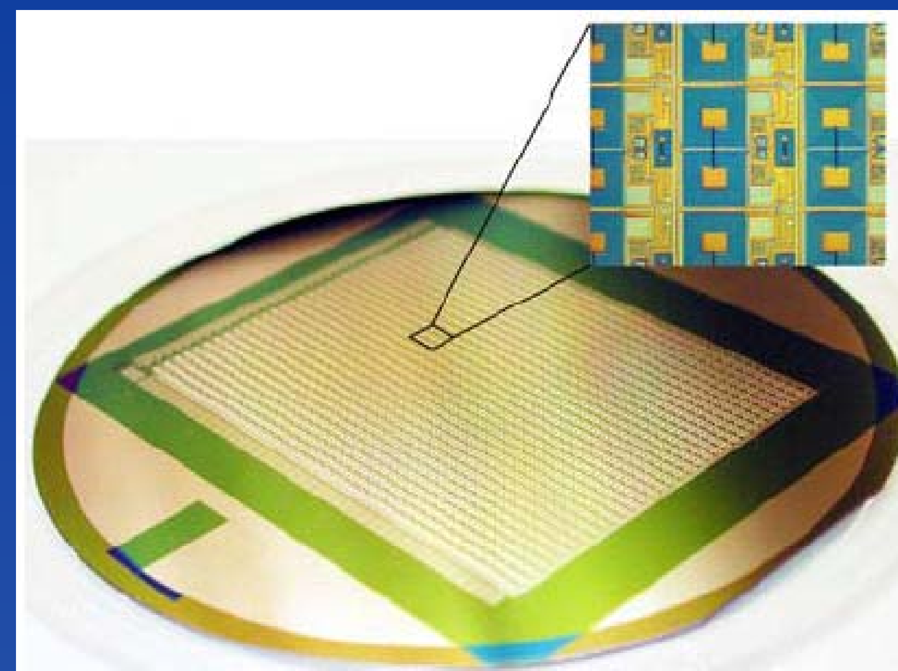
Input transformer

Active SQUID

Summing coil gradiometer



Dummy SQUID



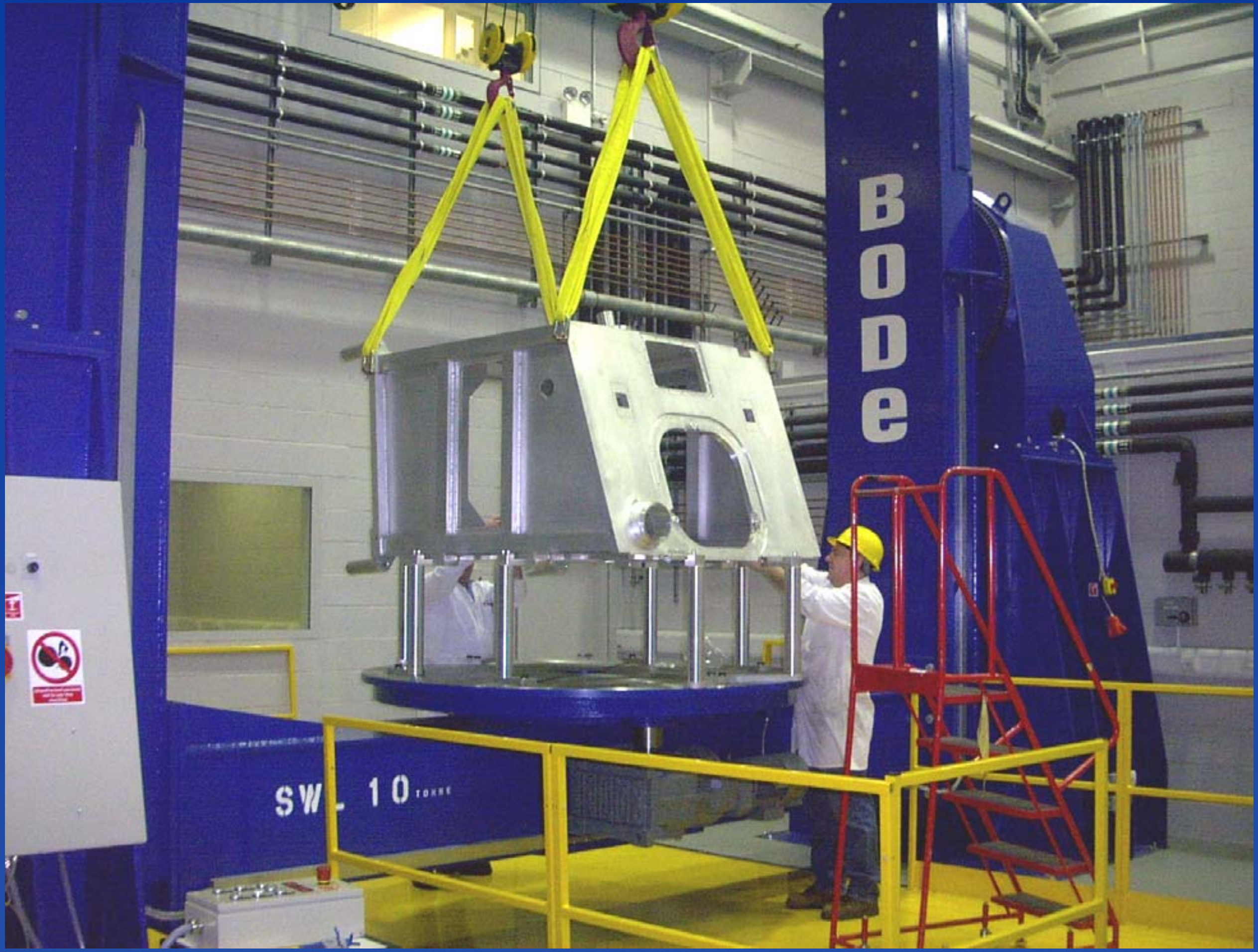
A full-sized (40 × 32 pixel) multiplexer wafer

The rest…

- Now we just need to get the arrays cold, bring light to them and operate them

- So we require…
- Test programmes
- Cryogenics
- Optics
- Software
- Electronics
- Telescope modifications

It's large...

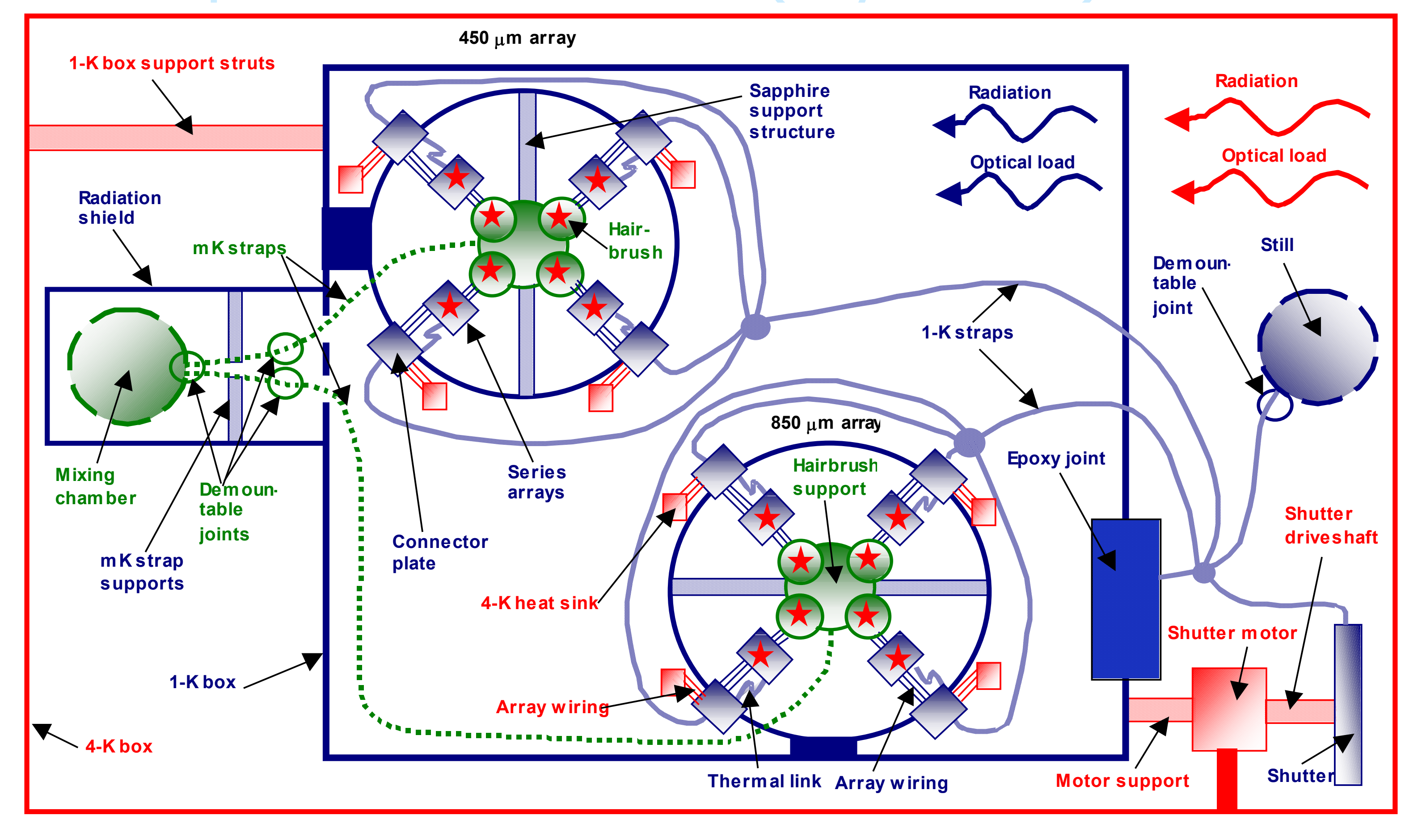


4-K box

...complex thermally...

1 'dry' dilution fridge (Leiden Cryogenics)

3 pulse tube coolers (Cryomech)



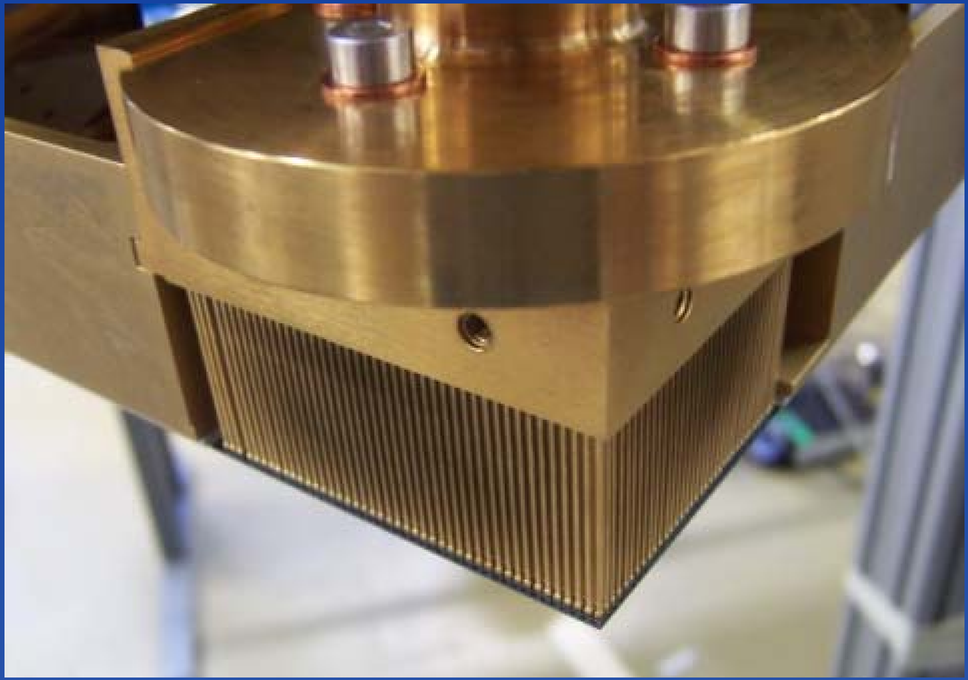
…with a novel dilution fridge…

- Leiden Cryogenics has developed a “dry” dilution fridge cooled with a pulse tube cooler rather than a helium bath
- Specification: 500 μW at 120 mK
- Large reduction in operating costs at telescope
- Many other applications: turnkey cooling down to mK temperatures

Leiden Cryogenics BV
Leader in LT Techniques

…and many solutions to find

- Example: making good thermal contact to silicon wafer without thermal contraction breaking it.
- Solution: “hairbrush”:



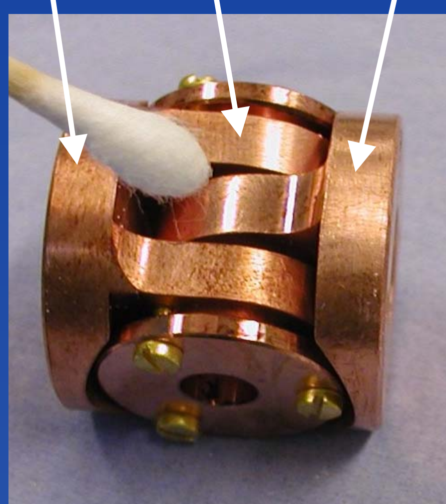
…and many solutions to find

- Need to support arrays rigidly with low heat leak
- Solution: “sapphire interface support”: 2.5 µW heat leak from 1 K to 100 mK

Thermal isolation

Cold side

Warm side



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But it's all worth it.

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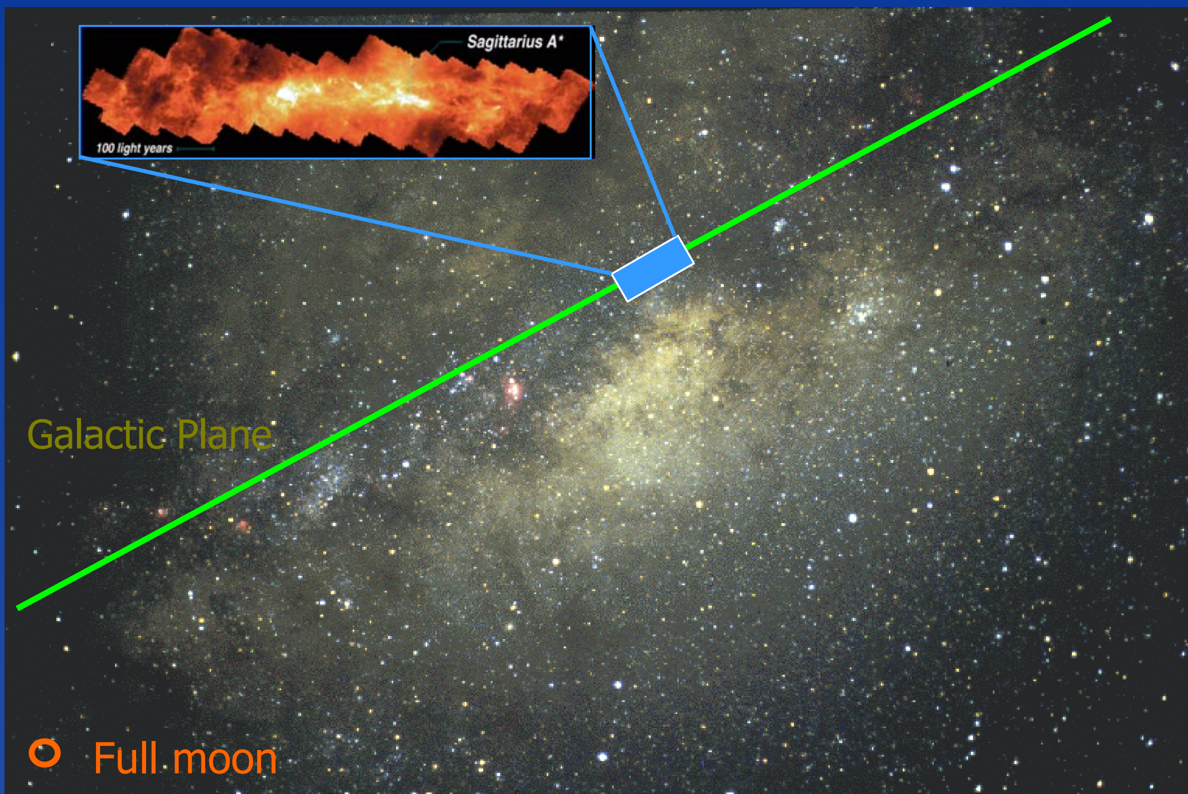


SCUBA Galactic Centre Survey

⇓

~120 hrs over 2 years of excellent weather telescope time

SCUBA-2 could map the ENTIRE AREA shown above in just a couple of hours to the same S/N...

And…

- Many other applications possible for the technology developed:

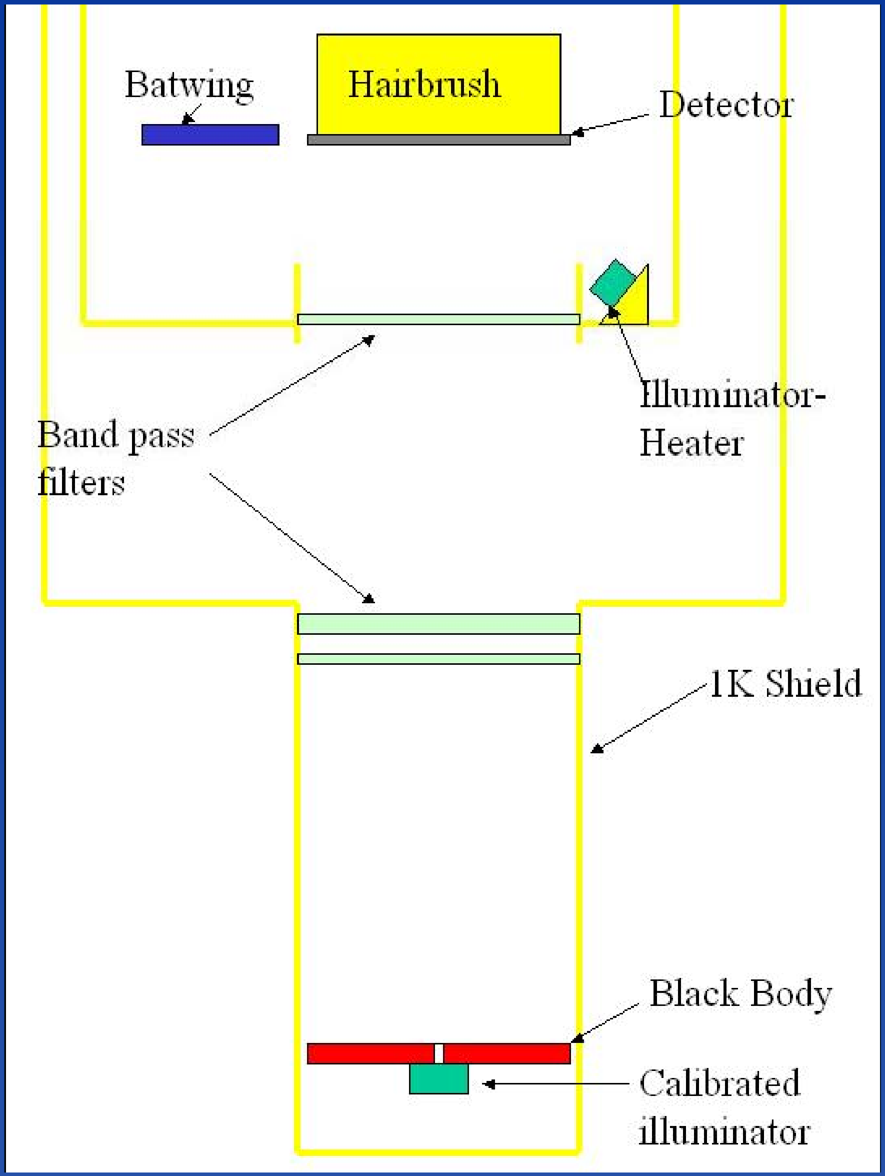
- Future sub-mm astronomy instruments
- THz imaging (medical, security…)
- Turnkey mK cryogenic operation
- Construction of other large mK instruments (considerable research into design aspects such as thermal straps)

Prototype tests

- Electrical and optical tests of prototype array carried out late 2004/early 2005 at Cardiff
- First test of multiplexer integrated with detectors
- Testbed mimics electrical, mechanical and thermal interfaces of instrument
- Detector “array unit” can be mounted in testbed without modification.

Testbed layout

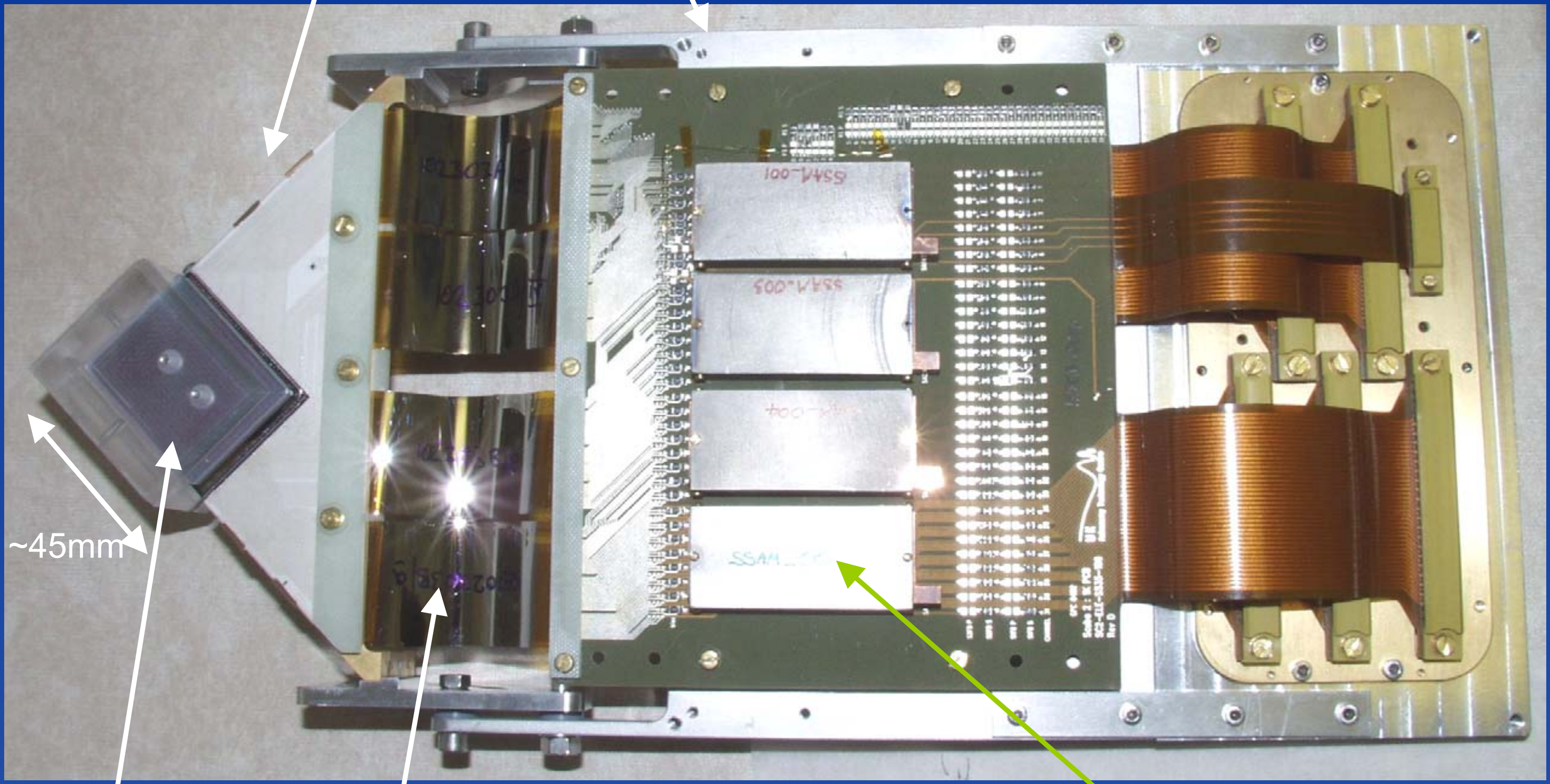
Cooled using Leiden Cryogenics custom built (wet) dilution refrigerator



Sub-Array Module

60 mK

1 K

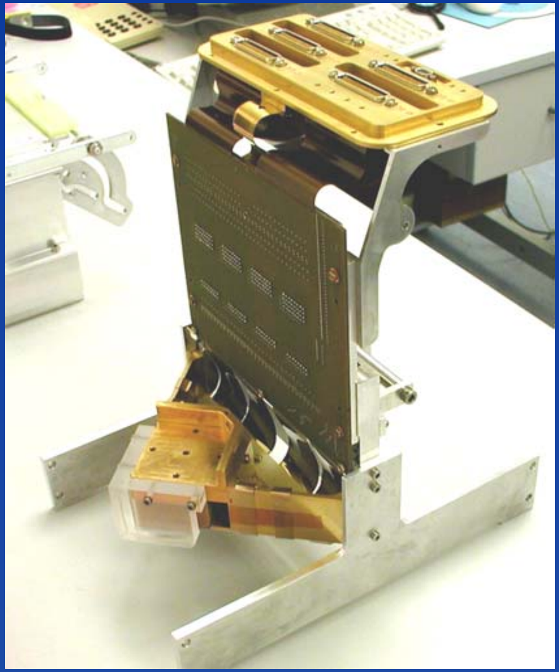


Detector array

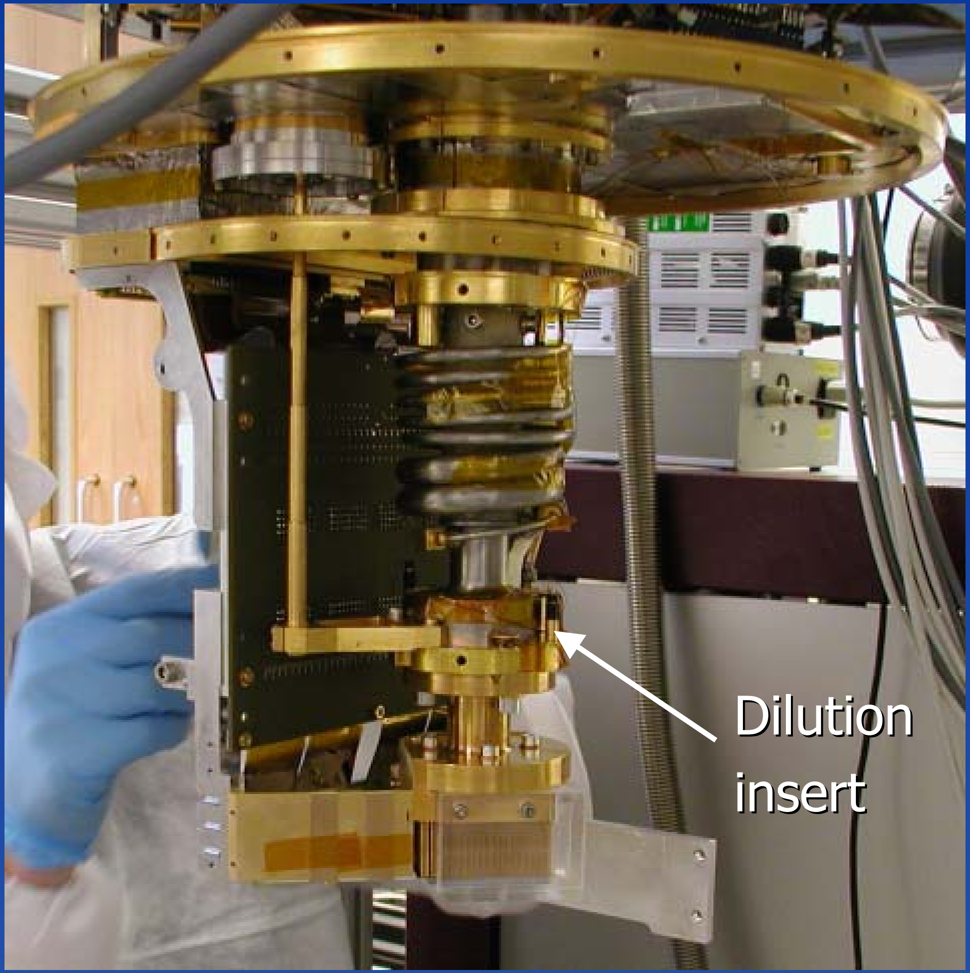
Ribbon cables: Niobium film on kapton

Series array unit in niobium cans (need to be at 1-K because of heat dissipation)

Installation



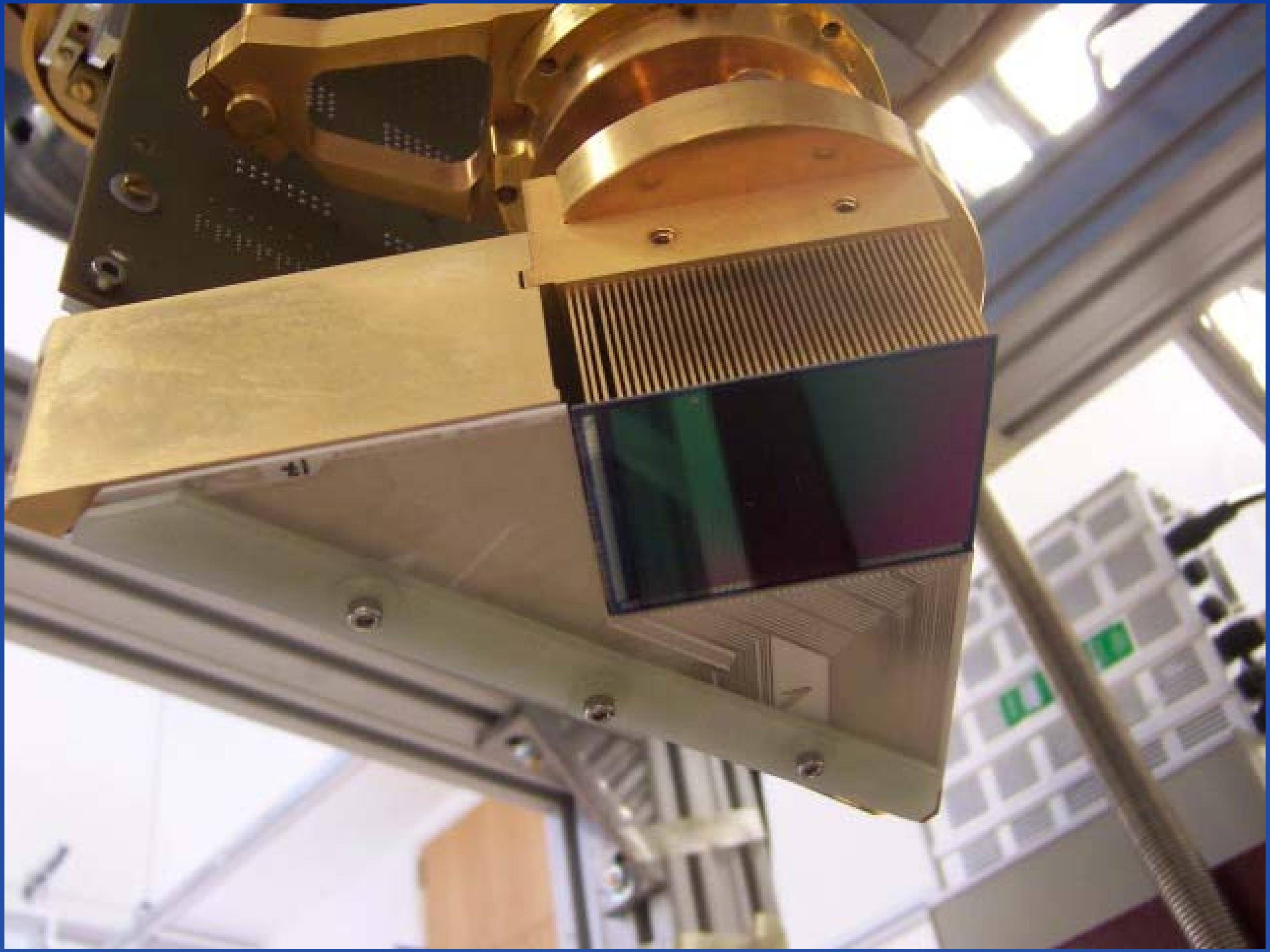
Folded and ready for installation



Installed in Cardiff test facility

Keeping it clean

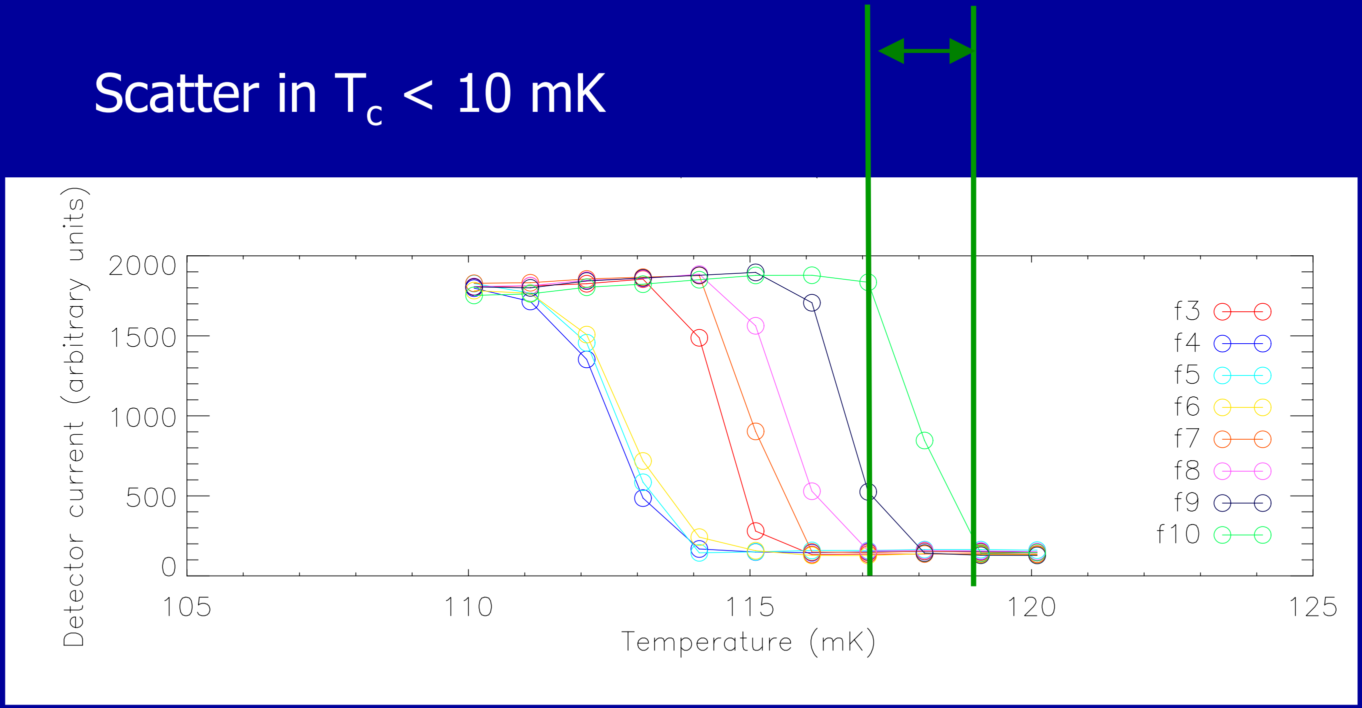
Ready to go



Test results

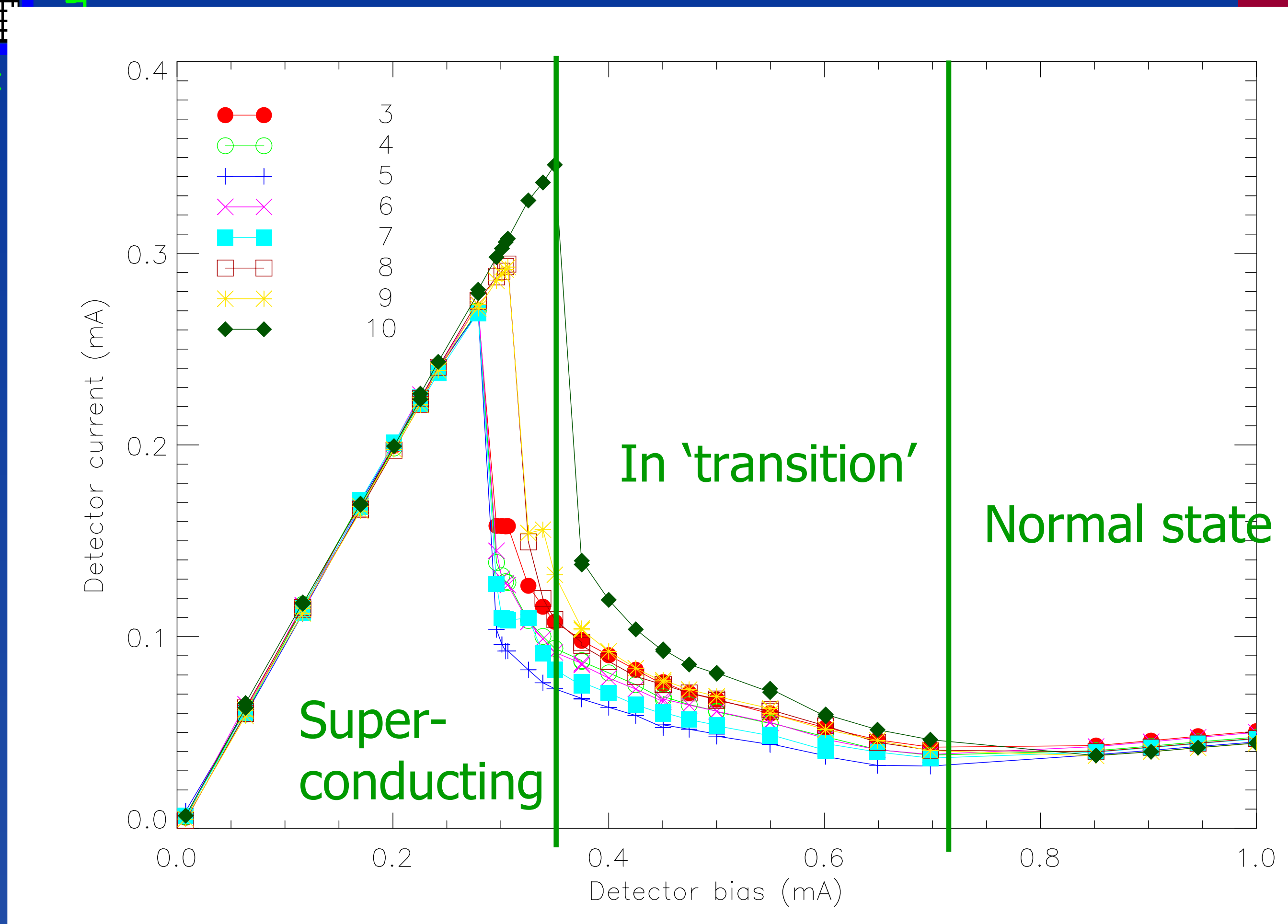
Transition width ~ 2 mK

Scatter in T_c < 10 mK



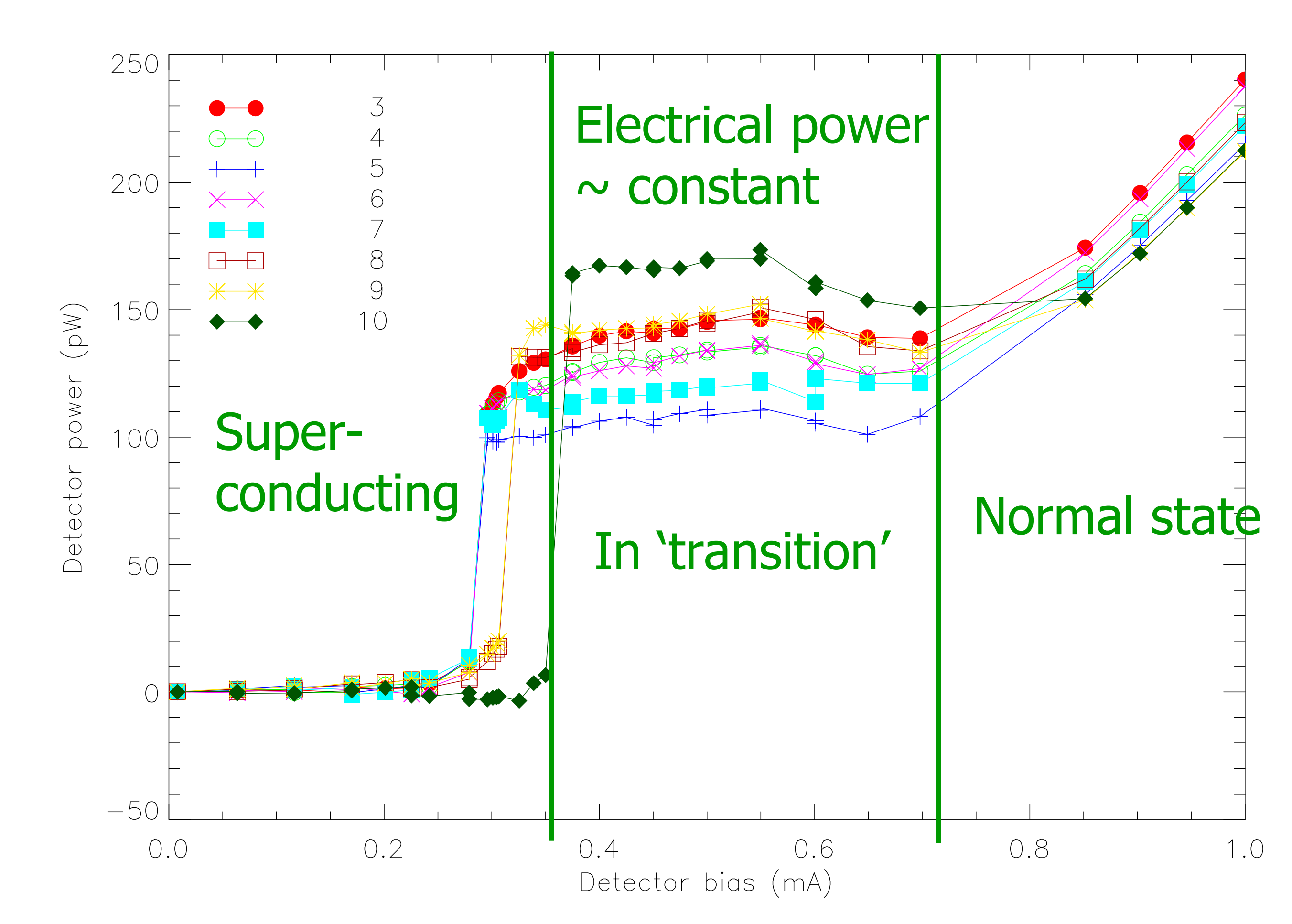
Detector resistance (in arbitrary units) as a function of heat sink temperature

Test results



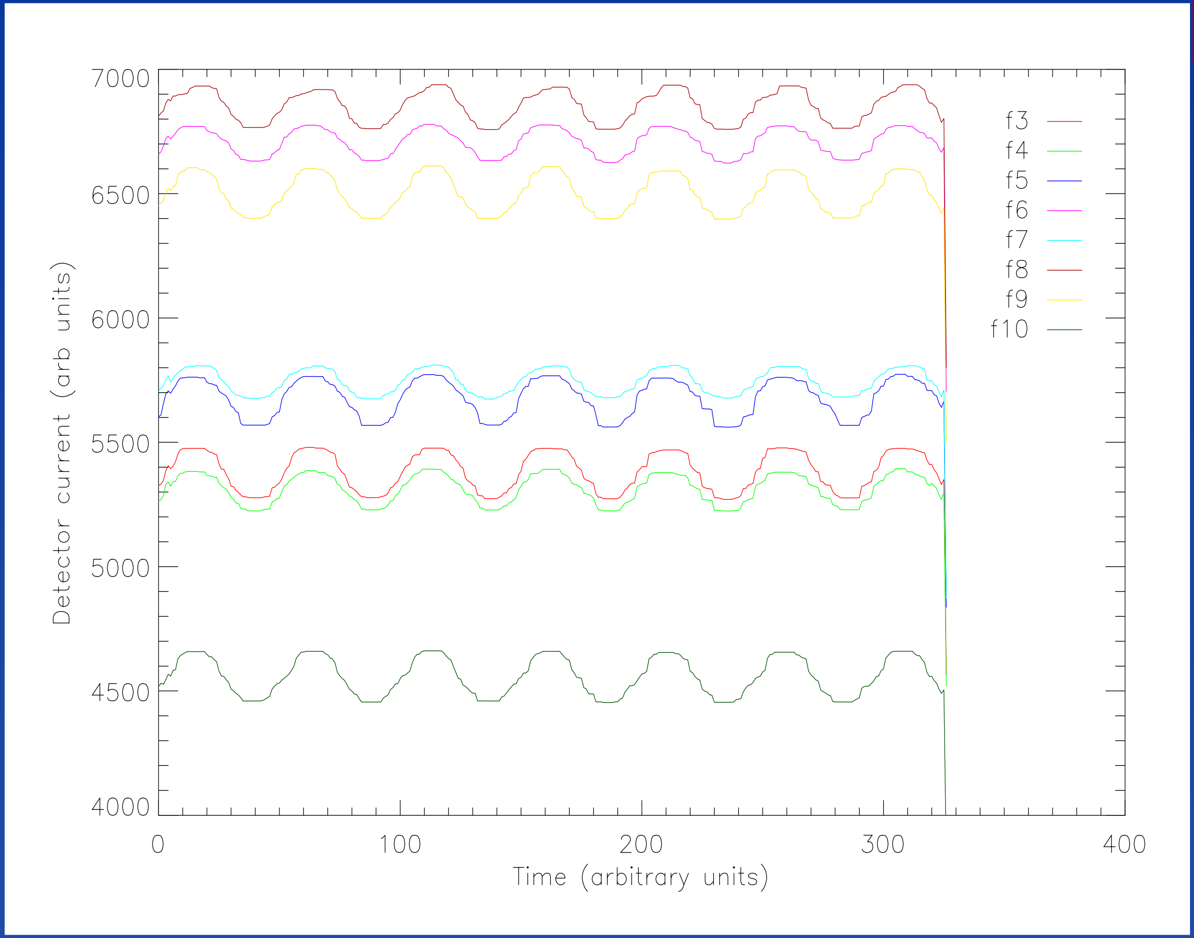
Detector current as a function of bias ("load curve")

Test results



Detector power as a function of bias

Test results



Eight pixels responding to modulated sub-mm illumination

Noise

- Noise measured on several pixels
- Noise spectrum measured while modulating signal from sub-mm illuminator at 2 Hz.
- NEP ~ 2.5×10^{-17}
- Well within specifications
- Compare SCUBA:
- NEP ~ 1×10^{-16} (at 15 Hz, compared to ~ kHz for SCUBA-2)

Conclusions

- Detectors and multiplexer work
  - Behaviour is stable and repeatable
  - Presence of detectors doesn’t prevent multiplexer operation
  - Pixels detect sub-mm radiation well
- Pixel uniformity is good (sufficient for operation)
- Noise properties are good and within specifications
- Successful tests on prototype have enabled us to start manufacture of science grade arrays
- Many other applications for the technology developed, inside and outside astronomy

COMMON-USER SUBMILLIMETRE BOLOMETER ARRAY - 2

SCUBA 2

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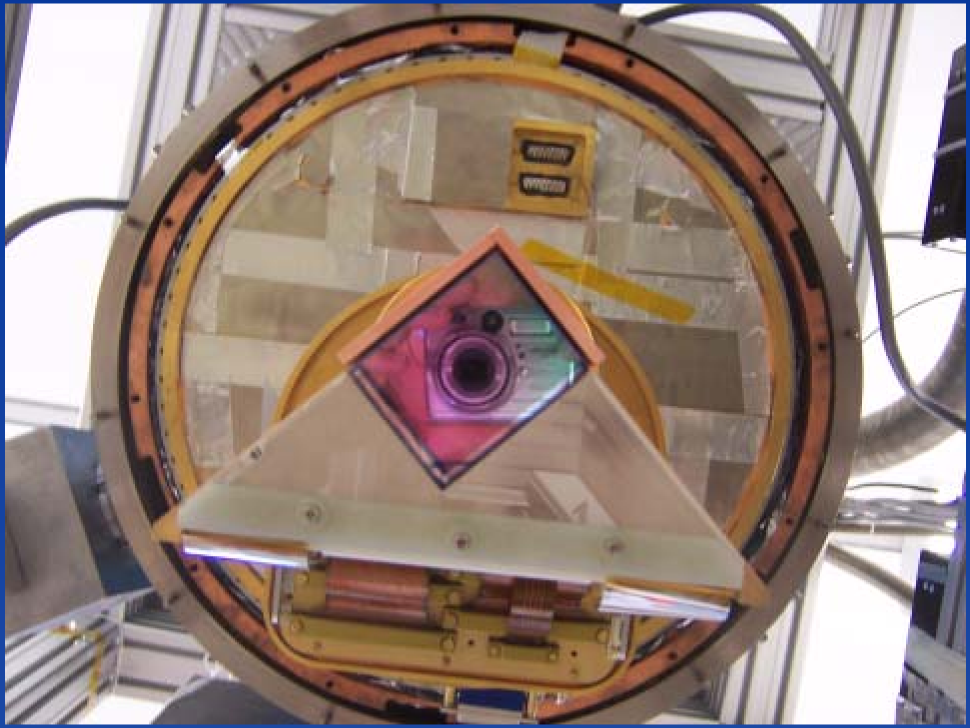

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