Constellation-X
Technology Presentation to the SEU Roadmap Technology Subcommittee

May 6, 2002

Goddard Space Flight Center

http://constellation.gsfc.nasa.gov

Constellation-X Mission Update

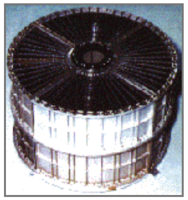
▪ *Introduction*	*Jean Grady (GSFC)*
▪ *Flowdown of Science Requirements*	*Jay Bookbinder (SAO)*
▪ *SXT Optics Technology*	*Rob Petre (GSFC)*
▪ *X-ray Calorimeter Technology*	*Rich Kelley (GSFC)*
▪ *Cryocooler and ADR Technologies*	*Rich Kelley (GSFC)*
▪ *CCD and Grating Technologies*	*Jay Bookbinder (SAO)*
▪ *Hard X-ray Telescope Optics and Detector Technologies*	*Fiona Harrison (Caltech)*

Introduction

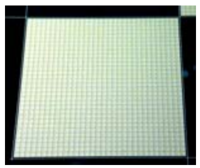
- Constellation-X technology development is on-going
  - Current emphasis on SXT optics and X-ray calorimeters
  - Ramp-up planned for FY2003
- Technology roadmaps revised in summer and fall 2002
  - Plan to achieve Technology Readiness Level (TRL) 6 for all technologies prior to start of Implementation in 2007
- Parallel technologies under consideration in several areas
  - X-ray calorimeters
  - CCD’s
  - Gratings
  - HXT optics
  - Cryocoolers
- All technologies can be demonstrated on the ground

Constellation-X Summary Technology Roadmap

X-ray Mirrors

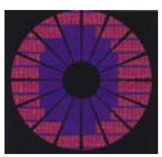


X-ray Calorimeters

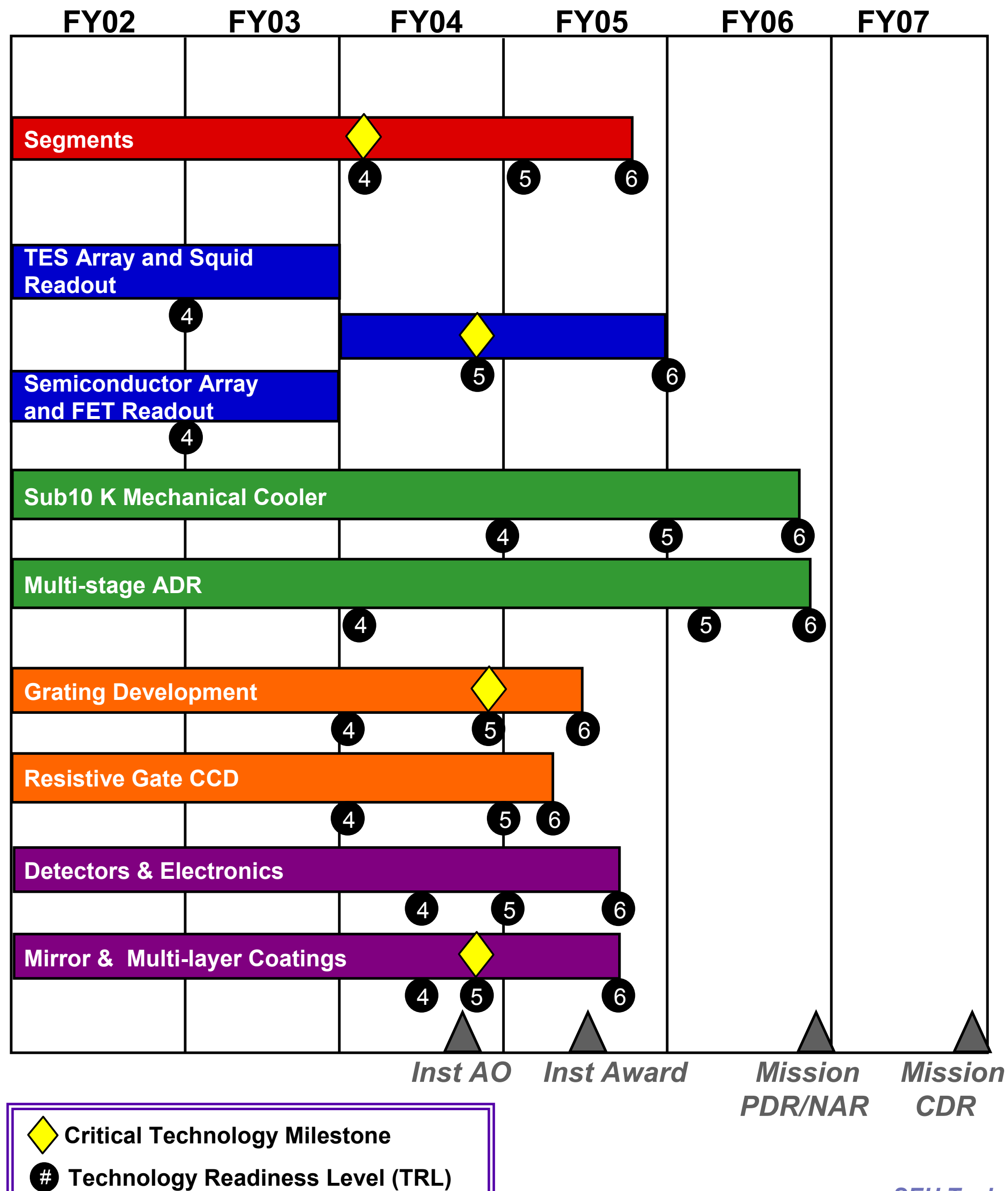


Cryocoolers

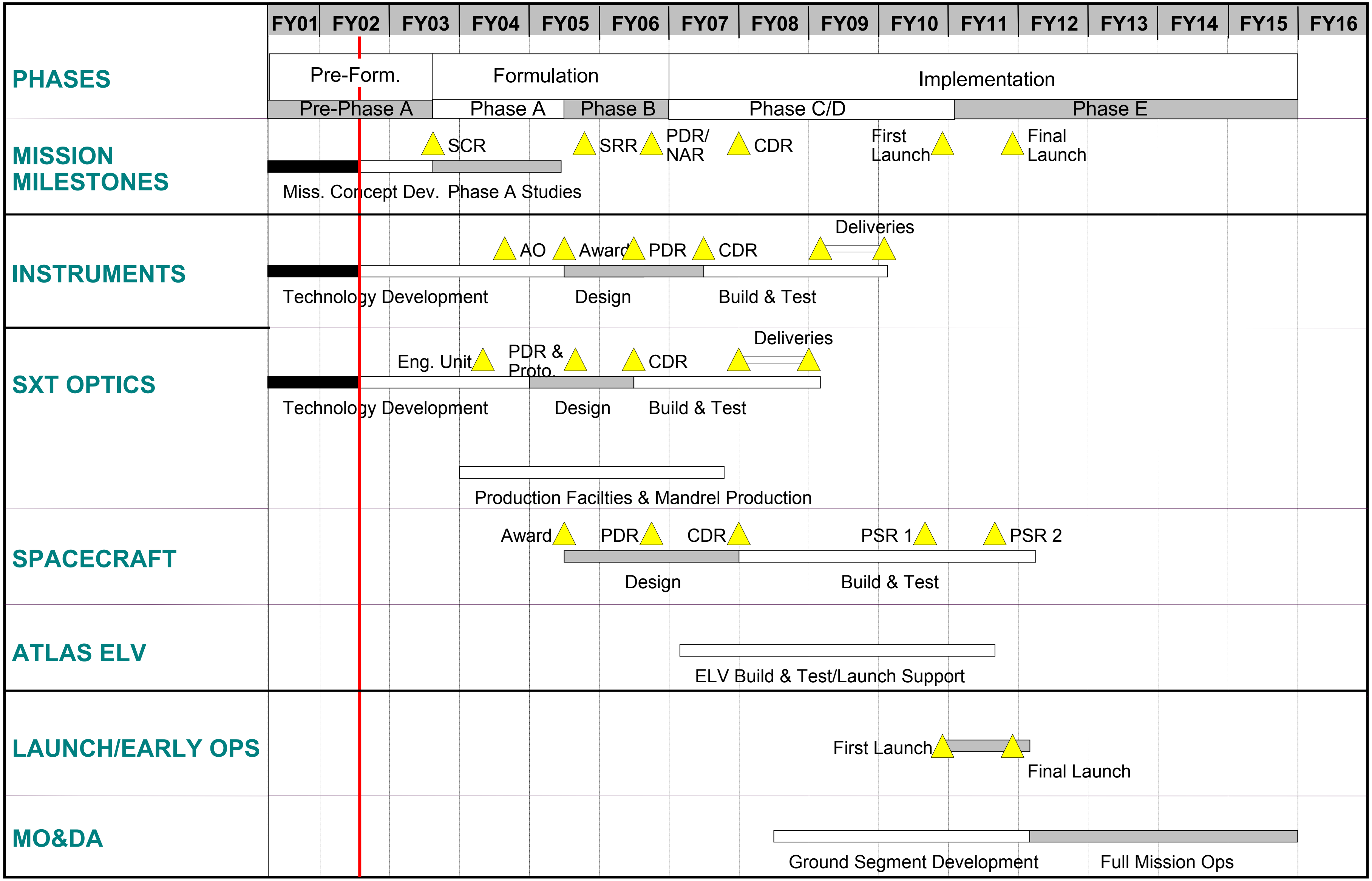
Grating/CCD



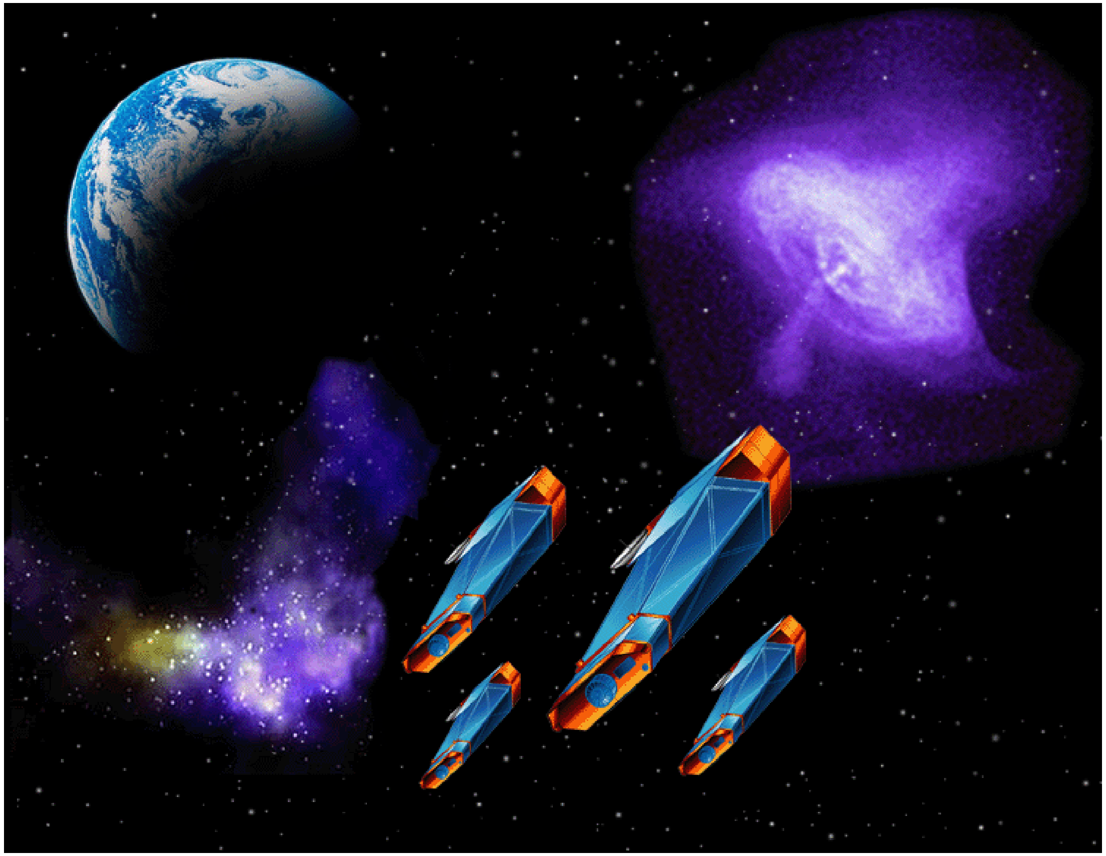
Hard X-ray Telescope



Constellation-X Project Master Schedule



Science Overview

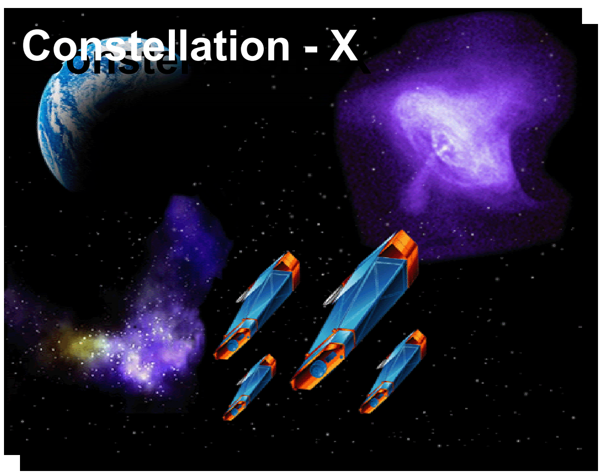


Jay Bookbinder

Smithsonian Astrophysical Observatory

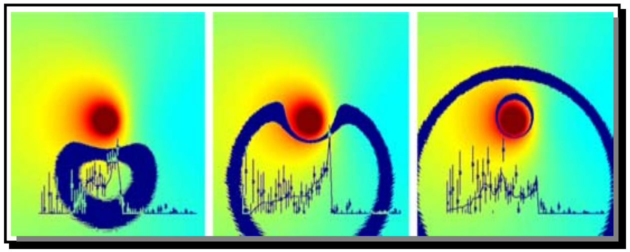
The Constellation X-ray Mission

Constellation-X is X-ray astronomy's equivalent of the Keck telescope

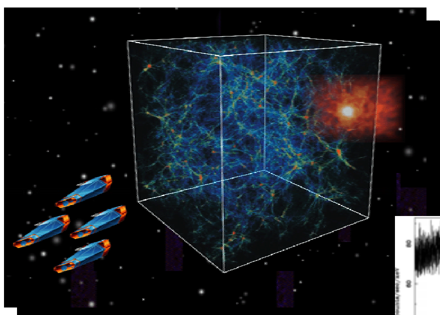


- **Collecting area: 30,000 cm2 at 1 keV**
  - *25 to 100 times Chandra and XMM for high resolution spectroscopy*
- **Spectral resolving power: 3,000 at 6.4 keV**
  - *25 times Chandra grating 5 times Astro-E2*
- **Band Pass: 0.25 to 40 keV**
  - *100 times more sensitive than Rossi XTE at 40 keV*

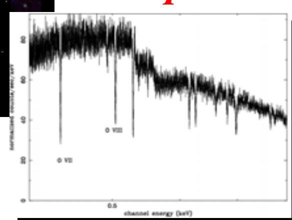
Constellation-X will open new windows towards understanding the Universe



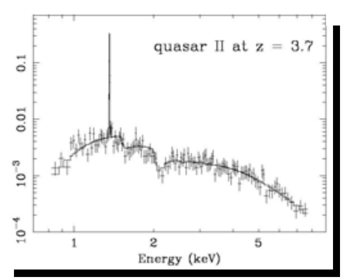
- Observe the effects of General Relativity near black hole event horizons
  - *Probe 100,000 times closer to black hole than before*
  - *Determine black hole spin and mass from iron profiles over a wide range of luminosity and redshift*



Absorption



- Map formation and evolution of dark matter structures throughout the Universe
  - *Detect ionized gas in the hot Inter Galactic Medium via absorption lines in spectra of background quasars*
  - *Map the distribution of dark and baryonic matter trapped in the gravitational potential of clusters*
  - *Observe the faintest, most distant clusters to determine redshift and mass to constrain Cosmological models and parameters*

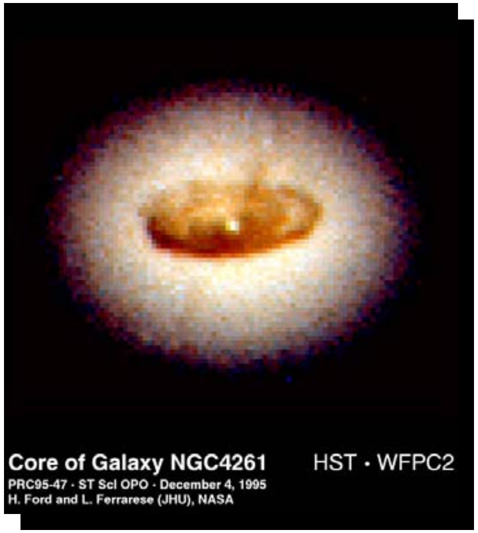


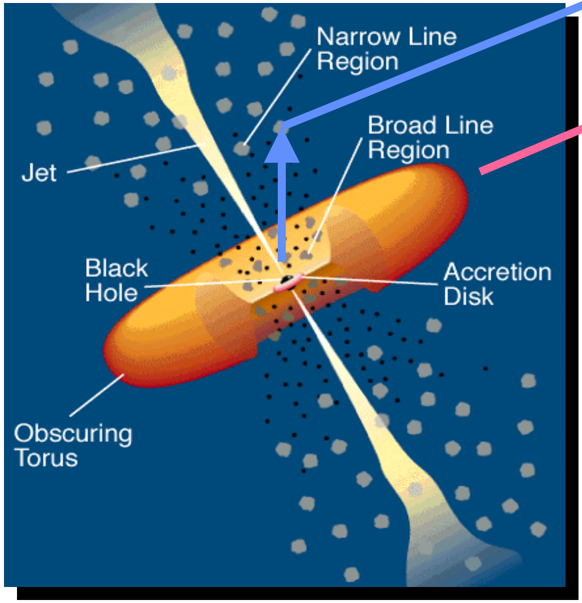
Chandra Deep Field

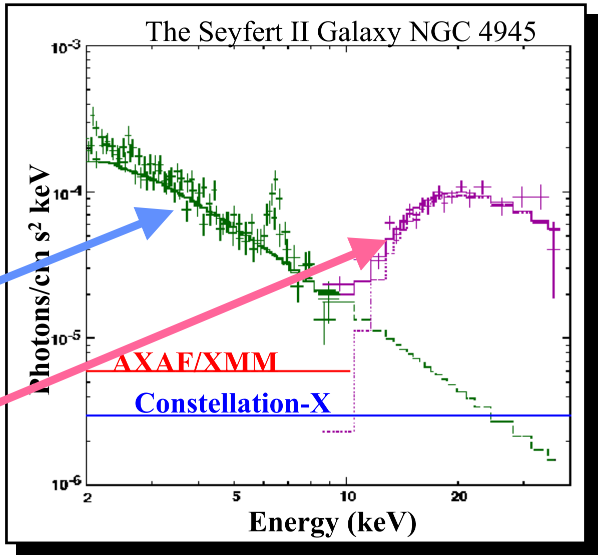
- Determine the nature of faint X-ray sources discovered by Chandra
  - *Obtain detailed spectra to determine physical processes prevalent in redshifts ranging to ~5*

Hidden Black Holes

Many black holes may be hidden behind an inner torus or thick disk of material







Only visible above 10 keV where current missions have poor sensitivity

Constellation-X will use multi-layer coatings on focusing optics to increase sensitivity at 40 keV by >100 over Rossi XTE

Science Flowdown

Primary Science Objectives…

- Measure the X-ray spectra of the faintest sources in the ROSAT Deep Surveys) and the Chandra deep fields in less than 10^5 seconds.
- Test General Relativity in the strong gravity limit by mapping the inner emission regions of black holes.
- Search for the "dark matter" or "missing baryons" from observations of the intergalactic medium (IGM)
- Study the interchange of matter and energy between stars and the ISM, the enrichment of the IGM and ICM and the evolution of clusters of galaxies.

via detailed science observation plans are drivers for:

Key Measurement Requirements

- **Bandpass: 0.2 to 40 keV**
- **Spatial Resolution: =< 15", =<1'**
- **Spectral Resolution 2eV, 0.05A < 10keV**
- **Sensitivities**

Which result in the mission implementation

- **HXT**
  6 – 40 keV
  <1'
- **SXT**
  0.2 – 10 keV
  <15"
- Grating (0.2 to 1.5 keV)
  Calorimeter (1 to 10 keV)

SXT Requirements Flow Down

Representative Science Measurements	*Measurement Capabilities Requirement (Goal)*	*Significant Engineering Implications/Key Technologies*
Determine the nature of faintest Chandra sources **Determine black hole mass and spin using iron K-a lines** **Measure IGM baryon density using O VII and O VIII resonant absorption lines** **Study chemical enrichment of galaxies via dispersion of nucleosynthesis elements by SN explosions and stellar winds.**	***Telescope Angular Resolution:*** ▪ **15 arcsec (5 arcsec)** ***Field of View*:** ▪ **2.5 arcmin (5 arcmin)** ***Observation Sensitivities:*** ▪ **1000 count for 2 x 10-15 ergs cm-2 s-1 in 105 sec** ***Bandpass:*** ▪ **0.2 (0.1) to 10 keV** ***Minimum Time Resolution*:** ▪ **100 (50) mseconds** ***Spectral Resolution:*** ▪ **2eV; 0.05A**	***Observation Sensitivities: => Effective areas of:*** ▪ **1000 cm^2 at 0.25 keV** ▪ **15000 cm^2 at 1.25 keV** ▪ **6000 cm^2 at ~6 keV** ***Telescope Angular Resolution:*** ▪ **Stable 10m Optical Bench** ▪ **Figure/finish on optics** ▪ **Ass'y process In-orbit focus and alignment** ▪ **Tight thermal control on mirror assemblies** ***Bandpass*** ▪ **Thin optical blocking filters** ▪ **Calorimeter** ▪ **Grating** ▪ **CCD**

PROVEN technologies (meets requirements)

ENHANCING technologies

ENABLING technologies (development required)

HXT Requirements Flow Down

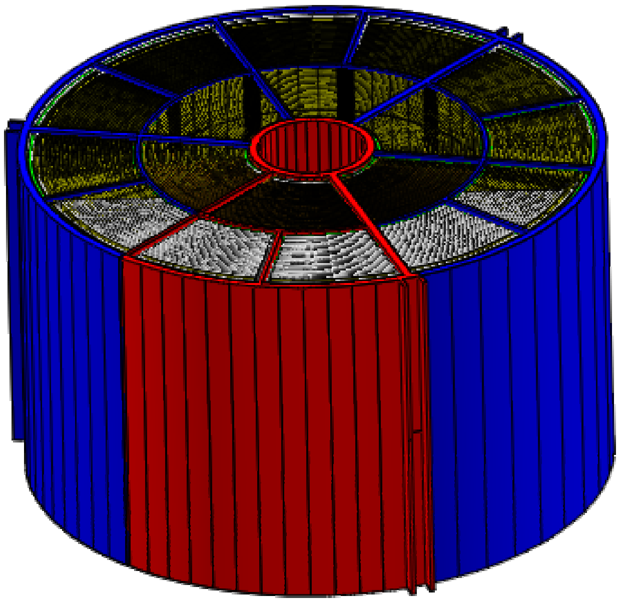
Representative Science Measurements selected from Primary Science Objectives	*Measurement Capabilities Requirement (Goal)*	*Significant Engineering Implications & Key Technologies*
Search for black holes hidden behind an inner torus or thick disk of material **Measure stellar flare densities and temperature**	***Observation Sensitivities:*** ▪ **S/N > 10 in 105 sec** ***Telescope Angular Resolution:*** ▪ **1 arcmin [30 arcsec]** ***Bandpass:*** ▪ **8 to 40 [4 to 80] keV** ***Minimum spectral resolving power:*** ▪ **10 [100]** ***Minimum Time Resolution:*** ▪ **1 millisecond**	**Observation Sensitivity:** ➔ ***Effective Area:*** ▪ **1500 cm^2 at 40 keV** ***Telescope Angular Resolution:*** ▪ **10m Optical Bench** ▪ **Figure/finish on low mass optics** ***Bandpass*** ▪ **Multilayer coatings to achieve higher energy response.** ▪ **High-quantum efficiency and 5 keV at low energy threshold**

PROVEN technologies (meets requirements)

ENHANCING technologies

ENABLING technologies (development required)

The Constellation-X Spectroscopy X-ray Telescope (SXT) Mirror



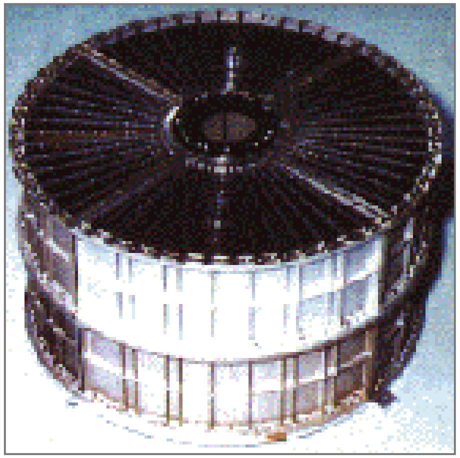
R. Petre and the Constellation-X SXT Team
Goddard Space Flight Center

SXT Mirror Performance Requirements

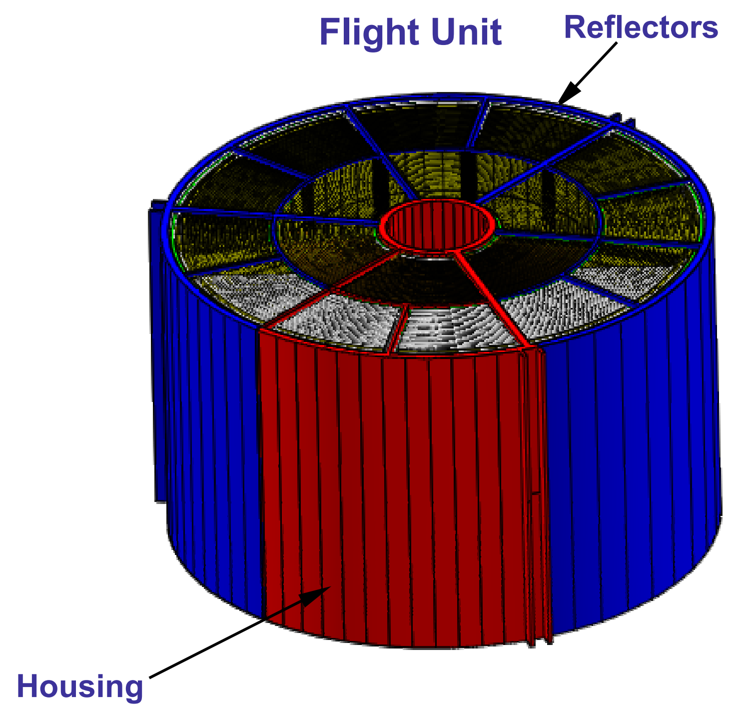
- Effective area
  - Collecting area for high resolution spectroscopy > 15,000 cm2 at 1 keV;
  - 6,000 cm2 at 6.4 keV.
  - Mirror must provide 30,000 cm2 at 1 keV; 7,500 cm2 at 6.4 keV.
- Angular resolution
  - HPD of entire telescope < 15”
  - Mirror HPD < 10”
- Bandpass
  - Entire telescope 0.25-10 keV
- Constrained Mass (mission driven)

Constellation-X SXT Mirror

- SXT Mirror Implementation
- Constellation-X consists of four identical spacecraft and sets of instrumentation.
- Each SXT mirror is a Wolter I grazing incidence mirror with a 10 m focal length and a 1.6 m diameter.
- The mirror is composed of many (100-250) nested Wolter-I reflectors.
- The SXT mirror is azimuthally segmented.



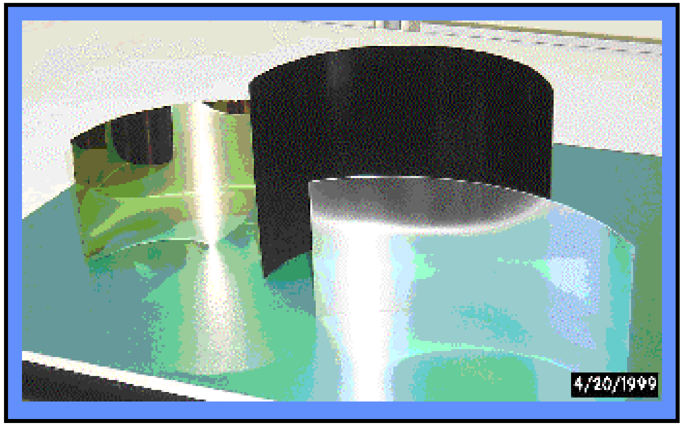
Con-X mirror draws from the heritage of the Astro-E mirrror segmented mirror and its predecessors



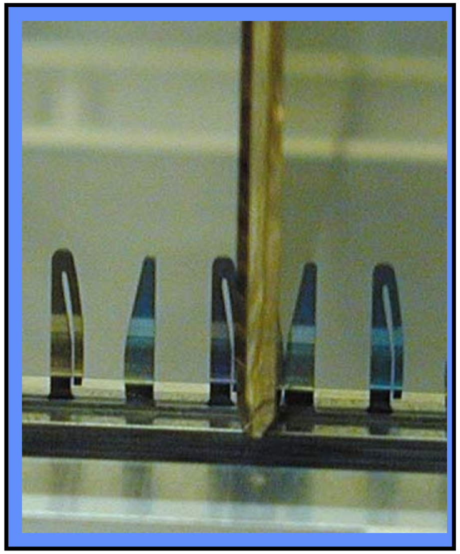
- 1.6 m outer diameter
- 10 m focal length
- 20-50 cm reflector length
- 18 Small Modules
  - (6 inner, 12 outer)
- 70-250 nested reflector pairs
- mirror mass ≤500 kg

SXT Key Components

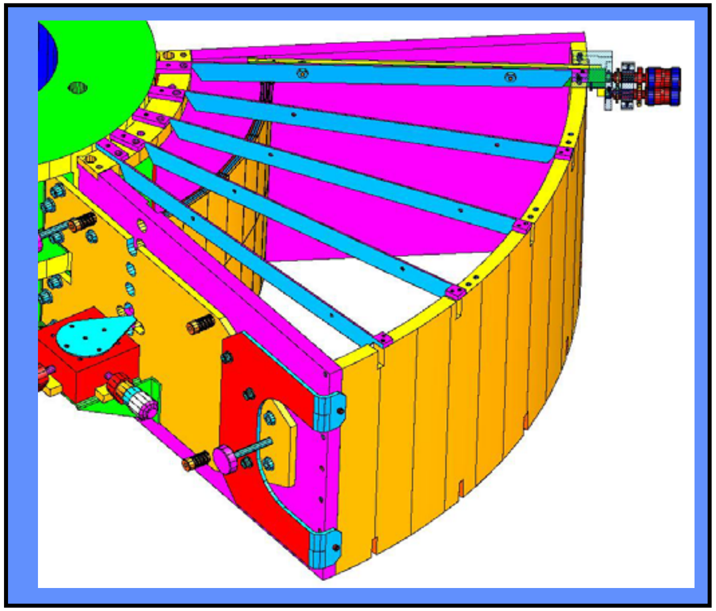
Precision 1.6 m diameter segmented mandrel under fabrication at Carl Zeiss (Oberkochgn, Germany)



Thin, thermally formed glass reflector substrates



Si microstructures for reflector alignment



Engineering unit housing with precision positioners

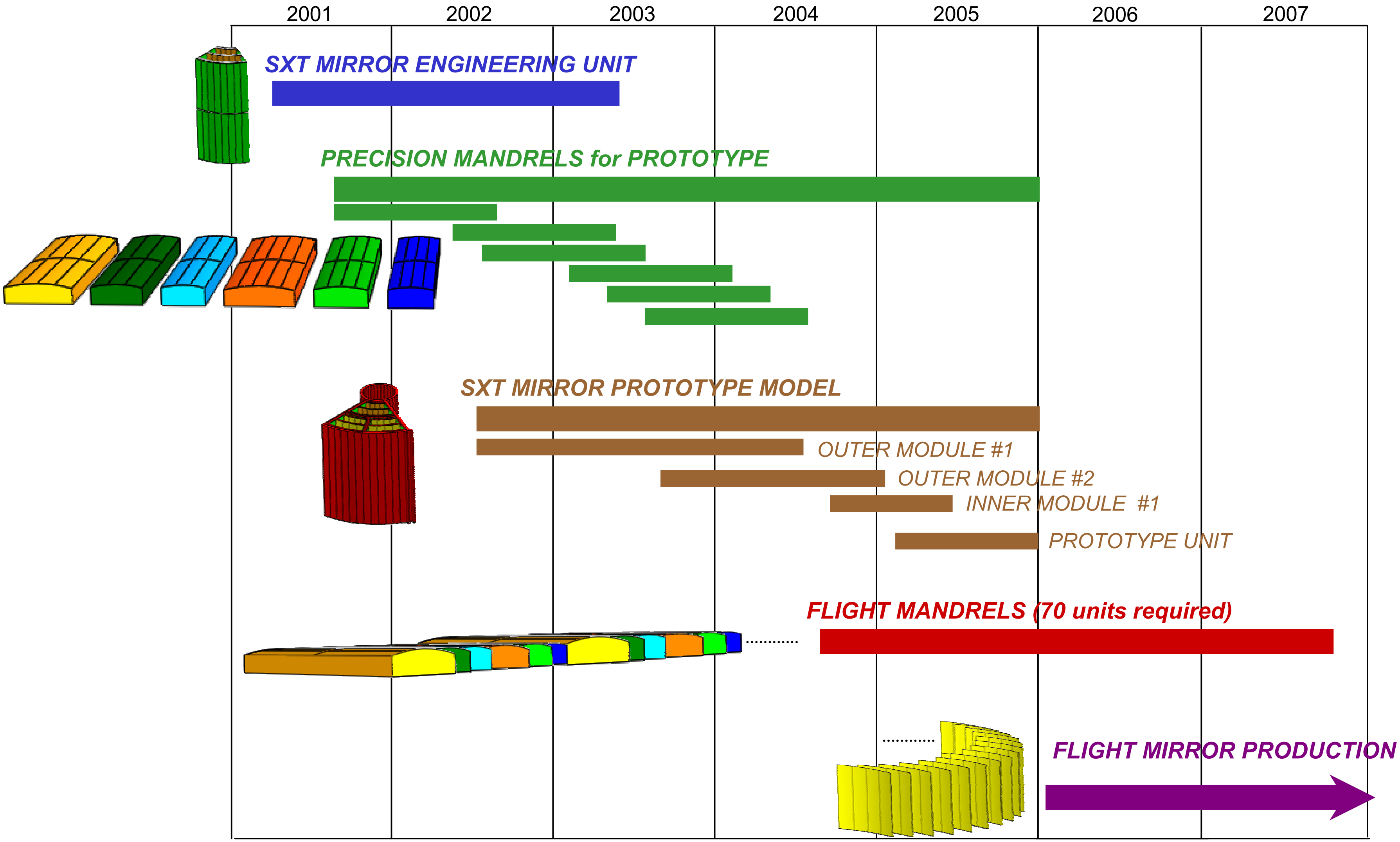
Constellation-X SXT Mirror

- Metrics and Status
- Angular resolution of a mirror assembly
  - Metric: 10 arc second half power diameter (mirror only)
  - Status: Individual components should allow attainment of metric
  - Demonstration: X-ray performance measurement, before and after environmental tests
- Viable mass production approach
  - Metric: Sufficient reflector production and module alignment rate to allow production of 1 SXT mirror per year
  - Status: Reflector production and alignment processes still being developed
  - Demonstration: During prototype development
- Phased engineering unit and prototype development aimed at attaining both metrics

SXT Prototype Development

	Optical Assembly Pathfinder		Eng. Unit	Prototype		
Configuration						
Module Type	Inner	Inner	Inner	Outer	Inner	Outer & Inner
Housing Material	Aluminum	Titanium	Composite	Composite	Composite	Composite
Focal Length	8.5m	8.5m	8.5m	10.0m	10.0m	10.0m
Reflector Length (P&H)	2 x 20 cm	2 x 20 cm	2 x 20 cm	2 x 50 cm (TBR)	2 x 50 cm (TBR)	2 x 50 cm (TBR)
Nominal Reflector Diameter(s)	50 cm	50 cm±	50 cm±	160 cm± 120 cm± 100 cm±	90 cm± (TBR) 70 cm± (TBR) 50 cm± (TBR)	160 cm± 40 cm± 120 cm± 70 cm± 100 cm± 50 cm±
Goals	▪Align 1 optical surface pair (P&H) ▪Evaluate optic alignment techniques, optics assembly design & process, & optics metrology	▪Align up to 3 optical surface pairs (3P,3H) ▪Evaluate tooling and alignment techniques for mass production schemes	▪Align 3 optical surface pairs to achieve <10 arc sec. ▪Environmental and X-ray test	▪Flight-like configuration outer module ▪Largest optical surfaces ▪Environmental and X-ray test	▪Flight-like configuration inner module ▪Environmental (TBR) and X-ray test	▪Demonstrate module to module alignment ▪Environmental and X-ray test
Timeframe	Q4 of FY02	Q2 of FY03	Q1 of FY04	Q4 of FY05	Q3 of FY06	Q4 of FY06

SXT Technology Roadmap

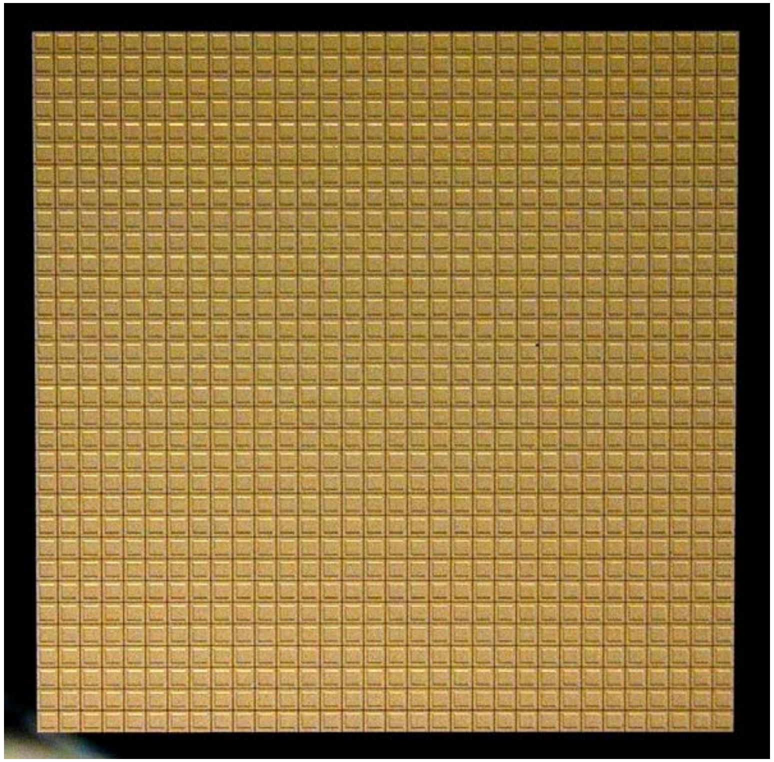


Constellation-X SXT Mirror

- Is the required capability a reasonable extension of the current capability or does it require a significant advancement or new approach?
  - Meeting the angular resolution requirement originally required significant advancement beyond the previous (Astro-E) approaches. The groundwork was laid in the previous years of the program, so the required capability is now an extension of the existing approach.
  - Mass production and alignment will draw heavily from the Astro-E approach, but will incorporate different components.

COMPONENT	ASTRO-E	CONSTELLATION-X
Substrate	Thermally & mechanically formed Al foil	Thermally formed glass foil
Forming mandrel	Off-the-shelf quartz cone	Precisely figured quartz cone
Replication mandrel	Durant cylindrical glass tubing	Figured and polished Zerodur (WI surfaces)
Surface production	Epoxy replication	Epoxy replication
Alignment structure	EDM aluminum combs	Si microstructures
Alignment method	Gang mechanical/optical alignment of full module	Optical alignment of individual reflectors or groups of reflectors; mechanical alignment using microstructures if possible
Alignment light source	Collimated optical beam	AXAF Centroid Detector Assembly

X-Ray Microcalorimeter

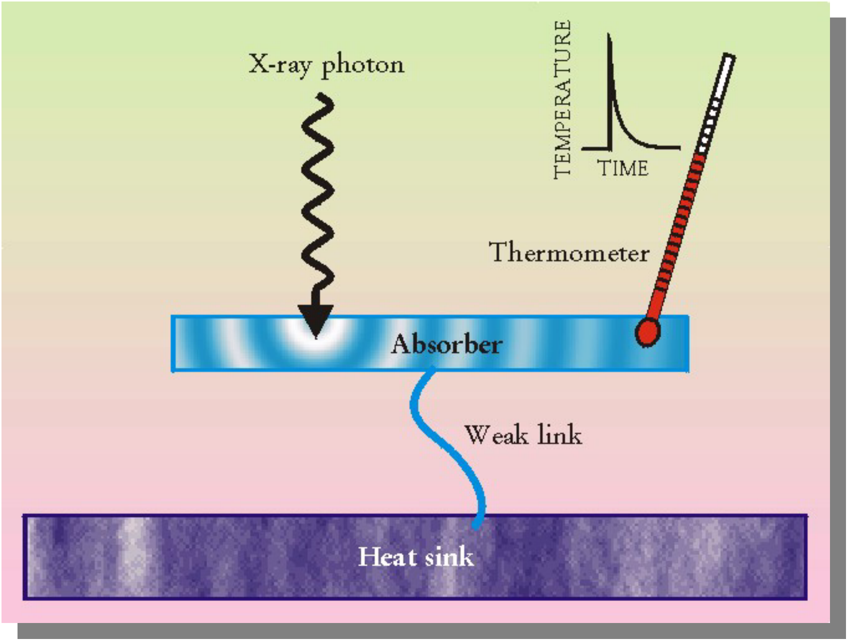


Richard Kelley
Goddard Space Flight Center

X-ray Microcalorimeter

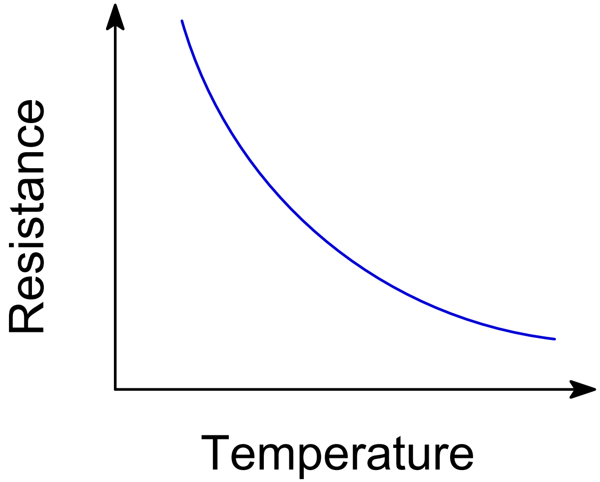
Features: High resolution, non-dispersive spectroscopy with high quantum efficiency over K- and L- atomic transition band.

Pursuing two thermometer approaches:

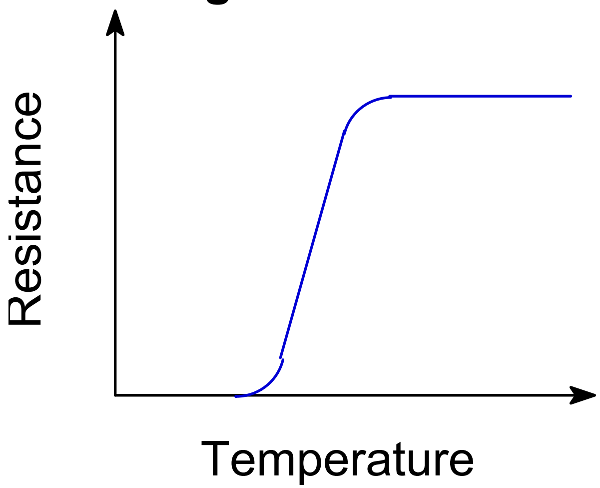


Partners: GSFC, NIST, U Wisc, SAO, LLNL, Stanford

Semiconductor Thermometer (Doped Ge or Si)



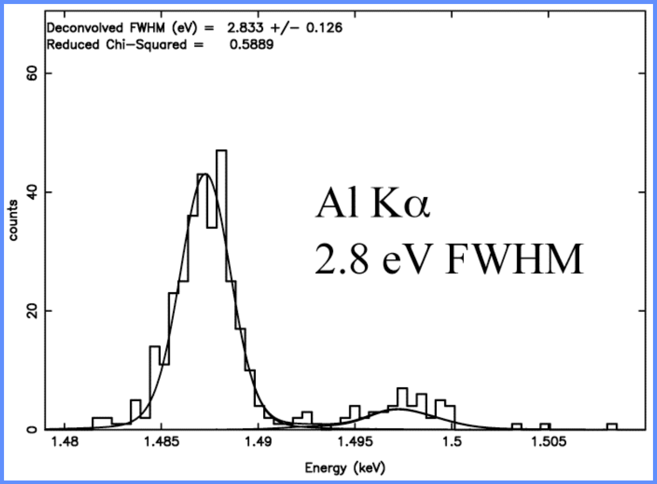
Superconducting Transition Edge Thermometer

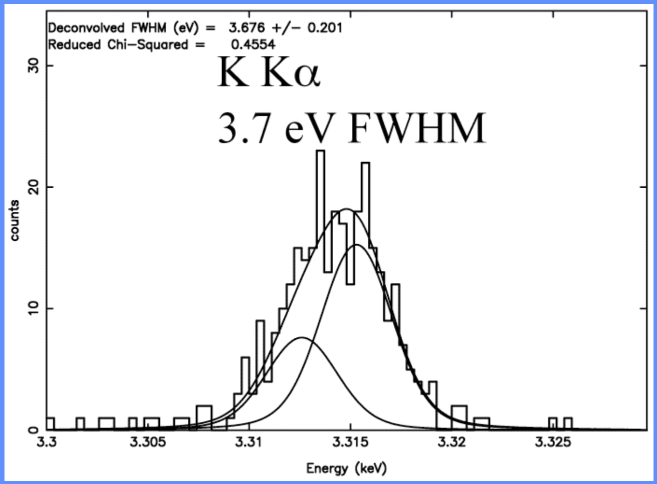


Detector Requirements

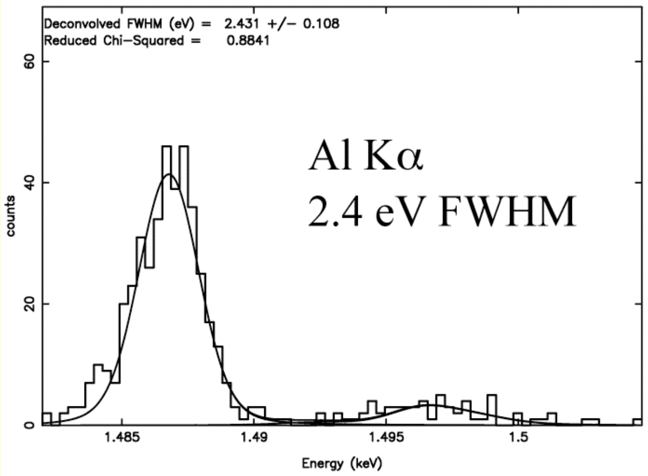
Level 1 Requirement		Derived Requirement
Energy Resolution	R=3000 from 6 to 8.5 keV (2 eV at 6 keV)	same
Pixel Size	1/3 of HPD	15" HPD $\Rightarrow$ 5" $\therefore$ 250 μm
Field of View	2.5 arcmin	30 $\times$ 30 array
Counting Rate	"handle" up to 1000 cps/pixel	τ_{eff} = 300 - 500 μsec
Detection Efficiency	Provide top level A_{eff}	TBD, but approximately: QE ~ 90% at 6 keV array fill factor ~ 90%

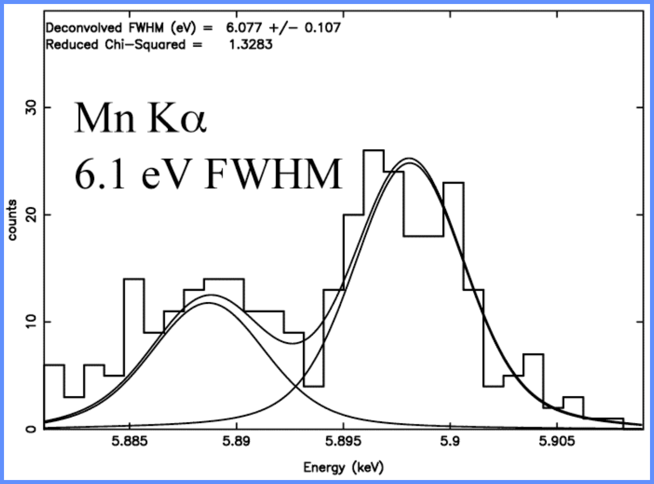
500 x 500 μm TES on 5 mm membrane





300 x 300 μm TES on 3 mm membrane

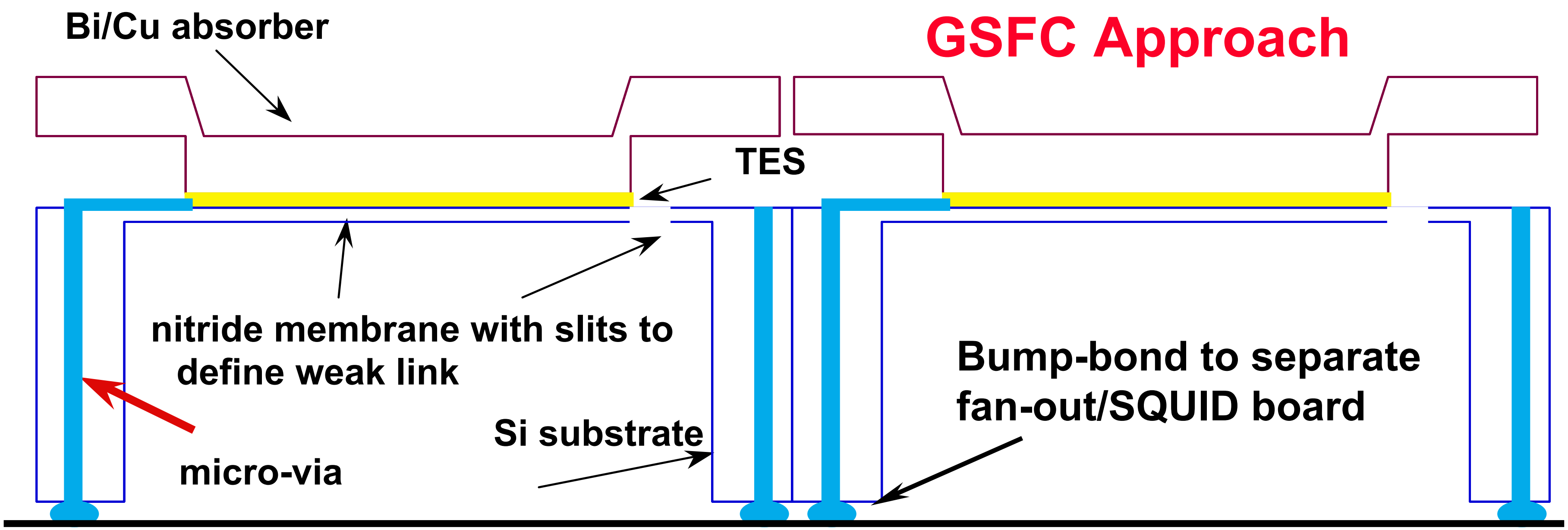




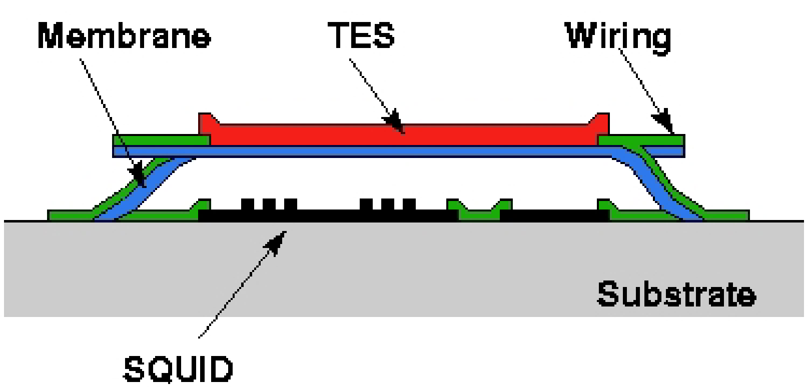
GSFC

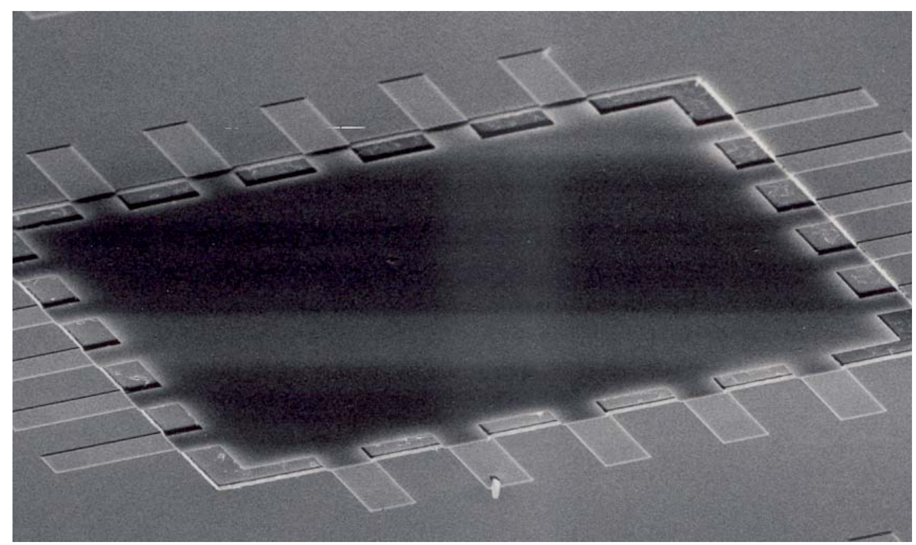
TES Array Concepts

GSFC Approach

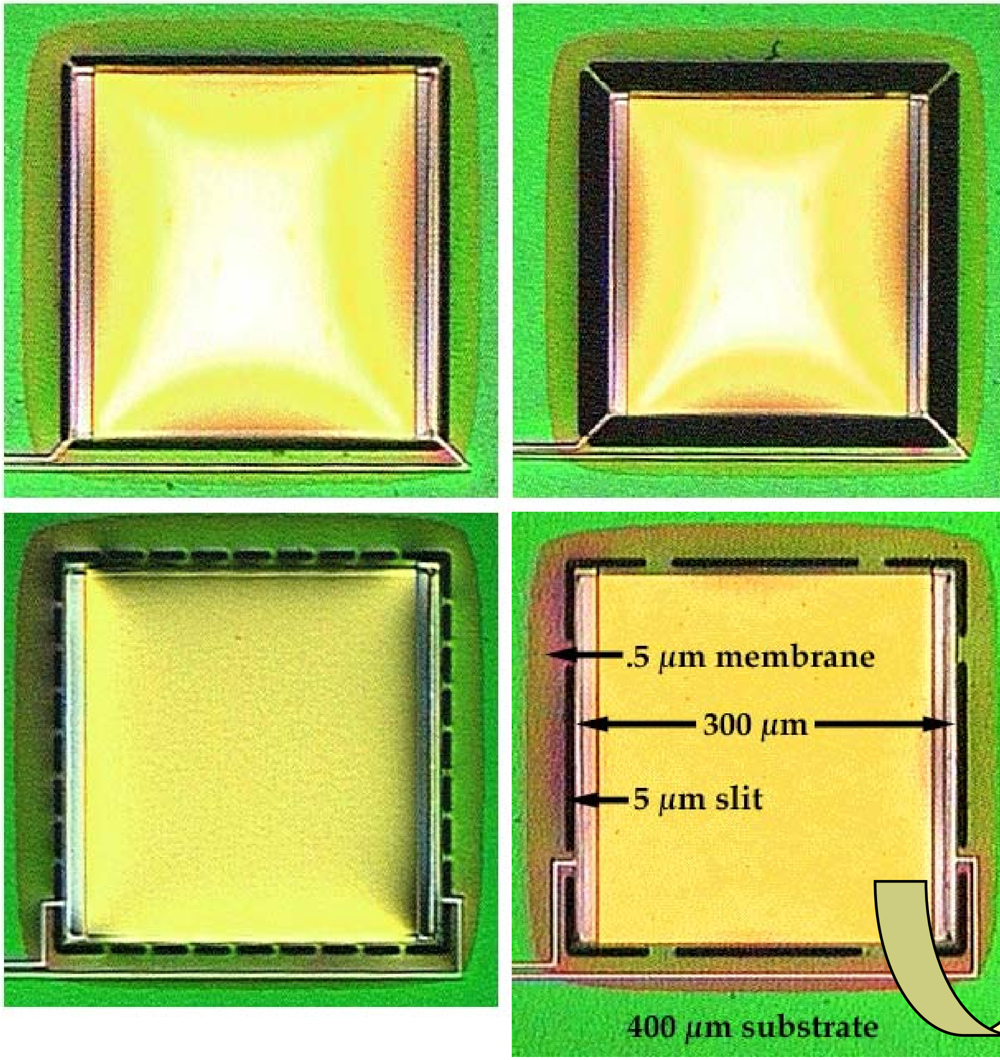


NIST Idea:

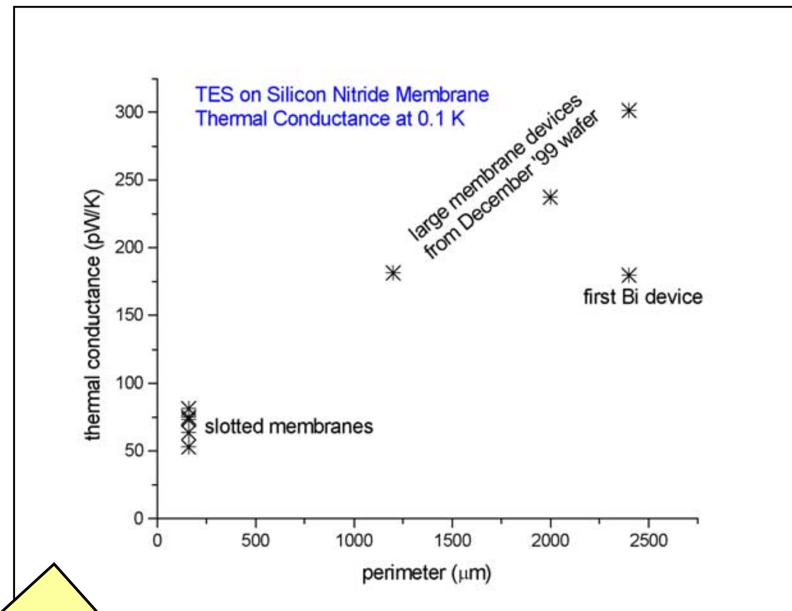




Testing Pixels with Con-X size

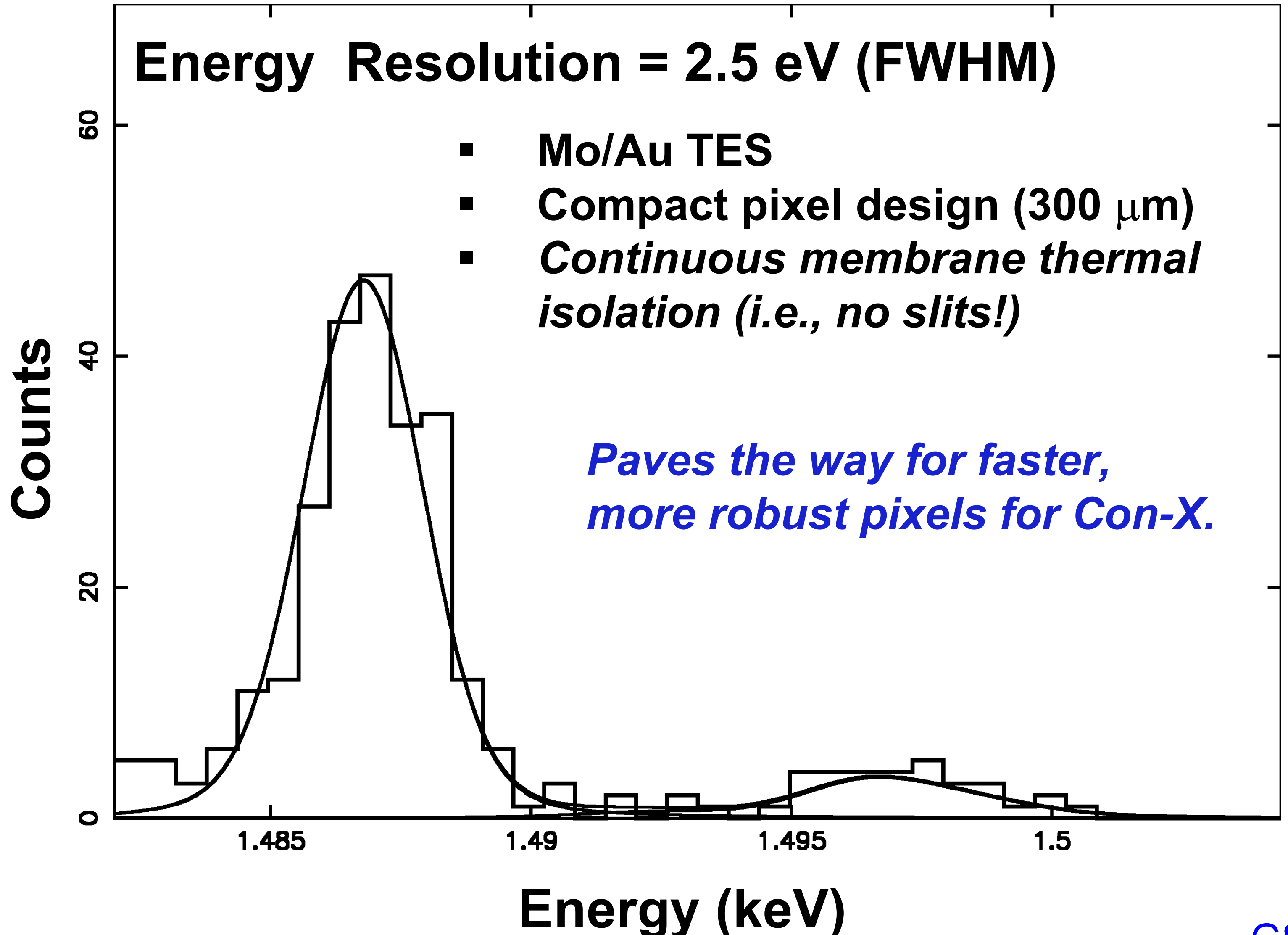


Individual TES devices designed to have different thermal conductance to allow parameterization.



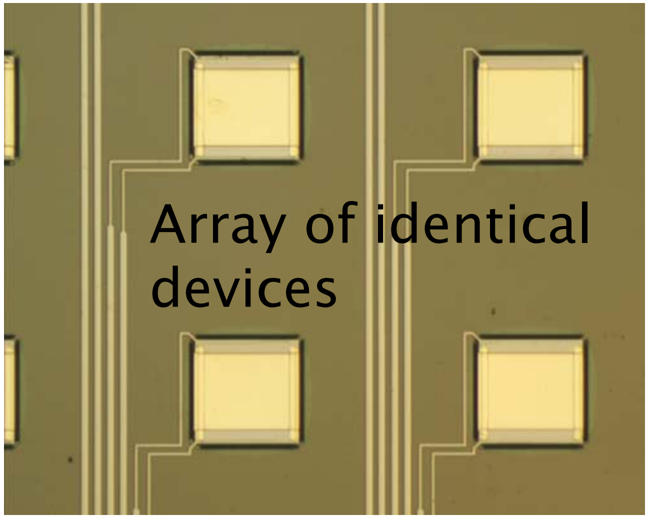
GSFC

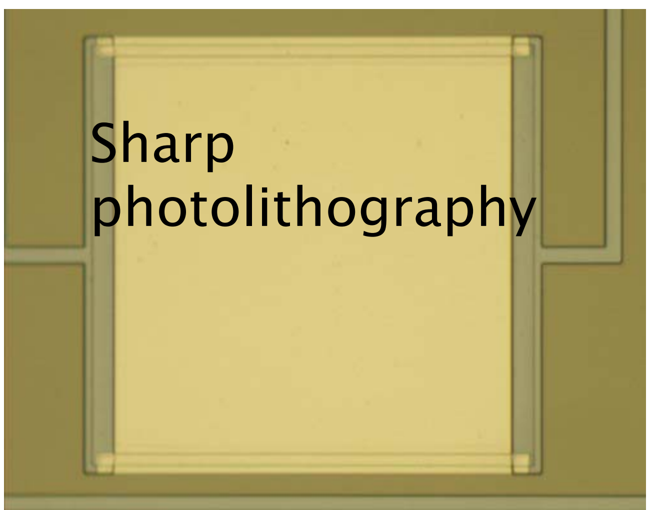
Results from Compact TES Pixels

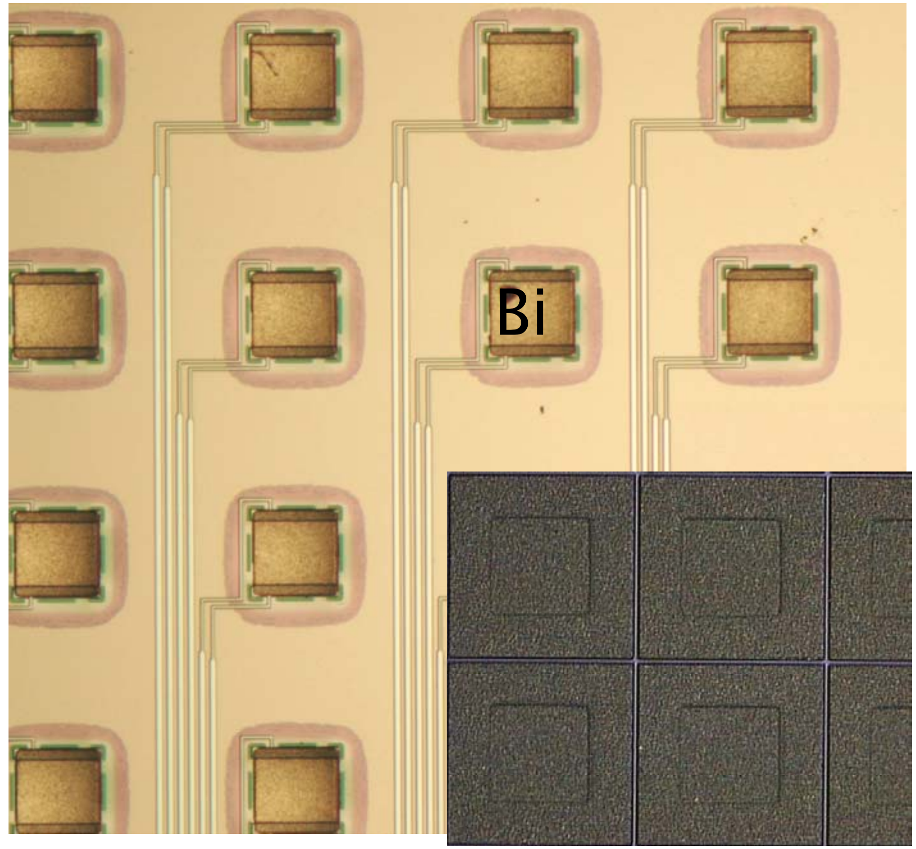


GSFC

TES Fabrication Examples





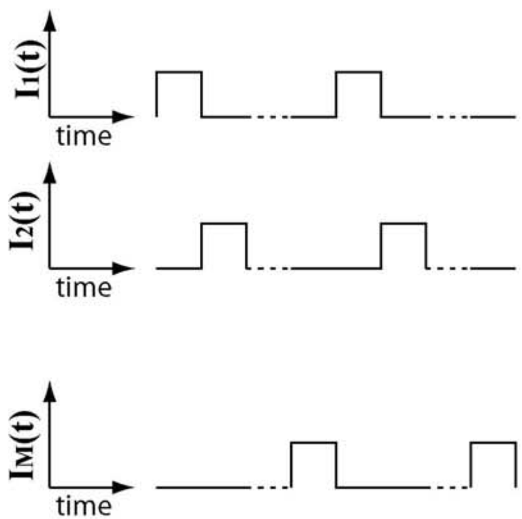


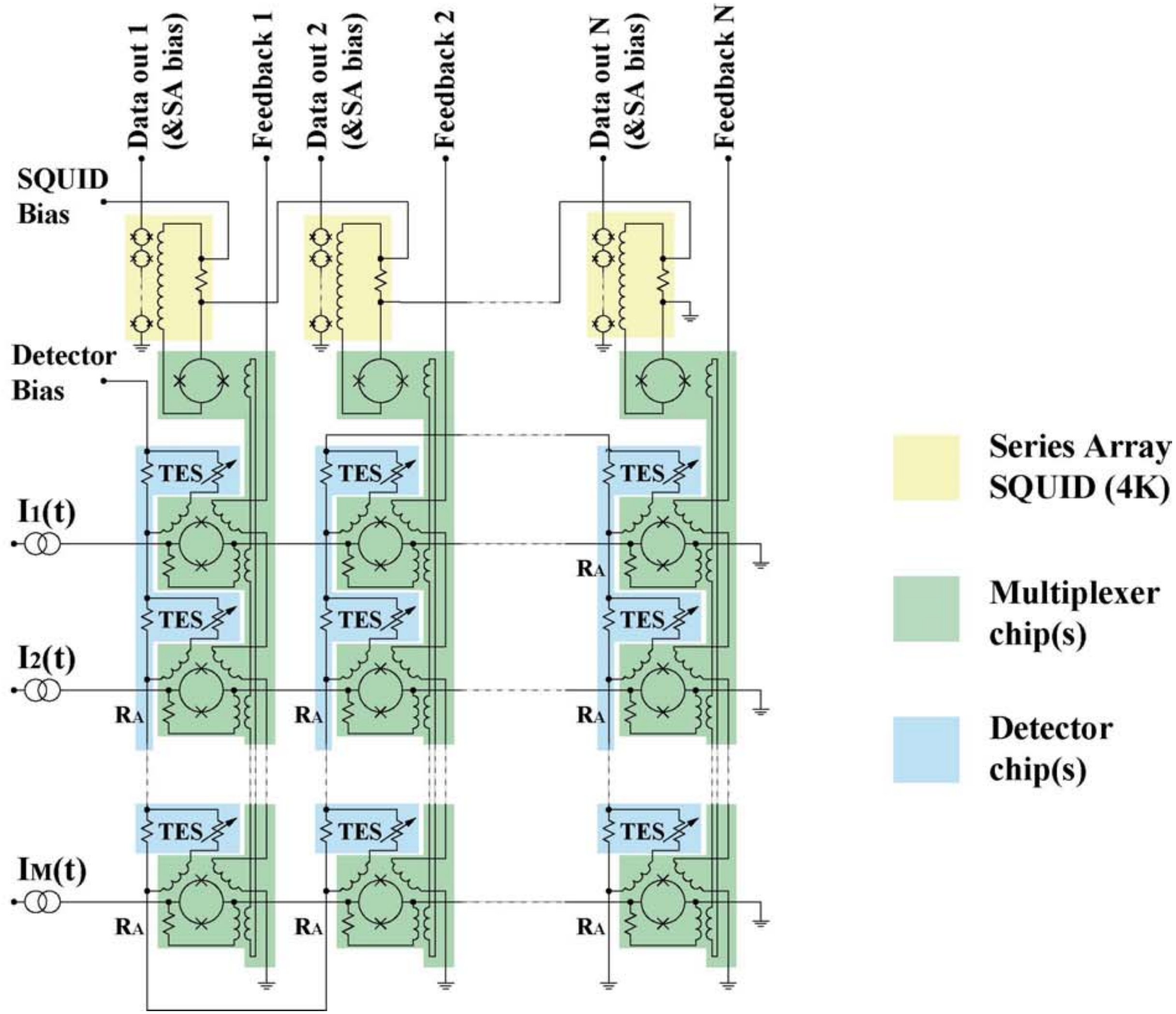
Array of identical 150 micron devices. Soon will make these with 250 and 400 micron "mushroom" absorbers. The Bi absorbers shown are the size of the stem in the mushroom.

GSFC

SQUID Multiplexer Scheme

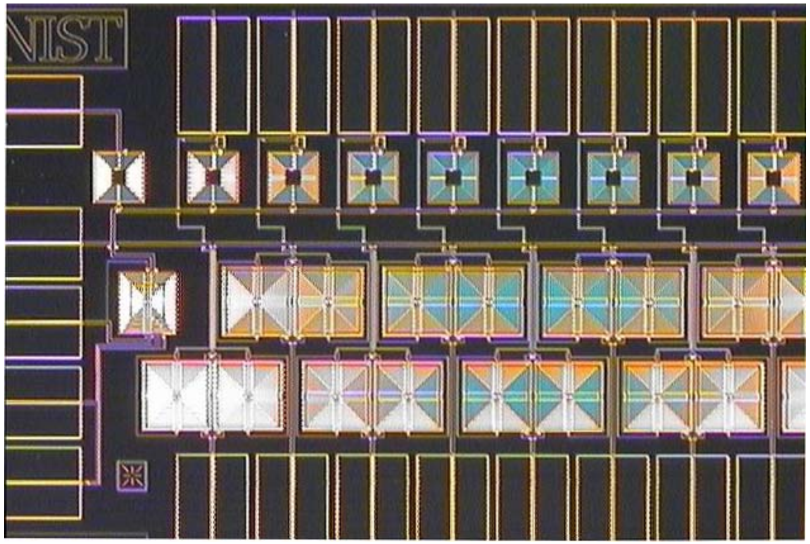
Boxcar Modulation Functions
(can be from Cryogenic CMOS MUX)

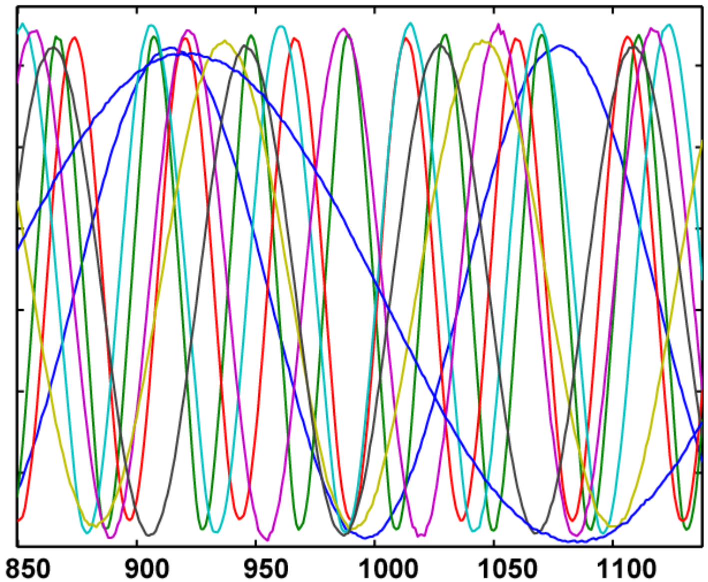




NIST/Boulder

SQUID Multiplexer



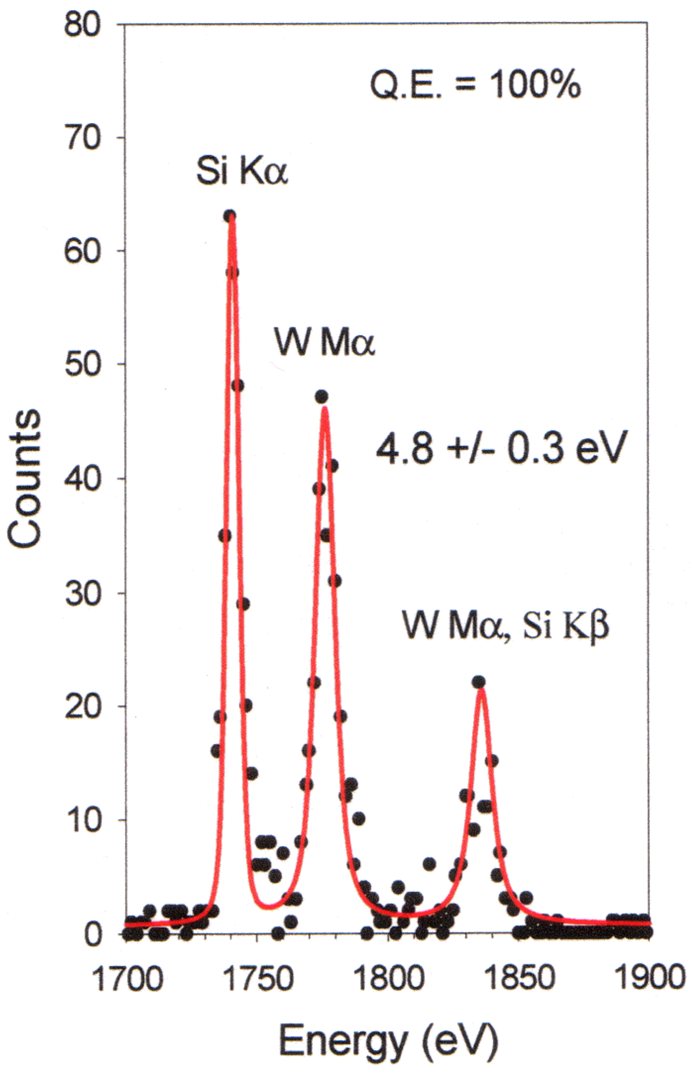


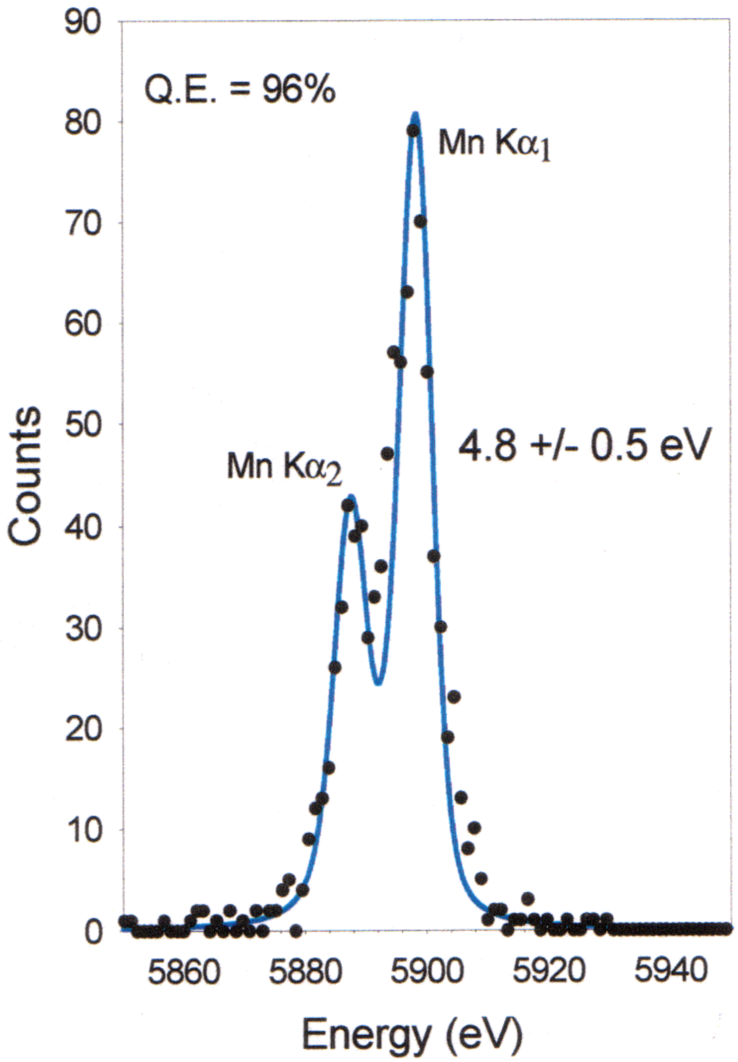
- 32-channel MUX. (Need 32 chips to instrument kilopixel array.)
- First-generation MUX deployed in astronomical instrument (FIBRE) with GSFC
- Second generation improves crosstalk & power

- Switched digital feedback is working
- Can sample at 1.6 MHz line rate
- Sufficient performance for 2 $\times$ 8 demo array
- Need to increase bandwidth for full instrument

NIST/Boulder

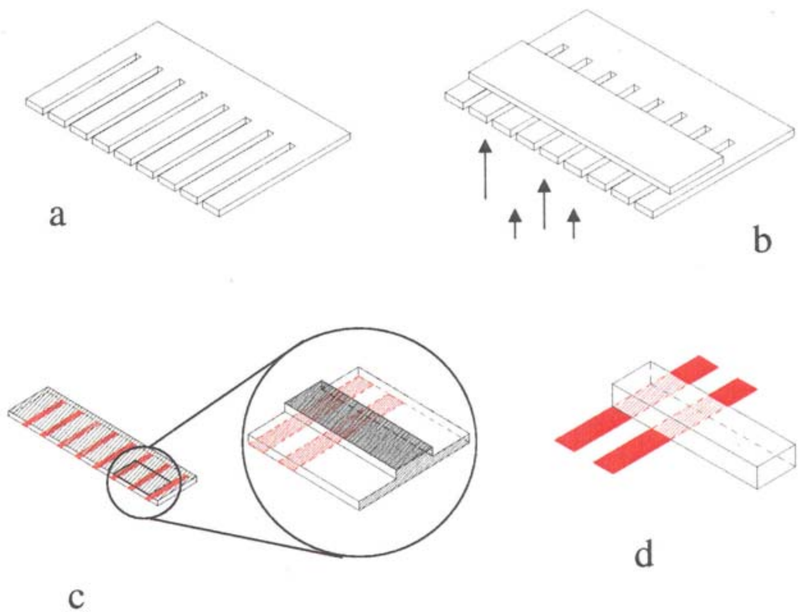
NTD Calorimeter with Sn Absorbers

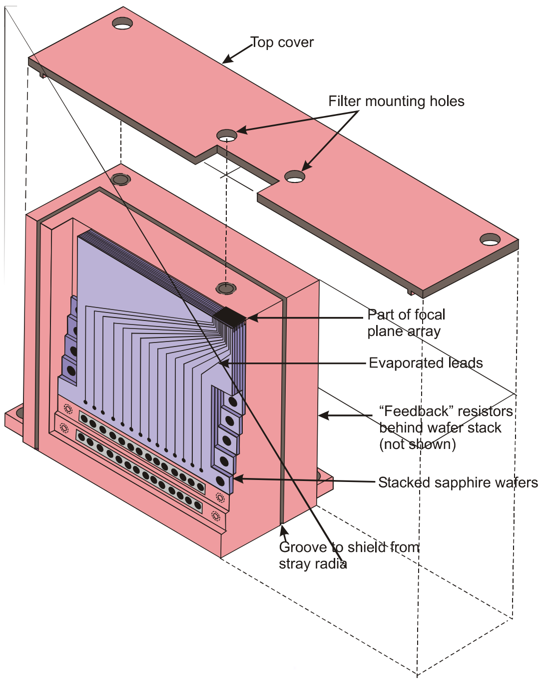




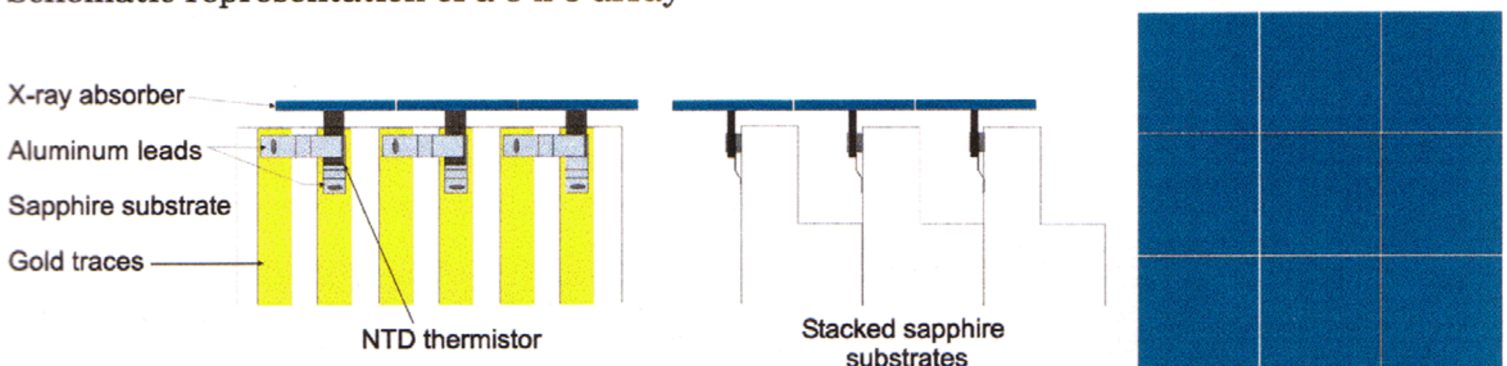
SAO

NTD Ge Microcalorimeter Array





Schematic representation of a 3 x 3 array



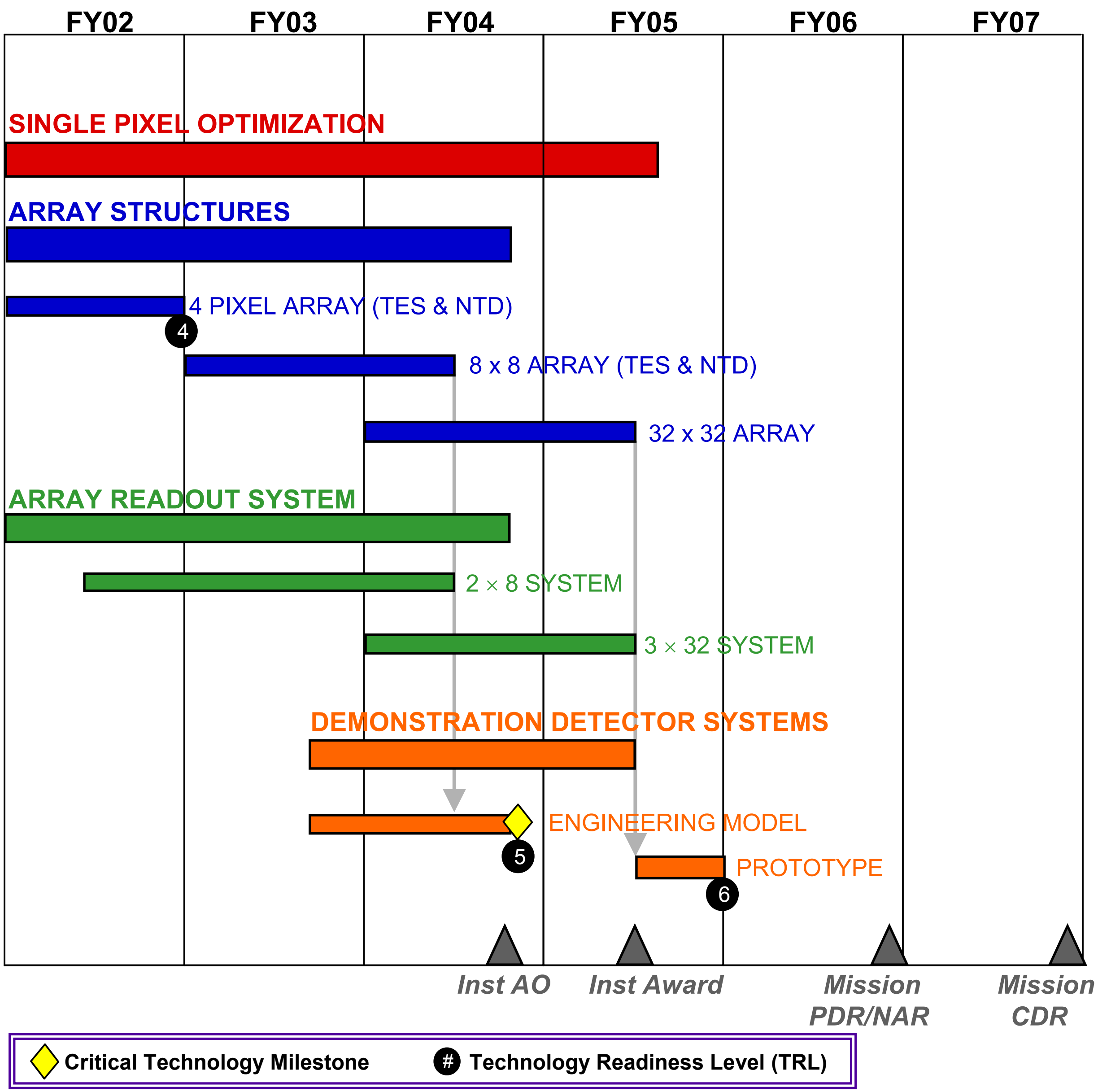
Front View

Side View

Top View

SAO

Calorimeter Technology Roadmap



X-Ray Microcalorimeter Back Up Charts

Overall Status as of Today

Thermometer Types:	Energy Resolution
Al/Ag, Mo/Au, Mo/Cu TES	2.0 - 2.5 eV at 1.5 keV
NTD Ge semiconductor	4 - 6 eV at 6 keV

Array Size

Only single pixel *test results* thus far. (small arrays have been fabricated)

Counting rate

Pulse decay time constants of ~ 300 μsec

Readout Schemes

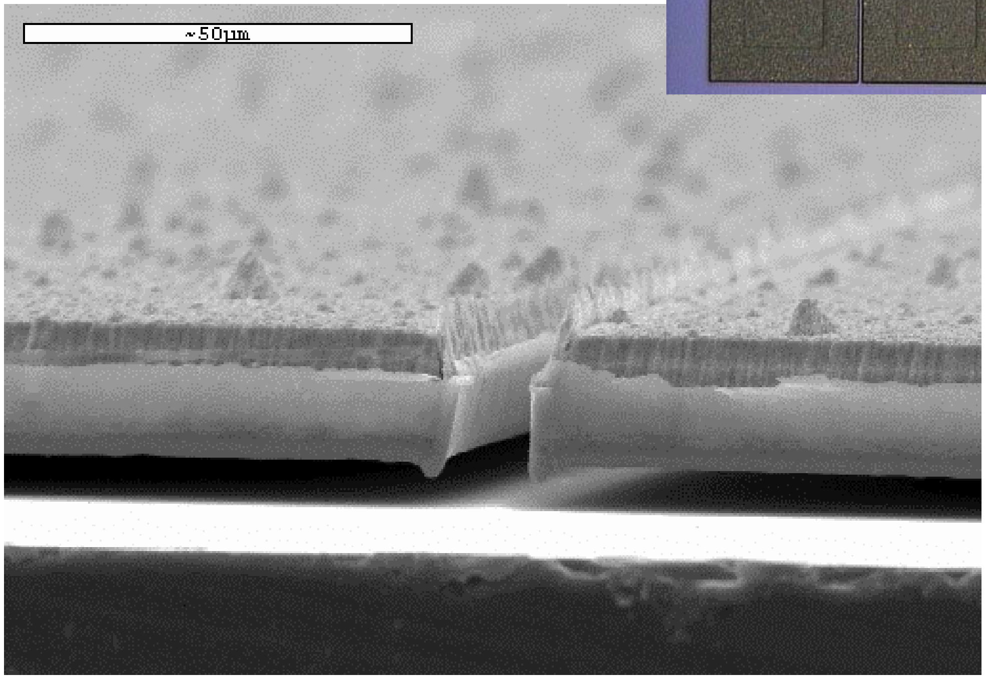
32 channel XRS system, analytical designs for larger JFET systems; MUX designs and functional systems for IR TES.

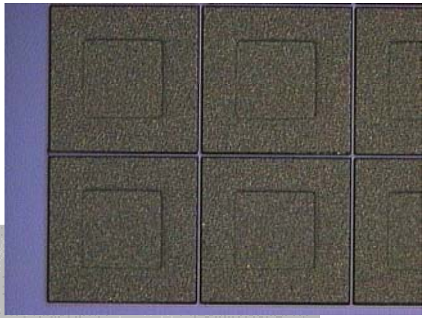
For TRL-6, we need to demonstrate

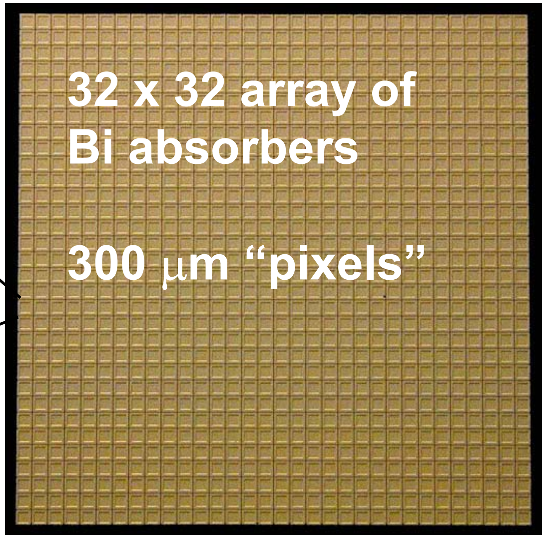
- 2-4 eV at 6 keV (and below) with high degree of pixel-pixel uniformity (how much?)
- Robust array scheme with high-yield process.
- Faster pulses (< 300 μsec)
- Large array readout schemes compatible with extended life mission.

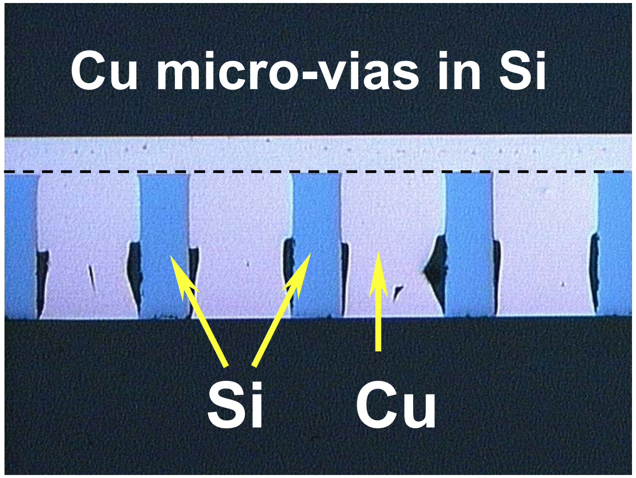
Micromachined Bi Absorbers

Proof of concept for fabricating x-ray absorbers in array format with high filling factor.

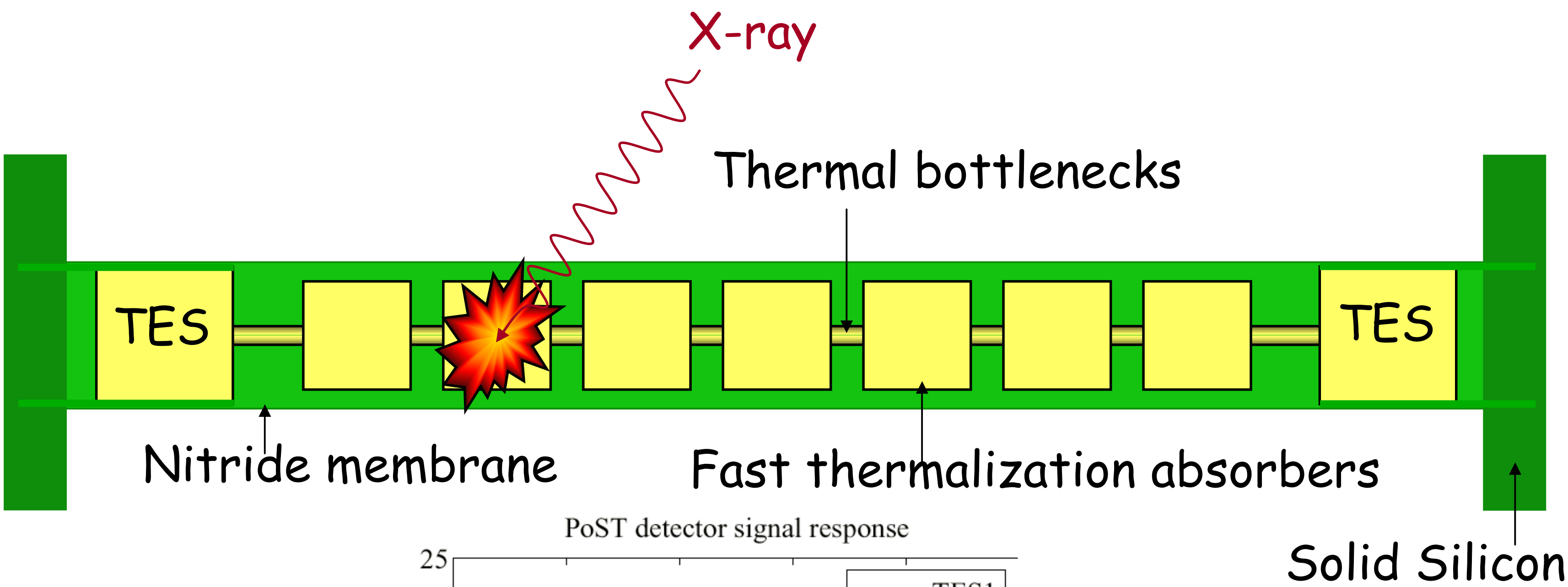


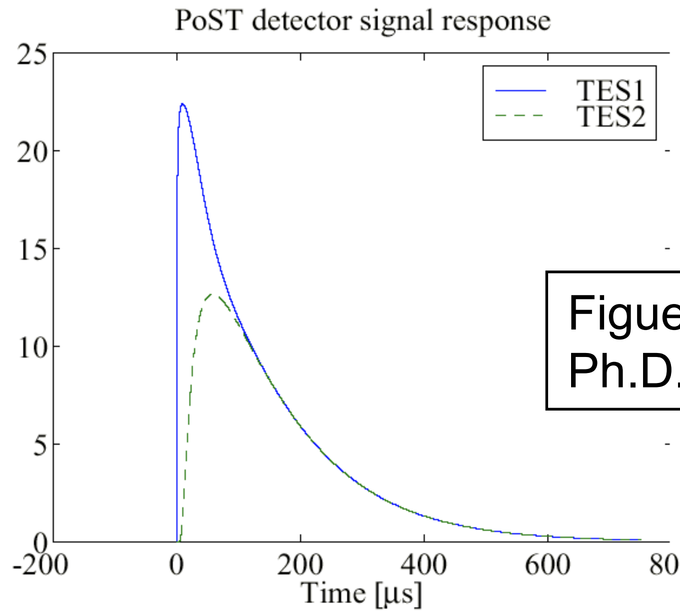






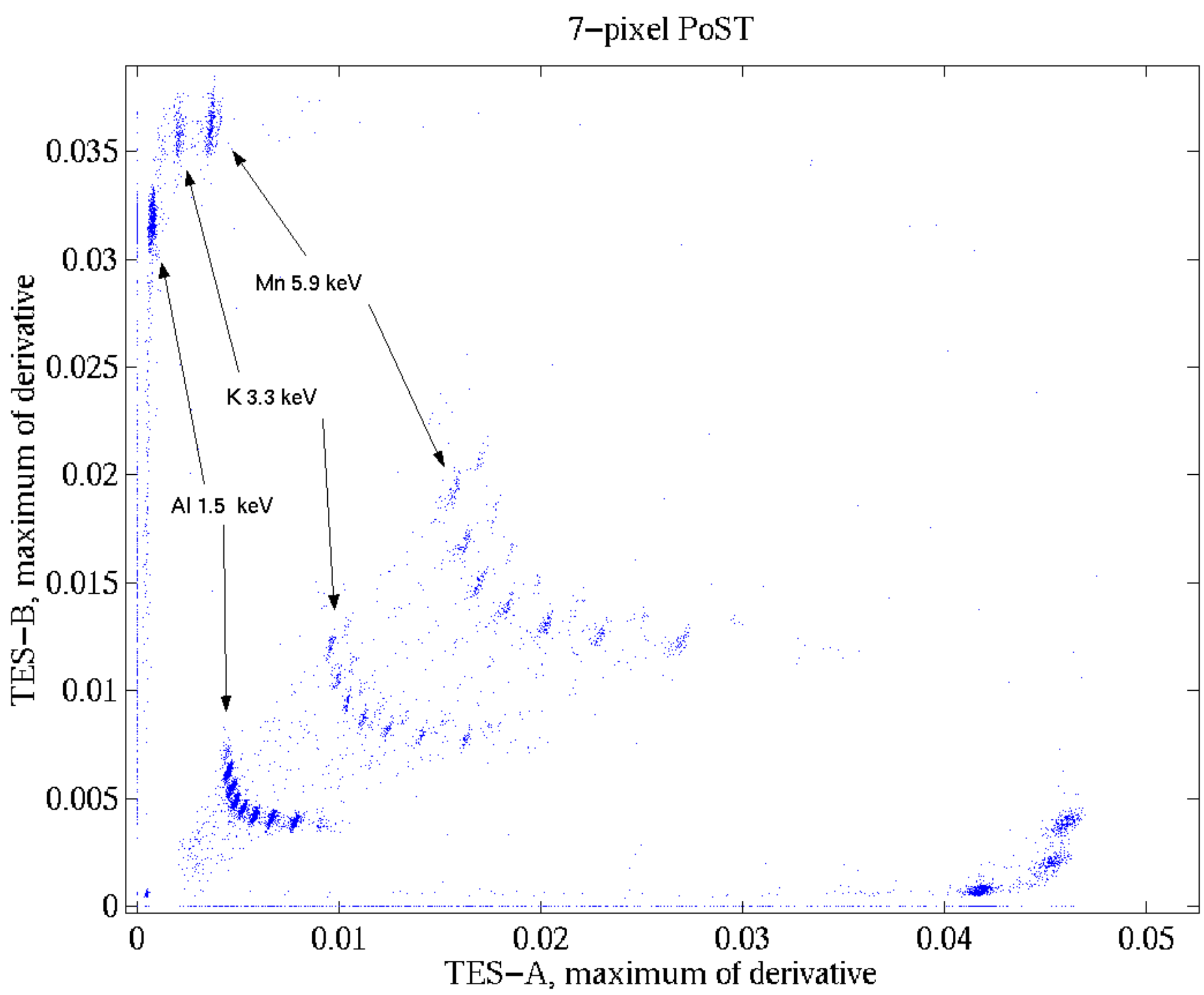
Position-Sensing TES (PoST)





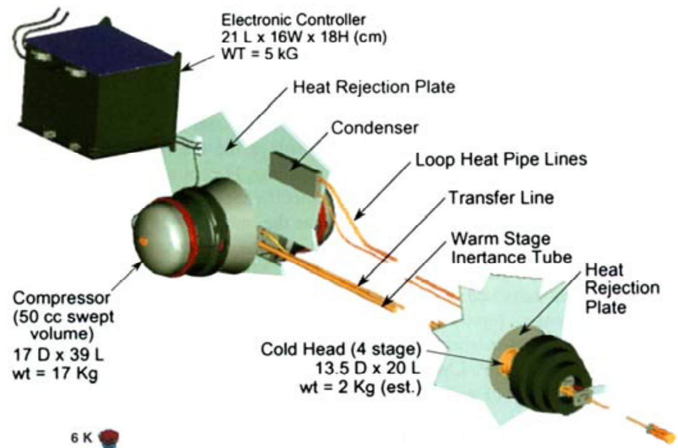
Figueroa-Feliciano *et al.* 2001;
Ph.D. dissertation 2001

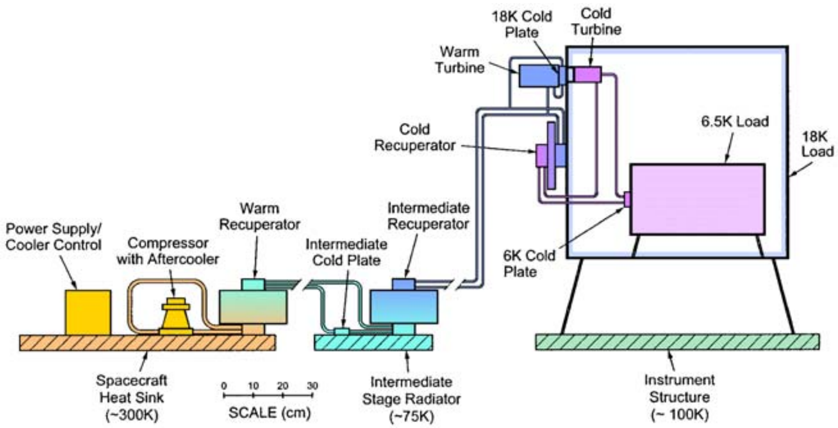
First Results with PoST

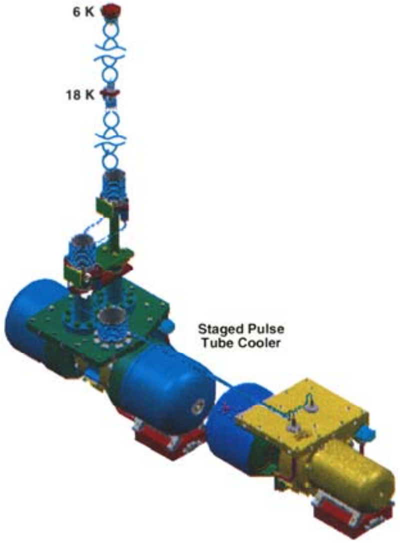


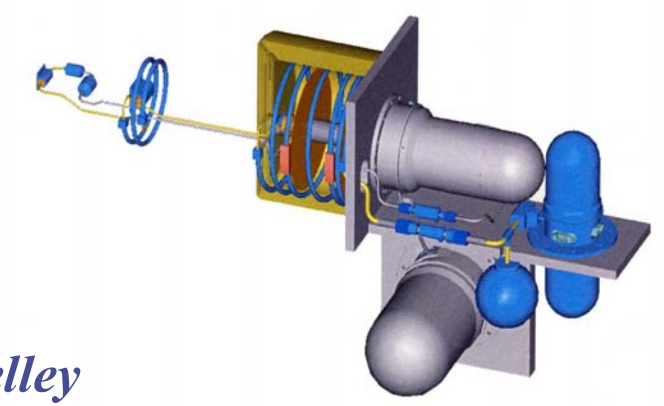
ACTDP Cryocoolers

Advanced Cryocooler Technology Development Program









Dr. Richard Kelley
Goddard Space Flight Center

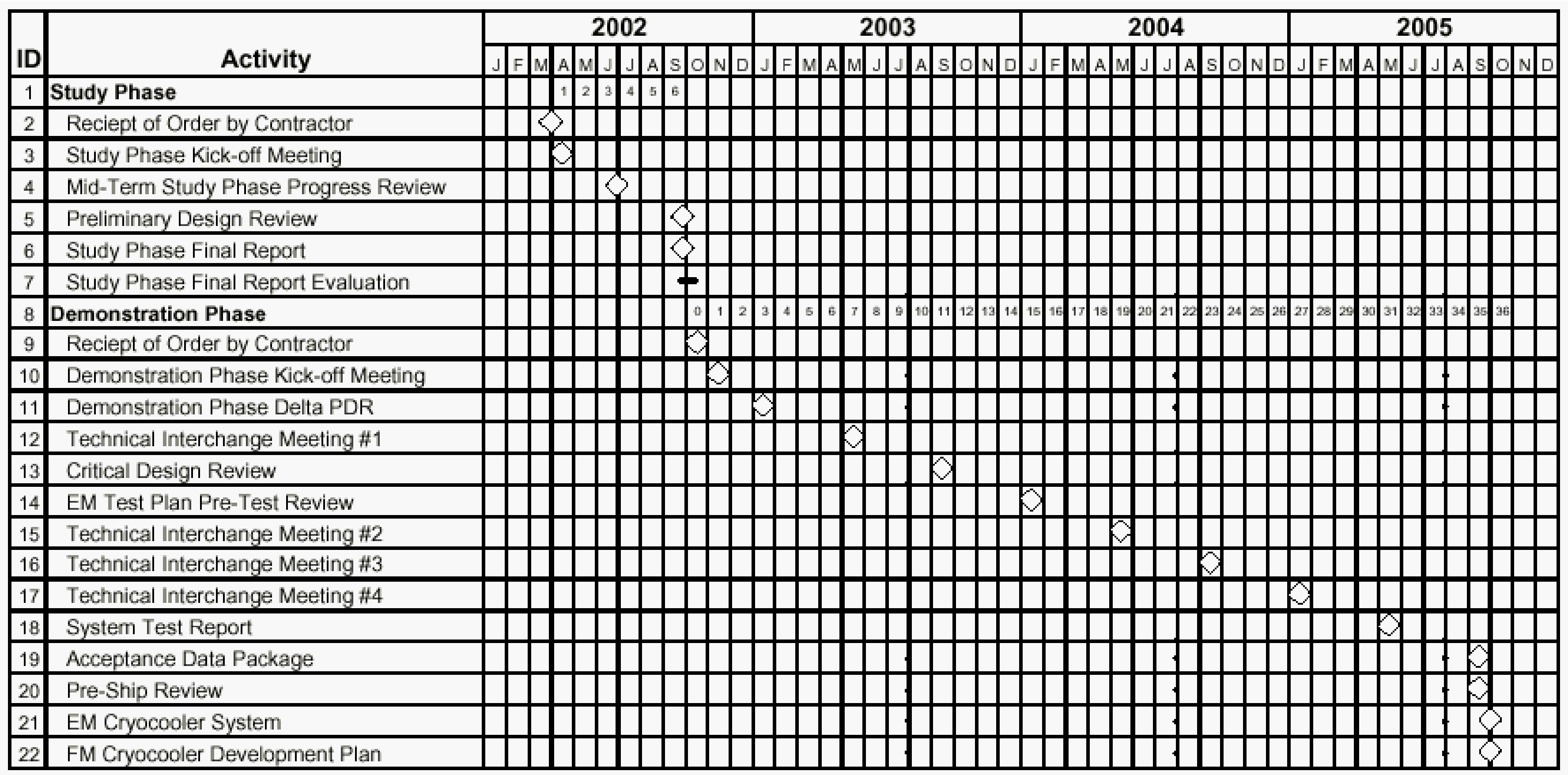
ACD TDP Cryocoolers

- **Primary participants in ACTDP**
  – Constellation-X, TPF, NGST
- **Common needs**
  – Reliable long-life cooling near 6 K
- **ACTDP cooling requirements = metrics**
  – 7.5 mW @ 6K; 250 mW @ 18 K
  – For < 150 W beginning of life input power
- **Four study phase contracts**
  – Ball; Lockheed-Martin; TRW; Creare
  – Each proposed mix of technology: existing and next-step coming out of IRAD, SBIR, &c.
- **September down-select to two demonstration coolers**
  – May 2005 completion of TRL-5 cooler and BB electronics
  – Tested to meet ACTDP requirements

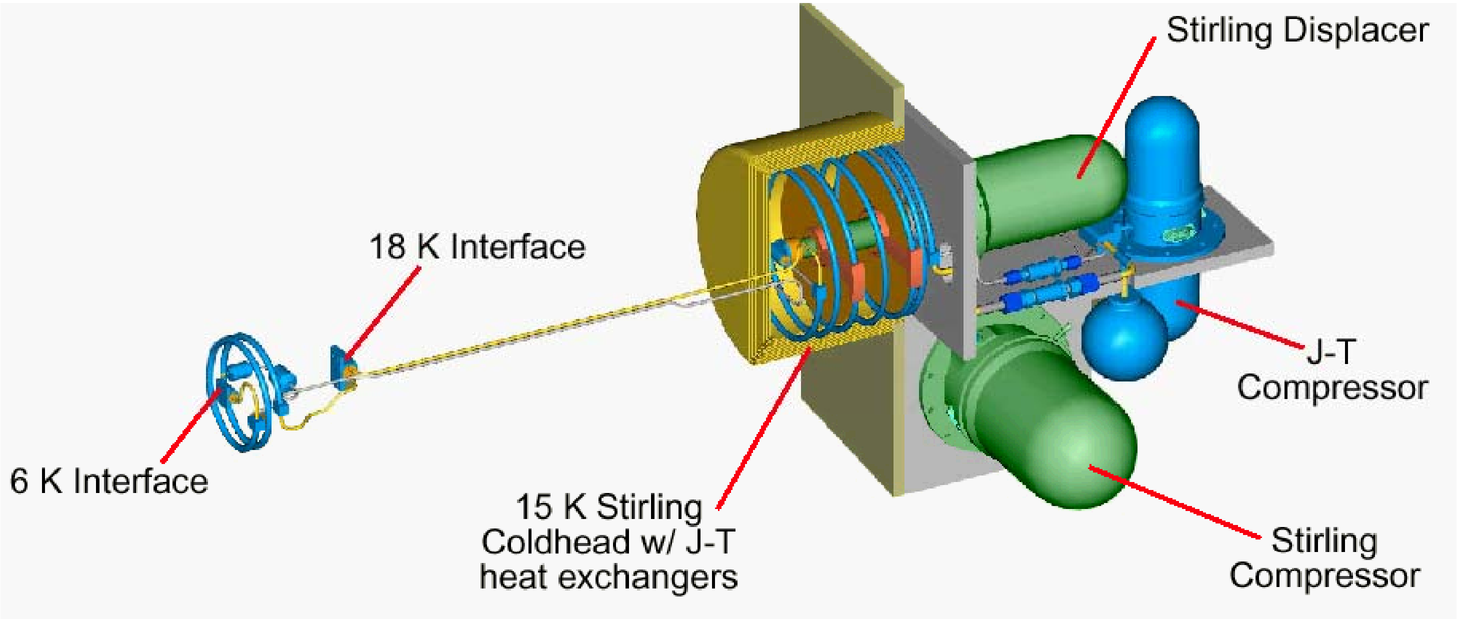
ACD□TDP Acquisition Schedule

ID	Activity	Start Date	End Date
1	TA released	11/30/01	11/30/0
2	Proposal development period	11/30/01	01/25/02
3	Question & Answer responses	11/30/01	01/25/02
4	PRP member support arrangements	11/30/01	01/25/02
5	PRP/PRC meeting plan / arrangements	11/30/01	01/25/02
6	ACTDP proposal model development	11/30/01	01/25/02
7	Evaluation package preparation	11/30/01	01/25/02
8	Proposals due	01/25/02	01/25/02
9	Proposal compliance screening	01/25/02	02/01/02
10	All evaluation packages shipped	02/01/02	02/01/02
11	Independent technical evaluations	02/01/02	02/17/02
12	Technical peer review meeting	02/20/02	02/22/02
13	PRP findings report / presentation	02/21/02	03/01/02
14	Programmatic review evaluation/meeting	03/04/02	03/08/02
15	Selection & announcement processes	03/11/02	03/15/02
16	Contract negotiations / start work	03/18/02	03/29/02
17	Technology Concept Study Phase	04/01/02	09/27/02
18	Study Phase preliminary design reviews	09/03/02	09/06/02
19	Study Phase Final Reports due	09/27/02	09/27/02
20	Independent technical evaluations	09/30/02	10/11/02
21	Technical peer review meeting	10/15/02	10/15/02
22	PRP findings report / presentation	10/15/02	10/18/02
23	Programmatic review evaluation/meeting	10/21/02	10/25/02
24	Down-selection / Announcements	10/25/02	10/25/02

ACD□TDP Development Schedule

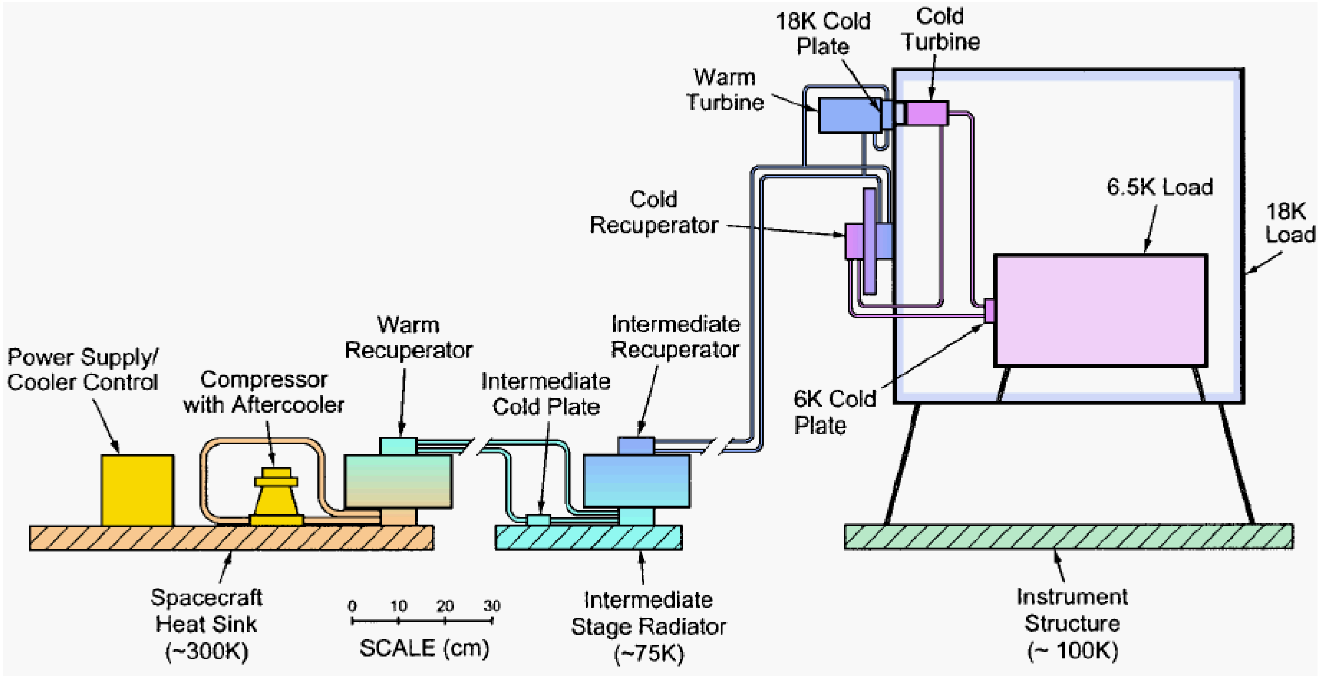


Ball ACTDP Cryocooler Concept



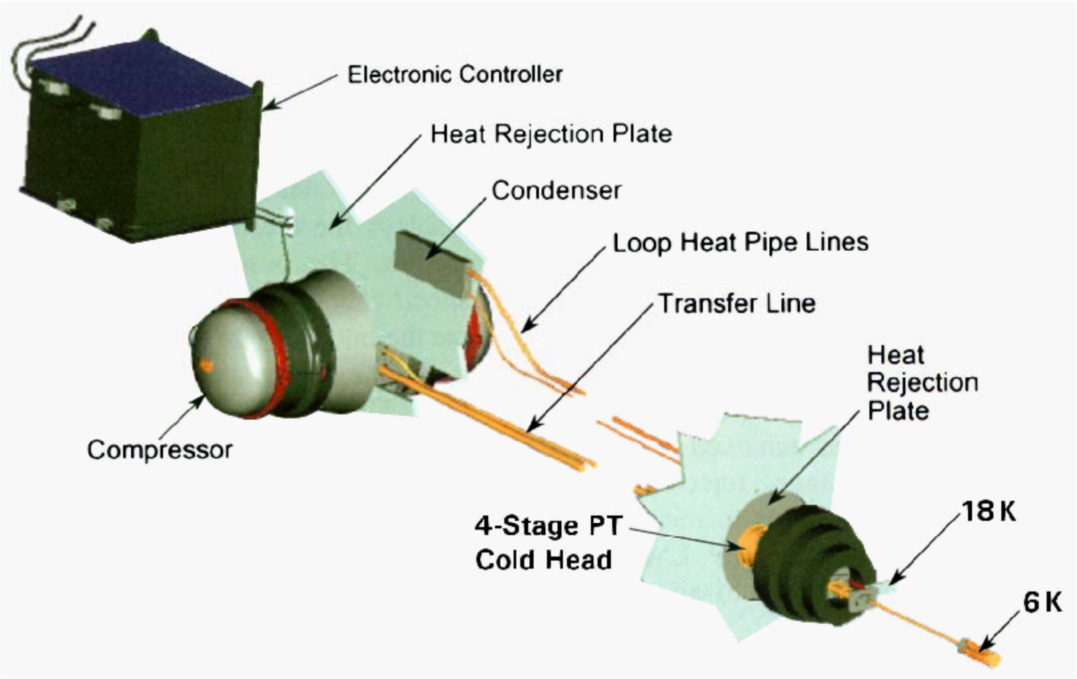
Ball Aerospace's ACTDP cryocooler concept utilizes a multistage Stirling refrigerator to precool a J-T loop powered by a linear-motion Oxford-style compressor. The J-T loop provides remote cooling of the 6 K and 18 K loads and isolates the loads from compressor-generated vibration and EMI. No intermediate radiative precooling is required, and the compressor elements are easily separated by over 3 meters from the cryogenic loads. The multistage refrigerator is based on leveraging existing Ball flight-quality Stirling compressors, J-T cold-end technology, and drive electronics; these technologies are configured and adapted to meet the specific needs of the ACTDP mission requirements. The baseline concept shown in the accompanying illustration has a projected total system mass of 27 kg (including flight drive electronics) and has an estimated input power of approximately 150 watts into the drive electronics.

Creare ACTDP Cryocooler Concept



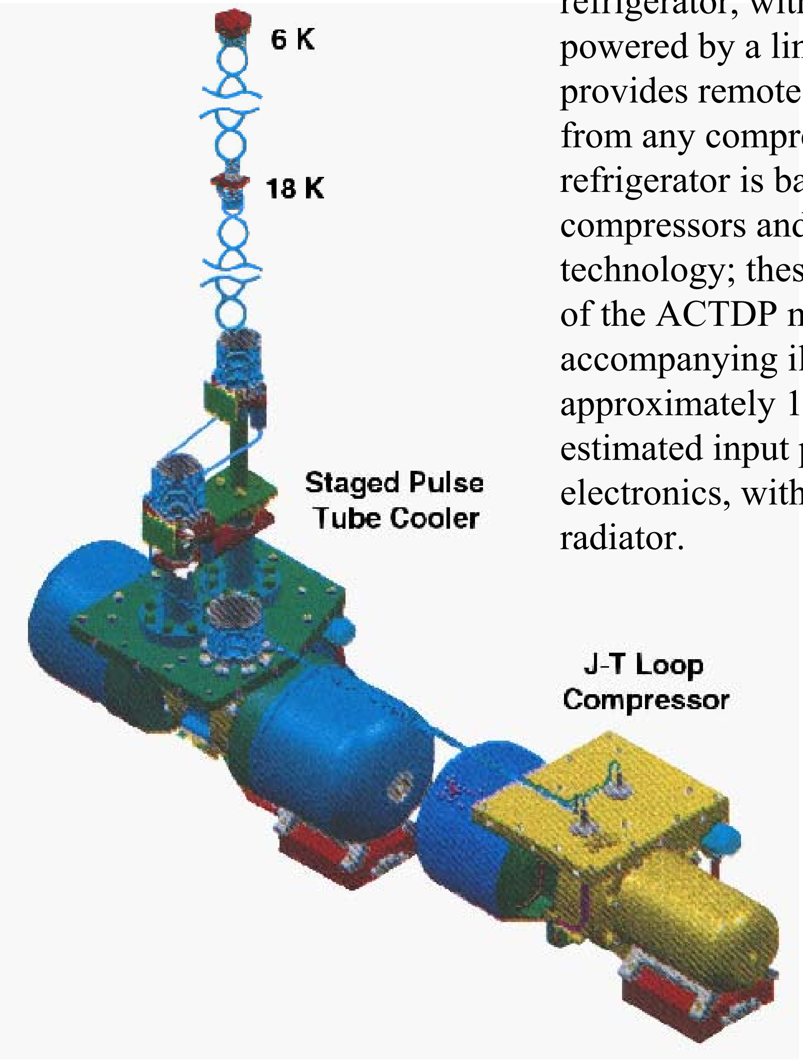
Creare's ACTDP cryocooler concept utilizes a multistage turbo-Brayton refrigerator with optional precooling by a cryoradiator. The turbo-Brayton loop, which has remotely located turbo-expanders operating at 6 K and 18 K, generates minimal vibration and allows the 6 K and 18 K loads to be widely separated from the loop's room-temperature compressor and electronics. The multistage refrigerator is based on leveraging existing Creare flight-quality turbo-Brayton compressors, expanders, and drive electronics as well as new developmental hardware aimed at low temperature operation; these are configured and adapted to meet the specific needs of the ACTDP mission requirements. The baseline concept, shown in the accompanying illustration, has a projected total system mass of 27 kg (including flight drive electronics) and has an estimated input power of approximately 105 watts into the drive electronics, with approximately 1.3 W dissipated at a 75 K intermediate temperature radiator.

Lockheed ACTDP Cryocooler Concept



Lockheed martin's ACTDP cryocooler concept utilizes a multistage pulse tube refrigerator, with optional cryoradiator precooling, to directly cool the 6 K and 18 K loads. The single-unit multistage refrigerator leverages existing Lockheed flight-quality pulse-tube compressors, cold heads, and drive electronics, and laboratory pulse tube technology that has demonstrated direct cooling down to 4K; these are being configured and adapted to meet the specific needs of the ACTDP mission requirements. The baseline concept, shown in the accompanying illustration, has a projected total system mass of approximately 26 kg (including flight drive electronics) and has an estimated input power of approximately 208 watts into the drive electronics when no intermediate radiative precooling is utilized. Use of a 120 K precooler dissipating 8 W is estimated to reduce the input power to on the order of 106 watts.

TRW ACTDP Cryocooler Concept



TRW's ACTDP cryocooler concept utilizes a multistage pulse tube refrigerator, with optional cryoradiator precooling, to precool a J-T loop powered by a linear-motion Oxford-style compressor. The J-T loop provides remote cooling of the 6 K and 18 K loads and isolates the loads from any compressor-generated vibration and EMI. The multistage refrigerator is based on leveraging existing TRW flight-quality pulse tube compressors and drive electronics, and developmental J-T cold-end technology; these are configured and adapted to meet the specific needs of the ACTDP mission requirements. The baseline concept shown in the accompanying illustration has a projected total system mass of approximately 17 kg (including flight drive electronics) and has an estimated input power of approximately 207 watts into the drive electronics, with 2 W dissipated at the 85 K intermediate temperature radiator.

Continuous ADR

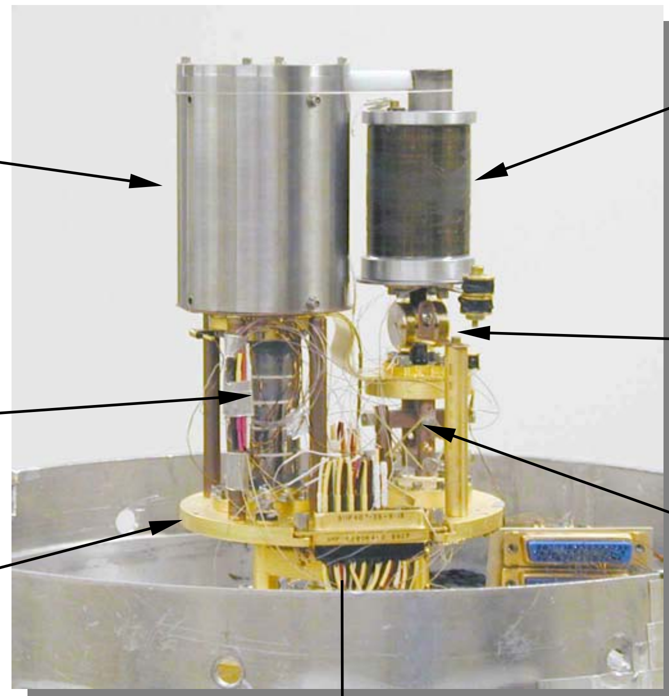
Continuous Adiabatic Demagnetization Refrigerator

Dr. Richard Kelley
Goddard Space Flight Center

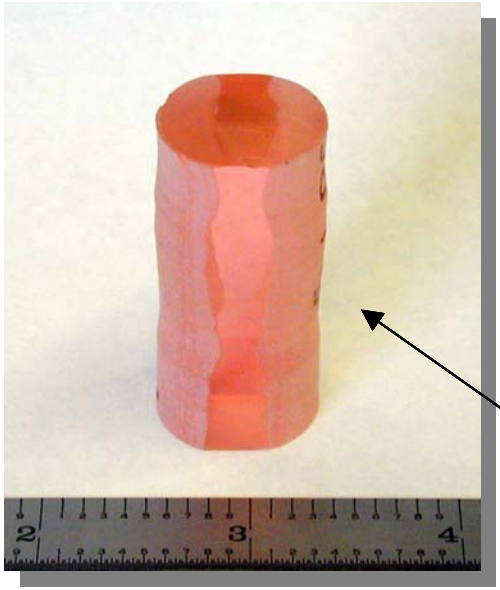
ADR

- **Technological Goals/Challenges**
  - Tight temperature control at or about 50 mK
  - Heat rejection from ADR to cryocooler at or about 6 K
- **Current development under CETDP and CTD**
  - Projecting need for 5 microwatts at 50 mK; have demonstrated 6 microwatts at 50 mK controlled to 8 microKelvin rms
  - Heat rejection to superfluid He at 1-2 K; next to 4.2 K normal He
- **Logical step beyond single stage ADR as used on ASTRO-E I & II and HAWC**
- **Ground testing sufficient throughout development as well as for final system tests (Calorimeter-ADR-cryocooler)**

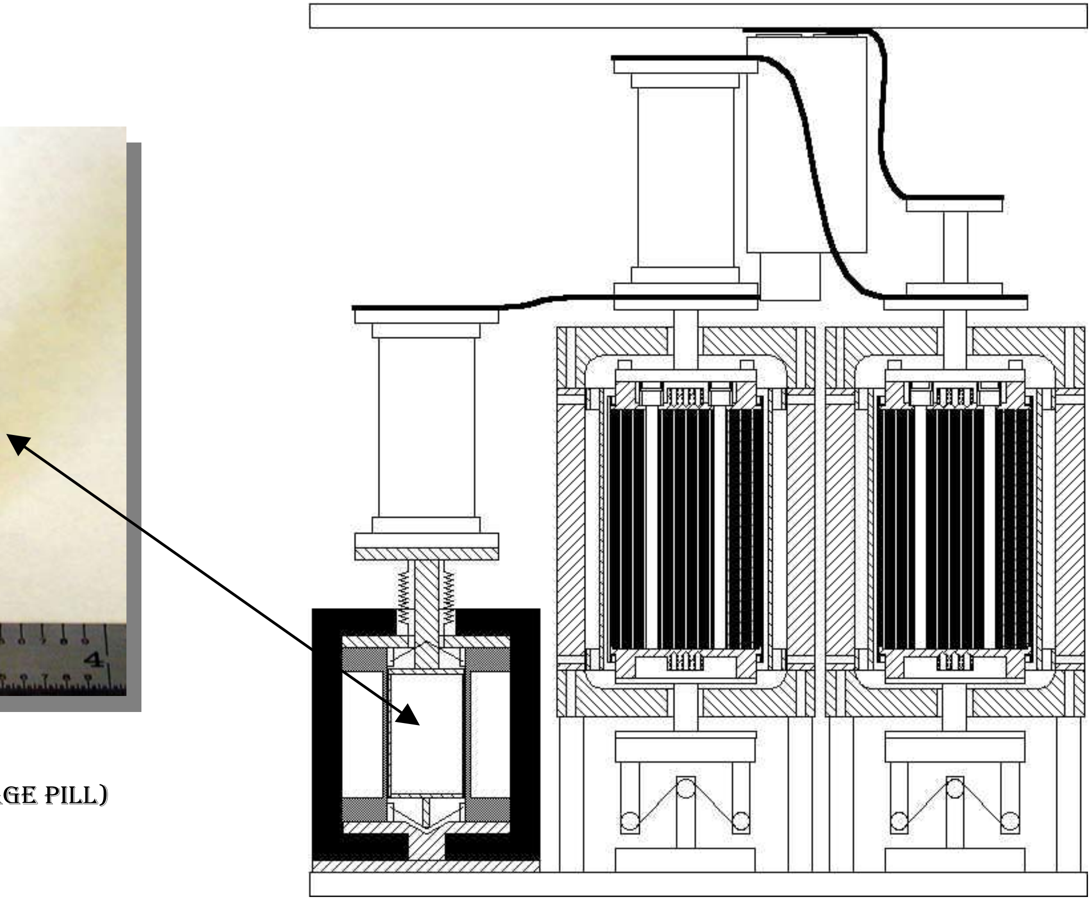
3-Stage Continuous ADR



4-Stage Continuous ADR

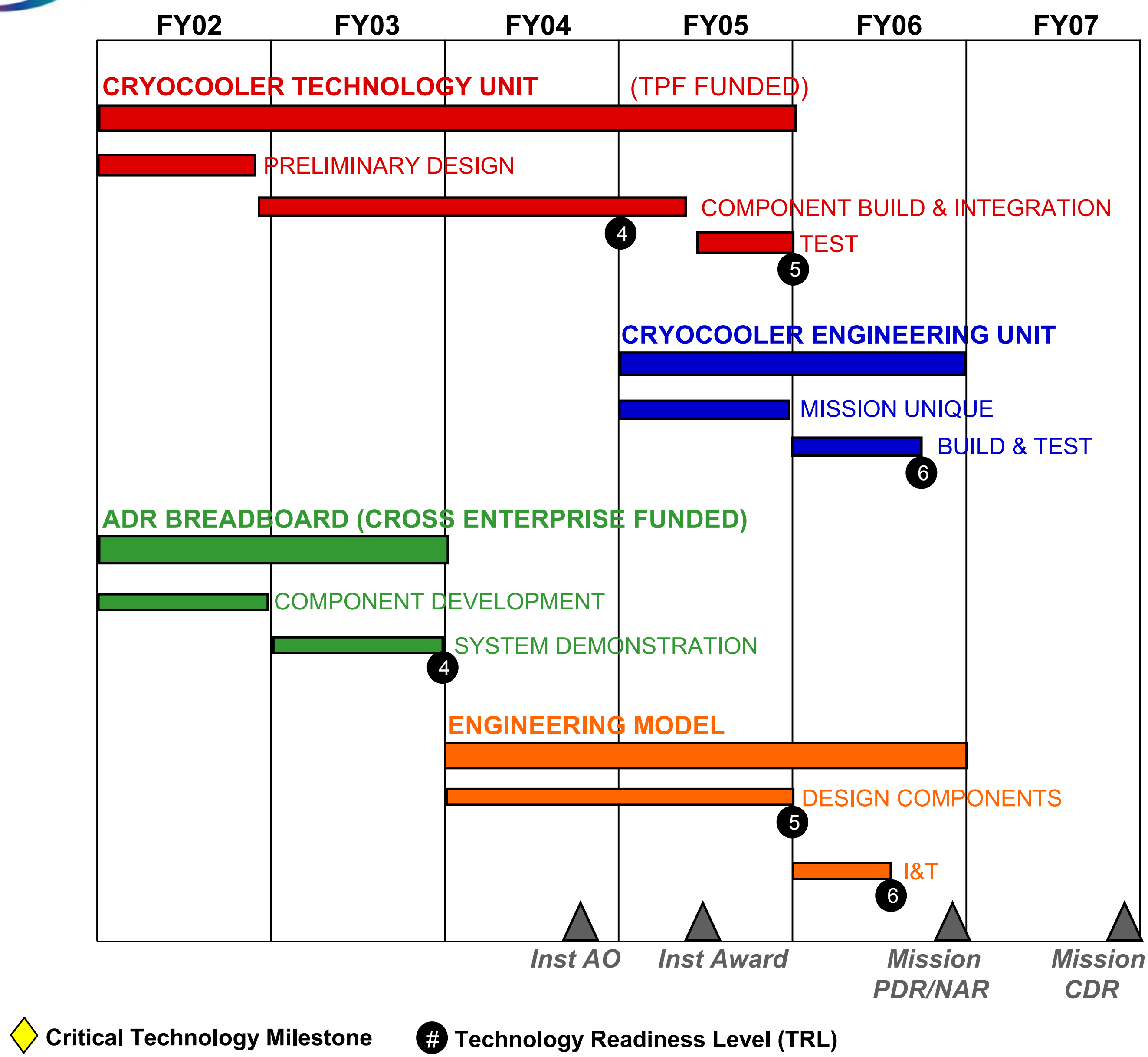


$GdLiF_4$ - 0.05 Ho
(Candidate for 4th stage pill)



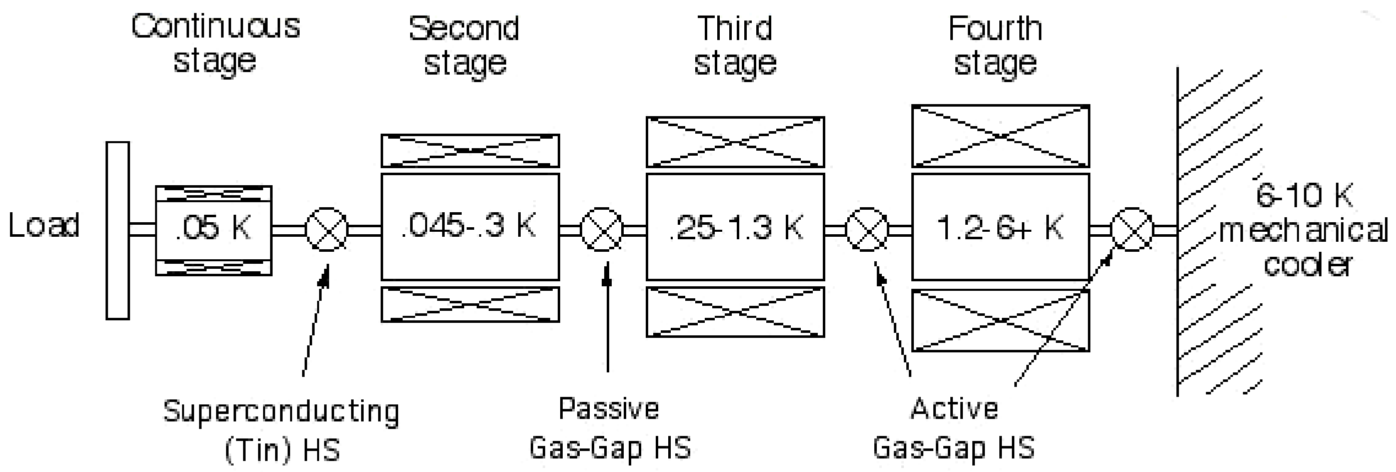
4-Stage Continuous ADR

Cryocooler/ADR Technology Roadmap



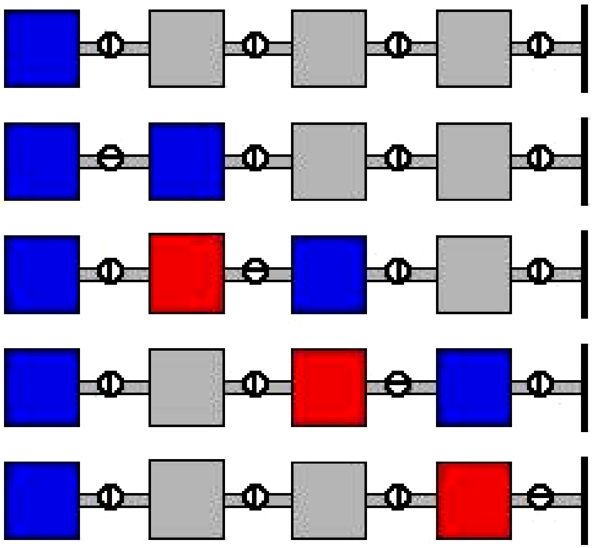
Continuous ADR
Back Up Charts

Advanced ADR Concept



- Load is cooled by a "continuous" stage
- Other stages work to push heat up to the heat sink
  - Number of stages and temperature range depends on heat switch properties
- Cycle time can be short, ~1 hour
  - Order of magnitude less refrigerant
  - Higher cooling power per unit mass

Recycling Sequence

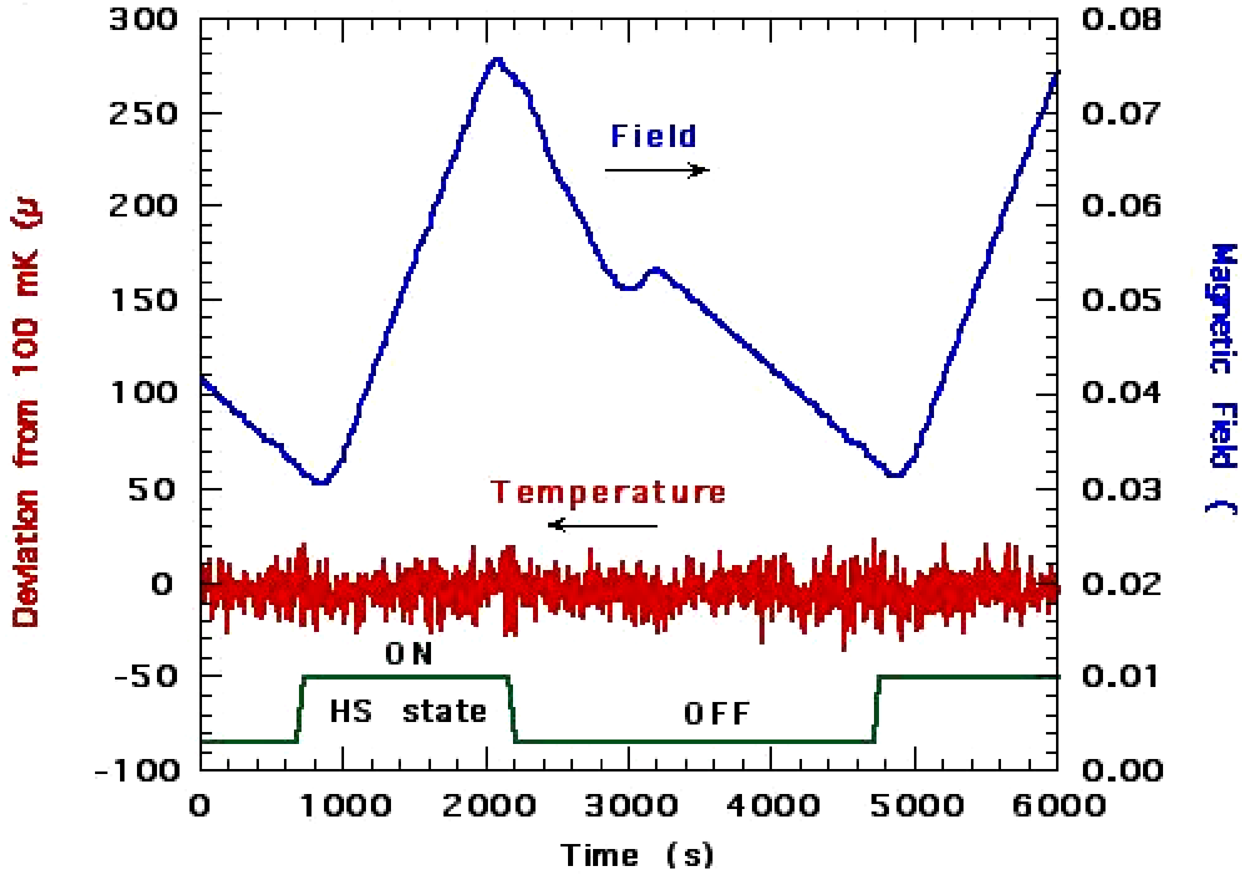


Current Status

- **Development ahead of schedule for FY01**
  - Built 3-stage ADR connected to a 1.3 K helium bath
  - Demonstrated continuous cooling
    - 2.5 μW at 60 mK, 10 μW at 100 mK
    - Temperature stability of 8 μK rms (limited by electronic noise of resistance bridge)
- **Key technology area for remainder of project is refrigerants for 1-10 K range**
  - Work on doped magnetic garnets is progressing well
- **Based on progress, anticipate completing 4-stage ADR operating with 10 K sink by FY03**
  - Advance TRL to 4

Temperature Stability

- Important issue for systems with reversing heat flows
  - No apparent correlation of temperature fluctuations with recycling events
  - Temperature noise is 8 μK rms



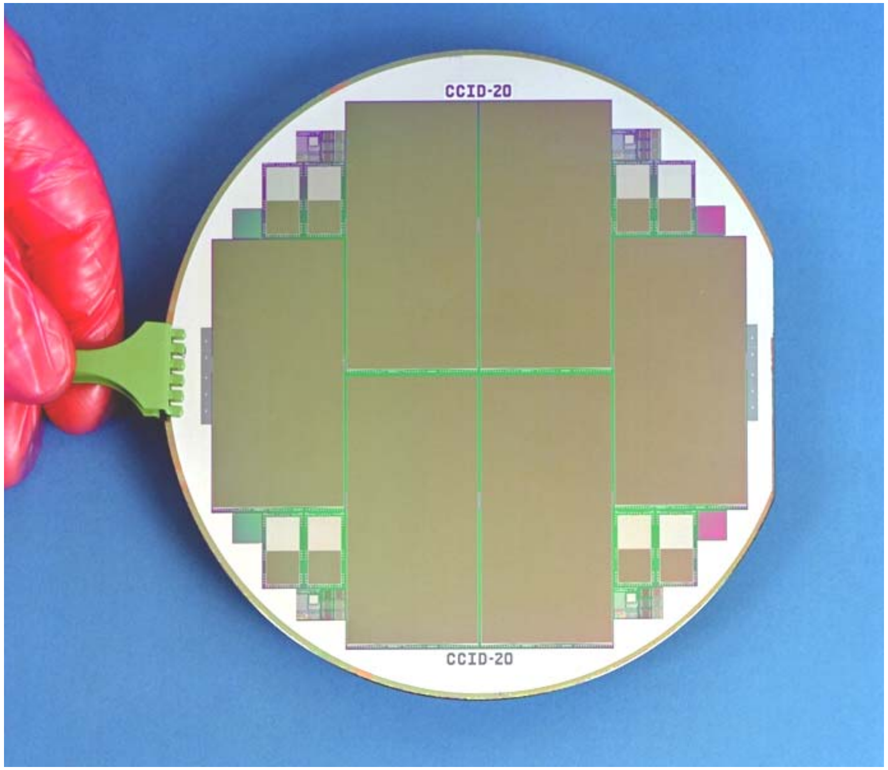
ADR Cooling Power

- Cooling power is the maximum *sustainable* added heat load
  - High heat loads can be tolerated for shorter periods of time

T (K)	Cooling Power (μW)
0.10	10
0.09	9
0.08	8
0.07	5.5
0.06	2.5

- Decrease is due to the low thermal conductance of the superconducting heat switch

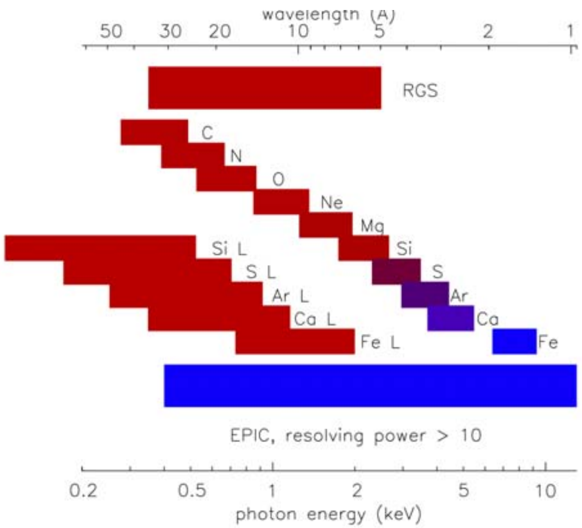
Grating/CCD



Jay Bookbinder
Smithsonian Astrophysical Observatory

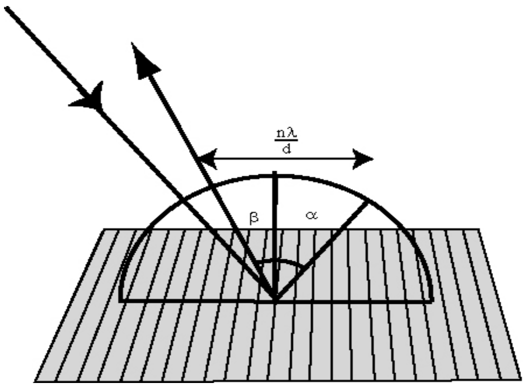
Grating/CCD Requirements

- **The Grating, CCD and SXT requirements are tightly linked. Requirements are tied to the SXT requirements, and are flowed down from the top level science requirements**
  - **Minimum System Resolving Power > 300**
  - **Bandpass to 0.2 keV to ~ 1.5 keV**
  - **Effective Area > 1000cm2 at 0.2 keV**
  - **CCD Energy resolution sufficient to separate orders**
- **Additional mission level constraints:**
  - **Mass**
  - **Power**
  - **Radiation hardness**
  - **Production yield**

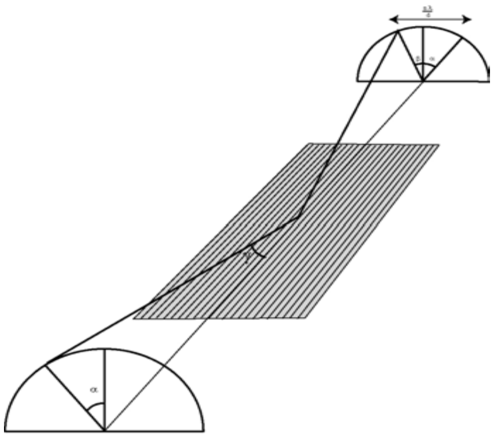


Grating Implementation

- Baseline: In plane reflection gratings
  - An extension of the XMM approach
  - New fabrication techniques (anisotropic etching) provides grating facets that are *atomically* smooth.
  - Master will be used to apply ruling pattern only; groove shape will be formed by processing.

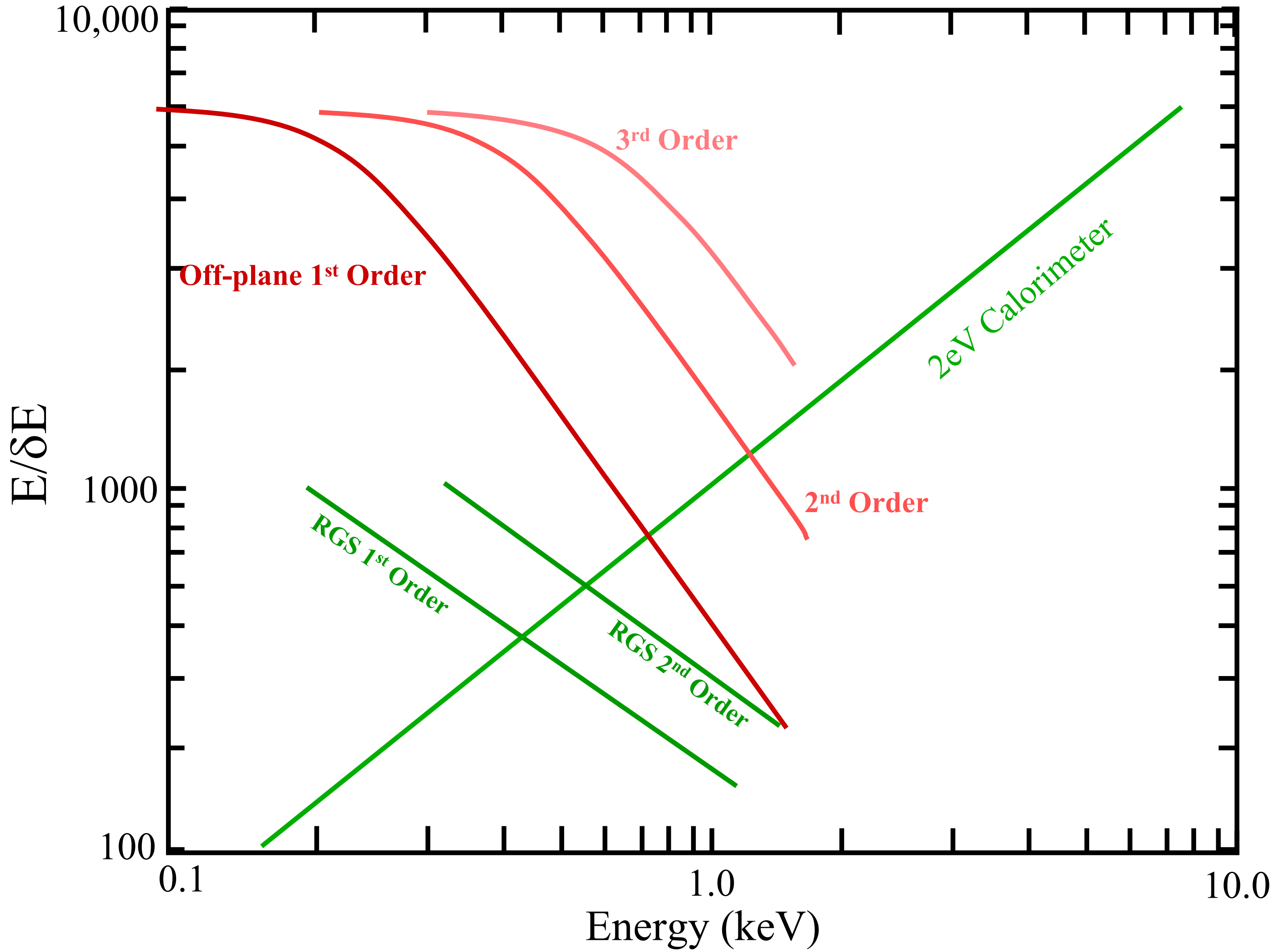


- Alternate approach: Off-plane gratings
  - Potential improvements in system resolution, throughput, alignment tolerances and/or number of gratings required
  - Con: Groove efficiencies not demonstrated in the higher ruling density radial configuration



- Decision Points
  - Off-plane test gratings in fabrication
  - Off-plane X-ray tests in late ’02
  - Selection end of FY’03

Resolution


10,000
1000
100
E/δE
0.1
1.0
10.0
Energy (keV)
Off-plane 1st Order
3rd Order
2nd Order
2eV Calorimeter
RGS 1st Order
RGS 2nd Order

Metrics and Status: Gratings

Reflection grating metrics:

- Substrate mass per unit area < 0.2 g/cm^2
- Substrate flatness < 0.5 micron

Status:

- Flatness of <1 micron on a 100 mm diameter wafer that meets the 0.2g/cm2 areal density requirement has been demonstrated with magneto-rheological figuring (MRF).

Off-plane metrics:

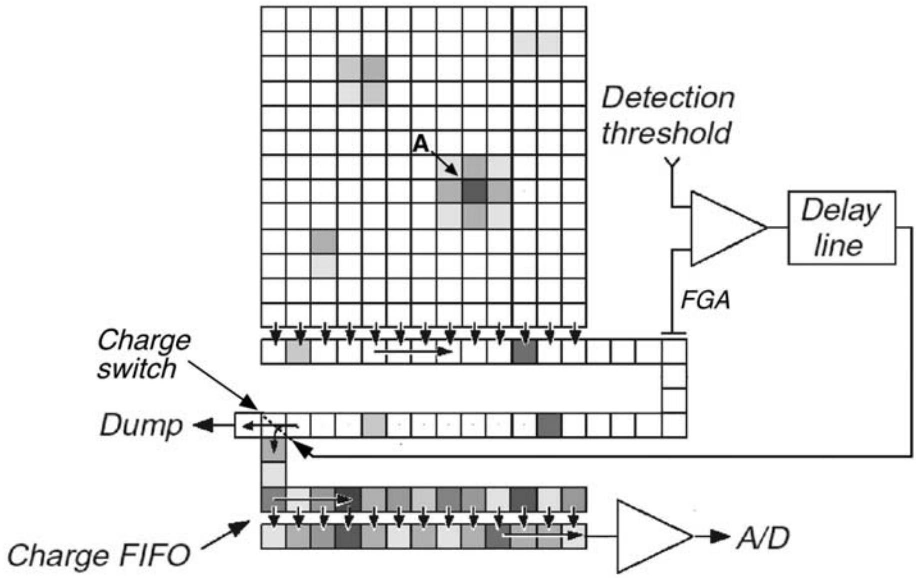
- Groove efficiency in radial groove geometry of >25%
- The substrate mass and flatness, and assembly tolerances would be relaxed for the off-plane grating approach in comparison with the baseline.

Status:

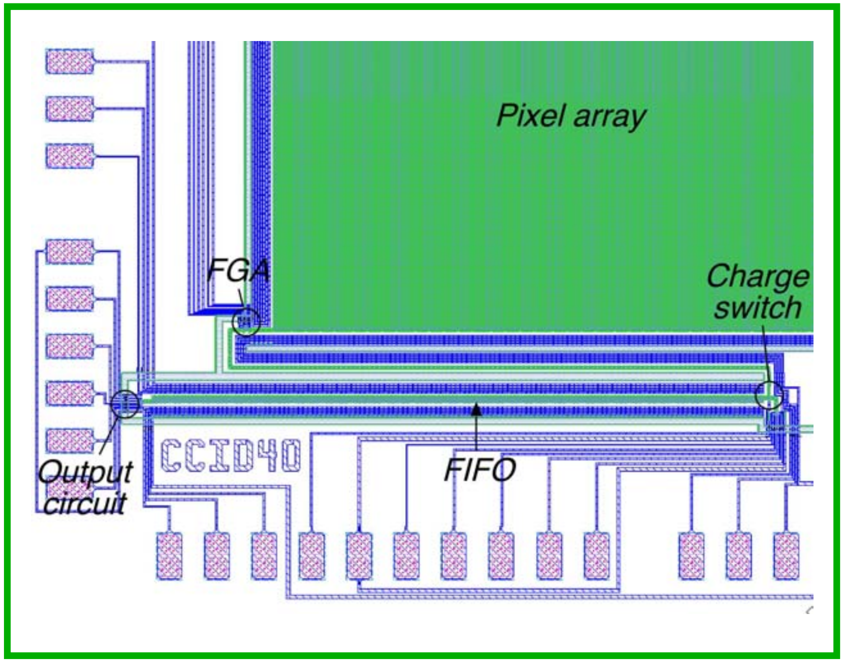
- Test grating is in process

CCD Implementation

- **Baseline approach is the Resistive Gate CCD (RGCCD)**
  - Concept baselined to achieve low power, rad hard, high yield
- **Alternate approach is the Event-driven CCD (EDCCD)**
  - EDCCD can be back illuminated with Molecular Beam Epitaxy (MBE) process
  - Project has begun the process of baselining the EDCCDs



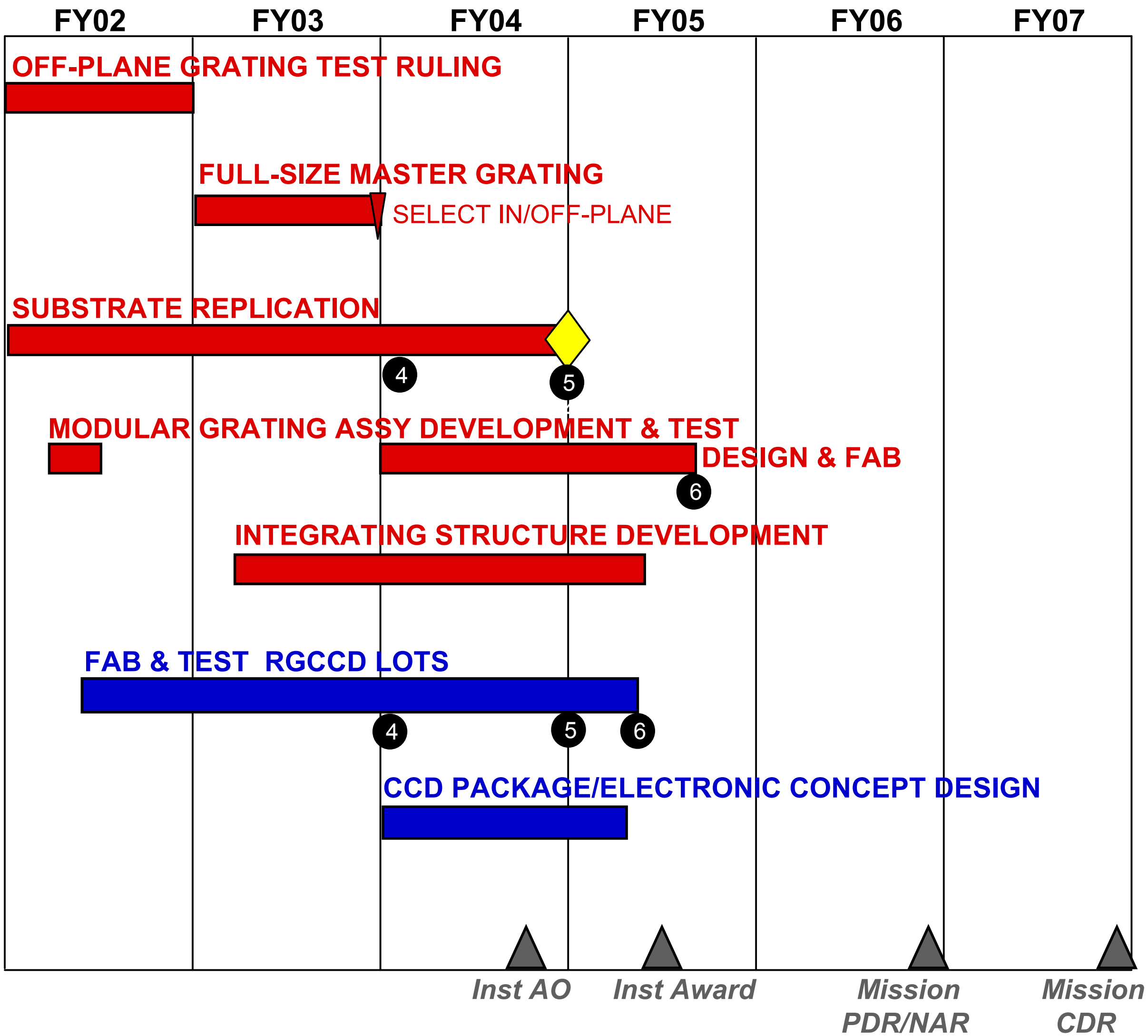
(Doty and Ricker 2002)



Metrics and Status: EDCCDs

- **CCD metrics:**
  - Frame rate: > 50 Hz
  - Power: 50 times less than current devices
  - QE: 75% at 0.25 keV
  - Radiation hardness: 10x greater than Chandra ACIS CCDs
  - Yield: >5%
- **Status**
  - EDCCD is based on conventional CCD technology, with standard serial and parallel registers.
  - Novelty is the read-out electronics - first lot is in fabrication
  - The MBE BI process has been demonstrated. Yield is >10% (cf. 0.2% for Chandra ACIS)
  - MBE processed chips show QE ~85% at 0.25 keV
  - The combination of EDCCD with MBE processing will be demonstrated in FY03.

Grating/CCD Technology Roadmap



Critical Technology Milestone # Technology Readiness Level (TRL)

Grating/CCD
Back Up Charts

Grating Critical Technology Milestone

- **Assembly of Three Flight Representative Lightweight Grating Substrates**
  - Substrates fabricated use procedures that can be applied to mass production and experience all processing steps that are included in the plan for the final flight gratings.
  - Substrate mass per unit area $\leq$ 0.2 gm/cm^2.
  - Substrate as-assembled flatness $\leq$ 2 arc-seconds in the dispersion direction.
  - Substrate mutual alignment $\leq$ 2 arc-seconds in the dispersion direction.

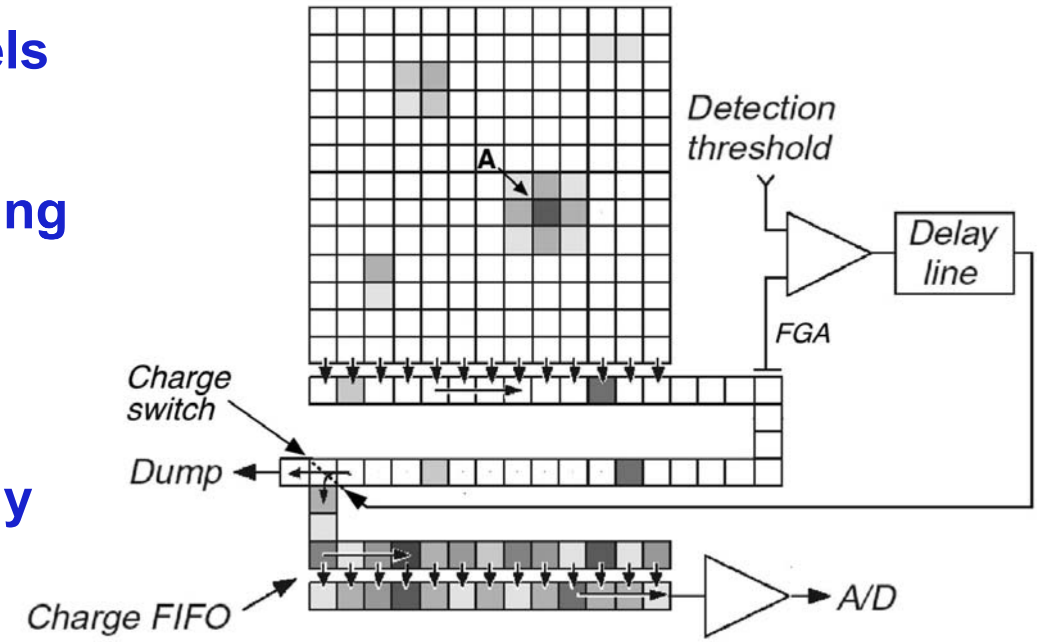
Advantages of EDCCD for Con-X

- System Constraints are relieved
  - Lower power dissipation at a given frame rate (>100 x less)
  - Reduced pileup concerns even for 5” optics (100 frames per sec)
  - Reduced shielding requirement (>10x more radhard)
  - Relaxed S/C stability and jitter requirements
- Improved Scientific Performance
  - Compatible with high yield back-illuminated (MBE) approach
  - Uses thinner optical blocking filter (OBF), since has 5 magnitudes less susceptibility to optical/IR
  - Improved QE for 0.1 - 1 keV band for which grating/CCD is optimum
  - Improved resolution for timing studies
  - Prospect of high yields (thus, can select near-ideal flight devices)
    - Conventional processing (cf RGCCD)

– Compilation of separately-tested innovations

Event-Driven CCD

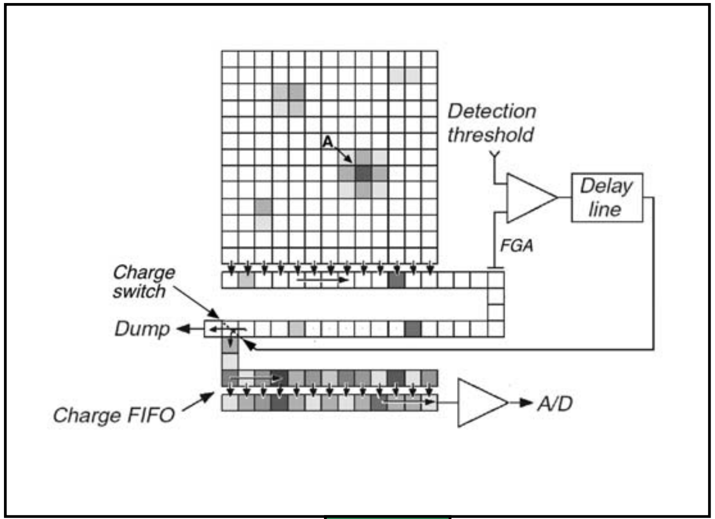
- Single photon imagery in X-ray astronomy results in sparse array utilization (< 10^{-3} of pixels have charge)
- Large power penalty for reading entire image just to examine pixels containing data
- In EDCCD, pixels are non-destructively sensed, and only those with signal charge are saved and digitized
- Novel approach (MIT patent applied for)

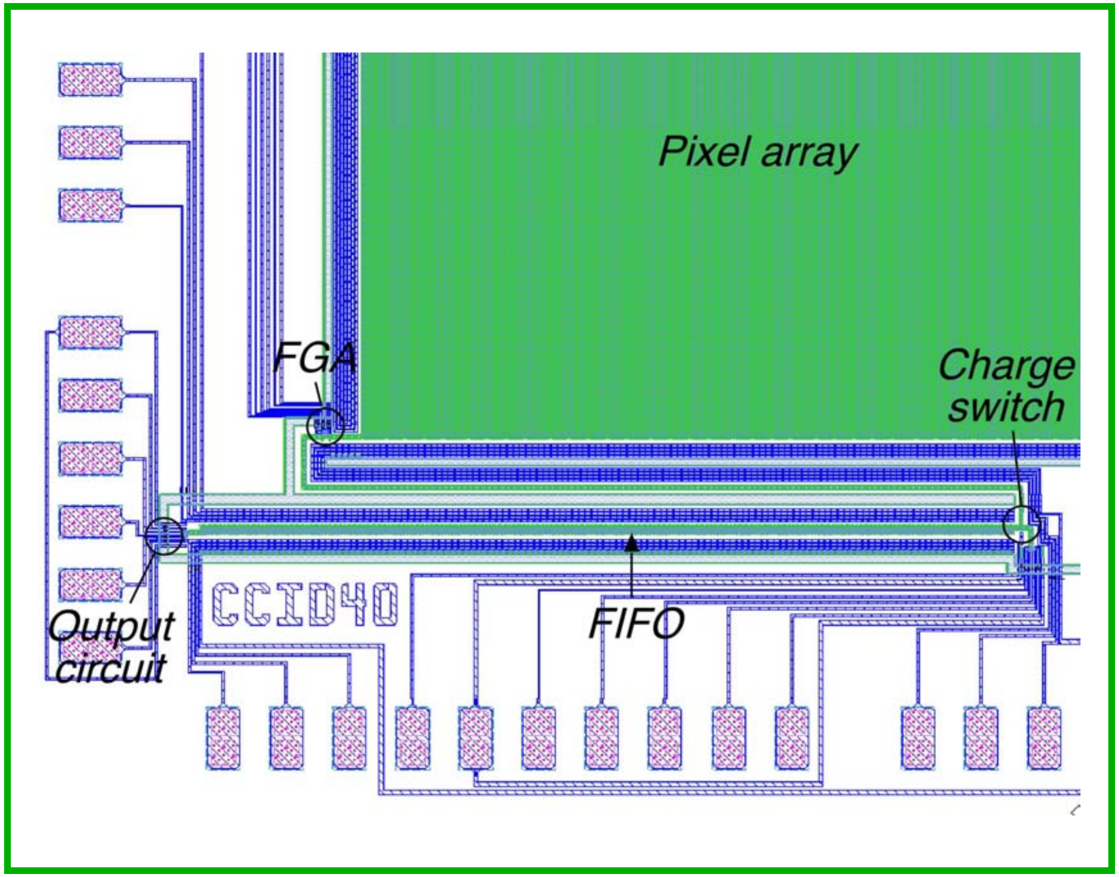


(Doty and Ricker 2002)

EDCCD Test Device Layout

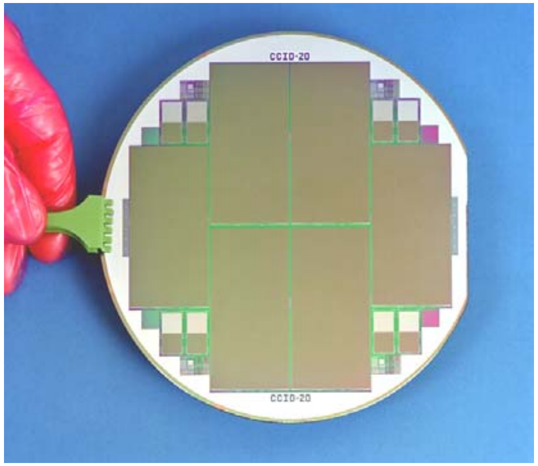
- 512 × 512-pixel device design completed 11/01



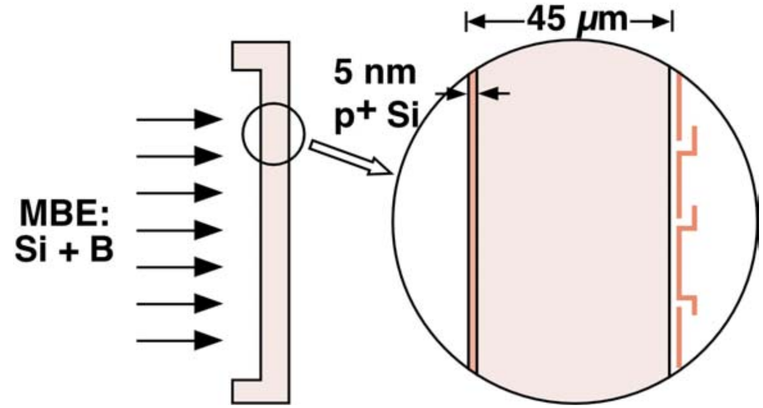


New Back-Illumination MBE Process

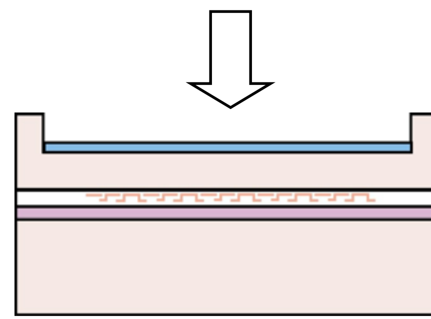
(Developed at MIT/LL in 2000-2001)



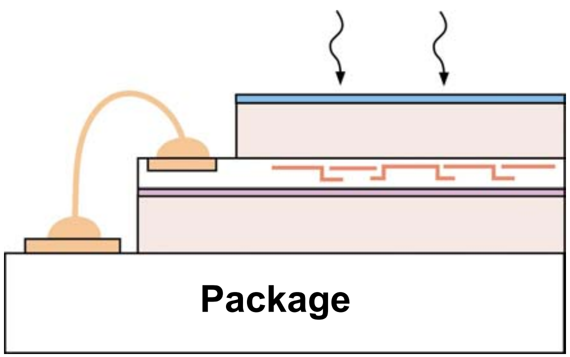
CCD wafer completed through frontside processing



Chemically thin center of wafer; grow p^+ on back surface by low temp MBE; deposit thin SiO_2 insulator and Al OBF



Epoxy thinned CCD to support wafer

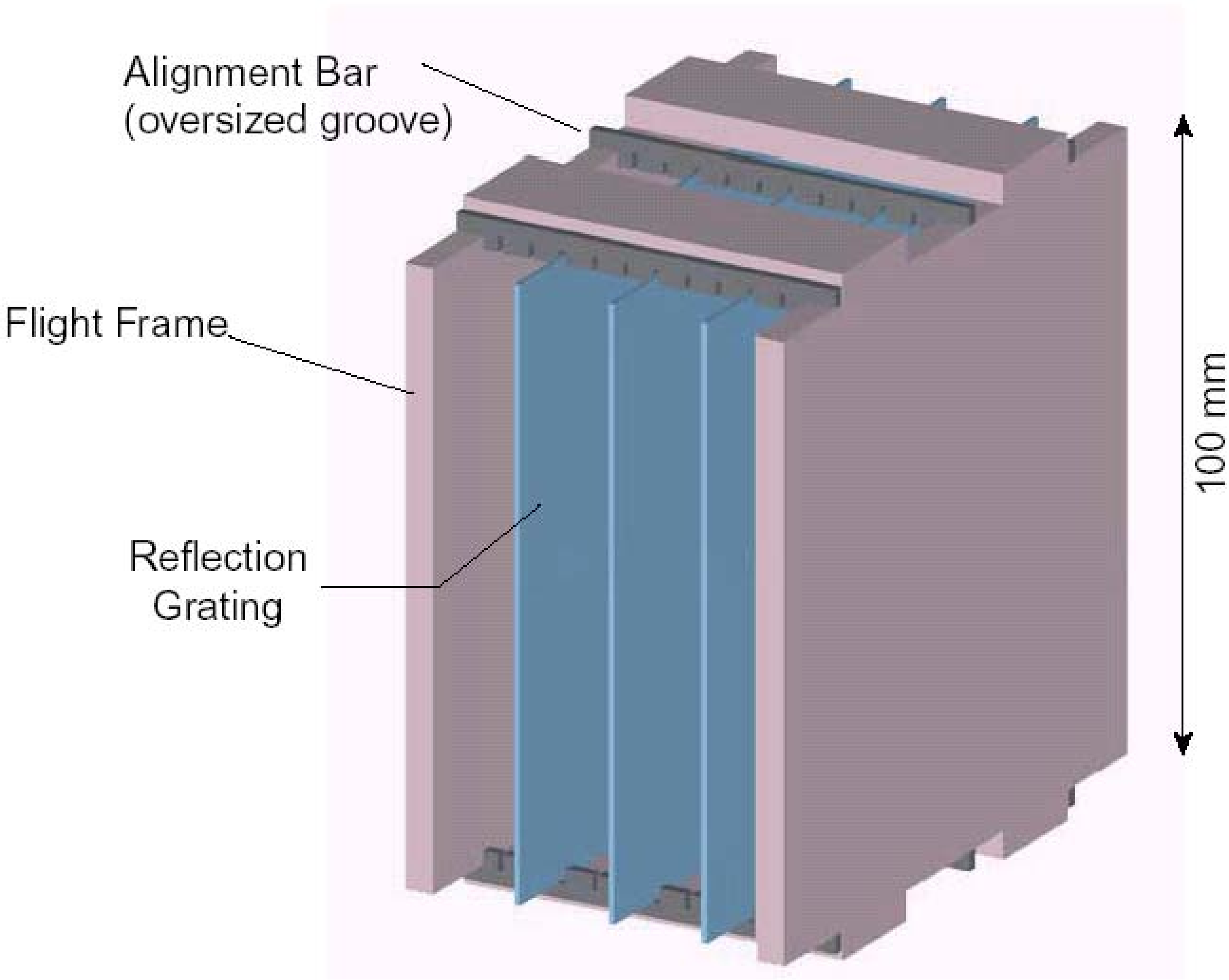


Etch to expose bond pads; saw wafer and package CCDs

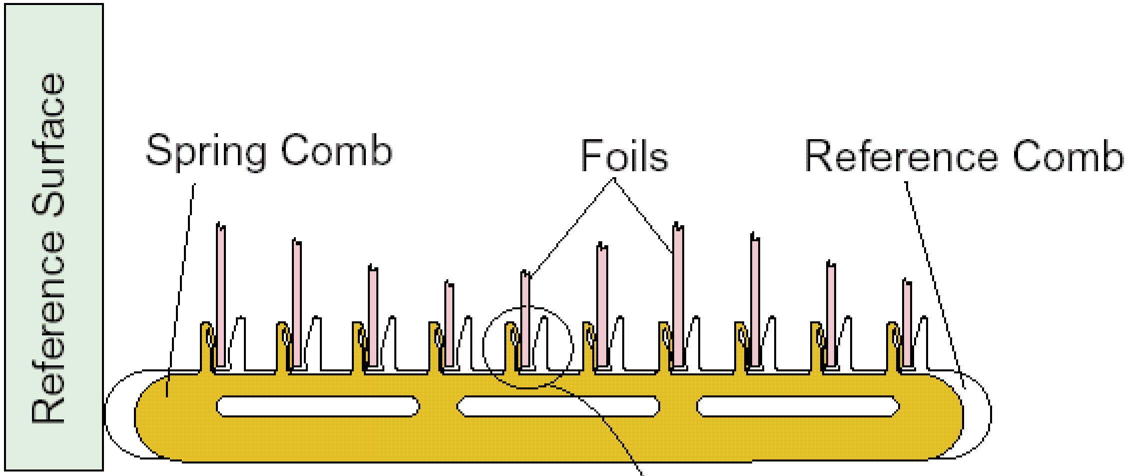
Radiation Hardness and High Frame Rates: Advantages of EDCCD

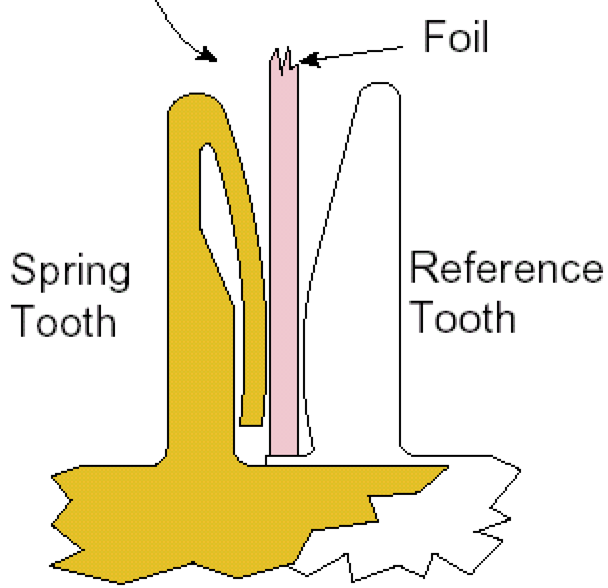
- Lower system power means that EDCCDs can operate at higher frame rates to reduce dark charge/frame
- Reduced dark signal allows higher device temperature
  - Thermally-generated carriers populate traps
  - Trapping times remain short compared to frame times, thus no frame-to-frame “memory” effects
  - Power and weight system savings from less demanding thermal systems
- High frame rates are advantageous for X-ray astronomy (signal amplitudes are independent of frame rate)

Grating Flight Module

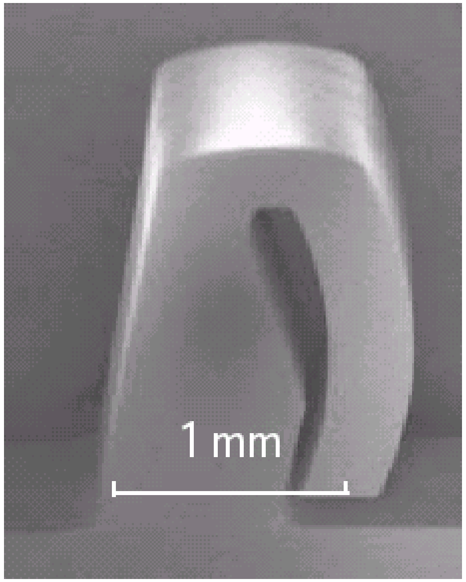


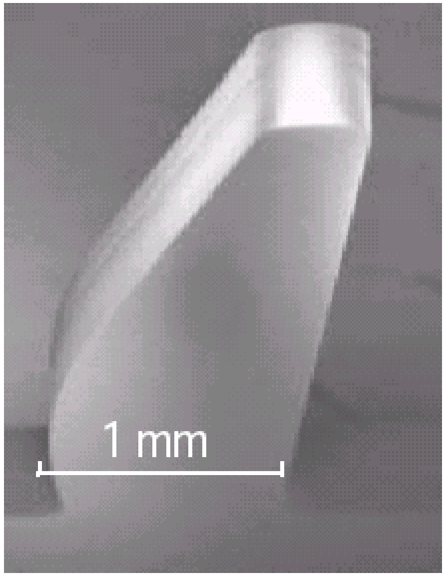
Grating Metrology Frame





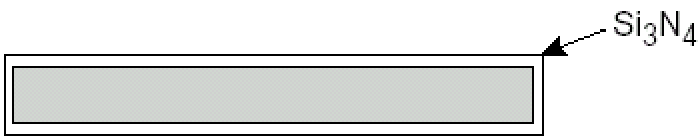
Scanning Electron Micrographs of Microcomb Teeth



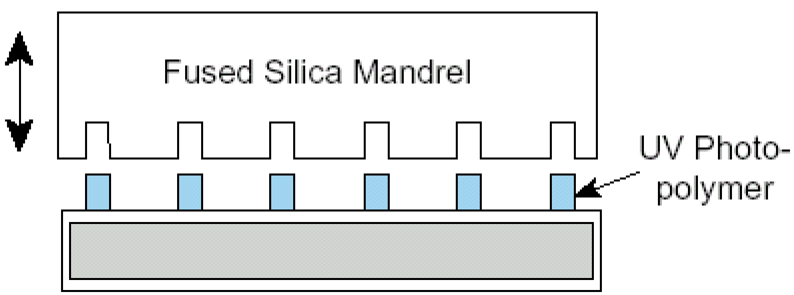


Reflection Grating Fabrication

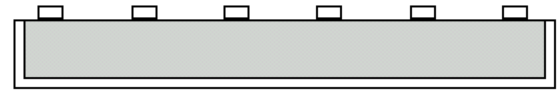
1) Procure off-cut silicon wafers.



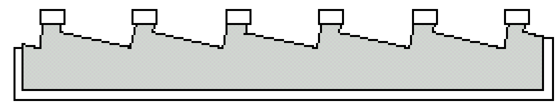
2) Flatten wafers and coat with silicon nitride.



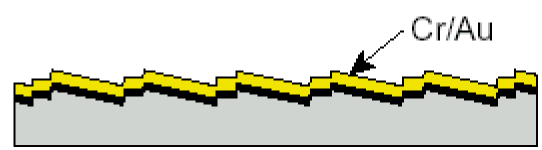
3) Replicate grating by UV nanoimprint lithography.



4) Plasma etch nitride and strip resist.

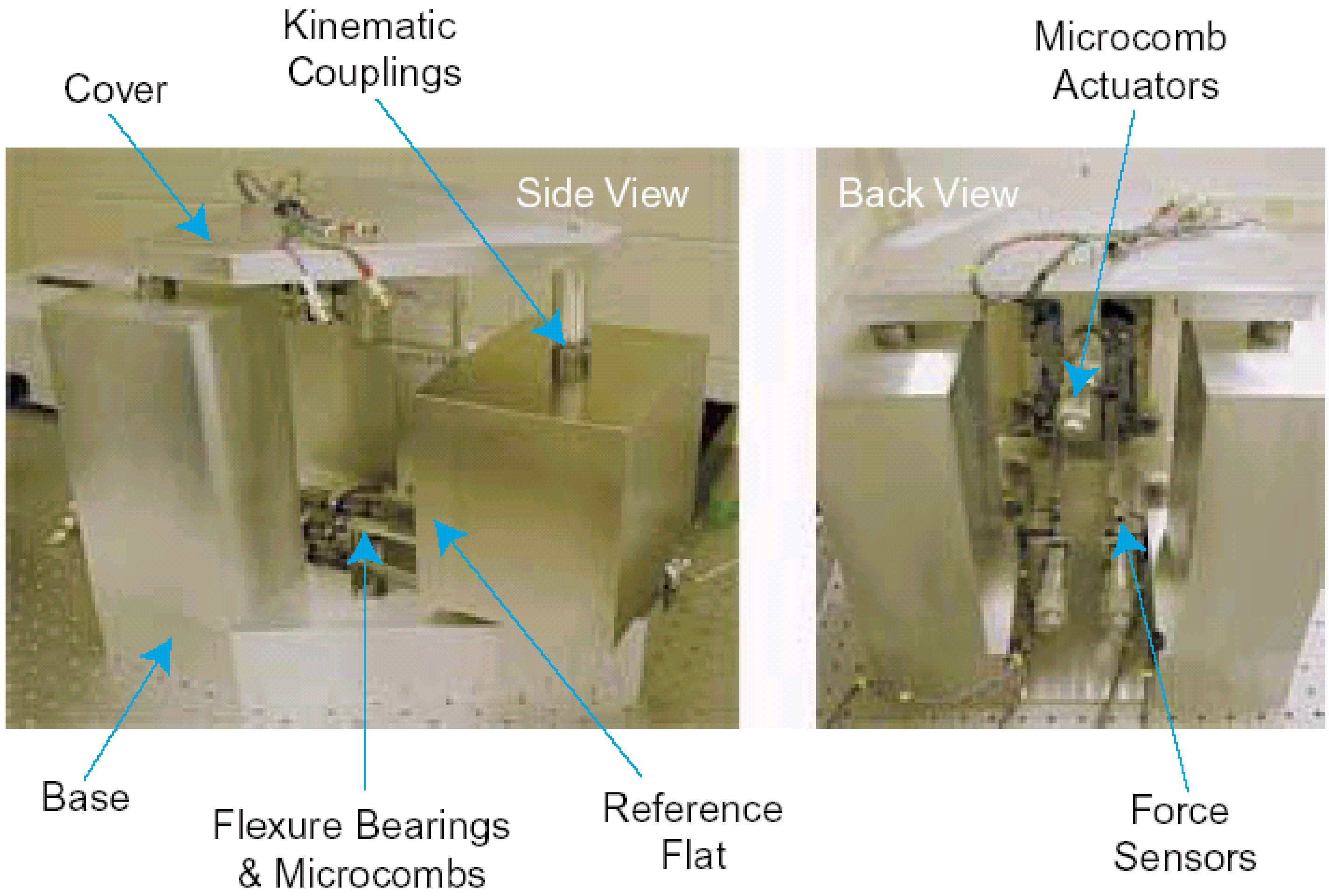


5) KOH etch silicon.

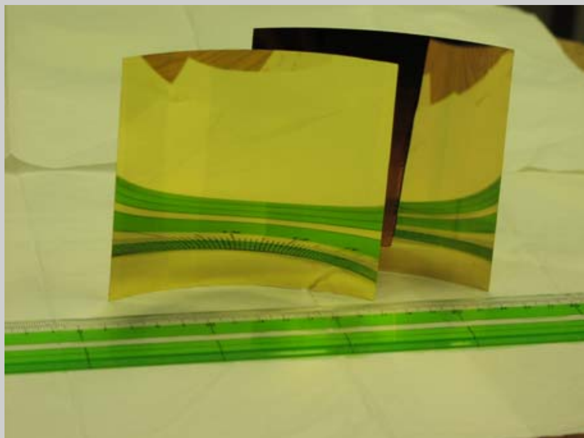


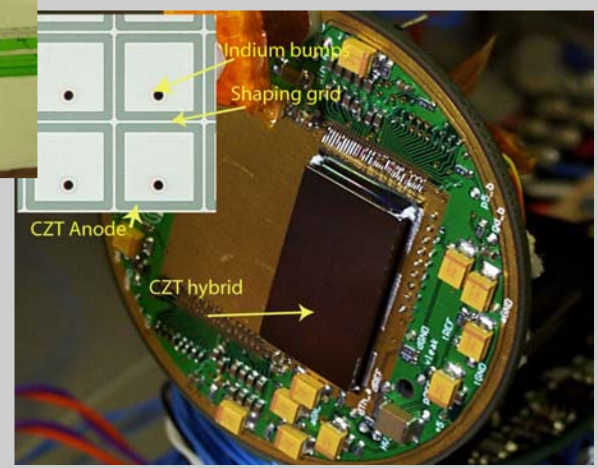
6) Strip nitride, trim nibs and sputter metal.

Grating Assembly Truss



The Hard X-ray Telescope





Fiona Harrison
California Institute of Technology (Caltech)

HXT Performance Requirements

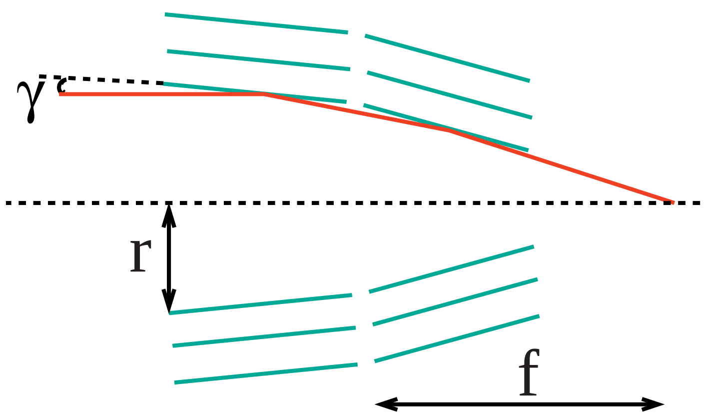
Baseline HXT Requirements	
Effective Area	$\geq$ 1500 cm^2 (5 - 40 keV)
Signal/Background	$\geq$ 1 for $T_{obs} > 2 \times 10^4$ s
FOV	$\geq$ 8 arcmin (5 - 40 keV)
Angular resolution	$\leq$ 1 arcmin HPD
$\Delta E/E$	$\leq$ 20% (5 - 30 keV)
Desirable Performance Enhancements	
Signal/Background	$\geq$ 1 for $T_{obs} > 2 \times 10^4$ s
Effective Area/	$\geq$ 1500 cm^2 (5 - 40 keV)
Bandpass	extend to 1 keV
Angular resolution	30” HPD
$\Delta E/E$	$\leq$ 5% at 40 keV
Mechanical Envelope	
Total Mass/Satellite	$\leq$ 250 kg
Geometric Aperture	< 0.75 m^2
Focal Length	10 meters

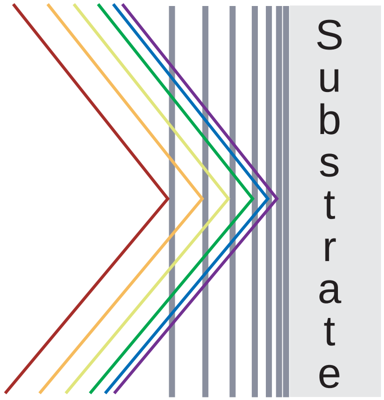
- **Match spectroscopic sensitivity of SXT for high-energy continuum observations**
- **Map non-thermal emission in extended sources**

HXT Technologies

Depth-graded multilayer mirrors

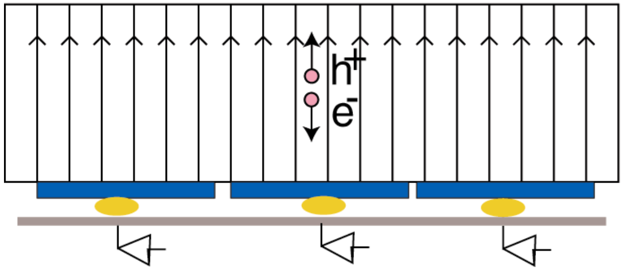
Conic-approximation grazing-incidence optics
Highly-nested thin shells (replicated full-shell or segmented)
Graded multilayer coatings extend energy range to E≥50 keV





Solid state CdZnTe pixel detectors

Wide-bandgap, high atomic number solid state pixel sensor coupled to custom low-noise ASIC

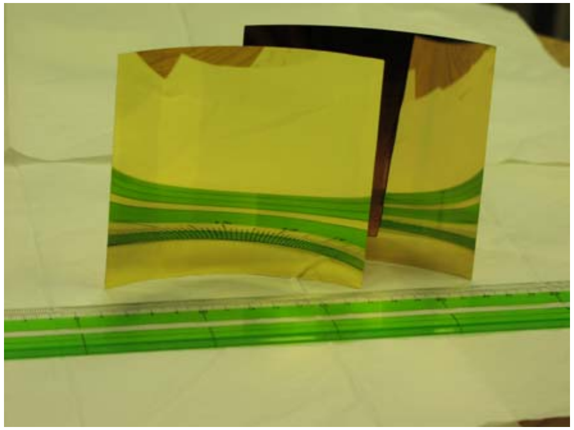


Mirrors

Segmented shells:

(Columbia,DSRI,GSFC,LLNL, CIT)

- **Thermally-formed glass microsheet with epoxy replication**
- **Direct ml deposition or replication segments (10/shell) assembled into full optic**

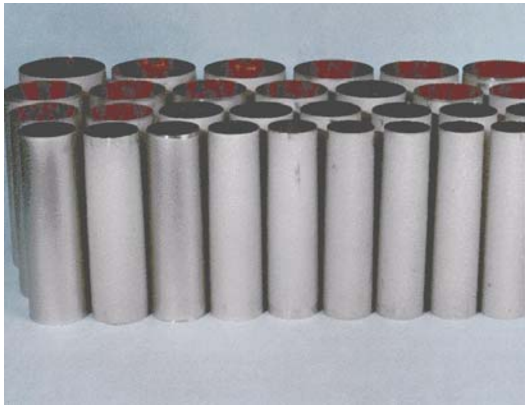


Replicated formed glass

Integral-replica shells:

(SAO, Brera, MSFC)

- **Thin (0.1 mm) replicated shells in full-figure of revolution**
- **Multilayers deposited on mandrel and replicated onto shell interior**



Ni replica shells

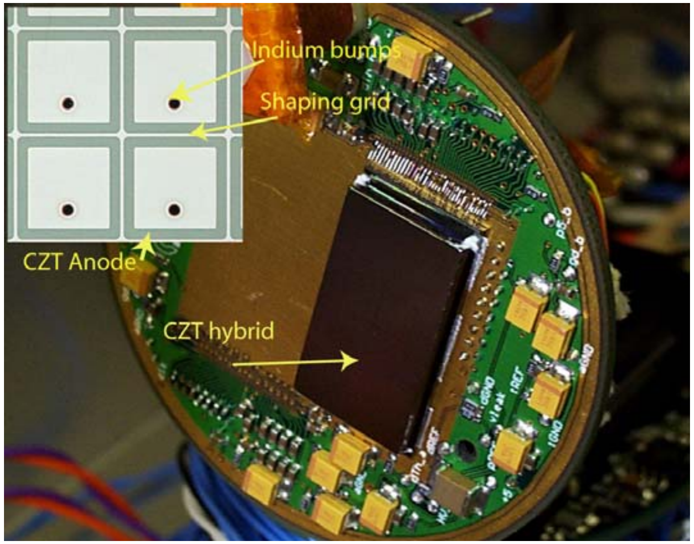
Why develop two options: Neither has demonstrated required performance (in an integrated optic). May exceed resolution goal and/or reduce mass compared to the requirement

Critical Developments

Key Technical issues to be demonstrated

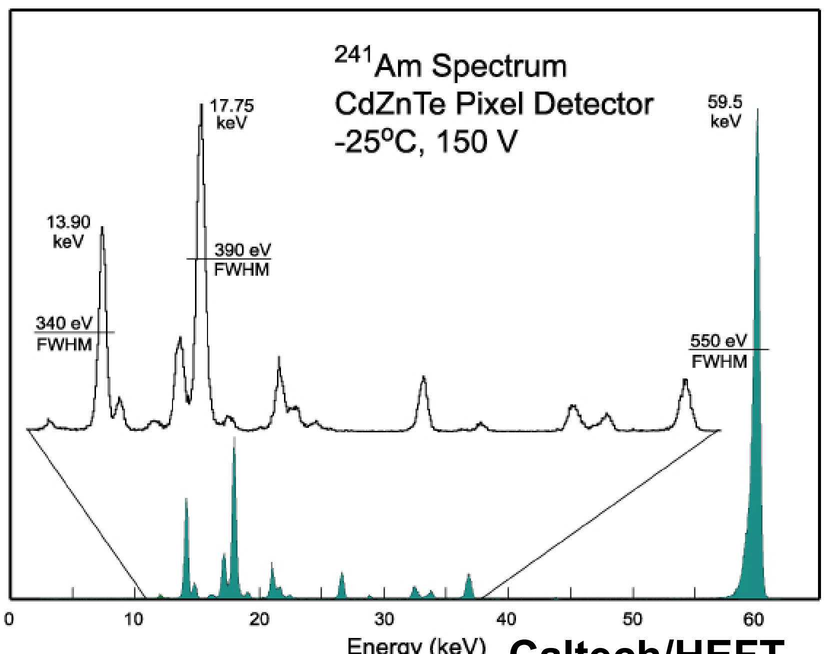
- Demonstrate the fabrication and assembly processes
  - Thin Ni shells yet to be produced in required dimensions
  - Epoxy replicated foils have not been mounted using precision technique
- Verify projected resolution
  - Neither Ni nor thin glass have demonstrated desired resolution
- Demonstrate that high-quality multilayers can be applied
  - Replication of multilayers from mandrels must be demonstrated for Ni
  - Surface roughness of epoxy replicas must be improved

CdZnTe Detector Status



Con-X Required Sensor Parameters

pixel size (1/4*Dq*f)	<720 mm
energy band	1 - 60 keV
fwhm energy resolution	<1.2 keV (6 keV)
dimensions (FOV*f)	2.3 x 2.3 cm
quantum efficiency	>90% (6 – 50 keV)



Caltech/HEFT

- Development largely leveraged from SR&T, balloon experiments (HEFT, Infocus)
- Low noise readout demonstrated
- Pixel detectors fabricated and bonded to readout, demonstrating performance

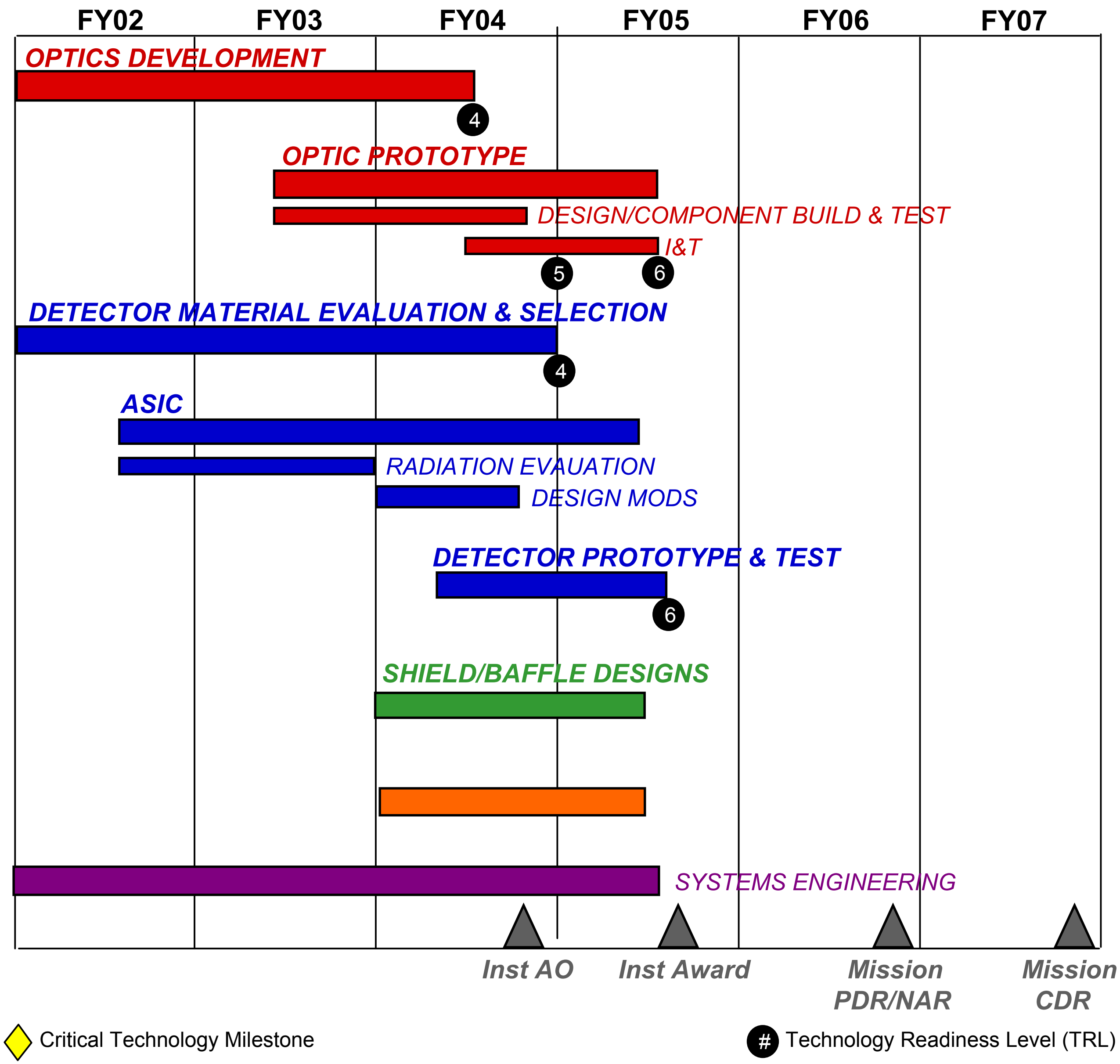
CdZnTe Development Requirements

- **Low-energy threshold and QE**
  - Readout threshold must be reduced from 8 keV -> 5 keV
  - Efficiency of different materials must be evaluated at E < 20 keV

- **Sensor packaging**
  - Packaging (bonding) techniques must be verified

- **Background and radiation damage**
  - Sensitive to e- trapping. Evaluate candidate materials (possible requires annealing)
  - Background model must be developed
    - Shielding optimization affects instrument mass

HXT Development Schedule



Acronyms

ADR	*Adiabatic Demagnetization Refrigerator*
AGN	*Active Galactic Nuclei*
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ASIC	*Application-specific Integrated Circuit*
CCDs	*Charged Coupled Devices*
CdZnTe	*Cadmium Zinc Telluroid*
CETDP	*Cross Enterprise Technology Development Program*
CTD	*Commercial Technology Development*
CVs	*cataclysmic variables*
EDCCD	*Event-Driven CCD*
EDM	*Electric Discharge Machining*
EUV	*Extreme Ultra Violet*
EV	*Electron Volt*
FAIR	*Filled Aperture Infrared Telescope*
HPD	*Half-Power Diameter*
HST	*Hubble Space Telescope*
HXT	*Hard X-ray Telescope*
ICM	*Intracluster Medium*
IGM	*Intergalactic Medium*
IPT	*Integrated Product Team*
ISM	*Interstellar Medium*
J-T	*Joule Thomson*
JFET	*Junction Field Effect Transistors*
kbps	*Kilobits Per Second*
keV	*Kilo Electron Volt*
Khz	*Kilo Hertz*

Acronyms (Cont.)

LTSI	*Lightweight optics*
MAXIM	*Microarcsecond X-ray Imaging Mission*
MBE	*Molecular Beam Epitaxy*
Mhz	*Mega Hertz*
MRF	*magneto-rheological figuring*
ms	*milliseconds*
NGST	*Next Generation Space Telescope*
QE	*quantum efficiency*
R&D	*Research and Development*
RGCCD	*Resistive Gate CCD*
rms	*route mean square*
ROSAT	*Roentgen Satellite*
SAFIRE	*Sub millimeter and Far Infrared Experiment*
SBIL	*Scanning Beam Interference Lithography*
SEU	*Structure and Evolution of the Universe*
SNRs	*Supernova Remnants*
SPECS	*Sub millimeter Probe of the Evolution of Cosmic Structure*
SPIRIT	*Space Infrared Interferometer Telescope*
SQUIDs	*Superconducting Quantum Interface Devices*
SR&T	*Scientific Research and Technology*
SUVO	*Space Ultraviolet Optical Observatory*
SXT	*Spectroscopy X-ray Telescope*
TES	*Develop Transition Edge Sensor*
TPF	*Terrestrial Planet Finder*
TRL	*Technology Readiness Level*
UV	*Ultraviolet*