Development of Low-Temperature Detectors For Generation-X and Other Missions Requiring High-Resolution, Large-Format, X-ray Detector Arrays

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**Technology Development:** Further developments of large-format, high-resolution, low-temperature, x-ray detectors will enable dramatic advances for the future of X-ray astronomy through missions such as Generation-X (Gen-X). In this paper we discuss the state of the art in these detectors, reviewing five different sensor technologies, and discuss which have the most potential of producing arrays of greater than one million pixels, 0.1 arcsecond angular scale, while giving an energy resolution of less than 2 eV in the 0.2-10 keV band. We conclude that transition edge sensor (TES) and metallic magnetic calorimeter (MMC) based microcalorimeters hold the most potential for meeting the requirements of mission concepts such as Generation-X, while microwave kinetic inductance detectors (MKIDs) hold potential for large format arrays, although this technology currently appears better matched to spectroscopy below 1 keV. As well as the further development of these sensor technologies, we also strongly recommend a research and development program to pursue multiplexing schemes utilizing microwave read-out that can be adapted to read out any of the leading candidate technologies of the future. When combined with position-sensitive detector versions of the leading sensor technologies, mega-pixel arrays can become a reality by the end of this decade. We describe the Generation-X roadmap for the development of this technology over the next 10 years, which includes estimates for the required level of effort and a schedule for intermediate milestones and final technology goals.
1. Introduction

A microcalorimeter x-ray spectrometer is a non-dispersive, high spectral resolution, imaging instrument that has been in development for x-ray astrophysics for more than 25 years and has successfully flown on both orbital and suborbital missions since 1995. The kind of dramatic impact that this technology will have in advancing x-ray astronomy has yet to be realized, due in part to the unfortunate early failure of the XRS instrument aboard Suzaku. However, in the next decade, Micro-X [Figueroa-Feliciano et al., 2006], Astro-H [Takahashi et al., 2008], and possibly the International X-ray Observatory (IXO), will take advantage of NASA’s investment in this technology. The microcalorimeters for these missions are all relatively mature. In order to make significant advances in astronomy beyond these missions there will have to be dramatic improvements in their capabilities. The main focus of this paper is the enhancements in future x-ray detector instruments that can be achieved by dramatically scaling up the number of pixels in arrays by three orders of magnitude, by reducing the physical scale of pixels to tens of microns, and by improving the energy resolution to better than 2.0 eV. The future mission concept that has driven this technology development plan is Generation-X (Gen-X).

Gen-X is an x-ray telescope designed to study the new frontier of astrophysics: the birth and evolution of the first stars, galaxies and black holes in the early Universe. X-ray astronomy offers an opportunity to detect these via the activity of the black holes, and the supernova explosions and gamma ray burst afterglows of the massive stars. However, such objects are beyond the grasp of current missions that are operating or even under development. The Gen-X team has conceived a mission based on an X-ray observatory with 50 m² collecting area at 1 keV (500 times larger than Chandra) and 0.1” angular resolution (several times better than Chandra and 50 times better than the IXO resolution goal). Such a high-energy observatory will be capable of detecting the earliest black holes and galaxies in the Universe, and will also study the chemical evolution of the Universe and extremes of density, gravity, magnetic fields, and kinetic energy that cannot be created in laboratories.

In 2008, NASA invited the Gen-X team to further develop its technology roadmap towards this concept through an “Astrophysics Strategic Mission Concept Study”, and requested that the results of this study be submitted to the 2010 Decadal survey. As part of this process we have been studying different technology options and developing a roadmap for the X-ray Microcalorimeter Spectrometer (XMS) instrument\(^1\) on Gen-X. There are many technical issues to consider when assessing the potential of low temperature detectors of the future, far too many to be appropriate to discuss in any detail in this paper. The latest version of this detailed study and plan is over 50 pages long and is available from the following website:

http://www.cfa.harvard.edu/heal/genx/technology/xms/.

There is significant overlap between technology development needed for Gen-X, and a number of mission concepts that would benefit from this such as Xenia [Kouveliotou, 2009], the Extreme Physics Explorer [Elvis, 2006], and Solar Physics missions such as RAM [Bookbinder et al, 2003]. In this paper we describe the requirements of the Gen-X high-resolution x-ray detector instrument and the various low temperature detector options that potentially could meet them.

\(^1\) The Gen-X team uses the term “microcalorimeter” to cover a range of low temperature sensor options under consideration, not all of which are calorimeters.
2. State of the art high-resolution x-ray detectors
The general principle of many low-temperature x-ray detectors is to measure the temperature rise when an x-ray photon is absorbed. In microcalorimeters, when an x-ray is absorbed, the temperature in the absorber increases by an amount E/C, where E is the x-ray energy and C is the heat capacity, and then recovers back to the steady-state temperature. A thermometer is integrated into the device to measure the temperature rise. To ensure high spectral resolution, the thermometer must be very well coupled to the absorber, and should be extremely sensitive to temperature changes.

Several low-temperature-detector technologies have been developed over the past few decades that have potential for very high energy resolution and could possibly be formatted in large arrays. These include:

1. Transition-Edge-Sensor Microcalorimeters (TES)
2. Magnetic Microcalorimeters (MMC)
3. Semi-conducting thermistors (SCT)
4. Superconducting tunnel junction detectors (STJ)
5. Microwave kinetic inductance detectors (MKIDS)

The progress of different microcalorimeter thermometer technology’s energy resolution at 6 keV is plotted as a function of time in Fig. 1. Although TESs, MMCs and SCTs are all microcalorimeter technologies, STJs and MKIDs are non-equilibrium detectors that count the number of quasi-particles generated when an x-ray photon is absorbed in a superconductor. The low temperature X-ray detector technology of choice for the current generation of x-ray astrophysics satellites is semi-conducting-thermistor-based microcalorimeters, in particular those using implanted silicon thermistors. This technology has been used for the XQC (X-ray Quantum Calorimeter) sounding rocket program [McCammon et al, 2002], on Astro-E and Astro-E2 (Suzaku) [Kelley et al., 2000] and at a facility at the Lawrence Livermore Electron Beam Ion Trap (EBIT) to carry out laboratory astrophysics [Porter et al, 2008]. This is a very well understood technology that has achieved an energy resolution of 3.2 eV FWHM at 6 keV [Porter et al, 2006]. If pixels are designed specifically to meet the Gen-X requirements, this technology does have the potential to meet the energy-resolution requirements. The drawback, in comparison with other options, is that there does not appear to be any reliable read-out technology that would allow them to have arrays of greater than a few hundred pixels. If one could be developed, then this technology could once again be reconsidered. We therefore recommend that further development of semi-conducting thermistors only occurs if new promising techniques for multiplexing are formulated.

The microcalorimeter technology that is most likely to be used for IXO is transition-edge-sensors (TES). This technology has been strongly supported by the x-ray astrophysics community for the
past couple of decades. It has been chosen for an upcoming sounding rocket mission called Micro-X [Figueroa-Feliciano, 2006, Wikus et al., 2008]. The key strengths of this technology are that it has already achieved a world record energy resolution 1.8 eV FWHM at 6 keV in an 8x8 array [Bandler et al., 2008], and that a multiplexing SQUID read-out has been developed that is close to meeting the requirements of the few-thousand-pixel array for IXO [Kilbourne et al, 2008]. Fig. 2 shows a prototype for the IXO core array. New concepts exist and are under development that could allow the read-out of the sort of number of pixels that will be required for Gen-X [Mates et al., 2007]. A potential drawback in an array with a million pixels is the amount of heat that is generated at the focal plane by each TES. There are a number of other significant technology issues related to the Gen-X design that will need to be investigated and these are outlined in our roadmap. TES remains a very promising technology for Gen-X, with perhaps the best potential for meeting the mission requirements, and as such is base-lined as one of the main technology areas recommended for continued substantial development in the next decade.

Magnetic microcalorimeters (MMC) should be able to meet the energy resolution requirements for Gen-X [Fleischmann et al., 2007, Bandler & Figueroa-Feliciano, 2009]. They have been under development for the past decade, but at a far lower level of support compared with other technologies. They have already achieved an energy resolution that is comparable to TESs and SCTs of 2.7 eV at 6 keV [Fleischmann et al., 2009]. MMCs have three significant potential advantages over other technologies. They have the potential to achieve higher energy resolution than any other technology. Sub-eV energy resolution may be possible. Fig. 3 shows how the predicted energy resolution should scale with decay time. They are dissipationless in their read-out within the focal plane array, meaning that scaling up arrays in size and number is potentially easier than for other technologies. And they can be directly connected to a metallic heat-bath without affecting the way in which they are read-out. Like TESs, the read-out for MMCs uses low noise SQUID amplifiers. This technology requires somewhat more demanding SQUID read-out properties that may reduce the number of channels that can be multiplexed in comparison with TESs.
Superconducting tunnel junctions (STJ) is a fourth technology that one might consider for the Gen-X high-resolution detector [Li et al., 2001; Friedrich 2008]. These detectors have the intrinsic advantage that they are very fast and thus can accommodate extremely high counting rates. Having intrinsic rise-times of 2-3 μs, and decay times around 20 μs, reasonably high energy resolution has been demonstrated under 1 keV (<10 eV at 277 eV) for count rates up to 10,000 cps [Frank et al., 1998]. However, they have not achieved a competitive energy resolution such as is needed by Gen-X for energies in the 1-10 keV band-pass. The best energy resolution in a single STJ at 6 keV is 12 eV FWHM [Angloher et al., 2000]. Not only is the measured performance not good enough for Gen-X, even the theoretical limits for most materials from which they can be made do not meet the requirements at 6 keV. Actual performance, though good, has only come close to the theoretical limits at energies below 1 keV. Although STJs could serve a niche for future applications that will require only moderate energy resolution and the need to accommodate very high counting rates, they are not presently competitive with microcalorimeters for high-resolution spectroscopy and we do not currently consider STJs as a serious option for Gen-X. Another drawback to tunnel junctions for this application is that there appears to no good multiplexing technology for their read-out.

Microwave Kinetic Inductance Detectors (MKIDs) is the fifth technology that might conceivably be used for Gen-X [Day et al., 2003; Mazin, 2004]. This technology has the inherent major advantage that its read-out can be most easily adapted to microwave multiplexing of thousands of channels per read-out amplifier, as its basic read-out already utilizes microwave amplifiers. If MKIDs for x-ray detection continue to develop, and current sources of excess noise are removed, they could achieve a very high sensitivity level. However, the biggest challenge with this approach will be in demonstrating the same energy resolution as the sensitivity would predict at high energies. This detector is one that also essentially counts quasi-particles produced in a superconducting absorber by trapping them at the sensitive element of a resonator. The energy resolution is fundamentally Fano-noise-limited such that an energy resolution of less than 2 eV at 6 keV is impossible in most superconductors, except perhaps when using some very low-energy-gap superconducting absorbers such as Re (1.7 eV), Mo (1.3 eV) or Hf (1.1 eV). The potential use of such absorbers would necessitate the use of even lower energy gap superconductors for trapping quasi-particles, necessitating lower temperatures of operation. In addition to energy resolution limitations due to Fano noise there are other processes that could potentially degrade the energy resolution for reasons that are almost the same as for STJs. The quasi-particles can also become trapped, either temporarily of permanently, at surfaces, defect sights, or impurity sights. For calorimeters in which thermal equilibrium is established, this is not a significant problem as electrons are thermalized in metals and zero band-gap semiconductors on very fast timescales. Since MKIDs and STJs are operated in a way in which the components are not in thermal equilibrium, they are not calorimeters. The potential high sensitivity of MKIDs is more easily utilized in infrared bolometers, where high resolving powers are not required. As x-ray detectors, the most important gate for this technology would be to overcome the inherent challenge of non-equilibrium detectors by demonstrating a high resolving power. If this happens, then this technology could become an attractive option for Gen-X.

To summarize, we feel that currently the two technologies with the most potential for meeting the Gen-X requirements are TESs and MMCs, and consequently much of the emphasis in the rest
of this paper concentrate on these two technologies. If the challenge of high resolving powers are ever overcome in MKIDs, then this option could also become one of the leading technology options for Gen-X, its inherent ease of multiplexability being extremely advantageous.

3. Gen-X X-ray Microcalorimeter Spectrometer (XMS)
In Table 1 we list the instrument design requirements for the Gen-X XMS detector array. A detailed discussion of these requirements can be found in the Gen-X roadmap [Bandler and Figueroa, 2009].

<table>
<thead>
<tr>
<th>Design Parameter</th>
<th>Requirement</th>
<th>Goal</th>
<th>Assumption or Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pixel Pitch</td>
<td>0.1”</td>
<td>0.03”</td>
<td>For 60 m focal length, 0.1” pixels are 30 µm in size.</td>
</tr>
<tr>
<td>Field of View</td>
<td>3’x3’</td>
<td>3’x3’</td>
<td>3’x3’ =&gt; 1800x1800 array of 0.1” pixels =&gt; 3.24 x 10^6 pixels.</td>
</tr>
<tr>
<td>Energy resolution</td>
<td>2 eV FWHM</td>
<td>1 eV FWHM</td>
<td>This is the requirement for energies up to 6 keV.</td>
</tr>
<tr>
<td>Count Rate</td>
<td>1 cps/pixel</td>
<td>10 cps/pixel</td>
<td></td>
</tr>
<tr>
<td>Quantum efficiency</td>
<td>0.60 @ 6 keV</td>
<td>0.80 @ 6 keV</td>
<td>Factoring in filter transitivity, this drops at lower energies.</td>
</tr>
<tr>
<td>Energy Range</td>
<td>200 eV – 10 keV</td>
<td>100 eV – 10 keV</td>
<td></td>
</tr>
<tr>
<td>Timing resolution</td>
<td>50 µs</td>
<td>10 µs</td>
<td></td>
</tr>
<tr>
<td>Calibration</td>
<td>0.5 eV – absolute</td>
<td>0.1 eV – absolute</td>
<td></td>
</tr>
<tr>
<td>Background rate</td>
<td>0.004 cts/ksec/arcsec^2</td>
<td>This is the desired residual background after antico vetoing in the 0.5-2 keV energy range.</td>
<td></td>
</tr>
</tbody>
</table>

Table 1: Baseline requirements

In Table 2 below we describe one basic possible detector array format and read-out that could meet the XMS instrument requirements that utilizes position sensitive microcalorimeters [Smith et al., 2008]. Other array-design approaches can be found in the instrument roadmap. These include an option that does not use position sensitivity, and also one- and two-dimensional-continuous-strip detector formats. Variations that include specialized sub-arrays (such as for high count-rate, low energy, high energy) and variations of the pixel size with off-axis angle are also not included here.

<table>
<thead>
<tr>
<th>Design Parameter</th>
<th>Design Option</th>
</tr>
</thead>
<tbody>
<tr>
<td>Array design</td>
<td>➢ 324,000 position sensitive calorimeters ➢ 0.1”x 1” (/10 via subpixel event location) ➢ 30 x 300 µm (0.1” effective pixel size)</td>
</tr>
<tr>
<td>Multiplexing Scheme</td>
<td>➢ up to 3.6 x 10^5 sensors ➢ 8 HEMT amplifiers ➢ 1265 RF SQUIDs multiplexed on each HEMT amplifier ➢ Code division multiplexing – 32 TESs per SQUID readout</td>
</tr>
</tbody>
</table>

Table 2: Example design for array and readout.
4. Multiplexing

Currently the use of time-division multiplexing is a promising approach for arrays of medium size, such as IXO [Reintsema et al., 2003, Dorisee et al., 2004, Beyer et al., 2008]. The ability to scale this approach to much larger arrays, such as is needed for Gen-X, is limited by both power dissipation and the tens of megahertz bandwidth of dc SQUIDs. In contrast, read-out consisting of a microwave multiplexer offers a path to meeting requirements of large format arrays such as Gen-X. Several different versions of this type of multiplexer exist, depending upon whether it is adapted for the read-out of TESs, MMCs or MKIDs. For TESs and MMCs, unshunted, non-hysteretic rf SQUIDs are incorporated into the read-out that have negligible power dissipation even for extremely large arrays [Mates, 2008]. Furthermore, rf SQUIDs can be coupled to high-Q microwave resonant circuits fabricated from superconducting coplanar waveguides with resonant frequencies of several gigahertz. In this approach, the bandwidth of each microcalorimeter is limited by the resonant circuit after amplification by the rf SQUID. A single high electron mobility transistor (HEMT) amplifier has the bandwidth and dynamic range to read out many hundreds of rf SQUIDs operated in superconducting microresonators tuned to different frequencies, all coupled to the same coplanar-waveguide feedline.

The detector technology that can perhaps mostly easily be implemented with microwave read-out are MKIDs, since in this case no SQUIDs or modulation techniques are necessary. While the essential components of this technology are the same for TES sensors and MMCs, their optimization is slightly different. The most important difference between the read-out of TESs and MMCs is the adjustment of the strength of the coupling between the SQUID and the resonator.

A more recent idea in microwave read-out that has the potential to further extend the number of channels per read-out amplifier with the TES approach is the integration of code-division multiplexing. This approach, which is being developed at NIST, is depicted in Fig. 5. In this approach, each individual SQUID can be used to read out many different pixels, potentially further reducing the number of HEMT amplifiers and read-out electronics channels. It works by introducing code-division multiplexing for the pixels attached to a single SQUID, and using single-pole double-throw (SPDT) switches to divert the current signal going to the SQUID so that it can either appear as a plus flux signal or a minus flux signal. These switches are similar to the low-power magnetic flux actuated switches that are currently being demonstrated to simplify and improve conventional time division multiplexing [Beyer et al., 2008]. For 32 pixels there would be a sequence of switching for the 32 input circuits to give arrangements of different plus and minus signals for the different channels. However all the pixels attached have a signal going into the summing coil going to just one SQUID at one time. The switching of different pixels between +1 and −1 is chosen to be in different orthogonal patterns, such that the resulting signals form matrices known as Walsh matrices. By appropriate diagonalization of the matrix of signals for the different plus and minus biases, one can uniquely determine the signal from each
individual channel for all times. Thus with this approach there is no energy resolution loss associated with multiplexing the 32 channels. If the output SQUID is a dissipationless rf SQUID in a microwave resonator, this approach dramatically increases the information that can be transmitted through each HEMT amplifier.

The potential benefit of using this approach for missions such as Gen-X is astounding. To make very rough estimates, one can conceive of an arrangement in which each HEMT can read out ~1250 SQUIDs, each with ~2-5 MHz of bandwidth. Then each SQUID can read out ~32 pixels. Thus ∼8 HEMTs and read-out electronics would be needed to read out ~3x10^5 TESs, which could be enough for an entire Gen-X array. The success of such an elegant approach to the read-out could mean that as few as 20 coax cables would be needed for the entire read-out.

In summary, the development of microwave multiplexing, whether directed towards the read-out of TESs, MMCs, or MKIDs, is an absolutely critical technology to develop over the next decade, and is a crucial part of our technology development program. At the moment the development of these techniques is being spearheaded by the groups in infrared astronomy in the US and in Europe. It is fortunate that much of the research in this field will ultimately benefit detectors for a variety of different wavelengths, and its further development is strongly supported.

5. Supporting technology development: filters, cooling, heat-sinking, wiring

The Gen-X roadmap describes some of the critical supporting technologies that must be developed to bring the XMS instrument to TRL-6. Here we summarize them. The further development of infrared blocking filters that minimize the loss of throughput at energies below 1 keV is an important technology to develop. Another part of this program is to investigate approaches for achieving the required heat-sinking of the focal-plane array, and to develop strategies to achieve high-density wiring within the focal plane array and between the array and the readout, such as the one shown in Fig. 6. In this approach, through-wafer microvias for electrical readout and a silicon-surface-machined microtrench for array heat sinking are combined into one monolithic structure for a TES array. The main idea behind this concept is to maximize the available spatial density for the electrical readout and at the same time to simplify and shorten the thermal path from a microtrench to the heat sink. Our technology plan also describes various approaches to accommodate the likely large heat loads from the various read-out options.
6. Development schedule for Gen-X

The plan for maturing the technical readiness to TRL-6 is phased by five two-year technology demonstration gates (TG) that are defined in terms of 16 specific performance requirements and design maturities that are given below. As well as describing gates, we have also defined the various TRL levels with performance, read-out, and array size requirements that reflect the framework of what is needed for Gen-X. The TRL definitions are based upon the same list of criteria as the gates, although the phasing is somewhat different. Currently TES technology is the most developed towards meeting Gen-X goals, and is considered to be at TRL-2.

We have attempted to define the gates and TRL levels in terms that are independent of sensor-technology approach. For each sensor technology, there are different approaches to meeting these goals in terms of multiplexing and position sensitive detectors. Since we do not a priori know which of these will be best suited for Gen-X at this time, we have developed gates for two main approaches: one that seeks to populate the Gen-X focal plane with individual sensors (one readout channel per pixel) and a second approach that uses some form of position-sensitive detector to sub-pixelate each absorber. The main difference between the two approaches is how many total readout channels need to come out of the focal plane and the associated wiring and heat loads that come with these design decisions.

TRL-1: Basic principles observed and reported
- Through modeling, demonstrate detector concepts that can potentially meet minimum Gen-X requirements.
- Produce a convincing multiplexing scheme that on paper can potentially meet Gen-X requirements.

TRL-2: Technology concept and/or application formulated
- Multiplex 16 pixels with less than 3 eV energy resolution at 6 keV (TG1).
- Demonstrate 2.0 eV energy resolution at 6 keV for any pixel size (TG1).

TRL-3: Technology proof of concept
- If technological approach requires position-sensitive detectors with N sub-pixels per sensor, demonstrate such a detector that reads out N/2 subpixels, with sub-pixels of a size necessary to meet Gen-X requirements with an energy resolution of 4 eV. If approach does not require sub-pixelation, demonstrate 4 eV energy resolution at 6 keV in 10 closed-packed single pixels that meets Gen-X pixel size requirements (TG1).
- Demonstration of a read-out concept that can be extended to meet Gen-X requirements that can read out any sized x-ray detector with better than 6 eV energy resolution at 6 keV (TG1).

TRL-4: Component validation in laboratory environment
- If technological approach requires position sensitive detectors with N sub-pixels per sensor, demonstrate 2.0 eV energy resolution at 6 keV in a single sensor with N subpixels that meets Gen-X size, quantum efficiency, and fill-factor requirements (TG2).
- Demonstrate multiplexing in which one channel simultaneously reads-out 100 sensors with design parameters that are commensurate with Gen-X requirements and with an energy resolution of less than 10 eV at 6 keV (TG2).
• Demonstrate multiplexing in which one channel simultaneously reads-out 1000 sensors with an energy resolution that is commensurate with Gen-X requirements (TG3).

**TRL-5 : Component and breadboard validation in relevant environment**
• Build a front-end assembly that can accommodate the required level of heat sinking and wiring density that will be necessary to build the XMS instrument (TG3).
• Demonstrate that infrared blocking filters can be constructed with the required size and transmission (TG4).
• Demonstrate that all components of the XMS can survive vibration and radiation testing (TG4).
• Demonstrate the pixel with an energy resolution of 2.0 eV at 10 cps with multiplexing in which one channel reads out 1000 sensors (TG4).
• Space qualify electronics suitable for multiplexed read-out of pixels (TG4).

**TRL-6 : Subsystem model demonstration in a relevant environment**
• Design cooling platform that can meet Gen-X-XMS requirements (TG5).
• Build a 1-megapixel array with all detectors “biased”, with read-out of 10 k 0.1” pixels with 2.0 eV energy resolution at 6 keV, and meeting all other Gen-X requirements (TG5).

7. Summary and schedule of funding for Gen-X XMS development

The estimated budget below assumes that funding for IXO microcalorimeter development and building will carry on throughout the first six years of this independent Gen-X development program, and highly leverages the expected progress of this program. Over this period, the relatively modest budget of approximately $1.9M per year is recommended. Of this, we allocate approximately $1.2M be directed towards detector development. During this period, we anticipate that at least two groups will receive funds to develop two detector technologies, a primary technology that currently appears to have the greatest potential and also some potential alternatives. We also anticipate some support of smaller, more focused research efforts that would work in collaboration with those leading technology efforts. These would initially be in support of the detector technologies with most potential, and later would be to investigate alternative parallel technical paths as new ideas evolve. At the same time it is expected that approximately $0.7M per year will be needed specifically to develop the necessary microwave multiplexing. From previous research programs that have lead to Astro-E, Suzaku, and now Astro-H and IXO, we know that approximately 80% of the program budgets is needed for the loaded costs to support staffing of these programs (including travel). The remainder of the costs is typically needed for providing cryogens, development of cryogenic apparatus, purchase of commercial electronics, and materials and supplies needed for the micro-fabrication processes. We have estimated that a total of 8 people are needed to support the fabrication, testing, and analysis of the different technologies described.

In the following four years, once the essential components of the instrument have been decided upon and demonstrated, somewhat greater funding will be needed to develop a larger prototype-demonstration system in a relevant environment. It is anticipated that there will only be one platform to demonstrate the prototype instrument, and only one multiplexing concept being refined and optimized. The following budget reflects our estimate of the budget and schedule necessary to bring the XMS technology to TRL-6 in the next decade in FY09 dollars. Each item is in units of one million dollars.
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**8. References**