The X-ray Polarimeter Innovation Pathway

This case describes the development of a photoelectric X-ray polarimeter, within NASA Goddard Space Flight Center's (Goddard's) Laboratory for High Energy Astrophysics (LHEA). After more than a decade of development, it will fly aboard the Gravity and Extreme magnetism SMEX (GEMS), to be launched in 2014. The X-ray polarimeter detector system, as the name suggests, will measure the polarization of astronomical sources emitting in the X-ray band, like black holes and neutron stars. Although efforts to measure X-ray polarization have been pursued since the dawn of X-ray Astrophysics, due to extreme technical challenges associated with achieving sufficient sensitivity, this information has been previously unobtainable. The data GEMS will return promises to constrain multiple open theoretical debates.

Gestation Period

In the years leading up to 2001, when Goddard's LHEA (Laboratory for High Energy Astrophysics) initiated explicit efforts towards the development of an X-ray Polarimeter, the groundwork for several foundational elements of the future program had already been laid.

By the late 1990s, three of the five individuals who would become core members of the GEMS polarimeter team had united and begun working together for two tangentially related purposes: Leveraging new developments in gas proportional counter technology to develop micropattern detector (MPGD) arrays for (1) a SMEX mission called LOBSTER and (2) for the Next Generation High Energy Gamma-ray (NGHEG) telescope. The two applications both valued large format detector arrays with low power draw, which made proportional gas counters a logical choice. The new developments in array architectures (MPGD's are very finely spaced arrays of proportional counters) and readout strategies promised finer resolution on these large format arrays [D11, D12].

The three technologists brought a varied skill set to the team. The first (heretofore referred to as CSA#6, begun his career as an astrophysicist on the XTE (X-ray Timing Experiment), which used Gas Proportional Counters. Along the way he had become involved with calibration and testing of the instruments, so when LOBSTER began development, it was only natural that he get involved [I60]. The second (CS#2) was an expert in gas proportional counters. He'd been trained as a high energy physicist and spent his career as a *concepts guy*, advancing, and finding new applications for the technology. He'd come to Goddard mid career to work on MOXE (Monitoring X-ray Experiment) and specifically to work on gas counters for that mission. MPGDs for LOBSTER being an exciting new application for the technology, he joined the team [I62]. That's when CSA#6 began working with CS#2. CS#2 met the third core member[1] about a year later, when, struggling with his detector set-up, he was introduced to a *guy who was known for making things work*. This "guy," an astrophysicist had been working on a similar problem in the domain of gamma-ray telescopes [I62].

The concept for micropattern gas detectors, which they were leveraging for LOBSTER and NGHEG, was invented in Europe in the 90s. The idea was a simple one – array proportional

[1] Who passed away during this study, and was therefore unavailable to be interviewed.

counters with very fine spacing – but the implementation was very challenging. At the time multiple strategies for reading out the devices were being explored (c.f. D30, D31). The three Goddard scientists began experimenting in their own right; fabricating devices by hand using a technique called UV laser ablation. After a few years of reading out the detectors with crossed-strips, they sought to read-out their gas counters in a pixelized way because "*[they] thought it would be really important for gamma-ray telescopes in the future*" [I62]. In order to get funding for the effort though, "*[they] were looking for a more immediate application of interest to justify the development*" [I40] (NGHEG was a little too far off since the current gamma-ray telescope GLAST was still in development at the time).

The application area of X-ray polarimetry presented a potentially good justification, both because it was a logical application of the technology, but also because polarimeters were the then head of the high energy physics group's "*favorite pet rock*." "*Every year he would ask us to figure out polarization and every year we would come up with nothing,*" remembers CS#2 [I62]. However, when CS#2 and CSA#6 sat down and tried to work out how pixelized read-outs of a gas counter would lead to polarimetry, their back-of-the-envelope calculations suggested it wouldn't work. Nonetheless, they decided the work was important enough to pursue [I77]. This early R&D work was conducted in part in their "free time" and in part funded by a combination of DDF (director's discretionary fund) [D1, D2] and APRA (level 2 funding) for applications to NGHEG [D11, D12]. As recall the scientists, although there were other larger funding avenues "*in those days, DDF was our most reliable source of funding. You could write a one page proposal and get $75K funding… a year!*" [I62]

A brief explanation of the technology (depicted graphically in Figure **Error! No text of specified style in document.**-1) is required in order to understand the implications of each component innovation described below. Both gas counters, and the polarimeters that are based on them, have four main components: a drift electrode, a gas medium and the corresponding casing, a signal amplifier and readout electronics. In historical gas counters, photons enter the detector from the top and are slowed down by the gas medium so that their incidence can be measured by passive wire leads at the bottom. The main design parameters in this system are the diffusion distance and the readout strategy. With respect to the diffusion distance, there is a fundamental tradeoff between quantum efficiency and modulation (essentially, a longer distance allows you to stop higher energy photons, but the stopping process creates random error that limits the measurement resolution). Thus early designs were only effective over an impractically small energy band. With respect to the readout strategy, where early detectors essentially measured the presence of a photon as a binary yes/no, later designs augmented the readout information in two ways. They added a signal amplification stage (GEM) and replaced the passive leads with active readouts with Cartesian position resolution. This is important because the angle of drift is the basis for constructing polarization information.

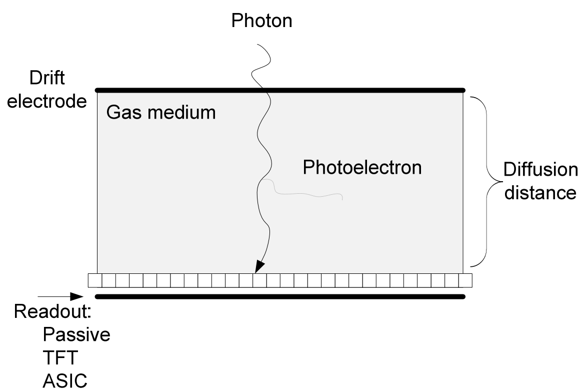

Figure Error! No text of specified style in document.**-1: Cartoon of Polarimeter Architecture**

During the NGHEG and LOBSTER efforts the team sought to improve both of the above described parameters. In terms of the readout electronics, they complimented their in-house exploration of "micro-well" detectors (which is a more sophisticated passive readout that allowed closer spaced pixels and therefore finer resolution devices) with a collaboration with a University Lab (UL#1) to develop TFT (thin film transistor) array readouts [D8, D11]. The goal with the TFT development was to embed an active anode in the gas counters that was optically thin and wide-area. The early TFT work showed enough promise that the Goddard and University team proposed an expanded study, awarded as an SR&T grant (Science Research and Technology, a NASA-level funding mechanisms providing in this case ~$220K per year for three years from 2001-2003). According to CS#2, although the part-time grad students worked hard, "*they never really got anything working*" [I77]. He believes that this was because he never managed to secure the critical mass of funding that would have been required to make a serious attempt.

The exploration of alternative active mediums was also initiated with DDF funding [D2]. The team found a small business (SB#1) with expertise applying porous dielectrics, and began collaborating with them. Instead of using gas (as is typical in *gas* counters, but which is technically difficult to manufacture) they investigated the use of thin window, porous dielectrics deposited on the active readout, as a cheap alternative to gas counters and CCDs in X-ray astrophysics. Following the year long DDF, the small business submitted an SBIR proposal to continue the work. Both phase I and a follow-on phase II contracts were awarded, providing funding for continued work through 2003 [D41]. This technological branch never yielded fruit.

While the Goddard team was focused on the application of MPGDs to All Sky Monitors and Gamma-ray telescopes, in Italy, a University group (UL#2) was committed to developing a practical x-ray polarimeter. A critical result from this group would serve to re-focus the efforts of the Goddard team around the application to polarimetery.

Focusing Event (Costa et al. 2001 Result)

Goddard's interest in using micropattern gas detectors for polarimetry was re-ignited in 2001, by "*fantastic results*" from a group in UL#2 [D29]. As recalls CS#2:

> *It's kinda funny. That group has been working on polarimeters for a while and had been doing it with strip-readout (one dimentional read out) and they'd never really gotten*

anywhere. In their papers it always said that if they'd had a pixilated readout it would be great. And I had never paid any attention … Then they submitted this Nature paper and somebody here – who I knew – was asked to review the paper… and because of my expertise they gave it to me to take a look… Assuming it was yet another nothing result, I took it home and forgot about it until it was bed time... when I remembered I was supposed to read it. That was a mistake because it got me so excited that I couldn't sleep! They had fantastic results reading out these detectors in a pixelized fashion. It meant we could make polarimetry work! [I62]

The UL#2 result proved that sensitive (up to a 100 times more sensitive than previously achieved) polarimetery was achievable using gas detectors read-out in a piexelized way. This breakthrough was significant enough that the work was published in Nature. However, substantial expansion of the active readout area would be required before the concept could be considered practical for X-ray astrophysics. The Goddard team believed that the expertise they'd been developing under the guise of MPGDs for LOBSTER and NGHEG could improve the UL#2 devices substantially. Thus, within weeks of learning of the UL#2 result, the Goddard team began writing proposals to pursue X-ray polarimeter development [I60, D14]. Although they continued with the LOBSTER work, and the other projects for which they had responsibilities, their hearts had shifted to polarimetery.

Making it work (2001 – Black et al. 2003)

Although UL#2's result was the demonstration of a physical property, their insight was an architectural one. Where CS#2 and CSA#6 had concluded that MPGDs would not yield polarimetry based on their back of the envelop calculations, UL#2 had constructed a laboratory experiment that proved a way that they could. However their polarimeter was not a practical instrument because it could only work in a narrow band. The Goddard team believed that they could make the UL#2 design practical (broadband) if the detectors could be made optically thin and stacked (see Figure **Error! No text of specified style in document.**-2) [D14]. The idea was that higher energy photons would be read-out by detectors deeper in the stack. In this way each detector could be tuned for a particular narrow band, with broadband characteristics achieved in combination. This concept leveraged much of the team's earlier work, including the thin-film fabrication techniques explored with UL#1.

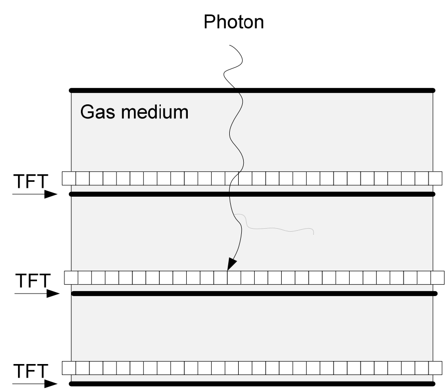

Figure Error! No text of specified style in document.**-2: Stacked, Optically Thin, Polarimeter Architecture**

Despite the excitement of the team, finding resources to support their development effort proved challenging at first. The stacked concept was initially outlined in a 2001 APRA proposal; a proposal that was not funded. The NASA funding managers were skeptical of any promise of polarimetry; X-ray polarimeters had been promised several times before, yet to date positive polarization measurements have only been made of one Astronomical source (the Crab Nebula, the brightest one). The funding managers were not convinced that this development effort would prove any more fruitful. So, the team returned to the ever faithful DDF, from which they received a year's funding to explore polarimeters based on the UL#2 concept [D4].

During that first year, they made a breakthrough that would vindicate them, enabled by a partially-planned chance encounter at the registration desk of a conference in Leicester, England. That's where CS#2 met IR#1, an industrial researcher from a large multinational's research park. Although CS#2 had registered for the conference before learning that IR#1 would be there, when he noticed the topic of IR#1s talk in the schedule, he made a point of meeting him [I62]. For years, CS#2 had been trying to read out his MPGDs with TFTs (Thin Film Transistors); now in IR#1, he'd finally met someone who had a functional TFT array for him to play with. CS#2 pitched his idea to IR#1 and, excited by the prospect, IR#1 invited CS#2 and his team to visit his research facility and "*give it a try*." So, CS#2 and the third core member got to work mocking up a gas counter polarimeter set up to be read out by the TFT. "*We finally got two detectors that actually worked, kluged together this thing, literally out of sheet metal and went down to [the research center] and set it down on one of their TFT arrays and sure enough it just worked! It was great!*" [I62] The trip was actually paid for initially out of pocket by CS#2 and his colleague (that's how important this was to them), although they were eventually reimbursed by a DDF the following year (which had been submitted in advance of the trip).

Armed with this extremely promising, albeit nascent, proof-of-concept, the team sought an opportunity to mature the lab experiment into a prototype instrument. They re-proposed to that year's APRA call; again it was rejected, but this time for different reasons; a response to an Announcement of Opportunity (AO) superseded the APRA funding.

Focusing Event (SMEX AO 2003 –> Category 3 Technology Funding)

In 2003 an AO for a SMEX mission was released [D36], presenting a focus for the team's efforts. As is typically done when a similarly important flight opportunity presents itself, the LHEA came together to strategize about what they should pitch [I61]. It was determined that an X-ray Polarimeter mission was the way to go. It was an important area of science and they were being "*laggard*;" "*it was the right mission for the time*" [I61] especially given the recent progress of the Goddard polarimetry team. A proposal was put together – called AXP (the Advanced X-ray Polarimeter) – based on the preliminary results obtained during the TFT experiments. Both UL#2 and IR#1 were listed as collaborators on the proposal. The design paired existing optics with the TFT read-out, amplified by a Gas Electron Multiplier (GEM).

In addition to partnering with IR#1 and UL#2, while preparing to pitch AXP, CSA#7 an experienced astrophysicists was brought on to lead up the effort on the science side. As she remembers it, it seemed an interesting project and the only other more logical person to fill the project scientist role was already overcommitted, so she volunteered [I61]. CS#1 remembers it slightly differently: "[the branch head] *pulled me aside one day and said [CS#2], I just wanted to* *give you a heads up that I'm assigning [CSA#7] as the project scientist. I interpreted that to be his way of telling me that he thought it was time to bring in a grown-up to keep us children on track*" [I62]. CS#2 went on to explain how CSA#7 added important credibility to the team. People were still a little skeptical about polarimetry, but CSA#7 had a reputation for only making well-supported statements; "*so they were more willing to take us seriously after she came on board*" [I62].

Despite the CSA#7 credibility factor, the AXP SMEX was not selected for further development because the selection committee was not willing to accept the risk posed by such an immature primary instrument. They did however rank the proposal as a "category 3" instrument and allocated $300K to mature the technology further. "Category 3" is a rating reserved for instruments that show enormous scientific potential but are technically too immature (and therefore risky) to be flown at that time. The idea is to give such instruments some time and resources with which to mature the concept for potential re-proposal at a later date. [I66]

Maturing the Capability, or just exploring some more…

The $300K over two years from the HQ Explorer Office was matched by a Goddard internal investment of an additional $200K [I61, D40]. This enabled the team to bring on an additional contractor – the fifth core member, CS#1, who brought polarimetry experience and a passion for working out instrument implementation issues – this provided an important complement to the creativity in concept generation, characteristic of the other contractor, as they moved forward with instrument development. For almost a year after the technology development award, the team focused on maturing the capability (nearly) as advertised. However, even during that first year, the TFT idea was superseded by a CMOS ASICS under development by the Italians, which had stronger heritage. Given the tight budget, they couldn't afford to pursue both options [I77].

The development path changed drastically in 2004, when CS#2 got distracted by a new diffusion suppression concept that could address what had been believed to be a fundamental limit of the device. This insight would lead to another round of breadboarding and a new architectural concept.

Making it work 2

At the time, it was believed that polarimeter sensitivity was fundamentally limited by a tradeoff between quantum efficiency and modulation (due to electron diffusion in the drift region). The insight was that a Time Projection Chamber (TPC) could create a virtual pixel detector, using time to derive a second coordinate from a strip readout. While TPCs had been in use for at least a decade, the novelty was in the virtual pixel encoding. This strategy effectively eliminated the diffusion tradeoff. As shown in Figure **Error! No text of specified style in document.**-3, since in a TPC, the photon enters from the side (rather than the top) diffusion distance can be increased without increasing the spacing between the two electrodes (the main source of the random error).

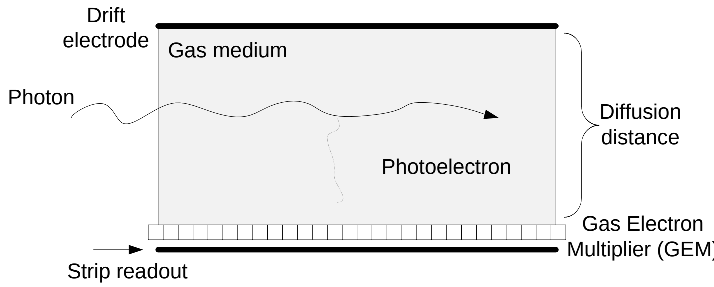

Figure Error! No text of specified style in document.**-3: Time Projection Chamber Polarimeter Architecture**

The inspiration for the TPC concept struck while CS#2 was visiting a researcher at a neighboring university. The visit was prompted by, of all things, the content of the Nuclear Instruments and Methods journal formatting template. As CS#2 was in the process of submitting the TFT paper, he noticed that the content of the template – suppressing diffusion with negative ions – might serve his purposes exactly [I62]. Since the author of that paper was located at a university down the road, CS#2 called him up and asked for a demo. The professor obliged. As recalled by CS#2: "*as I sat there watching the signals come in in slow motion, that's when I had the idea for the encoding scheme that would make pixelized images*" [I62]. Although the particular gas that was being used had too high a Z to be useful in an X-ray polarimeter (it would absorb too many of the photons), the Goddard team would explore the feasibility of suppressing diffusion with other gases at several future points in the development.

The idea of creating a virtual pixel readout in a TPC set-up was sufficiently unconventional that CS#2 kept it to himself initially because he didn't want to embarrass himself if it turned out to be as crazy as it seemed. "*I put myself in a quiet corner to figure out why it wouldn't work*" [I62] and consulted a few of his closer colleagues. Several simulations (and weeks) later, without having uncovered any violations of physical laws, the team decided to pursue the idea. So they "*built one up out of pieces off the side of the road, as [CS#2] liked to say. And it worked! It was great, it was super sensitive. It didn't do imaging, but it was super. It was a polarimeter, which is what we were trying to do*" [I24]. The whole effort was funded by a single DDF and what remained from the technology development funding. The challenge was now to get this revolutionary concept into a workable prototype that could win an opportunity as a next SMEX.

Treading water

Unlike in 2003 when a SMEX opportunity followed the TFT breakthrough almost immediately, now, following the TPC demonstration, there was no equivalent flight opportunity available. This lack of immediate flight opportunity was not necessarily a bad thing. In many ways, the 2003 SMEX had come too quickly; they received technology development funding precisely because the instrument was not yet mature enough to be approved for project development. In the same way, in 2005, the TPC-based concept was still very much a breadboard. However, moving from breadboard concept to mature enough for project development is a difficult proposition. This phase of development is often called the "valley of death" to evoke an image of a funding drought between research and development. As will become clear, the team did indeed face some degree of funding drought, but they also faced a gap between the competing objectives of always looking for a new better way, and making sure the existing system will always work.

From a funding perspective, where in the early years, DDF provided a relatively stable source of R&D funding; now in the mid 2000s, this was no longer the case. Once contractor salaries were removed, even the development funds from HQ really didn't get them very far: "*we were working off bread crumbs really*" [I24]. During the period from 2004 through 2008 the project stayed alive through creative scrounging for resources. IRADs (Internal R&D – the mechanism which superseded DDF) were awarded every year, totaling $500K over the period as well as supporting an average of 2 FTEs (civil servant salaries) per year. Once the AXP development funds ran out, the contractors wrote APRA (Astronomy and Physics Research Activity – HQ level funding) proposals to sustain themselves and found "day jobs[2]" to help free up resources to keep the project alive. Yet, by late 2005 the contractors were questioning the sanity of sticking with a program that couldn't pay them: "*frankly, we thought we were done. I was actively looking for a job, [the other contractor] had some job offers, but we decided to write two last proposals for the TPC stuff*" [I62, I24, I77]. Both APRAs were awarded in 2006, keeping the team alive [D35]. One was for a sounding rocket test of the technology that would become the GEMS instrument. The second was for a gamma-ray burst detector; a different design but sufficiently related to usefully push the concept forward. The team similarly submitted proposals for a solar polarimeter, one of which was funded in 2007, although they haven't yet had time to work on it [I77]. In both cases, the strategy was one of diversification. Now that they had a promising system, they wanted to re-frame it in as many ways as possible to maximize the likelihood of finding a flight opportunity. In a sense they were too successful in this respect. Where in 2005 they were scraping together resources to cover base salaries, two years later they had won more work than they could do.

Formal Project

In 2007 a new SMEX AO was released and the AXP proposal was recast as GEMS (the Gravity and Extreme Magnetism SMEX) and re-proposed [D37]. GEMS replaced the AXP concept with a TPC polarimeter. This time, with several more years of development and proof-of-concept under their belt, they were selected for phase A concept development in 2008, and in 2009, as the second SMEX mission.

Once the project entered phase B, everything changed for the core polarimetry team both in terms of work practices and resource availability. Now they had to deal with formal project management, and the schedule and budgeting that entailed. They were also joined by a team of engineers. Where until that point, they had continued to follow new technological insights as they arose; improving (and changing) the design as they went; never sticking with one design long enough to get a robust prototype; now as a project, producing an instrument that would be guaranteed to work was supposed to be the top priority. As with most projects of this type, the early teaming was characterized by a clash of cultures.

From the perspective of the scientists: "*they had this idea that we'll come up with requirements and they'll go off and build it and come back and present it to us. But that's not how it is. We're not far enough along with the stuff to really know exactly what you need to build… there's going to be some iteration because it's might not work as well as we'd hoped*" [I24]. From the perspective of the project management team: "*they're extremely intelligent, very passionate, they*

[2] E.g., CS#1 began working on a CubeSat that was tangentially related to her area of expertise.

really care, but they just don't get that there's a trade-off; we're on a capped mission, when we run out of money, we run out of money." "And that's just the money, with the schedule… they keep saying just a little longer, a little longer… they don't understand that they're holding up the whole project and there's a train moving behind them. If we don't finish on time they get nothing – no science" [I63].

Over the course of the project relationship, understanding has evolved. One key example of the scientists' shift to a project mindset is the decision to use normal gas with an ASIC developed for CERN, rather than the negative ion gas with which they'd been experimenting. Compared to the sensitivity of the negative ion solution described above, "*it's less sensitive but we're confident that it will work (which is not the case for the alternative) and that's important for a project like this*" [I77]. The design has now stabilized and efforts are truly focused on instrument development. The negative ion effort does continue however, under the auspices of the GRB polarimeter trajectory.

From a funding perspective, although winning the SMEX created a much more stable development environment than had previously been enjoyed, it also imposed many more constraints about how that money could be spent. As the second SMEX, GEMS was slated for launch in late 2014. And, following project approval, the $105M cost cap would be strictly enforced. Given that labor represents a significant project expense, the full project team could not be ramped-up until approximately 3 years prior to the planned launch. Yet, the need to maintain technical expertise and momentum in the polarimeter development presented a conflicting constraint. The GEMS project team persuaded the SMEX program office to provide an advance on the project money - $5M over 18 months – which would allow the polarimetry team to proceed fully staffed, while maintaining a part-time skeleton project team to manage their efforts. However, it became quickly apparent that some supplemental funds would be needed to mature the polarimeter sufficiently for easy insertion once the project "turned-on." This later conundrum has been mitigated as follows: The GEMS project has adhered rigidly to the budget provided by the project office, but some of the scientists may have applied for other technology development funding to pursue other applications for similar technologies. That the work is also directly relevant to the GEMS polarimeter is a pleasant side-benefit. Thanks to these years of pre-work, the team is confident that the polarimeter will be a success and the mission will yield important new discoveries.