Project Description

Primary Review Code: Mathematical and Physical Sciences

Secondary Review Code: Education and Human Resources

Background: The problems posed by the search for weak spatial and/or spectral features in a strongly absorbing or scattering background using active interrogation are familiar from fields as diverse as radiography and the search for dilute volatiles in the atmosphere using laser radar systems. One of the most effective techniques for the detection of targets with narrow spectral features using laser radar is differential absorption (as in DIAL, for Differential Absorption Lidar), in which a the intensity of the light scattered or absorbed by the obscuring background and the target molecules at the peak of one of its absorption features is compared in near real-time with the light scattered or absorbed by the obscuring background at a nearby wavelength at which target absorption or fluorescence is weak. By subtracting the intensity of the light detected at these two wavelengths, the small change in absorption or scatter due to the target molecules can be reliably detected in ambient backgrounds generating obscuring "returns" larger by several orders of magnitude.

One possible series of candidates for detection by this resonance absorption technique would be the nuclear transitions unique to the fissionable nuclear materials to be detected. In this case, detection of the nuclear fluorescence radiation emitted by the absorbing nuclei following excitation could provide a useful confirming signature of the presence of these materials.

But even when the sharp spectral features exploited in LIDAR systems are absent, the differences in the variation of absorption with wavelength can provide substantial enhancements in the contrast with which target structures or materials can be identified in radiography, making multi-color radiography and microscopy active and highly productive fields of development in medical and analytic x-ray science [1]. Indicative of the applicability of this approach to detection of concealed nuclear materials, a review of the tabulated linear mass attenuation coefficients for high and low Z absorbers (examples: aluminum and lead) quickly establishes that the attenuation due to low Z materials in the photon energy range from 0.5 to 1.0 MeV falls off much more slowly with photon energy than for high Z materials, making possible the detection of such high Z materials on the basis of their gross absorption features even in the absence of the line spectra most frequently relied on in differential absorption measurements [2].

An additional advantage of absorption measurements in the Gamma ray energy range around 1 MeV is the generally low mass absorption coefficients that apply at these energies [3]. Higher selectivities that might be possible at lower energies will be of little value if the probe Gamma beams are heavily absorbed in the cargo surrounding the nuclear materials to be detected. The reduced levels of energy absorption per unit volume at Gamma energies of the order of 1 MeV may also prove useful in reducing the dose received by individuals who may accidentally be exposed to these beams.

Although the rationale for implementation of the differential absorption technique at the energetic Gamma ray wavelengths usable for detection of nuclear materials concealed in cargo containers, aircraft, vehicles, etc, is clearly of potential interest given the theoretical possibilities for detection by these means, the absence of bright, tunable x-ray and gamma ray sources capable of generating the collimated, near monochromatic beams required by the technique do not exist at this time. Further clouding the prospects for this approach, the limited spectral resolution of existing gamma ray detectors complicates the determination of the spectral distinctions between the target nuclear materials and the obscuring ordinary or high-Z non-nuclear materials in which they may be concealed.

The solutions to these problems appear to lie in developments undertaken in the fields of lasers, optics and high energy physics in the decades immediately past. Through these prior efforts we now have both the concepts and the methods needed to develop both the bright, tunable, near monochromatic sources of the energetic gamma beams and the temporally and spatially resolved detectors needed to apply the differential absorption technique to the detection of concealed nuclear materials. These developments include:

1. the development of the inverse Compton scattering model for analysis of the operation of free-electron lasers and synchrotron radiation sources which has led both to the understanding of the utility of the upconversion of light to dramatically shorter wavelengths by the interaction of intense, longer wavelength light beams with intense, relativistic electron beams, and the intrinsic limits to this process set by the transition from undulator to wiggler radiation at high normalized vector potentials [4];

2. the analysis of the criteria for optimization of the luminosity of colliding beams systems developed for research in high energy particle physics, which has led to the understanding of the factors determining the luminosity of these systems – and of the comparable electron-optical colliders for production of energetic x-ray and gamma ray radiation – particularly, of the need to optimize the product of the peak and average intensities of the two colliding beams [5];

3. the analysis of the factors limiting the intensity and emittance of the electron beams available from the linear accelerators used to drive free-electron lasers and proposed for the next generation of linear colliders, which led to the development of the microwave thermionic and microwave photocathode electron guns now available for use in the energetic x-ray and gamma ray sources we propose to develop [6];

4. the analysis of optical cavity designs and development of the fine precision optomechanics needed to develop the stable optical storage cavities we propose to use to create the intense, multicolor, circulating optical pulses that will constitute the second (electromagnetic) component of the two colliding beams in our proposed energetic x-ray and gamma ray source [7];

5. the analysis and practical application of cavity electrodynamics in the development of laser and free-electron laser sources capable of generating the highly coherent optical pulse trains needed to pump these novel optical storage cavities [8];

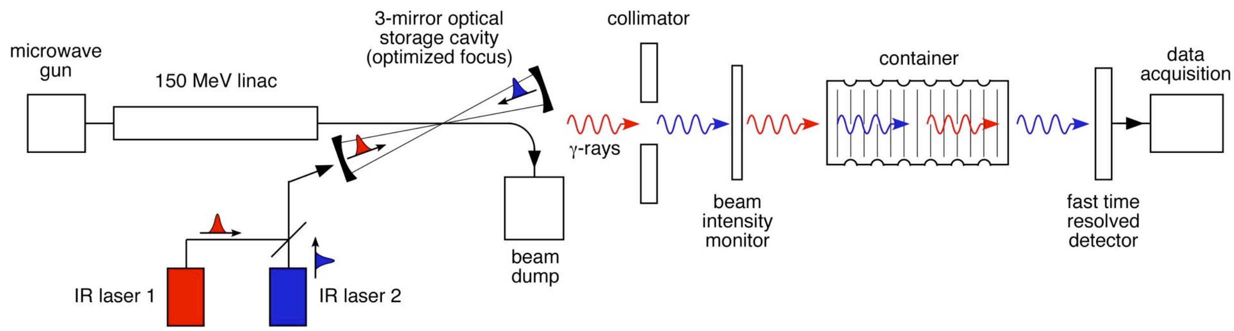
6. the availability of scintillators with favorable mass absorption coefficients and decay times adequate for determination of event timing at the picosecond level at relevant gamma ray energies [9];

7. the development of the fast, multichannel data acquisition systems needed to record the data generated by these detectors [10]; and

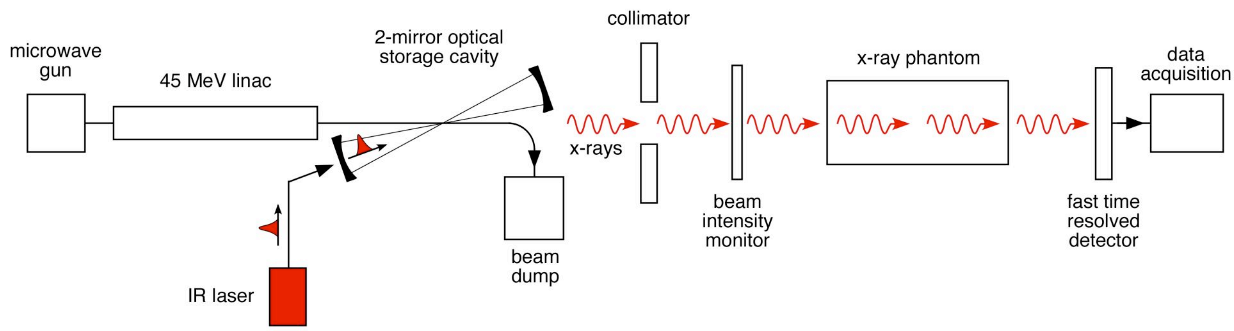
8. the demonstration of the utility of picosecond time gating to suppress the spatial blurring in transmission imaging systems due to multiple small angle scattering [11].

We have been privileged to participate in a number of these developments in the course of our prior research [12]. It is our purpose in the research outlined below to apply the experience and know-how gained in these prior efforts to the development of a practical system for detection of concealed nuclear materials using the differential absorption technique.

<u>Description of Proposed Research</u>: The projected configuration of a "full-up", fully capable differential absorption detection system is shown schematically in Figure 1A. The mode-locked and phase-locked picosecond optical pulses from two or more lower power pump lasers are coherently stored in a novel three mirror optical storage cavity to generate a sequence of intense circulating optical pulses brought to a diffraction limited focus in a near-concentric resonator to minimize the focal spot size. These circulating pulses are made to collide at a small angle with the high peak and average current, low emittance, energetic electron beam from a pulse microwave linac using a high duty cycle microwave thermionic or photo-



1A



1B

Figure 1. (1A) Configuration of operational gamma-ray differential absorption detection system for fissile nuclear materials; (1B) Configuration of proposed x-ray scaled prototype detection system for demonstration of e-beam optimization and stabilization, high rep-rate x-ray generation, picosecond time-gated x-ray detection, and differential absorption detection of scaled x-ray targets

cathode gun. The energetic x-rays and/or gamma rays generated by the collision of these two beams, which are emitted preferentially in the direction of the incident electrons, are monochromatized by collimation and directed at the container, vehicle or aircraft to be scanned. The intensities of each component of the multicolor, collimated beam are monitored by a stack of thin plates biased to time-resolved photocurrents generated by the beam as it passes through the stack for use in normalizing the counts detected after passage of the beam through the container.

Following passage through the object to be scanned, the energetic x-rays and/or gamma rays are detected by an array of detectors (scintillators + high speed semiconductor photodiodes or bulk photoconductive semiconductors depending on the energy of the photons to be detected) to minimize the full width half maximum temporal signatures of these photons, and acquired for analysis in a fast, multichannel data acquisition system, and processed to determine the time of arrival to better than 10 picoseconds. We have successfully demonstrated our ability to measure pulse risetimes of less than 200 picoseconds by these means, with the further ability to identify the time of arrival of the detected photons to within 10 picoseconds by postdetection analysis of the pulse waveform.

The time resolution of this detector system serves two critical functions in this system. Since the pulses of energetic x-rays and/or gamma rays emitted by the source are encoded by the times at which the optical pulses and electron bunches creating these bunches collide, the energies of the detected photons can be determined by their time of arrival without the need for detectors capable of high energy resolution, thus obviating the need for such detectors. Secondly, by gating the detectors to accept only those pulses which travel without scattering or absorption through the container and its cargo (the so-called “ballistic imaging” technique [13]), the spatial blurring caused by multiple small angle scattering can be suppressed to yield near ideal spatial projections of the contents of the container on the detector array.

The intensity of the gamma beams needed for such a system must be adequate to generate the counting statistics needed to distinguish the differential absorption due to the target nuclear materials, given the absorption and scatter attributable to the non-nuclear contents of the container and the quantum efficiency of the detector array. Assuming Poisson statistics, the number of detected photons needed for identification of the presence of concealed nuclear materials must be at least 36 times the square of the inverse of the fractional difference in absorption due to the presence of the material to be detected. Assuming a fractional absorption differential of the order of 1×10^{-3}, identification of the presence of such a material would require the detection of at least 3.6×10^{7} photons. Allowing for the attenuation of the incident photon beam by a factor of 100 in passage through the non-nuclear components of the cargo, the energetic x-ray or gamma source providing these photons would have to be capable of directing of the order of 10^{10} photons through the bulk of the nuclear material to be detected.

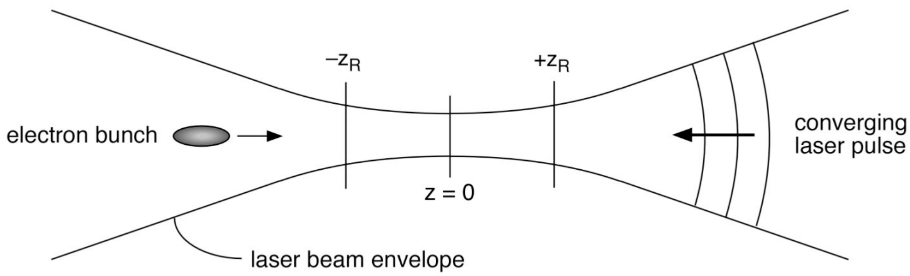
The need for statistics adequate to distinguish between small differences in absorption in such systems implies the need for gamma beam sources capable of delivering numbers of the order of $10^{12} - 10^{14}$ gammas per second into the solid angle and spectral bandwidth needed for operation of the system. This is a large number whose attainment will require careful optimization of the source of these photons, particularly, of the peak power and time-averaged current of the colliding optical pulses and electron bunches.

One approach that has proved highly successful in the generation of high peak power, tunable, monochromatic X-ray beams is inverse Compton scattering implemented through the collision of a focused, high peak power, picosecond pulsed laser beam with a focused, high peak current, low emittance relativistic laser beam focused to a waist to match the radius of the focused laser beam in the zone in which the two beams collide [14]. Very impressive peak X-ray powers have been obtained by this method, and active efforts are underway to scale this approach up into the Gamma region [15].

But this technique appears less well suited to applications requiring high average Gamma beam powers and lower peak Gamma count rates such as the differential absorption technique we propose to pursue. The reasons for this are in part fundamental and in part technical in nature. Although the back-scattered Gamma beam power in inverse Compton scattering scales linearly with the incident power of the pump laser beam at low laser powers, the optical electric and magnetic fields in these lasers eventually reach amplitudes at which they induce strongly relativistic motion in the coordinates transverse to the electrons' direction. This relativistic transverse motion both reduces the electrons' longitudinal velocities and strongly modulates the phase at which the electrons interact with the field. The result is both the reduction of the energy of the backscattered photons and the appearance of an increasing number of integral-order harmonics which eventually combine to convert the near monochromatic Gamma radiation available through this mechanism at low pump laser intensities to broad band "white light" of no value for applications requiring wavelength selectivity.

There is therefore a limit to the pump laser power which can be used for this technique, typically corresponding to a limit of the order of 0.1 to the magnitude of the normalized vector potential eA/mc^2 [16] of the pump laser beam. The good news is that this limit can readily be reached using the now widely available solid state terawatt laser technology. The bad news is that no further useful gains in Gamma beam intensity for applications in differential absorption or fluorescence measurements are available at higher pump laser powers.

In addition to this fundamental limit, it also appears that there is a practical limit of the order of a nanocoulomb (10^{10} electrons) that can be extracted from the cathode of high brightness electron guns and accelerated to the energies needed for operation of these Gamma beam sources [17]. The Gamma beam energy available from a single collision of this type is therefore limited to 10^{10} times the energy radiated by a single electron in passage through the focused waist of the pump laser at the power density corresponding to a normalized vector potential of the order of 0.1. For a 1 picosecond green pump laser pulse at 500 nm, this limit corresponds to the order of 10^{10} individual radiated Gamma photons.



$$\text{Avg. Radiated Power} \sim \frac{2\pi^2}{3}\, r_0^2\, \frac{P_0}{c\,\lambda_f}\, \frac{\langle i \rangle}{e}$$

Figure 2. Radiated X- and Gamma-ray Powers for Optimized Pump Laser Rayleigh Parameters

To obtain Gamma rates on the order of 10^{12} sec^{-1} collimated to an energy spread of 1%, it would be necessary to repeat such a "best case" collision at the rate of 10^{4} sec^{-1}, a very high number that begins to raise practical questions as to the feasibility of dissipating the waste heat deposited in the lasing media and optics of the pump laser system as well as the cathode of the photoinjectors used in these high peak current electron guns. And even if it were possible to solve these engineering-related problems, the high peak Gamma ray powers of these "isolated pulse" sources would pose formidable problems in detection and analysis given the high probability of pulse pileup.

More generally, when diffraction effects are taken into account the total radiated power of such colliding photon beam/electron beam sources scales, in optimized source designs, as the ratio of the product of the pump laser peak power and average electron current to the wavelength of the final-state photons (Figure 2) [18]. It is clear from this scaling law that the radiated Gamma ray power of these sources requires the optimization of the product of peak laser power and average electron current, not simply the highest peak laser power or electron current. While it has long been known that the same general scaling law applies to the luminosity of all colliding beam sources, the implications of this scaling law for design of the intense Gamma sources has not always been appreciated.

In particular, the engineering and fundamental limits to the gamma production rates using *isolated*, low rep rate, high peak power optical pulses and high peak current electron bunches have led us to pursue the alternate development of EUV, X-ray and Gamma ray sources based on the extended interactions of ~10 microsecond pulsed electron beams available from long-pulse microwave linacs, in which every available bunch is populated to the order of 10^{9} electrons using a microwave thermionic injector, and the colliding optical pulses are injected and stacked in a low loss cavity and thus made to *collide repeatedly* with the electron bunches by matching the round trip transit time to the interbunch spacing (or an integral multiple thereof for multicolor sources), as shown in Figure 1A. Such optical cavity-based sources can deliver tunable monoenergetic and multicolor gamma pulses with total scattered powers higher by three orders of magnitude – at a factor of ten lower peak electron current – than available from low rep rate systems that use high peak current electron bunches and isolated high peak power optical pulses of the same normalized vector potentials and optical power densities.

While scaling such systems to the average Gamma powers required for operation of a differential absorption detection system for fissile nuclear materials would require the system to be repetitively pulsed, the corresponding macropulse rates would still be 1/1000 or less than the repetition rates for "isolated pulse" inverse Compton sources.

Equally important, the complexity, size and cost of the laser and e-beam technologies required for our optical cavity-based approach are dramatically lower than for an equivalent "isolated pulse" system, requiring no drive laser for the system's e-beam injector and a modest, long-pulse, low peak power, mode-locked and phase-locked laser pump to drive the optical storage cavity.

Further discussions of the cavity-based approach can be found in our patents, US Patent 7382861 describing the means by which such systems can be designed to provide the multiple sequential “colors” required for operation of differential absorption-based imaging systems and other applications, US Patent Application 11/143106 describing the construction of optical cavities operable at the high circulating power densities required for operation at these large normalized vector potentials, and US Patent 4641103 describing the construction and operation of thermionic and photocathode microwave electron guns [19].

Scanning in such systems could be accomplished either by physically moving the container past the gamma beam source and detector, or by changing the angle at which the energetic electron beam passes through the storage cavity to take advantage of the alignment of the emitted gamma beam with the direction of the electrons motion through the fields with which the electrons collide in the storage cavity. But while e-beam steering is attractive in terms of the capability for fast raster scans of the contents of such containers, attention should also be given to the increased complexity of e-beam and gamma beam transport in systems incorporating such scanning.

Given the long-established demonstrations of the effectiveness of the microwave thermionic injector technology we have developed for use with our free-electron laser systems, the principle remaining developments on which the integration and demonstration of the “full-up”, fully capable differential absorption scanning system shown schematically in Figure 1A depends are:

A. the development of the novel three-mirror optical storage cavity shown in Figure 3 and described in US Patent Application 11/143106 needed to achieve the simultaneous constraints on focal spot size and free spectral range needed to create and maintain the high energy, multicolor circulating optical pulses needed for operation of the system. This is a challenging engineering task in its own right with substantial non-recurring development charges.

B. the development of the long pulse, picosecond mode locked, phase locked multicolor solid state lasers needed to provide the coherent train of optical pulses needed to pump the optical storage cavity in (A) above. Like the optical storage cavity, the development of these lasers is a significant engineering task with significant non-recurring engineering charges.

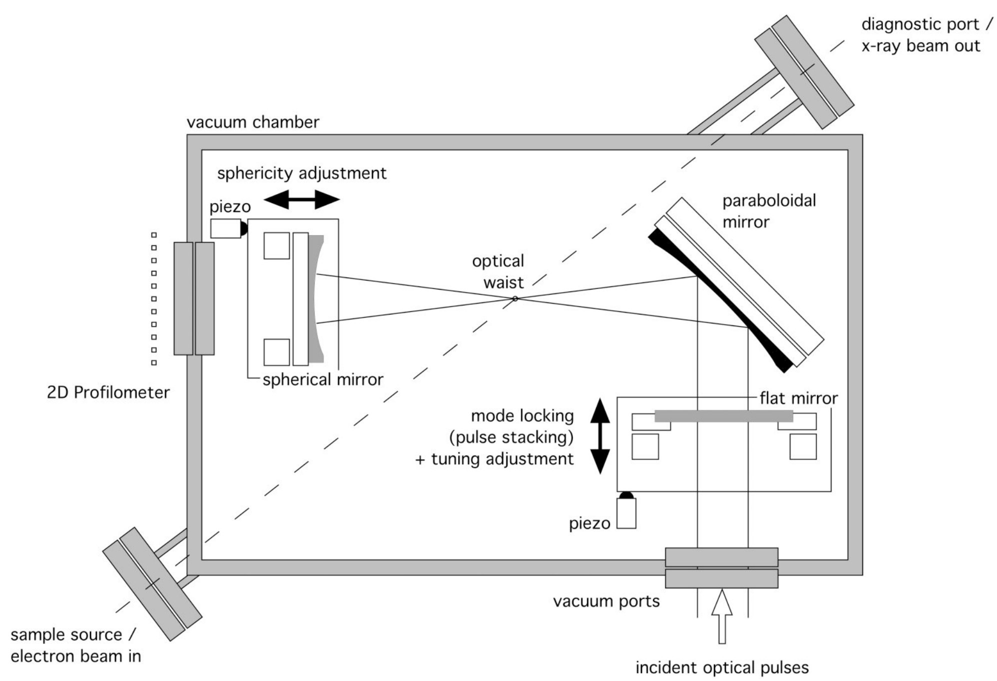


Figure 3. Schematic Drawing of High Circulating Power Stabilized Optical Storage Cavity

C. the development of the picosecond, time resolved high energy X-ray and Gamma ray detectors and data acquisition systems needed to detect the X-ray and/or Gamma ray photons passing through the container to be scanned with high quantum efficiency. Prior and parallel developments in the high energy physics programs for which we have been responsible have made it possible to develop these new systems at more modest cost.

D. The development of the electron beam diagnostics and controls needed to bring the electron bunches in our proposed system to a stable and well defined focus overlapping with the focal spot of the optical pulses circulating in the optical storage cavity. Our prior experience in the development of these diagnostics and controls is also applicable to reducing the costs to develop these systems.

The non-recurring engineering costs for tasks (A) and (B) above appear to exceed the funds available for such development given the funding levels projected for this program. It is accordingly our plan to seek private, non-government funding for the development of these new subsystems at no cost to the Government, based on the prospects for commercial development and sale of these systems for use in analytic and medical x-ray systems in the lower energy x-ray region at energies below 20 keV. There will be no significant difference between the optical storage cavities and laser pumps developed for these lower energy applications and needed for the high energy x-ray and gamma ray sources described above.

Given the constraints on available funding and the emphasis on hands-on student training in this program, we believe that the resources available through this program can best be utilized in investigating the underlying principles of operation of these cavity-based, rep-rated systems in the configuration shown schematically in Figure 1B. The system shown in Figure 1B can be integrated and tested using our existing microwave thermionic injector, 45 MeV linear accelerator, fully implemented diagnostic electron beam line, tunable infrared free-electron lasers, and existing facilities for radiation shielding, extraction and analysis of the monoenergetic x-rays that can be produced using this existing hardware.

Pictures of these existing components are shown in Figures 4-6. Figure 7 shows scale drawings of the entire system, end-to-end, from the system's thermionic microwave gun to the permanent magnet beam dump and massive copper beam dump at the end of the system. Figure 7 also includes a blown up scale drawing of the special achromatic chicane we have installed between the system's linac and FEL undulator to provide the dedicated space needed to install the bremmstrahlung and cavity-based x-ray sources to be developed as part of the proposed research. This section of beamline also provides the non-contacting diagnostics (via phase space tomography, the synchrotron radiation emitted by the electrons during passage through the edges of the dipole magnets in the chicane, and appropriately placed SLAC-type stripline beam position monitors) needed to optimize and stabilize the electron beam's position, emittance and energy spread.

Table 1

Linac:	Energy Range:	20 – 45 MeV
	Peak Current:	> 30 A
	Charge/Bunch:	> 0.1 nC
	Normalized Emittance:	< 4π mm-mrad
	Operating Frequency:	2856 MHz
	Macropulse Length:	up to 8 microseconds
	Macropulse Rep Rate:	up 20 Hz
MkIII FEL:	Tuning Range:	1.5 – 12 microns
	Energy/Pulse:	10 – 100 millijoules
	Transverse Coherence:	> 98% TEM00
	Coherence time:	> 1 microsecond

The capabilities of the microwave thermionic gun, linac, and FEL pump laser we propose to use in this research are summarized in Table 1. This system is available for use in the proposed source at no cost beyond the supplies and expendables needed to keep it in operation. The funds requested for upgrades to the electron transport system, diagnostics and controls for the system are for the revisions needed to bring the bunched electrons to a stable focus matching the focus of the circulating optical pulses in the optical storage cavity.

Detector and data acquisition development will in like manner benefit from the availability of the existing detector design, clean room assemble space, and test areas available in Watanabe Hall and the expertise of acquired by the Faculty and staff of the Department in the course of their extensive prior efforts in these facilities to develop the advanced detector systems for the world renowned neutrino, B-meson, and cosmic ray research which our colleagues have helped to lead in recent years.

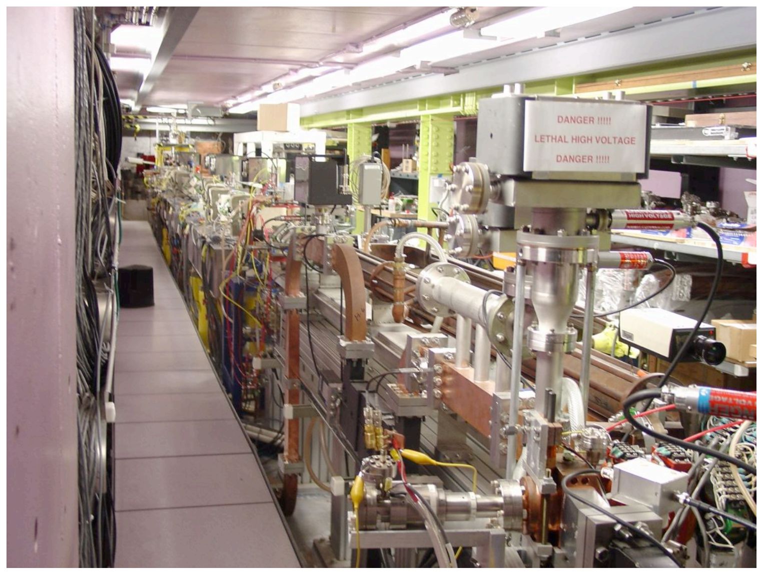


Figure 4.
S-Band Thermionic Gun and Linac for UH FEL/Light Source Test Bed

Figure 5.
Diagnostic Chicane for Characterization of 6D eBeam Phase Space via Phase Space Tomography

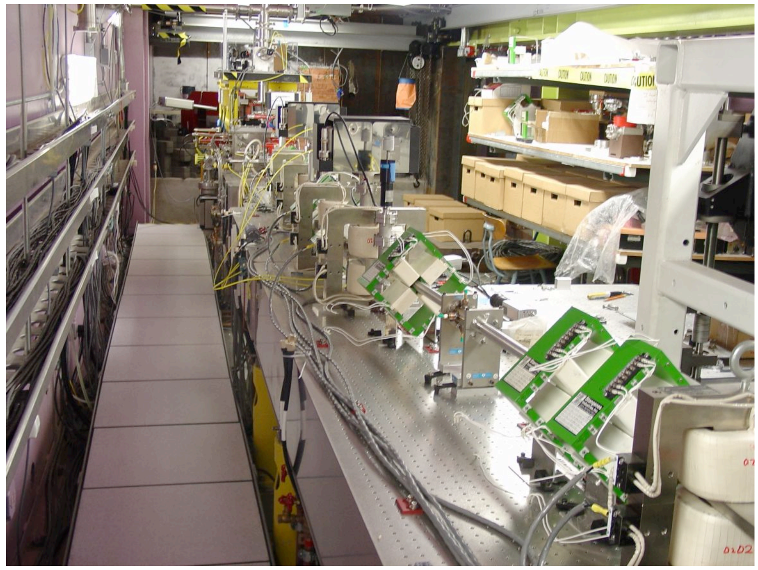


Figure 6.
Insertion Section for Installation of Initial Bremmstrahlung Converter Foil and Prototype 2 and 3-Mirror Optical Storage Cavities

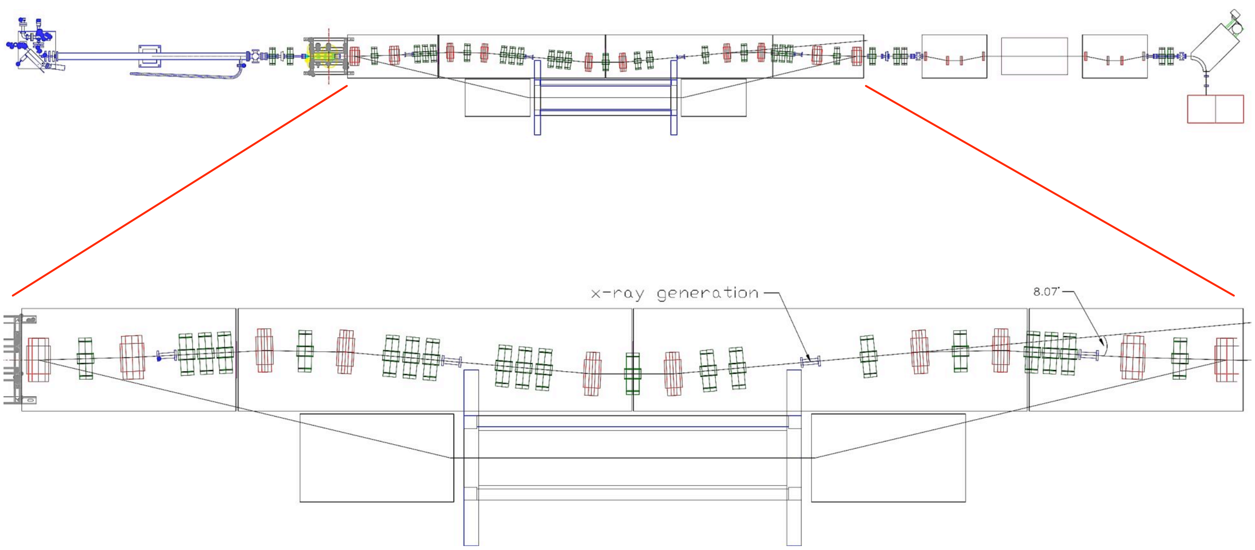


Figure 7. Plan View of UH FEL/Light Source Test Bed with enlarged view of Insertion Section showing path of radiated X-Rays. A 4" hole has been bored along this path through the vault's radiation shielding for installation of a beamline to the phantom and time resolved detector system to be used in the proposed imaging experiments.

To demonstrate and evaluate the key physical principles and technologies on which our proposed gamma ray scanning system depends, we propose to add to these major and highly capable existing systems:

(i) a simple bremmstrahlung x-ray and Gamma ray source consisting of a radiator that can be inserted in the beamline at the position of the proposed optical storage cavity to provide a broad-spectrum test beam for evaluation of the detector and data acquisition subsystems needed for the project

(ii) a simple two-mirror optical storage cavity with the feedback controls needed to accurately maintain its free spectral range at 2.856 GHz, but without the additional optical elements and controls needed for stabilization of the focal spot size. This simple two-mirror cavity will be installed at the location which has been provided for the "full-up" three-mirror optical storage cavity along the third leg of the diagnostic beam line as shown in Figure 7. Pending development and delivery of the mode-locked and phase- locked solid state laser needed to pump this cavity, the cavity will be pumped by the phase-locked beam available from our existing MkIII FEL system

(iii) a collimator and "stacked plate" time resolved photocurrent detector [20] to monochromatize and monitor the intensity of the x-rays generated by collisions in the broad band insertable radiator (i) and cavity (ii) above

(iv) prototypes of the time resolved detector and data acquisition systems needed to detect the photons passing through the targets to be scanned, and to identify their energies by detection of their time of arrival

(v) the additional electron optics, diagnostics and controls needed to bring the bunched electron beam to a stable focus matching the focus of the circulating optical pulses in the optical storage cavity (ii) above

(vi) a series of targets scaling the high energy absorption coefficients of nuclear materials concealed within civilian cargo container, vehicles and aircraft to x-ray energies to assess – insofar as possible – the utility of the differential absorption technique in detecting the presence of suspect high Z materials in these containers/vehicles/aircraft in these preliminary experiments.

Although this basic system will have neither the e-beam energy needed to produce the Gamma ray photons needed for detection of nuclear materials, nor the optical storage cavity technology needed to operate at the backscattered X-ray photon beam powers possible using an optimized three-mirror resonator, it will provide (1) the testbed needed to evaluate the potential utility of the cavity-based, time-gated differential absorption technique for detection of small differences in the photon energy dependence of the mass absorption coefficient in suitably designed targets, (2) the testbed needed to evaluate the picosecond detection and data acquisition technology needed for operation of these systems, (3) the e-beam optics, diagnostics and controls needed to focus and stabilize the electron beam required for operation of these systems, and (4) the hands-on opportunities needed to train the students and postdoctoral personnel in these technologies and the use of the differential absorption technique.

We believe that these steps are critical to the assessment of the utility of the time gated differential absorption technique, as well as the training of the technical personnel needed to implement the technique if successful.

Assuming the success of these developments and the availability of the advanced three-mirror optical resonator and solid state laser pumps for which we are independently seeking support from the private sector, we plan as part of our follow-on effort to work with the Bates Linear Accelerator Laboratory at MIT to install a duplicate thermionic microwave gun, optical storage cavity, collimator and beam intensity monitor, detector array and data acquisition electronics on the Bates linac to increase the energy of this initial series of experiments to the 0.8 – 1 MeV range needed for a "full-up" demonstration of the use of time-gated differential absorption for detection of fissile nuclear materials.

Alternatively, given appropriate funding, we could integrate these components with a high gradient pulse normal linac or cw superconducting linac of the appropriate energy in the space available in the shielded vault in which these fundamental proof-of-principle experiments will be conducted.

<u>Detector Development and Background</u>

Differentiating direct and scattered x-rays as a means of determining differential absorption requires exquisite timing at the picosecond level. For high energy photons (x- or gamma-rays) traveling at the speed of light, 1 picosecond corresponds to 300 microns spatially, about 3 times the width of a human hair. Therefore to achieve the needed timing performance, a compact detector and fast electronics are compulsory.

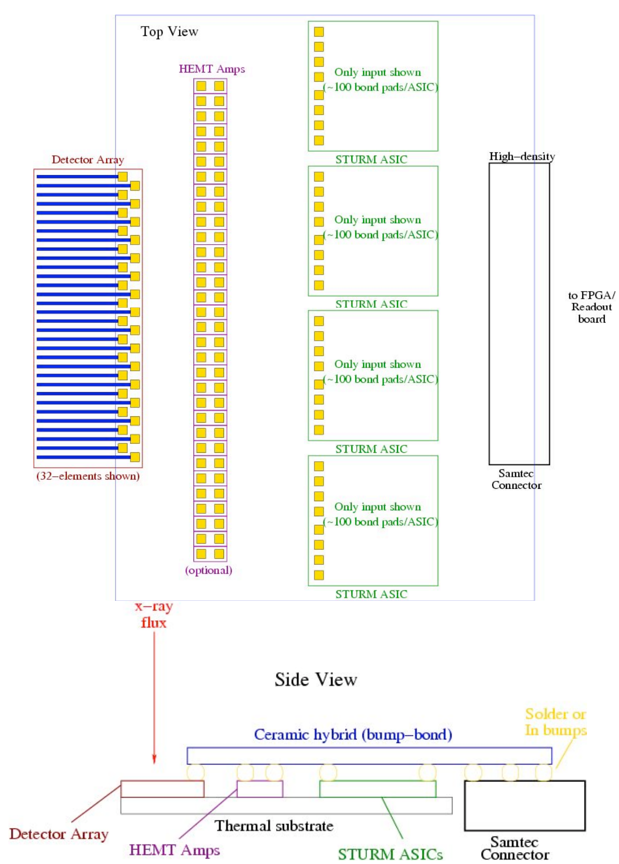
Our technical approach to addressing these very challenging requirements is to continue the natural evolution that has been pursued at the University of Hawaii on a number of relevant instrumentation development fronts:

1. high-speed (GSa/s) waveform sampling ASICs [21-24]
2. picosecond timing recording circuitry [25-29]
3. fast, high precision detectors [30-32]
4. high-efficiency x-ray pixel detectors [33-34]
5. high-speed, large volume data acquisition and recording systems [35-41]

A number of key technical challenges need to be addressed in order for this project to be successful:

1. Efficient stopping power with modest-cost detectors
2. High efficiency, excellent transit-time-spread photodetectors
3. Segmented depth of interaction readout

Considering these constraints, a good starting place is recent experience with developing a prototype x-ray detector for coded-aperture mask imaging of individual electron bunches in a storage ring [13]. A conceptual diagram of a proposed, eventual packaging implementation of such a detector+readout array is depicted in Figure 8. The readout electronics are directly coupled to a detector array to make a single sensor layer. To improve stopping-power, a high-Z scintillating material may be coupled to the front of the sensor array. A large stack of these structures may then be assembled to form a detector with the required interaction probability and timing performance (by keeping geometry compact) to permit x-ray timing measurement at the picosecond level. A very simple ASIC prototype has been developed, denoted the Sampler of Transients for the Uniformly Redundant Mask (STURM), as seen in Figure 9. While this 8 input channel, 3.3mm x 3.3mm device has a number of limitations, it has been successful enough to permit initial testing with a commercial sensor array. A first beam test was performed in March 2009 at the KEK (Japan) Photon Factory, where a 200ps risetime was measured by STURM, consistent with high-performance oscilloscope measurements. Using external delay taps, 8 successive analog "snapshots" were acquired at a spacing of 100ps, corresponding to an equivalent 10GSa/s acquisition. Better performance still is needed for the application proposed, and lessons learned from this development provide insight into directions the further R&D effort should be focused.



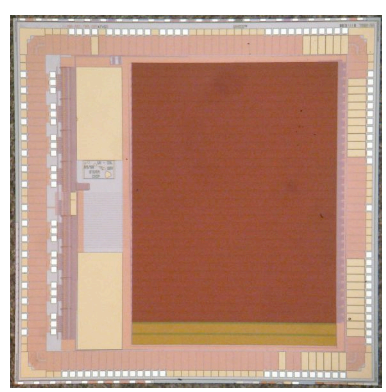


Figure 9. Die photograph of the STURM prototype ASIC.

Figure 8 (left). Integrated detector module concept.

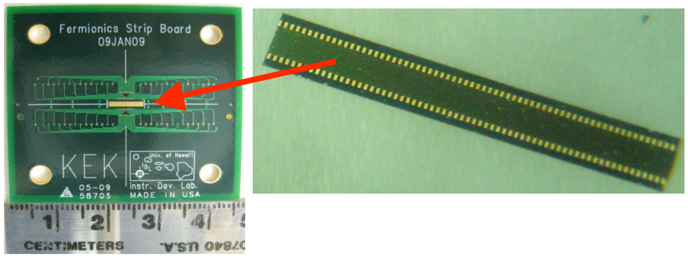


Figure 10. Photograph of a linear sensor array used for prototype x-ray detector evaluation.

Detector Options

A number of options are available for both the high-Z scintillator, as well as the photo-detector. Standard single-crystal materials, such as barium-fluoride, may be coupled to existing high-speed InGaAs sensors. An example of such a linear array, as was used in the x-ray beam test mentioned above, is shown in Figure 10. Optimization of such a composite detector configuration and constituent materials will be an ongoing task, with the expectation of two cycles of custom sensor fabrication.

ASIC Development

It is planned that iteration to the final ASIC will consist of specific steps to explore the trade-offs between sampling depth, analog bandwidth, and sampling speed. As mentioned above, the starting basis is experience with the design and operation of STURM ASIC.

Baseline Readout

A straw-man for the readout uses either USB2 or giga-bit fiber links as the digitized signal collector for the data acquisition, reduction and archiving system. If a single plane is 5mm thick, and a 1 meter thick detector is desired, 200 planes are needed. Each plane will consist of between 8-64 individual pixels, indicating a system channel count on the order of 1.6 – 12.8k channels. This number can readily be accommodated in a single compact PCI readout crate.

Development Plan

We plan for a 5-year development program, with roughly yearly upgrade cycles. Alternately improved readout ASICs and readout systems or new detectors will be installed and then operated extensively, to characterize performance and assess ways in which signal collection efficiency, timing, or other key parameters can be improved. From experience with the development of similar systems cited earlier, 3 ASIC runs and 2 dedicated sensor fabrication cycles are a minimum to deliver a detector system with adequate performance.

Relevance of Proposed Research to Nuclear Materials Detection: The successful implementation of any of the possible technical means for detection of nuclear materials requires both an effective technical solution and the ability to implement that solution on a widespread basis at an affordable cost with acceptable environmental impact. As a long established technique for detection of weakly absorbing materials, the time-gated differential absorption technique would appear to provide an effective means of detection given the availability of high brightness, tunable, multicolor monochromatic sources and time resolved detectors required for this approach.

We believe that the approach we have proposed for the generation and detection of the gamma ray beams needed to detect fissile materials offers a compelling combination of exceptional performance, high reliability and low cost based on its intrinsically efficient use of optical and electron pulse trains and on the simplicity of the systems used to generate those pulse trains. Indeed, if proved successful, it will most likely be the simplicity of these systems that will prove decisive in their application to the detection of concealed nuclear materials.

Broader Impact: There is a 100 year-old thread in physics and technology beginning with Einstein (stimulated emission and special relativity) and continuing with Thomson and Compton (scattering of light by free electrons), Weizsacker and Williams (equivalence of radiation scattered by electrons in real and virtual photon fields), Motz (invention and demonstration of undulator radiation), Phillips (undulator-based microwave amplifiers), Schawlow and Townes (special role of resonators in laser oscillators), Madey (undulator based free electron lasers and microwave electron guns), and the many efforts that have advanced the physics and technology of exponential gain in FELs, the SASE mechanism, and the high brightness, high peak current electron guns needed to drive these new short wavelength light sources in recent years. Enabled by this thread, the world now has the benefit of short wavelength undulator based synchrotron light sources of unprecedented brightness and now also X-ray Free Electron Lasers of extraordinary and unprecedented power.

But these powerful new light sources have also been characterized by unprecedented size and cost: more than $1 billion for the Advanced Photon Source at Argonne, and more than $400 million for the Linac Coherent Light Source at SLAC, measures – more than anything else – of the critical importance of these new light sources to the advance of science and technology in the United States.

And so it is that a portion of this thread has also been dedicated to the development of smaller and less expensive versions of these devices that could bring the benefit of some of their capabilities to bear in fields like homeland security, time-resolved macromolecular crystallography, advanced industrial and medical radiography, and EUV and X-ray industrial microscopy and lithography. It is this direction to which we have dedicated most of our resources in recent years as evidenced by the commercialization of the microwave electron gun and compact infrared FEL technology we have developed, the new approaches to the design and construction of optical resonators for wavelength stabilized and phase-coherent laser systems by Eric Szarmes, the invention of optical storage cavities capable of supporting the generation of high power X-Ray and Gamma ray beams, the development of the fully instrumented test bed for evaluation of these sources at UH, Gary Varner's efforts to develop the fast, time resolved detector and data acquisition systems needed to use these sources, and our present efforts to engage industry in the development of the specialized solid state laser systems and high power optical systems needed for commercialization of these smaller and lower power, but simpler, less expensive, applications-engineered and customer operable systems.

As an example, we believe that the generation of intense, high brightness monochromatic x-ray beams by these means will enable the operation x-ray sources with brightnesses comparable to those available at the Advanced Light Source but with the added capabilities of picosecond timing and time encoded multi-color operation for fast, time resolved chemical and structural determinations. In production quantity, such systems could be marketed for under $2 million, making them highly cost-effective research tools for academic, Government, and industrial research scientists and engineers.

The generation of the sustained, circulating, high peak power optical pulses that we will make possible as part of this effort may also provide the means for new directions in high field quantum electrodynamics and high field atomic and molecular physics, increasing by orders of magnitude the duty cycle over which experiments in these fields can be conducted.

If we are successful in this effort, there will thus not only be the light source and detector technology needed in the short term by the Department of Homeland Security for identification of the fissile nuclear materials hidden in containers, aircraft and ships which now constitutes one of the major potential threats to the United States, but also the greater community of applications and users of this technology at hard and soft X-ray wavelengths needed to maintain the vitality of the field and the further progress needed to track the emergence of future threats, further reduce size and costs, etc.

Critical to this greater effort, as emphasized in the objectives of the solicitation to which we are responding, we will through this program also train a new generation of undergraduate, graduate and postgraduate students in the special technical, management and communications skills they will need to contribute to future developments in this field. Hawai‘i and its students have traditionally been underserved with respect to the kind of opportunities for mentorship, training and advancement inherent in this type of research. If funded, we believe that our research will make a significant contribution both to the record of technically significant innovation here in Hawai‘i and the ability of our students to contribute to further developments of this kind in the State and the nation.

Role and Coordination of the Efforts of Senior Faculty and Staff: The research proposed above constitutes a closely coordinated multidisciplinary effort in the fields of lasers and optics, the generation, acceleration and transport of high peak current and average current, low emittance electron beams, and high quantum efficiency, sub-picosecond detectors and data acquisition systems relying as a whole on the capabilities of our group to design and fabricate the precision mechanical and vacuum systems, diagnostics and controls required for operation of these integrated systems. In our project these technical efforts are led by Eric Szarmes (lasers, optics and opto-mechanics), John Madey (accelerator, ebeam transport and diagnostic systems) and Gary Varner (detectors, data acquisition and data processing). Barry Lienert (senior research scientist) is responsible for the development of software control systems for the Laboratory's major accelerator and laser systems. The 5th year effort to test the operation of the integrated prototype time-gated differential absorption system we propose to develop will be directed by the Principal Investigator (John Madey) with the support of each of these participants as required.

We have worked for many years to develop the management principles and techniques needed to support efforts of this kind. Of utmost importance to such effort is joint planning and the development of a tracking system (usually referred to as a work breakdown structure) that can capture both the general features and details of the work to be done, identify the specific responsibilities of each participant, serve as the basis for allocation of the resources needed for execution, and track progress towards completion in terms of both time and expenditures. Developed through the collaborative efforts of all the participants at the outset of the project, administration of the plan becomes the responsibility of the Principal Investigator acting in support of his colleagues efforts as defined in this plan following initiation of the project.

Timelines: The timelines for each of the major efforts to be undertaken as part of the proposed research are summarized in Figure 11. These timelines, and the resources needed for their support, have been drafted to provide: (1) the time required for component and subsystem design, procurement and/or fabrication, (2) the time required for evaluation and revision of these subsystems, (3) the time required for system integration and commissioning, and (4) the time required for exploration of the capabilities of the integrated prototype time gated differential absorption detection system.

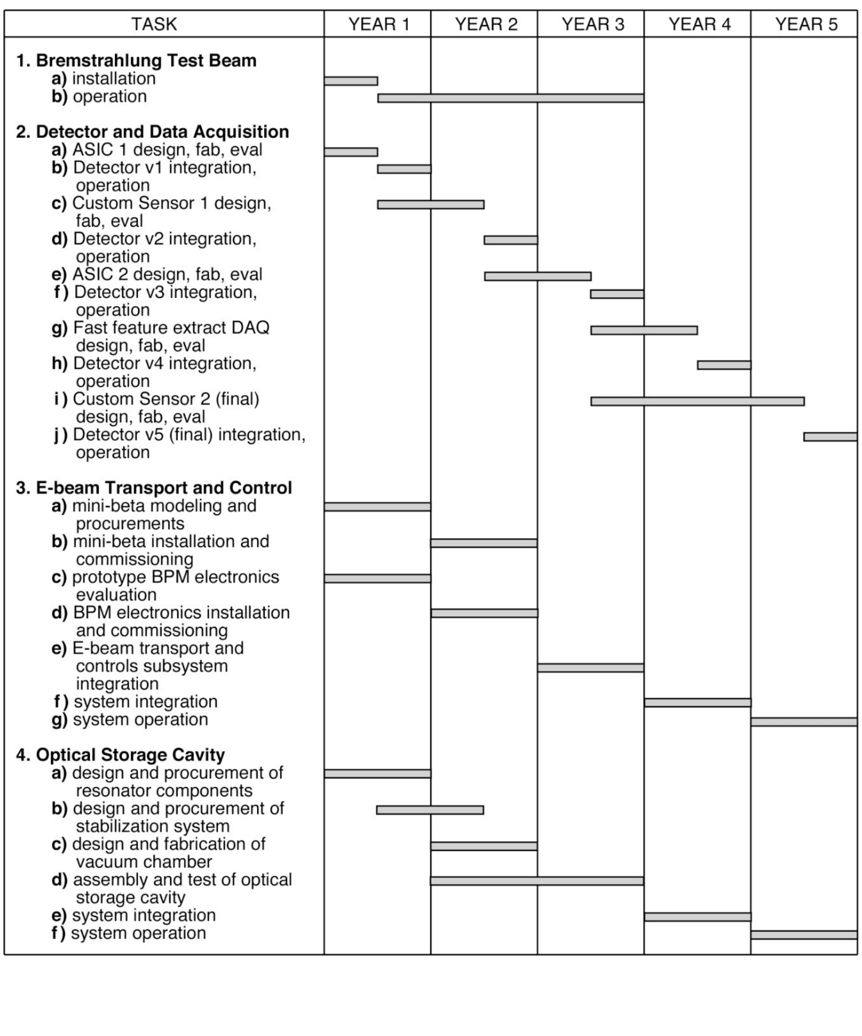


Figure 11. Project Timeline

Modes of Dissemination and Education:

The educational objectives of the research that we perform in these areas are met through a combination of classroom and laboratory instruction of our undergraduate and graduate students, through the faculty's supervision of the independent research carried out by our graduate students and of the technical support that they provide to other members of the group in their role as research assistants, through faculty supervision of the efforts of the postdoctoral students that report to them, through the special summer training experiences we offer to undergraduates and qualified high school students, and through the department and public lectures presented by the participating faculty.

Our guiding principle in each of these efforts is to provide those with whom we are communicating (be they students, academic colleagues, or people we address through written publications and public lectures) with both the fundamental insights needed to understand the physical basis of the phenomena being addressed and also as clear an understanding as possible of the technical, engineering and hands-on aspects of the efforts needed to explore or exploit these phenomena.

It is for this reason that the graduates of the programs of instruction we have offered to our undergraduate, graduate and postgraduate students have consistently moved on to senior research and management positions of responsibility in the universities, national laboratories, and companies in which they have found employment following their tenure with us.

The technical results of the proposed research will be published in the relevant technical journals and reported – as travel funds permit – in the relevant technical conferences.

Management Plan:

We have over the years found it most effective in multidisciplinary collaborations such as this one to work within the framework of a Work Breakdown Structure (WBS) in which the elements of the WBS are defined at the outset of the project to the satisfaction of all participants, with the Principal Investigator and his staff responsible for administration of the plan for the benefit of his colleagues following initiation of the project.

Included in this plan are (1) the identification of the individuals responsible for each task element, (2) the resources (personnel and budget) to be made available for each task element, and (3) the timelines estimated for completion of these task elements.

Services provided by the PI and his staff in this mode of operation include (1) weekly reviews of general project status and issues relative to the resources needed to pursue the proposed research, (2) a system for review of procurements to insure that all requisitions have been authorized by the individual responsible for the task to which the procurement will be charged, (3) a bar-code tracking system to identify and assign all incoming materials to the to the task to which the procurement was charged, (4) a standardized reporting format to document the function, design and operation of all special test equipment constructed in the course of the research, and (5) a centralized filing system for these reports and all other documentation and manuals for equipment purchased in the course of the project.

These services are over and above the more general administrative services provided by the University, College of Natural Sciences, and Department of Physics to the project, its faculty, students and staff.

Independent of these administrative support functions, the faculty members responsible for research in efforts such as these are encouraged to organize regular monthly scientifically-oriented meetings to address the work in progress for which they are responsible to provide the forums needed to establish effective scientific communications between all the participating groups.

The organization and preparation of general program reviews and final reports is the responsibility of the Principal Investigator with the support of the participating faculty.