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Title: On The Export Control Of High Speed Imaging For Nuclear Weapons Applications

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On The Export Control of High-Speed Imaging for Nuclear Weapons Applications

By

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Abstract

Since the Manhattan Project, the use of high-speed photography, and its cousins flash radiography[1] and schieleren photography have been a technological proliferation concern. Indeed, like the supercomputer, the development of high-speed photography as we now know it essentially grew out of the nuclear weapons program at Los Alamos[2,3,4]. Naturally, during the course of the last 75 years the technology associated with computers and cameras has been export controlled by the United States and others to prevent both proliferation among non-P5-nations and technological parity among potential adversaries among P5 nations. Here we revisit these issues as they relate to high-speed photographic technologies and make recommendations about how future restrictions, if any, should be guided.

Introduction

High-speed photography must be understood in the context of what optical engineers call, entendu[5]. In layman's terms, entendu, is the idea that the light which creates a photograph, or photographs, is a finite resource. As such it must be conserved to the greatest extent possible to create high-quality images. This conservation criterion creates immediate and real technical dilemmas whenever either faint light sources are used and/or when many photographs are taken in rapid succession with those light sources. The reason bright lights are commonly associated with Hollywood movies is that they are required!

Let us consider the specific nature of photography. Imagine we venture out on a bright, sunny day and photograph a mountain scene with a hand-held camera. While the aesthetic difficulty of this task may present challenges, the corresponding technical difficulty is quite low. There is plenty of light; we are taking a single, still photograph; and the subject isn't moving.

However, if we change just one of these elements, for example by taking the same photograph on a moonlit night, the difficulty is much higher requiring us to use longer exposures and perhaps even a tripod to hold the camera. Now imagine trying to photograph a running deer at night in front of the mountain scene. The photographic challenge becomes even greater. Next, imagine taking an ordinary movie of the running deer at night in front of the mountain scene. At this point, the difficulty is well beyond the ability of even good photographers with modern equipment to capture.

Notice that in our example we have yet to even delve into the high-speed photographic aspects. It may be that the deer is moving very quickly and that the 30-frame-per-second (FPS) frame rate of conventional video just isn't rapid enough to adequately capture the deer's rapid motion. Perhaps we need higher frame rates to do an adequately job. In this situation, it is reasonable to require one-hundred FPS or more.

Now consider the ramifications of splitting up the finite moonlight into smaller and smaller sub-units (frames). If we take a single, still, photograph, with a 1-second exposure, we can use all the light available during that second to take just one photograph. However, if we are required to take one-hundred frames per second, each frame is allowed only 1% of the light available to the still photographer – a much more difficult task. Now imagine we are presented with the task of taking not one-hundred FPS, or even one-thousand FPS, but one-million or even ten-million FPS. Those latter cases are in the realm of what is considered to be, "high-speed" photography. Perhaps from our example, it is easy to see why Ansel Adams was a still photographer, and not a high-speed photographer!

History and Representative Technologies

Ernst Mach, will forever be remembered for the experimental evaluation of the mystical sound barrier and the study of shock waves. Mach's motto, "Sehen heiβt verstehen", (seeing is understanding) is as true today as it was in the 19th century. Mach's development and use of schlieren photography ultimate lead to the military application in Germany's V-2 rocket program during World War II.

Schliere result from the disturbance of an otherwise homogeneous media. One common example is the turbulent candle plume. The plume, being hotter and less dense than the surrounding air, acts like a weak, negative lens[6], thereby making the turbulence surrounding the flame visible to the naked eye. Early schlieren photography, like that shown in Figure 1, recorded high-speed phenomena using single-frame, flash techniques. Prior to the invention of true, high-speed photography, a series of otherwise identical experiments were conducted to piece movies together, frame-by-frame.

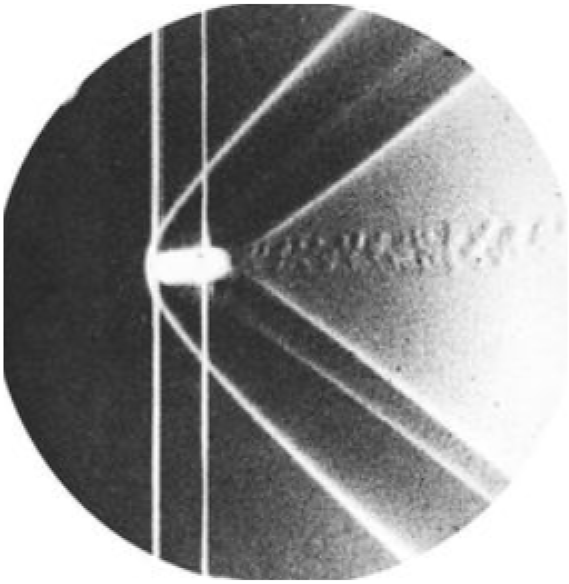


Figure 1 – Mach's schlieren photograph of an oblique shock wave around a supersonic bullet

The first modern use of high-speed photography was for the so-called photo-finish in horse racing as a spin-off of Muybridge's study of galloping horses and whether or not their hooves all left the ground. The Muybridge technique[7], which is still common today, used multiple cameras to capture the same scene at different times. He then pieced these individual frames together to make a short movie loop. By using this technique he was not limited by the available light or the film sensitivity, but rather by the number of cameras he could deploy on a given scene.

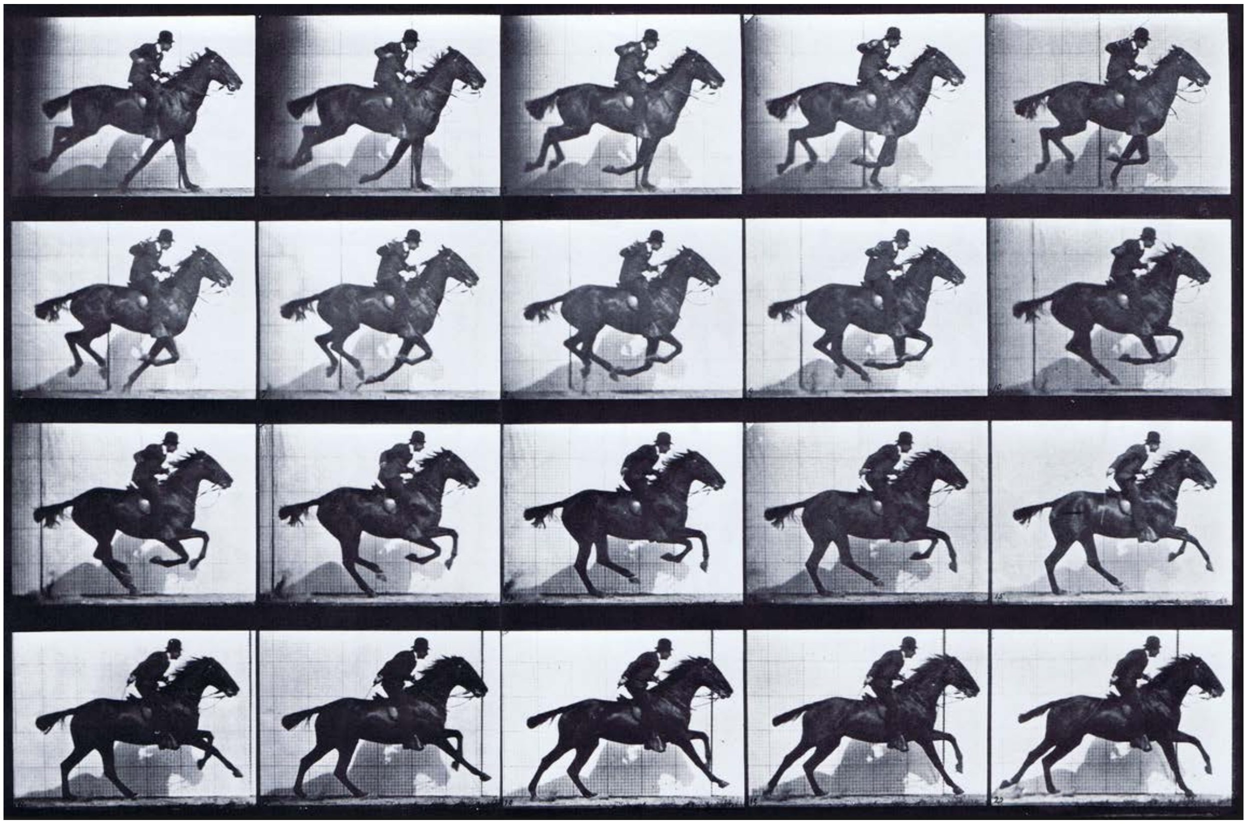


Figure 2 – Muybridge technique as applied to horse racing

The next generation of cameras developed by Eastman Kodak in the 1930s, utilized high-speed film reels. These cameras could take up to one-thousand frames per second by moving film across an image plane at high speed - around 100ft of film per second. Ultimately, both the Kodak technique, and that developed by Muybridge had physical limitations. The former by how fast film could be moved without breaking it, and the latter by how many cameras could be cost effectively employed at one time.

The Manhattan Project ushered in a completely new era in high-speed photography. Fortunately, perhaps, both conventional and nuclear explosives produce prodigious amounts of light which can be split thousands, or even millions of times and still remain bright enough to make a recording onto film. When Berlyn Brixner, the lead photographer on the Trinity atomic bomb test, asked the theorists how much light might be expected from the test, he was told to expect ten times that of a the noon-day sun[8] - a slight underestimate.

Photographs of that famous event underscored the beginning of two eras – the atomic age, and the age of high-speed photography. A typical movie loop of that first atomic test is shown in Figure 3.

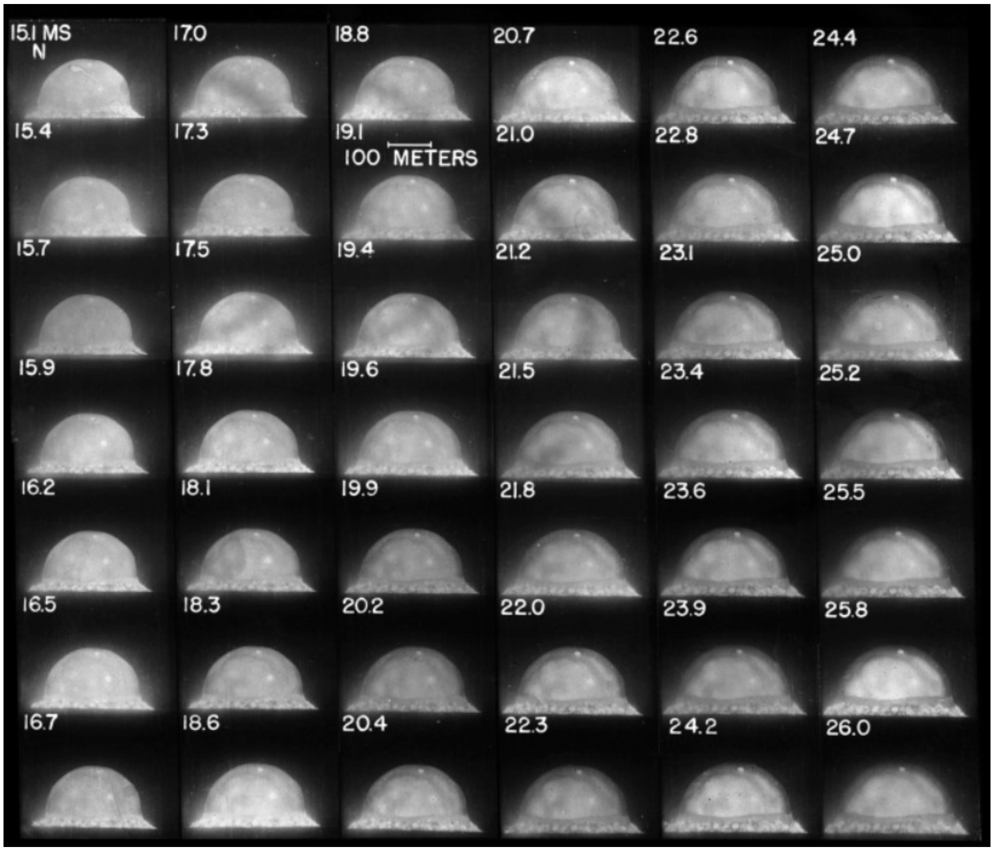


Figure 3 – High-speed photographs of the Trinity test. Timing numbers are milliseconds indicating a frame rate of about five-thousand FPS.

Brixner also developed the world's first functional, rotating-mirror framing camera[9][10]. Rather than moving the film at high speed as Kodak had done, this camera works by moving the image at high speed via a small, rotating, beryllium mirror. Provided enough light, such a camera can operate reliably at millions of frames per second[11]. A modern example of this type of camera is the Cordin 512 shown in Figure 4.

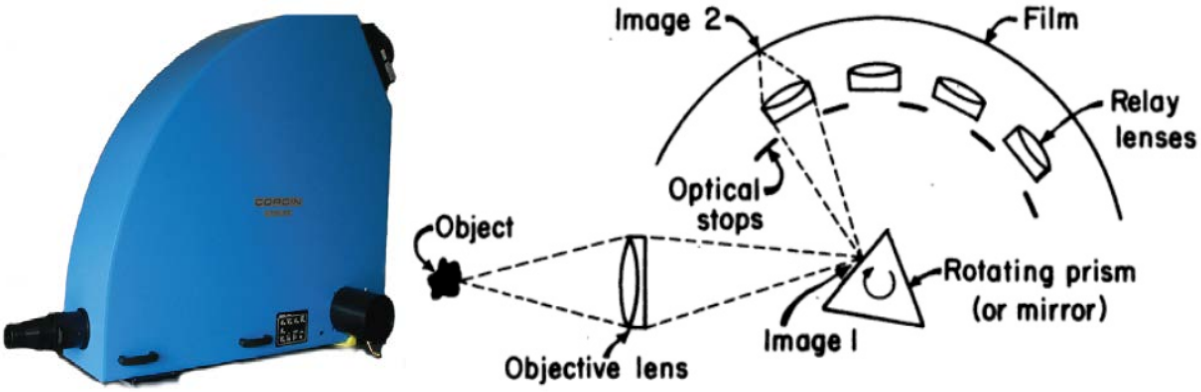


Figure 4 – Cordin 512, rotating mirror framing camera

In the post-WWII era, it was recognized that image tubes (aka televisions) could be used to rapidly move electronic images around and the electronic framing camera was born. In 1950, Morton Sultanoff, an engineer working for Aberdeen proving ground recorded an explosive shock wave using a million-frame-per-second, electronic-framing camera[12].

The scarce light often associated with high-speed imaging combined with the frequent need to shutter that light, led to the development of the micro-channel-plate image intensifier, or MCP. A micro-channel plate is essentially a collection of tiny photo-multipliers created by using small, straw-like holes with a high voltage across them end-to-end. As electrons are generated at one end of the straws on a photocathode they are accelerated and multiplied as they traverse the straws before impinging on the phosphor on the other end where they form an image. This process serves to both amplify and shutter the light as it can be controlled by the high-voltage pulse. MCP's are extremely useful for high-speed photography because they can be used in parallel combinations like the Muybridge camera by simply providing a series of short, shuttered images.

Obviously this approach is very expensive, but the overall utility is high. One example of this technology, as applied at Los Alamos' PHERMEX flash radiographic facility, is shown below in Figure 5.[13]

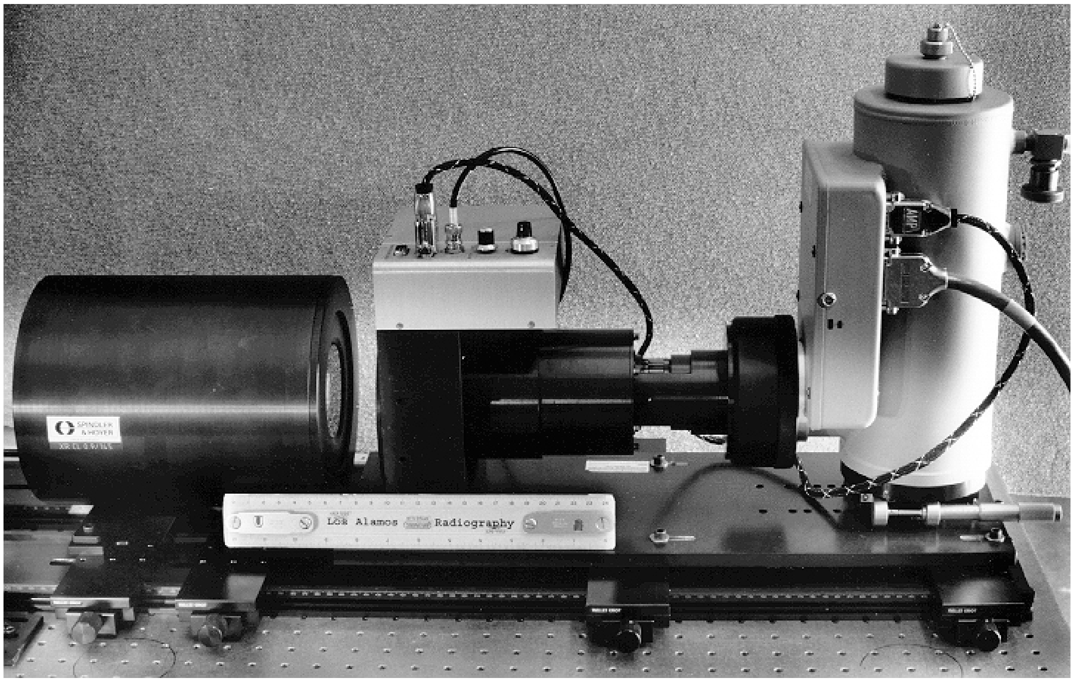


Figure 5 – PHERMEX camera showing large lens (left), MCP (middle), and LN-cooled CCD camera (right)

As CCDs became more dominant in the world of digital imaging, they had an immediate impact on high-speed photography. One notable example was the Silicon Mountain Devices' (SMD), million-frame-per second CCD. This device used specialized mask layer on a French, Thomson-CSF CCD to enable high speed photography. The SMD device utilized an on-chip mask to “hide” a series of 16 frames in an analog memory prior to readout using rapid series transfers. An experimental example of this device imaging an explosive, “rate stick” is shown in Figure 6.

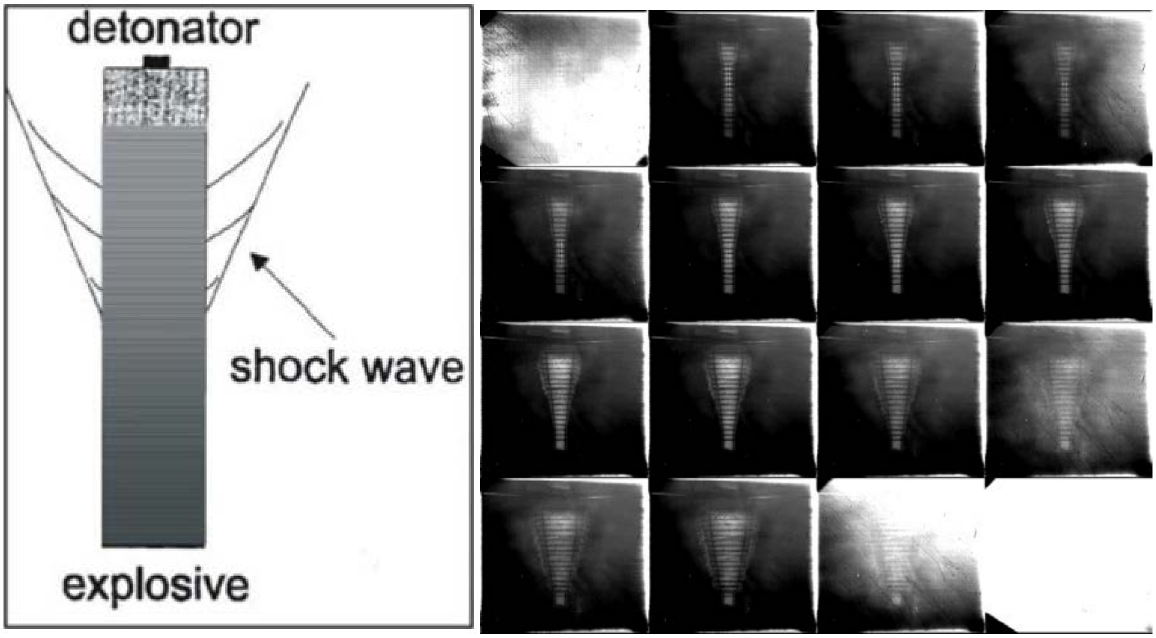


Figure 6 – SMD million-frame-per-second explosive “rate-stick” experiment[14].

Driven by consumer electronics, CMOS imagers are also playing an increasingly important role in high-speed imaging. The Los Alamos, “Camera On A Chip”, shown in Figure 7, won a 2007, R&D 100 award for the novel combination of CMOS imager and back-plane memory which allowed for the rapid transfer of data necessary for high-speed proton radiography[15].

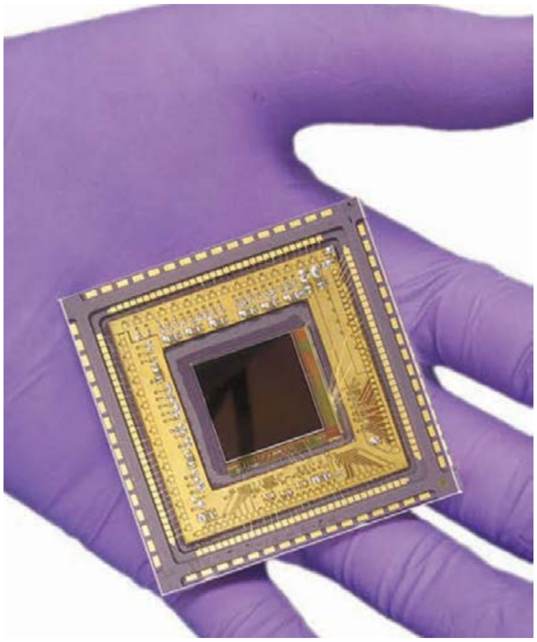


Figure 7 – Camera on a chip[16]

Another novel CCD, based upon the Hubble Space Telescope architecture, was developed jointly by MIT-Lincoln Laboratory and Los Alamos for use with high-speed flash radiography at DARHT[17,18,19]. This large-format device is approximately one hundred times more sensitive than the CMOS, Camera On Chip design, making it suitable for the very-low-light conditions of modern x-ray flash-radiography. This camera is illustrated in Figure 8.

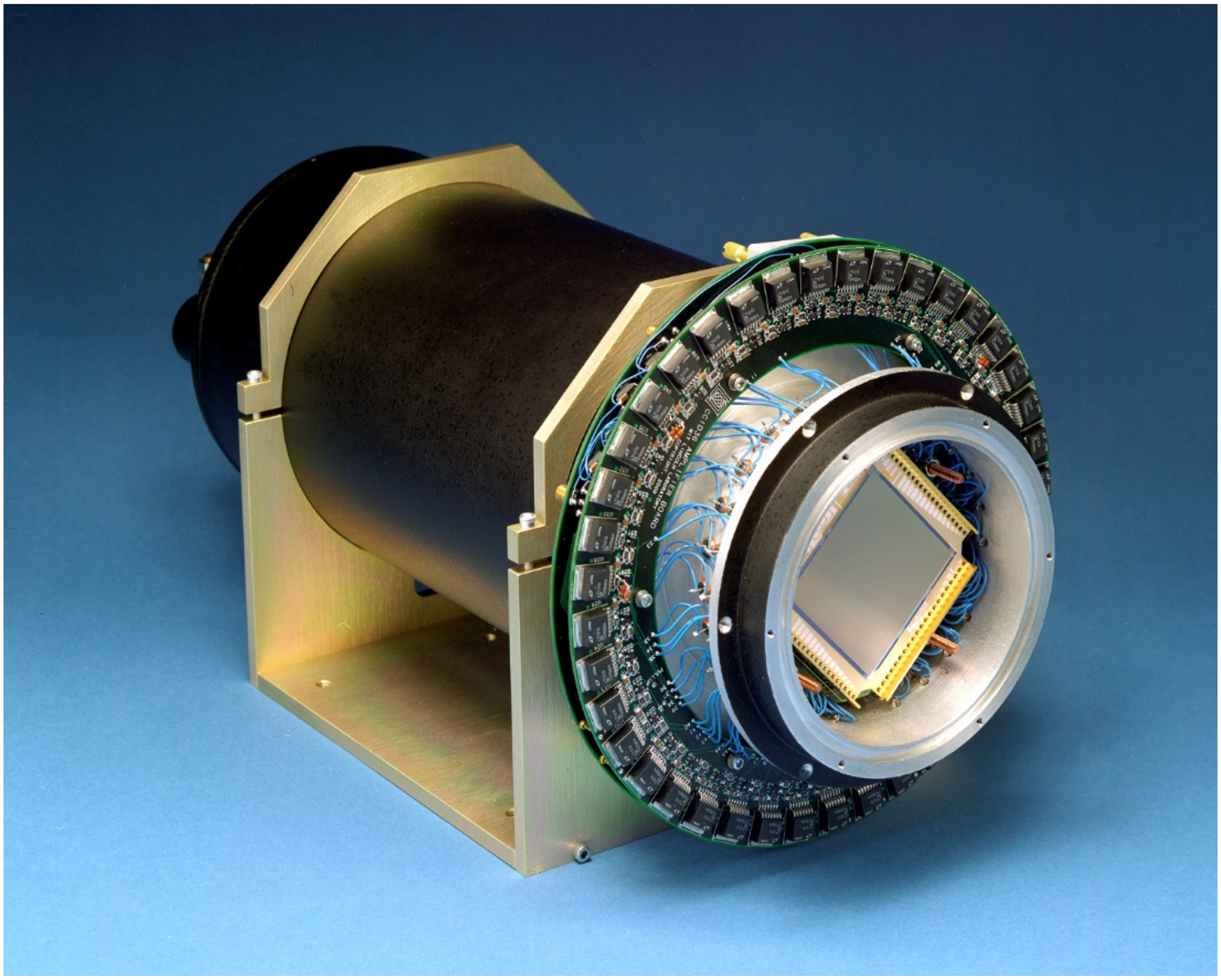
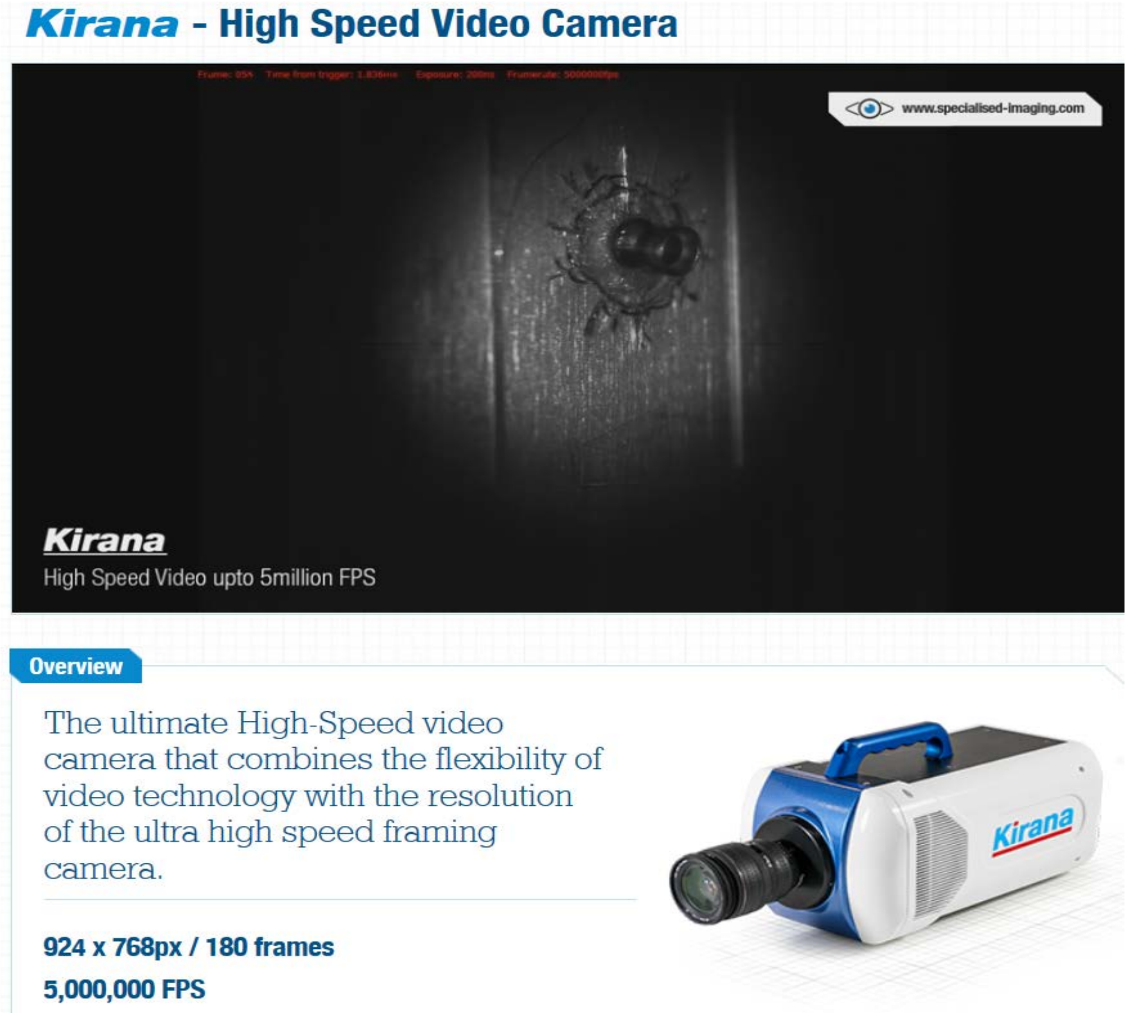


Figure 8 – DARHT Camera with MIT-LL high-speed CCD[20]

Commercial high-speed cameras are now manufactured by Specialized Imaging[21], Vision Research[22], Princeton Instruments[23], MACS in Australia[24], IX Cameras[25] in the UK, and Hadland[26]. These cameras have largely replaced the film-based, rotating-mirror-framing cameras, owing to their simplicity and compact size. One representative example is the Kirana high-speed video camera shown in Figure 9 which is capable of capturing 180frames at five-million FPS.



Kirana - High Speed Video Camera

Kirana

High Speed Video upto 5million FPS

Overview

The ultimate High-Speed video camera that combines the flexibility of video technology with the resolution of the ultra high speed framing camera.

924 x 768px / 180 frames

5,000,000 FPS

Figure 9 – Commercially available, Specialized Imaging, Kirana high-speed video camera

The modern “supercomputer” of high-speed cameras consists of an array of digital oscilloscopes on each and every pixel. This patented architecture[27] allows very large area detectors to operate at very high speeds with essentially unlimited memory depth. As such, it maximizes the entendu’ and, cost aside, creates an ideal imager. This type of camera is produced with dense electronics typical of a modern cell-phones, and pixels that operate in parallel fashion much in the same way a modern supercomputer does. The 2010 R&D 100 award-winning[28], MOXIE (Movies Of eXtreme Imaging Experiments) camera module, jointly developed by Varian, NSTec and Los Alamos, is shown in Figures 10 and 11.

MOXIE can image twenty million FPS and take thousands of frames at this sustained rate, limited only by available memory. It can be configured to asynchronously image any type of visible light, any type of ionizing radiation, and have single-photon sensitivity. Because of the modular construction, it can also be configured in a wide variety of formats and sizes. It is widely regarded as the fastest, most sensitive high-speed (true movie) camera in the world.

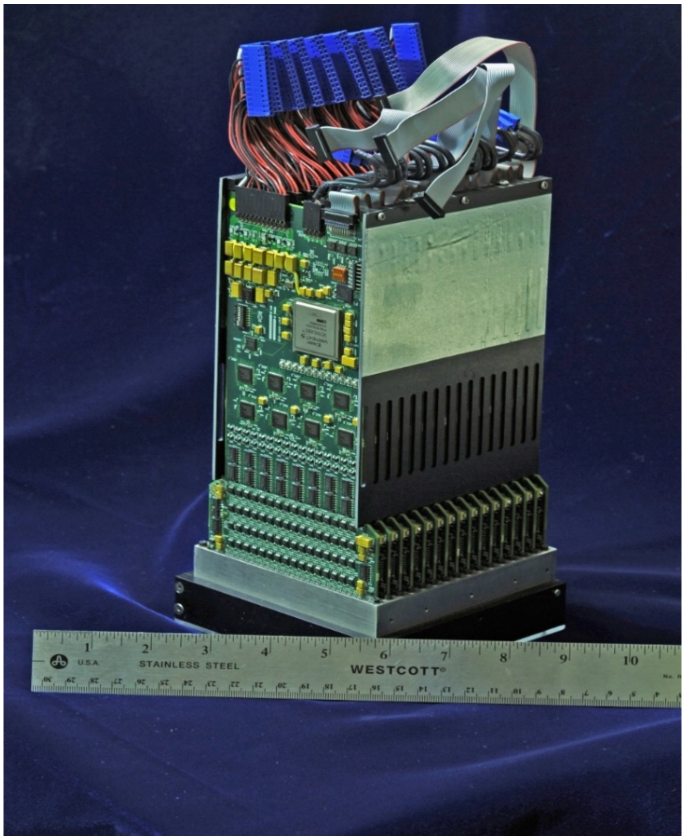


Figure 10 – The MOXIE high-speed camera module

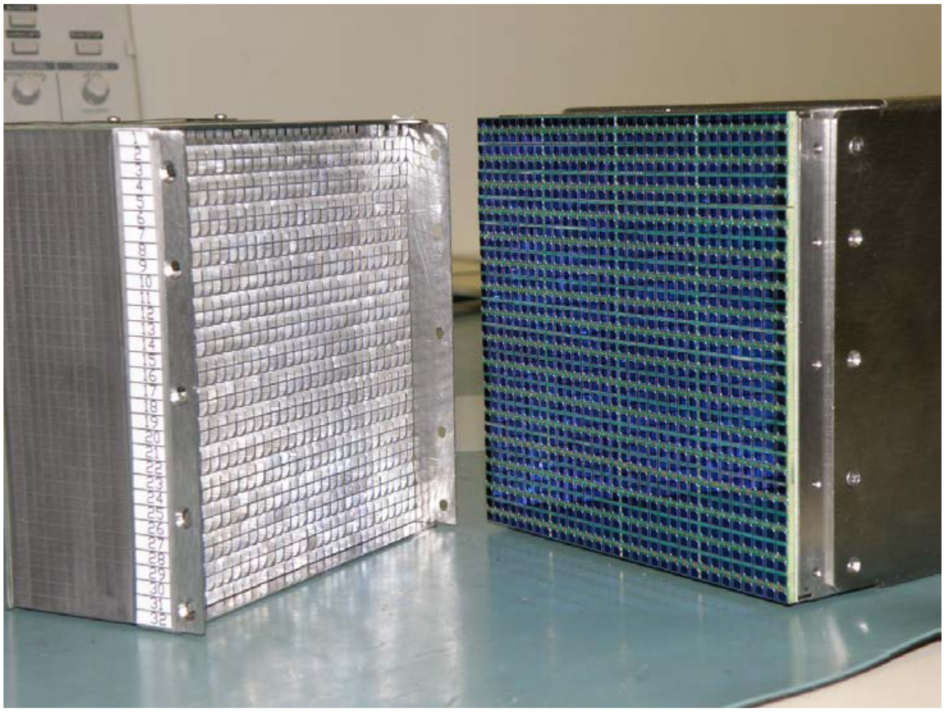


Figure 11 – MOXIE scintillator array (left) and focal plane array (right).

Recent advances in Silicon PhotoMultiplier (SiPM) technology[29] using avalanche photodiodes make MOXIE-like systems possible without the need for an analog gain stage. The particle physics and medical imaging communities are driving the wide commercial availability of these devices, not generally classified as “imagers”. Nonetheless, the technological consequence of SiPM technology, driven by huge market forces, means that future high-speed cameras[30] will be smaller, cheaper, faster, and have higher pixel counts and deeper memory than the MOXIE camera shown in Figure 10.

A representative example of a 2-D, SiPM array from SensL[31] is shown in Figure 12. Other suppliers include Ketek[32] (Germany) and Hamamatsu (Japan). One key feature of these devices is their 4-edge-buttable format[33] which makes the format and size of these arrays completely arbitrary limited only by cost - currently about $100 per pixel.

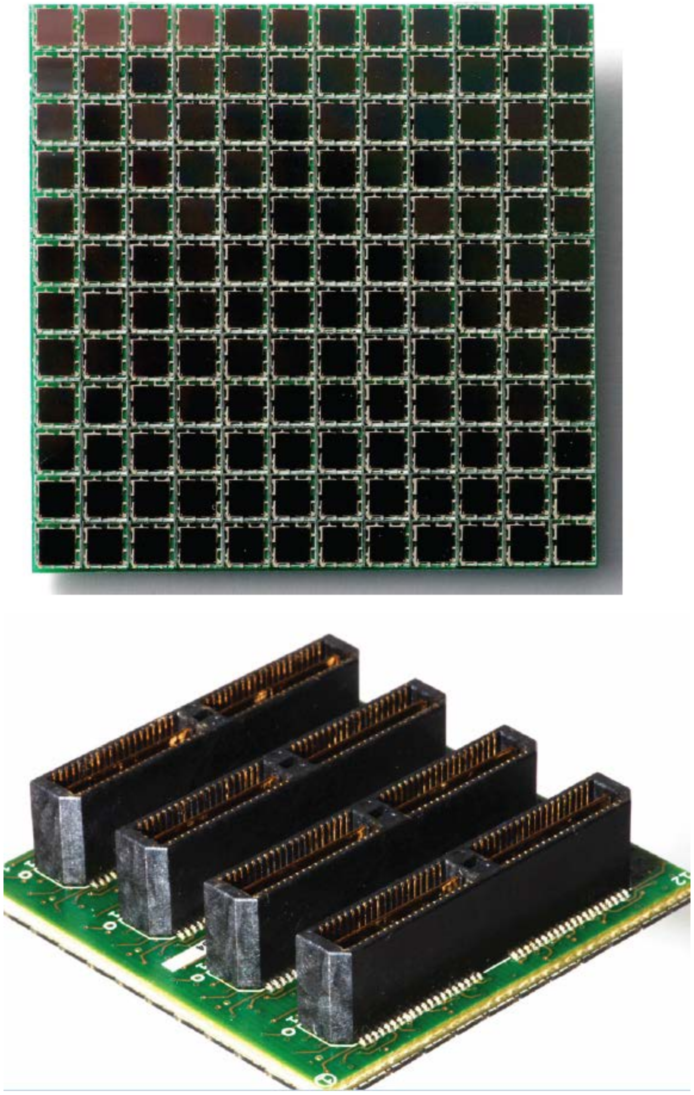


Figure 12 – SensL, 4-edge-buttable, silicon photomultiplier array.

Finally, the penultimate example of high speed photography has recently been developed. The use of single-photon counting electronics, so-called, Time-Correlated Single Photon Counting (TCSPC) electronics[34] enables the time-tagging of every-single-photon in a high-speed imager. These imagers are finding increasing use in the field of Fluorescence Lifetime Imaging (FLIM).

Other Components

Several related components are worth mentioning here. The first of these, a so-called, "streak" or "smear" camera is common in nuclear weapon development activities[35] and were also invented during the Manhattan Project to study explosive experiments. Where a conventional camera records an image with two, spatial dimensions, a streak camera has one spatial dimension and one time dimension. Streak cameras can be made using rotating mirrors (as with a conventional rotating mirror camera), or swept electronically using a "streak tube". Over the years, these have been manufactured by EG&G, Thomson CSF, Hadland, and Hamamatsu. They can be configured to have extremely fast time response on the order of a few picoseconds, or as a conventional framing-camera using the same tube. One representative example, the Hamamatsu C1587, is shown in Figure 13.

Figure 13 – Hamamatsu C1587 streak camera

A group at MIT recently demonstrated a "trillion frame per second" camera by combining thousands of laser light experiments from a streak tube into a single movie[36]. These experiments were noteworthy because, taken as an aggregate, they were the first time the motion of light itself was "filmed" in a high speed movie. Once again, Los Alamos invented this technique in 1991[37,38] to record the motion of electron beams (rather than visible light) in radiographic accelerators. Frames from these movies are shown in Figure 14.

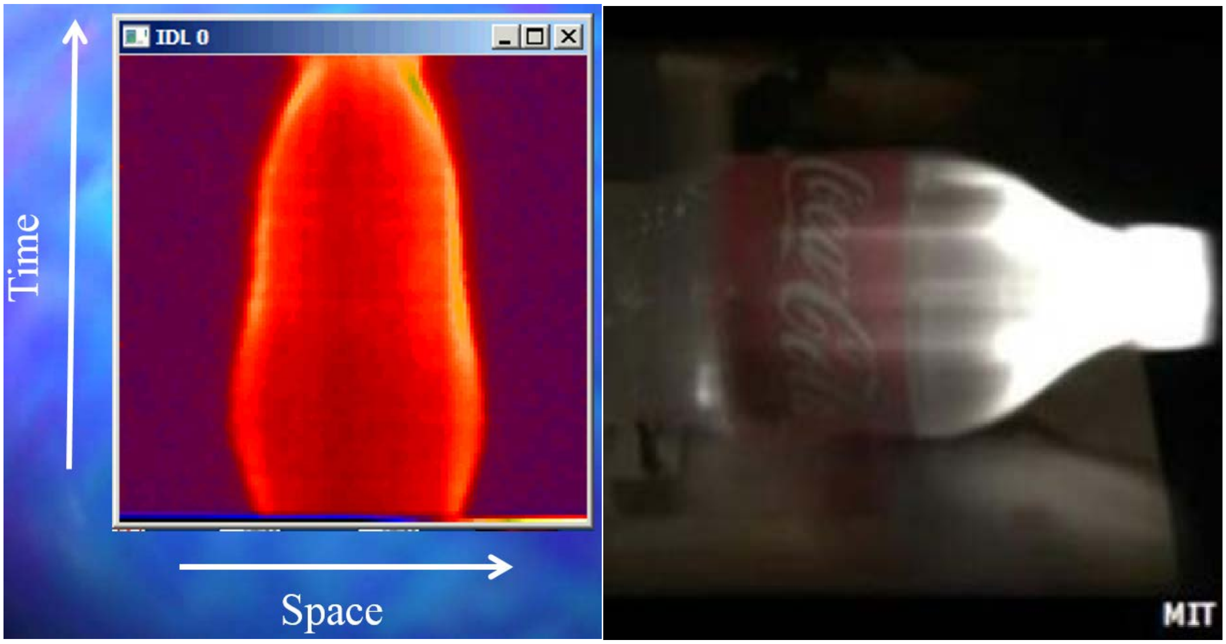


Figure 14 – Streak camera movie frame of an electron beam (left), and light scattered from a laser-pulse in a Coke bottle (right).

Another component worth discussion is the high-speed (optical "speed") lenses often associated with high-speed (physical "speed") photography. Because light is such a precious resource, exotic lenses are often used[39]. One representative example is the 145mm, f0.9 lens employed at PHERMEX shown below in Figure 15.

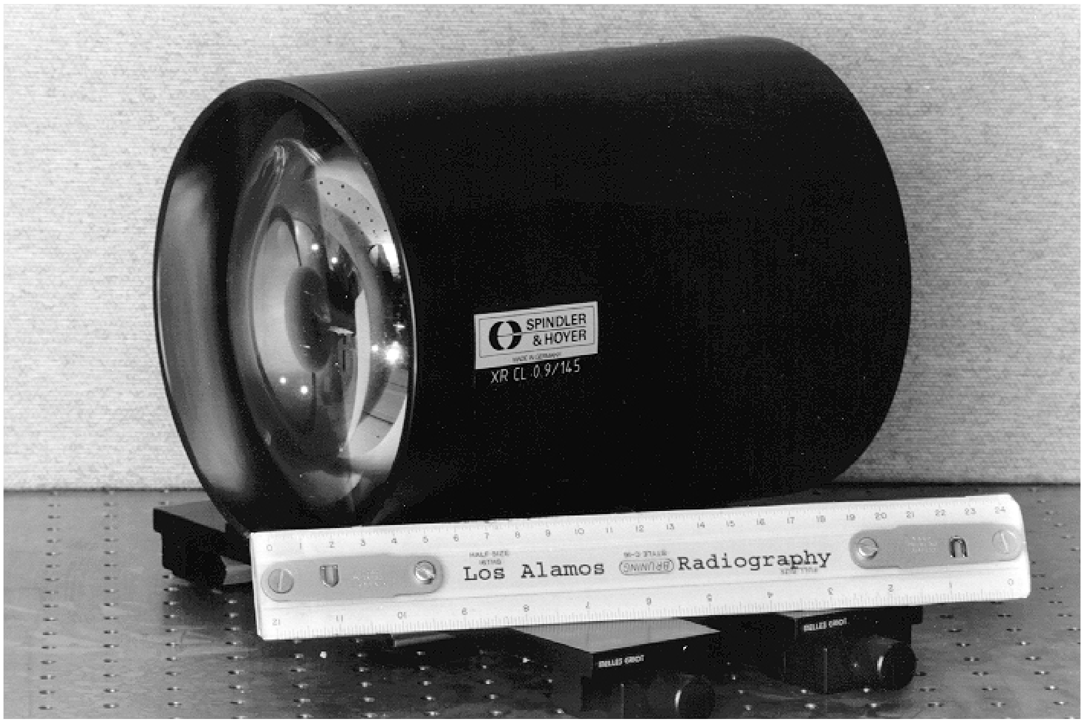


Figure 15 – F0.9, 145mm PHERMEX lens.

The final noteworthy technology associated with high-speed photography is the light source. While above ground nuclear tests provide ample light, conventional explosive tests, often used for related work, may not. One way to overcome this deficiency is with the use of artificial, flashed, light sources. Historically, so-called "argon candles" were used to create very bright flashes that physically overwhelmed the light associated with the explosive shots allowing the experimentalist to backlight the subject of interest[40] (as in Figure 16). The duration of the flash is proportional to the length of the fill tube and can be prompt for single-frame photography, or extended for motion picture-type photography. This type of light source is extraordinarily simple to make and available to anyone with access to explosives.

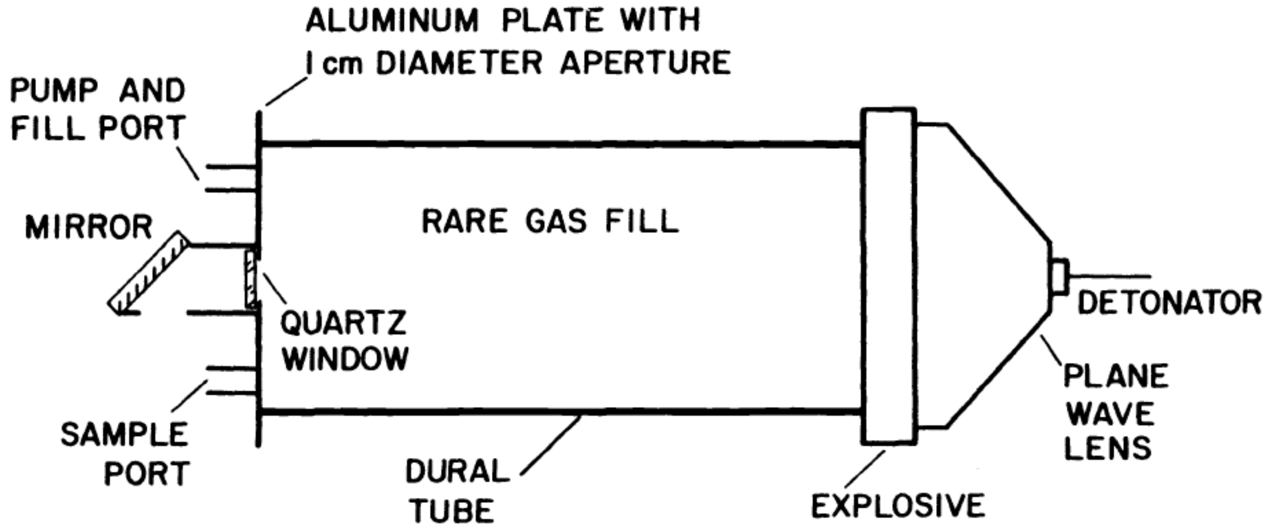


Figure 16 – Simple “argon candle” flash light source[41]

For those customers with environments that are not suited to explosive flash bulbs, commercial pulsed-power flash sources include those made by Prismscience[42], and Alien Bees[43].

Recently LED lighting has become more popular for high-speed applications and several companies manufacture those systems including NILA[44]. One commercially available LED lighting system is shown below in Figure 17.

Figure 17 – Commercial LED lighting system suitable for high-speed photography.

Example Data

We illustrate some classic types of data taken with high-speed photography below. Figure 18 shows a Viper, shape charge jet formation. These explosively driven jets are designed with hydrodynamic codes[45] and can be used as anti-armor, anti-tank weapons[46] as well as for well-perforators[47]. Example hydrocode calculations are illustrated in Figure 19.

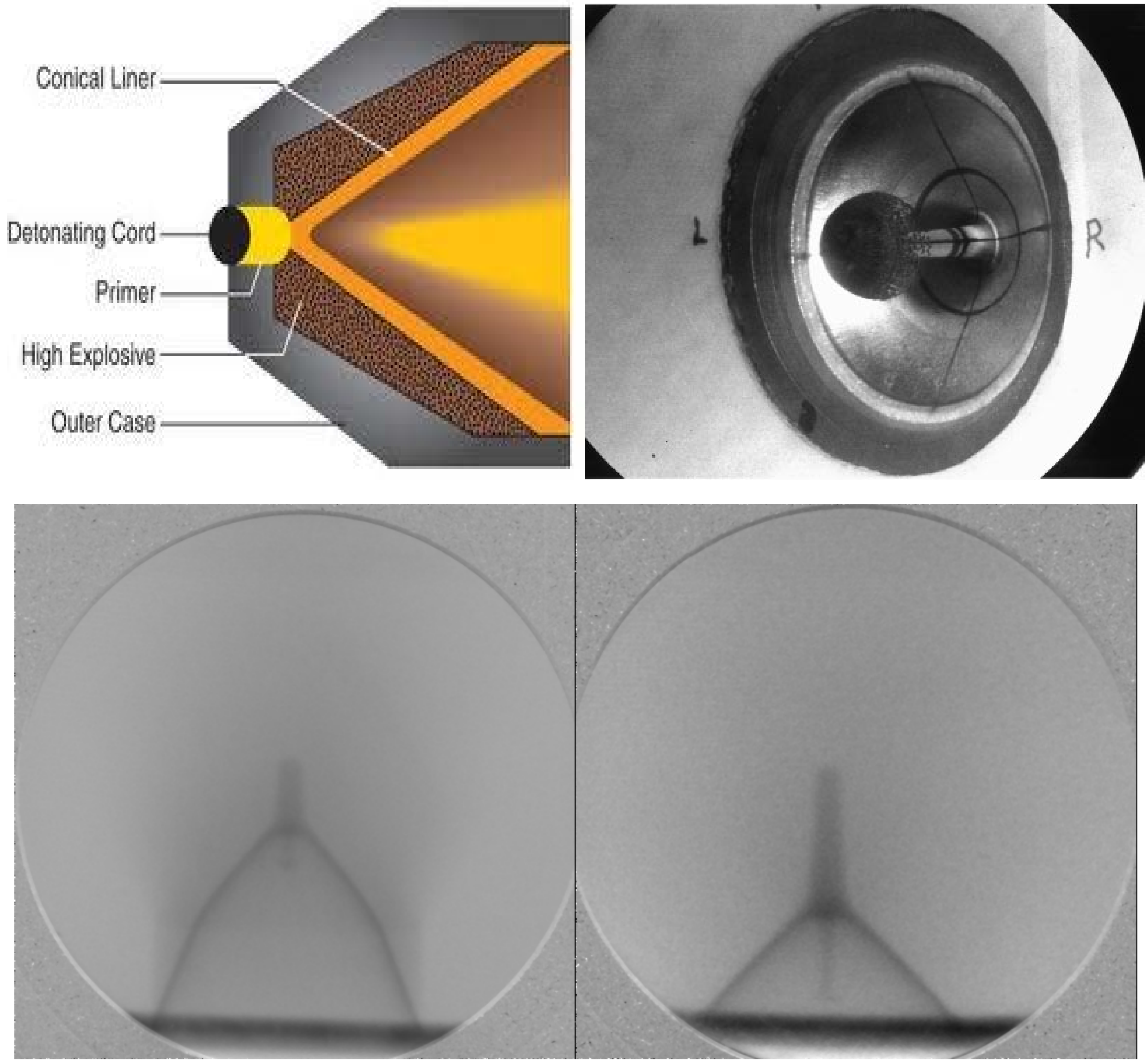


Figure 18 – Viper shaped charge (upper left), visible light photograph showing jet formation (upper right curtesy of LLNL), and time-sequenced PHERMEX radiographs[48] (lower left, right)

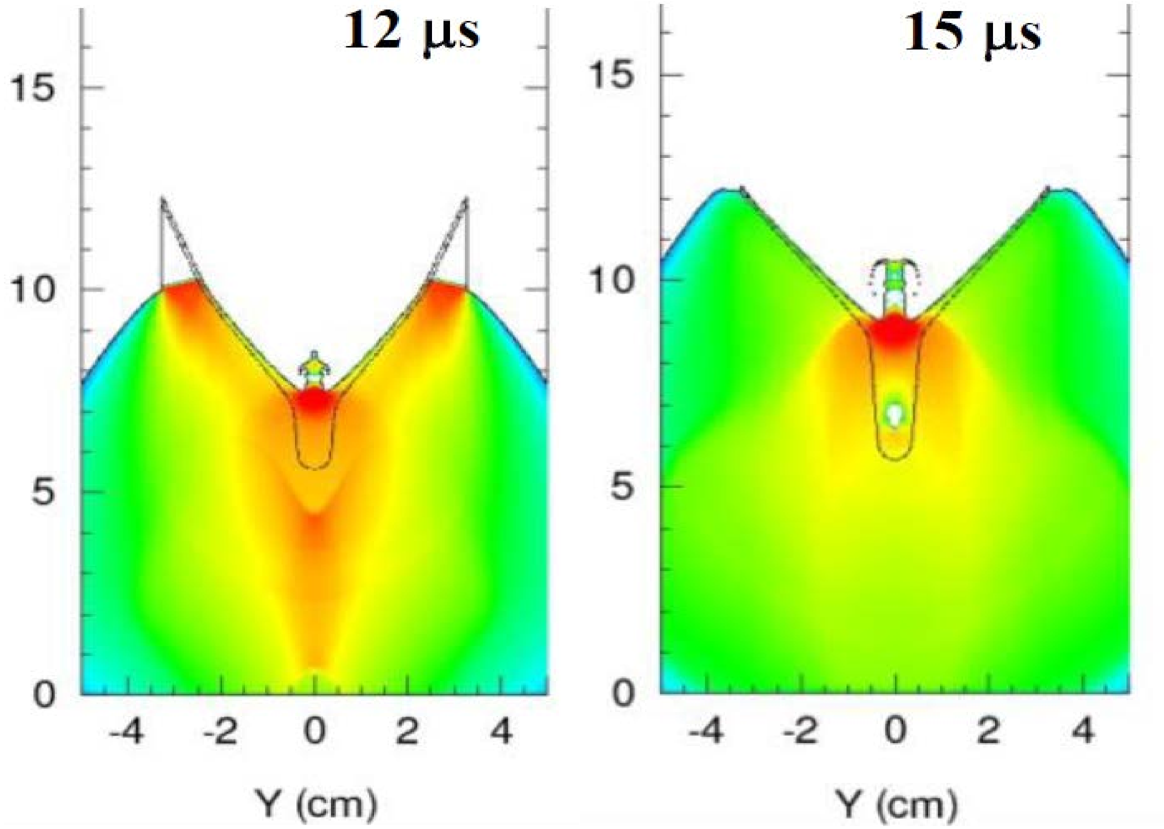
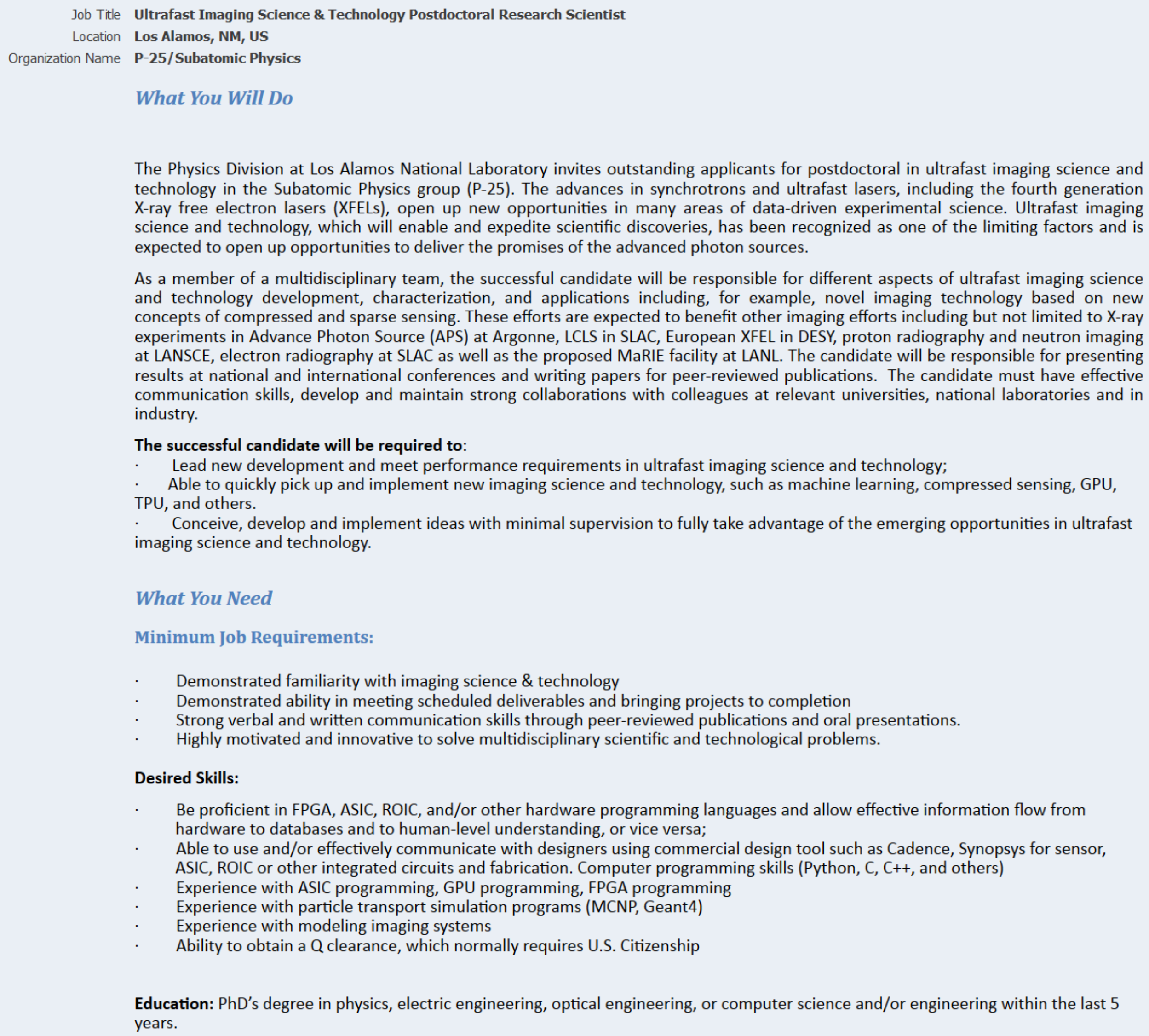


Figure 19 – Sample hydrocode calculation of Viper shaped charge jet formation

Dual-Use Applications

While high-speed photography has followed exponential growth typical of other high-technology applications like computers, the use remains somewhat more limited. Still, the number of applications has grown steadily over the years and now includes: combustion research, Hollywood productions[49], automotive and aircraft crash testing[50], mining[51], shock physics, beam dynamics[52], accelerators[53], cellular microscopy, ballistics, aerospace, micrometeorite hypervelocity-impact, detonics[54], electrical discharge[55], optics[56], and fracture mechanics[57] to name a few. Undoubtedly, as the use of digital cameras continues to replace film cameras, this progression will continue. The question then becomes, at what point do the limitations placed upon the use of such technology by export controls become counterproductive?

The job advertisement, illustrated in Figure 20, was recently placed in the Subatomic Physics Group at Los Alamos, is representative of this fast-growing need for high-speed imaging expertise. It is worth noting that none of this work is directly related to nuclear weapons. Indeed, much of the effort involves international collaboration.



Job Title	**Ultrafast Imaging Science & Technology Postdoctoral Research Scientist**
Location	**Los Alamos, NM, US**
Organization Name	**P-25/Subatomic Physics**

What You Will Do

The Physics Division at Los Alamos National Laboratory invites outstanding applicants for postdoctoral in ultrafast imaging science and technology in the Subatomic Physics group (P-25). The advances in synchrotrons and ultrafast lasers, including the fourth generation X-ray free electron lasers (XFELs), open up new opportunities in many areas of data-driven experimental science. Ultrafast imaging science and technology, which will enable and expedite scientific discoveries, has been recognized as one of the limiting factors and is expected to open up opportunities to deliver the promises of the advanced photon sources.

As a member of a multidisciplinary team, the successful candidate will be responsible for different aspects of ultrafast imaging science and technology development, characterization, and applications including, for example, novel imaging technology based on new concepts of compressed and sparse sensing. These efforts are expected to benefit other imaging efforts including but not limited to X-ray experiments in Advance Photon Source (APS) at Argonne, LCLS in SLAC, European XFEL in DESY, proton radiography and neutron imaging at LANSCE, electron radiography at SLAC as well as the proposed MaRIE facility at LANL. The candidate will be responsible for presenting results at national and international conferences and writing papers for peer-reviewed publications. The candidate must have effective communication skills, develop and maintain strong collaborations with colleagues at relevant universities, national laboratories and in industry.

The successful candidate will be required to:

- Lead new development and meet performance requirements in ultrafast imaging science and technology;
- Able to quickly pick up and implement new imaging science and technology, such as machine learning, compressed sensing, GPU, TPU, and others.
- Conceive, develop and implement ideas with minimal supervision to fully take advantage of the emerging opportunities in ultrafast imaging science and technology.

What You Need

Minimum Job Requirements:

- Demonstrated familiarity with imaging science & technology
- Demonstrated ability in meeting scheduled deliverables and bringing projects to completion
- Strong verbal and written communication skills through peer-reviewed publications and oral presentations.
- Highly motivated and innovative to solve multidisciplinary scientific and technological problems.

Desired Skills:

- Be proficient in FPGA, ASIC, ROIC, and/or other hardware programming languages and allow effective information flow from hardware to databases and to human-level understanding, or vice versa;
- Able to use and/or effectively communicate with designers using commercial design tool such as Cadence, Synopsys for sensor, ASIC, ROIC or other integrated circuits and fabrication. Computer programming skills (Python, C, C++, and others)
- Experience with ASIC programming, GPU programming, FPGA programming
- Experience with particle transport simulation programs (MCNP, Geant4)
- Experience with modeling imaging systems
- Ability to obtain a Q clearance, which normally requires U.S. Citizenship

Education: PhD's degree in physics, electric engineering, optical engineering, or computer science and/or engineering within the last 5 years.

Figure 20 – Illustration of expertise associated with high-speed photography

Moore's (Power) Law

Since 1965, at the height of the Cold War, the "law" coined by Intel's Gordon Moore has predicted the exponential growth of integrated circuit density and hence computational power. An equivalent "law" was proposed in 1998 by Kodak's Barry Hendy where he states that the number of pixels per dollar doubles every 18 months. We argue that because the technology associated with high-speed photography will likely continue to grow at a similar exponential pace into the foreseeable future. We will ultimately face a turning-point - much like that faced by practitioners of digital computers faced 20 years ago – where it will no-longer serve any beneficial purpose to limit the technology through export control mechanisms.

An illustration of this exponential growth among Los Alamos' cameras used for hydrotesting is provided in Figure 21. If anything, the exponential growth rate exceeds that predicted by Hendy.

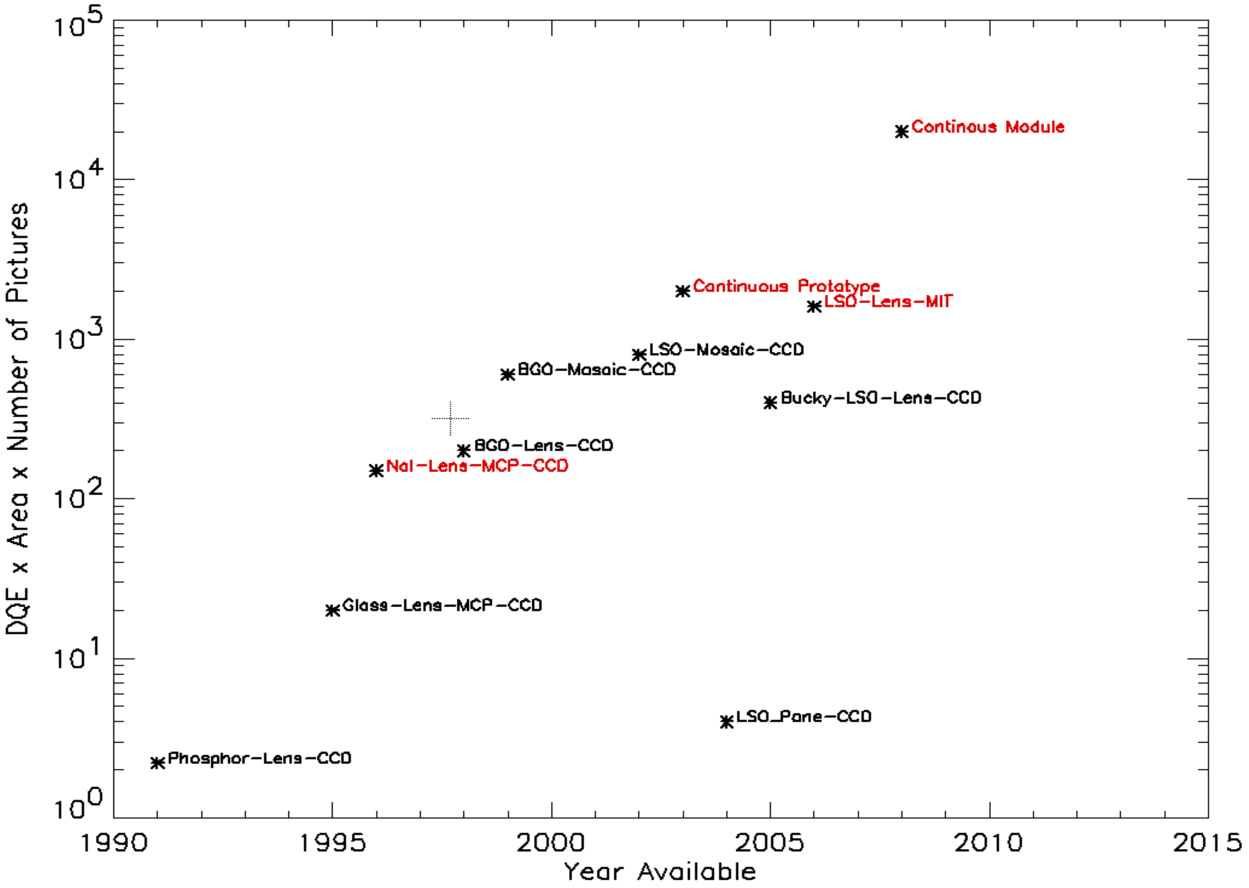


Figure 21 – Exponential growth associated with Los Alamos' hydrotesting cameras

One important consequence of the exponential growth of camera technology is that high speed photography is no longer an esoteric topic for Government Labs. As with computers, the average consumer now has access to affordable equipment that can perform at levels once would have been impossible just a few decades ago. A nice example of a "DIY" experiment[58] of a champagne glass being fractured with a bb-gun is shown below in Figure 22.

Figure 22 – A 2007, “DIY” high-speed photographs of a champagne glass shot with a bb-gun

Commerce Control Guidelines

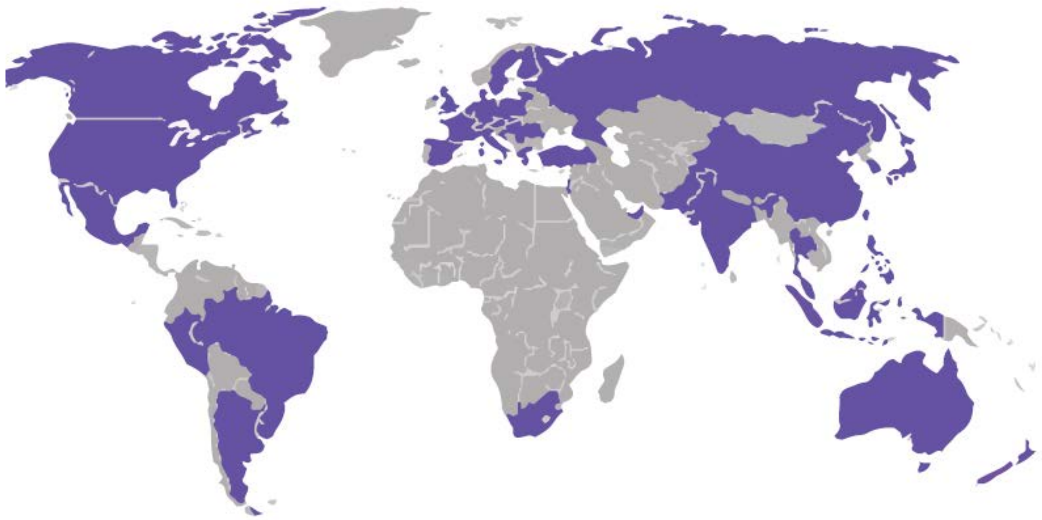
As with the computers of the day, the photographic techniques and hardware used by practitioners associated with the Manhattan Project and even early Pacific testing were extremely primitive by today’s standards. Put another way, any serious nation-state could develop their own, equivalent technology in short order regardless of the controls placed upon those technologies.

The existing commerce control language[59] generally controls high-speed photography of more than 225,000 FPS[60]. Similarly, The European Commission Delegated Regulations specify limits on cameras exceeding 1,000,000 FPS[61]. If we translate this rate into a generic measurement of high-explosives with detonation velocities of less than 10mm per microsecond[62], and particle velocities of 1-10mm per microsecond we find that such equipment is capable of resolving material positions to accuracies of 1-10mm.

The Wassenaar Arrangement[63] on the control of conventional arms also restricts cameras of various types including those with micro-channel-plate (MCP) image intensifiers and high-speed shutters. While these restrictions are generally geared toward night-vision and other, low-light applications, MCPs can be used for nuclear weapons work as well. For the purposes of this paper, the two applications (conventional vs. nuclear) are separate and distinct. Here we make no claims about the conventional arms utility or lack thereof.

Similar Nuclear Supplier’s Group (NSG) requirements[64] are placed upon flash radiographic equipment guided by the ability to resolve material interfaces at the sub-mm level[65].

One-stop shopping for such equipment is commercially available from Scandiflash in Sweden[66], Tech Bell in Israel[67], L3 Applied Technologies[68] in California and Hofstra Group[69] in Santa Fe[70]. The latter organization presently has customers in 50 countries as illustrated in Figure 23.



OUR CLIENTS

With over 1,500 customers in 50 countries, we have a bounty of exciting instrumentation problems for you to solve.

Figure 23 – Hofstra Group customers worldwide

Owing to the wide range of rapidly evolving technologies associated with high-speed photography, these guidelines are extraordinarily difficult to interpret. As a consequence, a range of interpretations, can be found among experts in the field. Despite this intrinsic complexity, it is still relatively common for technologies to come up for review which were not “caught” by the existing guidelines, but which nonetheless run counter to the spirit of those guidelines.

One notable example is the explicit assumption regarding the use “flash” radiography in the existing NSG requirements. When these guidelines were written, x-ray film was the only medium used for hydrotesting. Since that time electronic detectors with extremely high frame rates make “flash” radiography obsolete because “continuous” or “quasi-continuous” detectors are now used[71] – notably without restrictions.

Nuclear Weapons Applications

The list of ways that high-speed photography/radiography can be applied to nuclear weapons development and testing is surely extensive. Indeed an entire industry was developed during the height of the Cold War to support such efforts. In particular, Professor Harold Edgerton of MIT-LL[72] and his students Kenneth Germeshausen and Herbert Grier were the “E”, “G”, and “G” of the defense contractor, EG&G[73] which supplied much of the early equipment.

Potential nuclear weapon proliferators are clearly interested in high-speed photography. Two of the five units in the Iraqi Atomic Energy Commission’s, “Technical Research Branch”, were high-speed photography and radiography – a fact closely paralleling the early Manhattan Project plans[74,75].

With the US moratorium on nuclear testing and the rise of the Stockpile Stewardship program, the use of these technologies has become both more sophisticated and more necessary. Indeed all of the major SBSS facilities utilize high-speed photography[76,77]. It is no exaggeration to say that the US stockpile is certified today with images and supercomputers rather than craters and blast effects.

Consequently we are faced with a peculiar situation with regards to counter-proliferation. On the one hand, the United States might well want to limit technologies available to potential adversaries. On the other hand, we might support the use of those same technologies by those interested in supporting the Comprehensive Test Ban Treaty. In much the same way that Ronald Reagan saw a benefit to the United States when he proposed “sharing” the technology associated with the Strategic Defense Initiative to the former Soviet Union[78].

Equation Of State (EOS)

The 20th century ushered in both the need and the ability to measure extreme values of material properties. Some of these conditions, where materials are compressed to pressures of millions of atmospheres, are only seen within stars, explosives, and nuclear weapons. Indeed the Manhattan Project provided the impetus for the first use of what is now called, “precision detonics”. Experimentalists in many fields now consider high explosives as an extremely high-density power source.

The state variables normally considered are: temperature, pressure, volume, density, shock velocity, material velocity, and internal energy. One familiar form of these conditions is the so-called, ideal gas law, PV=NRT, which states that the product of pressure and volume in an ideal gas is proportional to its temperature.

If we consider the material properties across a high-pressure shock-boundary, the ten equations that describe these conditions are called the Rankine-Hugoniot jump equations[79] or simply, “the Hugoniot”. These variables are often characterized as a fit to experimental data – often loosely referred to in technical jargon as, “the Equations Of State” (EOS). It should be pointed out that other, related variables, like reflectance and luminosity may also be utilized.

Entire books are filled with tabulated EOS data and EOS fit parameters for explosives and various materials. One famous account was the result of more than 30 years of systematic experimental study by Charles Mader and others of Los Alamos[80]. Other versions are the so-called, Jones-Wilkens-Lee (JWL)-EOS, and the Preston-Tonks-Wallace (PTW) EOS[81].

The seminal description of shock phenomenon was written by Russian counterparts, Zel'dovich and Raizer[82]. Therein is a practical description of some experimental methods for determining Hugoniot curves. Since conservation laws connect four of the variables, the problem of determining all of the flow variables of a shock front reduces to an experimental determination of the remaining two.

In particular, the shock velocity and particle velocity can be measured using high-speed photography and/or flash radiography. The basic technique for doing so is called the, "free-surface method" (in Russia), or "flyer-plate method" (in the United States). The basic experimental setup consists of the following: a flat plate of the test material is placed against an explosive charge. When the detonation wave emerges, measurements are made on the free surface to determine velocity. A related technique, called the "collision method" (Russia), or "impact method" (United States), accelerates a plate of test material into another, target, plate. This method can be used to measure shock velocity and material velocity. There are many practical variations[83,84,85] on these methods, nearly all of which use either flash radiography, high-speed photography, or both to accurately measure the desired parameters.

Modern EOS measurements frequently use the Photon Doppler Velocimetry (PDV) technique[86] pioneered at Lawrence Livermore National Laboratory. This technique can be thought of as a radar gun that measures high velocities (up to 10km/s) with extraordinary accuracy. Using modern, high-speed (GHz) oscilloscopes, and ordinary lasers, it is a straightforward matter to make such measurements[87]. This technique has the advantage of continuous recording and modest probe cost. Consequently, regardless of the export controls placed upon high-speed cameras, the PDV diagnostic technique can often be used to equal or greater precision.

Conclusion

The late Dr. Al Bartlett, Manhattan Project veteran, and professor emeritus of physics at the University of Colorado, was fond of saying, "The greatest shortcoming of the human race is our inability to understand the exponential function."[88] Here we have surveyed the technology associated with high-speed imaging and flash radiography[89,90] and shown examples of the exponential growth of that technology during the latter half of the 21st century. That growth follows the familiar Moore's law and as with supercomputers developed during the same period, the ultimate implications for export control may well be the same.

Once the exclusive domain of nuclear testing labs, high-speed photography is now commercially available world-wide where it is widely used by amateurs and professionals alike. The time has come where we can say that we do not believe it serves any useful purpose to limit the export of high-speed photographic equipment as applied to nuclear weapons research.

Owing to their more limited application domains, higher cost, and much smaller market, it is our belief that streak-cameras and flash radiography equipment should, for the time being, maintain the existing export controls placed upon them subject to periodic review.

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[1] Venable, D., et al.. PHERMEX: A Pulsed High-Energy Radiographic Machine Emitting X-rays. Los Alamos Scientific Laboratory. LA-3241. 1967.

[2] Neal, T.. AGEX I – The Explosive Regime of Weapons Physics. Los Alamos National Laboratory. LA-UR-93-1350. 1993.

[3] Cunningham, G., & Morris, C.. The Development of Flash Radiography. Los Alamos Science. No. 28. 2003.

[4] Hawkins, D. et al.. Manhattan District History – Project Y – The Los Alamos Project. Los Alamos National Laboratory. LAMS-2543. 1961.

[5] https://en.wikipedia.org/wiki/Etendue

[6] Settles, G.. Schlieren and Shadograph Techniques – Visualizing Phenomena in Transparent Media. Springer Verlag. 2001.

[7] https://en.wikipedia.org/wiki/Eadweard_Muybridge

[8] https://en.wikipedia.org/wiki/Berlyn_Brixner

[9] Brixner, B.. A High-Speed, Rotating-Mirror, Framing Camera. Journal of the society of motion picture and television engineers.1952.

[10] US Patent 2668473. Brixner.

[11] Davis, B.. A High-Speed Rotating Mirror Framing Camera. Journal of Applied Optics. Vol. 1 No. 4. 1962.

[12] Earnshaw, K., et al.. An Ultra-High-Speed Image Dissecting Camera For Photographing Strong Shock Waves. Journal of Research of the National Bureau of Standards. Vol. 66C. No. 4. 1962

[13] Watson, S., et al.. Pulsed High-Energy Radiographic Machine Emitting X-Rays (PHERMEX) Flash Radiographic Camera", *SPIE* 2869, 22nd International Congress on High-Speed Photography and Photonics, 920 (May 28, 1997).

[14] Howard, N., Gardner, D.. Million Frame Per Second CCD With 16 Frames Of Storage. Silicon Mountain Design (Later DALSA & Quantum Imaging) & Los Alamos National Laboratory. 1999.

[15] Hogan, G., et al.. Proton Radiography. IEEE Particle Accelerator Conference. 1999.

[16] Kwiatkowski, K., et al.. A New, “Camera On A Chip” for Proton-Radiography Movies. Los Alamos Science, No. 30. 2006.

[17] Watson, S.. The DARHT Camera. Los Alamos Science No. 28. 2003.

[18] http://www.globalsecurity.org/wmd/facility/los_alamos-facility-darht.htm

[19] Mendez, J., & Watson, S.. A Multi-Frame Megahertz CCD Imager. Los Alamos National Laboratory. LA-UR-08-4206. 2008.

[20] Reich, R., et al.. Lincoln Laboratory High-Speed, Solid-State Imager Technology. 17th International Congress On High-Speed Photography and Photonics. SPIE Vol. 6279. 2007.

---

[21] http://specialised-imaging.com/

[22] https://www.photonicsonline.com/ecommcenter/visionresearch

[23] http://www.princetoninstruments.com/products/

[24] https://www.macsimage.com.au/

[25] http://www.ix-cameras.com/

[26] http://hadlandimaging.com/

[27] US Patent 8890081. Watson et al.

[28] https://www.rdmag.com/award-winners/2010/08/faster-speed-sight

[29] Grodzicka, M., et al.. Comparison of SensL and Hamamatsu 4×4 Channel SiPM Arrays in Gamma Spectrometry With Scintillators. Nuclear Instruments And Methods. Volume 856. 2017.

[30] Renker, D. New Developments On Photosensors For Particle Physics. Nuclear Instruments and Methods. Volume 598. 2009.

[31] http://www.sensl.com/downloads/ds/UM-ArraySMT.pdf

[32] https://www.ketek.net/sipm/sipm-products/oem-arrays/

[33] Yamamoto, K., et al.. Assembly Technology for 4-Side-Buttable MPPC. Nuclear Instruments And Methods. Volume 732. 2013.

[34] https://www.picoquant.com/images/uploads/page/files/7253/technote_tcspc.pdf

[35] Bonlie, J., et al.. A Performance Evaluation of Three High-Performance Streak Cameras. Lawrence Livermore National Laboratory. SPIE Vol. 981. High Speed Photography, Videography and Photonics. 1988.

[36] http://web.media.mit.edu/~raskar/trillionfps/

[37] Watson, S.. Los Alamos National Laboratory. “Family Days” presentation. 1991.

[38] Watson, S.. Frontiers In Science Lecture Series. Los Alamos National Laboratory. 2012.

[39] Watson, S., et al.. The DARHT Radiographic Camera Lenses: Design and Performance. Los Alamos National Laboratory DARHT Technical Note No. 100, LA-UR: 99-1112, 1999.

[40] https://en.wikipedia.org/wiki/Argon_flash

[41] Jones, C., & Davis, W.. Optical Properties of Explosive-Driven Shock Waves In Noble Gases. SPIE. 1983.

[42] http://prismscience.com/megasun.php

[43] https://www.paulcbuff.com/b1600.php

[44] http://www.nila.com/highspeed-lights/

---

[45] Kleiser, G., et al.. Control of Shaped Charge Jets Through Non-Uniform Confinement. 13th Hypervelocity Impact Syposium. 2015.

[46] Baker, E., et al.. Shaped Charge Jet Initiation and Characterization For IM Threat Testing. Procedia Engineering. 2013.

[47] Lee, W.. Computer Simulation of Shape Charge Problems. 2006.

[48] Watson, S.. *Shot H-2142 SPHEREX With 2-Pulse Cineradiography (U)*. Los Alamos Nat. Lab. LA-CP-98-140, 1998.

[49] Popular Science Magazine. Lights Camera Nanosecond Action!. July, 2003.

[50] Pendly, G.. High Speed Imaging Technology, Yesterday, Today, and Tomorrow. SPIE Vol. 4948. 2003.

[51] Persson, P., et al.. Rock Blasting And Explosive Engineering. CRC Press. 1994.

[52] Humphries, S.. Charged Particle Beams. Wiley Interscience. 1990.

[53] Wangler, T., et al.. RF Linear Accelerators. Wiley Interscience. 1998.

[54] Cooper, P.. Explosives Engineering. Wiley-Interscience. 1996.

[55] Mesyats, G., & Proskurovsky, D.. Pulsed Electrical Discharge in Vacuum. Springer Verlag. 1988.

[56] http://web.media.mit.edu/~raskar/trillionfps/

[57] Zukas, J., et al.. Impact Dynamics. Krieger Publishing. 1992.

[58] http://www.diyphotography.net/diy_high_speed_photography_at_home/

[59] Bureau of Industry and Security. Supplement No. 1. 6A003. December, 2016.

[60] Nuclear Supplier's Group (NSG) Part 2 Guidelines. INFCIRC/254/Rev. 10.

[61] European Commission. No. 428/2009. Section 6A003.

[62] Cooper, P.. Explosives Engineering. Wiley-Interscience. 1996.

[63] www.wassenaar.com

[64] Nuclear Supplier's Group (NSG) Part 2 Guidelines. INFCIRC/254/Rev. 10.

[65] Jamet, F.. Flash Radiography. Institut Franco Allemand. 1986.

[66] http://www.scandiflash.com/

[67] http://www.tech-bel.com/products-services/

[68] http://www2.l-3com.com/ati/solutions/irs_flash_x-ray.htm

[69] https://www.hofstragroup.com/category/measurement/imaging-photonics/

---

[70] http://public.hofstragroup.com/join.pdf

[71] Dr. Laura Smilowitz. Los Alamos National Laboratory. Private Communication. 2017.

[72] Edgerton, H.. Stopping Time – The Photographs Of Harold Edgerton. 2000.

[73] https://en.wikipedia.org/wiki/EG%26G

[74] Hawkins, D. et al.. Manhattan District History – Project Y – The Los Alamos Project. Los Alamos National Laboratory. LAMS-2543. 1961.

[75] Duelfer, C., et al.. Comprehensive Report of The Special Advisor to The DCI on Iraq's WMD. United States Central Intelligence Agency. 2004.

[76] Watson, S., et al.. Multiframe, High-Energy, Radiographic Cameras for Submicrosecond Imaging. Los Alamos National Laboratory. LA-UR-95-3570, 1995.

[77] https://en.wikipedia.org/wiki/Stockpile_stewardship

[78] https://en.wikipedia.org/wiki/Reykjav%C3%ADk_Summit

[79] Zukas, J., and Walters, W.. Explosive Effects and Applications. Springer-Verlag. 1998.

[80] Mader, C. L.. Numerical Modeling Of Explosives and Propellants 2nd Ed.. CRC Press. 1998.

[81] Tonks, P., et al.. Model of Plastic Deformation For Extreme Loading Conditions. Journal of Applied Physics. 2003.

[82] Zel'Dovich, Y., and Raizer. Y.. Physics of Shock Waves and High-Temperature Hydrodynamic Phenomena Volumes I & II. Academic Press. 1967.

[83] Quing. Z. et al.. A New Method For Determining The Equation Of State Of Aluminized Explosive. Chinese Physics Letters. 2015.

[84] Asay, J., et al.. High Pressure Shock Compression of Solids. Springer Verlag. 1993.

[85] Polk, J.. Determination of the Equation of State of Explosive Detonation Products From a Cylinder Expansion Test. Aberdine Proving Grounds. ARBRL-TR-02571. 1984.

[86] Cornell, R., et al.. Research and Development of High Performance Explosives. Journal of Visualized Experiments. 2016.

[87] Lorenz, K., et al.. A Simple and Rapid Evaluation of Explosive Performance – The Disc Acceleration Experiment. Lawrence Livermore National Laboratory. LLNL-JRL-652501. 2014.

[88] https://www.youtube.com/watch?v=kZA9Hnp3aV4

[89] Fry, D., et al.. Recent Developments In Electronic Radiography at Los Alamos. SPIE Penetrating Radiation Systems and Applications. Vol.3769. 1999.

[90] Ekdahl, C.. Modern Electron Accelerators for Radiography. IEEE Transactions In Plasma Science. 2002.