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Recent Development to Track Contraband Using Muon

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Abstract

The muon is one of nature's fundamental particles discovered in 1937 by Carl Anderson. A muon is an elementary subatomic particle similar to electron, but with a mass approximately 207 times greater and, sometimes it is called as a "heavy electron". Muons are generated naturally when cosmic rays collide with atoms in earth's upper atmosphere and, then raining down all the times upon the surface of earth. Muons can be artificially made by creating high-energy conditions that mimic cosmic rays colliding with atmosphere. A compact source of muons can be built using high-intensity laser systems where high peak power lasers accelerate electrons to relativistic speeds. These electrons are directed to a target made of tungsten or lead creating muon-antimuon pairs. Muons are highly penetrating and can easily pass through thick metal or rock easily. They are also sensitive to density through which they pass. Since muons are deeply penetrating than X-rays or gamma rays, muon tomography is used to create 3D images of entire cargo containers to detect shielded nuclear materials, explosives or other contraband. Other key applications are imaging volcano monitoring to predict eruptions, imaging tunnels, imaging pyramid interiors. It does not require any radiation source and hence it is harmless to humans. Unlike high energy X-ray systems, it does not require extensive shielding and, stations can be less expensive to build and maintain. The device analyses muon scattering and absorption rates in real time during scanning enabling prompt detection within 20 seconds.

Keywords: Muon, pion, laser-wakefield acceleration, CPA laser, linear plasma accelerator, scintillation detector

INTRODUCTION

If it is necessary to penetrate through meters of concrete, stone or metals, muons are the best particles. By detecting muons before and after they have passed through an object, one can determine how the particles have been absorbed or scattered, giving a sense of what materials lie within. Muons can detect contraband or a hidden person by measuring how their paths are altered by different materials. Muons are similar to electrons, but they are significantly heavier. This reduces their bremsstrahlung and allows them to penetrate much deeper into matter. Bremsstrahlung is a type of electromagnetic radiation produced when a fast moving charged particle like electron, muon is decelerated by strong electrostatic field of an atomic nucleus. In this process the particle's kinetic energy is converted into a photon as it slows down. These photons can be used to make a photographic image.

This unique property makes them an ideal probe for imaging the structures of dense materials. Muons can detect contraband or hidden person by measuring how their paths are altered by different materials. Since muons are highly penetrating, they can pass through dense objects like shipping containers, mountains, tunnels etc. All that is required is to place a muon detector underneath, within, or near the object of interest. The detector then tracks the number of muons going through the object from different directions, to form a three dimensional image of muons' path to create a 3D image of the container's density and atomic number. Muons lose energy as they burrow through materials. The denser the material is; the fewer muons make it through. So measuring how many muons have

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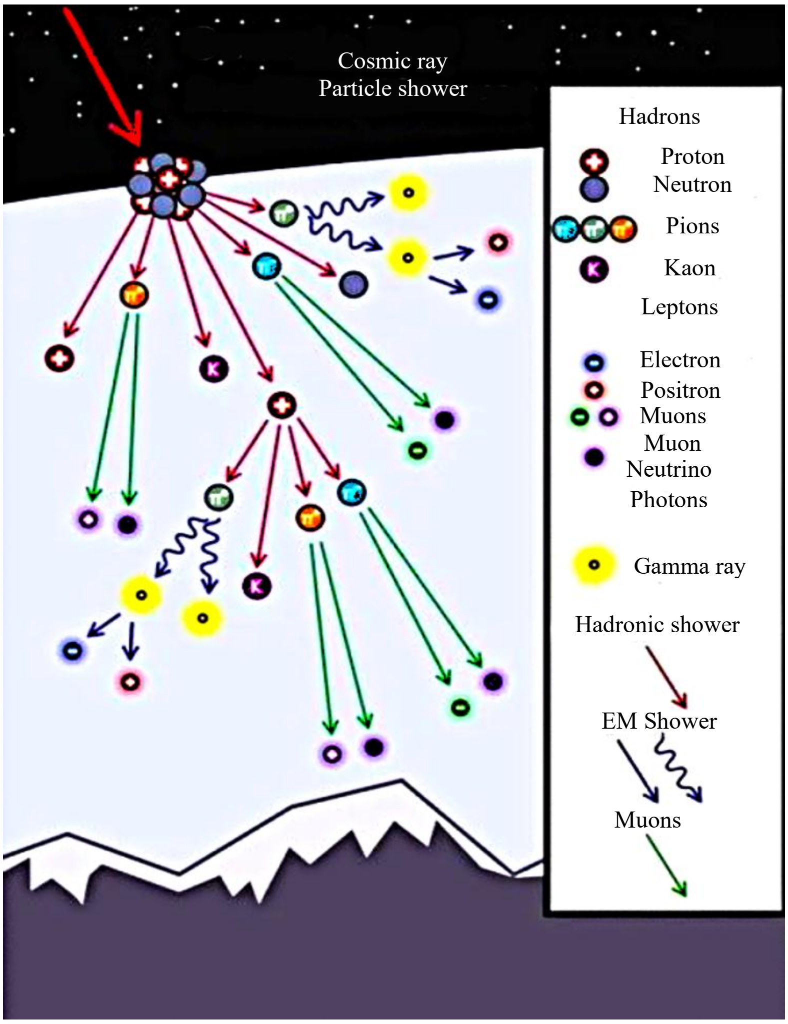
passed through an object can reveal how dense that object is and, expose contraband, which has different density and atomic properties from the container, appears as anomaly in the image identifying the hidden object. Using this technique one can also have a glimpse of the interiors of volcanoes, pyramids and other large stationary structures [1].

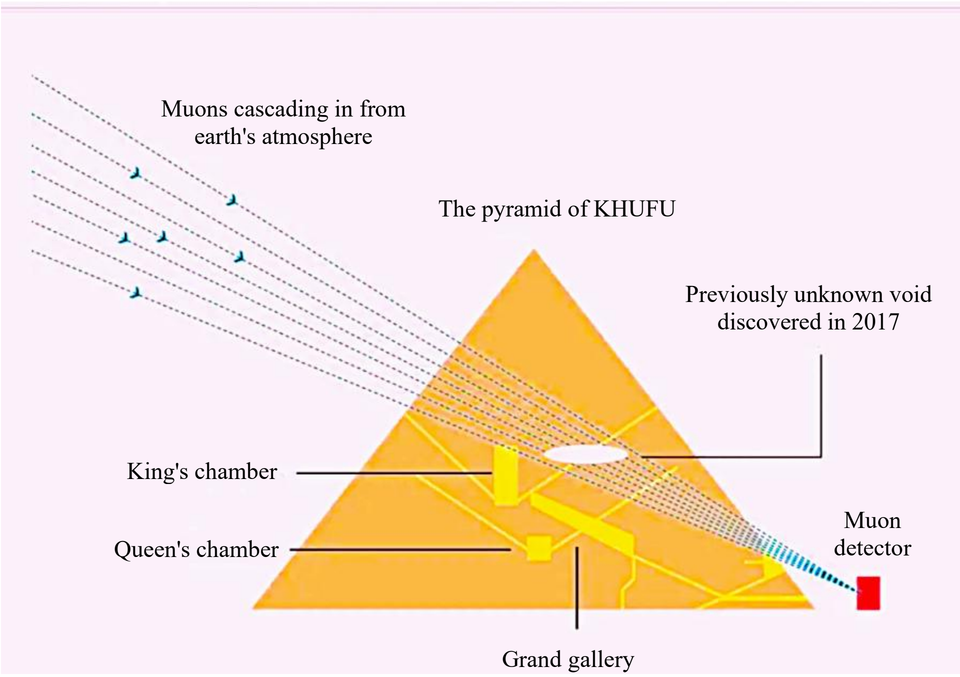
What is Muon

A muon is a type of fundamental particle, that means it is one of the basic building blocks of the universe. Like electrons and the quarks that make up protons and neutrons, muons cannot be split into smaller pieces. Muons are similar to electrons but weigh more than 207 times as much. Muons are unstable and decay into electron and two neutrinos in a short amount of time around 2.2 microseconds. Muons originate from the collision of cosmic rays with the atmospheric particles and also can be generated in particle accelerator collisions. Cosmic rays are high energy charged particles travelling near the speed of light, originating from supernovae beyond the solar system. As this occurs, the cosmic ray protons hit Earth's upper atmosphere, it collide with atomic nuclei of atmospheric oxygen and nitrogen and create a shower of secondary particles including pions, kaons and baryons. These pions, kaons and baryons are unstable and quickly decay into muons and nutrinos at high altitudes, at around 15 km that travel towards the Earth's surface at nearly the speed of light. It is estimated that more than one muon passes each minute through every square centimetre of the Earth's surface. Muons have a mass of about 105.7 MeV/c^2, which is about 207 times the mass of the electrons [2]. The cosmic event is shown in Figure 1.



www.vox.com, Brian Resnick, Nov 2, 2017

Figure 1. Generation of muons in the atmosphere.



BBC report by Jonathan Amos, 2 November 2017
Figure 2. Muography of the pyramid of KHUFU.

Muon Imaging of Pyramid

The great pyramid was built 4500 years ago by king Khufu of Egypt which is 139 m tall and 230 m wide, and has many large unexplored internal structures connected by narrow corridors. Without disturbing a single stone those cosmic muons were used to scan the pyramid through a process called muography, which works like an enormous passive X-ray. It is a non-invasive technology. Special muon detectors are placed around the pyramid to measure how many natural cosmic-ray muons pass through the structure from different angles. As muons pass through the pyramid's stone, some are scattered or absorbed. Denser materials stop muons, while less dense areas like chambers, corridors allow more muons to pass easily. Muon detectors are placed at strategic locations and they record the number of muons, their trajectories, and where they exit the structure. An excess of muons from a specific direction indicates a low density region like a chamber or corridor. By triangulating the data, a 3D map of the pyramid showing its internal arrangement can be made. Using this non-invasive technique previously unknown corridors and chambers were discovered in Khufu's pyramid in 2016. Schematic arrangement of the technique is shown in Figure 2 [11].

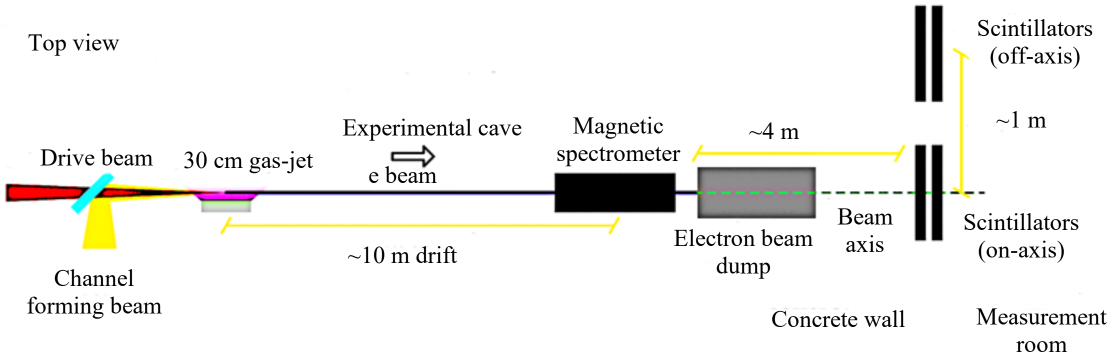
Artificial Generation of Muons

Traditionally scientists relied on cosmic rays for muography. But the number of muons that hit the earth is not enough for serious study. An alternative method for producing sufficient amount of muons involves proton accelerating facilities, which create low-energy muons by colliding with fixed carbon targets. Although this method is effective, the equipment is quite big and costly, limiting their usefulness for practical applications at site. Researchers have now developed a new method to produce ample quantities of muons economically by a very compact portable machine using ultra short high intensity pulsed lasers known as laser plasma accelerator (LPA). This advancement opens up new possibilities of detecting hidden objects and imaging at site using a portable compact detector.

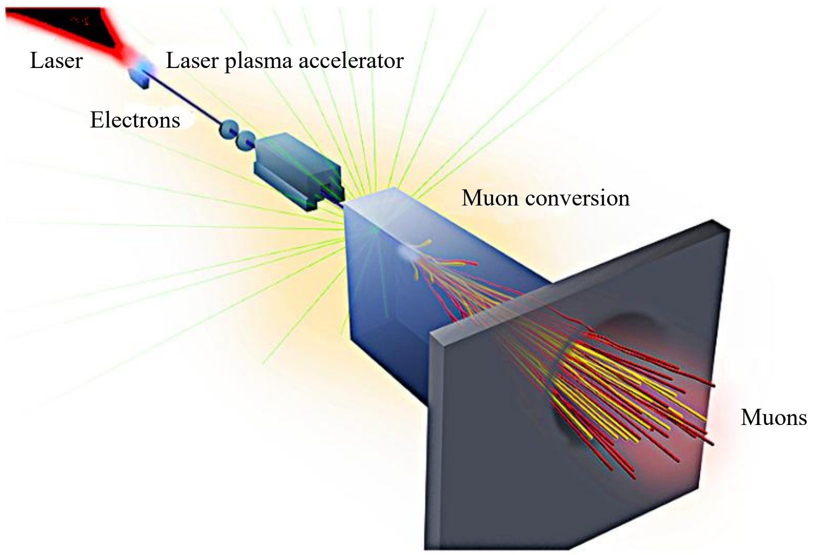
The Technology: Laser-Wakefield Acceleration

The aim of this technology is to shrink the size of the particle accelerator from hundreds of meters to a few meters by using extremely high electric fields within a laser created plasma. In this method a powerful ultrashort-pulse petawatt class laser is used to generate a beam of electrons. The laser is first fired into a gas jet or a pre-formed plasma channel. In LPA, ultra-short and tightly focussed laser pulse propagates into an under-dense gas. The pulse's extremely high electric field ionizes the gas atoms, freeing the electrons from the nuclei, so generating plasma. The radiation pressure of the intense laser pulse displaces these electrons and creates an electrostatic wave that produces accelerating fields orders of magnitude higher than what is possible in the traditional accelerators. The laser pulse creates a plasma Wakefield which is capable of producing accelerating fields significantly greater than those in traditional accelerators that traps and accelerates electrons to multi-GeV energies in a 30 cm plasma channel. The high energy, directional electron beam is then directed onto a target made from high density materials like tungsten. As the electron beam interacts with the target, it emits bremsstrahlung radiation, which facilitates the creation of lepton-antilepton pairs including muons. This method produces directional emission of muons, enhancing the efficiency of data collection. The LPA method can generate muon fluxes more than 40 times higher than cosmic rays for horizontal imaging and the system delivers over 20 muons per shot within the imaging aperture, offering exceptional resolution at unprecedented speed. Schematic arrangement of the setup is shown in Figure 3.

The generated muons are separated from the overwhelming background noise generated due to presence of electrons, positrons, and photons using specialized magnetic beam lines and shielding arrangements. The resulting muon beam is highly directional and has a short pulse duration.



Phys.org, Sanjukta Mondal Oct 14, 2025
Figure 3. Setup of LPA method to generate muons



Berkeley Lab, ATAP Division, News in brief, October 20, 2025
Figure 4. Schematic arrangement of laser assisted muon generator.

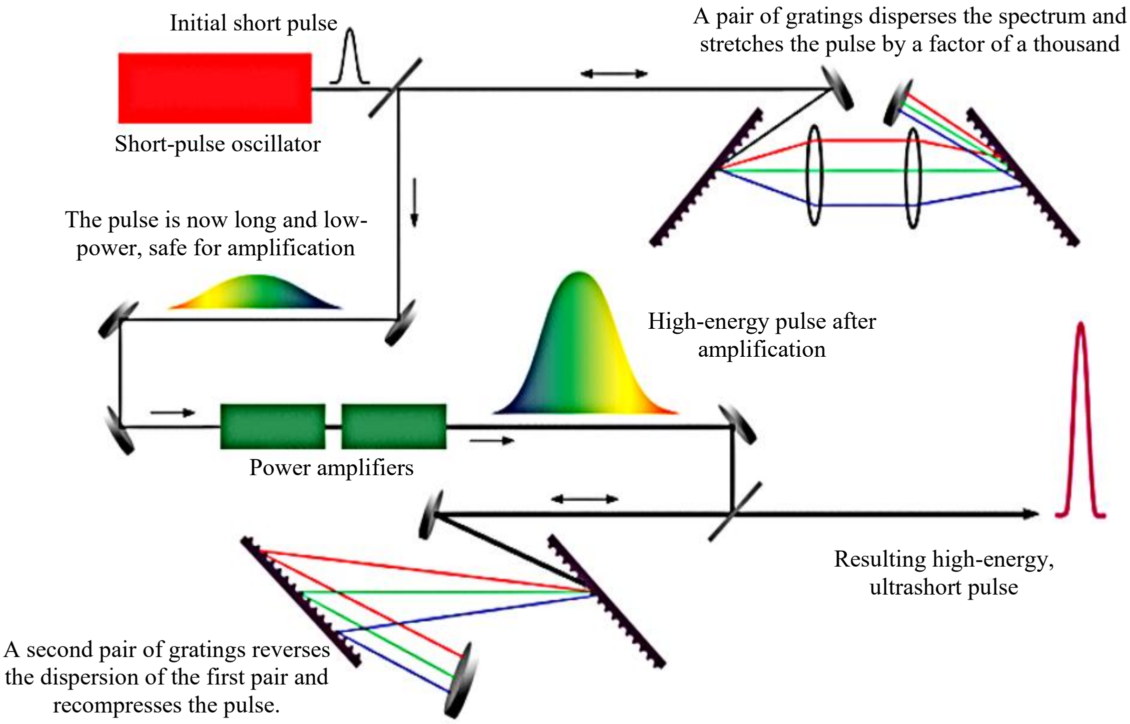
Key Advantages Are

The entire system can be installed in a small housing making it transportable and can provide on-demand muon source. The system is capable of guiding approximately 10^4 muons per second onto an application area using a 10 Hz petawatt laser. This can reduce imaging acquisition time from months using cosmic rays to merely a few seconds. Moreover, unlike natural cosmic rays which have unpredictable properties and directions, laser driven sources can produce controlled high energy muon beams suitable for radiography of hidden contrabands, nuclear materials or terrorists hidden in a tunnel. It can image the interior of large objects that are inaccessible to X-ray radiography. The penetrating muons can be exploited to make muon tomography which analyses how muons penetrate objects and then this information can be used to produce 3D images [3,9].

When muon passes through a special type of detector called scintillator it lights up and helps track the muons. Schematic arrangement of LPA muon generator is shown in Figure 4.

Ultrashort Pulsed Laser (USP)

Chirped pulse amplified (CPA) lasers are capable of producing several GeV electron beams in centimetre scale gas plasma and used in laser plasma accelerator(LPA) for muon conversion. A USP laser typically utilizes a solid laser medium such as a doted crystal or a solid state laser which is usually combined with an external pulse amplifier. This medium can be made from a variety of materials including glass, crystals such as titanium-sapphire, neodymium or ytterbium doted materials. Ytterbium-YAG or neodymium-YAG crystals are most common. USP lasers require a high mean power in the range several couple of watts. This means a laser (master oscillator) initially generates ultrashort pulses with a high frequency (repetition rate) and low pulse energy. Some of the pulses are selected and transmitted to a power amplifier and increases the pulse energy of selected pulses. Pulses are generated by a technique called mode coupling which involves synchronizing the different laser modes i.e. oscillation states within the laser resonator in such a way that they overlap and create a very short but highly intense laser pulse [4].



ResearchGate, V. Chvykov, Colorado State University, October 2018

Figure 5. Schematic diagram of CPA laser used IN LPA.

Chirped-Pulse Amplification

Conventional lasers cannot deliver peak power beyond 1014W/cm^2, and also limited by nonlinear effects and optical damage. CPA lasers can eliminate these problems by stretching the pulse duration before it reached the amplifier, keeping peak power at safe levels, and then compressing the output pulse to the original length. The technique uses optical gratings which are highly dispersive through which broadband light from a pulsed oscillator is passed and then delivered to the amplifier. This trick delays the light as a function of wavelength, stretching out the pulse to limit the instantaneous peak power in the amplifier. A second grating then compensated for dispersion, squeezes the extended pulse back into ultrashort pulse. This route makes it possible to use solid state media like ytterbium doped or neodymium doped crystals having capacity to store thousands times more energy than the conventional dye or excimer lasers. Petawatt lasers have pushed power densities to the 1023 W/cm^2 range in which acceleration increases electron mass by a factor of 10,000. Figure 5 shows the arrangement of CPA laser.

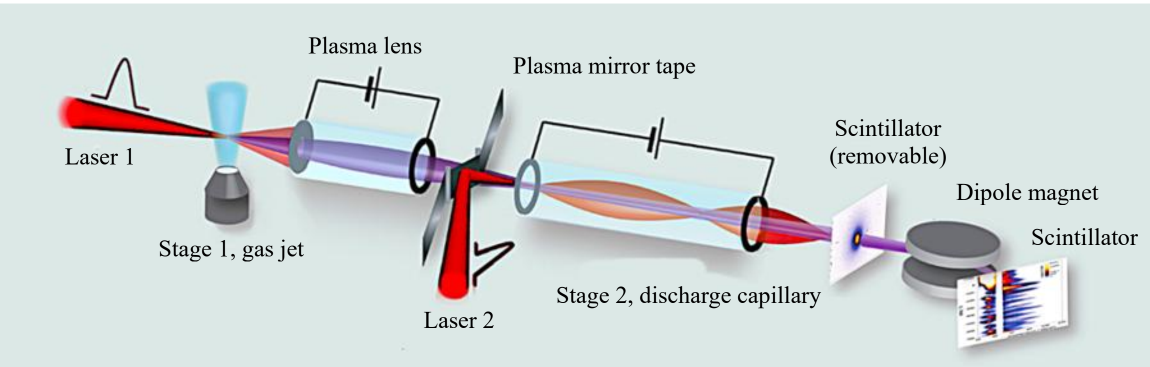
Short pulses from an oscillator are first dispersed in time by a factor of about 1000 by a pair of gratings that delay the blue end of the spectrum. The resultant pulses then pass through broadband power amplifiers, typically of Nd:glass or Ti:sapphire construction, and then are compressed by a second pair of gratings that delay the red end of the spectrum, compressing the pulse to extremely short duration and extremely high peak power. A typical laser based muon source metrics (Table 1).

Laser Plasma Accelerator (LPA)

Laser plasma accelerators can boost electron beams to multibillion electron volt energies (GeV) in a few centimeters- a distance thousands of times shorter than conventional accelerators. Schematic arrangement of a 2 stage LPA can boost the electron beam energy to 10 GeV (5GeV/stage) approximately and is shown in Figure 6.

Table 1. A typical laser based muon source metrics.

Metric	Value
Laser pulse energy	100J
Laser pulse duration	100 fs
Source repetition rate	10 Hz
Muons/pulse	1.5 X10^5
Muon energy	2 – 5 GeV
Muon pulse duration	100 ps at source
Muon beam divergence	4^0
Weight of the equipment	About 1.8 t, small enough
	To be placed in a truck.
Power consumption	100 kW



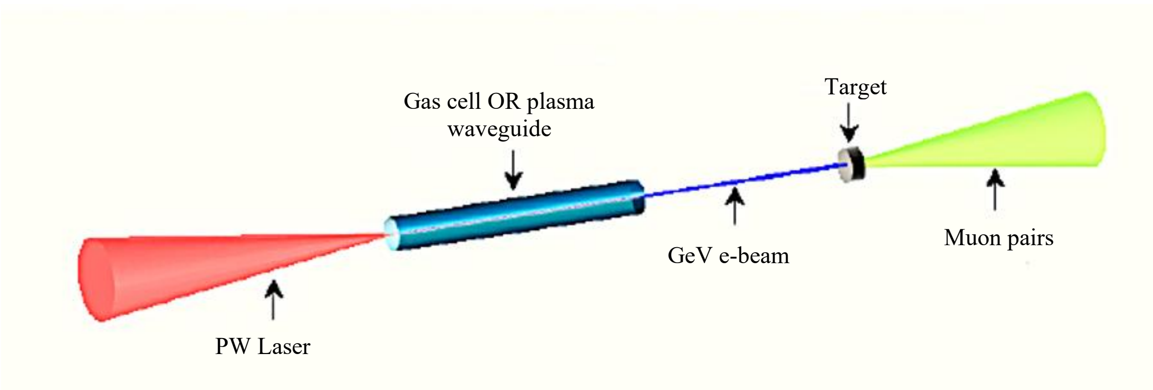
Berkley Lab, News, Glen Roberts Jr. February 1, 2016

Figure 6. Scheme of two stage linear plasma accelerator.

Laser beam can boost electron beams to multibillion electron volt energies in a few centimeters. Past those few centimeters, the laser pulse decays and energy gain stalls. Only by coupling a more number of LPAs in series, accelerating a well- shaped beam from one stage to other, electron beam of high energy of multi GeVs can be created. In the first stage, a jet of supersonic gas, a few hundred micrometers in diameter is used through which the laser pulse is injected ionizing the gas creating a plasma and leaving a wake to accelerate the free electrons. The powerful discharge current ionizes the gas and forms an optical waveguide through the plasma, but also creates a strong pulsed magnetic field that would make an excellent plasma lens and tightly focus the injector beam. Although, the concept of gas jet is simple but powerful enough to generate beam energies over a hundred million electron volts. The second stage consist of a block of sapphire with a thin horizontal tube inside, that is filled up with hydrogen gas and a potent electrical discharge ionizes it, separating electrons from the nuclei and forming a plasma. Immediately the discharge arc heats the plasma forming a thinner channel of plasma which acts as laser waveguide. The laser pulse drills through the waveguide like a racing car picking up free electrons in its wake and hurling them forward in a lightning speed. In the second stage the laser works in conjunction with a mirror to steer and focus the high intensity laser beam and to protect delicate downstream equipment from intense laser heat. Installation of the second laser with mirror within a few millimetre space between the two stages is a difficult task indeed. The electron beam would have to pass through a hole in the mirror. The reflected laser pulse would come close behind. But the power of the laser would be so high that during working the mirror would blow into pieces. So, a radical new concept has been evolved that utilises video cassette player tapes. VHS tapes are thin, stretch resistant and capable of running for hours at a stretch. The electron beam pierces the tape and thereafter it ionizes the surface forming a dense perfectly flat plasma, a highly efficient mirror followed by within a fraction of a second, entry of the laser pulse from the 2nd laser. The second laser pulse, known as laser Wakefield accelerator (LWFA) creates a Wakefield in the plasma which further accelerates the electron beam downstream diagnostics that measure the beam [5].

Generation of Muons

Figure 7,8 shows the mechanism of production of muon pairs (μ^+,μ^-) driven by GeV-LWFA (laser Wakefield accelerator). A petawatt (PW) class fs laser pulse drives Wakefield acceleration of electrons from a several-cm scale gas cell medium or preformed plasma waveguide and generates a powerful GeV electron beam. The electron beam interaction with a high-Z target like tungsten produces muon pairs in forward direction. The interaction between high energy electrons and the conversion target is a very complex process, involving many secondary radiation process such as gamma rays, neutrons, electrons etc. In simple language it can be split up in two steps. Firstly, the electrons interact with the target nuclei and produces a broad spectrum of photons with energy extending up to the incident electron energy by Bremsstrahlung process and secondly, the interaction of photons with the target nuclei produces muon pairs. The second process is the principal mechanism of muon pair production [6].



Bobbili Sanyasi Rao et al, Plasma Physics and controlled fusion, 13 July 2018
Figure 7. Mechanism of production of muon pairs.

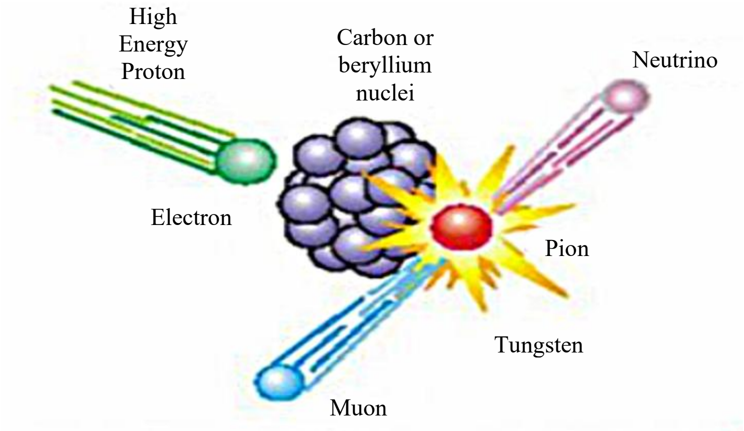


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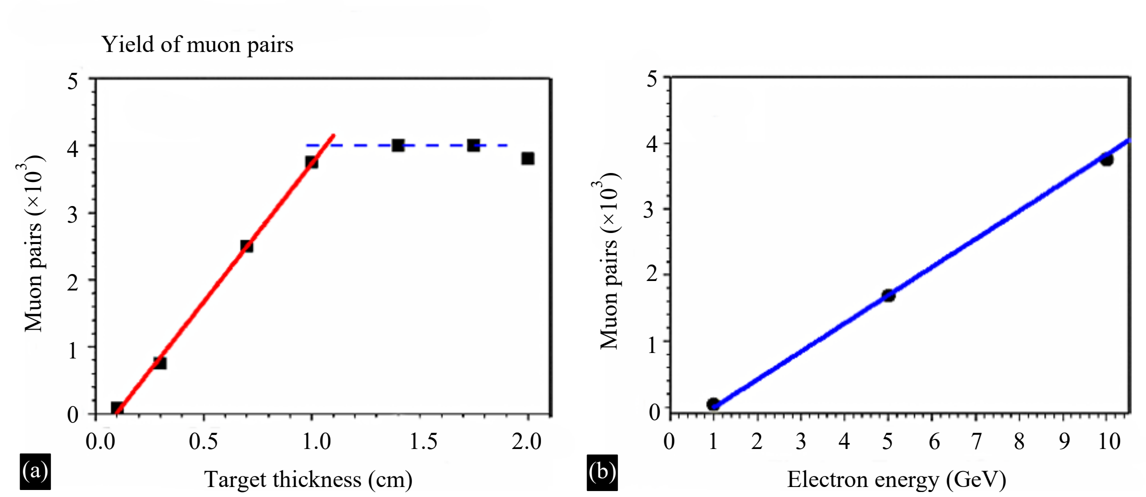
Figure 8. Tungsten bombarded with high energy electron.



Bobbili Sanyasi Rao et al, Plasma Physics and Controlled Fusion, 13 July 2018
Figure 9. Yield of muon pairs.

Tungsten, due to its high atomic number, Z, is chosen as a target for muon production of bremsstrahlung photon for high yield of muon pairs. The geometry of the target may be 2.5 cm disc shaped with thickness up to 1.2 cm. The target may be placed in the 10 GeV electron beam path at a distance of 50 cm from electron source. The yield of muon pairs for the 100 picocoulombs (pC) obtained as a function of target thickness is shown in Figure 9a. The yield increases from 100 pairs for 1 mm to about 3800 pairs for 10 mm. Further increase in thickness shows saturation at 4000 pairs as indicated in dash line in blue. Figure 9b shows the yield of muon pairs as a function of incident electron energy. The yield is about 40 pairs at 1GeV and increases linearly at a growth rate of about 425 pairs/GeV.

Scintillation Detector

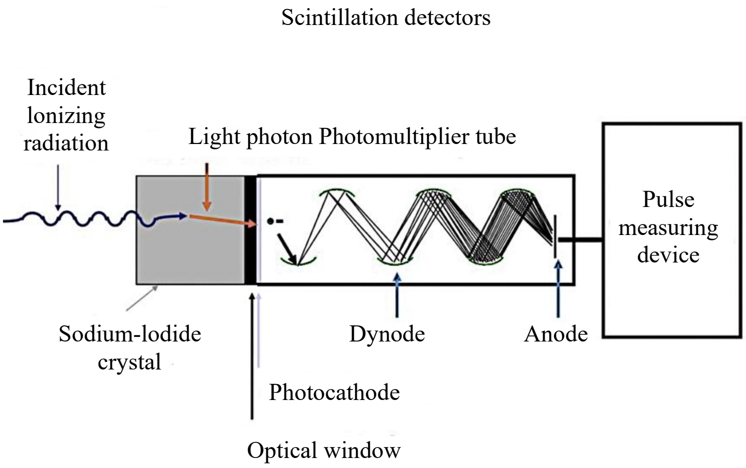
Scintillation detectors are a popular device used in particle physics due to their high efficiency and good timing resolution. It works on the principle of detecting the light emitted by a scintillator material when a muon passes through it. It is generally made of plastic or crystal that emits light when excited with the passage of a charged particle. Its working can be summarized as:

1. When a muon passes through the scintillating material it excites the atoms causing them to glow.
2. The emitted light is detected by a photodetector, such as photomultiplier tube (PMT). Photomultiplier tube are composed of photocathode followed by a series of dynodes as shown in Figure 10. The light photon strikes the photocathode, causing it to emit a photoelectron. The photoelectrons are focussed onto the first dynode. This produces electrons that are multiplied at

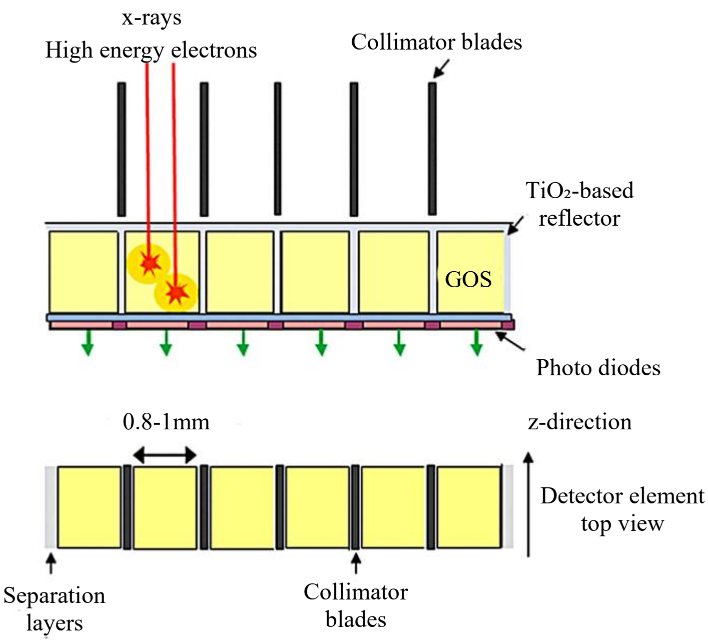
the second dynode. And again at the third, all the way to the chain. The amplified signal is then collected at the anode and passed out to the measurement circuits.

3. The signal from the PMT is amplified and processed to determine the energy and trajectory of the muon.

Figure 11 shows the typical construction of scintillator. It can be seen from Figure 11a, sectional elevation of the scintillator, that individual detector cells made of gadolinium oxysulfide/ plastic absorb the high energy electrons and convert their energy into visible light. The light is detected by photodiodes attached to the backside of each detector cell and converted into electric current. Collimator blades are needed to suppress scattered radiation. Further, the individual detector cells must be separated by optically in-transparent layers based on TiO_2 to prevent optical cross-talk and these are dead zones that do not produce light [7,8].



Pubs.sciepub.com, Sabitha Vadakedath et al, Biomedicine and Biotechnology, 2022
Figure 10. Schematic arrangement of scintillating detector.



Thomas Flohr et al, Chinese journal of Academic Radiology, March 2020
Figure 11. Typical construction of scintillating detector.

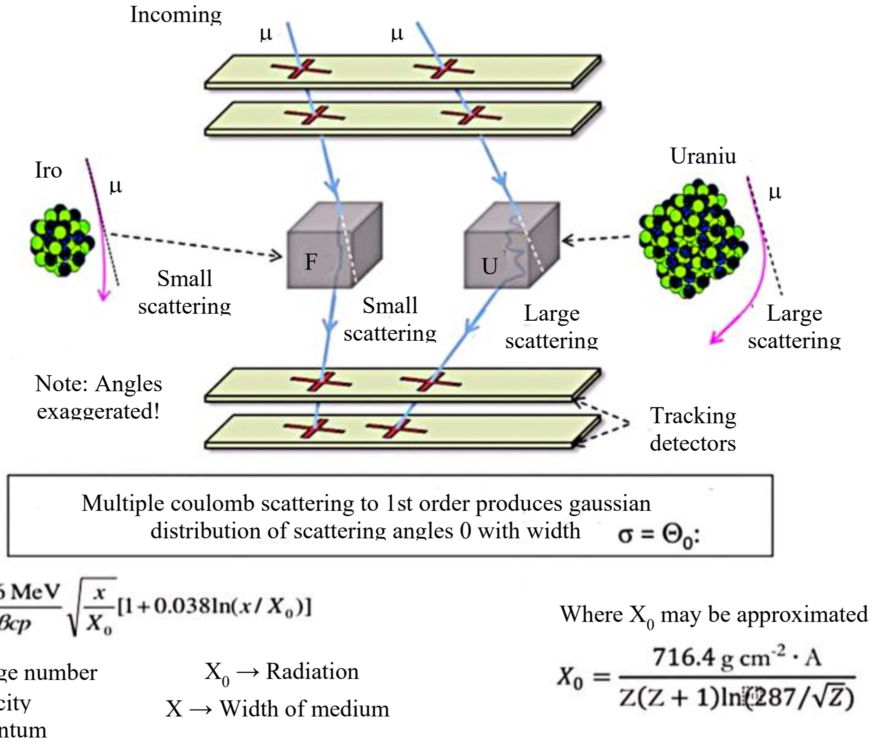
Muon Tomography

Muon tomography is a promising technique for detecting contrabands in containers, underground tunnels etc. It utilizes the scattering and absorption of muons to create a 3D images of concealed structure and contrabands. The technique works by analyzing muon scattering and absorption rates in real time during scanning, enabling a prompt detection of contrabands within a minute. Muon absorption depends on the density and composition of the material. Denser materials and those with higher atomic numbers will scatter muons more significantly or stop them entirely. By tracking the angles of incoming and outgoing muons, computers can create a 3D map of the cargo's density and atomic number. The tomography shows the localised regions of contrabands of reduced scattering density, appearing as voids or anomalies, within the surrounding dense matrix. In this mode, the target object is placed between two muon trackers as shown in Figure 12.

Setup For Detecting Hidden Tunnel

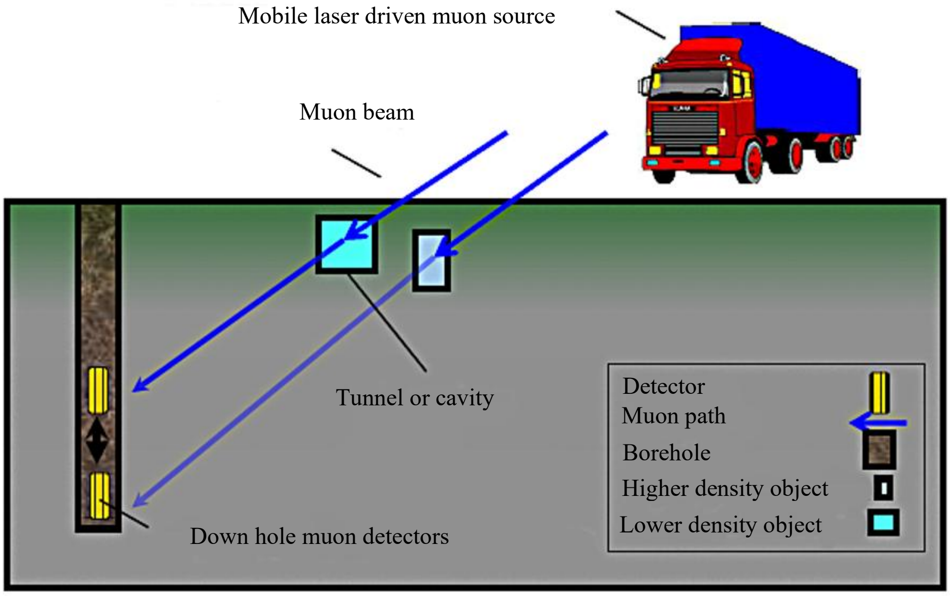
A typical setup for detecting a hidden underground tunnel used for smuggling personnel and contraband is shown in Figure – 13. Tunnel detection involves drilling boreholes at strategic locations where scintillator detectors like EJ-200 plastic bars/paddles in light tight boxes are placed to observe overlying rock or tunnel sections. Multiple detectors are often placed to create overlapping fields of view, essential for triangulation. Mobile laser driven muon source placed on the ground triggers the laser source and bombard earth with muons which travel through rock/soil. Tunnels are filled with air having low density, while rock is dense. Fewer muons pass through rock than the air leading to a shadow or reduced muon flux from the tunnel. Detectors measure the angle and location where muons enter and exit, mapping their path as shown in Figuure14 [6].

Scintillators emit light when a muon passes through. Photomultiplier tubes (PMTs) detects the light pulses from scintillators and convert them to electrical signals. Electronics and data acquisition system process signals from PMTs. The coincidence logic detects muons crossing multiple planes simultaneously to trigger data recording. The data logger then records muon arrival times, hit positions (x,y,z planes), and angles. Algorithms analyse the angular muon rates from different directions to build a 3D model, highlighting density variations showing voids or tunnels as shown in Figure 14 [9].



Muon imaging, IAEA-TECDOC -2012, Published: 2022

Figure 12. Philosophy of muon tracking.



International Atomic Energy Agency, Muon Imaging, Vienna 2022
Figure 13. Setup for detecting underground tunnel.

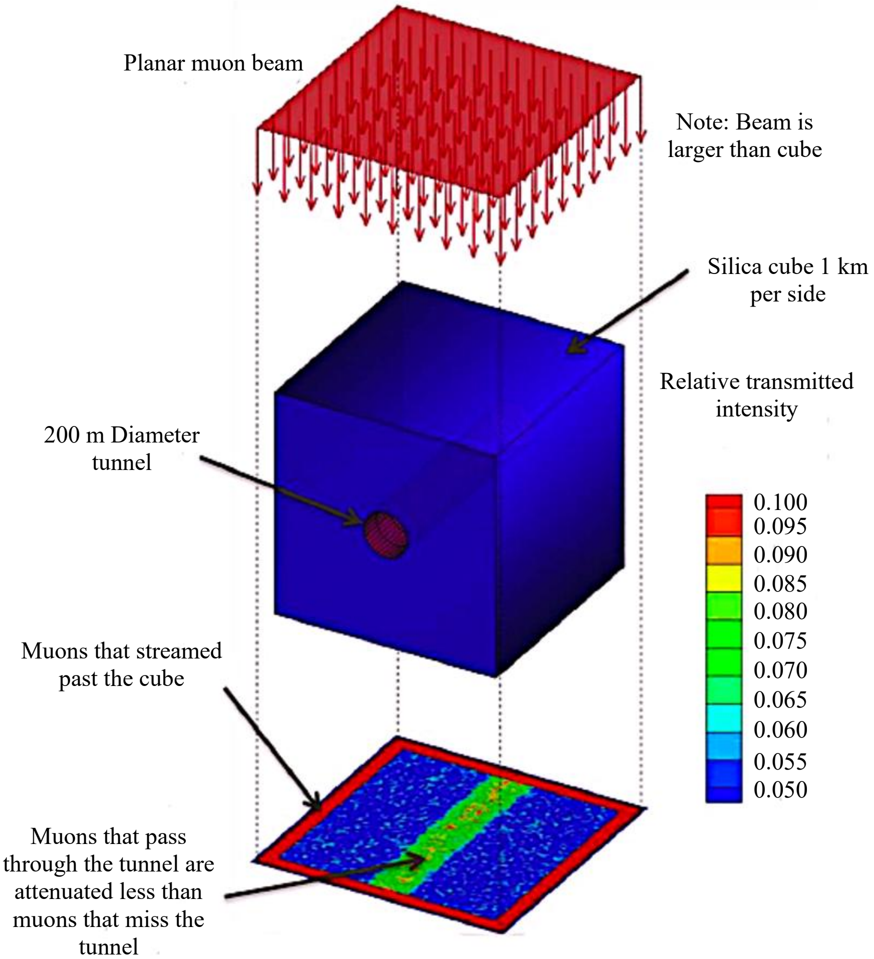


Figure 14. Mapping of muon path.

Using similar setup by placing a mobile laser driven muon source on one side of the cargo and a scintillator detector on the opposite side of the container of a ship or wagon the contraband can be easily detected [10,11].

CONCLUSION

Muon detection using mobile laser driven muon source can penetrate dense materials and is capable of making 3D images of shielded cargo, can identify high density materials like nuclear materials, drugs, tunnels etc. by how muons scatter or are absorbed. Detectors track incoming/outgoing muons, and algorithms map the scattering/absorption patterns to reveal hidden objects, distinguishing them from surrounding objects by their different atomic numbers and densities. This novel technology offers a passive and non-invasive security screening without hazardous radiation. The process is quick and quite economical. There are a great number of future applications in geoscience, geothermal engineering and mining engineering on earth and even on Mars and asteroids.

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