ELECTRON ACCELERATOR OPTIONS FOR PHOTO-DETECTION OF FISSILE MATERIALS

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Abstract

For national security, it is important to detect the presence of Special Nuclear Materials, especially Highly-Enriched Uranium (HEU). Generally used methods for such detection include interrogation by photons and neutrons. For example, photofission in HEU can be initiated with 14-MeV photons. The resulting delayed neutrons and photons from the fission fragments are clear signatures of the presence of HEU. One can generate high-energy photons using electron accelerators via various mechanisms. In this paper, we will describe two of them, namely Electron bremsstrahlung and Compton backscattered photons. We focus on these two mechanisms because they cover a wide range of accelerator requirements. Electron bremsstrahlung can be generated using a compact low-energy electron linac while the generation of Compton backscattered photons requires a high-energy electron accelerator of a few hundred MeV. We review these two options, describe their accelerator requirements, and compare their relative merits.

INTRODUCTION

High-energy photons can be used for detecting fissile materials. When a photon approaches a nucleus, it will transfer energy to the nucleus by setting up an oscillation of the protons relative to the neutrons. Such photonuclear excitation is known as Giant Dipole Resonance. The de-excitation of the nucleus will lead to the emission of *prompt* neutrons and gammas. In addition, the nucleus can de-excite via fissions if the nucleus is fissionable. Photofission cross section of U^{235} is shown in Figure 1. It has a broad maximum centered at photon energy of 14.5 MeV. Photofission will lead to fission fragments that are neutron rich and unstable. These unstable fission fragments will further decay by emitting more neutrons and gammas. These neutrons and gammas from fission-fragment decays come at a later time ranging from fraction of a second to a minute. The detection of neutrons and gammas at a delayed time is a good indication of the existence fissile material.

Figure 1 shows that photons between 9 and 20 MeV can induce photofissions for detecting fissile material. We have studied two methods for the production of gammas at such energy range: Compton BackScattering (CBS) and Electron Bremsstrahlung (EB). In this paper, we will describe and compare these two methods and the enabling accelerator technologies.

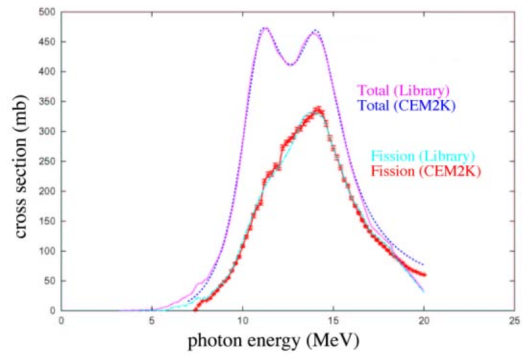

Figure 1: Total photo and photofission cross-sections for U^{235}

COMPTON BACKSCATTERING SOURCES

In CBS, a low-energy photon collides head on with a high-energy electron with a relativistic energy factor of γ. Scattered photons in the direction of the initial electron beam direction will have its energy up-shifted by a factor of $4\gamma^2$, becoming a high-energy photon. In our case, a FEL produces the low-energy (~ 6.4 eV) photons. It is powered by the same electron beam (~ 400 MeV) used for the backscattering. Figure 2 shows a schematic of such a system. It contains three subsystems: FEL Subsystem, Electron Beam Subsystem, and CBS Subsystem.

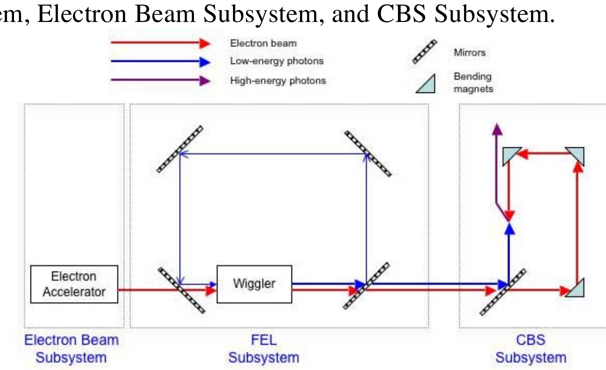

Figure 2: Schematic of a CBS Source

The nominal parameters of these subsystems are listed in Table 1. The parameters chosen for the Electron Beam and FEL subsystems are based on LANL experience, particularly the experience gained at the Advanced Free-Electron Laser Project (AFEL) [1]. The amount of *useful* photons, between 9 and 20 MeV, produced is estimated according to Ref. 2 and maximized by minimizing the laser and electron beams overlapping radius. The efficiency of converting electrons to useful photons is only at an order of 10^{-4}. The energy of the photons is correlated to

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their backscattered angle, so that photons with specific energy can be selected.

Table 1: Nominal subsystem parameters for a CBS source

Electron Beam	FEL	CBS
• 1300 MHz, 400 MeV • Medium beam quality (ε_n< 10 π mm mr) • 20-ps micro-pulses at 108 MHz; each with 0.5 nC • 6 mA average at 10% duty factor	• Photon energy 6.4 eV • Wiggler period 4 cm • Wiggler length 0.84 Tesla • Laser micro-pulse energy 1-mJ	• Laser-Electron micropulses overlap has a radius of ~10 μm • 3x10^{13} photons per second with energy between 9 and 16 MeV in a cone with half angle of 6 mr

ELECTRON BREMSSTRAHLUNG SOURCE

EB sources are widely used to produce photons for medical and industrial irradiations because of their simplicity. Figure 3 shows a schematic of an EB source. An electron beam (~ 20 MeV) is slowed down in a high-Z (tungsten) target and produces gamma radiations. The bremsstrahlung radiation is forward peaked with angular half width of 1/γ. The energy distribution is *broadband* from low energy to the *endpoint* energy, which is equal to the energy of the electron beam. This is an undesirable feature of the EB source, because a large amount of photons below 9 MeV, which are not useful for photofission, are produced and adds greatly to the total dose.

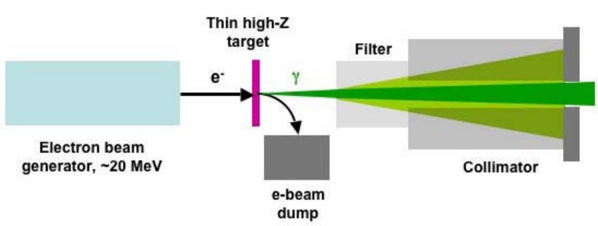

Figure 3: Schematic of an EB source

The task of designing an EB source is to optimize the fraction of high-energy photons, leading to maximum number of fission per unit dose, M. Analysis of results in Figure 4 showed that thinner targets has relatively larger fraction of high-energy photons. M increases by a factor of 3 if we use target with thickness of 0.1 mm instead of 3 mm. M also increases by allowing the bremsstrahlung to traverse a piece of material. The higher attenuation coefficient for lower energy photons will attenuate the lower energy photons as a high-pass filter. For example, M increases by a factor of 2 after bremsstrahlung traverses a 30-cm aluminum piece. The factor M is also higher at forward angle. Figure 5 showing the number of photons is dropping slower when photon energy increases at forward direction. Therefore, an optimum EB source will use thin target and filter and collimate the bremsstrahlung.

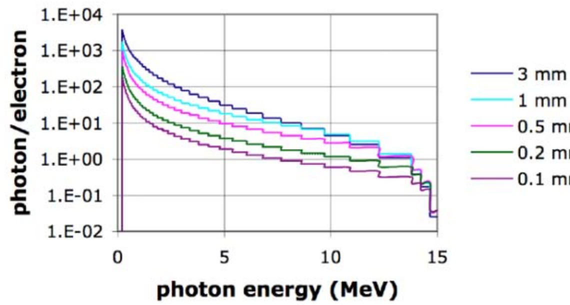

Figure 4: Bremsstrahlung spectra of a 15-MeV electron beam hitting tungsten targets of different thicknesses.

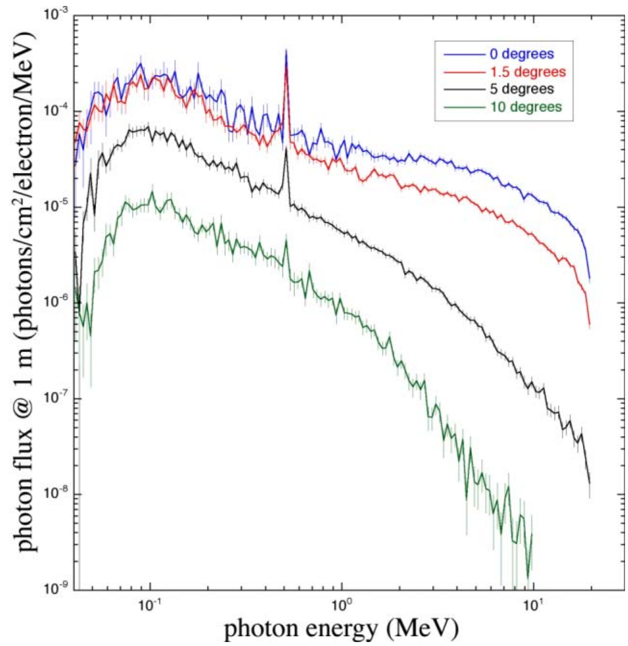

Figure 5: Bremsstrahlung spectra at different angles after traversing a 30-cm aluminum. The bremsstrahlung is produced by a 20-MeV electron beam hitting a 0.1 mm tungsten target.

ENABLING ELECTRON ACCELERATOR TECHNOLOGIES

CBS sources and EB sources have very different electron energy requirements and very different electron accelerator technologies. A brief status of the accelerator technologies will be described in this section.

The EB source requires an accelerator that produces 20-MeV electrons. Systems have been widely employed in medical and industrial areas. A study has been completed in 2004 [3]. The study concluded that an improved X-ray source could be made using an electron linac at 17 GHz, a klystron as RF source, and a solid-state Marx generator as modulator. By updating the technology in these three areas, the system will be improved in efficiency, reliability, flexibility, size, weight, and cost. The system is relative simple to build and can be transportability, easy for radiation shielding, and low cost. Although the study is for 10-MeV, the results are readily adaptable to 20 MeV with parameters shown in Table 2. Table 3 shows

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the reduction in sizes and weights of various subsystems compared to existing commercial EB source.

Table 2: Typical accelerator requirements for a EB source

Frequency (GHz)	17
Beam energy (MeV)	20
Beam current (mA, peak)	68.2
Duty cycle (%)	0.1
Beam power (kW, average)	1.4
Total power required (kW, average)	4.4
Length of structure (cm)	63
Diameter of structure (cm)	2.7

Table 3: Size and weight comparison of major components of an updated EB source to existing commercial unit

	Commercial Unit	Proposed Design (10 MeV design, est.)
HV Modulator	35 ft^3, 700 lbs	1.5 ft^3, 50 lbs
RF Source	8 ft^3, 350 lbs	2.5 ft^3, 60 lbs
Linac	21 ft^3, 1600 lbs	2.5 ft^3, 60 lbs

The CBS source requires an electron accelerator with 400-600 MeV. Generally speaking, accelerator technology for high-energy electron accelerators is well established. Three technologies have been studied for our applications. The first technology is room-temperature (RT) copper technology. The accelerating structures are made of oxygen-free copper and will be operating at room temperature. This technology has been used in most high-energy linacs, including LAMPF, AFEL, and most medical linacs. The second technology is superconducting (SC) technology using niobium elliptical cavities. This technology uses accelerating cavities with elliptical cross section and made out of niobium sheet. A good example of this technology is the TESLA Test Facility accelerator [4]. The operating temperature will be 2 ºK with superfluid liquid helium. The third technology is superconducting spoke cavity [5]. This is a SC technology developed in the last few years. Cavities will be made of niobium and operate at 4 ºK. Parameters of accelerators using these three technologies are compared in Table 4.

Table 4: Parameters of a CBS accelerator using three different technologies

	RT Copper	SC Elliptical	SC Spoke
Operating Temp (K)	293	2	4
Structure frequency (MHz)	1300	1300	350
Gradient (MeV/m)	10	25	13
Structure length (m)	50	20	39
Accelerator length (m)	63	29	43
Accelerator diameter (cm)	26	44	82
RF power (MW)	12.7	2.7	2.7
Total wall plug power (MW)	23	8	7

COMPARISON OF PHOTON-SOURCES PERFORMANCE

A performance comparison of the CBS sources and EB sources is summarized in Table 5. The delayed neutrons and gammas detected were calculated assuming a U^{235} package located 50 meters away. The package is shielded with 1” of iron and 1” of lead and has a target area of 500 cm^2. The comparison was done assuming a 100-mrem dose allowed around the package.

Table 5: Comparison of CBS source and EB source performance

	CBS source	**EB source**
Emitted particle/ m^2 on target @100 mrem	Delayed n = $2x10^5$ Delayed γ = $7x10^5$	Delayed n = $3x10^4$ Delayed γ = $1x10^5$
Efficiency of producing useful photons	10^{-4}	10^{-1} - 10^{-2}
System length (m)	30	1
Total power (MW, peak)	70	10
Flexibility	“Mono-energetic” beam	Broadband
Operational	Complicated	Simple

CONCLUSION

CBS source can produce more delayed neutrons and gammas for detection per radiation dose, but it is a less efficient system and much more complicated to operate. EB sources produce six times less signal with the same dose but they are compact and easy to operate.

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