Electron Accelerator Options for Photo-Detection of Fissile Materials

Dominic Chan

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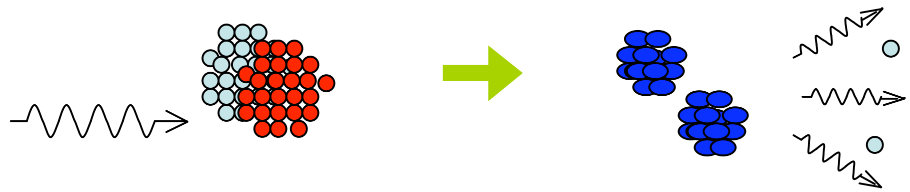
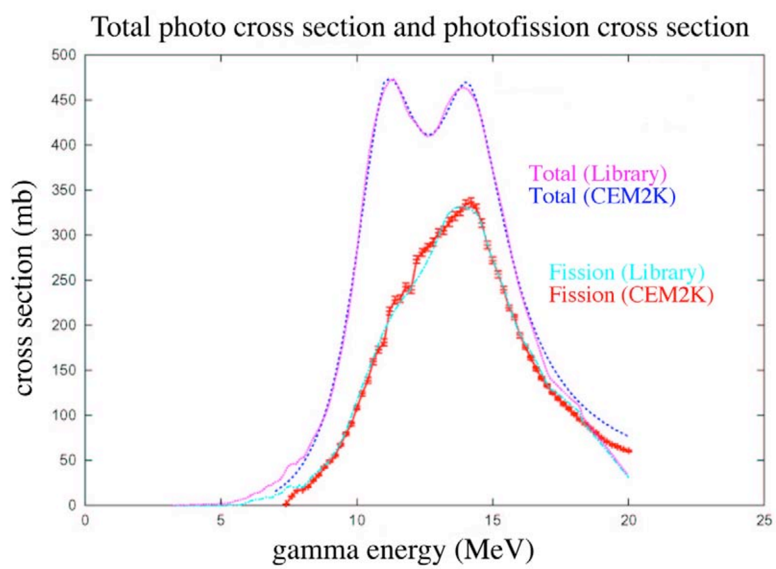
Gamma radiations with energy between 9 and 20 MeV can cause photofissions for detecting fissile material

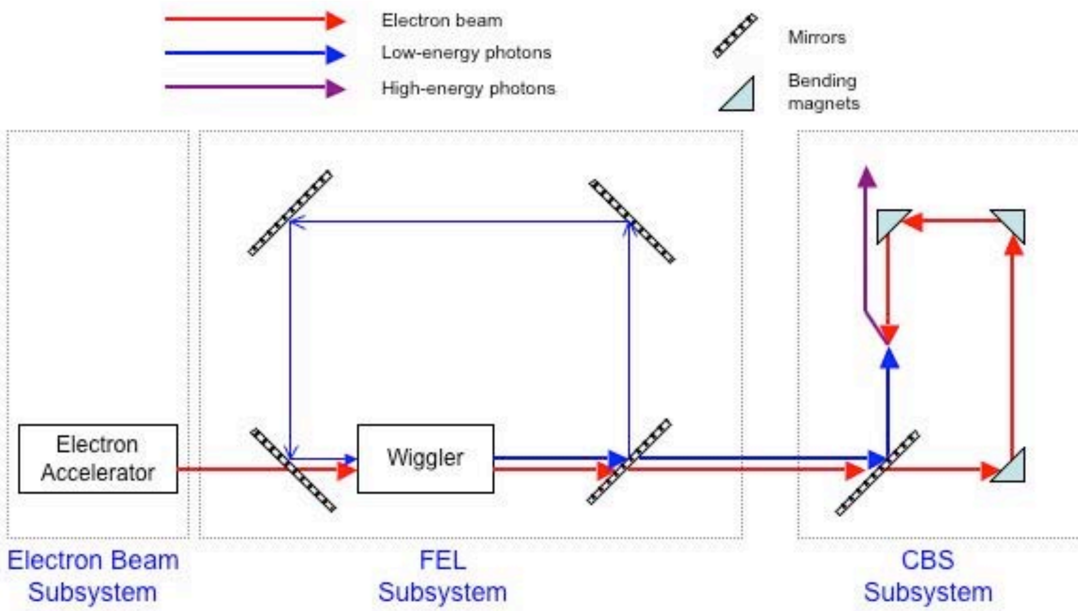


Nuclei are excited by gamma rays (Giant Dipole Resonance). If the nuclei are *fissionable*, one of the de-excitation channels is fission and fission fragments will decay emitting secondary gammas and neutrons. Because these secondary particles are from fission fragments, they come in a later time up to fractions of a minute. Detection of these *delayed* particles is a good signature of fission, or fissile material.



- The threshold energy of the reaction is ~ 7 MeV
- The photofission cross section peaks around 14.5 MeV, i. e. 80 $A^{-1/3}$
- Significant cross section up to 20 MeV
- Gammas between 9 and 20 MeV are *useful* gammas for fissile material detection

Compton sources provide directed beams with “discrete energy”



In a Compton source, low-energy photons collide with high-energy and upshift to high-energy gammas. Gamma energy is correlated with scattered angle.

Electron linac

- 1300 MHz, 400 MeV
- Medium beam quality ($\varepsilon_n < 10\ \pi$ mm mr)
- 20-ps micropulses at 108 MHz; each with 0.5 nC
- 6 mA average at 10% duty factor

Free-electron laser

- Photon energy 6.4 eV
- Wiggler period 4 cm
- Wiggler length 3 m
- Wiggler field 0.84 Tesla
- Laser micropulse energy 1 mJ

Compton backscattering

- Laser-Electron micropulses overlap has a radius of ~10 μm
- 3 x 10^{13} gammas per second with energy between 9 and 16 MeV in a cone with half angle of 6 mr

We have made estimations on how a Compton source can be used to detect a "terrorist package"

"Terrorist package" - a scenario

- U^{235} with shielding of 1" of iron and 1" of lead
- Package area of 500 cm^2
- Located at a target ship 50 m away
  - a survey spot of 1-m diameter (7,600 cm^2)

Using an *allowable* dose on target ship of 100 mrem

- Number of delayed neutrons is $7x10^4$
  - $1/10^{th}$ thickness of paraffin is 20 cm
- Number of delayed gammas is $3x10^5$
  - $1/10^{th}$ thickness of lead is 5 cm
- Beam time to reach 100 mrem is 1.4 ms
- Survey time is 4 ms
  - Beam spot size is 2,800 cm^2
  - Detection time not included; total time can be quite a bit higher

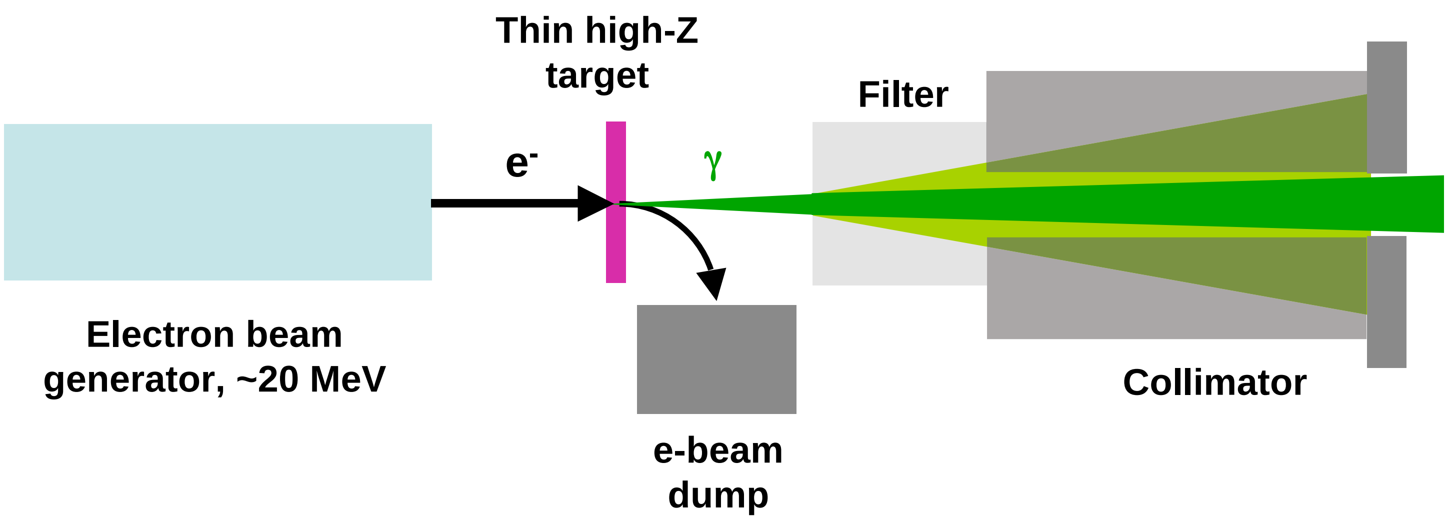
Compton source, though viable, has a low efficiency of 10^{-4} in converting electrons to *useful* gammas.

We studied Bremsstrahlung sources for comparison

We compare Compton source to Bremsstrahlung source because

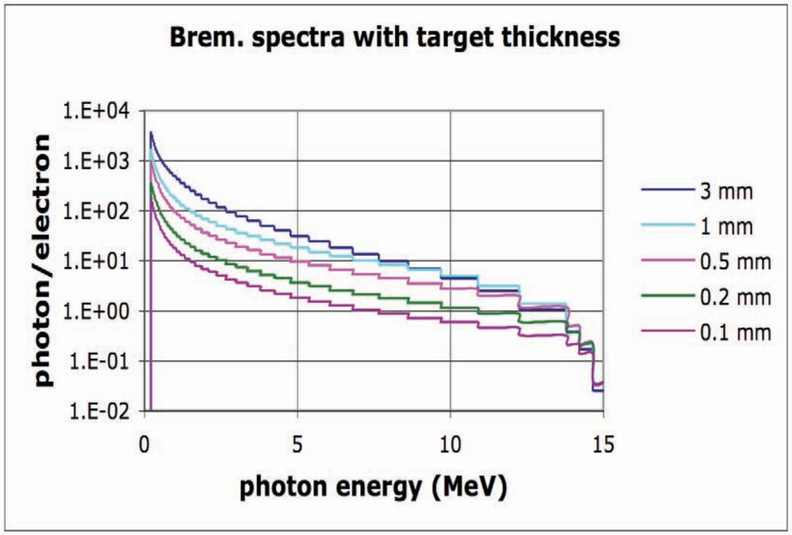
- Bremsstrahlung source has a 10^{-1} to 10^{-2} conversion efficiency from electron to *useful* gammas
- Feasibility of Bremsstrahlung sources already demonstrated in Los Alamos
- Compact Bremsstrahlung system design work completed in 2004

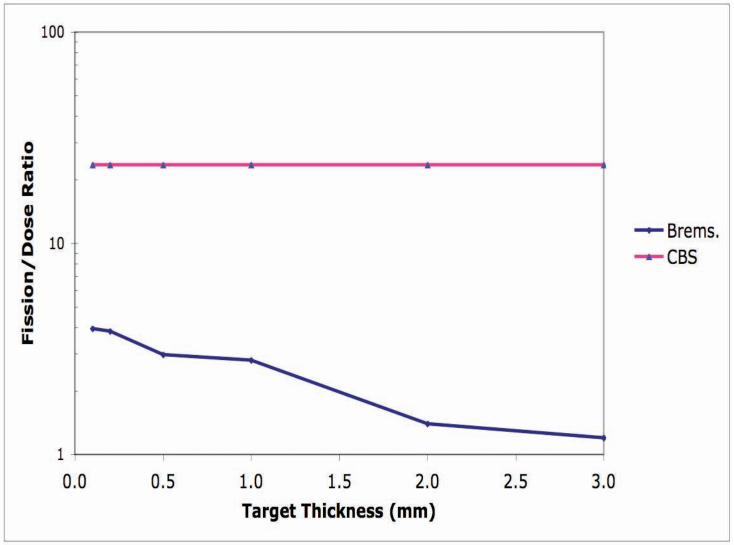
Schematic of a Bremsstrahlung source



Bremsstrahlung sources are broadband

Low-energy portion of bremsstrahlung causes unnecessary dose

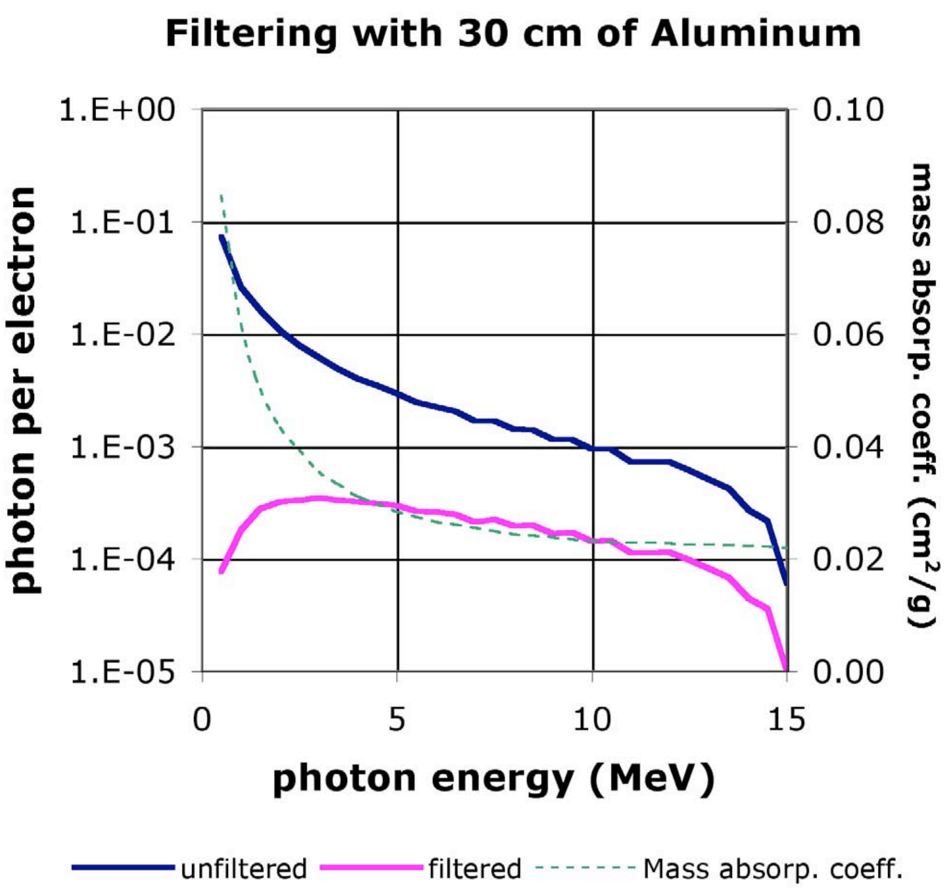




- More than 70% of the radiation dose is caused by gammas below 8 MeV
  – Compared to Compton source, for the same number of photofissions, the radiation dose caused by a Bremsstrahlung source is at least six times higher
- There are less lower energy gammas for thin targets
  – With the same allowable dose on target, thin targets have more fissions than thick targets

Thin targets should be used in a Bremsstrahlung source

Literatures show that a directed bremsstrahlung beam with hardened spectrum can be achieved by filtering and collimation

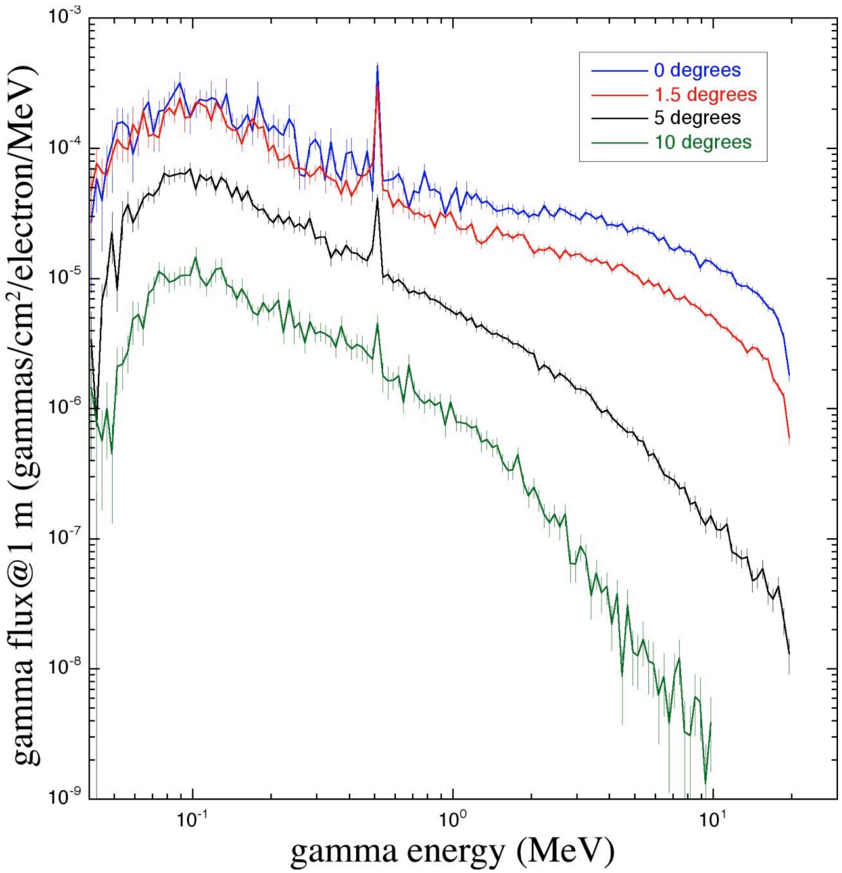


Example of filtering

- Low-energy portion, generally with higher attenuation coefficient, will be reduced more compared to high-energy portion of the bremsstrahlung
- With 30 cm of aluminum, the low-energy dose is reduced by a factor of two

Monte-Carlo calculations confirmed that a hardened spectrum can be obtained in the forward cone of filtered bremsstrahlung

Monte-Carlo calculation results



Bremsstrahlung with 0.1-mm tungsten target passed through a 30-cm Aluminum filter

- High-energy bremsstrahlung drops faster with angle
- A collimator will be used to eliminate the large-angle bremsstrahlung
- Optimizing the material choice, thicknesses, and geometry of target, filter and collimator will improve results

We have a compact, high-performance electron accelerator design for Bremsstrahlung sources

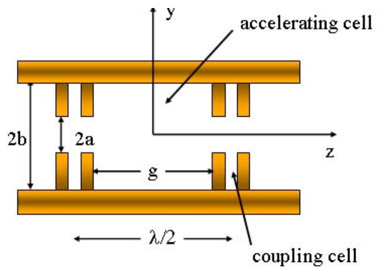
- 20-MeV electron accelerators are widely used in medical and industrial areas
- In 2004, our study shows that a Bremsstrahlung source incorporating up-to-date accelerator technology can greatly improve system performance

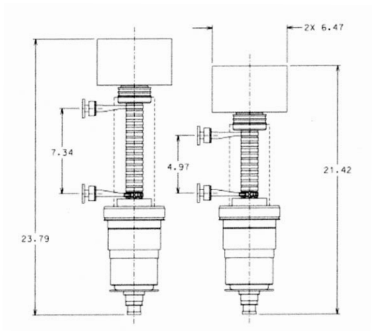
- Traditional system attributes
  - S-band (3 GHz) linacs
  - Powered by magnetrons
  - High-voltage modulated by pulse-forming network and transformer
  - Limited flexibility in energy and pulse format
  - Dimensions of each component about a few feet
  - Weight of each component about 500-1000 pounds; with total weight about 1800 pounds

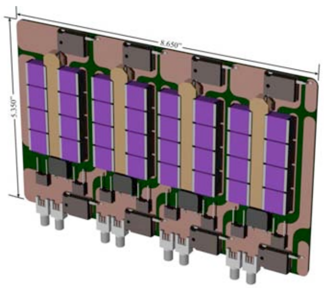
- Updated system attributes
  - X-band (17 GHz) linacs
  - Powered by klystrons
  - High-voltage modulated by Solid-state Marx generators as modulator
  - Great flexibility in energy and pulse format
  - Dimensions of each component about one feet
  - Weight of each component about 50 pounds; with total weight below 200 pounds

Updated technologies improved system performance

Smaller, lighter, power efficient, flexible, and reliable







<u>17-GHz π/2 mode *sw* linac</u>

- Better power efficiency
- Higher field gradient
- High operational stability
- Permanent-magnet focusing channel
- Smaller size
- Lower weight
- SLC technology

<u>Air-cooled klystron</u>

- Controlled and reliable operation
- Permanent-magnet focusing channel
- Smaller size
- Lower weight
- SLC technology

<u>Solid-state Marx generator</u>

- IGBT switching
- Modular design
- Flexible pulse format
- Solid-state reliability
- Easily reconfigurable
- Smaller size
- Lower weight

Superconducting-linac development for TESLA and ILC provides the needed technology for Compton sources

We have looked into three different technologies that can provide the 500-MeV electron accelerator for a Compton source

	RT Copper	SC Elliptical	SC Spoke
Operating Temperature (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

* Green column indicates desired technology

Comparison between fissile material detection systems based on Compton sources and Bremsstrahlung sources

	Compton-backscattering	Thin-target bremsstrahlung
Emitted particle/ m^2(target) @100 mrem	Delayed n = 2.0 E5 Delayed γ = 7.3 E5	Delayed n = 3.3 E4 Delayed γ = 1.2 E5
Efficiency for producing useful gammas	10^{-4}	10^{-1} - 10^{-2}
System length (m)	30	1
Total power (MW, peak)	70	10
Safety	*Discrete* beam	Broadband
System complexity	Complicated	Simple

- The total power required depends greatly on the accelerator technology chosen
- Green boxes indicate *pros*

Summary

Bremsstrahlung sources are efficient in producing gammas for interrogation of fissile materials and they are simple systems to operate. Because of their low-energy gammas, they produce less delayed particles for detection with specific radiation dose on interrogating target. This disadvantage can be minimized with thin targets, filtering and collimation.

Compton sources are complex systems, but they can produce gammas with specific energy as required.

Both types of sources are supported by well established but quite different electron accelerator technologies because of their different energy requirements.