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FIND: Fluorescence Imaging in the Nuclear Domain

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FIND: Fluorescence Imaging in the Nuclear Domain

Non-invasive detection and imaging of special nuclear materials with Thomson-Radiated Extreme X-ray sources

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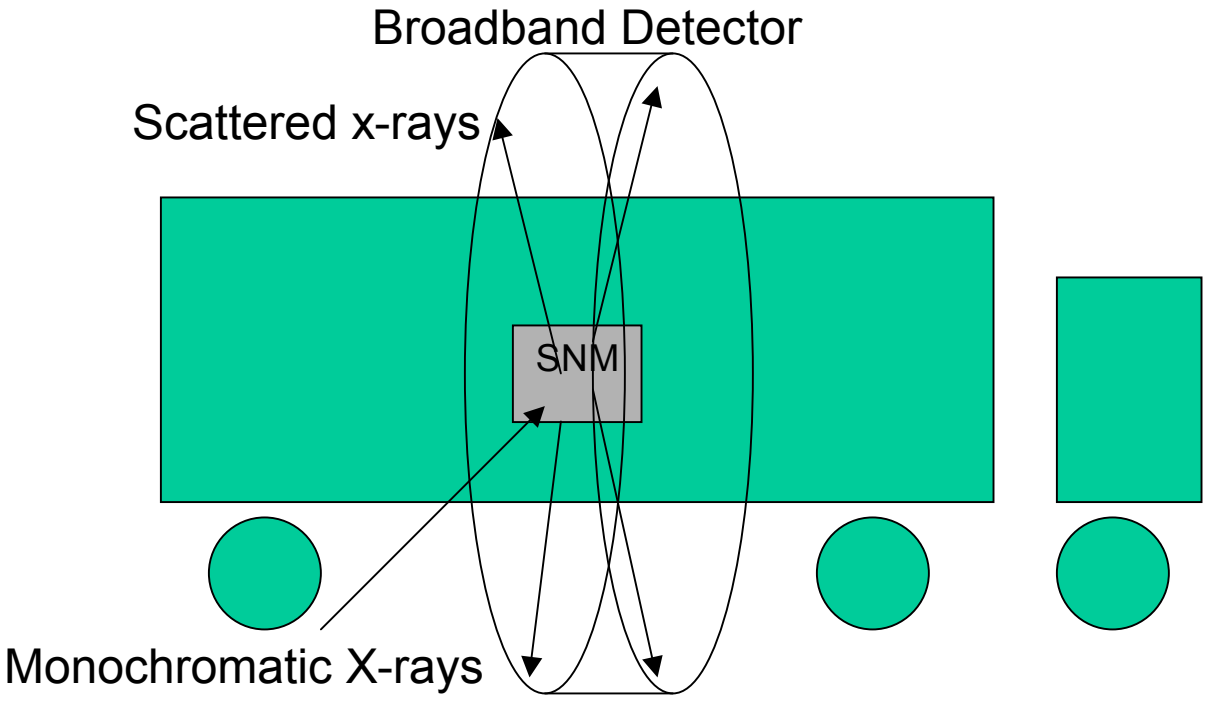

FIND: Fluorescence Imaging in the Nuclear Domain
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Summary:

This document examines the potential use of Thomson-Radiated Extreme X-ray (T-REX) sources for Fluorescence Imaging in the Nuclear Domain (FIND) of special nuclear materials. A back-of-the-envelope, relative comparison of T-REX sources vs. Bremsstrahlung sources for this application is presented. It is estimated that use of T-REX for FIND could be as much as 5x10^12 more effective than the use of anode based sources. Furthermore it is estimated that illumination of samples of dimension 1 cm on a side could produce up to ~10^9 detectable photons per second.

Background:

Nuclear resonance fluorescence (NRF) is a well-established technique for the study of photo-allowed nuclear transitions. In this technique a sample is exposed to broadband radiation in the 100 keV to several MeV range. The radiation is most commonly generated by impinging energetic electrons of several MeV onto a metal target. The emitted Bremstrahlung photons are collimated and illuminate the sample under test. Radiation that is resonant with allowed transitions of the nuclei is then re-radiated into 4π and detected by energy resolving detectors. Schematically this arrangement is shown in Figure 1.

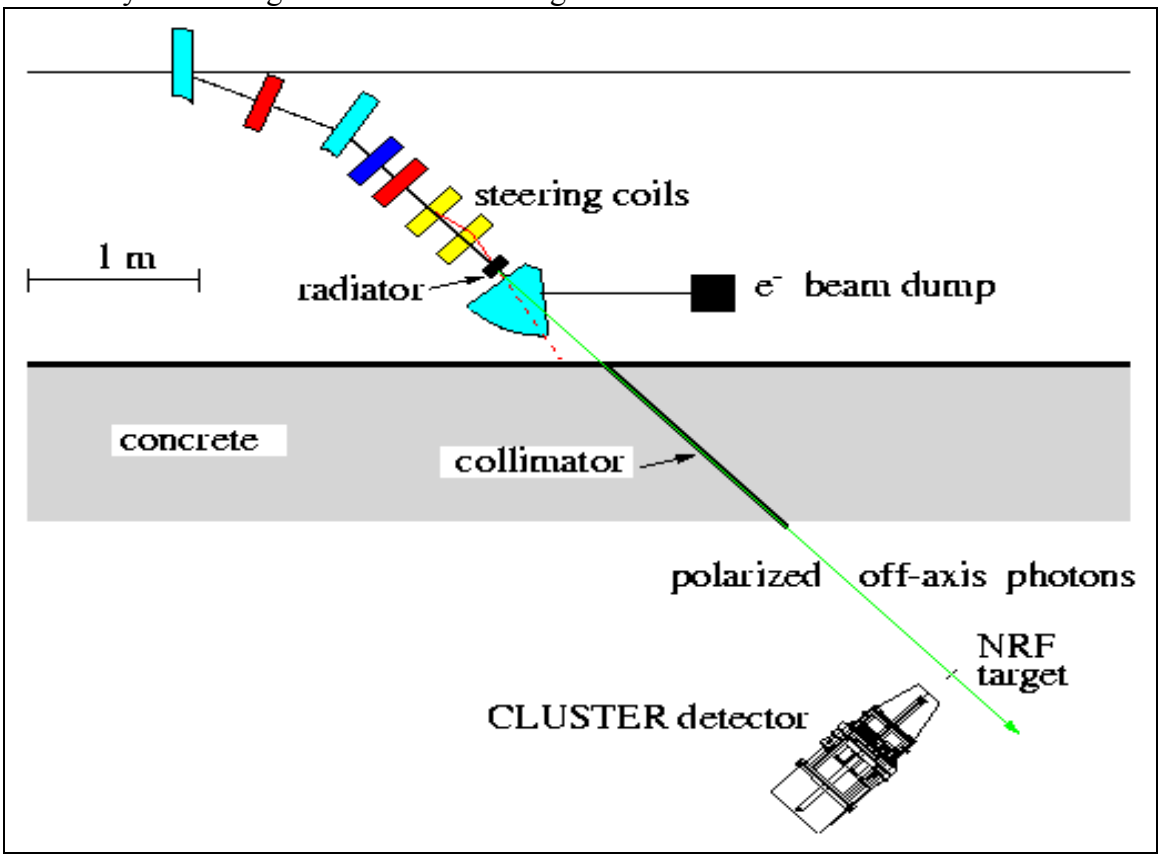

Figure 1. schematic of nuclear resonance fluorescence experiments ELBE (figure copied without permission from http://www.fz-rossendorf.de/pls/rois/Cms?pOid=10568&pNid=0)

A typical NRF spectrum is shown in Figure 2.

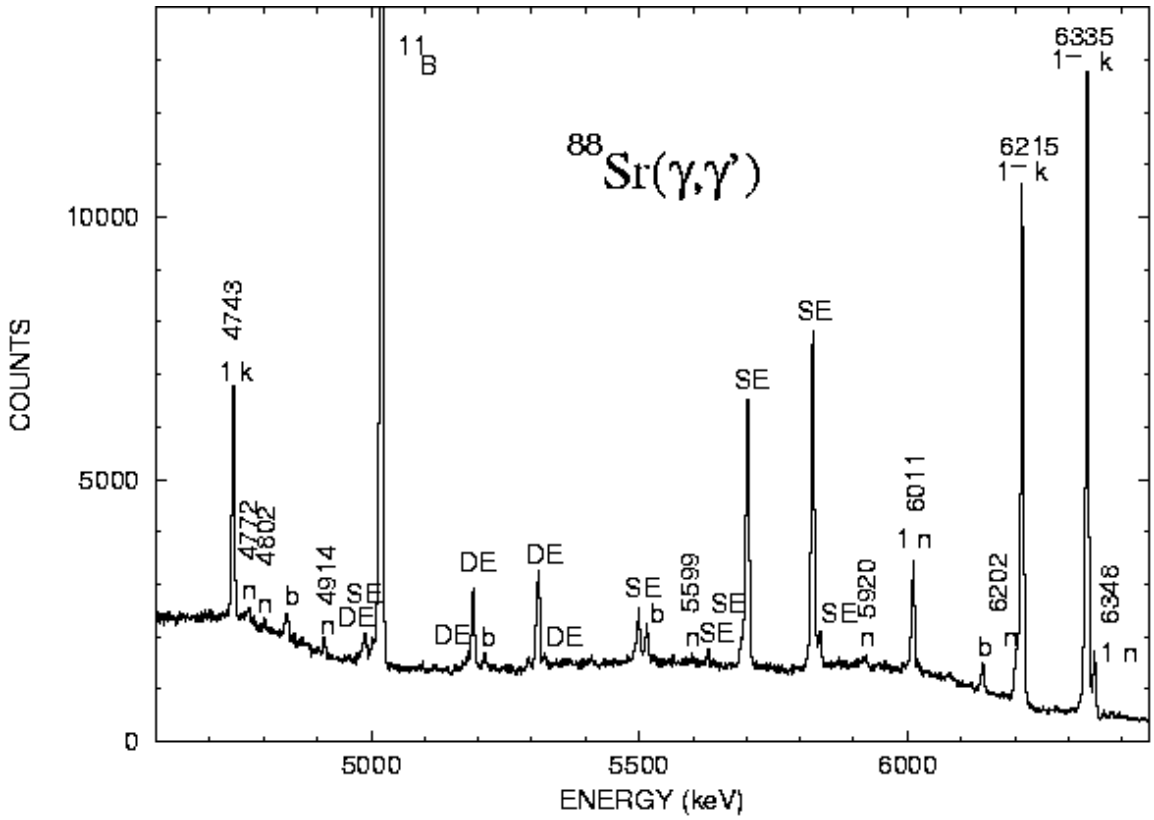

Figure 2. portion of the gamma NRF spectra of ^{88}Sr. (figure copied without permission from http://www.fz-rossendorf.de/pls/rois/Cms?pOid=10568&pNid=0)

The use of nuclear resonance fluorescence (NRF) to detect and characterize hidden materials has been proposed by Prof. Bertozzi of the MIT Bates Linear Accelerator Center (see Figure 3). With a collimated x-ray source it will be possible to not only detect and characterize material with NRF but also to image. We will refer to the overall imaging technique as Fluorescence Imaging in the Nuclear Domain or FIND.

The use of Thomson-Radiated Extreme X-ray (T-REX) sources (a full description of T-REX can be found in the white paper C. Barty and F. Hartemann) for FIND has significant advantages that are primarily the result of the tremendous spectral brightness of the T-REX source relative to anode based machines. The Bertozzi proposal suggests use of a common electron driven Bremsstrahlung x-ray source as the illuminator and requires high resolution Ge-detectors as analyzers. Specific details of the Bertozzi proposal are not available but from his poster and the description of NRF experiments at the ELBE facility in Europe it is possible to make the following back of the envelope comparison of FIND with T-REX as the illuminator and FIND with anode illumination.

Let us consider the task of detecting a 1 cm cubed volume of special nuclear material. From a descriptions of European experimental arrangements for nuclear resonance fluorescence studies, one learns that the collimated output of a high flux anode based machine into a sample area of approximately 20 cm in diameter is approximately 10^7 photons/MeV/sec. (For info on

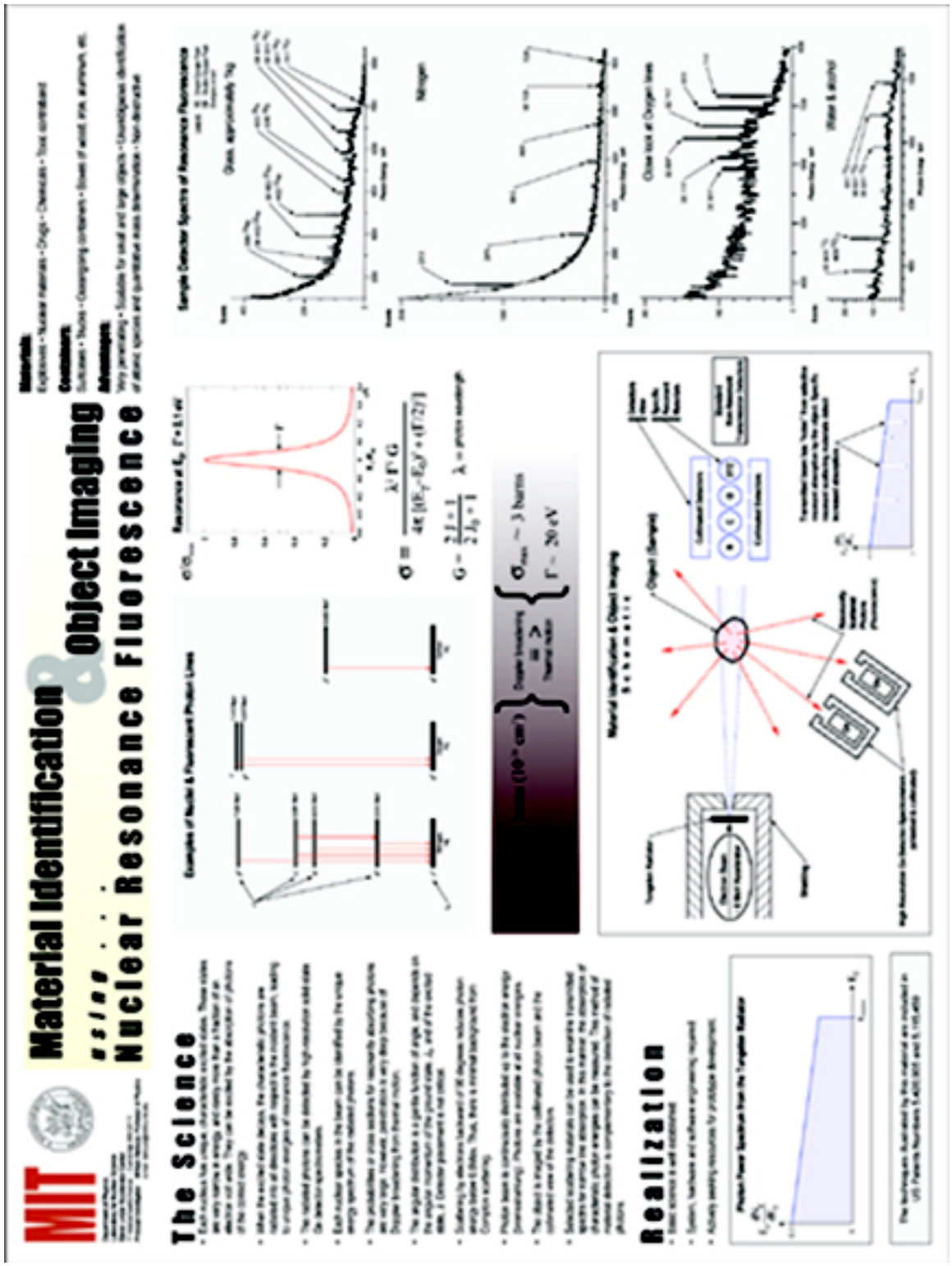

Figure 3. Bertozzi poster suggesting nuclear resonance fluorescence for material identification. This arrangement assumes use of a broadband Bremsstrahlung source.

the ELBE setup see http://www.fz-rossendorf.de/pls/rois/Cms?pOid=10568&pNid=0) In this arrangement the source is located about 3 meters from the interaction region. It is not possible to locate closer due to the shielding and collimation requirements of the source. The typical natural linewidth of nuclear resonances is of order femtoseconds (~0.1eV) or fractionally ~10^-7 at 1 MeV. Doppler or other broadening may increase the linewidth an order of magnitude. One would thus expect of order 1 to 10 photons per transition per second. It is not clear from the web description of experiments what the data acquisition time is for NRF measurements is but the data is presented in terms of 100's to 1000's of counts per transition. If we consider a 1 cm sample size the flux illuminating our test sample is approximately 0.01 photons per second.

A Nd:YAG version of T-REX (see T-REX white paper) is predicted to produce ~10^12 photons per second with a fractional bandwidth of order 10^-3. Therefore a correctly tuned T-REX source would produce between ~10^8 to 10^9 (call it 5x10^8) photons/second within a transition bandwidth of the material of interest. Furthermore the emission cone angle of a T-REX source is ~ $1/\gamma$ where γ is the normalized electron energy (γ = 500 in our example). Locating the source 5 meters from the sample allows ample shielding and produces a 1 cm diameter interaction region. T-REX would produce a useful flux onto the sample that is ~5x10^10 times higher than that from an anode based source. Furthermore because energy-resolving detectors are not needed for FIND with T-REX, lower cost and/or higher efficiency detectors could be utilized. This potentially allows a much greater solid angle of detection. An additional increase in relative performance of FIND with T-REX by another 2 orders of magnitude is thus not unreasonable. In total T-REX could perform FIND with >10^12 times higher signal rate.

It is interesting to note that the cross sections for NRF are large, of order 1 to 500 barns. A 1 cm cubed sample would thus scatter between 5% and 100% of the incident photons. For T-REX this would mean between 2.5x10^7 to 5x10^8 photons per second.

Atomic density of Plutonium = 4.88x10^22 atoms per cc

Un-scattered fraction = $e(-N\sigma L)$ = (5x10^22)(10^-24)(1) = 0.95 for 1 barn

or

Un-scattered fraction = $e(-N\sigma L)$ = (5x10^22)(5x10^-22)(1) = 10^(-11) for 500 barns