The Vanderbilt University Compton Scattering X-Ray Experiment*

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Abstract
The Vanderbilt University Free-Electron Laser Program is developing the capability to create near-monochromatic X-rays for medical purposes. For this experiment we feed-back the normal infrared FEL light to collide with the electron beam. This causes Compton backscattering of the incident photons which creates X-rays. These X-rays cannot feed a X-ray laser, but they have a collimated intensity and tunability which will make them highly suitable for medical imaging and therapy. This paper reviews the present design of the experiment and focuses on the X-ray beam transport to be used. This transport must re-direct the X-ray beam to match a beam chase located in the vault ceiling at an angle of 40 degrees with respect to the electron beam axis. A description of the creation mechanism, X-Ray and electron beam properties are included.

I. INTRODUCTION

Tunable near-monochromatic X-ray beams will be produced by the Vanderbilt Free Electron Laser (FEL) in the near future. A team of physicians and scientists has been formed to complete this project for imaging and treatment of breast cancer. Near-monochromatic X-rays between 14 and 18 keV offer the greatest potential for lowering radiation dose to the breast, while boosting the signal-to-noise in the beam that passes through. As the project progresses, additional research directions will be added. This could include other types of medical imaging and treatment along with various topics presently associated with synchrotron radiation research.

A test stand has been created using a conventional mammography X-ray unit to investigate the various transport components during the development and assembly stages of the project. Initially this stand is being used to measure reflectance of the mosaic crystals discussed later in this paper.

The Vanderbilt University FEL, built by Sierra Laser Systems, is fairly compact and lases in the mid-infrared from ~2 to 8 μm[1]. The operator computer is a Apple Macintosh II-ci running National Instruments LabVIEW 2 software. The electron beam is produced by an ~43 MeV, 2.856 GHz rf traveling-wave linac. This beam is created in an rf electron gun with a LaB6 cathode. The wiggler is a 2.3 cm period, Halbach type, hybrid design, using permanent magnets with steel pole pieces. There are 208 SmCo permanent magnets used in the wiggler. Further details of the accelerator, wiggler, and laser performance have been published elsewhere[2].

II. THE COMPTON X-RAY PROJECT

A. X-ray Creation

When a photon collides with a free electron, its energy and direction change to conserve energy and momentum. When the electron is relativistic, and the photon has a low energy, or $\lambda_L >> \lambda_C = h/mc = 2.42\times10^{-12} m$, where λ_C is the Compton wavelength and λ_L the wavelength of the incident photon, the wavelength of the scattered photon(λ_S) is given by the formula:

$$\lambda_S = \lambda_L(1+\gamma^2\phi^2)/4\gamma^2, \qquad (1)$$

where ϕ is the angle through which the electron is scattered and γ is the Lorentz factor. For an infrared photon with a 2 μm wavelength scattered in the backward direction ($\phi = 0$) by a 43 MeV electron, the wavelength of the scattered photon is 0.7Å. This corresponds to an X-ray with an energy of 17.6 keV. The intense monochromatic FEL infrared beam will be the light source for this experiment. Since this beam is very monochromatic, when combined with the monoenergetic FEL electron beam, the X-rays produced by Compton scattering are quite monochromatic, especially when compared with conventional X-ray sources.

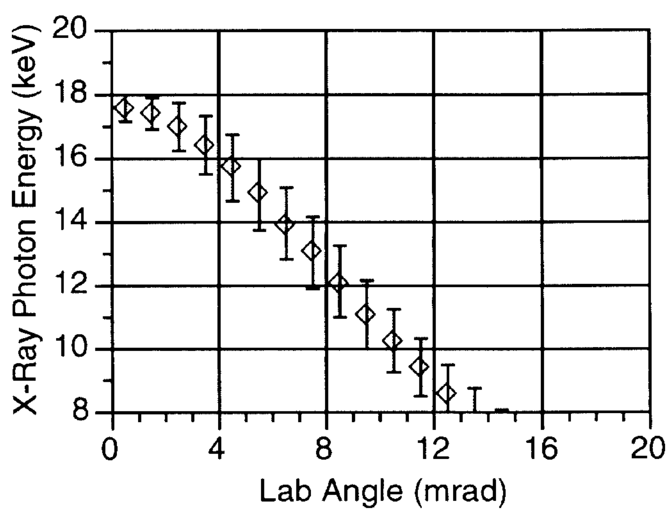

Figure 1. X-Ray Photon Energy Distribution as a Function of Angle.

The electron and the infrared beams will both be focused to create a 40 μm diameter interaction zone. The created X-ray beam will have a specific topology and bandwidth due to the electron beam's energy spread and emittance, and the photon beam's divergence (Figure 1). The central ray and off-axis rays will have a finite bandwidth. The off-axis rays will have decreasing average energy with increasing angle. Bandwidth considerations along with transport restrictions will define a

* Supported by the ONR, contract no. N 00014-91-C-0109.

"usable" containment angle of the beam. Interaction calculations, with a beam emittance of $4\pi \; mm \cdot mrad$ and an energy spread of 0.5% indicate that the Compton scattering should yield ~3.0 x 10^8 photons/sec in a 10 mrad full angle cone. The bandwidth for this X-ray beam is approximately 20% with a central maximum energy of 17.6 keV. By changing the photon wavelength and/or electron beam energy the central maximum can be tuned down to 14.5 keV. Enhancements of the FEL could bring the central maximum energy above 20 keV.

Additionally, Vanderbilt is developing a "Cerenkov-light" pumped free-electron laser resonator using our existing electron accelerator operating at reduced energy[3]. It will be continuously tunable between 200 and 50 microns in the far-infrared. If this beam is used to create another Compton source it could operate in the range from 100-400Å. This type of source could have many applications for additional research.

B. Applications

The creation of a powerful, tunable, near-monochromatic source of medium energy X-rays will herald a new and exceptionally diverse generation of diagnostic medical imaging techniques, as well as creating new therapeutic possibilities. In diagnostic radiology, higher keV radiation is associated with the production of unusable and objectionable scattered radiation. Photons of lower energy may add little to the diagnostic information obtained, but contribute heavily to the radiation dose to the patient. If it is possible to select radiation of optimal energy for the specific procedure, while eliminating those X-rays of higher and lower energy, radiologists and other scientists can significantly enhance their ability to perform very high contrast/low dose imaging. This could also assist in accomplishing *in vivo* trace element analysis and achieve 3-D X-ray imaging. An optimized system for breast imaging using monochromatic radiation such as that described here may reduce entrance exposure to the breast by a factor of 9 to 46[4].

III. THE X-RAY TRANSPORT

The use of the Compton X-ray facility at the Vanderbilt FEL is complicated by the design of the FEL building. The FEL is located in an accelerator vault beneath the laboratory level. In order to make near line-of-sight access between the two levels, a 12" PVC pipe was included within the 6 feet of concrete shielding. This pipe is oriented at an angle of ~40 Degrees in both θ and φ directions of a spherical coordinate system with z being the electron beam axis and x being beam left. Provision must be made to aim the X-rays up the pipe and into the laboratory.

A. Redirecting the Electron Beam

The original design for bringing the X-rays into the laboratory was to re-direct the electron beam along an alternate beamline and aim the electrons up the pipe[5]. The infrared beam would then be aimed in the down-pipe direction from within the vault. After the interaction, the electrons would be re-deflected before reaching the pipe and transported to the beam dump at the end of the vault. This design was abandoned due to the extreme complexity of the alternate beamline along with safety considerations. The design being presently implemented incorporates broad-band mosaic crystals to deflect the X-ray beam after creation.

B. Mosaic Crystals

Crystals with a relatively large mosaic spread can reflect a range of different X-ray energies. This broadening of the crystal bandwidth includes a reduction in the maximum reflection efficiency. When compared to a conventional X-ray source our system is very monochromatic, but compared to an X-ray spectroscopist's needs, it is very broad band. Using the Bragg condition for X-ray reflection from a crystal, we identified a few potential crystals to transport the X-ray beam through the 40° bend. Of the possible choices, LiF and graphite seemed the best candidates. Sparks[6] gives the relative efficiencies of these reflections.

From his data it can be concluded that while the LiF may be very efficient in its near perfect crystalline form, it suffers greatly when modified to allow for a large mosaic spread. The ~0.4° mosaic graphite however should accept most of the 10 mrad divergence cone along with ~1 keV in energy spread (~6% bandwidth which is more than 40% of the photon number shown in Figure 1) and reflect it with 25-50% efficiency. For our present experiments photon quantity is more important than a narrow bandwidth. The graphite mosaic crystals indicate a greater total photon flux delivered at ~6 % energy bandwidth. Four crystals in first order can bend X-rays with energies up to 20.5 keV to the laboratory.

C. Four Crystals in First Order

Sequential reflections from four mosaic graphite crystals can be used to transport the X-ray beam to the laboratory. With a single reflection efficiency of 0.25-0.5 the total efficiency within the bandwidth and divergence acceptance should be between 0.004-0.063. By moving the crystals out of the plane defined by the electron beam axis and the PVC pipe axis, lower energy X-rays can be deflected through the same angles allowing the beam to have a parallel, energy independent, fixed transverse position in the PVC pipe. The beam vectors and crystal normal vectors are easily defined for each energy. This was done with Mathematica and the parameter space of the various crystal positions was explored. For each position and energy a different set of orientation vectors and coordinate positions and z positions was generated.

D. The X-Ray Interaction Zone And Transport

The X-ray experimental setup is shown in Figure 2. This figure is from the mechanical assembly drawings of the modified electron beam-line. Shown in Figure 2 is the electron chicane, the IR transport and the crystals of the X-ray transport. The IR beam is brought within anti-coincidence with the pre-chicane electron beam using a thin beryllium mirror. The IR and electron beams are focussed to a small spot at the interaction zone. The created X-rays pass through the beryllium mirror and a beryllium vacuum window with >80% transmission and onto the mosaic crystal beam transport. The electron beam is deflected before reaching the mirror. Each of the four crystals has its orientation and position controlled by a goniometric stage as shown in figure 3. These stages allow orientation of a normal vector from a point on the front surface of the crystal through a solid angle of 40° by 60°. Coupled with a 25 mm linear stage, each crystal can be placed to allow transport through the 40° bend.

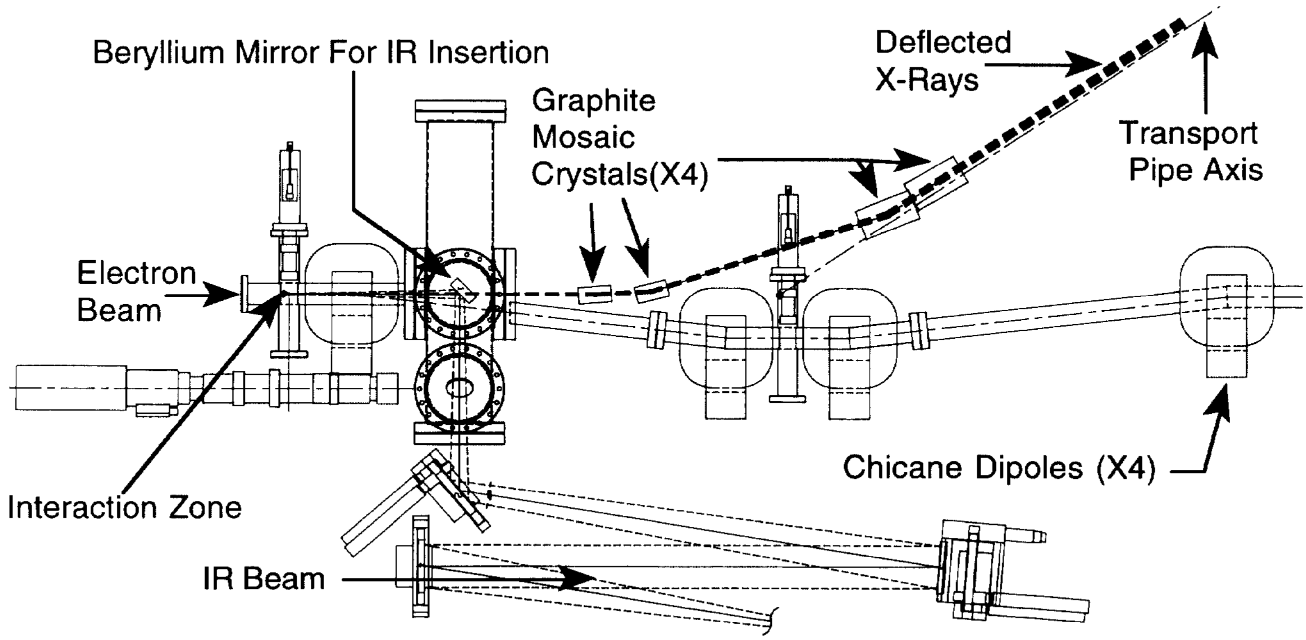

Figure 2. The Compton experiment assembly. This interaction zone and electron Chicane will be inserted into the present electron beamline. The system includes transports for the infrared, X-ray and electron beams.

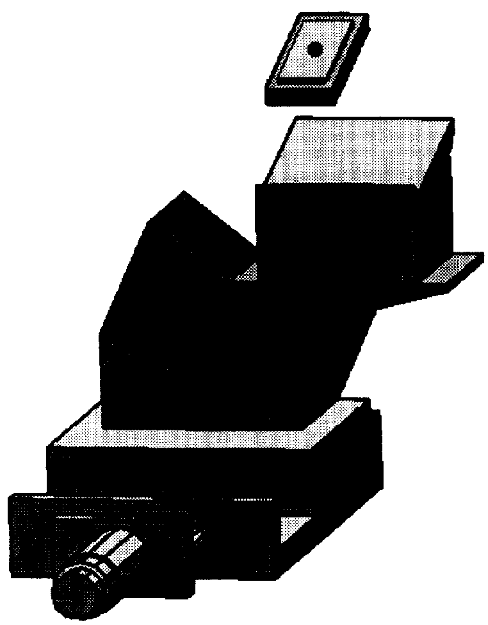

Figure 3. Each crystal will be controlled by a motion control goiniometer combining a 25mm linear stage, an angular shim, two angular stages and a crystal holder. The system is set to allow orthogonal orientation of the crystal.

IV. CONCLUSIONS

Tunable near-monochromatic X-ray beams will be produced by the Vanderbilt FEL in 1993. Interaction calculations, with an electron beam emittance of $4\pi\ mm \cdot mrad$ and an energy spread of 0.5% indicate that the Compton scattering should yield ~3.0 x 10^8 photons/sec in a 10 mrad full angle cone. The bandwidth for this X-ray beam is approximately 20% and should be initially tunable between 14.5-17.6 keV.

The four crystal transport system will accommodate X-rays from 14.5 keV to 20.5 keV with approximately 6% energy bandwidth. With reflectivities between 0.25-0.5 in first order, 4 crystals would transmit 0.004-0.063. Characterization of individual and paired crystals will be accomplished on the test-stand. This beam transport is being readied for insertion into the accelerator vault.

An optimized system for breast imaging using monochromatic radiation such as that described here may reduce entrance exposure to the breast by a factor of 9 to 46 times. Funding searches have been initiated to form this experiment into a compact hospital-sized instrument.

V. REFERENCES

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