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Abstract

Plasmas offer the possibility of high acceleration gradients. An intriguing possibility is using the higher plasma densities possible in solids to get extremely high accelerating gradients. Although solid state plasmas might produce high gradients they would face daunting problems. Crystal channeling has been suggested as one mechanism to address these problems. There is no experimental or theoretical guidance on channeling in very intense electron and laser beams. A very high density plasma in the crystal lattice could quench the channeling process. An experiment is currently under way at the A0 Photo-Injector Test Facility at Fermilab to investigate the upper intensity limit for the production of channeling radiation for electrons interacting with thin Si and diamond crystals. An electron beam with up to 10 nC per electron bunch of 10 ps pulse length will permit investigations of the electron-crystal interaction at charge densities several orders of magnitude larger than observed so far and see if the channeling signal quenches as the bunch charge is increased . The photon flux predicted at these experimental conditions results in 3 x 10^9 photons/sr pulse at a photon energy between 15 and 25 keV. An X-ray camera based on a CCD coupled scintillator-screen device has been specially developed to handle the predicted high photon rates. Later stages of the experiment may attempt solid-state plasma acceleration possibly by looking at head-to-tail effects due to the excitation of plasma wakes.

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1. Introduction

Recently there has been interesting progress in studies of plasma acceleration in gasses[1]. This has been due in part to the development of terawatt laser technology[2] a decade ago. Gas plasmas have already delivered gradients in the 100 GV/m range[3]. Since accelerating gradients are approximately $\sqrt{n}$ V/cm, where n is the plasma density, plasmas in solids can potentially deliver gradients 100 times higher than for gases. For example, for $n_e = 10^{22}/cm^3$, the gradient would be 100 GV/cm.

This possibility of very high gradients has led to speculation about utilizing channeling[4] as an adjunct to solid state plasma acceleration[5]. However at the plasma densities required for acceleration there are severe material limitations. Channeling could mitigate these problems and also introduce focusing to prevent beam blow-up from multiple scattering. There have been no studies of the channeling process under these conditions. At the intensities needed for solid state accelerators there might be significant problems since the crystal lattice could be severely disturbed or even vaporized. As the bunch intensity rises energy loss and plasma generation with the concomitant rise in crystal disorder will cause degradation in channeling[6] so that channeling might be quenched. A hypothetical quenching scenario at bunch charges of $n = 10^{12}$ is illustrated in Figure 1.

If channeling is to be considered for solid state acceleration more information is needed on the character and limitations of channeling under extreme conditions. Although existing channeling theory can serve as a guide, no channeling studies have been done under the non-equilibrium conditions that couple intense electron or laser energy into a crystal. Understanding of the behavior of solids under the conditions required for acceleration is in its early stages[7]. These processes are complicated but have been investigated in connection with terawatt laser technology and pellet fusion.

A systematic study of channeling with increasing bunch charge was carried out at Darmstadt[8] using their superconducting linac. Experiments have also been done at relatively high bunch charge at Stanford on the Stanford Mark III accelerator[9]. Both groups investigated channeling radiation from electron beams in the 5-30 MeV energy region. The experiments were several orders of magnitudes away from the plasma acceleration regime. The data from these experiments are plotted in Figure 1. No corrections have been made for the different conditions (energy, crystal thickness, …) for the two experiments.

The new Fermilab A0 Photo-Injector produces a bunch intensity high enough to approach and possibly enter the plasma acceleration regime. The accelerator typically operates with an energy of 16.5 MeV. An experiment is now underway at the photo-injector to investigate this region. It uses the earlier Darmstadt approach along with two detectors already employed at Darmstadt and the related computer software. Channeling radiation will be measured as a function of electron bunch intensity to investigate whether channeling is quenched as the electron bunch intensity is increased. If crystal disorder reaches the stage where channeling is quenched or extinguished the channeling radiation signal will diminish or disappear.

A later stage of the experiment may attempt solid-state plasma acceleration. Ancillary topics that may be investigated include the use of channeling radiation as a beam emittance diagnostic and the study of beam-solid interaction for picosecond-long, high intensity bunches.

2. The Experiment

Channeling radiation is straight-forward to observe. Particles moving along a crystal plane oscillate about the plane and radiate in the same way synchrotron radiation is produced in an accelerator. The electron beam is deflected by a magnet after it passes through the crystal. The undeflected channeling radiation is detected by an x-ray detector. Channeling also affects the transmitted electron beam. For electrons the multiple scattering increases because the electrons are on average closer to the atomic centers in the plane. This results in a dip in the transmitted beam along crystal planes. For channeling radiation one can study individual transitions (quasi-monochromatic lines), perhaps line widths, evolution with crystal thickness, and the effects of different elements and crystal orientations. In the relativistic regime the "line energy" of the radiation[10] goes as $p^{3/2}$ where p is the momentum. Using different crystals could also provide insights on the role of metals versus semiconductors. Initial studies at A0 will use silicon, although other crystals may be useful to probe factors like lattice vibrations and stopping power. Diamond is particularly interesting because of the high Debye temperature and its ability to withstand radiation damage.

The expected x-ray yield per electron for Si is on the order of 10^{-4} for a crystal about 20 μm thick. The typical number of electrons in a bunch at A0 is expected to be $5*10^{10}$ so that the characteristic number of x-rays per bunch might be $5*10^{6}$. These will be concentrated in a cone that has an angular width of $1/\gamma$ or 30 milliradians. In a pico-second long pulse several thousand photons will strike a 5 mm^2 detector 1 m downstream of the crystal.

The A0 linac emittance will be adjusted so that the angular divergence is less than the channeling critical angle (on the order of 1 milliradian). This will be done by spreading the beam out over a several mm diameter spot. The diameter of the 23 μm thick Si crystal installed at A0 is 25 mm. The normalized vertical emittance of the accelerator beam has been measured downstream of the 9-cell superconducting cavity in the photo-injector using a 6 mm tungsten mask with 50 micron wide slits spaced 0.5 mm apart[11]. The vertical beam spot size at the emittance slit was 1.4 mm (σ). The beamlets that emerged from the slits were measured on an OTR screen 38 cm downstream of the mask. The normalized emittance for a 10 bunch train with 1 nC/bunch was $\varepsilon_{n,y} = 5.5 \pm 0.8$ mm · mrad for typical conditions. This is in line with simulations using the PARMELA program[12].

The bunch length for 5 nC bunches has also been measured using an OTR screen 3.5 m after the 9-cell cavity viewed with a 2 ps resolution streak camera . The measured bunch length was $\sigma_t = 7.1 \pm 0.2$ ps. The driving laser pulse for the photo-injector was measured to be $\sigma_t = 4.1$ ps using the same camera.

Figure 2 shows a schematic of the Fermilab channeling radiation apparatus. This apparatus consists of a crystal mounted in a remotely controlled goniometer, a spectrometer magnet to deflect the electron beam, and two x-ray detectors.

A silicon detector is used to detect individual x-rays and measure their energies with a resolution of 160 eV at 5.9 keV. The detector is sensitive to channeling radiation x-rays in the 10-50 keV range. A Zr, Nb x-ray absorber with a total thickness of 500 μm upstream of the detector with an attenuation of 300 is used to cut the very high rate to a level of one photon per bunch. Channeling x-rays are separated from other sources by scanning through the characteristic channeling angular distribution which has a half width approximately equal to the Lindhard critical angle (on the order of 1.5 mrad).

A second absorption-based, energy-resolved X-ray detector (AberX) is used to measure higher x-ray fluxes where energy-resolved single photon counting is not possible. The system is based on a detector and a technique developed by Freudenberger[13] to study the feasibility of mammography using a lens-coupled scintillating screen CCD. The gadolinium-oxisulphide (Gd_2O_2S:Tb) scintillator has an active area of 50 x 50 mm^2 and is monitored by a slow scan CCD. X-ray energy resolution is achieved by the Ross-filter-technique[14]. This technique takes advantage of the absorption of X-rays by thin metallic foils. As shown in Figure 3, the thickness of pairs of foils made of different neighboring elements in the detector is adjusted to have similar absorption below and above the K-absorption edges of the two elements. After subtracting the intensity transmitted through the foils a signal corresponding only to the energy interval between the edges is achieved. AberX uses a series of critical K-edge absorbers placed on the face of the scintillator. Taking advantage of the homogeneity and the large active area of the detector, any two intensity signals can be subtracted and a number of Ross-filters can be monitored simultaneously. By a proper choice of absorbers it is possible to achieve a detection interval of about 9 to 27 keV covering the entire expected channeling radiation range. The energy resolution is better than 2 keV for the 17 - 27 keV. The detector is able to observe average fluxes larger than about 1000 photons/mm^2/s with any illumination time structure. The system is retractable from the x-ray beam path and operates in air.

3. Outlook

3.1. Solid State Plasma Acceleration

Several approaches to solid state plasma acceleration have been discussed. One, particle wake field acceleration, uses a particle beam as a plasma driver. A laser beam can also be used to drive a plasma. A third approach is to use a side injected laser to avoid problems with pump depletion and particle dephasing[15]. Pump depletion is particularly troubling for the high plasma densities in solids. Approaches using laser beams are limited by the optical absorption depth for materials like Si and Ge as well as surface reflection.

An initial search for plasma acceleration at A0 could be done by using the beam itself to generate a plasma. The associated wake field could affect the tail end of the bunch so that it gained or lost energy. This could be observed using the spectrometer magnet to look for a changing shape of the momentum distribution with higher bunch intensities and with the crystal aligned for channeling or a random direction

3.2 Behavior of Plasmas Generated by Picosecond Beams

The techniques employed for the experiment can also be used to probe the behavior of material in intense pico-second particle and laser beams, thereby opening a window on a variety of material science issues important for advanced accelerator technology. If aggressive solid state accelerator concepts do develop, this type of understanding could be important quite apart from channeling. Two approaches can be used. One is to employ the electron beam itself to alter the material state of the sample crystal in less than a picosecond. The other is to use a laser beam for the same purpose.

For the electron beam case the time distribution of channeling could be investigated by increasing the length of the electron pulse and seeing if the channeling radiation yield increased accordingly. This would be done as a function of instantaneous bunch charge. Most of the relevant solid state plasma processes occur over time intervals of 10-100 fs while the present A0 system operates in the pico-second regime, so that useful studies will require a development of a sub-picosecond capability.

Laser beam pump and probe studies could be done by splitting the laser beam so it could illuminate both the photocathode and the crystal. This splitting might be done prior to laser frequency doubling depending on intensity and wavelength requirements for the laser stimulation beam. An adjustable optical delay would be used to control the relative beam-laser phase. An important factor for laser irradiation will be the optical absorption depth of the crystal.

Time evolution of channeling behavior would be observed by strobing the photo-injector pulse across the laser pulse. The most interesting laser heating regime appears to occur for situations where the intensity is greater than 10^{13} W/cm^2 and the time to significant crystal disorder is less than 150 fs. It is probably still interesting to study less intense cases where effects might extend for picoseconds.

There is an additional practical complication of studies of laser radiation induced effects that must be considered. In part this is a natural aspect of Fourier transform issues related to very short pulses. Any short laser pulse will always have a low intensity foot in front. For very intense laser pulses this foot can carry the material well into the damage regime. Thus one may turn out to be studying laser damage at much lower intensities.

3.3 Other Applications

Channeling radiation may be able to provide sub-picosecond x-ray fluxes that are higher than some other approaches now under development[16]. Sub-picosecond x-ray processes are interesting because they can probe lattice vibration phenomena over a single oscillation. Existing synchrotron light sources are several order of magnitude away from this possibility. Potential study topics include lattice vibration measurements, picosecond time-resolved chemistry, and 3-D motion of atoms. These types of experiments could not be done with the present pulse length at A0 which is currently longer than 1 ps.

Figure captions:

1. Data from previous experiments
2. Apparatus plan
3. Transmission through 35 μm Zirconium (solid line) and 25 μm Niobium (dashed line) foils. The two curves essentially only differ from each other in the region between the absorption edges at 18.0 and 18.9 keV.

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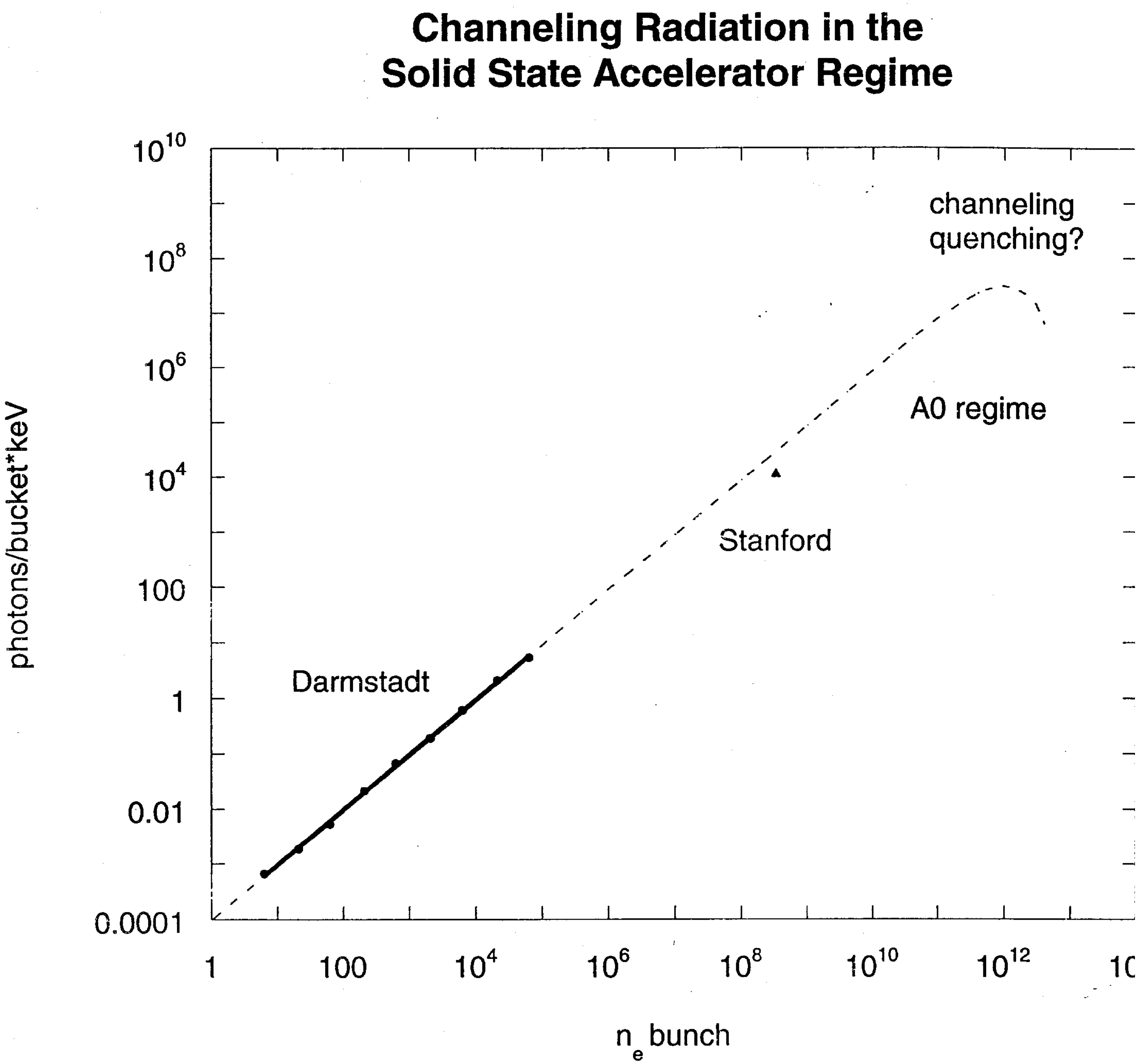
Channeling Radiation in the
Solid State Accelerator Regime
photons/bucket*keV
10^{10}
10^{8}
10^{6}
10^{4}
100
1
0.01
0.0001
channeling
quenching?
A0 regime
Stanford
Darmstadt
1
100
10^{4}
10^{6}
10^{8}
10^{10}
10^{12}
n_e bunch

Fig 1

Darmstadt-Fermilab experiment

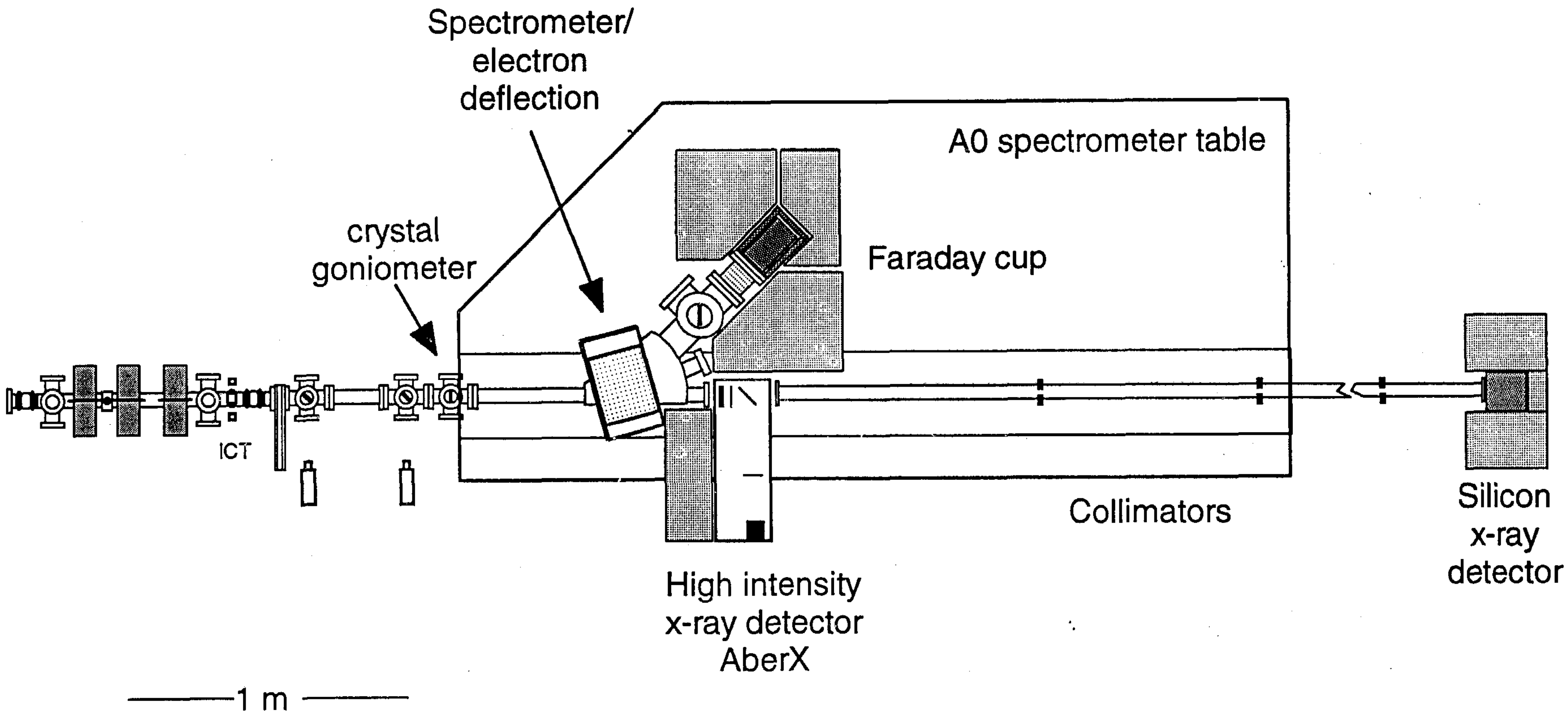

Fig 2

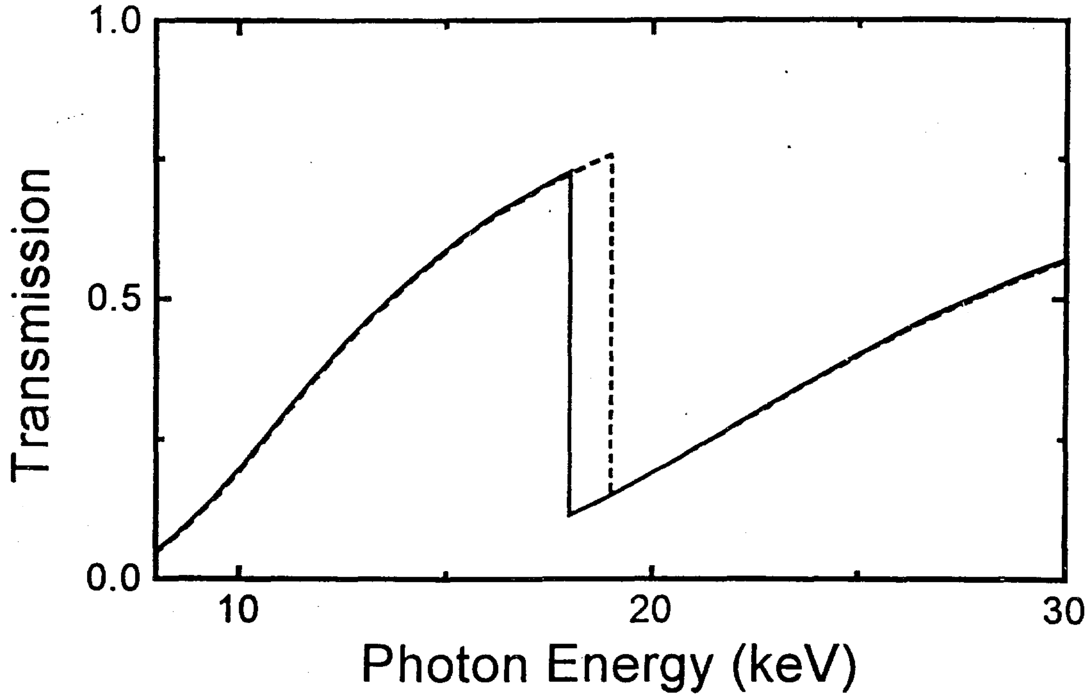

Fig 3