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Report:

X-ray photons of 15.81684 keV have been stored in backscattering geometry between two silicon crystal plates by Bragg diffraction. Depending on the thickness of the plates, up to 14 back and forth bounces, each separated by one nanosecond could be observed. These results demonstrate the feasibility of photon storage by Bragg reflection and are fundamental for a wide field of applications.

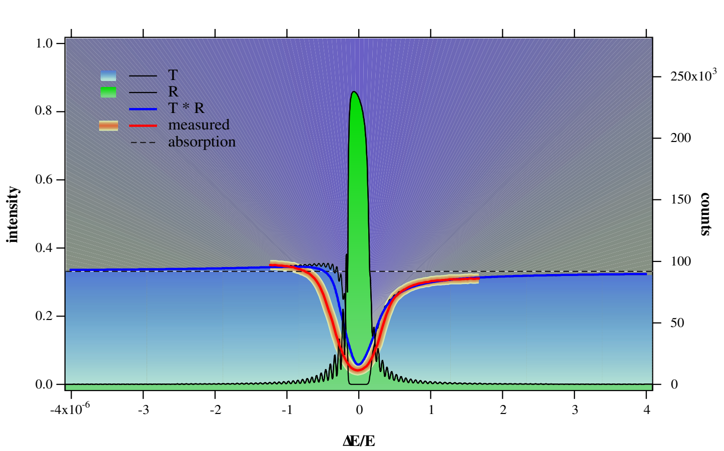

Figure 1: *Calculated reflection and transmission curves R and T of a 2 · 292 μm thick resonator as a function of energy deviation from the center of the Bragg reflection. The Monochromator delivers a similar curve to R, regardless of the small wiggles stemming from the slice thickness, thus the calculated curve for the simulation of an energy scan is the convolution T*R. The experimental data have been adapted to the intensity scale. The dashed line is the absorption far off the Bragg peak while experimental data is consistent with theory for anomalous absorption, the asymmetry around the Bragg position.*

The X-ray resonator consists of a pair of vertical plates cut into a monolithic silicon crystal, separated by 150 mm and with the 111 orientation along their surface normals. The plates are slightly wedge shaped in order to vary the effective crystal thickness between 50 μm and 500 μm by a horizontal translation perpendicular to the axis of the beam. The experiment was performed at the inelastic scattering beamline ID28 at ESRF. Energy resolution of the X-rays from the undulator source was achieved by Bragg diffraction from a Si 888 reflection at a Bragg angle of 89.865°. This provided an X-ray beam of 15.81684 keV with an energy resolution of 3.7 meV and a divergence of about 10 μrad. The absolute energy of the incoming photons could be varied through thermal expansion of the lattice spacing by an accurate temperature control of the monochromator. The resonator was aligned such that photons are Bragg reflected back exactly into the axis of the incident beam and a fast avalanche diode detector was placed behind the resonator, measuring the intensity transmitted through the crystal plates.

The Bragg condition for the resonator was determined by an energy variation of the incoming photons by the controlled thermal expansion of the monochromator lattice spacing. The result of such a scan is shown in figure 1. Exact Bragg condition is fulfilled when the transmitted intensity has a minimum. The observed FWHM on the relative energy scale is $\Delta E/E = 7.4 \cdot 10^{-7}$ and the minimum transmission through the two 292 µm slices is 17 % after consideration of normal absorption.

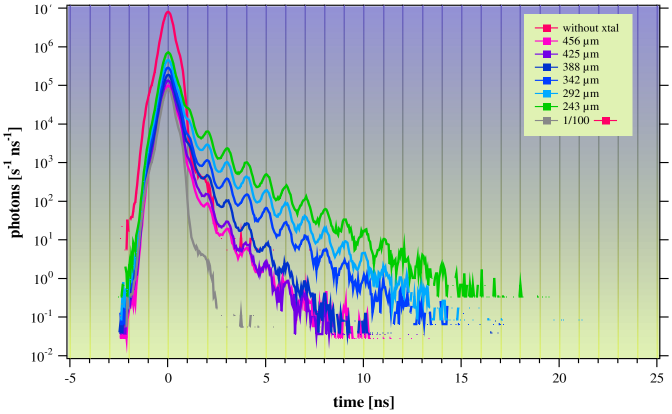

Figure 2: *Time pattern of stored photons at the exit of the resonator. Without the crystal in the beam, only a direct bunch of photons is observed at time 0 while many bunches appear when the device is in Bragg condition. Each peak in later times correspond to multiple back and forth travels inside the device. The widths of the peaks are dominated by the time resolution of the avalanche detector.*

The time dependence of the transmitted beam at the center of the Bragg reflection, i. e. at the dip in figure 1, is shown in figure 2 for various crystal thicknesses. The data was obtained in the ESRF 16 bunch mode where X-ray flashes of 100 ps duration, separated each by 176 ns allow to trigger accurate timing experiments. The time delay between a registered photon and the synchrotron bunch clock was measured stroboscopically. The first curve shows the time structure of the detector without the resonator in the beam. There are no delayed photons and the transmitted intensity maximum defines the zero time. The signal has a FWHM of 500 ps defining the time resolution of the experimental set up. The intensity decreases rapidly and the intrinsic structure arising from intrinsic capacities can be neglected in this experiment. The time patterns with the resonator in Bragg position differ qualitatively from the first curve and show a series of sequential maxima separated by 1.0 ns forming an exponential decay towards longer times. The maxima correspond to photons trapped within the resonator for 1, 2, 3 ... N successive reflections from both crystal plates. When the beam impinges onto the first crystal slice, there is a probability for transmission, the forward diffracted beam. The same holds for the second plate and therefore yielding a maximum signal at t = 0. But there is also a probability for reflection at each slice, permitting part of the beam going back and forth and thus traveling several times the length between the slices, i. e. multiples of 30 cm or of 1.0 ns in time, resulting in the observed peak separations. We observe up to 14 delayed peaks up to 14.0 ns and even intensity beyond for the 243 µm thick crystals. The delayed maxima are less intense for thicker crystal slices because the transmission probability for entering and leaving the resonator goes down, even in the absorptionless case and one has to compromise between transmission and reflectivity.

For the considered reflection the Pendellösung period is 150 µm and a resonator of this plate thickness would reach optimum storage, thus longest delay times. For thicker crystals less and less photons enter or exit the resonator due to back reflection and the total stored intensity decreases. Thinner crystals down to half a Pendellösung period could be interesting for a small number of bounces, i. e. small number of reflections, when higher transmission is advantageous at the cost of reduced reflectivity.

In this very fundamental experiment we have demonstrated the storage of photons up to 14 ns with so far highest energies. High intensity ratios of up to 50 % between neighboring bounces have been observed. Higher number of bounces were observed with thinner crystals. Discrepancies between the observed time patterns of transmitted intensity and calculations based on the dynamical theory of diffraction are most likely due to a slightly distorted resonator crystal.

Publication:

K.-D. Liss, R. Hock, M. Gomm, B. Waibel, A. Magerl, M. Krisch, R. Tucoulou, NATURE, **2000**, in press