ESRF	**Experiment title:** **Subluminal and Superluminal Propagation of X-rays in Cavities**	**Experiment number**: HC 1089
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Names and affiliations of applicants (* indicates experimentalists):

Kilian Heeg*, Lars Bocklage*, Kai-Sven Schulze*, Liudmila Dzemiantsova*, Ralf Röhlsberger*, Christian Swoboda*, Hans-Christian Wille, Kai Schlage, Jörg Evers, Daniel Schumacher, Ingo Uschmann

Report:

In our proposal we suggested a setup in which the group velocity of hard x-rays can be manipulated in a controlled fashion and slowed down to the range of a few m/s.

For the emergence of this effect we envisaged a thin-film cavity (waveguide) with embedded Mössbauer nuclei. This system is probed at the 14.4 keV resonance of ^{57}Fe. Recently, we have opened the field of nuclear quantum optics in this particular setting by developing a theoretical quantum framework [1] and by observing one of the key phenomena of quantum optics, electromagnetically induced transparency (EIT), where an opaque, resonant medium becomes transparent via quantum interference induced in an externally controllable way [2]. EIT is usually accompanied by a reduction of the group velocity of light (see e.g. [3]), however this phenomenon has been elusive to the lower energetic regimes so far.

In the experiment we used a cavity with a single ^{57}Fe layer, which was magnetized along the beam propagation direction. Originally we intended to measure the light which is propagating through the waveguide. However, we found the the coupling efficiencies and therefore the count rates at the detectors are too low. Hence, we focused on the x-rays which are reflected from the cavity, since our theoretical analysis predicted time delays of the same order as in the transmission case.

To suppress the non-resonant background we used a polarimeter [4] consisting of two Si(840) channelcuts in crossed setting with the sample in between. In this configuration the x-rays reflected directly from the cavity surface are suppressed as well and only the photons which have been rotated upon the interaction with the ^{57}Fe nuclei arrive at the detector. By this we can attribute any time delay to the light-matter interaction in the cavity.

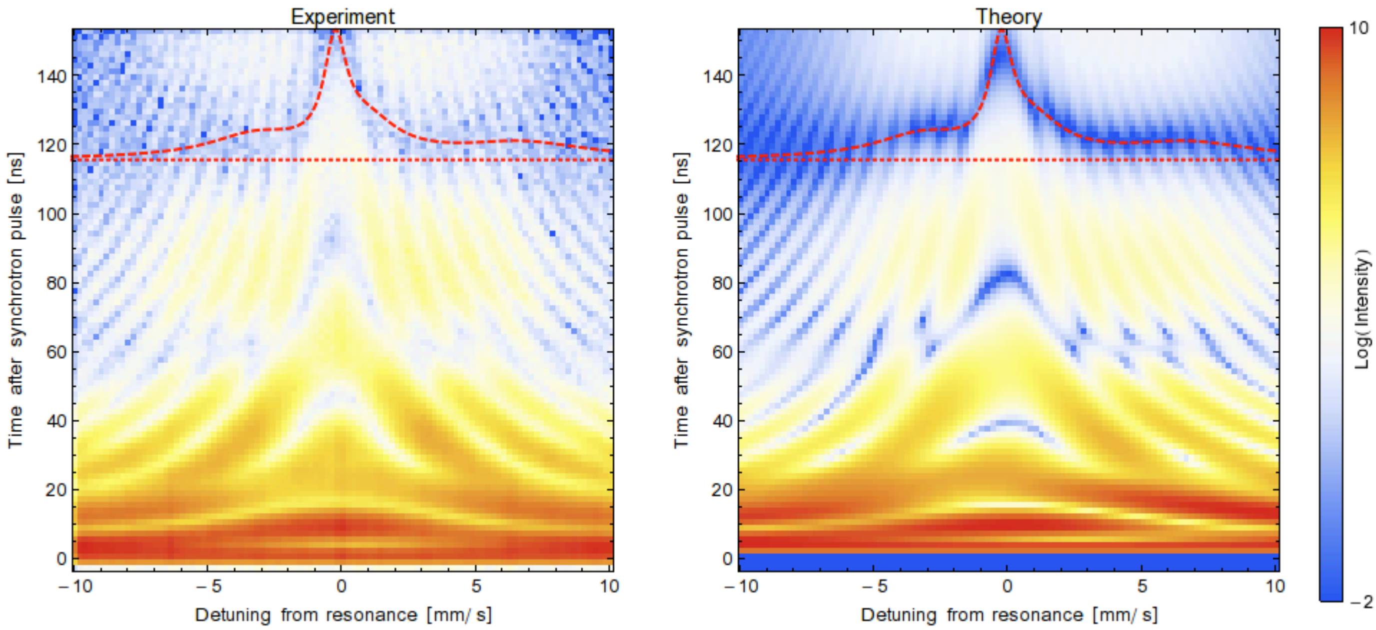

Fig. 1: The time- and energy resolved spectrum of the cavity and the Mössbauer drive. The time response in the center is delayed by ~30 ns relative to the responses at off-resonant driving. The red dashed line is an analytical prediction of the delay, relative to the dotted line.

In order to access the time delay of the light, we placed a thick single-line ^{57}Fe analyser foil which is mounted on a Doppler drive in the optical path. This foil has a characteristic time spectrum which is temporally shifted due to the time delay induced in the cavity. At the same time the Doppler drive allowed us to measure the frequency dependence of the delay. For all Doppler velocities a high-resolution time spectrum has been recorded. We emphasize that the employed cavity features superradiance, i.e. it emits the light on a very fast time scale, and thus a long period was necessary to collect sufficient statistics also for the tails of the spectra.

The recorded spectra together with a theoretical prediction are shown in Fig. 1. Clearly, the response in the center is delayed compared with the time spectra at the edges, which can be seen particularly in the intensity minima (blue color code). A deeper analysis gives the frequency dependent time delay as a function of the x-ray frequency.

Our successful experiment forms the next step towards the exploitation of a large range of quantum optical techniques in the x-ray regime, facilitated by novel experimental setups geared towards the specific properties of Mössbauer science. Since we employ novel experimental techniques which could be ported to other frequency ranges, we expect repercussions on research activities in quantum optics in general. It does therefore not only further extend the field of x-ray quantum optics, but have significant impact also in quantum control in other regimes of the electromagnetic spectrum.

[1] K. P. Heeg and Jörg Evers, *X-ray quantum optics with Mössbauer nuclei embedded in thin film cavities.* Phys. Rev. A **88**, 043828 (2013).

[2] R. Röhlsberger, H.-C. Wille, K. Schlage, and B. Sahoo, *Electromagnetically Induced Transparency with Resonant Nuclei in a Cavity*, Nature **482**, 199 (2012).

[3] L. Hau, S. E. Harris, Z. Dutton, and C. H. Behroozi, *Light speed reduction to 17 metres per second in an ultracold atomic gas.* Nature **397**, 594–598 (1999).

[4] B. Marx, I. Uschmann, S. Höfer, R. Lötzsch, O. Wehrhan, E. Förster, M. Kaluza, T. Stöhlker, H. Gies, C. Detlefs, T. Roth, J. Härtwig and G.G. Paulus, *Determination of high-purity polarization state of X-rays*, Opt. Commun. **284**, 915 (2011).