CASCADE with NRSE: Fast Intensity Modulation Techniques used in Quasielastic Neutron Scattering

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Abstract. Fast intensity modulation techniques require neutron detectors with a response time below 1µs, a demand which can not be fulfilled by standard neutron detector technology. Here we present the CASCADE neutron detector developed at the University of Heidelberg, which is based on stacked, thin ¹₀B layers as neutron converters and particularly addresses these needs. After explaining the CASCADE concept in context with fast intensity modulation techniques we report on two test runs performed at the RESEDA spectrometer at FRM II, Munich, which indeed prove MHz time resolution in this spectrometer system with a reasonably high detection efficiency.

1. Introduction

Neutron Spin Echo [1] (NSE) is a well established high-resolution inelastic neutron scattering technique. In contrast to other inelastic neutron scattering techniques, which measure the scattering function as a function of energy transfer between sample and scattered neutrons, NSE measures the intermediate scattering function as a function of Fourier time. Increasing resolution, i.e. increasing the Fourier time does not decrease the intensity of the incoming neutron beam, because the achievable Fourier time does not depend to first order upon the energy spread of the incoming neutron beam, an intriguing feature of the NSE technique.

All NSE methods base on polarized neutrons and the polarization of the scattered neutrons is the quantity of interest, rather than intensity. Beside the classical NSE technique, which relies upon the Lamor precession the neutron spin undergoes, while flying through static magnetic fields, several advanced schemes exist, which employ resonant spin flips in a magnetic rf-field [2]. Here we focus on one special technique out of several existing Neutron Resonance Spin Echo (NRSE) schemes. This technique is called Modulation of IntEnsity by Zero Effort (MIEZE) [3, 6, 7]. Within the MIEZE schemes, the rotating polarization of the neutron beam is transformed to a fast modulation of intensity by the help of a resonant spin flipper in combination with a polarizer. Thus, in contrast to all other spin echo methods, the change of intensity on time scales from 100µs down to below 1µs needs to be recorded, a demanding task for a neutron detector. While standard ³He-Counters are by far too slow for this purpose, other detection concepts, like the CASCADE scheme developed at the Physikalische
Institut at Heidelberg [4], are well suited for this task. Before we present the CASCADE scheme and its adaptation to MIEZE measurements, we have to discuss the MIEZE principle and the implication for a detector based on it.

2. The MIEZE principle

The MIEZE scheme exists in two variants I and II. For our test experiments we used RESEDA at FRM II, Munich, which is a spectrometer in a standard NRSE configuration. Because modifying a NRSE setup to become a MIEZE II setup requires much less effort compared to becoming a MIEZE I setup, our preferred setup schematically shown in figure 1 was a MIEZE II setup. In addition switching between NRSE and MIEZE II mode allows us to separately determine the performance of the detector and the performance of the whole spectrometer.

The upper part of figure 1 shows the location and polarity of the resonance spin flip coils, while the lower part shows the kinetic energy levels of partial spin-up and spin-down wave functions assumed to form a coherent mixture. A detailed discussion of this full quantum mechanical plane wave approach to NRSE techniques of R. Golub et al. is given in [3].

Neutrons, polarized with respect to the $x$-direction enter the setup from the left side. In the frame of the static magnetic field $B_0$, pointing along the $z$-direction, a neutron is seen as a coherent mixture of a partial spin up and a partial spin down wave packet. While entering the static $B_0$-field of the first spin flip coil, the up component is decelerated due to the field gradient, in contrast to the down component, which is accelerated. This effect is known as the longitudinal Stern-Gerlach effect. After a resonance spin flip, the same happens while leaving the first spin flip coil. Therefore the two partial wave packets spin-up and spin-down leave the coil at slightly different kinetic energy, drifting away from each other during the flight through the zero field region between the spin flip coils. At the end of the first spectrometer arm a second spin flip coil undoes the kinetic energy change, but leaves the two partial wave packets spatially separated. Therefore these wave packets arrive at different times at the sample region and thus probe the sample at different times. This time difference is precisely the Fourier time $\tau_{NRSE}$. In a standard NRSE setup, the two spin flip coils of the second spectrometer arm serve to undo the spatial separation of the partial wave packets and brings them back to overlap, resulting in the same coherent mixture of the partial spin-up and spin-down wave packet as at the entrance of the first spectrometer arm, i.e. the neutrons are polarized with respect to the $x$-direction. The polarization measures the time correlation of the sample at the different scattering times. In a MIEZE II setup the second spin flip coil of the second spectrometer arm is replaced by a neutron detector with a polarizer in front of it. At the location of the detector, the spatial separation of the two

![Figure 1. Scheme of the MIEZE II setup.](image-url)
partial wave packets, which can pass the second polarizer, is undone, but the kinetic energy is still different. So interference between the two partial wave packets surviving the second polarizer leads to an intensity distribution, fast modulated in time with the frequency $f_{\text{MIEZE}} = 2f_r$ ($f_r$: frequency of the rf in the second spectrometer arm) and in space. The wave length of the spatial variation of the intensity along the beam for a given time is to first order approximation given by $\lambda = \frac{v_0}{f_{\text{MIEZE}}}$, where $v_0$ is the mean velocity of the neutron beam. Therefore the spatial extension of the active detection material along the beam has to be small compared to this wave length $\lambda$, in order to avoid damping of the measured modulation through averaging. This is an important issue for the selection of a suitable detection mechanism for high resolution MIEZE applications. As the values of MIEZE frequencies reaches the MHz region, the value of the corresponding length $\lambda$ shrinks below 1mm for cold neutrons, requiring the thickness of the neutron converter inside a detector to be below 100µm.

3. The CASCADE detector
In general, solid converting materials have the advantage that high absorption can be realized over very short distances. Moreover, the thin conversion layers intrinsically provide the potential for sub microsecond time resolution, being necessary for neutron intensity modulation techniques. The CASCADE detector combines and exploits the advantages of gas detectors and the well-defined locus of conversion within solid neutron converting materials. In our case we use isotopically pure $^{10}\text{B}$ with the dominant absorption reaction: $\text{n} + ^{10}\text{B} \rightarrow \alpha + ^{7}\text{Li} + 2.3\text{MeV}$. For a single $^{10}\text{B}$ layer however, the maximum detection efficiency for thermal neutrons is only 5%, caused by the maximum penetration depth of 3.5µm of the $\alpha$ and $^7\text{Li}$ in boron. Therefore adding more Boron layers is imperative to reach a higher efficiency. For a position sensitive area detector, however, such additional layers must be transparent for charge while opaque for neutrons. We resolved this apparent contradiction by employing gas electron multiplier (GEM) foils invented and developed by Fabio Sauli at CERN in 1997. GEMs are micro-structured, flexible foils of a 50µm thick Kapton substrate, sandwiched between 5µm thick copper claddings on either side. The foil is structured with a regular hexagonal grid of 50µm diameter holes at a spacing of 140µm. Depending upon the potentials applied to the two copper claddings on top and bottom, every hole serves as an electrostatic lens, which allows to guide and image charge from one side of the foil through the holes to the other side without loss of in-plane position information. With larger potential differences, the field strength in the holes can be made strong enough to cause charge amplification.

In our test experiments at RESEDA, the CASCADE-MIEZE detector was equipped with these GEM-foils as charge transparent substrates partly carrying boron layers. The GEMs respective the boron layers are stacked one behind the other to cumulate the detection efficiency of every layer of

![Figure 2. Schematic Cross section of the CASCADE-MIEZE detector.](image-url)
1μm boron up to 20% for 5Å at RESEDA. The lateral position resolution is 2.5mm resulting from the ambient pressure of the counting gas. The charges generated by the fragmentation products in the gas spacing of 2mm between successive GEMs are channelled through the GEMs to the readout structure (see figure 2). The overall signal height is set to a convenient level by the potential difference on the Gain-GEMs. The two-dimensional signal readout is realized through a charge-sharing scheme. A cloud of charges when drifting onto the readout structure is collected by 128 x 128 electrode stripes corresponding to both dimensions x and y. Thus, simultaneous registration of signals on x- and y-readout-channels reveal the detection of a neutron at the corresponding (x, y) coordinates.

For MIEZE experiments it is essential to measure the fast oscillating neutron intensity. This requires a high time of flight resolution better than 1μs in case of several 100kHz MIEZE frequency. In addition, the neutron intensity is not only modulated in time but also in space along the propagation direction of the neutron beam. Therefore the thickness of the neutron converter has to be small compared to the longitudinal modulation period in order to avoid contrast damping due to averaging. For example in case of cold neutrons (λ = 5Å, v ≈ 800m/s) the modulation period is only 1.2mm in case of a MIEZE frequency of 654kHz. As a consequence for the CASCADE detector it is necessary to determine the particular boron layer in which the neutron was absorbed. For this purpose the detector is equipped with an additional readout channels sensing the mirror charge induced on each GEM when the cloud of charges passes through its holes. Because of the large capacity of more than 20nF between the copper claddings of a GEM, it is impractical to read the differential signal of one GEM. But also reading out the common mode signal between two GEMs was not successful because of strong AC-coupling. As a solution we introduced an AC-grounded Decoupling-Attenuation-GEM (DAT-GEM) in the detector stack to decouple the different GEMs and their boron layers (see fig. 2). As an alternative concept an AC-grounded grid with 28% optical transmission was successfully tested, where we could show that the passage of the electric field lines through the grid does not influence the decoupling properties. The CASCADE detector system is conceived as a standalone, position sensitive neutron detection device with high time of flight resolution. The sensitive area of 200mm x 200mm is read out on 128 independent channels for each coordinate, resulting in an overall image of 2^7 x 2^7 = 16384 points. The entire electronic readout is directly mounted onto the rear side of the device. To take usage of the high rates detector front, the bandwidth of readout electronics immediately comes into focus. In response to this problem, we decided to pioneer the transfer of highly integrated ASIC-based readout technology from high-energy physics into the field of neutron instrumentation. For the CASCADE detector, the CIPix ASIC, originally developed by the Heidelberg ASIC lab in 2000 for the DESY H1 experiment, is employed as readout device. A single chip provides 64 independent analogue channels comprising pre-amp, shaper and programmable discriminator. Each channel can accept statistical data at a rate of 330kHz at 10% dead time, resulting in an immediate specification for the individual pixel rate capability of the same size, no matter how the pixel is read out. Two-dimensional readout on 128 x 128 pixels is realized through a correlation in time of signals from x- and y-coordinates, using four CIPix chips. The overall detector readout bandwidth is in this case 2MHz at 10% dead time.

Four CIPix chips produce a data output of 3,2GB/sec. Such a challenging data load can only be handled in real time by massive parallel processing. This can be managed nowadays with a one-chip solution using a powerful Field-Programmable-Gate-Array. This FPGA is located in our case directly on the rear side of the CASCADE detector. It collects all the data from all CIPix chips simultaneously, manages the onboard SRAM (8MB) and communicates over an optical link to any PC. As shown in figure 3, inside the FPGA a real time event reconstruction algorithm evaluates the incoming data from the readout structure together with the time stamp information t to one neutron event (x, y, t). The time stamp is derived from a phase-locked-loop (PLL) circuit controlled by RESEDA’s MIEZE frequency f_{MIEZE}. The MIEZE frequency f_{MIEZE} triggers inside the FPGA the internal sweep refresh similar to a chopper pulse in TOF. With the 16-times higher frequency 16×f_{MIEZE} of the PLL the internal time bin counter of the FPGA is triggered. Thus the entire detector electronic runs phase synchronous to the
RESEDA rf-frequency and therefore synchronous to the oscillating neutron intensity. A fifth CIPix chip is used for coincident readout of all GEMs of the stack. These data are evaluated in parallel to identify, in which boron layer n the absorption of the neutron took place. So finally a complete TOF-spectra for each boron layer and each pixel of the readout structure is generated and stored in the SRAM. Communication with the detector module is realized through a fiber optical link, which decouples the system galvanically. It provides a high bandwidth data link (1GBit/sec), which serves to download the histograms of measurements, the module has acquired.

4. Experimental results

Two test runs were performed at FRM II, Munich using the RESEDA spectrometer. The mayor change was to replace the 3He-detector of RESEDA by the CASACDE detector. Depending on the use of the fourth spin flip coil, we could operate in a standard NRSE or. alternatively, in a MIEZE configuration.

In the first test run we used a CASCADE setup, with only one Boron layer. Thus we could verify the proper functioning of the complete setup beside the readout of the GEM stack and the boron layer identification. Figure 4 shows the results obtained at the highest MIEZE frequency, we could obtain at RESEDA. Because the analyzer restricts the neutron beam to a 32mm × 32mm window, only 20 × 20 pixels of the CASCADE detector could be used. Figure 4.b shows the histograms for two pixels. By fitting a sin-function to the phase histogram of each pixel, we could extract the contrast and phase of the intensity modulation for each pixel from the data, shown in figure 4.a and 4.c. The contrast of a MIEZE measurement corresponds exactly to the polarization of a NRSE measurement and can be directly compared. We used this comparison to extract an upper limit of 2% for contrast losses of our
MIEZE setup due to imperfections of the CASCADE detector. The major part of losses of polarization respectively contrast is caused by magnetic stray fields inside the spectrometer. There are reports on other experiments testing the feasibility of MIEZE using scintillation detectors [6, 7]. Unfortunately the information provided by these reports is not sufficient to distinguish between contrast losses due to the detection system and losses caused by other components.

Figure 5.a shows the phase pattern, while we turned the third spin flip coil by an amount of 3.1°. The purpose for these measurements was to demonstrate the capability of a position sensitive detector to measure the contrast in case of strong phase shift across the beam i.e. strongly distorted phase fronts. From this measurement we could extract a mean contrast over the total beam 36.9%. Without a position sensitive detector the contrast would amount to as little as 0.4%.

In the second test run the CASCADE detector was equipped with 4 boron layers as shown in the scheme figure 2. The Measurement of the complete spin echo group averaged over the full beam cross section for each boron layer is shown in figure 5.b. One measurement with the MIEZE setup results just in one Period of the spin echo group. By carefully tuning the first spectrometer arm, we managed to shift the spin echo group period by period through the CASCADE detector, thus by combining all the data we obtained an image of the complete spin echo group shown in figure 5.b. These measurements were performed at a MIEZE frequency of 72kHz. From detailed analysis of the data we could extract an upper limit of 1% for false identification of the converting boron layer, which would result in a loss of contrast.

In addition to results shown in this paper, we compared data taken with the NRSE and the MIEZE setup. We used a standard sample for elastic and one for quasi elastic scattering. The measured polarization, respectively contrast, agrees within a few percent.

5. Conclusion
Our results show clearly that a MIEZE setup with a CASCADE detector has a competitive performance with respect to standard NRSE techniques. The contrast of a intensity modulated signal up to a modulation frequency of 645kHz, was measured, with less than 2% contrast loss attributed to imperfections of the CASCADE detector. A detection efficiency of 20% for the neutrons of 5.3 Angstrom wavelength was observed and is consistent with the particular choice of boron layers and may be optimized.

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