PAPER • **OPEN ACCESS**

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Abstract. We present the basic design of the incoming neutron beam polarizer system recently installed at the TOF spectrometer NEAT at HZB and the first experimental test results. The recent upgrade of the instrument resulted in beam flux on the sample, which is one of the highest worldwide for this class of instruments. The substantial intensity gain obtained in the upgrade provides good conditions for polarized neutron experiments, considering the inherent cuts of neutron intensity by polarizing the beam. The neutron beam polarizer is placed inside a 3.8 m long evacuated neutron "guide changer", which allows us to move into the beam delivery guide one of 3 alternative straight neutron guide sections mounted in parallel on a linear translation stage. The new transmission polarizer takes up the inside volume of a 1.33 m long, 60 mm x 125 mm cross section straight guide portion. The focusing of the beam after the polarizer to the 30 mm x 50 mm sample area happens over a total length of 3.5 m, of which 2.92 cm is a converging guide assembly with m=4 supermirror coating and parabolic end. This guide section leaves 58 cm space between guide exit and sample axis for sample environment equipment, in particular for high field cryomagnets. The transmission polarizer contains 8 "V cavity" channels with non-polarizing supermirror coated, opaque side walls and neutron-transparent Si cavity plates, coated by m=3 polarizing supermirror on both sides. The nominal operational wavelength band width of the polarizer is 2.5 – 8 Å, with measured polarization efficiency between 92 and 96 % for well collimated beam. The beam transmission efficiency for the preferred neutron spin state is about 65 %. The first 110 cm of the neutron spin guide field after the exit of the polarizer is provided by the stray fields of the magnet around the polarizer and of a permanent guide field magnet acting in the same direction. This section contains a wavelength tunable single coil Mezei flipper with flipping efficiency > 99 %. The rest of the guide field magnets are solenoids around the glass neutron beam guide. The supermirror coating in the polarized neutron section of the beam guide has been manufactured using a non-magnetic Ni alloy, the guide exchanger housing and its mechanical parts are made of non-magnetic alloys, primarily stainless steel. The polarized beam delivery system is by now operational and it is available for polarized neutron beam experiments on samples in a magnetic field. A 14 T vertical field cryomagnet is on hand at the HZB Sample Environment Group for use on NEAT. The NEAT sample chamber has been designed and built with non-magnetic or weakly magnetic materials in order to allow both for polarized neutron beam experiments and for polarization analysis work.

1. Introduction

The upgraded NEAT time-of-flight (TOF) spectrometer offers today 75 times higher counting rates in quasi-elastic and inelastic neutron scattering work compared to its performance in 2010 when the full rebuilding started, based on novel design. Its data collection intensity at equal resolution is comparable to the world leading TOF instrument of the same type operated at a reactor neutron source, IN5 at ILL. This shows that the efficiency of the new design overcomes the more than an order of magnitude intensity advantage of the ILL cold neutron source compared to the one at the BER-II reactor at HZB. The upgraded instrument is in full user operation since early 2017. [1]

Using polarized neutrons allows us to extract most valuable additional information from neutron scattering experiments for the identification of the origin of various contributions to the measured scattering spectra. For a polarized incoming neutron beam the elastic and inelastic scattering cross sections will depend on the relative orientation of the neutron beam polarization to the preferred orientation of magnetic moments in the sample in a strong external magnetic field. In such experiments the data collection rate on the TOF spectrometer will scale with the incoming beam intensity on the sample. Thus with its large intensity gain of a factor of 75 compared to a few years ago (and 300 compared to the original status of NEAT when it was commissioned originally in 1995), NEAT now makes possible to make polarized neutron experiments with more than an order of magnitude higher intensity than it was available a few years ago for un-polarized neutron work.

Polarized neutrons are also most instrumental for the identification of nuclear spin incoherent scattering in non-magnetic materials, of which the most significant and important example is the one on H atoms. Here the intensity penalty for the use of polarization analysis of the scattered neutrons (in addition to the polarization of the incoming beam) is particularly high, because commonly the analyzer systems for the scattered beams very strongly limit the solid angle over which scattered neutrons can be polarization analyzed before detection. The high initial intensity of the basic spectrometer thus is even more decisive for successful polarization analysis work. The TOF spectroscopy group at HZB cooperates with FZ Jülich for the installation of a polarized ^{3}He gas cell as large solid angle neutron polarization analyzer on NEAT, with first test experiments envisaged for late 2018.

The present article reports about the design, installation, and first tests of the polarizer system for delivering polarized incoming neutron beam at NEAT. The instrument can now be switched remotely to polarized incoming beam mode of operation within a few seconds and the polarized beam operation is programmable anywhere in the incoming neutron wavelength band of 2 – 10 Å.

2. General layout of the polarizing neutron guide section

One of the advanced features of the neutron guide design at NEAT is the capability of exchanging the last, about 4.5 m long section of the neutron guide by automatic control. This allows us to switch between a point focused beam option for best intensity for small samples at higher energy resolution, and homogeneous beam intensity over 5.5 x 2 cm^2 sample area at lower energy resolution. Part of this latter guide configuration can be exchanged for a guide segment that contains the 133 cm long polarizer guide section within a permanent magnet (cf. Figure 1). The rest of the polarized neutron guide is surrounded by magnets – partly permanent magnets, partly solenoids – as magnetic guide fields for maintaining the neutron polarization in the beam over its propagation from the polarizer to the exit of the guide 58 cm from the sample. From here, the stray field of a high field magnet or of special guide field solenoids attached to the sample environment will guide the neutron beam polarization to the sample. The stray field of a high field magnet around the sample makes sure that on the sample the neutron polarization is either parallel or antiparallel to the magnetic field applied to the sample. The neutron spin flipper to reverse the polarization direction between parallel or antiparallel to the guide field is placed shortly after the polarizer at a distance of 3.2 m in front of the sample. The stray fields of the sample magnets do not interfere with the efficiency of the operation of the distant flipper.

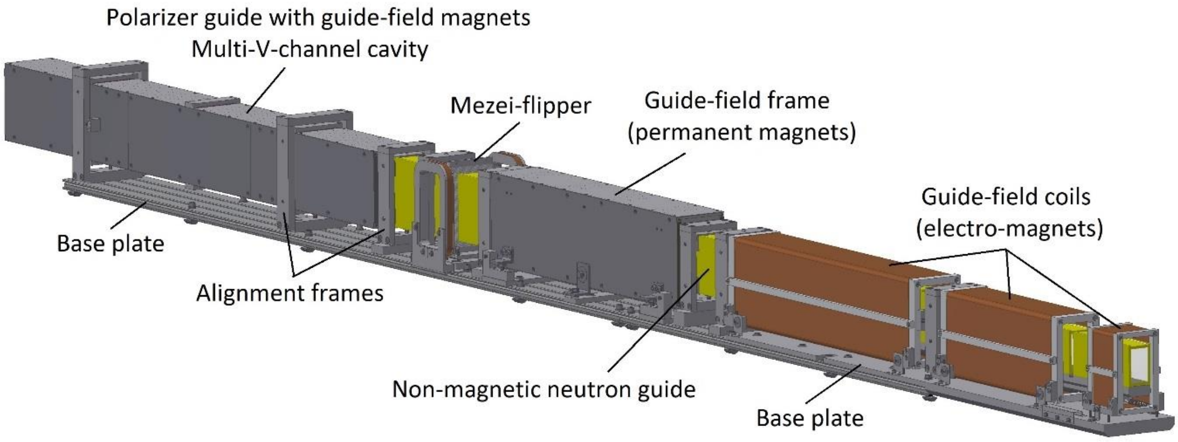

Figure 1. The layout of the polarizer and polarized beam guide, which is situated inside the 3.75 m long evacuated guide exchanger of NEAT

2.1. The multi V-channel cavity polarizer

A key feature of cavity type neutron polarizers [2] is that they are placed inside a neutron guide section and do not displace or deflect the beam compared to the transmission through the neutron guide without the polarizer. The principle of their operation is to remove by deflecting (the large majority of) the neutrons with one spin direction beyond the critical angle of reflection of the neutron guide walls, and thus make them to leave the guide. For this to happen the $\Theta_{guide}^{c} + \alpha < \Theta_{pol}^{c}$ relation has to hold, where Θ_{guide}^{c} and Θ_{pol}^{c} are, respectively, the mirror reflection cut-off angles of the coating of the guide walls and the same for the polarizer supermirror coating on the polarizer mirror plates placed inside the guide with an angle α to the guide axis. Consequently, in the present case, with $\Theta_{guide}^{c} = 1.5\Theta_{Ni}^{c}$ and $\Theta_{pol}^{c} = 3\Theta_{Ni}^{c}$, we find that $1.5\Theta_{Ni}^{c}$ must be $> \alpha = 0.32°$, i.e. for good polarization the neutron wavelength must be > 2.13 Å. Here Θ_{Ni}^{c} is the critical angle for neutron total reflection for a mirror made of natural Ni. Figure 2 shows the typical measured neutron reflectivity characteristics of the utilized, common state-of-the-art polarizing Fe/Si supermirror coating, which is commercially available from a number of manufacturers. The coating was deposited on both sides of the neutron-transparent Si substrate plates, which constitute the polarizing cavities inside the guide. On the other hand, the majority of neutrons with the opposite spin direction are not reflected by these polarizing mirrors, and continue to advance inside the guide by reflections on the guide walls.

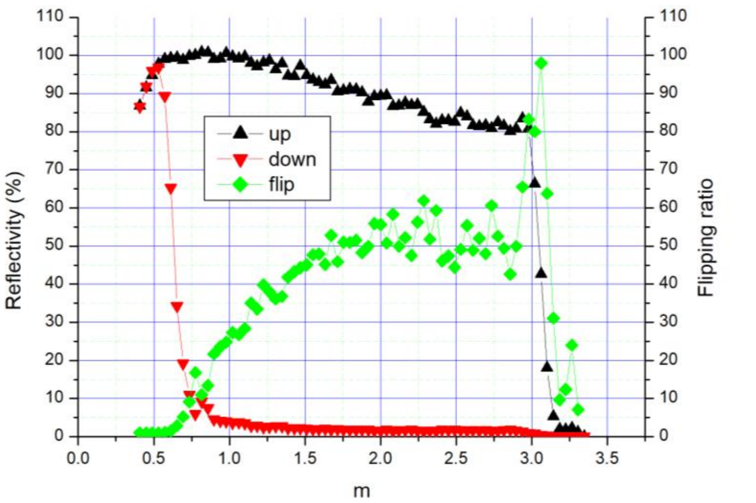

Figure 2. Measured neutron reflectivity for parallel and anti-parallel neutron spin orientations with respect to the direction of the magnetizing field applied to the polarizing supermirror coating (triangles) and the ratio of the two sets of values (lozenges). The abscissa m is the angle of grazing impact of the neutron beam to the polarizer plate in units of Θ_{Ni}^{c}.

Figure 3 shows the present arrangement of the polarizing mirrors in a V shaped pattern inside of 8 identical guide channels within the 125 mm total heights of the NEAT neutron guide. The neighboring guide channels are separated by 0.5 mm thick boron containing, highly neutron absorbing glass walls coated with $\Theta^{c}_{guide} / \Theta^{c}_{Ni} = m = 1.5$ ordinary non-polarizing supermirrors. The polarizer is followed by a $m = 4$ supermirror coated converging guide section that is part of the neutron optical system that focusses the beam to 30 mm height at the sample.

Note that the polarizer is in an environment of asymmetric forward – backward geometry: it follows a constant cross section straight guide section with $m = 1.5$ supermirror coating on the top and bottom and it is followed by a convergent beam focusing guide optics with $m = 4$ coating on the top and the bottom. For this reason it matters for its efficiency if the V shaped layout points forward or backward. The orientation in the figure is the more favorable, and it was used. The side walls of the guide in front (upstream) of the polarizer transport a higher beam divergence due to their $m = 3$ coating. In view of the above consideration on the relation between guide and polarizer coating properties, it would have been more difficult and expensive to build a polarizing cavity with walls oriented vertically, in particular since m clearly > 3 would have been required for the polarizing mirrors.

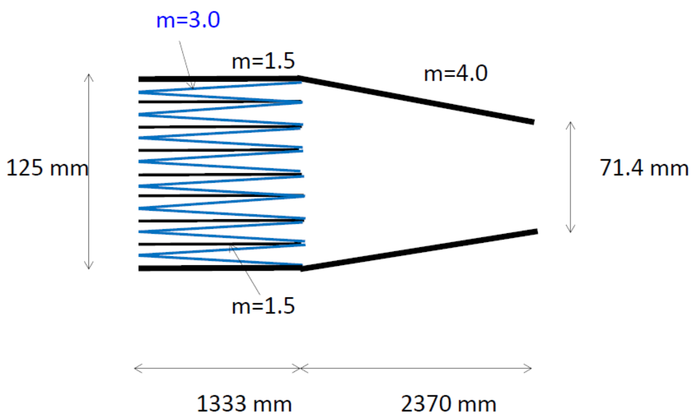

Figure 3. Vertical cut of the polarizer guide section followed by 2370 mm vertically converging guide up to the last pair of chopper discs of NEAT. After choppers #6 and 7# and a position sensitive beam monitor the guide continues to focus by a parabolic section to the sample area of 30 mm height. The V shaped structures with an angle to the horizontal beam axis are made from in total 208 pieces of Si wafers coated on both sides by polarizing Fe/Si supermirrors. The horizontal magnetizing field of 40 mT is perpendicular to the plane of the drawing.

Figure 4. The polarizer guide inside permanent and solenoid magnets in the active position, i.e. in the centre of the guide exchanger chamber (with removed vacuum cover).

Guides designed on the basis of the ballistic principle [3] can be conveniently equipped with neutron polarizer cavities or other supermirror based devices. Namely the ballistic guide concept implies the transport of the beam over most of the distance as low divergence beam in a large cross section guide, and to perform a phase space transformation by the converging/focusing end of the guide to a smaller cross section and higher divergence beam. For example on NEAT the sample positions is at 130 cm distance after the 71.4 mm high exit of the compressor guide on the right hand side of Figure 3. The major part of this distance is equipped with a further converging, parabolic shape guide ending with 50 mm height at 58 cm before the sample area. A supermirror based neutron optical polarizer works the more efficiently and is the more cost efficient to build the smaller is the divergence of the polarized beam to be produced (as it is clear from the basic relation considered above between reflectivity cut-off angles for cavity type polarizers). Therefore the polarizer is best placed in a large cross section portion of the guide.

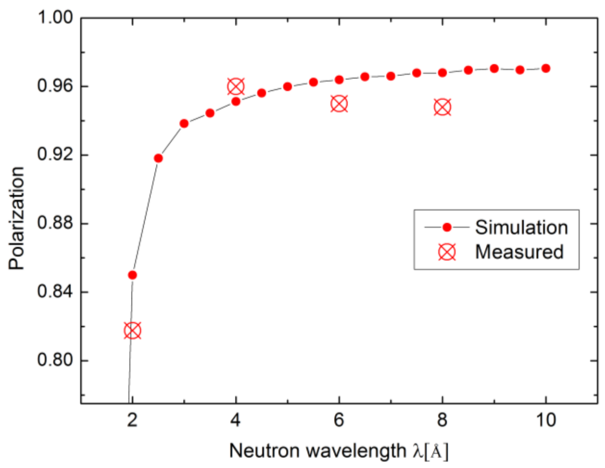

Figure 5. The polarization efficiency of the NEAT multi V-channel cavity polarizer in Figure 3 for well collimated neutron beams at different wavelengths (see in the text). The error of the measurement is ± 0.6 %, about the size of the data symbols.

Magnetic guide fields have to be provided around the neutron guide between the polarizer and the sample area. It has to be assured at the same time that the guide sections downstream from the polarizer do not contain magnetic materials, neither in their supermirror coating, nor in the optical /mechanical support structures. In particular, as it was also done in this case, the non-polarizing supermirror coatings on the guide and guide-channel walls must be manufactured using non-magnetic Ni alloys.

The polarizing efficiency of the polarizer in itself has been first estimated by ray tracing simulation calculations (based on, among other parameters, the performance of the polarizing supermirror coating shown in Figure 2) and determined by measurement with the help of a small beam area polarization analyzer (a single supermirror coated Si plate of known polarizing capability). In these basic experiments a horizontally well collimated beam (~0.2° FWHM, as defined by two appropriately positioned slits) was used without beam compression after the polarizer. Note that a supermirror based polarization analyzer that could handle the larger, (~5° at λ= 6 Å) divergence of the full beam focused to the sample would be a much more challenging technical realization than our polarizer device itself, built for the 3 times lower vertical beam divergence of the ballistic guide. The results shown in Figure 6 display good agreement between calculation and experiment, and the minimum effective wavelength for polarization indeed is close to the 2.13 Å elementary estimation calculated above. There is no intrinsic limitation on the wavelength band towards the higher wavelengths.

2.2. *The neutron spin flipper and guide fields*

The neutron spin flipper is of the type of flat DC magnetic field coils placed with their flat surfaces perpendicular to the neutron beam direction, as first described in Ref. [4] and shown here in Figure 6 in the actual configuration built in the present case. This type of spin flippers allow us to turn the direction of the incoming neutron spin polarization in principle into any direction in space for a well-defined neutron beam velocity. The latter condition is very well fulfilled: the incoming beam of NEAT is monochromatic to a precision better than a few %, and can be freely chosen within a large wavelength range > 1.5 Å. In order to achieve a given spin rotation angle, the magnitude and direction of the essentially homogeneous magnetic field inside the flipper coil has to be adequately set. This can be achieved by varying the horizontal magnetic guide field

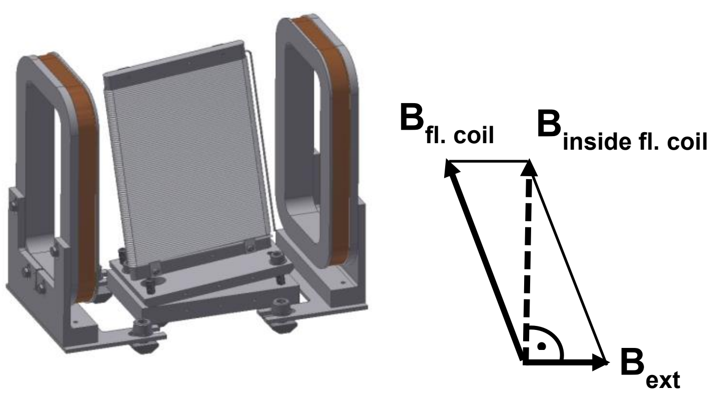

Figure 6. The flipper coil assembly placed at the location illustrated in Figure 1, which is at about 3.2 m from the sample axis. The diagram on the right hand side shows the magnetic field direction inside the flipper coil and its components.

outside the flipper coil by the DC current in the pair of Helmholtz coils and the DC current in the Mezei flipper coil, cf. Figure 6. For a 180° "spin flip" rotation, the field inside the flipper coil must be perpendicular to the (guide) field outside the flipper coil and of the right magnitude for the given flipper coil thickness (5 mm in the present case) and the given neutron beam velocity. It is to be avoided to work with an external field too close to zero around the flipper coil, because this could lead to loss of some beam polarization ("depolarization") outside the flipper coil. For this reason the flipper coil axis is tilted by 6° compared to the vertical direction (see Figure 6), and the vertical field inside the coil is produced as the sum of the non-zero horizontal external field and the field inside the Mezei coil along its tilted axis. To give a specific example, for 4 Å neutron wavelength the vertical field inside flipper coil has to 3.0 mT. At 6° coil tilt angle, this can be achieved as the sum of the flipper coil produced field of 3.016 mT and of 0.315 mT horizontal field at 96° with respect of the axis of the flipper coil, within its plane. The horizontal field from the permanent magnetizing and guide field magnets on both sides of the flipper at 27 and 17 cm distances, respectively (cf. Figure 1), is 0.5 mT at the position of the flipper. It can be tuned to the value needed for the flipper by the use of the Helmholtz pair. The values of the flipper and Helmholtz coil currents for each neutron wavelength are determined by experimentally optimizing the flipper action (i.e. maximal "flipper off" vs. "flipper on" counting rate ratio) and are tabulated for the instrumental wavelength range. The required precision of current setting and stability is ± 0.01 A. For example, for $\lambda = 4$ Å wavelength the required flipper and Helmholtz coil currents respectively are 2.40 A and 0.60 A. The flipper coil is placed in a 12 mm gap in the neutron guide.

The efficiency of the neutron spin flipper has been experimentally separately established on the polarized neutron test beamline V14 at HZB. The standard method was used that consist of calibrating 2 independent flippers against each other in the same beam set-up, observing both of them acting both individually and in combination. The efficiency was found to exceed 99 %.

The polarizer itself was placed inside a permanent magnet consisting of commercial permanent magnet blocks between two steel plates, providing ~40 mT horizontal field perpendicular to the beam direction in the whole volume over the 133 cm length of polarizing guide section, cf. Figure 1. The first section of the guide field after the flipper produced 2 mT field parallel in the direction of the magnetizing field applied to the polarizer. As also shown in Figure 1, this was followed by guide field solenoids around the beam guide, producing 1.2 mT magnetic guide field of direction parallel to the beam propagation. The last of these guide field solenoids (not shown in Figure 1) is placed inside the detector chamber, and ends at 58 cm from the sample. The polarization guide field from the end of this solenoid to the sample (and eventually beyond to the polarization analyzer system) will be provided by the sample environment system. For example, at studying a magnetically polarized sample in a high magnetic field (e.g. using an up to 14 T capability cryomagnet) the stray field of the magnet will largely overlap with the now installed guide field solenoids, and assure a good adiabatic passage of the neutron beam polarization all the way from the flipper area to the sample. No interference to the efficiency of the flipper by the stray field of magnets in the sample environment is to be expected due to the large distance (3.2 m) between the flipper and the sample.

3. Global system performance

In a few first test experiments we have established both an estimate of the beam polarization averaged over the large divergence of the beam at the sample and of the polarized neutron beam scattering intensity compared to the unpolarised neutron operation. For the first purpose, we have determined the beam polarization separately for several (actually 5) horizontally well collimated beams (~ 0.2° FWHM divergence) that arrive to the analyser at the sample stage from different directions within the incoming beam divergence of about 2.5°. The collimation was achieved by a fixed 0.5 mm wide slit just in front of the analysing supermirror (with m ~ 2) on the sample axis, the other – which could be horizontally shifted by a remote controlled translation stage – was 2 mm wide and located at 1.1 m distance upstream. The analyser supermirror at the sample position was individually aligned (by rocking) to the direction of each of these collimated partial beams. NEAT has a continuous, 2D position sensitive detector coverage at 3 m from the sample axis that allowed us to detect without any adjustment the neutron beams from the sample area in all directions. The average of the polarization measured for the different collimated incoming beams spread over different directions within the divergence of the full delivered beam was determined after correction for the separately calibrated polarization efficiency of the analyser supermirror. The average polarization so obtained for the whole beam and the whole system (including flipper operation) is 88.5 % at the 6 Å neutron wavelength used in this multi-beam test. A full test of the delivered beam polarization on the sample position will be performed later this year by using polarized ^{3}He cell analyser (to be provided by JCNS in the framework of our collaboration on polarization analysis in TOF spectroscopy). The polarized incoming beam delivery system of NEAT is now fully operational in the wavelength range 2 – 8 Å, for which the DC current settings for magnetic guide solenoids and the flipper system (flipper and Helmholtz coils) are tabulated for all wavelengths.

The polarized neutron beam intensity has been determined by measuring the full time-of-flight spectrum of water ice as a standard calibration sample. In this test all 3 beam delivery alternatives have been compared: high resolution, high intensity and polarized neutrons. Switching from one mechanical configuration to another can happen within the time of a few seconds, just by remotely moving the neutron guides laterally in the guide changer vacuum box, as shown in Figure 4. In changing from high resolution configuration to the others, in addition the choppers have to be re-phased, with the help of automatic look-up tables in the NEAT control system. It can be indeed observed in Figure 7, that the delivery of polarized incoming beam to the sample is established as a readily available option with modest penalty on data collection rates compared to the top of the line intensity conditions available now at the upgraded NEAT for common, un-polarized neutron scattering spectroscopy. This figure shows that the scattered neutron detection counting rate in polarized neutron mode of operation is 30 % of the high intensity mode counting rate. The NEAT polarized incoming neutron beam configuration without analyser can be useful for identifying magnetic effect on samples that can be magnetically polarized in a high magnetic field.

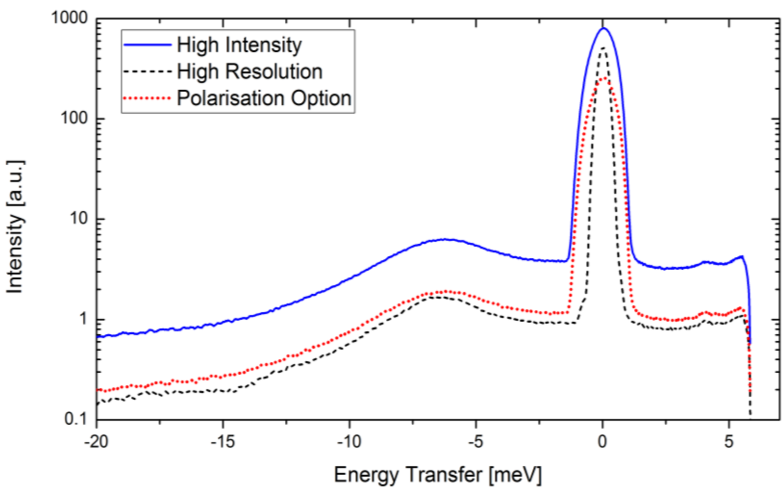

Figure 7. The TOF spectra measured on NEAT with 3 different options of neutron beam delivery that can be interchanged under instrument control commands in a short time.

4. Acknowledgements

This work has been supported by BMBF project # 05K2012 – POLNEAT as part of Rontgen Angstrom Cluster collaboration.

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