New Measurements with a Perfect Crystal Cavity for Neutrons

M.R.Jäkel\textsuperscript{a,b*}, C.J.Carlile\textsuperscript{b}, E.Jericha\textsuperscript{c}, D.E.Schwab\textsuperscript{a}, H.Rauch\textsuperscript{a}

\textsuperscript{a} Atominstitut der Österreichischen Universität en, Stadionallee 2, 1020 Wien, Austria

\textsuperscript{b} ISIS Pulsed Source, Rutherford Appleton Laboratory, Chilton, Didcot, Oxon OX11 0QX, UK

\textsuperscript{c} Institut für Kernphysik, TU Wien, Stadionallee 2, 1020 Wien, Austria

ABSTRACT

VESTA (the Viennese nEutron STorage Apparatus) is an experiment for storing cold neutrons with a wavelength of 6.27 Å, installed at the pulsed neutron source ISIS. A highly monochromatic neutron beam (\(\Delta k/k \sim 4 \times 10^{-5}\)) is trapped by Bragg reflections between two precisely parallel silicon crystal plates in backscattering geometry. Entry and exit of the neutrons into and from the storage system is achieved by using the Zeeman energy shift caused by a short pulsed magnetic field at the crystal plates when the neutron pulse, to be stored or released, is passing by. With a significantly improved signal to background ratio, it was possible to store up to 6 neutron pulses simultaneously for the first time. By varying the storage time separately for each pulse, the feasibility of neutron beam manipulations in time and space was demonstrated. The influence of the magnetic field strength on the transmission of a perfect crystal has been investigated. After optimizing the alignment of the storage cavity, neutrons were stored for up to 4.2 seconds, which corresponds to a flight path of 2.66 km inside VESTA, or to 2500 consecutive Bragg-reflections. Currently, a new storage device, “VESTA Type 2”, is under construction. In this case the energy shift for neutron entry and exit will be achieved by using a pulsed hf-spin flipper and a static NMR magnet. It can be expected that by removing the pulsed magnets of the existing device and by reducing other sources of vibration, the storage time and efficiency can be further improved.

Keywords : Neutron optics, neutron storage, cold neutrons, Bragg reflections, perfect crystals, Zeeman shift, quantum optics

1. INTRODUCTION

The storage of ultracold neutrons within material or magnetic bottles is a well-established technique (e.g. ref.\textsuperscript{1}). In this case the mean optical potential of the storage medium reaches the value of the kinetic energy of the neutrons which causes total reflection at all angles of incidence. The proportion of ultracold neutrons in a thermal or cold neutron spectrum is rather low (10\textsuperscript{-16}) and therefore efforts have been made to develop storage systems for cold and even thermal neutrons. Such a possibility of storing cold neutrons (6.27 Å) by Bragg reflection from perfect crystal plates has been successfully developed and applied over the last few years at the ISIS pulsed neutron source\textsuperscript{2,3,4}. Although primarily designed as a neutron optical device, VESTA could also be used for measuring fundamental properties of the neutron and quantum physics effects. Due to the high number of reflections of neutrons inside the device (several thousand) and the long flight path that results (several kilometers), it has the potential to become a powerful tool for testing neutron guide tubes and mirror materials. The dynamical theory of neutron diffraction can be validated and the scattering properties of diluted gases can be investigated. Of special interest is the question of the storable neutron intensity which is correlated to the accepted phase space density available at present neutron sources. For the storage times so far achieved, the dispersion of the neutron wave packet, representing the stored neutron beam, plays no significant role. It is therefore possible to store more than one neutron pulse inside VESTA while still keeping the packets separated in given volumes of real space. By varying the storage time for each pulse separately it was possible to increase the overall neutron intensity. As a limit, a stationary intensity equal to the peak flux of the source is feasible. This accumulated intensity can be released by a properly controlled magnetic field at the exit crystal, which opens up possibilities for an advanced neutron pulse tailoring device, independent of the source pulse

*Correspondence : M.R.Jaekel; Email : jaekel@ati.ac.at;
WWW: http://www.ati.ac.at/~neutropt/experiments/VESTA/Vesta.html
structure. In this respect many aspects of pulse shaping in charged particle physics can be adapted to the neutron case. Progress in this field may also be of interest for ongoing studies of new pulsed spallation neutron sources such as ESS and AUSTRON. The perfect crystal storage trap also represents a resonator cavity where analogies to the light resonator systems may be drawn. The two level system of neutrons inside a magnetic field permits energy exchange processes with an appropriate resonator coil, which may open perspectives for cooling and pulse compression systems. The phase space density of neutron sources is only of order $10^{-14}$, therefore the Fermion character of neutrons does not yet limit an increase of this value by neutron optical means. Such an increase would be equivalent to a much more costly increase of the primary neutron source strength.

2. EXPERIMENTAL SETUP

VESTA stores neutrons by Bragg reflection from perfect silicon crystal plates (1.064 m apart) in exact backscattering geometry. To ensure their parallelism the two mirror plates are fashioned from a single piece of a perfect silicon crystal and remain connected through a common base. The mirror plates are cut parallel to the (111) lattice planes, which reflect neutrons of 6.27Å at 90° Bragg angle. For a small momentum range of $\Delta k_z/k_z \sim 1.8 \times 10^{-5}$ the reflection probability from a perfect silicon crystal plate is nearly unity and even for a high number of reflections the reduction due to absorption remains small. This effect can be included in the general description of various loss processes during the storage. Located as a secondary instrument at the IRIS time-of-flight spectrometer and using neutrons from a 25K $\text{H}_2$ moderator, VESTA uses a pyrolytic graphite crystal to take around 30% of the neutron intensity in a narrow wavelength range (0.05Å) out of the main IRIS guide (Fig.1).

![Fig.1. Experimental set-up of VESTA. 1: IRIS neutron guide, 2: Pyrolytic graphite monochromator crystal, 3: Perfect silicon crystal mirror plate I, 4: Entrance magnet, 5: Neutron Guide, 6: Perfect silicon crystal mirror plate II, 7: Exit magnet, 8: Detector, 9: High Speed Shutter.](image)

To allow neutrons that fulfil the storage condition to enter the device, short pulses (1 ms) of a magnetic field ($B \leq 1.2 \text{ T}$) are applied when the ISIS neutron pulses reach the first crystal plate. This temporarily shifts the kinetic energy of the neutrons out of the total reflection region of the crystal (see section 5), and enables these neutrons to pass through the perfect crystal. Until another properly timed magnetic pulse is applied at the position of the second crystal plate, the neutrons are stored inside the cavity by successive Bragg reflections. To minimize lateral losses and losses due to gravitational effects a float glass neutron guide tube is inserted between the crystal plates. The silicon crystal and the neutron guide tube define the storage volume (both in real and k space) and are enclosed inside a vacuum vessel ($10^{-3}$ mbar) to reduce the scattering probability of residual gas molecules. Recently a high speed shutter has been installed in front of the storage device to remove the background caused by succeeding ISIS pulses which originate from the 50 Hz repetition rate of the neutron source and disturb the detection of the stored neutrons at specific times.
3. OPTIMIZATION OF THE EXISTING SETUP

Over the last two years many of the system parameters have been optimized including the alignment of the silicon crystal with respect to the incoming beam, the alignment of the neutron guide with respect to the perfect silicon crystal and the timing of the magnetic field pulses.

The alignment of the whole device, and therefore the silicon crystal, to the incoming beam determines the number of available neutrons for the storage process. This was performed by maximizing the incoming and stored neutron intensity. The most sensitive alignment is that of the neutron guide. As expected, it becomes increasingly important with longer storage times since the number of total reflections from the neutron guide surface is of the same order of magnitude as the reflections from the silicon mirror plates. This effect is shown in Fig. 2 for two different storage times. The width of the intensity curve as a function of the angle of alignment \( \theta \) is much smaller than the critical angle, \( \theta_c \), of the neutron guide (6.8 mrad).

![Fig. 2. Effect of the angular alignment of the neutron guide with respect to the perfect silicon crystal for different storage times.](image)

![Fig. 3. Effect of the delay time of the exit magnet pulse after 1024 Bragg reflections.](image)

The time for applying the first pulse to the entrance magnet has also been optimized to match the incoming neutron pulse from the source. It is given by the time that the neutrons need to travel along the 31 m IRIS neutron guide, reflect from the graphite crystal pre-monochromator, and reach the storage device. This time does not vary noticeably. The time for the second magnetic pulse can be calculated by the velocity of the neutrons to be stored and the flight path inside VESTA. For longer storage periods it has now been noticed that this time varies remarkably with temperature, since small changes in the distance between the mirror plates and changes of the spacing of the reflecting lattice plate \( d_{hkl} \) (and therefore the wavelength of the stored neutrons) are amplified by the high number of back and forth reflections. Both effects are additive and shift the arrival of the neutrons to shorter times at lower temperatures. Figure 3 shows typical results for an ISIS hall temperature of 17°C. This effect is significant enough to be noticed when the temperature around the device is changed e.g. by opening the doors of the experimental hall. The new setup will therefore contain an improved temperature control system for the storage cavity.

Since ISIS operates at 50 Hz, there are neutron bursts reaching VESTA every 20 ms. The reflection width of the pyrolytic graphite monochromator is much broader than that of the silicon crystal, causing the major part of the neutrons reflected out of the IRIS guide to pass through the storage system needlessly. Therefore, a pneumatic HIgh Speed Shutter (HISS) has been recently installed. After the passage of the neutron pulse from the graphite crystal into the cavity, the shutter closes within a few milliseconds. The shutter remains closed, thereby blocking subsequent pulses and eliminating background, until such times as the stored pulse is released and a further pulse is allowed into the cavity. The shutter has the effect of decoupling the storage process from the source periodicity. The signal to background ratio was improved by up to several orders of magnitude using this simple device (Fig. 4).

The tuning of the experimental setup led to a new storage record of 4.2 seconds which corresponds to a flight path of 2.66 km inside the storage device. Figure 5 shows the improvements over the last few years, from the early measurements ("Prototype") to the latest results ("Vesta II"). The recently improved signal to background ratio (Fig. 5-b) should, in principle, permit observation of neutrons that have been stored for up to 10 seconds.
Fig. 4. Improvement of the signal to background ratio due to the installation of the high speed shutter. (a) Stored neutrons released between two ISIS pulses after 480 Bragg Reflections. (b) Stored neutrons released after the same storage time since the installation of HISS.

Fig. 5. (a) Stored neutrons per pulse as a function of storage time. (b) Stored neutrons observed after 2500 Bragg Reflections

4. MULTIPLE PULSES

Since every stored neutron pulse has a width of approximately 150 µs (≈ 9 cm), in principle up to 20 pulses can be stacked, separated in space, in the storage volume. This feature is particularly attractive for monochromatic neutron intensity accumulation at pulsed sources. The experimental parameters of VESTA permit to take every second ISIS pulse for simultaneous neutron storage. In the present setup the magnetic field for the gating of the crystal plates is generated by discharging capacitor banks via the electromagnetic coil of the entrance and exit magnets. An auxiliary coil is used to recover the electric charge, presently with an efficiency of 80 percent. Charging the capacitors needs up to 2 seconds, while subsequent pulses used for neutron storage arrive every 40 to 120 ms. Therefore it is not possible to recharge the capacitors during multiple pulse storage. The loss in voltage at the capacitors causes a decreased magnetic field and so the transmission probability of each subsequent neutron pulse is reduced (Figs. 6 and 7).
The dependence of the transmission probability on the magnetic field was calculated and confirmed experimentally (Fig. 7). The maximum magnetic field used for the storage experiments does not quite shift the neutron energy as much as the full Darwin reflection width of the crystal. Therefore, the transmission probability through a single crystal plate is only about 70%.

Another aspect of these experiments is given by the temporal width of the magnetic pulses. By properly adjusting this width, the opportunity for effective neutron beam tailoring is offered. Applying this method, monochromatic neutron pulses of different shapes in time can be generated. For the present experiments the width of the magnetic field was approximately 1 ms. As a consequence of this, up to 3 neighboring stored neutron pulses are affected by one magnetic pulse. The experimental results for 6 simultaneously stored neutron pulses are shown in Fig. 8. The stored neutron intensity varies according to the different transmission probabilities corresponding to the respective strength of the magnetic field at the precise moment when neutrons are incident upon the crystal.

**Fig. 6.** Decreasing magnetic field strength for 6 successive magnetic pulses without recharging.

**Fig. 7.** Transmission probability $T(B)$ through the crystal plates for different magnetic fields. The solid line is calculated, the dots represent experimental values.

**Fig. 8.** Simultaneous storage of 6 neutron pulses. The numbers 1 to 6 signify the entry sequence of the stored pulses.
5. A NEW SETUP FOR VESTA

Up to now the necessary shift of the k-vector out of the total reflection region of the silicon crystal plates ("Darwin Width") has been achieved, at least to a large extent, by applying short pulses of magnetic fields (\(B \geq 1\) T) at the position of the crystal plates when the neutrons are about to enter or leave the cavity. This causes a change of the potential energy of \(\Delta E = -\mu B\) and, due to conservation of the total energy, a change of the k-vector \(\Delta k = \frac{\mu B m}{\hbar^2 k}\). (Fig. 9-a). Both spin states are shifted temporarily out of the Darwin width during their passage through the mirror plate. A second method of gating the neutron storage apparatus is based on a prototype version proposed in ref 7. A static magnetic field produces the longitudinal Zeeman splitting and a single photon exchange with the electromagnetic field of a resonance-coil causes a spin flip (Fig. 9-b, magnetic field amplitude \(B_c\), frequency \(\omega_{\text{rf}}(B)\), effective coil length \(D_c\)). This changes the total energy of the neutron and results in a kinetic energy change at the exit of the static field. Neutrons which initially do not belong to the Darwin plateau region are therefore brought into the total reflection region. The k vector for the whole storage period is changed by \(\Delta k = \frac{2 \mu B m}{\hbar^2 k}\). Again both spin states are affected and can be stored. Even depolarization effects do not change this feature.

![Fig 9. Comparison between (a) the current and (b) the proposed method of changing the kinetic energy to allow neutrons to become trapped within the storage cavity.](image)

This setup has a number of advantages: Only the much lower magnetic field of the resonance coil has to be pulsed (\(B_c < 1\) mT) and the total k shift is twice that of the old setup for the same magnetic field strength. Storage probabilities for those neutrons which fulfil the back reflection condition of about 90 % are expected. By removing the pulsed high voltage components we will eliminate vibrations caused by the pulsed magnets and electromagnetic disturbances, which presently affect the data acquisition.

![Fig. 10. Proposed "Vesta Type 2" setup based on an active neutron magnetic resonance system placed in the middle of the crystal cavity.](image)
The magnetic field will no longer be applied at the position of the crystal plates (Fig. 10) giving better access to the silicon crystal. The switching times will be shorter and the entrance and exit controls will be easier. Pulsed high frequency resonator coils have been tested in connection with the development of fast spin-flip choppers. Since static magnetic fields are used for the Zeeman splitting, there will be no decrease of intensity when storing multiple pulses as described in section 4. The time for switching the hf-coil can be more easily adjusted to the neutron pulse width to permit entry to the cavity and for variable delay times for neutron exit.

6. CONCLUSIONS

The existing perfect crystal neutron storage trap VESTA has been improved to store neutrons over time intervals of more than 4 seconds. It has also been demonstrated that multiple pulse storage is feasible, which opens up new horizons for advanced beam tailoring devices and for a more flexible use of the neutron intensity produced at pulsed sources. The main intrinsic loss factor is associated with vibrations arising from the pulsed magnetic fields needed to introduce neutrons into the perfect crystal cavity. Therefore an alternative filling method based on pulsed high frequency resonance Spin flippers will be used for the next version of VESTA. Better vibration isolation from the ground, better vacuum and temperature stability conditions and an advanced positioning system will increase the performance of the new system to achieve storage times up to 10 seconds and Q-factors in the order of 104. In this case more quantum cavity phenomena known in atomic laser cavity physics can be adapted to the neutron case. One project under preparation deals with realization of the ZENO-effect experiment where the transition between the two Zeeman levels should be inhibited by successively applying only small spin rotations at each neutron passage. The related freezing of the initial state, in the case of continuous measurements, is rather controversially discussed in the literature (e.g. 11).

7. ACKNOWLEDGMENT

We are pleased to acknowledge that this work has been supported by the TMR European Network PECNO (Perfect Crystal Neutron Optics, ERB FMRXCT 96-0057) and by the project "A perfect crystal neutron accumulator" of the Austrian Fonds zur Förderung der wissenschaftlichen Forschung (project No. 13332-PHY) and we thank ISIS staff for their support.

8. REFERENCES