Neutron beam tailoring by means of a novel pulsed spatial magnetic spin resonator

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Abstract. Since long neutron spin resonance in an arrangement of crossed homogeneous and spatially alternating transversal magnetic fields is known to allow for wavelength-selective polarisation manipulation. Combined with a pair of highly efficient polarising supermirrors it is an elegant method to single out a specific wavelength from an initially polychromatic polarised neutron beam, based upon the fact that in its rest frame each neutron creates its individual frequency. A spin flip process can then take place only if this individual frequency equals the neutron Larmor frequency in the homogeneous field. Here, we present the first experimental results we have obtained with a conceptually novel type of such spatial spin resonator, consisting of a series of separate modules which can be controlled independently from each other. Thus it becomes possible to vary e.g. the amplitude distribution of the spatially alternating transversal field without any geometric modification of the setup. Moreover this device fulfils the requirements for fast electronic switching of each module, which will be an important asset for the possible decoupling of the minimal neutron pulse duration and the achievable wavelength resolution. We compare the actual performance of this prototype resonator system with the theoretically expected behaviour.

1. Introduction
Spatial magnetic neutron spin resonance, first proposed more than four decades ago by Drabkin [1], is a meanwhile well understood method to achieve wavelength-selective spin flipping of polarised thermal and cold neutron beams [2, 3]. Combined with a pair of polarising supermirrors it has found since then a series of applications, as e.g. a neutron monochromator with variable output wavelength at fixed take-off angle [4–6], as an electronically tunable energy analyser in inverted geometry neutron time-of-flight spectrometers [7], or as neutron time-of-flight focusing device [8]. Essentially stimulated by the implementation of new generations of pulsed high-flux neutron sources, there is a still ongoing development [9, 10] and an increasing need [11] of high performance supermirror arrangements and of increasingly sophisticated polarisation manipulation devices. Probably the most appealing feature inherent to a spatial magnetic spin resonator becomes evident if it is operating in a chopped mode, namely the potential feasibility of decoupling its wavelength resolution from the minimally achievable duration of the transmitted neutron pulses. Following this goal we have realised a novel design of such a resonator, based upon a sequence of individually switchable stages, each consisting of a low-inductance single-turn aluminium coil. Although it has not yet been optimised with respect to fast beam chopping [12], this prototype resonator allows for a wavelength-selective creation of
neutron pulses of virtually arbitrary length. The first instalment of this novel type of resonator in a real experiment is envisaged for the setup of the PERC (Proton Electron Radiation Channel) project [13, 14], which searches for new physics beyond the Standard Model of particle physics via ultra-high precision measurements of the beta-decay of free neutrons. Here we present the essential conceptual details of the magnetic field design of this resonator prototype as well as first experimental results, both in static and pulsed mode of operation.

2. Design of the resonator prototype

Without going into detail, we just remind that spatial neutron spin resonance is based upon the nuclear magnetic resonance-like superposition of a static field $B_0$ and a crossed time-dependent magnetic field $B_1(t)$, with the conceptual difference that here - in the most simple arrangement - the transversally oscillating field component is just produced by a zigzag-folded conducting aluminium foil, so that according to its speed (viz. wavelength) each neutron in its own rest frame creates its individual frequency $\omega(\lambda)$, governed only by the spatial period $2a$ of the conducting foil. A complete polarisation reversal takes then place if $\omega(\lambda)$ equals the Larmor frequency $\omega_0 = |\gamma|B_0$, which is controlled by the strength of the static field ($\gamma = -1.83 \times 10^8 \text{s}^{-1}\text{T}^{-1}$), and if the amplitude of $B_1(t)$ is properly tuned so that upon passage through the oscillating field region a total spin rotation angle of $\pi$ (or odd multiples of $\pi$) around $B_1$ is accumulated. Disturbing subsidiary maxima of the spin-flip probability, which can be attributed to cut-off effects in the Fourier spectrum of $B_1(t)$, can be suppressed quite effectively by appropriate amplitude modulation of the transversal field oscillations [15].

Figure 1. Schematic sketch of the experimental setup at the polarised neutron beamline of the 250 kW research reactor of the Vienna University of Technology. 1st and 2nd order Bragg reflection at the (002) lattice planes of a highly oriented pyrolitic graphite single crystal delivers a dichromatic incident neutron beam ($\lambda_{1,2} = 2.6 \pm 0.04$ and $1.3 \pm 0.02$ Å, respectively). The resonator prototype, composed of 10 separate single-turn coils of $a=1$ cm thickness (each made of a 0.3 mm thin aluminium foil) is placed between two polarising supermirrors acting as polariser and analyser, respectively. A rectangular Helmoltz-type coil pair (not shown here) produces a variable vertical homogeneous field $B_0$ whose strength determines the ‘resonance’ wavelength $\lambda_0$, where the spin-flip probability of the resonator reaches its (sharp) maximum. A standard DC spinflipper is used only to determine the polarisation degree of the beam as well as the spinflip efficiency of the resonator, but is otherwise not activated (see Subsection 3.1).

The design of a prototype of a spatial magnetic spin resonator requires hence two major steps: i) to calculate for each specific resonator configuration the three-dimensional magnetic field distribution both for the static field that is produced by a Helmoltz-type coil pair and for the spatially alternating field generated by the sequence of resonator elements, and ii) then to solve the spin equation of motion along many possible particle trajectories. In a previous work [11] magnetic field simulations for a neutron spin resonator for the above mentioned PERC project have revealed that a thickness $a=1$ cm of each resonator element should be quite appropriate
Figure 2. Detailed sketch and photo of a single-turn coil. For the present prototype setup the coil current is supplied just via point contacts.

Figure 3. (Left) Simulated transversal magnetic field distribution of the resonator prototype without (‘rectangular’) amplitude modulation and with ‘Gaussian’ shaped amplitude. The two other field components are small and hence not explicitly shown, but they were taken into account in the derivation of the final polarisation vector. Notice that each resonator period requires two single-turn coils producing oppositely oriented transversal fields. The coils are numbered consecutively from 1 to 10. (Right) Numerical integration of the spin equation of motion yields the expected polarisation of the neutron beam after its passage through the respective field configuration.

to flip cold neutrons with a central wavelength of 5 Å. However, at the tangential beamline of the 250 kW research reactor of the Vienna University of Technology no cold source is available. Hence, we use a dichromatic 2.6 Å and 1.3 Å thermal neutron beam produced by 1\textsuperscript{st} and 2\textsuperscript{nd} order Bragg reflection at the (002) lattice planes of a highly oriented pyrolithic graphite single crystal. To achieve similar conditions as within PERC, we selected the 2.6 Å component of the
Figure 4. Simulated exit polarisation of a beam initially fully polarised in vertical direction after its passage through the resonator along different neutron trajectories. While the field is obviously very homogeneous in z-direction, it decreases quite strongly towards the borders in y-direction [12].

spectrum to evaluate the performance of a prototype resonator which consists of 10 individual single-turn coils, each with a thickness $a = 2$ cm (see Fig. 1). In Fig. 2 the geometry of such a single-turn coil is sketched and illustrated by a photo.

According to the chosen geometry of the resonator elements as well as their total number, the wavelength resolution would be given as $\Delta \lambda / \lambda = 0.68 / n \approx 13.6 \times 10^{-2}$, where $n = L / 2a$ is the number of resonator periods, provided a polychromatic incident beam is available. In our case, however, the actual wavelength resolution is defined by the spectral width $\Delta \lambda_M$ delivered by the monochromator crystal. The main purpose of the simulations presented here was to find a resonator configuration which is just sufficient to invert the polarisation of the 1st order neutrons with a wavelength of 2.6 Å, and to obtain a detailed knowledge of the homogeneity of the magnetic fields following from the specific geometry of this resonator. Using the CST-Studio Suite™ the three-dimensional magnetic field distribution was simulated both for 'rectangular' and 'Gaussian' shaped amplitude modulation of the transversal field oscillations. Subsequently, assuming an incident beam fully polarised in z-direction, all three components of the polarisation vector behind the resonator were calculated for a band of wavelengths ranging from 1 to 4 Å by means of numerical integration of the spin equation of motion $d\mathbf{P}/dt = \gamma \mathbf{P} \times \mathbf{B}$. In Fig. 3 both the transversal field component $B_1(x)$ along the beam axis and the resulting polarisations are shown for these two different resonator configurations. In order to quantify the homogeneity of the magnetic field, a series of simulations for different neutron trajectories through the resonator were performed. Their results are plotted in Fig. 4. It is clearly seen that the simulated results for neutron trajectories at distances of up to 4 cm off the center in z-direction and of up to 1 cm in y-direction are completely indistinguishable from each other. Since in our experimental setup the dimensions of the neutron beam are 2 cm in z-direction and 1 cm in y-direction, one can thus expect that for both field configurations the flipping efficiency of the resonator will be definitely homogeneous over the whole beam cross-section.

3. First experimental results
The resonator prototype was built as exactly as possible according to the underlying design simulations: i.e. 10 individually switchable single-turn aluminium coils with a foil thickness of 0.3 mm, a height of 120 mm, a lateral dimension of 60 mm and a downstream thickness of 20 mm. To avoid electric short-circuits a gap of 1 mm between neighbouring coils was established by thin insulating frames. As sketched in Fig. 1 the resonator is placed between two between two
polarising supermirrors acting as polariser and analyser, respectively. A rectangular Helmholtz-coil pair is used to define the resonator’s static magnetic field $B_0$, which is required to guide the neutron spin as well as to define the resonance wavelength $\lambda_0$. The strength of the spatially alternating field $B_1$ is controlled by the (individually tunable) current that is fed to each sub-coil of the resonator. Each coil can be powered with a current of up to 15 A in order to create a magnetic field of up to 0.25 mT. Due to the already mentioned lack of a ‘white’ neutron beam we tuned the static field $B_0$ to match the resonance condition for neutrons with 2.6 Å wavelength. In Fig. 5 the transmitted neutron intensity is plotted as a function of the DC current in the

![Graph showing transmitted neutron intensity as a function of $B_0$-field-current (A)](image)

**Figure 5.** The amplitude of the alternating field $B_1$ of the resonator prototype was modulated according to the different shaping functions shown as insets. A ’Gaussian-shaped’ field indeed minimises the disturbing subsidiary maxima (viz. intensity minima) in the spinflip efficiency compared to the case of no amplitude modulation (open squares). However, as expected, an ’inverse-Gauss-shaping’ leads to a drastic enhancement of these disturbing maxima.

Helmholtz-type coil pair both without (i.e. ‘rectangular’) and with ‘Gaussian’ shaping of the alternating field amplitude. For purpose of demonstration the effect of ‘inverse’ Gaussian shaping is shown too.

Additionally, in order to resolve the two discrete spectral components of the incident dichromatic neutron beam, a mechanical Fermi-type neutron chopper was used to perform neutron time-of-flight measurements. As can be seen explicitly in Fig. 6, tuning the resonator to one of the two available neutron wavelengths strongly suppresses the respective spectral contribution. The inset shows the operational simplicity and hence reliability of the corresponding tuning procedure.

### 3.1. Resonator efficiency

To analyse the efficiency of the resonator a second spin flipper was used, in this case a simple standard DC coil flipper. From the combination of four different neutron intensities accumulated during successive experimental runs with $i$ both the resonator and the DC flipper turned off ($I_0$), $ii$ with inactive resonator but activated DC flipper ($I_F$), $iii$ with activated resonator but inactive flipper ($I_R$), and $iv$ finally with both devices activated ($I_{RF}$) one can use the following...
Figure 6. \(\text{Left}\) Results of time-of-flight measurements using a mechanical chopper when the resonator is not activated. The two available spectral contributions are clearly separated according to their different arrival times at the detector. \(\text{Right}\) As expected, activation of the resonator and tuning it to a resonance wavelength of 2.6 \(\text{Å}\) minimises the contribution of the corresponding spectral component. In the inset the detected count rate is plotted against the DC current that is fed to the Helmholtz coil pair which generates the static resonator field \(B_0\) and thus defines the respective resonance wavelength.

relations to determine the efficiencies \(e_R\) and \(e_F\), respectively, of both the resonator and the DC flipper, as well as the product \(P^2\) of the (identical) polarisation powers of polarising and analysing supermirror:

\[
\frac{I_F}{I_0} = \frac{1 - e_F P^2}{1 + P^2}, \\
\frac{I_R}{I_0} = \frac{1 - e_R P^2}{1 + P^2}, \\
\frac{I_{RF}}{I_0} = \frac{1 + e_R e_F P^2}{1 + P^2}
\]

Since an initially fully polarised beam would leave any flipping device which exhibits a spinflip probability of 50% like an unpolarised one with respect to its spin ‘up’ and spin ‘down’ contributions, the simple relation \(e = 2k - 1\) holds between the efficiency \(e\) and the spinflip probability \(k\). Averaging of the results of a series of repeated measurements the following values for the polarisation degree product and the spinflip probabilities of the resonator and the DC flipper were obtained: \(P^2 = 0.838 \pm 0.044\), \(k_R = 0.990 \pm 0.024\), \(k_F = 1.018 \pm 0.030\). This means that even this rather simple prototype resonator exhibits almost perfect performance. The rather poor polarisation product is very likely due to an admixture of unpolarised neutrons which have passed the mirrors without reflection. An improved mirror alignment will be required in order to suppress this contribution.

4. Pulsed mode of operation
The creation of wavelength-selected neutron pulses of arbitrary time structure will be the ultimate goal for this new type of neutron spin resonator. Here, we present first results of a prototype driven in ‘classic’ pulse mode, i.e. by turning the whole resonator on and off again.
Thereby the neutron passage time through the resonator defines the shortest possible pulse length, which in our case is roughly about 140 $\mu$s. In Fig. 7 neutron pulses with a duration of 140 $\mu$s and 500 $\mu$s, respectively are shown. A ‘travelling wave’ mode of operation, where at any moment of time only one section of the resonator after the other is activated and deactivated, should allow to produce much shorter pulses and to decouple the minimal neutron pulse width from the achievable wavelength resolution, which for given resonator period depends upon its total length, as has been proposed for the first time in [16]. To realise this ambitious goal we have developed a quite sophisticated computer controlled pulsed power supply. Its details as well as the results of the corresponding experiments, which meanwhile have begun, will soon be presented in forthcoming publications.

![Figure 7](image.png)

**Figure 7.** Time-of-flight spectrum obtained by operating the resonator prototype in a ‘classical’ way by pulsing it as a whole in order to create neutron pulses of 140$\mu$s and 500$\mu$s, respectively.

It is worth to mention that the achievable ‘switching ratio’, i.e. the ratio between maximal and minimal intensity, becomes nearly completely independent of the efficiency of any type of pulsed flipping device, provided an additional static spin flipper - which can easily be designed to yield virtually 100% efficiency - is inserted into the beam path [17]. Thus the quality of the pair of polarisers remains as the only crucial quantity which has to be pushed to its limits in order to achieve a satisfactory overall performance of the setup and to minimise the unmodulated wavelength independent background intensity. Meanwhile switching ratios well beyond $10^2$ have been realised by using crossed pairs of supermirrors [9], and neutron polarisation degrees of 99.99% have been achieved by means of $^3$He spinfilters [10], so that switching ratios of the order of $10^4$ are seemingly feasible. However, with current technologies such an extremely high degree of polarisation can be attained only on the cost of an enormous loss of beam intensity. This is a severe problem which has to be solved before the implementation of our device as integrated monochromator & chopper for neutron time-of-flight spectroscopy may become a really useful option. However, we are quite sure that for the specific configuration of the already mentioned PERC project - where our new spin resonator has to undergo its first test under realistic experimental conditions - it will be possible to minimise the disturbing influence of the unmodulated background by gating the neutron decay product detectors according to the pulse structure of the spatial spin resonator. But this implementation is a complex task still requiring
considerable technological efforts and its treatment is beyond the scope of the present article.

5. Conclusion and outlook
We have simulated and designed a novel pulsed spatial magnetic neutron spin resonator. We could show that the experimental results of our fully working prototype fit very well to the data we got from our simulations. The next step will be to enhance the performance of this resonator in order to create shorter and sharper pulses utilising a ‘travelling-wave’ mode operation. Based upon the experience gained by studying the performance of the present prototype, we will then begin to design a more elaborate resonator system with at least one order of magnitude larger number of elements and bigger dimensions to allow for the passage of beams with larger cross-sectional area, provided, of course, that we can raise the required monetary funding for this project.

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