



PNCMI 2012 - Polarized Neutrons for Condensed Matter Investigations 2012

Wavelength-selected neutron pulses formed by a spatial magnetic neutron spin resonator

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Abstract

We present a novel type of spatial magnetic neutron spin resonator whose time and wavelength resolution can be decoupled from each other by means of a travelling wave mode of operation. Combined with a pair of highly efficient polarisers such a device could act simultaneously as monochromator and chopper, able to produce short neutron pulses, whose wavelength, spectral width and duration could be varied almost instantaneously by purely electronic means without any mechanical modification of the experimental setup. To demonstrate the practical feasibility of this technique we have designed and built a first prototype resonator consisting of ten individually switchable modules which allows to produce neutron pulses in the microsecond regime. It was installed at a polarised 2.6 Å neutron beamline at the 250 kW TRIGA research reactor of the Vienna University of Technology where it could deliver pulses of 55 μs duration, which is about three times less than the passage time of the neutrons through the resonator itself. In order to further improve the achievable wavelength resolution to about 3% a second prototype resonator, consisting of 48 individual modules with optimised field homogeneity and enlarged beam cross-section of 6 × 6 cm² was developed. We present the results of first measurements which demonstrate the successful operation of this device.

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Selection and peer-review under responsibility of the Organizing Committee of the 9th International Workshop on Polarised Neutrons in Condensed Matter Investigations

Keywords: polarised neutrons, magnetic spin resonator, travelling wave mode, spin flipper

PACS: 03.75.Be, 29.25.Dz, 76.60.Lz, 42.60.Da, 13.37.Mo

2000 MSC: 65C20, 78A30, 78M10

1. Introduction

The neutron spin resonator exploits the fact that upon passage of polarised neutrons through a spatially alternating transverse static magnetic field each neutron in its rest frame experiences an alternating field

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with a fundamental frequency ω ,

$$\omega(\lambda) = \frac{\pi h}{m} \cdot \frac{1}{a\lambda}, \quad (1)$$

depending on the neutron velocity (*viz.* wavelength λ) and the spatial period $2a$ of the resonator. If this frequency equals the LARMOR precession frequency $\omega_0 = |\gamma|B_0$ ($\gamma = -1.833 \times 10^8 \text{ s}^{-1} \text{ T}^{-1}$ neutron gyromagnetic ratio), about a guide or *selector* field B_0 , a resonant spin flip will take place, if in addition the amplitude condition

$$\frac{B_1}{B_0} \cdot \frac{L}{a} = (2k+1) \frac{\pi}{2} \quad (k=0, 1, 2, \dots) \quad (2)$$

is fulfilled. Here, B_1 denotes the amplitude of the horizontally oriented alternating resonator field, B_0 the magnitude of the vertically oriented guide field and $L = 2Na$ the total length of the resonator with N periods. This property is used to pick out a desired wavelength band of adjustable width from an initially polychromatic neutron beam. Drabkin first proposed neutron magnetic spin resonance in the early sixties already [1]. A particularly thorough analysis of neutron magnetic spin resonance was given by the seminal paper of Agamalyan, Drabkin and Sbitnev [2], taking into account higher harmonics of the alternating transversal field and demonstrating how subsidiary side maxima of the spinflip probability, which are caused by Fourier expansion cut-off effects, can be suppressed quite effectively by modulating the width of the resonator and hence the amplitude of the transversal field oscillations. Since then some novel applications for neutron instrumentation were realised, conceptually based upon this meanwhile quite well established technique [3–8]. Recently a new type of spatial magnetic spin resonator, consisting of individually switch- and adjustable resonator elements has been developed and successfully tested at the TRIGA Mark II reactor in Vienna [9–11]. Furthermore, first neutron pulses were created by this resonator by periodically switching the resonator as a whole on and off. However, by means of such a simple pulsed mode of operation no pulse lengths shorter than 140 μs could be achieved. Here, we demonstrate how much shorter and sharply defined neutron pulses can be created by driving such a magnetic spin resonator system in a *travelling wave* (TW) mode of operation.

2. Travelling wave mode

A first resonator prototype, consisting of ten individually adjustable resonator elements, was described quite recently [9]. The electronic hardware was optimised in order to allow for fast electronic switching of currents of up to 15 A within less than about 5 μs . Furthermore, the micro-controller firmware, as well as the PC software were totally revised in order to fulfil the requirements for travelling wave mode of operation, where all the resonator elements have to be switched sequentially according to the specific requirements of the TW mode of operation. The measurements were performed at the tangential beamline of the TRIGA Mark II research reactor in Vienna, at a mean wavelength of $\lambda = 2.64 \pm 0.04 \text{ \AA}$. A highly oriented pyrolytic graphite (HOPG) filter eliminates the second order wavelength contribution in the incident spectrum almost completely (Fig. 1). The beam ($2 \times 1 \text{ cm}^2$) is polarised by a TiCo-supermirror polariser with a degree of polarisation $P = 95 \%$. Since our beam is monochromatic, a simple static DC-coil spin flipper is sufficient to invert the spin state of the incident neutrons. Of course, a broadband flipping device, e.g. a gradient RF-flipper [12] will be required for polychromatic beams. Finally, an identical supermirror placed in front of the detector is used to analyse the beam after passage through the resonator. The resonator and the static flipper are located within a pair of Helmholtz coils which produce a vertical homogeneous magnetic guide field B_0 extending from the polariser downstream to the analyser. This field is required both to avoid depolarisation of the transmitted beam and to define the ‘resonance wavelength’

$$\lambda_0 = \frac{\pi h}{|\gamma|m} \times \frac{1}{aB_0}, \quad (3)$$

i.e. the spectral component which undergoes a spin flip process upon passage through the transversally oscillating resonator field and hence will be able to pass the analyser. The current flowing through each of the ten elements of the prototype resonator can be switched on and off separately with individually controllable

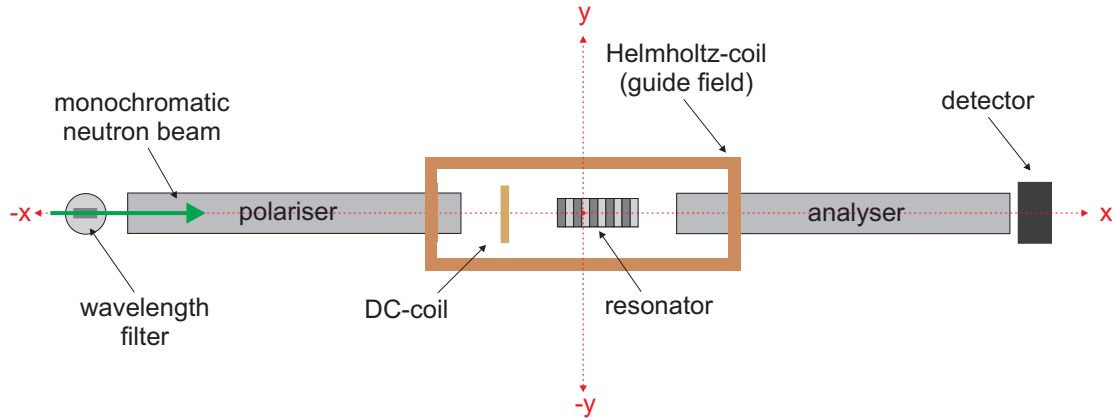


Fig. 1. Sketch of the beamline setup at the TRIGA Mark II reactor of the Vienna University of Technology. The 2nd-order wavelength of the incident beam is eliminated by an *HOPG* crystal filter to provide for monochromatic $\lambda = 2.64 \pm 0.04 \text{ \AA}$ neutrons.

amplitude by means of MOSFET power switches. Whenever a periodic trigger signal repeatedly releases a TW mode cycle of the resonator elements, a time-of-flight analyser (channel width $0.5 \mu\text{s}$) is started to record the arrival time of each neutron at the detector.

Fig. 2 shows two different neutron time-of-flight distributions obtained with periodic current pulses of $55 \mu\text{s}$ duration, which turned out to be the optimal choice for the given experimental setup. It is clearly seen that in the standard mode of operation, where all resonator modules are activated simultaneously, this pulse width is not compatible with the fact that for the given resonance wavelength $\lambda_0 = 2.64 \text{ \AA}$ the neutron passage time through our prototype resonator ($L_{\text{eff}} = 21.5 \text{ cm}$) is about $150 \mu\text{s}$. In the travelling wave mode, however, the pulse rises so steeply that it can reach its full intensity maximum. It is worth, however, to have a closer look at the achieved minimal pulse width $\Delta t = 55 \mu\text{s}$. According to the given spectral width of the incident beam the time-of-flight dispersion along the 116 cm long flight path from the resonator entrance to the detector causes a time uncertainty $\Delta t_{\lambda} \approx 25 \mu\text{s}$. Since the effective thickness of the high pressure ^3He detector is approximately 0.5 cm the associated time spread is $\Delta t_D \approx 3.6 \mu\text{s}$. The rise and fall time of the field pulses contribute $\Delta t_B \approx 5 \mu\text{s}$, so that a total effective pulse width

$$\Delta t_{\text{theor}} = \sqrt{\Delta t_{\lambda}^2 + \Delta t_D^2 + \Delta t_B^2 + \Delta t_M^2} \approx 29.8 \mu\text{s} \quad (4)$$

could be expected if only a single module should contribute a time uncertainty $\Delta t_M \approx 14 \mu\text{s}$ according to its thickness of 2 cm . The discrepancy between the observed and the theoretically expected value indicates that the return field of each module has to be taken into account as well.

Nevertheless, it is a clear advantage of this kind of resonator compared to mechanical chopper systems that the selected wavelength-band and the time structure of the neutron beam are mutually independent from each other and can be varied almost arbitrarily in an instant by purely electronic means. A shortcoming of this promising technique is, at least at the moment, the background intensity in the ‘dark’ state of the resonator, originating from the rather poor performance of our supermirror polarisers. From previous experiments we knew that by very careful adjustment in the optimal case the so-called ‘flipping ratio’, i.e. the intensity ratio between spin-up and spin down neutron polarisation, could be made as large as 45. But since a forthcoming reactor shut-down for at least six months was announced we did not care for such a time-consuming background optimisation. It is worth to mention here that by means of crossed pairs of supermirrors flipping ratios of well beyond 10^2 have been achieved [13], however at the cost of transmitted intensity. And by using spin polarised ^3He -cells, which meanwhile have allowed to reach extremely high degrees of neutron polarisation of up to 99.99% [14], switching ratios of more than 10^3 should become feasible.

However, due to the intrinsic loss of intensity of at least one order of magnitude even with the best available polarisers, spin resonance choppers will be superior to mechanical devices only for experimental

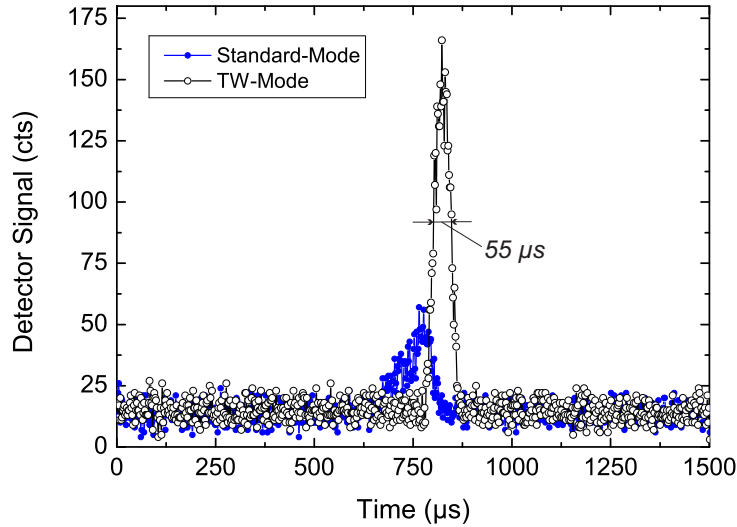


Fig. 2. Comparison of time-of-flight spectra taken with our pulsed prototype resonator ($L_{\text{eff}} = 21.5$ cm, $a_{\text{eff}} = 2.2$ mm) driven in travelling wave mode of operation (*open circle*) and in standard pulsed mode (*full circles*), where all modules of the resonator are activated simultaneously. It is obvious that in the standard mode this pulse width is not compatible with the fact that for the given resonance wavelength $\lambda_0 = 2.64$ Å the required neutron passage time through our prototype resonator is about $142 \mu\text{s}$. In the travelling wave mode, however, the pulse rises so steeply that it can reach its full intensity maximum.

arrangements which a priori require the use of polarised neutrons. It is of particular importance that unlike to conventional mechanical chopper systems the minimally achievable pulse duration of spinflip choppers does not depend on the chosen beam diameter. In principle a similar decoupling of beam size and time resolution can also be achieved by means of so-called *Fourier* multi-slit disk choppers [15]. But so far this kind of neutron time-of-flight technique has not found widespread application and turned out to be of advantage mainly for specific experimental situations [16]. Again, the advantage of our purely electronically tuneable device will be its extreme flexibility. Absolutely no mechanical modification of the experimental setup is required if, instead of the standard TOF procedure, either the Fourier- or, alternatively, the correlation time-of-flight technique [17] shall be applied. There, the TOF spectrum is obtained by cross-correlation of the registered intensity pattern and the digital shift register sequence that is used to control the spin resonator and to modulate the incident beam according to a pseudorandom sequence of arbitrary length and duty cycle. One is completely free to decide to use one of these alternative techniques whenever they seem to be the appropriate choice for the given experimental conditions.

3. Development of a new resonator prototype

At lowest order ($k=0$) the relative wavelength resolution of such a Drabkin-type neutron spin resonator is $\Delta\lambda/\lambda \approx 1.6 a/L = 0.8/N$, where again, N is the number of resonator periods. For the prototype resonator described in the previous section a value $\Delta\lambda/\lambda \approx 16\%$ was achieved. In order to improve the resolution a new resonator with 48 half-period modules was designed, roughly yielding $\Delta\lambda/\lambda \approx 3\%$. To optimise the field homogeneity each of these modules consisted of a central low-inductance single-turn aluminium coil (foil thickness: 0.3 mm, spacing: $d = 10$ mm, height: $h = 18$ cm, width: $w_1 = 8$ cm) and two smaller supplementary coils (width: $w_2 = 3$ cm) of equal height and thickness, mounted side by side at a polyethylene diaphragm as shown Fig. 3. Particularly careful design and fabrication was required to ensure the electric insulation between these three coils as well as between adjacent modules, which in turn were closely packed and fixed within a massive polyethylene box frame. According to this construction principle the separation between the coils of adjacent modules was 1 mm, resulting in an effective resonator half-period $a = 11,6$ mm. A commercially available simulation software (CST-Studio SuiteTM) was used to calculate

the three-dimensional field distribution of the complete resonator assembly. It was found that within each module a field homogeneity $\Delta B/B \approx 0.01$ could be achieved across an area of $6 \times 6 \text{ cm}^2$ perpendicular to the direction of the transmitted neutron beam. Such a large possible beam cross-section will be of crucial importance for future applications, but plays no role for the moment since in our test setup the available beam size is only $2 \times 1 \text{ cm}^2$.

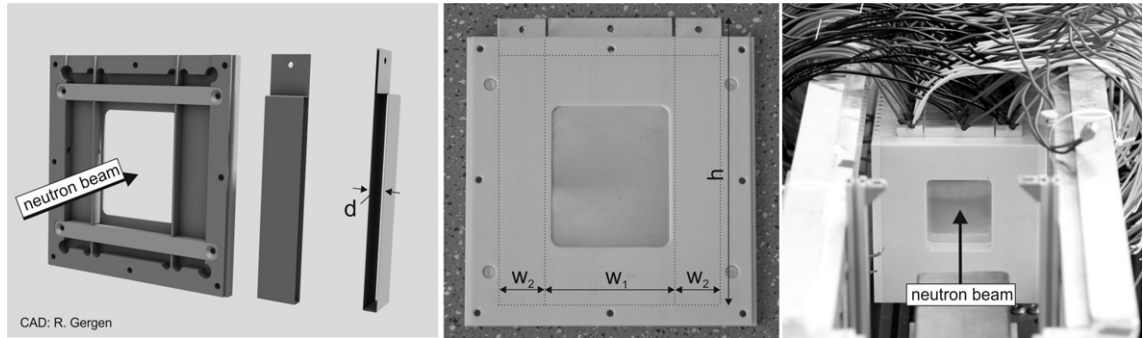


Fig. 3. CAD detail of one half-period module of the new resonator prototype consisting of a central low-inductance single-turn aluminium coil (foil thickness: 0.3 mm, spacing: $d = 10 \text{ mm}$, height: $h = 18 \text{ cm}$, width: $w_1 = 8 \text{ cm}$) and two smaller supplementary coils (width: $w_2 = 3 \text{ cm}$) of equal height and thickness, mounted side by side at a polyethylene diaphragm (left & middle). 48 of such modules are stacked together and fixed within a polyethylene frame (right).

Besides of its higher resolution another important advantage of the new resonator is its much higher flexibility with respect to possible spatiotemporal magnetic field configurations. However, to fully exploit its flexibility, it will be necessary to set the field within each module of the resonator almost instantaneously to any desired value within the limits $-B_1^{\max} \leq B_1 \leq +B_1^{\max}$. Currently we are developing a quite sophisticated electronic circuitry comprising 96 rapidly switchable bipolar current sources with a maximum current of $\pm 20 \text{ A}$ (one for each main coil and one for each pair of supplementary coils). Compared to this complexity it requires almost negligible effort to control the required vertical field component B_0 within the resonance region.

In order to fully understand and to optimally exploit the features of the new resonator prototype we have performed a series of computer simulations. At first, the three-dimensional field distribution was determined for various resonator configurations by means of the above mentioned CST-Studio SuiteTM. This field distribution was then used as input for the calculation of the evolution of the neutron polarisation vector along a set of different beam trajectories by means of dedicated software *SPARTAN* we have developed just for this specific purpose. From previous simulation studies of a resonator without supplementary coil pairs we were aware that the field inhomogeneity in horizontal direction may cause some reduction of the polarisation degree of the transmitted beam due to violation of the amplitude condition (2). Now, it becomes manifest that due to the improved horizontal field homogeneity of the new resonator the differences between the final polarisation vectors are negligibly small for any off-center neutron trajectory of a non-divergent beam within an area of $6 \times 6 \text{ cm}^2$. Likewise no significant derogation of the resonator's performance can be expected for trajectories with an angular deviation of less than about $\pm 1, 5^\circ$. As a typical example Fig. 4 shows the evolution of all three components of the neutron polarisation vector along the central trajectory when 32 consecutive modules of the resonator are activated², assuming a monochromatic neutron beam with a wavelength $\lambda = 2.6 \text{ \AA}$ that is initially fully polarised in $+z$ -direction, i.e. $\mathbf{P}_1 = (0, 0, 1)$. It is clearly seen that P_z evolves smoothly from $+1$ at the entrance to -1 at the exit of the resonator, provided that both the amplitude B_1 of the transversal field oscillations and the strength of the vertical selector field B_0 are precisely tuned for full spinflip according to eqs. (2) and (3). In this case the components P_x and P_y are zero except within the transversally oscillating field region, where the polarisation vector undergoes a

²To understand why not all 48 stages are used see the caption of Fig. 5.

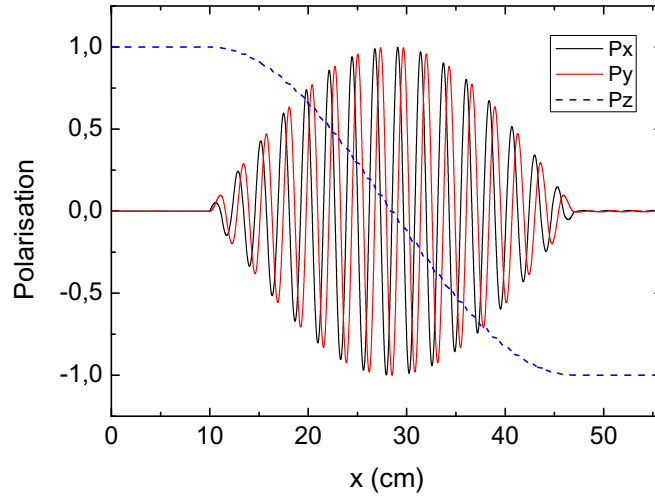


Fig. 4. Evolution of the polarisation vector during the neutron passage through a resonator with half-period $a = 1$ cm when 32 consecutive modules are activated and tuned for full spinflip.

spherical spiral motion from the $+z$ to the $-z$ direction with the precession frequency ω_0 . Since for this just described simulation no suppression of subsidiary maxima of the resonant spinflip probability was intended and hence a constant amplitude of the transversally oscillating field was assumed, the exit polarisation behind the resonator should exhibit a sinc^2 -shaped modulation³ wavelength dependence according to the Fourier spectrum of a resonance region of given finite length. Indeed, the dashed curve in the bottom graph of Fig. 5 represents just this expected behavior.

It is quite interesting to compare this curve, which was obtained by activating 32 consecutive modules of our resonator, with the result of a simulation of a modified arrangement, where 16 modules at the center of the resonator were deactivated, in order to implement a section where free spin precession around the vertical field can take place. However, the other 2×16 modules in front and behind the central inactive ones were in operation (see top graph of Fig. 5) so that exactly the same amplitude condition as for 32 consecutive modules had to be fulfilled. The central graph of Fig. 5 shows the evolution of the z - and x -component of the polarisation vector upon passage through this twin resonator arrangement which has some conceptual similarities with Ramsey's famous double resonance technique, bearing in mind that spin precession is an intrinsic interference phenomenon. Although the magnetic field and the evolution of the polarisation upon passage through the activated modules is identical to that for the case of 32 consecutive modules, the wavelength dependence of the spinflip probability is much narrower and the side maxima are drastically enhanced. Taking into account that by means of the new electronic power supply system which will allow to control the status of each module independently of all others and thus to establish almost arbitrary resonator configurations, much more detailed investigations have still to be done, however, in order to find out to what extent further improvements and/or innovative applications of our new spin resonator are realistically feasible.

4. Measurements

The experimental setup to perform first test measurements with the new resonator prototype was nearly the same as that one used for the neutron time-of-flight measurements described in Section 2. However, due to its much larger dimensions a new 208 cm long Helmholtz-coil pair guide field had to be installed,

³ $\text{sinc}(x) \equiv \sin(x)/x$

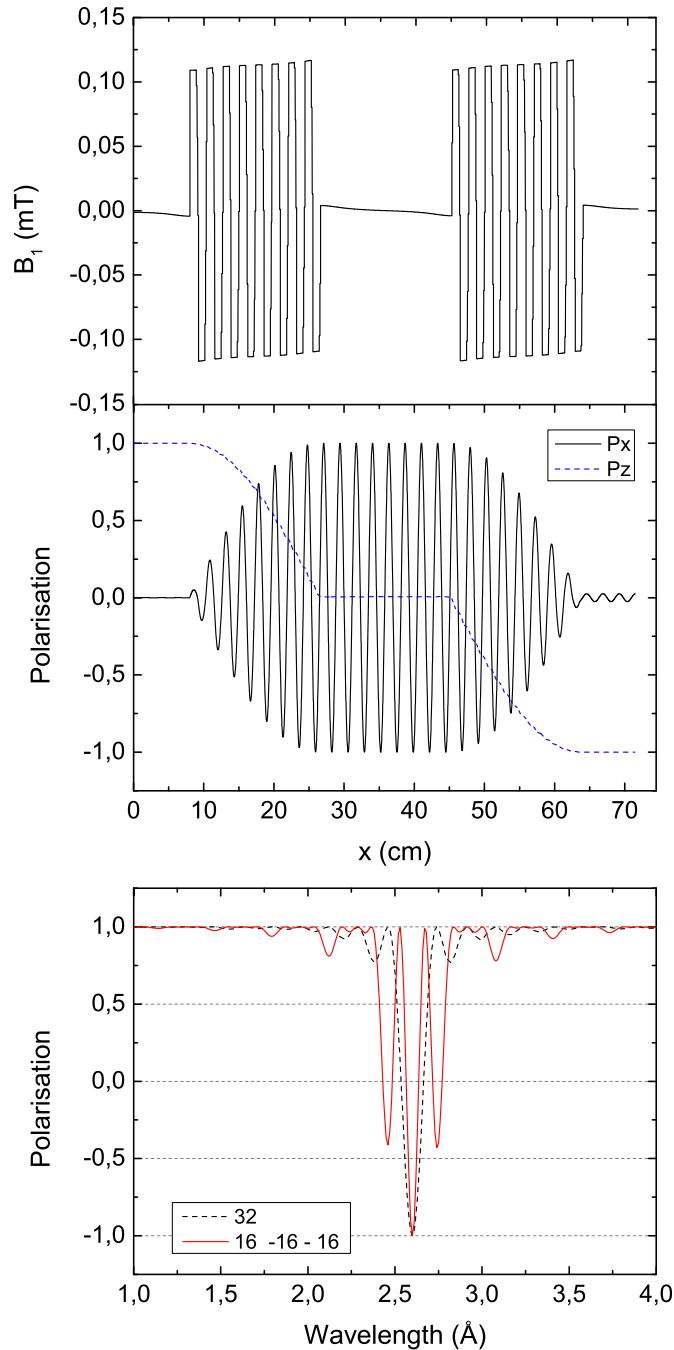


Fig. 5. Transversal magnetic resonator field $B_1(x)$ of a 48-element-resonator, configured for double resonance: i.e. 16 elements activated, 16 elements turned off, followed by 16 activated elements (*top*). The evolution of the z - and x -components of the polarisation vector during the passage of neutrons with $\lambda = 2.6 \text{ \AA}$ through such a configuration exhibits a region of free precession in the xy -plane (*middle*). Plotting the polarisation versus the neutron wavelength shows a completely different behaviour compared to the resonator driven in normal mode of operation: the main peak is much sharper and the subsidiary maxima are strongly enhanced. Notice that exactly the same amplitude condition holds as for the case of 32 consecutive modules (*bottom*).

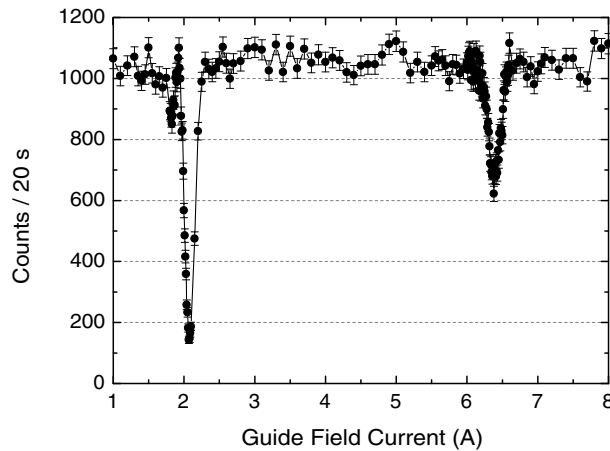


Fig. 6. Measured intensity as a function of the vertical guide/selector field current when the coils of the modules are connected pairwise in such a way as to form a resonator consisting of only 24 modules with a doubled half period $a \approx 23$ mm. Since in this configuration the required vertical field strength is reduced accordingly by a factor 2, it is possible to visualise the influence of the 3rd harmonic of the resonator's frequency spectrum at the threefold value of the guide field without exceeding the given 12 A current limit. Notice, that the current fed to the resonator modules was kept constant to produce a horizontal field amplitude $B_1 = 1.1$ mT, so that the amplitude condition for full spinflip is fulfilled only for the basic but not for the 3rd harmonic.

consisting of about 2×200 loops of 2 mm thick enameled copper wire wound on anodized rectangular aluminium frames (width: 25 cm) and producing a homogeneous vertical magnetic field of 6.17 mT at the maximum current of 12 A. For the first tuning procedure of the resonator only the central coils of each module were used which were connected pairwise in such a way as to form a resonator consisting of only 24 modules with a doubled half period $a \approx 23$ mm. Since the required vertical field strength is reduced accordingly by a factor 2, we were able to visualise the influence of the 3rd harmonic of the resonator's frequency spectrum at the threefold value of the guide field without exceeding the given 12 A current limit (Fig. 6). However, the current supplied to the coils of the resonator was kept constant during the variation of the vertical guide/selector field, which means that the amplitude condition (2) to achieve full polarisation inversion was fulfilled only for the basic but not for the 3rd harmonic.

It has to be mentioned that because of limited space at the beamline it was unavoidable to keep the distance between the resonator and the supermirror polariser very short. Thus, the strong permanent magnets of the polariser led to some irregularities in the magnetic field distribution, which turned out to be responsible for a strong side wings asymmetry of the observed resonance spectrum.

In Fig. 7 the experimental result is shown (black curve, full circles) that is obtained when the resonator is configured to comprise 24 consecutive active modules with a half-period of 1 cm. The red curve (open circles) shows, on the other hand, the first measurement utilising the above mentioned twin resonator mode with a sequence of 12 active, 12 inactive, followed again by 12 active modules. As expected from the theoretical simulations, there the central flipping maximum gets clearly narrower and it is accompanied by strongly enhanced side peaks.

5. Conclusions and outlook

We have demonstrated for the first time experimentally that by means of a travelling wave mode of operation it is possible to decouple the achievable time resolution of a magnetic neutron spin resonator from its wavelength resolution. In combination with a pair of highly efficient polarisers such a device could act simultaneously both as monochromator and chopper, able to produce short neutron pulses whose wavelength, spectral width and duration could be varied almost instantaneously by purely electronic means without any mechanical modification of the experimental setup. Furthermore, we have designed and built

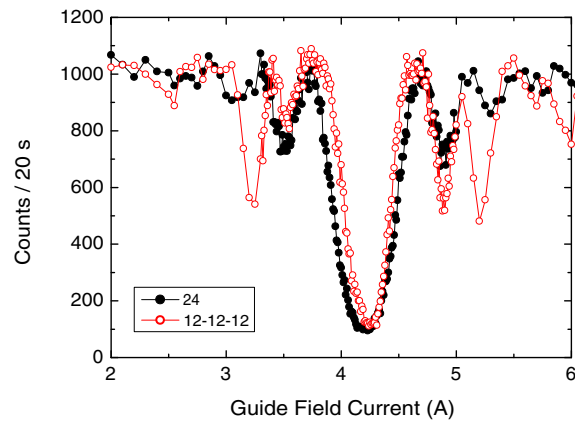


Fig. 7. Transmitted intensity versus guide/selector field current if 24 consecutive modules with a half-period of 11.6 mm are activated and B_1 is tuned for full spinflip of 2.64 Å neutrons. (black curve, *full* circles). The red curve (*open* circles) shows the corresponding result for a double resonance arrangement with a sequence of 12 active, 12 inactive, followed again by 12 active modules. As expected from the theoretical simulations, the central flipping maximum is narrower and the side peaks are strongly enhanced.

a more elaborate resonator prototype with 48 consecutively stacked modules which yields a wavelength resolution $\Delta\lambda/\lambda \approx 3\%$. In order to improve the homogeneity of the transversally alternating field and allowing for an enlarged beam cross-section of $6 \times 6 \text{ cm}^2$ each of these 11.6 mm thick modules consists of a central single-turn aluminium coil and a pair of supplementary side coils. Currently we are developing a complex power supply system comprising 96 programmable pulsed bipolar current sources, which will enable us to control each module independently from all others and thus will allow to establish and to experimentally test any desired resonator configuration. Finally, in the course of theoretical simulations it turned out that an arrangement of two spatially separated resonators exhibits some interesting features with respect to the achievable wavelength resolution. Continuative investigations have to be done, however, to examine whether reasonable applications of such an arrangement can at least be conceived.

Acknowledgement

Financial support by the Austrian Fonds zur Förderung der wissenschaftlichen Forschung (Project No. I 528 -N20, MONOPOL) and by the FP7 Grant Agreement No. 226507-NMI3 (Integrated Infrastructure Initiative for Neutron Scattering and Muon Spectroscopy) is gratefully acknowledged.

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