ACCELERATOR/DECELERATOR OF SLOW NEUTRONS

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Abstract

An accelerator/decelerator for slow neutron beams has been demonstrated. The energy of a neutron can be increased or decreased by flipping the neutron spin (directly coupled to magnetic dipole moment) in magnetic field. This device is a combination of a gradient magnetic field and an RF magnetic field. Test experiments were performed by using very slow neutrons at High-Flux Reactor at Institut Laue-Langevin. Acceleration and deceleration for focusing of neutrons at the detector position was observed. Focusing neutrons enables us to transport the neutrons while maintaining density from source to experimental position. This will be a powerful technique for measurement of the permanent electric dipole moment of neutrons, which require a high density of neutrons.

INTRODUCTION

Particle accelerators have continually evolved since their invention, and nowadays are applied not only in physics experiments but also in various fields such as medical science. The properties of the beam should be optimized for each use by accelerating, decelerating, focusing and/or defocusing. Recently the neutron beam becomes important as a probe for new science including particle physics with extremely high precision. Although the ray of neutrons has been handled by some optical devices, for example, mirrors and lenses, it is impossible to control the velocity by the electric field used in an ordinary accelerator because the neutron is an electrically neutral particle. A neutron accelerator which manipulates the velocity has the advantage that experiments can be performed with high precision.

One of the most useful applications of the neutron accelerator is space-time focusing. In the case of pulsed neutrons, during transport of the neutrons to the experimental area, the neutron pulses spatially spread as some neutrons travel faster whereas some travel slower. The density decreases according to the velocity spread of the neutron pulse. When fast neutrons are magnetically decelerated and/or slow neutrons are accelerated properly in the middle of the transport, these neutrons can reach the experimental area at the same time (Fig. 1) [1, 2, 3, 4]. The density can be kept from the source to the arrival position by focusing. This enables us to utilize instantaneous-intense pulsed neutrons in order to suppress the systematic errors for some experiments which require dense neutrons, for example, search for neutron electric dipole moment (nEDM) to reveal the origin of matter in the universe. Although experimental searches have been pursued in the world [5, 6, 7, 8, 9], the nEDM has not yet been observed. The present upper limit is $|d_n| < 2.9 \times 10^{-26} e\mathrm{cm}$ (90% C.L.) [9], which is very close to the predictions of some physics beyond the standard model of particle physics, for example, supersymmetry. Using the space-time focusing and high power pulsed neutron source, we can improve experimental sensitivity by one or two orders of magnitude to search for nEDM.

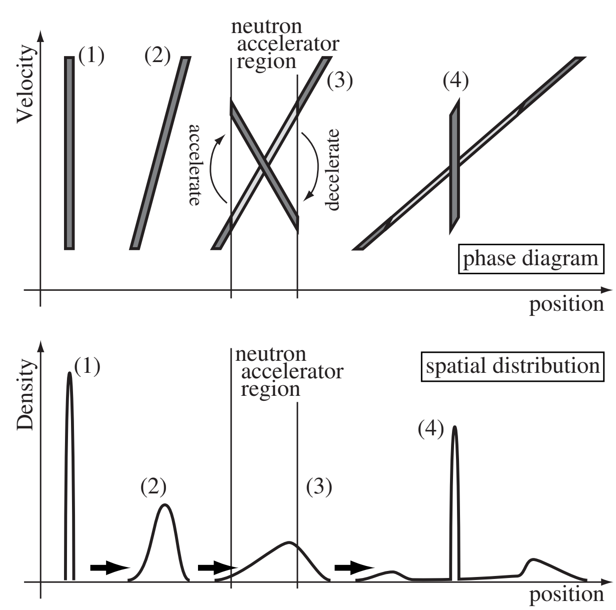

Figure 1: Concept of space-time focusing by using neutron accelerator. (1) Neutrons are generated as a pulse. (2) Neutrons spread spatially during transport. (3) Neutrons are accelerated/decelerated properly. (4) Some neutrons are focused at the experimental position. This figure illustrates the behavior of polarized neutrons.

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NEUTRON ACCELERATOR FOR FOCUSING

For the acceleration/deceleration of neutrons, we can utilize flipping of neutron spin in magnetic field. Although this change is too small to be used for the focusing of fast neutrons, it is enough to realize the focusing with very slow neutrons. Such slow neutrons which have the kinetic energy of less than about 200 neV, called as ultracold neutrons (UCNs), are used in nEDM experiments. In this demonstration, we use adiabatic fast passage method (AFP), which is one of the spin flippers [12]. When a neutron passes through an RF magnetic field in the surrounding static field with smooth gradient, the neutron's spin flips with energy gain or loss corresponding to spin polarization. The change of the neutron kinetic energy is written as $2\mu B$, where B is the magnetic field at the spin flip position and μ is magnetic dipole moment of neutron. After the magnetic field, the velocity becomes into $\sqrt{v^2 \pm 2\mu B/m}$ from the incident velocity of v, where m is neutron mass and $\pm$ is represented gain and loss of the energy. In the case of deceleration, the time of flight of a neutron with the initial velocity v is written as

$$T = \int_0^{L_f} \sqrt{\frac{m}{2(E_0 - \mu B(z))}}\, dz + \int_{L_f}^{L} \sqrt{\frac{m}{2(E_0 - 2\mu B(L_f) + \mu B(z))}}\, dz, \quad (1)$$

where L_f is spin flip position, L is detector position and $E_0 = mv^2/2$ is initial kinetic energy of the neutron. When we select L_f for each velocity of the neutron properly, the time of flight can be kept constant. Because the spin flip occurs under the resonance condition, which is written as

$$\hbar\omega = 2\mu B(L_f), \quad (2)$$

where ω is the frequency of RF field, changing the frequency can be utilized to select the spin flip position (Fig. 2). There is a time lag for arriving at the spin flip position for each velocity, therefore, the frequency is represented as a function of time $\omega(t)$, which can be calculated the equations above numerically when T and $B(z)$ are given. The AFP spin flipper with time-changing RF frequency is required for focusing of neutrons.

We made the prototype of the magnetic accelerator in order to demonstrate the space-time focusing. A closeup view of the accelerator system is shown in Fig. 3. This consists of a compact static magnet to generate the gradient field with 1 T at the maximum and an RF coil to generate the resonance RF field. The change of neutron kinetic energy corresponding to 1 T is 120 neV, The magnet has anisotropic inter-poles in order to generate a homogeneous gradient of the magnetic field along the direction of neutron beam (Fig. 4) [13, 14]. The strength of the field decrease from 1 T to 0.5 T in 20 cm. The RF coil is an one-turn coil with length of 20 cm, which covers the gradient of the static field (Fig. 5). The RF frequency can be

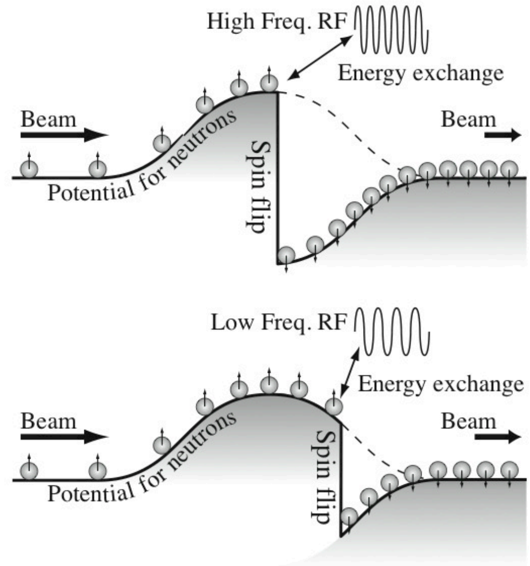

Figure 2: Control of deceleration by using AFP spin flipper with variable frequency RF. Top and bottom shows large and small deceleration respectively.

modulated automatically from 30 MHz to 15 MHz by using electric circuits with variable capacitors and a signal generator (Fig. 6). The control of the capacitors selects the spin flip position L_f, which can be synchronized with the neutron pulse. The RF power is supplied by a wideband amplifier with 1 kW output.

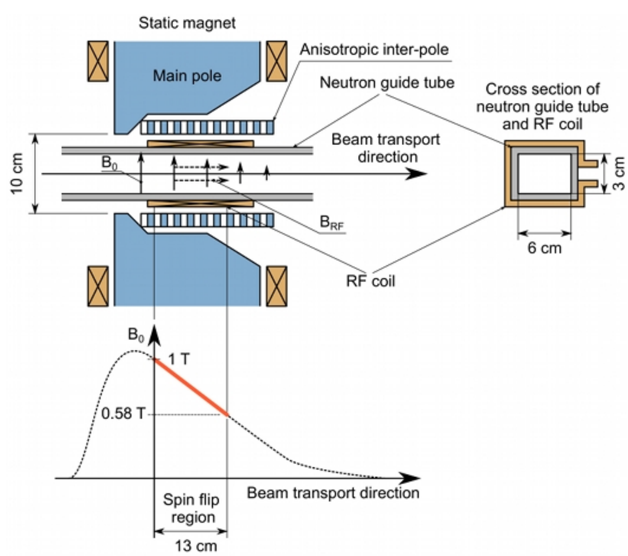

Figure 3: Closeup view of the magnetic accelerator system together with the illustration of the magnetic field gradient in the beam transport direction.

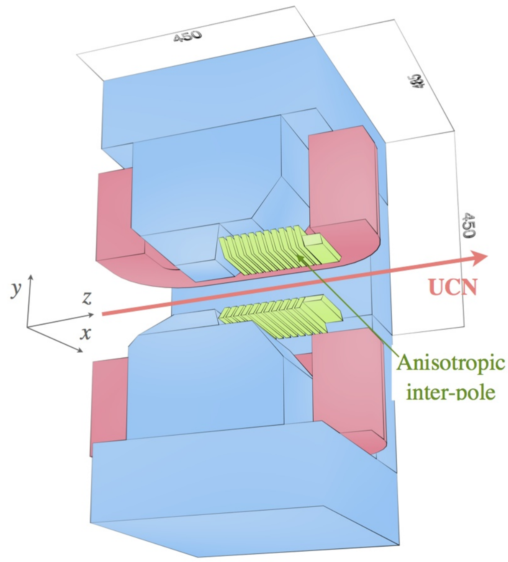

Figure 4: Magnet with anisotropic inter-poles.

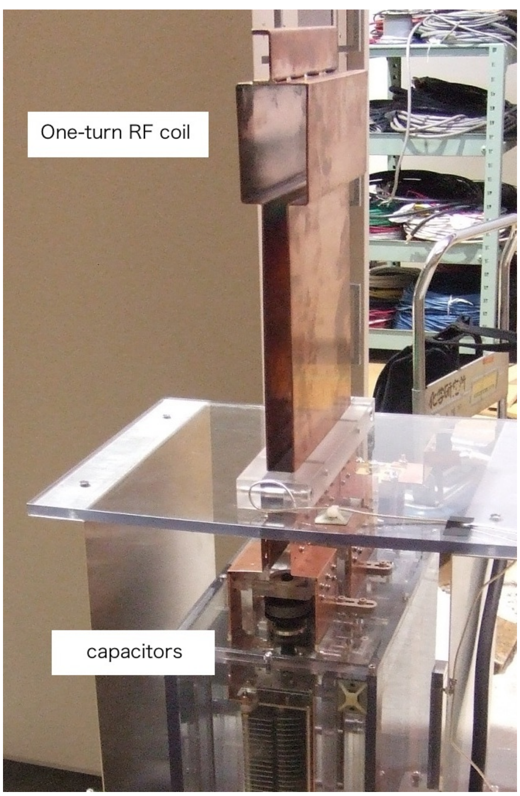

Figure 5: One-turn coil for RF and capacitors.

EXPERIMENTS AND RESULTS

The space-time focusing experiment was performed at the PF2 TES beam line in the High Flux Reactor at Institut Laue Langevin. The whole experimental setup is shown in Fig. 7. Very slow neutrons including UCNs were provided

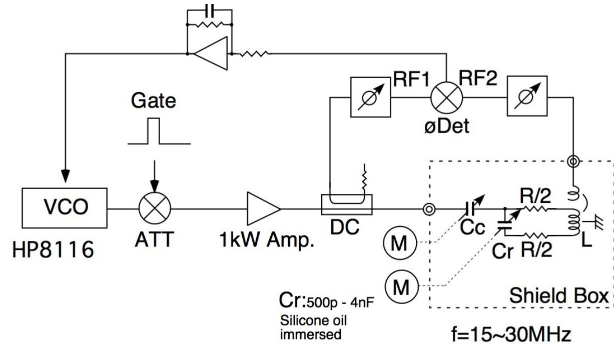

Figure 6: Electric circuit to match the resonance condition of RF.

from the turbine, which decelerates the neutrons from the reactor by using continuous reflections off rotating mirrors [15]. A mechanical shutter is used to supply pulsed neutrons. The shutter opened for 20 ms once every 2 s. A neutron-absorbing cadmium pipe is inserted just before the shutter in order to reduce the number of reflections by limiting the neutron divergence. A neutron detector, which is a ^{3}He gas detector, is set at 5.6 m downstream from the shutter. The neutrons were transported with reflections off the mirror inside the guide tube. The size of the guide is 6 cm in vertical and 3 cm in horizontal. The guide consists of assembled glass plates with nickel coating, which has high reflectivity for neutrons. Since we are going to accelerate/decelerate neutron velocity only in the transport direction, non-specular reflection at the guide surface should be suppressed as much as possible. The glass plates were polished and aligned parallel enough to keep the velocity in the transport direction. The measurements of the neutron velocity distribution through the guide tube were consistent with the simulations without non-specular reflections at the surfaces. The static magnet and RF coil were arranged midway between the shutter and the detector. The RF coil was wound to the guide tube.

We measured the TOF spectrum of the neutrons through this setup for two cases. The RF was ON and OFF. The

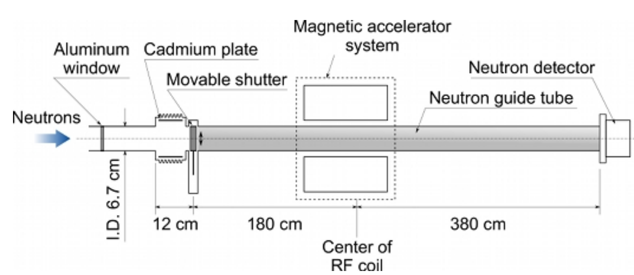

Figure 7: Experimental setup. Neutron accelerator is installed in the middle of the guide tube. The RF and data acquisition systems are synchronized with the shutter operation.

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static magnetic field is constantly applied throughout the experiments. In the case of RF-OFF, the spins of the neutrons are not flipped and the net velocities are not changed before and after the static magnet. In the case of RF-ON, the RF field is applied only when neutrons with velocity from 5.7 m/s to 5.0 m/s reach the accelerator position. This caused the partial change of the shape of the TOF spectrum, which enables us to compare the case of RF-ON to that of RF-OFF easily. In the arrival time-lag of 80 ms between the neutrons of the velocity range, the frequency of the RF is swept from 28.6 MHz to 17.5 MHz, which are corresponding to 120 neV and 70 neV of the energy exchange respectively. For this demonstration, the variable capacitor were moved with the constant speed as the approximation of the frequency function $\omega(t)$. The measurement time was about 4 h for both cases. The measured TOF spectra are shown in Fig. 8. The top and bottom histograms represent the cases of RF OFF and ON, respectively. The lines show the Monte Carlo simulations with and without focusing. The non-specular reflections at the guide surfaces are not considered in these simulations. For RF-ON case, the line is calculated with spin flip efficiency of 0.5. Both of the observed histograms are in good agreement with the simulations. The ratio of these two histograms is shown in Fig. 9. The decelerated neutrons focused at the time between 1.2 s and 1.4 s can be seen. The loss of constant energy makes only defused spectrum and can not make the excess indicated in the figure.

CONCLUSION

We have successfully developed the accelerator/decelerator for slow neutrons and demonstrated neutron space-time focusing for transport of UCNs with keeping density. The results are in good agreement with simple simulations with controlling the velocities of neutrons [16]. The efficiency of the spin flip was low, however, this can be improved with the amplitude of the RF field.

This result shows the feasibility of neutron accelerator for effective transport of UCNs for various experiments. The neutrons can be gathered only in the experimental area at the focus time. When a shutter at the entrance of the experimental area closes just after the injection of the focused pulse, the UCNs can be localized only in the experimental area with high density without spreading in the guide tubes. The combination of this device and a highly-instantaneously-intense pulsed source, for example, SNS and J-PARC, enable us to utilize neutrons most effectively. It should be mentioned that the excitation current of our magnet and its stray field is constant during the experiment in contrast to the method mentioned in reference [3]. This is fairly advantageous to nEDM experiments, which requires an extremely precise magnetic field control. The constant excitation of the magnet eases a quick modulation of the accelerating energy. In addition, since this device can manipulate the longitudinal phase space distribution of the neutrons flexibly, it can adjust not only the time

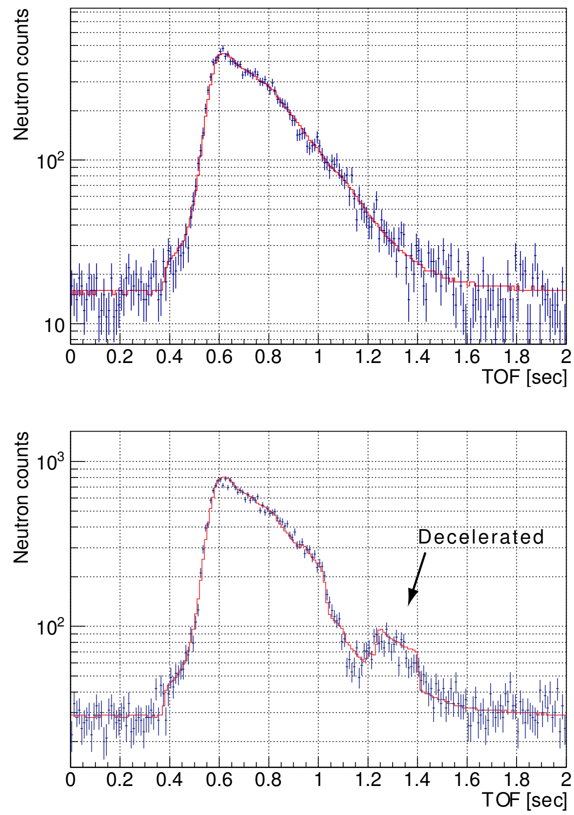

Figure 8: Neutron TOF spectra. Top and bottom show the case of RF OFF and ON respectively. Lines show the simulations.

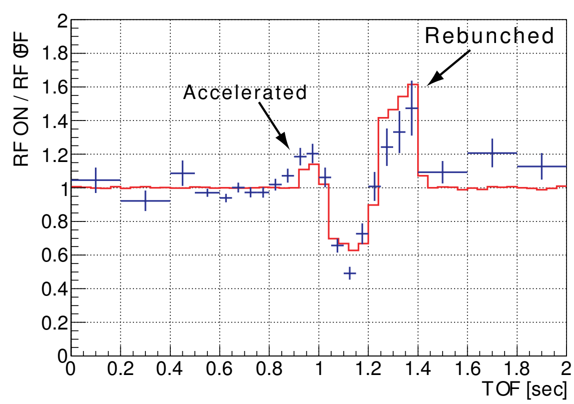

Figure 9: The ratio of these two TOF histograms. Line shows the simulation with focusing.

structure but also the energy distribution, suggested in reference [1, 2]. These features widen the application of this system. We are now planning the new nEDM experiment using this focusing technique at J-PARC [17].

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REFERENCES

[1] J. Summhammer, L. Niel, and H. Rauch, Z. Phys. B62, 269 (1986).

[2] L. Niel and H. Rauch, Z. Physik B74, 133 (1989).

[3] A. I. Frank. and R. Gähler, Phys. At. Nucl. **63**, 545 (2000).

[4] H. M. Shimizu, Y. Iwashita, M. Kitaguchi, K. Mishima, and T. Yoshioka, Nucl. Instr. and Meth. **A 634**, 55-27 (2011).

[5] J. Simith, E. M. Purcell and N. F. Ramsey, Phys. Rev. **108**, 120-122 (1957).

[6] W. B. Dress, P. D. Miller, J. M. Pendlebury, P. Perrin, and N. F. Ramsey, Phys. Rev. D **15**, 9-21 (1977).

[7] K. F. Smith, et al., Phys. Lett. B **234**, 191-196 (1990).

[8] I. S. Altarev et al., Phys. Lett. B **276**, 242 (1992).

[9] C. A. Baker, et al., Phys. Rev. Lett. **97**, 131801 (2006).

[10] B. Alefeld, G. Badurek, and H. Rauch, Z.Physik B41, 231 (1981).

[11] H. Weinfurter, et. al., Z.Physik B72, 195 (1988).

[12] A. Abragam, *Principles of Nuclear Magnetism*, Oxford University Press, Oxford (1961).

[13] Y. Arimoto, et al., Physica Procedia **17**, 20-29 (2011).

[14] Y. Arimoto et al., IEEE Trans. Appl. Supercond. **22** 4500704 (2012).

[15] A. Steyerl et al., Phys. Lett. A **116**, 347 (1986).

[16] Y. Arimoto, et. al., Phys. Rev. A **86**, 023843 (2012).

[17] Proposal to J-PARC, http://j-parc.jp/jhf-np/pac_1001/pdf/KEK_J-PARC-PAC2009-11.pdf

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