REBUNCHING ULTRACOLD NEUTRONS BY MAGNETIC DECELERATION FOR THE NEUTRON EDM EXPERIMENTAL AT J-PARC

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Abstract

Ultra cold neutrons (UCN), which have energies less than 300 neV, can be accelerated or decelerated by controlling static magnetic and RF fields. Neutron kinetic energies can inclease or declease when their spin flip. This method can be used to rebunch a pulsed beam of neutrons to a storage bottle that can store UCN with high density. High UCN densities can be achieved for precision measurements of neutron properties such as the Electric Dipole Moment. The results of a recent first test experiments and present status of our development are reported.

INTRODUCTION

The measurement of neutron electric dipole moments (nEDM) is one of the methods of exploring new physics beyond the Standard Model of elementary particles. Some new theories predict a few orders of magnitude larger nEDM than the Standard Model prediction of nEDM as small as 10^{-30} to 10^{-32} $\mathrm{e \cdot cm}$. For example, the supersymmetry theory predicts nEDM around 10^{-27} to 10^{-28} $\mathrm{e \cdot cm}$. The present upper limit of nEDM is 2.9×10^{-26} $\mathrm{e \cdot cm}$ (90% C.L.) in the Institut Laue-Langevin (ILL) experiments [1].

Today's nEDM experiments are performed by using ultracold neutrons (UCN), whose kinetic energies are less than about 300 neV. Such UCN can be stored in the bottle coated with high potential materials like nickel. When nEDM $\boldsymbol{d}$ exists, the Larmor frequency of UCN ν_n is given by

$$h\nu_n = 2\boldsymbol{\mu} \cdot \boldsymbol{B} \pm 2\boldsymbol{d} \cdot \boldsymbol{E}, \tag{1}$$

where h is the Planck constant, $\boldsymbol{\mu}$ is the magnetic moment of UCN, and plus or minus is consistent with parallel or antiparallel $\boldsymbol{E}$ and $\boldsymbol{B}$ fields, respectively. The precession of stored UCN spin is measured. Therefore it is important to make the homogeneous field in the bottle and accordingly to increase the density of UCN. We are planning to build a pulsed spallation UCN source which generates denser UCN at J-PARC [2].

One of the most important apparatuses in our plan is a neutron accelerator to focus UCN in the bottle with acceleration or deceleration. We call it "UCN rebuncher". The rebuncher enables us to transport UCNs from the source to the bottle with keeping density.

THE PRINCIPLE OF THE UCN REBUNCHER

The UCN rebuncher consists of a gradient magnetic field and a neutron spin flipper. Neutrons do not have electric charges but spin magnetic moments $\boldsymbol{\mu}$ and possess potential energies $-\boldsymbol{\mu}\cdot\boldsymbol{B}$ in magnetic fields $\boldsymbol{B}$. The potential energy of about 60 neV is comparable to the fields of 1 T. Ordinarily their kinetic energies do not change between coming in and going out the fields by the upward and downward slope of the potential. However, if their spins are flipped in the fields, the influences of the potential slope are not canceled and accordingly their final velocities change [3] [4].

Neutron spins are flipped with a resonance spin flipper. In this method the resonance frequency f_s producing the spin flip is given by

$$f_s = \frac{2|\mu_z|B_z}{h}, \tag{2}$$

where h is the Planck constant, B_z is the magnetic field strength perpendicular to the transit axis of UCN, and μ_z is the neutron magnetic moment parallel or antiparallel with B_z, respectively. Since B_z is in proportion to f_s, the position to produce the spin flip moves as the resonance frequency changes continuously. When the width of the neutron pulse in generation is sufficiently narrow, it is possible to consider the correspondence between the positions, the velocities and the arrival timings of the neutrons almost one-to-one. Hence the whole mechanism works like an optical lens temporally if the frequency is suitably swept. Figure 1 shows the diagram of such time-focus.

The RF resonant circuits of the UCN rebuncher are shown in Figure 2. For minimization of power losses the LC resonant circuits of a one-turn coil L and three variable capacitors C_r are made. The RF pulses modulated to the LC resonant frequencies are applied from a RF power amplifier. Variable capacitors C_c are coupling capacitors for the impedance matching between LC resonant circuits and outer power supply circuits. The C_c and C_r are controlled with stepping motors separately which enable us to optimize the changing C_c and C_r.

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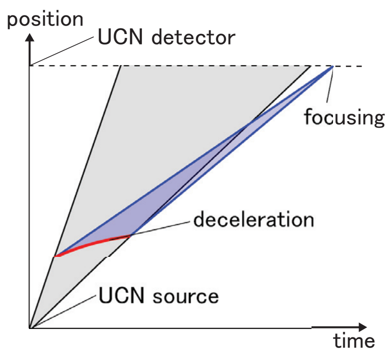

Figure 1: The diagram of the time-focus.

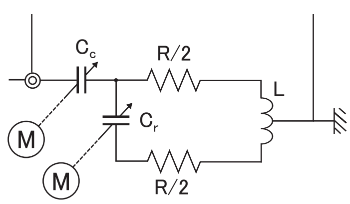

Figure 2: The RF circuits of the UCN rebuncher.

THE EXPERIMENTAL DEMONSTRATION

We carried out the experimental demonstration of UCN rebuncher at the PF2 TES port in ILL in 2011 [5]. The experimental setup is shown in Figure 3. The shutter opened for 20 ms every 2 s to make UCN pulses.

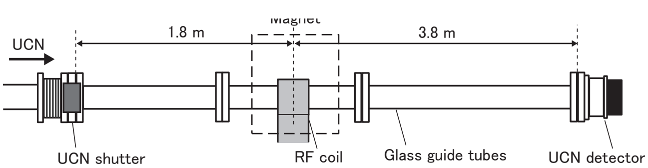

Figure 3: The setup of UCN rebuncher experiments in ILL.

We used the electromagnet with gradient fields which have 1 T in maximum. Figure4 shows the UCN-transit axial distribution of the magnetic fields strength perpendicular to the axis. The magnetic field gradients of the region between z = 490 mm and z = 730 mm are almost constant by using the anisotropic-inter-pole magnet [6] [7]. The spins of UCN are flipped between z = 500 mm and z = 700 mm. The apparatus emitted the RF fields with frequencies of 17.5 MHz to 28.6 MHz, consequently could increase or decrease the kinetic energies of UCN by the range from 73 neV to 118 neV. Figure shows the result of a focusing experiment with decelerating around 5 m/s UCN under the input power of 1 kW. The statistics around 1300 ms rise about 1.4 times with focus. The results are consistent with numerical simulations in which the spin flip rate is 0.5. We have succeeded in the demonstration of the UCN rebuncher.

The width of the rebunched peak become 10 times larger than the incident pulse width 20 ms since the controlling the motors was not optimized fit the sweeping curves of LC frequencies into the arrival timing of UCN. It was expected from the design that a 1 kW power supply makes the flipping ratio nearly 1.0. However, the insufficient capacitances of C_c caused the partial reflections of RF power.

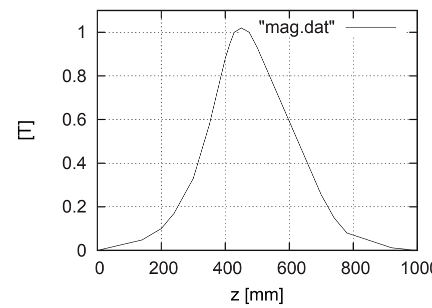

Figure 4: The UCN-transit axial distribution of the magnetic fields strength perpendicular to the axis.

Now we are developing the new UCN rebuncher in order to improve upon these problems. Figure 6 shows the CAD image of the new rebuncher. We are installing six variable capacitors and two coupling capacitors in it and consequently the RF field frequencies widen between about 10 MHz to 30 MHz ideally. We plan to operate it under 3 kW power supplys to increase the spin flip ratio. The next experiment to check the performance of the rebuncher will be carried out by using our UCN test port with the turbine method which we have developed and established at the BL05/NOP beamline in the Materials and Life Science Facility (MLF) of the J-PARC. The pulse width of the UCN this port outputs is lower than 2 ms, hence it is expected that the more obvious and sharp peak than in ILL appears.

SUMMARY

We have succeeded in the experimental demonstration of the acceleration, the deceleration and the rebunch of UCN with a combination of static magnetic fields and a neutron spin flipper. UCN were temporally focused on the position of a detector with deceleration. The calculated spin flipping rate is, however, about fifty percent because of insufficient coupling capacitances and the low level output of RF power amplifier. The next version of UCN rebuncher is under development not only to improve the problems but to widen the range of the LC resonant frequency.

We plan to test the device using our UCN test port in J-PARC which generates more sharp UCN pulse than in ILL experiment. On the basis of these results, we will start the development of large-sized UCN rebunchers for our nEDM experiments in J-PARC.

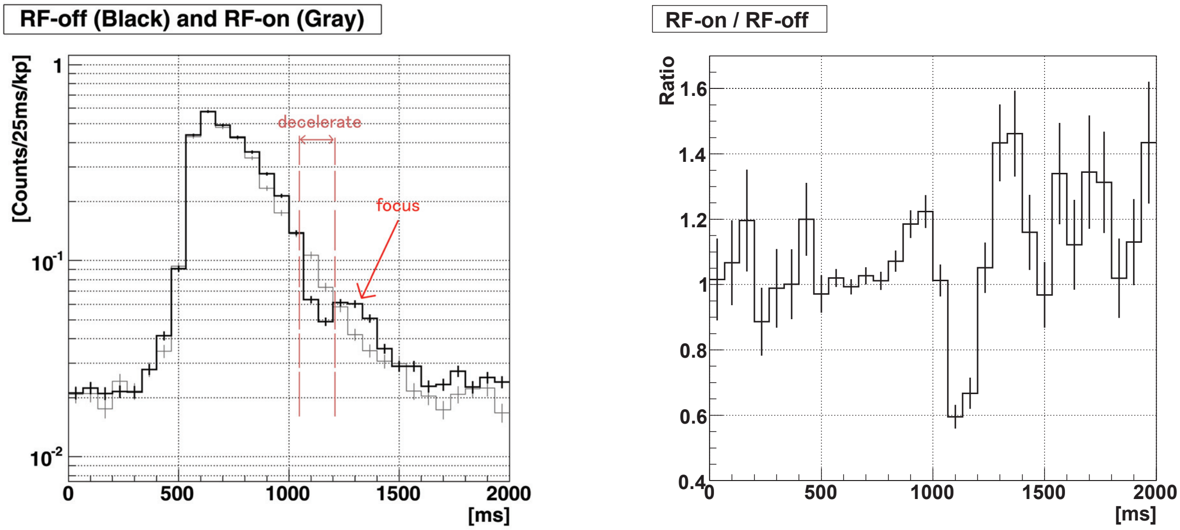

Figure 5: The result of the focusing experiment. (Left) The comparison of Time-of-Flight spectrums with or without the RF-power inputs. (Right) The proportions of the result with the RF-power inputs to without.

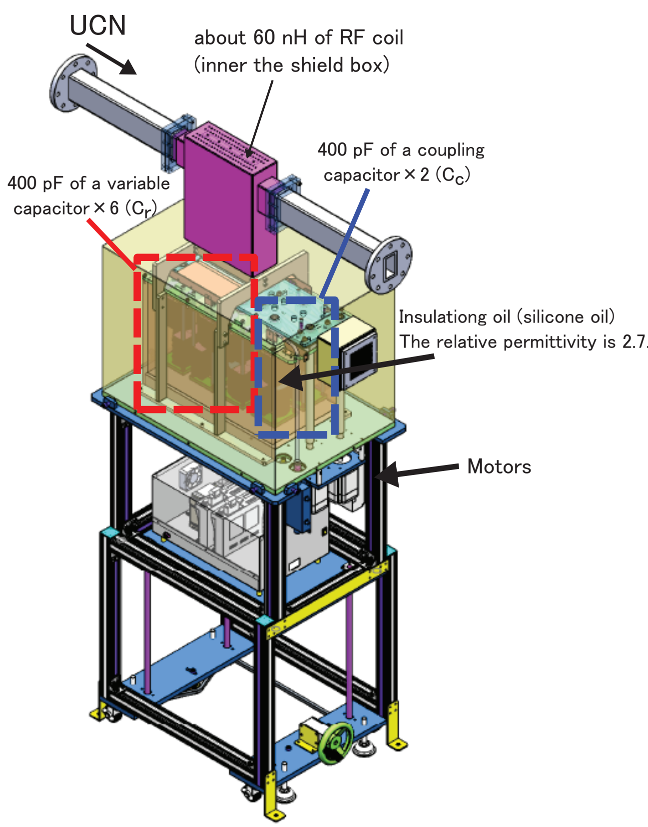

Figure 6: The CAD image of the new UCN rebuncher.

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