DEVELOPMENT OF SLOW NEUTRON ACCELERATOR FOR REBUNCHING PULSED NEUTRONS

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Abstract

Nowadays most measurements of the neutron electric dipole moment (EDM) are carried out with ultra cold neutrons (UCN), whose kinetic energies are lower than about 300 neV, and with a small storage bottle to reduce the systematic errors. In such experiments highly dense UCNs are desired. The pulsed spallation neutron source can produce such UCNs. However, the pulsed UCNs with broad velocities diffuse in guide tubes. It becomes an advantage to focus and rebunch UCNs temporally upon the bottle by controlling their velocities in neutron EDM experiments at those facilities. Low energy neutrons can be accelerated or decelerated by the technique of the AFP-NMR method with the RF magnetic field and the gradient magnetic field. We demonstrated such accelerator in ILL. We have been developing the advanced apparatus which makes it possible to handle the UCNs of the broader energy range.

INTRODUCTION

The time-reversal symmetry is broken directly if a neutron has electric dipole moment (EDM). Furthermore, the existence of large EDM is the evidence of new physics. The physics beyond the standard model like supersymmetry theory predicts several orders of magnitude larger neutron EDM than the prediction of Standard model, which is 10^{-30} to 10^{-32} $\mathrm{e \cdot cm}$. Therefore the searches of the neutron EDM is being carried out. At present the upper limit is 2.9×10^{-26} $\mathrm{e \cdot cm}$ (90% C.L.) [1].

In EDM experiment, polarized ultracold neutrons (UCNs), whose kinetic energies are lower than 300 neV, are stored in an experimental bottle. The spin rotation of UCN is measured by the Ramsey resonance technique after strong electric field is applied to the bottle. The bottle should be small in order to decrease the systematic error due to nonuniform magnetic field. Highly dense UCNs are desired in order to decrease statistical error. In future, such UCNs will be produced with the spallation neutron source and the superthermal converter.

We are proposing to construct such source at J-PARC by using its linac beam and to carry out EDM searches [2]. The peak power of the beam will become 20 MW at RCS 1 MW operation and extremely highly dense UCNs can be produced. However, the source produces pulsed UCNs and the pulse diffuses widely during transport according to their own velocity distribution.

We are developing a neutron accelerator named "UCN rebuncher" in order to control the velocity of UCN and to focus UCNs on the entrance of the bottle [3].

UCN REBUNCHER

Figure 1 shows the principle of the neutron acceleration using the magnetic field. A neutron has the magnetic moment $\boldsymbol{\mu}$ and it obtains the magnetic potential energy $-\boldsymbol{\mu} \cdot \boldsymbol{B}$ in the magnetic flux density $\boldsymbol{B}$. The absolute value of the energy is about 60 neV per 1 Tesla. If the neutron spin is flipped in the magnetic field, the variation of the kinetic energy by the field is not canceled when the neutron escapes out of the field. Hence the kinetic energy of an UCN can be controlled by flipping its spin in the suitable magnetic flux density [4, 5]. The controlled UCNs will be focused on a certain point temporally with suitable acceleration or deceleration.

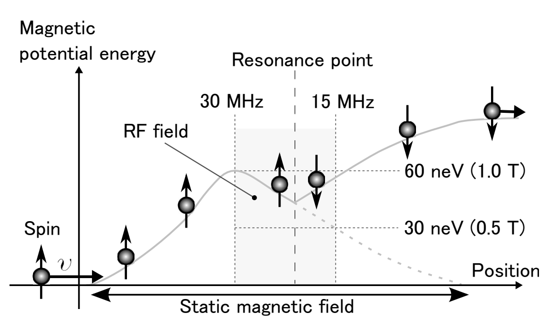

Figure 1: The principle of the neutron acceleration.

The spin is flipped by the adiabatic fast passage (AFP) NMR method. In the method a RF magnetic field is applied to neutrons in a gradient magnetic field. The spin flip occurs around the magnetic flux density B given by the Larmor frequency f, that is $\mathrm{B} = hf/2|\mu|$, where h is the Planck constant and μ is the neutron magnetic moment parallel or antiparallel with B. The flipping ratio depends on the adiabatic parameter k, which is given by

$$k = \frac{-\gamma_n B_1^2}{dB_0/dt} = \frac{-\gamma_n B_1^2}{v dB_0/dx}, \quad (1)$$

where γ_n is the gyromagnetic ratio of neutrons, B_1 is the RF magnetic flux density, dB_0/dt is the temporal variation of the static magnetic field, v is the neutron velocity and dB_0/dx is the spatial gradient of the static magnetic field along the transport axis, x, respectively. When k is over 1.4, the flipping ratio is more than 90% [6]. Our anisotropic-inter-pole magnet produces the constant magnetic field gradient of 3.2 T/m [7, 8]. Therefore the strength of B_1 needs to be more than 1.1 mT in order to achieve $k > 1.4$ with the UCN of 5 m/s.

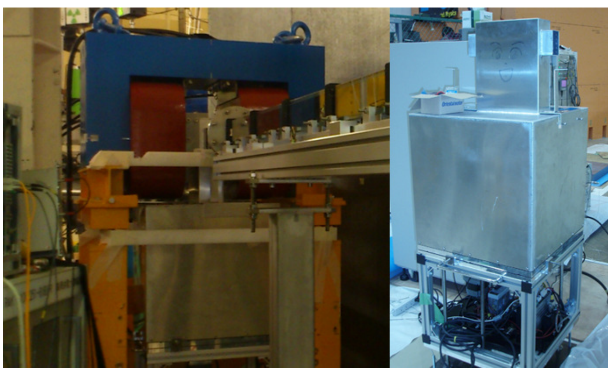

Figure 2: The proof-of-principle experiment at ILL.

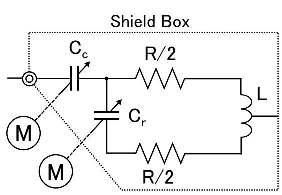

Figure 3: The RF circuits of the UCN rebuncher.

We developed the first rebuncher and carried out the proof-of-principle experiment of the rebuncher at ILL in 2011 (see Figure 2). In the rebuncher, RF fields were produced from LC circuit. Figure 3 shows the lumped element model of the rebuncher circuit. The capacitance C_r of three variable capacitors was controlled by a pulse motor. The RF power was supplied from the power amplifier of 1 kW. Another variable capacitor, C_c, was put in the circuit for the impedance matching. C_r and C_c were swept simultaneously with independent motion for about 0.2 seconds according to the time-of-flight of UCNs.

The rebuncher swept the RF frequencies from 17.5 MHz to 28.6 MHz. The cross section of the RF coil was 5 cm × 8 cm. The UCNs around 5 m/s were decelerated and focused on the moment of the detection of 4 m/s UCNs. As a result, the count rate was increased by 1.4 times at the focused spot [3]. The spin flipping ratio was estimated at about 50% from the comparison of data and simulations.

However, the performance of the rebuncher required for J-PARC P33 are the frequency sweep from 6 MHz to 30 MHz, the coil cross section of 12 cm × 12 cm and the spin flipping ratio of nearly 100%. A simple Monte Carlo simulation shows that the increase of the counts at the focused spot will become over 5 times greater by an ideal focusing than without the rebuncher.

One of the causes of the less focus was that the capacitors could not rotate with the suitable acceleration. Imperfect sweep of the RF frequency caused the weak focus. Another cause is the low spin flipping ratio, namely the low flux density of RF field, arising from the impedance mismatch.

SECOND REBUNCHER

We develop the second rebuncher in order to expand the frequency range and to minimize the impedance mismatch. That includes the six capacitors as C_r and two capacitors as C_c. The capacitance range of one capacitor is from 19 pF to 406 pF. These capacitors are immersed in the tank of silicone oil KF-96, whose relative permittivity is about 2.7, for the electrical insulation.

The rebuncher could produce the RF fields from 7.1 MHz to 34.9 MHz with the three capacitors as C_r and one capacitor as C_c. The magnetic flux density was measured at the center of the RF coil and the value scaled at 3 kW supply was more than 2.1 mT in all frequencies. It corresponds to $k > 5.0$ and hence the spin flipping ratio will be more than 95%.

For the matching circuit we use the additional resonance circuit which consists of power feed cable and C_c. The cable is connected to the inside of the RF coil and works as another coil. As a result the voltage standing wave ratio (VSWR) became below 1.2 in the all frequency range.

Powerful motors are installed in the rebuncher. Above the frequency of 8 MHz the capacitors C_r could be rotated with the motion, which realizes the ideal frequency sweep, within ±5 ms differences.

MODIFICATION

In the second rebuncher, the tension pulleys for the gear belt that synchronizes with the motion of the capacitors could not sustain the large starting torque and slid at the rotation. The rebuncher was not supposed to last for long-run experiments of a few weeks. The problem arose from the use of heavy capacitors made by brass and small stoppers fixed by a plastic screw.

Therefore the second rebuncher was modified in order to solve the problem. Figure 4 shows the arrangement of the components of the rebuncher. The rotor plates of the capacitors were replaced with copper-plated aluminum plates. The torque decreases by 1/3 times. The tension pulleys are mounted firmly with bigger fixtures.

The unused joints for capacitors were removed and only four capacitors are arranged in line. The volume of the oil tank becomes the half. The inductance of the circuit decreased due to the removal of the electrode plates for un-

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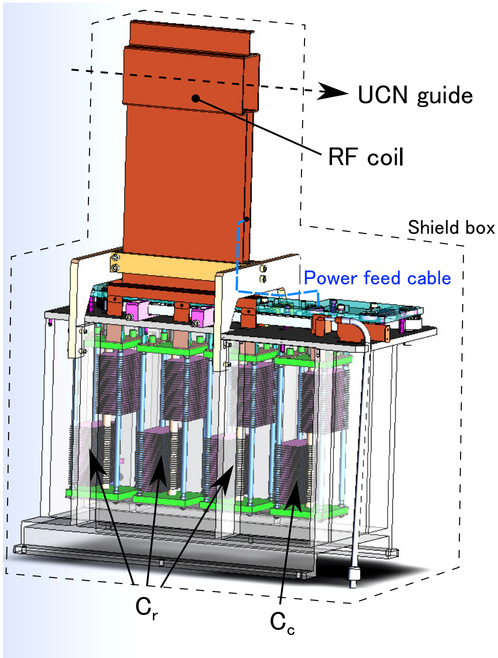

Figure 4: The compositions in the RF cavity of the modified rebuncher.

used capacitors. Therefore the frequency of the RF field rises slightly. The modified rebuncher produced the RF fields from 8.4 MHz to 36.1 MHz

The distribution of the magnetic field in the RF cavity also changes by the compact arrangement of the electrodes and the capacitors. The resonance condition of the matching circuit is affected considerably by the field and accordingly the VSWR becomes worse. Figure 5 shows a result of the measurement of VSWR. The VSWR is below 2.0 from 13 MHz to 35 MHz. The frequency range in which the VSWR is good decreases by half.

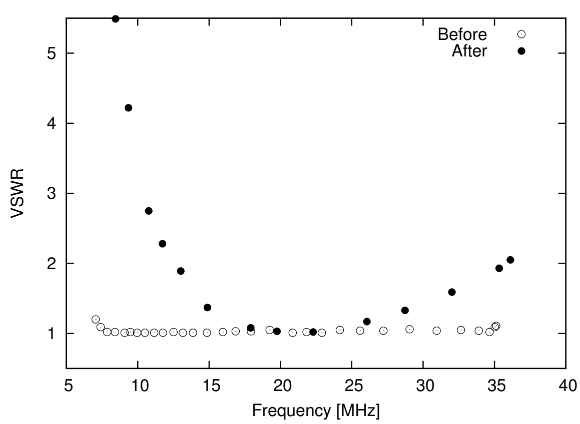

Figure 5: The VSWR before and after modification. The white dots are before modification and the black dots are after.

At present we search for the connection point of power feed cable in the RF coil which realizes the VSWR below 2.0 in wider frequency range than at least 20 MHz bandwidth below 30 MHz.

DISCUSSION

We developed the rebuncher with wider frequency range and stronger field for better efficiency of UCN focusing. The second rebuncher produced the RF fields from 7.1 MHz to 34.9 MHz and the VSWR was below 1.2 in the all frequency range. The RF flux density scaled at 3 kW supply RF power was more than 2.1 mT and the expected spin flipping ratio was more than 95%. The rotation of variable capacitors could realize the almost ideal sweep of the frequency above 8 MHz.

We improved the second rebuncher for a long operation. The modified rebuncher produced the RF fields from 8.4 MHz to 36.1 MHz while the VSWR was below 2.0 from 13 MHz to 35 MHz. Since the VSWR increases with the modification, we search for the power feeding scheme in order to improve the VSWR in wider frequency range below 30 MHz.

When the rebuncher works as designed, the neutron counts on the focused spot will increase by over 5 times greater than without focusing. Our neutron EDM searches in J-PARC will be carried out efficiently with such rebuncher.

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