DEVELOPMENT OF ULTRACOLD NEUTRON ACCELERATOR FOR TIME FOCUSING OF PULSED NEUTRONS

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Abstract

Low energy neutron accelerator can be realized by the combination of an adiabatic fast passage spin flipper and a gradient magnetic field. Neutrons have magnetic moments, so that the accumulated potential energies are not canceled before and after passage of a magnetic field and their kinetic energies change in case their spins are flipped in the field. This accelerator handles lower kinetic energy neutrons than approximately 300 neV. Currently we have developed the advanced version which makes it possible to handle broader kinetic energy range. The design and measured characteristics are described.

INTRODUCTION

A non-zero neutron electric dipole moment (nEDM) implies the breaking of time-reversal invariance and the larger nEDM than the prediction of Standard model, which is 10^{-30} to 10^{-32} e · cm, is the evidence of new physics. Therefore research and developments are prompted to update the present nEDM upper limit of 2.9×10^{-26} e · cm [1]. In nEDM experiment, polarized ultracold neutron (UCN), whose kinetic energy is 100–200 neV, is stored in an experimental bottle, and then the nEDM is evaluated with the rotation phase shift of UCN spin precession induced in a superposition of a strong electric and a faint magnetic field parallel each other measured by the Ramsey resonance technique. The bottle should be small enough to have less spurious nEDM signals due to nonuniform electric and magnetic field [2]. Therefore spatially high-dense UCN is required in order to decrease the statistical errors. Such UCN is produced with the spallation neutron source and the superthermal converter, which is sometimes a pulsed source and has a very high peak flux.

We also have proposed a nEDM search with a spallation UCN source (J-PARC P33) [3]. In our plan, the repetition frequency of UCN production is 2 Hz. Because even the extremely dense UCN diffuses during transport according to their own velocity distribution, we are developing a neutron accelerator named ĄgUCN rebuncherĄh in order to control the velocity of UCN and to time-focus UCNs on the mouth of the bottle.

UCN REBUNCHER

A neutron has the magnetic dipole moment $\boldsymbol{\mu}$, and hence in a magnetic flux density $\boldsymbol{B}$ it has a potential energy that is expressed by $-\boldsymbol{\mu} \cdot \boldsymbol{B}$. The absolute value corresponds to 60 neV at a magnetic flux density of 1 T. The energy is lost as the neutron escapes from the magnetic field because such a potential energy is conservative. If the spin of the neutron is flipped in the field, the cancellation is prevented and therefore the kinetic energy of the neutron escaping from the field increases or decreases according to its spin direction [4]. If acceleration/deceleration of the pulsed neutron beam with velocity range is modulated suitably and its velocity-position phase space distribution is rotated, the beam is time-focused at some point [5]. This is the mechanism of the UCN rebuncher.

The spin-flip of a neutron and the kinetic energy control can be realized with the combination of a gradient magnetic field and an adiabatic fast passage (AFP) spin flipper [6]. If a neutron flies to x direction, a gradient magnetic field is applied in the z direcition and an alternating magnetic field of the frequency f is applied parallel to the neutron path, the spin-flip occurs around the point of the resonant magnetic field $B_z = hf/2|\mu|$, where h is the Planck constant. If f is modulated, the strength of B_z for the resonance also changes and hence the spin-flip point moves in the gradient field. Thus each neutron gains a different kinetic energy. Consequently, the phase space distribution of neutrons can be controlled.

The spin-flip probability p depends on the adiabatic parameter k, which are given by [5]

$$p = 1 - \frac{1}{1+k^2} \sin^2\left(\frac{\pi}{2}\sqrt{1+k^2}\right), \quad (1)$$

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

where γ_n is the gyromagnetic ratio of neutrons, B_1 is the rotating magnetic field strength, dB_0/dt is the temporal change of the static magnetic field for a UCN, v is the neutron velocity and dB_0/dx is the spatial gradient of the static magnetic field. If k is more than 1.4, the spin-flip probability is more than 0.9. An anisotropic-inter-pole magnet we have developed produces the linearly gradient magnetic field of 3.2 T/m [7,8]. A RF field works as the rotating field. Therefore the strength of the RF magnetic field needs to be more than 0.7 mT in order to achieve $k > 1.4$ with the UCN of 5 m/s.

We developed the prototype of the rebuncher and carried out the demonstration experiment of the rebuncher at ILL in

2011 [5]. The rebuncher could generate RF magnetic field at frequencies from 17.5 to 28.6 MHz. The cross section of the one-turn RF coil was 5 cm × 8 cm. The RF magnetic field was generated by an RF resonator consists of one-turn coil L and four variable capacitors, as shown in Figure 1. In the figure, C_r is for a LC resonant circuit and C_c is for an impedance matching. C_r and C_c were controlled by motors separately. A phase-lock loop circuit detected a resonance frequency of the cavity and tuned the excitation frequency automatically. The electric power was supplied by an 1-kW amplifier. In the demonstration experiment, UCNs around 5 m/s were time-dependently decelerated and focused on the detection timing of 4 m/s UCNs and as a result the count rate was increased by 1.4 times. The achieved spin-flip probability was estimated at 0.5. In contrast, our goals of the performance are the frequency range from 6 to 30 MHz, the coil cross section of 12 cm × 12 cm and the spin-flip probability of nearly 1. Therefore we are developing the next version of this apparatus (second rebuncher) in order to improve these points.

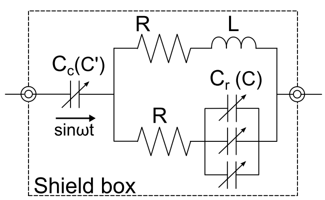

Figure 1: A schematic diagram in the rebuncher RF cavity. C and C' are the total capacitance of C_r and C_c.

PRESENT STATUS OF THE REBUNCHER

The photograph of the second rebuncher is shown in Figure 2. The capacitance range of a capacitor is from 20 to 400 pF and these capacitors are immersed in the tank of silicone oil KF-96. Rotor plates of this capacitors are copper coated aluminum plates for rapid acceleratrions of rotations. The electric power is planned to be supplied by a 3-kW amplifier. The present rebuncher can generate RF magnetic field at frequencies from 8.3 to 28.8 MHz, which corresponds to the energy control range from 33 to 115 neV. The resonant frequencies were adjusted by increasing the capacitance and decreasing the inductance in order to increase the current (magnetic field), because the total impedance of the LC_rR circuit as shown in Figure. 1 at the resonant frequency is calculated as follows,

$$Z = \frac{L}{2RC} + \frac{R}{2}. \quad (3)$$

Hence the coil cross section of this version is approximately the same as the first version.

The 3-kW equivalent field strengths, which were measured with a 1 cm^2 square coil probe and 0.4 W power input at the minimum voltage standing wave ratio (VSWR), are shown in Figure 3 and 4. At the frequency of 28.8 MHz, the field strength more than 1 mT will be achieved inside of the almost entire coil on the center axis of the coil, as shown in Figure 3. At the center of the coil, the field strength more than 1 mT will be achieved at the whole frequency range, as shown in Figure 4.

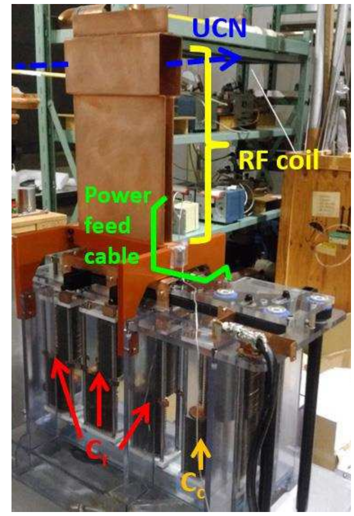

Figure 2: A photograph of the parts structure inside the RF cavity.

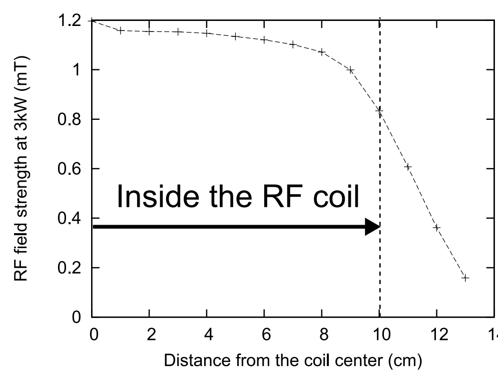

Figure 3: The 3-kW equivalent RF magnetic field strengths on the center axis of the RF coil at the frequency of 28.8 MHz.

The VSWR of the RF cavity is shown in Figure 5. It shows that the VSWR is good (under 2) at the frequencies more than 10 MHz, even though without the dynamic adjustment of the C_c capacitance. It means that the power reflection is below 10% above 10 MHz. The low VSWR is realized by connecting the power feed cable to the inner surface of the coil (inductive coupling).

The present frequency sweep curve caught by the PLL circuit at the rapidly accelerating rotation of the C_r, with an example of ideal sweep curve, is shown in Figure 6. The ideal curve was calculated on the assumption that the pulsed up-spin UCN of 4–5 m/s is decelerated and focused. The slope of the detected curve around 10 MHz well matches with the ideal curve. Since the resonant frequency is proportional to $1/\sqrt{\theta}$, where θ is the rotation angle of the capacitor C_r, the angular velocity rapidly increases to realize a linearly

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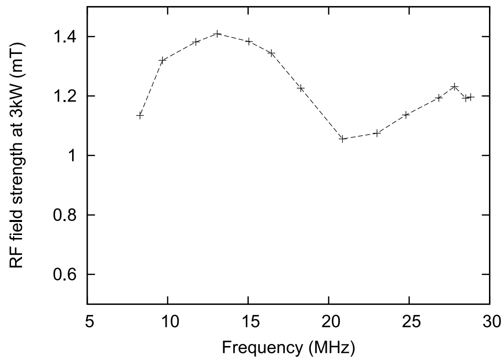

Figure 4: The 3-kW equivalent RF magnetic field strengths with respect to the input signal frequency. The data set was measured at the center of the RF coil.

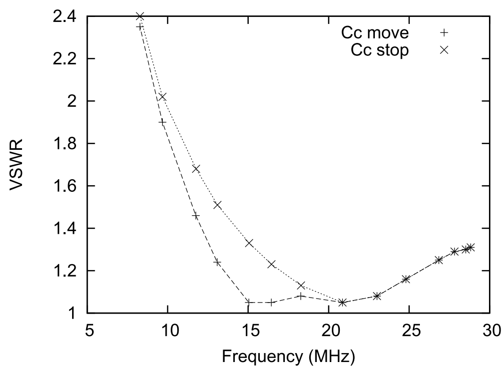

Figure 5: The VSWR of the RF cavity with respect to the input signal frequency. The plus markers were measured with adjusting the capacitance of C_c. The cross markers were measured at the maximum C_c capacitance.

decreasing frequency curve. Therefore, the ideal curve in the range more than 10 MHz, where the angular velocity is enough slower, can be realized by fine-tuning the motion of the motors.

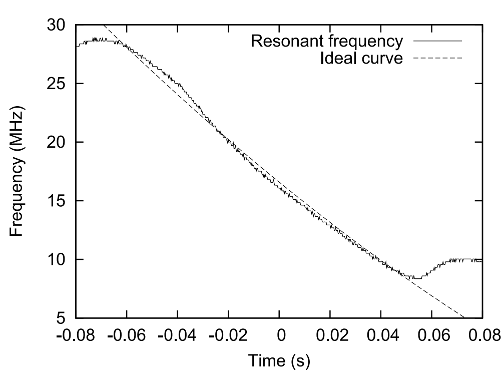

Figure 6: The comparison of detected and ideal frequency sweep curves. The former and the latter are the solid and dashed line, respectively.

We will carry out 3 kW power supply tests soon after the adjustment of the motor rotation in such a way that the measured curve fits within 5 ms from the ideal curve. The UCN focusing test is planned to be performed at the J-PARC/MLF BL05 in this December.

SUMMARY

We are developping the second version of the prototype rebuncher. The rebuncher is an important apparatus in our planned nEDM enperiment. The present rebuncher generates the RF magnetic fields at frequencies from 8.3 to 28.8 MHz. The VSWR of the RF cavity is under 2 at the frequencies more than 10 MHz. The 3-kW equivalent RF magnetic field strengths are more than 1 mT at the all frequencies and hence the spin-flip probability of approximately 1 can be realized. The rotation of variable capacitors can realize the almost ideal frequency sweep in the range more than 10 MHz. Therefore the precise UCN focusing with a high spin-flip probability is expected in the frequency range. We will carry out 3 kW power supply tests soon and then the UCN focusing test will be performed at the J-PARC/MLF BL05. The second rebuncher is near completion.

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