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THE DEVELOPMENT OF A LOW ENERGY NEUTRON ACCELERATOR FOR REBUNCHING PULSED NEUTRONS

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Abstract

Low energy neutrons can be accelerated or decelerated by the technique of AFP-NMR with RF in a gradient magnetic fields. The neutrons have magnetic moments, hence their potential energy are not cancelled before and after passage of magnetic fields and their kinetic energy change finally when their spins are flipped in the fields. Nowadays most measurements of the neutron electric dipole moment (nEDM) are carried out with ultra cold neutrons (UCN), whose kinetic energies are lower than about $300\ \mathrm{neV}$, and with a small storage bottle to reduce the systematic errors. In such experiments highly dense UCNs are desired. The spallation neutron sources generate high-density neutrons at the target, however, the pulsed neutrons with spread velocities are diffused in guide tubes during long beam transport. It is necessary to concentrate UCN temporally upon the bottle by controlling their velocities for nEDM experiments at those facilities. We demonstrated such rebuncher and have been developed the advanced apparatus which makes it possible to handle broader energy range UCN. The design, measured specification of the new rebuncher is described in detail.

INTRODUCTION

A particle that has both spin and electric dipole moment (EDM) directly breaks the time-reversal symmetry. EDM arises from an asymmetric charge distribution along the spin in hadrons, for example. Under time-reversal transformation, spin directions turn over but EDM directions do not. EDM searches are performed with neutrons, atoms, and muons.

In recent neutron EDM experiments, it is usual to use Ultra-Cold Neutrons (UCNs), whose kinetic energies are lower than about $300\ \mathrm{neV}$. Polarized UCNs are stored in an experimental bottle like gas. Static magnetic fields are applied to the bottle and their spins are flipped by $\pi/2$ radians with RF magnetic fields. Then strong static electric fields are also applied in parallel or anti-parallel direction with the static magnetic field for a few minutes. If neutron EDM exists, the EDM vector begins precession around the electric field axis. Hence the spins are not polarized perfectly by next $\pi/2$ flip and EDM is measured from the rotation angles. The angles increase as the application time of the electric fields become longer. From this point of view, UCNs are more suitable than slow neutron beams for EDM searches. The present upper limit of neutron EDM is $2.9\times10^{-26}\ \mathrm{e\cdot cm}$ (90% C.L.) [1]. The existence of neutron EDM slightly shifts the Larmor frequency of neutrons. The frequency ν_n is given by $h\nu_n = 2\boldsymbol{\mu}\cdot\boldsymbol{B} \pm 2\boldsymbol{d}\cdot\boldsymbol{E}$, where h is Planck constant, $\boldsymbol{\mu}$ is the magnetic moment of neutrons, $\boldsymbol{d}$ is EDM, and the double sign corresponds to the case for electric field $\boldsymbol{E}$ parallel or anti-parallel to magnetic field $\boldsymbol{B}$, respectively. In estimating EDM value, the effect of $\boldsymbol{B}$ is canceled in calculation. However, non-uniformity in $\boldsymbol{B}$ of $10^{-12}\ \mathrm{T}$ misleads to show as EDM of $10^{-27}\ \mathrm{e\cdot cm}$. Therefore small experimental bottles are desired in order to achieve enough field uniformly for less systematic errors, while highly dense UCNs should be supplied to decrease statistical errors.

The UCN sources based on the superthermal method and the spallation neutron sources are developed at PSI, RCNP and so on to generate 100 times denser UCNs than usual sources. Our group NOP (Neutron Optics and Physics) is also planning to construct such source at J-PARC by using its linac beam [2].

J-PARC produces high intensity pulsed proton beam and highly intensive UCNs can be generated for an instant. However, an EDM bottle should be set several meters apart from the source to escape from background radiation and stray magnetic fields. High density UCNs at the source must diffuse widely according to their own velocity distribution.

In order to fully take advantage of such sources in EDM experiments, density of UCN should be kept while transport from source to the bottle. When pulsed UCNs are accelerated properly, the density can be recovered at the bottle position. So we are developing a neutron accelerator named "UCN rebuncher". The proof-of-principle experiment of the first rebuncher was carried out at ILL in 2011 [3]. UCNs of $5\ \mathrm{m/s}$ were decelerated and the detected count rates of UCN at $4\ \mathrm{m/s}$ were increased by 1.4 times. At present the upgraded second rebuncher is under development to focus UCNs more sharply.

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PRINCIPLE OF UCN REBUNCHER

Neutrons do not have electric charge and cannot be handled by electric fields. However, they have magnetic moments hence have potential energies $-\boldsymbol{\mu} \cdot \boldsymbol{B}$ in magnetic fields. The potential energy of about $60\ \mathrm{neV}$ is given in the fields of $1\ \mathrm{T}$. According to the law of conservation of energy, the kinetic energies of neutrons increase or decrease in magnetic fields.

Ordinarily such accelerations are canceled after they went through magnetic fields. It is necessary to flip their spins in the magnetic field area in order to keep their kinetic energy changes and to control their velocities [4][5].

Neutron spins are flipped with a resonance spin flipper. Especially the adiabatic fast passage (AFP) technique in NMR is convenient. AFP-NMR is realized when static magnetic fields are swept slowly from strong to weak intensity under applying RF magnetic fields perpendicular to the static fields. A slow gradient field can be also usable as such field and neutron spins are flipped just around the resonance point. Magnetic field flux density B_z at the point is given by $B_z = hf/2|\mu_z|$, where h is the Planck constant, f is the resonance frequency, and μ_z is the neutron magnetic moment parallel or antiparallel with B_z. If f is equal to $30\ \mathrm{MHz}$, B_z corresponds to about $1\ \mathrm{T}$ and neutron kinetic energies change by $\pm 120\ \mathrm{neV}$. The energy modification can be controlled by adjusting the frequency during the travel of UCN in the gradient magnetic field, where UCNs meet the magnetic field level for their spin-flips somewhere in the gradient magnet. Although this energy change is rather tiny, the decrease of $120\ \mathrm{neV}$ is enough to decelerate UCNs of $7\ \mathrm{m/s}$ to $5\ \mathrm{m/s}$.

The flipping ratio is limited by the RF intensities and the sweeping speed of static fields. The adiabatic parameter k, which is an index of the flipping ratio, is given by

$$k = \frac{-\gamma_n B_1^2}{dB_0/dt} = \frac{-\gamma_n B_1^2}{v dB_0/dx} \gg 1, \tag{1}$$

where γ_n is the gyromagnetic ratio of neutrons, B_1 is the RF intensity, B_0 is the static field intensity, x is the transit axis of neutrons, and v is the neutron velocity in the x direction, respectively. If v is equal to $5\ \mathrm{m/s}$ and B_0 is equal to $3.2\ \mathrm{T/m}$, B_1 need to be more than $1.1\ \mathrm{mT}$ to achieve the flipping ratio of beyond 90% [6].

When incident neutrons are short-pulse UCNs and spin flipper is set up a few meters apart from the source, it is possible to consider that the UCNs of different velocities arrive in the flipper one after another. Hence the spin of each UCN can be flipped by different and suitable frequency one by one and UCNs are focused and rebunched temporally on an optional point.

RF fields are generated by LC circuit made up of an RF coil and variable capacitors to minimize the power loss (Figure 1). The capacitance C_r of the variable capacitors is controlled by motors to sweep the RF frequencies. The resonant frequency $1/2\pi\sqrt{LC_r}$, where L is the inductance of the coil, changes continuously according to the capacitance. RF power with the resonant frequency is supplied.

In Figure 1, another variable capacitor is installed outside of the LC circuit. It works for impedance matching. The matching condition changes with the frequency sweep. Hence the capacitance C_c is also swept with another motor. The quality of rebunch depends on the mechanical control of these motors.

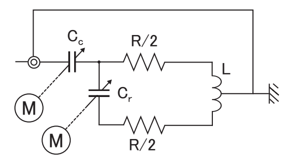

Figure 1: The RF circuits of the UCN rebuncher.

SPECIFICATION OF UCN REBUNCHER

The first rebuncher could sweep the RF frequencies only from $17.5\ \mathrm{MHz}$ to $28.6\ \mathrm{MHz}$. The anisotropic-inter-pole magnet realized almost constant gradient of static magnetic fields for the RF coil length of $20\ \mathrm{cm}$ between $0.25\ \mathrm{T}$ to $0.93\ \mathrm{T}$ [7][8]. RF power amplifiers of $1\ \mathrm{kW}$ were used.

However, in our plan the frequency range of $6\ \mathrm{MHz}$ to $30\ \mathrm{MHz}$ should be achieved for EDM searches in J-PARC. C_c was not enough to match the impedance of below $17.5\ \mathrm{MHz}$. The torque of motors was slightly small and frequency sweep could not catch up with the arrival of UCNs. The peak width of focused UCNs was about $200\ \mathrm{ms}$ though constant UCNs were chopped into the pulse of $20\ \mathrm{ms}$ width. Furthermore the control of two motors was not synchronized perfectly and estimated flipping ratio was about 50% due to the partial power reflection. Therefore the second rebuncher has been developed to solve these problems (Figure 2).

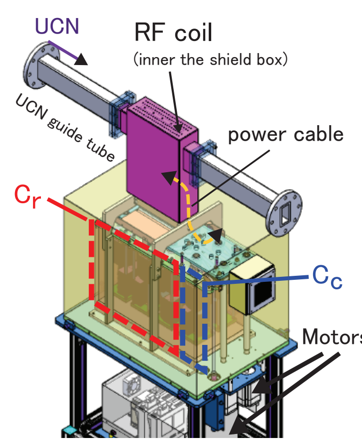

Figure 2: The RF cavity of the second rebuncher.

The second rebuncher is made up of larger capacitors and more powerful motors. It can sweep the RF frequency from $7\ \mathrm{MHz}$ to $35\ \mathrm{MHz}$. RF power amplifier of $3\ \mathrm{kW}$ is prepared. In order to decrease power losses the electrodes of stators are only used and the ball bearings of variable capacitors are eliminated from the circuit. The quality factor

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of the circuit is more than 180, which is twice larger than that of the first rebuncher.

The power losses were greatly suppressed, however, it also reduced the necessary capacitance range of C_c to be from 10 pF to 200 pF. It is difficult to make such capacitor. Hence, for temporary treatment additional small capacitors were connected between C_c and a network analyzer in order to make the combined capacitance smaller than the minimum capacitance of C_c. An additional capacitor was replaced with another according to realized capacitance range. The mentioned characteristics of this circuit were measured in this way.

RF field strength the RF coil was also measured with the network analyzer through the induced electromotive force in one turn probe coil. Scaled strength of the magnetic fields at the center of the coil was more than 2.1 mT in all frequencies when the power of 3 kW is applied (see Figure 3). It corresponds to the adiabatic parameter of over 5.0 and the spin flipping ratio of 95%.

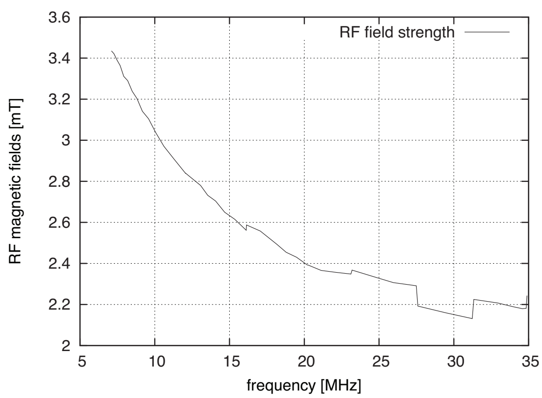

Figure 3: The RF field strength at 3 kW applied.

For better impedance matching we tried to connect the power feed line through the C_c to the inside of RF coil (see Figure 2). The LC circuit is coupled not only capacitively but inductively with the outside of RF cavity. Consequently the voltage standing wave ratio (VSWR) becomes below 1.2 over frequency range of 8 MHz to 35 MHz. However, this method is unstable and it is difficult to reproduce the impedance matching condition. The range of frequencies in which the impedance is matched well is reduced by half when the cable moves to its side by a few millimeters.

The rotation of C_r is measured by monitoring the voltage drop of RF waves through C_r with an oscilloscope. The drop is inversely proportional to the capacitance of C_r. Therefore the voltage change represents the rotation angle of the rotor plates of C_r. It was shown that the actual frequency sweep calculated from the rotation is fitted relatively within ± 5 ms width around ideal sweep in frequency range of 8 MHz to 35 MHz. In this measurement C_r were made by brass and heavy.

At present the second rebuncher is under modification to solve above problems. For long-run experiments the rotors of C_r are replaced with copper-plated aluminum plates and for easy reproduction of the impedance matching condition the power feed line is tightly fixed, for example. The UCN focusing test with the improved rebuncher will be carried out at the BL05/NOP beamline in J-PARC/MLF. A neutron Doppler-shifter [9] had been developed and installed there. The apparatus produces pulsed UCNs of 8.33 Hz and the pulse width at production is lower than 2 ms. Simple Monte Carlo simulations, in which only the time of flight and the spin-flip according to the preset probability are calcurated, suggest that count rates at focused point increase five times more than without focusing if ideal sweep is achieved.

SUMMARY

The first UCN rebuncher has been developed. It is a neutron accelerator composed of a static magnetic field and a RF spin flipper. It focuses UCNs in an experimental bottle and makes it possible to carry out EDM searches with pulsed UCN sources. However, the first spin flipper covered RF frequencies of 17.5 MHz to 28.6 MHz rather than our final goal of 6 MHz to 30 MHz.

Hence the second rebuncher has been developed. In the second rebuncher the range of frequencies is 7 MHz to 35 MHz and the flipping ratio of over 95% will be realized at the power input of 3 kW. The mechanical control is fitted to almost ideal sweep even though heavy variable capacitors are used.

Now the second rebuncher is improved to solve additional problems. UCN focusing test will be performed in J-PARC/MLF. Test experiments will be performed to demonstrate clear focusing of UCNs.

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