REBUNCHING LOW ENERGY NEUTRONS BY MAGNETIC ACCELERATION AND DECELERATION

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Abstract

Acceleration control for neutrons was demonstrated. Ultra cold neutrons (UCN) - neutrons with energies less than 300 neV - can be accelerated or decelerated by means of static magnetic and RF fields. Neutrons have a magnetic dipole moment, and hence their kinetic energies vary depending on their spin in magnetic fields. Their kinetic energies are restored when they leave the magnetic field area if their spin did not flip. A spin flip can be triggered by applying an RF field whose frequency coincides with the spin precession frequency of a neutron in this magnetic field. This allows to tune the kinetic energy of neutrons. This method can be used to rebunch a pulsed beam of neutrons to a storage bottle that can store UCN. By opening and closing the storage bottle synchronously with the rebuncher, high UCN densities can be achieved for precision measurements of neutron properties such as the Electric Dipole Moment.

INTRODUCTION

The neutron, which has been one of the most well known fundamental particles since Chadwick discovered it, has not been considered as an acceleration object in the accelerator community. The chargeless property takes an important role in not only materials science but also fundamental physics. nEDM (neutron Electric Dipole Moment) search using UCN (Ultra Cold Neutron) is one of such distinguishing activities to explore new physics beyond standard theory. Finite neutron EDM breaks time reversal symmetry, which also leads CP violation if CPT symmetry holds (see Fig.1). In order to raise the detection sensitivity of the nEDM, statistics and systematic errors have to be minimized and spatial density of UCN in a measurement storage cell has to be maximized. As to the neutron density, the instantaneous power of J-PARC is the highest in the world. Since the storage cell for such high precision measurement cannot be located close to the production target, the high peak neutron density at the moderator diffuses along the neutron guide towards the nEDM measurement storage cell because of the velocity spread. This situation can be recovered by using a so-called rebuncher. The magnetic dipole moment of a neutron enables us to manipulate its energy by flipping its spin in a magnetic field[1]. Hence, we have developed a UCN rebuncher for neutrons.

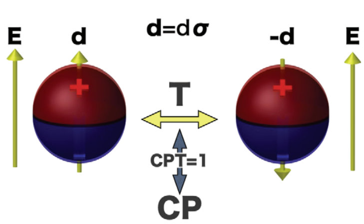

Figure 1: Finite neutron EDM violates T symmetry.

SPIN FLIP IN MAGNETIC FIELD

Because of the magnetic dipole moment, a neutron feels a potential in a magnetic field and its energy does not change when the magnetic dipole moment is preserved (see Fig. 2). Since the magnetic dipole moment and the spin are directly connected, this condition is equivalent to preservation of spin direction. The spin can be flipped by applying an RF magnetic field. The frequency matches the spin precession frequency in the magnetic field B, which is given by:

$$\omega = 2\mu B/\hbar,$$

where ω, μ, and $\hbar$ are the angular frequency, magnetic dipole moment, magnetic and Plank constant, respectively. The frequency is proportional to the magnetic field, and the coefficient is 29.6 MHz/T. Thus we can control the

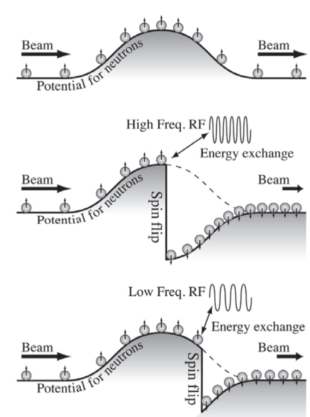

Figure 2: Neutron deceleration/acceleration in magnetic field. Top: no net acceleration. Center: maximum deceleration. Bottom: middle deceleration.

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magnitude of the deceleration/acceleration by RF frequency modulation in the gradient magnetic field, where the polarity depends on the spin direction relative to magnetic field direction. If the magnetic field region is short enough compared with the total drift length, the deceleration/acceleration takes place practically at the magnet position.

This scheme is preferable for precise nEDM measurement, because the rebuncher static magnetic field would not interfere the required extremely precise magnetic field at the storage cell[2].

GRADIENT FIELD MAGNET

The uniform gradient field can be generated by the magnet with inter-poles [3,4]. Fig. 3 shows the difference between the magnet with and without inter-pole technology. The gradient field is usually generated by changing the magnet gap along the axis, which controls the magnetic resistance (see Fig. 3). Because the distribution of the fringing field increases with the gap size, the magnetic field distribution also becomes blurry and such a magnet has to have wider magnet width for uniform distribution along the transversal direction. On the other hand, the magnet with inter-pole can generate a uniform distribution along the transversal direction for the limited footprint, while that in longitudinal direction has constant gradient. The less stray field should also benefit the precise magnetic field measurement. Fig. 4 shows the fabricated gradient magnet with inter-poles.

The neutrons are transported in a neutron guide, whose interior mirror surfaces can reflect neutrons efficiently. This guide is inserted in the gap and the inner volume is immersed in the magnetic field gap. Owing to the inter-pole structure, ideal field distribution is achieved (see Fig. 5). Figure 6 shows the cross sectional layout during the experiment. This magnet provides longitudinal magnetic field in the volume of 3 x 6 cm cross section with 13cm in axial direction.

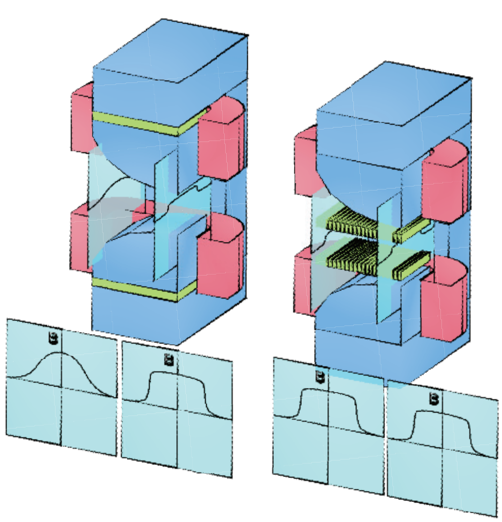

Figure 3: Left: Conventional magnet. Right Magnet with inter-pole. Latter can generate uniform gradient field.

RF MAGNETIC FIELD GENERATOR

The RF magnetic field that resonates the spin precession has to be perpendicular to the static magnetic field. While the direction of the static field is horizontal, the direction of RF magnetic field is longitudinal. This RF magnetic filed is generated by a one-turn coil loaded by three 500 pF variable capacitors. The one turn coil is wound around the neutron guide, which is composed of four glass plates glued together. The inner surface of the guide is coated by Ni evaporation to maximize the reflection of UCN. The variable capacitors are driven by

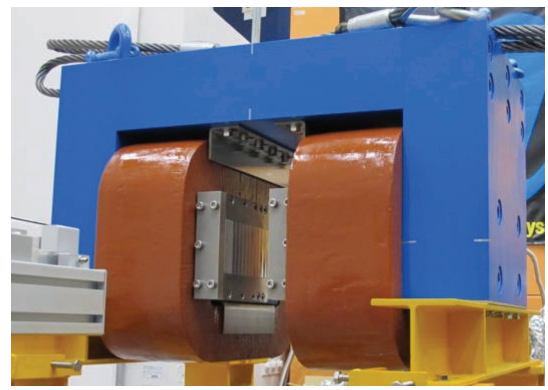

Figure 4: The inter-pole in the fabricated gradient magnet.

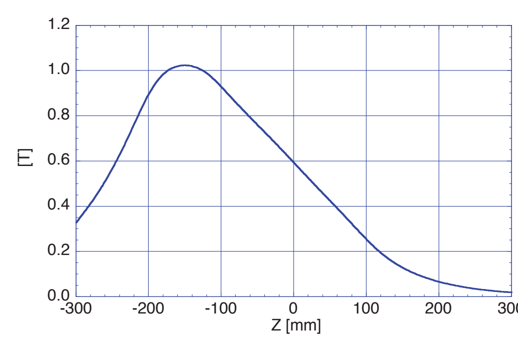

Figure 5: Measured magnetic field distribution.

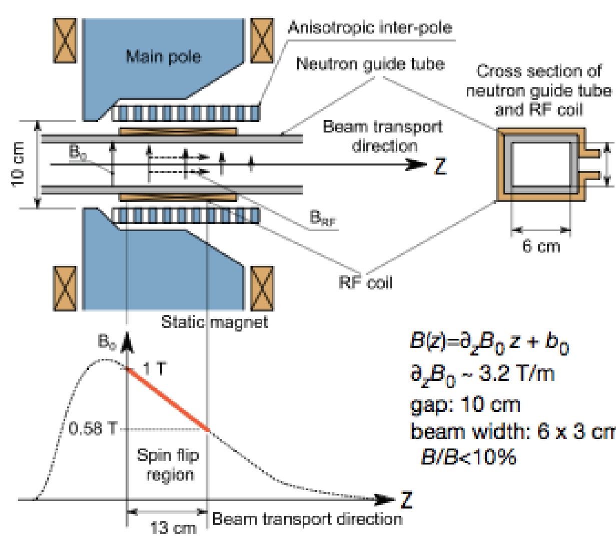

Figure 6: One-turn RF coil is wound on neutron guide installed in the gradient magnet.

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pulse motor to sweep the frequency from 15MHz to 30MHz in 0.2 s. Fig. 8 shows the rebuncher resonator with the shield case. The neutron guide goes through the square hole and the top box part is inserted in the magnet gap. The required amplitude of the RF magnetic field is about 10 Gauss.

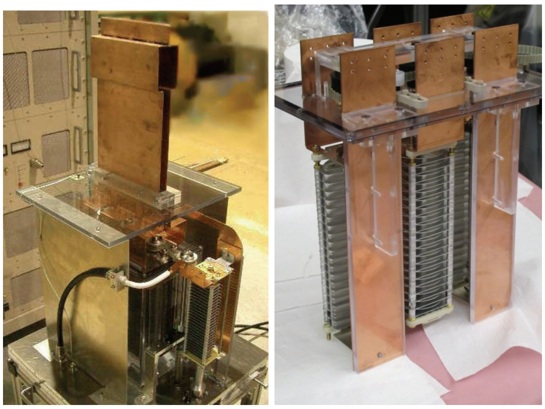

Figure 7: Left: one turn coil to wrap the neutron guide. Right: three variable capacitors.

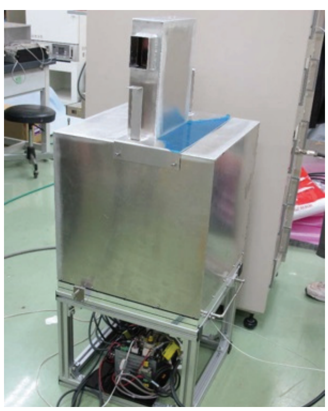

Figure 8: The rebuncher resonator with the shield case.

As mentioned above, the resonant frequency is controlled by the variable capacitor Cr. The coupling between the power feeding coaxial cable and the resonator is adjusted by another variable capacitor Cc, which is also driven by a pulse motor. The matching is achieved by adjusting Cc at enough many points of Cr and their positions and corresponding frequencies are recorded (see Fig.9). Thus the required values for Cr and Cc are given by the interpolated values from the data. The Cr and Cc are driven so as to modulate the resonant frequency as function of time for the rebunching action.

1kW RF power is fed to the resonator. We use a VCO (HP8116) for the wide frequency range, whose frequency should be matched to that of the sweeping resonator. This is controlled by the PLL (Phase Locked Loop) circuit as shown in Fig. 10.

Although the rebuncher was originally designed for an experiment at J-PARC, the experiment was performed at ILL, Grenoble, because of the earthquake disaster in Japan. The results will be published elsewhere, soon.

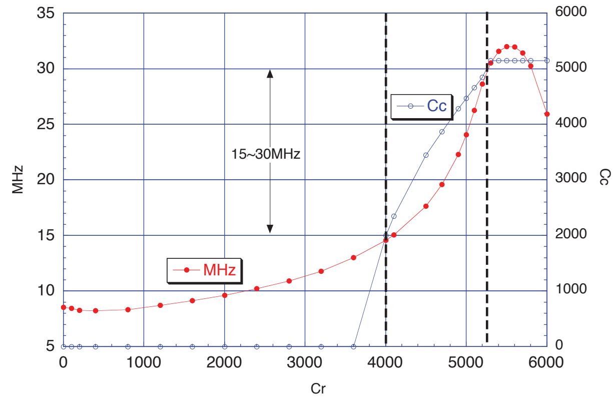

Figure 9: Matched Cc position and resonant frequency as functions of Cr.

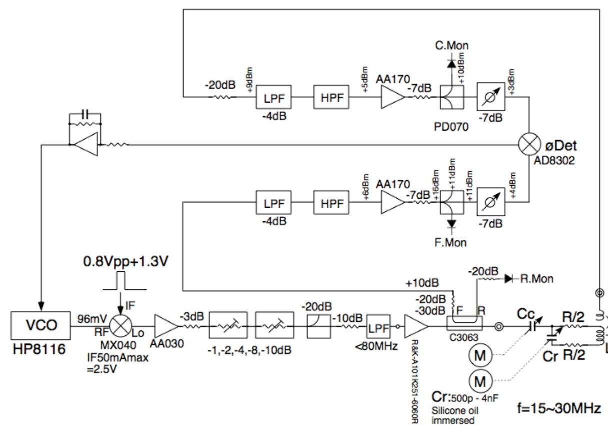

Figure 10: Phase Locked Loop Circuit for tracking the sweeping resonance frequency.

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