Progress in Development of a Francium Atomic Beam: towards a Measurement of an Electron EDM

著者	Sato T., Arikawa H., Ezure S., Harada K., Hayamizu T., Inoue T., Ishikawa T., Itoh M., Kato T., Kawamura H., Sakemi Y.
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I. 7. Progress in Development of a Francium Atomic Beam: towards a Measurement of an Electron EDM

Sato T.[1], Arikawa H.[2], Ezure S.[2], Harada K.[2], Hayamizu T.[2], Inoue T.[2], Ishikawa T.[2],
Itoh M.[2], Kato T.[2], Kawamura H.[2], and Sakemi Y.[2]

[1]Department of Physics, Tokyo Institute of Technology
[2]Cyclotron and Radioisotope Center, Tohoku University

An electric dipole moment (EDM) is a non-trivial distribution of the electric charge in the non-degenerate system of elementary particles. A non-zero EDM of an elementary particle violates time reversal symmetry, and hence CP-symmetry, which is necessary to explain the evolution mechanism of this matter dominated universe. The EDM is one of the most promising candidates to search for the physics beyond the Standard Model (SM), because the almost all contributions for the predicted finite value of the EDM come from the physics beyond the SM due to the small contribution from the SM.

The final objective of our project is to search for the electron EDM (e-EDM) using an enhancement mechanism of e-EDM in a paramagnetic atomic system, the francium (Fr, Z=82) which is the heaviest alkali element and has the e-EDM enhancement factor of approximately 895$^{1)}$. Final sensitivity for the e-EDM in this project is expected as $|d_e| \sim 10^{-28}$ e・cm, which is approximately an order of magnitude smaller than the current experimental e-EDM limit in the atomic system obtained in Tl experiment with $|d_e| \sim 10^{-27}$ e・cm$^{2)}$.

In this project, ^{210}Fr is produced as a keV energetic ion beam by the fusion reaction of ^{18}O + ^{197}Au in a thermal ionizer$^{3)}$, and then the Fr ions are transported to a neutralizer$^{4)}$. After the neutralization, the Fr atoms will be slowed down by a Zeeman slower, and then introduced to a magneto-optical trap (MOT) in order to cool down to the milli-kelvin temperature$^{5)}$, which is necessary to transport to a final optical trap used for the EDM measurement$^{6)}$ with high loading and trapping efficiency. In this scheme, there is a concern about the loss of the Fr atoms in the Zeeman slower tube due to the divergence of the beam. In order to reduce the loss of the atoms during the cooling scheme, a cooling of the transverse velocity of the beam can be adopted. Here, a design of the apparatus for the transverse cooling of the atomic beam is discussed.

The neutralizer enables us to convert the keV ion beam to the thermal neutral atomic beam. The divergence of the atomic beam is approximately 100 mrad, on the other hand, the acceptance of the Zeeman slower is typicaly about 1 mrad. Consequently, the transport efficiency from the neutralizer to the MOT is limited as approximately 0.8%. The beam divergence comes from the transverse velocity of the beam; thus, a decrease of the transverse velocity causes a decrease of the beam divergence.

The transverse cooling has been applied to metastable He7), Rb8), metastable Ar9) and other atoms. The cooling of the transverse component of the velocity is realized by the pressure force from laser lights. When the two counter-propagating laser lights irradiate the moving atom, the atom feels the asymmetric pressure force from the laser light because the difference of the absorption probability of the light due to the Doppler shift of the absorption line. As a result, in the case of irradiation of red shift light, the atom feels the force opposite to the direction of the motion; thus, the atomic beam is collimated. In order to cool down hot Fr atoms effectively, the cooling laser light tuned near the resonance of the D2 transition of Fr is reflected many times typically up to ~100 between a pair of the mirrors as shown in Fig. 1. Moreover, to correct the difference of the Doppler shift corresponding to the transverse velocity of the atom, two mirrors are set as slightly non-parallel7). The two-dimensional collimating is realized with the use of two pairs of the mirrors.

In order to study the design for an efficient cooling, a Monte-Carlo simulation of the transverse cooling was performed10). The setup in the simulation is shown in Fig. 2. Each particle was produced on the surface of the neutralization target of the neutralizer. The initial position of the particle was randomized in the diameter of the 2 mm corresponding to the realistic shape of the neutralization target. The initial velocity distribution of the particle obeyed to the thermal Boltzmann distribution of 1000 ^{o}C. Atoms whose velocities were over 400 m/s were ignored, because of the limit of the cooling velocity of 2 m length Zeeman slower. Three-dimensional components of the velocity of the atoms were randomized. Only the particles which go through the extraction hole of the neutralizer were used for the estimation of the transport efficiency. After the neutralizer, the two-dimensional transverse cooling was performed. For the pressure force of the laser light, the Lorentz-type force was used. The equation of the motion of the particle was solved by the 4th order of the Runge-Kutta method. After the transverse cooling, a two-dimensional optical molasses was applied in order to match the atomic beam axis to the Zeeman slower axis(7). After the optical molasses, two chambers for the differential pumping and the Zeeman slower were considered. In this simulation, these were treated as simple beam collimators. The particle which reached the area of the diameter of 30 mm were used for the numerator of the efficiency calculation.

In order to determine the optimum length of the mirror, the mirror length dependence of the transport efficiency was studied. The result of the simulation is shown in Fig. 3. The initial laser angle and mirror tilt were optimized for each mirror length. The transport efficiency was improved as an increase of the mirror length. However, the region over 400 mm, the efficiency was saturated. In practice, considering the difficulty of making a huge size mirror, the 400 mm mirror was appropriate.

In order to study about the requirement for the apparatus, the transport efficiency dependence of the laser and mirror condition was calculated. Figure 4 shows the laser detuning, initial laser angle and mirror tilt dependence of the transport efficiency at the mirror length of the 400 mm. For the laser detuning, the positive detuning was suitable because the laser irradiation with too small initial laser angle is practically difficult. For the mirror tilt, the change of the 0.5 mrad mirror tilt caused the decrease of the approximately 3% of the transport efficiency. The mirror adjustment system should have 0.1 mrad accuracy.

Based on this simulation works, the construction of the transverse cooling is in progress. In the first step, the test experiment using Rb atoms whose chemical properties are similar to the Fr will be performed. The transverse cooling will be installed in the Fr production and transport beam line.

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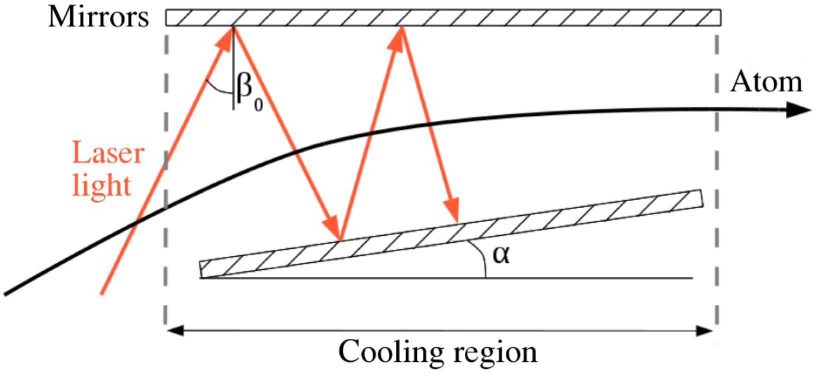

Figure 1. Schematic view of a transverse cooling. α is a mirror tilt angle and β_0 is a initial angle of incidence of the laser light.

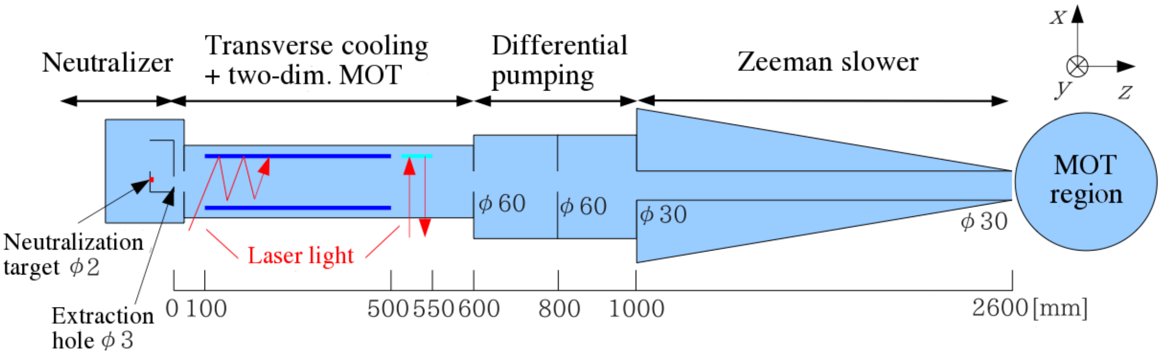

Figure 2. Setup of the simulation of the transverse cooling.

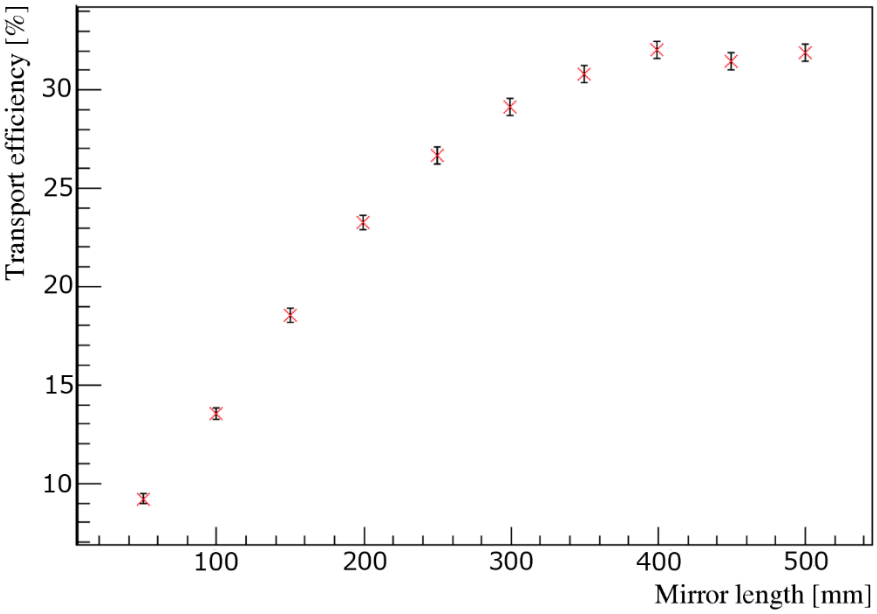

Figure 3. Mirror length dependence of the transport efficiency.

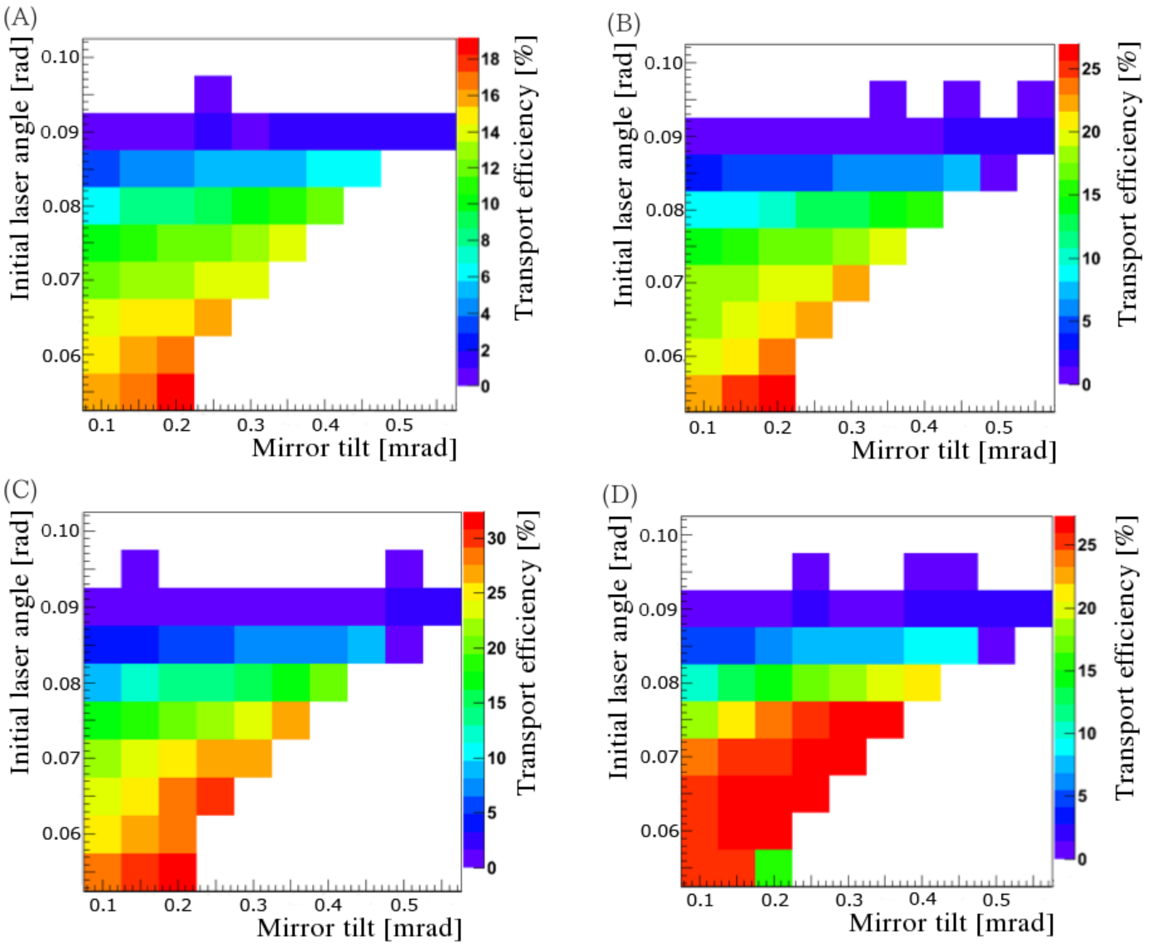

Figure 4. Laser detuning, initial laser angle and mirror tilt dependence of the transport efficiency. (A) -5 MHz, (B) 0 MHz, (C) 5 MHz and (D) 10 MHz detuning.