Radio frequency quadrupole cooler buncher for ^{6}He CRES experiment

D. McClain, G. Chubarian, V. Iacob, V.S. Kolhinen, D. Melconian, M. Nasser, A. Ozmetin,
B. Schroeder, and P.D. Shidling

The ^{6}HeCRES collaboration uses the cyclotron radiation emission spectroscopy (CRES) technique developed by the Project-8 collaboration [1] to measure the β spectrum of ^{6}He from radiation emitted due to the cyclotron radiation as a charged particle precesses in a magnetic field. The cyclotron frequency, *f*, of an electron is dependent on the kinetic energy E_e of the electron according to

$$f = \frac{1}{2\pi}\frac{eB}{m_e + E_e},$$

where *e* is the electron charge, B is the magnetic field, and m_e is the rest mass of the electron. The incredible sensitivity of the CRES technique is this ability to use the frequency measurement to deduce the energy of the electron [2].

The experiment consists of a rectangular waveguide with a U-shape turn to read frequencies from either end to negate any Doppler shifts. The rectangular waveguide is split on one side of the U shape to include a circular waveguide that exists as a decay volume for the ^{6}He as shown in Fig. 1.

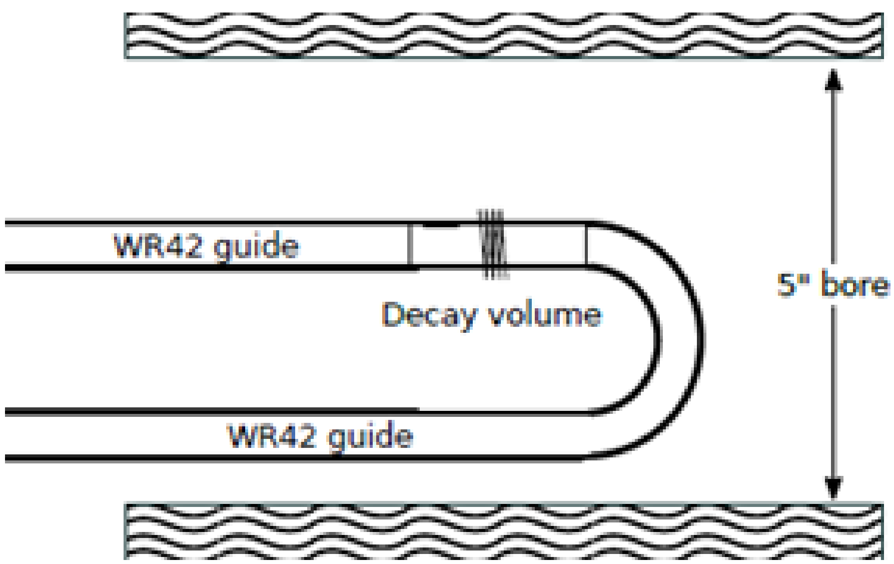

Fig. 1. Drawing of the U-shaped waveguide in the magnet.

The current phase of the project involves pumping ^{6}He gas into a decay volume via twenty-five holes along the side, each approximately 1-mm in diameter. The decay volume is ~10 cm in length and 1.156 cm in diameter. This radius propagates frequencies between 18–24 GHz well. The magnetic field can be varied from 0.5–7 T to shift our 18–24 GHz window to different energies and scan the whole *β* spectrum. The decay volume also has a coil around it creating a magnetic trap. This setup allows ^{6}He atoms to freely move about within the decay volume. The emitted βs of the ^{6}He nuclei that are near the walls are lost, and because of an increasing cyclotron radius with higher energy, higher energy βs would be more likely to hit the wall as show in Fig. 2, resulting a bias toward lower energies in our energy spectrum. With this issue it is still expected to get the uncertainty of $b_{Fierz} < 10^{-3}$ [3].

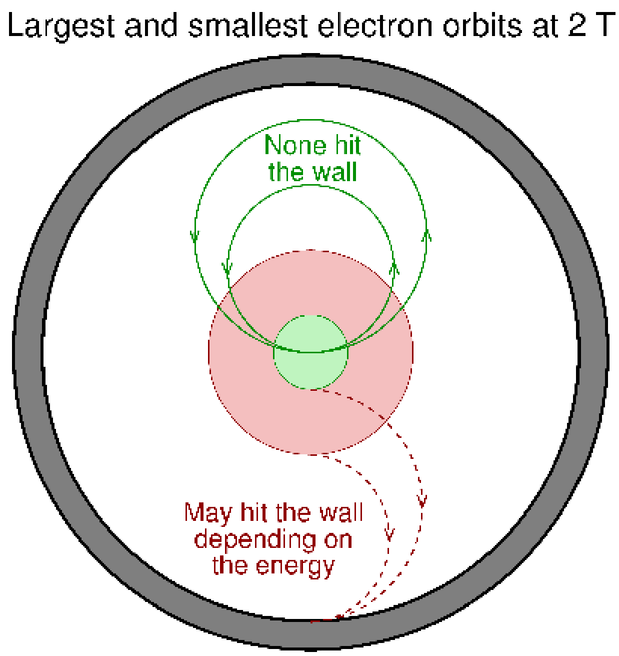

Fig. 2. The geometric effect of wall collisions in the case where there is no radial confinement of the ^{6}He.

The next phase of the experiment involves the implementation of an ion trap to radially confine the ^{6}He ions and eliminate wall collisions, effectively bringing our expected precision to 10^{-4}. This however requires more modifications to the experimental setup as we would no longer be able to pump in neutral ^{6}He into holes within the trap. The waveguide will need to be modified to have a hole that allows a beam of ^{6}He ions to flow in and to the Penning trap. We will also need to cool and bunch the ions for efficient transfer to the Penning trap.

In order to accomplish this, SimION was used to simulate the radiofrequency quadrupole trap (RFQ) in cooling ^{6}He ions. An RFQ's stability relies on the Mathieu parameter, q, to keep an ion of mass m contained while inside the RFQ:

$$q = \frac{4QV_{RF}}{mr_0^2\Omega^2}.$$

Here Q is the ion's charge, V_{RF} is the RF voltage applied to with a frequency Ω, and $2r_0$ is the distance between opposite electrodes of the RFQ. The ion's motion in the RFQ is stable for the Mathieu parameter between 0.4–0.6. Note that larger potential will correspond to an increased maximum rate that the RFQ can handle. Our design for the 6He-CRES RFQ is largely a rescaled version of the TAMUTRAP RFQ [4], where we increased r_0 from 6 mm to 15 mm, which allows us to operate with V_{RF} = 200V, and frequencies between 0.5–1.5 MHz. These parameters in the simulation gives us a time spread of <1 μs and an energy spread of <3 eV which will help us plan the rest of the beamline after the RFQ. The RFQ design has been completed in Autodesk Inventor as shown in Fig. 3. The construction and first tests of the RFQ should be completed by the end of 2021.

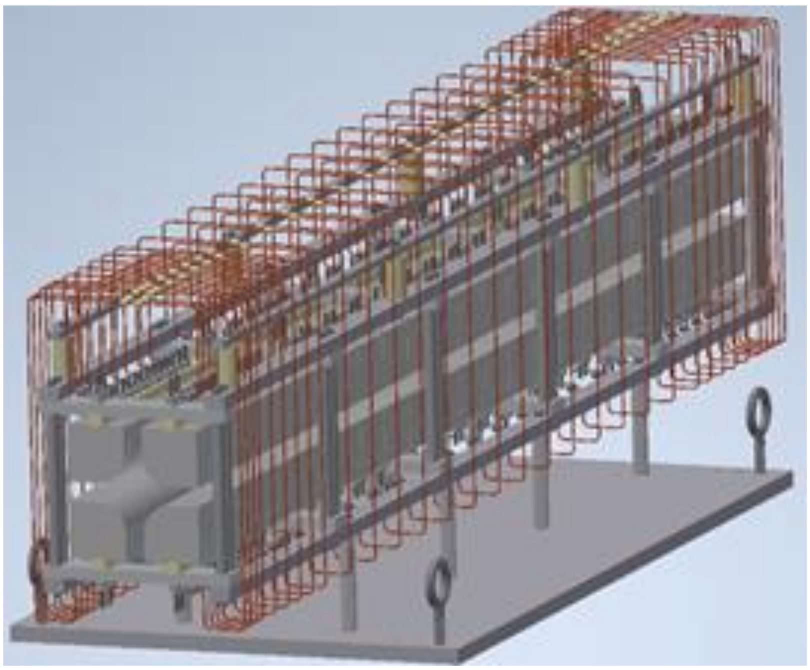

Fig. 3. The geometric effect of wall collisions in the case where there is no radial confinement of the ^{6}He.

[1] D.M. Asner *et al*., Phys. Rev. Lett. **114**, 162501 (2015).

[2] A.A. Esfahani *et al.*, J. Phys. G **44**, 054004 (2017).

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