3D FIELD EFFECTS ON THE MULTIPLE CHARGE BEAM DYNAMICS IN THE SUPERCONDUCTING DRIVER LINAC FOR RIA*

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Abstract

The Rare Isotope Accelerator (RIA) driver linac design is being studied at NSCL. In the low energy part of the superconducting linac, transverse steering of the beam in the 80.5 MHz and 161 MHz quarter-wave resonators (QWRs) is caused by the combination of the 3D electric and magnetic rf fields. A transverse rms emittance growth of ~20% is predicted due to the high frequency QWR. Possible modifications to the geometry of the QWR are studied.

1 INTRODUCTION

The RIA project proposes to use a superconducting driver linac for the acceleration of light and heavy ions [1]. The bunch spacing in the driver linac is determined by the RFQ frequency, which must be a sub-harmonic of the 805 MHz 6-cell axisymmetric cavities used in the high-β part of the linac, in which uranium ions are accelerated from ~85 to 400 MeV/u.

Two alternative starting frequencies of 57.5 and 80.5 MHz have been proposed [2,3]. The 80.5 MHz starting frequency is low enough to have an adequate longitudinal acceptance [4], and high enough to simplify microphonics control [5]. At the same time, the first superconducting (SC) cavity type can be nearly identical to an existing QWR [6].

QWRs have an inherent asymmetry leading to a dipole component in the electric and magnetic fields that increases with frequency for a given beam aperture [7,8]. The asymmetric field steers the beam off axis and can lead to an effective transverse emittance growth for multi-charge state beams.

In this paper, we will quantify the emittance growth, identify the fields responsible for it, and apply the geometry modification to partially compensate for the asymmetry effect.

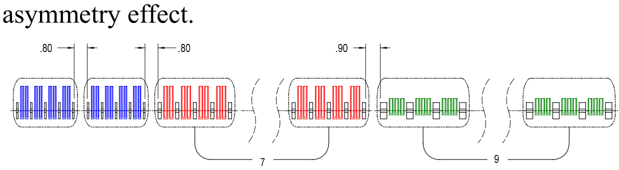

Figure 1: Low-β part of the driver linac extends from RFQ (~0.3 MeV/u uranium) to the first stripping station (~13 MeV/u uranium). It consists of 72 QWR at 80.5 MHz (blue and red) and 81 QWR at 161 MHz (green) in 18 cryomodules with 81 SC focusing solenoids (black). Cold-element to cold-element inter-cryostat drifts are specified in meters.

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2 MULTI-CHARGE BEAM DYNAMICS

A detailed beam dynamics analysis of the steering and emittance growth in the whole RIA driver linac was done using LANA code [9]. Realistic 3D electromagnetic fields calculated with MAFIA and ANALYST [10] were used in the simulations. Two charge states of uranium $^{238}U^{28,29+}$ were simulated together.

The low-β part of the linac is designed to accelerate two charge states of uranium from the exit of the RFQ at ~300 keV/u to the first stripping station at ~13 MeV/u. A total of 153 QWR cavities are used in this part, as schematically shown in Fig. 1. The first 72 QWRs operate at 80.5 MHz with β_{opt}=0.047 (16 cavities, Fig. 1 blue) and β_{opt} =0.07 (56 cavities, red), and the last 81 QWR operates at 161 MHz with β_{opt} =0.14 (green).

Contrary to expectations, the motion of the beam center of mass can be well-controlled by strong periodic focusing [3,11]. A beam center displacement of <2 mm and a divergence of <1 mrad are achieved throughout the low-β part of the linac.

The systematic studies confirm that the transverse rms emittance for individual charge states does not increase significantly. At the same time, the multi-charge transverse rms emittance in the vertical plane grows by about 20%, as expected. This occurs mostly in the high frequency QWR section, as shown in Fig. 2. The 100% emittance shows similar behavior, but reflects the effect of the radial dependence of the field as well. However, the emittance growth is still acceptable and does not cause any beam loss in the simulations.

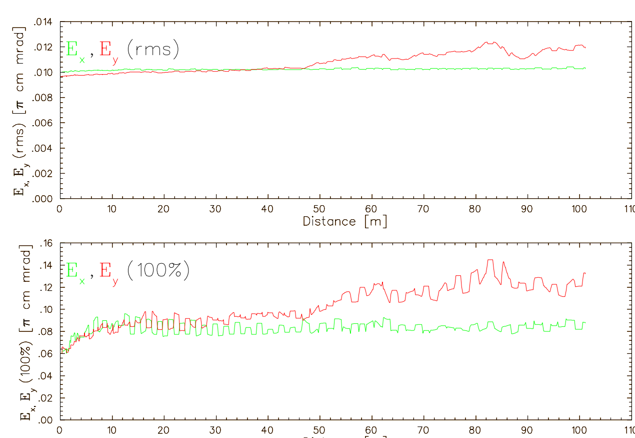

Figure 2: Multi-charge $^{238}U^{28,29+}$ beam rms and 100% emittances along the low-β part of the RIA driver linac.

The emittance increase is small compared to the ~50% transverse emittance growth at the first stripping station and ~250% growth at the second stripping station.

3 QWR REALISTIC FIELD EFFECTS

The following effects of the QWR realistic fields on multiple charge state beam dynamics, leading to effective transverse emittance growth, were considered in this study:

1. vertical electric and magnetic steering [7,8];
2. different rf-defocusing in the vertical and horizontal directions [12];
3. radial and rf-phase dependence of the steering and rf defocusing.

While the first two effects are described in the literature and are confirmed here, the last effect is the main focus of the present research.

Fig. 3 shows the calculated field components in a QWR cavity along the beam axis and along two lines parallel to the beam axis but displaced ±1 cm in the horizontal plane. The *x*-axis of the coordinate system is chosen to be horizontal and directed to the left from the beam axis looking downstream, the *y*-axis points up, and the *z*-axis coincides with the beam axis.

Modifications of the QWR geometry can be applied to mitigate the vertical steering [8]. The optimization of the QWR geometry is in progress in order to minimize the steering effect for this type of cavity. The optimization includes reshaping of the central electrode and the beam ports on the outer conductor, as shown in Fig. 4. The surfaces of the central electrode and the beam ports are tapered vertically.

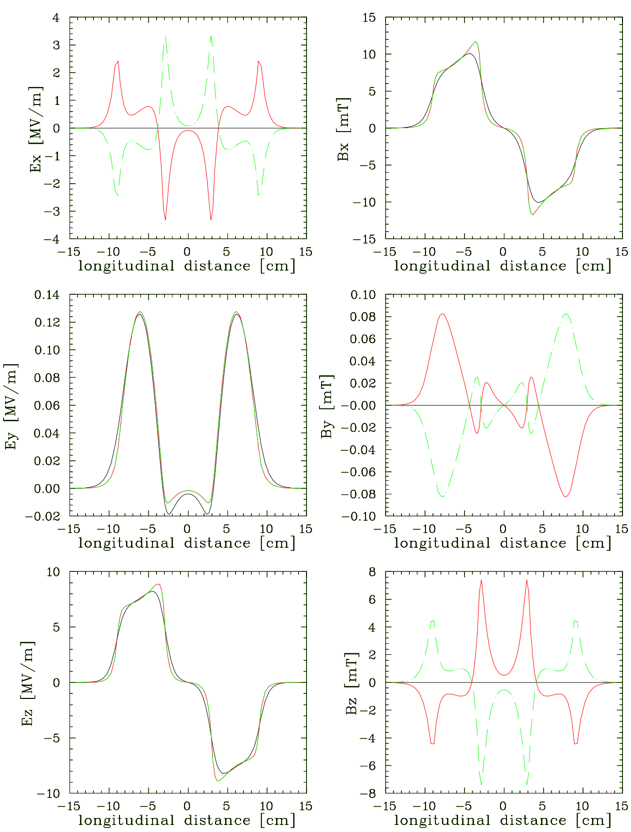

Figure 3: Electric and magnetic rf-field components in the uncorrected 161 MHz QWR along the axis (solid black) and along the lines x=1 cm (solid red) and x=-1 cm (dashed green).

In the modified geometry, an additional vertical electric field is introduced. The simulations demonstrate partial cancellation of the magnetic field steering with the introduced electric field.

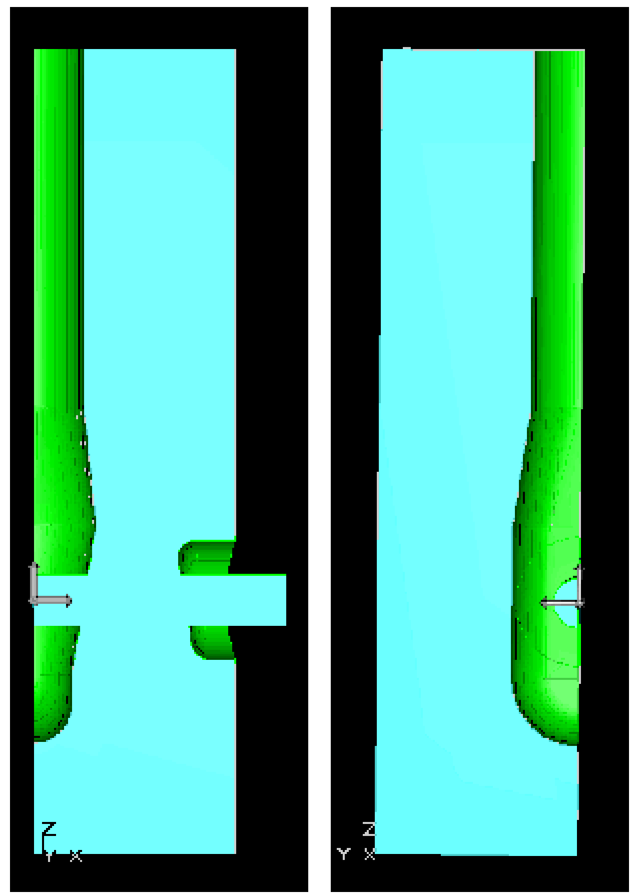
Figure 4: Side view (left) and view along the beam axis (right) of the modified QWR geometry that minimizes the steering effect over most of the velocity range.

4 SINGLE PARTICLE DYNAMICS

Single particle beam dynamics analysis was done to investigate the steering and defocusing perturbations of the realistic field in a QWR.

The difference between the vertical and horizontal rf defocusing at the exit of the QWR cavity for a proton displaced 5 mm from the axis is shown in Fig. 5. In the useful velocity range of β=0.11–0.17, the defocusing change due to the reference phase variation, needed for the longitudinal beam dynamics matching [3], is comparable to the vertical/horizontal defocusing difference. The periodic focusing system has to be designed to accommodate relatively large variation in the rf defocusing [11].

Fig. 6 shows the dependence of the vertical steering on the beam offset from axis. The vertical steering does not

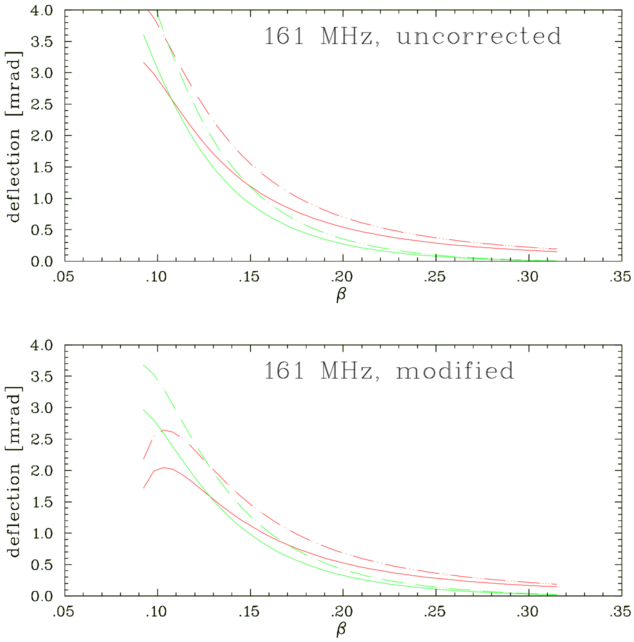

Figure 5: RF-defocusing of a proton displaced by 5 mm from axis in the vertical (red) and horizontal (green) directions for -30° (solid) and -40° (dashed) average phase in the center of accelerating gaps in the uncorrected (top) and modified (bottom) 161 MHz QWR.

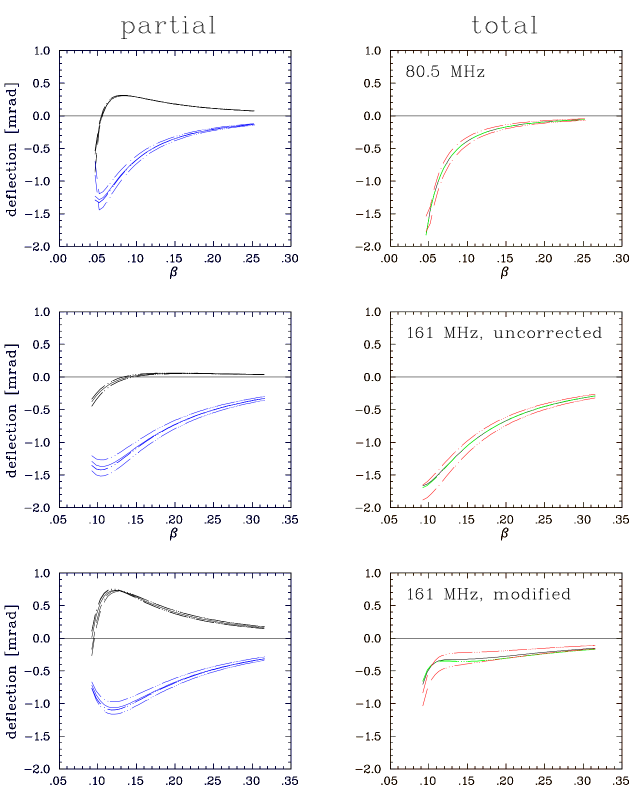

Figure 6: Vertical deflection in the 80.5 (top), 161 MHz uncorrected (middle) and modified (bottom) QWRs without the defocusing effect for an off-axis proton beam (±1 cm vertically – red and ±1 cm horizontally – green) at the exit of the QWR as function of β. The partial contribution from electric (black) and magnetic (blue) is shown on the left, and the total effect – on the right.

significantly depend on the horizontal position, and varies by ~10% within two thirds of the vertical aperture. In the horizontal plane additional distortion of the beam is caused by the vertical magnetic field, but this effect is negligibly small.

5 CONCLUSION

The results of this study show that QWRs can be successfully used for the low-β part of the RIA driver linac. Strong periodic focusing after every 2-3 cavities is required to mitigate significant rf-phase dependence of the rf defocusing in the QWR cavities as well as the horizontal/vertical asymmetry. The 80.5 MHz QWRs have a negligible steering effect, but 161 MHz QWRs without compensation can produce ~20% growth in vertical transverse rms emittance. Full emittance in the vertical plane grows at a higher rate due to the nonlinear radial dependence of the steering, but is still acceptable for RIA. Proper modifications of the QWR cavity design can effectively mitigate this emittance growth. Corrections based on the detailed studies of the effects are underway for the 161 MHz QWR structures.

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