BEAM STEERING CORRECTION IN FRIB QUARTER-WAVE RESONATORS*

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Abstract

Superconducting Quarter-Wave Resonators (QWRs) are used in the Facility for Rare Isotope Beams (FRIB) driver linac to accelerate stable ion beams from 0.5MeV/u to >16 MeV/u. QWR beam steering can cause additional transverse oscillations of the beam centroid, which reduce the linac acceptance and induce emittance growth, and thus increase the probability of beam loss in the high power cw machine. We have studied, with both an analytical model and 3D beam dynamics simulations, correction methods for the FRIB QWRs steering effect. We found that slightly shifting the position of cavity in cryomodule can provide effective steering cancellation in FRIB QWRs without need of cavity shape modifications, and allows to eliminate transverse beam oscillations and to improve beam quality. Calculation and simulation methods and results are presented and discussed.

INTRODUCTION

Since 2001 beam steering in superconducting Quarter-Wave Resonators (QWRs) and its effect on beams have been described in several papers [1-7], and two main analytical models have been developed to fully represent it [2,3]. It can be shown that steering is mainly caused by transverse magnetic field which is presented in the characteristic TEM mode of QWRs, and that the strength of the deflecting kick increases with the resonator optimum velocity (β_{opt}). Different techniques can be used to correct steering. On the lattice side, the main one is the installation of steerers along the beam line. This method has the disadvantage of producing a beam trajectory which oscillates around the canonical axis, and requires a large number of steerers whose field has to be properly adjusted according to the beam energy and A/q (mass-to-charge ratio). Other methods have been proposed in the past, like alternate orientation of QWRs, but they were never used because of technical difficulties and because of their unsatisfactory results [4]. The use of symmetric cavities like Half-Wave Resonators (HWRs) removes the problem completely, but this is difficult to apply at low frequency (say, below 160 MHz) because of the large size of HWRs, nearly two times larger than those of QWRs with similar frequency and β_{opt}. However, steering in QWRs can be corrected directly at the resonator by using essentially two types of correction schemes: one is beam port shaping, and the other is resonator axis displacement [2]. The first method is based on properly inclining the resonator surface around the beam ports, which is otherwise perpendicular to the beam axis. This slightly inclined acceleration gap introduces extra transverse electric field components to compensate the magnetic kick. The second method uses rf defocusing to obtain the same result. In this case, beam deflection caused by rf defocusing is proportional to the distance from the beam port axis, and the resonator can be positioned in such a way that rf defocusing and magnetic kick are exactly compensated at the beam axis. Both methods are equally effective for beams with different A/q, and both work well in all the range of β in which the cavity is used and start failing at very low β/β_{opt} [3]. In both cases correction is increasingly difficult while increasing β_{opt}: in the first method, the beam port tilting angle at some point becomes too large, and undesired field components appear; while in the second method, the displacement of the resonator axis at some point starts becoming comparable with the beam port aperture, reducing the resonator transverse acceptance significantly. Below β_{opt}=0.1 excellent correction can be obtained simply by QWR displacement, if sufficient aperture is available. Especially above β_{opt}=0.1, beam port tilting can give a more precise correction than resonator displacement, however, it requires much more complex resonator shape and implies a cost increase that cannot always be justified.

Figure 1: Two types of QWRs (β_{opt}=0.041 left, β_{opt}=0.085 right) used in FRIB linac, both operate at 80.5MHz.

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The FRIB linac hosts a total of 106 QWRs, 12 of them with β_{opt}=0.041 and 94 with β_{opt}=0.085, as shown in Figure 1. This large number gives to the choice of the correction method a non-negligible economical impact.

STEERING IN THE FRIB QWR CAVITIES

Steering and its correction in the two types of FRIB QWRs (Figure 1) have been evaluated in following four steps:

1. Simulation of the resonator EM field by means of the codes MW Studio Suite and Accelerator Analyst;
2. Calculation of the steering and of optimum correction by means of the analytical model described in [3]. The model allows to calculate a set of geometrical constants from the resonator EM field map; these constants are inserted in a formula that gives the curve of the steering angle $\Delta y'$ vs. β for any value of A/q, ϕ_s, E_a and y (the beam displacement from the resonator axis). Steering correction, i.e. finding the values of the parameters which give lowest $\Delta y'(\beta)$ in the desired β range, can be performed in two different ways:
   a. by choosing the value of y which minimizes $\Delta y'(\beta)$; this corresponds to displacing the resonator from its axis by an amount $-y$;
   b. by optimizing the geometrical constants G_{Ey1} and G_{Ey2} (their values depend on the cavity geometry in the beam port region) for minimum $\Delta y'(\beta)$; this corresponds to modifying tilting angles of the resonator beam ports.
3. Verification, in a single cavity described by a 3D field map, of the analytical results $\Delta y'(\beta,y)$ with 3D beam transport simulation codes.
4. 3D Beam transport simulation through the all QWR linac, with and without steering correction, and evaluation of the result.

Clearly, cavity optimization could be done directly with the 3D simulations of step 3, skipping step 2. However, it is easy to see that the analytical model, giving immediately the full $\Delta y'(\beta)$ curve after changing any of the G_{Ey1} and G_{Ey2} or y values, allows to skip a large number of time consuming simulation runs and, last but not least, allows a much clearer understanding of how steering depends on these parameters that include all important information. This is straightforward in the case of the resonator displacement, where there is only one parameter to optimize; however, even in the case of correction with beam port tilting, it is much faster to determine first the optimum G_{Ey1}, G_{Ey2} values and then find the tilting angles that produce these numbers in a cavity, rather than generating several cavity geometries, calculating the 3D field maps and running a 3D tracking code at several β values for each of them, to find the optimum shape.

RESULTS OF THE ANALYTICAL MODEL

Starting from the EM field maps of our QWRs we have calculated all analytical parameters for the steering, finding as expected a significant steering of up to 2.4×q/A mrad in the β_{opt}=0.041 resonators, and up to 7×q/A mrad in the β_{opt}=0.085 ones, as the red line shown in Figure 2. We first optimized the vertical positions of the cavities to minimize the steering effect. It was found that at the values of y=-0.2 mm and y=-1.5 mm for the low- and the high-β cavities, respectively, the steering was reduced down to fully satisfactory values over all the range of β where cavities are being used, as the green line shown in Figure 2. Since cavity displacement would slightly reduce the effective beam port aperture, we decided to increase it from 30 to 34 mm. This aperture change did not modify significantly the resonator performance and did not increase its cost either.

In order to evaluate the possibility of correcting steering by means of beam port tilting, we have also optimized the parameters G_{Ey1} and G_{Ey2}. In the lower β cavity we could not further improve the previous result. In the higher β cavity, above β_{opt} this method could reach even better correction than previously obtained, as the blue curve shown in the bottom of Figure 2. However, this reduction of an already small value was not expected to give significant effects to the beam. Thus we chose to leave the cavities unchanged and to use the axis offset correction method. Moreover, beam port tilting would require modifications to the cavity shape that would have increased the cavity cost.

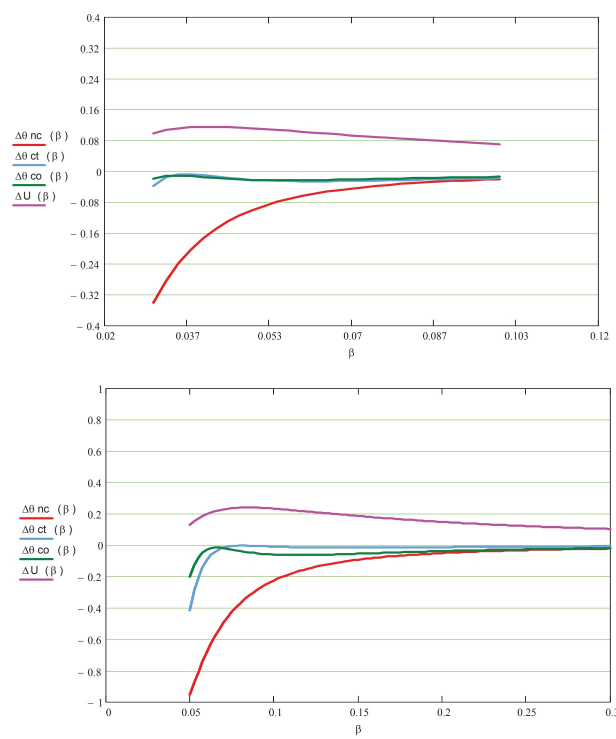

Figure 2: Beam steering angle Δy' (mrad) vs. β in β_{opt}=0.041 (top) and in β_{opt}=0.085 (bottom) QWRs, at FRIB acceleration voltages and assuming ϕ_s=-30 deg synchronous phase for uranium beam (A/q=7), calculated with our analytical model. Red: without correction; green: with optimum axis displacement; blue: with tilted beam ports. The pink curve shows the energy gain in MeV/u.

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SINGLE CAVITY 3D BEAM STEERING SIMULATION

The results of the analytical model have been finally verified by 3D tracking with CST MW STUDIO in single cavities. Both steering and optimum cavity displacement have been confirmed with good precision, as shown in Figure 3 for the case of a β_{opt}=0.085 QWR.

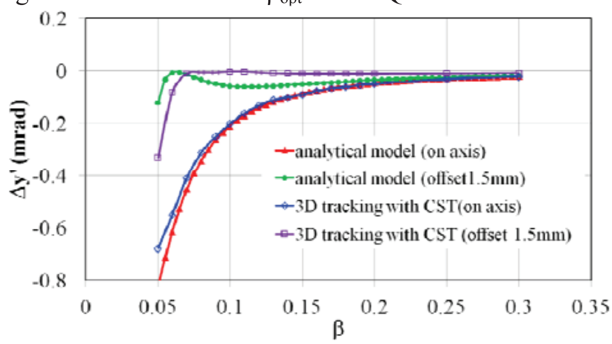


Figure 3: Results of beam steering angle Δy' vs. β in a β_{opt}=0.085 QWR with analytical model (solid markers) as in Figure 2 and with CST MW STUDIO (hollowed markers).

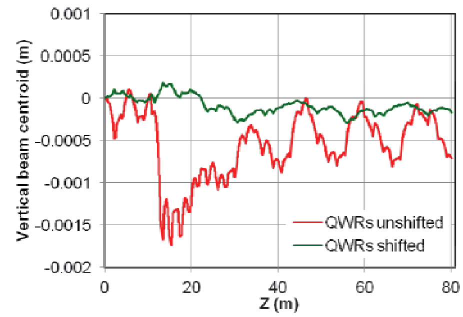
LINAC BEAM SIMULATION WITH STEERING CORRECTION

The steering effect from QWRs in FRIB linac must be corrected, otherwise beam centroid oscillation will be too large to maintain good beam quality. In the previous FRIB design, this effect was compensated by means of the external steerers embedded in the superconducting solenoids in the QWR cryomodules [8]. Those steerers are mainly used to correct orbit due to the misalignment of the superconducting solenoids. The settings of steerers had to be adjusted differently for any different A/q, and with the misalignment of the superconducting solenoids it was difficult to make orbit correction in an efficient way.

Two charge states (33+, 34+) of uranium particles were tracked through FRIB QWR segment that consists of 3 β_{opt} =0.041 and 11 β_{opt} =0.085 cryomodules. Figure 4 shows the result of beam centroid in the vertical and horizontal planes along the segment. The red traces correspond to the QWRs without offset, while the green traces are the results after the QWRs vertically offset down by 0.2mm and 1.5mm for β_{opt}=0.041 and β_{opt}=0.085 QWRs, respectively, based on the analytical calculation described in the previous section. Beam centroid oscillation in horizontal plane is due to the coupling from vertical plane with solenoid focusing. The offset of maximum beam centroid was automatically reduced from ~2 mm to ~0.2mm after the displacement of QWRs. The emittiance growth of the two-charge-state uranium seems also minimized with the cavity offset [9]. It should be noted that, differently from magnetic steerers, cavity displacement gives, at a given β, the same steering correction factor for any beam A/q and synchronous phase and for any accelerating gradient.

CONCLUSIONS

Beam steering in FRIB QWRs could be corrected by simply adding a constant offset in the resonators alignment. This offset could be precisely calculated by means of an analytical model which allows reducing significantly the number of time consuming simulation runs. This correction removed beam oscillations around the linac axis and reduced emittance growth, requiring a minimum use of magnetic steerers. This improvement of the beam performance requires only a small modification of the cryomodule design with no impact to the linac cost.



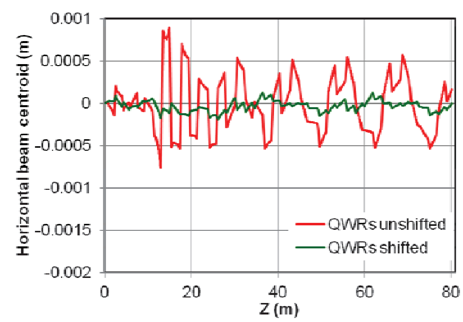


Figure 4: Beam centroid of two-charge-state uranium along FRIB QWR segment in both vertical (top) and horizontal (bottom) planes without (red) and with (green) QWRs offset.

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