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TRIUMF U-Turn around 480 MeV

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Abstract: In this note we summarize the results of simulations that we performed about the U-turn of beam around 480 MeV. Our objective is to find a feasible solution for the machine operation when BL2C runs at ∼110 MeV and BL1B runs at 480 MeV with a wire foil which is too narrow to fully intercept the circulating beam at high energy. We thus want to make the beam U-turned before it dumps on the HE probe or gets lost, hoping to reduce the tank radioactivation.

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1 Motivation

One of the operation modes of TRIUMF cyclotron is that BL4C runs at around 110 MeV with a wide foil of 0.400 inch (or 0.250 inch) taking 100 μA while BL1B runs at 480 MeV with a thin wire foil taking $\leq$10 nA. Because the wire foil is too narrow to fully intercept the circulating beam at 480 MeV, a HE probe has to be put in to fully intercept the circulating beam of $\sim 2\mu$A running beyond 480 MeV. This causes radio-activation in the tank.

So a question was raised: is it possible to make the beam turn around at ~480 MeV and decelerate back such that we don't need to use the HE probe to intercept the beam at all? To answer this question, simulations were performed, with goal to find a feasible solution to the trim coils for making such a U-turn.

2 Natural U-Turn

We began the simulation of natural U-turn to look at the maximum turning radius. This was performed by purely utilizing the standard field map "policyinita6.dat" which is deemed to be representative in terms of the field isochronism, without superimposing any extra field. As is shown in Fig. 1, the maximum turning radius reaches as far as ~316.0 inch.

However, the beam unlikely travels that far in reality. Instead, the beam likely gets lost earlier than that, because the beam orbit in the axial direction tilts up drastically between the radii ~308 inch and 312 inch, in a gradient of $dz/dr \geq 1$ inch/3 inch, as shown in Fig. 2. This is arisen from the large "natural" B_r component in that area, because the outer circumference of the sectors was flame cut (±0.5 inch) [1] with no capacity for shimming. Also there were many trim coil terminations, iron supports etc. at the outside. Such a construction results in radial gradients for the B_r component and for other components at the outside.

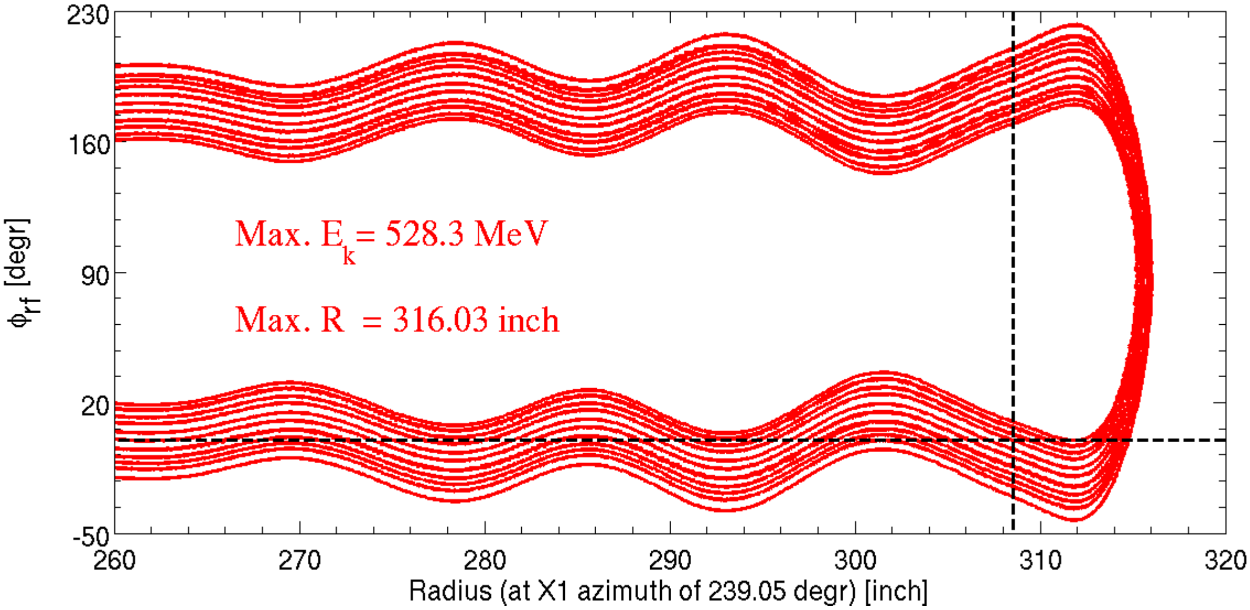

Figure 1: *Simulation result of natural U-turn for a beam of rf phase band being* $\sim 42°$*, showing the maximum turning energy and radius to be 528.3 MeV and 316.0 inch (at X1 azimuth). The vertical dash line marks the extraction radius of 480 MeV.*

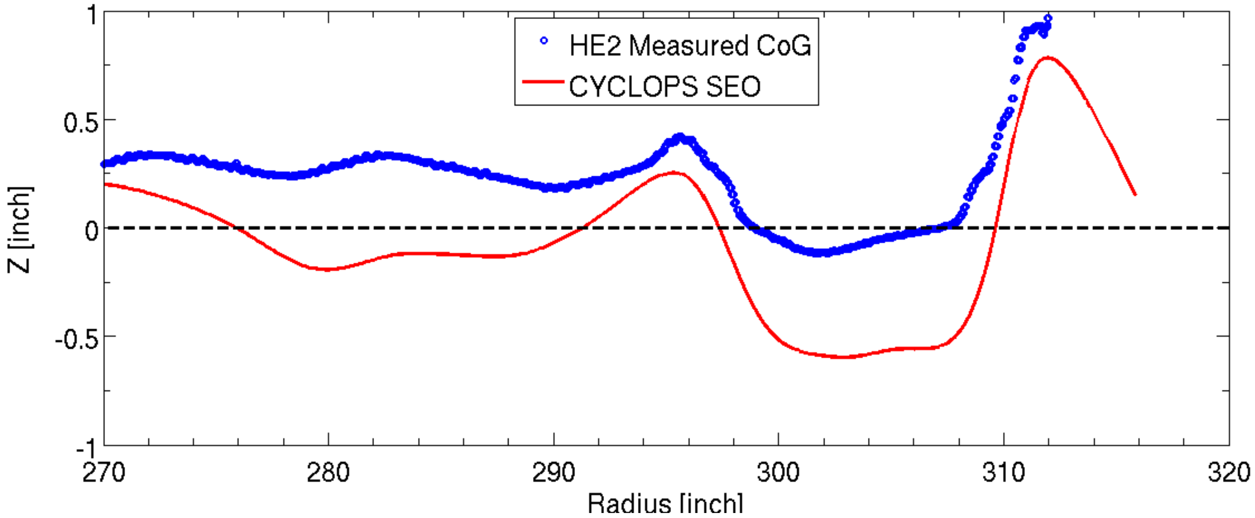

Figure 2: `CYCLOPS` *calculated vertical equilibrium orbit and HE2 probe measured vertical centre of gravity of beam near the extraction region, both showing a drastic tilt up of the beam orbit between* ∼*308 inch and 312 inch, in a gradient of* $dz/dr \geq 1$ *inch/3 inch.*

3 U-Turn around 480 MeV

In the energy region of $\geq$480 MeV, there are 5 sets of trim coils, namely TC52, 51, 50, 48 and 47, currently being wired in the B_z and B_r double modes, while the other 3 sets namely TC53, 49 and 46 are wired in the B_r single mode. For our purpose we'll be only looking at the options of the trim coils which have the B_z mode available.

Fig. 3 shows the radial distribution of B_z in the median plane due to TC50, 51 plus 52, and a bump field created by combining them in the prescribed excitations such that the inner tail is zeroed out to allow to minimize perturbation to the circulating beam. **Keep in mind that what matters to the beam's phase shift is the integral of this bump field strength along the kinetic energy**. As a result of this bump field, only fraction of particles (of preceding phases) turn around earlier than in the natural U-turn, while the lagging phase particles turn around as in the natural U-turn. See Fig. 4. This is because this bump field is not strong enough, i.e. not wide enough and/or not high enough. The height is limited by the maximum available electric current outputs of the associated power supplies.

Should be pointed out that the created bump field can be either positive or negative, relative to the direction of main field of the cyclotron. But the field strengths will be different from each other, because any changes made to the B_z component should keep the B_r component unchanged (unless it's intentional), in order to minimize perturbation to the orbit.

Fig. 5−Fig. 8 show the simulation results by using combinations of TC48, 50, 52, and TC47, 50, 52, respectively. In either case, the U-turn occurs at around 480 MeV, and the needed amount of excitations in Ampere-turns are within the output limits of the associated power supplies. This is promising. We should give them a try to determine the preferred one, in terms of machine tunability and BL1B current stability etc.

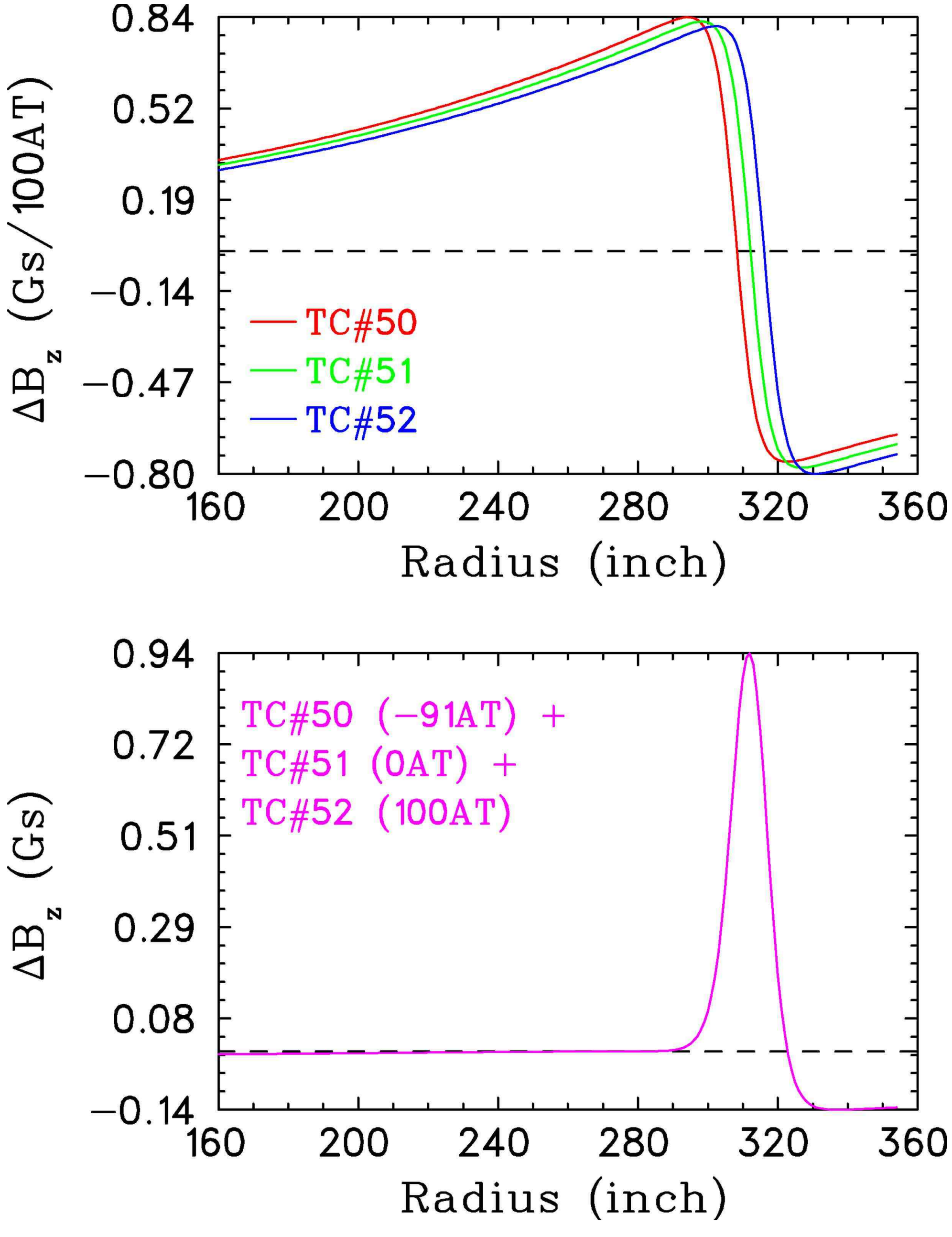

Figure 3: *(Upper) Radial distribution of* B_z *in the median plane due to TC50, 51 plus 52, and (Lower) a field bump created by combining these 3 coils in respective excitations given in the bracket so that the inner tail is zeroed out.*

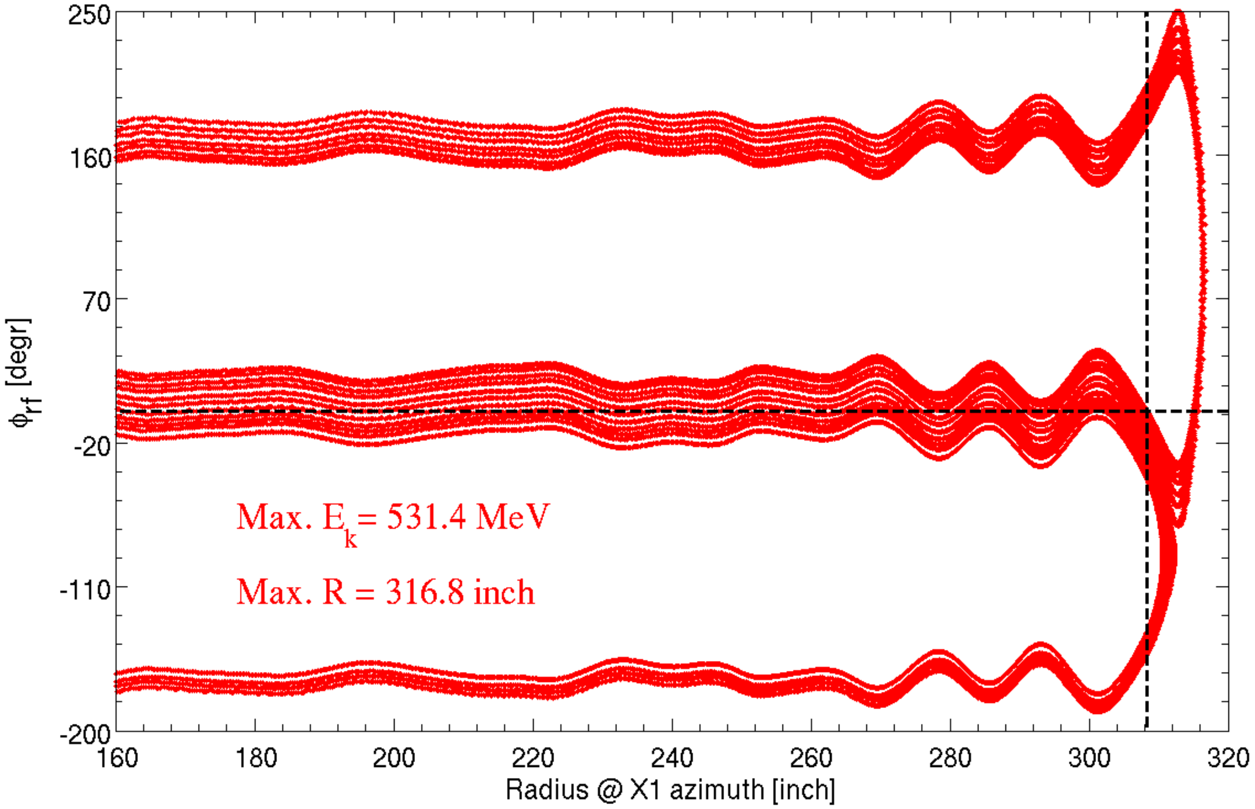

Figure 4: *As a result of the field bump shown in Fig. 3, only fraction of particles (of preceding phases) can turn around earlier than in the natural U-turn, while the lagging phase particles turn around as in the natural U-turn.*

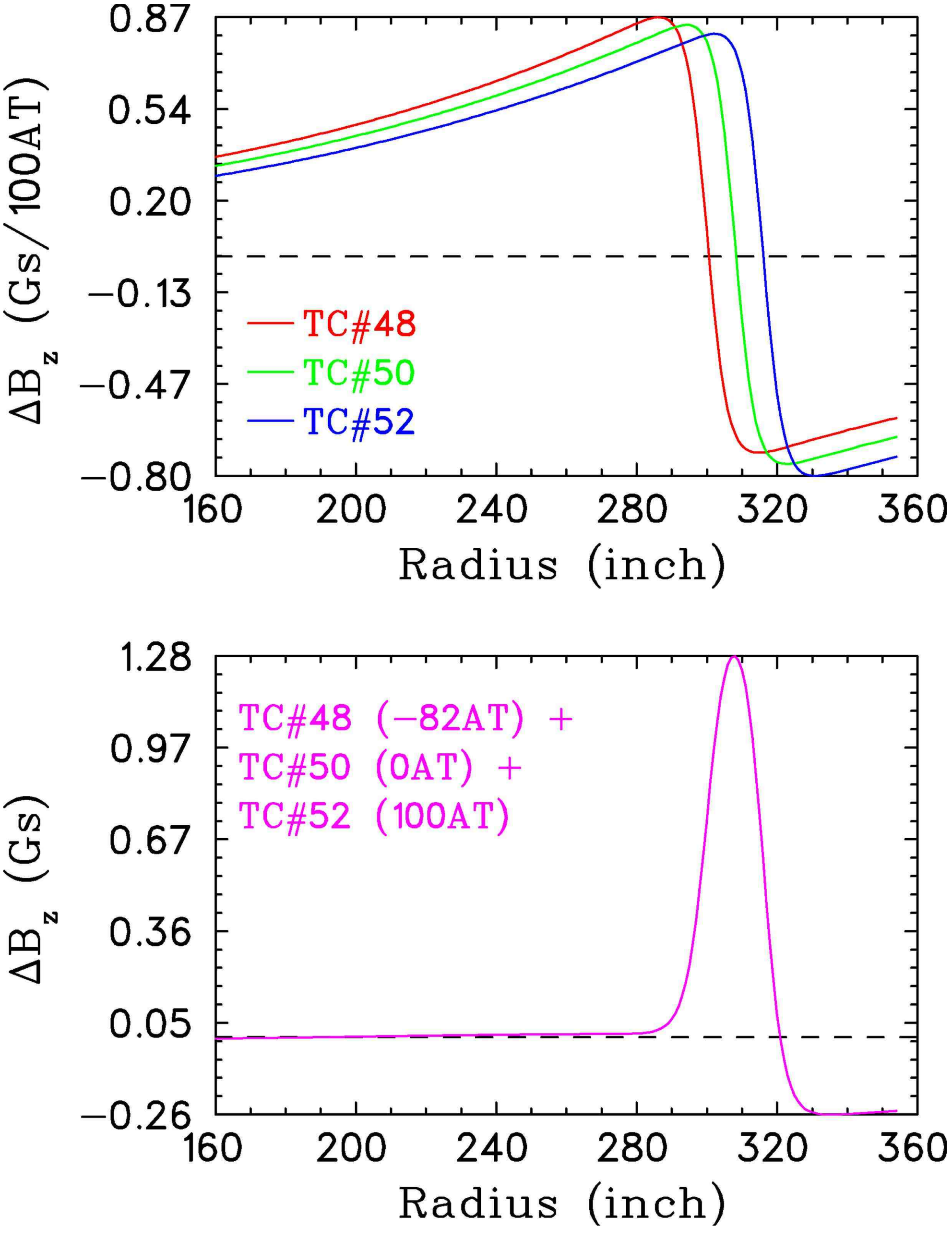

Figure 5: *(Upper) Radial distribution of* B_z *in the median plane due to TC48, 50 and 52, and (Lower) a field bump created by combining these 3 coils in the excitations given in the bracket such that the inner tail is zeroed out.*

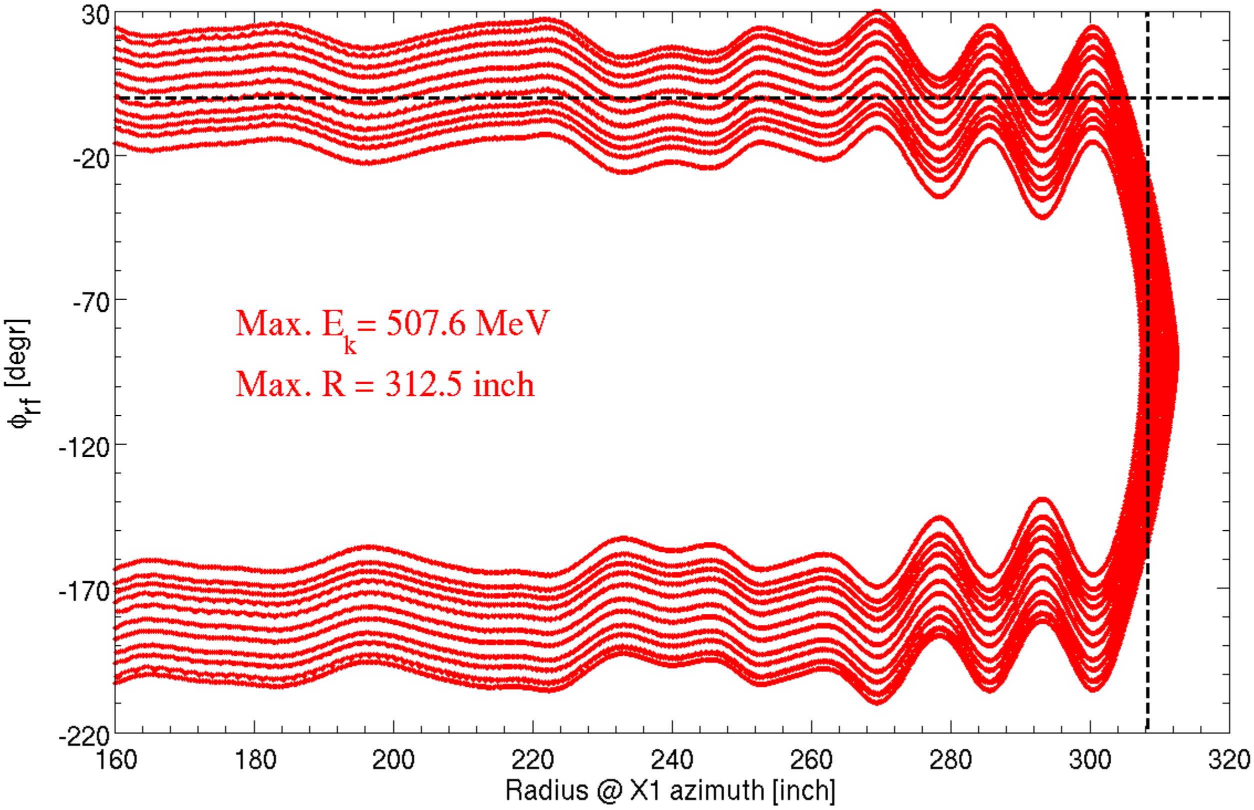

Figure 6: *As a result of the field bump created with TC48, 50 and 52 as shown in Fig. 5, the beam can get U-turned at around 480 MeV. This requires the amount of changes for the B_z excitations to be respectively TC48=-123.0 AT, TC50=0, TC52=150 AT. These changes shall be within the output limits of the power supplies.*

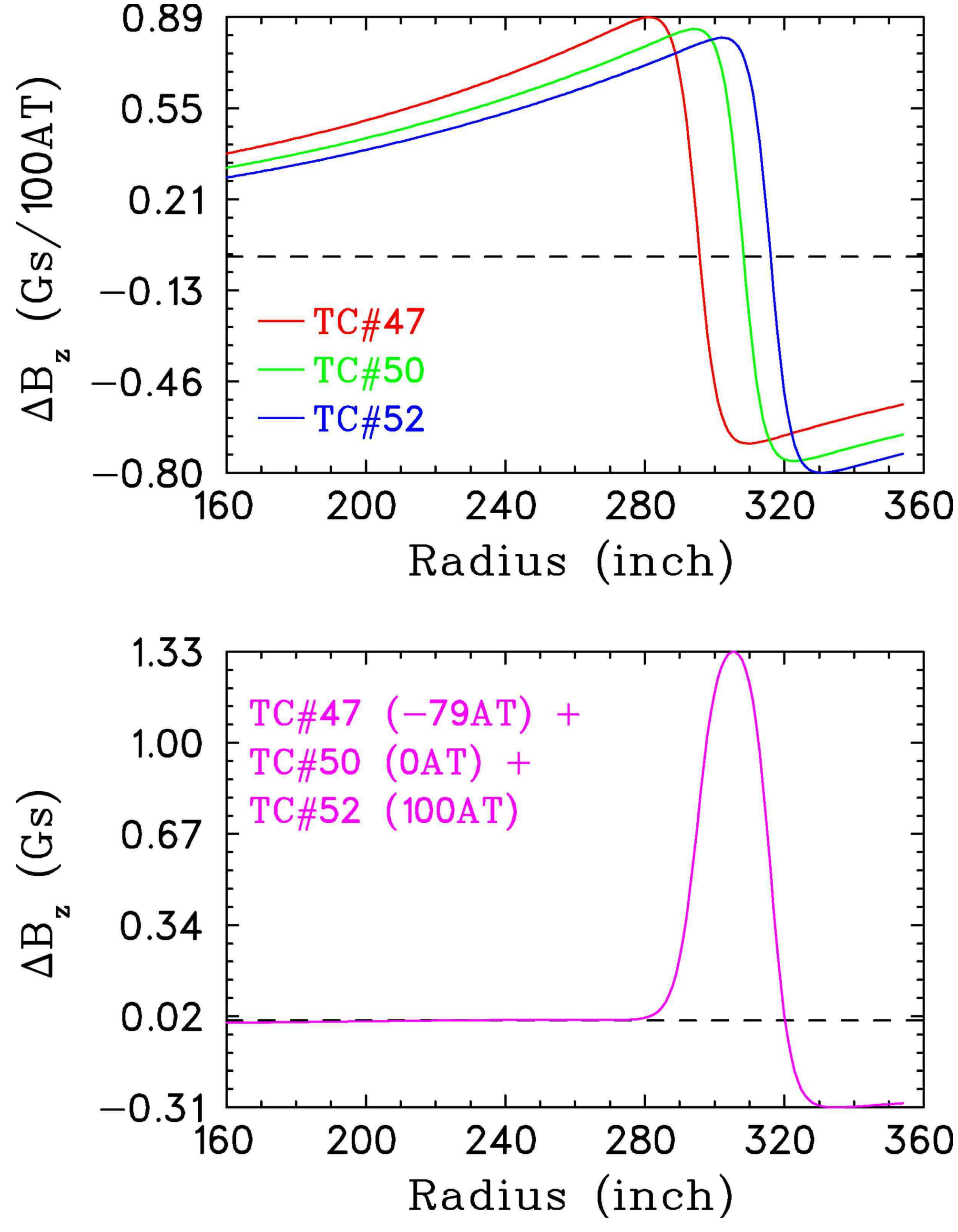

Figure 7: *(Upper) Radial distribution of* B_z *in the median plane due to TC47, 50, 52, and (Lower) a field bump created by combining these 3 coils in the excitations given in the bracket such that the inner tail is zeroed out.*

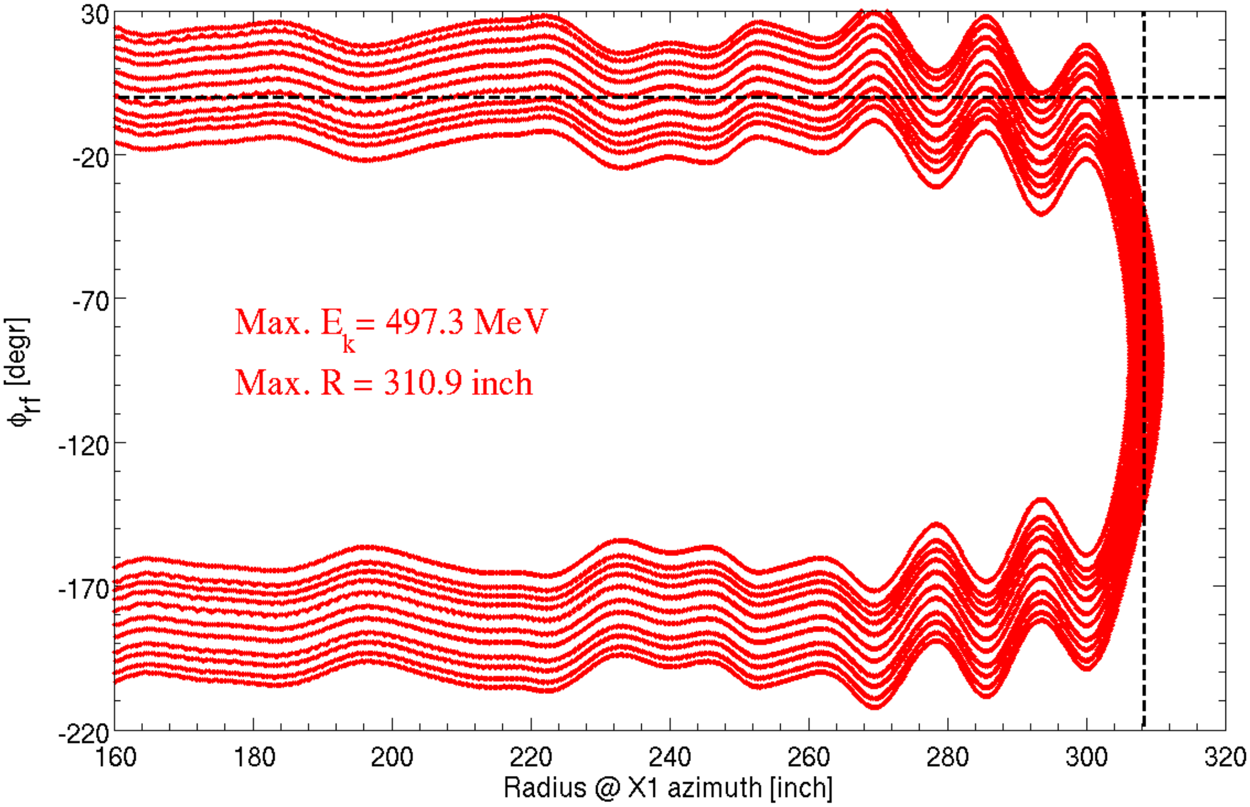

Figure 8: *As a result of the field bump created with TC47, 50 and 52 as shown in Fig. 7, the beam can get U-turned at around 480 MeV. This requires the amount of changes for the* B_z *excitations to be respectively TC47=-98.8 AT, TC50=0, TC52=125 AT. These changes shall be within the output limits of the power supplies.*

4 Measurements

We took measurements on 2018-Oct-30 Beam Development shift. The results are summarized as follows.

- Under the production tune (i.e. before we changed anything to the trim coil settings), the HE1 scans showed a drastic beam loss at around 310 inch; specifically, when the probe jogged to ~ 310.400 inch, its current read-back completely dropped to zero. This is consistent with the fore-mentioned orbit calculation result.
- Changing the trim coil settings by -98.8 AT for TC47 and $+125$ AT for TC52 in the B_z mode, the beam did get U-turned and decelerated back to pass through the 2C foil (of 0.250 inch wide) again. This was demonstrated by a measurement taken with the BL2C capacitive probe which detects the beam pulse's time structure, as shown in Fig. 9 (from an oscilloscope).
- Nevertheless, the power supply for the top coil of TC47 needed to reverse polarity (w.r.t. the production setting) in order to create the required field bump. This reversal could only be fulfilled manually because this power supply currently does not have polarity switch capability. So the controls for the B_r component due to the doublet screwed up (because the control system was reading wrong polarity from this power supply). Thus, some work will have to be done on the power supply to allow us to tune the new doublet properly.

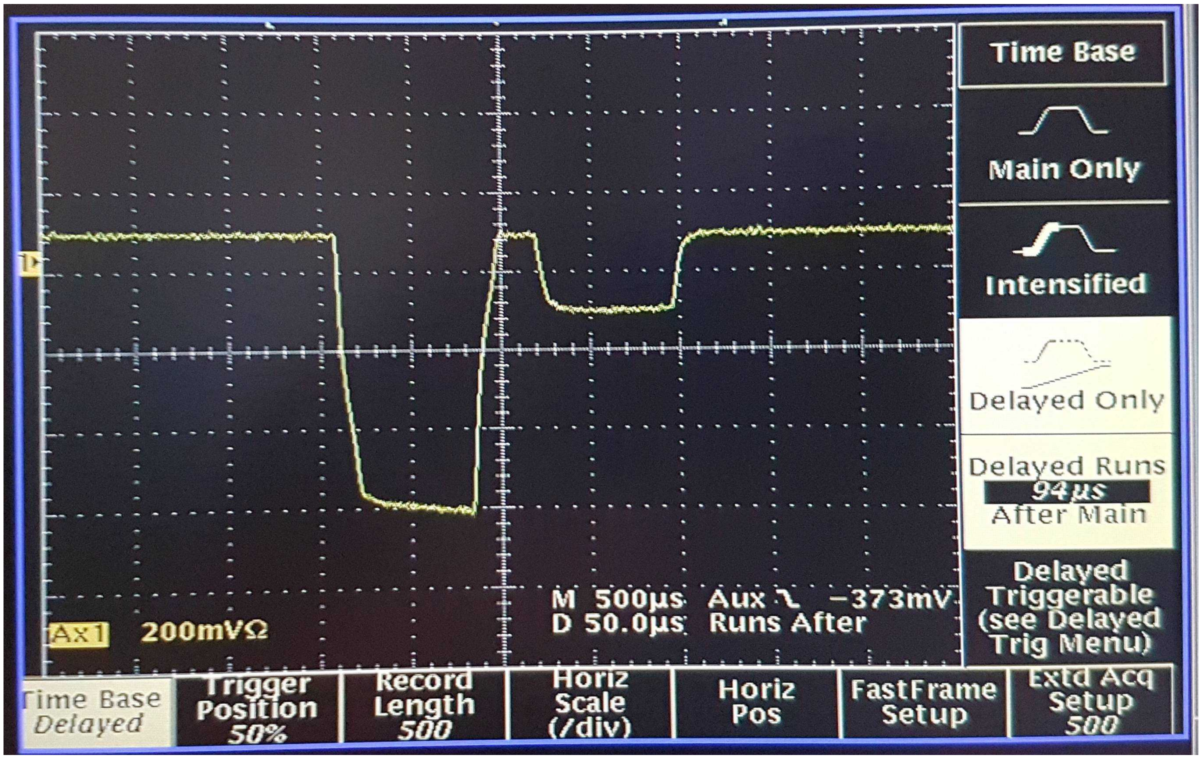

Figure 9: *Time structure of the beam pulses extracted down to BL2C, measured with capacitive probe in the BL2C. The small pulse is the fraction of beam that missed the foil on the first pass, shifted to the decelerating phase due to the created B_z field bump, came back to the 2C foil and got extracted; while the large pulse is the beam that gets extracted on the first pass of foil. Remember that the repetition rate of ISIS pulser is 1.126 kHz; for example at 10% duty factor, the beam pulse is about* $10\%/1.126\,kHz = 89\,\mu s$ *long in the time domain.*

References

[1] G.H. Mackenzie, private communication, Nov.20, 2006.