TRIUMF Beam Physics Note
TRI-BN-17-UTurn
May 16, 2017

TRIUMF U-Turn around 206 MeV

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Abstract: In this note we summarize the results of simulation and measurement that we performed about the U-turn of beam around 206 MeV. Our objective is to find a feasible solution for the machine operation when BL2C4 runs as a single user at ∼110 MeV with a 0.400 inch (or 0.250 inch) foil taking large fraction of the circulating beam (100 uA) while still leaving small amount running to high energy where it's dumped on a diagnostic probe at ∼500 MeV, causing radioactivation. We wish to make the beam U-turned before it dumps on the HE probe, so we shall expect to reduce the tank radioactivation. Machine operation has demonstrated that with a combination of trim coils TC29, 36 and 43, the beam U-turn works all right.

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1 Objective

Our objective is to create a localized field bump in B_z while keeping B_r unchanged after a radius of ~190 inch (i.e. after the BL2C4 110 MeV extraction radius), and therefore to make a 180° phase slip to the entire beam of ~ 50° phase band, so that the whole beam will turn round and decelerate back and pass through the BL2C4 extraction foil again and end up getting extracted. Such a scheme shall be useful for one of the operation modes of the cyclotron where the BL2C4 is running as a single user (at ~110 MeV) with a 0.400 inch (or 0.250 inch) foil taking large fraction of the circulating beam (100 uA) while still leaving small amount of beam running to high energy where it's dumped on a diagnostic probe at ~500 MeV, causing radioactivation. This new configuration shall help reduce the cyclotron radioactivation.

TRIUMF cyclotron is equipped with 56 pairs of co-axial trim coils, covering the entire energy range of the machine. With a proper combination of 3 of these coils, one can always create a localized field bump in B_z with tails zeroed out at both inner and outer radii, to minimize any unintentional perturbation to the beam. But in practice, there exists 2 constraints. One is that the B_r component due to these coils must remain unchanged, otherwise it will cause beam shift vertically (unless it's intentional). The other is that the power supplies for these trim coils have certain upper limits in their outputs of electric current and also most of the power supplies are already running close to their upper limits. As a consequence of this practical constraint, we are left with very few options only.

2 Calculations

Within the present power supply's output limits, we worked out a viable solution with 3 trim coils TC29, 36, and 43 in combination. Fig. 1 shows the radial distribution of B_z in the median plane due to each of these coils, as well as a field bump created by combining them in a proper ratio of excitation such that the tail is zeroed out in both ends. Keep in mind that what matters to the beam's phase slip is just the integral of this bump field strength along the kinetic energy, represented as

$$\Delta(\sin\phi) \simeq -\frac{2\pi\, h}{E_p}\int_{E_1}^{E_2}\frac{\Delta B_z}{B_z}\, dE \tag{1}$$

where E_p denotes the peak energy gain per turn. This is shown in Fig. 1.

Depending on the strength (i.e. height) of the bump field created, some trailing particles may not completely turn around, instead they are still accelerated to 500 MeV. See Fig. 2. The height of the bump field is limited by the maximum available current outputs of the associated power supplies.

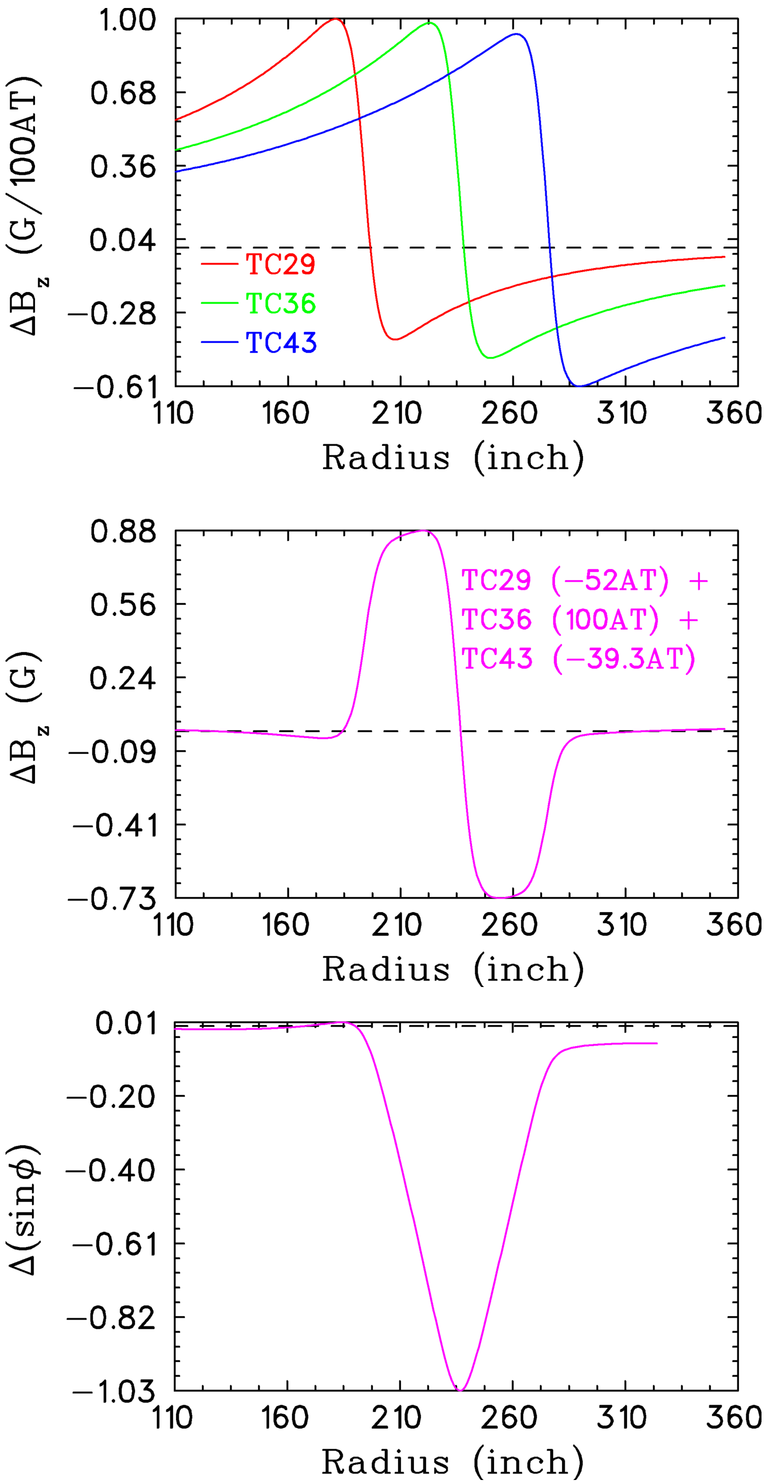

Figure 1: *(Top) Radial distribution of B_z in the median plane due to trim colis TC29, 36 and 43 at 100 Ampere-turn excitation for each. (Middle) A field bump created by combining these 3 coils in a proper ratio of excitation such that the inner and outer tails both are zeroed out.* **(Bottom) Phase shift due to the Ampere-turn changes as shown in the middle graph, where $\Delta(\sin\phi)$ varies from 0 to -1 and then back to ~ 0. This corresponds to the central rf phase ϕ slipping from $0°$ to $-90°$ and then further down to $-180°$,** *as is shown in Fig. 2.*

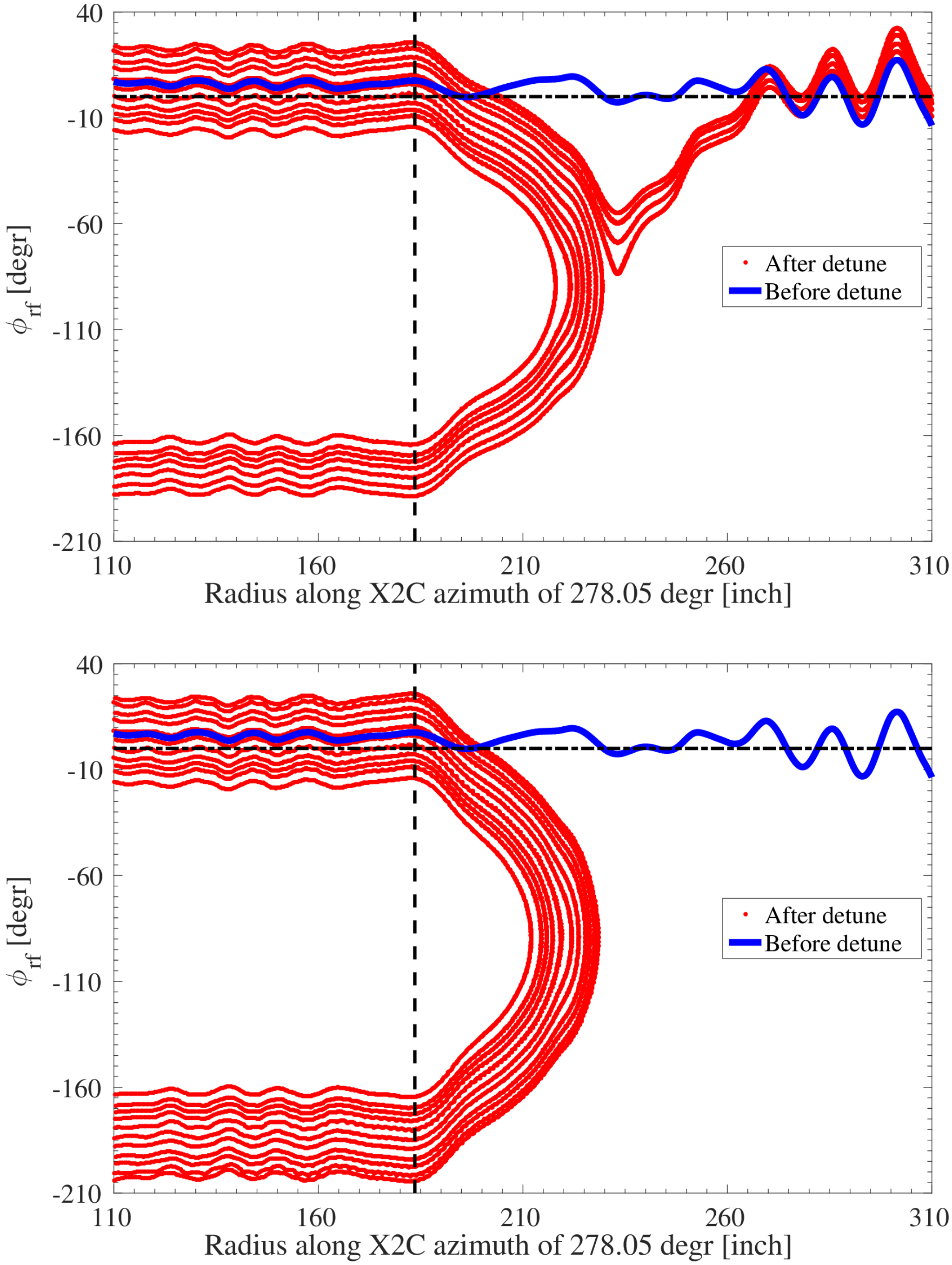

Figure 2: *Simulation results showing that some lagging particles may not completely turn around but still get accelerated to 500 MeV, depending on the strength of the bump field as shown in Fig. 1. The changes in Ampere-turns for the 3 trim coils are respectively: TC29=* -52.0 *AT, TC36=* $+100.0$ *AT and TC43=* -39.3 *AT (upper); and TC29=* -67.6 *AT, TC36=* $+130.0$ *AT and TC43=* -51.1 *AT (lower). The vertical dash-line marks the extraction radius of 110 MeV for the BL2C.*

Should be pointed out that the created bump field can be made either positive or negative, relative to the direction of main magnetic field. If we invert the Ampere-turn changes of the trim coils from the fore-mentioned values of TC29= -52.0 AT, TC36= $+100.0$ AT and TC43= -39.3 AT to TC29= $+52.0$ AT, TC36= -100.0 AT and TC43= $+39.3$ AT, we'll shift the whole bunch's rf central phase from 0 to $-\pi$ instead of to $+\pi$, and thus end up getting some preceding instead of lagging particles not completely turned around but still accelerated to 500 MeV. See Fig.3.

In fact, we're using $U_a \cos \phi_{rf}$ to calculate the energy gain of beam at dee gap crossing. The particles of rf phase angles between -25° and $+25^\circ$ receive an energy gain around the rf crest. The neighboring two bunches are $\sim$43.3 ns apart in the time domain because $f_{rf} = 23.055$ MHz=1/(43.3 ns).

The field bump created is to change the isochronism of beam revolution, gradually slipping the whole bunch's rf phase from the peak energy gain to a peak energy loss, i.e. from $[-25^\circ, +25^\circ]$ to $[-205^\circ, -155^\circ]$. As a result, the decelerated bunch will fall apart from the accelerated bunch by 43.3/2=21.7 ns in the time domain.

In the real space (r, θ), the decelerated bunch is still circulating in the same direction as the accelerated bunch (even if at passing through the stripping foil), that is, circulating counterclockwise from top view; the beam still has kinetic energy, but the orbital radius becomes smaller and smaller towards the machine centre (i.e. the orbit is spiraling inward).

3 Measurements

With actual measurement we demonstrated that the beam was indeed U-turned under the triplet excitation indicated in the Fig. 2 bottom. As is shown in Fig. 4, with increase of the triplet setting, the current of beam running to 480 MeV (BL2A) is decreasing (all the way down to zero), while the BL2C current is increasing. The total current (BL2C+BL2A) didn't appear to be constant, maybe because a fraction of the U-turned beam missed the BL2C foil and was decelerated to the centre region and ended up on the centre post.

A further measurement was taken with a capacitive probe installed in the BL2C to detect the beam pulse's time structure. As shown in Fig. 5, when the triplet is armed, there are smaller pulses showing up; these are the fraction of the beam that missed the BL2C foil on the first pass, shifted to the decelerating phase due to the B_z field bump, came back to the BL2C foil and ended up getting extracted.

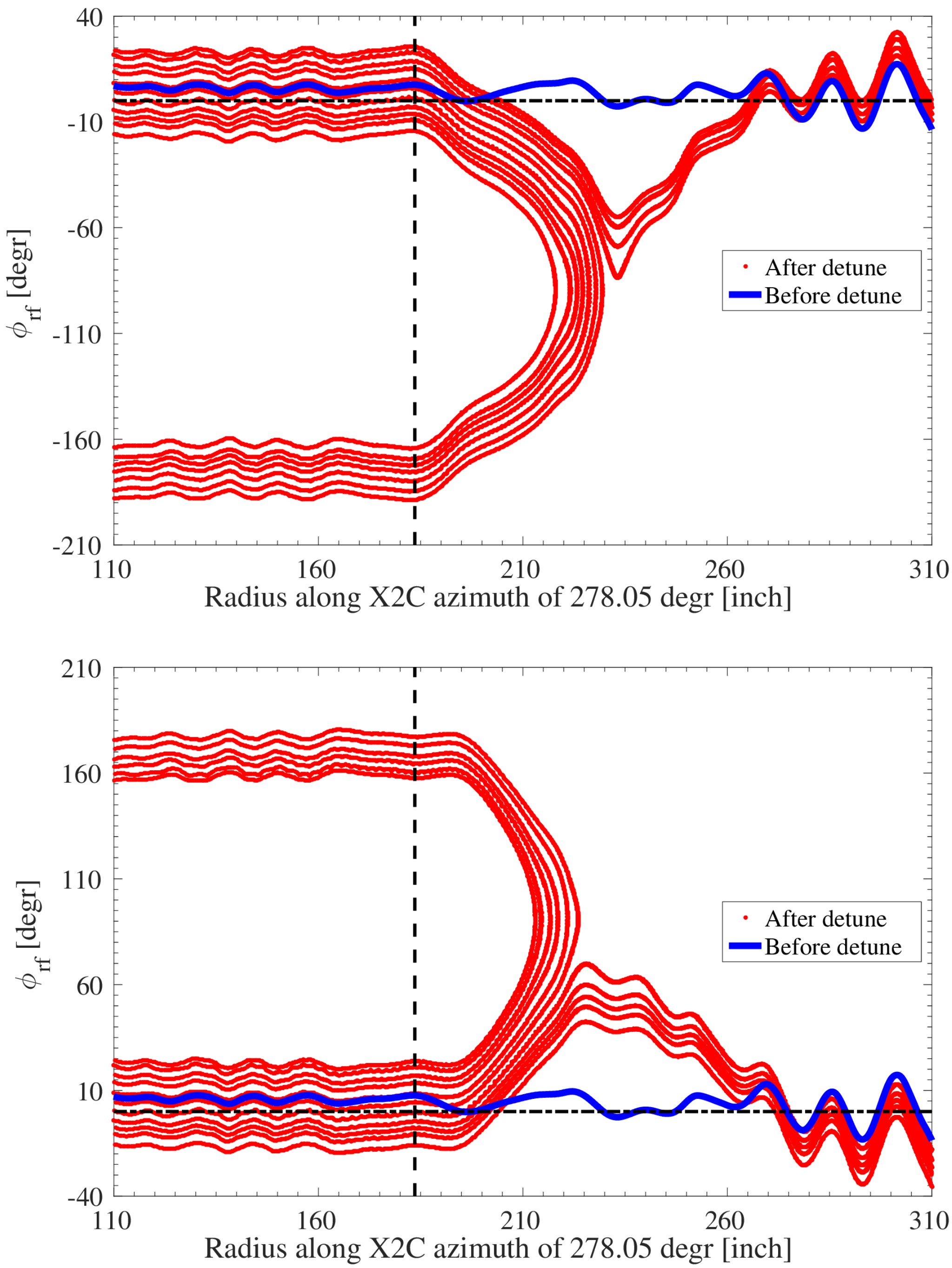

Figure 3: *Simulation results showing that either lagging (upper) or preceding (lower) particles may not completely turn around but still get accelerated to 500 MeV, depending on the sign (positive of negative) of the bump field created. The Ampere-turn changes for the 3 trim coils are respectively: TC29= -52.0 AT, TC36= $+100.0$ AT and TC43= -39.3 AT (upper), as well as TC29= $+52.0$ AT, TC36= -100.0 AT and TC43= $+39.3$ AT (lower). The vertical dash-line marks the extraction radius of 110 MeV for the BL2C.*

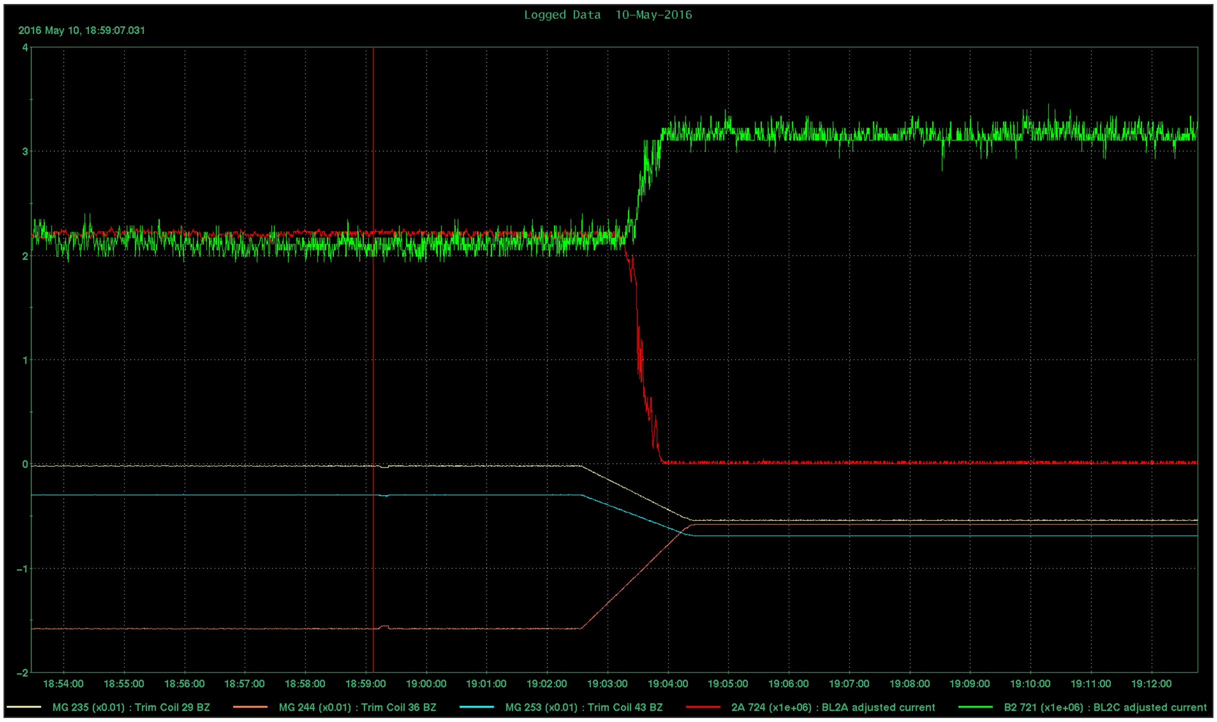

Figure 4: *Actual measurement showing that with increase of the trim coil triplet setting, the BL2A current (red) is decreasing all the way down to zero while the BL2C current (green) is increasing.*

4 Acknowledgment

The capacitive probe measurement taken by T. Planche was appreciated.

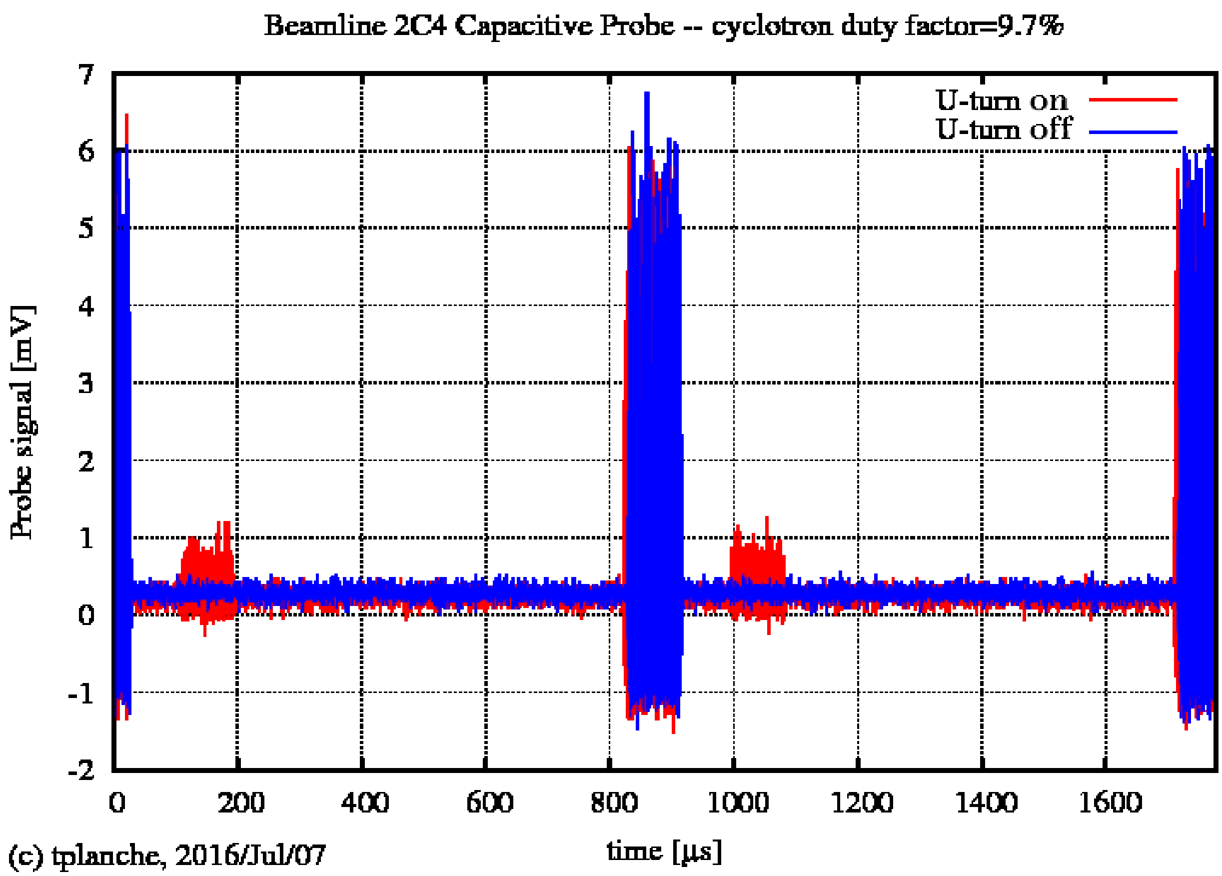

Figure 5: *Time structure of the beam pulses down to BL2C, measured with capacitive probe. The ISIS pulser was set to 100 DAC (i.e. 9.7% duty factor). The smaller pulses are the fraction of the beam that missed the foil on the first pass, shifted to the decelerating phase due to the* B_z *field bump, came back to the 2C foil and got extracted. Remember that the repetition rate of ISIS pulser is 1.126 kHz, so at 9.7% duty factor, the beam pulse is about* $9.7\%/1.126\,kHz = 86\,\mu s$ *long in the time domain.*