Simple modelling of the RF dipole BT.KRF

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Abstract
In this note, we describe a simple computational model of the RF dipole BT.KRF. The objective is an easier interpretation of the output signals from the pick-up BT.UES40V downstream of BT.KRF. The computed results agree well with measured data; this shows the validity of the model. Examples are given which might be used as reference for an optimization.

Introduction
The RF dipole BT.KRF is used for one mode of vertical beam recombination in the PS Booster (PSB). The beams to be recombined enter BT.KRF with nominally 5.26 mrad angle difference. At the vertical pick-up BT.UES40V, placed 4.32 m downstream of BT.KRF, the beam entering from below (from rings 2 and 1) would end up at a vertical position of +11 mm, the one entering from above (from rings 3 and 4) at -11 mm, without the action of the RF dipole. BT.KRF deflects the incoming beams up and down to bring these values for both beams close to zero — at least for the bunch's center of gravity.

But unlike a kicker magnet, an RF dipole sinusoidally changes the deflection angle $\alpha$ of the incoming particle beams like

$$\alpha(t) = A \sin(\omega t - \phi_0),$$

where $A$ is proportional to the RF amplitude. The values for BT.KRF are $A_{\text{max}} = 5$ mrad and $\omega = 2\pi 8.03$ MHz. When the phases are properly adjusted, the bunch center is deflected more than its head and tail — this gives a typical bunch shape and a typical response in the pick-up BT.UES40V.

When parameters of the beams (bunch intensity, shape and phase, initial transverse position and angle) as well as of the RF dipole (amplitude and phase) are non-ideal, the interpretation of the output signal is difficult. In this note, we try to model the action of the RF dipole on the $\Delta$-output of BT.UES40V for different parameters for a better understanding of these signals. After a short description of the simple computational model we give results of this computation. The results are compared to measured data.
The computational model

The \( \Sigma \)-output (sum) of the pick-up is proportional to the intensity of the passing bunch, the \( \Delta \)-output (difference) proportional to the product of its intensity and its vertical offset. If the intensities of the beams from ring 3(4) and ring 2(1) are denoted \( i_3(\phi) \) and \( i_2(\phi) \), respectively, and their transverse positions at BT.UES40V are denoted \( p_3(\phi) \) and \( p_2(\phi) \), the pick-up output signals are proportional to

\[
\Sigma(\phi) = i_3(\phi) + i_2(\phi) \quad (1)
\]

and

\[
\Delta(\phi) = i_3(\phi)p_3(\phi) + i_2(\phi)p_2(\phi) . \quad (2)
\]

\( \phi \) corresponds to time, \( \phi = \omega t \).

The longitudinal distribution of the bunches is assumed to be gaussian, i.e. we have for a series of bunches \( k \):

\[
i_3(\phi) = i_{3,\text{max}}\sum_k \exp \left\{ -\frac{1}{2} \left( \frac{\phi - \phi_3 - 2k\pi}{\omega \sigma} \right)^2 \right\} , \quad (3)
\]

similarly for the beam from ring 2. \( \phi_3 + 2k\pi \) is the bunch phase, \( \sigma \) its RMS length.

The vertical position of the beam from ring 3 at BT.UES40V is given by

\[
p_3(\phi) = L (\alpha_{0,3} + A \sin(\phi - \phi_0)) , \quad (4)
\]

where \( L = 4.32 \, \text{m}, \alpha_{0,3} = -2.63 \, \text{mrad}, \) and \( \phi_0 \) is the RF phase. For the beam from ring 2 a similar equation holds with \( \alpha_{0,2} = +2.63 \, \text{mrad} \).

In the following, we present the calculated (odd Figure numbers) and measured signals (even Figure numbers) at the \( \Sigma \)- and \( \Delta \)-outputs of pick-up BT.UES40V. In the calculated results, the \( \Delta \)-output of the pick-up according to (2) with (3) and (4) is plotted with a solid line, the \( \Sigma \)-output (1) with a dotted line, and the RF signal \( \sim A \sin(\phi - \phi_0) \) with a dashed line. The vertical units are arbitrary – when the \( \Sigma \)- and \( \Delta \)-output are equal, the vertical offset is 11 mm.

These results are compared with measured data which are given in the even numbered Figures. There the upper trace gives the \( \Delta \)-, the lower trace the \( \Sigma \)-output. The vertical units are chosen such that for equal voltages the vertical offset is 10 mm (except Figure 22 on page 14).
The reference case

Figures 1 and 2 show the reference case. The RF amplitude is $A = 1.3 \omega_0$, the other parameters are $\phi_0 = 0$, $4\sigma = 40$ ns, $\phi_3 = \pi/2 + 10^\circ$, and $\phi_5 = -\pi/2 - 10^\circ$. The $\pm 10^\circ$ phase offset of the bunches is used to group them in pairs. Each such pair will be in one RF bucket in the PS ring later; the grouping improves the matching into these buckets.

![Figure 1. Calculated output of BT.UES40V. Reference case.](image1)

![Figure 2. Measured output of BT.UES40V. Reference case. Upper trace(Δ): 100 mV/div, lower trace(Σ): 500 mV/div, timebase: 120 ns/div.](image2)
Delaying the RF by +10 ns

Figures 3 and 4 show the calculated and measured output, respectively, for a RF phase delay of $\phi_0 = \omega \times 10 \text{ ns} = 30^\circ$, i.e. the RF is arriving too late.

![Figure 3. Calculated output of BT.UES40V. RF delayed by +10 ns.](image)

![Figure 4. Measured output of BT.UES40V. RF delayed by +10 ns. Upper trace(Δ): 100 mV/div, lower trace(Σ): 500 mV/div, timebase: 120 ns/div.](image)
Shifting the RF by $-10$ ns

Figures 5 and 6 show the calculated and measured output for a RF phase shifted by $\phi_0 = -\omega 10 \text{ ns} = -30^\circ$, i.e. the RF is arriving too early.

**Figure 5.** Calculated output of BT.UES40V. RF delayed by $-10$ ns.

**Figure 6.** Measured output of BT.UES40V. RF delayed by $-10$ ns. Upper trace($\Delta$): 100 mV/div, lower trace($\Sigma$): 500 mV/div, timebase: 120 ns/div.
Increasing the RF amplitude

Figures 7 and 8 show the calculated and measured output of BT.UES40V for an increase of the RF amplitude by 10 %.

Figure 7. Calculated output of BT.UES40V. RF dipole amplitude increased by 10 %.

Figure 8. Measured output of BT.UES40V. RF dipole amplitude increased by 10 %. Upper trace(Δ): 100 mV/div, lower trace(Σ): 500 mV/div, timebase: 120 ns/div.
Common offset by +3.4 mm

Figures 9 and 10 show the calculated and measured output of BT.UES40V for an offset of both beams by 0.8 mrad, corresponding to 3.4 mm upwards at the pick-up. This corresponds to a change of the current in the vertical dipole BT.DVT50 from nominally -3.7 A to 0.

Figure 9. Calculated output of BT.UES40V. Common offset of +3.4 mm.

Figure 10. Measured output of BT.UES40V. Common offset of +3.4 mm. Upper trace(Δ): 100 mV/div, lower trace(Σ): 500 mV/div, timebase: 120 ns/div.
Common offset by $-3.4$ mm

Figures 11 and 12 show the calculated and measured output of BT.UES40V for an offset of both beams by $-0.8$ mrad, corresponding to $3.4$ mm downwards at the pick-up. This corresponds to a change of the current in the vertical dipole BT.DVT50 from nominally $-3.7$ A to $-7$ A.

![Figure 11. Calculated output of BT.UES40V. Common offset of $-3.4$ mm.](image1)

![Figure 12. Measured output of BT.UES40V. Common offset of $-3.4$ mm. Upper trace($\Delta$): 100 mV/div, lower trace($\Sigma$): 500 mV/div, timebase: 120 ns/div.](image2)
Offset of the beam from ring 2

Figures 13 and 14 show the calculated and measured output of BT.UES40V for an offset of the beam from ring 2 alone by -1.3 mrad or -5.7 mm. This simulates the change of the current in the vertical dipole BT2.DVT40 from nominally 10 A to 0.

![Graph showing the calculated output of BT.UES40V for offsetting beam 2 by -5.7 mm.](image1.png)

**Figure 13.** Calculated output of BT.UES40V. Offsetting beam 2 by -5.7 mm.

![Graph showing the measured output of BT.UES40V for offsetting beam 2 by -5.7 mm.](image2.png)

**Figure 14.** Measured output of BT.UES40V. Offsetting beam 2 by -5.7 mm. Upper trace(Δ): 100 mV/div, lower trace(Σ): 500 mV/div, timebase: 120 ns/div.
Offset of the beam from ring 3 by -11 mm

Figures 15 and 16 show the calculated and measured output of BT.UES40V for an offset of the beam from ring 3 alone by -2.63 mrad or -11 mm. This simulates the change of the current in the vertical dipole BT3.DVT40 from nominally 64 A to 44 A.

**Figure 15. Calculated output of BT.UES40V.** Offsetting beam 3 by -11 mm.

**Figure 16. Measured output of BT.UES40V.** Offsetting beam 3 by -11 mm. Upper trace(Δ): 100 mV/div, lower trace(Σ): 500 mV/div, timebase: 120 ns/div.
Offset of the beam from ring 3 by +6.8 mm

Figures 17 and 18 show the calculated and measured output of BT.UES40V for an offset of the beam from ring 3 alone by +1.6 mrad or +6.8 mm. This simulates the change of the current in the vertical dipole BT3.DVT40 from nominally 64 A to 74 A.

Figure 17. Calculated output of BT.UES40V. Offsetting beam 3 by +6.8 mm.

Figure 18. Measured output of BT.UES40V. Offsetting beam 3 by +6.8 mm. Upper trace(Δ): 100 mV/div, lower trace(Σ): 500 mV/div, timebase: 120 ns/div.
Decreasing the angle difference

Figures 19 and 20 show the calculated and measured output of BT.UES40V for an angle difference of the incoming beams decreased from 5.26 mrad to 4.21 mrad. This simulates the change of the current in the vertical septum magnet BT.SMV30 from nominally 1350 A to 1650 A. In our simplified model, this could be compensated by a change of the RF amplitude.

Figure 19. Calculated output of BT.UES40V. Decreasing the angle difference.

Figure 20. Measured output of BT.UES40V. Decreasing the angle difference. Upper trace(Δ): 100 mV/div, lower trace(Σ): 500 mV/div, timebase: 120 ns/div.
Increasing the angle difference

Finally, Figures 21 and 22 show the calculated and measured output of BT.UES40V for an angle difference of the incoming beams increased to 6.31 mrad. This simulates the change of the current in the vertical septum magnet BT.SMV30 to 1150 A. Note that the Δ-output signal in Figure 22 is magnified by a factor 2. The calculated and measured curves do not well agree in this case.

Figure 21. Calculated output of BT.UES40V. Increasing the angle difference.

Figure 22. Measured output of BT.UES40V. Increasing the angle difference. Upper trace(Δ): 50 mV/div, lower trace(Σ): 500 mV/div, timebase: 120 ns/div.
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