Algorithm for the Deflector Plates of the 1 MHz Chopper for the Kaon Factory

M. J. Barnes, G. D. Wait
TRIUMF, 4004 Wesbrook Mall, Vancouver, B.C., Canada V6T 2A3

Abstract

The Kaon Factory at TRIUMF requires a 1 MHz chopper to create appropriate gaps in the extracted 1 GeV/c H^- beam from the cyclotron. Deflection of bunches to be eliminated by the 1 MHz chopper will be predominantly provided by an electric field between a set of deflector plates, although there will be a magnetic component of deflection too. Previous simulations to calculate angular deflection of beam particles in the deflector plates approximated the plates as 8 sections, and only considered plates of one length. This paper presents the results of time-domain mathematical simulations to assess errors introduced by approximating the deflector plates using a finite number of sections. In order to validate the mathematical model of the deflector plates the predictions are compared with analytical equations for angular deflection for the situation where centre-fed plates are energized by a 'step-function'. Predictions of angular deflection are presented for four configurations of deflector plates in order to confirm that centre-feeding is the best option considered.

I. Introduction

A novel design concept has been developed for a 1 MHz chopper for suppressing 5 bunches in the Kaon factory Accumulator injection line [1–5]. Deflection of the bunches to be eliminated is predominantly provided by an electric field between the deflector plates, although there will be a magnetic component of kick [2,6,7]. When the deflector plates are fully charged, with flat-top pulses, there is no net current flow in the plates, and thus the deflection of particles passing between the plates is totally attributable to the electric field. However while the plates are charging up, or there is ripple on the pulse, there is a current flow: this current flow results in a magnetic field which either assists or opposes the effect of the electric field [7]. In order to predict the effects of the electric and magnetic components of kick upon beam deflection it is necessary to simulate tracking of the beam bunches through the deflector plates of the chopper [8]: this has been achieved using version 4·03 of the circuit analysis package PSpice together with its Analog Behavioral Model option [9]. The quality of the predictions is related to the number of transmission line sections utilized to represent the deflector plates. Details of the mathematical model are given elsewhere [3,6,8].

II. Number of Sections used to Approximate Deflector Plates

Simulation of the deflector plates by a finite number of sections results in errors in the rising and falling edges of the predicted angular deflection. In order to assess the significance of these errors, which are themselves a function of deflector plate length and trapezoid rise [fall] time, sets of studies have been carried out where the physical length of the plates (ℓ) and trapezoid rise [fall] time ($t_{v(r/f)}$) have been systematically changed:

- $\ell = 3{\cdot}78$ m and $t_{v(r/f)[0\% \rightarrow 100\%]} = 20$ ns;
- $\ell = 2$ m and $t_{v(r/f)[0\% \rightarrow 100\%]} = 20$ ns;
- $\ell = 3{\cdot}78$ m and $t_{v(r/f)[0\% \rightarrow 100\%]} = 6{\cdot}67$ ns.

During each of the above sets of studies the number of sections (N) used to represent the deflector plates was increased from 8 to 80 in increments of 8. The maximum relative error in the total angular deflection (i.e. sum of magnetic and electric components of angular deflection) between adjacent numbers of sections (e.g. maximum error of 8 section prediction w.r.t. 16 section prediction, and maximum error of 16 section prediction w.r.t. 24 section prediction, etc.) were noted, and normalized to the ideal flat-top total angular deflection. Figure 1 shows the relative errors between adjacent numbers of sections for each of the above three sets of simulations.

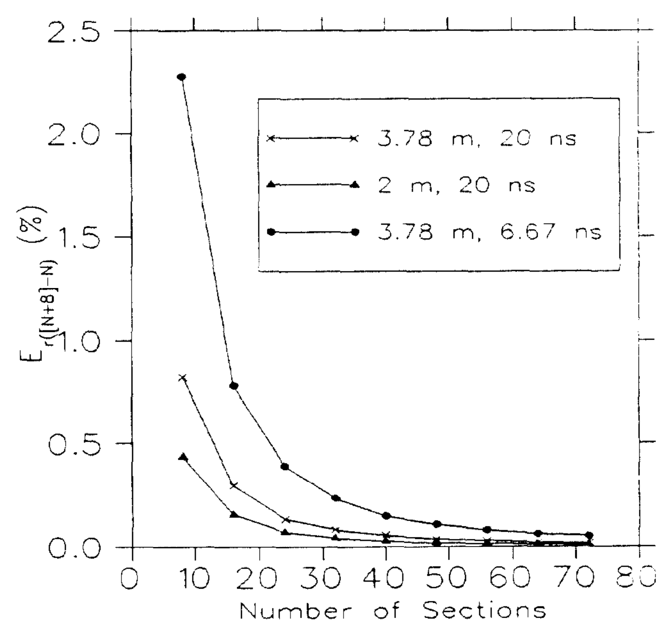

Figure 1: Dependence of maximum relative error ($E_{(r[N+8]-N)}$) upon number of sections, length of plates, and trapezoid rise-time

In order to estimate the absolute error introduced when an 80 section representation is utilized it is necessary to curve fit to each of the individual curves shown in figure 1 [6]. For the case where the deflector plates are represented as having a physical length of 3·78 m, and voltage trapezoid rise-time (0 % → 100 %) of 20 ns, the data can be approximated by [6]:

$$\ln(100 \times E_{r([N+8]-N)}) = [-1 \cdot 7581 \times \ln(N)] + 8 \cdot 1664 \quad (1)$$

The absolute error in the 80 section representation ($E_{r(\infty-80)}$) can be approximately determined by assuming that the relative errors between adjacent numbers of sections are cumulative (this should be a worst-case assumption):

$$E_{r(\infty-80)} = \sum_{n=10}^{\infty} \left(\frac{e^{[(-1 \cdot 7581 \times \ln(8 \times n))+8 \cdot 1664]}}{100} \right) \qquad (2)$$

Evaluation of equation 2 gives an estimated value, for the absolute error in the 80 section prediction, of 0·22 %. Similarly calculating $E_{r(\infty-80)}$ for the other two sets of studies results in values for $E_{r(\infty-80)}$ of 0·114 % (ℓ = 2m & $t_{v(r/f)[0\%\rightarrow100\%]}$ = 20 ns) and 0·615 % (ℓ = 3·78m & $t_{v(r/f)[0\%\rightarrow100\%]}$ = 6·67 ns), respectively.

Absolute error ($E_{r[\infty-N]}$) in the predicted total angular deflection, normalized to the ideal flat-top total angular deflection, for 'N' sections (where $N < 80$) is determined from the following equation:

$$E_{r(\infty-N)} = E_{r(\infty-80)} + E_{r(80-N)} \qquad (3)$$

where $E_{r(80-N)}$ is the relative error of N sections w.r.t. 80 sections.

Fig. 2 shows a plot of the estimated absolute error in angular deflection, as a function of the number of sections, for the three cases studied. Thus for the first set of studies (ℓ = 3·78 m & $t_{v(r/f)[0\%\rightarrow100\%]}$ = 20 ns) the absolute error in the angular deflection introduced by representing the deflector plates by 8 sections is about 1·7 %: in order to reduce the absolute error below say 0·5 % requires approximately 28 sections. However increasing the number of sections by a factor of 3, from 8 to 24, resulted in an increase in cpu time by a factor of about 5.

For the 2 m plates excited by a trapezoid with a rise-time (0 % → 100 %) of 20 ns, an 8 section representation of the deflector plates results in an absolute error in the angular deflection of about 0·9 %: a 16 section representation results in an absolute error of approximately 0·5 %.

For the 3·78 m plates excited by a trapezoid with a rise-time (0 % → 100 %) of 6·67 ns, an 8 section representation of the deflector plates results in an absolute error of about 4·5 %: a 42 section representation would be needed to reduce the absolute error below 1 %: 102 sections are required to reduce the absolute error to approximately 0·5 %.

For both a given driving voltage rise-time and number of sections, the absolute errors in the predicted angular deflection are proportional to the length of the deflector plates (see fig. 2). Similarly, for a given plate length and number of sections, the absolute error in the predicted angular deflection is approximately inversely proportional to the rise-time of the driving voltage (see fig. 2).

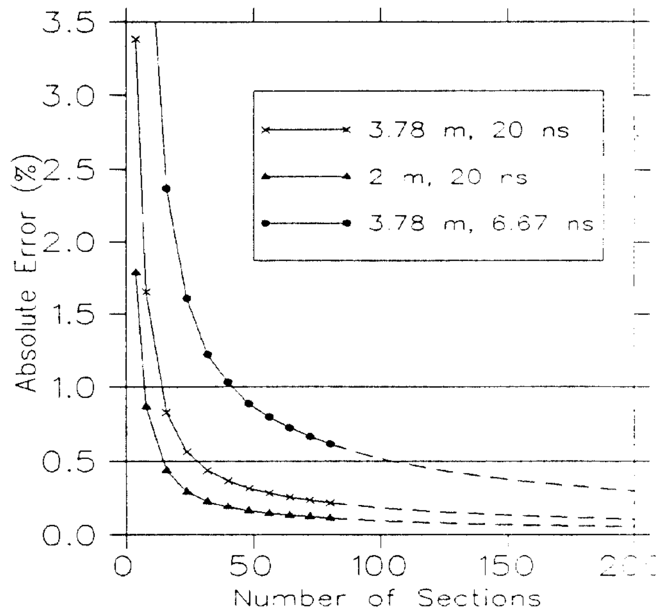

Figure 2: Dependence of estimated value of absolute error ($E_{[\infty-N]}$) upon number of sections, length of plates, and trapezoid rise-time

III. Validation of Mathematical Model

Analytical equations for the electric (Θ_e), magnetic (Θ_m) and total (Θ_t) angular deflection, for centre-fed deflector plates driven by an ideal step-function, have been derived [6]. Figure 3 shows the predicted components of angular deflection, obtained using PSpice, together with the components calculated from the analytical equations. For the PSpice simulation, the deflector plates were modelled using 80 sections and the rise-time of the driving voltage ($t_{v(r)[0\%\rightarrow100\%]}$) was 0·3 ns. The predictions lag the results of the analytical equations by about 0·15 ns (i.e. $t_{v(r)[0\%\rightarrow100\%]}/2$): the lag reduces to approximately 0·1 ns when $t_{v(r)[0\%\rightarrow100\%]}$ is decreased to 0·2 ns.

IV. Methods of Feeding the Plates

In order to confirm that centre-feeding deflector plates is an optimum configuration for minimizing the rise-time of the total angular deflection, four configurations of deflector plates have been simulated:

- centre-fed plates;
- end-fed with the particle beam and initial switch-on wave propagating in the same direction;
- end-fed with the particle beam and initial switch-on wave propagating in opposing directions;
- plates fed from both ends simultaneously.

The total angular deflection for each of the above four configurations, is shown in figure 4. A minimum rise-time (10 % → 90 %) for the total angular deflection (20·7 ns) is achieved with the centre-fed plates [6]. For the centre fed configuration the magnetic angular deflection helps to improve the rise-time of the total angular deflection, by opposing the initial lead-in to the 'S-curve' electric angular deflection and adding to the top of the 'S-curve' electric angular deflection [$t_{\Theta_e(r/f)[10\%\rightarrow90\%]} = 23 \cdot 5ns$].

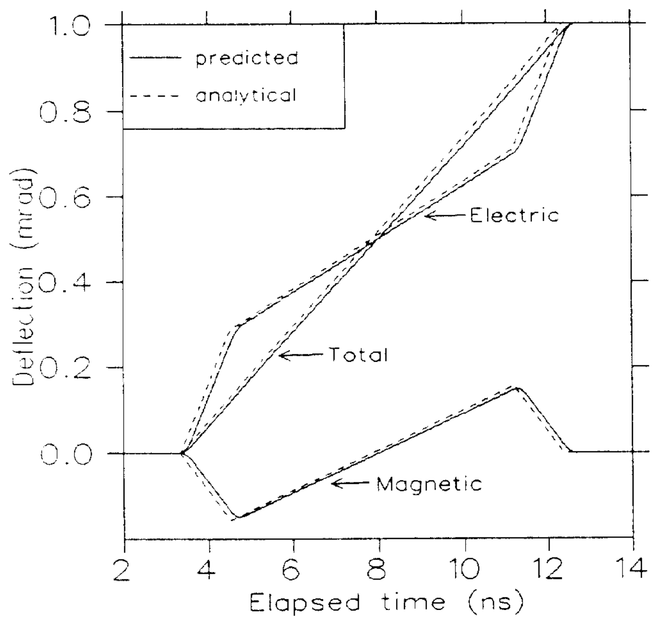

Figure 3: Angular deflection determined by equivalent circuit (PSpice) and analytical equations

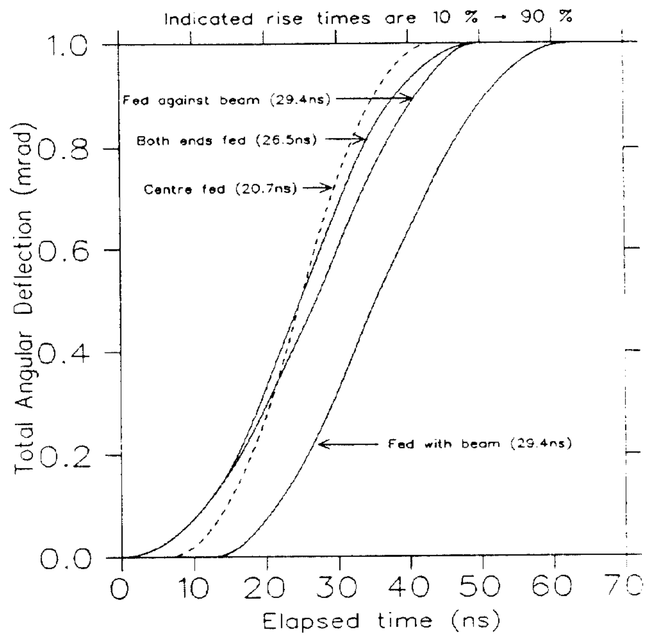

Figure 4: Dependence of rise time of total angular deflection upon method of feeding the deflector plates: ℓ = 3.8 m. $t_{v(r)[0\%-100\%]}$ = 20 ns

For the configuration where both ends of the plates are fed simultaneously, the magnetic angular deflection adds to the lead-in to the 'S-curve' electric angular deflection, and opposes the electric angular deflection at the top of the 'S-curve', therefore extending the total angular deflection rise-time to 26·5 ns [6].

For the configurations where the deflector plates are fed at only one-end, the magnetic angular deflection is unidirectional: hence if the magnetic angular deflection opposes the initial lead-in to the electric angular deflection it will also oppose the electric angular deflection at the top of the 'S-curve'. Similarly if the magnetic angular deflection adds to the electric angular deflection at the top of the 'S-curve' it will also add to the initial lead-in to the 'S-curve' [6]. In addition, if the electric component of angular deflection rise-time alone is considered (and the magnetic component neglected), the rise-time for the situations where the deflector plates are fed at one end only is significantly greater than that which results from centre-feeding the deflector plates (for both end fed configurations $t_{\Theta_e(r/f)[10\%\rightarrow 90\%]}$=28·7ns, c.f. 23·5 ns for the centre-fed configuration).

V. Conclusion

The mathematical representation developed for the purposes of tracking particles through the deflector plates of the 1 MHz chopper permits the angular deflection resulting from both the magnetic and electric components of the field to be predicted. The quality of these predictions is dependent upon the number of sections used to represent the deflector plates, the length of the deflector plates, and the maximum rate-of-change of the driving voltage waveform. The mathematical model has been shown to give predictions for angular deflection which are in good agreement with analytical equations.

Four different methods of feeding deflector plates have been considered: it is concluded that centre-feeding results in a minimum rise-time for total angular deflection.

VI. References

[1] G. D. Wait., M. J. Barnes, C. B. Figley "A 1 MHz Beam Chopper for the Kaon Factory". TRI-DN-89-K70.

[2] M. J. Barnes, G. D. Wait, D. C. Fiander "Mathematical Modelling of the 1MHz Beam Chopper for the Kaon Factory", (Proceedings of European Particle Accelerator Conference, June 1990).

[3] M. J. Barnes, D. C. Fiander, C. B. Figley, V. Rödel, G. D. Wait, G. Waters. "A 1 MHz Beam Chopper for the Kaon Factory", (Proceedings of European Particle Accelerator Conference, June 1990).

[4] TRIUMF KAON FACTORY STUDY, Accelerator Design Report, May 1990.

[5] G. D. Wait, M. J. Barnes, D. Bishop, G. Waters, C. B. Figley. "Prototype Studies of a 1 MHz Chopper for the Kaon Factory", Proceedings of this Conference.

[6] M. J. Barnes, G. D. Wait. "Simulation of Deflector Plates and Assessment of Rise-Times for the 1 MHz Chopper". TRI-DN-90-K149.

[7] D. C. Fiander, G. D. Wait, M. J. Barnes. "Advantages of Center Feeding the Deflector Plates for the 1MHz Chopper System". TRI-DN-89-K45.

[8] M. J. Barnes, G. D. Wait. "Results of Calculations on the Beam Deflection Due to the 1 MHz Chopper for the Kaon Factory", Proceedings of this Conference.

[9] MicroSim Corporation, PSpice version 4·03, released January 1990.