MATHEMATICAL MODELLING OF THE 1 MHz BEAM CHOPPER FOR THE KAON FACTORY

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Abstract

The proposed KAON factory at TRIUMF requires a 1 MHz (10^6 discrete pulses/s) beam chopper to create appropriate beam gaps in the extracted cyclotron beam. A novel technique, which gives relatively high energy efficiency, has been proposed for the chopper [1]. The novel aspect of the chopper, which is an electric field device, is the use of a transmission line on which pulses are stored. Deflection of the bunches to be eliminated will be predominantly provided by an electric field between the deflector plates of the chopper, although there may be a magnetic component of kick as well [2].

At the driving end of the transmission line there will be two tetrodes, a charger and a clipper: inevitably there is stray capacitance and inductance associated with this circuitry. The presence of the parasitic elements adversely affects losses in both the charger and clipper circuits, and distorts the stored voltage pulse: this may also cause beam bunches to be kicked when ideally they should receive no kick, and cause variations in the kick-strength 'flat-top' [3,4].

In order to assess the effect of stray capacitance and other circuit parameters upon particle deflection, simulations have been performed using the PSpice circuit analysis package. The simulations include tracking of beam particles through the deflector plates of the 1 MHz chopper [3], and a representative model of the tetrodes [4].

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]. The concept involves the storage of pulses in a very low loss 50 Ω transmission line that has a one way propagation delay (τ_{sd}) of approximately 1 μs and has one end connected to the deflector plates: at the opposite end of the storage cable there will be two tetrodes, a charger and a clipper (fig. 1).

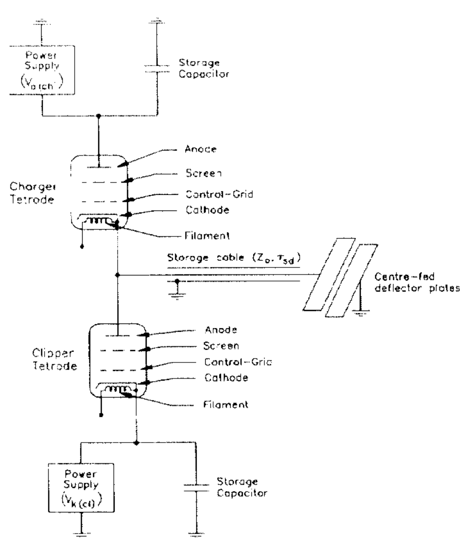

Fig. 1: Schematic Diagram of the Electrical Circuit of the 1 MHz Chopper

The required chopper deflection angle of 1 mrad at 452 MeV, for the 5 bunches to be removed, can be achieved with a set of plates, which are open-circuit at each end, with any practical combination of plate voltage and length with a product of 37.5kV·m, for a plate separation of 50mm [1].

Deflection of the bunches to be eliminated is predominantly provided by an electric field between the deflector plates, although there may be a magnetic component of kick too [2]. 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 [2].

The delay of the storage cable, which interconnects the tetrodes and deflector plates, also affects the nature of the kick [3,4]. In addition, because of the non-linear nature of the CY1172 tetrode characteristics [6], the magnitude of both the control-grid drive and the charger tetrode anode voltage, for a given screen voltage, affects the stored voltage pulse, and hence the nature of the kick strength [4].

Mathematical Simulation

Deflector Plates

In order to predict the effect of the magnetic component of kick upon beam deflection it is necessary to simulate tracking of the beam bunches through the deflector plates of the chopper. The equivalent circuit, including the deflector plates, simulated is shown in fig. 2.

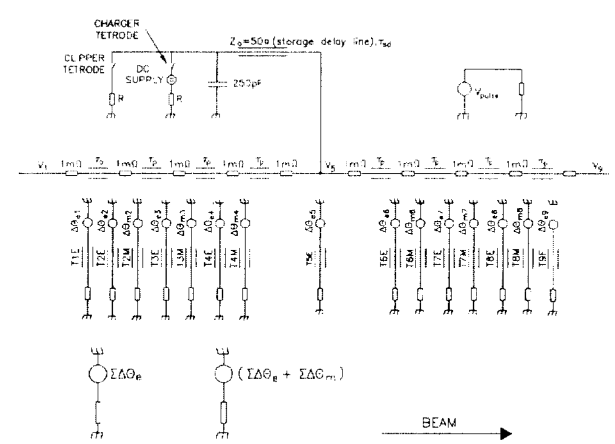

Fig. 2: Simplified equivalent circuit of 1 MHz chopper, for determining kick of a particle in a 'dc beam'.

For small incremental angles of deflection ($\Delta\Theta_e$), due to the electric field over a short length ($\Delta\ell$) of deflector plate, the total deflection, due to the electrical field, is given approximately by [3]:

$$\Theta_e[rads] = \sum_{n=1}^{N+1}(\Delta\Theta_{en}) = \sum_{n=1}^{N+1}\left(\frac{1}{(N+1)} \times \left[\frac{\ell}{d \times p \times \beta}\right] \times V_n\right) \quad (1)$$

where:
$\beta \times c$ is particle velocity (β = 0.74 for beam from the cyclotron);
p is the beam momentum (1.03 GeV/c for beam from the cyclotron);
d is the separation of the deflector plates (m);
V_n is the potential difference between the inner and outer conductors, of the transmission lines representing the deflector plates, at the

instant of time a particular beam particle passed that node (V);
ℓ is the total physical length of the deflector plates (m);
N is the number of delay lines used to simulate the deflector plates.

For small angles of deflection ($\Delta\Theta_m$), due to the magnetic field over a short length of deflector plate, the total deflection, due to the magnetic field, is given approximately by [3]:

$$\Theta_m[rads] = \sum_{n=2}^{N}(\Delta\Theta_{mn}) = \sum_{n=2}^{N}\left(\frac{0.2998}{(N+1)} \times \left[\frac{(2 \times Z_0) \times \ell}{d \times p \times c}\right] \times I_n\right) \quad (2)$$

where:
$(2 \times Z_0)$ is the characteristic impedance of the plates (Ω) [1,5];
I_n is the current flowing in the n^{th} ($1m\Omega$) monitoring resistor, at the instant of time the particular beam particle of interest passed the monitoring resistor (A).

The above equations are coded, using the PSpice Analog Behavioral Model option [7], such that $\Delta\Theta_{en}$ and $\Delta\Theta_{mn}$ are calculated at each compute step, from the voltage at deflector plate node n (V_n) and the current through the n^{th} monitoring resistor, respectively.

The single-way propagation delay (τ_p) of each of the N transmission lines representing the deflector plates is given by:

$$\tau_p = \left(\frac{\ell}{N \times c}\right) \quad (3)$$

The single-way propagation delay of each of the transmission lines T1E through to T9E, and T2M through to T8M, (fig. 2) is equal to the transit time of a beam bunch from the deflector plate node of interest to the exit of the deflector plates, e.g. the delay of transmission line T7M (τ_{T7M}) is given by:

$$\tau_{T7M} = \left(\frac{\tau_p \times (N+1-7)}{\beta}\right) = \left(\frac{\tau_p \times 2}{\beta}\right) \quad (4)$$

The instantaneous sum of the output of transmission lines T1E through to T9E (equation 1), and lines T2M through to T8M (equation 2), is equal to the deflection, attributable to the electric and magnetic fields respectively, experienced by a beam particle exiting the plates at that instant of time.

Fig. 3 shows a typical prediction for both Θ_e and Θ_m for a 'dc beam': time domain plots of beam bunch particle density may be superimposed upon a graph of total deflection angle ($\Theta_e + \Theta_m$) to assess the effect of non-ideal voltage pulses upon beam deflection [3].

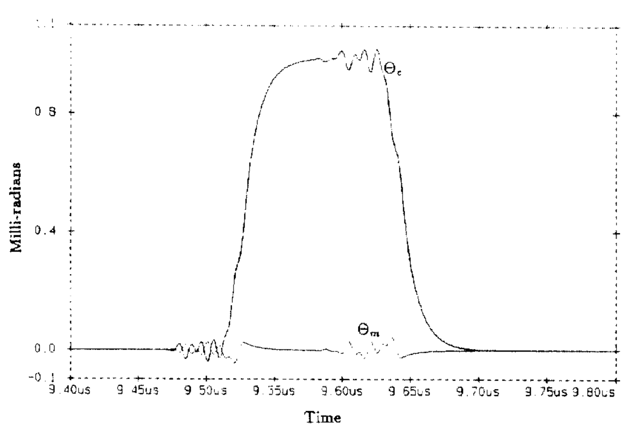

Fig. 3: Typical prediction for Θ_e and Θ_m.

Tetrode

In order to take into account the non-linear characteristics of the CY1172 tetrode, it is necessary to simulate these characteristics. The equivalent circuit of the tetrode, simulated using the PSpice Analog Behavioral Model option, is shown in fig. 4: values for the five parasitic capacitances shown are given in the CY1172 data sheets [6].

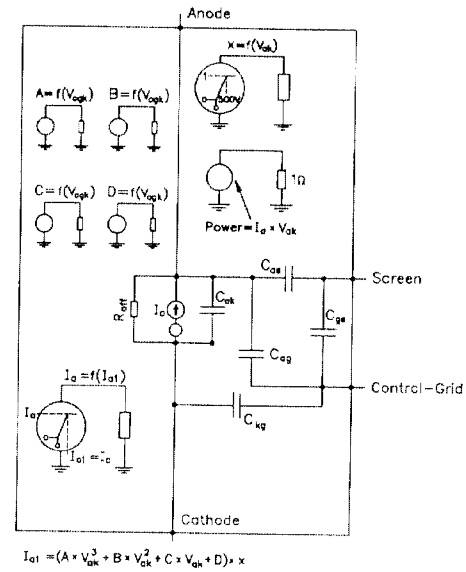

Fig. 4: Sub-circuit utilized for CY1172 tetrode.

A cubic equation of the form:

$$I_a = \left(A \times \left(\frac{V_{ak}}{10^4}\right)^3 + B \times \left(\frac{V_{ak}}{10^4}\right)^2 + C \times \left(\frac{V_{ak}}{10^4}\right) + D\right) \times x \quad (5)$$

is used to calculate anode current (I_a), from anode-cathode voltage (V_{ak}) and control-grid drive, for a given screen voltage. A set of tabulated data defines the transfer function between the control-grid voltage and each of the coefficients (A, B, C & D). The coefficients have been calculated by curve fitting to typical constant-current characteristics for the CY1172 tetrode [6]: for a screen voltage of 800V the curves were fitted, for a given control-grid drive, over a range of anode-cathode voltages of 1kV and above [4]. Since the constant-grid drive characteristics must pass through the origin, and the D coefficients in the curve fit are non-zero [4], the x coefficient shown in equation 5 is required, e.g.:

- x=1 for $V_{ak} \geq 500V$;
- x varies linearly between 0 and 1, for V_{ak} in the range 0 to 500V;
- x=0 for $V_{ak} \leq 0V$.

Fig. 5 shows the simulated constant control-grid voltage characteristics, in 50V increments from -600V to 100V, for a screen voltage of 800V.

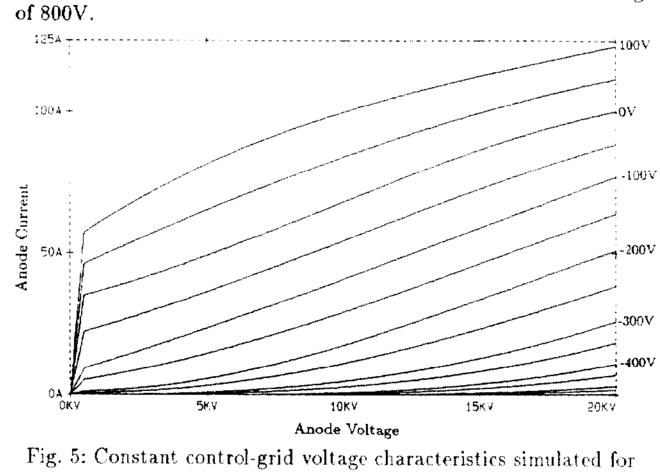

Fig. 5: Constant control-grid voltage characteristics simulated for the CY1172 tetrode [V_{sk}=800V].

A schematic of the circuit simulated using PSpice is shown in fig. 1: however the deflector plates are not simulated, and hence the kick is assumed to be directly proportional to the voltage at the open-circuit (output) end of the storage cable. Fig. 6 shows the effect of varying the charger tetrode anode voltage upon the maximum value of either the field rise or fall time in the deflector plates; the charger tetrode control-grid drive is simulated as being trapezoidal, with a flat-top of 0V for 100ns, and 15ns rise and fall-times [4].

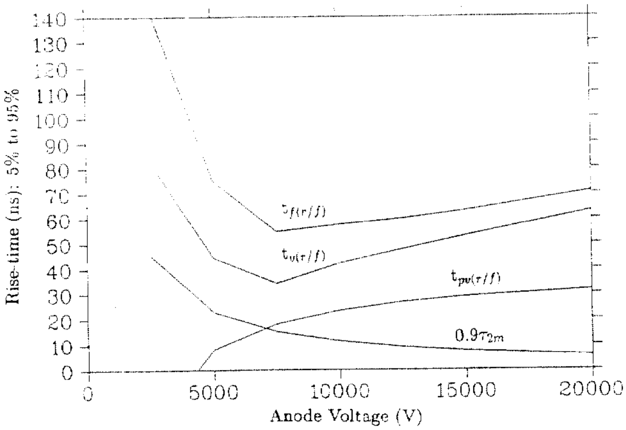

Fig. 6: Dependence of rise-time upon charger tetrode anode voltage (τ_{sd}=498ns).

The 5% to 95% field rise/fall time ($t_{f(r/f)[5\%\rightarrow95\%]}$) is given by [2,8]:

$$t_{f(r/f)[5\%\rightarrow95\%]} = t_{v(r/f)[5\%\rightarrow95\%]} + \left(\frac{0.9 \times \tau_{2m}}{\beta}\right) \quad (6)$$

Where the fill-time (τ_{2m}) is given by:

$$\tau_{2m} = \left(\frac{p \times \beta}{E \times c}\right) \times tan(\Theta_e) \quad (7)$$

and:
$t_{v(r/f)[5\%\rightarrow95\%]}$ is the voltage pulse rise/fall time between 5% and 95% of its 'flat-top' and dc levels;
E is assumed to be equal to the charger tetrode's anode voltage divided by the deflector plate separation.

As the deflector plates are increased in length, to compensate for reduced anode voltage, their fill-time increases (equation 7), and thus the maximum permissible rise and fall times of the stored voltage pulse ($t_{pv(r/f)}$) decrease (fig. 6). $t_{pv(r/f)[5\%\rightarrow95\%]}$ is given by [4]:

$$t_{pv(r/f)[5\%\rightarrow95\%]} = 39 \times 10^{-9} - \left(\frac{0.9 \times \tau_{2m}}{\beta}\right) \quad (8)$$

Where 39ns is the maximum permissible rise/fall time of the field [1].

The magnitude of charger tetrode anode voltage which minimizes field rise/fall time, for τ_{sd} 2ns less than nominal, is approximately 7.5kV for the CY1172 tetrode (fig. 6). The minimum difference between the predicted voltage pulse rise/fall time, and its permissible rise/fall time also corresponds to an anode voltage of approximately 7.5kV: however the resultant rise/fall time (55 ns) is outside the specified 39ns [1].

Fig. 7 shows shows the predicted steady-state voltage pulse at the output of the storage cable, when τ_{sd} is 1ns less than nominal, 300nH of lumped (stray) inductance is in series with both the charger and clipper tetrodes, 150pF of stray capacitance is lumped between the charger tetrode cathode and ground, and a 26MHz to 45MHz band-pass filter is represented as being connected at the output of the storage cable. The filter is required to attenuate ripple created by the interaction of the parasitic components associated with the charger and clipper circuits [4].

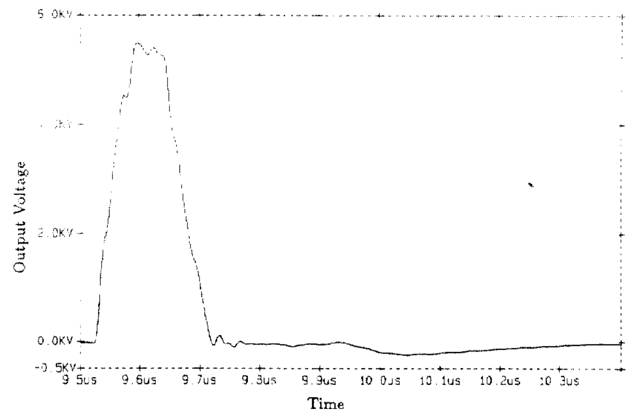

Fig. 7: 'Steady-state' voltage at output of storage cable.

Discussion

The mathematical representation developed for the purposes of tracking particles through the deflector plates of the 1MHz chopper, permits the kick resulting from both the magnetic and electric components of the field to be determined. The quality of the predictions is related to the number of transmission lines utilized to represent the deflector plates.

The mathematical model of the tetrode is believed to be representative for anode-cathode voltages greater than the screen-cathode voltage. Anode-cathode voltages approximately equal to or less than the screen-cathode voltage may result in significant screen current [6], and thus screen dissipation: the present representation of the tetrode does not simulate screen current. Similarly the current mathematical model of the tetrode is valid for a fixed screen voltage. Further development of the tetrode model is required so that the effect of screen current, and the consequent change in screen voltage, may be simulated.

The rise and fall times of the stored voltage pulse are significantly effected by circuit capacitance [4]. Hence, research into the minimization of the effects of parasitic components in the charger and clipper circuitry is presently being undertaken: the results of this research will be presented at a future date.

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