A CHOPPER-BUNCHER DESIGN FOR THE MONTREAL CW ELECTRON ACCELERATOR

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Introduction

Linear accelerators generally have Chopper Bunchers following the electron source where energy modulation significantly changes the velocity of the electrons so that the beam pulses can be bunched by a drift space. The current design is intended for use with buncher is the University of Montreal Dynamitron which is being considered as a test injector for a CW Microtron with linear accelerator sections excited at 2.45 GHz. The Dynamitron can produce up to 2 ma of electrons at 3.5 MeV, in which case $\beta = 0.992$ so bunching by a drift space becomes inpractical. The requirements on the chopper-buncher are that it produces clean beam pulses of maximum intensity which are phase locked to the RF of the accelerator. The admittance and beam stability requirements of the microtron place fairly stringent requirements on both the transverse and longitudinal emittance of the beam. The injected beam should match these characteristics in order to avoid beam spill and simplify beam diagnostics in the microtron.

Principle of operation

The chopper-buncher employs accelerating cavities driven synchronously with the accelerator RF, to modulate the beam energy by ± 30 KeV, after which the beam is injected into an achromatic magnet[1] in which the path length, and hence the delay, is a function of the energy, fig. 1. This phase dependent delay produces the bunching effect.

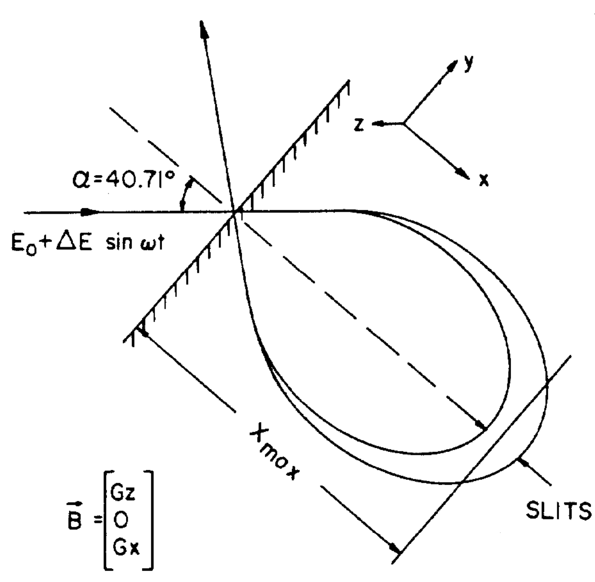

Fig. 1. A magnetic quadrupole field acts as an achromatic magnetic mirror. The delay depends on the particle energy and can be selected by slits on the symmetry axis.

The magnet produces an intermediate image with energy dispersion on the symmetry plane, so slits at this point can be used to select a phase window and chop the beam. Furthermore the current differential from these slits can be used to stabilize the beam energy. A single system of this type produces two pulses per RF cycle, fig. 2, one bunched and a second debunched pulse 180° later. The latter is eliminated by a second modulating cavity plus achromatic mirror magnet, which has the added advantage of providing a beam parallel to the axis of the injector, fig. 3.

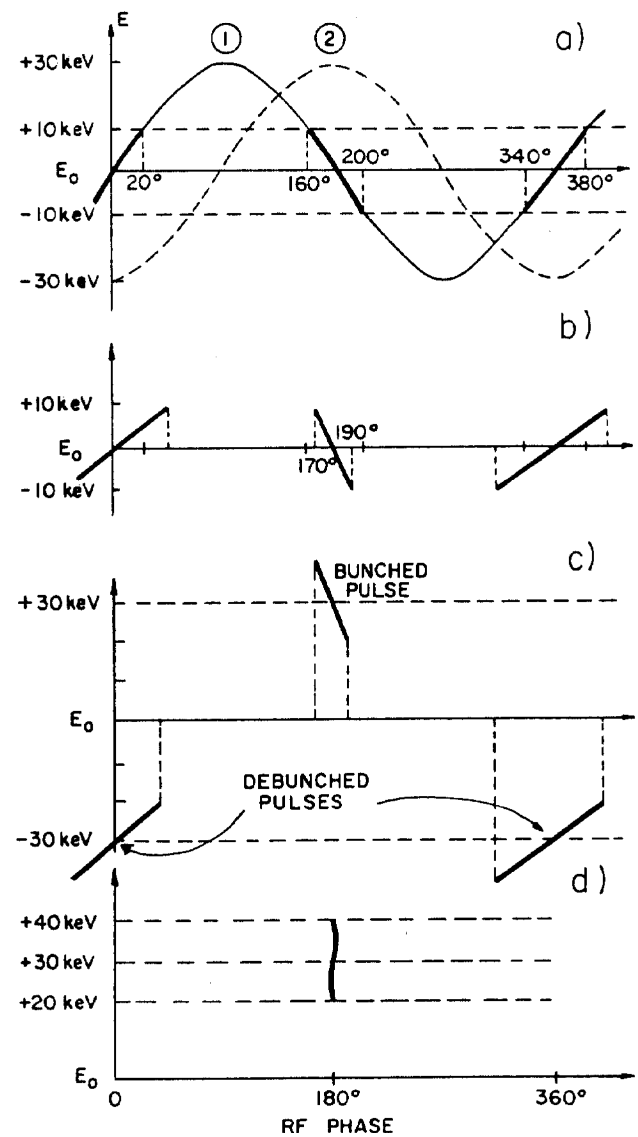

Fig. 2. a) Energy modulation of the beam by cavities 1 and 2
b) Chopped and partially bunched beam pulses after the first magnet
c) after the second energy modulating cavity and
c) At the output of the second magnet.

After consideration of a number of different achromatic magnet systems[2] the magnetic mirror proposed by Euge[1] was chosen for detailed study. This system has the advantage that only a single magnet is required, and that it is achromatic over a wide energy range. Furthermore

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he beam entrance and exit is in a region of zero field thus detailed design of pole edges to control the focussing properties of the fringing fields is not required. The use of a current sheet magnet to produce the required quadrupole field, as first suggested by Hand and Panofsky[3] and more recently developed for Multipole magnets by Ikegami,[4,5] leads to a compact and efficient design, with adequate space and access for the chopper slits, which are at the center of the magnetic field.

Chopper-Buncher

A cavity excited in the TM_{010} mode, at the fundamental frequency of the accelerator, modulates the energy of the 3.5 MeV DC beam from the Dynamitron by ΔE = 30 KeV so

$$E(t) = E_o + \Delta E \sin \omega t \qquad (1)$$

For particles entering a pure quadrupole magnetic field at the achromatic angle of 40.71° the trajectories have a total length S and maximum excursion X_{max} of

$$S = 2.554\, X_{max} = 0.2681\, (P/G)^{\frac{1}{2}} \qquad (2)$$

where P is the particle momentum in MeV/c and the quadrupole field is $\bar{B} = (Gz,\ 0,\ Gx)$. The time delay through the magnet is

$$\Delta t = \frac{S}{BC} = \frac{0.2681}{C\sqrt{G}} \cdot \frac{\sqrt{P}}{\beta} \qquad (3)$$

Then substituting from (1) and keeping only leading terms in ΔE

$$\Delta t = \frac{0.2681}{\beta_o C}\left(\frac{P_o}{G}\right)^{\frac{1}{2}} \left\{1+\frac{(E_o + M_o C^2)\Delta E \operatorname{Sin} \omega t}{2\, P_o^2}\right\} \qquad (4)$$

For bunching $\Delta t(180) = \Delta t(180 \pm \Delta\varphi)$ where $2\Delta\varphi$ is the phase acceptance of the chopper. The energy modulation ΔE, phase acceptance $2\Delta\varphi$ and the magnetic field gradient G are chosen so as to optimize the beam pulse intensity while keeping the resulting energy spread and phase width of the injected beam within the acceptance of the Microtron and the required energy resolution of the accelerator. For a phase acceptance of φ = 160° to 200°, i.e. 11 percent, and recalling that the bunching is produced by two magnets, G = 4.24 x 10^{-2} Tesla/Meter thus X_{max} = 1.02 meters for ΔE = 30 KeV.

The second cavity increases the energy of the partially bunched pulse and decreases that of the debunched pulse, thus the latter can be eliminated by the slits in the second bunching magnet. The slit width required for $\Delta\varphi$ = 20° is

$$X_{max} = 0.1050\ \frac{(E_o+M_oC^2)}{\sqrt{P_o^{\ 3}}\,G}\ \Delta E \operatorname{Sin} \Delta$$

$$= 2.6 \text{ mm}$$

Magnet orbits

A computer program was written to numerically solve the equations of motion of electrons in a magnetic field of the form[1]

$$Bx = G\, n\, x^{n-1} z$$

$$By = 0$$

$$Bz = G\left[x^n - \frac{n(n-1)}{2}\, x^{n-2} z^2\right]$$

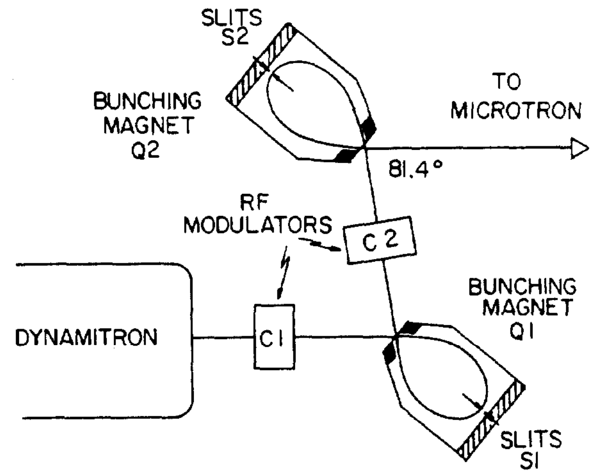

Fig. 3. Chopper-Buncher system with two energy modulating cavities C1, and C2, two achromatic bunching magnets Q1 and Q2, slits S1 chop the beam and slits S2 remove the debunched beam pulse.

which obeys the field equations to first order, and reduces to a pure quadrupole field for n = 1. This field form allowed us to investigate the focussing properties of the field as a function of n, and thus see what effect deviations from a pure quadrupole field might produce. Orbits were calculated for a range of angles α with the x axis (normal to the field boundary), and the z axis, as well as for initial displacements in the z direction. The computed results agreed with the analytical values for the maximum excursion into the field[1]

$$x_{max} = \left[\frac{(n+1)B\rho}{G}\ (1+\sin\alpha)\right]^{\frac{1}{(n+1)}}$$

Thus for a pure quadrupole field and α = 40.71°, the computed entrance angle for achromatism

$$x_{max} = 0.1050\left(\frac{P}{G}\right)^{\frac{1}{2}}$$

the maximum y extension is

$$y_{max} = 0.0345\left(\frac{P}{G}\right)^{\frac{1}{2}} = 0.3282\, x_{max}$$

and the orbit length is

$$S = 0.2681\left(\frac{P}{G}\right)^{\frac{1}{2}} = 2.554\, x_{max}$$

Thus the minimum rectangular area for such a magnet would be $A > 2\, x_{max}\, y_{max} = 0.014\ (P/G)$, with momentum P in MeV/C and G in Tesla/meter.

The first order transfer matrix elements were determined from the orbits. For magnetic fields which are independent of the y co ordinate, the transfer matrix in the horizontal, or x-y plane, from the entrance to the exit of the field can be written as

$$\begin{bmatrix} h_f \\ h'_f \end{bmatrix} = \begin{bmatrix} -1 & A \\ 0 & -1 \end{bmatrix} \begin{bmatrix} h_i \\ h'_i \end{bmatrix} \Rightarrow \begin{bmatrix} -1 & -1.28 \\ 0 & -1 \end{bmatrix} \quad \begin{matrix} \text{for } n = 1 \\ \text{and } x_{max} = 1 \end{matrix}$$

where h and h' are the displacements from and angles to the median orbit. Furthermore the orbits are symmetrical with respect to the x axis so the transfer matrix from the entrance to the centerline, i.e. the slit position can be written as

$$\begin{bmatrix} h_c \\ h'_c \end{bmatrix} = \begin{bmatrix} 0 & f \\ -1/f & A/2f \end{bmatrix} \begin{bmatrix} h_i \\ h'_i \end{bmatrix} \Rightarrow \begin{bmatrix} 0 & 0.23 \\ -4.3 & -2.8 \end{bmatrix}$$

Only two parameters need be derived from the orbit calculations and, for a quadrupole field these are $A = -1.28\ x_{max}$ and $f = 0.23\ x_{max}$. Thus horizontal displacements of the beam are reproduced with magnification -1 at the exit, and have only a small effect on the precision of the beam chopping by the slits. Variation of the entrance angle h_i changes the displacement at the slits and also the orbit length. For particles of energy $E_o = 3.5$ MeV in a field for which $x_{max} = 1$ meter the entrance angle corresponding to a displacement of half the slit width i.e. 1.35 mm corresponds to $h_i = 5.9$ m Rad. and a change in the time delay through the magnet of $\delta t = 0.47$ ps which corresponds to $\delta = 0.4^o$ of RF phase. Thus the bunching magnet allows a fairly wide choice of horizontal beam emittance characteristics. The vertical or z transfer matrices can be written as

$$\begin{bmatrix} z_f \\ z'_f \end{bmatrix} = \begin{bmatrix} M & F(1-M^2) \\ -1/F & M \end{bmatrix} \begin{bmatrix} z_i \\ z'_i \end{bmatrix} \Rightarrow \begin{bmatrix} -0.74 & 4.2 \\ -0.11 & -0.74 \end{bmatrix}$$

and

$$\begin{bmatrix} z_c \\ z'_c \end{bmatrix} = \begin{bmatrix} f_o/2F & f_o\frac{(1-M)}{2} \\ -1/f_o & \frac{F(1+M)}{f_o} \end{bmatrix} \begin{bmatrix} z_i \\ z'_i \end{bmatrix} = \begin{bmatrix} 0.08 & 1.2 \\ -0.72 & 1.7 \end{bmatrix}$$

The orbit calculations give $M = -0.74$, $F = 9.26\ x_{max}$ and $f_o = 1.39\ x_{max}$ for a quadrupole field.

Thus vertical displacements of the input beam produce negligible displacement at the slits and similar but negative displacements at the output. However, vertical input divergence is magnified at the output and thus an essentially parallel beam is required. This poses a problem, namely that the height of the beam at the slits will be small, and thus they will require careful design to handle the large power dissipation per unit area. Changes in the field index n by 20 percent do not alter this conclusion.

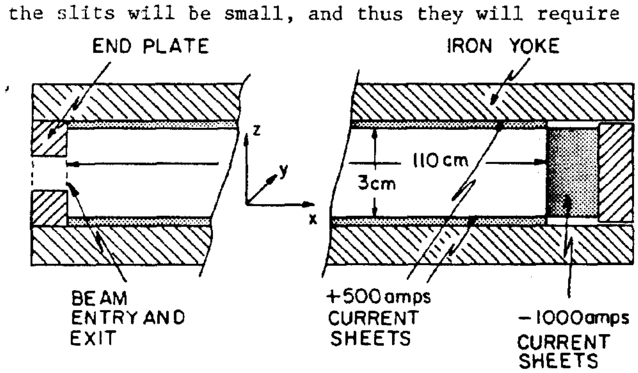

Fig. 4. Current Sheet Half-Quadrupole Bunching magnet design.

Magnet Design

The particle orbits extend one meter and 0.7 meter in the x and y directions but only 1 cm in the z direction, and furthermore only half the quadrupole field is required for the bunching magnets. The current sheet magnet therefore has many advantages over the standard design which relies on the hyperbolic shape of the pole pieces to give the quadrupole field. The latter would be very expensive to machine, be very large, and require considerably more power[6]. The Panofsky design consists of a simple iron yoke with a rectangular cavity.

The magnet excitation is provided by uniform current sheets on the sides of the cavity, with current perpendicular to the diagram and in opposite directions on orthogonal sides. Placing both vertical current sheets on one side of the cavity moves the zero field axis to the center line of the opposite side, fig. 4, thus the beam port does not perturb the field distribution. The allignment of the current sheets is not critical[7] and they will consist of parallel thin copper bars clamped to the pole faces. Different current densities in the horizontal current sheets produce a dipole field, and a uniform current density gradient an octupole field[5]. thus the final field can be easily corrected for deviations from the desired quadrupole field by adjusting the current density distribution or via trim coils.

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