BEAM BUMP METHOD OF TARGET ENGAGEMENT

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Abstract

At the Cambridge Electron Accelerator we have developed a technique of engaging a thin tungsten target, located in a field-free straight section, with a 6 Gev electron beam. A distortion (bump) of the equilibrium orbit of the synchrotron is produced by powering backleg windings on four selected synchrotron magnets in a prescribed way. This method is equally useful for engaging a radially-inside or radially-outside target. Smooth spills of the electron beam on the target have been achieved for periods of 100 to 3000 micro-seconds at energies of 0.5 to 6.0 Gev. The backleg windings are powered by pulse-forming networks which can be operated asynchronously (e.g. 59 out of 60 pps.) Three such systems exist at the laboratory enabling up to three experimenters to perform experiments at the same time. Each experimenter receives an allotted number of pulses out of the 60 machine pulses which are available each second.

Introduction

To distort the equilibrium orbit of an electron synchrotron in order to cause electrons to engage a thin target is allowable provided the new equilibrium orbit is within the aperture of the vacuum chamber and provided the oscillations which the electrons make with respect to the new orbit are stable.

The equation for the horizontal transverse displacement (Y) of a particle from the ideal equilibrium orbit is given by[1]

$$\frac{d^2Y}{ds^2} + K(s) = 0 \qquad (1)$$

and when a field disturbance is created in one magnet, the equation of horizontal motion becomes:

$$\frac{d^2Y}{ds^2} + K(s) = \frac{\Delta B_r}{B_o \rho} \qquad (2)$$

where : K (s) is a periodic coefficient equal to $1 - n(s)/\rho(s)$.

ΔB_r is $B_z - B_o$ and

$B_o \rho$ is the magnetic rigidity.

Referring directly to Ref. 1, page 19, and carrying on the reasoning indicated there, we find that the solution for Y (s) is of the form

$$Y(s) = a\, \beta^{1/2} \cos(\nu\phi + \delta). \qquad (3)$$

The expectation value of the amplitude squared is

$$\langle V(\phi)\rangle = \frac{\nu^2}{4\sin^2\pi\nu} \int_{\phi}^{\phi+2\pi}\int_{\phi}^{\phi+2\pi} \langle f(\psi) f(\chi)\rangle \cos(\nu\phi + \delta)\, d\psi\, d\chi . \qquad (4)$$

It can be shown that the following simplifications are reasonable.

a. $$< f(\psi) f(\chi) > = \beta_r^3 \left[\frac{\Delta B_r}{B_o \rho} \right]^2$$

b. $$\cos(\nu\phi + \delta) \approx 1$$

c. $$\iint d(\psi) d(\chi) = \frac{L^2}{\nu^2 \beta_r^2}$$

where L is the length of the disturbed magnet.

The expectation value of the amplitude squared becomes

$$< V(\phi) > = \frac{\nu^2}{4 \sin^2 \pi\nu} \left[\beta_r^3 \left(\frac{\Delta B_r}{B_o \rho} \right)^2 \frac{L^2}{\nu^2 \beta_r^2} \right] \tag{5}$$

$$= \left[\frac{1}{2 \sin \pi\nu} \cdot \beta_r^{1/2} \cdot \frac{\Delta B_r}{B_o \rho} \right]^2 \tag{6}$$

Now $y = \beta^{1/2} V^{1/2}$, and if we define ϕ as: $2\pi\nu$ degrees for one revolution, we obtain

$$y(s) = \beta^{1/2} \left[\frac{\beta_r^{1/2}}{2 \sin \pi\nu} \cdot \frac{L}{\rho} \frac{\Delta B}{B_o} \right] \cos(\phi + \delta) \tag{7}$$

$$y(s) = \left(\frac{\beta}{\beta_{max}} \right)^{1/2} \left[\frac{\beta_{max}^{1/2} \cdot \beta_r^{1/2}}{2 \sin \pi\nu} \frac{L}{\rho} \right] \frac{\Delta B}{B_o} \cos(\phi + \delta) \tag{8}$$

If we consider two magnetic disturbances $\Delta B/B_o$, one in a closed magnet (c) and the other in an open magnet (o), and if we insert in Equation (8) the CEA machine constants, we arrive at the following equations for the amplitude of the distorted equilibrium orbit as a function of ϕ, which is measured from the center of the disturbed magnet

$$y_c = \left(\frac{\beta}{\beta_{max}} \right)^{1/2} 38.8 \frac{\Delta B}{B_o} \cos(\phi - 72^\circ) \tag{9}$$

$$y_o = \left(\frac{\beta}{\beta_{max}} \right)^{1/2} 16.4 \frac{\Delta B}{B_o} \cos(\phi - 72^\circ) \tag{10}$$

It is clear that the effect of a magnetic disturbance in a single magnet is to cause a relatively large orbit distortion which varies with ϕ and oscillates ν times about the ideal equilibrium orbit and closes on itself at the center of the disturbed magnet. This is the new equilibrium orbit and particles make betatron oscillations about this new orbit.

Basis of Design Adopted

The simplest way of achieving a distorted equilibrium orbit is to power a winding on the backleg of one of the 48 synchrotron magnets. To produce a large distortion at one specified straight section and relatively little distortion elsewhere requires that more than one magnet be disturbed. Ideally the disturbed magnets should individually produce distorted equilibrium orbits which add at the specified straight section and cancel at other locations. If adequate cancelation is to be achieved, the amplitudes of the distortions must be approximately equal; this requires that the number of turns in the backleg winding of an open magnet should be twice that appropriate to a closed magnet. (See Equation 9 and 10.)

A further consideration is that there be no interaction between the beam bump power circuit and the main synchrotron power circuit. Each backleg winding has induced in it 82.5 volts per turn due to the changing magnetic field at 6 Gev excitation. It was very desirable to have these induced voltages cancel so as to ease the requirements on the beam bump power circuit. By canceling the induced voltages, we also cancel any voltages induced in the main magnet circuit due to powering the backleg windings.

The system which satisfies the requirements best employs four magnets, which are powered in series. The separations between magnets are 192°, 144°, and 192° respectively of betatron phase. The four distortions added together produce a large amplitude at the proper straight section, but leave a much smaller residual orbit distortion elsewhere. Therefore by producing two orbit distortions of equal amplitude but opposite polarity on two magnets preceding the straight section, and by doing the same on two magnets following the straight section, we obtain the resultant amplitude versus betatron phase (ϕ) as shown in Fig. 1 and 2. The actual amplitude function is the resultant amplitude multiplied by $(\beta/\beta_{max})^{\frac{1}{2}}$. In addition it must be kept in mind that these amplitudes are quite small compared with the radius of the machine and so we display the undistorted equilibrium orbit as a straight line.

In order to produce a 1.4" distortion of the equilibrium orbit the field disturbance must be 1.3% for a closed magnet and 2.6% for an open magnet. At 6.0 Gev, B_o = 7600 gauss, and therefore ΔB_c = 100 gauss and ΔB_o must equal $2 \times \Delta B_c$. Our main magnet coils which contain 40 turns, are situated above and below the gaps and produce 1 gauss for 4 ampere turns. From the backleg to the gaps the coefficient of coupling (k) is approximately 70% so we need 5.65 ampere-turns for 1 gauss. The ampere-turns requirement for a ΔB_c of 100 gauss is 570 ampere-turns. Each closed magnets has two turns on its backleg, which makes the peak current required 285 amperes. Each open magnet has four turns on its backleg since twice the field disturbance is needed. The choice of number of turns was based on current and voltage ratings of available silicon controlled rectifiers.

Photon Beams Produced

Let us assume that electrons on the distorted equilibrium orbit engage the target by grazing it at the location where the orbit distortion is a maximum. Then near that location we have[2]

$$y(s) = a\,\beta^{1/2}\cos\phi \qquad (11)$$

$$\frac{dy}{ds} = -a\,\beta^{1/2}\sin\phi\frac{d\phi}{ds} + a\frac{\beta^{-1/2}}{2}\cos\phi\frac{d\beta}{ds} \qquad (12)$$

$$\text{but } \frac{d\phi}{ds} = 1/\beta \text{ and } -1/2\frac{d\beta}{ds} = \alpha$$

so that

$$\frac{dy}{ds} = -\frac{a}{\beta^{1/2}}\left[\sin\phi + \alpha\cos\phi\right] \qquad (13)$$

For a beam just engaging the target at the location of maximum amplitude,

$$\cos\phi = 1 \quad \text{and} \quad \sin\phi = 0$$

$$\left(\frac{dy}{ds}\right)_o = -\frac{a\,\alpha}{\beta^{1/2}} \qquad (14)$$

$$y = y_o = a\,\beta^{1/2} \qquad a = y_o/\beta^{1/2}$$

therefore

$$\left(\frac{dy}{ds}\right)_o = -\frac{\alpha}{\beta}\,y_o \qquad (15)$$

where y_o is positive for a radially inside target. α is -2.0 where an open magnet preceeds the straight section and is +2.0 where a closed magnet preceeds the straight section. β is 289 inches at the straight section. The final expression for the slope of the beam striking the target is

$$\left(\frac{dy}{ds}\right)_o = \pm\left(\frac{1}{144\,\text{in}}\right)y_o \qquad (16)$$

\+ when the straight section is preceded by an open magnet,

\- when the straight section is preceded by a closed magnet.

It should be clear that the photon beams produced by beam bumping come out of the machine referenced with respect to the straight section axis and at an angle with respect to that axis of ± 7 milliradians for a target located 1 inch radially inside or radially outside. These results agree generally with the beams that have been produced at the CEA.

Description of System

The backleg windings are 1/0 AWG cable (heavily stranded for ease of winding) with a 600v insulation. They terminate in boxes on the backs of the upstream ends of the box girders upon which the synchrotron magnets rest. Some magnets have up to 3 windings since the same magnet may be involved in three different beam bumps. The key to which magnets are being used in a given bump is given by the number of the straight section. The straight section number is the same as the number of the magnet that follows it and at CEA even numbered magnets (2→48) are open magnets, and odd numbered magnets (1→47) are closed. So if a bump is desired at straight section X then backleg windings on magnets (X-6), (X-2), (X+1) and (X+5) are powered in series. There are sets of series backleg windings to produce bumps at straight sections 4, 5, 7, 8, 10, 11, 14, and an additional set designated 4* for use with the external electron beam system. Beam bump 4* produces a bump at the middle of magnet 4.

The sets of backleg windings are connected in series by 4/0 cable AWG 19 stranded with a 600v insulation cable which runs to the power building basement where they are terminated at a patch board. If current enters the terminal marked (+) it will produce an inside bump and if current enters the terminal marked (-) an outside bump is produced.

The windings are powered by two different pulse-forming networks. One uses a d-c resonant charging of a capacitor bank with a holdoff diode in the charging circuit and a silicon-controlled rectifier (SCR) to discharge the capacitor bank into the beam bump windings. This produces a half sinusoid of current of 6 milliseconds duration. Spill times of up to 0.8 ms. have been achieved with this system. (See Fig. 3.) The other is a d-c resonant charging of a lumped line with a holdoff diode in the charging circuit; the lumped line is discharged through the beam bump windings and produces a rectangular current pulse of 6 ms. duration. (See Fig. 4.)

The advantage of the lumped line is that for experiments where the beam energy variation during spill time is not important, spill times as great as 3 ms. are achieved. The beam energy variation over this spill time is approximately 9%. At present we have two capacitor discharge pulse-forming networks and one lumped line.

The pulse-forming networks are powered from supplies which can produce a half sinusoid of current of 150 amperes peak with 11 ms. duration. They are voltage regulated via a hybrid magamp-transistor regulator and have a 0.24 farad electrolytic capacitor bank. The performance of these supplies has been good at all repetition rates up to 60 per second. They do not mind omission of a pulse and the voltages on our pulse-forming networks stay within 1/2% during the missed pulses.

Beam Bump Logic

We have developed a versatile binary logic circuit that is capable of firing the three beam bump circuits on a schedule such that of 64 successive machine pulses, X pulses go to user #1, Y pulses to user #2 and Z pulses to user #3. (The sum X, Y, and Z is 64.)

Therefore we can in one eight hour running period have up to three experiments taking data on three different beams during the shift.

Conclusions

The beam bump method of target engagement has greatly increased the efficiency of operation of the CEA laboratory. It enables experimenters to try out their equipment and debug it on "parasite time", i.e. before becoming prime user. It enables CEA to make use of outside targets as well as inside targets. The smooth spills attainable with beam bumps eliminate the problems incurred at low energy due to beam -RF interaction.

Prospects are that more beam bump circuits of the lumped line type will be developed.

Acknowledgements

The program for development of the beam bump system was instituted and guided by T. L. Collins, starting in 1959. Feasibility studies and experiments were made by several members of the CEA staff, including: M. Fotino, J. dePagter, and R. Fessel. The lumped line pulse-forming network was proposed

by G. A. Voss and built by B. Vetter. W. Colby did considerable work on the early circuits.

Electronic circuitry for beam sharing was developed by L. Law and R. I. Samuel.

Bibliography

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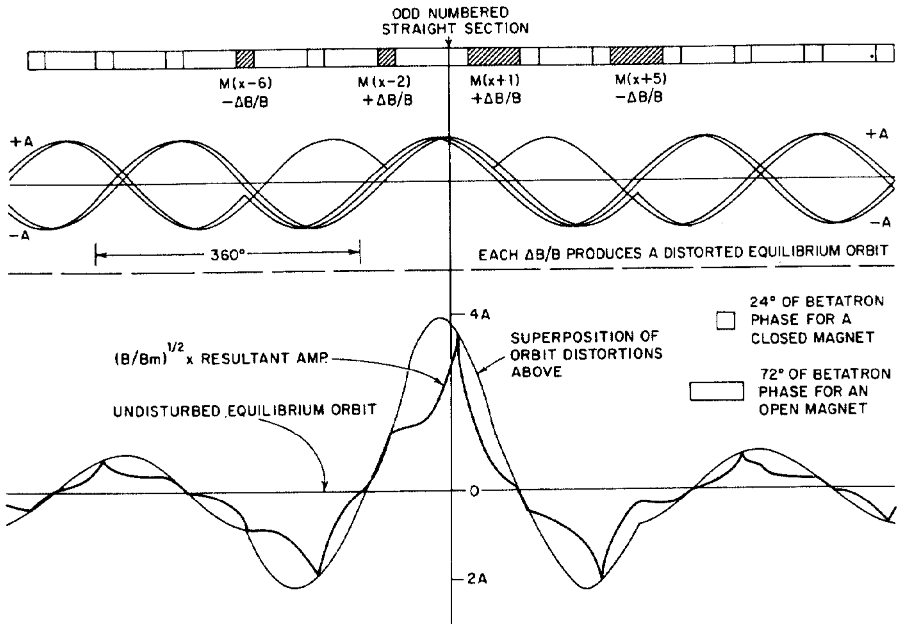

Fig. 1. Resultant Equilibrium Orbit vs Betatron Phase (ϕ) for $\frac{\Delta B}{B}$ in four magnets. (Odd straight section Beam Bump).

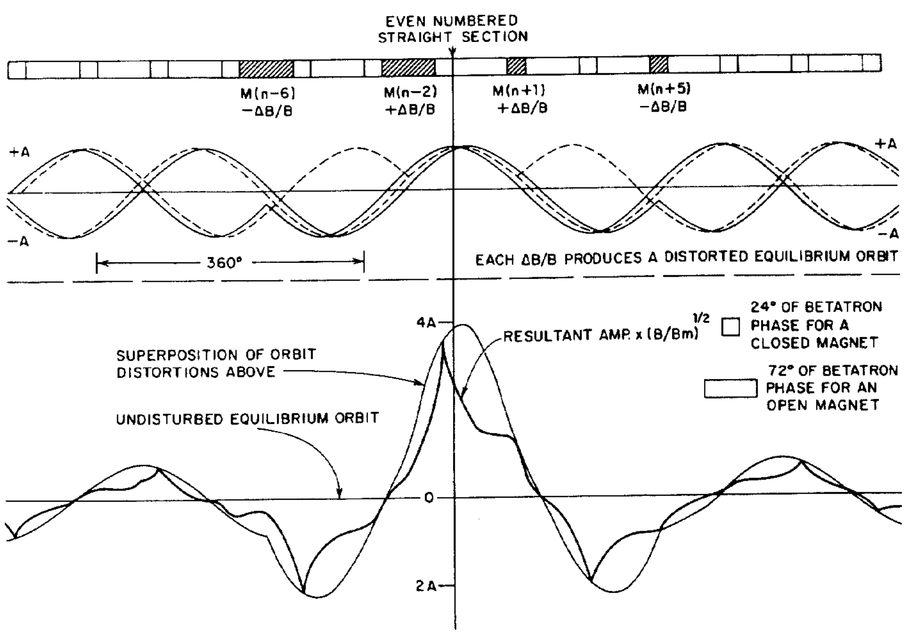

Fig. 2. Resultant Equilibrium Orbit vs Betatron Phase (ϕ) for $\frac{\Delta B}{B}$ in four magnets. (Even straight section Beam Bump).

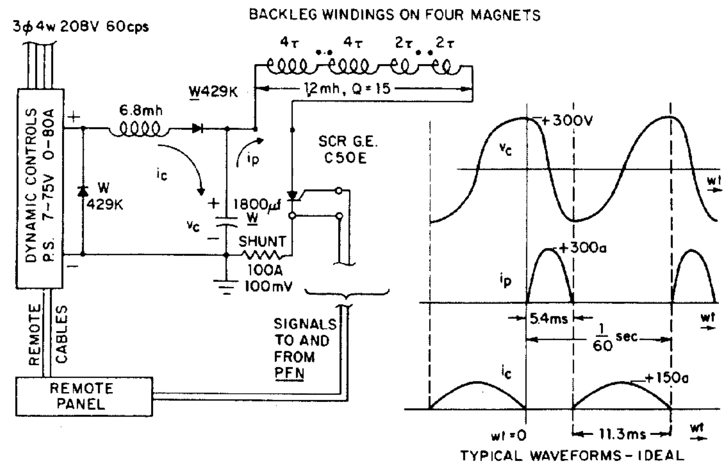

Fig. 3. Beam Bump Schematic (Resonant Discharge (CKT).

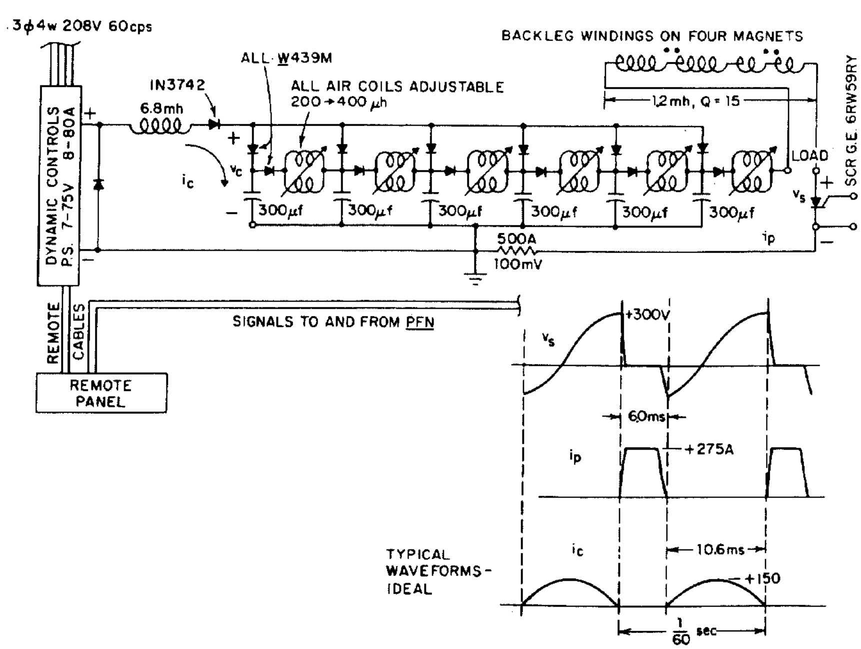

Fig. 4. Beam Bump Schematic (Lumped Line CKT.)