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AGS DIVISION TECHNICAL NOTE

No. 61

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June 20, 1969

A FRONT BITER FOR THE 200 MeV PROTON BEAM: PRELIMINARY CONSIDERATIONS

If it becomes desirable to dump the first few microseconds of the 200 microsecond linac beam, some sort of fast angular deflection of the beam is necessary. Calculations on this subject by W.H. Moore[1], show that a convenient spot to situate this "kicker" would be between quadrupoles Q_4 and Q_5 in the 200 MeV transport line, allowing the beam to drift through Q_5 and dissipate in an absorber just upstream of Q_6. The distance between the centers of quadrupoles Q_4 and Q_5 is 4 meters. The quadrupoles are about 50 centimeters long. The end of the deflection system should be separated from the quadrupole by a reasonable distance, say, 20 centimeters. If we allow 2.5 meters for the kicker and locate it as shown in Figure 1a, then the beam will drift about 70 centimeters to the end of Q_5 after leaving the end of the kicker deflection system. A 3 inch beam pipe will be used through Q_5 and thus the beam must not be allowed to scrape on this aperture. (See Figure 1b). For the simple geometry shown (and neglecting the vertical movement of the beam caused by Q_5 over the length of Q_5) we see that a reasonable guess for Y_{exit} is 2.4 centimeters.

Now

$$Y_{exit} = \alpha \left[\frac{\ell}{2} + b \right]$$

where α = Angle of Deflection
ℓ = Length of Deflection Field
b = Drift Length

then
$$\alpha = \frac{Y_{exit}}{\left[\frac{\ell}{2} + b\right]} = \frac{2.40 \times 10^{-2}}{\frac{2.5}{2} + .7} = 12.3 \text{ mrad}$$

MAGNETIC DEFLECTION

From the equation for the force on a particle in a magnetic field

$$\vec{F} = e\vec{v} \times \vec{B}$$

and the small angle approximation

$$\alpha \simeq \frac{\ell}{\rho}$$

it is easily shown that

$$\alpha = \frac{e}{m_o \gamma \beta C} B\ell$$

For protons at 200 MeV,

$$\frac{e}{m_o \gamma \beta C} = \frac{1}{2.15}$$

and
$$\alpha = \frac{B\ell}{2.15}$$

If we now specify α = 12.3 mrad and ℓ = 2.5 m, then

$$B = \frac{2.15 \times 12.3 \times 10^{-3}}{2.5}$$

$$B = 106 \text{ gauss}$$

Considering a picture-frame magnet of high-mu ferrite, for a single turn:

$$I = \frac{Bg}{\mu_o}$$

where g is the gap. Allowing g = 5.0 cm.

$$I = \frac{(106 \times 10^{-4})(5 \times 10^{-2})}{12.57 \times 10^{-7}} = 422 \text{ amps}$$

also

$$L = \frac{\mu_o N^2 A}{g}$$

and for a 5.0 cm width, with one turn,

$$L = 3.14 \ \mu h$$

A risetime (to within 1% of final value) of .5 microseconds requires a time constant of .1 microseconds in the case of a simple RL circuit. Allowing for some stray inductance

$$R = \frac{L}{t} = \frac{4 \times 10^{-6}}{.1 \times 10^{-6}} = 40 \text{ ohms}$$

The voltage required for, say, 450 amps is 18kV. The peak power is

$$P_{pk} = 450 \times 18 \times 10^{3} = 8.1 \text{ Mw}$$

To deliver this power for some 10 microseconds will require either a PFN or some storage capacity. If a capacitor is used and we allow a 1% droop;

$$C = \frac{i\Delta t}{\Delta V} = \frac{450 \times 10^{-5}}{180} = 2.5 \times 10^{-5} = 25 \ \mu f$$

While this value of capacity is still reasonable, any circuit used as a simple on-off switch will still need a commutation circuit for turn off, with attendent complexities, and increased stray inductance.

If a PFN is used, the delay time must be at least 5 microseconds, leading to a 10 microsecond pulse. If the maximum desired risetime is .5 microseconds, the $t_d/t_r = 10$. The number of sections, n, where

$$n \approx \left[t_d/t_r \right]^{3/2}$$

is equal to 32 for our parameters. A reasonable impedance is 50 ohms, leading to

$$V = (450)\ (50) = 22.5 \text{ Kv}$$

In practice, the risetime is also influenced by the L/R_o time constant of the magnet and termination, and things such as PFN impedance, voltage and current must be traded off for the best compromise. It is possible to change the current since the magnet may be constructed[2] in such a way as to have several sections magnetically in series and electrically in parallel.

ELECTROSTATIC DEFLECTION

If we consider two parallel plates with a dc field between them, then the problem is much the same as that for an electrostatic cathode ray tube.

Let E_y = electric field in the transverse (y) direction

v_y = transverse component of particle velocity

Then

$$\frac{dp_y}{dt} = eE_y$$

$$p_y = \int eE_y dt = eE_y t \quad (P_{yo} = 0)$$

$$p_y = mv_y$$

$$v_y = \frac{e}{m} E_y t$$

Now

$$y = \int v_y dt = \frac{eE_y}{m_o\gamma} \int t\, dt = \frac{eE_y}{m_o\gamma} \frac{t^2}{2}$$

$$y = \frac{e}{m_o} \frac{E_y}{2\gamma} \frac{\ell^2}{\beta^2 c^2}$$

and $\alpha = \frac{2y}{\ell}$ for small angles.

Then $\alpha = \frac{e}{\gamma m_o \beta^2 c^2} E_y \ell$

For 200 MeV protons, $\frac{e}{\gamma m_o \beta^2 c^2} = \frac{1.6 \times 10^{-19}}{1.21 \times .91 \times 10^{-30} \times (.566)^2 (3 \times 10^8)^2 \times 1.84 \times 10^3}$

$$= .274 \times 10^{-8}$$

$$\alpha = .274 \times 10^{-8}\, E_y \ell$$

In our case,

$$E_y = \frac{12.3 \times 10^{-3}}{.274 \times 10^{-8} \times 2.5} = 1.8 \text{ Mv/m}$$

$$= 18 \text{ Kv/cm}$$

For a 5.0 cm gap,

$$V = E_y g = (18)(5.0) = 90 \text{ Kv}$$

This appears to be a reasonable number. The circuits to be used allow for some variations: One would have two plates charged to $\pm$ 45 kV, which deflect that portion of the beam which is to be dumped. When the beam hash has passed, a sparkgap or thyratron fires and discharges the electric field allowing the rest of the 200 microsecond beam to pass through the transport channel. It is also possible, of course, to ground one plate and charge the other to 90 kV. If we consider the symmetrical or push-pull driven system and allow the horizontal width of the plates to be 30 centimeters then the capacity to ground of each plate turns out to be approximately 120 pf. Figure 2 shows a possible overall schematic of the electrostatic system using spark-gaps as discharge devices. A 52 ohm resistor is used in series with the gap to limit the current due to discharging the RG/19 cable. It will limit the current to about 1000 amperes peak, and also provides a termination of sorts for the cable. If the power supply is installed in the end of the linac building as planned at present, there will be approximately 130 foot of cable between the power supply and the plates. The spark gaps will be located as near the plates as possible to give the minimum risetime and maximum ringing frequency. The capacity of the cable is about 4,000 picofarads. A series resistor of 12.5 megohms will be added, making the time constant of voltage rise at the plates 50 milliseconds. This allows ten time constants between pulses at a maximum of 2 pps through the transport channel. If the gap is fired at the beginning of the 200 microsecond beam it will recharge to

$$\frac{.200}{50} \times 100\% = 0.4\%$$

at the end of 200 microseconds. This slightly increasing field will have the effect of smearing the vertical phase space picture by

$$12.3 \times 10^{-3} \times .004 = 49.2 \text{ microradians}$$

This appears to be a reasonable amount when compared with the 4 milliradians of total vertical angularity estimated by Bill Moore.

SYSTEM CONSIDERATIONS

From the above considerations it would seem that an electrostatic system is to be preferred from a standpoint of cost and simplicity. It does not require any pulse forming networks or a large energy storage components. In addition, the average power of the electrostatic system is lower than that of a magnetic system. For the electrostatic case the energy lost per cycle is simply the energy stored in the cable capacity, that is

$$\frac{1}{2} CV^2 = \frac{8 \times 10^{-9} \times (4.5 \times 10^4)^2}{2} = 8.1 \text{ joules} \qquad \text{(2 cables)}$$

In the magnetic case we must consider the power lost in the 50 ohm pulse forming network termination. Now

$$dE = pdt \cong I^2 R\Delta t = (422)^2 \times 50 \times 10^{-5}$$

$$= 89 \text{ joules}$$

If capacitor storage is used, the energy is 81 joules.

Although a spark gap has been shown here, no attempt is made to preclude use of a thyratron. One reason thyratrons have been used in devices of this sort is their ability to operate over wide ranges of anode voltage. The sealed, gas-filled or vacuum spark gap considered here is operable only over a range of about 35% to 80% of its maximum rated static breakdown. In this application, however, this is of little importance and an adjustable range of $\pm$ 10% should be adequate. From an engineering and reliability standpoint it would also seem desirable to eliminate components associated with the thyratron such as filament transformers and reservior supplies. If one uses the push-pull scheme shown in Figure 2, one thyratron would have to have its cathode at high voltage potential and its anode at ground. This necessitates floating the filament system. In the case of a spark gap there is a definite preferred cathode-anode configuration and thus the trigger transformer secondary for one plate must be floated. The cost difference between a thyratron and spark gap is about 4 to 1 with

a typical 60 kilovolt spark gap costing about $400.00. A final question to be considered is the useful life of a spark gap in this type of service. Although primarily designed for crowbar[3] service where heavy currents are handled on an intermittent basis, people at BNL have had good success using a sealed spark gap in a repetitive type situation, provided that current limiting is used.[4] In the event that a decision is made to construct this device, it would still seem prudent to run some accelerated life tests at design voltage and current.

REFERENCE:

1. W.H. Moore, "Extraction and Disposal of a Short Pulse from the Primary 200 MeV Proton Beam," AGSCD Technical Note No. 106, April 18, 1969.
2. E.B. Forsyth, "The Fast Kicker of the AGS External Beam System," Accelerator Department (AGS) Internal Report EBF-3, October 27, 1964.
3. A. Michaelson and H.N. Price, "Triggered Vacuum Gaps as Energy Diverters in Electronic Equipment," Proc. of the 10th Modulator Symposium, May 21, 1968.
4. J.G. Cottingham, private communication.

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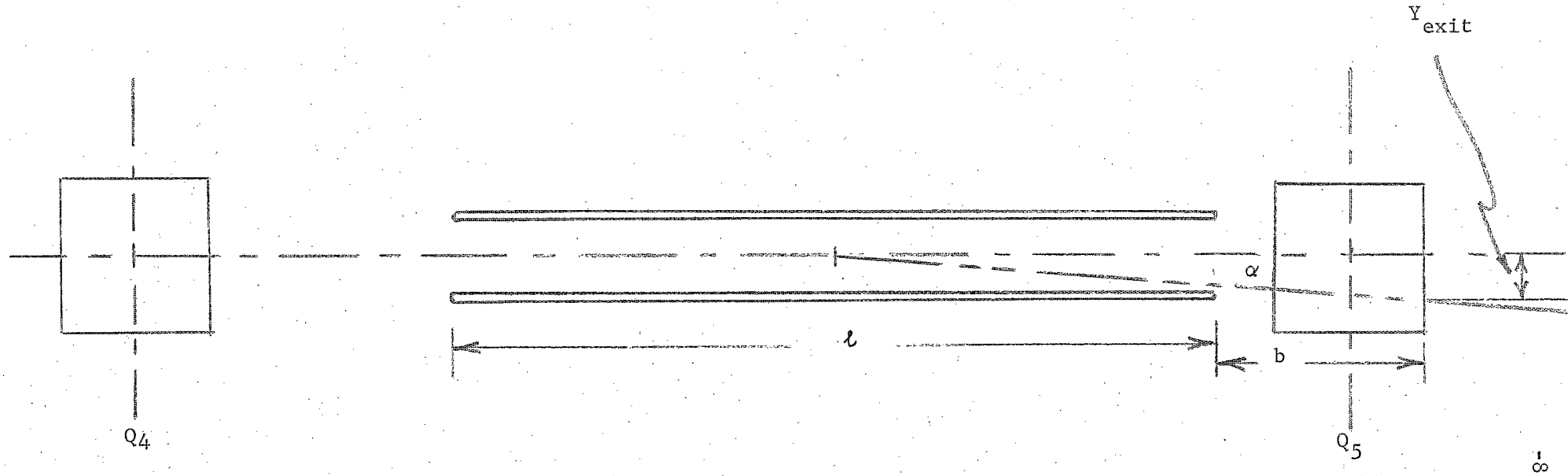

FIGURE 1a

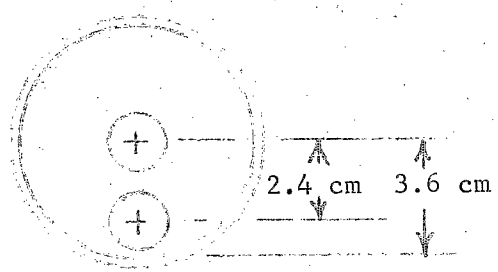

FIGURE 1b

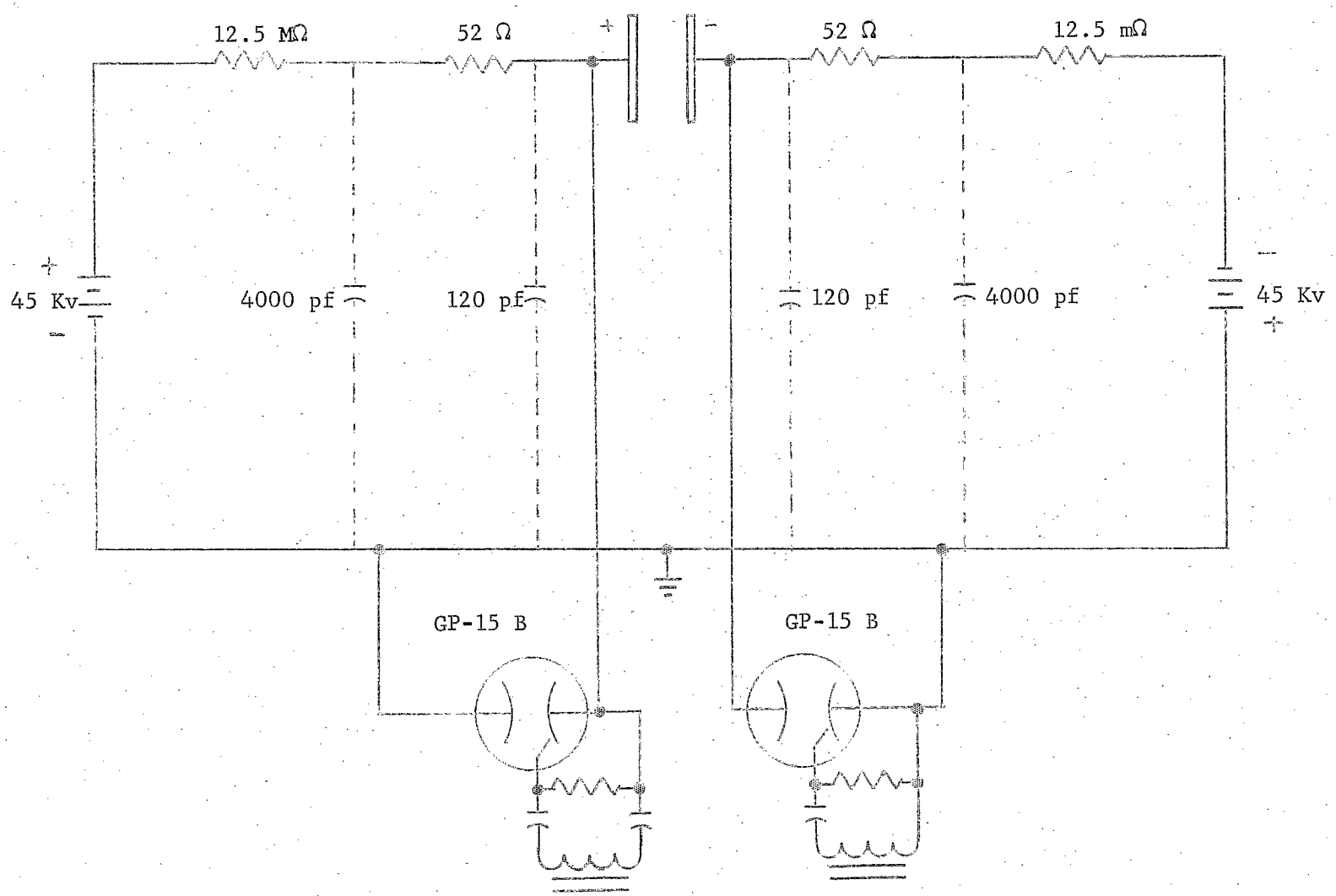

FIGURE 2 - SIMPLIFIED SCHEMATIC FOR ELECTROSTATIC FRONT BITER