

REMOVAL OF THE RF MICROSTRUCTURE FROM A PROTON LINEAR ACCELERATOR BEAM *

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Summary

The rf microstructure in the primary proton beam of a proton linear accelerator may consist typically of 0.2 ns pulses spaced by 5 ns. This pulsed time structure can be removed to obtain a higher effective duty factor for the proton beam by utilizing the transverse phase space occupied by the beam. An anisochronous beam transport system can produce debunching. One such system consists of a sector magnet with a strong field gradient which bends the beam through 45° and fans it out. A second magnet, of uniform field, bends it through 90° , and a third magnet, identical with the first, recombines the beam and renders it again parallel. The rf microstructure has now been removed, since protons from one side of the beam have travelled farther than the protons from the other side of the beam. Removal of the rf microstructure in the secondary meson beams could be accomplished with a magnet system similar to but smaller than that for the proton beam. For a sector-focussed cyclotron the above scheme for removing the rf microstructure would require an excessively large magnet system.

1. Introduction: Duty Factor

The fraction of the time that particles are emitted from an accelerator is called the duty factor and it is most important in determining the usefulness of an accelerator for doing experiments. The macroscopic duty factor is determined by the pulsed nature of an accelerator. In addition, the radiofrequency acceleration used in high energy proton accelerators entails in general that particles can be emitted from the machine during only a fraction of the rf cycle and this fraction is called the microscopic duty factor.

A typical time structure of the output beam from a proton linear accelerator designed as a meson factory¹ is shown in Figure 1. Since the beam consists of 0.2 ns pulses separated by 5 ns time intervals, which is the rf period, the microscopic duty factor is 0.04. The macroscopic duty factor is 0.06. For a sector focussed cyclotron the microscopic duty factor² is typically between 0.01 and 0.06 and the rf period between pulses is about 100 ns.

The relatively low rf frequency used for a cyclotron implies the need of a magnetic storage ring to remove completely the rf structure; however, no practical design of a proton storage ring which will provide a very high efficiency for extraction of the proton beam has been devised as yet. Other techniques to increase the duty factor by smaller amounts have been suggested.³ The small microscopic duty factor for a cyclotron together with the 100 ns pulse spacing will be very disadvantageous for coincidence experiments with short resolution times. Increase in the macroscopic duty factor for a linear accelerator also would require a proton storage ring.

Several methods exist to remove the rf microstructure in the proton beam from a linear accelerator which occurs at a much higher frequency of 200 Mc/sec. Only for some types of experiments need this structure be removed. For experiments involving time of flight measurements, the sharp time definition of individual pulses is necessary, and for experiments which do not have resolution times of less than 5 ns, the microscopic time structure is unimportant. However, for some coincidence experiments with short resolution times the microscopic time structure of the primary proton beam may be disadvantageous.⁴

2. Techniques for Removing the rf Microstructure of Beams from a Proton Linear Accelerator.

The rf structure may be removed either inside or outside the linear accelerator.

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Inside the machine, a proposal of Teng's⁵ suggested running the later sections of the linac at the phase unstable fixed point in the phase-energy diagram. By dephasing the beam in this way, he shows that it is possible to spread the beam over a phase of 2π , but in doing so the energy spread of the beam becomes very large, and it is uncertain what defocusing properties within the structure might arise. Furthermore, one is using a considerable portion of the accelerator merely to dephase the beam, and not to accelerate it. For phase angles considerably smaller than 2π , the properties look more reasonable, but the argument against using a portion of the linac to dephase and not to accelerate remains.

The simplest method of debunching outside the machine allows the proton beam to drift over a sufficiently long path so that the inherent velocity spread of the particles will smooth out the rf microstructure. However, for a typical high energy linac the energy spread of the beam is likely to be only 0.1% of the beam energy, and this implies that the protons are spread over 5 ns in a drift length of 1500 meters, which is inconveniently long.

Debunching using an anisochronous transport system seems more feasible.⁶ In such a system, some protons in each group are constrained to travel longer or shorter paths than the median. For example a path difference of 124.5 cm corresponds to a 5 ns spread in time for 750 MeV protons. The protons may be separated using either the momentum spread in the beam, which is approximately 0.05% for a high energy machine, or the natural beam width of about 2 cm.

The method using momentum has been investigated by Teng⁵ and by Parain.⁷ However, large distances and magnets are involved to obtain a spread of 125 cm (of the order of 100 m long or more). This would render such a device uneconomic to build for a high energy machine, unless the momentum spread was much larger than that designed.

The transverse phase space occupied by the beam may be employed for debunching. A system employing this technique was devised using a series of quadrupoles. (See Figure 2) The center ray through the system travels a shorter distance than the extremum rays. The quadrupoles involved are of extremely large aperture (66.5 inches) which would be expensive to build.

What appears to be a more compact and economical system is shown in Figures 3

and 4. A sector magnet with a strong field gradient bends the beam through 45° and fans it out. A second magnet, of uniform field, bends it through 90° , and a third magnet, identical with the first, recombines the beam and renders it parallel, but the fine structure has now been removed, since the protons from one side of the beam have travelled farther than the protons from the other side of the beam. This system has the following advantages:

- 1) It is more compact than the quadrupole or momentum dependent systems. (Approximately 17 meters by 6 meters for the beam parameters discussed previously).
- 2) The field gradient magnets have narrow pole tips. Only the zero gradient magnet has very wide pole tips, and for this magnet the gap may be almost as narrow as the beam.
- 3) Only three magnets are required.
- 4) Each magnet employs normal entry and exit in the first approximation.

Tight restrictions on the transfer matrices are required, to keep the beam compact in a direction normal to the magnet pole faces. Since the end magnets are strongly defocusing in the plane of the magnets (Figure 3) they must be strongly focussing in the perpendicular direction. To keep the beam compact, it must emerge from the magnet in a plane parallel to the pole faces.

The following expressions can be derived for the motion of the particles in the first magnet

$$\begin{bmatrix} y \\ y' \end{bmatrix} = \begin{bmatrix} \cos \alpha_y' & \rho_y' \sin \alpha_y' \\ -\frac{1}{\rho_y'} \sin \alpha_y' & \cos \alpha_y' \end{bmatrix} \begin{bmatrix} y_0 \\ y_0' \end{bmatrix}$$

where

$$\begin{aligned} \alpha_y' &= n^{1/2} \alpha \\ -n &= \frac{\rho}{B} \frac{\partial B}{\partial \rho} \\ \rho_y' &= \frac{\rho}{n^{1/2}} \end{aligned}$$

and

$$\alpha = \text{angle of magnet} = \frac{\pi}{4}$$

$$\rho = \text{radius of magnet} = 450 \text{ cm}$$

$$B = \text{magnet field} = 10 \text{ kgauss}$$

For the beam to emerge parallel after passing through the magnet

$$y' = 0 \text{ for } y_0' = 0$$

$$\sin \alpha_y' = 0, \alpha_y' = 0, \pi \text{ etc.}$$

$$n^{1/2} \alpha = 0, \pi, \text{ etc.}$$

Since $\alpha = \frac{\pi}{4}$, $n^{1/2} = 0, 4, 8$ etc. Thus n is restricted to be 0, 16, 64 etc. and $n = 16$ is the only suitable value.

The x matrix for the first magnet is

$$\begin{bmatrix} x \\ x' \end{bmatrix} = \begin{bmatrix} \cosh \alpha' & \rho' \sinh \alpha' \\ \frac{1}{\rho'} \sinh \alpha' & \cosh \alpha' \end{bmatrix} \begin{bmatrix} x_0 \\ x_0' \end{bmatrix}$$

where

$$\alpha' = (n-1)^{1/2} \alpha = 3.87 \frac{\pi}{4} = 3.04$$

$$\rho' = \frac{\rho}{(n-1)^{1/2}} = 116 \text{ cm}$$

$$\begin{bmatrix} x \\ x' \end{bmatrix} = \begin{bmatrix} 10.4956, 116 \times 10.4479 \\ \frac{1}{116} \times 10.4479, 10.4956 \end{bmatrix} \begin{bmatrix} x_0 \\ x_0' \end{bmatrix}$$

For the drift space of length L between the first and second magnets,

$$\begin{bmatrix} x \\ x' \end{bmatrix} = \begin{bmatrix} 1 & L \\ 0 & 1 \end{bmatrix} \begin{bmatrix} x_0 \\ x_0' \end{bmatrix}$$

For half the second magnet (which brings the particle to the center of symmetry of the system)

$$\begin{bmatrix} x \\ x' \end{bmatrix} = \begin{bmatrix} \cos \alpha, & \rho \sin \alpha \\ \frac{-1}{\rho} \sin \alpha, & \cos \alpha \end{bmatrix} \begin{bmatrix} x_0 \\ x_0' \end{bmatrix}$$

$$= 0.707 \begin{bmatrix} 1 & 450 \\ -\frac{1}{450} & 1 \end{bmatrix} \begin{bmatrix} x_0 \\ x_0' \end{bmatrix}$$

We adjust L, so that the value of x' at the center of the system is 0, when $x_0' = 0$. This gives L approximately 333 cm.

The transfer matrix to the center of the system then becomes

$$\begin{bmatrix} x \\ x' \end{bmatrix} = \begin{bmatrix} 57.2 & 6672 \\ 0 & \frac{1}{57.2} \end{bmatrix} \begin{bmatrix} x_0 \\ x_0' \end{bmatrix}$$

The beam diverges from 2 cm at the input to 114 cm at the center of the second magnet.

If the transfer matrix for half the system is

$$\begin{bmatrix} a & b \\ c & d \end{bmatrix}$$

that for the whole system becomes

$$\begin{bmatrix} ad + bc & 2bd \\ 2ac & ad - bc \end{bmatrix}$$

leading to a transfer matrix of

$$\begin{bmatrix} x \\ x' \end{bmatrix} = \begin{bmatrix} 1 & 233 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} x_0 \\ x_0' \end{bmatrix}$$

The total path difference through the system for the edges of the beam is 140.2 cm.

The transfer matrix in the y direction is

$$\begin{bmatrix} y \\ y' \end{bmatrix} = \begin{bmatrix} 1 & 1373 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} y_0 \\ y_0' \end{bmatrix}$$

The inherent spread in angle of the incident beam which amounts to 1 milliradian will spread the beam through 0.233 cm in the x direction and 1.4 cm in the y direction as it emerges from the system.

The microstructure of the proton beam is not completely removed. As can be seen by examining Figure 5, the time structure will now be the same as the beam profile, since the first particles to arrive for one pulse come from one edge of the beam, and the last to arrive come from the opposite edge.

It should be noticed that this device resembles in some respects a Mobley³ magnet, and could also be used, if preceded

by an electrostatic deflector, for the opposite purpose of providing very short pulses from the beam.

For the secondary meson beams such an anisochronous beam transport system can also be used to remove the time microstructure. However, the use of a quadrupole muon channel spreads the muon time distribution, and the stopping times of low energy mesons, particularly in low density targets, also wipes out the rf microstructure. Furthermore, as for the primary proton beam, often it will not be desirable or necessary to remove the microstructure from the secondary beams.

References

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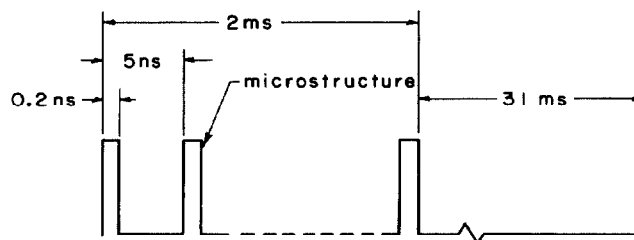


Fig. 1. Time structure of the proton beam from the linear accelerator.

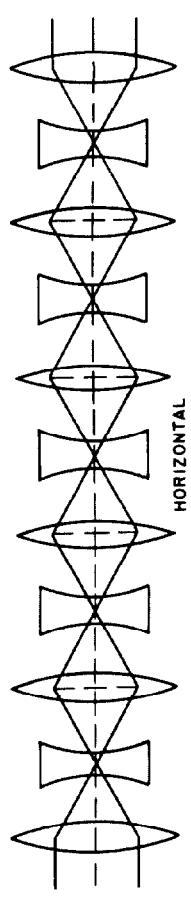
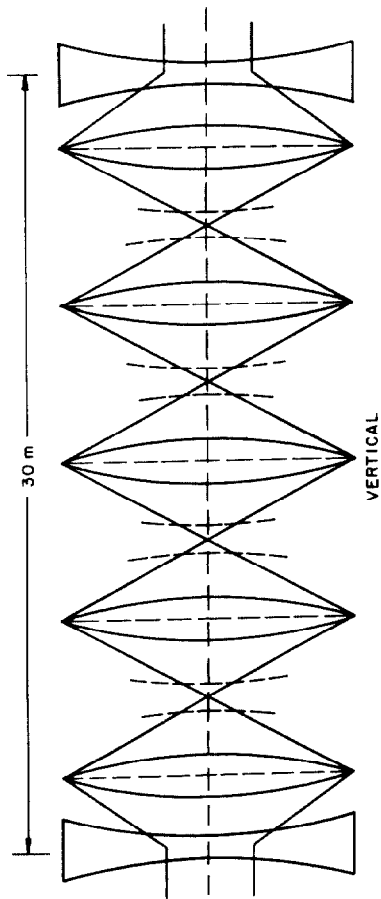


Fig. 2. Quadrupole debunching system.

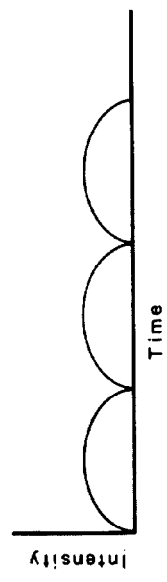


Fig. 5. Time structure of the beam after passing through the anisochronous magnet system.

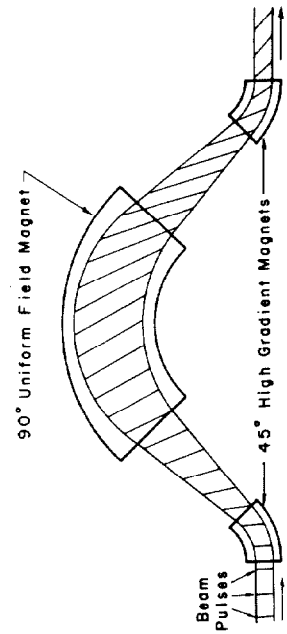


Fig. 3. Operation of the anisochronous magnet system.

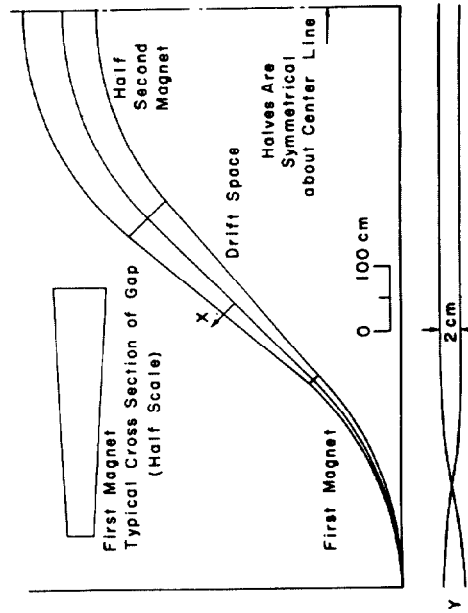


Fig. 4. Scale drawing of the anisochronous magnet system.