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PARTICLE ACCELERATION BY FLUX PUMPING

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Flux pumping is a technique used to excite a superconducting magnet by switching the superconducting conductor in a manner such that a transformer core can be included in the magnet exciting circuit while magnetic flux is increasing in the core, but switched out of the circuit while the flux is decreasing. The advantage of flux pumping is that a relatively small transformer and power supply can be used to induce, and then control, a large current in the magnet.

This is reminiscent of Kerst's betatron where the electrons are accelerated by magnetic induction due to a flux bar which is included within the orbit. Each turn of the electron in its orbit is equivalent to a turn of wire around the flux bar, and, because so many revolutions are made by the electrons, a high energy can be reached. The limitation to the energy that can be reached by the electrons is due to the saturation of the flux bar. Also, for large heavy-ion accelerators the flux bar would become excessively large because of the betatron condition for stable acceleration in a circular orbit, which is that the average value of $\dot{B}$ within the area included by the orbit should be twice the value of $\dot{B}$ at the orbit--this implies that the flux bar be roughly as large as the orbit. In practice, betatron acceleration has been effective only for electrons up to about 100 MeV, although 300 MeV was reached by Kerst.

What is suggested here, analogous to flux pumping, is that the orbit be "switched" such that a flux bar can be included within the orbit or switched out of the orbit. In that case, a much smaller flux bar could be used. Presumably the flux bar would, in cross section, be long and narrow and located in one of the straight sections of the magnet. If the flux bar is excited by an alternating current, the period of which is shorter than the period of excitation of the magnet, then while the flux is increasing the orbit of the ion must be guided to enclose the flux bar, but while the flux is decreasing the orbit must be guided to the other side of the flux bar so that it is not enclosed. By switching the orbit back and forth to correspond to the frequency of excitation of the flux bar, it is clear that the energy of the ion can be pumped up. Furthermore, by using the same flux bar to excite the magnet by flux pumping, then the acceleration should exactly follow the excitation of the magnet, and the orbit should remain fixed at a constant radius.* If the flux bar is excited at 60 Hz, and if the rise time of the magnetic field is 10 seconds, then the flux bar would be 600 times smaller than if one betatron flux bar were to be used.

All well and good, but can the beam be switched from one side of the flux bar to the other 600 times without significant loss? There are two possibilities. One is to have a gap in the flux bar and a vacuum box such that the beam can be switched from the guiding magnets on one side of the

*Of course the betatron condition should be corrected for the straight sections of total length L, i.e., $\dot{\phi} \simeq 2\dot{B}\,(\pi R^2 + LR)\,\dot{B}$.

flux bar right through the flux bar to the oppositely deflecting guiding magnets on the other side at a relatively slow rate, i. e., corresponding to many turns of the particle around its orbit. In that case the orbit would always be in a good vacuum. Unfortunately, the field in the flux-bar gap would be at a maximum negative value at one time of switching, and then be at its maximum positive value at the next switching time, and presumably at about 10 kG at each switching time. Thus the beam would probably be broadened each time it was switched so that its optical quality must be seriously degraded--perhaps to the point of significant loss of beam.

Another possibility is to have the vacuum donut split so that it goes around one side or the other of the flux bar. In that case, the beam would have to be switched very precisely from one tube to the other in a small fraction of the orbiting time, all of the fraction of the beam occurring during the switching time would be lost by colliding with the flux bar. This method clearly would work best for machines with rather large orbits--say, of the order of several meters in radius. Presumably a gap would be left in the beam during the switching, which would be synchronized by detecting the rotation of the gap around the orbit.

If the switching can be solved, and admittedly that would be a serious problem for a small machine, there is the advantage of simplicity in not having a complicated and expensive rf system for the acceleration. Another advantage would be in increased intensity because the beam need not be bunched and hence the space-charge limit would be increased. It would also be as easy to accelerate deuterons, or α particles, or carbon nuclei, as it would be to accelerate protons, for no changes need be made. Indeed the heavier particles would have a longer orbiting period, hence the switching would be simpler.

This revival of betatron acceleration may make the principle applicable to heavy particles and for energies up to several GeV. As an example, consider a one-GeV proton synchrotron in the form of a race track, as shown in Fig. 1; the radius of curvature of the orbit is 5.6 meters, the length of each straight section is 2 meters. One straight could be used for injection and extraction, the other for acceleration by flux pumping. Let us also assume that the ramping time to a maximum field of 10 kG is 10 seconds, in which case the energy gained per turn would be about 700 eV. If the flux bar were excited at 60 Hz, and if the value of B in the iron of the flux bar were not to exceed 10 kG, then the area would be about 0.15 m^2. Thus the flux bar might be 10-cm wide and about 150-cm long, which would just about fit in the straight section. The orbiting time of a one-GeV proton would be about 0.15 μsec, so the switching time should be of the order of 10^{-8} sec. Also illustrated in the figure is a more complicated orbit which makes possible the use of the return flux as well.

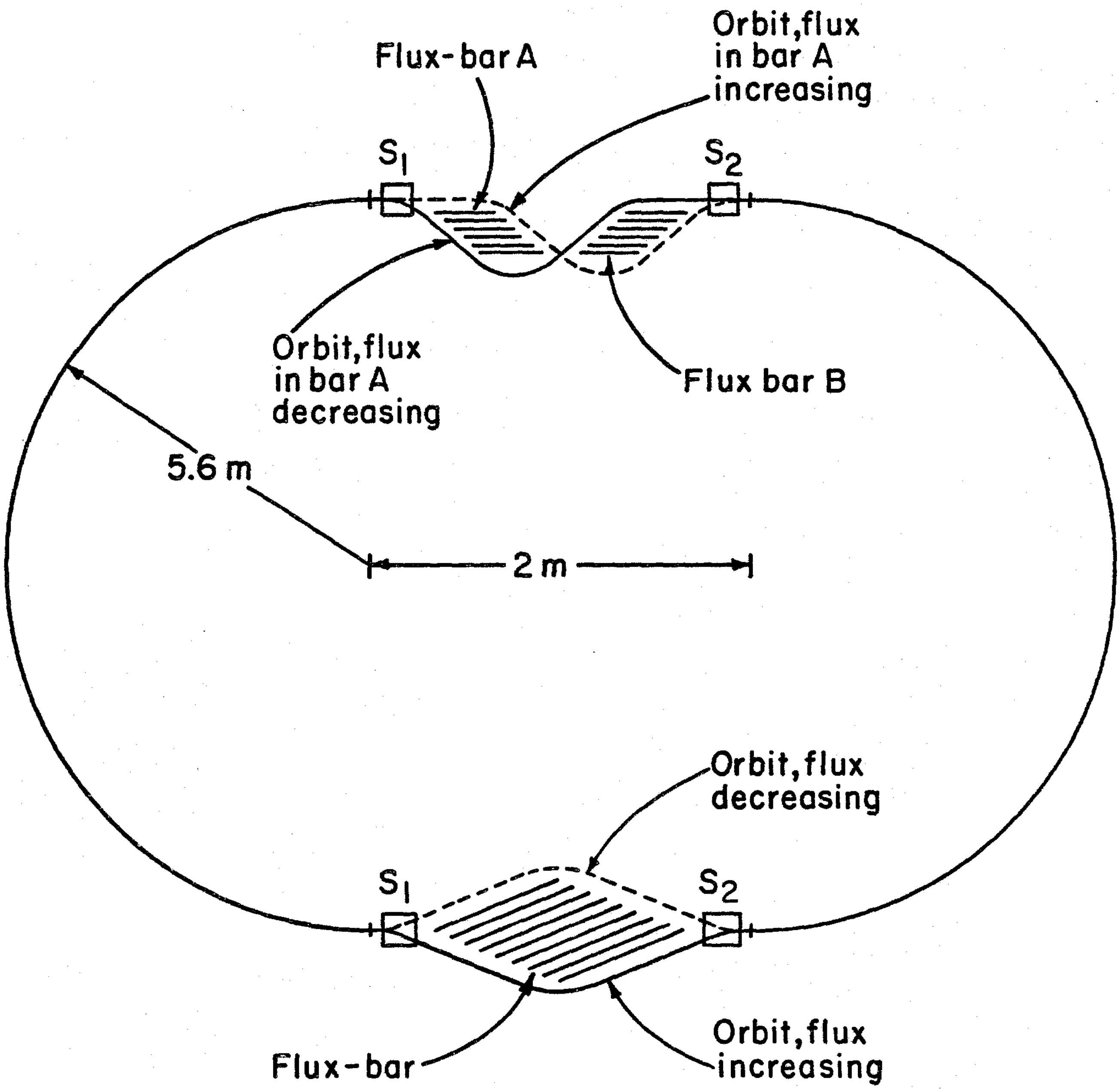
Flux-bar A
Orbit, flux
in bar A
increasing
S1
S2
Orbit, flux
in bar A
decreasing
Flux bar B
5.6 m
2 m
Orbit, flux
decreasing
S1
S2
Flux-bar
Orbit, flux
increasing

Fig. 1