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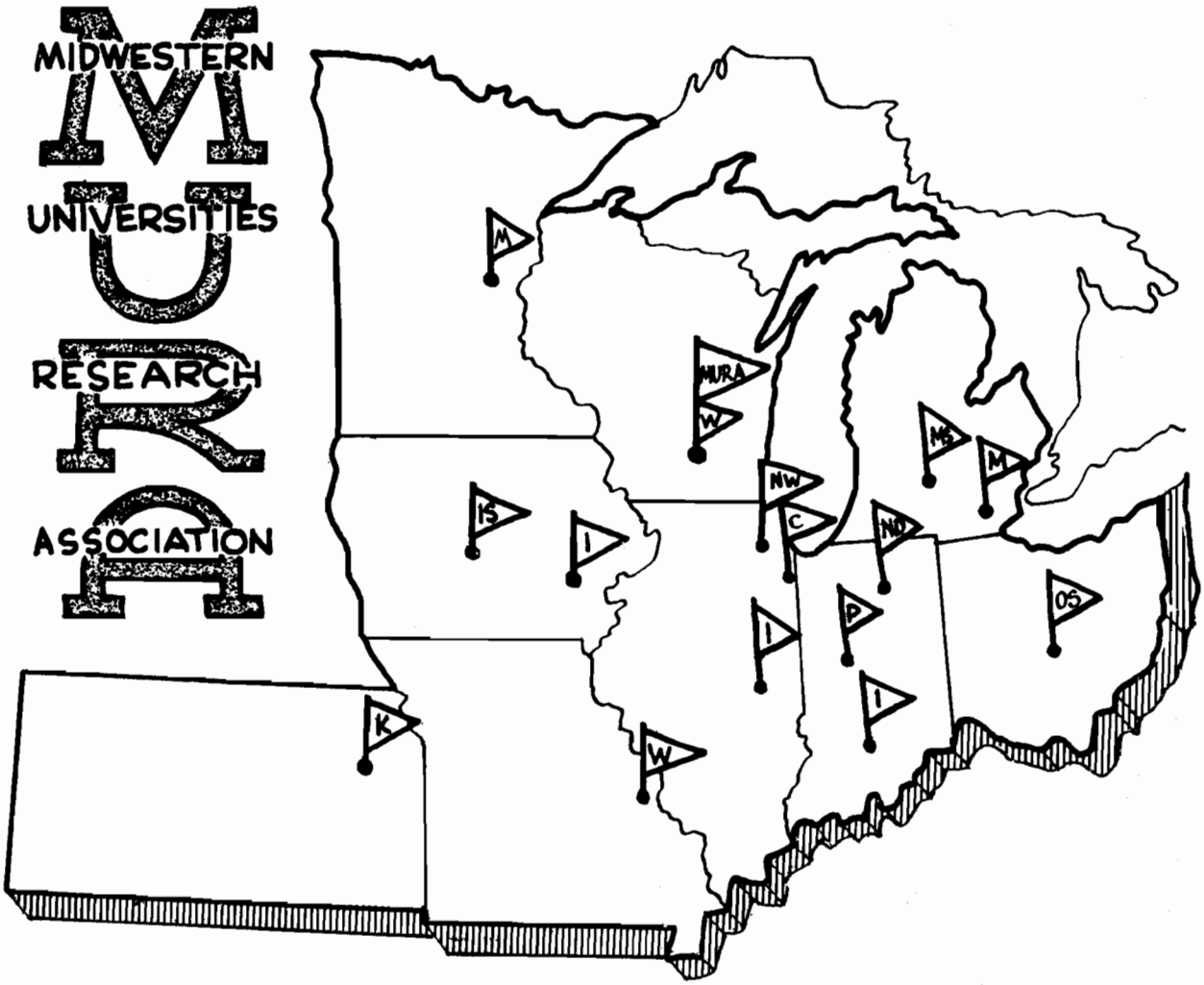

AN FFAG ACCELERATOR FOR ACHIEVING 9 BEV CENTER-OF-MASS COLLISIONS BETWEEN ELECTRONS AND PROTONS

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ABSTRACT

The possibility of an electron-proton colliding-beam spiral sector FFAG accelerator is explored. A single 10,000 ton magnet structure with rf systems for both protons and electrons could be used for accelerating and stacking 5 Bev electrons and 4 Bev protons circulating in opposite directions. The expected electron-proton interaction rate is 10^6 less per centimeter than could be achieved with a 45 Bev electron linear accelerator and a liquid hydrogen target. The limit on electron current is set by the practical power which must be supplied to make up radiation losses, and on proton current density by space charge forces.

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Since the alternating gradient focusing principle was first discussed in 1952,[1] a great variety of accelerators have been proposed or discussed for the multi-Bev energy range. For protons there is the alternating gradient synchrotron, the constant-gradient synchrotron,[2] the proton linear accelerator,[3] the proton microtron,[4] the proton synchrocyclotron[5] (as discussed at Los Alamos and at Harwell), FFAG synchrotrons[6] (radial and spiral sector), colliding-beam FFAG synchrotrons[7] (tangent spiral sector[8] or single Ohkawa radial sector[9, 10, 11]), and storage rings of various descriptions using fixed field[12] or pulsed[13] machines as injectors, and Budker machines.[14] For electrons, alternating gradient synchrotrons[15] (the Cambridge accelerator) and linear accelerators[16] (the Stanford proposal) can be built and constant frequency electron cyclotrons to extreme relativistic energies (vertical sector, reversed field FFAG) have been proposed.[17]

The colliding-beam concept applied to electron-electron scattering at energies of 50 to 500 Mev in discussions by groups at MURA,[18] Princeton[19] and Stanford, and in the U.S.S.R.[20] If only by way of completeness, it seems appropriate to indicate what an electron-proton colliding-beams accelerator would be like. A single FFAG spiral sector accelerator with an electron beam circulating in one direction and a proton beam in the other direction would achieve beam-beam collisions with none of the complexities of two-way machines or of beam transfer. In fact in this respect such a synchroclash system is the essence of simplicity in that contra-circulating beams are achieved simply by virtue of the opposite electrical charge on the particles. It may be noted that, in the limit of no betatron oscillation, in each collision the center of mass is automatically at rest.

As an example of such a machine, a set of parameters has been drawn up for a separated spiral sector FFAG synchrotron to accelerate protons to 6.5 Bev at 15 kilogauss, or electrons to 5 Bev and protons to 4 Bev at 10 kilogauss. The parameters follow in Table I.

TABLE I

R	35 meters	maximum orbit radius
k	50	
N	25	number of spiral sectors
ϕ	9.1°	spiral angle (angle between normal to magnet edge and radius vector)
ν_x	~ 7	(smooth approximation)
ν_z	~ 4	
W	10,000 tons	magnet iron weight
ΔR	2.2 meters	radial aperture
E_{ip}	50 Mev	injection kinetic energy for protons
E_{ie}	150 Mev	injection kinetic energy for electrons
E_{fp}	4 Bev	final kinetic energy for protons (10,000 gauss)
	6.5 Bev	final kinetic energy for protons (15,000 gauss)
E_{fe}	5 Bev	final kinetic energy for electrons (10,000 gauss)
C	2.2	circumference factor
E_{tp}	6 Bev	transition energy for protons
E_{te}	3 Mev	transition energy for electrons

The maximum current density, J, available using beam stacking with protons is found from the expression I. 7.6 of Reference 9.

$$J = I_o \frac{\nu \Delta\nu a_z k \gamma^2}{R^3 P}$$

where $I_o = 3 \times 10^7$

$a_z = 2$ cm

$P = 10^{-3}$ (injection energy resolution)

$\Delta\nu = 1/4$ (allowable error in ν)

$\gamma = 5$ For these values J is 175 amperes per square centimeter. While this might be increased by non-scaling tricks at high energy, it would certainly be decreased by a factor of from 2 to 10 by azimuthal bunching at injection and phase space density losses during acceleration. The space charge limit for an unneutralized 4 Bev proton beam (formula I. 7. 1 of Reference 9) is 700 amperes total, or less than 50 amperes per square centimeter in the above.

The phase space density for electrons will be strongly modified by the radiation processes. If we assume phase space is strongly damped, the interaction rate per unit length depends only on the proton density and the total electron current. Thus the interaction density, $\mathcal{N}$, is given by

$$\mathcal{N} = 2c\rho_p n_e \sigma$$

where ρ_p is the proton density, and n_e the number of electrons per unit length. For J = 40 amperes per square centimeter of protons and an electron current of 100 amperes, $\mathcal{N} \cong 10^{31}\sigma$ per centimeter. For the electron linear accelerator of the Stanford Proposal with an average current of 10 microamperes and a liquid hydrogen target, $\mathcal{N} \cong 10^{35}\sigma$ per centimeter.

The overriding limitation of the accelerator described above is the radiation loss of the electrons. While the voltage gain per turn could be met (3.2 million volts per turn), to supply this to a 100 ampere circulating electron beam would require 320 megawatts (continuous) of rf power. This would be less serious if the accelerator were of much larger radius, however such a radius increase would correspondingly reduce the maximum proton current density. Assuming a more reasonable current of electrons, for example one ampere, the rf system required seems not unreasonable. Since at 4 Bev the proton frequency (β = .96) is very different from the injection electron frequency, two completely separate rf systems would be used. Assuming the problem of radial straight sections in spiral sector accelerators can be solved (as seems reasonable), the proton rf system could be analogous to that in Reference 8. The electron rf voltage would be modulated by about 6% from injection. Radiation losses could be supplied by phase displacement or by a holding cavity; in either case without affecting protons on the same orbit.

Injection of protons would be accomplished by a 50 Mev proton linear accelerator with an instantaneous current of 5 milliamperes and using a programmed bump for multiturn injection (Reference 9). Injection of electrons onto the same orbit in the opposite direction would require a 150 Mev electron linear accelerator. With an instantaneous current of 40 milliamperes and one turn injection, 100 amperes of stacked electron beam could be built up with 2,500 stacks (comparable to the number of stacks required for protons).

The physical problems that could be attacked with such an accelerator would be entirely comparable to those anticipated by the Stanford group: electron-proton

scattering and production of particles by electromagnetic fields on protons. Except for reactions on heavy nuclei (which would behave principally like a collection of individual nucleons at these energies) and on neutrons (in deuterium), this accelerator would have access to the same range of physics as the large linear accelerator. The loss of interaction density by a factor of as much as 10^6 (for reasonable electron currents) as compared to the Stanford Proposal might be partly compensated for by the somewhat greater energy, 100 % duty factor, and multiplicity of simultaneously available experimental areas (essentially the entire circumference). However, the interacting region is less readily accessible than the external beam targets of a linac, and there might be severe problems in collimating a target zone from the remainder of the line "target" extending around the machine.

In conclusion, it should be emphasized that no attempt is being made to suggest that such a machine be built or that all of the problems arising in such a machine have been anticipated. The purpose here is to point out the possibility of such a machine and the major features, virtues, and disadvantages that might be expected in such a design.

It is appropriate to note here the obvious storage ring extension of the proton-electron scattering situation. A machine such as the Cambridge alternating gradient synchrotron might operate (with an unbiased magnet supply) to accelerate protons and electrons in opposite pulses and inject them into a single simple storage ring in opposite directions.

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