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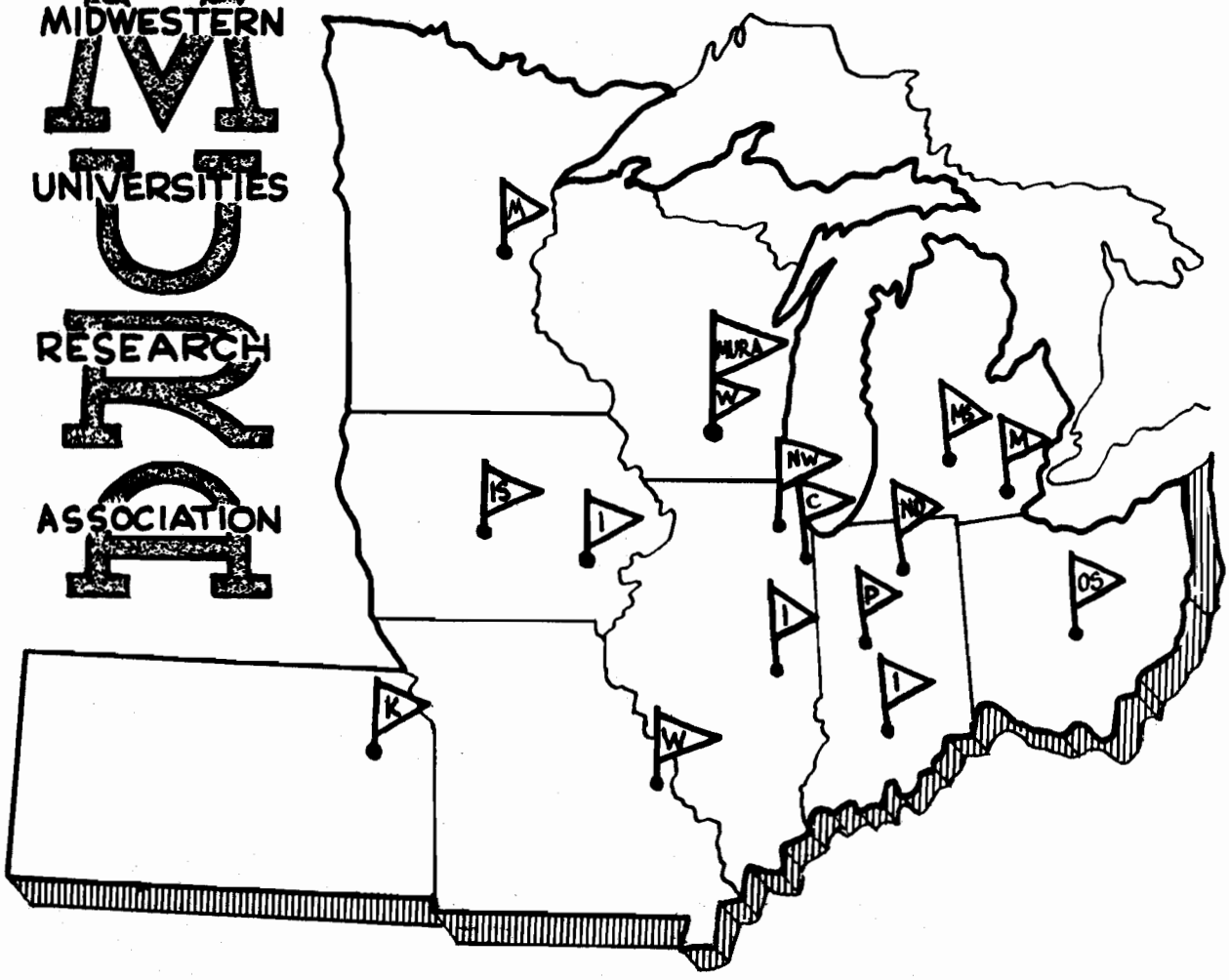

POSSIBLE HIGH CURRENT 10 BEV PROTON ACCELERATORS

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POSSIBLE HIGH CURRENT 10 BEV PROTON ACCELERATORS

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ABSTRACT

The accelerated currents achievable by FFAG accelerators, proton linear accelerators and high repetition rate A. G. synchrotrons are calculated. It is shown that time-average currents of order 10 microamperes may be expected from FFAG accelerators. An A. G. synchrotron which could realize this same current is shown to be a rather extreme design, with a repetition rate of 10 cycles per second and approximately 9 megajoules stored energy. The linear accelerator appears to be capable of yielding time-average currents of approximately 1.5 microamperes. For both the A. G. synchrotron and the FFAG accelerator, injection energies higher than 50 Mev appear to offer certain advantages.

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I. INTRODUCTION

Recent discussions have re-emphasized the high current, single beam aspects of FFAG accelerators. It is of interest to explore the high-current potentialities of other types of accelerators for comparison.

The most promising high-current accelerators for 10 Bev would seem to be

1. Radial Sector FFAG Synchrotrons
2. Spiral Sector FFAG Synchrotrons
3. Proton Linear Accelerators
4. High Repetition Rate A. G. Synchrotrons

II. FFAG SYNCHROTRONS

Alternatives 1 and 2 are familiar to MURA in their potentialities and problems. From MURA-430 and the MURA 1958 Proposal, the injection space-charge limited current is

$$I = I_o \, (\nu \Delta \nu) \left(\frac{a}{R}\right)^2 (\beta \gamma)^3$$

and the corresponding injected charge is

$$q = \frac{I}{f} = \frac{I}{\beta c} \, 2 \pi R ,$$

$$q = \frac{2\pi}{10} \left(\frac{a^2}{R}\right) \beta^2 \gamma^3 (\nu \Delta \nu) .$$

Here $I_o = 3 \times 10^7$, $\Delta \nu$ is usually taken as 1/4, and a and R are in meters.

For the proposal two-way machine of 15 Bev,

q = 8.75 microcoulombs, or 5.5×10^{13} protons per pulse.

At 10 pulses injected per second, this corresponds to 87 microamperes time-average current. No rf bunching is included in these figures; the actual current would probably be from 10 to 40 microamperes. At 10 Bev, the current would be 2/3 to 3/2 times the 15 Bev current depending on whether the vertical aperture were scaled down with radius or held constant.

III. 10 BEV PROTON LINEAR ACCELERATOR

The proton linear accelerator described by Blewett (Brookhaven Report JPB-7, Dec. 31, 1956) has been reconsidered in light of the Stanford linear accelerator proposal. Blewett proposed a 200 Mev, 200 mc proton linac injecting into a 200 Mev to 10 Bev, 3000 mc microwave linac similar to the Stanford proposal except with its design adjusted to accelerate protons rather than the completely relativistic electrons. The parameters would be those of the Stanford Stage I (30 Bev) cut to one-third (3000 feet). At 360 pulses per second and a one-microsecond pulse length (as anticipated by Stanford), the current expected would be about 3×10^{-4} of the instantaneous proton linac current, usually considered to be 5 milliamperes. Thus a time-average current of 1.5 microamperes might be expected, assuming that the beam is properly debunched and rebunched between the two types of accelerator. Any increase in current from the 200 Mev stage could probably be accepted by the microwave stage. No attempt has been made to analyze the rf phase-space density of the final beam. Unlike the electron linac, the protons in the microwave section are phase focused.

The cost of such a combination linac might be expected to be approximately half of the Stanford Stage I proposal, or in the vicinity of $50 million. It would require 160 22-megawatt klystrons at a time-average power consumption of 5 megawatts and a klystron replacement rate of 60 per month.

IV. 10 BEV HIGH CURRENT A.G.S.

The Oak Ridge proposal discusses a high current, pulsed field accelerator using as an injector a 900 Mev FFAG cyclotron. Alternatively, one might employ the conventional 50 Mev linac as an injector and use a large aperture and high repetition rate to attain high current. This latter is explored below, in the spirit of MURA-28 (LWJ-4, Internal).

If one chooses an operating point, σ , on the diagonal of the stability diagram, and chooses the tolerable change in guide field over the usable radial aperture of the accelerator, the general design features of an A.G.S. accelerator are largely determined. Thus, we take $x_o = 2 Z_o$ (the semi-radial aperture equal twice the mean semi-vertical aperture), $\sigma = \frac{\pi}{2}$, and allow the field to vary by a factor of two over the useful radial aperture. In addition, we specify a "circumference factor" of 1.4 due to the insertion of straight sections. Therefore,

$$\nu \cong \frac{N}{4}$$

$$n = \frac{\rho}{B}\left(\frac{dB}{dR}\right) = \frac{R}{1.4\,B}\left(\frac{dB}{dR}\right)$$

$$n \cong N^2 / 16 .$$

From $B = 1.4\,B_o$ at $x = x_o$ and $B = 0.7\,B_o$ at $x = -x_o$,

$$n \cong \frac{R}{4\,x_o}$$

$$N \cong 2\sqrt{\frac{R}{x_o}}$$

$$\nu \cong \frac{1}{2}\sqrt{\frac{R}{x_o}}$$

Taking $B_o = 10,000$ gauss, $x_o = 30$ cm, $R = 50$ meters (for 10 Bev protons)

$$N \cong 25$$

$$n \cong 40$$

$$\nu \cong 6\ .$$

The useful aperture would be 60 cm wide, 21 cm high (inside) and 42 cm high (outside).

The same formulas used in the discussion of FFAG apply to the space-charge limit. For an oscillation amplitude of $\pm$ 6 to $\pm$ 10 centimeters, the space-charge limit corresponds to 5×10^{13} to 10^{14} protons per pulse. At 10 pulses per second this corresponds to about 50 to 100 microamperes time-average current. Again, rf bunching would reduce this to 10 to 40 microamperes. The betatron phase space available in one dimension is

$$V \cong \frac{\nu a^2}{2\,R} \cong 2 \times 10^{-2} \text{ cm rad.}$$

The phase space in one dimension from the linac is

$$v \cong 0.75 \times 10^{-3} \text{ cm rad.}$$

Therefore, at most (V/v) turns could be injected with a time-varying bump in one dimension (as in the MURA proposal), corresponding to 27 turns with these numbers. With a 5 milliampere linac, the space-charge limit corresponds to 500 turns. To approach the above currents, an almost perfect matching of both radial and vertical phase space would have to be realized. By way of contrast, the MURA proposal injection parameters correspond to a phase space such that the space-charge limit could be reached with an injector filling about 1/3 of the radial phase space alone. Thus, betatron phase space, rather than space-charge limit, might hold the current of such a pulsed accelerator to only a few micro-amperes.

Assuming biased magnet operation, some relevant engineering parameters follow.

B (bias level)		5000 gauss
B (a. c.)	$\pm$	5000 gauss
E stored in a. c. component of field (assuming an equal energy stored outside the useful field region)		9 megajoules
ωE (at 10 cycles per second)		600,000 kva
Cost of condenser bank (at \$15/kva)	$\sim$	\$10 million
(a choke of the same ωE rating also required)		
Magnet Q (assumed)		30
Power line load (10 cps)		20 megawatts
(not including D. C. power to maintain the 5000 gauss bias field)		
Required proton voltage gain per turn		300 kv

Clearly the high stored energy would be a major factor affecting the cost of such a machine. The prevalent design trend at 10 cps is toward condenser banks rather than rotating machinery. The large rf voltage required and high rate-of-frequency modulation would also be expensive. These figures represent a rather extreme design. The space-charge limit goes as $a^{3/2} R^{-1/2}$ (according to the relations between ν, a, R, x_o and q) and the phase space volume as $a^3 R^{-1}$. The poor phase space match between the injector and accelerator above reflects a charge density in phase space, $\rho = q/V$, proportional to $R^{1/2} a^{-3/2}$ (characteristic of the accelerator) too large relative to that of the injector. It appears that a current of about 10 microamperes time average represents what might be realized with a rather extreme alternating gradient synchrotron.

V. INJECTORS

It should be noted that in the FFAG and A.G. synchrotrons, a 50 Mev linac would be run at its maximum (assumed 5 milliampere) current with a duty cycle of 1/2% to 1%. The 200 Mev linac for the high energy proton linac would have a duty cycle of .03%, however the charging time of the 200 mc section is 100 microseconds (or more) requiring an rf duty cycle of 3%. Thus the synchrotrons are pushing existing 200 mc linac practice, and the linear accelerator slightly exceeding it from the standpoint of duty cycle.

It is tempting to consider the effect of raising the injection energy to increase the space-charge limit, increase the injection field,

decrease the rf modulation rate and frequency swing, further reduce gas scattering, and, in FFAG synchrotrons, reduce the radial aperture. In a given (circular) accelerator, the injected space-charge limited charge, q, is proportional to $\beta^2 \gamma^3$. The following table is useful for comparison.

E Injection	q_E/q_{50}	$1/\beta$
50 Mev	1	3.0
100 Mev	1.93	2.35
200 Mev	4.52	1.76

Thus a 200 Mev linac would increase the space-charge limit by over a factor of four and reduce the required frequency modulation to less than 2:1. This should only serve to emphasize that the injection energy should be left as an adjustable parameter in optimizing a particular accelerator design.

While a 200 Mev beam might be too stiff to inflect into an A. G. S. with the conventional one-turn inflector, the multiturn inflector of the type discussed for FFAG synchrotrons requires only a slowly time-varying magnetic bump, and this technique is equally applicable to alternating gradient synchrotrons.

VI. CONCLUSIONS

Barring more revolutionary linear accelerators and pulsed-field synchrotrons than those discussed above, there seems to be no reason

to divert attention away from FFAG accelerators as the means of producing high currents. FFAG accelerators appear to be capable of definitely larger currents than linear accelerators. On the other hand, FFAG accelerators are not orders of magnitude better than the rather extreme A.G. synchrotron described above in ultimate current, although the great inherent flexibility possible with rf manipulation is a very attractive feature of FFAG. Although almost no attention has been given to costs, superficial estimates indicate that none of the above alternatives is cheap; probably all would cost $50 million or more for a complete accelerator installation. Finally, a ten microampere time-averaged current is feasible; it seems that this should be maintained as an order-of-magnitude goal for alternative designs.