A 3-BEV HIGH INTENSITY PROTON SYNCHROTRON

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(presented by M. G. White)

Princeton University and the University of Pennsylvania under contract with the United States Atomic Energy Commission are cooperating on the design, construction, and operating of a 3-Bev high intensity proton synchrotron. The accelerator is to be a weak focusing synchrotron excited at 20 cycles per second by a resonant magnet. An injection time of 30 μsec, coupled with the 20 cps pulse rate will be accomplished by a 3 Mev Van de Graaff modulated upwards by 34 Kev during the 30 μsec injection time. Assuming a pulse proton current of 5 ma out of the inflector an average input current of 2.5 μamp can be achieved. Calculations indicate that at least 0.08 microamperes average will certainly be accelerated to 3 Bev and that probably an average current of 0.8-1.0 microamperes can be achieved. Even the smallest current expected is some 50 times the Cosmotron present average current.

A major reason for choosing constant gradient rather than alternating gradient focusing is that the latter does not readily lend itself to multiturn injection due to the strong momentum compaction. Since our goal is a high intensity synchrotron we strongly favored the constant gradient accelerator on this basis alone. However, equally important is our wish to have a strong, well focused, external beam. From experiments on the Cosmotron it is known that good external beams can be obtained by a straight-forward technique. While it is probable that the alternating gradient accelerator can eventually be made to yield a strong, well focused external beam it is by no means certain that such will be the case. On these two counts we decided to use weak focusing rather than strong focusing, but our design includes removable pole tips so that we can readily install strong focusing if we are able to solve the problems of multiturn injection and satisfactory ejection. However, our magnet gap is already so small that alternating gradient focusing does not achieve an important reduction in energy storage and overall cost of the machine.

The high pulse rate of 20 cps is made practicable by the use of an 11 inch by 3.0 inch pole gap (fig. 1) with consequent reduction in magnetic energy storage to about 1/10 of the Cosmotron figure. The magnet will be made up of 16 sectors, each 11.5 feet long (fig. 2) and composed of punched sheets of 0.025 inch transformer grade steel. Removable pole tips will permit easier installation of exciting coils as well as making possible future changes in pole tip profile if such proves to be desirable. Air cooling of the 350 tons of transformer iron will be necessary to carry off the 130 kW of hysteresis loss. In order to secure a highly uniform magnetic performance in each sector it is planned to carry out a thorough randomizing of the 86,400 laminations during the stacking process. Model tests on an ac magnet may show the desirability of using laminations thinner than 0.025 inches. We have made accurate tests of a $^1/_3$ scale dc model which show that we may expect 6-7 inches of good "n" at low fields and 3.5 inches of good "n" at the top field of 13.8 kg. on the orbit (fig. 3). Our net vertical aperture will be $2^1/_4$ to 3 inches depending on the vacuum chamber design.

Such small apertures as those quoted above call for several basic improvements over existing synchrotrons and great care in magnet design. The improvements which we expect to employ are: (*a*) vacuum of 10^{-6} mm. Hg., or better; (*b*) modulated Van de Graaff energy to reduce radial betatron oscillation due to injection process;

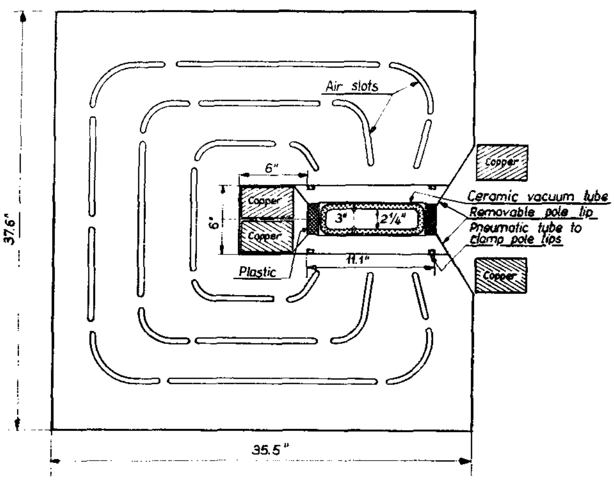

Fig. 1.

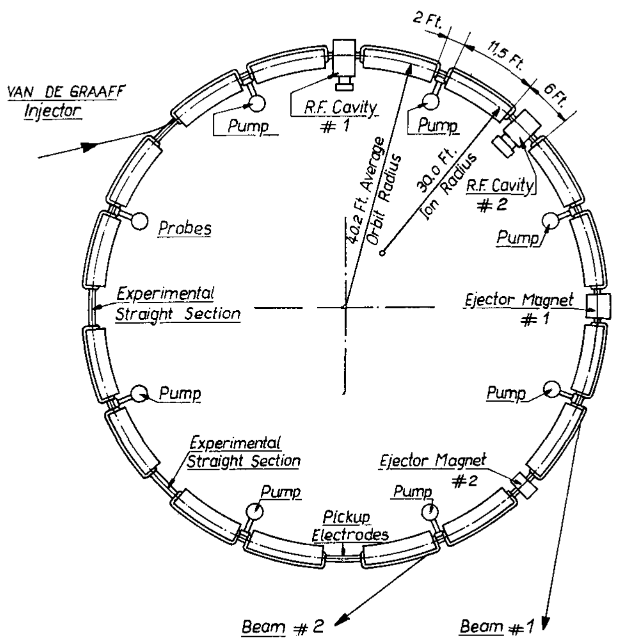

Fig. 2. Plan view of magnet.

(*c*) improved Van de Graaff stability and emittance; (*d*) use of the 12th harmonic of orbital frequency to reduce radial oscillations due to synchrotron phase oscillations; (*e*) use of several rf acceleration points to minimize radial oscillations due to step-wise increase in particle energy.

Due to the short acceleration time of $^1/_{40}$ seconds we find that a residual air pressure of 10^{-6} mm. of Hg. causes no more than a 1 % loss of beam. The vertical beam height near injection time, assuming an ideal magnet and a Van de Graaff "acceptance" of 0.4×10^{-3} cm. $\times$ radians, will be 0.6 inches total. With gas scattering essentially absent the major cause of vertical beam spreading is no longer operative. From Cosmotron diaphragm experiments we expect that a 2-$^1/_4$ inch vertical aperture will cause essentially no loss in accelerated beam.

Radial aperture requirements are as follows: (*a*) Injection for 10 turns at a $dB/dt = 47 \times 10^3$ gauss/sec will just fill the 6.0 inch region of good "n" in which $0.5 < n < 0.75$; (*b*) radial oscillations due to synchrotron phase oscillations will be 5.9 inches peak-to-peak; (*c*) step-wise rf acceleration at four points leads to 0.8 inch aperture loss; (*d*) injection errors due mismatch of $\pm$ 600 volts between Van de Graaff energy and magnetic field costs 0.3 inches of aperture; (*e*) magnetic field errors of 0.5 gauss RMS averaged over 6 inch sections of the magnet leads to about 0.5 inches of radial aperture loss; (*f*) azimuthal variations in the "n" may be expected from Cosmotron experience to cost 0.07 inches of radial aperture; (*g*) a frequency tracking error of 0.025 % will cost 0.4 inches aperture loss. Comparing the total of these aperture reductions with the 6 inch region of good "n", we find that we have left 4.0 inches of aperture in which to accommodate the 5.9 inches of synchrotron oscillation. If nothing is done to improve matters the result will be that the fraction of protons which are stably trapped by the rf will be reduced from the ideal figure of about 55 % to 25 %. However, by using pole face windings at injection time a small increase in good n region can be obtained. Careful attention to the various sources of aperture loss listed above may be expected to improve matters a bit. However, assuming that only 25 % of the protons survive to reach 3 Bev we calculate a theoretical average current of 0.6 microamperes, a figure which is approximately 380 times the present Cosmotron figure. The figure of 0.08 microampere quoted in the Table of Parameters assumes only 3 % of the injected protons survive to 3 Bev, a figure which approximates the Cosmotron efficiency and is considerably below that achieved in the Bevatron. Even this low efficiency yields an average current some 50 times the Cosmotron current.

Radiofrequency acceleration presents a particularly difficult problem since we require the following: (*a*) fre-

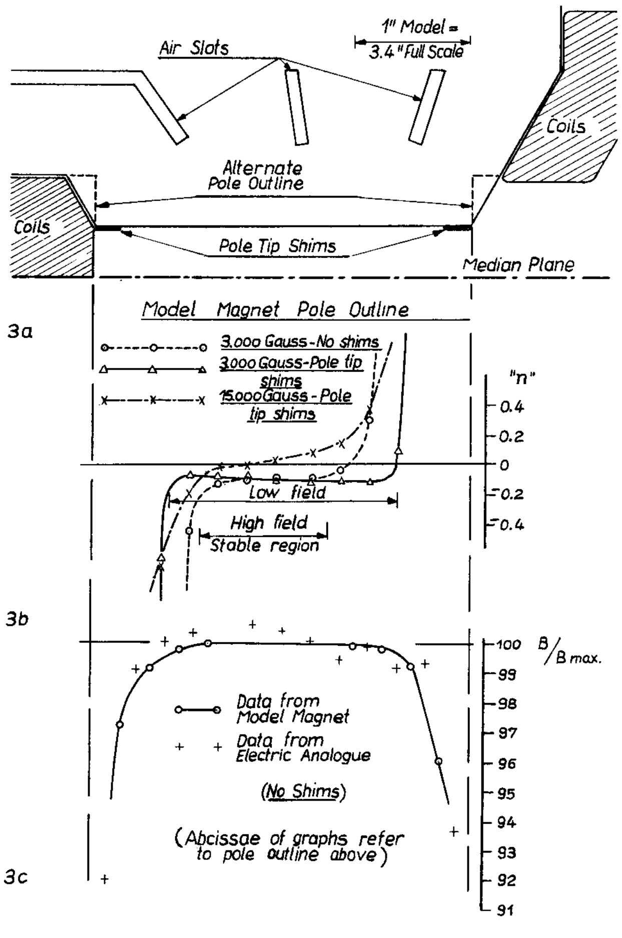

Fig. 3.

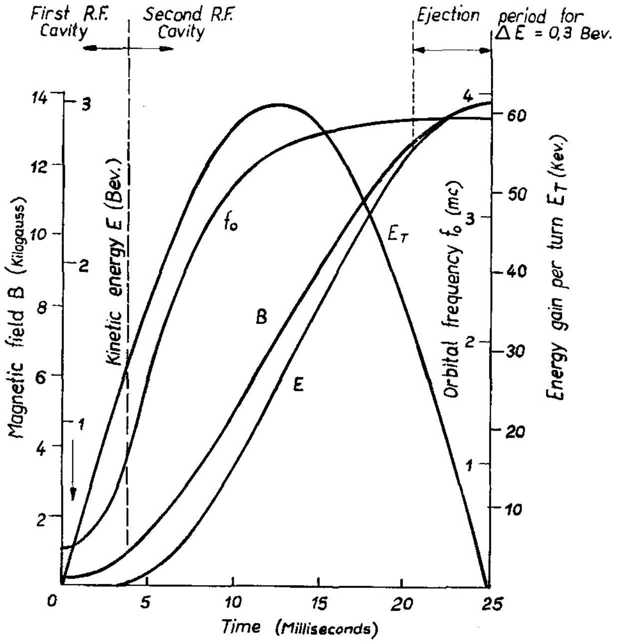

Fig. 4.

quency swing of 12.2:1; (*b*) gap voltage which is modulated from 6.8 kV at injection to 122 kV at the point where dB/dt is a maximum and back to almost zero at the time when dB/dt = 0; (*c*) frequency tracking to an accuracy of $\pm$ 0.025% near injection and 0.14% near ejection (fig. 4). The present solution is to use four ferrite tuned resonant cavities for the early part of the cycle going from 3.8 to 13 (+) mc/sec and shifting over to a mechanically tuned resonant cavity for the high voltage, high frequency portion of the cycle from 13 (–) mc to 45 mc. It is also practicable to use the ferrite tuned cavities all the way if the particles ride at 45° phase angle rather than 30°. This reduces the required maximum total cavity voltage to 86 kV. A careful study of ferrites will be required to settle the question. An important aspect of the radiofrequency problem which works in our favor is the highly repetitive nature of the magnetic cycle. Unlike the case of pulsed magnet excitation we may except each magnet cycle to be essentially identical with the preceding ten or twenty cycles. In consequence, it is practicable to use long time averaging techniques to establish the proper frequency versus time curve. This also makes practicable a mechanically tuned cavity with slow-acting trimmer controls which are servo controlled by the average behavior of the beam.

As was shown by Westendorp[1]), use of a field biased magnet materially reduces the required capacitor bank and also leads to substantial savings in power dissipation. For these reasons alone we would have chosen field biasing, but in addition the injection, rf acceleration and ejection problems are greatly eased by such biasing. In fact, a 3 Bev proton synchrotron is not feasible without field biasing since a normal sine wave excitation has a maximum dB/dt at the moment of injection with a consequent large radial shrinkage per turn and large required acceleration voltage. Field biasing permits independent choice of injection B and dB/dt. We have evolved a unique way to excite a field biased magnet which has certain advantages over the conventional circuit. Fig. 5 shows, for convenience, an eight sector magnet in which the resonant capacitor bank and dc isolation choke are broken up into 8 sections and inserted between each magnet sector. This has the effect of distributing the exciting voltage around the magnet making practicable the use of multiturn exciting coils in each magnet sector. The conventional circuit, in which all the capacity is placed across the entire magnet inductance, would have called for 7000 volts peak and 23,500 amperes across 16 coils in series, each of 4-turns. The maximum voltage between coil and ground would be 3500 volts, but there would be only 437 volts across each coil. Since the copper in such a coil would have to be laminated in order to avoid eddy currents a very difficult coil problem would be presented. By subdividing the capacitor bank and dc isolation choke into 16 sections as indicated, we can use a much higher voltage across each magnet sector and still keep the voltage to ground reasonable. This has the desirable effect of permitting the use of a coil of, say, 64 turns carrying 1469 amperes at a voltage of 7000 volts across the coil. Since each coil is at ac ground at its middle, apart from the dc potential, the maximum voltage between coil magnet frame is 3500 volts as before. However, a 64-turn coil requires no further laminating in order to avoid eddy currents since the area of each conductor

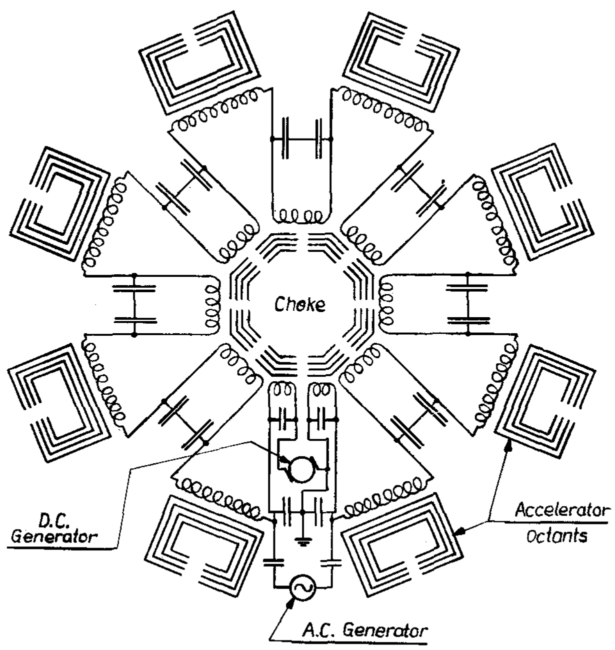

Fig. 5. Magnet power circuit with distributed capacitor bank (Drawn for magnet with 8 sections.)

is about $^1/_2$ square inch. For reasons of concenience we may actually use, not a 64-turn coil, but, perhaps, a 32-turn coil. This would require 2938 amperes at 3500 volts ac across the coil. The dc requirement is 1500 amperes at 440 volts.

The choke coil for dc isolation presents an interesting engineering problem in optimum design. It must have an inductance approximately equal to that of the synchrotron magnet. By making use of the mutual inductance between the 16 sectors it is possible to arrive at a choke whose size and cost are but a small fraction of that of the main magnet. It is planned to locate the choke on the axis of the magnet but above it and exterior to the ten feet of earth and concrete over the accelerator. The 16 capacitor banks will radiate out from the choke like spokes in a wheel each carrying current to a magnet semi-octant. In this way complete symmetry of current paths is obtained thus minimizing the chance of producing low order field "bumps" over the ion orbit.

Because of the high beam power (in the kilowatt range) it will be necessary to totally shield the accelerator and the external beam area. This will be accomplished by piling concrete and earth around and over the important areas. Considerable thought is being devoted to designing really adequate observation areas in which several experimental setups can be undergoing simultaneous testing while the beam is being used by a given experiment.

Serious consideration is being given to several schemes which would produce two beams of 3 Bev particles travelling in opposite directions in some common region. The energy available in the center-of-mass system would be equivalent to the amount available in the collision of a 30 Bev proton with a stationary nucleon. As was emphasized by D. W. Kerst, two such beams, each circulating in a magnetic field, can be caused to pass and repass many times, thus yielding a reasonable nuclear interaction rate.

TABLE OF PARAMETERS

Kinetic energy (max.)	3.0	Bev
Magnet excitation frequency	20, 10	cps
Magnetic field (max.)	13.8	kilogauss
Orbit radius	30.0	ft.
Number of magnet sections	16	
Straight section length	2 and 6	ft.
Length of magnetic sector	11.5	ft.
Average magnet radius	40.2	ft.
Vacuum chamber cross section	2-1/4 × 10	in. × in.
Magnet gap	3 × 11.1	in. × in.
Iron external dimensions	37.6 × 35.5	in. × in.
Coil window	6 × 6	in. × in.
Iron weight	350	tons
Copper weight	27	tons
Ampere turns (max.)	9.4×10^4	amp. turns
Stored energy, magnet	1.3×10^6	Joules
Copper losses, magnet	480	kilowatts
Iron losses, magnet	130	kilowatts
Stored energy, choke	1.5×10^6	Joules
Copper losses, choke	335	kilowatts
Stored energy, condenser bank	4.5×10^5	Joules
Volt amp., condenser	6.0×10^4	K V A
Condenser losses	180	kilowatts
D. C. bias power, total	620	kilowatts
A. C. power, total	505	kilowatts
Injection energy	3	Mev
Magnetic field at injection	270	gauss
Rate of energy gain (max.)		
20 cps	61	Kev/turn
10 cps	30.5	Kev/turn
Rate of energy gain (injection) 20 cps	3.4	Kev/turn
Change in orbit radius per turn 20 cps	0.8	inch
Orbital frequency (max.)	3.8	mc/sec
Orbital frequency (injection)	0.31	mc/sec
Peak rf voltage (30° phase) 20 cps	122	kilovolts
Peak rf voltage (45° phase) 20 cps	86	kilovolts
Peak rf voltage (30° phase) 10 cps	61	kilovolts
Peak rf voltage (45° phase) 10 cps	43	kilovolts
Number of rf cavities	2	
Harmonic order	12	
Frequency range cavity No. 1	3.8 to 13(+)	mc/sec
Frequency range cavity No. 2	13(–) to 45	mc/sec
Cavity length	90	cm.
Cavity diameter	130	cm.
Estimated Q	1000	
Peak rf power	50	kilowatts
Injection current	5	milliamperes
Injected pulse length	30	μsec

Injected charge	10^{12}	Protons/pulse	Protons per sec (average)	5×10^{11}	Protons/sec
Charge accelerated to full energy (est.)	2.5×10^{10}	Protons/pulse	Proton current	0.08×10^{-6}	amperes
			Beam power	240	watts

LIST OF REFERENCES

1. Westendorp, W. F. The use of direct current in induction electron accelerators. J. appl. Phys., *16*, p. 657-60, 1945.