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20 Gev from the Cornell 10 Gev Synchrotron?

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The Cornell electron synchrotron has been designed and is being built to give 10 Gev. However, the radius of curvature was made extra large, 100m, in order to minimize RF problems associated with the large amount of radiation by the electrons and this leaves open the ultimate energy of the machine. By the time that we were making the final design it appeared possible to reach 15 Gev, and the magnet was then "beefed up" so as to reach that energy without saturation. Many of the components were designed for 15 Gev where it was convenient and not too expensive and all the components were designed to be consistent with a later expansion to 15 Gev. There has been some technological progress since the design was made, so it is fair to ask now if it is practical to reach 20 Gev.

In raising the energy from 10 to 20 Gev, three technical questions must be answered: can we supply the 160 Mev per turn that will be necessary instead of 10 Mev per turn for 10 Gev; can we double the excitation of the magnet; and can the growth of radial oscillations be prevented? Finally, we must ask about the cost of the increase.

Providing the factor of 16 increase in the RF voltage needed for 20 Gev would seem to present the most serious problem in raising the energy. It can be solved by installing more of the waveguide accelerators and by using more powerful klystrons. Thus, for 10 Gev operation, we expect to place 16 ft. lengths of 714Mc waveguide, which we call "synacs", in each of the four 20 ft. - long straight sections. We can double this by placing four more of these synacs in the two 40 ft. - long straight sections. The voltage gradient will not be excessive: it will be 0.8MV/ft., which is small compared to the voltage gradient in an L band linac where the gradient is about twice as great. We supply 400 KW peak RF power to energize the present four synacs to give the 10 Mev/turn that is necessary for 10 Gev operation, hence supplying 800 KW to the eight units would make 20 Mev/turn, and to raise this to 160 Mev/turn would then require a peak power of 51 MW. We expect to use a version of the TRADEX Klystron which has a rated peak power of 5 MW at 1200 Mc. Scaling it to our frequency, 714 Mc, should increase the peak power rating to 7 MW, hence if we power each of the 8 synacs with one of these tubes we should be able to supply 56 MW which is slightly more than required.

So much for the peak power. The average power rating of these tubes is 200 kw each, or 1.6 MW for all eight tubes. Running at 60 cycles per second would require about 6 MW average power. Were we to drop to a repetition rate of 10 cycles per second, we would need 1 MW average power which is well within the average power dissipation of the tubes.

To realize the installation of this RF power, our first step would be to have two or three of the TRADEX Klystrons built for our frequency. We would then install two of the synac units in the 30 ft. X 40 ft. underground chamber at the 40 ft. long straight section. At full power these should make 41 MV in the two synacs which, together with the 10 MV from the other stations, should allow us to reach 15 Gev at 10 cycles per second. To reach 20 Gev it would be necessary to install two more synacs in the 40 ft. straight section in the Synchrotron Hall and to replace the four old klystrons installed for 10 Gev by the new klystrons. Tigner has calculated another possibility, namely, installing six synacs with two klystrons per synac which would allow us to reach 18 Gev at 30 cycles per second or 15 Gev at 40 cycles per second.

Installing the additional RF power would have an additional advantage in that it would enable us to get more beam intensity at lower energies. Thus, at 10 Gev, we will be limited by the RF power to beams of roughly 10^{13} electrons/sec. This corresponds to a current from the linac of about 10 ma. The linac has given a current some thirty times greater, and it is conceivable that we could accelerate such a current by using the extra power installed to reach 20 Gev, assuming that other limitations such as beam blow-up or radiation damage do not interpose insurmountable difficulties.

Now let us turn to the problem of doubling the excitation of the magnet. As I have mentioned, it is already designed to reach 15 Gev except for a few modifications of the primary power supply. Because the return yokes of the magnet are only 1 1/4" thick, saturation becomes noticeable at 15 Gev excitation, where it is 2%. At 20 Gev excitation the saturation has increased to 7.5%, which is not excessive. One way of exciting the magnet to the 20 Gev level is to add identical condensers in parallel with those already installed. This would cause the frequency to drop from 60 cycles to about 40, but the voltage on the condensers and magnet would remain about the same as for 15 Gev operation so that all the present components would be useable. Because of the lower frequency, the chokes will probably saturate, but this can be prevented by inserting identical chokes in series with those already installed. Thus we would have to double the number of chokes and to add about 2/3 the number of condensers that are presently being used. There is adequate room for these additional components in the tunnel right under the presently installed condensers and chokes.

The DC bias on the magnet is now being provided by six separate DC supplies placed at regular intervals around the ring - so as to keep the voltage down. The number of these supplies would simply be doubled. The DC power necessary for 20 Gev operation would be about 2 MW as compared to 0.36 MW for 10 Gev.

The AC power would increase to about 1 MW, to be compared to the 0.4 MW for 10 Gev. At present this power is carried away by water which is heated from about 18°C to 27°C for 10 Gev operation. One way of dissipating the roughly four times greater power would be simply to double the flow of water and to allow the temperature rise to double.

The orbit dynamics of the magnet may present the most serious problem in attaining 20 Gev electrons. The beam grows in size due to fluctuations of energy caused by the emission of synchrotron radiation. This synchrotron radiation also leads to an antidamping of the betatron oscillations. Calculations by D. A. Edwards[1] show that the r.m.s. radial extent of the beam will be 1 cm at 10 Gev, 5 cm at 15 Gev, and at 20 Gev clearly the beam would be completely blown up. It was for this reason that provision for excitation of the magnet was originally limited to 15 Gev. A new development, however, has been the successful development by K. W. Robinson[2] of a special damping magnet.

Robinson's magnet works by transferring some of the damping of the synchrotron oscillations to the radial betatron oscillations. The synchrotron oscillations damp because the radiation loss by electrons of energy lower than the average is very much less than the loss by electrons of average energy. Since the radiation loss is proportional to $B^2\ell$, by making a large magnetic field B over a short distance ℓ in the straight sections, the radiation loss can be made arbitrarily large compared to that due to the bending magnet. He makes a large negative gradient of $B^2\ell$ with respect to radius, and he alternates B so that both the overall bending and focusing effects are close to zero.

Physically, Robinson's magnet consists of five pairs of poles with alternating fields. The pole separation is 1/2" and the poles are 3 1/2" long in the direction of the beam - the first and last poles are one-half as long as the others. The total length of the magnet is 26". At CEA, the beam is bumped to the position of maximum gradient when the energy has reached 5 Gev. The field in their synchrotron is then 6.3 KG and the field in their DC damping magnet is 13.2 gauss. For our case, with

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[1] D. A. Edwards CSDS-15, June 15, 1964

[2] K. W. Robinson CEAL-TM-155, December 10, 1965

20 Gev, the synchrotron field would be about the same, but the length around our magnet will be greater by a factor of four, hence we would need four AC magnets similar to Robinson's to do the job. In fact, it will probably be more expedient for us to make a larger number of much smaller magnets (perhaps 24) and to distribute them around the orbit in the small straight sections between unit magnets where there is about 6" of clear space. We may also want to make the magnet apertures rather small, as at C.E.A., and to bump the beam into the magnets after the energy has exceeded about 10 Gev.

Were there no damping of the radial betatron oscillations, the beam would grow to an r.m.s. width of several cm. However, it will be much smaller than this because the Robinson magnet provides positive damping.

One might worry also about the intense synchrotron radiation at 20 Gev - some 300 KW for a beam of 10^{13} electrons/sec. The radiation spectrum extends almost uniformly up to an energy of about 180 Kev where it drops off rapidly, but there is still a small amount of radiation at photon energies as high as 1 Mev. The power radiated per unit energy in the constant part of the spectrum per electron varies as E/R and will be only 2/3 of that from our 2 Gev synchrotron in the region where the two spectra overlap, i.e., up to about 22 Kev. Hence for many phenomena, such as those concerned with the emission of secondary electrons, the radiation will not lead to serious problems. The synchrotron radiation will be intercepted by water-cooled copper scrapers that are to be inserted in the vacuum boxes in the spaces between magnets.

Now let us consider the cost of increasing the energy, first to 15 Gev and then to 20 Gev. Most of the components of the magnet are already capable of 15 Gev excitation, i.e., the condensers, chokes, and the D.C. supplies. Only the A.C. power supply need be increased by paralleling additional components. This will cost approximately <u>50K$</u>. As has been mentioned before, the RF for 15 Gev could be supplied by adding two synac units at a cost of 100K$ which would be powered by two

TRADEX tubes which might cost 300K$ - largely development costs. The DC power supply, 800 KW would come to about 200K$ and various ancillary parts would probably cost another 50K$, making a total of roughly 700K$ to get to 15 Gev.

To reach 20 Gev would require purchasing about 300K$ worth of extra condensers, chokes, and D.C. power supplies. It would cost approximately 50K$ to increase the A.C. power excitation from the 15 Gev level to 20 Gev. The Robinson magnets would cost between 10 and 40K$ depending upon where they are built. Thus to increase the capability of the magnet to be able to reach 20 Gev will cost roughly an additional 400K$. The RF costs are much more difficult to estimate at all reliably. Assuming that six new synacs will have to be installed, we can guess that they will cost about 300K$. The six TRADEX tubes to power these might cost 50K$ apiece to make 300K$. We could use the power supply to be obtained for 15 Gev excitation at a lower duty cycle, i.e., at about 2 pulses per second, in which case we would be able to get some 20 Gev electrons at a cost of about one million dollars in addition to the 700K$ which might be spent to reach 15 Gev excitation. To increase the duty cycle to 10 pulses per second would cost an additional 600K$. Cost estimates being what they are, we should figure on about 2.5M$ as the cost of going from 10 Gev to 20 Gev operation, apart from the experimental equipment and the usual factors that allow for inflation and contingencies.

It appears then that all the questions that have been raised concerning the increase have been answered in the affirmative and furthermore that the cost will not be too excessive. Insofar as this is true, we can assume that the Cornell synchrotron has an eventual capability of accelerating electrons to an energy of 20 Gev - and perhaps even higher.

I have relied heavily on discussions with Maury Tigner about RF problems and Raphael Littauer about magnet problems in reaching these conclusions.