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ON THE PROBLEMS OF THE DESIGN AND CONSTRUCTION OF ALTERNATING GRADIENT PROTON SYNCHROTRONS

by J. B. Adams

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Introduction

This talk is aimed at pointing out the difficulties encountered in designing a large Alternating Gradient Proton Synchrotron and the sort of problems that have to be solved in order to build such a machine successfully in a reasonable time. The difficulties have arisen in many forms and in many ways. Originally there was the problem of how such a machine using the Alternating Gradient principle worked in what we now regard as the simple linear approximation. It took about six months or more to discover all the resonances and stop bands and other forms of instability inherent in the Alternating Gradient principle. During the course of this work we found that in order to build such a machine it was necessary to impose very tight tolerances on the magnetic field guilding the protons around the circular orbit and on the focussing field holding the particles in stable oscillations about the circular orbit. Also we found that at one particular instant in the accelerating cycle the tolerances on the frequency of the voltage used to accelerate the protons became so tight that no conceivable stable generator could possibly hold the frequency steady enough.

Gradually all the various difficulties came to light and we could sit back and ask the very pertinent question, "Is it really worth while going on with this idea, or would it be better to build a scaled up version of the Cosmotron?" We could draw up a sort of balance sheet. In fact, on the side was the economy of a machine using the alternating gradient principle. In the alternating gradient or A.G. machine the large number of free oscillations round the circumference means that the amplitude of oscillation for a given injected beam is much smaller. Also the phenomenan called "momentum compaction" means that for a given range of energy oscillation during a synchrotron oscillation the resulting radial swing of the protons is very small indeed. Both these facts result in being able to use a vacuum chamber in the A.G. machine which is less than a tenth of the cross section area of that required for a constant gradient or C.G. machine such as the Cosmotron or Bevatron. And of course, the volume of the magnetic field to guide and focus the protons in this vacuum chamber is similarly reduced. Thus, for roughly twice the weight of steel as is used in the Cosmotron which gives a maximum proton energy of 3 GeV, we can build a machine to give about 25 GeV. Also the energy required to supply this magnetic field is about the same as is used for the Cosmotron.

On the other side of the balance sheet, however, we had the tight tolerances and whether we could rely on modern technology and the European industry to meet these tolerances.

Since we had a limited budget, the choice in terms of proton energy was between about a 10 GeV C.G. machine or a 25 GeV A.G. machine.

We decided, after a very detailed investigation, that we could overcome the technological difficulties and so we put our money on the A.G. machine.

On the other side of the Atlantic the Brookhaven team were facing exactly the same dilemma. They also decided to back the A.G. machine. I wouldn't claim that these two decisions were uncorrelated. It is very comforting to us to have another group working with us in close collaboration of these problems.

I am only going to mention what we regard as the most difficult problems that we have to overcome during the construction of our machine. If we cannot solve these, then the machine certainly will not work.

The first concerns the errors likely to be made in setting up the guiding magnetic field for the protons. If machine physicists have hearts it is certain that the word "misalignment" will be found written on them.

Misalignments or errors in the guiding field of the particles

This problem was one of the first objections pointed out by John Lawson right at the beginning of the development of the Alternating Gradient Proton Synchrotron.

If one displaces a section of the magnet of a constant gradient machine radially and calculates the peak amplitude of the resulting free oscillation of the particles due to the displaced sector and then one does the same calculation for an alternating gradient machine for the same sector length and displacement one finds that the ratio of peak amplitude for the A.G. machine is about 100 times greater than for the C.G. machine. This is due to the shorter wavelength of free oscillations in the case of the A.G. machine and the new sinusoidal motion of the particles of that machine. In other words the A.G. machine is about 100 times as sensitive as a C.G. machine such as the Cosmotron to the misalignment of parts of the magnet ring.

To illustrate the tolerances required on the alignment of the magnet units one can calculate the peak deviation of the closed orbit, i.e. the orbit about which free oscillations take place for a random arrangement of magnet units. In the CERN machine where we have 100 units, if the ends of these units have a random distribution between radial limits of ± 0.5 mms, then the peak displacement of the closed orbit is 0.5 cms. Since the vacuum chamber measures 8 x 12 cms. this is about the largest closed orbit deviation we can allow. The tolerances we are hoping to achieve therefore are that the ends of these 100 magnet units are aligned to a perfect circle to within 0.6 mms r.m.s. and to a perfect plane to within 0.3 mms r.m.s.

The misalignments occur in practice in three separable ways. There will be errors in our measurements of the magnetic field, there will be errors in setting up the magnets in a perfect circle and in a perfect plane, and lastly, having measured the magnet and set it up as best we can there may be secular changes afterwards.

Let us look for a moment at the procedure of measuring the magnet. The magnet is not a complete ring, it is composed of about 100 separate units each 5 metres long and each weighing about 40 tons. The units in turn are made up of 10 magnet blocks, 50 cms. long weighing 4 tons each. So we have about 1000 of these blocks to measure. The pertinent measurement for this problem is to determine the position of the median plane and the equilibrium orbit. The median plane is the magnetic symetry plane and the equilibrium orbit is the line of constant vertical magnetic field in median plane measured at some standard current in the coils energising the magnet. The procedure to be followed to arrive at a complete magnet is then as follows.

We first determine the position of the median plane and equilibrium orbit in each of the 1000 blocks. This will take about 20 people at least six months work. Then the blocks are arranged into units following some definite plan such as minimising the effect of remanent field variations. The units are complete in themselves mechanically and can be transported on a railway system like shunting trains. There are one hundred of them. The units are now measured again to determine the equilibrium orbit and magnetplant in the inlet. Incidentally, these measurements have to be done statically at all field levels from the injection field of 150 gauss to the ejection field of 12,000 gauss and also dynamically in order to allow for eddy current effects during the correct [illegible] of the magnet. This may take a further three months and as a result a new stacking order for the units round the ring will be worked out.

While this has been going on another group of people will be busy determining the perfect circle and the perfect plane in the ring building. This can only be done after the concrete foundations have had time to age and after the constant temperature and humidity apparatus in the ring building is functioning correctly. The whole building has to be kept to ± 1°C to maintain the required tolerances. The surveying will take at least six months.

When the ring building and the magnet units are ready, the units will be driven into place and aligned to the perfect circle and plane. Further magnetic checks will be made and after several months settling readjustments will be made on the alignment of the units. These will be repeated until the magnet has settled down.

Perhaps I should just mention the tolerances on the setting up of the perfect circle and plane. The ring building is a hollow torus of rectangular crosssection buried in the ground for shielding reasons. There are four radial trenches and a central marker station on the same level as the ring building underground. By using survey tapes and the best theodolites we can set up four promising marker stations in the ring building working from the central marker. The radius of the machine is 100 metres and survey tapes can be relied on to measure this distance to a few parts in 10^6. The oddities can measure to 10^{-6} radius by repeated measurements i.e. in 100 m 0.1 mms. So the primary markers can be set up to better than 1 mm to a perfect circle. Because the ring building is not very wide we cannot see between the four primary markers and have to set up a further four secondary markers from the primary ones. This is again done with tapes and the theodolites. These eight markers are now in sight of each other and they are used to set up the magnet units. We expect to align the units to an R & S tolerances of 0.1 mms to the perfect circle and plane by these means.

We now come to the question of what happens after the units are set up and after the expected ageing time.

The subsequent stability can be divided up into two time periods. There is the variation in the alignment during the 1 sec. accelerating time. In other words if we align the units for a field of 150 gauss there may be completely misalignes at 1000 gauss. This is a question of the relative behaviour of the individual units. There are these variations that take place in a few months or a few years due to site movements, foundation movements, steel ageing, mechanical movements and so on.

I would like to mention just one cause of variations in the alignment of the units during the acceleration time of 1 sec. This is due to random variations of the remnant fields in the gaps of the 100 magnet units.

If we align all the units perfectly at the injection field of 150 gauss but there are variations in the remnant field between the units, then at some higher field, say 1000 gauss, these remnant fields are less important and at 10,000 gauss they are quite negligible. In other words such a magnet which is perfectly aligned at 150 gauss will be completely misaligned in a random fashion at higher fields. We find that if the remnant field in the magnet units differ by 1 gauss and they are perfectly aligned at 150 gauss then at 10,000 gauss there will be a random misalignment between the units of 1.6 mms which is right outside the permissable tolerances. To keep within the tolerances we must not have random variation in the remanent fields between the units of greater than 0.2 gauss. If now we measuredthe blocks that go to make up a unit and then stack the blocks into units to minimise this effect we can place a tolerance of 2 gauss on the variations between the remanent fields of the blocks themselves. The remnant fields measure on models is about 40 gauss so we are asking for a 5% tolerance on the remnant field in the blocks. It can easily be shown that the remnant field in the magnet gap is nothing to do with the remnant field in the iron of the magnet but just due to the coercive force in the iron. Thus we are asking for a tolerance of 5% on the coercive force of the steel of our magnet. We have measured about 100 samples of steel and two full scale models of our magnet. We find that in a model made out of one batch of steel there is a variation of ± 6% in the coercive force of the steel along the length of the model. Some steel taken from a factory over a period of 6 months had a variation of 30% in its coercive force. If we heat treat steel that has come by the normal processes for a factory we can decrease the coercive force by as much as 50%. Mechanical vibration ages the steel and increases the coercive force again. So in general our tolerance of 5% on the coercive force seems to demand a very tight tolerance on the composition of the steel, particularly silicon additions, and on the heat treatment it gets at the factory.

We now come to the long term stability of the magnet and as an example I would like to mention the work done on the design of the ring building to ensure long term stability. We decided at the start that we could not do any better than rely on the underlying sandstone rock on our site as a foundation. We considered also floating the magnet, but decided that it was not practicable.

The magnet foundation is therefore made as a heavy concrete ring with conc pillars founded in this sandstone layer. The ring building is completely separate from the magnet foundation and serves only to hold off the screenin earth and prevent it pressing in and distorting the foundation. The foundat and the magnet itself has to be temperature controlled to ± 1°C to prevent subsequent distortions of the ring. It is interesting to note the computatio we have made on the permissable distortion of the magnet foundations. Althou the units themselves must be aligned to the perfect circle and plane to within few tenths of a mm the perfect circle and plane can distort as a whole without too serious effects. For instance the circle could go elleptical so that the major and minor axis differed by 2 cms without serious trouble. The important thing is that the foundation should not sag by more than 2 mms with a sag length equal to the free oscillation wavelength. Measurements so far taken on the site indicate that these tolerances can be kept but we are building a full scale section of the ring building and foundation on the site to make further checks on our calculations.

That is all I want to say for the moment about misaligmments but it should be enough to show that the problem is formidable.

I now come to an entirely different problem concerned with what is called transistor energy in an A.G. machine. This problem happens to be peculiar to the A.G. principle and does not occur in other machines and sine it brings its difficulties it seems worth mentioning.

Transition Energy

The transition energy comes about as follows. A particle having more ene than some reference particle moves arround a circle of greater radius and at hi velocity than those of the reference particle. Because its radius is greater the particle takes longer to go round than the reference particle but because i velocity is greater it takes less time to go round. It does not matter particularly which effect wins. In a Linear Accelerator there is no radius effect, only a velocity effect, and the particles are phase stable at a particu phase of the accelerating waveform. In a C.G. Proton Synchrotron velocity eff is always smaller than the radius effect so particles are phase stable at a pha shifted by 180° from that appropriate to a linear accelerator. If it should happen that the radius effect and the velocity effect are equal however, then all particles at all radii take the same time to go round once and we lose phas stability. The energy where those two effects are equal is called the Energy. To add to our difficulties it happens that we have a Transistion Ener in an A.G. machine. Let us just look at the other circular accelerators first however. In a cyclotron we start with the two effects equal but very soon afterwards the radius effect wins and the particles are phase stable about the synchrotron phase angle. In a C.G. synchrotron the radius effect predominates right from the start so in effect the Transistion Energy occurs at negative energies. In an A.G. machine, because of the momentum compaction, the radial increase for a given energy increase is very small but the velocity effect is unchanged. So to begin with the velocity effect predominates and the stable phase angle is as in a linear accelerator. As the particles reach relativistic velocities the velocity effect decreases until it becomes equal t the radius effect and thereafter the radius effect predominates.

In the new Fixed Field Alternating Gradient machines with a radially decreasing field, the Trasnsistion Energy can be placed above the maximum ene the machine so one never reaches it and for these machines where the field increases outwards in radius the radial effect is negative and so never equals the velocity effect.

Thus the Transistion Energy problem only encountered in an A.G. machine the type we are building.

At low energy the velocity effect predominates as in a linear accelerator and after the transition energy the radius effect is larger as in a synchrotro So we must change the position of the stable phase by 180° minus twice the stable phase angle at the transition energy. This is not too difficult since it does not have to be done very quickly. We can take up to a few hundred μ secs during the switch over.

Since at the Transition Energy phase stability dissapears, the tolerance on the frequency of the accelerating voltage becomes very small indeed. At injection the frequency change to give 1 cm shift in the closed orbit is about 1 part in 10^3. A few MeV before the Transition Energy the frequency change for the same displacement is 1 part in 10^6 and it becomes infinitely small at the Transition Energy. No form of frequency stabiliser can ever achieve this accuracy and the control has to come from the beam itself. In fact we plan to use the frequency computer only for the first few GeV then switch over to beam control for the rest of the cycle.

Non Linearity in the guiding field

The last difficulty that I want to mention is a theoretical one and concerns non linearities in the magnetic field guiding the particles round the orbit. Hisorically non linearities were first thought of as beneficial in tha they might slacken the tolerances imposed on 'n' the field gradient to keep between the resonances given by the linear theory. This idea except in very special cases has been shown not to be a good one and in fact most of the studies on non linear systems have revealed further causes of instability due to the non linearities themselves.

There are three main effects of non linearities,

1. Modification of the resonances and stopbands found in a linear theory,
2. Introduction of new sub resonances and stopbands not possible in a linear machine,
3. Sweeping of the working point inside the stable diamond during the radial synchrotron oscillation.

1. The computing done at CERN and Brookhaven has shown that for the sort of non linearities that cannot be avoided in A.G. machines the linear stopbands are not seriously modified. They are shifted and the width varies with amplitude particularly but not so much that the linear theory need be modified in principle.

Sometime ago, using computing methods, we explored the possibility of exciting sub harmonics in non linear systems. In a linear system the fundamental resonances are excited by errors in the guiding field and stopbands are excited by errors in the focussing field. In terms of Q which is the number of free oscillations per revolution this means that at integral Q values we observe resonances and at half integral Q values we find stopbands in any practical machine. Normally the machine is designed so that during the whole of the accelerating cycle the Q value lies between a resonance and a stopband. Our object in computing for non linear systems was to see if given types of non linearity excited resonances or stopbands when Q was integer plus $\frac{1}{3}$ or $\frac{1}{4}$ etc. because if this happened we would hope to stay between these new sub resonances and sub stopbands by placing much closer tolerances on the variation of the parameters of the machine during the accelerating cycle. The computing confirmed our worse fears. Quadratic non linearities excited stopbands at Q values of integer plus $\frac{1}{3}$ and 2/3. Cubic non linearities excited stopbands at Q values of integer plus $\frac{1}{4}$ and $\frac{3}{4}$. We have developed an explanation of this behaviour in terms of new closed orbits in non linear systems, closing every 3 or 4 revolutions. Just recently Sturrock at Cambridge has developed a first order theory that predicts similar results. Also Moser working with Courant senior at New York has developed a theory covering similar sub resonances that occur in celestial phenomena. Particular examples he quotes are firstly that certain bands of the asteroids are missing corresponding to sub harmonics of their motion where the perturbing force comes from planet Jupiter and secondly the rings of Saturn are divided into bands where the gaps can be ascribed to perturbations due to the moons of Saturn. Thus there seems very good reason for believing that sub resonances will be excited in our machine but the problem remains, how many are there, and in a dynamic system, do they increase the amplitude of the free oscillation of the particles seriously if by chance the resonances are crossed during the accelerating cycle. On this latter point we have computed the dynamic behaviour of perturbed non linear systems that indicates an uncorrelated diffusion of the particles as they go through a sub harmonic stopband. In other words, there is a net increase in these amplitudes of oscillation every time such a stopband is crossed. Obviously the best thing is to stay between the stopbands but this may prove to be impossible in practice due to the synchrotron oscillation in a non linear system.

3. During a synchrotron oscillation cycle the closed orbit i.e. the orbit about which all particles perform free oscillations, moves in and out in radius. If the field is non linear then particles with small oscillations about this closed orbit oscillate in fields of differing focussing strengths i.e. n varies across the vacuum chamber. Therefore, instead of keeping always at one point between the resonances during the operation, the working point moves continuously between the resonances. If the non linearity is too high then the working point will cross a resonance during the synchrotron oscillation cycle and all the particles will be lost (or some for a sub resonance). There is nothing that can be done about this except to keep the non linearities small and also the synchrotron oscillation amplitudes by using a high harmonic number

Our views on non linearities at the moment are therefore that they are very much a nuisance and should be kept as small as possible. In fact, during the whole accelerating cycle the field at the edge of the vacuum chamber must not deviate from the correct field by more than a few μ. In practical magnets this is a very tight tolerance indeed. Even if we succeed in limiting the non linearities to this small value it looks as if we will have to place much tight tolerances on the variations of the focussing forces i.e. the field index 'n' during the accelerating cycle.

Incidentally, Hine and myself should at this moment be working on this problem at Brookhaven using their electron analogue model which is a completel scaled model of the final machine using electrons instead of protons. This model is about 7 m radius and has cost about £250,000 to build. It is equipp with non linear lenses so that one can add quadratic or cubic non linearities to the fluids and see what happens. The model is designed so that during acceleration the Transition Energy is passed and one can study what happens at this critical point.

Scale of the job

Lastly I would like to draw your attention to the scale of the job that any group building such a machine must face up to. Take for example the CERN machine which is 100 m/300 ft in radius. To hold the tolerances the ring building has to be kept to within ± 1°C in temperature.

Over the area of the ring the foundations must not move more than a few

The magnets have to be set up round a perfect circle and in a perfect pl to within a few tenths of a mm. They must stay there during a cycle, over many cycles and over a few years.

We need 4000 tons of steel machined to within a few hundreds of a mm of uniform steel with close tolerances on its composition and heat treatment.

There are 1,000 magnet blocks each of which has to be measured accurat and arranged statistically to minimise variations between blocks. A staff 20 people doing the measurements will take well over six months to complete them.

Each magnet unit weighs 40 tons and has to be assembled and moved int correct place by a complicated railway system. This is equivalent to shu about 100 railway engines into position correct to a few tenths of a mm. time scale and planning of the steel production, steel testing before manu into blocks, assembly into blocks, factory testing, delivery to site, hand 1,000 blocks on the site, the measurement programme and final assembly and setting up has to be planned carefully and requires very good engineering physicists to carry it out.

On the power side, only two generating plants of the size we want ha made in the world and both are in the States. Nobody in Europe (that includes England) have ever made anything so large.

The Linac giving 50 MeV particles is no negligible device. Only a few years ago such a Linac was considered in the forefront of technological development. Only one such machine is working successfully in the world yet and that at 30 MeV. One could go on taking each part of the job. In fact this machine is a challenge to nearly every branch of technology quite apart from the theoretical uncertainties peculiar to A.G. machines on which very little is yet known.

And what is most important is that a machine of half the energy is not very much easier to make.

To do all this work in a reasonable time calls for a large and competent staff so it might be useful to note the staff figures for such a machine. In the case of the CERN proton synchrotron the Division is divided up into groups responsible for the component parts of the machine. The staff figures for the end of this year, which are still not the peak figures are shown in the table.

STAFF (END 1955)

	S.S.O. + L4 up	S.O. L5	S.E.O. T1, T2	E.O. + LA A.E.O. T3, T4	Total
R.F. Group	5(4)	3(2)	1(0)	7(5)	16(11)
Magnet Group	6(4)	6(5)	- -	10(7)	22(16)
Linac Group	7(6)	7(6)	-	7(4)	21(16)
Engineering	3(3)	3(1)	5(5)	12(8)	23(17)
Survey	-	-	-	-	-
Power Eng.	-	-	-	-	-
D.O.	-	-	-	-	-
Controls	-	-	-	-	-
Vacuum	-	-	-	-	-
Theory	5(5)	2(0)	- -	4(4)	9(9)
Workshops	-	-			
Mech.	-	-	1(1)	13(12)	14(13)
Electronics	-	-	1(0)	3(3)	4(3)
Glass blower	-	-	-	1(1)	1(1)
Stores etc.	-	-	-	5(4)	5(4)
Admin.	-	-	2(1)	5(5)	7(6)
Total, End of 1955	26	19	10	67	122
Total, April 1955	(22)	(14)	(7)	(53)	(96)

Numbers in brackets show present complement

Brookhaven staff figures are very similar to ours and the total is alm exactly the same.

For a much smaller machine namely a 3 GeV constant gradient proton synch being built at Suclayi, France by Winter, the staff total is 60 at the moment and 90 by the end of the year.

So unless everyone is being widely extravagent in staff which I am quite sure is not the case then any machine between 5 and 20 GeV will need a peak staff of about 100 people all included. At Harwell it is not usual to inclu D.O. staff, mechanics and stores but that would only bring the C.E.R.N. figur down to 90 or 95.

This is a lot of people and calls for a lot of planning and organization but such a project needs them if it is to be carried out energetically and thoroughly. Both the Cosmotic and the Bevatron used similar staffs during the construction period.

Another point worth noting is that such machines during their operating life cost as much per year to run as they cost per year to construct. I use run in the widest sense, salaries, apparatus for nuclear physics, power bills and so on.

In England there are no such large machines. For example the Lineport cyclotron might be compared in complexity with our Linac injector. Proton Synchrotrons are not just a bit bigger and a little more complicated than th English machines. They are an order of magnitude bigger in every way and t is the point that I hope I have demonstrated in this talk.