EXPERIMENTAL RING-SHAPED 200-650 MEV STRONG-FOCUSING PROTON ACCELERATOR

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(presented by E. G. Komar)

The Scientific Research Institute of Electro-physical Instruments in Leningrad is about to complete assembly work on and start up a strong-focusing synchrotron designed for accelerating protons up to 650 Mev or, after various modifications, for accelerating electrons up to 1,300 Mev. The accelerator design provides for the possibility of extensive experimentation aimed at acquiring experience in adjusting and studying the operational conditions for strong-focusing accelerators and experimentally checking a number of theoretical problems. With these objects in view, liberal tolerances have been allowed for the magnetic characteristics of the equipment and a number of independent adjusting devices installed to permit the parameters of the synchrotron to be readily changed during experimental work.

Account has been taken in designing the accelerator of the limited floor space and available equipment. During the first period of research, the synchrotron is to accelerate protons up to 200 Mev. It represents the first strong-focusing proton accelerator.

1. *Specifications of the accelerator*

Maximum kinetic energy of protons with H∼10,000 Oersted	650 Mev
(At present, with H∼5,000 Oersted)	200 Mev
Diameter of the equilibrium orbit	10 m.
Diameter of the equilibrium orbit including straight sections	11 m.
Length of the orbit	33.5 m.
Number of magnets :	34 (17 pairs)
C-shaped bending magnets	31
E-shaped bending magnets	1
Straight X-shaped magnets	2
Length of the magnets	731.4 mm.
Radius of curvature of bending magnets	3,725 mm.
Length of interval between the magnets	250.8 mm.
Magnet gap at the equilibrium orbit	125 mm.
Magnetic field index n in a vertically focusing magnet	28.5
Magnetic field index in a horizontally focusing magnet	27.5
Number of vertical oscillations per revolution	3.30
Number of horizontal oscillations per revolution	3.20
Logarithmic derivative of the orbit length by momentum	0.09
Chamber with ellipsoid-shaped cross-section	78 × 139 mm.
Required pressure in chamber	$2\text{-}4.10^{-6}$ mm.Hg
Tolerance for n	± 1%
Tolerance for length of magnet	± 1 mm.
Tolerance for length of interval	± 3 mm.
Tolerance for azimuthal non-uniformity of the mean intensity of an individual magnet field at the ideal equilibrium orbit	± 1%
Acceleration time (up to the energy of 200 Mev)	0.65 sec.
Number of operating pulses per minute	4
Average energy acquired per revolution	106 eV
Voltage at each of the two accelerating electrodes	550 V
Frequency range of the accelerating voltage (at acceleration up to 200 Mev)	0.3-5Mc/s
Frequency range of the synchronous oscillations at acceleration up to 200 Mev)	1,460-1,060 c/s
Energy of particles at injection	0.5 Mev
Field at injection	274 Oersted
Diameter of injected beam	⩽ 4 mm.
Angular divergence of injected beam	⩽ 10′

2. *Brief description of the synchrotron*

The accelerator's magnet system consists of 34 independent magnets of which 32 are bending and 2 straight. The 2 straight "X-magnets" are mounted diametrically and have opposite focusing properties. In them are accelerating electrodes. One of the bending magnets, installed at the place of beam injection, has an E-shaped frame, i.e. its neutral pole is located on the inner side of the yoke. The other 31 magnets (the "C-magnets") have the neutral pole on the outside. The general view of the magnets and the diagram of their arrangement are shown in fig. 1.

The number of electromagnets and their parameters have been so chosen that the number of free oscillations per revolution will be small and correspond approximately to the median distance between adjacent parametric resonances. A selection of greater frequency of free oscillations would have led to more rigid requirements in respect of the magnet system which would have complicated the experiments carried out with the synchrotron.

In establishing more exact parameters for it, account was taken of the fringing field at the intervals between the magnets, which proves to be significant.

The dimensions of the operating chamber of the synchrotron are such that the tolerances on its magnetic characteristics are more liberal than in other strong-focusing plants. No account was taken, in evaluating them, of the possibilities afforded by the presence of the adjusting devices and this makes it possible to investigate the latter's effect without disturbing the operation of the synchrotron. Additional free space is reserved in the operating chamber, so that a study can be made of the influence of artificially introduced disturbances (in particular, the non-linearities of the magnetic field) and how to compensate them.

3. *Injection*

Inside injection was used in view of the limited floor space. In this case, the magnetic field helps to inflect the particles to the equilibrium orbit at the point where they are introduced. The injector is placed vertically inside the electromagnet ring. Injection is of the single turn type.

A 500-600 Kev cascade generator is used as a preliminary accelerator. The bend of the beam by 90° is effected by means of a bending magnet which enables the energy of particles to be stabilized to within $\pm 1\%$.

For greater accuracy of injection, the following appliances are installed to permit control of the movement of the beam: (1) A double magnet corrector consisting of two magnets with straight pole pieces and capable of producing a parallel shift of the beam in the horizontal and vertical directions by $\pm$ 20 mm. (2) Bending condensers for controlling the beam by an angle in the region from 0 to $10'$. (3) A strong-focusing magnet lens consisting of two identical quadrupole magnets with hyperbolic pole pieces. The lens permits control of the angle of beam divergence and its shape. (4) Three pairs of deflecting plates (two pairs outside and one pair inside the accelerator chamber) which inflect the beam to the equilibrium orbit. The time of voltage removal from the inflector plates is insignificant compared with the time of circulation of a particle (3.3×10^{-6} sec.) and amounts to 0.5×10^{-6} sec.

These devices make it possible to investigate the effect of the injection parameters on the accelerator's operational conditions.

4. *Adjusting devices*

The necessity of observing rigid tolerances for magnetic characteristics is one of the major problems arising in designing strong-focusing accelerators, and the use of adjusting devices which would permit greater tolerances is of great importance. They are intended to change the gradients and the field on the equilibrium orbit independently so as to ensure separate adjustment of the frequency and amplitude of free oscillations.

The accelerator as described above is equipped with several devices of this kind.

Windings are provided in the gap which make it possible to set up uniform radial and vertical magnetic fields. The radial field permits a shift in the plane of the equilibrium orbit.

In conjunction with the field set up by the additional windings on the electromagnet pole cores, the vertical field allows both the gradient and the field on the equilibrium orbit to be independently changed.

These windings help to compensate the random harmonics of azimuthal non-uniformity of the magnetic field thereby making it possible in principle to relax considerably the tolerance requirements in respect of the magnet characteristics and their setting.

The additional windings may be used either permanently in the operation of the accelerator or during adjustment with a view to determining any necessary corrections in assembly. In the latter case, the dimensions of the windings are found to be extremely small, as they are used only for weak magnetic fields at the beginning of the acceleration cycle.

Special devices have been provided for precise shifting of the magnets in the radial and vertical directions.

Apart from the additional windings and assembling operations, arrangements have been made for the special additional power supply to the quadrupole X-magnets with a zero field on the equilibrium orbit in order to adjust the frequency of free oscillations. The decrease of 1% in the value of the index in the bending magnets is compensated by changing the gradients in both X-magnets within the approximate range of -8% to $+8\%$. A change in the index in one X-magnet alone permits the relationship of frequency of the vertical and horizontal oscillations to be altered artificially.

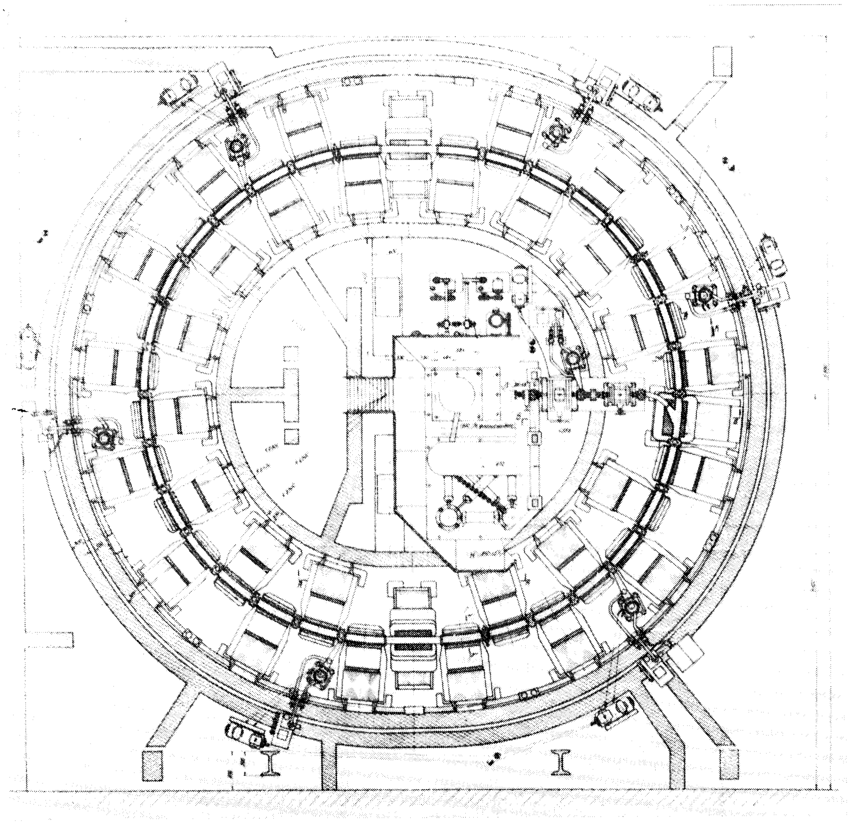

Fig. 1.

DISCUSSION

M. H. Blewett: I would like to add some information about the Brookhaven A.G. magnet. The magnet is, in general, similar to the CERN design, with the same unpleasant problems that C. A. Ramm has discussed in his lecture.

The following differences are worth pointing out:

1. The $\frac{1}{2}$F, $\frac{1}{2}$D magnets are separated and have separate coils, which is mechanically favourable because it allows having each magnet straight. The back legs alternate every 15 degrees along the orbit. Each group (15° in azimuth) is separated by straight (no field) sections of 3 meters. This will make experiments easier when the machine is being operated because, for different target locations, it will allow the study of emergent particles at all angles both on the inside and the outside of the proton orbit.

2. About the magnet shape (profile). I agree with Ramm about saturation at the sharp corner where the field is maximum but my calculations showed that saturation extends throughout the length of the pole (shown as a shaded region in the figure). Thus, iron has been added on this side and the rounded corner is displaced (as shown in the figure). This extends the pole and the equilibrium orbit is no longer at the centre of the profile. Moreover, to extend the region of constant gradient on the low-field side, iron has been removed from the open side of the pole. This increases the asymmetry in location of the equilibrium orbit so that, finally, the equilibrium orbit is 1 inch from the geometric center of the pole.

This asymmetry gives a small difference in field values between the open and closed sections at remanent and injection fields but this difference alternates regularly and rapidly along the orbit and calculations show that the effect on the particles is very small.

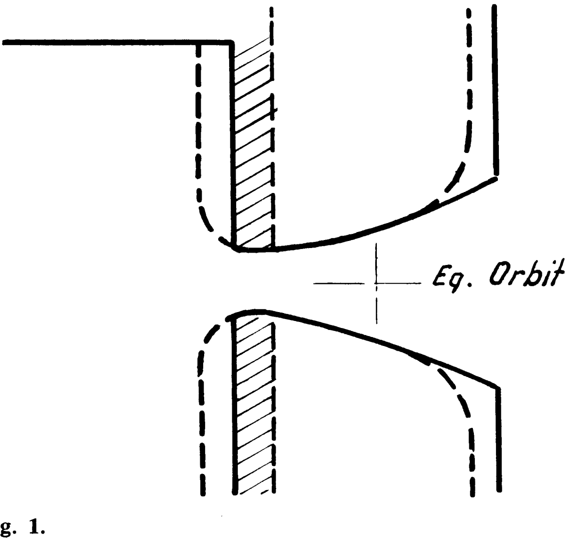

Fig. 1.

3. In connection with ageing, some promising results have been obtained from a special processing of low-silicon steel carried out on a laboratory scale by one manufacturer. Steel sheets, after cutting, were artificially aged by keeping them at 150 °C for 5 days. The coercive force increased and the low-induction permeability decreased, as expected. But a stress-relieving anneal, made for about 2 hours at 1450 °F brought these parameters back to almost their original values and produced a fair degree of stability against further ageing.

4. At present we plan only to use quadrupole and sextupole lenses, but no pole face windings.

M. G. N. Hine: I would like to comment about one inconvenience of having a large gap between $\frac{1}{2}$F and $\frac{1}{2}$D sectors. As shown by the sketch fig. 2.

The stray fields increase the equivalent length of F and D magnets in opposite directions: in fact the equivalent length is greater for the wide part of the gap than for the narrow one. On the equilibrium orbit both sectors appear to have the same increase in length, but for trajectories displaced radially with respect to the equilibrium orbit, the F sector appears longer, and the D shorter (or *vice versa*). 2 cm. radial displacements already bring the working point a long way across the working diamond.

If the $\frac{1}{2}$F and $\frac{1}{2}$D sectors are joined (with a small proper spacing of some few cm.) the effects cancel out almost completely with the junction effect, as was shown by a series of measurements taken at CERN. See the following sketch fig. 3.

M. H. Blewett: The effect remarked by Hine is true, but our calculations show that it should be fairly easy to compensate with sextupole lenses.

H. Bruck: In the steel delivered for the proton-synchrotron at Saclay we have remarked a correlation between the dispersion of the remnant field of the blocs and the variation of the maximum temperature in the annealing process of the steel. During the temperature rise, the maximum temperature of 630 °C (fig. 4) was slightly overcome for a short time, and of different amounts. We found experimentally the law relating the variations of the remanant field value to these variations of the maximum temperature:

$$\frac{1}{B_{\text{rem}}} \cdot \frac{d\,B_{\text{rem}}}{d\theta_{\max}} = -\,3.5^{-3}\,(^{\circ}\text{C})^{-1}$$

To the temperature dispersion $\delta\theta_{\max} = \pm\,13\ ^{\circ}\text{C}$ corresponds a dispersion

$$\delta\,B_{\text{rem}}/B_{\text{rem}_{\max}} = \pm\,4\%$$

F. S. Shoemaker: Some steel is rolled in packs of several layers. This process often causes the difference from sheet to sheet in a batch to be much larger than the difference from batch to batch.

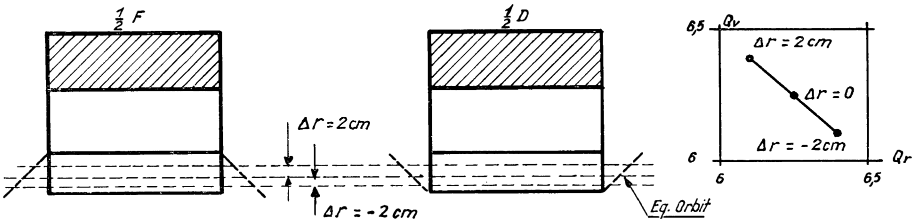

Fig. 2.

S. D. Winter: 1. The same effect as mentioned by F. S. Shoemaker exists in annealing, where there is a temperature gradient through the batch.

2. The method of the wrinkled magnet suggested by Bruck to correct bad effects of saturation on n seems only applicable when n increases with B, since it is based on saturation of the protruding sheets. However, the figures shown by Ramm about the effect of rounding off the sharp corner suggest that the method of Bruck would have been applicable also in this case, giving the advantage of a larger "n-plateau" at medium fields.

H. Bruck: The method of the wrinkled polar surface can be used whatever the n error is, because it is a general method that re-establishes the pole faces as an equipotential surface in a predetermined way whatever may be the form of the pole faces or the nature of the n error.

G. Brianti: In the annealing process of steel, the cooling time has an influence as important as the maximum temperature on the final magnetic properties. The rate of cooling also affects ageing very much.

E. G. Komar (to H. Bruck and M. H. Blewett): Have you taken dynamic measurements at Saclay and at Brookhaven? If so, did you find any difference between the static data and dynamic results?

E. G. Komar (to J. W. Blamey): Did you take measurements of eddy current effects in the Australian machine?

H. Bruck: All measurements made at present in Saclay are dynamic. No appreciable distortion of n and of ampère-turns consumption were detectable, though the models measured has laminations 1 cm. thick. The speed of rise of the field was $B_0 = 20$ kg/sec.

M. H. Blewett: We have made measurements at Brookhaven on model magnets, full-scale in cross section of both the open and closed shapes, each about 1 meter long, with laminations 1 inch thick. There were strong eddy-current effects present in the dynamic fields and gradients but the shape of the remanent field was such that these effects were almost entirely compensated. Thus, the n-value at injection (120 gauss) values was very closely

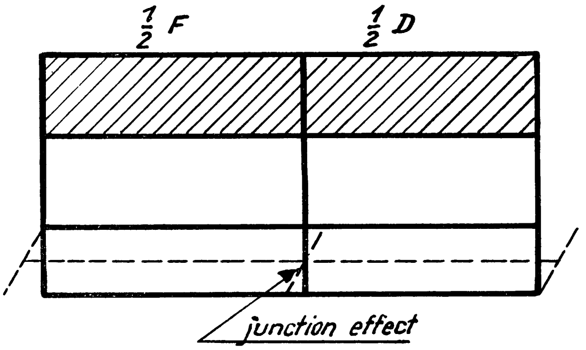

Fig. 3.

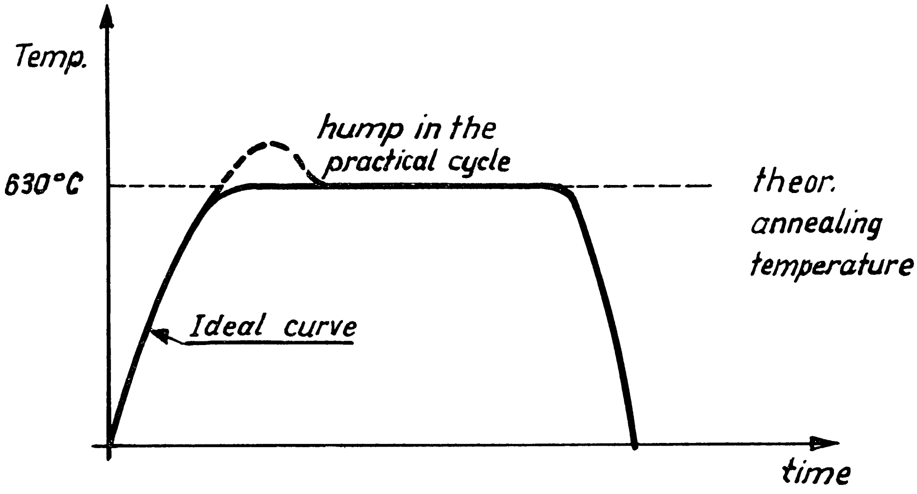

Fig. 4.

the same as that at higher fields and remained constant until saturation was reached.

However, it is fairly certain that the Brookhaven A.G. magnet will consist of 1 mm. thick laminations because of the influence of eddy currents on the values of the remanent field, that is, because of the fact that the remanent field value for thick laminations changes radically with the magnet pulse length.

We are now in the process of making measurements on magnet models with laminations about 1 mm. thick.

J. W. Blamey: The magnetic fields of first order eddy currents in the copper conductors and other parts were computed. But also second order effects involving eddy currents with a continuous range of time constants up to a few milliseconds may be dangerous.

No experimental measurements of eddy current fields have been made. The half quadrant model working on 50 cycle A.C. was built for other purposes such as measurement of field distribution at the ends.

Neither full computation nor experimental determination of eddy current fields can be justified, even if possible. Measurement will be made on the full sized magnet, and currents through correcting conductor uniformity disposed around the vacuum box will be regulated with time to give continuous correction for eddy currents.