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ON THE USE OF ELECTRIC CURRENTS TO INCREASE THE RADIAL EXTENT OF THE FOCUSING REGION IN THE INFN ELECTRON-SYNCHROTRON

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(presented by G. Salvini)

1. *Introduction*

The gap for the donut in the present design of our electron-synchrotron has dimensions 22.7 cm. (horizontal) × 8.6 cm. (vertical), (see [1]) and also the main data of our project at the end of these notes).

The profile of the pole tips is given in fig. 1. As usual, we provided tips at the inside and outside of the poles for maximizing the region where our field has an n-value which is focusing (for our constant field-exponent n, we choose the value $n_0 = 0.61$). In fig. 1 (full points) is given the extension of this useful area (area A), as measured in direct current without any correcting coil.

The solid dots indicate the position where n has a value:

$$n_0 - .15 \leqslant n \leqslant n_0 + .15$$

As well known, the dimensions of the gap are mainly fixed by the requirements at low fields, that is when the n value in the gap may be corrected with convenient electric currents. In fact the amplitudes of the betatron and synchrotron oscillations of the beam decrease during the acceleration, and therefore a large gap is required at injection, while its dimensions could really be reduced during the acceleration (see § 3). Therefore we consider convenient any device which allows an enlargement of the useful region A of fig. 1 at low field, without changing the shape of the iron poles, that is without requiring increase of power and weight of the magnet.

The convenience of enlarging the region A at injection is an obvious consequence of the theory, and some proposal were made in the past[2]. For instance Dr. Wilson mentioned his attempt of using poles which were enlarged radially with a thin wing of iron, which could saturate at high field.

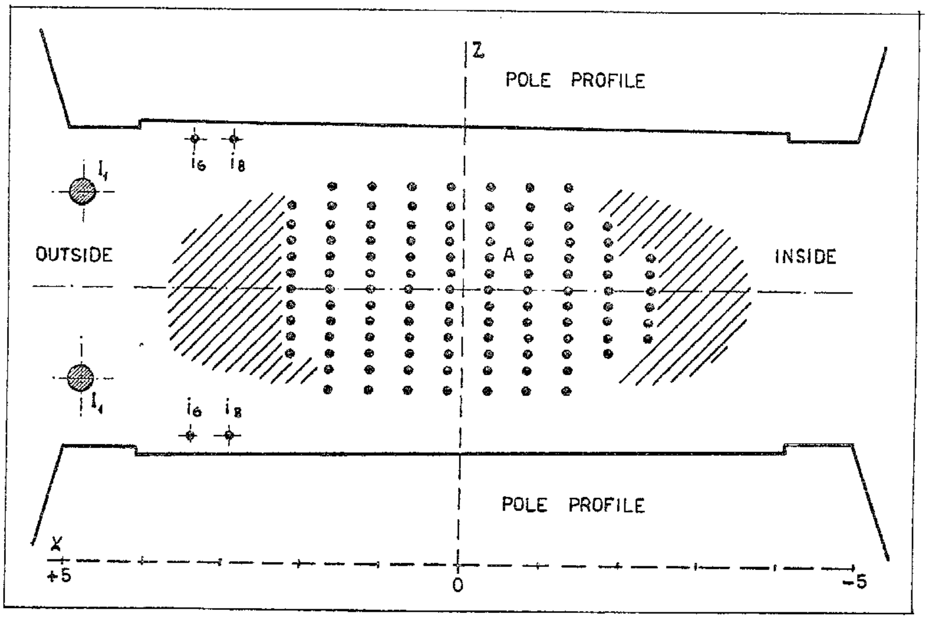

Fig. 1.

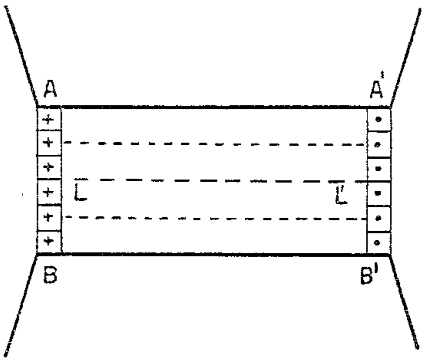

Fig. 2a.

The present note is concerned with the attempt of enlarging the region A at low field by a distribution of electric currents (widening coils = w. coils) inside the gap.

The results are quite promising on the d.c. models (§ 4, 5), but still many tests (§ 6) have to be done before we can positively trust this technique for actual use in our e.s.

The w. coils we employed are not supposed to change with the azimuth in each quadrant, and can therefore be represented by points or circles as in fig. 1 (currents I_1, i_6, i_8).

2. *Two examples will give an intuitive idea of the line we followed in our research for enlarging the region A*

a) If a magnet is excited with its excitation coils linearly distributed along the gap (see fig. 2,a), the magnetic potential will be linearly distributed from the equipotential A A' (upper pole) to the equipotential B B' (lower pole).

The magnetic equipotential lines inside the gap will be parallel lines (L L' is one of them) and the magnetic field will be rather uniform in all the gap[3]). The situation will be different, and we would have a non uniform field, in case the excitation coils are removed from the gap and they are brought in positions like M M', N N' (fig. 2,b). In this case the equipotential lines which go from M to M' will be no longer straight, and the field **B** will have the behaviour indicated in the same fig. 2,b.

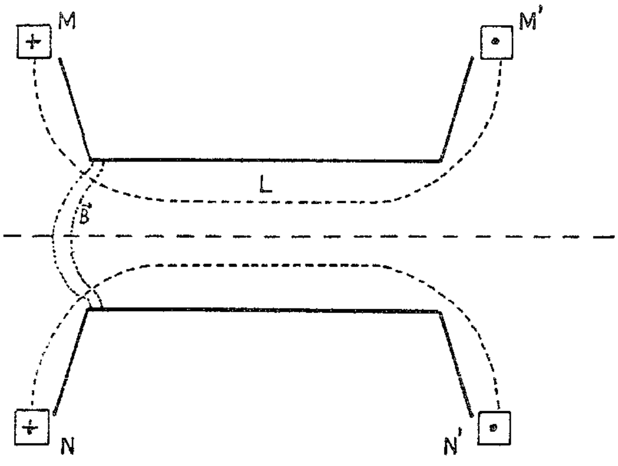

Fig. 2b.

In a sense we can say that bringing the excitation in the position of fig. 2,a is equivalent, in the region A A' B B', to enlarge the poles radially from $-\infty$ to $+\infty$.

b) The problem of enlarging the useful area A may be considered equivalent to that of straightening the equipotential lines L (fig. 2,b), so that they become more parallel and the region where **B** is uniform, is enlarged (we consider in this example that the focusing field of the e.s. is different from a uniform one by a small perturbation).

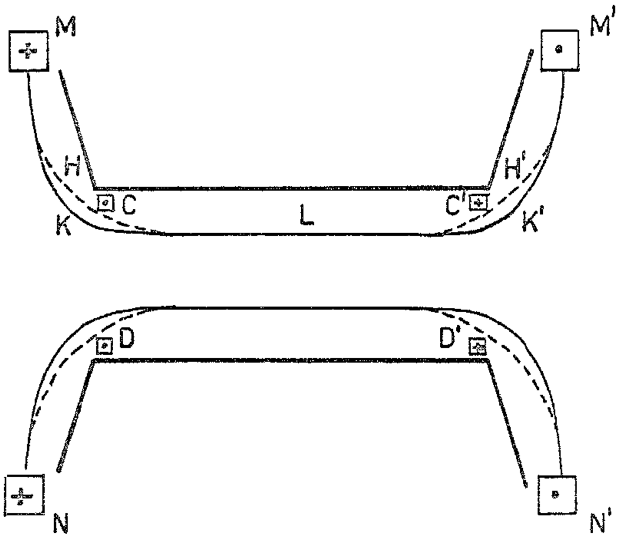

Fig. 2c.

We cannot dispose the excitation coils of the magnet as in fig. 2,a, at least in our present design, but we can try to straighten the equipotentials in another way, which is by sending electric currents inside the gap, for instance in the position C C' D D', with an opposite sign, that is C, D opposite to M, N, and C', D' opposite in sign to M', N' (see fig. 2,c).

A line MHLH'M' will be straightened in the new line MKLK'M' for the effect of the opposite currents C, D, C', D'. Therefore, using such a set of opposite currents, the magnetic field **B** will become more uniform.

3. *Time dependence of the enlargement of the region A*

We cannot provide the enlargement of the useful region for the full cycle, for obvious reasons (lack of room and excitation difficulties). But, as we said at the beginning, this requirement need to be fulfilled, because the oscillations of the particles are much larger at very low fields than at higher fields.

The most important oscillations are those due to the process of injection, more than those due to gas scattering and field inhomogeneities[4].

The energy dependence of the damping of the betatron and synchrotron oscillations is well known: the amplitude of the former vary like the energy to $-\frac{1}{2}$ [5] the amplitude of the latter vary like the energy to $-{}^3/_4$ [6].

The long lasting term is therefore the betatron term; accordingly we can calculate at which energy the betatron oscillations, which at the injection have the amplitude of the enlarged region, will be reduced to the amplitude of the region marked with full points in fig. 1.

As we found possible to get an enlargement factor of about 1,5, we can calculate that if at the injection the particles occupy a radial extension of 1,5 (in arbitrary units), at about 50 gauss they should be reduced to an extension 1.

This calculation is probably a little too optimistic; in practice we are planning to run the w. coils up to 100 gauss; the required values of currents are not too large, as we shall see in § 5.

4. *The method*

a) The field inside the gap may be expressed with a map of the field where the value of $n = n\,(x, z)$ is given for different positions x, z. The coordinaties x, z indicate the positions in the cross section of the gap (see, for instance, fig. 1).

Suppose we have such a map : $n = n\,(x, z)$. From this we can easily derive a map $dB_z/dx = dB_z\,(x,z)/dx$. In fact :

$$n = -\,dB_z(x,z)/dx \cdot (r_0 + x)/B_z(x,z) \quad ,$$

where r_0 is the radius of the equilibrium orbit in our synchrotron, B_z is the vertical component of the field in the point of coordinates x, z.

Let us denote by $[dB_z/dx]_0 = N^0$ the values we obtained with the best position of our tips in the poles, without w. coils. The useful region will have an extension as already indicated in fig. 1 (full points).

The w. coils have the purpose of changing the value of $dB_z/dx = N$ in the points which would otherwise be out of the useful region, so that the region A may include those points too.

Suppose that $N^p(x,z)$ is the value of N which a point x,z should have to be focusing. The correction of the widening coils has to be in this case :

$$\Delta N = N^p - N^0 \tag{1}$$

If we have at our disposal a total number of m currents, each of these will contribute to change the value of N of an amount which is proportional to the value i_l of the current and independent (with good approximation) of the values of the currents in the other coils. Thus we can write :

$$\Delta N_r = \sum_{l=1}^{m} i_l \cdot K_{r,l} \tag{2}$$

where the index r indicates a particular point of coordinates x, z. The coefficients $K_{r,l}$ are specific of a given point r and of a given current l.

These coefficients $K_{r,l}$ may be determined experimentally (as we did) by measuring Δ N (with a fluxmeter) when only one of the currents i_l is different from zero.

All the experimental data of interest for the formulation of the problem have been obtained by magnetic measurements performed on a magnetic model of the synchrotron in a 1 : 2,3 scale. The instrument employed is an electronic fluxmeter of the type described by Dicke [7] and improved by Dr. G. Ghigo [8] (see our report MM/02), whose sensitivity is of 50 lines. All measurements were made on a static field of 280 gauss to minimize the influence of possible remanent field and to avoid too high values of the widening currents. At such field it is possible to measure the variation ΔB_z of the vertical component B_z on a base $\Delta r = 0{,}5$ cm., with a 4% accuracy, when n has a value of the order of one.

Having at our disposal m currents, we may adjust m points. The values of the currents we need will be obtained by resolving the system (consequence of (2)) :

$$\begin{aligned} \Delta N_1 &= \sum_{l=1}^{m} i_l \cdot K_{1,l} \\ &\;\;\vdots \\ \Delta N_m &= \sum_{l=1}^{m} i_l \cdot K_{m,l} \end{aligned} \tag{3}$$

of m equations in the m unknown quantities i_l, in which $\Delta N_1, \ldots\ldots, \Delta N_m$ are given by (1).

b) At this point the main question is the following : will the other points of the map which are around the m chosen points assume also a good N value, as an effect of the i_l currents, or not?

Our results (§ 5) give a positive reply to these questions.

5. *Results*

We will not report here our numerous attempts with 3, 4, ..., 10 currents; we prefer to summarize our results as follows :

— It is possible to avoid ill-conditioned systems : in fact, by choosing the position of the current, we may avoid too low values of the determinant of the $K_{r,l}$'s and too high (and critical) values of the currents i_l.

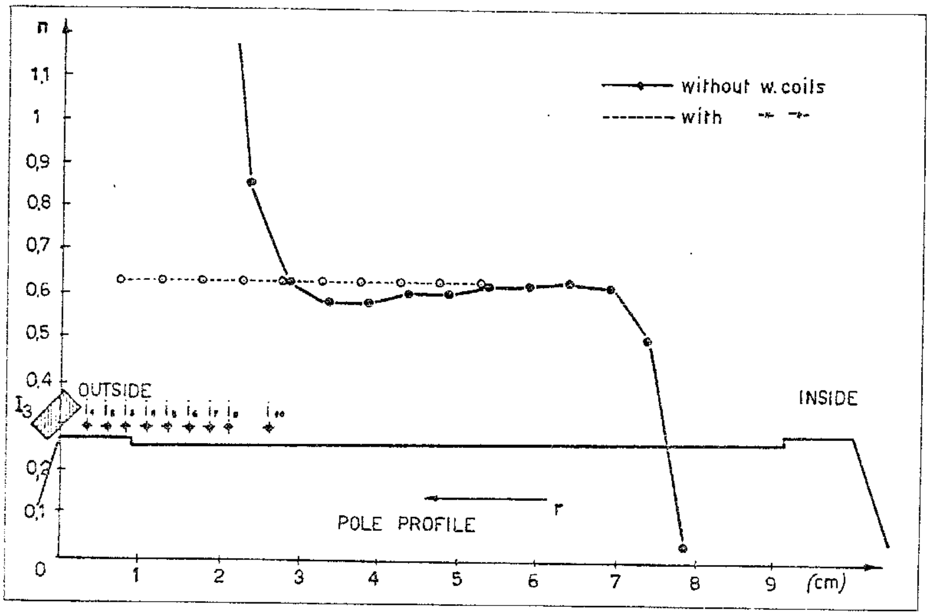

Fig. 3.

— To have a general information on the conditions of the systems [3] we solved a system of 10 currents in ten points.

The system was solved with the Finac electronic computer of the Istituto Superiore del Calcolo.

The results of the system are given in fig. 3. The values of the currents $i_1, \ldots, i_{10}$ range from –12 to + 10 Ampere with a field of 280 Gauss. The current I_3 has a value of – 172 Ampere.

Of course we aim to obtain the enlargement of the useful region A with a number of independent currents smaller than 10.

After experimental examination of many currents in many places we arrived to the conclusion that a good arrangement may be the following: one strong current (of the order of 100-200 Ampere at 150 gauss in a position like I_1 of fig. 1. Two or three small currents in some position below the poles.

The results of fig. 4 were obtained with only three currents I_1, i_6, i_8, whose positions are plotted in fig. 1. In fig. 4 the values of n are given versus the radial position, taken in the median plane (curve a). As we see from comparison with curve b) (which gives the best values without the currents and with the field shaped from the pole tips

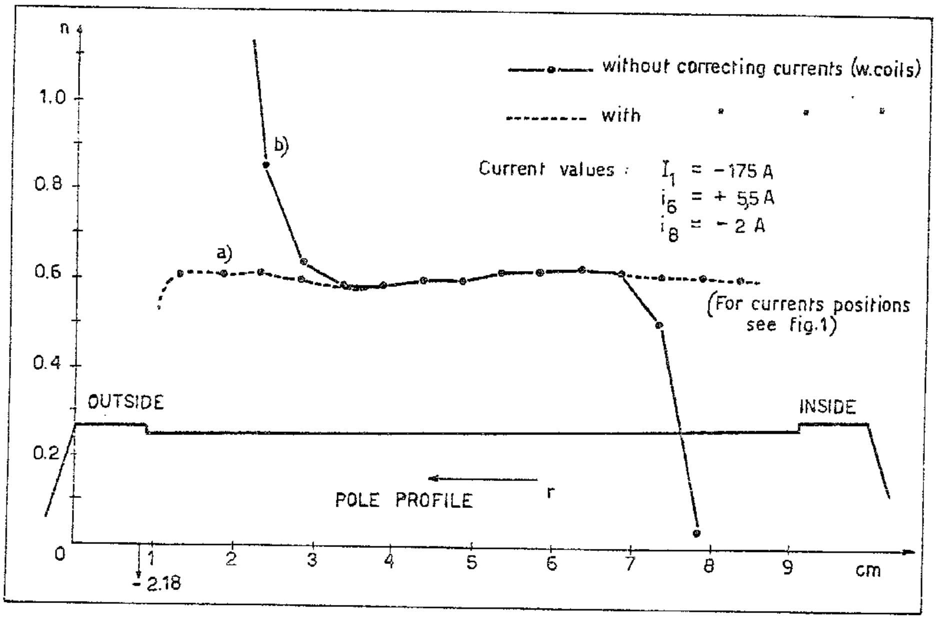

Fig. 1.

only), the enlargement of the left half of the aperture is of the order of 50%. The results refer to 280 gauss for the following values of the currents:

$I_1 = -175$ Amp.; $i_6 = +5{,}5$ Amp.; $i_8 = -2$ Amp.

The minus sign means that the current flows in the same direction as the excitation current in the main internal coil. The uncertainty in the value of n is of the order of $\pm .06$.

It is encouraging to note the relatively low value of the currents. We did not try yet to enlarge the right half of the gap, but we reasonably expect the same gain on that side too. The estimated enlargement on the right side is indicated by the dotted line.

The points out of the median plane benefit also of the correction of the w. coils (otherwise the correction would be useless or damaging). In fig. 1 we indicate in the dashed region the enlargement of the useful region by means of the w. coils. Only a small number of measurements were taken out of the median plane, and more are in program on the full-size model which is going to be ready. In fact the present results still are affected by large errors.

— Perhaps it is possible to get a good result with only one coil of many turns in series, conveniently disposed with only one value of the current. This would make the problem easier than with 3 or more independent currents.

6. *Difficulties*

Before one can consider reliable the described method of enlarging the useful region at injection one has to solve the following problems.

— The geometrical position of the enlarging coils has to be very accurate, if we have to adjust points which have, without w. coils, a value of the index n of a few units. We estimate that for the current I_1 a precision of the order of $\pm .2$ mm. in position is required.

— The currents i_l will obviously change with time with the same law as the vector **B**. If we have to adjust points with high n-values (for instance $n = 2$), we need a precision in the instantaneous value of the current of the order of 1%.

Considering that in our synchrotron 1) we have at injection $B_z = 22.7$ gauss; $dB_z/dt = 1.5 \times 10^5$ gauss/sec, we obtain:

$$\Delta t = \frac{22.7}{1.5 \times 10^5 \times 10^2} = 15 \times 10^{-7} = 1.5 \times 10^{-6} \text{ sec.}$$

Thus, if we shall pulse the currents i_l, the time shifts between the currents and the field B shall not fluctuate by more than 1 or 2 μseconds.

The electronic equipment for producing and controlling the currents i_l in the final arrangement is being studied by Dr. Amman.

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