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MAGNET OF A SYNCHROTRON.

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## FIELD STABILIZATION IN A D.C.—A.C. EXCITED MAGNET OF A SYNCHROTRON

G. GHIGO and I. F. QUERCIA

*Istituto Nazionale di Fisica Nucleare Sezione Acceleratore, Roma*

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The shape of the magnetic field of an Electron-Synchrotron is quite critical at injection. If the machine is fed with an A.C. current and with a bias D.C. current, the shape of the field at injection is quite sensitive to the values of the peak A.C. current and of the D.C. current. A device is described that is sensitive to the difference between peak A.C. and

D.C. current and which keeps this difference constant by controlling the value of the D.C. current. The apparatus was applied to model magnets of the 1 GeV Italian Electron-Synchrotron, and is planned for controlling the supply of the Synchrotron.

1. In the design of an Electron-Synchrotron much care must be given to the values of the magnetic parameters at the time of injection. In fact the field in the gap at injection is only a few gauss, and both the remanent field and the eddy currents have a very large effect on the space and time distribution of the field. For keeping the field distribution the same in every cycle it is very important to keep constant the value of the peak reverse field, and the value of the rate of rise of the field at injection time.

will be of course composed of an A.C. sinusoidal component and a D.C. component. As fig. 1 shows, the peak reverse value of the field  $B_r$ , is just the difference between the peak value of the A.C. component  $B_a$ , and the value of the D.C. component  $B_c$ . Suppose that we want a peak positive value of the field of 9260 gauss, and a peak reverse field  $B_r = 200$  gauss: this gives  $B_a = 4730$  gauss and  $B_c = 4530$  gauss.

If we will be able to stabilize the D.C. current and the A.C. current feeding the magnet in such a way that independent variations of  $B_a$  and  $B_c$  will be limited at  $\pm 0.1\%$ , the possible variation of  $B_r$  will still be about 5%. Moreover this variation of  $B_r$  is accompanied by a change of about 2.5% of the rate of the rise

$$\dot{B} = \frac{dB}{dt}$$

of the field at injection.

To reach a 0.1% stability in the performance of the heavy machinery that supplies the magnet is not very easy, and to ask for a higher degree of stability is very expensive, or may be impossible.

For this reason we considered the possibility of approaching the problem in a quite different way. We started from the observation that what we need is some kind of stabilization of the reverse peak value of the magnetic field; we can let the A.C. magnetic field vary in a reasonable

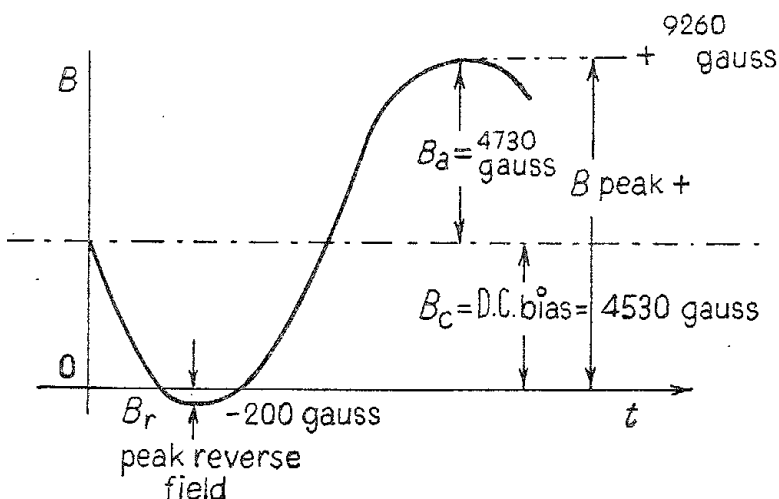


Fig. 1

In the project for 1 GeV Italian Electron-Synchrotron (4) we shall excite the magnet with a 20 c/s sinusoidal current and with a bias direct current. The resulting magnetic field in the gap

range if we are able to track the A.C. field with the D.C. field in such a way that the peak reverse value of the total field is maintained within allowed limits.

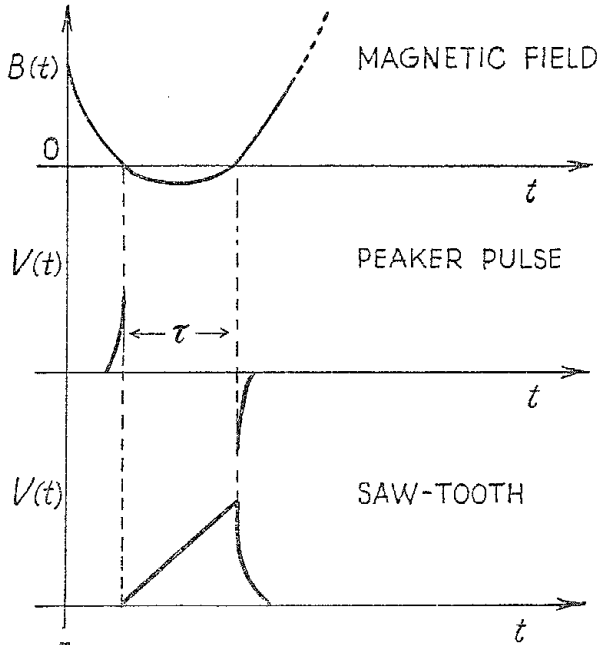


Fig. 2

This of course leads to the problem of measuring the value of the peak reverse field.

The most obvious way to measure it, seems to be to measure the difference between the peak value of the A.C. current, and the value of the D.C. current. Unfortunately the currents to be measured are so high that a voltage drop of 1 Volt corresponds to some kilowatt of power,

of some millivolts which can not be easily suppressed. For these reasons we found it more convenient to leave the idea of measuring the components of the current feeding the magnet and to use a device sensitive directly to the peak value of the reverse magnetic field.

2. The device consists of a probe containing a peaking strip surrounded by a pick-up coil. The probe is placed in the fringing field of the synchrotron magnet. As is well known (see for instance ref. <sup>1</sup>) a voltage pulse is generated by the peaking strip in the pick-up coil, every time the magnetic field crosses the null value. Pulses change their polarity according to the sign of the time derivative of the magnetic field.

Following the wave forms shown in fig. 2, the first positive pulse starts a saw-tooth wave form generator, while the second negative pulse stops the saw-tooth. The peak value of the saw-tooth wave results to be function of the peak reverse value of the magnetic field.

Through a vacuum tube peak voltmeter, the peak value of the saw-tooth is compared with a reference voltage; the error voltage drives a power amplifier that controls the excitation current of the D.C. generator feeding the magnet. The block diagram of the apparatus is shown in fig. 3. The control loop acts as follows: suppose the peak reverse magnetic field is increasing; the time  $\tau$  between the two peaker pulses also

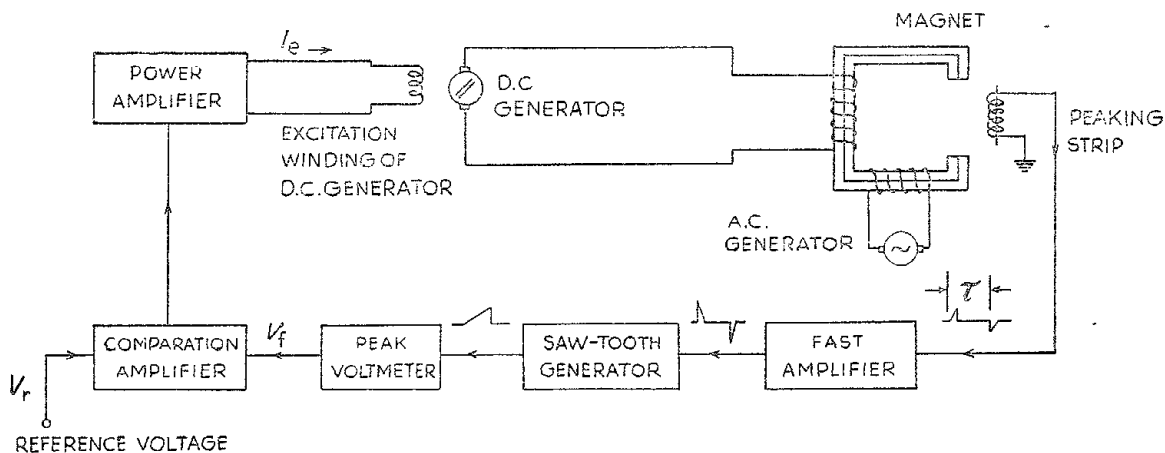


Fig. 3

and we can not hope to be able to measure D.C. voltages of less than 1 Volt with an accuracy better than 10 mV. In fact any electronic device for measuring D.C. voltages is affected by a drift

increases; the peak of the saw-tooth wave is raised and the voltage  $V_f$  developed by the peak voltmeter is no more equal to the reference

<sup>1</sup> G. Diambrini, Nuovo Cimento X 3 (1956) 336.

voltage  $V_r$ . The error voltage ( $V_i - V_r$ ) drives the current amplifier resulting in an increase  $dI_e$  of the excitation current of the D.C. generator. The D.C. bias of the magnet is raised, and the peak value of the reverse field is adjusted to the correct value.

3. It is easy to show that the effect of the device is to reduce the variation  $dB_r$  of the peak reverse field as consequence of a variation  $dB_a$  of the peak value of A.C. field, according to the formula:

$$dB_r = \frac{dB_a}{1+L}$$

where  $L$  is the gain of the feed-back loop. (see for instance ref. <sup>2</sup>). Of course, according to the general rules of feed-back loops<sup>3</sup>, the value of the loop gain  $L$  is limited by the Nyquist stability criterion. In our case part of the loop

frequency response of the open loop to be of the "dominant lag" type (see e.g. (2)).

It can be demonstrated that a loop like this is stable if the zero frequency loop gain  $L(0)$ , is limited by the following relation:

$$L(0) < \frac{T}{\theta}.$$

The latter equation shows that we must choose a compromise between the stabilization factor  $1 + L$  and the response speed of the loop.

If we want to increase the stabilization effect of the system, we must increase the time-lag  $T$ ; as a consequence we loose any control over fast transient in the value of the peak reverse field  $B_r$ .

4. We have applied the stabilization system described in the previous paragraphs to a model

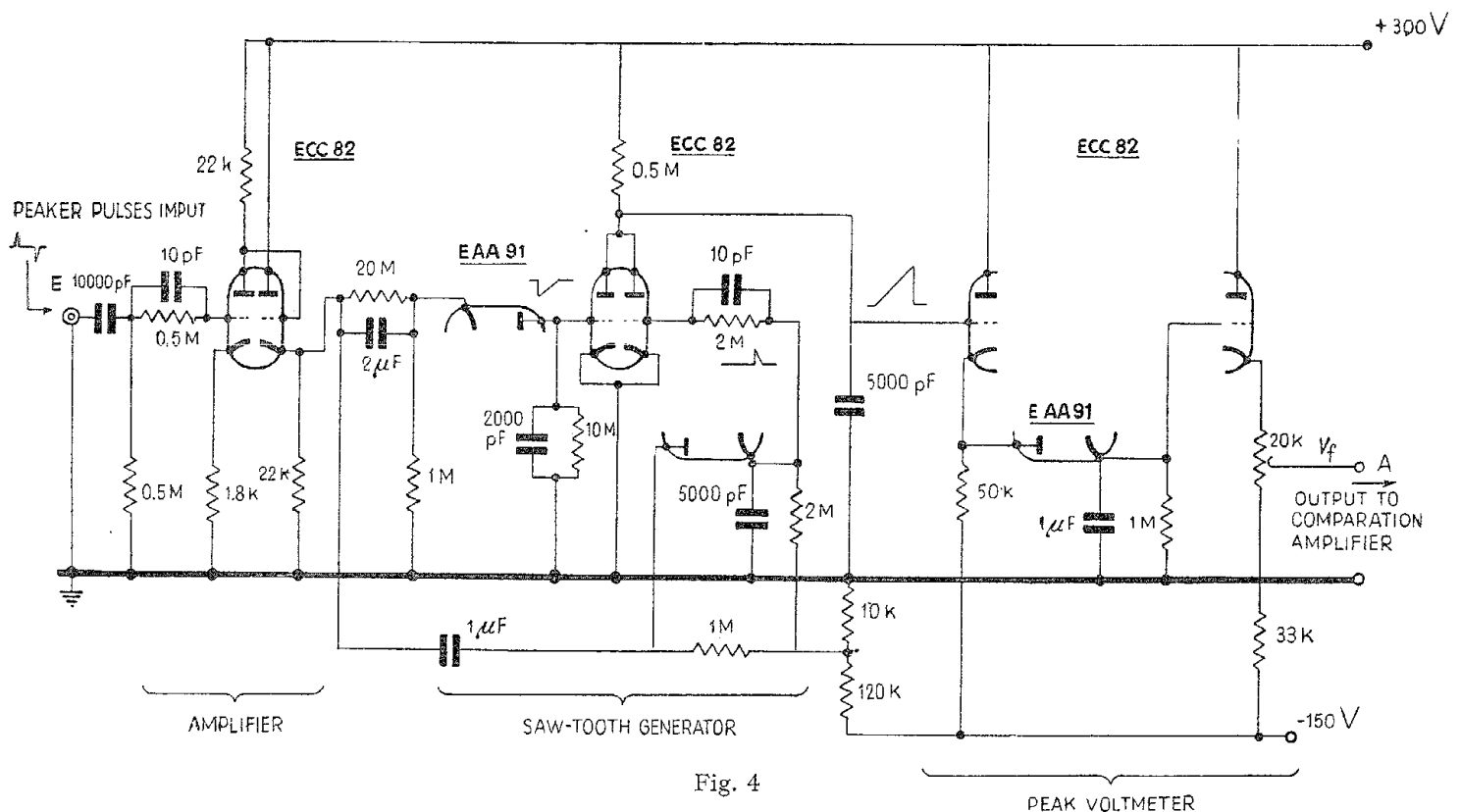


Fig. 4

carries an intermittent information, with a repetition rate corresponding to the frequency of the A.C. generator supplying the magnet. This fact introduces an unavoidable delay time  $\theta$  between two successive informations.

Moreover we can suppose that the electro-mechanical part of the system introduces a very big time lag  $T$ , so that we can consider the

magnet of the 1 GeV electronsynchrotron to be built in Frascati<sup>4</sup>). The magnet excitation coil

<sup>2</sup>) J. G. Thomason, Linear Feed-back Analysis (Mc Graw Hill, 1955).

<sup>3</sup>) H. W. Bode, Network Analysis and Feed-back amplifiers design, (D. van Nostrand Co., 1953).

<sup>4</sup>) G. Salvini, Caratteristiche dello Elettrosincrotrone da 1000 MeV (I.N.F.N. Sezione Acceleratore G. 19, 31 Ottobre 1955).

was paralleled by a condenser bank in resonance at 50 c/s.

The  $Q$  value of the resonating LC circuit was about 20. The A.C. excitation current was taken from a transformer directly from the mains.

The D.C. bias excitation current was supplied from a 13 kW generator driven by an asynchronous motor. The field of the D.C. generator, was supplied by a smaller 0.2 kW, D.C. generator. The field of this small D.C. generator was supplied from the electronic power amplifier to be described later.

Variations of the peak value of the A.C. field of the order of  $\pm 10\%$  were observed, due the instability of both the voltage and frequency of the mains. In fact the A.C. current in the magnet was very sensitive to the value of the frequency as a consequence of the high  $Q$  value of the LC resonating circuit.

We had to operate the magnet with the following approximate values of the field:

A change of only  $-5\%$  of the  $B_a$  value causes the reverse field to disappear completely, with the consequence of changing drastically the remanent field in the iron of the magnet, and of course the slope of the field at injection.

As sensitive element we used a Mu-metal wire of 0.05 mm diameter and about 40 mm length. This peaking strip was surrounded in the middle by a 400 turns pick-up coil. Pulses of about 60 mV induced in the pick-up coil, were amplified by a conventional fast amplifier of gain 100, and injected in the electronic device of fig. 4. The peak value  $V_f$  of the saw-tooth wave form was compared with a reference voltage  $V_r$  in the electronic device of fig. 5, and the resulting error voltage drove the power amplifier (two 807 valves).

The zero frequency loop gain  $L(0)$  can be changed simply by changing the RC time constant of the saw-tooth wave generator.

In order to choose the correct value of loop

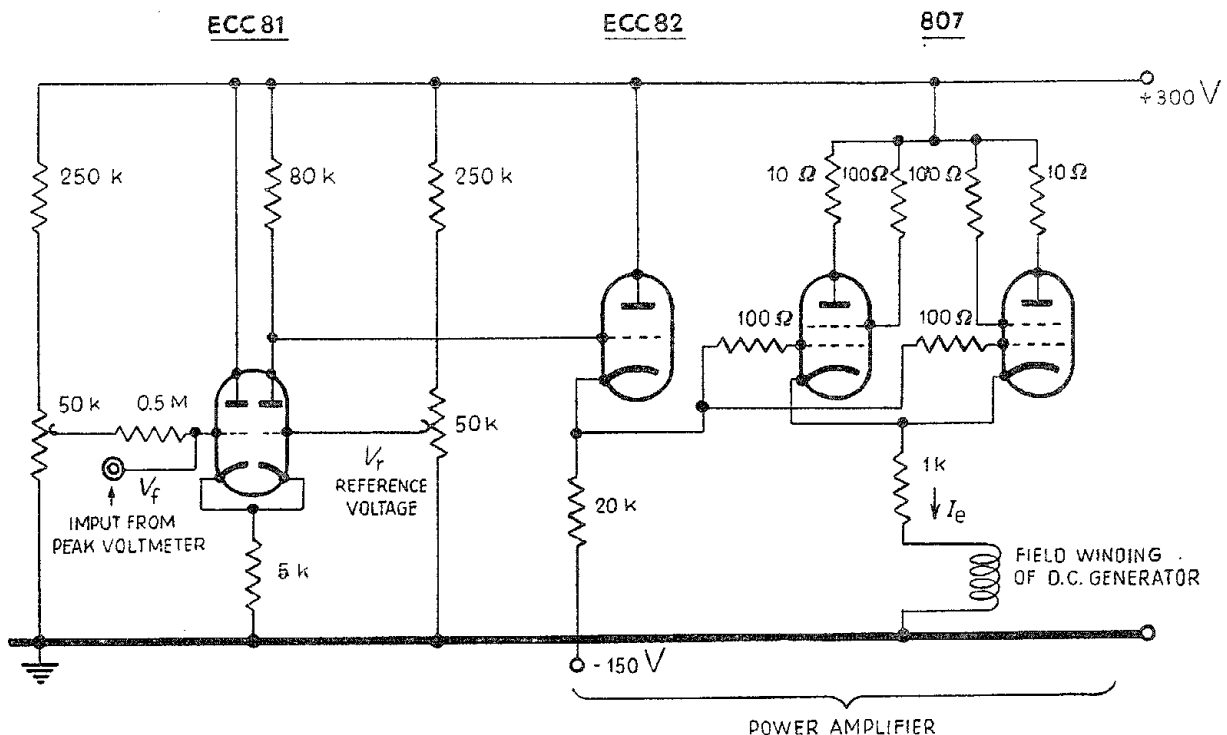


Fig. 5

Peak positive value of the field  $\approx 8500$  gauss.

Peak reverse value of the field  $\approx 200$  gauss.

It follows that the A.C. component of the field has a peak value  $B_a \approx 4,350$  gauss, and the D.C. component has a valued of  $B_c \approx 4150$  gauss.

gain, supposing that the main lag-time  $T$  is introduced by the chain: D.C. exciter—D.C. Generator—Magnet, we measured the rate of rise of the magnetic field in the gap due to a step pulse of current supplied by the power amplifier.

We observed a rise time corresponding to

$T = 0.9$  seconds. Because the delay between two successive informations corresponds to  $1/50$  of a second, according to the discussion of § 3, we decided to have a loop gain  $L(0) = 30$ .

In the operating conditions we had a loop gain of:

$$L(0) = 32.5.$$

With this device the long term stability of the peak reverse value of  $B_r$  was observed to be about  $\pm 10\%$ .

to control the field in the magnet of our Electron-Synchrotron.

Of course it is possible to use other quantities, than the time  $\tau$ , for measuring and controlling the shape of the field at injection. For instance the Cornell Synchrotron Group developed a device<sup>5)</sup> that samples the value of

$$\dot{B} = \frac{dB}{dt}$$

at injection time, and controls the A.C. compo-

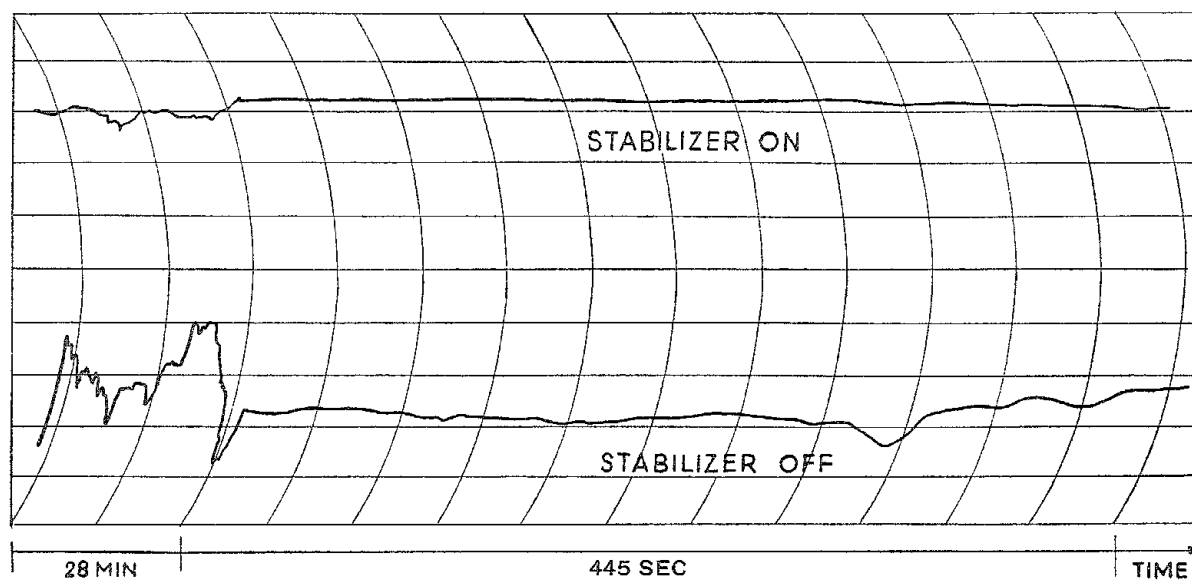


Fig. 6

Fig. 6 is a time record of the time interval  $\tau$  with and without the stabilization device.

5. With some modification in the output power stage we have used the device described in the previous paragraphs for stabilizing the peak reverse field in a bigger model of our Synchrotron magnet. We obtained good results, and now we hope to be able with a similar device

to control the field in the magnet of our Electron-Synchrotron magnet.

We would like to emphasize that our device can find a wider application whenever it is necessary to control the relative values of a D.C. and an A.C. current.

<sup>5)</sup> A. Silverman, Private Communication.