THE CERN STORAGE RING PROJECT

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Summary

CERN has carried out over a number of years a detailed study on the possibility of adding a set of Intersecting Storage Rings (ISR) to its 28 GeV Proton Synchrotron. The plans presented by CERN were accepted by the CERN Council at its meeting in June 1965 and the necessary funds for the construction were allocated in December of the same year. The ISR will consist of two concentric magnet rings of about 150 m mean radius. The two rings are slightly distorted so as to cross each other at 8 points, around which the colliding beam experimentation will take place. With about 20 A of stacked protons in each ring, the interaction rate will be about 1.5 x 10^5 interactions/sec. in each of the crossing points. The construction has started and the lecture will give a description of the project and its present status. It is hoped that the running-in of the facility will start in 1971.

General Description

The great interest in colliding beam devices lies in the very high attainable interaction energy. The CERN Proton Synchrotron (CPS) delivers protons up to 28 GeV. Head-on collisions between such protons would mean 56 GeV c.m. energy, whereas the same protons against a stationary target would only give 7.5 GeV c.m. energy. To reach 56 GeV c.m. energy with an ordinary accelerator would require an accelerator energy of more than 1600 GeV.

The possibility of adding a colliding beam device to the CPS was studied for several years, resulting in a detailed proposal in 1964 of a set of intersecting storage rings, to be constructed next to the CPS but on the French side of the French-Swiss border[1]. The project was authorized in 1965 and the French government put the land at the disposal of CERN.

A simplified lay-out is shown in Fig. 1. After the particles have been accelerated in the CPS, they will be ejected by a fast kicker into the beam transfer line leading to the ISR. The pulses will be guided alternately into one or the other of the two branches, according to which of the two rings we want to fill. The two rings have alternating gradient focusing and the magnets look rather similar to proton synchrotron magnets.

A fast injection system places each pulse from the CPS near the inner wall of the vacuum chamber of the appropriate ring, where the particles are being picked up by an r.f. accelerating system and accelerated to near the outside wall of the chamber. The cavities are then switched off and the whole system is ready for the next pulse.

Several hundred CPS pulses can, in this way, be accumulated in each of the two rings, resulting in very intense circulating proton beams. The two rings are somewhat distorted so as to cross in eight intersecting points, and it is around these points that colliding beam experimentation can take place. Two of the intersecting areas will be equipped with special experimental halls from the beginning, but it will also be possible to carry out some experimentation around the other ones, as the tunnel is rather wide.

This project, in addition to providing for a p-p colliding beam facility, also provides for extensions and more flexibility for conventional physics with the CPS beam. A large new experimental area is being built for this purpose north-west of the ISR, and beams can either reach this area via an ejection system on one of the ISR rings or directly from the CPS via a tunnel by-passing the ISR. The former possibility will give extremely good flexibility of duty cycle and average intensity. The latter possibility is being provided in order to enable us to run experiments in the West Area while the ISR is unoperative (e.g. during installation of colliding beam experiments) or is being run for colliding beam experimentation.

Main Parameters

The main parameters are presented in Table I. Some comments and explanations may be of interest.

The average diameter of the ISR has for several reasons been chosen considerably larger than that of the CPS :

At the top energy of the CPS the good field region has to occupy only a very small fraction of the aperture whereas in the ISR the full aperture is required at top energy. For this reason we have arrived at the equilibrium orbit field of 12 kG at 28 GeV/c in the ISR, whereas in the CPS the equilibrium orbit field is 13.4 kG at the same momentum.

In order to have a proper intersecting angle between the two beams the rings have to be considerably distorted from a circle. This leads to a rather small packing factor in the inner arcs compared with the outer ones, tending to increase the average radius above the one needed with a more even packing.

Table I

ISR Parameter List

Maximum total energy	E_{max}	28 GeV
Average radius	R	150 m
Intersection angle	α	15^{o}
Number of magnet periods	N	48
Number of superperiods	S	4
Number of intersections		8
Q value	Q	8.75
Maximum horizontal β value	$\beta_{H\ max}$	41 m
Maximum vertical β value	$\beta_{V\ max}$	50 m
Maximum momentum compaction	$\alpha_{p\ max}$	2.3 m
Number of magnets per ring		132
Maximum field	B_o	1.2 T
Bending radius	ϱ	78.5 m
Profile parameter	n/ϱ	3 m^{-1}
Gap height		0.1 m
Harmonic number	h	30
RF voltage per turn	50 V	to 20 kV
Design pressure		10^{-9} torr
Vacuum chamber dimensions	16 x 5.2 cm^2	
Long straight section length		16.8 m

The last very important factor leading to an increased circumference is the desirability of very long straight sections in the intersection regions to facilitate the experimentation.

All this has led to the choice of a circumference for the ISR 1.5 times that of the CPS.

There are less clear-cut criteria for such things as the aperture, and therefore the transverse dimensions for the magnet. The aperture must be chosen as a compromise between the obvious desirability of stacking large currents (having high interaction rate) and the desirability to keep the cost down. We have arrived at requiring a good-field region of 16 cm x 5.2 cm.

The choice of frequency of the r.f. system is easy, as efficient stacking requires the CPS bunches to fall into buckets in the ISR. Consequently, the frequency must be the same as that of the CPS at its ejection energy, and the harmonic number is therefore 1.5 times larger.

The other parameters of our project come mainly as consequences of optimisation procedures taking into account accelerator theory, technical considerations and the experience acquired on the CPS and other accelerators.

Expected Performance

As already mentioned in the introduction, the ISR can offer c.m. energies up to 56 GeV, which is far above the c.m. energy obtainable with any existing or planned accelerator. This is the main justification for the ISR.

The weak feature of a colliding beam device is always the intensity. Much effort has therefore gone into obtaining high interaction rates, and we shall examine this point a little closer.

In proton storage rings, where there is only a negligible radiation loss, the intensity to which one can build up a circulating beam is limited by the phase space available, compared with the phase space occupied by the beam in the synchrotron. In principle, the stacking process can be both in longitudinal and in transverse phase space. For the initial operation it is planned to stack only in the longitudinal phase space, and for the performance estimates we shall assume this. However, possible future improvements will also be described briefly.

In addition to the inherent phase space density of the particles coming from the CPS, the efficiency by which these particles can be stacked governs the ultimate intensity. Both computations and experiments on our storage ring model have demonstrated that the beam can be transferred with very little reduction in longitudinal phase space density if the total number of stacked pulses is large, say of the order of a hundred or more. Even down to ten stacked pulses the efficiency can be kept above 70%.

The following general formula holds for the number of stacked particles within a momentum bite Δp

$$N_s = \eta \varrho_o \, 2\pi \, h_{ISR} \, \Delta p \qquad (1)$$

where η is the stacking efficiency mentioned above, h_{ISR} is the harmonic number in the ISR and ϱ_o is the phase space density in an occupied ISR stacking bucket. For the time being we assume that all twenty bunches from the CPS are transferred into twenty of the thirty ISR buckets and that then the stacking takes place in such a way that the ten empty buckets are suppressed during the time it takes to go through the already existing stack[2]. With this assumption ϱ_o is also equal to the phase space density within the CPS bunches.

Let us look at the actual numbers that can be put into formula (1). Although theoretically η can be high, there may in practice be transfer imperfections that are not easy to estimate now. For safety we therefore prefer to put $\eta = 0.5$ in the subsequent evaluations.

For the CPS performance we can safely assume 10^{12} p/p in 20 bunches, each of a momentum spread of ± 7.5 MeV/c and phase width of ± 1/4 radian. This gives $\varrho_o = 8.5 \times 10^3$ protons/eV/c. Since $h_{ISR} = 30$, we get as numerical estimate

$$N_s = 0.8 \times 10^6 \, \Delta p \qquad (1a)$$

where Δp is measured in eV/c.

Let us, for example, assume that we want to work with a momentum definition of 2°/oo full width at 25 GeV/c. This would give as the number of stacked particles

$$N_s = 4 \times 10^{13}$$

which means that at least 40 pulses need to be stacked in each ring (with the CPS performance, as assumed above), probably somewhat more in order to be able to scrape off the less densely populated tails of the stack.

In the ISR there will be room for $\Delta p/p = 0.02$ within the stack, perhaps a little more. If we insert this figure, we get

$$N_{s\,max} = 4 \times 10^{14}$$

which is equivalent to about 20 A circulating current.

The number of stacked particles is of interest only insofar as they govern the interaction rate. Assuming the beam to be rectangular, we can derive the following interaction rate formula[3, 4]

$$N_{IS} = \frac{c\,\sigma}{h \tan\frac{\alpha}{2}} \left(\frac{N_r}{2\pi R}\right)^2 \qquad (2)$$

where we have assumed that the two rings are identically filled with N_r particles in each, c is the particle velocity, σ is the cross-section of the reaction under consideration, h is the beam height, and R is the mean radius of a ring.

It is interesting to notice that this formula does not contain explicitly the width of the beam. If, therefore, by various methods, for instance the one proposed by Terwilliger[5], one changes the beam width locally in the interaction region, one influences only the size of the source of interactions, not its luminosity.

However, the interaction rate depends strongly on the momentum bite, as it is proportional to the square of the acceptable momentum spread, as seen from (1) and (2). Acceptable may either mean what is acceptable to the machine, i.e. about 2%, or to the experiment in question, which may be much smaller.

Inserting numbers into (2), we arrive at the following interaction rates per intersection region

$$N_{IR} \simeq 10^{34} \left(\frac{\Delta p}{p}\right) \sigma \text{ interactions/sec.} \qquad (2a)$$

where σ is measured in cm^2.

The total cross-section of a p-p collision is 4×10^{-26} cm^2, which gives a total interaction rate per intersection region of

$$N_{IR\ total} \simeq \begin{cases} 1.6 \times 10^3 \text{ interactions/sec. with } \frac{\Delta p}{p} = 2°/oo \\ 1.6 \times 10^5 \text{ interactions/sec. with } \frac{\Delta p}{p} = 2°/o. \end{cases}$$

A typical beam size would be 2 cm x 1 cm for the 2°/oo case and 6 cm x 1 cm for the 2% case, giving the interaction volume of 16 cm^3 and 140 cm^3, respectively.

As already mentioned, these estimates are based on the CPS performance at present and a straight-forward injection into the ISR of all 20 CPS bunches. There are, however, important improvement possibilities for the future. Recently, Keil and Sessler have shown that if one could fill an ISR bucket with several CPS bunches by a method of multiturn injection, one can increase the amount of stacked particles within a given momentum bite[6]. In particular, a method of two-turn injection seems quite feasible, and the same method can perhaps also be used up to four turns when highest possible intensity is required at a momentum spread much below the maximum 2%.

The planned new injector for the CPS may provide for a number of advantages and intensity improvement possibilities for the ISR. With this new injector it is aimed at a factor of ten in increased intensity per CPS pulse. The first obvious advantage of this is that it will reduce the filling time of the ISR to its design current by this same factor, which will be particularly useful if the beam life time should have been overestimated.

How much the ISR intensity itself will increase from the CPS improvement programme depends on the beam properties from the improved CPS. Up to a short time ago we were rather concerned about longitudinal phase space blow-up due to space charge forces at transition. Such blow-ups were observed on the CPS at less than 10^{12} particles. Methods to suppress this have, however, been invented and have recently been successfully tried. This, together with further development of the relevant theory, has made us hopeful that transition blow-up can be avoided up to the planned CPS intensities. If that should become true, the whole increase in CPS intensity can be used to increase ISR intensity.

Further, Courant, Keil and Sessler have pointed to the fact that the multi-ring injector planned for the CPS makes it possible to use injection methods into the CPS which would be particularly favourable to the ISR and which could give further intensity improvements[8].

Altogether, from a filling point of view, there are prospects of improving the maximum interaction rates by more than two orders of magnitude and the interaction rates for experiments requiring low momentum bites by more than three orders of magnitude. Equally important would be the corresponding improvement in the ratio of interaction rate to background by an order of magnitude.

This illustrates the importance of finding the various performance limitations that can occur in such a device; in particular those due to collective phenomena which have drawn much attention recently, since such effects have been observed in many accelerators and storage rings, sometimes limiting the performance to values below estimates made in advance. We shall discuss briefly various limitations.

Transverse Space Charge

The ISR will be provided with clearing electrodes between the magnets to remove the neutralizing electrons. The normal space charge formula for a de-neutralized beam with the ISR parameters inserted, gives a space charge limit of

$$I_{s.c.} = 200 \text{ A}.$$

This limit is chiefly governed by image effects in the walls and there are prospects of raising the limit by giving the walls suitable properties.

If the beam had been permitted to neutralize itself, the limit would drop to about 10 A, which illustrates that some sort of clearing is imperative.

Resistive Wall Effects

Resistive wall effects will lead to instabilities with unacceptable growth times unless something is done to damp the coherent oscillations. We plan to suppress such oscillations by Landau-damping. A spread of betatron frequencies will be caused by a sextupole component in the magnetic field. If we succeed in stacking intense beams with small $\Delta p/p$, an octupole component may also be needed, and that can be provided by the pole face windings. The further possibility of feed-back exists, but we hope not to have to use it.

Effects from reactive walls can lead to trouble. It is believed, however, that this can be taken care of by proper choice of electrical characteristics of the components in the vacuum system. This is being studied at the moment.

Beam-beam Interaction

Beam-beam interactions lead to non-linear defocusing forces which may produce slow quasi-stockastic growth of oscillation amplitudes. Computer studies by Keil, Hine, Courant and others indicate that this phenomenon should not become serious until the change in Q due to the linear component of beam-beam interactions is at least 0.05 unit. This limit is reached in the ISR at circulating currents of about 500 A. The phenomenon is, however, not yet well understood in detail, and further mathematical and computational studies are under way.

Longitudinal Instabilities

Applying the now conventional theory for the normal negative mass effect to the ISR parameters, one finds that there is always enough energy spread to avoid instability. However, again there is the possibility of beam-equipment interaction, imposing certain requirements on the equipment. For example, the clearing electrodes must be terminated properly. The theory for this is developed and is being applied at the moment.

Altogether, there seems to be good prospects for the ISR to be able to support beams in the several hundred ampere range, making some of the improvement possibilities mentioned earlier very interesting for the future. It is nevertheless not necessarily the highest maximum intensities that will be most important with the future intensity increases, but that one may reach practical interaction rates for experiments inherently requiring very good momentum definition.

Present Status

The project is now well into its construction phase with all major parameters fixed and unchangeable. The main civil-engineering contract was placed early in the autumn and the contractor moved on to the site a few months later and is now well advanced with the excavation work. Fig. 2 shows the situation. The main tunnel which has a cross-section of 15 m x 6.5 m will be done by cut and fill method. The beam transfer tunnels on the other hand, being much smaller in cross-section (4 m x 4 m) will be done by tunneling. The first part to be ready is the new experimental hall, which we hope to start using from mid-1968 when the magnet delivery would begin.

The Meyrin site is not a particularly favourable one for accelerator construction, and the foundation problem has to be taken rather seriously. The basis for the solution that we have adopted is to build into the foundations a correlation between the movement of neighbouring F and D fields. The magnet units will be supported by a number of independent concrete beams resting at their ends on the underlying "rock". These beams will support either single large magnet units (outer arcs), combinations of one large and one small unit (ends of outer arcs) or groups of four small units (inner arcs). By this method, acceptable limits are foreseen for the vertical orbit distortions arising from the predicted, random vertical movements of the foundations (swelling and settling of the "rock"); localized larger movements are expected to be less harmful by about an order of magnitude.

The magnet specifications have been determined from model work and computations and have gone out for tendering in December last year. Fig. 3 shows a photo of a full-sized magnet unit model. There will, altogether, be 264 such units, of which 144 will have only half of the length of the one showed on the photo. The short units are for the inner arcs.

Elaborate pole-face windings are foreseen to provide for a good field over the whole aperture at top energy.

A d.c. power supply of 6.9 MW (3750 A at 1840 V) will be required for each ring. This must have a current reproducibility and long-term stability of 10^{-4} with a short-term stability of 3×10^{-5}. We are in contact with industry, for the time being leaving them rather free in the choice of system they want to propose.

A model and a prototype of an r.f. cavity are in operation in the laboratory (Fig. 4). Six such cavities will be needed for each ring. A system for suppressing buckets requiring fast on and off switching of the cavities seems feasible and is being developed[2].

The more emphasis one puts on performance the more important beam observation becomes. We are developing rather compact combined vertical and horizontal pick-up electrodes. 52 such stations will be installed in each ring. These stations will be used not only to observe the beam in the process of being stacked, but also for a continuous survey of the stacked beam by passing empty buckets regularly through it.

The vacuum requirements are particularly stringent. A vacuum of 10^{-9} torr or better is required in the major part of the vacuum chamber to give a beam life of more than 10 hours. To reduce background in the interaction regions it is desirable that these be in the 10^{-10} - 10^{-11} torr range. In the design we have been able to profit from several years of experience with the electron storage ring CESAR. Altogether, the system will consist of 240 titanium sputter pumps and the same number of titanium sublimation pumps, pumping about 1500 m of vacuum chamber with its bellows, flanges, valves, etc. The inside chamber dimensions are 160 mm x 52 mm. Fig. 5 shows a prototype vacuum chamber section.

Cryopumping will be used in the interaction regions.

To guide the CPS beam to the two ISR rings and to the West Area, about 1.5 km of transfer channels are needed. It is a truly three-dimensional system since the level of the ISR beams is about 12 m higher than that of the CPS beam. The optical properties of these beam transfer lines have been determined and the design of the components is well under way. It is required to have the possibility of quick changes in the field of some of the components and a laminated construction has been chosen both for the bending magnets and the quadrupoles.

The inflector into the ISR is in principle the same as the fast ejection system of the CPS, but there are important differences. The fast kicker magnet must operate in ultra-high vacuum and must be baked out. This limits the choice of construction materials; the magnet is to be made of ferrite with titanium conductors and ceramic insulators. The pulse should be flat to within ± 2%. The adoption of a stacking system with 10 suppressed buckets has made it possible to reduce considerably the requirements for the rise and fall times. In fact, up to several hundred nanosecond fall time can now be tolerated, leading to a simpler construction than earlier envisaged. Prototype inflector magnets have been working well in the laboratory (Fig. 6).

Time Schedule

As already mentioned, the largest single contract, the one for the civil engineering, has been placed. For the major technical items we shall go through the tendering procedure during this year, hoping to place most of the orders late in the year and early next year. Delivery of big items should start during the latter half of 1968, and the installation should be finished by the end of 1970. We hope to be ready for the running-in of the machine as a whole by mid-1971.

References

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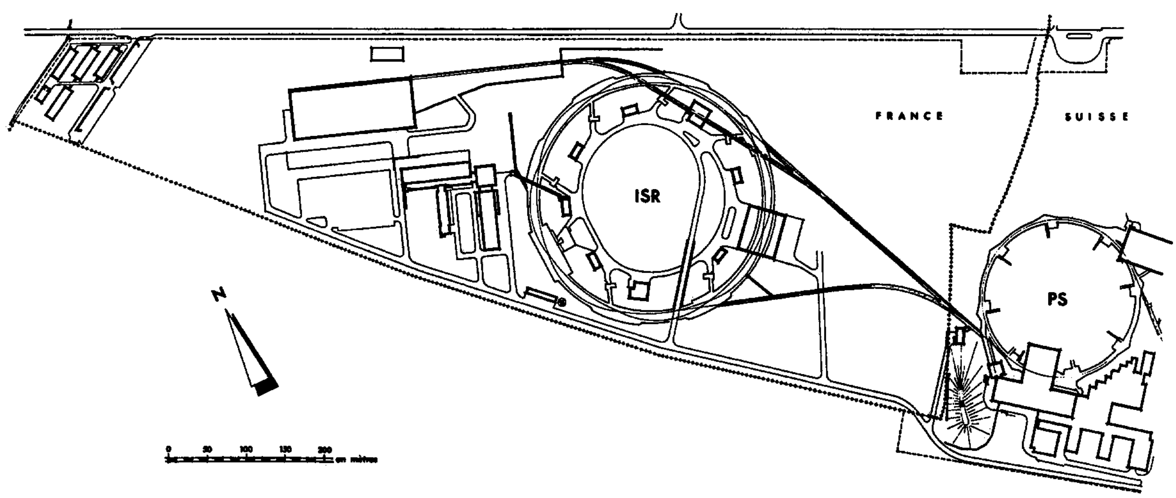

Fig. 1. Layout of the CERN Intersecting Storage Rings.

Fig. 2. Excavation work on the ISR site February 1967.

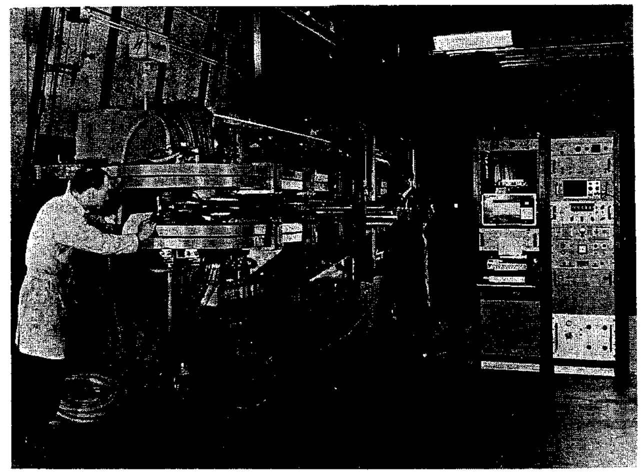

Fig. 3. Prototype of long magnet unit.

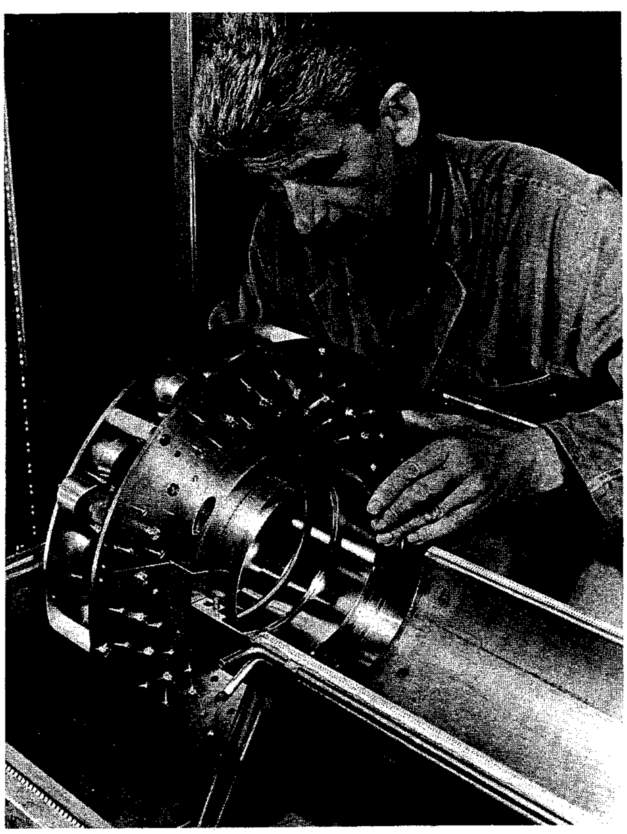

Fig. 4. Inside of an RF cavity.

Fig. 5. Vacuum chamber section.

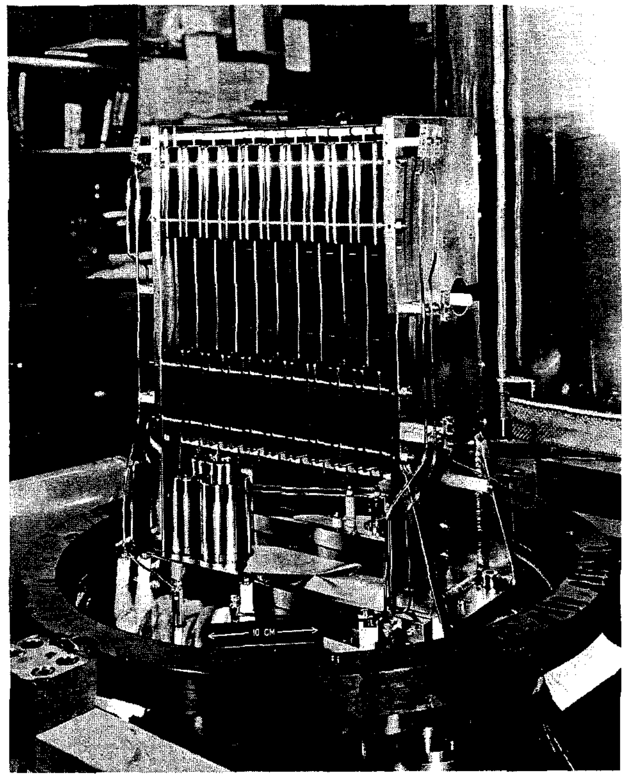

Fig. 6. Model of inflector magnet.