The longitudinal stability (so-called negative mass instability has been checked by applying the theory of Nielsen et al. (12) and Neil and Sessler (13). There is always enough energy spread in the ISR to secure stability.

As will be remembered, when the electron storage ring AdA was put into operation a few years ago the beam lifetime showed strong dependence on the beam intensity. This effect, going under the name of the Touschek Effect, was soon explained (14), and the application of their theory shows that the effect is negligible for proton storage rings.

Altogether we feel confident that the ultimate ISR performance will be in the neighbourhood of the estimates that we have given in our Study Group Report (2), of which the above is a summary, and with such a performance and with the experimental flexibility that we shall be able to incorporate in the project, we hope that the device will be a very useful one, opening up a new energy range and in some respects new ways of doing high-energy physics.

The total cost of the ISR project is estimated to be 334 MSF. The construction time will be 6 years.

The plans for the ISR project are the result of a joint effort of the CERN Study Group on New Accelerator Projects. This group has had valuable assistance from other people from CERN as well as from other laboratories.

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DISCUSSION

See Session IV, after Bonaudi's talk.

CHARACTERISTIC FEATURES OF THE CERN ISR MAGNET SYSTEM

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(Presented by L. Resegotti)

1. SUPERPERIODICITY OF THE MAIN MAGNET STRUCTURE

Experiments with colliding beams of protons are possible with several geometries of storage rings (1) « Circular » rings can provide one interaction region, if they are tangential, two if they cross at an angle.

The « concentric » arrangement, proposed first by Woods and O'Neill (2) allows a much larger

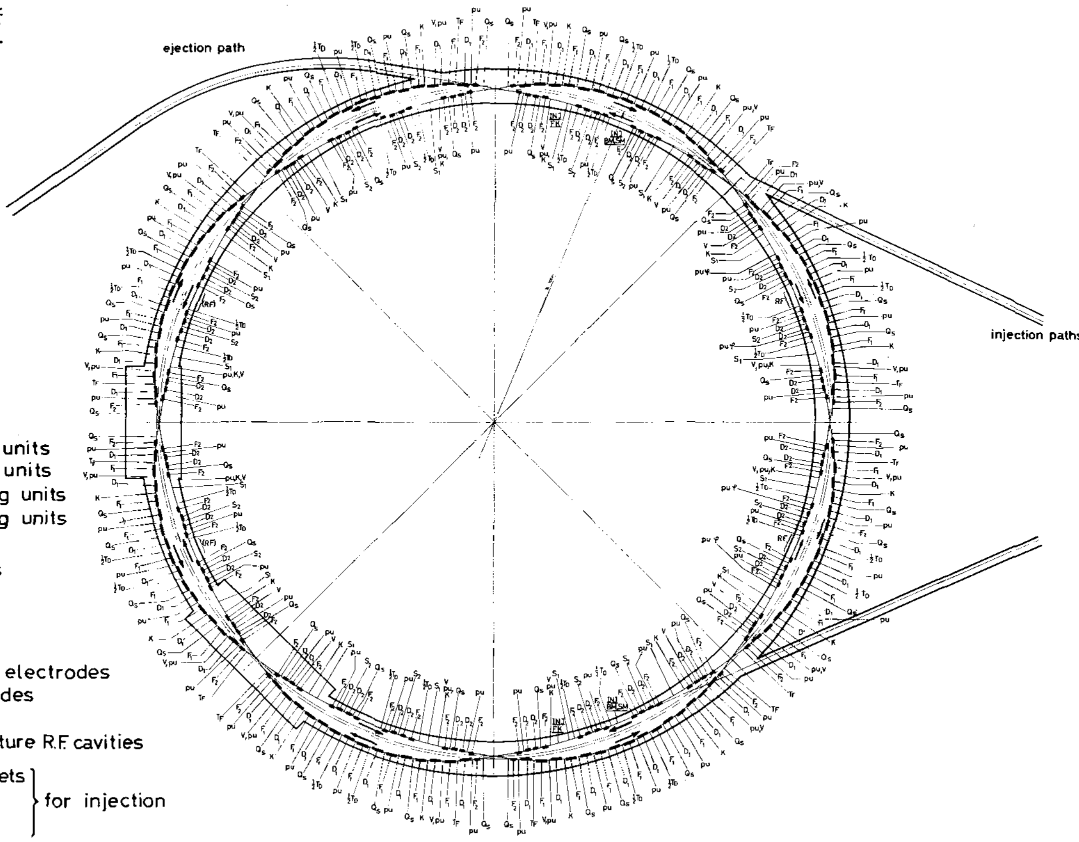


Fig. 1 - General layout of magnets and straight sections in the ISR.

number of intersections, at the expense of suitably distorting the two rings. In the simplest form of this arrangement, each ring is composed of two sets of arcs of different average curvature, which are alternatively internal and external to the circle on whose circumference the intersection points lay: in the CERN design each ring has 4 outer and 4 inner arcs, with 8 intersections (3). The way of obtaining this geometry with minimum disturbance to the orbit pattern consists in inserting straight sections in the middle of some F and D sectors of the normal structure. This procedure allows at the same time to make available the long field free sections required by experimentation around the interaction regions. They should be mid-F, where the beams have the minimum height, since the interaction rate is inversely proportional to beam height.

The layout of the storage rings described in the previous paragraph entails certain restrictions in the choice of the magnet parameters. The superperiodicity, S, limits the choice of Q values, because it originates stopbands around all multiples of S/2 and non-linear resonances at Q values multiple of S/3, S/4, ... etc. The ratio of the number of periods in the outer and inner arcs, which determines the crossing angle, must be kept to the minimum compatible with the space requirements around the interaction points, in order to limit the increase in machine diameter.

In our proposed design, where $S = 4$, the only practical values of Q would be 7.25 and 8.75: the second one is the most advantageous for both planes. Among the few integers corresponding to an acceptable total number of periods per ring, 4 and 8 periods were chosen for the inner and for the outer arcs respectively: the resulting crossing angle is 15° (Fig. 1).

Despite the optimization of straight section location, the modulation of the amplitude function β, due to superperiodicity is quite substantial, as is shown for example in Fig. 2, for the proposed ISR parameters. The height of the beam envelope varies along the ring by about a factor two. This modulation could only be avoided by matching in betatron phase space, which would lead to more harmfull variations of the momentum compaction function.

The modulation of the β function increases the sensitivity to field, alignment and gradient errors, and therefore the ISR magnet must be built to tighter tolerances than the CPS magnet.

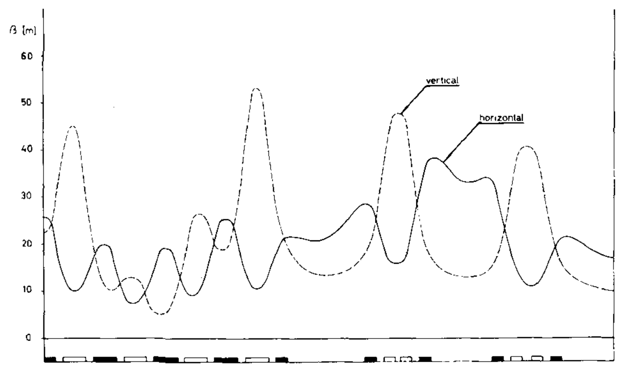


Fig. 2 - Variation of β over half a superperiod of the ISR for Q = 8.75.

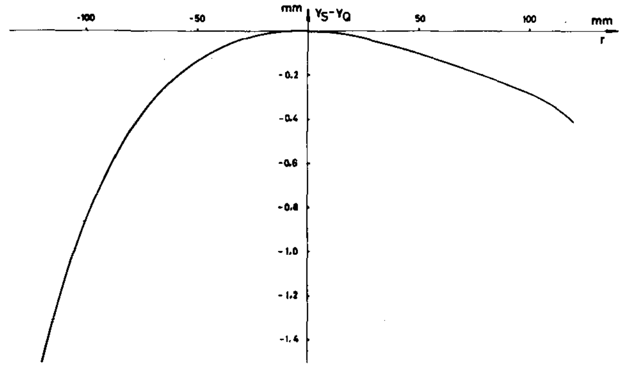


Fig. 3 - Difference between the profiles of an F magnet of the ISR with and without sextupole correction.

2. SEXTUPOLE COMPONENT IN THE FIELD PATTERN

In proton storage rings, intense circulating beams are obtained by stacking in longitudinal phase space: this implies a substantial momentum spread inside the vacuum chamber. In order to maintain the betatron oscillations of all particles within the region of stability, it may therefore become necessary to reduce the dependence of Q on particle momentum.

For example, in our proposed design the distance from the injection orbit to the bottom of the stack corresponds approximately to a momentum variation of 1.5% and the momentum spread in the stack is 2.5%, so that the total momentum range is about 4%. If the machine were entirely linear, the corresponding variation of Q_V would be about 0.5 and that of Q_H about 0.3. Taking into account also the influence of the expected radial variation of the effective focusing length of the magnet units, the overall momentum dependence of Q would be approximately

$$\Delta Q(H) = -16\,\Delta p/p \qquad \Delta Q(V) = -0.8\,\Delta p/p$$

In either case parts of the stack would either cross or come very near to the stopbands at $Q = 8.5$ and $Q = 9$.

Obviously, the maximum distance from the adjacent stopbands is obtained for all momenta simultaneously if the Q values are made independent of momentum.

H. G. Hereward (4) has estimated that a small increase of Q with momentum should be sufficient to stabilize the coherent oscillations produced by the resistive wall effect at high beam currents.

On the basis of these two arguments, we have decided to make the Q values independent of momentum in the basic magnet structure. The simplest way of achieving this is to introduce a sextupole component in the field distribution of the magnets. The required sextupole components may be quite appreciable. In our design, the gradients at the outer edge of the aperture are 6% higher in D units and 9% in F units than those at the inner edge of the aperture. Fig. 3 shows for comparison the differences between the ideal profiles for an F magnet with and without this correction. Some separate sextupole lenses will permit us to introduce a small momentum dependence of the Q values in the direction required.

3. DISTRIBUTED CORRECTIONS BY MEANS OF POLEFACE WINDINGS

In a proton synchrotron, only a fraction of the aperture is occupied by the beam near maximum energy, because of the adiabatic damping of the betatron oscillations during acceleration. In the proton storage rings, on the contrary, the whole radial aperture is used during the process of injection and stacking, and this process is carried out most efficiently at the highest energy, where the emittance of the injected beam is the smallest. A schematic cross section across the vacuum chamber of the proposed ISR at the location of the injection kicker is given in Fig. 4. We propose to correct the field distortion arising from steel saturation near the maximum field by means of poleface windings.

Since the storage rings operate at constant field, the current in individual turns, or sections, of the poleface windings could be separately adjusted and thus an accurate correction would be possible over the whole aperture and at all field levels. This flexible correction system could be used also for producing arbitrary changes in focusing strength: in particular it would be possible to create in this way a distributed quadrupole field for adjustments of Q. If necessary, also octupole effects could be introduced.

An adequate flexibility in adjustment of the correction would be achieved by having 12 independent current loops on each pole: model measurements may show the possibility of a reduction of this number. All corresponding loops on the poles of magnets of same type (i.e. for F or D) could be connected in series, giving two groups of 12 independent circuits per ring. Each circuit would be powered by a separate power supply, but the reference voltages for the current regulations of the power supplies of each group could be produced by adjustable potentiometric division of the same two voltages

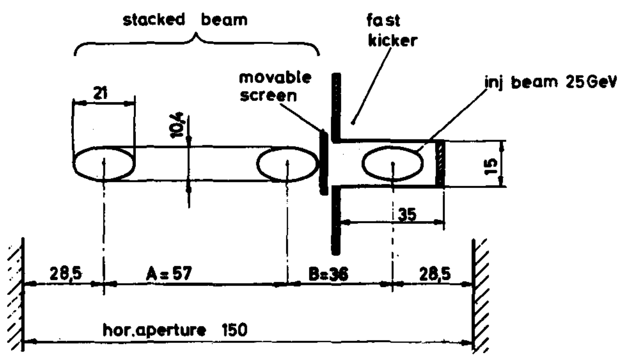
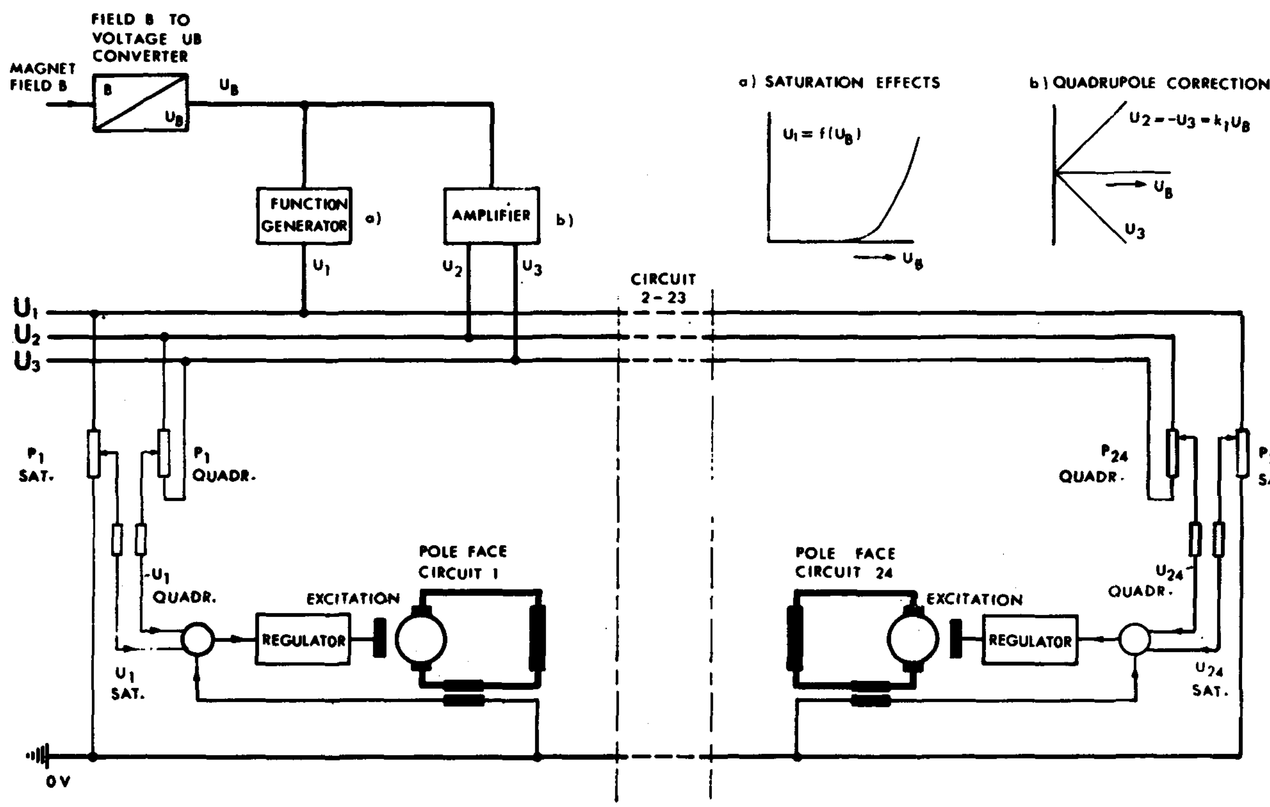


Fig. 4 - Schematic cross section through kicher magnet.

Fig. 5 - Pole face winding power supply.



controlled by the equilibrium field B through function generators, the one corresponding to saturation correction, and the second to the chosen Q-shift (see Fig. 5). In this way the correction would be automatically adapted to changes in B during acceleration or deceleration by phase displacement. An arbitrary adjustment of the quadrupole correction could be made by manual control of the proportionality constant in the second function generator. Independent adjustments of local current densities could be made by means of the individual potentiometers. Control schemes based on the use of a digital computer are also being considered (5). Fig. 6 shows an approximate estimate of the linear current density distributions required in the poleface windings of the proposed FODO magnet of the ISR, to compensate saturation effects, alone or together with Q shifts of ± 0.25. Fig. 7 shows some constructional details of the poleface windings for our first magnet model.

The poleface windings take space in the magnet gap; their construction is not easy and their circuitry is complex. The choice of this method of correction is therefore controversial. The possibility of using only magnetic lenses was also considered, but was found to have other drawbacks. The operation of lenses concentrated in the inner arcs would increase the modulation of the beam envelope. This effect is illustrated by the example of 2 pairs of quadrupoles per inner arc at the positions marked S_1 and S_2 in Fig. 1: the maximum values of the β functions for changes of Q_V by Q_H by ± 0.25 are given in Table I. These additional lenses in the inner arcs would also reduce the space available for injection, ejection and acceleration equipment. Moreover, the flexibility in correction would be less than with poleface windings.

4. SUPERPOSITION OF CLOSED ORBITS AND VERTICAL BEAM STEERING

The width of the stacked beam can be reduced considerably at some interaction regions by superposing there the closed orbits for different momenta. This superposition does not change the total interaction rate which, for beams crossing at an angle, is independent of beam width, but permits to reduce the interaction volume proportionally to the square of the beam width, (the minimum volume is set by the amplitude of the betatron oscillations and for our case is about 4 cm^3, independently of beam intensity). It may be useful for experiments where the size of the source is important and the inherent lack of momentum definition is tolerable. Terwilliger (6) has shown that this superposition of orbits can be achieved by applying a harmonic gradient perturbation to the magnet structure, with a harmonic number close to Q.

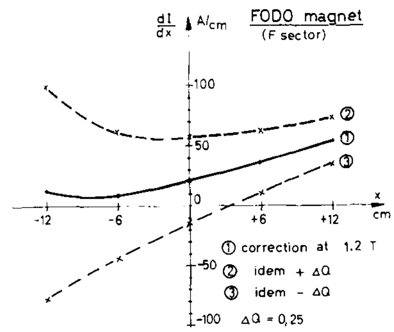


Fig. 6 - Linear current density distribution in pole face windings.

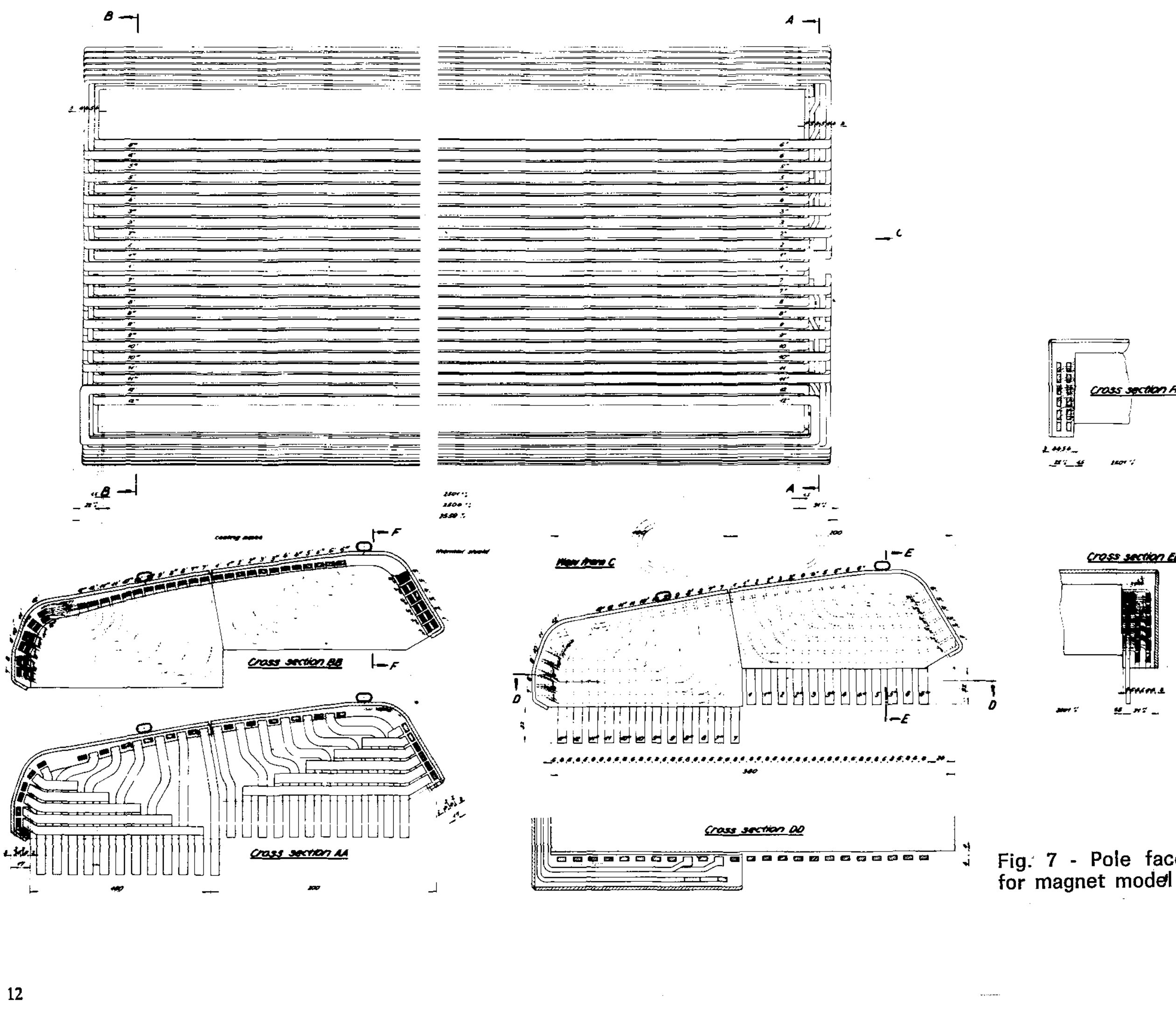


Fig. 7 - Pole face windings for magnet model 1.

In Fig. 8 a distribution of Terwilliger quadrupoles T_F and T_D is given, together with the momentum compaction α_p (s) over one superperiod.

A simpler, but essential, feature of the ISR are the radial-field magnets to steer the two beams in the vertical plane, so that they collide over their whole height in the interaction regions. It is planned to place in each ring 8 pairs of these magnets, at a distance of about one quarter betatron oscillation wavelength on each side of the interaction regions. Since the effects of two equal and opposite kicks at half wavelength from each other are only felt in the region between them, these radial field magnets will allow to adjust independently the vertical position of the beam in each interaction region. The positions of the radial field magnets in the present design are shown in Fig. 1.

TABLE I

Effects of separate quadrupole adjustments of Q

$Q_H = Q_V$	9.000	8.750	8.500
C_F	− 0.0156	0	0.0146 m^{-1}
C_D	0.0155	0	− 0.0142 m^{-1}
$\beta_{H\,max}$	44.3	38.0	59.0 m
$\beta_{V\,max}$	56.4	53.0	81.4 m
$\alpha_{p\,max}$	2.35	2,26	2.65 m

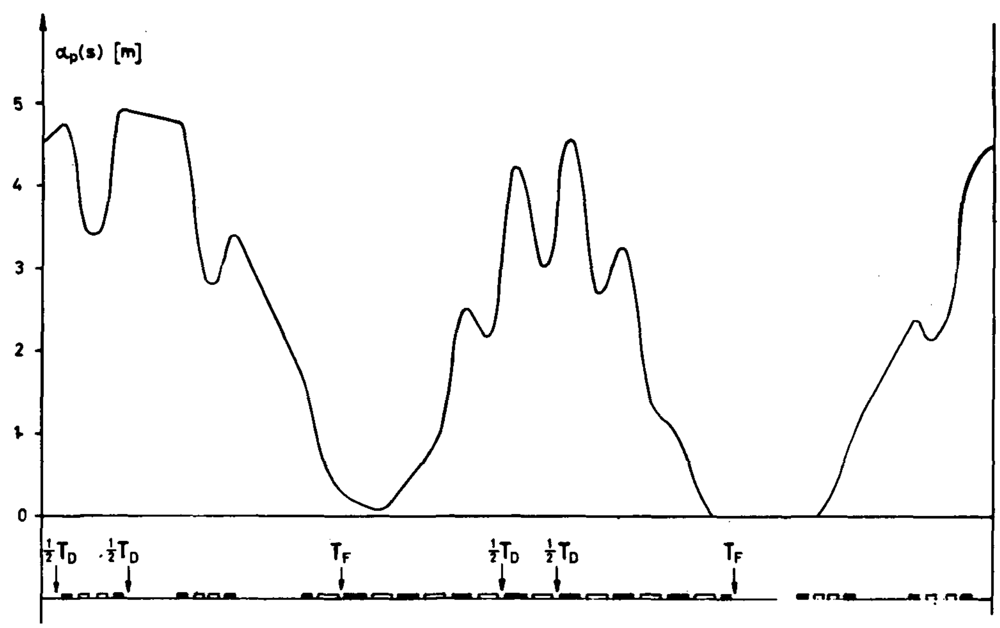


Fig. 8 - Momentum compaction with Terwillinger scheme.

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DISCUSSION

COURANT: In the original design of the storage ring a few years ago you contemplated separate focusing and bending magnets. When and why did you abandon this scheme in favour of gradient bending magnets?

RESEGOTTI: The structure with separate focusing and bending functions was abandoned in favour of the alternating gradient structure because the former turned out to be at least 50% more expensive. Moreover, the "open shaped" gradient magnets of the present design offer the best accessibility of the vacuum chamber and of its baking system.