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PROGRESS REPORT ON NEW CPS INJECTOR

1. Introduction

As already reported, W. Hardt and P. Lapostolle in October 1965 accepted the responsability of directing a study, the purpose of which was to compare the properties of two types of injectors considered for the CPS: a 200 MeV linac and a slow-cycling 600 MeV booster synchrotron for which the TART scheme served as an example.

The results, presented in detail in a draft note[1)], may be summarized as follows.

The comparison clearly demonstrated the advantage of a 600 MeV circular injector over a 200 MeV linac. While costing about the same, the circular injector studied would give a theoretical intensity gain in the CPS of a factor twelve, compared with five for a linac.

The practical limit will probably be lower and will be influenced both by the limitations set by the CPS exploitation conditions at high intensity (induced radio-activity, radiation damage, shielding), and by the necessity of keeping a beam of sufficient quality (small emittance) for physics experiments including those with the ISR. It is impossible at this stage to determine this limit with certainty but we consider it reasonable to base our plans on an upper limit of 10^{13} protons per pulse, taking into account the CPS repetition rates and energies we expect to be used after the first part of the improvement programme. Though the practical limit may perhaps be reached with either injector, the circular injector will have a safety factor which would allow operation of higher reliability and quality, and spare capacity for contingencies and improvements. This circular injector will now be discussed in more detail.

2. Principle of the circular injector

While probably not the final version (see Section 8 below), the TART scheme was taken as an example of a slow-cycling 600 MeV circular injector because it had been worked out in greatest detail[2]. This scheme uses two separate interlaced synchrotrons of half the CPS circumference operating in parallel (Fig. 1). Cost is reduced by using the same tunnel and focusing lenses for both beams (Fig. 2). The existing (improved) 50 MeV linac injects successively a particle beam into each of the two rings. After 0.7 s of acceleration the 10 particle bunches of the first ring are transferred into the CPS, followed immediately by those from the second ring. Thus the 20 buckets of CPS are filled in one revolution with theoretically no loss of particles in the transfer process.

Some of the main parameters are as follows:

mean ring radius		$R = 50.000$ m
magnetic bending radius		$\rho = 6.000$ m
length of F-magnet		$L_F = 2.094$ m
length of lenses		$L_{LD} = L_{LF} = 0.300$ m
length of straight sections	between lenses	$L_{SS,L} = 4.035$ m
	between lens and magnet	$L_{SS,M} = 3.194$ m
profile parameter of F-magnet		$n/\rho = 1.100\ m^{-1}$
magnetic field at injection		$B_{inj} = 0.172$ T
magnetic field at transfer		$B_{tf} = 0.677$ T
lens strength (radial divergence)		D lenses, $+ 0.394\ m^{-1}$
		F lenses, $- 0.390\ m^{-1}$
betatron oscillations per revolution		$Q_H = Q_V = 11.25$
horizontal design acceptance		$A_H = 250\pi\ \mu$rad m
vertical design acceptance		$A_V = 140\pi\ \mu$rad m
RF peak voltage		$\hat{U} = 23$ kV
harmonic number		$h = 10$
sine of synchronous phase angle		$\sin \phi_s = 0.059$

Aperture requirements (half-aperture in mm) including closed orbit deviations, momentum displacement, and various errors, plus ~ 20% contingency in aperture

	horizontal	vertical
F - magnet	92	32
F - lens	110	24
D - lens	33 + 13 for crossing	78

Since the main object of the new injector is to raise the space-charge limit of the CPS (and to provide the correspondingly higher beam current in an acceptable form) a brief discussion of this limit is in order.

While the complex space-charge phenomena are not yet fully understood, it is believed that the intensity estimates should be based on the limit set by the transverse "single particle" Q-shift

$$N = r_p^{-1} \; B \; E_V[1 + (E_H/E_V)^{\frac{1}{2}}] \; \Delta Q_V \beta^2 \gamma^3 / F \qquad (1)$$

where

N = maximum number of particles in synchrotron

r_p = classical radius of proton = $1.5 \; 10^{-18}$ m

B = bunching factor = ratio of the average to the maximum linear particle density (≈ 0.3 at present)

$E_{V,H}$ = beam emittance in vertical (horizontal) phase plane in units of metre radian (i.e. including the π in the number)

Q_V = number of vertical betatron oscillations per revolution

ΔQ_V = allowable shift of Q_V (say 0.25 as a rather conservative value)

β = v/c = particle velocity in terms of speed of light

γ = $(1 - \beta^2)^{-\frac{1}{2}}$

F = Laslett's correction factor for image effects ($\approx$ 1 to 1.5 in the cases considered here).

From Eq. (1) it is easy to see that, provided the transfer energy into the CPS is sufficiently high, the limit imposed by space charge effects will first appear at injection from the 50 MeV linac into the booster synchrotron. This limit may be raised as follows:

- Compared to the present situation in the CPS the value of B can be increased by a factor of about 1.5 due to the slower cycling and therefore smaller synchronous RF phase angle.
- Since the beam emittance decreases adiabatically as $(\beta\gamma)^{-1}$ the emittance at 50 MeV may be increased by the factor $(\beta\gamma)_{600\ \mathrm{MeV}}/(\beta\gamma)_{50\ \mathrm{MeV}} \approx 4$, and still fit into the CPS at transfer.
- If interlaced rings are used, Eq. (1) applies to each ring separately so that the total number of transferable particles increases linearly with the number of rings, all other conditions being equal.

Taking $(E_H/E_V)^{\frac{1}{2}}$ and F as unchanged, the TART scheme (two interlaced rings) thus raises the intensity limit at injection by a factor of 12 compared with injection into the CPS, and this should make it possible to accelerate safely 10^{13} particles per pulse.

3. Transverse phase space

In studying the transverse phase space situation one wants to consider separately the questions of

a) the number of injectable particles and ease of injection (keeping also in mind the possibility of further improvement);

b) the limitation by space-charge effects on the number of particles injected that are accelerated;

c) the resulting beam quality and its influence on beam utilisation for physics.

a) Utilisation of linac beam

In the case of multiturn injection into a synchrotron only a fraction ϵ_A of the offered intensity is accepted and only a fraction ϵ_{tp} of the accepted particles will later be trapped into the longitudinal phase space. The number of particles accelerated in the synchrotron, N, is then

$$N = n_t \epsilon_A \epsilon_{tp} I_L T/e \qquad (2)$$

where

n_t = number of injected turns
I_L = current from the linac
$T = 2 \pi R/c \beta_{inj}$ = particle revolution period in synchrotron
e = elementary charge = $1.6 \ 10^{-19}$ Coulomb.

While maintaining the desirable long revolution period, the booster synchrotron has the advantage of increasing ϵ_{tp} by a factor of about 1.5 due to the lower rate of field rise and therefore smaller stable phase angle. With $T_{50}/T_{200} \approx 1.8$, and negligible losses during beam transfer into the CPS, the number of protons accelerated (for n_t, ϵ_A and I_L constant) is according to Eq.(2) a factor 2.7 higher than in the case linac 200 MeV - CPS.

The number of turns which can be accepted in the synchrotron depends on the ratio of machine acceptance to linac beam emittance. The horizontal design acceptance of TART is large enough that the current increase of linac brightness (compared with 1965 values) should make it possible to inject a number of particles sufficient for accelerating 10^{13} particles per pulse.

b) Space-charge limit

This basic point has already been dealt with in Section 2. It is worth adding that the large acceptance of the circular booster reduces image effects, and consequently even a vertical beam emittance of only 30π μrad m gives a space-charge limit of 5 10^{12} particles per pulse in TART. Several methods exist to go higher; one is increasing the beam height, by means of a vertical beam-spreader, as much as required within the limitation of the 140 π μrad m vertical design acceptance. The uncertainties of space-charge theory and the desirability for physics of a high density in vertical phase space make this flexibility very welcome.

c) Density in transverse phase space

As discussed in more detail in Section 5 below, not only the number of particles accelerated but also the final beam diameter is of importance, i.e. the particle density in transverse phase space has to be considered in comparing different solutions for increasing intensity.

In this respect, the circular injector is markedly superior for the reasons given in 2 and 3 a) above, even if the slight dilution during transfer is allowed for.

The particle density being at a premium, one must underline at this point the importance of increasing the linac current and its brightness as much as possible, even if this requires some reconstruction of the present Linac. For some purposes it may be advantageous to accept a reduced beam current if a higher brightness results.

4. Longitudinal phase space

a) Injection and transfer

As already stated in 3 a) above the trapping efficiency in the circular injector is higher because of the slow cycling. On the other hand, if there is to be 100% capture efficiency and no dilution in longitudinal phase space at transfer, some RF gymnastics are required in the TART to match its output bunches to the given RF buckets of the CPS.

b) Passage through transition energy in the CPS

The tendency of the longitudinal space-charge forces to distort the bunch area is strongest at transition and will result in particle loss unless remedial action is taken. The most powerful and simplest methods seem to be:

(i) the triple phase switch, which, in linear approximation, corrects the effect of longitudinal space-charge force exactly. The normal phase jump is made at transition but after an interval the phase is switched back to what is now the unstable position. The bunch is distorted, compensating the effect of space-charge forces; when the compensation is complete the phase is again switched to the stable position.

(ii) an artificial blow-up of the bunch size before transition in order to decrease the space-charge forces at transition and so minimise the final bunch size.

The present theory of bunch shape disturbance at transition is too rough to predict the final bunch size. But it seems possible to accelerate 10^{13} particles per pulse without substantial loss by applying method i), and adding method ii) if necessary. However, the momentum spread in the final beam may increase.

5. Beam utilisation for physics

a) Production of secondary particles

The efficiency of internal targets and the rate of small angle production of secondaries and of scattering by external targets of small transverse dimensions are functions not only of the absolute primary intensity but, depending on the experiment, more or less strong functions of beam emittance. The circular injector has the advantage of ensuring both a good phase space density and a certain flexibility as regards the beam emittance [cp.3 b) and c)].

However, with the highest intensity, the beam emittance will inevitably be increased [cp. 2 and 3 a) above]. First estimates indicate, however, that for the increase expected, the decrease in internal target efficiency should not greatly exceed 10%. To maintain the present beam spot sizes on external targets more powerful lenses would be required which might advantageously be of the superconducting type.

b) External primary beam design

There should be no major technical difficulties but costs will increase. It would cost more to transport the increased emittance beam; notably the aperture of the lenses must be greater or their spacing smaller.

External beams of increased intensity would require only about 10 to 15% more shielding per beam; so that the increased cost would be due rather to the increase in number of external beams and targets which will be desirable both for the experimental physics programme and to avoid excessive radiation damage and induced radio-activity in the ring (cp. 7 below).

If, however, the intensity of external beams in one region exceeds about 10^{12} particles/second the muon level would be such that either costly muon dumps or the deflection of the residual proton beam into the ground would be necessary.

c) Deuteron acceleration

About 7 mA of deuterons have been accelerated to 23 MeV using the existing Linac; this is about 1/10 of the maximum proton current accelerated. It would be unwise to hope for more than a few 10^{10} deuterons per pulse in the CPS, since it is necessary to jump from the 40th to the 20th harmonic to cover the increased frequency swing.

With a circular injector one solution would be to give it a second RF system for deuterons or to halve the frequency of its proton RF system and so avoid a harmonic jump, the frequency range of the CPS RF system being maintained (meaning extra effort and cost). In this case one could expect to accelerate between 10^{10} and 10^{11} deuterons per pulse. For higher intensities it would be necessary to modify the 50 MeV Linac.

d) Implications for the ISR

The interaction rate for protons within a given momentum interval Δp is approximately proportional to:

$$\frac{(\Delta p)^2 \, \eta^2 \, N^2}{A^2 h} \qquad (3)$$

where η is the stacking efficiency, h the beam height, N the number of particles accelerated per pulse in the CPS and A the longitudinal phase plane area of the CPS bunches at transfer into the ISR. Since both A and h have a tendency to increase with increasing N it is not, offhand, guaranteed that increasing the CPS intensity brings about an increase of the ISR interaction rate; but, so long as the interaction rate does not actually decrease with increasing N a high intensity is desirable in itself because of the correspondingly reduced fill-time of the ISR.

The changed conditions due to the new injector will lead to an increase of A by s small factor, and a full TART aperture at 50 MeV, if this is necessary, will double h. However, these effects may be masked by the blow-up in the longitudinal phase plane due to space charge forces near transition energy [cp.4 b) above]. A blow-up of this nature occurs already at present CPS intensities and there is experimental evidence that, under present conditions, the longitudinal phase-plane density, N/A, starts to decrease with increasing N for intensities somewhat below 10^{12} particles per pulse.

It is expected that this effect can be largely compensated, but $\eta^2 N^2 (A^2 h)^{-1}$ will not increase indefinitly with increasing N, and it may well have a flat maximum somewhere in the region of a few 10^{12} particles per pulse.

For this reason and in view of how much is at stake for the ISR project, it seems essential to maintain the possibility of feeding the ISR with a beam of at least the present intensity and quality. This can be done by keeping available direct 50 MeV injection into the CPS and the full frequency swing of its present RF system, but further study may show that it can also be done by way of the booster synchrotron, perhaps running at reduced intensity but with a very well defined beam.

6. Site

Two sites were found acceptable for locating TART as shown in Fig. 1. A 3-ring or 1-ring booster synchrotron (of smaller radius) would be even easier to place conveniently.

7. Problems of high intensity

These have been looked into in a preliminary way and will require more study. Already a number of CPS modifications seem indispensable, such as a new RF system to take care of the strongly increased beam loading, the use of more radiation resistant water hoses, vacuum joints, coil insulation etc., a monitoring system for internal beam loss, reduced use of internal targets (in conjunction with beam dumps) and extra radiation shielding of the ring and of external beams.

The exploitation of the machine will depend in large measure on the efficiency of the fast and slow extraction systems, and it is hoped to make substantial improvements in the efficiency of the latter. The very high efficiency of transfer, from booster synchrotron to CPS should more than outweigh extra induced radio-activity due to the higher energy of any particles lost in this process in the CPS.

8. Current work

Exploring further the possibilities opened up by the TART proposal, the Berkeley Group has worked out parameters of a PS injector with 4 rings (QUART). W. Hardt continued his systematic study of interlaced rings$^{3)}$. He concludes tentatively that three would be the optimum number of rings for a CPS injector. Work is progressing on this optimisation.

In parallel we are evaluating the ideas put forward very recently notably at Brookhaven on the interest of using a single ring of small diameter$^{4)}$. The basic principle of this method is to accelerate a beam of large emittance, thereby increasing the space-charge limit and the number of particles which can be accomodated. Using multiturn extraction for the transfer, this large beam emittance is cut up so that the emittance of the beam to be transferred into the CPS is essentially the same as that obtained from the other injectors.

Steady progress is being made in the study of radiation damage, remote handling equipment and high intensity exploitation in general.

The recent (May 1966) potential improvements of the PS linac brightness should greatly help in evaluating the future performance of these new injectors.

9. Conclusions

The work done so far has permitted us to select with certainty the circular injector for further study. The next steps consist in first deciding on the number of rings to be adopted and then optimising the design of that particular booster. In parallel the use of the increased intensity will be studied, both as regards CPS operation and physics experiments.

Studies will also be persued with the CPS, to obtain a better understanding of the space-charge limit.

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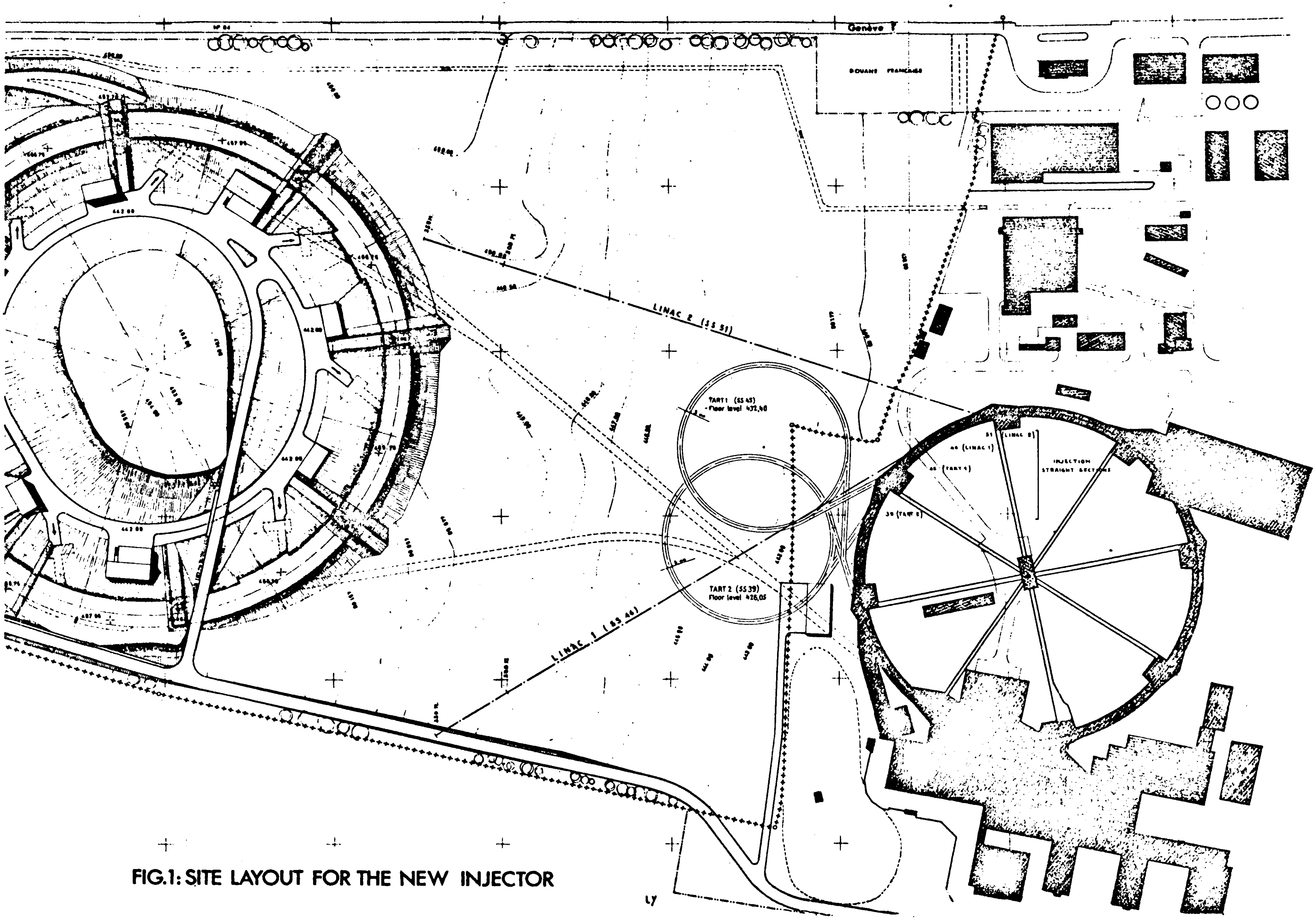

FIG.1: SITE LAYOUT FOR THE NEW INJECTOR

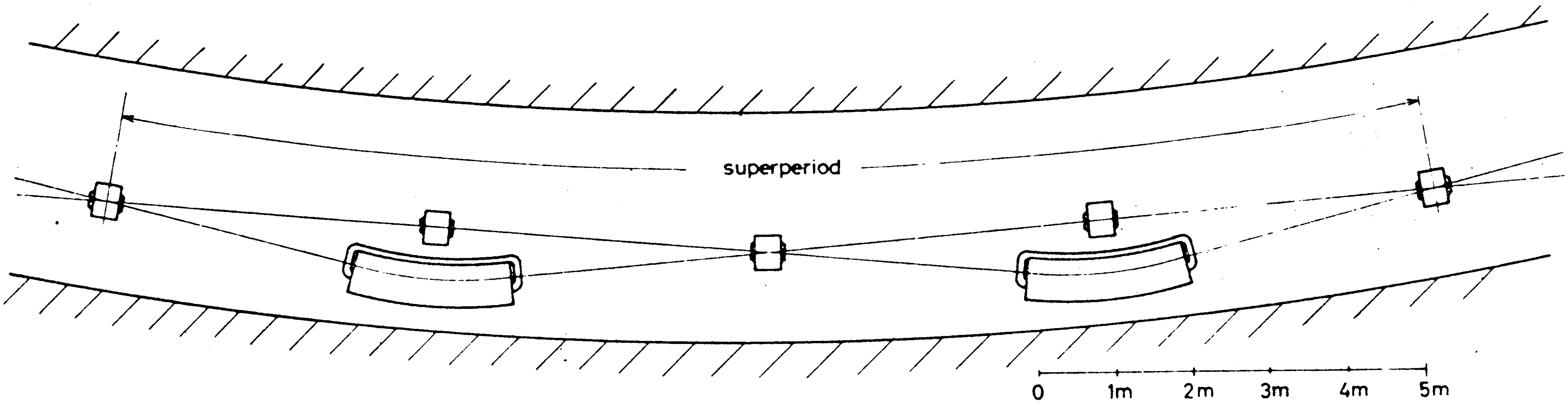

FIG. 2

TART STUCTURE OF A SUPERPERIOD