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PRESENT IDEAS ON 25-GeV PROTON STORAGE RINGS

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1. Introduction.

When the C.P.S. came into operation it became clear that the intensity of this machine could probably be raised within a few years to the point where colliding beam experiments in a set of storage rings would be feasible. During the first year of operation the intensity has been increased by more than an order of magnitude, and there are still good prospects of further increases, making storage rings even more interesting.

The main effort of the Accelerator Research Group has therefore recently been put on a study of the principle of stacking without the complication of FFAG acceleration being built into the same device, and a small storage ring to try out the principle is under construction.

Although it will certainly be 1½ - 2 years before we start getting detailed results from this model, paper studies related to storage rings for the P.S. have been started and will continue in parallel with the model studies.

It is felt that a summary of our present thoughts on this subject is useful already at this stage, especially since a project like this would require ground outside the present site. Till results of the more detailed studies are available, the conclusions should be considered to be rather tentative.

2. The Principle of a Storage Ring System.

Fig. 1 shows a sketch of a synchrotron with a storage ring system. The particles are accelerated in for instance a synchrotron (called PS in Fig. 1) to its final energy. A fast ejection system then takes out all the particles in one revolution and puts them into a beam transport system. A fast injection system then puts the particles into one or the other of the two storage rings, where they are picked up by the S.R. radio-frequency system and brought into the stacking region (near the middle of the vacuum chamber). Each time the P.S. has brought a new pulse up to full energy the process is repeated, and the pulses are stacked side by side in the longitudinal phase plane of the storage rings.

Each pulse occupies a very small fraction of the longitudinal phase-plane available in the vacuum chamber of the storage rings. One can therefore build up very high beam intensities (in ordinary space) near the middle of the vacuum chambers.

The two storage rings can have one or two common straight sections, in which colliding beam experiments can be carried out.

In addition there are several other uses one can foresee for the storage rings. We shall sum up some of these in the next section.

Before leaving the basic principles it should, however, be mentioned that the rings need not be tangential. They could be nearly tangential with interaction regions crossing each other at small angles (Fig. 1 b). From the point of view of the nuclear physics experiments and observations in the interaction region there is a great difference between the tangential and nearly tangential layouts and a thorough study of the advantages and disadvantages must be made.

Nearly concentric rings will also be studied. From a physics point of view they have about the same features as the nearly tangential system, but they may render some saving in building cost.

3. The Usefulness of a Set of 25-GeV Storage Rings for Nuclear Physics Experiments.

A set of storage rings can basically serve two purposes: as a means for carrying out physics experiments in an energy range otherwise inaccessible and as a means of increasing the flexibility of the P.S. on experiments in the energy range of the P.S.

It is probably a matter of taste on which purpose to put most emphasis. In listing the possibilities, we shall start with the use of the storage rings in the energy range of the present P.S. (∼7 GeV in the centre of mass system).

In the discussion that follows it should be noted that although we shall mainly talk about 25 GeV for each ring (in the laboratory system) the rings are capable of storing any given energy between say 10 GeV and 25 GeV, but, of course, only one energy at a time.

(a) "D.C." proton beams.

Since the storage rings have constant magnetic field, it is possible to use one of them to bombard a target with a continuous (unpulsed and unbunched) beam, equal to the mean current of the P.S. If it is desired to have two such experiments going on simultaneously, the available P.S. mean output can be shared between the two rings in any proportion, and one can even envisage a third simultaneous experiment using some fraction of the beam within the P.S.

The life of the beam in the storage ring can be at least many hours, so that experiments requiring very low intensities can use it while the CPS is in use in the normal way. One can spend about an hour at the beginning of a shift to fill a storage ring and then use the P.S. and the Storage ring independently of each other till the ring is empty.

(b) Extremely high intensity short pulses.

One expects to get at least 10^{14} protons into each ring. All these particles can be taken out in one 2μs single burst.

If one is interested in shorter bursts, this can probably also be done, but then all particles cannot be taken in one burst. One could for instance use a chopper type of ejector or one could envisage forming 20 bunches and take them out one at a time. Each would then be shorter than 100 ns and could contain of the order of 10^{13} particles.

(c) Storing of other stable particles.

The storage rings can be used for other stable particles, e.g. antiprotons. The storage ring separates away very efficiently other particles, giving a very clean beam of the particles to which the storage ring is adjusted.

(d) Increase in the possibility of working on many experiments in parallel.

This possibility is already contained in the points mentioned above. But it is worth underlining that it is possible to carry out also experiments that in principle could be done directly on the P.S., in areas that are quite independent of each other and preparation can go on without disturbing current experiments.

f) Colliding beam experiments

One ofthe most interesting ways of using a set of storage rings, and in fact the only real justificatkon for building two rings rather than one, is to carry out colliding beam experiments. This gives one the possibility of probing into the very high energy region, up to 50 GeV in the centre of mass system (equivalent in energy to experiments on stationary targets, bombarded with 1300 GeV protons). This is much higher in energy than one can, on present knowledge, imagine from any "classical" machine. The limitation with this type of experiment lies in the low rate of events one can expect, of the order of 10^5 per second.

4. Present Ideas on a Possible Storage Ring Set Design.

We shall mainly consider tangential or nearly tangential rings as shown in Fig. 1. Each ring is in principle not very different from the P.S. It is therefore reasonable to start from the P.S. design and make the necessary and desirable modifications to fit the specific Storage Ring requirements.

a) Magnet.

The pole tips of the P.S. start saturating at top energy. One can therefore not hope to go higher in field than one does in the P.S. Consequently, a 25 GeV Storage Ring will require the same diameter as the P.S. The only way of reducing the Storage Ring diameter would therefore be to stack at a lower energy. This, however, would reduce considerably the advantages and interest of the storage rings, and the gain in cost will be small remembering that we only gain on the magnet and ring building whereas the other facilities will be nearly unchanged. We therefore recommend to stack at full energy.

In making two new rings one might consider deviating considerably from the focusing properties of the P.S. At first sight one would like to increase the focusing strength, in order to reduce the radial extent of the stack. However, frequency tolerances and the like will make it impossible to stack at an energy near the transition energy. If we want to have the possibility of stacking say from 10 GeV and upwards, we should not make stronger focusing than we have in the P.S. On the other hand, one would not like to have weaker focusing either, as that would increase the stacking space needed.

Altogether it looks to be a fair compromise to make the rings with bending and focusing properties like the P.S. magnet. We shall later consider in some more detail the aperture requirements. Here we shall only mention that it looks as if a horizontal aperture nearly equal to the horizontal aperture of the P.S. will be needed. One can therefore imagine to make the magnet yoke very similar to that of the P.S.

In this connection it should be remembered that storage rings are D.C. or near to D.C. devices and do not need such thin laminations in the magnet as the P.S., although a laminated magnet may still turn out to be the best technical and economical solution.

The P.S. magnet is wasteful in vertical aperture when used for storage rings, as probably only 2-3 cm vertical aperture is really required. We shall therefore also look into the following arrangement: To split focusing and bending in such a way that each ring consists of 100 bending magnets with no gradient and small vertical aperture, and 200 quadrupole lenses. Assuming that one in this case can go to 18 kG, the bending magnets will become 3 m long and the lenses can each be made about 0.6 m long with a field gradient of about 1.8 kG/cm. A unit consisting of one bending magnet and two lenses (equivalent ot a P.S. unit) would therefore not require more space than a P.S. unit. One further saves space by the fact that no quadrupole correcting devices will be needed. Such corrections can be taken directly on the power supply to the main quadrupoles.

Further advantages of such a system would be its flexibility in adjusting focusing properties and thus transition energy, which would be important since one wants to use the system for a large energy range, and economic considerations make it necessary to be in the saturating region at top energy.

If the solution of tangential rings (Fig. 1a) is chosen special magnets will be required in the interaction region and its immediate neighbourhood. Here bending and focusing must in any case be separated. A possible arrangement is shown in Fig. 2. Since the structure in this region differs a little from the main part of the ring, the half-integral and integral stop bands will be a little widened, and one must choose the parameters to make this widening as small as possible. This would again be an argument for splitting the focusing and bending everywhere, for then one can make the interaction region closer in properties to the rest of the rings.

In the solution of Fig. 1b with the rings crossing at a small angle, one does not need special magnet design for the interaction region and its neighbourhood. A possible arrangement is shown in Fig. 3.

The tolerances on the magnet will be as for the P.S., or perhaps a little tighter.

b) <u>Magnet power supply and cooling.</u>

If the magnets were exact copies of the P.S. magnets, a D.C. power supply of 7.5 MW would be required for each ring with a current stability better than 10^{-3}

It will be necessary to make a re-evaluation of the most economical coil cross section and power level.

Taking into account the possible reduction of vertical aperture and the possible splitting of bending and focusing a total power requirement below 10 MW can be expected. This would then be divided over 2 to 6 power supplies.

A cooling installation with demineralized water similar in nature to that of the P.S., but of higher capacity, would be necessary. This would be split in 2 or 4 circuits.

c) <u>R.F. system.</u>

There are basically two different ways of picking up and moving the particles sideways in the ring by the R.F. system:

i) One can debunch completely in the P.S. and rebunch again in the ring. This makes the R.F. system of the ring independent of that in the P.S.

ii) One can transfer the bunches from the P.S. and pick them up by matched buckets in the storage ring. This requires the frequencies and phases of the two systems to be locked to each other.

The disadvantage of the former method is that one cannot in practice make a complete debunching and bunching process ideal and one loses phases plane density. Further, with the experience we have with phase lock on the P.S. one should not have difficulties in using this just after the beam transfer. We therefore assume that the latter of the methods above will be used.

This means that we know the frequency of the system as it has to be equal to the top frequency of the P.S., i.e. ~ 9 MHz. The frequency modulation required is about 1 o/oo.

The R.F. voltage requirement for the Storage Ring depends to some extent on the future development of flat top operation of the P.S. It seems likely that the maximum R.F. voltage in the storage ring can be made to be less than 1/10 of the R.F. voltage in the P.S. The small frequency modulation and the low power requirement indicate that the R.F. system can be made very much smaller and simpler than that of the P.S.

In one respect, however, the R.F. system of the storage ring becomes more difficult than that of the P.S. In the S.R. one can use beam control only while the bunches are still far away from the stack, and programmed acceleration must take over soon after the beam transfer. This means that a system with little frequency-modulation noise must be developed.

d) Vacuum.

The required vacuum is governed by two considerations:

i) The life time of the beam must be much longer than the filling time of the rings.

ii) The beam-beam reaction rates must be larger than the beam-gas reaction rates.

If we aim at a beam life of the order of 24 hours, the mean pressure round the ring should not exceed 10^{-8} Torr, but the consideration (ii) sets an upper limit of about 10^{-9} Torr on the pressure in the interaction region.

In the state of ultra-high vacuum technique at the present day it is possible to meet these rrequirements by electropolishing the inside of the chamber, baking it at a moderate temperature, and having about 100 ultra-high vacuum pumping stations per ring.

The art of producing ultra-high vacuum on a large scale at reasonable cost is advancing rapidly, and it is only in the interaction region and near it that we are working near the present-day practical limit.

With the assumptions made earlier the vacuum chamber size would be as for the P.S. or smaller.

e) Beam handling.

Much progress has been made on a fast ejector for the P.S., which is expected to be able to kick single bunches out of the P.S. This indicates that one can hope to transfer the beam from the P.S. to the S.R. with not more than one bunch out of the twenty lost in the process.

The kicker must be shielded from the stack during the time it is on. With the times involved this can be done mechanically. The distance from the injection orbit to the bottom of the stack is therefore only determined by the physical size of the kicker and the shield. Preliminary estimates indicate that a distance of 3 cm from the injection orbit to the stack should be sufficient.

In addition to the fast ejector and inflectors, a beam transport system is needed in between. This must consist of 20-40 rather small conventional quadrupole lenses and a few bending magnets. The aperture need only be a few cm.

f) Buildings and space needed.

A storage ring set-up would require a tunnel for the beam transport, a tunnel for each of the rings, and experimental areas.

The tunnels will have a cross section approximately equal to that of the P.S. tunnel. If a solution with consentric rings is chosen only one ring tunnel is needed, but it must then have a considerably larger cross section.

In principle one large experimental area in the interaction region is enough. However, to be able to make the maximum use of the rings, it is recommended to have in addition one independent experimental area for each ring.

A possible layout is shown in Fig. 4. As seen the rings are tentatively placed north-west of the P.S. just inside France. It is difficult to see any other suitable situation for the rings. One condition for being able to realize a S.R. project seems therefore to be that CERN can acquire this land.

g) Primary services.

An extension of electric power and cooling water supplies will be necessary.

The total amounts will depend on the occupation of the new experimental areas.

However, a need for 20 MW extra power and 10,000 l/min extra primary cooling water should be expected as a minimum.

h) Cost and construction time.

A cost estimate of the S.R. project will be greatly facilitated by the similarity between the storage ring and P.S. It is too early to give a detailed cost estimate, especially since there is a possibility of reducing the steel requirement compared with the P.S. However, depending on the exact layout of the ring and especially the amount of buildings (experimental areas and laboratories) added to the site the total cost will be between the cost of the P.S. and twice that cost.

This could be compared with proposals for new machines in U.S.A., which are estimated to cost from four to ten times as much as the P.S.

Assuming that a team of some five to ten people spend about one year on a design study that would establish the main parameters of the scheme, together with cost estimates and a construction programme, and we then ask for approval of the project, we would estimate the construction time at 4 to 5 years from the date of approval.

5. Expected Performances.

An estimate of performance depends very much on the assumptions one makes, especially about the performance of the P.S. We shall therefore start from the present performance of the P.S. and afterwards discuss possible modifications that could improve this performance.

a) With present performance of the P.S.

The P.S. accelerates now 3×10^{11} particles per pulse. The detailed bunch size and shape at the high-energy end of the cycle is not known. More is known about the bunch at the injection end of the cycle, as it then effectively fills the bucket.

In a $(\Delta p/m_0 c\ ,\ \theta)$ plane the area of the P.S. bucket at injection is 5.5×10^{-3}, and each such bucket contains 1.5×10^{10} particles since there are 20 buckets altogether. The buckets have the highest density in the middle, but conservatively we assume even distribution, which we then reckon balanced out by the optimistic assumption that the phase plane density is not diluted as the bunch is accelerated, at least not in the neighbourhood of the centre of the bunch.

We now introduce the concept "stacking efficiency" η by which we mean the phase plane density in the stack divided by the phase plane density in the bunch as it leaves the synchrotron. We are then able to calculate the radial width of a stack in terms of the number of particles N it contains and the stacking efficiency η. One arrives at the result:

$$\Delta R \simeq 3 \times 10^{-14} \frac{N}{\eta} \text{ cm}$$

The stacking efficiency η is still unknown, and one of the objects of the storage ring model we are building is to study the stacking process and measure this quantity. Preliminary estimates indicate that it may be possible to make η between 50 and 100 o/o. Let us therefore assume $\eta \simeq 0.5$ and let us further assume that we want to stack 10^{14} particles in each ring. Such a stack will then require a space of

$$\Delta R \simeq 6 \text{ cm}$$

This is too big to get high reaction rates in the interaction region. One would therefore in such a case make use of a field perturbation as proposed by Terwilliger to reduce the radial spread in the interaction region. This scheme increases the stack width in other regions by a factor two, so a-12-cm aperture would be required only to accommodate the stack. Preliminary studies indicate that it may be possible to modify the Terwilliger scheme so as to eliminate this factor of two, and under (b) below we also consider less pessimistic assumptions about the C.P.S. beam.

The time it takes to build up such a stack depends on how much of the outer region of the bunches one has to scrape off because the phase space density has been diluted in this region. So far we have only assumed that there is a central core that is not appreciably diluted. If we make the assumption that the density is not diluted at all, it takes about 300 pulses to fill each ring with the above assumptions. We must therefore expect that 500-1000 pulses will be needed.

b) <u>Expected improvement of the P.S. beam.</u>

Returning to the assumptions about the P.S. beam, one might expect two kinds of improvement:

i) an improvement of phase plane density without increase in the beam from the linac.

ii) an improvement in the ion source.

With the debuncher in operation, a reduction in B and rather careful trapping adjustments one can at maximum gain a factor 2 by the former method. Although one should continue to improve the trapping efficiency of the P.S. along these lines, we prefer here not really to count on this factor, but rather take it as a safety factor.

Much more promising are the prospects of an improvement in ion source current over the next five years. Already now it has been reported from Argonne that they have injected 150 mA protons into an acceptance approximately equal to that of our linac. This is about a factor 5 up on our ion source performance at the moment.

Therefore it altogether does not look unduly optimistic to expect an improvement of the phase plane density of a factor five before the rings can be put into operation. The magnitude of a storage ring project is such that it would be perfectly reasonable, if it should turn out to be necessary, to couple it with a programme of substantial modifications to the present C.P.S. Linac.

This means that one can expect to stack 10^{14} particles in little more than 1 cm, and the stacking time would only be of the order of 100 pulses to reach this intensity.

With this assumption one is left with the problem of deciding whether one should try to make the horizontal aperture correspondingly smaller and thus save on the magnet, or instead keep the aperture approximately as on the present P.S. magnet and rather be able to stack more pulses. A decision on this should be deferred till further studies have been made both of expected performance and on cost.

6. Techniques and Problems of Experiments with Colliding Beams.

The particles emerging from the colliding beam region must be expected to cover a wide range of energies: statistically scattered protons conserve the energy of the primary protons, particles created in high multiplicity events may have rather low energies.

There is little doubt that for exploratory studies and the study of multiple production some sort of track chamber (scintillation or bubble chamber) enveloping the colliding beam region, as proposed by L.W. Jones and G.K. O'Neill, would be the desirable instrument. For the study of specified events, counter techniques would be adequate; in fact, the steady and moderate particle flux is appealing for counter experiments and coincidence techniques.

There is a limitation on the accessibility of very small forward or backward angles with respect to the primary beams. Secondary particles emerging at angles below 10^{-3} radians will not separate from the primary beam; up to about 10^{-2} radian, elastically scattered protons may stay inside the vacuum chamber, so that a minimum of a few degrees is required for intercepting particles by external analysing devices. Unfortunately, high energy events have a tendency of being strongly peaked in forward or backward direction; means may therefore have to be looked for to detect secondary particles very close to the stacked beams. The idea to obtain a separation of primary beams and secondary particles by having the centre of mass not entirely at rest in the laboratory (by beams intersecting at an angle, or by a differencein primary momenta) does not prove helpful, unless one would go so far as to sacrifice most of the justification of colliding beams. On the other hand, those events resulting in secondary particles of large angles, may be the most interesting ones

The collision region represents a source of appreciable extension. For counter measurements of angular distributions, particle directions can be defined in the focal plane of appropriate lenses viewing the interaction volume. In practice, such techniques would be limited to larger angles. A required accuracy in definition of momenta and angles of secondary particles in the c. of mass system implies a corresponding definition of primary momenta. E.g.,a 1 o/o spread or difference in primary momenta corresponds to about 1 o/o spread in secondary momenta, and 0.01 radian spread in secondary angle for elastic scattering by 90° in the c. of mass system. Requirements on accuracy might therefore in certain cases limit the number of pulses permissible in the stack because of momentum spread.

The discrimination between colliding beam events and background due to residual gas will in general have to make use of the kinematics of the events. At large angles with the beam, discrimination should be less difficult, because most of the secondaries from stationary targets come out at small angles.

7. Conclusion.

There are many problems that need considerably more careful study in order to arrive at definite conclusions about design and performance of a set of storage rings for the P.S. Some of these are going to be studied on the model we are building and some can only be considered theoretically. One can mention such things as further studies of phase-plane properties of the CPS, beam transfer, stacking efficiency, beam stability, effect of beam interaction, magnet arrangement, ground investigations, etc.

However, it is already now felt that a storage ring system is a feasible project if it is desirable from a nuclear physics point ov view, and that one should rather soon take some practical steps necessary to make it possible to realize such a project. The first two steps would be to obtain the necessary land, or an option on it, so as to begin investigation of subsoil and rock conditions; and to set up a small design-study group which would prepare a project in sufficient detail for CERN Council consideration.

One should also consider a set of storage rings in relation to other big projects in this field in the world. Discussions have already started on the possibility of a really big project on an international basis. This would then be a machine in the 300 - 1000 GeV range. However, it would be natural to have an intermediate stage. Plans are at present being developed in U.S.A. for a synchrotron somewhere in the range 100-300 GeV. An equally natural intermediate stage would be to add storage rings to one of the 25-30 GeV machines in the world. This would give some information about the very high energy range and therefore help in deciding about desirability of a 300-1000 GeV machine on an international basis. Since U.S.A. will very probably start on a 100-300 GeV synchrotron it seems reasonable that CERN should start on the other project in the intermediate range, the storage rings.

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Fig. 1 Set of storage rings with synchrotron

A Tangential rings

B Nearly tangential rings

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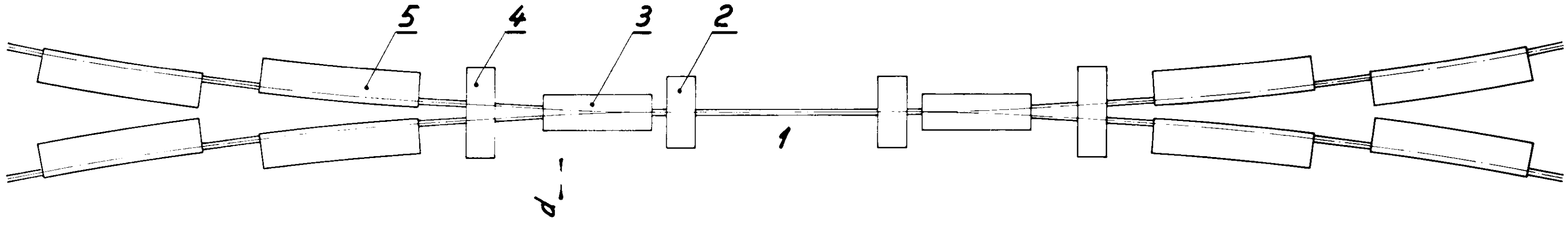
Fig. 2 Interaction region

Tangential rings



1 Interaction region

2 Quadrupole lens

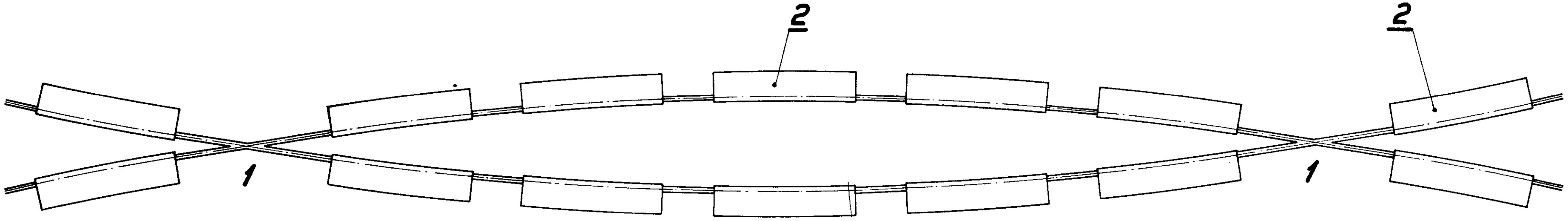
3 Homogeneous field magnet 18 kG

4 Quadrupole lens of special design (two apertures with $d = \sim 35\,\mathrm{cm}$)

5 Alternating gradient magnet units

Fig. 3 Interaction region

Nearly tangential rings



1 Interaction regions

2 Alternating gradient magnet units

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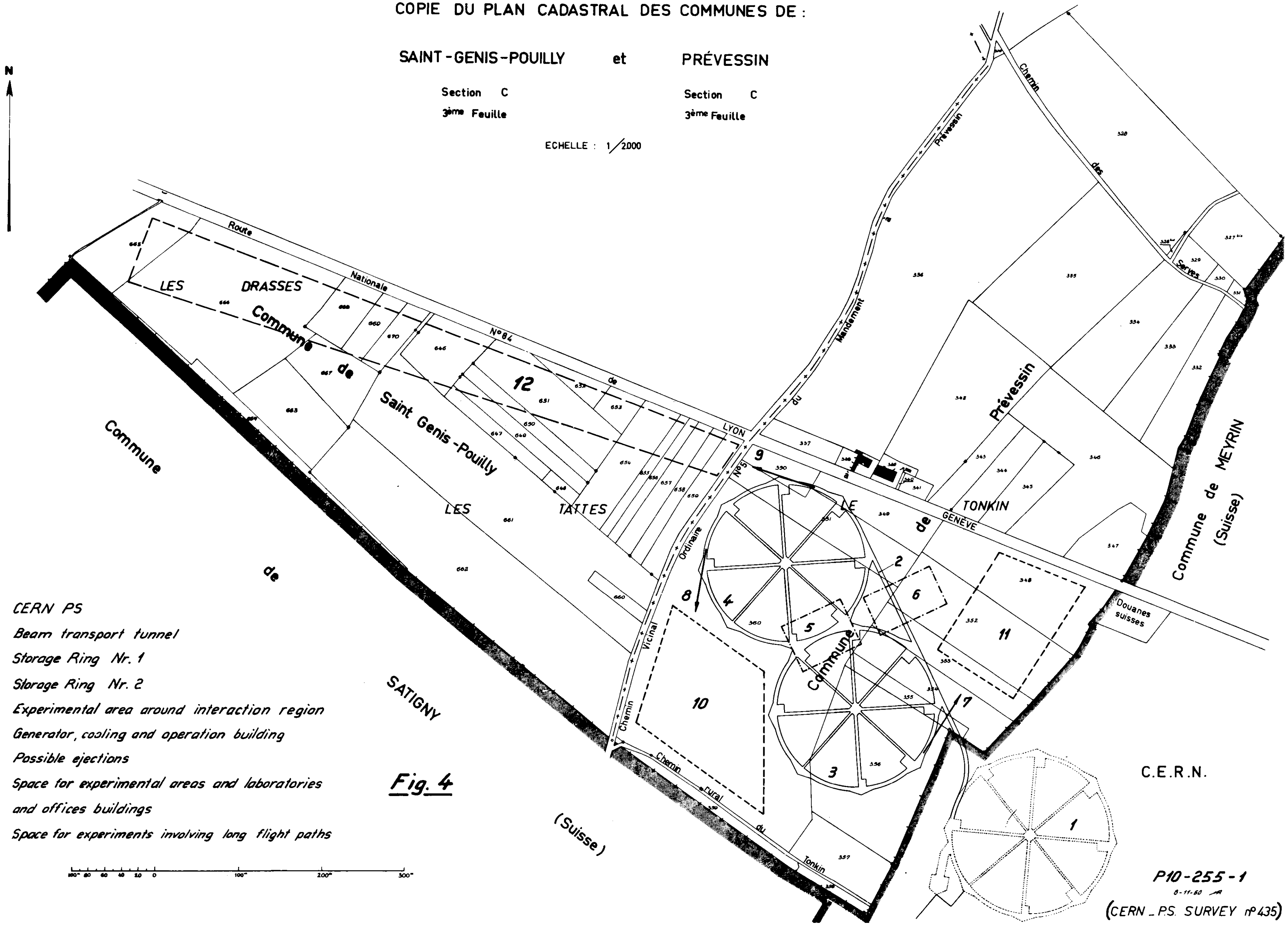

1 CERN PS
2 Beam transport tunnel
3 Storage Ring Nr. 1
4 Storage Ring Nr. 2
5 Experimental area around interaction region
6 Generator, cooling and operation building
7-8-9 Possible ejections
10-11 Space for experimental areas and laboratories and offices buildings
12 Space for experiments involving long flight paths

Fig. 4

P10-255-1
8-11-60
(CERN_PS SURVEY n°435)