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STORAGE RINGS AND TANGENT ACCELERATORS

R. Meunier, M. Spighel and J.P. Stroot

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STORAGE RINGS AND TANGENT ACCELERATORS

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I. INTRODUCTION

This note presents a comparative study of the performance, of interest to the physics programme, of intersecting storage rings (ISR) at 25 GeV as described in CERN 542) with that of two tangent accelerators (AT).

The comparison is first conducted using two accelerators of the same 25 GeV energy, that are entirely independent of the present CERN Proton Synchrotron and that are specially designed for colliding beam experiments. The choice of their parameters should allow for suitable straight sections in the collision area, and also for a circulating proton beam with a smaller cross-section than that of the present CERN PS beam, which is technically feasible.

Due to adiabatic damping of betatron and synchrotron oscillations, the proton density is larger the greater the final energy of the accelerated beam.

In colliding experiments with two different beams, the performance is determined by the widest one. So it is of the same order of magnitude for two unequal energy tangent accelerators as for symmetric ones of the lowest energy.

The comparison of ISR to two AT of 25 GeV is thus extended to the case of two AT, one being 25 GeV and the other 50 GeV, stressing the advantages of such a solution, such as larger c.m. energy (70 GeV), c.m. movement which can be of help in searching for low velocity massive particles and, last but not least, the availability of higher energy facilities*).

Also considered is the extension of the AT beam collision experiments at the future very high energy accelerators, where it seems to be the only practical solution.

*) These energies have been chosen, with the assumption that the total cost of these two AT (25 and 50 GeV) should be comparable to the cost of the ISR project.

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In the ISR, a circulating proton current greater than in the AT can be achieved, since the space charge limitations apply to the stacking energy in the ISR, and to a lower injection energy in the AT. However, the progress made with alternating gradient proton synchrotrons has led to a considerable increase in the final accelerated beam, by applying the necessary corrections during the transitory period when instability occurs.

During the stacking of the present FS beam into the ISR there would be a certain reduction of the proton density of the circulating beam. This operation, which is avoided in the AT, is accompanied by an increase in the diameter of the stacked beams. Since the interaction rate in the collision area does not depend only on the number of circulating protons, but also on their density, and since the momentum spread is greater in the ISR than in the AT, the following questions are posed:

(a) How much does storage increase the interaction rate?

(b) What effect does reduced accuracy concerning momentum have on the analysis of events, particularly when neutral particles are omitted?

It was Professor Amaldi's report on 2 April, 1963, on the work of the European Committee on Future Accelerators, which gave rise to studies which were described in a note \(^2\) entitled "Sur l'utilisation des faisceaux croisés", written in May 1963 and distributed as a personal communication.

A brief study of the ISR parameters proposed in April, 1963, showed that the over-all interaction rate of the ISR was clearly better than that of the AT, but the instantaneous rate during the duty cycle was comparable. With respect to background and the accurate reconstruction of events, the two tangent FS rings were superior.

After presentation to the Council of the "Report on the Design Study of Intersecting Storage Rings (ISR) for the CERN Proton Synchrotron" \(^1\), CERN/542, a further comparison was made from the point of view of experimental work.

A note \(^3\) entitled "Doux projets possibles d'intersections de faisceaux" was distributed in June 1964 to a limited number of people at CERN.
This note showed that the interaction rate for both the ISR and AT solutions was comparable if the same experimental accuracy was maintained, but that the total interaction rate of the ISR was actually superior if good energy definition in the centre of mass was neglected. It is also suggested to build one accelerator of larger energy (up to 75 GeV).

The possibility of bunching the beam by means of an r.f. system (as in an accelerator and in the solution consisting of tangent accelerators), and the advisability of reducing the angle of collision to 7.5°, or even 0°, in order to increase the collision rate while improving the layout for certain types of experiment, are being studied with a view to incorporating these developments in the ISR if this is technically feasible.

The ISR should be compared objectively with two AT, not in the light of the present situation, but of that which may reasonably be expected when construction takes place in 5 or 6 years' time; the PS will then be accelerating $5 \times 10^{12}$ to $10^{13}$ p/pulse, which means a certain improvement of the ISR project; filling time is shorter and energy resolution is better for equal interaction rates. The ISR at that time should be compared to AT with $5 \times 10^{12}$ to $10^{13}$ p/pulse.

It should be noted, however, that the number of $4 \times 10^{14}$ circulating protons in the ISR seems to be a maximum. The increase in PS intensity will therefore mean that, as it is progressively improved, the number of pulses to be stacked in order to fill the ISR can be reduced.

The number of pulses to be stacked has been progressively reduced from 500 in 1963 to 40 and, in the event of good $\Delta p/p$ definition, it would be reduced to 20 or even less.

The question as to whether storage serves any useful purpose is therefore coming more to the fore as less pulses are stacked, and it may well be asked whether storage remains an attractive solution which is likely to be of interest when ordinary accelerators are accelerating $5 \times 10^{12}$ to $10^{13}$ p/pulse, when stacking entails an inevitable loss of proton density.
for instance, even for a few bunched bursts with a cross-section of 0.2 cm² in the present PS, one obtains a 2 cm² beam when it is injected into the ISR.

In an attempt to answer this question, we will now give the bases of calculation and the parameters adopted in order to make a comparison between the ISR and the AT, bearing in mind the probable improvements to the PS and PS-type accelerators.

II. COMPARISON OF THE BEAM COLLISION INTERACTION RATE FOR THE ISR AND THE AT

The number of interactions per second of beam collisions is expressed by the equation:

\[ N_{\text{int}} = \sigma_{pp} \times \tau \times N_{\text{inc}} \times \frac{S}{L} \]

where

- \( N_c \) = the number of protons per cm³ in the target beam;
- \( \frac{S}{L} \) = effective length of the interaction area (relativistic effect);
- \( N_{\text{inc}} \) = the number of incident protons per second;
- \( \tau \) = duty cycle;
- \( \sigma_{pp} \) = proton-proton collision cross-section.

For storage rings, this equation may be written:

\[ (N_{\text{int}})_{\text{ISR}} = c \tau \sigma \frac{1}{h} \left( \frac{N}{L} \right)^2 = c \frac{\tau \sigma}{S} \left( \frac{N}{L} \right)^2 \frac{1}{L} \]

where

- \( N \) = the total number of circulating protons in each ring;
- \( L \) = the length of each ring;
- \( h \) = the height of the collision area;
- \( \alpha \) = the angle of collision of the beams;
- \( S \) = the surface of the cross-section of each beam.
In the case of tangent accelerators with bunching, for the collision of two proton bunches one can write:

\[
N_c \ell = \frac{N}{L} \frac{\lambda}{S}
\]

\[
N_{\text{int}} \text{ per bunch} = \frac{N}{L} \lambda
\]

where

\( \lambda \) = the distance between the bunches, i.e. the wavelength of the accelerating r.f.

The total number of interactions is then written as:

\[
\left( N_{\text{int}} \right)_{AT} = \tau \sigma \frac{c}{\lambda} \left( \frac{N}{L} \right)^2 \frac{\lambda^2}{S} = c \tau \sigma \left( \frac{N}{L} \right)^2 \frac{\lambda}{S}
\]

The ratio between the length of the bunches and their spacing out does not appear explicitly, since the length of a bunch is taken as the length of interaction. The advantage of bunching is to have in a short interaction length (about 240 cm for the bunches of the present PS) the same collision rate as if the machines were tangent for a length equal to the accelerating wavelength (30 m in the case of the PS).

Bunching increases the number of useful interactions by one order of magnitude.

This improvement can be made to the ISR only for the storage of a few pulses and cannot be applied to full storage.

III. BACKGROUND

The proximity of the experiment and of the circulating beam imposes extremely severe conditions on the detection system. The proton flux through the vacuum chamber is about \(10^{15}\) to \(10^{20}\) times greater than the particle flux to be detected. Such an attenuation factor poses serious problems. Any improvement as regards background is of primary importance.

*) In case of two accelerators of unequal energies, bunches have to be synchronized for maximum collision efficiency. This problem will certainly be solved as it is not one of principle.
The detectors placed near the interaction areas are exposed to two kinds of stray flux:

(a) **Local background.** This consists of stray events from the interaction area, which are due to residual gas. If the rate is reasonable, it is supposed that the equipment makes it possible to distinguish them from true events.

(b) **Ambient background.** This consists of the radiation received by each detector from the two machines outside the collision area itself. This radiation is partly due to the over-all radioactivity of the machines and partly to the secondary particles created upstream by interaction with the residual gas and by the halo of scattering on the structure of the machine. The first type (radioactivity) should always be lower for the AT than for the ISR, on account of the weaker circulating current, the ratio being the same as that of the circulating currents in analogue vacuum conditions. In both cases, the circulating beam is dumped without increase of radioactivity near the collision section.

The second type, of an instantaneous nature, is not negligible when planning a collision experiment and may even represent a fundamental limitation to the intensity of the stacked beam. The number of $2 \times 10^{13}$ circulating protons in the ISR in a $10^{-10}$ mm Hg vacuum should not be exceeded, in order to avoid saturating the detectors with ambient background during pp elastic scattering experiments. The number of interactions is then reduced by a factor 1600 as compared to the maximum announced (report CERN/542).

If $\delta$ is the density of the residual gas, the local background (LB) due to collisions on the residual gas in the interaction area is:

$$\text{(LB)}_{AT} = 2 \sigma r \sigma_{\text{gas}} \delta \frac{N}{L}$$

$$\text{(LB)}_{ISR} = 2 \sigma r \sigma_{\text{gas}} \delta \frac{N}{L} = c r \sigma_{\text{gas}} \delta \frac{N}{L}.$$  

In the case of the ISR, the signal to local background ratio is expressed as:

$$\frac{N_{\text{int}}}{\text{LB}}_{\text{ISR}} = \frac{\sigma}{\sigma_{\text{gas}}} \frac{1}{S} \frac{N}{L \cdot S}.$$
In the case of the AT:

\[
\left( \frac{N_{\text{int}}}{L^B} \right)_{\text{ISR}} = 2 \sigma_{\text{gas}} \frac{1}{\delta} \frac{t}{L} \cdot \frac{N}{L^S}.
\]

The ambient background is proportional to \(N/L\) in the case of the ISR and to \(N \times \lambda/(L \cdot t)\) in the case of the AT.

The signal to ambient background ratio, with an equal vacuum and for similar experimental conditions, is in both cases proportional to \(N \cdot t/L \cdot S\). Bunching of the circulating beam plays no part.

Under equal physical conditions, one finds:

\[
\left( \frac{N_{\text{int}}}{\text{ambient background}} \right)_{\text{ISR}} = \left( \frac{N_{\text{int}}}{\text{ambient background}} \right)_{\text{AT}}
\]

\[
\left( \frac{N^t}{L \cdot S} \right)_{\text{ISR}} = \left( \frac{N^t}{L \cdot S} \right)_{\text{TA}}
\]

IV. TABLES

Table 1 compares the ISR and AT solutions for various choices of parameters explained later. Table 2 compares the two solutions for any resolutions equal to about \(10^{-3}\).
Table 1

Comparison of the ISR and AT for various choices of parameters

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Number of protons injected per burst</td>
<td>$5 \times 10^{18}$</td>
</tr>
<tr>
<td>2</td>
<td>Number of circulating protons</td>
<td>$4 \times 10^{14}$</td>
</tr>
<tr>
<td>3</td>
<td>Angle of collision</td>
<td>$15^\circ$</td>
</tr>
<tr>
<td>4</td>
<td>$\tau$ - duty cycle</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>Width of beam in cm</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Height of beam in cm</td>
<td>1.5</td>
</tr>
<tr>
<td>6</td>
<td>$\ell$ - effective length of the interaction area in cm</td>
<td>15</td>
</tr>
<tr>
<td>7</td>
<td>S - Surface of beam cross-section in cm$^2$</td>
<td>3</td>
</tr>
<tr>
<td>8</td>
<td>Number of interactions normalized to the ISR rate with $4 \times 10^{14}$ circulating protons and a $15^\circ$ angle of collision (without taking into account the duty cycle)</td>
<td>1</td>
</tr>
<tr>
<td>9</td>
<td>Normalized intensity of interactions (taking into account the duty cycle)</td>
<td>1</td>
</tr>
<tr>
<td>10</td>
<td>Ap/p in the centre of mass - Total width</td>
<td>$1.4 \times 10^{-3}$</td>
</tr>
<tr>
<td></td>
<td>$\Delta E$ - error on energy in the centre of mass</td>
<td>700 MeV</td>
</tr>
<tr>
<td>11</td>
<td>Number of interactions per second</td>
<td>$10^8$</td>
</tr>
<tr>
<td>12</td>
<td>Figure of merit of the signal to local background ratio independently of the residual pressure of the gas and its cross-section</td>
<td>1</td>
</tr>
<tr>
<td>13</td>
<td>Figure of merit of the signal to ambient background ratio independently of the residual pressure of the gas and its cross-section</td>
<td>1</td>
</tr>
</tbody>
</table>
Remarks on Table 1

1) The ISR and the AT are compared, taking into account the improvement of the machines, which in a few years will lead to intensities of $5 \times 10^{12}$ to $10^{13}$ protons per accelerating cycle.

2) $4 \times 10^{14}$ is the maximum intensity planned in the ISR for reasons of stability.

4) The time lost in filling the ISR with a few bursts when the PS accelerates $5 \times 10^{12}$ to $10^{13}$ protons/burst is neglected.

It is supposed that one can envisage two PS machines operating at higher repetition rates and with longer flat tops. A duty cycle of 0.4 per PS is therefore envisaged.

5) AT beam dimensions are larger than in the present PS because high intensities will probably be obtained by using a 200 MeV injector.

These values are used together with the same hypothesis as in CERN/542, page 56, to obtain the ISR beam dimensions taking into account the $5 \times 10^{12}$ to $10^{13}$ protons injected burst dimensions and the injection errors. With $10^{12}$ protons per burst the ISR beam height is only 1 cm, when the present PS beam diameter is 0.5 cm.

6) $b/(\tan a/2)$ is the effective length of the interaction area for the ISR. For the AT, the effective length is the length of a bucket.

8) The numbers are calculated on the assumptions mentioned in 1) to 7) for the choice of parameters. They are given as relative values; namely, in the first case (first column) they are arbitrarily given the value 1. The length L of the storage rings is taken as 1.5 times greater than the length L of an accelerator.

10) The total width $A_p/p$ of the momentum available in the centre of mass is equal to the total width of each of the beams

$$\frac{A_p}{p} = \frac{1}{2} \left( \frac{A_{p1}}{p_1} + \frac{A_{p2}}{p_2} \right).$$
The present PS has a $\Delta p/p$ of $5.4 \times 10^{-4}$. An improved PS with a 200 MeV linac injector delivers a beam with a momentum bite twice as large as the present PS with a 50 MeV injector. Thus AT $\Delta p/p$ is taken to be about $1.1 \times 10^{-3}$.

Stacking efficiency in longitudinal phase space is about 0.5 in ISR. As long as the number $n$ of stacked bursts is less than the injector bunching factor $B$, we take

$$\left( \frac{\Delta p}{p} \right)_{\text{ISR}} \approx 2 \times \left( \frac{\Delta p}{p} \right)_{\text{PS}}, \quad 1 < n \leq B$$

For $n > B$, we take

$$\left( \frac{\Delta p}{p} \right)_{\text{ISR}} \approx 2 \times \frac{B}{n} \times \left( \frac{\Delta p}{p} \right)_{\text{PS}}, \quad n > B$$

11) $\sigma_{pp} = 40$ mb.

12) Relative value, since neither the vacuum which will be achieved nor the chemical composition of the residual gas are known. A value of 1 is taken for the first case.

13) Same remark as for 12).
Table 2

Comparison of ISR and AT at a resolution of $\approx 10^{-3}$

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Number of protons injected per burst</td>
<td>$5 \times 10^{12}$</td>
<td>$10^{13}$</td>
</tr>
<tr>
<td>2 $\Delta p/p$ in the centre of mass - Total width</td>
<td>$2.2 \times 10^{-3}$</td>
<td>$2.2 \times 10^{-3}$</td>
</tr>
<tr>
<td>$\Delta E$ - error on energy in the centre of mass</td>
<td>110 MeV</td>
<td>110 MeV</td>
</tr>
<tr>
<td>3 Maximum number of circulating protons to satisfy $\Delta p/p \approx 10^{-3}$</td>
<td>$6 \times 10^{13}$</td>
<td>$1.2 \times 10^{14}$</td>
</tr>
<tr>
<td>4 Angle of collision</td>
<td>15°</td>
<td>15°</td>
</tr>
<tr>
<td>5 $\tau$ - duty cycle</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>6 Relative intensity of interactions (taking into account the duty cycle)</td>
<td>0.022</td>
<td>0.09</td>
</tr>
<tr>
<td>7 Figure of merit of the signal to local background ratio</td>
<td>0.15</td>
<td>0.3</td>
</tr>
<tr>
<td>8 Figure of merit of the signal to ambient background ratio</td>
<td>0.15</td>
<td>0.3</td>
</tr>
<tr>
<td>9 Number of interactions per second</td>
<td>$2.4 \times 10^3$</td>
<td>$10^4$</td>
</tr>
</tbody>
</table>
V. EXPERIMENTAL FACTORS LIKELY TO INFLUENCE THE CHOICE OF A SOLUTION

The tables, giving the results of the calculations based on the hypotheses described in the previous paragraphs, show the similarity of performance of the ISR and the AT, with a maximum of circulating protons, but also the marked superiority of the AT, which give four to five times more collisions per second than the ISR, when they are compared at an experimental accuracy on energy of $\approx 10^{-3}$, which is necessary for almost all experiments.

Accuracy is a more important experimental factor than the number of interactions. The discovery of $\Omega^-$ depended on a single bubble chamber photograph, owing to the accuracy of the energy and momentum balance.

If elastic scattering experiments already call for an accurate energy balance in order to eliminate the contributions from quasi-elastic and inelastic reactions, this accuracy is all the more necessary for experiments attempting to show the production of nucleon isobars, resonances or, more generally, new particles. The production of neutral particles during these processes makes it nearly always impossible to reconstruct the events, if the centre-of-mass energy is not well known.

Determining the vertex from the accurate measurement of two charged traces improves the accuracy of the ISR very little, since the accuracy of the relation between the position of the interaction and the energy of two protons is limited to the dimension of the area occupied by monokinetic protons (of the order of a cm). In order to make an energy record with a good probability of avoiding error on the number of $\pi^0$, the error on the energy record must be determined in a 50 MeV wide band. The error is equally divided between the initial and final products of the reaction. The necessary accuracy is therefore $10^{-3}$ on the energy of each beam.

The performances of the ISR and the AT should therefore be compared under the conditions of experimental accuracy required for an unequivocal record of the reaction. In this case, Table 2, drawn up for a $\Delta p/p$ accuracy of about $10^{-3}$, shows clearly that the AT solution gives four to five times more interactions per second than the ISR.
It also shows that the AT are fundamentally superior with respect to local and ambient background which, under equivalent physical conditions, are three to eight times lower in the case of the AT. The factor 3-8 may be decisive in making experiments possible.

VI. TANGENT ACCELERATORS OF UNEQUAL ENERGIES

The advantages of AT over ISR for colliding beam experiments are still present when the energy of one of the AT is increased. New possibilities appear.

The rate of interactions between the beams of a 25 GeV accelerator and a 50 GeV one is essentially the same as that of two 25 GeV accelerators, as is shown by a single computation.

A common linac injector can feed both rings.

AT magnets are of a smaller cross-section than ISR ones. The mean steel weight of one metre of ISR magnets is 8.5 tons as compared to 4.2 tons for one metre of magnet of the 300 GeV project. The copper weights are 1.2 ton and 0.37 ton, respectively.

The maximum induction in the magnet ring is less in ISR than in AT because of greater sensitivity of stacking to saturation. It results in a larger orbit diameter.

A vacuum of $10^{-7}$ to $10^{-8}$ mm Hg is sufficient in AT except in the colliding beam region where $10^{-10}$ or better is required as over the whole length of the ISR.

Accelerator tunnels are of smaller cross-section than ISR ones.

Taking into account the longer length of AT tunnels, it is still reasonable to think that AT are more economical than ISR. The cost of 25 GeV ISR probably covers the cost of a 25 GeV + 50 GeV accelerator pair.

Further benefit is brought by the larger c.m. energy: 70 GeV, while the c.m. itself has a small velocity of $c/3$.  

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Also 50 GeV facilities are provided which can be run concurrently with the colliding beams experiments.

On the other hand, the AT configuration requires a larger site than does the ISR.

The eventual use of the present PS as a very high energy injector into two tangent post accelerators, one of 25 GeV and one of 50 to 60 GeV, is a possible solution after improvement of the PS beam intensity. Post accelerator magnets could be made very small and thus be less expensive. Less flexibility in tuning the parameters for this solution, a loss in beam density during the beam transfer, and a shorter duty cycle would probably deteriorate the collision interaction rate compared to fully independent tangent accelerators.

VII. Tangent Accelerators at Very High Energies

If \( n (>1) \) is the ratio between the energies of two unequal AT, the available c.m. fraction of the total energy is given by \( 2n/n+1 \).

So a 30 GeV accelerator tangent to the future 300 GeV PS would give 190 GeV in the c.m., i.e. nearly 60% of the total 330 GeV and one-third of the 600 GeV that would be provided by two colliding 300 GeV ISR or AT beams. The interaction rate would be determined by the 30 GeV beam proton density.

As we have suggested at 25 GeV, larger post accelerators can be built tangent to existing or future accelerators.

The economy of building accelerators as a cascade of successive tangent rings with intermediate beam collision facilities should be considered until entirely new technology would appear in the field.
Acknowledgments

We should like to express our thanks to Professor A. Schoch for helping us in numerous discussions by his critical appreciation of a great number of questions raised by these studies. Our thanks are also due to Dr. C. Rubbia, with whom we had many fruitful discussions on accelerators and colliding beam experiments. We are also grateful to Dr. L. Dick for many discussions and exchanges of ideas.

We should like to thank Professors W. Paul and P. Preiswerk for encouraging us to continue and complete this work.
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1) Report on the design study of intersecting storage rings (ISR), CERN/542, April 1964.
