PS/AA/AGR/afm

15 July 1982

AA Long Term Note 11

A VERY MUCH IMPROVED SCHEME FOR ANTIPROTON PRODUCTION FOR CERN WITH THE SPS AND THE ISR

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CERN, June 1982

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INTRODUCTION

I certainly believe that the idea of using the SPS and the ISR rings for the antiproton production in CERN must have arrived to many people in the past and several times (see for instance AA Long Term Note 4, apr. 21, 1982). Nevertheless I thought also about it and wanted to see if one can do considerably better in production rate compared to the present performance of the AA-ring.

My first consideration was that it makes more sense to demand one or two orders of magnitude of improvement on the present production rate and that a factor of only few would have not sufficed, though, of course, welcomed.

One should be able to realize that such a demand can be satisfied only with larger primary proton energy and larger energy of the antiprotons selected out of the target. Clearly the SPS represents a better source for large proton energies, but it is also the Collider. An alternate use of the SPS as the antiproton source and as collider could make sense only if several times 10^{11} antiprotons can be produced in an hour, that is extremely fast. Then one could spend one or two hours to produce antiprotons and follow with a longer period of ten or twenty hours in colliding beam mode.

To get a large production rate, it is also necessary to select a relatively higher energy for the antiprotons. Moreover, one can take a few ideas from the very recent Antiproton Source scheme for Fermilab where two auxiliary rings are proposed : a Debuncher Ring and an Accumulator Ring. Similarly also in CERN one needs two of these rings, and a look of the site map clearly suggests the use of ISR rings.

The scheme we propose here makes use as much it can of the available transport lines and rings so that civil engineering of the project is reduced to a minimum. As one can see the two ISR rings will remain practically unmodified.

A proton pulse of 3 10^{12} particles out of the CPS at 27 GeV is accelerated into the SPS to 200 GeV and extracted to a target to produce antiprotons at 9.5 GeV with 4 % of momentum spread. The antiprotons are quickly injected into one of the ISR rings where they are "rotated" and "debunched" and then transferred into the second ISR ring where they are "accumulated" with stack-tail momentum stochastic cooling. The production rate expected is of 6 10^{11} in two hours, a number of antiprotons necessary for a luminosity of 10^{30} $cm^{-2}s^{-1}$ at 220 GeV in the SPS. Clearly at the beginning and only then a longer period of time is required to "prime the pump", that is to prepare a larger stack fron which extract the required number of antiprotons.

This scheme of course does not improve the peak luminosity, but only the production rate of about a factor 30 over the present AA-scheme and a factor of 2 over the Fermilab scheme.

To get larger peak luminosity one should improve the performance of the collider, that is the SPS. I believe that to make use of more antiprotons at this purpose high energy cooling in the colliding beam mode is required. But, anyway, it is the average luminosity over a long period of time that eventually will benefit from the higher production rate we propose here.

It is also clear to myself that the antiproton source proposed in this paper will eventually be very much suited as the injector to LEP as proton-antiproton collider.

THE SEQUENCE OF THE EVENTS

The scheme works as follows :

Step 1. The CPS is loaded with four Booster batches for a total number of 3 10^{12} particles. This reduced beam intensity will garantee a small betatron and longitudinal emittance. The beam in the CPS is accelerated with the standard 9.5 MHz RF system. Therefore, there are 20 bunches each with 1.5 10^{11} protons. Because the beam has to be transferred to the SPS with a single turn extraction (to preserve the length of the pulse and the bunching) then it ought to be injected in the SPS above the transition energy. We propose here acceleration of the beam to 27 GeV in the CPS.

Step 2. If it is not already done, it may be required to compress each of the 20 bunches with by now conventional techniques so that they match and fit the 200 MHz RF buckets in the SPS. This can be done on a short flat-top at 27 GeV just before extraction. Consider for instance lowering the RF voltage slowly until bunches extend over $\pm 90°$ and then raise again the voltage suddenly to full voltage. Because of the mismatch created the bunches will rotate. After a quarter of phase oscillation the bunches have the narrowest width and will be extracted and transferred to the SPS at 27 GeV.

Step 3. The 20 bunches are captured by stationary buckets of the 200 MHz RF system. There will be one bunch every 21 buckets. This beam will be accelerated to an energy of 200 GeV. For this energy the SPS cycle time should match the CPS cycle time which we take here to be 2.4 second long. At 200 GeV, on a short flat-top, the beam will be RF manipulated in a way similar to the one proposed for the Fermilab most recent $\bar{p}$-collection scheme, and similar to the one described in the previous step in the CPS. We expect a full bunch length of about 2 ns and separation of 105 ns between bunches. This corresponds to a bunching factor of 50.

We also assume here that the proton beam in the SPS is similar for what concerns momentum spread and betatron emittance to the one in the Main Ring at Fermilab.

At the end of all manipulations the beam is extracted from the SPS.

Step 4. The beam is sent toward a target shown in Fig. 1. In the same figure we have shown the trajectory of the primary proton beam from the Linac, through the Booster, the CPS, the SPS and down to the target. This can be made of tungsten of 5 or 6 cm long. The energy of 200 GEV has been chosen in agreement with the shortest cycle as possible. (At Fermilab the same energy is limited to 125 GeV because of the limitation of the extraction line from a medium straight section that is used).

If we assume a spot size on the target of $\sigma = 0.22$ mm (rms radius) which corresponds to a beta value $\beta \sim 1$ m there should be any problem by impinging 3 10^{12} protons energy 2.4 s as it has been proven at Fermilab.

One can collect (for instance with a lithium lens) :

$$\Delta p/p = 4\ \%$$

$$\varepsilon_H = \varepsilon_V = 20\ \pi\ \text{mm.mrad}$$

where $\Delta p/p$ is the momentum spread and ε the betatron emittance.

For a reason that we will see later but that has to do with the transition energy in the ISR we assume a $\bar{p}$ collection (kinetic) energy of 9.5 GeV. From the graph of Fig. 2 (prepared by C. Hojvat) we then expect to collect 2.4 10^8 $\bar{p}$'s energy pulse (against 1.0 10^8 at Fermilab) which corresponds to a flux (rate of production) :

$$\phi = \frac{dN_{\bar{p}}}{dt} = 10^8\ s^{-1}$$

twice what one could do with the present scheme at Fermilab.

For instance, 6 10^{11} antiprotons necessary for a luminosity of 10^{30} $cm^{-2}s^{-1}$ at 270 GeV in the SPS could be collected in a period of only <u>two</u> hours.

Clearly at the moment of production the $\bar{p}$-beam preserves the bunch structure of the proton beam.

The antiproton beam is then injected in one of the ISR ring after having been transported down to the T60 line. Maybe this line should be modified to make sure a momentum spread of 4 % and an emittance of 20 π mm.mrad is carried through at 10.5 GeV/c.

Step 5. The trajectory of the antiproton beam is shown in Fig. 3, where the two ISR intersecting rings are shown for convenience circular and concentric to each other. As we said the beam is transported down to T60 and injected in one of the ISR through a line shown with dashes in Fig. 3. This could be the only element which requires civil engineer construction in this proposed scheme.

The injection to the ISR can be made at one long straight section. Transfer from one ring to the other can also be made in the same location.

To avoid crossing between beams it would be convenient to move one of the two rings by say 5 cm up with respect to the other.

The first ring the beam is injected into will act as the "Debuncher Ring". The narrow bunches of antiprotons will be captured by stationary buckets made by an RF system at 9.5 MHz. The actual value of the frequency will depend on the spacing between proton bunches at 200 GeV at the moment they are hitting the target. The scheme of "debunching" is very similar to the one proposed for Fermilab. Because of the initial mismatch, if enough RF voltage is applied, the bunches will rotate very fast because also the phase oscillation period is short. After a quarter of phase oscillation which can take few tens of revolution, the bunches extend over ±90° and have a small momentum spread. By reversing suddenly the phase of the RF amplifier driver the voltage can then be lowered in few turns to a value where stationary, matched buckets hold the bunches. Then, by paraphasing the voltage is turned down even more and slowly so that in about 10-20 ms the beam is completely (adiabatically) debunched. Because the original bunching factor was 50 in principle one can expect a reduction of the momentum spread by the same amount. Actually, the ISR circumference is 1.5 times larger than the CPS, therefore the maximum reduction that one could expect for the momentum spread is of about 35. Allowing for some dilution, then the variation could be :

$$\Delta p/p = 4\ \% \quad \text{at injection}$$

$$\downarrow$$

$$0.3\ \% \quad \text{after "debunching"},$$

quantities which are very similar to those for Fermilab.

In order to minimize the amount of RF voltage required for the "rotation" we have chosen the energy of the antiprotons very close to the transition energy value of the ISR ($\gamma_T = 9.1$), so that :

$$\eta = \frac{1}{\gamma^2} - \frac{1}{\gamma_T^2} = -0.004 \quad .$$

Then 1.5 MV is necessary at 9.5 MHz. The RF system to supply this voltage is pulsed for very short times (0.1 ms every 2.4 s), therefore a high gradient cavity system can be employed. The whole system should take only one (or at most two) of the eight long straight sections.

A smaller value of η, though would make the requirement on the voltage smaller, is nevertheless not effective from the "rotation" point of view because of various non-linearities involved.

Step 6. The bunch rotation and debunching takes only a very short period of time. Another function that can be accomplished in the "Debuncher Ring" is <u>fast</u> stochastic cooling in both momentum and betatron (H and V) phase space. A reduction of a factor two or three in momentum spread and a factor three or four in emittance, for both planes, would help considerably the performance in the second of the ISR rings, the "Accumulator Ring".

At this purpose some minor modifications of the ISR lattice in the "debuncher" mode are required : (i) There are eight long straight sections each 16 m long against nine in the Fermilab debuncher each 10 m long. Each long straight section should be made with identically zero dispersion. This, I believe, was already done in the past and should not subtract too much drift space. (ii) For stochastic cooling a large bandwidth system is required (at least 2 GHz), therefore pick-ups and kickers should be located in sections where the beta-value is reasonably small over a length of about 10 m. A value of $\beta^* = 5$m in both planes has already been proposed for Fermilab and it seems right also for the scheme we are proposing here. Also an insertion with this moderate low value of beta should be quite feasible for the ISR.

The η value of -0.004 seems to be large enough for both momentum and betatron stochastic cooling.

In conclusion, the functions of the eight long straight sections in the ISR-Debuncher ring could be as follows :

2 for stochastic cooling pick-ups,
2 for stochastic cooling kickers,
2 for 12 MHz, 1 MV RF system,
2 for injection, ejection, etc.

Momentum cooling in the Debuncher Ring is similar to the momentum precooling in the AA-ring, but at much higher frequency (2-9 GHz). A High quality notch filter(s) is here required.

Step 7. At the end of the 2.4 s period the beam is extracted from the ISR-Debuncher Ring and transferred to the ISR-Accumulator Ring, which is the second of the ISR rings properly modified to operate in the "Accumulator" mode.

No momentum or betatron precooling exist in the Accumulator Ring. They have already been accomplished in the first ring. Therefore, there is no need for ferrite pick-ups with shutters.

Each pulse coming from the Debuncher every 2.4 s is RF captured and displaced to the inside at the front of the stack-tail stochastic cooling system. The creation of the stack-tail with momentum stochastic cooling is the main function of the Accumulator. We could choose the same bandwidth (1-2 GHz) as proposed for the Fermilab Accumulator. Notice that the flux is at least twice as large with this scheme than in Fermilab but also the initial density is as much as larger, therefore there should not be problem with too large power requirements which should stay in the few kW range.

The transition energy should be adjusted so that :

$$\eta = \frac{1}{\gamma^2} - \frac{1}{\gamma_T^2} = \pm 0.01$$

which corresponds to $\gamma_T = 7.4$. The lattice should be modified accordingly.

The pick-ups for the stochastic cooling will be located in one of the eight long straight sections with moderately high dispersion. We propose here a value of $\alpha_p = 5$ m. Four of the long straight sections will have this value of dispersion and alternate with the other four where there is no dispersion. In the latter, kickers and RF systems can be located.

To minimize the effect of the contribution of the betatron beam size, we also propose a value of $\beta_H \sim \beta_V \sim 8$ m in the middle of all light long straight section.

All this does not seem to require too major changes in the ISR lattice, so that the two rings will preserve their basic geometry.

One major feature of the ISR-Accumulator ring is the very large momentum aperture available for the stack-tail system 3 % against 1 % in the Fermilab Accumulator. This should make the system capable to accept even larger fluxes and to be more stable. Also higher top densities can be reached in the core. As a goal we propose here a final density of 2 10^5 eV^{-1}.

Step 8. Once the particles reach the core region they will be also subjected to betatron cooling in both planes. The requirement here is to reduce the betatron emittance from the initial value of 5 π mm.mrad down to 1 or 2 π mm.mrad, to a value which matches the proton beam emittance in the SPS. The reduction has to occur in about one hour period so it is slow, but also more particles are present in the beam. We do not foresee any need for tail betatron cooling here.

The distribution of all the functions in the two ISR modified rings is as shown in Fig. 4 and 5.

Step 9. Once enough particles have been collected and the required final density has been reached, a portion of the beam is "RF-unstacked" toward the injection-extraction region and extracted. This beam will be transported to the CPS as shown in Fig. 3 through the already existing TT1 transport line. Care has to be taken here because the CPS circumference is 2/3 of the ISR ring and the antiproton beam must be bunched to a length small enough to fit not only the circumference of the CPS but also the standing-by RF buckets.

Step 10. The antiproton beam is accelerated in the CPS from 9.5 GeV to 27 GeV. This beam is then RF manipulated in one single bunch with 10^{11} particles short enough to fit one of the RF buckets in the SPS AT 200 MHz.

Step 11. The antiproton bunch is transferred from the CPS to the SPS at 27 GeV through the TT70 transport line. It is immediately captured by one of the RF buckets of matched shape.

Steps 9, 10 and 11 will be repeated until the wanted number of $\bar{p}$-bunches have been injected and located at the required place : for instance 6 bunches at equal distance.

Prior to the injection of the first antiproton bunch, an equivalent number of proton bunches of the same intensity have been prepared and circulated in the SPS at 27 GeV. This is done by discontinuing the antiproton production.

Dtep 12. Both beams are accelerated to the top energy of 220 GeV and made collide with each other.

In Table I we make a comparison of performance between different antiprotons sources.

Table I - Comparison of Performance between different Antiproton Sources

	CERN CPS - AA	Fermilab	CERN SPS - ISR
TARGETRY			
Primary Proton Energy [GeV]	27	125	200
Cycle Period [s]	2.4	2.0	2.4
No. of Protons on Target/Cycle	1×10^{13}	2×10^{12}	3×10^{12}
Antiproton Kinetic Energy [GeV]	2.6	8.0	9.5
$\Delta p/p$ (full) accepted [%]	1.5	4.0	4.0
β-Emittance (H and V) [π mm.mrad]	100	20	20
Yield $\equiv N_{\bar{p}}/N_p$	10^{-6}	5×10^{-5}	8×10^{-5}
No. of Antiprotons/Pulse	1×10^7	10^8	2.4×10^8
Production Rate (Flux) [$\bar{p}$'s/s]	4×10^6	0.5×10^8	10^8
DEBUNCHING AND PRECOOLING			
No. of $\bar{p}$-bunches/Pulse	5	80	20
Bunching Factor	-	20	50(35)
Debuncher Radius [m]	25	81	150
Transition Energy [γ_T]	2.5	12	9.5
$\eta = \gamma^{-2} \quad \gamma_T^{-2}$	-0.09	-0.004	-0.004
RF Frequency [MHz]	1.85	53	9.1
RF Voltage [MV]	0.014	4	1.5
$\Delta p/p$ (full) after Debunching [%]		0.3	0.3
$\Delta p/p$ (full) after Precooling [%]	0.2	0.1	0.1
β-Emittance after Precooling [$\pi\ 10^{-6}$ m]	-	7	5
ACCUMULATION			
Initial Density, dN/dE [eV^{-1}]	2	10	24
No. of Long Straight Sections (LSS)	12	6	8
Length of LSS [m]	5	15	16
α_p in LSS with Kickers [m]	0 and 7	9	5
β (H and V) in LSS [m]	15	7	8
Transition Energy [γ_T]	2.5	5.7	7.4
$\eta = \gamma^{-2} - \gamma_T^{-2}$	-0.09	0.02	0.01
$\Delta p/p$, Stack Full Width [%]	3	1	2
Final Density [eV^{-1}]	0.5×10^5	1×10^5	2×10^5
Time co collect $N_{\bar{p}} = 6\ 10^{11}$ [h]	60	4	2

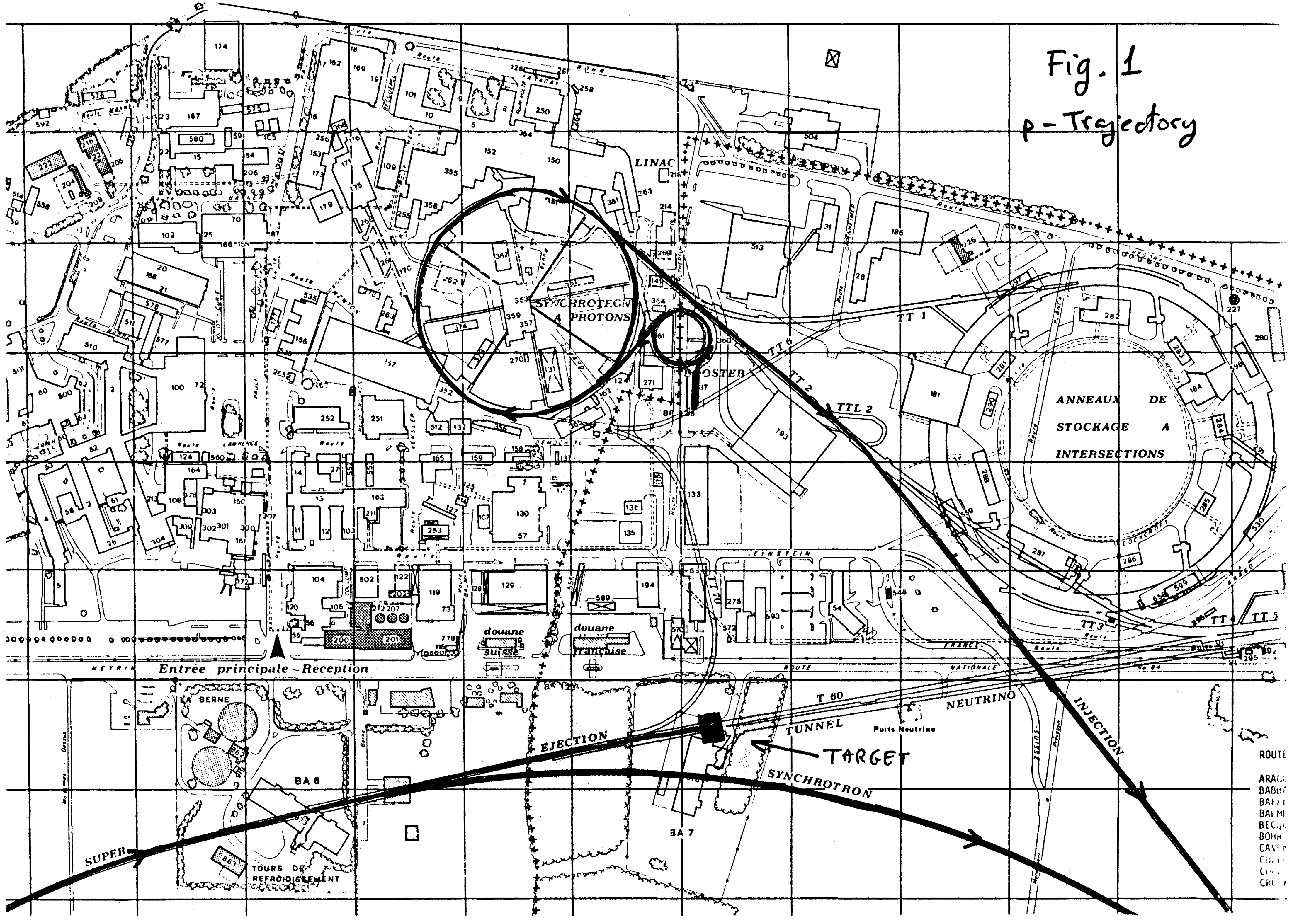
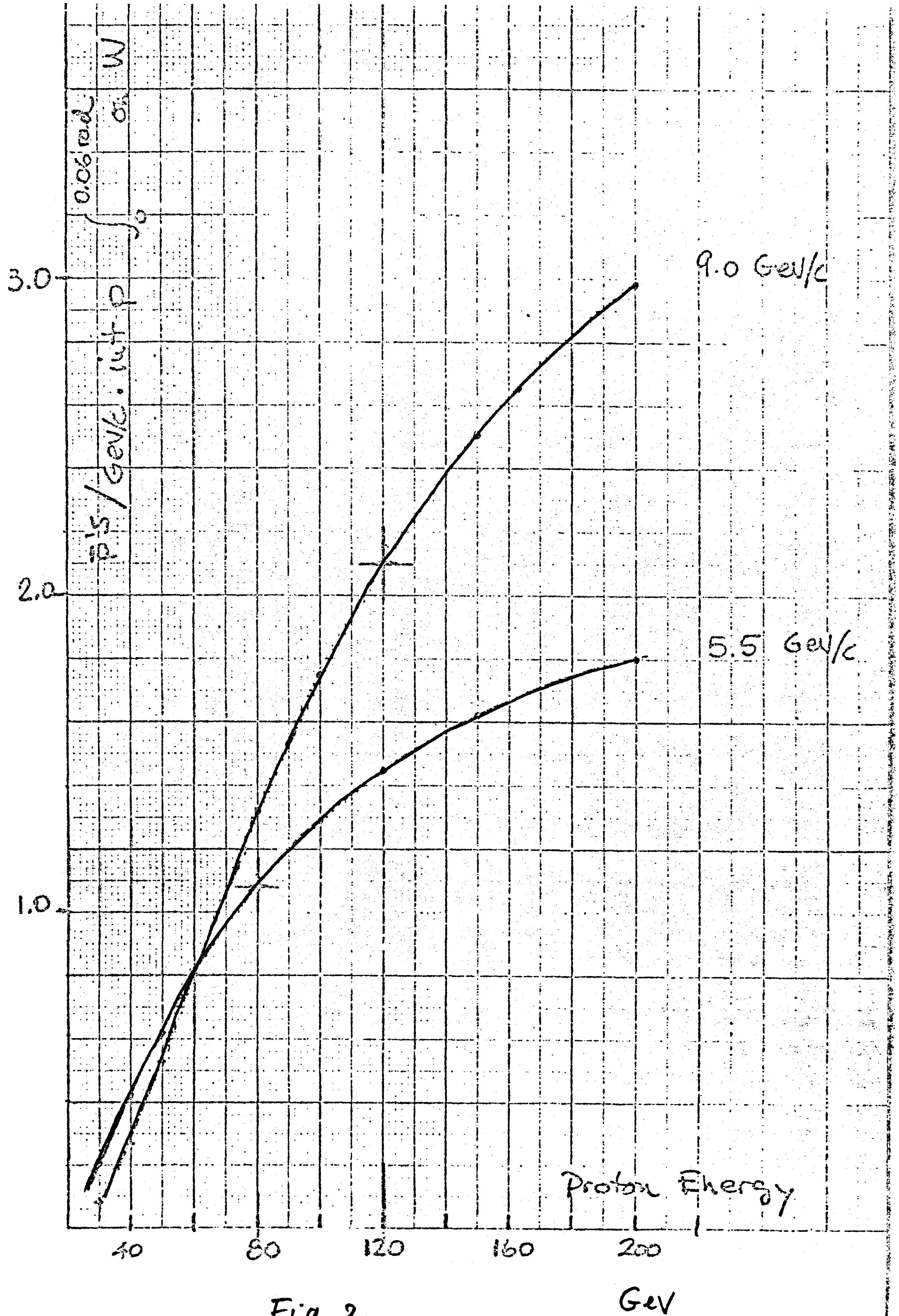


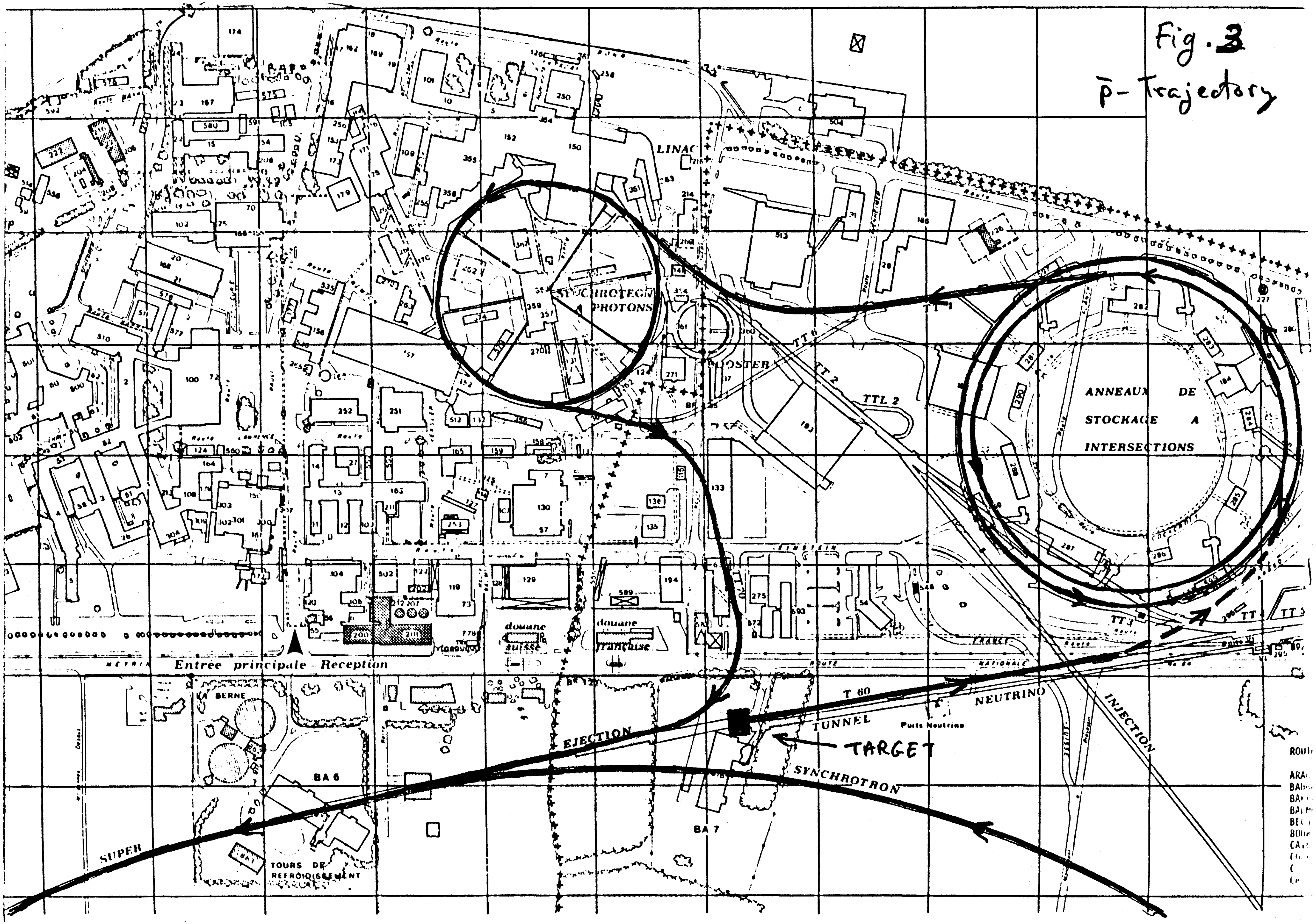
Fig. 1
p-Trajectory



$\int_0^{0.06\,rad} \frac{d^2N}{dp\,d\Omega}\,d\Omega$ / GeV/c . int p
3.0
2.0
1.0
9.0 GeV/c
5.5 GeV/c
Proton Energy
40
80
120
160
200
GeV

Fig. 2

Fig. 3
$\bar{p}$- Trajectory



One type of long straight section

$\alpha_p = 0\,m \; , \; \beta = 5\,m \; , \; \gamma_T = 9.1$

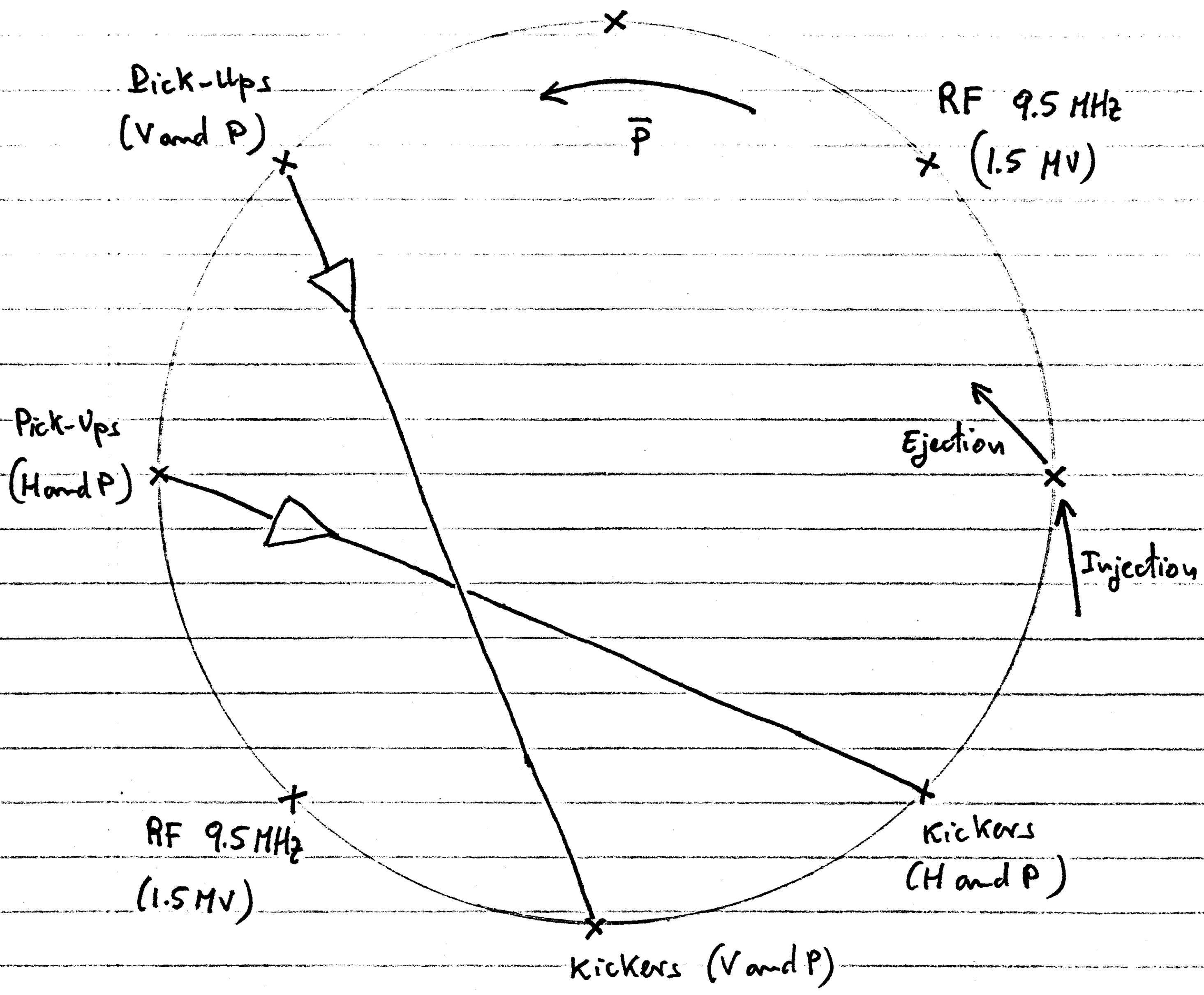


Fig. 4 – The ISR-Debuncher Ring

Two types of long straight section

$\alpha_p = 0$ and $5\ m$, $\beta = 8m$, $\gamma_T = 7.4$

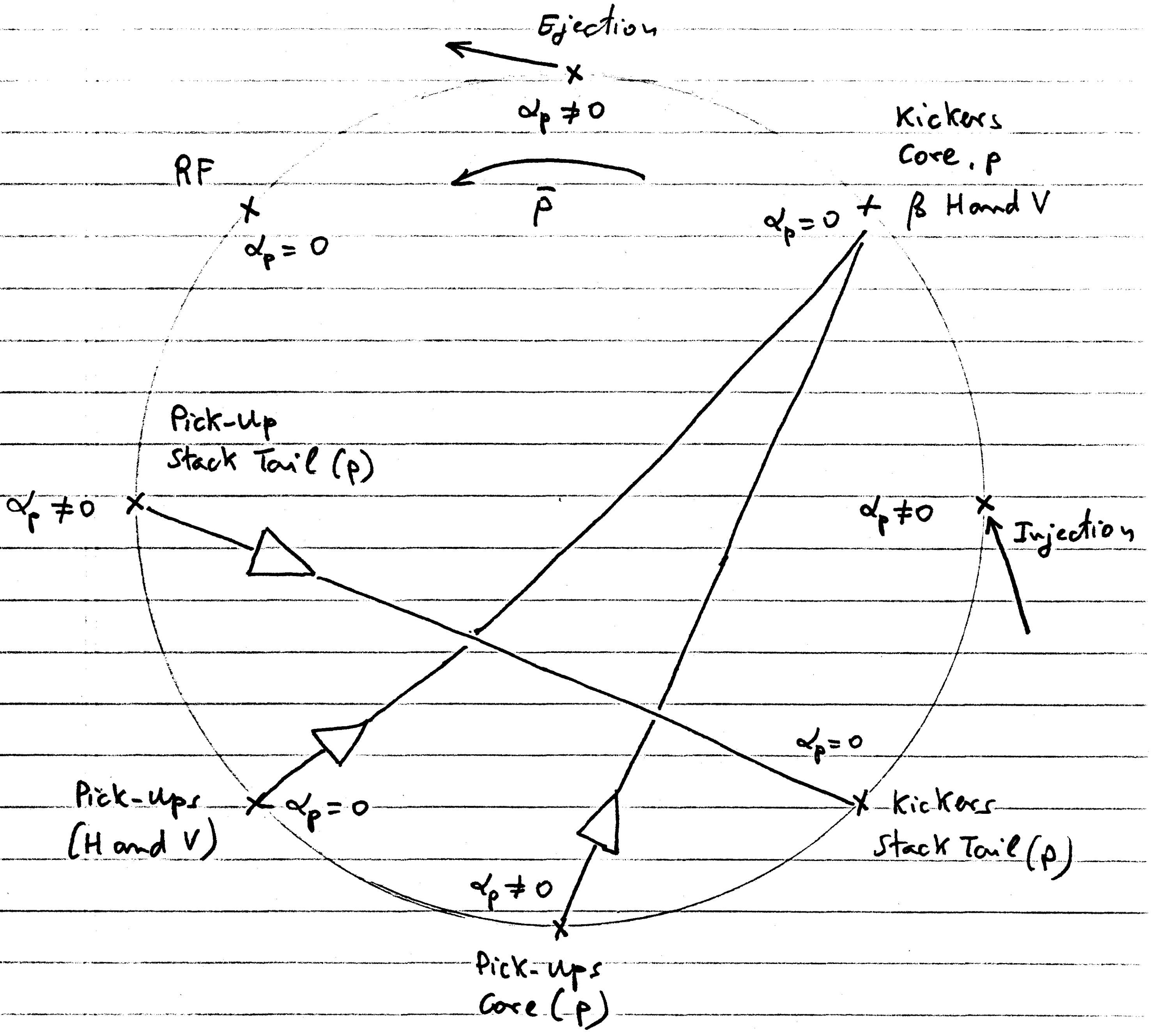


Fig. 5 - The ISR- Accumulator Ring