REPORT OF GROUP III

EXTRACTION AND EXTERNAL BEAMS

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1. INTRODUCTION

In order to be consistent with the first ICFA workshop the group has concentrated on problems related to a 20 TeV proton synchrotron, as described by Stiening [1].

The main accelerator parameters which are relevant for the present paper are given in Table I.

TABLE I

Assumed main accelerator parameters

Maximum energy	20 TeV
Maximum magnetic field in dipoles	10 T
Circumference of accelerator	73.34 km
Period length	76.4 m
Betatron wave number (Q-value)	240
Beam current	10^{15} ppp
Repetition time	100 s
Flat top duration	20 s
Stored energy in the beam at 20 TeV	3200 MJ
Average beam power	32 MW
Revolution time of the protons	244 μsec

As will become clear in this paper, it is relatively straightforward to design an extraction channel or beam line for 20 TeV, but the thermal effects related to the assumed high beam current and the energy of 20 TeV are truly impressive and will need much further study. In all cases the temperature increases quoted in the present paper have been calculated using the data or extrapolations of the data given in the paper by Lebedev et al.[2].

2. Extraction

2.1 The extraction channel

The standard design of the extraction channel for slow and usually also for fast extraction from high energy accelerators is a three-stage system consisting of an electrostatic septum (ES) made of an array of thin wires, followed by a water-cooled thin septum magnet (MST) and a water-cooled thick septum magnet (MSE), as shown in Fig.1. Since the transverse dimensions of the machine quadrupoles and dipoles are roughly independent of the maximum energy of the accelerator, the total beam displacement at the downstream end of the field free section which contains the extraction channel, must be about the same as for lower energy machines, say 0.5 m. This can be achieved if we extrapolate from lower energy designs by increasing both the length of the components of the extraction channel and the length of the field free section proportional to $\sqrt{p}$.

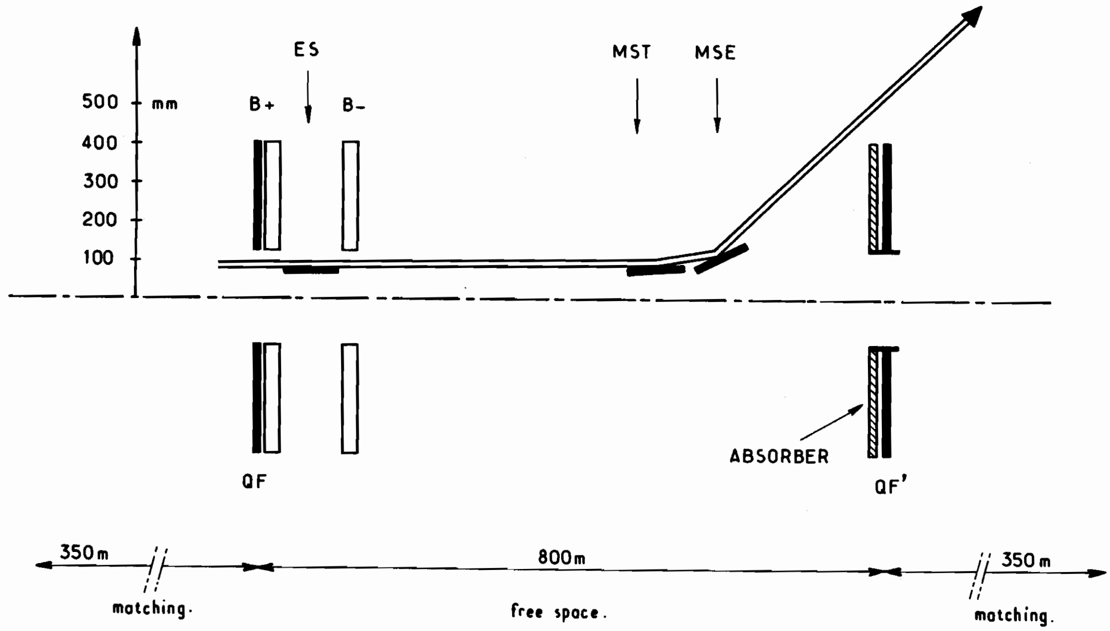

Fig. 1 Schematic layout of extraction channel

The main parameters of the extraction channel shown in Fig. 1 are given in Table II.

TABLE II

Main parameters of the extraction elements shown in Fig. 1

	ES	MST	MSE
Overall length	70 m	70 m	70 m
Field length	55 m	55 m	55 m
Field strength	100 kV/cm	0.5 T	1.8 T
Septum thickness	0.15 mm	4 mm	16 mm
Deflection	0.0275 mrad	0.4 mrad	1.45 mrad

With this layout the separation between the circulating and the extracted beam is 10 mm at the entrance of the MST and 28 mm at the entrance of the MSE. The ES will consist of a number of modules with a length of about 3m each. Assuming a wire thickness of 0.1 mm, these modules must be straight and aligned within 0.05 mm to achieve an effective septum thickness of 0.15 mm. If the amplitude increase per revolution of the resonant oscillation at the ES is 20 mm, the ES will absorb 1% of the protons, so that the extraction efficiency is about 99%.

2.2 The long straight section

To accommodate the extraction channel, a field free space of adequate length must be provided. In the 400 GeV SPS at CERN it is still practical to design a satisfactory long straight section (LSS) by leaving out the dipole magnets in two consecutive lattice periods while maintaining the regular quadrupole periodicity. For much higher energies this procedure is not practical since the period length does not increase sufficiently with energy. Therefore it is preferable to design a matched LSS of the type foreseen for the 3 TeV machine UNK [2, 3].

Each LSS of UNK has a total length of 484 m, with 4 matching quadrupoles at either end, and a free length of 160 m in the central part. The horizontal transfer matrix across the matched LSS is the unity matrix, and the total horizontal betatron phase advance across the LSS is 2π so that also the momentum compaction function α_p elsewhere in the lattice is not disturbed.

The parameters of the matching sections for UNK have been chosen such that $\beta_H \approx 1200$ m at the entrance of the ES, compared to $\beta_H(\max) = 150$ m in the regular lattice [2]. In this way one can obtain a step size of about 20 mm and an extraction efficiency of 99% with a moderate amplitude of the resonant oscillations in the regular lattice.

Figure 1 is a preliminary attempt to scale up the LSS of UNK to a 20 TeV machine. Each of the matching sections is estimated to be about 350 m long, with a central free space of 800 m, giving a total LSS length of 1500 m. Because of the greater length of this LSS the optimum horizontal phase advance across the LSS should probably be 4π rather than 2π as in the case of UNK. The value of β_H at the entrance of the ES should be about 10 x larger than in the F quadrupoles of the regular lattice, so that the horizontal aperture of QF and QF' in Fig. 1 must be about $\sqrt{10}$ times larger than the aperture of the regular machine quadrupoles.

2.3 Thermal effects

In existing 400 GeV machines the wires of the ES are usually made of tungsten from which most of the intercepted protons escape through multiple Coulomb scattering without undergoing a nuclear interaction. Therefore the septum wires are heated only by the ionization loss of the primary protons. At 20 TeV, however, very few protons will leave the array of septum wires through elastic scattering and nearly all protons will undergo nuclear interactions, which lead to a much increased rate of energy deposition in the wires. Therefore it is best to make the septum wires of the lightest possible material, i.e. beryllium. To obtain rough quantitative results, we have made the following assumptions:

i) The proton loss on the septum is 1% of $10^{15} = 10^{13}$ ppp.

ii) The beryllium septum wires are 0.1 mm thick and 30 mm long. The supports act as infinite heat sinks at both ends.

iii) The spill is uniform and lasts 20 s, giving a reduction factor of 0.035 for ΔT by heat conduction to the extremities of the wire, compared to a fast spill.

iv) The vertical beam size corresponds to $\sigma = 2.5$ mm.

Extrapolation from the values quoted in ref. 2 results in an estimated temperature rise $\Delta T = 2600°C$. This is clearly too much and it indicates that the maximum permissible intensity is about 10^{14} ppp if we allow a maximum temperature of 300°C, always assuming a uniform spill without important spikes.

If instead of slow extraction, 20 bursts of 2.5×10^{12} protons are extracted at 1 s intervals, one also finds $T_{max} \approx 300°C$.

If the extraction is properly adjusted, the MST fits well in the hole between the extracted and circulating beam and should not be subject to heating by the beam. In this connection it is worth mentioning that it was recently found at the CERN-SPS that a single burst of a fast extracted beam of 1.2×10^{13} protons at 400 GeV which hit the copper septum of the MST, destroyed this septum. Therefore the extraction must be inhibited if the ES voltage is wrong, e.g. due to sparking just before or during extraction.

Another very important problem is the quenching of the superconducting machine magnets due to the heating by radiation produced by the 1% beam losses in the ES or small beam losses occurring somewhat further downstream of the LSS. Also these problems have been studied extensively by the UNK group[2,3,4].

The first machine quadrupole downstream of the extraction system i.e. QF' in Fig. 1, is exposed most intensively to the radiation from the ES. It can be protected by the following measures [2,3]:

i) The orbit of the circulating beam is distorted by the two bumper magnets B_+ and B_- shown in Fig. 1, which have equal but opposite strengths and give the beam an outward angle of 0.5 mrad in the ES region. In this way most of the forward cone of the radiation produced in the ES passes outside the superconducting windings of QF'.

ii) One or more absorbers of several metres length upstream of QF'.

iii) A thick walled (say 1 cm) vacuum chamber inside QF' and in a number of subsequent machine magnets. This, of course, reduces the machine aperture locally.

iv) If it would turn out that all these measures are not sufficient, the ultimate solution would be to replace QF' and the first subsequent machine magnets by iron and copper magnets.

To estimate permissible beam losses downstream of the extraction LSS,one can use the data of Table III, which is an extrapolation to 20 TeV of data presented in ref. 4 and which gives a rough estimate of the maximum permissible beam loss at a point without quenching of the superconducting magnets.

TABLE III

Maximum permissible beam loss at a point without quenching of the superconducting magnets at 20 TeV

Duration of loss	Maximum loss
1 ms	~ 10^6 protons
0.1 s	~ 10^7 protons
1 s	~ 10^8 protons
20 s	~ 2 x 10^9 protons

The data given in Table III must be considered as order of magnitude figures only, but in any case represent such a small fraction of the beam current that it will certainly be necessary to tune up the extraction at very low beam currents. Furthermore a very efficient beam dumping system is needed to remove the beam from the machine whenever the losses become too high.

2.4 Types of extraction

For slow extraction during 20 s, third integral extraction is the most convenient type of extraction. This gives good results in present accelerators with a flat top duration of 2s but there appears to be no reason why this duration cannot be extended by an order of magnitude.

Bubble chambers are likely to require many (say 10 to 100) short (~ 1 ms) bursts during the 20 s flat top. For hadron physics which needs only low intensity of the primary beam it is simplest to use slow extraction and to kick at regular intervals the beam during 1 ms onto the target of the hadron beam line. For neutrino experiments, where a higher intensity during the bursts is required, the above method is not practical. The most obvious procedure would be to briefly enhance the slow extraction, e.g. by kicking some of the protons into the unstable region with a kicker magnet or by squeezing the unstable region with a pulsed quadrupole. However, the revolution time is 244 μs and therefore it is not sure that sufficiently short bursts can be achieved. From this point of view half-integral extraction would be better.

3. Beam dumping

Because of the large energy stored in the beam a reliable and efficient beam dumping system is required, which can remove the beam from the accelerator before components are damaged or superconducting magnets quench because of overheating by beam losses. In practice the beam dumping system would consist of a fast kicker magnet [5] which deflects the beam into an extraction channel, preferably without electrostatic septum but with only pulsed septum magnets. The fast kicker magnet(s) can be located in between the matching quadrupoles at the upstream end of the LSS.

A complete design of a convincing beam dumping system is a complicated matter and was not possible within the framework of the ICFA workshop. Therefore we shall restrict ourselves here to a number of general remarks about beam dumping, in addition to the preliminary design study made in ref. 5.

At low to medium energy the circulating beam occupies the major part of the vacuum chamber aperture but the strength of the dumping magnets can be modest. At high energy the dumping magnets must be strong but the beam is small so that a smaller deflection in the fast kicker magnet would be acceptable. Therefore it is preferable to have two separate dumping systems, one for low to medium energy and one for higher energies.

The polarities of the matching quadrupoles of a LSS such as shown in Fig.1, are optimized for horizontal extraction. Therefore one would be tempted to use horizontal beam dumping and to bring the circulating beam close to the extraction septa with bumpers to reduce the required strength of the kicker magnet. However, this is not possible since an adequate horizontal aperture must be preserved for the resonant oscillations of slow extraction. From this point of view beam dumping by vertical kicking is preferable. If the machine is designed with 8 LSS, one could optimize 4 LSS for horizontal extraction and 4 LSS for vertical extraction and still preserve a fourfold superperiodicity of the lattice which should be sufficient.

With a kicker rise time of 2.5 μs the 10^{15} ppp which are swept across a beryllium absorber in front of the first septum magnet of the extraction channel for beam dumping produce a temperature rise $\Delta T \sim 2000$ °C. For an electrostatic septum one finds $\Delta T \approx 260$°C. The former ΔT is far too large whereas $\Delta T = 260$°C should just be acceptable and from this point of view one would conclude that the first element of the extraction channel for beam dumping should also be an electrostatic septum.

However, an ES is a complicated device and can be avoided if there is a gap in the circulating beam and if the rise time of the kicker magnet fits in this gap. During slow extraction the beam should be debunched and have no RF structure. However, for Q = 240, the gap is reduced by only about 1 μs in 20s. This favours a high Q-value, but not necessarily as high as 240, since the gap in the beam can be made considerably longer. If the gap is made as long as 24 μs $\approx 0.1 \times T_{rev}$, one could even use kicker magnets with thin steel laminations [5].

Let us assume that the beam has a circular cross-section with $\sigma = 2.5$ mm at the extraction point. Passing through a quadrupole of focal length F and a drift space L increases σ by a factor L/F. If we take F = 50 m, corresponding to 75 T/m x 18 m at 20 TeV, we find $\sigma = 5$ mm after a drift space L = 100 m, giving $\Delta T = 100$°C in a beryllium exit window.

If the beam is allowed to pass through a drift space L = 6000 m, we obtain $\sigma = 300$ mm, corresponding to about 1.2 m diameter. We then find $\Delta T = 100$°C in a water dump and $\Delta T = 240$°C in a beryllium dump. The drift space of 6 km can, of course, be reduced by a substantial factor by increasing the strength, i.e. the length of the quadrupole, or by adding sweeper magnets. The drift space must be evacuated to avoid that most of the protons interact in the air before reaching the external dump.

4. The external proton beam and targets

4.1 General

The length and geometry of the external proton beam (EPB) will depend strongly on the geography of the site. If the accelerator tunnel is far underground, substantial vertical bends, using superconducting magnets, must bring the EPB to the surface. Otherwise a relatively short stub may be sufficient.

Quenching of the superconducting magnets prevents the use of secondary emission position monitors, which are loss points of about 4 x 10^{-5},for steering the EPB, except at very low beam intensity.

For the same reason the magnets in the splitter and target areas cannot be superconducting but must be made of steel and copper. Pulsing these magnets will reduce their power consumption by a factor 20/100.

4.2 Beam splitters

Since it is usually necessary to deliver simultaneously slow extracted protons to several external targets the EPB must incorporate one or more beam splitter stations. These can be of two different types.

1) Electrostatic septum followed by steel septum magnets with wedge shaped poles (FNAL).
2) Steel septum magnets alone (CERN), protected by a wedge shaped beryllium absorber.

Since both systems have proved to operate satisfactorily, there are no obvious reasons to prefer the one or the other. The length of a steel septum splitter station is about one half of that of the length of an electrostatic septum splitter station. The steel septum splitter must be protected by a wedge shaped beryllium absorber. This requires careful beam steering but this is necessary in any case to minimize the losses in the splitter region.

The beam losses in the ES splitter are smaller than in the steel septum splitter but in the latter case the maximum temperature is lower since the beam can be blown up to a larger cross-section.

Assuming a uniform spill of 10^{15} protons during 20s, typical values for an electrostatic splitter made of 0.1 mm thick beryllium wires would be σ_V = 2.5 mm, σ_H = 10 mm, beam loss ~ 0.4%,$\Delta T \approx$ 1000°C.

For a steel septum splitter, protected by a beryllium wedge shaped absorber, corresponding typical values would be σ_V = 20 mm, σ_H = 1 mm, beam loss ~ 1.5%,$\Delta T \approx$ 500°C in the beryllium absorber.

4.3 External targets

At first sight it would appear that the heating problems of the target and the beam stopper downstream of the target are particularly severe, since the beam is focused to a small spot of, say, 1 mm radius. On the other hand, one is much more free in the choice of the geometry of a target than e.g. of an ES for extraction. One can easily think of a rotating beryllium block to distribute the heat deposition over a large area during the 20s slow spill and make water cooling channels close to the beam spot.

For some stationary geometries with efficient water cooling which have been considered, for a uniform spill of 10^{15} protons in 20s, and a beam spot with $\sigma = 1$ mm at the target, we found $\Delta T \approx 1000°C$ for a 0.5 m long beryllium target and $\Delta T \approx 6000°C$ for a beryllium beam stopper just downstream of the target.

However, the beam stopper could be moved further downstream where the beam spot is larger and in general these figures can certainly be improved by making more clever designs involving rotating targets and dumps or sweeping magnets upstream of the dump.

It appears therefore that the most severe intensity limitation encountered by the EPB is the electrostatic septum for extraction.

5. Secondary beams

5.1 Scaling laws

We shall start by considering which scaling laws could be used to extrapolate the length of the secondary beams from present 400 GeV accelerators to a 20 TeV machine.

For hadron beams we assume that the transverse beam dimensions and lateral displacements, i.e. the resolution in $\Delta p/p$, are independent of p. In that case the length of the magnetic elements and the total length of the beams scale as $\sqrt{p}$.

For decay channels the total length scales with p if we wish that the fraction of particles which decays, is a constant. On the other hand, the decay angles scale as 1/p and therefore the spacing of the quadrupoles, of constant aperture and strength, is proportional to p, so that the total number of quadrupoles remains the same.

5.2 Layout for hadron areas

The general features of the layout of the North Area of the CERN-SPS have been found to be quite convenient and a scaled up version for a 20 TeV hadron area is shown in Fig. 2.

The target area is underground and momentum selection is in the vertical plane. Therefore most of the μ's are stopped underground and those μ's which manage to find their way up the secondary beam tunnels are directed upwards and will pass above the experiments. Two hadron targets are fed by two 2-way splitters. If each target has a set of "wobbling" magnets [6,7], it can provide two good hadron beams. A third target is used to produce the combined μ and ν beam described below.

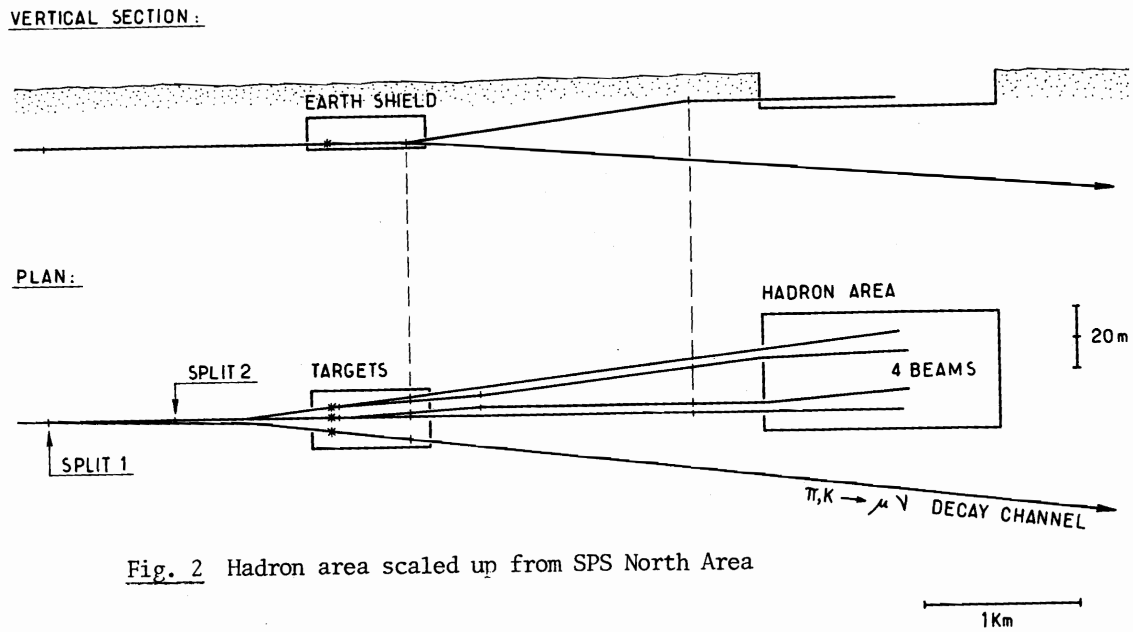

Fig. 2 Hadron area scaled up from SPS North Area

The area which houses the hadron experiments is about 1.5 km long. It does not look realistic to cover such an extended area entirely with one large hall and therefore it will be necessary to build a number of smaller, local enclosures to accommodate specific experiments or parts of experiments.

Figure 3 shows a target area with transmission targets as an alternative to Fig. 2. This has the obvious advantage that it avoids the use of splitter stations. The drawback is, however, that the settings of the wobbler magnets are constrained by the need to preserve the direction of the ongoing EPB so that each transmission target can produce only one good secondary hadron beam.

Therefore the layout of Fig. 2 with two splitters and two end targets looks preferable to the layout of Fig.3.

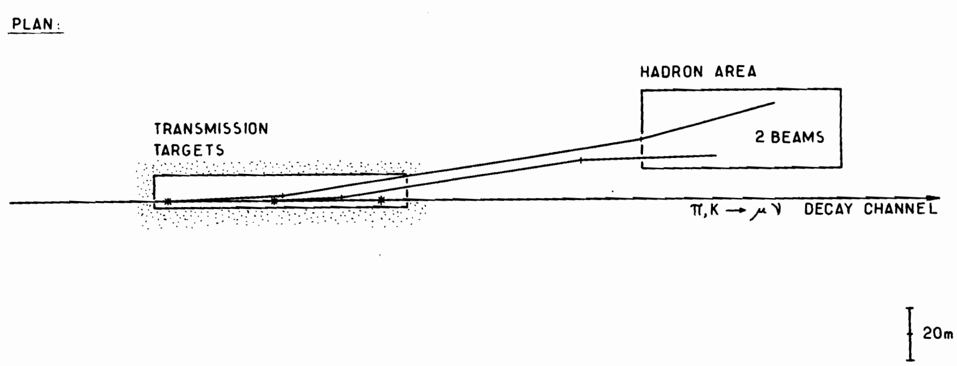

Fig. 3 Hadron area with transmission targets

5.3 Combined μ/ν Hi-band beam

Figure 4 shows, on a very distorted scale, a possible layout for a μ/ν beam. It consists of the following parts:

i) Front section for acceptance and momentum selection of the $K^{\pm}$ and $\pi^{\pm}$.

ii) Decay channel consisting of 200 mm aperture quadrupoles, arranged in a regular FODO lattice with a spacing of 1 km between quadrupoles. The total length of the decay channel is 30 km so that 5% of the π's will decay at 10 TeV.

iii) Momentum selection for the μ's, with magnetized iron collimators to disperse the halo surrounding the beam.

iv) Earth shield of about 10 km thickness.

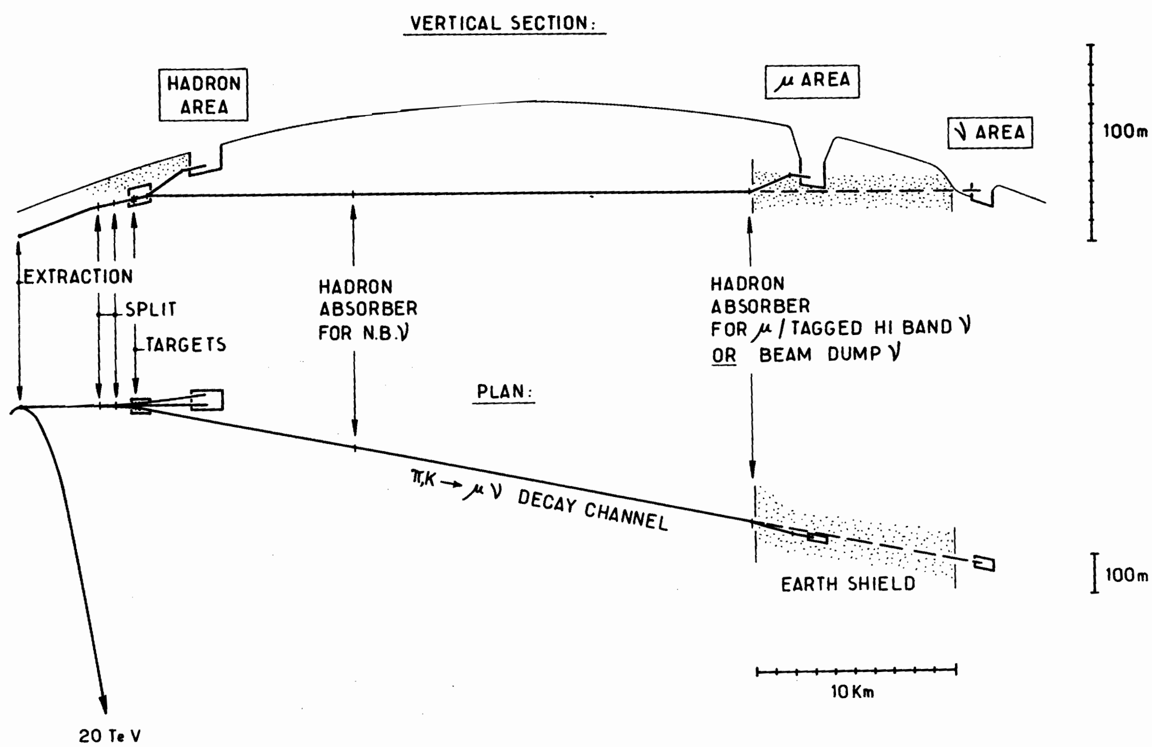

Fig. 4 Experimental Area layout with hadron beams and μ/ν beam

It is interesting to note from Fig. 4 that the curvature of the surface of the earth over the length of the μ/ν beam has a sagitta of about 30 m.

The angular divergence of the high energy neutrinos produced in the decay channel is $\pm$ 0.02 mrad, so that the diameter of the neutrino beam at the detector for the high energy end of the neutrino energy spectrum is about 1.2 m. Therefore this decay channel can be used to produce simultaneously a μ-beam and a so-called Hi-band neutrino beam of large intensity.

The collection efficiency of the μ's is about 10%. It has been pointed out by Kaftanov [8]) that by setting the μ-beam to detect low energy μ's in coincidence with ν-events, a high energy, tagged ν-beam can be obtained.

5.4 Separation of π from K and p by synchrotron radiation

If a particle with rest mass m passes through a length L with magnetic field B, it suffers a mean momentum loss due to synchrotron radiation which is given by :

$$\frac{\Delta p}{p} = 3 \times 10^{-13} \frac{B^2 L p}{m^2}$$

At the very high energies under consideration this effect can be used to separate π's with m_π = 0.14 GeV/c from heavier hadrons.

Let us assume a total deflection of 6 mrad, produced by 16 magnets, each 5 m long, some of which have positive polarity while the others have negative polarity, always with |B| = 10 T.

The fourth column of Table IV shows the momentum loss of the π's while the fifth column gives the separation which can be obtained with reasonable beam optics and shows that π-separation should be feasible above 10 GeV/c and possibly down to 5 GeV/c

TABLE IV

Separation of π's from heavier hadrons by energy loss through synchrotron radiation

p(TeV/c)	number of magnets with B ↑ and B ↓		$\frac{\Delta p}{p_\pi}$ (%)	$\Delta \dot{y}_\pi$ (mm)
	n (B ↑)	n (B ↓)		
15	11	5	0.18	6
10	10	6	0.12	4
5	9	7	0.06	2

6. CONCLUSIONS

The design problems in connection with extraction and secondary beams for very high energy accelerators are not so much caused by the higher energy but are strongly influenced by the anticipated increased beam intensity per pulse and the enormous energy stored in the beam.

Suitable layouts for extraction and external primary and secondary beams can be found. Their lengths scale as E^n where n is close to 1/2 for charged particle beams and n ≃ 1 for decay channels.

Thermal effects in the superconducting machine magnets and extraction septa, caused by beam losses, may limit the beam intensity to a value below 10^{15} ppp, and a great deal of work will be necessary to achieve a much closer control over small beam losses than is customary in existing accelerators.

The accelerator should have an elaborate system of scrapers which can absorb particles which would otherwise hit the vacuum chamber, and above all it must have a fast and efficient beam dumping system to extract the beam whenever loss monitors or other devices indicate that some machine components may start to be overheated or superconducting magnets come close to quenching.

The study of these thermal effects and the design of a good beam dumping system will require much more work than could be done within the framework of the present ICFA workshop.

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