CERN/MPS/DL - 70-11
3.11.1970 - fm

MC/49

BEAM EXTRACTION FROM THE 300 GeV SYNCHROTRON

(Chapter 12 of 300 GeV Design Report)

Report by the Ejection Study Group

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PS/345

Chapter 12

THE EJECTION SYSTEM

12.1. INTRODUCTION

This report describes extraction systems for the 300 GeV accelerator. It was found possible to place all the extraction elements in the lattice without introducing a special insertion. These elements allow extraction up to the highest energy envisaged for the conventional stage of the machine. For the superconducting stage some of these elements will obviously have to be redesigned.

The extraction channel elements used for both fast and slow extractions are described. Several schemes of fast and slow extraction are discussed. The ejection losses are evaluated and their spatial distribution analysed.

Indications on the required magnetic field and ripple tolerances are given. Beam sharing between different channels is briefly discussed and cost estimates given.

12.2. THE LATTICE FROM THE EXTRACTION POINT OF VIEW

The use of separated functions, focusing quadrupoles and bending magnets, allows one to conceive the extraction in a new perspective. The study is then conducted in the following way :

- Selection of a period number and quadrupole lay-out,
- Localisation of the extraction elements in the superperiod,
- Lay-out of the bending magnets.

This process allows to make the machine as compact as desired (with the restriction that 3 consecutive long straight sections are required for the RF); it is also possible to envisage numerous solutions for the extraction system.

The superperiodicity is not imposed by the extraction; the number of beam outlets must be as small as possible (1 for project A, 2 for project B).

Three types of straight sections are used for extraction.

- Long straight sections

In this project without special insertion, the length of the long straight section is determined by the distance between two quadrupoles. In this straight section is placed the longest element of the system, the extractor magnet. The extractor magnet makes the beam go from an orbit near the edge of the vacuum chamber to the outside of the quadrupoles and bending magnets.

The displacement which must be produced by this magnet is a function of the outer dimensions of the quadrupoles and bending magnets. For a given angular deflection a long available free space makes it easier to achieve the required displacement. Hence it is better for extraction to have a small number of periods if one wants to avoid special insertion.

In the first proposal of this type of lattice, (Laisné, Parain, 1969) the number of periods was 84. This number has been increased in this project (Wilson, 1970) for considerations linked to the use of the CPS as an injector. Nevertheless the length of the long straight section is quite adequate for the envisaged extraction elements.

- Medium straight sections

These sections are obtained by removing one of the 4 magnets in a half period. These straight sections are used to place the full aperture fast kicker (12.6.1) and the beam scraper (12.7.3). These medium straight sections have the periodicity of the superperiod.

- Short straight sections

There are two straight sections of this type per period. A few sections will be used to place dipoles, quadrupoles and sextupoles.

12.3. EXPECTED BEAM PROPERTIES

Observations at the CPS (Brouzet, 1969; Brouzet et al, 1970) show that already in the 10^{12} p/p range there are considerable transverse and longitudinal blow-ups which cannot be neglected in the design of the extraction of a high intensity machine.

The underlying mechanism of these phenomena is still very obscure and it would not be realistic to attempt any sort of scaling of the PS data to another machine.

We have therefore taken a somewhat arbitary blow-up factor of about 2 between injection and utilisation energy. It is expected that if higher values did occur and were found intolerable, suitable compensation methods would be developed.

One gets then the following set of expected values (a : half diameter)

	200 GeV/c	300 GeV/c	400 GeV/c
E_H ($\pi 10^{-6}$ rad m)	0.6	0.45	0.30
a_H(mm) ($\hat{\beta}_H = 110$ m)	8.1	7.0	6.2
E_V ($\pi 10^{-6}$ rad m)	0.35	0.23	0.18
a_V(mm) ($\hat{\beta}_V = 110$ m)	6.2	5.0	4.5
$\Delta p/p$	$\pm 5.10^{-4}$	$\pm 3.5 \, . \, 10^{-4}$	$\pm 3.10^{-4}$
ΔR(mm) ($\hat{\alpha}_p = 4.9$ m)	± 2.5	± 2.0	± 1.5

The expected radial beam size is critical for fast extraction with a fast kicker at 50 GeV. If this operation is required it would be necessary to decrease the intensity down to a level where the emittance and the blow-up are sufficiently reduced.

If debunching of the slowly extracted beam is necessary for counter experiments it could easily be achieved using well proven RF gymnastics techniques developed at the CPS. However, it is necessary to have in the coasting beam a high enough momentum spread to ensure its stability against rebunching under the effect of the coupling impedance created by the RF structure.

This problem was studied for the previous 300 GeV Machine (Hereward, 1969); there an energy spread blow-up would have been necessary. However, the parameters of this machine are from this respect more favorable and no blow-up seems to be needed (Zettler, 1970).

12.4. THE EXTRACTION CHANNEL

The extraction channel is composed of 3 elements

- An electrostatic septum S_1 (Fig. 12.1)
- A copper septum magnet S_2 (Fig. 12.2)
- An iron septum extractor magnet S_3 (Fig. 12.3)

S_1 and S_2 produce an horizontal deflection. S_3 gives an upward vertical deflection. This was chosen on the basis of the following estimate of the main quadrupoles and bending magnet outer dimensions (half horizontal x half vertical).

F quadrupole :	270	x	190	mm
BI bending magnet:	419	x	246.5	mm

One clearly sees that the required vertical displacement to avoid the first downstream magnet is half of the necessary horizontal one.

This vertical deflection is a sizeable fraction of what is needed in the external transport line to bring the beam back to ground level.

The lay-out of the channel is based on the following assumptions :

1) the same channel is used for both the slow and the fast ejections,
2) all the elements stay at a fixed position (no displacement during the accelerating cycle),
3) the elements are designed for 400 GeV but the channel could be extended up to a higher energy,

4) at the present time no magnetic element of the main ring has been modified, such as magnets with holes in the yoke, etc.,

5) the radial position of the three elements is set near the beam envelope at injection which is at 44 mm in the focusing quadrupole between S_1 and S_2.

The selection of the lay-out of the 3 septa was done by optimization of the deflections and apertures required for the elements (Laisné, Parain, 1970; Laisné, 1970 b).

	S_1	S_2	S_3
Position in lattice (Fig.12.4)	19	25	33 to 35
Septum thickness (mm)	0.15	2	10
Length (m)	6	6	13
Field strength	100 kV/cm	0.123 T	1.5 T
Vertical aperture (mm)	12	12	200
Horizontal aperture (mm)	18	20	30
Deflection (mrad)	0.15	0.55	14.6

These elements are more fully described below.

12.4.1. MAIN RING APERTURES

The apertures were calculated for the lowest design energy of 200 GeV. However it is possible to extract down to about 50 GeV but with a beam of reduced emittance.

The apertures in the quadrupoles located between S_1 and S_3 on one side, and all around the machine on the other side, are sufficient as explained below.

In the slow ejection situation the F quadrupole after S_1 must accomodate beyond the septum position (44 mm), 15 mm corresponding to the jump (see sect.12.5) and 3 mm for the exit angle of the beam. The extreme beam position is 62 mm which is also the nominal value of the F quadrupole half-aperture.

In the fast extraction case one must add to the same 44 mm the beam diameter at 200 GeV (16.2 mm).

In the D quadrupole following S_2, the beam envelope is at 17.5 mm. Here in addition to the jump and the exit angle taking into account the β-function, it is necessary to add the 10 mm "hole" created by S_2. This gives a total of 34.2 mm to be compared with the 27 mm half aperture of the D quadrupole.

For fast extraction, using the same reasoning as for the F quadrupole one finds 33.9 mm. This additional aperture of 7 mm is quite compatible with the quadrupole design provided that one builds an enlarged vacuum chamber (which could be made with a stressed foil as proposed by (Penicaud, 1970)); the field quality in this enlarged aperture region is not critical. As shown in section 12.5, an extra aperture all around the machine is not needed. This is made possible at the cost of somewhat more sophisticated schemes.

12.4.2. THE ELECTROSTATIC DEFLECTOR S_1 (Fig. 12.1)

The 6 m long electrostatic deflector S_1 will provide a working field of 100 kV/cm in order to achieve a delfection angle θ = 0.15 mrad at the nominal momentum p = 400 GeV/c. This gap will be adjustable and set at 18 mm to accomodate the jump for the slow ejection, with a corresponding voltage of - 180 kV applied to the cathode.

The anode, at ground potential, will constitute the septum of the deflector, hence it has to be as thin as possible and yet meet stringent geometrical and electrical requirements. A possible compromise is to use a metal foil of thickness $\leq$ 0.1 mm, which will give an apparent septum thickness of about 0.15 mm over the total length of S_1. The sagitta d of the trajectories in the electrostatic field of S_1 will be d $\approx$ 0.11 mm. It is possible that an array of wires could be made thinner than a foil septum but it is not yet clear that it could stand such a high electric field.

The position and angle of both electrodes will be remotely adjustable under vacuum for setting up the optimum ejection conditions. S_1 may thus be run at a larger gap for ejection at smaller momentum values (say 3 to 4 cm at 50 GeV/c), especially for fast ejection when the beam dimensions have not yet shrunk below the nominal value of 18 mm which is considered for the slow ejection jump at S_1. The electrostatic field will then be smaller since the total voltage is not to exceed 250 kV but will always be more than sufficient to provide the required deflection angle.

For operation at higher momentum values, say 500 GeV, the same value $\theta = 0.15$ mrad could be obtained by increasing the length of S_1 to 7.5 m at the same field level since enough space is available, but one hopes from the progress of the CPS septum prototype that the required field of 125 kV/cm will be attainable (Germain et al, 1970).

In order to reduce the proton losses on S_1 and therefore to improve the high voltage behaviour and ease the maintenance problems, an array of thin wires will be used upstream and aligned with S_1 to Coulomb scatter most of the protons away from S_1 (Maschke, 1967; Ranft, 1970).

12.4.3. THE COPPER SEPTUM MAGNET S_2 (Fig. 12.2)

The 6 m long copper septum delfector S_2 will have to provide at 400 GeV a deflection of .55 mrad. The needed field strength is 0.123 T. In a 12 mm high gap with the allowed 2 mm thickness the current density is 48 A/mm^2, which is a conservative figure chosen in order to allow operation over flat-tops longer than the nominal 700 ms.

This magnet has characteristics comparable to a device under development at the CPS (Bertolotto, 1970). The septum is made of directly cooled tubes. The cooling channels are of necessity very narrow and the small water flow would mean that the magnet would have to be made in sections of about 1 m long.

This magnet is pulsed and is in series with S_3.

12.4.4. THE IRON SEPTUM EXTRACTOR MAGNET S_3 (Fig. 12.3)

In addition to the reason given at the beginning of the chapter, power consumption and reliability make us prefer to use an iron septum. This magnet is similar in principle to a device used for the ISR injection (De Raad, 1970). The beam has to be raised to a height of 280 mm above the median plane, by the end of the 28 m straight section.

With an effective iron septum thickness of 10 mm, one might expect to achieve 1.5 T with a tolerable fringe field.

The horizontal aperture must be 30 mm if one takes the 200 GeV beam emittance and the deflection given by S_2.

The vertical aperture of 200 mm makes allowance for the beam displacement inside the magnet. The length of 13 m could be made with 2 sections of about the same length as the main ring bending magnet.

If we assume a current density of 25 A/mm^2 in the conductors the power is about 200 kW, assuming a 50% duty cycle. Pulsed operation seems necessary in view of the fringe field to be expected. However the extra voltage required for pulsing would not be large, if the rise time is of the order of 1 second.

If one chooses a suitable number of turns S_2 and S_3 can be powered in series. Further details on the design of these elements are given in (Harold 1969 and 1970).

12.5. SLOW EXTRACTION

Slow extraction has been the subject of a considerable amount of theoretical and experimental studies in the last year. Efficiencies of 95% have been achieved at the CPS (Baconnier et al 1969 and 1970) and further improvements are under way.

Two main types of resonant extraction have been developed. Integer at CERN, 1/3 integer at BNL. A non-resonant scheme using a target has been proposed for the NAL accelerator.

In order to limit radiation damage, a high extraction efficiency is obviously needed. The loss on the septum is given by the ratio of its thickness to the "jump". The jump is the increase of betatron amplitude per turn. For a 1% loss on a .15 mm thick septum (S_1) it is necessary to take a 15 mm jump. This coarse estimate does not take into account the particle distribution on the septum which decrease the efficiency. But we have not included the positive effect of the scattering wires placed in front of S_1 (see section 12.7).

In the resonant extraction, particles leave the stable area along a well defined trajectory, the separatrix. Its angle and position are determined by the elements (quadrupoles and sextupoles) creating the resonance. The extraction channel requires a well defined orientation of the separatrix at its entrance.

The particlesof different momenta are driven into the resonance by a slope in the main magnetic field flat-top. This insures that the extracted particles have always the same radial position in spite of the beam momentum spread.

12.5.1. INTEGER RESONANCE

The integer resonance is excited by a quadrupólar field which moves Q_H to the nearest integer value. A system of two quadrupoles placed one period apart (position 2082 and 2102, Fig. 12.5) tunes Q_H on the resonance. The orientation of the separatrix can be adjusted by a suitable choice of the quadrupole strength ratio (Laisné, 1970 a). A third quadrupole is added (position 2112) in order to allow variation of the chromaticity of the extraction system (Strolin, 1969).

These 3 quadrupoles must be able to produce strength of 30 T (1.2 m x 25 T/m). The non-linearity needed is produced by one sextupole (in 2082) of 120 T/m strength (0.8 m x 150 T/m^2).

If it were felt necessary to avoid filling up completely the short straight section 2082 one could decrease the needed quadrupole strength by using the main machine quadrupole to produce part of the needed Q shift.

This lay-out allows one to make a closed orbit bump (produced by the same dipole magnets as used in the fast extraction, see section 12.6) to adjust the orbit position near the electrostatic septum S_1. The bump does not interact with the extraction quadrupoles and the sextupole, hence does not affect the resonance process. The particles reach their largest oscillation amplitude at the level of the S_1 septum. At the cost of this complication, no extra aperture is needed.

12.5.2. THIRD INTEGER RESONANCE

To produce this resonance it is necessary to move the Q_H value to the nearest 2/3 integer value. In order to produce the separatrix orientation two quadrupoles located symmetrically with respect to S_1 are needed. The phase advance between the quadrupoles and S_1 must be close to π. With such a scheme one can adjust the slope of the separatrix within a range of $\pm 25^{\circ}$. The perturbation outside the extraction region produced by these quadrupoles can be made negligible.

The quadrupoles of strength 9 T (1 m x 9 T/m) must be located symmetrically with respect to S_1. The resonance is excited by a pair of sextupoles placed at the opposite ends of a diameter. The necessary strength is 100 T/m (1 m x 100 T/m^2; 0.4 T on the pole tip).

The septum radial position is 44 mm. To avoid losses around the ring and to avoid increasing the aperture, it is necessary to produce a 10 mm orbit bump near S_1. (This can again be produced by the set of dipoles used for fast extraction). This orbit bump leads to an apparent radial position of 34 mm for S_1. It avoids the beam losses due to particles leaving the admittance on the other separatrices (Erb and Merle, 1970).

12.5.3. SLOW EXTRACTION WITH TARGET

An extraction scheme proposed by NAL (Maschke, 1970) using a scattering target has been considered for this project (Steinbach, 1970). A simple and efficient lay-out would consist of a tungsten target located about $\lambda/8$ upstream of the electrostatic septum S_1. This choise takes into account the values of the phase advance and of the β function. A long burst would be created on this target and dipoles excited so that the target shadow be cast just inside S_1. (Again the same set of dipoles foreseen for fast extraction can be used).

With the pessimistic assumption that all the protons hitting the .15 mm thick septum are lost, the calculated efficiency is about 90% for a 2 mm long tungsten target. With a first stage wire septum the multiple Coulomb scattering in the wires would increase this efficiency to approximately 95% for a .5 mm long target.

However the target action produces a slight blow-up of the vertical beam emittance.

12.5.4. COMPARISON OF SLOW EXTRACTION SCHEMES

Extraction with target requires a minimum number of elements (no special quadrupoles nor sextupoles). The rather low efficiency given by the first studies might be tolerable for operation in the low intensity range. But this scheme has not been sufficiently studied to assess its value for higher intensities.

Integer and 1/3 integer resonances have been compared from many points of view. One of them is beam survival. For the 1/3 integer it is proportional to spill speed. It was found both by analytical and numerical computation (Faure, Hilaire and Strolin, 1970) that 2% of the beam survives a 500 ms spill. On the other hand no beam survival arises in the integer extraction driven by a dipole.

The ripple requirements for the bending magnets (see section 12.8) are stricter for the integer; on the other hand the 1/3 integer resonance imposes stronger tolerances for the quadrupole ripple. From the power supply point of view it is maybe easier to achieve a smaller ripple in the quadrupole supply but dipolar defects on the closed orbit in the extraction region are easier to correct.

The integer resonance is, in principle, more sensitive to the beam momentum spread but the adopted scheme (Strolin, 1969) avoids this drawback.

Both types of resonances lead to radial extracted beam emittances smaller than the one of the circulating beam. This emittance reduction is larger for the integer resonance.

The two resonance schemes use similar elements - quadrupoles and sextupoles with a different lay-out - from this point of view no immediate choice would be necessary.

However for the purpose of the adopted lay-out and the cost estimates we have selected the integer resonance which on the balance of available evidence seems somewhat preferable.

12.6. FAST EXTRACTION

The fast extraction scheme envisaged uses the same extraction channel as the slowly extracted beam. It consists of a beam bump system, that brings the closed orbit parallel to the three septa and a device which shifts the beam over the first septum. The latter may be either a full aperture kicker magnet or a fast bump system as envisaged at BNL (Blumberg, 1970).

12.6.1. FAST EXTRACTION WITH A FULL APERTURE KICKER

In the lattice, the positions of the fast kicker (F.K.) and of the electrostatic septum (S_1) are foreseen to be at the location 3 and 19 (Fig. 12.4) respectively. The phase shift between the two elements then is $\Delta\phi = 82.4^\circ$, which results in a kick -to-jump ratio of 1.32 10^{-2} mrad/mm. Taking into account a suitable safety clearance on both sides of the septum the required jump is 15 mm at 400 GeV. This corresponds to a maximum field strength for the kicker magnet of 0.260 T.m.

A rough estimate of a suitable full aperture kicker magnet gives the following parameters :

Magnetic strength (at 400 GeV)	: 0.260 T.m
Aperture	: 120 mm(radial) x 30 mm(vertical)
Rise time	: 100 ns
Line voltage	: 80 kV
Impedance	: 20 Ω
Modules	: 9 x 400 mm
Total length	: 4.6 m

The theoretical efficiency for full beam extraction is $\eta > 99\%$ when the ring is completely filled. To achieve the rather wide gap of the electrostatic septum required at low extraction energies (50 GeV) the cathode is movable (section 12.4). The possibility of using a single fast kicker for the two fast extraction channels (West and North) deserves to be further studied.

12.6.2. FAST EXTRACTION BY BEAM SHAVING

With this scheme "fast bumps" are used instead of a full aperture kicker. For full beam extraction during one machine revolution, the bump rise time will be around the machine revolution time ($\sim$ 20 μs) rather than the 100 ns for the fast kicker.

With the apparent septum thickness of 0.15 mm, in the above case, the theoretical efficiency is 98%, not taking into account the fraction of protons outscattered after hitting the wire septum.

By reducing the fast bump amplitude it is possible to shave only a fraction of the beam emittance and therefore extract a small fraction (a few percent of the beam).

The favorable positionsof the fast dipole magnets, giving an adequate phase shift, are the locations 3 and 42 (Fig. 12.4). At 400 GeV the required magnetic strength is of the order of 0.25 T.m.

From the point of cost estimates this solution is by far the most favorable one, but has not yet been sufficiently studied.

12.6.3. CLOSED ORBIT BUMPS

For the fast extraction a set of 6 dipoles are necessary to bring the closed orbit parallel to the septa (von Holtey, 1969). They are positionned (Fig. 12.5) at locations 2, 12, 22, 29, 42 and 62. At 400 GeV the required strengths are less than 1 T with 1 m magnets. The residual closed orbit distortion outside the extraction region is less than 2%.

The same set of dipoles is adequate for the various slow extraction schemes.

12.7. EJECTION LOSSES AND SCRAPERS

12.7.1. ABSORPTION AND COULOMB SCATTERING OF PROTONS IN SEPTA, SCATTERING TARGETS AND SCRAPERS

The interaction of primary protons with the ejection system elements is inevitable. The most important of these elements are the following : the (wire and foil) first septa used for slow and fast ejection, scattering targets which can be used for slow ejection (12.5.3) or halo removal and beam scrapers used to collect protons scattered in septa or scattering targets. The fractions of primary protons interacting inelastically in these devices and scattered out can be calculated with Monte Carlo techniques, taking into account the phase space distributions of the circulating beam and reasonable misalignments of the elements considered for a variety of situations (Ranft, 1969 a, 1969 b, 1970; Shoemaker, 1969; Teng, 1969).

Less than 20% of the protons hitting a wire septum are absorbed. In a corresponding foil system, absorption amounts to more than 60%.

If scattered protons hit the edge of a scraper, less than 10% are scattered out again. Outscattering can reach however up to 70% with grazing incidence of the protons, the alignment of the scraper is therefore important.

12.7.2. THE BEAM LOSS DISTRIBUTION IN THE MAIN RING

There are two contributions to the loss distribution in the main ring : i) Secondary particles created by protons interacting in ejection elements hit the vacuum chamber or other machine components downstream. ii) A large fraction of the Coulomb scattered protons may reach the wall downstream of the scattering point or at any position around the ring depending on particularities of the closed orbit (random losses). The two types of loss distributions can be calculated with the Monte Carlo method (Ranft, 1967, 1969 c, 1969 d). Corresponding calculations agree with loss distributions measured at the CPS downstream of targets and ejection septa (CLR, 1968).

Secondary beam losses are practically concentrated on the first 25 m downstream the loss point if there are machine elements in this region. About 50% of the protons scattered from a foil septum are expected to be lost on the wall in the first $\lambda/2$ downstream the septum, the other 50% must be expected to lead to random losses somewhere around the ring if no scraper is used.

12.7.3. SCRAPERS TO REMOVE SCATTERED PROTONS

A large fraction of the protons scattered in the septum can be expected to lead to random losses. A scraper should concentrate these losses as soon as possible after the septum. Two mechanisms can be used to drive the scattered protons onto the scraper, ionization energy loss (Ranft, 1969 c, 1969 e), and Coulomb scattering (Ranft, 1969 f). The system using Coulomb scattering is more efficient in the lattice proposed. A scraper positionned about 0.4 λ downstream the ejection septum is expected to remove all protons which could lead to random losses with an efficiency of about 90% or better.

The scraper position is indicated in Fig. 12.4 (Lay-out of ejection components). The scraper should be at least 3 m long out of a heavy material like Fe, vertically and radially adjustable and faced (about 0.1 mm) with a light material.

12.7.4. HALO SCRAPER

Halo trimming might be necessary before the beam ejection, It is proposed that this is also done in the ejection straight section to localize the radiation problem. Halo protons are Coulomb scattered in horizontal and vertical scattering targets located near the first septum. The scattered protons are scraped by the scraper 0.4 λ downstream the septum. This scheme avoids to position scrapers in other superperiods correct with respect to the phase of the resonant orbit. The same scraper positions should however, be reserved in all superperiods. The scraper could also be used for low intensity or low energy beam dump.

12.7.5. BEAM DUMP

Scrapers cannot be used for internal beam dumping at intensities much larger than a few times 10^{12} protons. At higher intensities a set of fast bumps sweeping the beam into a simplified but obviously less efficient extractor channel seems presently the most favourable system. The beam could, if necessary, be directed away from the tunnel by additional magnets. The conditions under which a full intensity beam has to be dumped are not yet well understood and a detailed investigation of such a system has still to be done after having gained experience at lower intensities. The necessary space in a long straight section has to be reversed.

12.7.6. BEAM LOSS ESTIMATE

One should take slightly pessimistic beam loss figures in assessing the radiation problems.

- Loss on the electrostatic septum	1%
- Halo removed by the scraper	1%
- Random losses around the ring resulting from the test and setting up periods integrated over the year	1%

(The percentage are relative to the circulating beam).

12.8. TOLERANCES

12.8.1. FIELD TOLERANCES

The influence of magnetic field errors has been studied using a particle tracking computer programme (Hilaire, 1969 b; Faure et al, 1969; Erb and Merle, 1969, 1970). The principal effect of the field error is to curve the separatrix. The jump width over the septum decreases together with the efficiency and the apparent emittance increases.

The criterion taken for an acceptable non-linearity amount is to limit the jump reduction to about 10% compared to the ideal linear case.

For the third integral slow resonant extraction, taking the non-linearities individually, acceptable values for $\frac{\Delta B}{B}$ at $x = 40$ mm are :

$$\left.\begin{array}{lll}\text{Sextupole errors} & : & S < 1.5 \times 10^{-3} \\ \text{Decapole errors} & : & D < 3.5 \times 10^{-3} \\ \text{14-pole errors} & : & V < 4.5 \times 10^{-3}\end{array}\right\} \text{ for bending magnets}$$

$$\text{Octupole errors} \quad : \quad OK < 2 \times 10^{-3} \qquad \text{for the quadrupoles}$$

This last value has also been confirmed by analytical calculations (Bennett, 1970).

For the integer resonance the allowed tolerances are larger by a factor 2.

Higher values lead to insufficient jump widths and even to complete stability.

The main conclusions are :

a) The limits given above are really sharp limits. So for instance, for $S = 1.5 \times 10^{-3}$ a still very good situation was found, while for $S = 2 \times 10^{-3}$ the particle motion has become completely stable.

b) It seems that mainly the value of the field error $\Delta B/B$ at the limit of the aperture is relevant, and that the analytic form taken for $\Delta B/B$ (x) changes the results only within a factor 2.

c) Computations up to now allow the preliminary conclusion that for reasonable strengths of the extraction lenses and a reasonable (small) number of correcting elements the maximum tolerable field error $\Delta B/B$ at $x = 40$ mm is about 3×10^{-3}

12.8.2. EFFECT OF RIPPLE ON THE SLOWLY EJECTED BEAM

During the beam extraction the rate of variation of the stable area must remain constant during the spill time in order to get a uniform intensity beam.

Numerical (Hilaire, 1969 a) and analytical (Wilson, 1969) evaluations are in good agreement. Numerical calculations assume $f = 80$ Hz as ripple frequency; the sensitivity to ripple varies as $1/f$. According to these calculations, the ripple tolerances on the sextupoles are not very severe. The extracted beam will be 100% modulated with a relative ripple of 10.10^{-2} in the 1/3 integer resonance and 3.10^{-2} in the integer resonance.

For evaluating the tolerances in the main bending magnets and quadrupoles a simplified model was used assuming that ripple only occurs in a single element.

In the case of a quadrupole at β_{max}, 100% modulation is produced with a 1.5 10^{-3} ripple in the 1/3 integer resonance and 7.10^{-2} in the integer resonance. This ripple distributed over all the machine quadrupoles corresponds to $\frac{\Delta I}{I} = 6.10^{-6}$ for 100% modulation in the 1/3 integer.

For a bending magnet at β_{max}, the same amount of modulation is produced by a 1.5 10^{-3} ripple in the 1/3 integer resonance and 0.5 10^{-4} in the integer resonance.

These results show the well-known sensitivity of the 1/3 integer resonance to the quadrupolar ripple and of the integer one to dipolar ripple. In any case it is necessary to plan for correction at the beam level with a suitable servo-system. However one must not forget that a servo-system cannot properly compensate the ripple if it is already initially too strong.

12.9. BEAM SHARING

The presnece of two experimental areas (North and West) and the existence of two main modes of beam utilisation (fast extraction for feeding bubble chambers and slow extraction for counter experiments) has led us to consider briefly various beam sharing schemes.

a) Sharing between one fast and one slow ejection or two fast extractions into two different channels can be consecutive or simultaneous.

   i) Consecutive sharing does not create any fundamental problem and can be easily done at two different energies but does not lead to the optimum beam duty cycle.

   ii) Producing a fast ejection burst during a slow spill when the beam is debunched appears feasible with fast extraction by beam shaving (see 12.6.2). An unacceptable intensity modulation of the slowly ejected beam would result if fast kickers were used.

b) Sharing between two slow extraction channels

i) Consecutive sharing at the same energy with the debunched beam appears possible but results in a lower beam duty cycle per channel.

ii) Consecutive sharing at different energies during the same pulse (say 200 GeV in the West Hall and 400 GeV.in the North Area) requires that one works with a bunched beam in the first extraction; since the rest of the beam must be accelerated further this may be quite acceptable for many experiments, bearing in mind that the RF structure will be at 180 MHz. One might also envisage either partial or full debunching followed by adaibatic retrapping at the end of the first spill, but there is no operational experience of the efficiency which could then be expected.

iii) Simultaneous slow extraction at the same energy into the West and North area channels asks for an additional phase shift between the outgoing separatrices corresponding to the two areas. This comes about because the lattice superperiodicity of 6 is not commensurate with the betatron wave number, therefore the separatrix has a different angle in homolog positions of the two different extraction sections.

To bring the separatrix at the same favorable angle with respect to the two extraction channels, two solutions have been studied.

- The two channels are geometrically shifted as studied in (Kissler, 1970), but this would require to remove more bending magnets and lead to a lower top energy and is therefore not acceptable.

- The separatrix at the level of S_1 of the second channel is shifted by a pair of quadrupoles (Hilaire, 1970). However, the possible shift is only of about 30° it is quite suitable for the 1/3 integer resonance where one has 3 separatrices but is not sufficient in the integer resonance.

12.10. INSTRUMENTATION

Experience at the CPS (Dekkers, 1969; Steinbach, 1969) has shown that a considerable amount of instrumentation is required to achieve a high efficiency operational extraction.

In addition to the general purpose instrumentation of the main ring such as current transformer, pick-up electrodes, beam probe scanners, ionic beam scanner, Q-measuring device, magnetic field peaking strips, wide-band pick-up station, air ionization chambers for loss measurements, etc. for our purpose, one should have the equipment listed below.

MAIN RING

Position and profile detectors

.1. Miniscanner	controlled by computer, scanning of the beam with an insulated target placed in front of each septa and linked mechanically to them.
2. Beam position pick-up	in front of the fast kicker.

Losses

1. Ionization chambers	placed near septa; measurement of loss used for efficiency calculations.
2. Cerenkov counter	directive counter useful for better localisation of losses.

Ripple compensation	magnetic element chosen according to type of extraction - closed loop compensation with detector in external beam can servo the shape of slow extraction as well.

EXTERNAL BEAM

Beam intensity

1. Transformers	toroidal transformer placed around the beam; working well for fast extraction; will probably work for slow extraction.
2. SEC	Secondary Emission Chamber.

3. Telescope	2 or 3 scintillators aligned to look at target.
4. Charge of insulated target	measured by electrometer + A/D conversion.
Position and profile detectors	
1. Screens + TV	remote-controlled, 1 per focus + 1 per splitting
2. SEC with strips	also used for emittance measurements (choice of place accordingly), 1 per branch.
3. SEPD	Slow Extraction Position Detector, 1 per movement correcting element.
Movement compensation	one of the beam transport elements must have additional windings for this purpose.
Debunching	
1. Telescope with scintillators	delayed coicidences and/or time between pulses measurement devices could give information to obtain effective length (computer treatment).
2. Remote-controlled counter movable in the beam	sapphire could be used, enough light to deduce the time structure.

12.11. COST ESTIMATES

This estimation is based as much as possible on the extrapolation of corresponding elements ordered for the CPS (Barbalat, 1970).

Although in this report the elements are all calculated at the nominal energy of 400 GeV, it was assumed for the cost calculation that at lower energy stages, smaller less expensive elements would be installed.

The prices are given for one extraction channel in the table in thousands of Swiss Francs.

	200 GeV	300 GeV	400 GeV
Extraction channel (including power supplies)			
Electrostatic septum S_1	500	500	500
Copper septum magnet S_2	300	400	550
Iron septum magnet S_3	500	900	1450
	1300	1600	2500
Lenses (including power supplies)			
Dipoles (6)	500	650	800
Quadrupoles and sextupoles (4)	500	650	800
	1000	1300	1600
Fast Kickers * (including electronics)	5000	6250	7500
Scraper and Target	300	400	500
Development	1500	2000	2500
Electronics and controls	1000	1250	1500
Instrumentation	500	600	700
	10600	13400	16800
Installation	4000	4500	5000
	14600	17900	21800

Installation costs are only a very rough estimate, they cover water, cables, bus bars, electricity mains, cable ducts, etc., bearing in mind that the ring tunnel is 40 m below ground level. Buildings for power supplies are not included.

* In the case of the use of fast bump (12.6.2) for fast extraction by beam shaving the cost would be considerably reduced but this scheme has not been studied far enough to make cost estimates possible.

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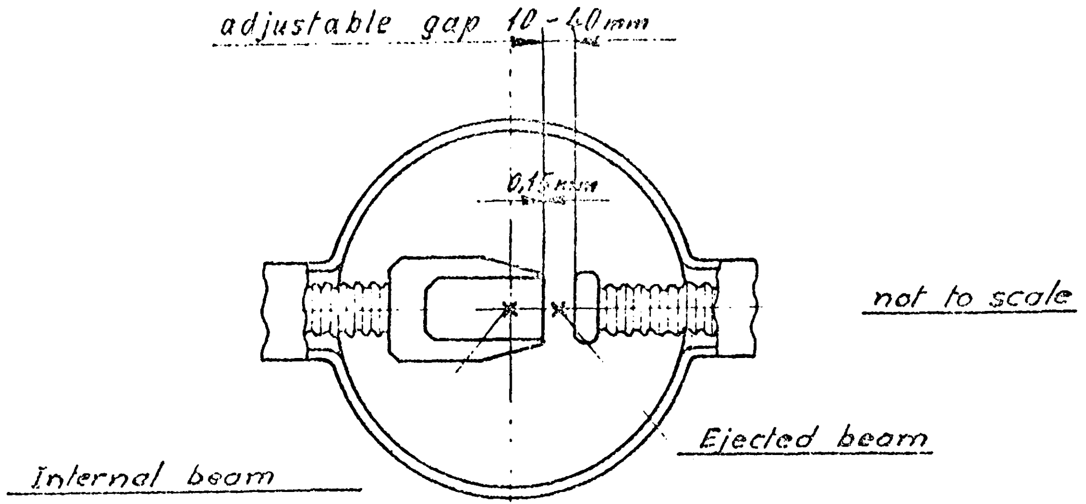


Fig. 12-1 Electrostatic septum S_1

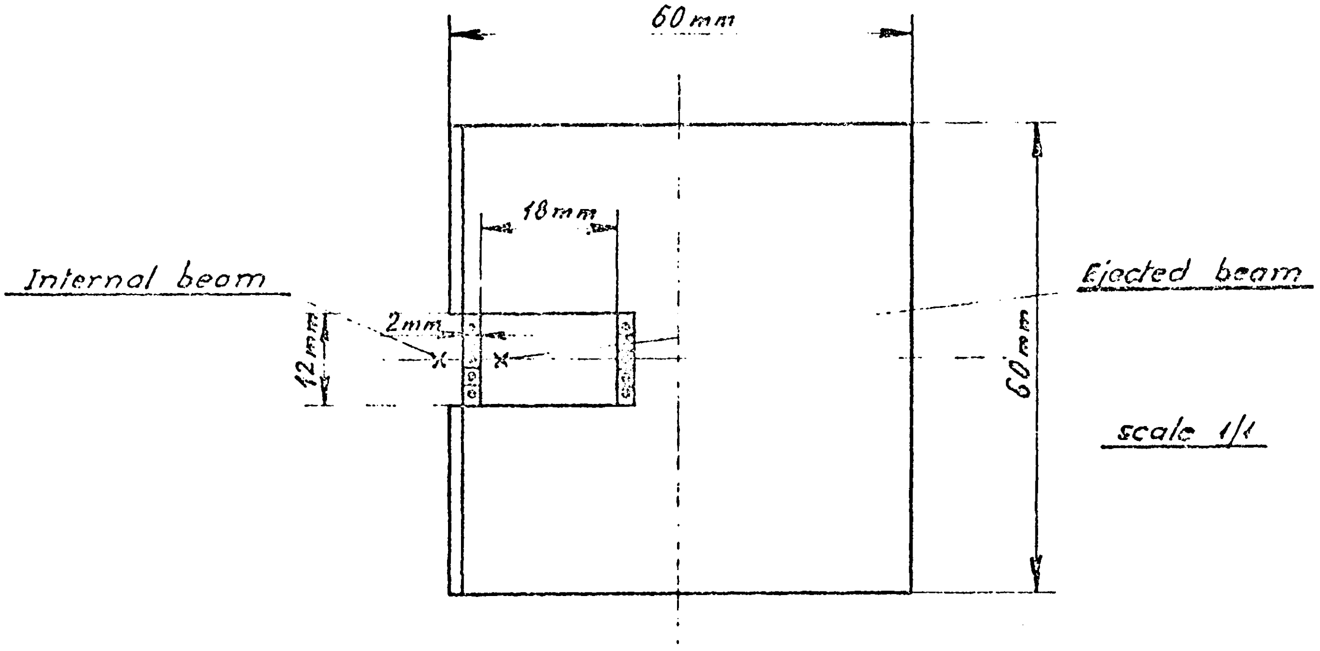


Fig. 12-2 Copper septum magnet S_2

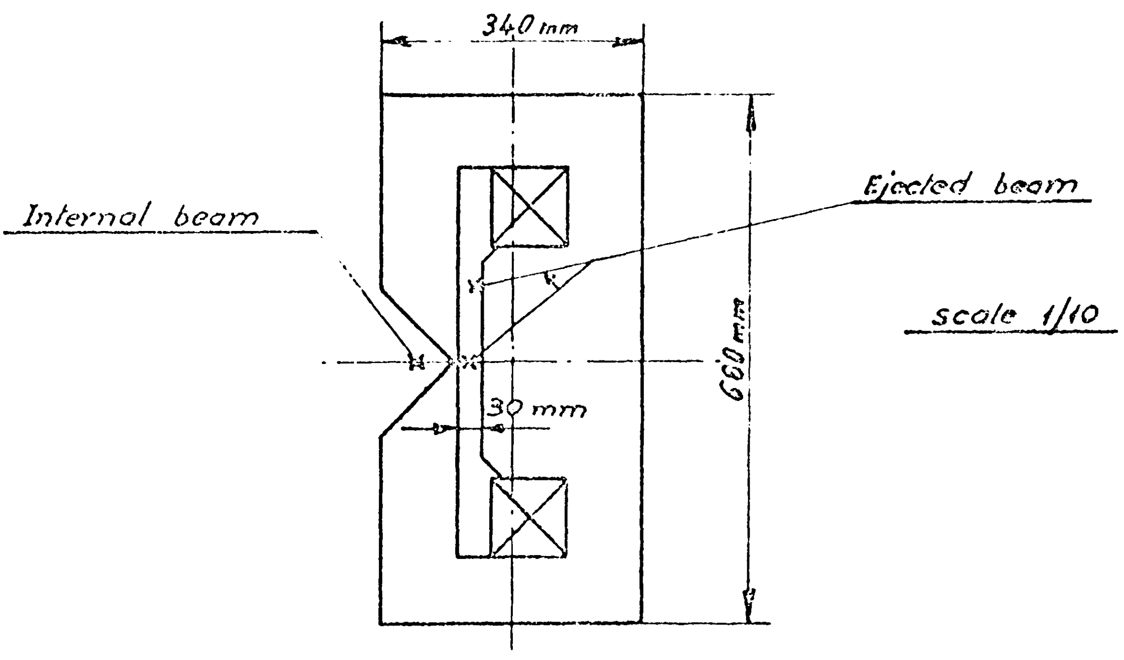
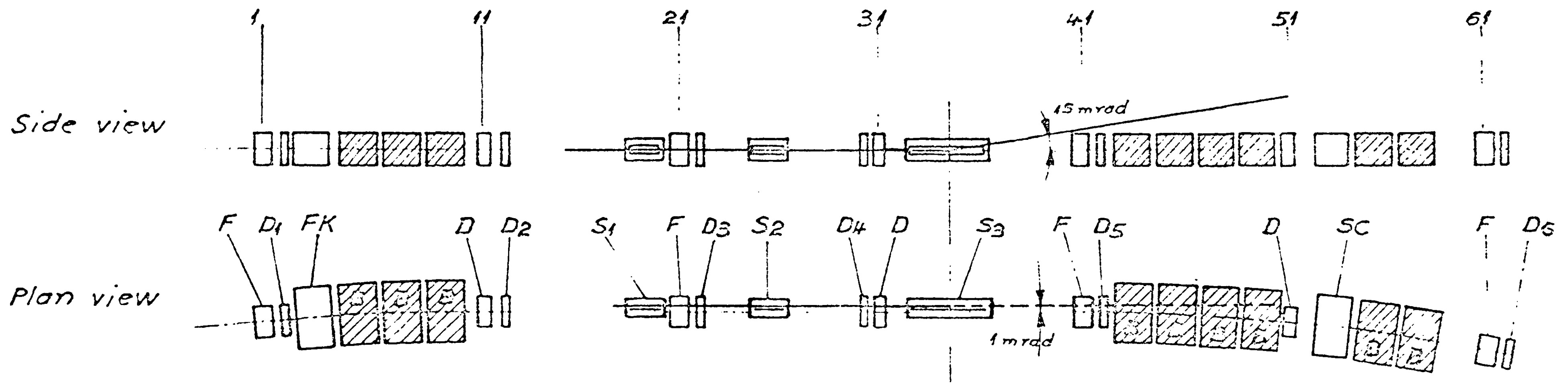


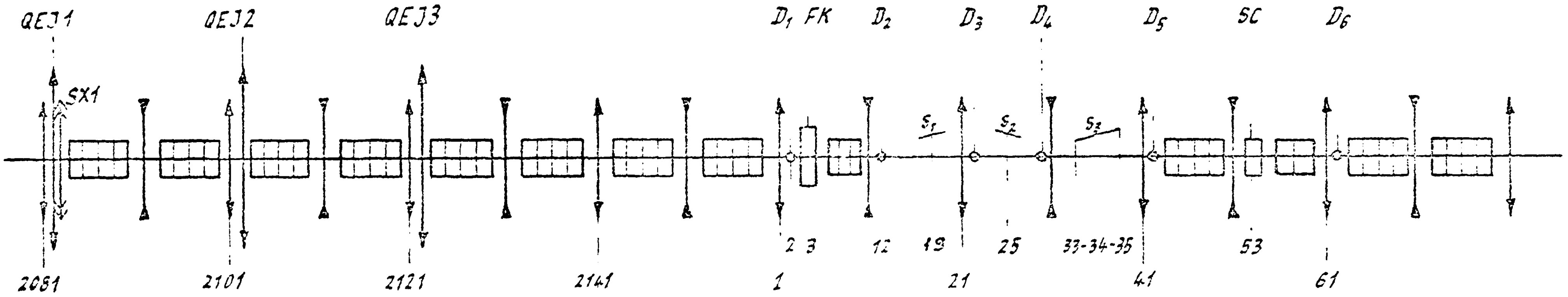
Fig. 12-3 Iron septum extractor magnet S_3



				position
D_1	Dipole for extraction	1.0 m	1 T	2
D_2	" " "	"	"	12
D_3	" " "	"	"	22
D_4	" " "	"	"	29
D_5	" " "	"	"	42
D_6	" " "	"	"	62
FK	Fast kicker	4.6 m	0.260 T.m	3
S_1	Electrostatic septum	6.0 m	100 kV/cm	19
S_2	Copper septum magnet	6.0 m	0.12 T	25
S_3	Iron septum extractor magnet	13.0 m	1.5 T	33-35
SC	Scraper	3.0 m	—	53
F	Main focusing quadrupole			
D	Main defocusing quadrupole			
B	Main bending magnels			

Fig. 12-4 Extraction channel

Figure 12-5 Location of extraction elements



QEJ1	Integer resonance quadrupole	1.2 m	25 T/m	2062 *
QEJ2	" " "	"	"	2102
QEJ3	" " "	"	"	2122
SX1	" " sextupole	0.8 m	150 T/m²	2082
FK	Fast kicker	4.6 m	0.260 T.m	3
S_1	Electrostatic septum	6.0 m	100 kV/cm	19
S_2	Copper septum magnet	6.0m	0.12 T	25
S_3	Iron septum extractor magnet	13.0m	1.5 T	33-34-35
SC	Scraper	3.0m	———	53
D1	Dipole for extraction	1.0 m	1 T	2
D2	" " "	"	"	12
D3	" " "	"	"	22
D4	" " "	"	"	29
D5	" " "	"	"	42
D6	" " "	"	"	62

* Position number refer to the computer programme listing corresponding to the lattice.