1. Introduction

Resonant extraction has already a long history at CERN. It was first proposed in 1961 by H. G. Hereward [1], its feasibility was demonstrated in 1963 by a series of tests in the PS South Hall [2]. One proceeded then to design [3] and build an operational system for supplying the beams of the East experimental area and in 1965 a 70% extraction efficiency was reported [4]. The scheme was improved by the addition of a thin septum quadrupole lens proposed by C. Bovet [3] and in 1967 efficiencies up to 80% had been reported [5].

However, the process remained incompletely understood. There was a discrepancy between the theoretical values of the parameters and the optimum settings found experimentally. More important, the practical extraction efficiency remained well below the predicted value and even below the peak reported tests results.

New studies were therefore undertaken in 1968; first to understand the process which was actually taking place in the PS slow extraction and reconcile the experimental and the theoretical values of the parameters. The second purpose was to seek through this understanding to achieve the higher efficiency required by the high intensity on which the second stage of the CPS Improvement Programme is based [6, 7]. These studies received an added momentum from the Study Group on high efficiency extraction set up by the 300 GeV steering committee which took an active interest in this work [8].

From the theoretical point of view, we approached the problem by developing an analytical theory which could explain the behaviour of the slow extraction parameters. On the experimental side, we made a considerable effort to improve the instrumentation both to observe the dynamics of the extraction process and to find the loss pattern.
2. Analytical theory

We can give here only a brief outline of this theory which is described more fully elsewhere [9, 10]. But before, it is necessary to give a short description of the present CPS slow extraction scheme.

2.1. The CPS slow extraction

The CPS slow extraction operates with a $Q_H$ of the order of 6.25. A strong quadrupole reduces this $Q$ value and introduces a large quadrupolar stop band at 6.0. Because of the dipole effect of the quadrupole the closed orbit is momentum dependent. A set of 6 sextupoles introduces the non linearity necessary to achieve a separation between stable and unstable particles. This non linearity is (because the sextupoles strength has a sixth harmonic distribution) closed orbit dependent. These two effects combine to make the stable area momentum dependent. Therefore the spill can be achieved by reduction of the flat top field. This rather complicated mechanism is necessary to introduce a non linearity into a fundamentally linear parametric resonance.

The quadrupole is located in s.s. 61, two units upstream from a 0.6 mm thin septum quadrupole lens (placed in s.s. 63). This septum quadrupole separates the particles which will be ejected from the spiralling beam and improves the extracted beam optics [5], in particular by reducing the beam size at the extraction septum dipole. Further, because the particle performs an additional turn in the resonant process before reaching the 6mm thick septum dipole (in s.s. 62), there is an additional jump enhancement by a factor of about 2. Finally to avoid plunging the septum magnets, an outward closed orbit bump is produced by a set of backleg windings on 6 CPS magnet units (51, 58, 60, 61, 66 and 67). The achieved bump is a superposition of several components: $\lambda$ and $\lambda/2$ long bumps of equal amplitude, so that the outside amplitude (s.s. 63) is twice the inside amplitude (s.s. 56), and a dipole kick which compensates the dipole component introduced in the quadrupole by the resulting off-centered closed orbit.

2.2. Stable and unstable closed orbits

a) Ideal machine

A closed orbit passing, before one excites a quadrupole, at a distance $e$ from the geometrical centre of the quadrupole of strength $D$, in a machine where the phase advance per turn is $\varphi=2\pi Q_H$ has an amplitude given by:

$$
\rho = \frac{e}{D \sin \frac{\varphi}{2} - \cos \frac{\varphi}{2}}.
$$

(1)
In the PS the main effect of the sextupoles [9, 10] on this new orbit is to give an added phase shift \( \Delta \varphi \) function of the amplitude

\[
\Delta \varphi = - \rho \ n \ S
\]

(2)

\( n \) is a function of the sextupole location and \( S \) the sextupole strength.

By coupling (1) and (2), providing \( \rho \) is small one finds:

\[
A\rho^2 + 2B\rho - e = 0
\]

(3)

which is the equation of a parabola

\[
A = - \frac{nS}{D} \left( \cos \pi Q + \frac{D}{2} \sin \pi Q \right)
\]

\[
B = - \frac{1}{D} \left( \sin \pi Q - \frac{D}{2} \cos \pi Q \right).
\]

Fig 1 is a plot of \( e \) (a measure of the momentum) as a function of \( \rho \). For a given value of \( e \), equation (3) gives two solutions, \( \rho_s \) corresponding to the stable fixed point, \( \rho_u \) to the unstable fixed point closed orbit amplitude.

The \( Q_H \) in a machine is normally a function of the energy, therefore the coefficients of equation (3) depend on the mean radius. Since the usual way to modify \( e \) is to change the beam mean radial position, equation (3) is no longer a parabola as can be seen on the second curve of Fig. 1.

Fig. 1 clearly shows how this \( Q_H \) variation with radius helps to keep the closed orbit amplitude of the stable part of the beam within reasonable limits for far off-momentum particles. Nevertheless this closed orbit effect strongly reduces the machine energy-wise and limits the energy spread that can be given to the debunched beam. It accounts for the preinjection losses observed in certain situations [10, 11].

**b) Real machine**

The previous description must be completed to include the effects of the unperturbed closed orbit, the presence of orbit bumps and of the vertical betatron motion. Each of these effects can be taken into account by introducing an equivalent displacement \( X_i \) and an equivalent angular deflection or radial kick \( k_i \) in s. s. 61 where the quadrupole is situated.

The effect of these \( X_i \) and \( k_i \) is to modify the mean radius \( \overline{\Delta R} \) from which the quantity \( e \) has to be counted. \( \overline{\Delta R} \) is given by:

\[
\overline{\Delta R} = - \frac{k}{D} + \Delta - X
\]

where \( X \) and \( k \) are the sum of the various equivalent displacements \( X_i \) and kicks \( k_i \), \( D \) is the quadrupole strength and \( \Delta \) the quadrupole misalignment from the machine centre line.
The mean radial position \( \bar{R}_0 \) and hence the Q value at which the extraction works is therefore a function of the closed orbit, of the current in the orbit bump coils, of the vertical amplitude of oscillation of the particles and of the current in the quadrupole.

It is only by taking into account this complex parameter interrelation that we were able to find an agreement with the observed dynamical particle behaviour (see 3.1).

2.3. Notion in the radial phase plane

The phase space trajectories can be calculated as H. G. Hereward did \[1\] once one knows the matrices around the fixed points.

These matrices are easily found in our model and from them we deduce the separatrix equation in s.s. 11. S. s. 11 is a straight section of symmetry where the phase space is similar to s.s. 63 (where the septum quadrupole is):

\[
y^2 = a \left( x - \frac{\delta}{2} \right)^2 (x + \delta),
\]

where \( y \) is the normalised angle,
\( x \) is the normalised position counted from the middle of the fixed points,
\( \delta \) is the distance between the two fixed points,
\( a \) is a constant dependent on quadrupole and sextupole strength.

The jump along the separatrix is found by assimilating the motion to a linear one at the vicinity of the point where the jump is to be calculated.

The same linear approach was used to evaluate the effect in s.s. 62 of the s.s. 63 septum quadrupole which aims at clearing the septum in s.s. 62 one turn (minus one magnet) later.

The effect of this transformation is to shift the phase and enhance the amplitude of the deflection vector in such a way as to increase the clearance at the extractor magnet in s.s. 62.

2.4. Vertical study

We have also calculated the vertical Q shift produced by the quadrupole and the sextupoles on an orbit of amplitude \( \rho \). Because of the effect described in 2.2, the vertical behaviour is momentum dependent. Although we found that Q \(_v\) was shifted towards the third integer stop-band \( 6 \frac{1}{3} \), this stop-band is quite narrow because the excitation does not have the symmetry plane of the CPS: the present evidence does not indicate that it is responsible for any significant inefficiency of our extraction.
2.5. Computer simulation

The results of this analytical theory are in good agreement with computer calculations using the usual simulation method of tracking particles around a computer model of the machine. In order to take the vertical effects into account we wrote a program which follows the particles in the full four-dimensional transverse phase space [12].

3. Experimental verification

The experimental confirmation of this theory was done in several steps.

— Checking of the operational parameter settings with theory,
— Jump and beam distribution measurements in front of the septa,
— Loss measurements,
— External beam intensity calibration and efficiency measurements.

3.1. Parameter checking

We made systematic measurements [13] to verify by beam dynamics methods the real effect of the major ejection parameters quadrupole and bump coils on the closed orbit and on the radial Q for various mean radial positions.

A very sensitive check was based on the fact that in the centre of this quadrupole the dipolar component is zero and the amplitude of the closed orbit is independent of the quadrupole current.

Closed orbit amplitudes were accurately measured with fork shaped targets.

3.2. Jump amplitude and radial beam distribution

These measurements were made possible thanks to the availability of "miniscanners" in front of the septa. Miniscanners are beryllium-copper flags (20×0.3×20 mm in the vertical, radial and longitudinal directions respectively) which can be moved radially in front of the septa. A charge measurement [14] gives the particle density at the flag position. Care had to be taken to avoid working under bad vacuum conditions to avoid perturbations of the signal by ionic effects. The data were transferred to the PS process control computer [15] and handled by a data treatment program [16, 17] to average out intensity fluctuations and check the stability of the extraction process during the measurements.

Several ejection situations were analysed [17]. A typical beam distribution is given in Fig. 2. The observed values of the jump when varying the quadrupole strength check within the measurement accuracy of ±0.5 mm with the values expected from the theory. (The two dotted lines of Fig. 3 correspond to the zero emittance and full beam emittances separatrices).
3.3. Loss analysis

The difficulties of an absolute calibration of a slowly ejected beam are well known. We therefore felt that any efficiency measurement had to be backed up by corresponding loss measurements [17].

We relied on two different systems:
— Air ionization chamber (AIC) placed on each of the 100 PS magnets [19, 20],
— A remote handled argon ionization chamber [21] installed on a telemanipulator [22] to study in detail the ejection region and the ejected beam line.

These tools proved to be very useful to reach the optimum tuning. The AIC corresponding to the septa locations were calibrated by losing the whole beam on the septum magnet. Although this did not correspond exactly to the normal geometrical configuration during extraction, it is sufficiently accurate in view of the observed beam.

The other AIC were used to verify the absence of measurable random losses in the other sections of the ring.

With these methods we found for an optimised situation:
— a 6—7% loss on the septum quadrupole
— a 0.5—1% loss on the septum dipole
— a <1% loss in the ejected beam line (at the threshold limit of the detector).

The measured loss on the septa checks with the values found by integrating the radial distributions in front of the septa (Fig. 2). For the septum quadrupole we assumed an apparent thickness of 0.7 mm rather than the nominal 0.6 mm, to allow for construction errors.

3.4. Slow extraction efficiency

In spite of the apparent wealth of available detectors [23, 24] the precise absolute calibration of a slow external beam is a very difficult problem.

The current is too low for using beam current transformers, Secondary emission chambers [25] which are our normal monitors during machine operation cannot be calibrated independently. Activation of Al and C foils alone does not give an accurate absolute value due to the error in the cross-section and to the calibration of the counting efficiency [26].

We therefore preferred to make a measurement related to the better known fast extraction beam intensity [28].

We set up a 100% efficient fast extraction of a beam collimated by an internal fork target. This efficiency was checked by beam current transformers [26, 27] and loss detectors [19, 20, 21, 22], both in the internal and external beam.

We used the ratio of the Al and C foils activation in the fast and in the slow beam to measure the ratio of slow and fast extracted protons.
With a sufficiently large number of pulses we can have an error of the order of 1% on this ratio.

We had optimised the slow extracted beam efficiency, which meant:
- Energy selected to be at 19.2 GeV/c to avoid using poleface-windings which modify all the machine magnetic behaviour,
- Adjustment of the debunching to avoid pre-ejection losses described in 2.2,
- Optimum radial beam distribution in front of the septa, adjusted by observation with miniscanners,
- Spill length limited to 50 ms to avoid parasitic longitudinal effects,
- No measurable loss around the ring,
- Minimum loss on the septa checked by AIC
- Minimum loss in the extracted beam channel checked by the Argon chamber and the telemanipulator.

Under these conditions we measured a slow extraction efficiency of 90.7±3.1% [28].

The corresponding loss of 9.3±3.1% checks within the error margin with the losses found by the air ionisation chambers (6.4±4.3%) and by the radial beam distribution measured by miniscanners 62 and 63 (7.1±1.3%).

Furthermore the ratio of total counts in the secondary emission chambers placed in the fast and in the slow beam was measured as 1.18±0.02 in agreement with the activated foil ratio of 1.20±0.014.

4. Conclusion

This study has shown that the radial behaviour of the CPS slow extraction could be explained and that predicted extraction efficiencies could be obtained. In the practical case of the CPS no evidence was found that the integer resonance scheme introduced a fundamental limitation.

However, we would like to check further the vertical behaviour, although we do not expect any major effects there. We must extend this work to the top CPS energy where poleface-windings are used. We must investigate in more detail the longitudinal effects which seem to influence both the beam quality (high frequency structure) and the burst length [29]. Finally we have to do a series of emittance measurements and to compensate the position drift of our extracted beam.

Acknowledgements

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Fig. 1. Closed orbit amplitudes
Fig. 2. Radial beam distribution inside septum magnets.
Fig 3. Jump at thin sepium location as a function of the quadrupole current.

REFERENCES

1. H. G. Hereward. The possibility of resonant extraction from the CPS. CERN AR/Int. OS/61—5.
2. C. Bovet, G. R. Lambertson, K. H. Reich. Measurements on slow beam ejection from the CPS, CERN 64—25.
10. Y. Baconnier. Theoretical analysis of the CPS slow extraction (To be published).
12. O. Barbalat. Fortran programmes for the CPS resonant extraction calculations. CERN, MPS/Int. DL 69—1.


26. S. Battisti. Etude des transformateurs de mesure de courant (to be published)

