IMPLEMENTATION OF THE PROPOSED MULTI-TURN EXTRACTION AT THE CERN PROTON SYNCHROTRON

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Abstract

Following the positive results of the three-year measurement campaign at the CERN Proton Synchrotron, concerning beam splitting with stable islands in the transverse phase space, a study of a possible implementation of the proposed Multi-Turn Extraction (MTE) was undertaken. The novel approach would allow a substantial reduction of beam losses, with respect to the present scheme, when delivering the high-intensity proton beams required for the planned CERN Neutrino to Gran Sasso Project (CNGS). Major modifications to the ring layout are foreseen, such as a new design of the extraction bumps including also the installation of three additional kickers to create a closed-bump over the five turns used to extract the split beam. The ring aperture was reviewed and improvements proposed to reduce possible beam losses during beam splitting and extraction. The goal consists of implementing the proposed changes by the end of the 2007/2008 PS shutdown and to commission the novel extraction during the 2008 physics run.

INTRODUCTION

As part of the preparation for the future high intensity proton beam for the CNGS Project [1], a critical review of the key processes used to generate such a beam was carried out [2], in view of a potential upgrade beyond the present nominal intensity value of 3.3×10^{13} protons per Proton Synchrotron (PS) batch. Among other issues, efforts have been devoted to the improvement of the present extraction scheme from the PS to the Super Proton Synchrotron (SPS), the so-called Continuous Transfer (CT). This extraction mode was developed in the mid-seventies [3] with the aim of delivering a beam at 14 GeV/*c* to the SPS, five PS turns long and with a reduced horizontal beam emittance to overcome the SPS aperture limitation in the vertical plane (a special optics in the transfer line joining PS and SPS allows exchanging the transverse planes (optical parameters and emittances). This approach consists of slicing the beam by means of an electrostatic septum: with the horizontal tune set to 6.25 this method produces one continuous ribbon four turns long plus an additional slice, representing the beam core, for a total beam length of five PS turns (see Fig. 1). While this extraction mode is sufficient for the present performance, a number of drawbacks come to bear when the intensity is further increased, such as the beam losses intrinsically involved with the extraction mode, and also the properties of phase space matching of the different slices.

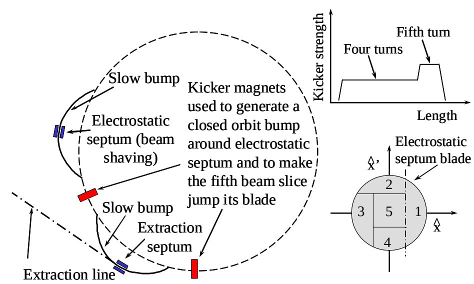

Figure 1: Principle of the CT extraction from the PS machine: the extraction scheme (left), the kicker strength as a function of time (upper right), the beam slices in the normalised phase space (lower right).

To overcome these problems a novel MTE was proposed. In this scheme the beam will be split in transverse phase space by generating stable islands around the origin and by slowly moving them towards higher amplitudes. Hence particles may get trapped inside islands thus generating well separated beamlets [4, 5].

Since no intercepting device is used, particle losses are limited to the fraction of the beam improperly deflected during the kicker rise time. Furthermore, the extracted beam should better match the phase space structure. Following the encouraging results of numerical simulations a measurement campaign in the PS machine was launched in 2002 and continued throughout the whole of 2003 and 2004. High-intensity beam splitting without any measurable losses was observed in summer 2004 (see Ref. [6] and references therein). The efforts continued to increase the fraction of trapped particles.

In parallel, the study of the implementation of the proposed scheme in the PS machine was launched and pursued in 2005, when no experimental activity could take place due to the long shutdown of the PS and SPS accelerators. In May 2006, a design report was issued [6] to prepare the launching of an official CERN project.

NOVEL MULTI-TURN EXTRACTION

The novel MTE technique relies on the use of nonlinear magnetic fields (sextupolar and octupolar) to generate stable islands in the horizontal phase space. The specific resonance to be crossed is the fourth-order in the case under study [4, 5]. The evolution of the beam distribution during the resonance crossing is shown in Fig. 2.

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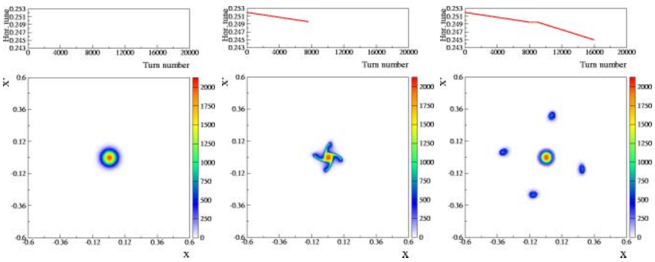

Figure 2: Evolution of the beam distribution during resonance crossing. The initial state is represented by a bi-Gaussian beam (left); at resonance-crossing some particles are trapped inside the moving islands (centre); at the end of the process, the particles trapped in the islands are moved towards higher amplitudes (right).

When the tune is changed the islands move through the phase space and some particles are trapped inside the islands. At some stage a complete separation between the islands, containing the beamlets, and the central core occurs and the distance between the islands can be increased at will by simply acting on the tune or on the strength of the nonlinear elements.

Once the islands are separated, the whole structure can be pushed towards an extraction septum by means of a closed slow bump. Then kicker magnets generate a fast closed bump and one island jumps beyond the septum blade so that the beamlets are extracted out of the machine. The outer islands are extracted over four turns. The fifth island, i.e. the beam core, is extracted using a classical single-turn extraction.

IMPLEMENTATION

The conceptual design of the MTE can be sketched as:

- Beam splitting: two sets, of two sextupoles and one octupole per set, will be used to split the initial single beam into the five islands, prior to extraction. The choice of two sets is mainly dictated by the need to control and adjust the islands phase at extraction.
- Extraction: the extraction point is in Straight Section (SS) 16 (Fig. 2), where the magnetic septum for the beam extraction towards the SPS is located. Two bumps will be used, namely to displace the beam toward the magnetic septum blade (slow bump) and to extract the islands over five turns (fast bump).
- Slow bump: a set of dipole magnets will be used to generate the slow closed orbit distortion around the magnetic septum. Presently, four dipoles powered with a series/parallel circuit are used to extract the beams towards the SPS. In the proposed scheme six magnets, independently powered, are foreseen. The large number of elements is imposed by the aperture constraints, as it will allow shaping the bump so as to overcome potential aperture bottlenecks.
- Fast bump: three new kickers will be used to generate the fast bump to displace the beam beyond the blade of the magnetic septum. The pulse length should correspond to five PS turns. Due to the need of ejecting the centre core of the beam, an additional kick will have to be applied at the fifth turn. For this purpose the kicker used for the fast extraction will be re-used together with a new device.
- Trajectory correction in the transfer line towards the SPS: even though in principle the extraction conditions for the novel MTE do not change from turn to turn, as one single island is used to extract the beam, the feed-down effects of the machine nonlinearities (particularly from the pole face windings in the main magnets) due to the extraction bumps could generate turn-by-turn variations of the beamlets positions at PS extraction. Such an effect could have a negative impact on the emittance after filamentation in the SPS. Hence, two kickers, capable of generating a deflection changing from turn to turn, will be used in the TT2 transfer line to correct for the variation in the extraction conditions (position and angle). These two devices are already used for the present CT extraction mode.

The challenge consists of implementing the MTE scheme within the tight boundary conditions given by the PS ring layout. This layout does not allow installation of new elements without a knock-on effect, with potential consequences far away from the original straight section (Fig. 3 indicates the sections to be modified).

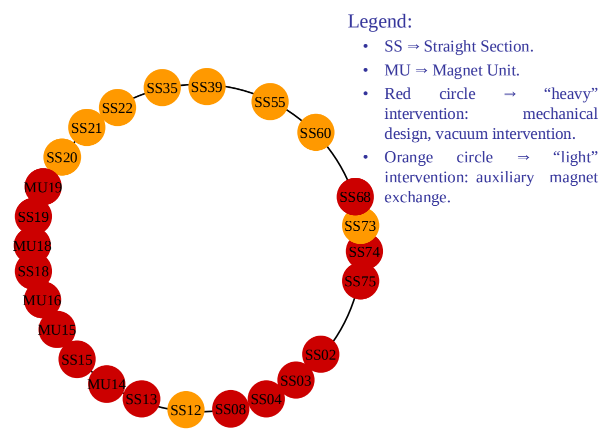

Figure 3: Required changes to implement the MTE.

A crucial issue for the implementation of the MTE is the available aperture, as the situation is particularly critical in the extraction region. Due to the very principle of the novel MTE, once the beam is split, there will be five islands circulating in the ring with different closed orbits. Detailed computations of the available aperture allowed identifying a number of critical locations in the ring and to start the design of special vacuum chambers. As an example, the horizontal beam envelope for the five islands at extraction, i.e. when both the slow and the fast bumps are active, is shown in Fig. 4. The special enlarged vacuum chambers in the extraction region around SS16 are clearly seen. The envelope is computed using the quadratic sum of the betatronic and dispersive contributions at 5 σ and 2 σ, respectively.

Another issue in the design of the MTE concerns the impedance of the additional kickers. Very little kicker hardware can be developed within the desired tight time scale and budget. Instead, existing spare devices or equipment stemming from earlier installations will be used. Hence, both the rise time and the impedance could not be fully optimised for the needs of the MTE. The results of an intense experimental programme led to the conclusion that an expected increase of the PS impedance of the order of 10 % is acceptable. A further outcome of these investigations was a critical review of the techniques used to measure the impedance of a device [7].

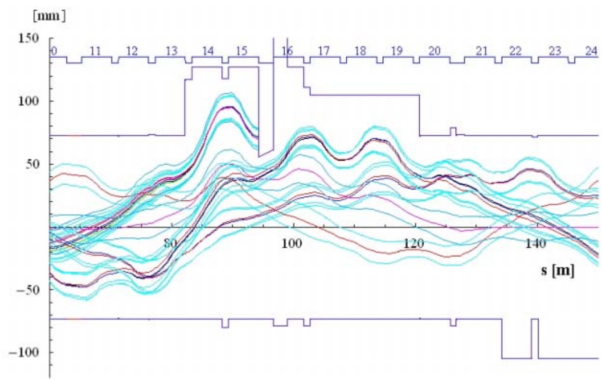

Figure 4: Superposition of horizontal beam envelope for the five islands at extraction. The numbers in the upper part identify the main magnets.

BEAM LOSS ANALYSIS

The beam losses were estimated analytically. The key parameters are the kicker performance and the longitudinal beam structure. The estimate of the total beam losses was performed by assuming a bi-Gaussian beam distribution in the horizontal phase space and a magnetic septum thickness of 3 mm, which correspond to about 1.5 σ of the measured width of a beamlet. It was further assumed that the septum is located at 4 σ with respect to the beam core. The kicker rise time is of the order of 350 ns for the first four extracted turns [8, 9] and 80 ns for the fifth one (in all the cases, the rise time is expressed for 10 %-90 % of the amplitude).

The longitudinal distribution will be imposed by the SPS. Hence three cases, namely continuous beam, i.e. partially recaptured on h=420, and bunched beam on h=16 or h=8 have been considered. For the last two cases, the bunch length is fixed to 80 ns and 100 ns, respectively (the first value being an estimate, while the second represents a measured value). The bunch distribution is assumed to be parabolic. In Fig. 5 the details of the kick time-dependence and of the longitudinal beam structure for h=8 are shown. The numerical values of the beam losses are listed in Table 1. In all cases 2 % to 3 % beam losses have been added to the computed losses to account for the observed losses during resonance crossing.

It is evident that capture losses are dominating. For the present CT the overall losses were estimated to be of the order of 9 % to 13 % [6], depending on the assumed electrostatic septum width. Therefore, the novel extraction should reduce the losses by a factor of 3 to 4.

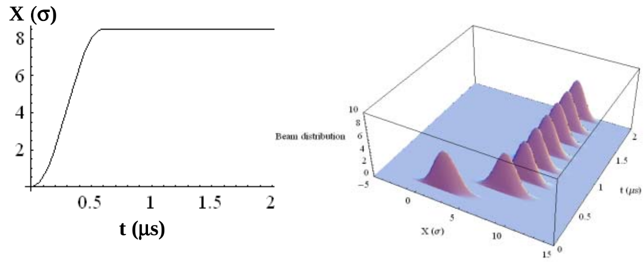

Figure 5: Kick time-dependence (left) and longitudinal and horizontal beam distribution (right) used in the analytical computations of the total beam losses for the MTE.

Table 1: Total beam losses for the nominal MTE layout as a function of the longitudinal beam distribution.

	Beam losses (%)		
	Continuous	Bunched h=16	Bunched h=8
Extraction	1	0.9	0.6
Capture + extraction	3 to 4	2.9 to 3.9	2.6 to 3.6

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