CERN – AB DEPARTMENT

CERN-AB-2006-021

DESIGN AND TESTS OF A LOW-LOSS MULTI-TURN EJECTION FOR THE CERN PS

M. Giovannozzi for the PS Multi-Turn Extraction Study Group

Abstract

Following the positive results of a three-year measurement campaign at the CERN Proton Synchrotron, a study of a possible implementation of the proposed Multi-Turn Extraction (MTE) based on beam splitting with stable islands in the transverse phase space was undertaken. A substantial reduction of beam losses, with respect to the present extraction scheme, could be achieved with the proposed technique when delivering the high-intensity proton beams required for the planned CERN Neutrino to Gran Sasso Project. Major modifications to the ring layout are needed, 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 are proposed to reduce possible beam losses between beam splitting and extraction. The goal is to implement the proposed changes by beginning of 2008 and to commission the novel extraction during the 2008 PS physics run.

Invited paper at the 39th ICFA Advanced Beam Dynamics Workshop on High Intensity High Brightness Hadron Beams 2006, Tsukuba, Japan, May 29 - June 2, 2006

Geneva, Switzerland
July 6, 2006

DESIGN AND TESTS OF A LOW-LOSS MULTI-TURN EJECTION FOR THE CERN PS

M. Giovannozzi for the PS Multi-Turn Extraction Study Group‡, CERN, Geneva, Switzerland
.

Abstract

Following the positive results of a three-year measurement campaign at the CERN Proton Synchrotron, a study of a possible implementation of the proposed Multi-Turn Extraction (MTE) based on beam splitting with stable islands in the transverse phase space was undertaken. A substantial reduction of beam losses, with respect to the present extraction scheme, could be achieved with the proposed technique when delivering the high-intensity proton beams required for the planned CERN Neutrino to Gran Sasso Project. Major modifications to the ring layout are needed, 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 are proposed to reduce possible beam losses between beam splitting and extraction. The goal is to implement the proposed changes by beginning of 2008 and to commission the novel extraction during the 2008 PS physics run.

INTRODUCTION

As part of the preparation for the future high intensity proton beam for the CERN Neutrino to Gran Sasso (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 the PS and SPS allows exchanging the two transverse planes). This approach consists in slicing the beam by means of an electrostatic septum: with the horizontal tune set to 6.25 this method allows generating 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.

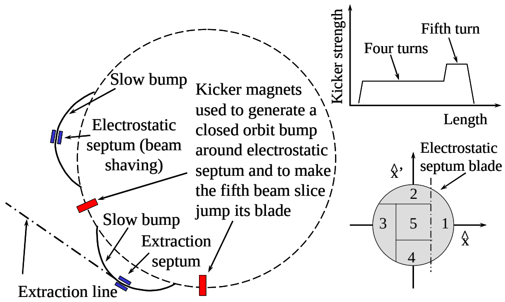

Figure 1: Principle of the CT extraction from the PS machine: the extraction scheme (left), the kicker strength as a function of time (upper right), the beam slices in the normalised phase space (lower right).

To overcome these problems a novel MTE was proposed. In this scheme the beam will be separated in transverse phase space by generating stable islands inside the region where the beam sits 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 [6] and continued throughout the whole of 2003 and 2004 [7, 8]. High-intensity beam splitting without any measurable losses was observed in summer 2004 [9]. 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 [10] to prepare the launching of an official CERN project.

NOVEL MULTI-TURN EXTRACTION

The novel 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

‡ The members of the PS Multi-Turn Extraction Study Group are: M. J. Barnes, O. E. Berrig, A. Beuret, J. Borburgh, P. Bourquin, R. Brown, J.-P. Burnet, F. Caspers, J.-M. Cravero, T. Dobers, T. Fowler, S. Gilardoni, M. Giovannozzi (Study Group Leader), M. Hourican, W. Kalbreier, T. Kroyer, F. di Maio, M. Martini, E. Métral, V. Mertens, K. D. Metzmacher, C. Rossi, J.-P. Royer, L. Sermeus, R. Steerenberg, G. Villiger, T. Zickler.

under study [4, 5]. A good model consists of choosing a simple FODO cell with a sextupole and an octupole located at the same position, both represented in the single-kick approximation. For the application under study, only the horizontal plane is relevant. The dynamics of such a system is generated by a 2D one-turn transfer map of the form:

$$\begin{pmatrix} X_{n+1} \\ X'_{n+1} \end{pmatrix} = R(\omega_n) \begin{pmatrix} X_n \\ X'_n + X_n^2 + \kappa X_n^3 \end{pmatrix}, \quad (1)$$

where the coordinates (X, X') are adimensional normalised coordinates [5], $R(\omega)$ represents a rotation matrix of an angle $\omega = 2\pi\nu$. κ depends on the ratio between the strength of the sextupole and the octupole with a weight given by the value of the optical beta-function at the location of the nonlinear magnetic elements [5], namely

$$\kappa = \frac{2}{3} \frac{K_3}{K_2^2} \frac{1}{\beta_x} \quad (X, \; X') = \lambda (x, \; x') \quad \lambda = \frac{1}{2} K_2 \beta_x^{3/2}, \quad (2)$$

where $(x, \; x')$ stand for normalised Courant-Snyder coordinates. The evolution of the beam distribution during the resonance crossing is shown in Fig. 2.

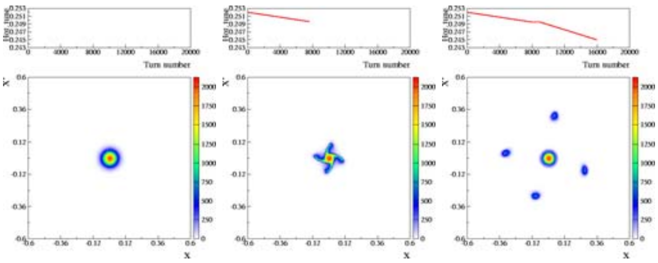

Figure 2: Evolution of the beam distribution during resonance crossing. The initial state is represented by a bi-Gaussian beam (left); at resonance-crossing some particles are trapped inside the moving islands (centre); at the end of the process, the particles trapped in the islands are moved towards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

When the tune is changed the islands move through the phase space region where the charged particles sit and some are trapped inside the islands. At some stage a complete separation between the beamlets and the central core occurs and the distance between the beamlets can be increased at will by simply acting on the tune or on the strength of the nonlinear elements. It is worthwhile stressing that the beam after trapping is made by two disconnected parts: the beamlets, which are indeed one single structure closing-up after four turns around the machine, and the central core.

Once the various beamlets 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 in four turns. The fifth beamlet, i.e. the beam core, is extracted using a classical single-turn extraction. The advantage of this approach is that, at least for the first four turn, the optical parameters are by definition identical. This is intrinsic to the method, as the same stable island is used to extract the beam.

MEASUREMENT RESULTS FOR MTE

The intense experimental campaign on the CERN PS, undertaken since the end of 2001 [6-9], entailed the development of new measurement systems, such as the turn-by-turn orbit measurement system, as well as the installation of sextupoles and octupoles to generate the stable islands. The magnetic elements and the beam instrumentation used in the experimental campaign are shown in Fig. 3. The tune is changed by means of two families of focusing and defocusing quadrupoles, normally used to tune the machine. Sextupoles and octupoles are used to generate the stable islands; the fast-extraction kicker is used to displace the beam and induce betatron oscillations for phase space measurements; a wire scanner is used to measure the horizontal beam profile; two pickups are used to record the betatron oscillations.

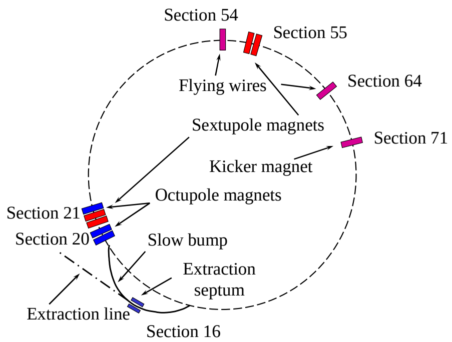

Figure 3: Schematic layout of the PS machine with the elements used for the experimental study of the novel MTE.

Trapping measurement with a high intensity beam represents the most important test for this novel approach. A sequence of transverse beam profiles during the splitting process is shown in Fig. 4 (top) together with the best result achieved (bottom left: intensity as a function of time; bottom right: measured horizontal beam profile at the end of the capture process). The injected intensity is slightly above 6×10^{12} protons and small losses are visible up to transition crossing (second vertical red line). Afterwards the intensity stays remarkably constant up to extraction, which is performed by means of a kicker in a single turn after having merged back the beamlets in order to reduce the beam size in the horizontal plane to match the septum acceptance. The beam profile after the splitting reveals a number of peaks due to the projection of the beamlets onto the horizontal axis. Another important point is that the left-most beamlet is very well separated and the region between it and the central core is depleted. This feature is crucial for having small or no losses at all at extraction, as it guarantees no interaction between the extraction septum blade and the beam.

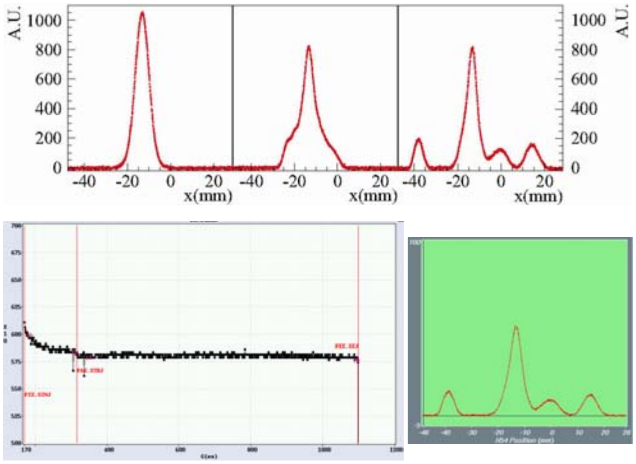

Figure 4: Sequence of beam profiles during splitting (upper) and best result achieved with a high intensity beam, whose intensity as a function of time (lower left) and horizontal beam profile at the end of the capture process (lower right) is shown.

A test was performed to increase the fraction of particles trapped inside the islands. By changing the strength of the octupoles during resonance-crossing it was indeed possible to increase the fraction of particles inside the islands, achieving a value of 18 % against a previous value of about 13 %. For the optimal performance of the SPS machine, the allowed fraction of particles inside each beamlets is limited to (20±5) % for the central core and (20±1) % for the other beamlets. However, the price to pay was the presence of slightly higher losses during resonance crossing up to the level of 2 % - 3 % of the total beam intensity.

LOSSES ANALYSIS

Present CT

In Ref. [10] a detailed analysis of the optical properties of the sliced beam for the CT is presented. In particular it is worth recalling that it is not possible to generate slices with equal emittance and intensity. The results concerning the way of slicing to make equal intensities, i.e. the relative beam-electrostatic septum position, are used in the computation of the beam losses.

For the computation of the losses the beam was assumed to be follow a Gaussian distribution in the transverse dimensions and be uniform in the longitudinal dimension (the beam is debunched before extraction).

Other crucial parameters are the width of the electrostatic septum and its angle relative to the beam, where measured values have been used. The beam divergence along the septum was neglected as it is very small. For the horizontal rms normalised beam emittance a value of ε_H* of 9.3 μm was taken which corresponds to the value measured for the 2004 operation during the high intensity run. Parenthetically, it is worth mentioning that during the last year of high intensity proton operation for the CERN neutrino experiments, the horizontal rms normalised emittance was much larger being about 16.6 μm. It is clear that although a larger emittance implies possible aperture bottlenecks, it also implies smaller local beam densities, hence smaller losses on the electrostatic septum during the extraction process.

The losses for the first four turns have been estimated by integrating the beam distribution over the septum width at the amplitude given by the analytical computations, assuming the same intensity for the various slices. In the case of the last slice, the extraction losses are mainly given by the finite rise time of the kickers, which is of the order of 820 ns (5 % - 95 % of the kick amplitude). The rise of the kick amplitude is modelled by a sine function. It is also assumed that the losses on the magnetic septum can be neglected, as the slices jump beyond the magnetic septum thanks to the kick imparted by the electrostatic septum.

Under these assumptions, the dependence of the beam losses on the septum angle relative to the beam, the septum thickness, the beam emittance, and the kicker rise time for the fifth turn have been derived. The most effective parameter for loss reduction was identified by computing numerically the Jacobian of the function expressing the total losses. If $\boldsymbol{L = L(p_1, p_2, \cdots p_n)}$ represents the function giving the total relative losses, then the quantities $\boldsymbol{\Delta L_i = \left|(\partial L / \partial p_i)_{p_{io}}\, p_{io}\right|}$ are calculated, where p_{io} represents the nominal value of the i-th parameter are computed. The ΔL_i are normalised so that they can be compared to give an indication of the relative effectiveness of each free parameter. The results are reported in Table 1. It is clear that the most efficient parameter is the relative angle between the electrostatic septum and the beam, followed by the horizontal emittance and the width of the electrostatic septum. The rise time of the extraction kickers is an effective parameter only in the case of bunched beams, when its relative importance is equivalent to the width of the electrostatic septum.

Table 1: Effectiveness of the free parameters in reducing the total losses at extraction for the CT.

Longitudinal structure	ΔL_1 p_1=emittance	ΔL_2 p_2=septum angle	ΔL_3 p_3=kicker rise time	ΔL_4 p_4=septum width
Continuous	7.51	12.18	0.38	2.88
Bunched h=16	6.52	11.24	2.02	2.63
Bunched h=8	6.27	10.86	2.59	2.05

Novel MTE

The beam losses were also 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 [11, 12] 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. 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 one represents a measured value). The longitudinal beam distribution for the two types of bunched structures is parabolic. In Fig. 5 the details of the kicker wave form and of the longitudinal beam structure in the case h=8 are shown.

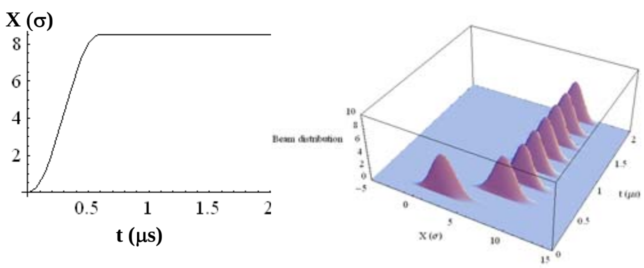

Figure 5: Kicker wave form (left) and longitudinal and transverse beam distribution (right) used in the analytical computations of the total beam losses for the novel MTE.

The numerical values of the beam losses are listed in Table 2. In all cases 2 % - 3 % beam losses have been added to the computed losses to account for the observed losses during resonance crossing.

Table 2: 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	3-4	2.9-3.9	2.6-3.6

It is evident that capture losses are dominating. It is worthwhile mentioning that for the present CT the overall losses were estimated in the previous section to be of the order of 9 % to 13 %, depending on the assumed electrostatic septum width. Therefore, the novel extraction should reduce losses by a factor of 3 to 4.

IMPLEMENTATION

The experimental campaign was completed by the end of the 2004. During the long shut down of the PS machine, which will be re-started in spring 2006, the analysis of the required modifications to implement the proposed MTE took place. Its conceptual design can be sketched as follows:

- Beam splitting: two pairs of two sextupoles and one octupole each will be used to separate the initial single beam into the five beamlets, prior to extraction. Contrary to the experimental setup, where only one set of two sextupoles and one octupole was used, the choice of two pairs is mainly dictated by the need to control and adjust the phase of the islands at the extraction point.
- Extraction: the extraction point is in the Straight Section (SS) 16, where the magnetic septum for the beam extraction towards the SPS is located. In the proposed scheme, the electrostatic septum in SS31, presently used for slicing the beam in the context of the CT extraction in SS31 is no longer required, thus simplifying the overall scheme. Moreover, this will have the added benefit of less highly-radioactive material to be maintained. Two bumps will be used to displace the beam toward the magnetic septum blade (slow bump) and to extract the beamlets over five turns (fast bump).
- Slow bump: a set of dipole magnets (bumpers) will be used to generate the slow bump around the magnetic septum. Presently, four bumpers 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 bumpers is imposed by the aperture constraints, i.e. it will allow shaping carefully the bump so as to overcome the potential aperture bottlenecks.
- Fast bump: three new kickers will be used to generate the fast bump used 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. To this aim the kicker used for the fast extraction will be used.
- 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 in implementing the proposed scheme within the tight boundary conditions given by the

PS ring layout that do not allow to install new elements without a knock-on effect, with potential consequences far away from the original straight section. An idea of the impact of the changes of the PS ring required for the implementation of the MTE can be derived from Fig. 6, where the ensemble of section to be modified is marked.

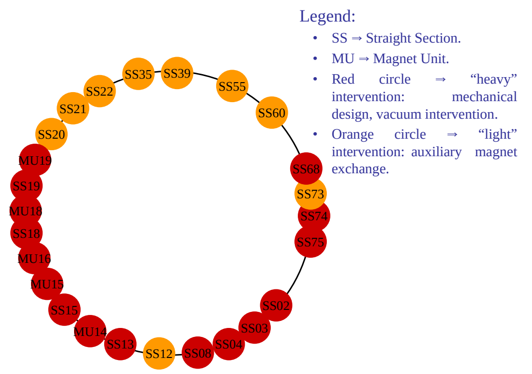

Figure 6: Summary of the changes required to implement the MTE.

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 beamlets circulating in the ring with different closed orbits. Detailed computations of the available aperture allowed to identify 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 beamlets at extraction, i.e. when both the slow and the fast bumps are active, is shown in Fig. 7. The special enlarged vacuum chambers in the extraction region are clearly seen. The envelope is computed using the quadratic sum of the betatronic and dispersive contributions at five and two sigma, respectively.

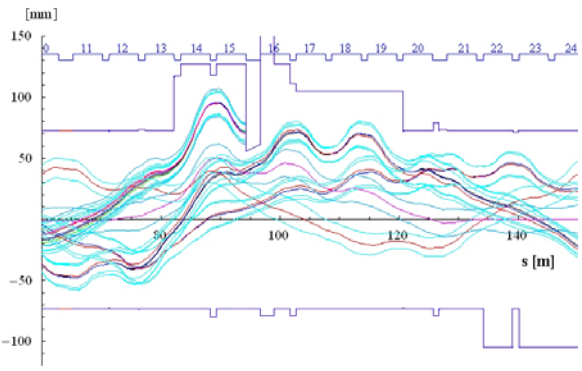

Figure 7: Superposition of the horizontal beam envelope for the five beamlets when both the slow and fast bumps are active. The numbers in the upper part identify the main magnets. A fraction of the PS circumference around the extraction point (position 16) is shown.

The last issue in the design of the MTE concerns the impedance of the new kickers required for generating the fast bump. No new kicker hardware can be developed within the desired tight time scale and budget, instead, existing 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 this novel extraction. Following an intense programme of measurements of the proposed kickers the conclusion was drawn that the increase of the PS impedance should be of the order of 10 %, which is tolerable for ensuring the appropriate quality of the beams required, e.g., for the future LHC. Parenthetically, an offspring of the investigations on the kickers for the MTE was the critical review of the standard techniques used to measure the impedance of a device, i.e. single- or two-wire approach.

ACKNOWLEDGEMENTS

We are particularly indebted to R. Cappi, the originator of the proposal to use stable resonances to split the beam. J.-P. Riunaud had a key role in supporting and encouraging the research. We would like to express our gratitude to O. Aberle, G. Arduini, S. Baird, C. Bal, D. Cornuet, B. Dehning, R. Garoby, J. Hansen, E. Jensen, J. Koopman, E. Mahner, and F. Ruggiero. Finally, we would like to acknowledge the contribution of M. Benedikt and M. Chanel for preparing the PS Booster beams and S. Hancock for the support with the longitudinal beam dynamics in the PS.

REFERENCES

[1] K. Elsener (Ed.) *et al.*, CERN 98-02 (1998).
[2] R. Cappi (Ed.) *et al.*, CERN-PS (AE) 2001-041 (2001).
[3] C. Bovet *et al.*, in 1973 Particle Accelerator Conference, edited by D. W. Dupen (IEEE, New York, 1973) p. 438.
[4] R. Cappi, M. Giovannozzi, Phys. Rev. Lett. 88, (2002) 104801.
[5] R. Cappi, M. Giovannozzi, Phys. Rev. ST Accel. Beams 7, 024001, 2003.
[6] R. Cappi, M. Giovannozzi, in proceedings of PAC 2003, edited by C. Horak (IEEE Computer Society Press, Piscataway, NY, 2003), p. 2910.
[7] R. Cappi *et al.*, in proceedings of EPAC04, edited by J. Poole and C. Petit-Jean-Genaz (Institute of Physics, London - UK, 2004), p. 175.
[8] M. Giovannozzi *et al.*, CERN-AB-2004-095 (2004).
[9] M. Giovannozzi *et al.*, in proceedings of PAC 2005, edited by C. Horak (IEEE Computer Society Press, Piscataway, NY, 2006), p. 117.
[10] M. Giovannozzi (Ed.) *et al.*, "The CERN PS Multi-Turn Extraction Based On Beam Splitting In Stable Of Transverse Phase Space - Design Report", in preparation.
[11] M. J. Barnes, T. Fowler, K. Metzmacher, L. Sermeus, to be publ. in proc. of Power Modulator Symposium, Washington DC, May 14-18, 2006.
[12] M. J. Barnes, T. Fowler, K. Metzmacher, L. Sermeus, "KFA13/21 kicker systems for the PS multiturn extraction scheme", CERN Technical Design Note, EDMS 742509, 2006.