ELECTRON-CLOUD STUDIES FOR TRANSVERSELY SPLIT BEAMS

S. S. Gilardoni, M. Giovannozzi, G. Iadarola, G. Rumolo, CERN, Geneva, Switzerland
N. Pradhan, CERN, Geneva, Switzerland and University of Mississippi, MS, USA

Abstract

Recently, resonance crossing has been proposed as a means of manipulating the transverse beam distribution. This technique has application, among other topics, to injection and extraction schemes. Moreover, the transversely split beams might also be used as a mitigation measure of electron-cloud effects. The results of detailed numerical simulations are discussed in this paper, possibly opening new options for scrubbing of beam pipes in circular accelerators.

TRANSVERSE BEAM SPLITTING

In recent years, a novel beam manipulation has been proposed, which is based on beam splitting by resonance crossing in the horizontal plane [1, 2]. The process is based on the use of non-linear beam dynamics. Stable islands are created by means of sextupole and octupole magnets, which are responsible for making the beam dynamics non-linear. An adiabatic tune variation is then applied so that a given resonance is crossed. During the resonance crossing stage particles can be trapped into the islands and transported to high amplitudes. The net result is to split the beam in the horizontal phase space so that from the initial single Gaussian multiple quasi-Gaussian distributions are generated. Examples of this process for the case of the third- and fourth-order resonance are shown in Fig. 1 and 2, respectively.

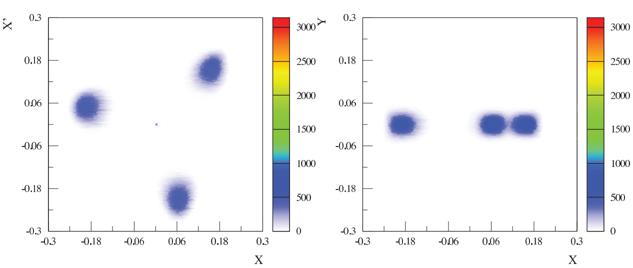

Figure 1: Phase space portraits of the final beam distribution after crossing the third-order resonance. Two of the six projections of the 4D transverse phase space are shown here, namely horizontal phase space (left), and physical space (right). The three beamlets are clearly visible in both the horizontal and physical space.

The difference between the two cases is striking and it can be summarised as follows: for an unstable resonance of order n the beam is split in n Gaussian beamlets with the centre of phase space almost completely depleted. Whereas in case of a stable resonance of order n, $n + 1$ Gaussian beamlets are created. This is a consequence of the stability of the resonance, which makes it possible for the beam at the centre of phase space to remain there, thus creating an additional beamlet. It is worth stressing the intrinsically different properties of the beamlets at non-zero amplitude with respect to the one at the origin. Indeed, while the beamlet around the origin represents a structure with periodicity equal to one machine turn, the other beamlets represent a single structure that winds up around the ring and closes up in a periodic way after n machine turns.

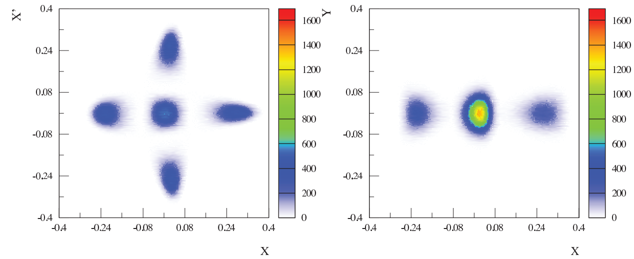

Figure 2: Phase space portraits of the final beam distribution after crossing the fourth-order resonance. Two of the six projections of the 4D phase space are shown, namely horizontal phase space (left), and physical space (right). The five beamlets are visible in the horizontal phase space, while the effect of projection is visible in the physical space.

It is also clear that properties like emittance and intensity are by definition the same for the n beamlets away from the centre as they are indeed one single structure. On the other hand, whenever it exists, the central beamlet does not need to have the same properties as the external ones. This implies that an additional degree of freedom is available (for the case of stable resonances) when defining the protocol for crossing the resonance. In fact, one can control the sharing of both emittance and intensity between the two phase space structures.

The technique of beam splitting had been originally proposed to perform multi-turn extraction from the CERN PS machine [1–6], but soon afterwards it has been realised that many more applications could be based on resonance crossing. Indeed, this technique could be time-reversed so to envisage a multi-turn injection based on beamlets' merging [7]. Such an approach would be very appealing as it allows beam shaping, which is a very interesting aspect in view of mitigating space charge effects [8]. Furthermore, the stability of the fourth-order resonance has been studied in detail proposing a method to turn it into an unstable resonance in view of generating a split beam with only four beamlets [9].

In parallel, detailed experimental studies have been performed at the PS [6] in view of an operational implementation of the novel technique to transfer beam from the PS to the SPS [10]. On a different front, intense efforts were devoted to the more theoretical aspect of the beam splitting with the goal of understanding the detail of the splitting process in a quantitative way with the help of adiabatic theory [11].

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ELECTRON CLOUD MITIGATION BY BEAM INDUCED SCRUBBING

Electron cloud (EC) effects (see [12] and references therein) have been observed in several accelerators running with intense beams of positively charged particles. In some cases, like for the CERN SPS and LHC, EC effects like vacuum degradation, heat load on the beam chambers, and beam quality degradation represent a serious limitation to the machine performance. An effective suppression of the electron cloud can be obtained through the installation of solenoids and/or cleaning electrodes or by coating the beam chambers of the accelerator with materials having low Secondary Electron Yield (SEY), e.g., amorphous carbon. However, these techniques can be very expensive, especially for large accelerators like the SPS or the LHC.

An alternative solution is based on beam induced scrubbing. During dedicated periods, the accelerator is operated with beam conditions that enhance the EC formation. The accumulation of electron dose on the chamber walls has the effect of decreasing the SEY of the surface and therefore mitigates the EC. In this framework it is particularly interesting to identify beam configurations that maximize the efficiency of the scrubbing process. A successful example in this sense is given by the "doublet" beam successfully used for scrubbing at the SPS in 2014 [13]. In this paper we investigate the effectiveness of transversely split beams for scrubbing purposes.

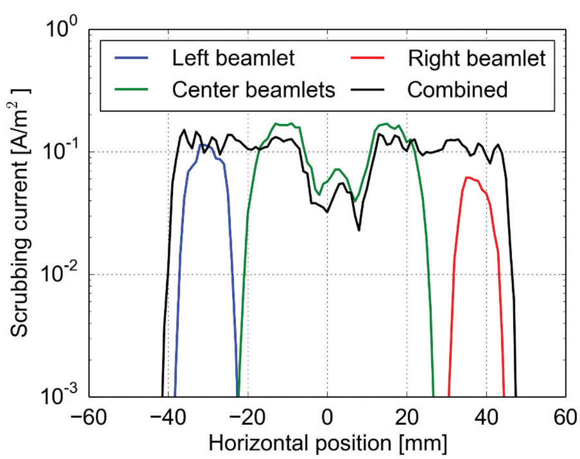

Figure 3: Comparison of the electron density as a function of the horizontal position for special single-beamlet beams and for a five-beamlet beam. The non-linear interaction between the beam distribution and the EC is clearly visible.

ELECTRON CLOUD BUILDBUILD UPUP WITH TRANSVERSELY SPLIT BEAMS

Although the results presented in this paper are quite general, it has been necessary to make a choice for the accelerator model to be used. The decision has been taken to use the SPS lattice for at least two reasons: firstly, such a model is very well known, both in terms of beam dynamics and EC build up, with a good wealth of available data to compare with. Secondly, the results obtained could be readily used for preparing an experimental verification of the new observations.

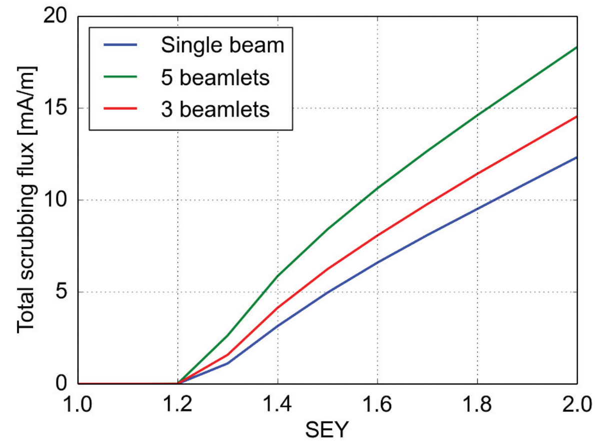

Figure 4: Electron current density as a function of the SEY for a standard beam and split beams in three or five beamlets.

In particular we decided to study the LHC-type beam with 25 ns spacing and the bunch intensity foreseen for the High Luminosity LHC upgrade, i.e., $\approx 2.5 \times 10^{11}$ protons per bunch (ppb), at the injection energy of 26 GeV.

EC simulations have been carried out using the PyECLOUD code [12] for the SPS bending magnets of MBB type, which are equipped with a vacuum chamber that for these purposes is well approximated by an ellipse with semi-axes of 64.5 mm and 24 mm, in the horizontal and vertical plane, respectively. The magnetic field at injection energy is 0.12 T.

Different beam distributions after crossing of either the third- or the fourth-order resonance have been generated. The final beamlets' position has been varied by acting on the value of the transverse tune at the end of the resonance crossing process. The number of initial conditions for each simulation was 10^6 and 0.8×10^6 for the case of crossing the fourth- and third-order resonance, respectively.

The first crucial test that has been performed is the verification whether the electron cloud build up depends linearly on the beam distribution. In the case of the split beam, which is made of multiple quasi-Gaussian beamlets, it is particularly relevant to assess whether the EC build up is the sum of electron distributions generated by each beamlets separately. To address this question we launched simulations with the complete split beam and separating the beamlets. The results of these simulations are shown in Fig. 3, where one can clearly observe how the whole process is non-linear and that an enhancement of the EC build up can be achieved.

Figure 4 shows the dependence of the electron current on the chamber's wall as a function of the SEY of the surface for the standard 25 ns beam, and for the split beams with three and five beamlets, respectively. We notice that the multipacting threshold, namely the minimum SEY for which

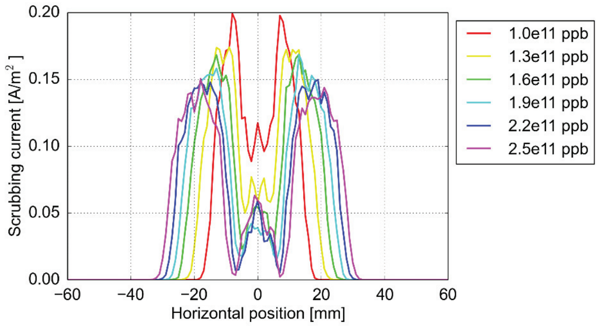

Figure 5: Electron current density as a function of the horizontal position for the standard beam.

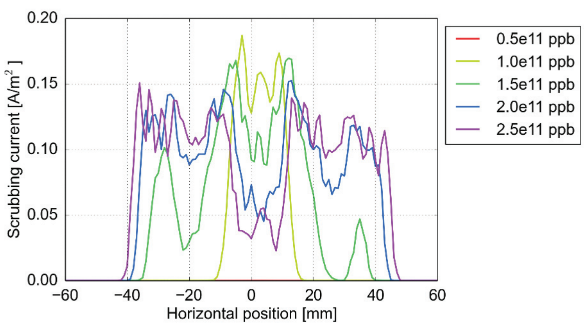

Figure 6: Electron current density as a function of the horizontal position for the split beam with five beamlets.

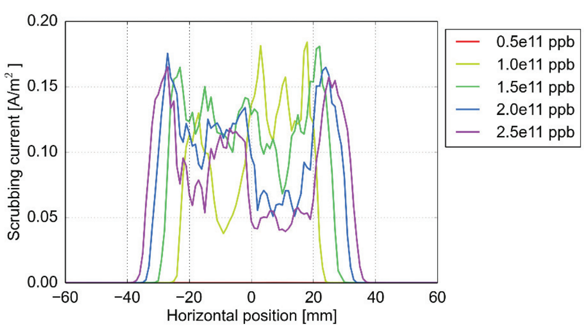

Figure 7: Electron current density as a function of the horizontal position for the split beam with three beamlets.

an EC can develop is very similar in the three cases (around 1.2) while an enhancement of the total current with respect to the standard beam can be observed for SEY values above the multipacting threshold, stronger for the case with five islands.

Another interesting feature of the EC build up with split beam can be observed in Figs. 5,6 and 7 where we show the scrubbing current density as a function of the horizontal coordinate, for different values of bunch intensity. For the split beams, the scrubbing flux covers a wider part of the vacuum chamber compared to the case of the standard beam, especially for the largest values of bunch intensities. Also with respect to this aspect, the case with five beamlets performs better than the one with three-beamles.

CONCLUSIONS

In this paper the results of electron cloud build up simulations performed using transversely split beams have been presented. The transverse distribution of split beams has proven to have a strong impact on the characteristics of the electron cloud phenomena.

The interaction between the electrons and the beamlets is non-linear, so that the cloud distribution in the presence of all the beamlets is not equal to the superposition of the distributions obtained for each individual beamlet.

The use of split beam allows increasing the surface of the vacuum chamber that is conditioned with respect to a given dose delivered to the chamber for the case of a standard Gaussian beam of the same total intensity.

It is planned to pursue these studies to include several more aspects. For instance, the behaviour of the electron cloud generation for different external fields as well as the dependence on the islands' phase.

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