EXPERIMENTAL STUDY OF THE ELECTRON CLOUD INSTABILITY AT THE CERN-SPS

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Abstract

The electron cloud instability limits the performance of many existing proton and positron rings. A simulation study carried out with the HEADTAIL code revealed that the threshold for its onset decreases with increasing beam energy, if the 6D emittance of the bunch is kept constant and the longitudinal matching to the bucket is preserved. Experiments have been carried out at the CERN-SPS to study the dependence of the vertical electron cloud instability on the energy and on the beam size. The reduction of the physical transverse emittance as a function of energy is considered in fact to be the main reason for the unusual dependence of this instability on energy.

INTRODUCTION

Studies for the Large Hadron Collider (LHC) performance upgrade include the improvement of the existing LHC injectors and the design of new rings in the injector chain [1]. Several scenarios, aimed at overcoming the existing bottlenecks, are presently being taken into consideration. The most promising option requires raising the injection momentum into the existing SPS from the present 26 GeV/c to 50 GeV/c. This is believed to improve the machine performance in many regards (e.g., less space charge and intra beam scattering, more rigid beams against coupled bunch instabilities, no transition crossing, lower injection and capture losses) [2]. Furthermore, it would allow for an upgrade of the SPS to a 1 TeV extraction energy ring, with the related advantages for injection into the LHC. This scenario is based on the replacement of the present SPS injector, the Proton Synchrotron (PS) ring, by the PS2 [3].
However, the steps for the realization of this upgrade plan crucially depend on the effect of a higher injection energy on the collective phenomena that are presently considered as the main limitations in the SPS performance. In particular, the vertical single bunch ECI [4] limited for a long time the number of batches that could be injected into the SPS and it is currently overcome by operating the ring with large vertical chromaticity after a scrubbing run [5].

An intuitive semi-analytical approach to the ECI using a broad-band resonator with beam dependent parameters [6] shows that its scaling may become alarmingly unfavourable at high energies far from transition, under the further assumptions of constant bunch length and normalized transverse emittances.
However, a comprehensive study of the effect of higher injection energy on the ECI has been carried out via simulations and experiments in the CERN-SPS. Table 1 shows a list of the essential parameters used for the numerical study (typical LHC-type bunch in the SPS). The main assumptions of our model (reflecting the real situation) are:

- The longitudinal emittance and the bunch length are kept constant. The momentum spread $\Delta p/p_0$ and the matched voltage are re-adjusted with the energy. The matched voltage scales like $|\eta|/\gamma$.

- The normalised transverse emittances are constant. Consequently the transverse beam sizes are scaled as $\sqrt{1/\gamma}$.

Table 1: Parameters used in our study

Parameter	Symbol	Value
Momentum	p_0 (GeV/c)	14–450
Norm. transv. emitt.	$\epsilon_{x,y}$ (μm)	2.8
Long. emitt.	ϵ_z (eVs)	0.35
Bunch length	σ_z (m)	0.3
Bunch population	N	1.1×10^{11}
Vertical tune	Q_y	26.13
Momentum comp.	α	0.00192

SIMULATION STUDY WITH HEADTAIL

The dependence of the ECI threshold on energy was simulated with the HEADTAIL code [7]. The action of the electron cloud on the bunch is lumped in one or more points along the ring. The N_{sl} slices of which the bunch is made, successively interact with the electron cloud. The electrons are modeled as N_e macro-particles, whose distribution in the pipe cross-section comes from the build up code ECLOUD [8]. Each slice sees the electron cloud as deformed by the interaction with the preceding slices. The distortion of the cloud distribution induced by the bunch passing through is the mechanism that couples the motion of subsequent slices and can give rise to instability. To gain an insight into the physical mechanism that determines the type of dependence of the instability threshold on energy, we have identified the thresholds at different momenta. The result of a scan over a few points extending to 270 GeV/c is displayed in Fig. 1 for a maximum SEY (δ_{max}) of 1.4. The threshold for instability decreases with increasing energy and levels off to the threshold for electron cloud build up for momenta higher than 100 GeV/c. Our explanation for this anomalous behaviour is that, although the bunch becomes more rigid at higher energies, and therefore less sensitive to collective effects, it also shrinks transversely, which enhances the effect of the electron cloud pinch. In addition, the matched voltage scales like $|\eta|/\gamma$, causing a decrease of the synchrotron tune far above transition. This translates into a slower longitudinal motion and therefore larger time scales for damping.

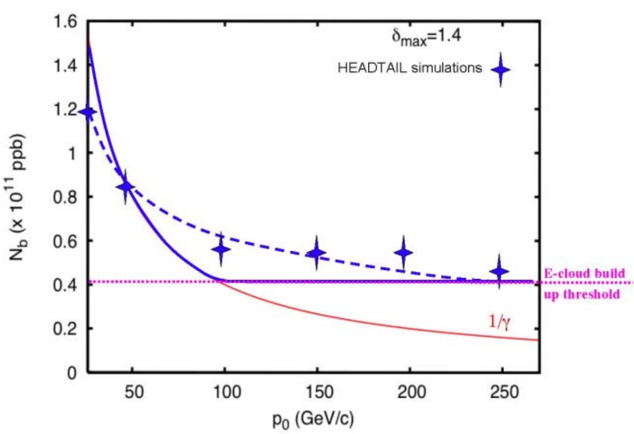

Figure 1: Simulated ECI thresholds at different momenta, study done with quasi-self-consistent e-cloud distribution.

To prove that the main cause of the destabilization of the beam at higher energies lies in the smaller transverse sizes, we simulated the ECI at 26 GeV/c for beams with different emittances in both transverse planes. It was found that emittance values about a factor 1.5 larger than nominal are sufficient to stabilize the SPS bunch against ECI (see Fig. 2). This feature is also inherent to ECI and can distinguish it from other types of collective instabilities, which do not depend on $\epsilon_{x,y}$ to the first order (except space charge, which is weak at the energies under consideration in this paper).

EXPERIMENTAL VERIFICATION AT THE CERN-SPS

An experimental study to prove the scaling law found by simulations was carried out at the CERN-SPS during the 2007 run. An LHC-type beam made of 4 batches with 72 bunches each, was injected into the SPS at 26 GeV/c during a flat bottom of about 11 s, then accelerated to an intermediate plateau of 55 GeV/c (about 6 s) and eventually taken to 270 GeV/c and dumped. The 55 GeV/c flat portion would serve to show that the beam still suffers from ECI at this higher energy. In addition, it could be used to prove that artificially enlarging the beam size would be an efficient tool to suppress this effect. Actually, the observation

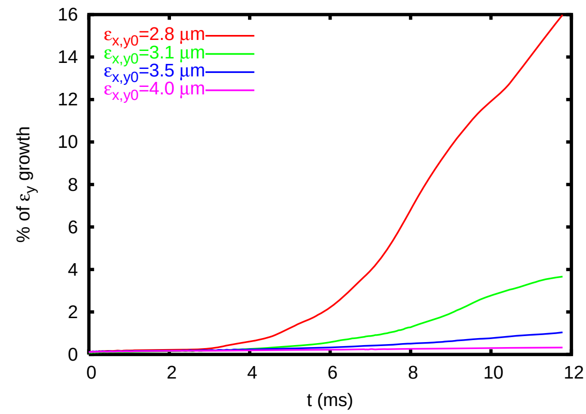

Figure 2: Simulated percents of vertical emittance growth due to ECI for LHC-type beams in the SPS having different initial transverse emittances (as labelled).

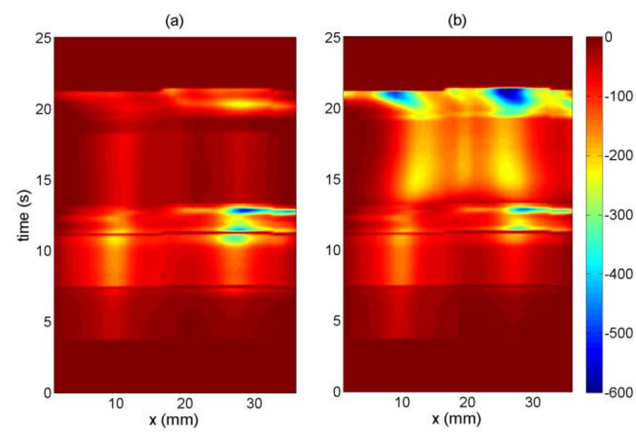

Figure 3: Evolution of the electron flux (nA) at different horizontal positions in the beam pipe along the cycle. (a) is without transverse damper excitation, (b) is with the damper on.

of the beam behaviour at this energy had a two-fold interest, because the value is close to the new injection energy. After reaching stable conditions with a 4-batch LHC-type beam inside the SPS (tunes $Q_x = 26.13$, $Q_y = 26.185$, and vertical chromaticity $\xi_y = 0.15$ along the whole cycle), the beam was intentionally driven unstable at 55 GeV/c by reducing the vertical chromaticity to $\xi_y = 0.05$ toward the end of the plateau. The evolution of EC in the machine was monitored through the signal of an EC detector (see Fig. 3). As Fig. 4 depicts, the ECI manifested itself with the loss of the bunches in the tail of the fourth batch.

The instability was proven to be independent of the operation of the SPS transverse feedback system. The two vertical dampers were switched on and off (alternately and together) with no evident effect on the appearance of the instability. Most of the measurements were taken eventually with both dampers on in order to rule out the onset of coupled-bunch modes. After proving that the ECI appeared at 55 GeV/c, it was attempted to suppress it through transverse emittance blow-up. The longitudinal beam parameters were kept unchanged in this exercise, and they were constantly monitored ($4\sigma_z$=3 ns in the flat parts of the

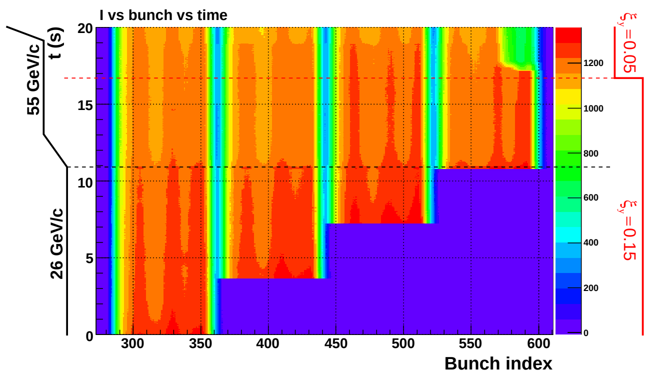

Figure 4: Top picture: Evolution of the bunch by bunch intensity with the 4 injections, a small uniform loss at the start of the first ramp, and the final loss at the tail of the fourth batch after lowering the vertical chromaticity.

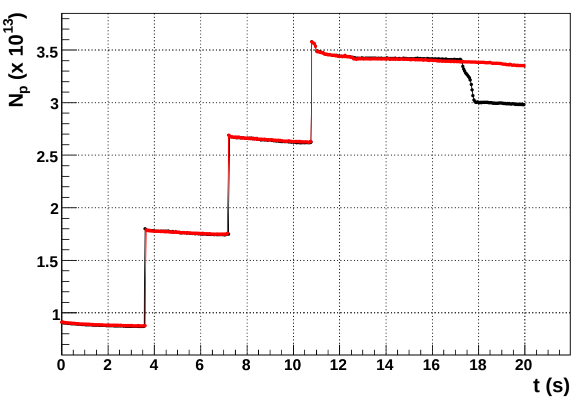

Figure 5: Typical beam intensity as a function of time along the cycle. The red trace shows a stable shot when the damper excitation was on, whereas the black trace shows a loss due to a vertical instability occurring with the damper excitation off. In both cases, chromaticity is reduced at 17 s.

cycle). The transverse blow-up was introduced at the end of the ramp to 55 GeV/c by means of transverse damper excitation. Testing the method during stable operation with high chromaticity, it was measured that the beam size at the wire scanner location was increased by a factor 2 horizontally and by a factor 1.4 vertically (which would translate in factors of emittance increase of 4 and 2, respectively). As predicted by simulations, the transversely enlarged beam remained stable also when lowering chromaticity to 0.05. Turning on and off the damper excitation several times, we could observe that the instability would systematically disappear for large beam sizes and re-appear for small beam sizes (Fig. 5).

CONCLUSIONS

In summary, the 55 GeV/c experiment described above shows that one of the bottle-necks for LHC-type beams in the SPS, i.e. the ECI, is still present at higher energy and can lead to beam loss, if it is not suppressed by high chromaticity. Furthermore, it demonstrates the principle that the ECI depends critically on the transverse beam size, as was anticipated by simulations, and can be cured by using beams with larger transverse emittances. This evidence can be inferred as an indirect way to prove the physical interpretation of the counterintuitive decrease of the ECI threshold with energy.

In conclusion, both simulations and experiments show that the ECI becomes more severe with increasing beam energy. As a consequence, upgrade plans with higher injection energy for proton machines which suffer from ECI must foresee a program of EC suppression. Promising EC countermeasures exist and their effectiveness is presently under study. They consist mainly of different types of coating, grooved surfaces and clearing electrodes. These techniques normally reduce the effective SEY at the inner pipe surfaces.

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