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Simulation study of electron cloud build up in the SPS MKD kickers

G. Rumolo

Abstract

During the 2008 run, an unusual behavior characterizing pressure and temperature increase in some of the dump kickers of the SPS was noticed. In particular, it was observed that 1) the MKDV2 kicker would exhibit maximum heating with 75 ns spaced LHC beams and 2) the pressure rise was specially critical in MKDV1 in presence of 50 ns spaced LHC beams [1]. While the anomalous heating of MKDV2 with 75 ns beams could be tentatively explained by the denser beam current spectrum that would more likely hit one of the kicker impedance peaks, the fast pressure rise in MKDV1 with 50 ns spaced beams was ascribed to a surface effect, namely beam induced multipacting leading to electron cloud formation. This report summarizes a simulation study that was done in order to check whether the electron cloud behavior in the dump kickers could explain the experimental observations.

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1 Introduction and motivation for the study

The SPS has several sets of kicker magnets: MKP kicker magnets for injection into the SPS; an MKQ system for tune (Q) measurement; an MKD system for dumping the beam; and two MKE systems for extracting the beam towards the LHC. The operational experience shows that the MKD system is the most problematic in terms of outgassing, whereas the MKE kickers have been identified as the main contributors to the SPS impedance. The function of the MKD system is to extract and sweep the beam to distribute the beam energy over a large volume of an absorber block. The system consists of two vertical kickers, known as MKDV1 and MKDV2, and three horizontal kickers namely MKDH1, MKDH2 and MKDH3. The MKE4 fast extraction system serves both the anti-clockwise ring of the LHC and the CNGS facility. The MKE4 system has five horizontal kickers: 3 of these are large aperture (L type) and 2 are small aperture (S type). The MKE6 fast extraction system serves the clockwise ring of the LHC and has three horizontal kickers: 2 of these are L type and 1 is S type. All the SPS kickers, except the MKDH, are ferrite loaded transmission line type magnets with a rectangular shaped aperture through which the beam passes. In general 8C-11 ferrite is used as magnetic material, while the MKDH magnets use 0.35 mm thick steel laminations. All of the MKE kickers, but none of the MKDV kickers, were originally equipped with transition pieces installed between the magnet and vacuum tank [2]. In the shut-down 2008/09, transition pieces were added to MKDV2. Only one of the MKE kickers, MKE6-L10, is entirely serigraphed [3], to reduce its longitudinal coupling impedance. Table 1 summarizes the aperture dimensions, cell length, and number of cells for each of the MKD kicker magnets installed in the SPS

Table 1: MKD system parameters

Kicker magnet	Nb of magnets	H_{ap} (mm)	V_{ap} (mm)	Length (mm) $\times$ Nb of cells
MKDV1	1	56	75	512×5
MKDV2	1	56	83	512×5
MKDH1/2	2	97.1	56	1256×1
MKDH3	1	106.1	60	1256×1

Various MDs were carried out in 2008 to study the effect of bunch spacings of 25 ns, 50 ns and 75 ns. During operation, with 25 ns bunch spacing, the MKDV1 magnet has a higher temperature than MKDV2, as expected since the calculated longitudinal beam coupling impedance is higher for MKDV1 [2]. However it was noticed that with 75 ns bunch spacing operation the temperature of MKDV2 would quickly and considerably exceed that of MKDV1. This behavior is believed to be explained by the absence of transition pieces in MKDV2, which causes several narrow resonances between 100 MHz and 1 GHz in the impedance of the kicker. These peaks are more likely to hit a peak of the spectrum of the 75 ns beam, which is three times denser than that of the 25 ns beam [4].
Measurements of MKDV1 and MKDV2 pressure were logged with 16 ms to 1 s resolution during the MDs. It was observed that a fast pressure rise, especially pronounced in MKDV1, would appear with 50 ns bunch spacing. The fine time structure of the pressure rise shows a peak of pressure every 24.6 s, which corresponds to the SPS super-cycle. Figure 1 displays pressure data together with the sum over the fast Beam Current Transformer (BCT) channels. With the assumed synchronization between pressure and beam current data, the pressure increases rapidly at the end of acceleration, as the bunch sizes decrease, and reduces as rapidly after the beam is dumped. The speed at which the pressure rises, as soon as acceleration of beam with 50 ns bunch spacing begins, suggests that the phenomenon is a surface effect, possibly electron cloud formation. The rate of pressure fall is reasonably consistent with the installed pumping rate [5].

Figure 2 shows pressure rise in the 2 MKDV kickers versus bunch intensity, for 50 ns bunch spacing and 4 batches: the instantaneous pressure rise in the MKDV kickers exhibits a clear threshold effect with

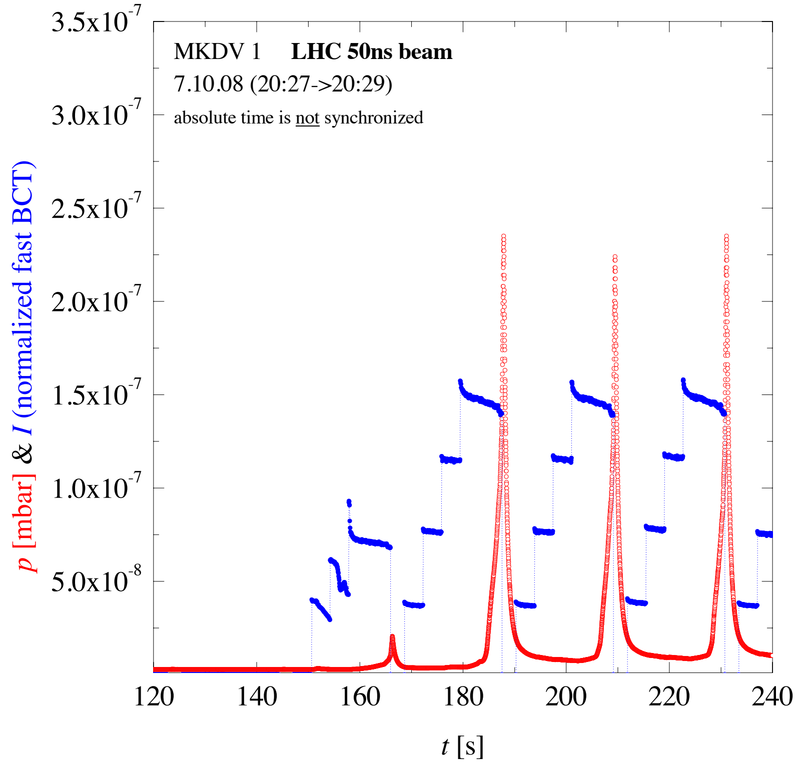

Figure 1: Beam current in the SPS (blue) and pressure in the MKDV1 (red) with a 50 ns beam (courtesy E. Mahner).

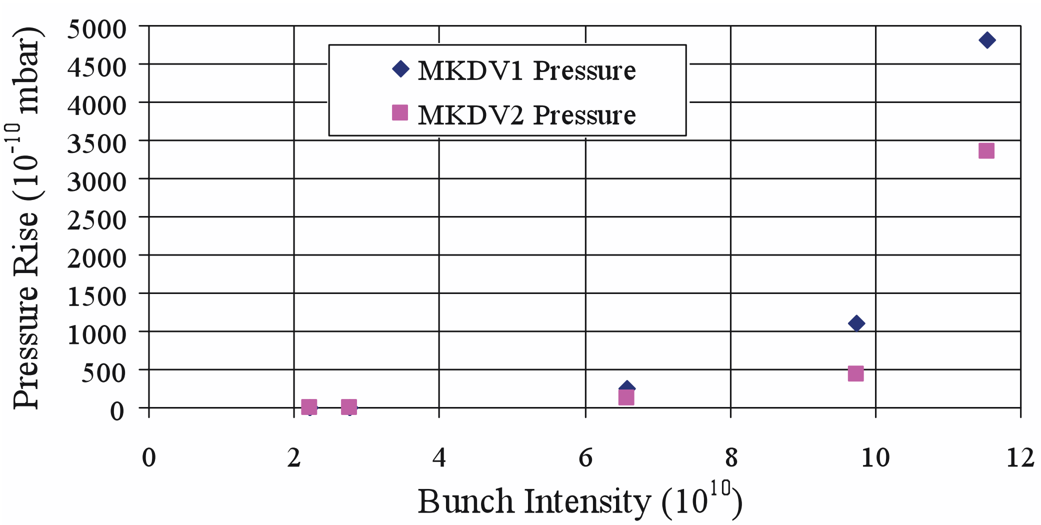

Figure 2: Measured pressure rise in the MKDV1 and MKDV2 with a 50 ns beam for different intensities per bunch. A significant rise occurs above a bunch population of about 6×10^{10} (courtesy K. Cornelis).

the bunch intensity ($N_b > 6 \times 10^{10}$ protons/bunch). The pressure rise also shows thresholds with number of batches and bunch length. All these threshold effects are in principle consistent with electron cloud as primary source of the pressure rise. Furthermore, MKDV1 is also affected by a pressure rise with the 25 ns beam, but with a different profile along the cycle and at a reduced level (Fig. 3). No pressure rise is observed in the MKDV kickers when a 75 ns beam is circulating in the SPS. The simulation study of electron cloud build up in the MKD kickers, described in the next Section, is mainly aimed at assessing whether the explanation of electron cloud induced pressure rise is compatible with all the experimental observations.

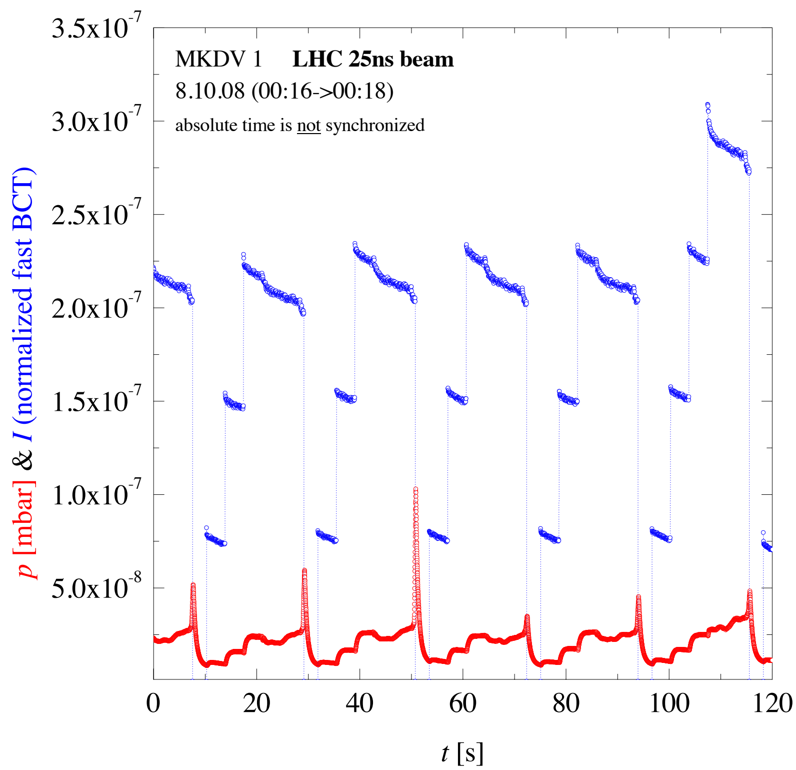

Figure 3: Beam current in the SPS (blue) and pressure in the MKDV1 (red) with a 25 ns beam. The vertical scale has been chosen to be the same as in Fig. 1 to ease a direct comparison between the two figures (courtesy E. Mahner).

2 Electron cloud simulations with ECLOUD

An intensive simulation campaign was carried out to determine whether all the observations of pressure rise summarized in the previous section could fit in the general picture of electron induced outgassing. Assuming a monotonic dependence of pressure on the density of electrons accumulated in the kicker aperture, the condition is obviously that the beam parameters used during the MDs should be consistent with an electron cloud in the MKD kickers, which

- affects MKDV1 more than any other MKD kicker
- builds up for 25 ns beams and 50 ns beams, but does not build up for 75 ns beams
- has a threshold current at about 6×10^{10} p/b for 50 ns beams
- is worse at top energy for 50 ns beams than at any energy for 25 ns beams

We have used the ECLOUD code to carry out this study [6]. The apertures of the kicker magnets can be found in Table 1. Tables 2 and 3 contain some machine and beam parameters used for the simulations, which were taken from the optics database and from measurements.

Table 2: Beta functions at the kicker locations

	β_x **(m)**	β_y **(m)**
MKDV1	25.57	86.7
MKDV2	31.1	75.8
MKDH1	35.65	67.64
MKDH2	40.05	61.1
MKDH3	44.9	55

Table 3: SPS beam parameters

Description	**Symbol and Unit**	**Value**
Protons/bunch	N_b	10^{11}
Normalized emittances	$\epsilon_{xN,yN}$ (μm)	
(25,75 ns)		3
(50 ns)		1
R.m.s. bunch length	σ_z (ns)	
(25,50,75 ns at 26 GeV/c)		0.6
(25 ns at 450 GeV/c)		0.35
(50,75 ns at 450 GeV/c)		0.31

2.1 Threshold study

First, we scanned several values of Seconday Electron Yield to find the threshold for electron cloud formation in MKDV1 for 25, 50, and 75 ns spaced beams. Since the kicker region is field-free while the beam is circulating and the kicker is not firing, we have first done all the simulation in a field-free region. The two plots in the first row of Fig. 4 display the expected electron cloud build up for 25 ns spaced beams for different values of SEY both at injection energy (26 GeV/c, left plot)) and after acceleration (450 GeV/c, right plot). It is clear that, for the same value of SEY, saturation at top energy happens at density values which are about 1.5 larger than at injection. While the threshold SEY seems to lie between 1.3 and 1.4 at injection energy, it is clearly below 1.3 after acceleration.

Similarly, the two plots in the second row of Fig. 4 show the build up plots for 50 ns spaced beams. In this case, we had to use values of SEY higher than 1.5 to see considerable build up and determine the threshold. The threshold is found to lie betwen 1.6 and 1.7 both at injection energy and at top energy. The saturation values of the electron cloud density is again about a factor 1.5 higher for the beam after acceleration above threshold (i.e., for $\delta_{max} = 1.8$ in the figure). With 75 ns beams, the threshold SEY for electron cloud build up appears to be even higher than 1.8, as seen in Fig. 5. With $\delta_{max} = 2.1$, multipacting can be observed with 75 ns beams, but the electron cloud density does not saturate over 4 batches. Therefore, we could suppose that the maximum SEY of the ferrite in the MKDV1 kicker is about 1.8, so that we would have electron cloud both with 25 and 50 ns beams, but not with 75 ns beams. The electron cloud would also be worse at top energy in both cases, compatibly with the existence of pressure peaks after acceleration. Furthermore, with $\delta_{max} = 1.8$ the 50 ns beam has an intensity threshold of electron cloud build up at around 5×10^{10} p/b, which matches well the experimental observation (see Fig. 2). Nevertheless, it still remains unexplained why the peak observed with the 50 ns beam would be higher than the one measured when the 25 ns beam is circulating inside the SPS.

Fixing the maximum to 1.8 and simulating the electron cloud formation in all the MKD kickers (both the MKDHs and the MKDVs), it turns out that, due to the geometry, the strongest electron cloud

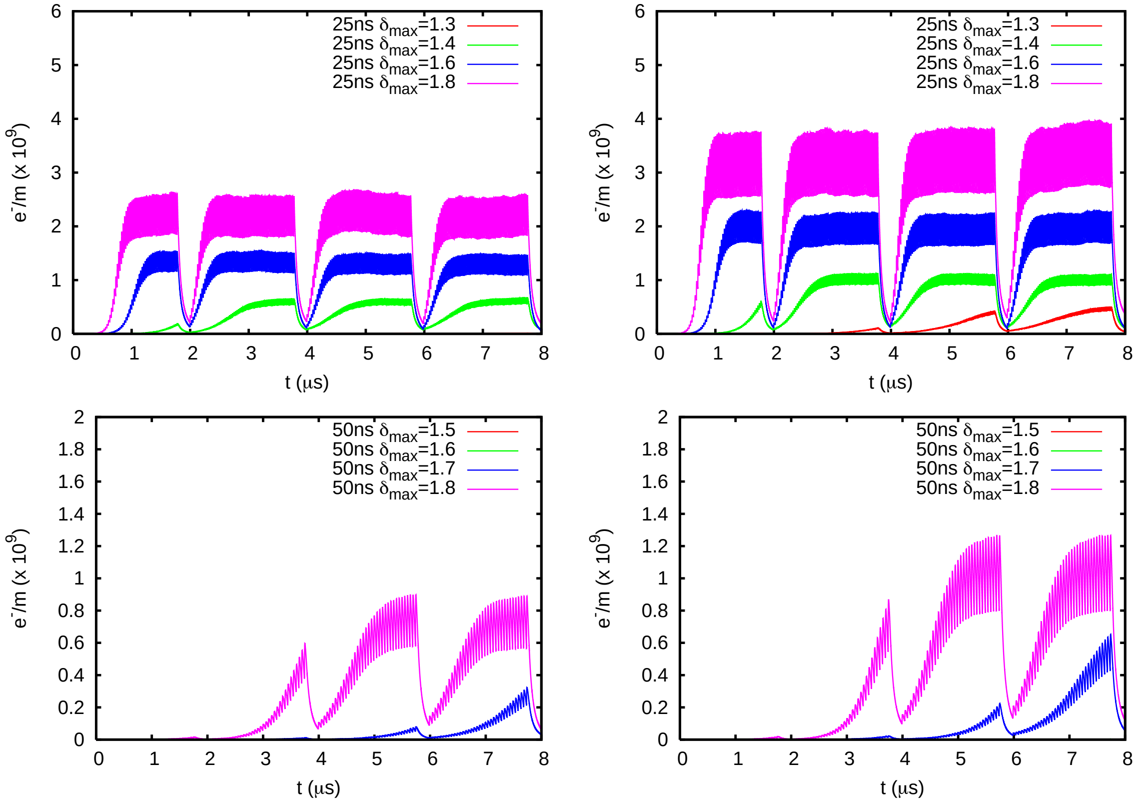

Figure 4: Electron cloud build up in MKDV1 for a 25 ns beam (upper row) and for a 50 ns beam (lower row) and for several values of maximum SEY. The plots on the left side show the evolution at injection energy and those on the right side are the results of the simulations with the top energy parameters.

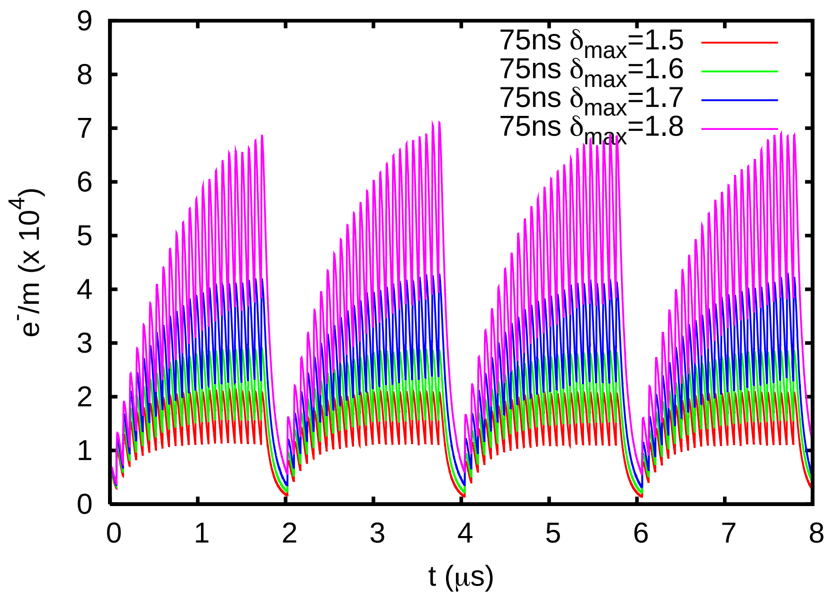

Figure 5: Electron cloud build up in MKDV1 for a 75 ns beam at top energy and for several values of the maximum SEY. All the simulated cases are still below the threshold of electron cloud build up for this kind of beam.

must indeed be expected in the MKDV1 both for 25 and 50 ns beams.

2.2 Simulations in dipole f elds

The region inside the kicker magnet permanently has a remnant horizontal dipole magnetic field of the order of about 1 Gauss [7]. This fact has led us to try simulations with a small horizontal dipole field to check whether this could have a significant influence on the amount of build up to be expected for 25 and 50 ns beams. In particular, we ran electron cloud build up simulations for a maximum SEY of 1.8 and in the three following cases:

1. Realistic value of remnant magnetic field (i.e., 1 G)
2. Value of the magnetic field such that we could be hitting a cyclotron resonance with the 50 ns beam but not with the 25 ns one. The resonance condition is obtained when the bunch spacing is a multiple of the cyclotron period of the electrons in the dipole field [8], and therefore reads:

$$B = n\frac{2\pi m_e}{e\tau_b} \tag{1}$$

   where m_e is the electron mass, n an integer and τ_b the bunch spacing. Being trivially $50 = 2\times25$ ns, obviously for each even n_{50} that fulfills the above condition for $\tau_b = 50$ ns, there will be also a $n_{25} = n_{50}/2$ that fulfills the same condition for $\tau_b = 25$ ns. So we should look only at the odd n matching the condition (1) for 50 ns beams. If we choose the lowest value $n = 1$, we obtain a dipole field of 7.15 G. We have run simulations between 5 and 9 G to possibly find the effect of the resonance on the 50 ns beam.
3. Unrealisticlly high value of the remnant field, B=30 G, in order to check whether that could have a strong effect on the build up evolution.

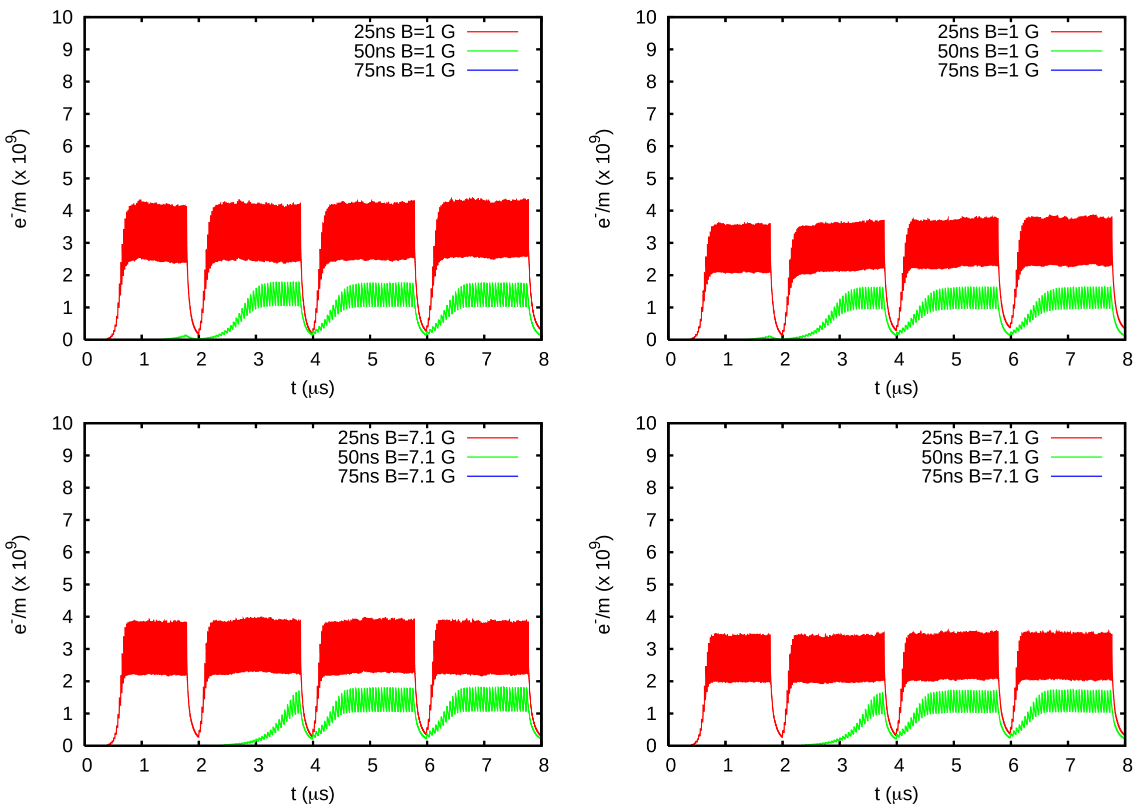

Figure 6: Electron cloud build up in MKDV1 for 25, 50 and 75 ns beams at injection energy (left column) and at top energy (right column), and for two different values of the remnant magnetic field in the MKDV1 (as labeled).

Figure 6 displays the results of the first two sets of simulations, points 1. and 2. above (i.e., with a realistic value for the remnant magnetic field and scanning the magnetic field in the vicinity of its resonant value). The upper row shows the build up at injection and the bottom row the build up at top energy. The plots are all very similar, and show that the expected resonance effect for the 50 ns beam does not appear with the SPS parameters. This is perhaps due to the bunch length, which does not satisfy the condition of short bunch with respect to the electron motion. The 75 ns beam is still below threshold for electron cloud build up also with a magnetic field of this strength. The build up evolution for the 25 and the 50 ns beams look similar at injection and at top energy, except that the saturation value of the cloud density for the 25 ns beam even seems to become now slightly lower at top energy than at injection. However, the main outcome is that the level of electron cloud produced with the 25 ns beam is predicted to be still about a factor 2–3 higher than what is produced with the 50 ns beam in all cases. The presence of a small horizontal dipole field cannot justify alone the observation of a higher electron cloud with the 50 ns beam.

The results of the simulations relative to point 3. show that with a stronger magnetic field also the LHC nominal 75 ns beam falls below threshold for electron cloud formation (with a maximum SEY of 1.8). However, the stonger electron cloud keeps being generated by the 25 ns beams.

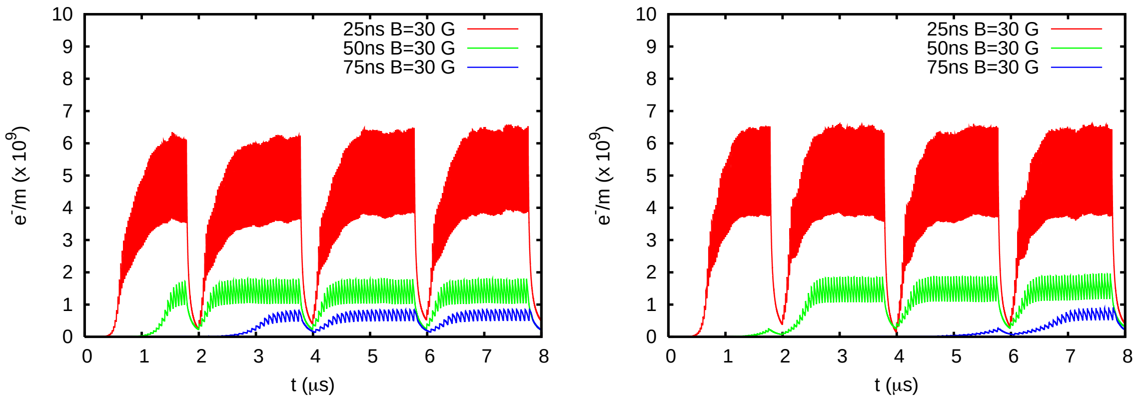

Figure 7: Electron cloud build up in MKDV1 for 25, 50 and 75 ns beams at injection energy (left) and at top energy (right), and for 30 G of horizontal magnetic field in the MKDV1.

2.2.1 Scanning E$_{max}$

All the simulations shown in the previous subsections were carried out assuming that the peak of the SEY occurs at $E_{max} = 230$ eV. Moving the location of this peak at different energies has been shown to potentially have a significant impact on the features of the electron cloud build up. In fact, this value was already used in the past as a relatively free parameter to match some given experimental observations [9]. Therefore, we have tried to scan this value between 120 and 320 eV in order to see how this would possibly affect the electron cloud build up of the 25, 50 and 75 ns beams. The results of this scan are displayed in Fig. 8. It is evident that, when changing in the considered range, the position of the SEY peak does not affect much the build up evolution for any of the spacings. In particular, while the 25 ns beam seems to hardly change with the different values of E_{max}, the 50 ns beam shows a trend of enhanced electron cloud moving toward the lower values of E_{max}. Also for the 75 ns beam an electron cloud starts to form when E_{max} is set to the lowest value of the scan, i.e. $E_{max} = 120$ eV.

2.3 Energy spectra

Finally, since the gas desorption is a function not only of the flux of electrons hitting the chamber but also of their energy, we have looked at the energy spectrum of the electrons impinging against the beam pipe both for the 25 and the 50 ns beams, at injection and at top energy. These four spectra are shown in Fig. 9. They are zoomed in the lower part of the plot in order to highlight the high energy region of the

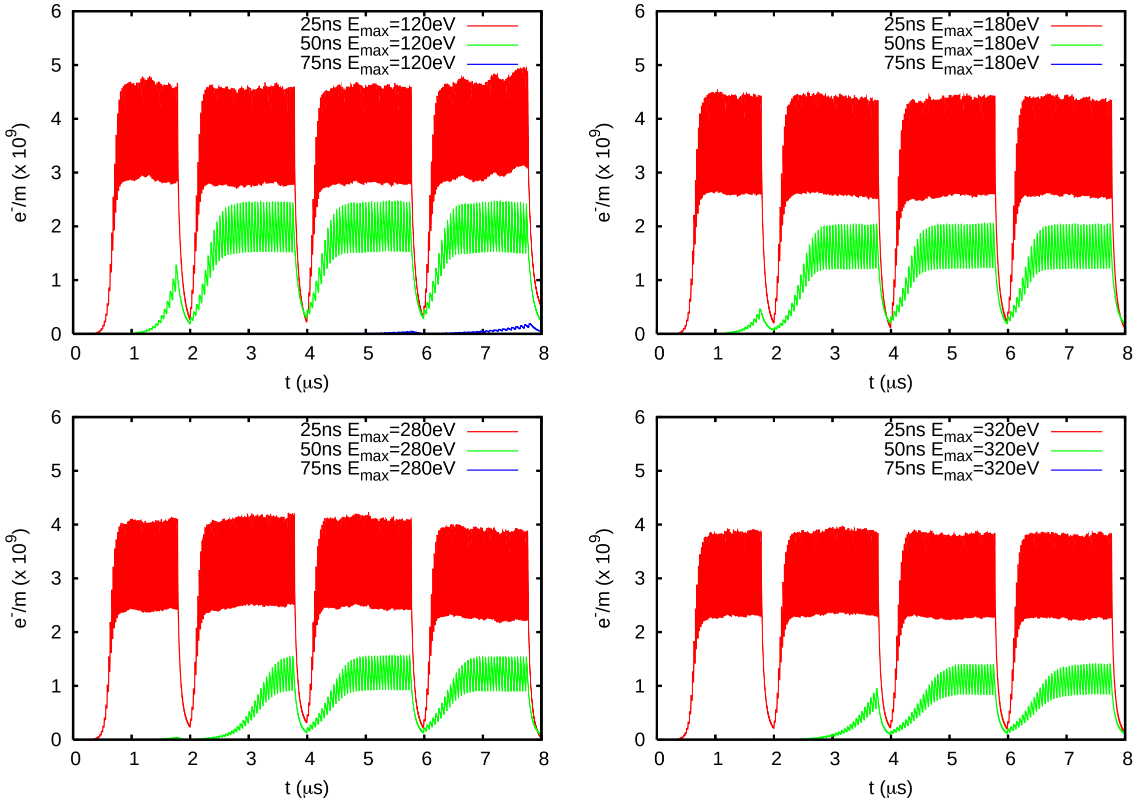

Figure 8: Electron cloud build up in MKDV1 for 25, 50 and 75 ns beams at top energy and with B=1 G, for four different values of the energy at which the SEY is maximum, E_{max} (as labeled).

spectra, which would be otherwise hidden by the usual high peak at low energy. The figure shows that at injection energy there is no significant difference between the energy spectra corresponding to the 25 ns beam and to the 50 ns beam. At top energy, both spectra tend to extend more toward higher energy values. In particular, the spectrum of the 50 ns beam reaches energy values slightly higher, with a peak at 550 eV. However, this small difference would not be sufficient to justify the stronger desorption with the 50 ns beam, which could cause a more significant pressure rise.
Indipendently of the bunch spacing, the electrons are distributed quite uniformly over the chamber cross section, because the kicker region is field free or with a weak dipole field. Thus, the reason why the 50 ns beam produces a denser electron cloud is also unlikely to lie in that the electrons hit unscrubbed zones of the chamber wall.

3 Summary of the results and conclusions

ECLOUD simulations in the MKD kickers have shown that, if the maximum SEY is high enough (above 1.8), there can be significant electron cloud build up inside all the MKD kickers, with higher saturation density in the MKDV1, both with the nominal intensity 25 and 50 ns LHC beams circulating in the SPS. With a maximum SEY of 1.8, no electron cloud is predicted to build up with 75 ns beams or with 50 ns beams with an intensity below 5×10^{10} p/b. In field free region the saturation value of the electron cloud density is a factor 1.5 higher at top energy than at injection. The differences between the electron cloud build up at injection and at top energy tend to vanish when the remnant magnetic field in the kicker is also taken into account. Neither in field free region nor with a horizontal dipole field from 1 up to 30 G, we are able to find a case in which the electron cloud created by a 50 ns beam has higher density than the one created by a 25 ns beam. The possible cyclotron resonance expected for the 50 ns beam with a remnant field of 7.15 G is not seen in simulations. Also, a scan in E_{max} shows that the electron cloud

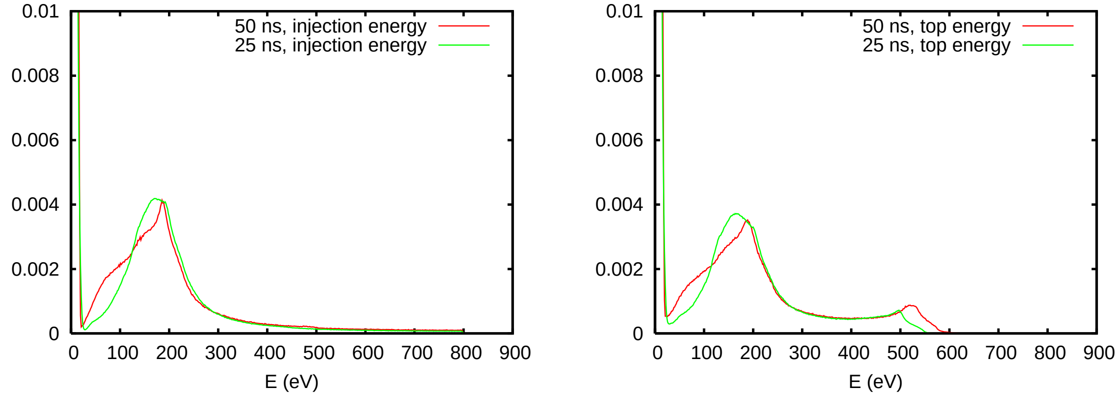

Figure 9: Energy spectra of the electrons hitting the chamber wall at injection (left) and top energy (right) for the 25 and the 50 ns beams.

build up is not significantly affected by this parameter. The energy spectra of the electrons impinging against the chamber walls are very similar for the 25 and the 50 ns beam, both at injection and at top energy.
In summary, while we can find a set of SEY parameters for the MKD kickers that reasonably matches most of the experimental observations, all the simulations done still cannot explain why the pressure rise, if caused primarily by electron cloud, should be more severe with 50 ns beams than with 25 ns beams.

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References

[1] Minutes of the APC meeting held on September 26th 2008, https://ab-div.web.cern.ch/ab-div/Meetings/APC/2008/apc080926/minutes_080926.html

[2] M.J. Barnes *et al.*, "Measurement of Longitudinal and Transverse Impedance of Kicker Magnets Using the Coaxial Wire Method", Proc. of PAC09, May 4-8, 2009, Vancouver, Canada

[3] E. Gaxiola *et al.*, "The Fast Extraction Kicker System in SPS LSS6", LHC Project Report 913

[4] M.J. Barnes *et al.*, "Measurement and Analysis of SPS Kicker Magnets Heating and Outgassing with Different Bunch Spacing", Proc. of PAC09, May 4-8, 2009, Vancouver, Canada

[5] M.J. Barnes, E. Mahner, V. Senaj, "SPS Kicker-Magnet Outgassing with Different Bunch Spacings", in Proc. of ECM Workshop, November 20-21, 2008, CERN

[6] G. Rumolo and F. Zimmermann, "Practical User Guide for ECLOUD", CERN-SL-Note-2002-016-AP

[7] M.J. Barnes, V. Senaj, private communication

[8] C.M. Celata, M.A. Furman, J-L. Vay, and J.W. Yu, Phys. Rev. ST Accel. Beams 11, 091002 (2008)

[9] G. Rumolo and W. Fischer, "Observations on background in PHOBOS and related electron cloud simulations", BNL Int-Report C-A/AP/146 (03/04)