ELECTRON CLOUD IN THE CERN ACCELERATOR COMPLEX

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Abstract

Operation with closely spaced bunched beams causes the build-up of an Electron Cloud (EC) in both the LHC and the two last synchrotrons of its injector chain (PS and SPS). Pressure rise and beam instabilities are observed at the PS during the last stage of preparation of the LHC beams. The SPS was affected by coherent and incoherent emittance growth along the LHC bunch train over many years, before scrubbing has finally suppressed the EC in a large fraction of the machine. When the LHC started regular operation with 50 ns beams in 2011, EC phenomena appeared in the arcs during the early phases, and in the interaction regions with two beams all along the run. Operation with 25 ns beams (late 2012 and 2015), which is nominal for LHC, has been hampered by EC induced high heat load in the cold arcs, bunch dependent emittance growth and degraded beam lifetime. Dedicated and parasitic machine scrubbing is presently the weapon used at the LHC to combat EC in this mode of operation. This talk summarises the EC experience in the CERN machines (PS, SPS, LHC) and highlights the dangers for future operation with more intense beams as well as the strategies to mitigate or suppress the effect.

AN OVERVIEW OF ELECTRON CLOUD IN THE CERN ACCELERATORS

The Proton Synchrotron (PS)

In the PS, the electron cloud (EC) was first observed in 2001 during the last part of the cycle for the production of the the so-called LHC-type beams, i.e. the beams of the type needed for the LHC filling. The production scheme of these beams in the PS is based on two or three steps of bunch splitting in order to obtain at the exit of the PS bunch trains with 50 ns or 25 ns spacing, respectively. In either case, the final stage of bunch splitting takes place at the top energy (26 GeV/c) and is followed by adiabatic bunch shortening and fast bunch rotation shortly before extraction [1]. These two processes are meant to shorten the bunches from their 15 ns length after the last splitting to 12 and then 4 ns, respectively, and make them suitable to be injected into the SPS. Therefore, these beams only circulate in the PS for few tens of msec with a structure prone to EC formation (beam parameters are summarized in Table 1).
During this short time before extraction, an EC was initially revealed in 2001 by the presence of a baseline drift in the signal from the pick up as well as beam transverse instabilities [2]. In March 2007, an experiment for dedicated EC measurements was set up at the PS to be able to directly measure the electron signal by using a shielded biased pick up [3] and confirm its presence in the machine in the last phase of the LHC beams production. These studies confirmed that the EC develops during the last 40 to 50 ms before ejection, i.e. when the bunches are shortened by the RF gymnastics.

Table 1: Relevant beam parameters in the PS during the flat top RF gymnastics for the two bunch spacings of 50 and 25 ns

	50 ns	**25 ns**
Beam energy (GeV)	26	
Bunch intensity ($\times10^{11}$ ppb)	1.3-2.0	1.3-1.6
Bunch length (ns)	15 → 12 → 4	
Number of bunches	36	72
Transv. norm. emittances (μm)	1-2	2-3

In the years 2011-2014, new systematic measurements of EC and effects on the beam have been performed at the CERN-PS with the goals of:

- Studying the dependence of the EC build-up evolution on some controllable beam parameters (bunch spacing, bunch intensity, bunch length);
- Collecting time resolved experimental data of EC build-up in some desired sets of beam conditions;
- Characterising the EC instability at 26 GeV.

These sets of data can serve two purposes. First, comparing them with build-up and instability simulations will allow us to validate (or improve) the simulation model on which our tools are based. Second, by matching the simulations to the experimental data in all the different beam conditions, we can pin down the secondary electron yield, SEY or δ_{max}, of the beam chamber and extrapolate then how much EC we can expect in the PS with the higher intensity beams foreseen in the frame of the LHC Injector Upgrade (LIU) project [4], and whether that can be detrimental to the beam.

The Super Proton Synchrotron (SPS)

The SPS has been suffering from EC formation since it first began to take and accelerate 25 ns beams produced in the PS with the scheme explained above. Observations of pressure rise, beam instability, emittance growth were first made in the early 2000 and all these effects strongly limited the capability of this accelerator of handling LHC-type beams [5]. While the coherent instabilities could be suppressed by the use of the transverse damper (against the horizontal coupled bunch oscillations) and running with sufficiently high chromaticity (against the strong single bunch effect in the vertical plane), emittance growth and positive tune shift along the bunch train could still be measured, pointing to the continuing presence of a strong EC inside the beam chamber. All

ISBN 978-3-95450-178-6

this led to the decision to have in 2002 the first dedicated scrubbing run, in which the SPS was operated exclusively with 25 ns beams for one full week. The goal was to use the bombardment from the EC itself to clean the beam chamber inner surface, and therefore lower its Secondary Electron Yield (SEY) and reduce, in turn, the amount of EC build-up. The strategy proved successful [6] and the week of scrubbing run was then repeated at the beginning of the 2003, 2004, 2006 and 2007 runs to provide the necessary machine cleaning. During these years, dedicated experiments were conducted in the SPS to study in detail the EC formation in cold regions (COLDEX) or in NEG coated chambers [7], or to benchmark simulation codes with machine observations [8]. From 2006 on, EC studies in the SPS acquired new momentum in the framework of the SPS upgrade studies [9] and the experimental activity over the following years was mainly focused to find the scaling law of the EC instability with beam energy [10] and to validate the efficiency of amorphous carbon (a-C) coating of the beam chamber [11]. From 2011 onwards, the nominal 25 and 50 ns LHC beams in the SPS appeared to be undegraded with no signs of the strong EC effect that was present during the first years of SPS operation. The achievable parameters are summarized in Table 2. The three values of bunch length quoted in this table correspond to injection into 2 MV buckets, after shortening at flat bottom by increase of the RF voltage to 3 MV, and at flat top after controlled longitudinal emittance blow up during the accelerating ramp.

All the EC machine development activity of the last few years at the SPS has been devoted to defining the status of the 25 ns beams in this machine and use the direct EC measurements in chambers equipped with strip monitors to understand beam induced scrubbing in different chamber geometries and with different materials. A comprehensive report of all observations in terms of beam behaviour, pressure rise and dedicated EC measurements during the 2012 scrubbing studies was published [12].

Table 2: Relevant Beam Parameters of the SPS 50 and 25 ns Beams

	50 ns	25 ns
Beam energy (GeV)	$26 \rightarrow 450$	
Bunch intensity ($\times 10^{11}$ ppb)	1.2-1.8	1.1-1.3
Bunch length (ns)	$4 \rightarrow 2.8 \rightarrow 1.5$	
Number of bunches	144	288
Transv. norm. emittances (μm)	1-2	2-3

After the Long Shutdown 1 (2013-14), during which the whole SPS was exposed to air and the surfaces of the beam chambers were expected to return to high values of SEY, the two main questions to answer were:

- How long it would take to recover the previous SPS performance through beam induced scrubbing;
- Up to which beam intensity the SPS could be successfully scrubbed in view of future operation with higher intensity/higher brightness beams.

Seven days were dedicated to scrubbing run and scrubbing studies in the late 2014, during which the SPS performance with 25 ns beams was successfully recovered and first tests of injection of high intensity 25 ns beams were conducted. At the beginning, these beams caused large pressure rises and were hampered by violent instabilities and emittance blow up at the tails of the trains. Further studies with high intensity were conducted over 10 days of SPS scrubbing in 2015. Over these days, the beam could be successfully stabilised and losses decreased. The scrubbing campaign in 2015 with high intensity beams was so successful that scrubbing became the baseline for the upgrade of the SPS to higher intensity and higher brightness beams [13].

The Large Hadron Collider (LHC)

Several studies conducted in the past predicted that also the LHC would suffer from heat load, pressure rise and beam instabilities due to EC, when operating with trains made of closely spaced proton bunches (e.g. [14]). Since mid 2010 LHC entered this mode of operation. In the first phase, beams with 150 ns bunch spacing were injected, accelerated and brought to collision. During this period of operation, the only possible signature of EC build-up was a pressure rise observed in the common vacuum chamber, close to the Interaction Regions. Subsequently, at the end of October 2010, machine studies with tighter bunch spacings were initiated with the goal to characterize the EC build-up in the LHC, its effects and possible cures. The study of the 75 ns and 50 ns beams took place in dedicated MD sessions, during which the strong EC effects seen initially gradually decreased. Since the EC effects with 75 ns appeared significantly less pronounced than with 50 ns beams, this bunch spacing could be regarded as a relatively safe option for the 2011 run [15].

The LHC operation was therefore resumed in 2011 directly with 75 ns beams. However, at the beginning of April, 10 days were devoted to scrubbing of the LHC with 50 ns beams. The goal was to prepare the machine to switch to 50 ns beams and thus extend the luminosity reach for the 2011 run. During the scrubbing run, up to 1020 bunches per beam were injected into the LHC in batches of 36 and stored at injection energy. The quality of the beam significantly increased over this period. The success of the scrubbing run was proved by the subsequent smooth LHC physics operation with 50 ns spaced beams. Between mid April and end June the number of bunches collided in the LHC was increased up to its maximum value of 1380 per beam, while the intensity per bunch and the transverse emittances remained constant at their nominal values (i.e., 1.15×10^{11} ppb and 2.5 μm). The switch to 50 ns beams with lower transverse emittances (1.5 μm) and the adiabatic increase of the bunch current to 1.5×10^{11} ppb did not cause any significant recrudescence of the EC effects. Beams with 25 ns spacing were injected

ISBN 978-3-95450-178-6

into the LHC only during five MD sessions of the 2011 run. They appeared to suffer from strong instabilities at injection (damped with high chromaticity) and exhibited poor lifetime and blown up emittances even by the end of these study periods. However, the heat loads measured in the arcs with this type of beams could be used for extrapolating the evolution of the SEY on the beam screen in the arcs, which was estimated to decrease from an initial value above 2.0 to about 1.5 [16]. The year 2012 was a physics production year and the LHC mainly ran with high intensity 50 ns beams (1.7×10^{11} ppb). At the end of the run, in preparation for the high energy run of the LHC after the upcoming Long Shutdown 1 (LS1) with 25 ns beams, a dedicated scrubbing run took place with this type of beams, followed by test ramps and a pilot physics run to provide data for the experiments with the new spacing. The SEY of the beam screens did not seem to decrease much more than it had already (it remained between 1.4 and 1.5, beyond resolution with our method for estimating its value), as the scrubbing seemed to have entered its slow phase in which increasingly larger electron fluxes are needed to lower even slightly the SEY [17]. The main conclusion from the 2012 experience was that LHC operation with 25 ns would be possible in the post-LS1 operation, although it would be probably hampered by EC to a large extent and for a long time. In this scenario, the following two options were envisaged [18]:

1. Proceed with the standard 25 ns beams and hope to progress with the slow scrubbing while in parallel providing data to the experiments (scrubbing with physics)

2. Switch to low EC filling schemes still based on 25 ns bunch spacing - allowing for more bunches and higher bunch intensity with respect to the 50 ns beams (e.g. the 8b+4e [19])

After machine recommissioning with low intensity bunches, LHC multi-bunch operation was therefore resumed in 2015 with a first extended scrubbing run to allow a brief physics run with 50 ns beams. It immediately became apparent that the SEY of the beam screens in the arcs had been reset to the high values they had back in 2010. The first 10 days of scrubbing served the purpose to lower again the SEY to values between 1.4 and 1.5. A second scrubbing run over two weeks improved the LHC performance with 25 ns beams and ended with the demonstration that filling schemes at least up to 1200 bunches per beam could be successfully employed for physics. At this point, LHC entered the phase of intensity ramp-up and the option of possible scrubbing with physics was chosen. The technique seemed to work to some extent: by October 2015, 2242 bunches per beam were successfully put in collision, although several cycles of deconditioning/reconditioning were observed to occur and the achievement was only made possible by a gradual relaxing of the filling pattern in order to alleviate the EC heat load and not exceed the capacity of the cryogenic system, which ran very close to the limit. In particular, operation switched from trains of 144 bunches to trains of 72, and eventually to trains of 36 bunches to keep the heat load in the beam screen of the arcs below the limit of 135 W per half cell (W/hc) for one of the sectors.

In 2016, only a short scrubbing run took place, during which trains of 144 and 216 bunches were successfully injected and kept stable in the LHC at 450 GeV. The machine performance showed that conditioning had not been lost from the previous year and an intensity ramp-up could be safely carried out. However, due this time to limitations in the SPS, only filling patterns with trains of 72 bunches could be used for filling the LHC. Within about one month of the beginning of the intensity ramp-up, the LHC was filled with 2040 bunches per beam and LHC reached its nominal peak luminosity of 10^{34} cm^{-2} s^{-1}. The heat load in the beam screen of the arcs ran constantly close to the limit (160 W/hc), allowing potentially only for marginal increase now in either bunch intensity or number of bunches (or marginal decrease of bunch length). The final step has been for now to switch to trains of 2x48 bunches, which allows for a small decrease of the heat load for a slightly higher number of bunches (2076) and paves the way to switching to low transverse emittance variants of the LHC beams for the near future.

The LHC beam parameters are summarised in Table 3.

Table 3: Relevant beam parameters of the LHC 50 and 25 ns beams

	50 ns	25 ns
Beam energy (TeV)	0.45 → 3.5/4 → 6.5	
Bunch intensity ($\times 10^{11}$ ppb)	1.1-1.7	1.1
Bunch length (ns)	1.0-1.5	
Number of bunches	1400	2800
Transv. norm. emittances (μm)	1-2	2-3

SOME HIGHLIGHTS OF STUDIES IN THE DIFFERENT MACHINES

PS Measurements

Between 2011 and 2014, several EC studies took place in the PS in order to cover build-up in different sets of beam parameters or different locations (specifically, a straight section and a main magnet unit), as well as the instabilities at 26 GeV. EC build-up data were recorded for 25 ns and 50 ns beams and the bunch intensities were scanned in a wide range from well below nominal values to slightly above. The direct EC signals were recorded shortly before extraction, when in normal conditions each bunch of the beam has been already fully rotated (4 ns bunch length). However, specifically for these measurements, the bunch length at this time for a fixed bunch intensity was also targeted to 6.5 or 15 ns by simply adjusting or fully removing, respectively, the final step of the fast bunch rotation. This allowed studying the dependence of the EC build-up not only on the bunch intensity but also on the bunch length. The measurements

ISBN 978-3-95450-178-6

taken in the straight section 98 (SS84) were very successful and could be successfully benchmarked against simulations with the PyECLOUD code [20]. Measurements in the main magnet unit 98 (MU98), which had been also equipped with a shielded pick up fully specified through detailed build-up simulations, were unfortunately not successful because, due to a design flaw, the recorded signal turned out to be dominated by the electromagnetic signal induced by the beam passage. Instability measurements were carried out by removing the bunch rotation at the end of the LHC magnetic cycle and extending the cycle by few milliseconds before extraction and after adiabatic bunch shortening to 10 ns. The instability, which appeared mainly in the horizontal plane, could be recorded with a wideband pick up all along the beam over several turns, revealing a clear coupled-bunch pattern extended from the tail of the train towards the head (see Fig. 1). Although this instability can be potentially a problem for higher intensity 25 ns beams for the future LIU program, it has been proven that the transverse feedback system is able to delay its occurrence by few tens of milliseconds. This is deemed to be sufficient to preserve the beam stability for the future LHC-type beams with double intensity and double brightness.

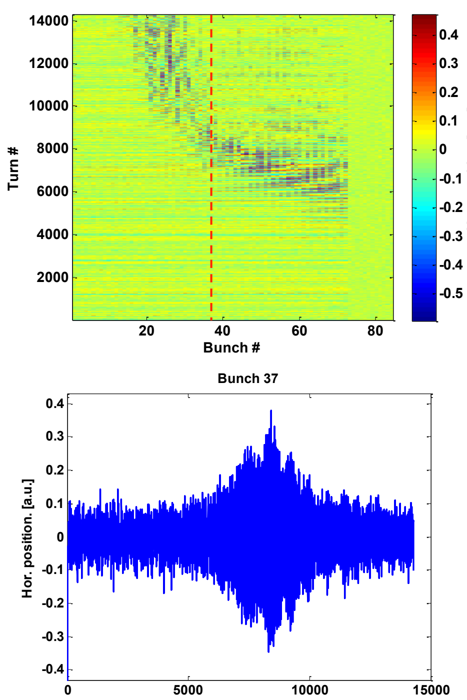

Figure 1: Bunch-by-bunch and turn-by-turn horizontal position along a train of 72 bunches in the PS at 26 GeV. The top plot shows the full 2D data set, with the cut highlighted by a dashed line displayed separately in the bottom plot. The instability is revealed by the exponentially growing signal.

SPS Studies

One of the key points to be addressed to understand the EC in the SPS is to determine the values of SEY thresholds for its formation in the different beam chambers and try to deduce what parts are critical for both present and future LHC beams. Figure 2 shows the electron flux to the chamber wall as a function of the SEY for four different values of bunch current and for four typical SPS chambers, i.e. MBA and MBB-type for dipoles plus QD and QF for quadrupoles (shapes and sizes of these chambers can be found in [20]). The following interesting features can be observed:

- The EC build-up is fairly insensitive to bunch intensity for dipoles, while thresholds tend to become slightly lower for lower currents in quadrupoles (or the behaviour is non-monotonic).
- Above the SEY threshold, the electron flux always becomes quickly larger for larger bunch currents.
- MBA-type chambers have higher SEY threshold value and therefore are the easiest to scrub, while MBB-type and quadrupole chambers have lower SEY threshold (comparable or lower values than those to which StSt potentially scrubs) and might be expected to suffer from large EC build-up even after extensive scrubbing.

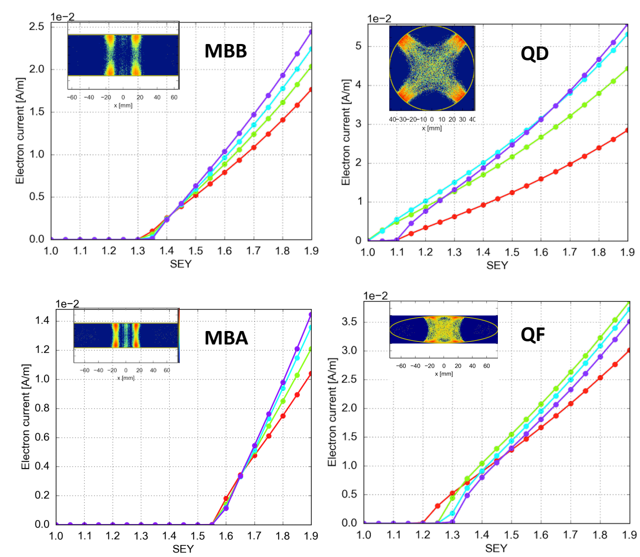

Figure 2: SEY curves for EC formation in the four types of SPS chambers (dipoles on the left and quadrupoles on the right side) and for four different bunch intensities (red $1.0{\times}10^{11}$ p/b, green $1.5{\times}10^{11}$ p/b, turquoise $2.0{\times}10^{11}$ p/b, purple $2.5{\times}10^{11}$ p/b).

Considering all the results of the above study as well as the results from the scrubbing campaigns in 2014 and 2015 with larger bunch currents than nominal (2.0×10^{11} p/b), it was decided to apply a-C coating [21] to the quadrupole chambers and some of the drift chambers during the Long Shutdown 2 (LS2), while relying in general on scrubbing for longer term operation of the SPS with LIU-type beam intensities. However, the MBB chambers along a full arc will also be coated in LS2, so that everything will be ready for full machine coating during the next shutdown if scrubbing will turn out not to be sufficient to guarantee the desired beam quality during Run 3.

ISBN 978-3-95450-178-6

LHC Observations

The main EC indicators in LHC are the heat load in the arcs as well as the beam stability and lifetime (which can be guaranteed only with machine settings in certain ranges). The heat load data from the cryogenic system give the total power dissipated (in W/half-cell) on the beam screens of both beams 1 and 2. Using the measured heat load it is possible to estimate the SEY of the arc chamber walls and monitor the progress of scrubbing. The exact procedure is based on the comparison of the heat load data with PyECLOUD simulations, run with realistic bunch-by-bunch intensities and lengths [16]. In high EC operation, i.e. with 25 ns beams, the beam stability can be only preserved with large chromaticity values. However, due to the tune footprint in presence of large chromaticity and strong EC, this also implies that the tunes must be kept far away from any dangerous resonance line in order not to trigger incoherent losses. Figure 3 shows the estimated tune footprint at LHC injection with large chromaticity and EC in all the cold arcs (dipoles and quadrupoles). Incoherent losses were observed when the vertical tune of the LHC was 0.31 at injection because of the proximity to the third order resonance. This could be easily avoided by lowering the vertical tune at injection to values around 0.29 (and consequently lowering the horizontal tune to keep the safety margin between the two that would avoid the onset of instabilities from coupling [22]).

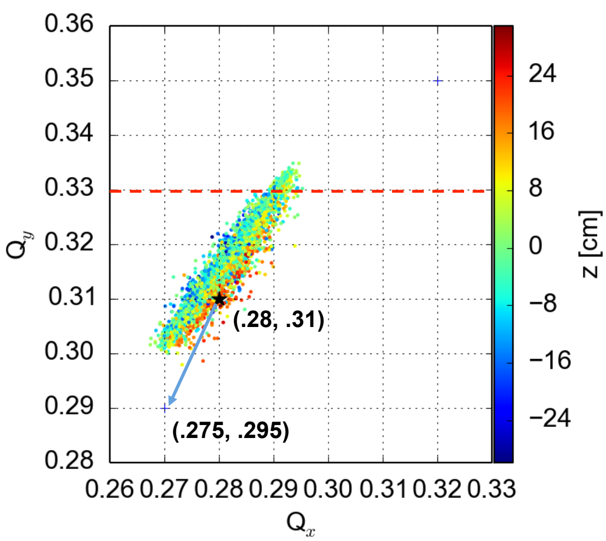

Figure 3: Tune footprint of the beam in LHC with octupoles powered to -20 A, chromaticities $Q'_{x,y}$ set to 15/20, and assuming an EC density of 5×10^{11} e/m^3 uniformly distributed along the whole ring.

The present strategy to run LHC with 25 ns beams is to use scrubbing runs just long enough as to gain enough margin for a smooth intensity ramp-up for physics, and then accumulate additional parasitic scrubbing while providing the beam to the experiments. Though this allows for a clear optimisation of the use of the LHC machine time, it has been observed that the machine in advanced state of scrubbing undergoes cycles of deconditioning/reconditioning. Scrubbing appears to be reasonably well preserved during Technical Stops and Machine Development sessions with low intensity/low energy beams, while deconditioning mainly occurs when running with low e-cloud/high synchrotron radiation schemes. The reason could be that synchrotron radiation can clean other parts of the beam chamber but it pollutes the previously scrubbed ones. However, this phenomenon is not worrisome, as recovery can then be achieved rather quickly. Scrubbing with physics has been pursued in 2015 and 2016. Lately, the time scale of the improvement appears to have become significantly longer, as no clear trend can be observed in the normalised heat load data, if we remove the uncertainty due to changing beam parameters and recalbrations of the measurements. Further scrubbing might be achieved in future by means of the use of longer trains or electron cloud enhancing schemes (e.g. the doublets [23]), or by attempting scrubbing at higher beam screen temperature if this is demonstrated to be effective. A few aspects of the EC effects in the LHC are presently still under investigation, like the different heat loads measured in different sectors (spread of about a factor three) and their different evolutions, the behaviour of EC with energy in dipoles and quadrupoles, and the EC driven instabilities at 6.5 TeV.

CONCLUSIONS AND OUTLOOK

Thanks to intensive measurements and highly improved simulation tools, we have reached a deep knowledge and understanding of EC phenomena in the different CERN accelerators. For the present beam parameters (25 ns beams), PS and SPS can deliver the required beams well within their original specs, while LHC still suffers from electron cloud, but is now operating thanks to scrubbing with physics.
For future beam parameters (double intensity, double brightness), the SPS will again rely on scrubbing, while being prepared to full a-C coating of the most EC prone chambers if that will not be sufficient during Run 3. HL-LHC operation will depend on the evolution of scrubbing during Run 2 and the experimental dependence of EC on bunch intensity. It may use EC free filling patterns like the 8b+4e, if needed. In general, anti-EC coatings inside the beam chambers are strongly recommended to be included in the baselines of all future projects.

ACKNOWLEDGMENTS

The authors would like to thank G. Arduini, V. Baglin, B. Bradu, G. Bregliozzi, K. Brodzinski, X. Buffat, R. Cappi, L. Carver, F. Caspers, P. Chiggiato, S. Claudet, P. Costa-Pinto, J. Esteban-Müller, S. Gilardoni, M. Giovannozzi, B. Goddard, M. Hostettler, M. Jimenez, V. Kain, E. Mahner, E. Métral, H. Neupert, A. Oeftiger, Y. Papaphilippou, G. Papotti, T. Pieloni, M. Pivi, S. Rioja-Funetelsaz, E. Rogez, B. Salvant, E. Shaposhnikova, G. Sterbini, M. Taborelli, L. Tavian, C. Yin-Vallgren, M. Van Gompel, C. Zannini, F. Zimmermann for their contributions.

ISBN 978-3-95450-178-6

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ISBN 978-3-95450-178-6