LHC - CHALLENGES IN HANDLING BEAMS EXCEEDING 100 MJ

R. Schmidt, CERN, Geneva, Switzerland

Abstract

The Large Hadron Collider (LHC) at CERN operates at 4 TeV with high intensity beams, with bunch intensities exceeding the nominal value by several 10 %. The energy stored in each beams is beyond 130 MJ, less than a factor of three from the nominal value at 7 TeV. With these parameters, operation entered into a regime where various effects due to high intensity bunches are observed (instabilities, beam-beam effects, e-cloud effects). The highly efficient collimation system limits beam losses that threaten to quench superconducting magnets. The correct functioning of the machine protection systems is vital during the different operational phases. Already a small fraction of the stored energy is sufficient to damage accelerator equipment or experiments in case of uncontrolled beam loss. Safe operation in presence of such high intensity proton beams is guaranteed by the interplay of many different systems: beam dumping system, beam interlocks, beam instrumentation, equipment monitoring, collimators and absorbers. The experience gained with the key systems of machine protection and collimation will be discussed.

INTRODUCTION

The LHC has a long history. Even before the drawing-board stage, the farsighted John Adams noted in 1977 that the tunnel for the future LEP collider should also be big enough to accommodate another ring of magnets. In 1984 a workshop was organised under the joint sponsorship of ECFA and CERN to discuss the feasibility of large hadron colliders in the LEP tunnel [1]. The design converged later to a collider with an energy of 7 TeV and a nominal luminosity of $10^{34} cm^{-2} s^{-1}$. It took about 25 years from 1984 to first proton collisions in 2009, followed by runs in 2010, 2011 and 2012. Due to nonconformities of the interconnections between magnets the energy was limited to 3.5 TeV in 2010 and 2011, and to 4.0 TeV in 2012. Integrated and peak luminosities during 2012 are shown in Figure 1 and Figure 2. The peak luminosity is more than $7.5 \times 10^{33} cm^{-2} s^{-1}$ and an integrated luminosity of more than 14 fb^{-1} was recorded by the experiments. Despite the operation at lower energy, the LHC experiments published already exciting results, a new particle with a mass of about 125 GeV with parameters that are compatible with the Standard-Model Higgs [2]. The nominal parameters for the LHC are compared with the parameters for 2011 and 2012 in Figure **3**.

HIGH LUMINOSITY

The LHC nominal luminosity exceeds the luminosity of other hadron colliders by a factor of 20. This is achieved by operating with a large number of bunches in two separated beam pipes, only crossing in the four experiments. For nominal operation at 7 TeV the energy stored in each beam exceeds with more than 360 MJ the values for other accelerators by two orders of magnitude. Figure 4 shows the nominal parameters for operation at 7 TeV and the parameters in 2011 and 2012. When operating at 4 TeV instead of 7 TeV, a peak luminosity of $7.5 \times 10^{33} cm^{-2} s^{-1}$ was achieved despite operating with bunches every 50 ns instead of nominal 25 ns. This was only possible with emittances much smaller than nominal, and bunch currents more than 30% higher than nominal.

The luminosity depends on the emittance and the intensity per bunch (=> high brightness beams), determined to a large extent by the chain of injectors (LINAC, Booster, PS and SPS). The beam structure (25 ns or 50 ns bunch spacing) and the number of bunches is also prepared in the injectors. A large amount of work is going on to understand and improve the beam parameters in the injector complex, with a direct impact on LHC performance (see several papers in this workshop). An ambitious improvement program is on the way during the next decade to further improve the beam parameters that can be delivered to LHC as well as to other physics experiments at CERN [3].

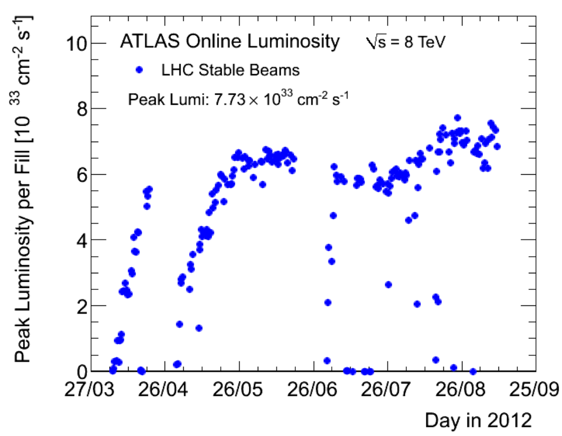

Figure 1**:** Peak luminosity for fills in 2012.

EXPERIMENTAL INSERTIONS

In four of the eight LHC insertions the beams are brought together into a common vacuum over ~260 m to collide in the experiments. To avoid a large number of head-on collisions the beams are crossing in the experiment at an angle. The total crossing angle is about 300 μrad. When the beams are travelling through the common chamber, there are a number of parasitic crossings. A separation of about 10 σ between the beams is required for all parasitic crossings, about 64 when operating with 1380 bunches (50 ns bunch spacing).

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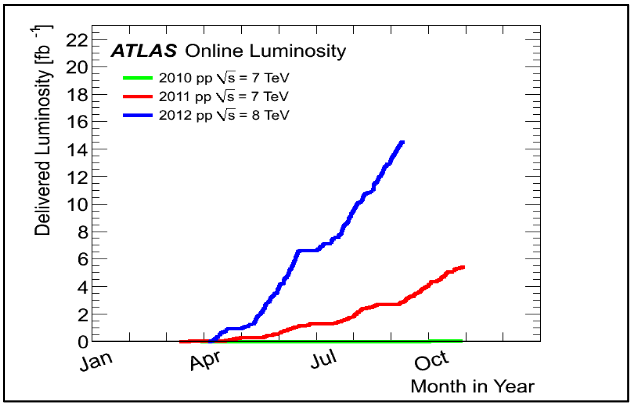

Figure 2: Integrated luminosity from ATLAS during 2012.

The quadrupole triplets in the low-beta insertions focus the beam down with a β-function at the collision point of about 0.6 m (ATLAS and CMS). The beam size in the triplet is large and the aperture is limited. Further squeezing will only be possible with a reduced emittance after the energy increase from 4 TeV to about 6.5 TeV planned for 2014/15.

An example for the crossing scheme in the insertion with the ATLAS detector is shown in Figure 5. In the arcs the beams are circulating in separate vacuum chambers, with a distance of 194 mm. In the insertion the beams are brought together and follow the same orbit in the horizontal plane. In the vertical plane the beams are deflected to collide with a vertical angle. The orbits for the beams are different to ensure sufficient separation at the location of parasitic crossings.

CHALLENGES

Operation with high intensity beams is challenging:

- Handling of beams with a large amount of stored energy.
- Injecting beams, performing the energy ramp and bringing the beams into collisions without quenching or damaging accelerator and experiments.
- Safely dumping very small beams with an energy of more than 130 MJ.

		Nominal	2011	2012
Proton energy	[TeV]	7.0	3.5	4.0
Current in main dipoles	[kA]	11.85	6.0	6.8
Stored energy, dipole circuit (154 dipoles)	[GJ]	1.07	~0.28	~0.35
Protons per bunch	-	1.15×10^{11}	$\sim 1.5 \times 10^{11}$	$\sim 1.5 \times 10^{11}$
Number of bunches	-	2808	1380	1380
Bunch spacing	[ns]	25	50	50
Normalized emittance	[mm]	3.75	2.0 - 3.0	2.0 - 3.0
β* in IP1 and IP5	[m]	0.55	1.5 / 1.0	0.6
Stored energy / beam	[MJ]	362	~116	>130
Peak luminosity for ATLAS and CMS	[$cm^{-2}s^{-1}$]	1.0×10^{34}	0.36×10^{34}	$\sim 0.76 \times 10^{34}$
Integrated luminosity for ATLAS and CMS	[fb^{-1}]	-	5.6	>14.5 (9/2012)

Figure 3: LHC parameter: nominal, for 2011 and 2012.

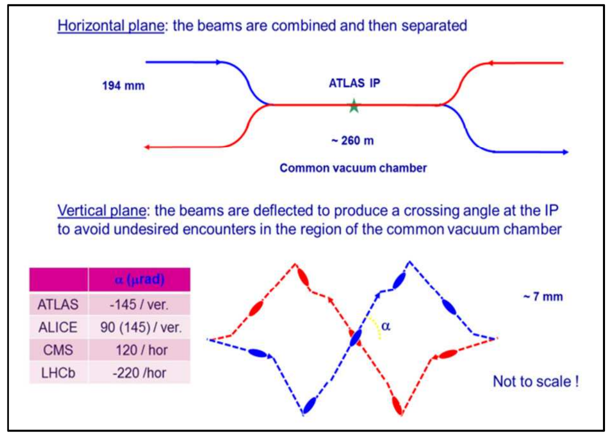

Figure 4: Layout of the crossing about ATLAS (illustration drawing, not showing all parasitic crossings).

- Detecting all failures in time that could lead to uncontrolled beam losses and safely dumping the beams.
- Avoiding beam losses, in particular in the superconducting magnets. Beam induced magnet quenching requires only a tiny fraction of the beam, say 10^{-8}-10^{-7}, of beam hitting a superconducting magnet when operating at high energy.
- Beam cleaning by capturing particles in the betatron and momentum cleaning insertions, thus minimising particle losses around the machine.
- Radiation, in particular in experimental areas from beam collisions causes single event upsets in the electronics that is installed inside or close to the LHC tunnel.
- Keeping the beams stable with head-on and long range beam-beam effects, causing tune spreads and tune shifts varying for different bunches.
- Ensuring beam stability, in particular due to relatively high impedance when the collimator jaws are close to beam. The position of the collimator jaws depends on energy and beta function at the collision points. The jaws are driven towards the beam centre during the energy ramp.
- Heating of components close to the beam (kicker magnets, collimators, …).
- Electron cloud effects, in particular when operating with bunches with a spacing of 25 ns. Photo electrons, generated by beam losses – are accelerated by the following bunches and can lead to instabilities and to heat load for the cryogenic system.

MACHINE PROTECTION

Particles in LHC are lost due to a variety of reasons:

- Particle losses due to beam-gas interactions
- Particle losses due to the collisions in the experiments
- Particle losses due to the beam halo touching the aperture

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- Particle losses due to instabilities
- Particle losses due to equipment failures (e.g. power converters, magnets, RF trips, kicker magnet failures, …)
- The beams need to be dumped at the end of a physics fill

Continuous beam losses are inherent to the operation of accelerators and are taken into account during the design. Accidental beam losses are due to a multitude of failure mechanisms. The number of possible failures leading to accidental beam loss is (nearly) infinite.

It has been shown in a controlled experiment at the SPS that already less than 0.1% of the maximum energy stored in an LHC beam can seriously damage equipment, e.g. drilling holes into vacuum chamber and magnet in case of uncontrolled beam loss [4]. Already the beam injected from the SPS into the LHC has significant damage potential (2 MJ).

It was calculated by sophisticated computer codes that in case of a wrong deflection of the beam, e.g. by the beam dump kicker magnets, the beam would penetrate up to 30 m into the superconducting magnets (see [5] for the report on an experiment to validate these simulations).

An uncontrolled loss of the full beam at top energy around all LHC would have disastrous consequences, and might damage the LHC accelerator beyond repair.

A sophisticated protection scheme prevents beam induced damage and quenches:

- Whenever the beams need to be dumped, the extraction kickers fire and the beams are extracted into the beam dump blocks, the only element that can withstand the full beam without risk of damage. The beam dump blocks are installed in a distance of about 800 m, to increase the beam size in the drift space. To further dilute the energy, two dilution kickers are fired to distribute the bunches into a shape similar to a circle (see Figure 6).
- A sophisticated collimation system captures beam losses in two insertions (betatron and momentum cleaning), thus preventing too high beam losses around the accelerator. The efficiency of the collimation system is in the order of 99.99%. The positions of some collimator jaws are as close as 1 mm from the beam centre (see Figure **6**).
- There are many systems to detect abnormal conditions, such as equipment failures and beam losses. Most important system is the Beam Loss Monitoring System with more than 3500 ionisation chambers distributed around the LHC. When the beam loss measured with a BLM increases above a predefined threshold, the beams are dumped. Figure 7 show the beam losses around the LHC.

LHC OPERATIONAL CYCLE

Phases in the operational cycle are injection at 450 GeV, energy ramp to 4 TeV, squeeze, adjust and stable beams (see Figure 8 as an example for a cycle during 2012):

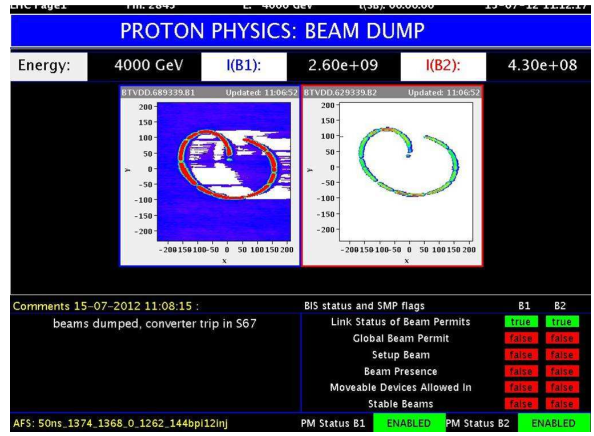

Figure 5: Screen in front of the beam dump block, dump of 1370 bunches.

- Injection starts with the injection of a low intensity bunch (about 5×10^9 protons). The energy of 700 J stored in this bunch is so low that damage by beam impact is excluded. Only if this bunch is circulating demonstrating that there is no major obstruction in LHC, a batch with 6 or 12 bunches is injected (60 – 130 kJ). This is still below the threshold for serious damage. Only if the injection of this batch is successful, batches with 72 or 144 bunches are injected until about 1380 bunches per beam are circulating. The total energy in one beam is in the order of 15 MJ.
- The next phase is the ramp of the magnets to increase the energy from 450 GeV to 7 TeV. During the ramp most of the collimator jaws move towards the beam.
- After the acceleration to 4 TeV the beams are squeezed, e.g. the β-function in the collision points is reduced from 11 m to 0.6 m (for ATLAS and CMS, and from 11 m to 3.5 m (for LHCb). The β-function at ALICE remains constant. The jaws of a few collimators in the experimental insertions are adjusted.
- During all previous phases the beams are separated at the collision points. In the "adjust" phase the beams are brought into collisions, for ATLAS and CMS to head-on collisions, for LHCb to collisions with an offset to limit the luminosity, and for ALICE high intensity bunches collide with satellite bunches to limit the luminosity.
- Stable beam are declared and the physics experiments take data, possibly for many hours. The data taking period finishes when the luminosity decreases and operation decides to dump the beams, or when a failure is detected that leads to a beam dump.

Figure 9 shows the statistics for the fills during one week. During 2012 until September, 185 fills went into stable beams. 120 fills were dumped after a failure or beam losses above the threshold were detected. Only 65

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fills were dumped by the operator (sometimes in anticipation of a failure, e.g. of the cryogenic system).

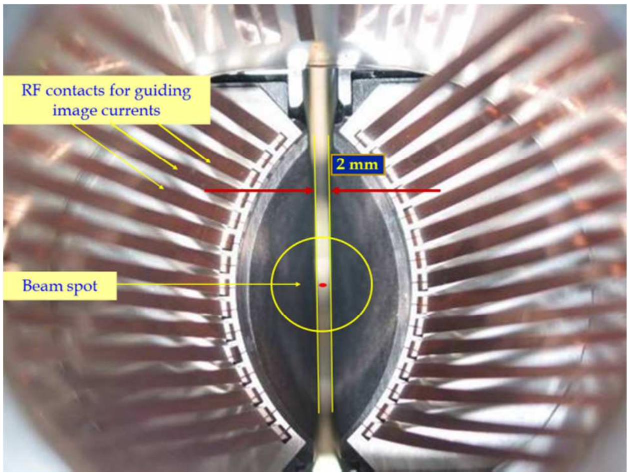

Figure 6: Collimator seen from the beam.

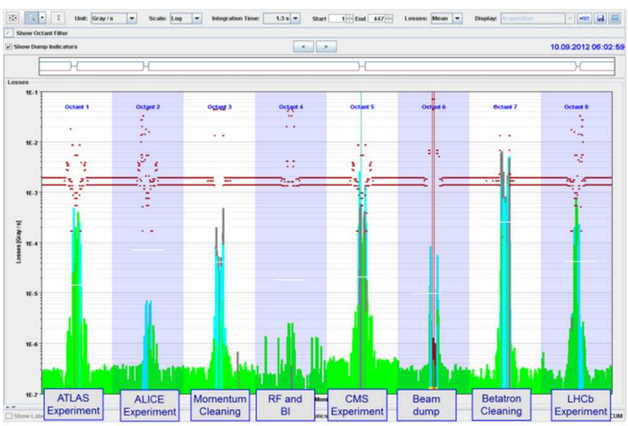

Figure 7: Typical beam losses during luminosity operation (fill 3047) measured around LHC, in logarithmic scale. Losses are high in the two high luminosity insertions and in the cleaning insertions. Losses in the other insertions are much lower and very small in the arcs.

OBSERVATIONS DURING OPERATION

During 2011 the LHC was operating at 3.5 TeV, with a β-function at the high luminosity experiment of 1.0 m. The closest collimator jaws were positioned at 5.7 σ from the beam centre (σ as Gaussian beam size is assumed for nominal emittance). The beam losses during ramp, squeeze and adjust for fill 1875 (1092 bunches per beam) were than 0.2% very low (Figure 10).

At the start of 2012 the LHC was commissioned to operate at an increased energy of 4.0 TeV and lower beta function at the experiments. During a period of 10 days the number of bunches was increased to about 1380, the maximum value for operation with 50 ns bunch spacing.

Operation resumed after a technical stop. After three weeks a luminosity of more than $6 \times 10^{33} cm^{-2} s^{-1}$ was achieved. To further increase the luminosity turned out to be rather difficult, since beam losses due to instabilities and other effects started to limit the intensity per bunch.

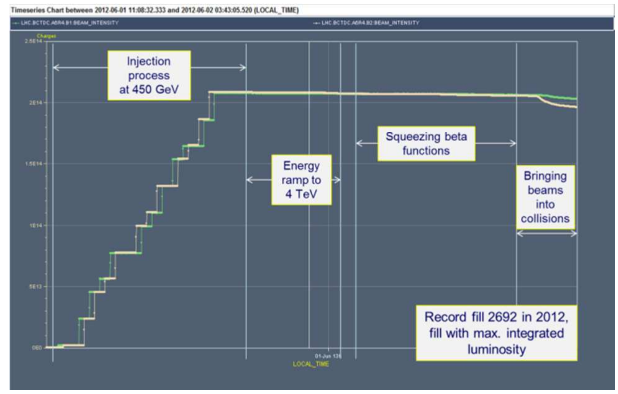

Figure 8: LHC operational cycle.

Fill	Duration	Ibeam	Lpeak [e30 cm-2s-1]	Lint [pb-1]	Dump
2723	2:26	2.03E+14	6406	46.06	Trip of ROD.A81B1, SEU?
2724	1:13	2.03E+14	6329	25.905	Electrical perturbation
2725	7:04	2.05E+14	6520	115.5	Trip of S81
2726	8:58	2.05E+14	6499	142.5	Elecitrical perturbation, FMCM
2728	11:41	2.06E+14	6525	171.5	Operator dump
2729	3:28	2.06E+14	6502	67.7	BLM self trigger
2732	1:52	2.06E+14	6592.5	40	QPS trigger RQX.R1, SEU?
2733	12:34	2.06E+14	6674	183	Triplet RQX.L2 tripped.
2734	15:33	2.01E+14	6257.5	203.5	Operator dump
2736	17:29	2.02E+14	6465.5	233	Operator dump
2737	3:36	1.99E+14	6021	66.1	RF Trip 2B2
Total	51.1%			1301	

Figure 9: Example of the fills during one week.

After another technical stop end of June operation resumed but initially it was not possible to achieve the same peak luminosity that had been obtained before the technical stop. In particular, when increasing the bunch current, beam instabilities created beam losses during squeeze and adjust, leading for several fills to a beam dump.

Parameters that have an influence on the beam stability are betatron tunes, chromaticity, the strength of the octupole magnets installed for Landau damping, the parameters of the transverse damper, and beam-beam effects (both head-on and long-range). A moderate increase of the beam current was possible after changing a some parameters: the sign of the octupole field was changed, the chromaticity was increased from value of about 1-3 to 10-12, the crossing angle at the ALICE collision point was increased from 95 to 145 μrad (see [6,7] for details on these subjects).

During squeezing and adjust, the beam losses went up to an energy of about 20 MJ [8]. The collimation system captures most particles and losses outside the collimation insertions are limited (see Figure 13).

The collimation system was designed to capture beam losses with a power of more than 500 kW without quenching magnets in the adjacent arcs [9]. Initially, the BLM thresholds were set conservatively to dump the

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beams already when the power exceeded some 10 kW. The thresholds have been carefully increased during 2011 and 2012, and for the time being set to about 200 kW.

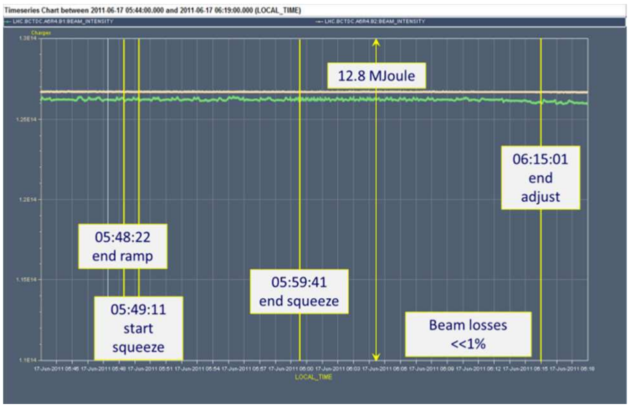

Figure 10: Beam intensity during ramp, squeeze and adjust for fill 1875 in 2011, with 1092 bunches per beam.

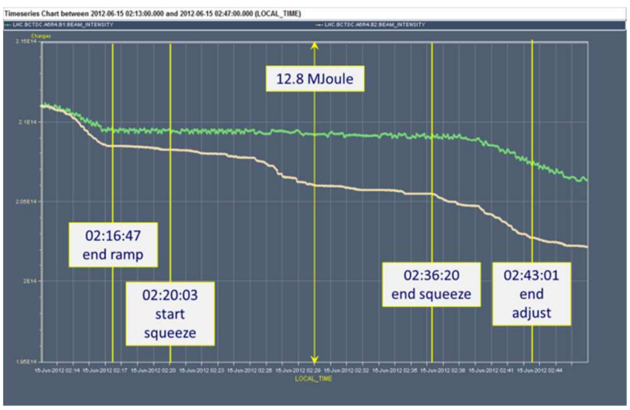

Figure 11: Beam intensity during ramp, squeeze and adjust for fill 2733 in 2012, with 1380 bunches per beam.

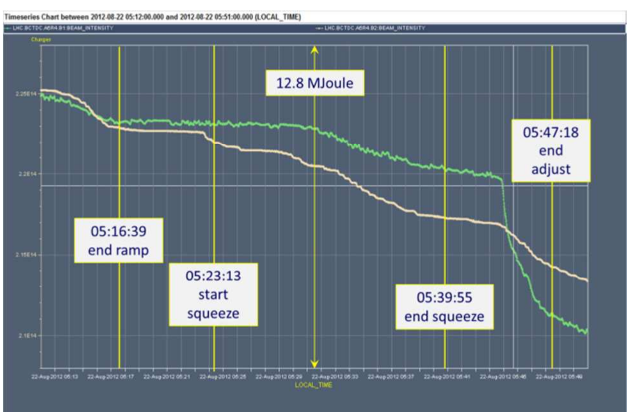

Figure 12: Beam intensity during ramp, squeeze and adjust for fill 2993 in 2012, with 1374 bunches per beam.

A surprising observation was made when increasing the number of bunches. Very fast beam losses within a few turns are observed that can exceeded the threshold of the BLMs and dump the beam. It is believed that these losses are coming from dust particles falling through the beam, since beam parameters such as tune, orbit etc. do not change [10]. UFOs dumped about seven fills during 2012.

CONCLUSIONS

The integrated luminosity delivered to the experiment surpasses our expectations, although operation with beams above 130 MJ stored energy is still challenging and requires a lot of optimisation. A further increase of bunch intensity is not straightforward.

When operating with stored beams there was no beam induced magnet quench, despite operating with 130 MJ beams with a quench limit in the order of 10 mJ. The beam loss monitors are fully covering the entire accelerator for all type of fast and slow beam losses and dump the beams in time before a magnet quenches. The only occasion when magnets quenched was at injection. The injection kicker magnets failed with a partial discharge. Most of the beam was absorbed by injection absorbers, but a small part of the beam was scattered into the magnets.

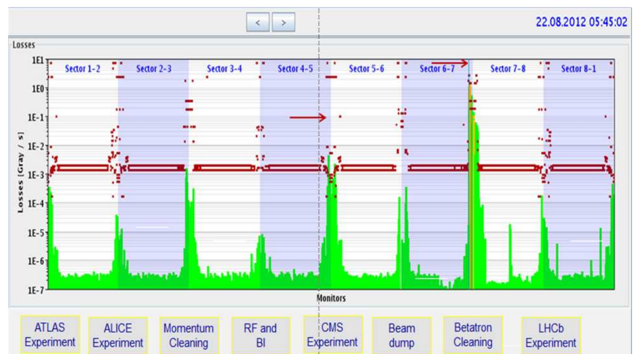

Figure 13: Beam losses for fill 2993 during start adjust.

ACKNOWLEDGMENT

Thanks to the large number of colleagues inside and outside CERN who contributed to the success of the LHC operation.

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