LHC 2010 OPERATION - AS VIEWED FROM THE EXPERIMENTS

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Abstract

This paper tries to summarize how the LHC experiments have perceived the 2010 run. A critical review of LHC operation, beam conditions and luminosity delivery will be given,a as well as proposals for improvements.

INTRODUCTION

First, a brief review of the 2010 LHC run is presented, with emphasis on physics operation. Second, lessons from the 2010 run, as seen by the experiments, are listed and proposals for improvements are made.

SUMMARY OF 2010 RUN

LHC proton operation started on February 28 and stopped on November 4. The LHC proton run can be divided in three phases:

- Phase 1: The initial phase started with commissioning to 3.5 TeV and first collisions at $\sqrt{s} = 7$ TeV. It proceeded with a first optics squeeze ($\beta^* = 2$ m at all IPs), and continued with an increase in the number of bunches (from 2 to 13) of small intensity (1 to $2 \cdot 10^{10}$ p). During this phase, physics collisions at 0.45 TeV/beam were also delivered, at injection optics and with close to nominal bunch intensities. The LHC physics fills of this phase are listed in table 1.

- Phase 2: After successfully testing physics collisions with nominal bunches at injection energy, the machine was prepared for collisions at 3.5 TeV/beam with $\beta^* = 3.5$ m at all IPs and with a small number of bunches of nominal intensity. The beam intensities and luminosities were pushed up by increasing the number of bunches from 3 to 50. This phase ended with a 1-month period of physics production with stable conditions and a stored beam energy of about 2 MJ (August). The LHC physics fills of this phase are listed in table 2.

- Phase 3: Finally, the machine was commissioned to work with bunch trains of 150 ns spacing (and nominal bunch intensities). The total number of bunches was increased from 24 to 368 (about 20 MJ per beam). A single test fill with 50 ns was attempted at the end. The LHC physics fills of this phase are listed in table 3.

The state of the LHCb dipole spectrometer and of the ALICE dipole and solenoid spectrometers are indicated in the tables. The polarity ('+' or '−') refers to the power converter polarity ('0' means 'off'). For IP2, the solenoid and dipole were always in the same state.

There were six techical stops (starting on March 15, April 26, May 31, July 19, August 30, October 19) of 2 to 4 days during the proton run. During the ion run, a 3-day interruption of ion operation took place from November 17 to 20 to accomodate electron cloud studies with high intensity

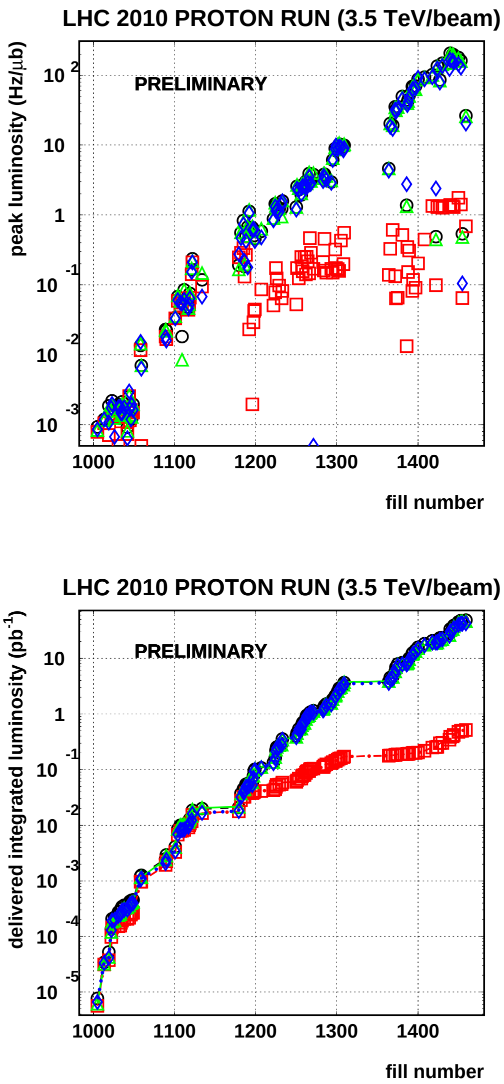
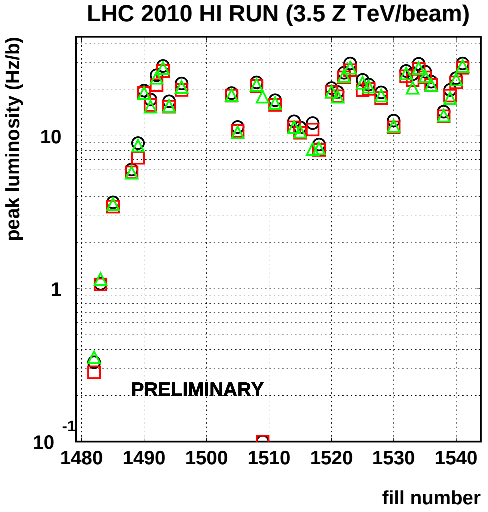


Figure 1: Overview of 2010 proton run. The top (bottom) graph shows the evolution of the peak (integrated) luminosity in the four interaction points. Symbols: ○ IP1, □ IP2, △ IP5, ◇ IP8.



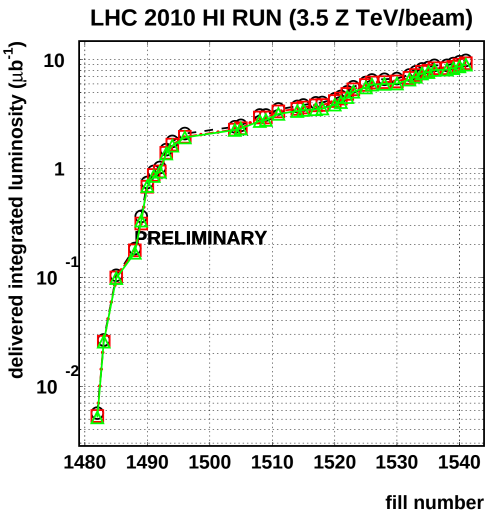


Figure 2: Overview of 2010 ion run. The top (bottom) graph shows the evolution of the peak (integrated) luminosity in the three interaction points. Symbols: ○ IP1, □ IP2, △ IP5, ◇ IP8.

proton beams (with 50 and 75 ns spacing).

An external crossing half-angle was introduced at IP1 (-100 μrad) and IP5 ($+100$ μrad) between the first and second phase. The angle at IP1 allowed LHCf to collect data with a different momentum coverage. The LHCf detector was dismounted during the July technical stop (the last 2010 physics fill for LHCf was fill 1233).

In order to facilitate operation with bunch trains, all IPs were set up with an external crossing angle between the second and third phase, An external horizontal crossing half-angle of $+100$ μrad in IP5 and of -100 μrad in IP8 was used (for LHCb the polarity reversals were applied to the internal angle only). External vertical crossing half-angles of -100 μrad in IP1 and of ± 110 μrad in IP2 were used (for ALICE the polarity reversals were applied to the spectrometers and to the external angle).

Since fill 1190, IR2 was operated with a horizontal parallel separation of 3 to 4 nominal beam sizes ($\sigma_{\rm beam} \approx 60$ μm) to maintain a luminosity between $\sim 10^{29}$ $\rm Hz/cm^2$ and $2 \cdot 10^{30}$ $\rm Hz/cm^2$.

A number of special activities were organized:

- A few fills at $\sqrt{s} = 0.9$ TeV were delivered (1068, 1069, 1128) to complement the 2009 physics run and to test collisions with nominal bunch intensities. This allowed the experiments to collect several million events.
- A first series of Van der Meer scans was carried out in Phase 1, fills 1058, 1059, 1089 and 1090 [1], which yielded a direct luminosity calibration. A second series of Van der Meer scans was organized in Phase 3, this time during dedicated fills (1386 and 1422), to obtain a more precise luminosity calibration (at the level of 5%).
- Length scale calibration measurements for the Van der Meer scans were performed in fills 1393 (IP1), 1422 (IP8 and IP5), 1439 (IP5) and 1455 (IP2).
- Beam-based alignment of the TOTEM Roman Pots was done during fill 1359 and followed by a short data-taking period (of about 1 hour) with the pots positioned at about $7\sigma_{\rm beam}$ from the beam orbit. A second special data-taking period was delivered for TOTEM during fill 1455 (about 4 hours).
- During fill 1455, about one hour was dedicated to the technical test of a longitudinal scan. The phase between the beams was varied from -15 and +15 ns in steps of 5 ns (and 0.2 ns between -1 and +1 ns) . Possible applications of such scans are: longitudinal separation and collapse to collisions, measurement of the crossing angle and measurement of satellite bunch distributions.

The LHC ion run drastically benefited from the operational and commissioning experience of the proton run. Ion operation started on November 4 and stopped on December 6. The beam rigidity and the optics remained untouched ($E = 3.5$ ZTeV and $\beta^* = 3.5$ m), from the start of the ion run. Only the crossing angles were modified such as to give zero net angle in all IPs (IP1, IP2 and IP5), which is an advantage for interpreting data of the Zero-Degree Calorimeters (ZDC). The TCTVB collimators in IR2 were opened enough to not create any shadow on the ALICE ZDC. The bunch intensity was between 6 and $12 \cdot 10^7$ Pb from the first fill (thus exceeding 'nominal' intensity). The number of bunches was rapidly increased from 2 to 121, and later to 137. All LHC physics fills of the ion run are listed in table 4.

Van der Meer scans for luminosity calibration with ions were carried out in fill 1533 for IP1, IP2 and IP5. Note that

Fill nr.	Stable beams start	stop	E (TeV)	Filling scheme	Magnets IP8	IP2	β^* (m)
1005	Tue 30.03 13:22	Tue 30.03 16:29	3.5	Single_2b_1_1_1	+	-	11/10
1013	Wed 31.03 21:03	Thu 01.04 05:05	3.5	Single_2b_1_1_1	+	-	11/10
1019	Sat 03.04 04:23	Sat 03.04 07:23	3.5	Single_2b_1_1_1	-	-	11/10
1022	Sun 04.04 17:26	Mon 05.04 13:29	3.5	Single_2b_1_1_1	-	-	11/10
1023	Tue 06.04 02:44	Tue 06.04 14:59	3.5	Single_2b_1_1_1	+	-	11/10
1026	Wed 07.04 10:28	Wed 07.04 12:52	3.5	Single_2b_1_1_1	+	-	11/10
1031	Sat 10.04 06:13	Sat 10.04 15:47	3.5	Single_2b_1_1_1	+	+	11/10
1033	Mon 12.04 01:24	Mon 12.04 03:23	3.5	Single_2b_1_1_1	0	+	11/10
1034	Mon 12.04 08:54	Mon 12.04 17:25	3.5	Single_2b_1_1_1	0	+	11/10
1035	Tue 13.04 05:01	Tue 13.04 09:31	3.5	Single_2b_1_1_1	+	+	11/10
1038	Wed 14.04 05:50	Wed 14.04 10:53	3.5	Single_2b_1_1_1	+	+	11/10
1042*	Thu 15.04 06:22	Thu 15.04 08:54	3.5	Single_2b_1_1_1	+	+	11/10
1044	Fri 16.04 05:50	Fri 16.04 09:12	3.5	Single_2b_1_1_1	+	+	11/10
1045	Sat 17.04 05:55	Sat 17.04 14:58	3.5	Single_2b_1_1_1	+	+	11/10
1046	Sun 18.04 06:06	Sun 18.04 06:55	3.5	Single_2b_1_1_1	+	+	11/10
1047	Sun 18.04 11:28	Sun 18.04 14:39	3.5	Single_2b_1_1_1	+	+	11/10
1049	Mon 19.04 03:55	Mon 19.04 05:14	3.5	Single_2b_1_1_1	+	+	11/10
1058†	Sat 24.04 03:13	Sun 25.04 09:30	3.5	Single_3b_2_2_2	+	+	2
1059†	Mon 26.04 01:34	Mon 26.04 06:32	3.5	Single_2b_1_1_1	+	+	2
1068	Sun 02.05 14:33	Sun 02.05 21:44	0.45	Single_2b_1_1_1	+	+	11/10
1069	Mon 03.05 02:03	Mon 03.05 09:18	0.45	Single_2b_1_1_1	-	+	11/10
1089†	Sat 08.05 22:33	Sun 09.05 18:55	3.5	Single_2b_1_1_1	-	0	2
1090†	Mon 10.05 04:31	Mon 10.05 10:57	3.5	Single_2b_1_1_1	-	+	2
1101	Fri 14.05 12:57	Fri 14.05 23:39	3.5	Single_4b_2_2_2	+	+	2
1104	Sat 15.05 16:54	Sun 16.05 14:14	3.5	Single_6b_3_3_3	-	+	2
1107	Mon 17.05 06:27	Mon 17.05 15:25	3.5	Single_6b_3_3_3	-	+	2
1109	Tue 18.05 04:54	Tue 18.05 05:35	3.5	Single_6b_3_3_3	-	+	2
1112	Wed 19.05 06:10	Wed 19.05 07:33	3.5	Single_6b_3_3_3	+	+	2
1117	Sat 22.05 03:39	Sat 22.05 11:42	3.5	Single_6b_3_3_3	+	+	2
1118	Sun 23.05 06:05	Sun 23.05 12:34	3.5	Single_6b_3_3_3	+	+	2
1119	Sun 23.05 20:45	Mon 24.05 00:18	3.5	Single_6b_3_3_3	+	+	2
1121	Mon 24.05 15:01	Mon 24.05 17:27	3.5	Single_13b_8_8_8	+	+	2
1122	Tue 25.05 03:15	Tue 25.05 12:27	3.5	Single_13b_8_8_8	+	+	2
1128	Thu 27.05 15:07	Thu 27.05 16:03	0.45	Single_7b_4_4_4	+	+	11/10
1134	Sat 05.06 13:42	Sat 05.06 17:28	3.5	Single_13b_8_8_8	+	-	2

Table 1: All fills with STABLE BEAMS during the first phase of the 2010 LHC proton run. Magnets: IP8 = LHCb dipole, IP2 = ALICE dipole & solenoid. *The CMS solenoid was off during fill 1042. †Fill includes Van der Meer scans.

LHCb was switched off during the ion run (including the spectrometer bump).

In total, the LHC operated 1074 hours in STABLE BEAMS (851 hours with p and 223 hours with Pb) out of about 6600 hours. There were 147 fills with STABLE BEAMS (110 with p and 37 with Pb).

Figure 1 shows on the top graph the peak luminosity as a function of physics fill number. The peak luminosity increased from $8 \cdot 10^{26}$ Hz/cm^2 to $2 \cdot 10^{29}$ Hz/cm^2 (Phase1), then further to $4.6 \cdot 10^{30}$ Hz/cm^2 (Phase 2) and finally reached $2 \cdot 10^{32}$ Hz/cm^2 (Phase 3). The integrated delivered luminosities (2010 totals) were approximately 48 pb^{-1} (IP1), 0.5 pb^{-1} (IP2), 47 pb^{-1} (IP5) and 42 pb^{-1} (IP8).

Figure 2 shows the corresponding graphs for the ion run (LHCb switched off). In this case, the luminosity was increased from $3 \cdot 10^{23}$ Hz/cm^2 to $3 \cdot 10^{25}$ Hz/cm^2. The integrated delivered luminosities were approximately $9.9\ \mu$b^{-1} (IP1), $9.3\ \mu$b^{-1} (IP2) and $9\ \mu$b^{-1} (IP5).

Other yearly summary plots are available at the LHC Programme Coordinations site [2].

2010 LESSONS

Modus operandi: The early June experience with machine operation alternating between commissioning (at day time) and physics (at night) showed that this mode of operation had reached its limits (though its was useful during the initial phase). Subsequently, a clear separation between major commissioning steps and physics production was put in place, to the benefit of the LHC machine and LHC experiments. For 2011, such a separation between commissioning blocks (of several days) and physics production (of several weeks) should be maintained.

Technical stops: The impact of technical stops on operation, and in particular the recovery from a stop, was discussed elsewhere (see [3]). Originally, a 3-day stop every fourth week was planned for the LHC. From the 2010 experience, it seems that a space of 6 weeks between the start of two subsequent (4-day long) technical stops is acceptable. The frequency and length of such stops needs to be further optimized. The cooperation between the Technical Stop Coordinator and the LHC Machine Coordinator was strengthened in the course of 2010. This improved the supervision of interventions (hardware and software changes) and helped reducing collateral effects of technical stops on operation. Further strengthening of this cooperation will help minimizing the machine downtime.

Increasing stored beam energy: The increase of beam intensity (stored energy) in the LHC machine was driven by both machine protection aspects and operational considerations. The human factor and improvement of operational

Fill	Stable beams		E	Filling	Magnets		β^*
nr.	start	stop	(TeV)	scheme	IP8	IP2	(m)
1179	Fri 25.06 01:35	Fri 25.06 03:57	3.5	Single_3b_2_2_2	+	-	3.5
1182	Sat 26.06 19:28	Sun 27.06 10:15	3.5	Single_3b_2_2_2	+	-	3.5
1185	Tue 29.06 11:57	Tue 29.06 16:11	3.5	Single_3b_2_2_2	+	-	3.5
1186	Wed 30.06 08:15	Wed 30.06 10:36	3.5	Single_3b_2_2_2	+	-	3.5
1188	Thu 01.07 02:56	Thu 01.07 10:47	3.5	Single_3b_2_2_2	+	-	3.5
1190	Fri 02.07 05:40	Fri 02.07 06:27	3.5	Single_7b_4_4_4	+	-	3.5
1192	Fri 02.07 17:30	Fri 02.07 18:04	3.5	Single_7b_4_4_4	+	-	3.5
1196	Sun 04.07 00:46	Sun 04.07 01:35	3.5	Single_7b_4_4_4	+	-	3.5
1197	Sun 04.07 06:22	Sun 04.07 18:16	3.5	Single_7b_4_4_4	+	-	3.5
1198	Mon 05.07 02:28	Mon 05.07 13:43	3.5	Single_7b_4_4_4	+	-	3.5
1199	Mon 05.07 23:11	Tue 06.07 02:58	3.5	Single_10b_4_2_4	+	-	3.5
1207	Fri 09.07 04:16	Fri 09.07 10:17	3.5	Single_10b_4_2_4	+	-	3.5
1222	Mon 12.07 03:02	Mon 12.07 11:56	3.5	Single_9b_6_6_6	+	-	3.5
1224	Tue 13.07 05:08	Tue 13.07 14:59	3.5	Single_12b_8_8_8	-	-	3.5
1225	Wed 14.07 02:13	Wed 14.07 17:02	3.5	Single_12b_8_8_8	-	-	3.5
1226	Thu 15.07 04:19	Thu 15.07 13:15	3.5	Single_13b_8_8_8	-	-	3.5
1229	Sat 17.07 00:44	Sat 17.07 04:36	3.5	Single_13b_8_8_8	-	-	3.5
1232	Sat 17.07 19:19	Sun 18.07 01:11	3.5	Single_13b_8_8_8	-	-	3.5
1233	Sun 18.07 10:56	Mon 19.07 05:58	3.5	Single_13b_8_8_8	-	-	3.5
1250	Wed 28.07 22:28	Thu 29.07 10:35	3.5	Single_13b_8_8_8	+	-	3.5
1251	Thu 29.07 23:28	Fri 30.07 07:25	3.5	Multi_25b_16_16_16_hyb	+	-	3.5
1253	Fri 30.07 23:11	Sat 31.07 12:20	3.5	Multi_25b_16_16_16	+	-	3.5
1256	Sun 01.08 03:50	Sun 01.08 04:49	3.5	Multi_25b_16_16_16	+	-	3.5
1257	Sun 01.08 22:00	Mon 02.08 12:35	3.5	Multi_25b_16_16_16	+	-	3.5
1258	Tue 03.08 00:22	Tue 03.08 07:39	3.5	Multi_25b_16_16_16	+	-	3.5
1260	Wed 04.08 04:31	Wed 04.08 06:38	3.5	Multi_25b_16_16_16	+	-	3.5
1262	Wed 04.08 17:40	Thu 05.08 11:19	3.5	Multi_25b_16_16_16	+	-	3.5
1263	Fri 06.08 03:52	Fri 06.08 19:08	3.5	Multi_25b_16_16_16	+	-	3.5
1264	Sat 07.08 01:42	Sat 07.08 02:14	3.5	Multi_25b_16_16_16	+	-	3.5
1266	Sat 07.08 23:12	Sun 08.08 01:10	3.5	Multi_25b_16_16_16	+	-	3.5
1267	Sun 08.08 05:18	Sun 08.08 18:52	3.5	Multi_25b_16_16_16	+	-	3.5
1268	Mon 09.08 01:29	Mon 09.08 04:02	3.5	Multi_25b_16_16_16	+	-	3.5
1271	Tue 10.08 07:24	Tue 10.08 12:22	3.5	Multi_25b_16_16_16	+	-	3.5
1283	Fri 13.08 23:06	Sat 14.08 12:04	3.5	Multi_25b_16_16_16	+	-	3.5
1284	Sat 14.08 15:44	Sat 14.08 19:13	3.5	Multi_25b_16_16_16	+	-	3.5
1285	Sun 15.08 00:39	Sun 15.08 13:02	3.5	Multi_25b_16_16_16	+	-	3.5
1287	Sun 15.08 23:01	Mon 16.08 09:24	3.5	Multi_25b_16_16_16	+	-	3.5
1293	Tue 18.08 09:12	Tue 18.08 21:13	3.5	Multi_25b_16_16_16	-	-	3.5
1295	Thu 19.08 23:36	Fri 20.08 14:19	3.5	1250ns_48b_36_16_36	-	-	3.5
1298	Mon 23.08 00:52	Mon 23.08 13:50	3.5	1250ns_48b_36_16_36	-	-	3.5
1299	Tue 24.08 00:11	Tue 24.08 03:26	3.5	1250ns_48b_36_16_36	-	-	3.5
1301	Tue 24.08 17:35	Wed 25.08 07:53	3.5	1000ns_50b_35_14_35	-	-	3.5
1303	Thu 26.08 04:21	Thu 26.08 17:26	3.5	1000ns_47b_32_14_32	-	-	3.5
1305	Fri 27.08 06:11	Fri 27.08 09:41	3.5	1000ns_50b_35_14_35	-	-	3.5
1308	Sat 28.08 22:43	Sun 29.08 12:22	3.5	1000ns_50b_35_14_35	-	-	3.5
1309	Sun 29.08 18:17	Mon 30.08 05:35	3.5	1000ns_50b_35_14_35	+	-	3.5

Table 2: All fills with STABLE BEAMS during the second phase of the 2010 LHC proton run. Magnets: IP8 = LHCb dipole, IP2 = ALICE dipole & solenoid.

procedures shaped the 'learning curve'. Operation in 2011 and beyond will greatly benefit from the enormous experience acquired during 2010. In future years, intensity increase should be largely driven by the state of the machine protection system and by intrinsic performance limitations of the machine itself (such as e-cloud effects).

Filling the LHC: The LHC currently hosts seven approved experiments (ALICE, ATLAS, CMS, LHCb, LHCf, TOTEM, MoEDAL) with diverse requirements on beam conditions. Filling the LHC in such a way that all experiments are adequately served is a challenge. Constructing filling schemes became increasingly complex toward the end of the 2010 proton run, mainly due to the following features:

- The use of an intermediate intensity batch ($< 10^{12}p$) before transfering a high intensity batch from the SPS imposed to use the same number of bunches per PS batch throughout the whole filling process. This is due to the fact that the number of bunches from the booster to the PS can not be dynamically driven by the LHC. For 150 ns operation, this precluded the use of 12-bunch trains from the PS. The implications were a small fraction of lost collisions (more train edges) and a reduced reach in total number of bunches as compared to 12-bunch trains. For future years, ideally, the LHC should be able to drive dynamically the number of booster bunches to the PS.
- The compulsory use of the intermediate intensity batch also introduced a difficulty in constructing well-balanced filling schemes. Besides the breaking of the four-fold symmetry, it also "consumes" 950 ns of the LHC circumference. Ideally, this batch should be dumped before starting the actual LHC filling, or it should be possible to inject a full intensity batch over the intermediate batch. Preferably, the deployed solution should work for any bunch spacing (150, 75, 50, 25 ns).
- The Abort Gap Keeper (AGK) window length was set

Fill nr.	Stable beams start	stop	E (TeV)	Filling scheme	Magnets IP8	IP2	β^* (m)
1364	Wed 22.09 16:54	Thu 23.09 06:37	3.5	150ns_24b_16_16_16_8bpi	-	+	3.5
1366	Thu 23.09 19:10	Fri 24.09 09:12	3.5	150ns_56b_47_16_47_8bpi	-	+	3.5
1369	Sat 25.09 09:38	Sat 25.09 11:05	3.5	150ns_56b_47_16_47_8bpi	-	-	3.5
1372	Sat 25.09 19:39	Sun 26.09 11:18	3.5	150ns_104b_93_8_93_8bpi	-	-	3.5
1373	Sun 26.09 21:27	Mon 27.09 09:58	3.5	150ns_104b_93_8_93_8bpi	-	-	3.5
1375	Tue 28.09 02:23	Tue 28.09 11:23	3.5	150ns_104b_93_8_93_8bpi	-	-	3.5
1381	Thu 30.09 02:25	Thu 30.09 05:28	3.5	150ns_152b_140_16_140_8+8bpi11inj	-	-	3.5
1386†	Fri 01.10 13:30	Fri 01.10 16:24	3.5	Single_19b_6_1_12_allVdm	-	-	3.5
1387	Sat 02.10 05:08	Sat 02.10 07:06	3.5	150ns_152b_140_16_140_8+8bpi11inj	-	-	3.5
1388	Sat 02.10 10:57	Sat 02.10 13:08	3.5	150ns_152b_140_16_140_8+8bpi11inj	-	-	3.5
1389	Sun 03.10 13:16	Sun 03.10 20:27	3.5	150ns_152b_140_16_140_8+8bpi11inj	-	-	3.5
1393‡	Mon 04.10 20:00	Tue 05.10 09:43	3.5	150ns_200b_186_8_186_8+8bpi17inj	-	-	3.5
1394	Tue 05.10 23:58	Wed 06.10 01:41	3.5	150ns_200b_186_8_186_8+8bpi17inj	-	-	3.5
1397	Thu 07.10 04:23	Thu 07.10 10:54	3.5	150ns_200b_186_8_186_8+8bpi17inj	-	-	3.5
1400	Fri 08.10 02:36	Fri 08.10 09:10	3.5	150ns_248b_233_16_233_3x8bpi15inj	-	-	3.5
1408	Mon 11.10 21:20	Tue 12.10 07:17	3.5	150ns_248b_233_16_233_3x8bpi15inj	-	-	3.5
1418	Thu 14.10 03:38	Thu 14.10 12:06	3.5	150ns_248b_233_16_233_3x8bpi15inj	-	-	3.5
1422†	Fri 15.10 13:14	Fri 15.10 18:27	3.5	Single_16b_3_1_12_allVdmB	-	-	3.5
1424	Sat 16.10 02:30	Sat 16.10 03:23	3.5	150ns_312b_295_16_295_3x8bpi19inj	-	-	3.5
1427	Sat 16.10 22:56	Sun 17.10 09:31	3.5	150ns_312b_295_16_295_3x8bpi19inj	-	-	3.5
1430	Mon 18.10 04:25	Mon 18.10 05:03	3.5	150ns_312b_295_16_295_3x8bpi19inj	-	-	3.5
1439‡	Sun 24.10 09:59	Sun 24.10 20:41	3.5	150ns_312b_295_16_295_3x8bpi19inj	+	-	3.5
1440	Mon 25.10 02:35	Mon 25.10 13:54	3.5	150ns_368b_348_15_344_4x8bpi19inj	+	-	3.5
1443	Tue 26.10 05:35	Tue 26.10 07:49	3.5	150ns_368b_348_15_344_4x8bpi19inj	+	-	3.5
1444	Tue 26.10 13:35	Tue 26.10 20:47	3.5	150ns_368b_348_15_344_4x8bpi19inj	+	-	3.5
1450	Thu 28.10 00:45	Thu 28.10 15:17	3.5	150ns_368b_348_15_344_4x8bpi19inj	+	-	3.5
1453	Fri 29.10 04:16	Fri 29.10 10:36	3.5	150ns_368b_348_15_344_4x8bpi19inj	+	-	3.5
1455‡	Sat 30.10 05:33	Sat 30.10 06:32	3.5	Single_5b_5_1_1	+	-	3.5
1459	Sun 31.10 01:24	Sun 31.10 07:25	3.5	50ns_109b_91_12_90_12bpi10inj	+	-	3.5

Table 3: All fills with STABLE BEAMS during the third phase of the 2010 LHC proton run. Magnets: IP8 = LHCb dipole, IP2 = ALICE dipole & solenoid. †Fill includes Van der Meer scans (and length scale calibrations). ‡Fill includes a length scale calibration.

to match the nominal transfer from the SPS of 288 bunches of 25 ns spacing, i.e. a length of about $8\ \mu$s (3200 LHC Rf buckets). The AGK prevented injection of the first bunch of a batch to fall in an LHC RF bucket larger than about 32040 ($35640 - 3200 - 400$, where the 400 comes from the abort gap). In practice, the longest proton batch used was about $5\ \mu$s (and $3.5\ \mu$s for ion operation). Therefore, the $8\ \mu$s AGK window introduced a dead space of at least $3\ \mu$s which, when combined with the four-fold symmetry requirements, created difficulties and limitations for constructing well-balanced filling schemes. For 2011 operation, it is likely that the transfer of full $8\ \mu$s batches will actually be used (for e-cloud scrubbing and for physics).
For the ion run, the smaller the dead space, the less collisions will be lost at IP2 (ALICE). Note that the possibility to rephase the abort gap near IP2 was discussed, but finally not implemented due to potential disruptions in the DAQ of some of the experiment. This option might be reconsidered for the 2011 Pb run.

- When the BPM sensitivity is set for high intensity bunches, the BPMs cannot measure low intensiy bunches (below $\sim 5 \cdot 10^{10} p$). For this reason, it was decided (initially) not to operate with schemes mixing high and low intensity bunches, as the trajectory of the latter bunches would have been invisible. This precluded the option of using the intensity of special bunches for adjusting the interaction rate at low-luminosity experiments (ALICE, LHCf, TOTEM). For IP2, the alternative method of parallel separation was used with great success. For TOTEM, a single test with small bunches was performed in the last proton physics fill (1459), showing no particular issues related to the small bunch. Since TOTEM is at the same IP as CMS, parallel separation cannot be used. For 2011, the use of a few small intensity bunches during physics fills would allow TOTEM to collect low pile-up data in parallel to high-luminosity production for CMS. This trick could be used as long as the small intensity bunches do not occupy space otherwise usable by high intensity bunches (for example, if operating at 400 bunches with 75 ns spacing).

- Much of the turn-around time was spent at LHC injection (2 to 5 hours ?). This was due to several reasons: loss of injection requests because of the management of injection checks, non-dedicated injector operation for LHC filling (long supercycle), lengthy beam checks at injection, handshakes with the experiments, etc. For details see [4]. For 2011, an improved treatment of injection requests/checks, dedicated operation of the injector complex for LHC filling, more automated beam quality checks, are expected to give a much reduced turn-around time for physics.

Polarity reversals: The spectrometer polarity changes interfered with beam commissioning and operation. In 2010, the LHCb dipole polarity was reversed 12 times. The ALICE dipole and solenoid polarities were reversed 5 times.

Fill	Stable beams		E	Filling	Magnets		β^*
nr.	start	stop	(TeV)	scheme	IP8	IP2	(m)
1482	Mon 08.11 11:19	Mon 08.11 20:02	3.5	Single_2b_1_1_0_1bpi2inj_IONS	0	-	3.5
1483	Tue 09.11 01:01	Tue 09.11 09:58	3.5	Single_5b_4_4_0_1bpi5inj_IONS	0	-	3.5
1485	Tue 09.11 22:49	Wed 10.11 12:43	3.5	500ns_17b_16_16_0_4bpi5inj_IONS	0	-	3.5
1488	Fri 12.11 00:53	Fri 12.11 06:39	3.5	500ns_69b_65_66_0_4bpi18inj_IONS	0	-	3.5
1489	Sat 13.11 01:04	Sat 13.11 10:41	3.5	500ns_69b_65_66_0_4bpi18inj_IONS	0	-	3.5
1490	Sun 14.11 00:32	Sun 14.11 08:21	3.5	500ns_121b_113_114_0_4bpi31inj_IONS	0	-	3.5
1491	Sun 14.11 18:04	Mon 15.11 00:38	3.5	500ns_121b_113_114_0_4bpi31inj_IONS	0	-	3.5
1492	Mon 15.11 07:42	Mon 15.11 08:44	3.5	500ns_121b_113_114_0_4bpi31inj_IONS	0	-	3.5
1493	Mon 15.11 12:48	Mon 15.11 22:04	3.5	500ns_121b_113_114_0_4bpi31inj_IONS	0	-	3.5
1494	Tue 16.11 02:28	Tue 16.11 09:00	3.5	500ns_121b_113_114_0_4bpi31inj_IONS	0	-	3.5
1496	Wed 17.11 00:33	Wed 17.11 06:14	3.5	500ns_121b_113_114_0_4bpi31inj_IONS	0	-	3.5
1504	Sat 20.11 23:00	Sun 21.11 06:16	3.5	500ns_121b_113_114_0_4bpi31inj_IONS	0	-	3.5
1505	Sun 21.11 11:00	Sun 21.11 13:05	3.5	500ns_121b_113_114_0_4bpi31inj_IONS	0	-	3.5
1508	Mon 22.11 01:36	Mon 22.11 09:49	3.5	500ns_121b_113_114_0_4bpi31inj_IONS	0	-	3.5
1509	Mon 22.11 14:06	Mon 22.11 15:16	3.5	500ns_121b_113_114_0_4bpi31inj_IONS	0	-	3.5
1511	Mon 22.11 21:59	Tue 23.11 08:00	3.5	500ns_121b_113_114_0_4bpi31inj_IONS	0	-	3.5
1514	Wed 24.11 02:04	Wed 24.11 08:31	3.5	500ns_121b_113_114_0_4bpi31inj_IONS	0	+	3.5
1515	Wed 24.11 14:01	Wed 24.11 17:00	3.5	500ns_121b_113_114_0_4bpi31inj_IONS	0	+	3.5
1517	Wed 24.11 22:02	Thu 25.11 03:34	3.5	500ns_121b_113_114_0_4bpi31inj_IONS	0	+	3.5
1518	Thu 25.11 06:58	Thu 25.11 08:06	3.5	500ns_121b_113_114_0_4bpi31inj_IONS	0	+	3.5
1520	Thu 25.11 18:11	Thu 25.11 23:58	3.5	500ns_121b_113_114_0_4bpi31inj_IONS	0	+	3.5
1521	Fri 26.11 05:43	Fri 26.11 09:51	3.5	500ns_121b_113_114_0_4bpi31inj_IONS	0	+	3.5
1522*	Fri 26.11 13:32	Fri 26.11 21:35	3.5	500ns_121b_113_114_0_4bpi31inj_IONS	0	+	3.5
1523*	Sat 27.11 03:59	Sat 27.11 12:23	3.5	500ns_121b_113_114_0_4bpi31inj_IONS	0	+	3.5
1525	Sat 27.11 23:54	Sun 28.11 09:51	3.5	500ns_121b_113_114_0_4bpi31inj_IONS	0	+	3.5
1526	Sun 28.11 13:22	Sun 28.11 18:59	3.5	500ns_121b_113_114_0_4bpi31inj_IONS	0	+	3.5
1528	Mon 29.11 02:05	Mon 29.11 03:41	3.5	500ns_121b_113_114_0_4bpi31inj_IONS	0	+	3.5
1530	Mon 29.11 14:54	Mon 29.11 17:06	3.5	500ns_121b_113_114_0_4bpi31inj_IONS	0	+	3.5
1532	Mon 29.11 23:56	Tue 30.11 08:05	3.5	500ns_121b_113_114_0_4bpi31inj_IONS	0	+	3.5
1533†	Tue 30.11 13:31	Tue 30.11 22:04	3.5	500ns_121b_113_114_0_4bpi31inj_IONS	0	+	3.5
1534	Wed 01.12 08:38	Wed 01.12 15:18	3.5	500ns_121b_113_114_0_4bpi31inj_IONS	0	+	3.5
1535	Wed 01.12 22:49	Thu 02.12 01:38	3.5	500ns_121b_113_114_0_4bpi31inj_IONS	0	+	3.5
1536	Sat 04.12 13:54	Sat 04.12 20:38	3.5	500ns_137b_129_130_0_8bpi18inj_IONS	0	+	3.5
1538	Sun 05.12 11:07	Sun 05.12 11:22	3.5	500ns_137b_129_130_0_8bpi18inj_IONS	0	+	3.5
1539	Sun 05.12 17:59	Sun 05.12 23:41	3.5	500ns_137b_129_130_0_8bpi18inj_IONS	0	+	3.5
1540	Mon 06.12 04:01	Mon 06.12 09:56	3.5	500ns_137b_129_130_0_8bpi18inj_IONS	0	+	3.5
1541	Mon 06.12 14:10	Mon 06.12 18:00	3.5	500ns_137b_129_130_0_8bpi18inj_IONS	0	+	3.5

Table 4: All fills with STABLE BEAMS during the 2010 LHC ion run. Magnets: IP8 = LHCb dipole, IP2 = ALICE dipole & solenoid. *The ATLAS solenoid was off during fills 1522 and 1523. †Fill includes Van der Meer scans.

In addition, ALICE, ATLAS, CMS and LHCb requested "field off" collisions (see tables 1 to 4). The LHCb reversal had little impact (one spectrometer magnet and fixed external angle, when present), while the ALICE reversals (two magnets and a changing external angle, when present) required more attention due to the fact that the solenoid introduces a trajectory change in the horizontal plane which is not compensated by dedicated magnets (contrary to the dipole spectrometer fields). The number of polarity change requests will be similar in 2011. Acquiring similar data sets in both polarities for every new type of beam conditions is important for understanding systematic uncertainties in the experiments. Making the polarity reversals as transparent as possible for operation is important. In addition, keeping the beam conditions (pile-up, luminosity) at IP2 and IP8 as stable as possible will also contribute reducing the number of change requests. For 2011, two settings of tertiary collimators in IR2 should be validated (corresponding to the two polarities).

IR2 tertiary collimators: The TCTVB collimators in IR2 created a shadow to the ALICE ZDC during proton operation. The collimators were opened for the ion run and should again be opened for the 2011 ion run. The final solution is to replace the TCTVB by a different type located further downstream of the current TCTVB (much like in IR1 and IR5). This change is already planned and should take place as soon as possible.

Bunch current measurements: The luminosity calibration measurements highlighted the importance for the experiments of the LHC beam instrumentation, most prominently of the Beam Current Transformers (BCTs). This triggered a joint machine-experiments activity to extract best results on the bunch population product normalisation [5]. A few issues were encountered during 2010:

- The DCCT did not behave as expected when bunch trains were introduced (150 ns spacing). This was traced back to a saturation effect in the DCCT amplifier cards.
- Given our current understanding, the DCCT scale factor is now the main source of uncertainty. Calibration studies, in particular assessment of stability, are becoming increasingly important for the experiments. Such studies have started at the end of 2010 and should be pursued.
- The FBCT exhibited a dependence on bunch length and beam position. This needs to be understood and corrected. The experiments (ATLAS in particular) offer a cross-check of the FBCT data by measuring the

relative bunch populations with their beam pick-ups (BPTX).

- The raw FBCT data (not zero-suppressed data) were initially not logged. Given the importance of these data for the luminosity calibration, they should be logged in 2011. This may help understanding the offset and linearity of the FBCT.

- Cross-comparison of the BCT systems A and B would also be desirable, at least during luiminosity calibration measurements. In general, it would be useful to have a mechanism to trace when a BCT system underwent a development period and when it was considered stable.

This joint effort should be continued in 2011 to bring the beam and bunch current measurements to their specified accuracy. In a recent workshop [6], it was concluded that a luminosity calibration accuracy smaller than 5% seems feasible and would have significant impact on physics results. This may require additional beam-based measurements for narrowing down systematic uncertainties (of BCTs, beam displacements, beam-beam effects, pile-up, etc.), see [1, 6] for a discussion. Further desired improvements on beam instrumentation are given below.

Longitudinal profile: Ghost and satellite charge measurement and/or control could become a limiting factor in the precision reach of the bunch current normalisation for luminosity calibration. The Longitudinal Density Monitor was deployed (for ring 1) during the ion run. Its potential to thoroughly address the ghost charge issue was demonstrated. The luminosity normalisation experiments would greatly benefit from the full deployment, commissioning and calibration of these devices for both rings.

Emittance measurements: Emittance measurements were used for estimating the emittance growth during the luminosity calibration measurements. If needed, a correction to the measured convoluted shapes was applied. They were also used for studying the evolution of the specific luminosity during a fill. Bunch-by-bunch measurements became available during the year. Flexibility and ease of use of such measurements could be improved. Ideally, a user should be able to rapidly change between single bunch or multi-bunch acquisition (on a pre-defined set on bunch slots). A file-driven bunch slot selection could be considered. In 2011, bunch-by-bunch emittance measurements will be crucial to understand beam-beam effects. Continuous and automated logging of the emittance of each bunch (e.g. with the BSRT) would be extremely valuable.

The experiments support the effort to perform a cross calibration of the various emittance measuring devices (wire scanners, beam-gas ionisation monitors, synchrotron light monitors). With decreasing β^* and beam emittances, the beam sizes at the IPs may well become of the order of the vertex resolution, which will render the extraction of beam sizes from vertex detector data less reliable.

Beam position in IRs: The stability and accuracy of IR BPMs was not yet at the level of the design specifications. This will become increasingly important in 2011, with the use of smaller beams, higher intensities, and for forward experiments (such as TOTEM and ALFA). In particular, the BPMWF monitors should be commissioned and calibrated.

Luminosity Scan application: The Luminosity Scan application was extensively used for Van der Meer scans and associated length scale calibration scans. However, new scan procedures were proposed (to understand systematics or to speed up the procedure) which were not compatible with the application functionality. It has been proposed to upgrade the application functionality such as to allow the user to encode the scan sequence in an input file. Such a modification would greatly enhance the flexibility and functionality. Additionally, the possibility to scan simultaneously at different IPs has been implemented in the course of 2010. This may greatly reduce the cost of Van der Meer scans. The data exchange protocol and possible (cross-IP) systematic effects are yet to be tested [1].

Scan range (envelope): The scan range of luminosity calibration experiments was defined on the basis of tertiary collimator margins and restricted to $\pm 3\sigma_{\rm beam}$ displacements for each beam independently. This was sufficient for most experiments, but introduced some limitations for the special case of IR2 when operating with separated beams. In 2011, it is considered to move the tertiary collimators with the beams. This might facilitate larger scan ranges, which would be an advantage for Van der Meer scans.

Optics measurements: Optics measurements were carried out on several occasions and revealed again the excellent quality of the machine. The experiments are interested in these measurements, in particular in the IR optics. The β^* values enter in the luminosity formula. When combined with emittance measurements, these data allow one to cross-check the luminosity numbers in a totally independent manner. They may also allow one to understand possible differences between the various IPs (in particular, IP1 and IP5). A systematic and formal publishing mechanism of these results is of interest to the experiments. In the future, with the decrease of β^* values, waist position measurements and hourglas effects will become important. In addition, forward experiments (such as TOTEM and ALFA) have stringent requirements on the measurements of the machine optics.

Injection: Towards the end of 2010, injection losses became large enough to provoke BCM-triggered dumps in LHCb. This was traced back to ejection of uncaptured beam from previous injections. This was temporarily circumvented by permanently increasing the fastest running sum threshold of the BCM system by a factor 3. For 2011, both ALICE and LHCb will implement a more sophisticated mechanism to mitigate the effect of injection losses. A kicker pre-pulse from the RF (point 4) will be used to reduce the thresholds during a short time. However, AL-

ICE and LHCb would like that ways to reduce the losses by cleaning in the LHC (and by shielding, in the long term ?) are pursued.

Handshake: Generally, handshake between the machine and experiments worked well. Minor issues with the exact timing of the procedures were discussed and revisited (e.g. removal of the "imminent" flag). Training of shift crews in the experiment control rooms will be further improved to avoid the occasional loss of time due to misunderstandings. It is important to remember that a handshake is only required when the machine is about to go from a safer state to a less safe state (as gauged by the experiments). Occasionally, a DUMP handshake was initiated while the machine was in ADJUST mode. This is not required (the DUMP mode is not considered less safe than the ADJUST mode for the detectors). The procedures and documentation are now being revisited for 2011 [7].

Data exchange: The principal mechanism for data exchange between the machine and experiments relies on DIP. The service worked relatively well in 2010. A few hiccups were observed. As an example, the LHC fill number was occasionally not correctly transmitted (or not changed at the source ?). On the experiments side, this generates book-keeping errors which need to be treated manually. A method to force the fill number change during the LHC cycle is being discussed. Mechanisms for automated restart of DIP servers and automated signalling of lost DIP services could and should be further developed.

The data published by the experiments were not always archived in the LHC Logging Database, for various reasons (lack of human resources on both sides, occasional service breakdown, insufficient data integrity, etc.). The LHC and the experiments could benefit from a better documentation (definition) of the data to be transmitted from the experiments to the LHC.

In order to alleviate the impact of the missing data, a separate (offline) path for data exchange was set up. Summary files provided by the experiments for physics fills were stored as text files in a dedicated storage space on AFS [8]. These files contain luminosity data and luminous region characterisation data (sizes and positions). Additionally, LHCb (and initially also CMS) provided individual beam sizes and positions from beam-gas imaging. Some experiments delivered data per bunch pair for some of the fills. An advantage of these data files is that the data can be regenerated by the experiments quite easily (for example, if new detector calibration data are available).

These data were used to analyse (specific) luminosities, also per colliding pair [9]. Unfortunately, the bunch-by-bunch data were not produced coherently by all experiments (incomplete data set).

In 2011, this independent data path will be maintained and possibly improved. The persistency of these data is an issue. The idea of allowing these offline data to be stored centrally in the LDB (or a new central database) should be considered.

Vacuum: Strong pressure rises in the neighborhood of the IPs have been observed toward the end of the 2010 proton run, when e-cloud effects became important. This has raised the question "how much pressure increase could the experiments tolerate during physics fills ?". A precise and definitive answer cannot be given. ATLAS has, for example, seen effects of the pressure rise on the jet rate (increase of the "fake" jet rate), although it is believed that means to reduce this effect could be implemented. In general, a pressure not exceeding 10^{-8} mbar seemed bearable. Nevertheless, the experience and impact of such vacuum degradations needs to be further investigated and monitored.

Ghost charge / satellite bunches: The amount of charge outside the nominal buckets ("ghost charge") was larger in certain fills. In some occasions, this was traced back to issues in the SPS (800 MHz cavities). However, the amount of ghost charge is also expected to increase with the reduction of bunch spacing (in bunch trains). The experiments were asked to re-assess their requirements on the amount of proton charge not contained in the nominal (colliding) RF buckets. As a starting point, it seems that a fraction of up to 5% ghost charge (relative to the total beam intensity) could be acceptable. However, as for vacuum pressure degradation, a definitive answer cannot be given. The effects should be further investigated and monitored. For the special case of luminosity calibration runs (typically with largely spaced bunches) the required limits on ghost charge are more stringent (< 0.5%) and also depend on the ability to quantify the amount of ghost charge.

CONCLUSION

The LHC produced first pp physics collisions at $\sqrt{s} =$ 7 TeV in March 2010, starting with a luminosity of about $8 \cdot 10^{26}\ \mathrm{Hz/cm^2}$ and finally reached $2 \cdot 10^{32}\ \mathrm{Hz/cm^2}$ in October 2010, thus brilliantly surpassing the target.

The experiments took advantage of the gradual luminosity increase to step through (i) calibration of the detectors, (ii) "re-discovery" of particle physics (quarkonia, weak bosons, top quarks, ...), thus gauging the level of understanding of their detectors, and finally (iii) to actually produce physics results.

Cooperation between machine and experiments was again excellent and needs to be steadily continued, both for forthcoming operation and for offline data analysis. A detailed list of suggestions and points for possible improvements was presented. These now have to be followed up.

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[4] See S. Redaelli in these proceedings and in proceedings of the December 2010 LHC Beam Operation workshop, Evian.

[5] Bunch Current Normalisation Working Group (BCNWG), see http://lpc.web.cern.ch/lpc/bcnwg.htm.

[6] LHC Lumi Days workshop, see http://indico.cern.ch/conferenceDisplay.py?confId=109784.

[7] "LHC-EXPERIMENTS HANDSHAKE PROTOCOL OVER DIP", EDMS document 1031913, R. Alemany et al., see https://edms.cern.ch/document/1031913.

[8] See `/afs/cern.ch/user/l/lpc/w0/2010/measurements/`. Data summary files explained in the text file `README.filecontents`.

[9] See G. Papotti in these proceedings.