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Beam Commissioning Procedure

OVERALL STRATEGY FOR EARLY LUMINOSITY OPERATION WITH PROTONS

Abstract

A staged approach is proposed for the early operation of the LHC for luminosity production with protons. The different stages from first collisions through to 25ns operation, where nominal performance should be reached, are outlined, together with expected performance levels. Both TOTEM and ion running have to be accommodated into this approach.

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History of Changes

Rev. No.	*Date*	*Pages*	*Description of Changes*
0.1	2004-07-23	All	Draft for discussion at LHC-OP
0.2	2004-10-06		TOTEM and ion running added, submitted for Engineering Check
0.3	2004-11-16	Cover	No changes, submitted for approval
1.0	2004-12-16	4,5,6,7,8	IP2 considerations added Setting collimators with nominal beta added Caution about high intensity 75ns added Numerous details corrected

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1. INTRODUCTION

In order to debug the LHC machine and experiments a pilot physics run with few bunches and low luminosity is envisaged. First commissioning with beam, from first injection through to first collisions, will be made with this in mind. The pilot physics run is proposed to last about one month, and is expected to be an interleaved mixture of physics runs and machine development in order to increase performance in this mode. Following this, attention will shift to many-bunch operation; first with 75ns and later with 25ns bunch spacing. As well as following this primary commissioning line, setting up and making the first runs for both TOTEM and with ions will have to be accommodated.

Performance estimates are based on the standard luminosity equation

$$L = \frac{N^2 k_b f \gamma}{4\pi \varepsilon_n \beta^*} F \quad ,$$

where N is the number of protons per bunch, k_b the number of bunches per beam, f the revolution frequency, γ the relativistic factor, ε_n the normalised emittance, β^* the value of the betatron function at the interaction point, and F the reduction factor caused by the crossing angle, which is 1 for head on collisions and about 0.85 for the nominal crossing angle.

2. PILOT PHYSICS RUN

The bunch pattern will be based on the transfer of 43 single bunches from the PS to the LHC via the SPS [1]. With 43 bunches per beam there will be no parasitic bunch crossings and the crossing angle scheme is therefore not needed. In order to provide collisions in LHCb a certain number of bunches in one beam will need to be displaced by 75ns. The number of displaced bunches can vary from fill to fill if required, but it should be noted that increasing the number of bunches colliding in LHCb results in an equivalent reduction in the luminosity of the other experiments.

The choice of physics energy for the pilot physics run is left open at the moment, but a lower energy is likely to be chosen as it should be somewhat easier to commission [2]. For the first fills there will be no beta-squeeze, and initial bunch intensities in the region of 10^{10} protons are foreseen.

During the pilot physics running period the performance will slowly be pushed upwards as the machine parameters are tuned and the beam intensity increases. This pilot physics period will therefore consist of physics fills interspersed with continued machine commissioning and development. The following improvements, not necessarily in this order, are likely during this period:

- Move to 156 bunches per beam [1]. This requires the injection of up to 4 trains of 4 equally spaced PS bunches per SPS supercycle and is transparent to the LHC. The crossing angle scheme is still not required. Displacement of some bunch trains will be required to give collisions in LHCb. For the same bunch intensity the luminosity will increase by a factor 4.
- Partial Optics Squeeze. The full beta-squeeze from 18m to 0.55m in the two high luminosity experiments in points 1 and 5 would bring an increase in luminosity by a factor of approximately 33. However, the final part of the squeeze will be the most difficult to achieve, and it is likely that the squeeze will be commissioned from 18m to around 2m during the pilot run. This brings an increase in luminosity by a factor 9 for the high luminosity experiments. IP2 and IP8 will not be changed.

- Increase bunch intensity. An initial bunch intensity of 10^{10} is just 10% of the nominal intensity – but is still enough to cause considerable damage in the machine. As the control of the machine parameters improves, the bunch intensity can be increased slowly. A practical limitation will come from the event pile up in the experiments, leading to a maximum bunch intensity in physics for this period of $4\ 10^{10}$. This bunch intensity increase will bring a further factor 16 increase in the luminosity. For machine development purposes, higher bunch currents may well be used.

Performance levels that can be expected during this phase are summarised in Table 1, although as the performance is pushed the complications increase and the full benefit of the above factors might not be realised. It should be pointed out that here, as everywhere else in this note for luminosity physics conditions, a nominal transverse emittance of 3.75μm is assumed in collision, even for significantly reduced bunch intensities, since it may take some time to learn how to master emittance preservation in the LHC.

Beam energy (TeV)	6.0, 6.5 or 7.0	6.0, 6.5 or 7.0	6.0, 6.5 or 7.0
Number of bunches (per beam)	43	43	156
β* in IP 1, 2, 5, 8 (m)	18,10,18,10	2,10,2,10	2,10,2,10
Crossing Angle (μR)	0	0	0
Transverse emittance (μm)	3.75	3.75	3.75
Bunch spacing (μs)	2.025	2.025	0.525
Bunch Intensity	$1\ 10^{10}$	$4\ 10^{10}$	$4\ 10^{10}$
Luminosity in IP 1 & 5 ($cm^{-2}\ s^{-1}$)	$\sim 3\ 10^{28}$	$\sim 5\ 10^{30}$	$\sim 2\ 10^{31}$
Luminosity in IP 2 ($cm^{-2}\ s^{-1}$)	$\sim 6\ 10^{28}$	$\sim 1\ 10^{30}$	$\sim 4\ 10^{30}$

Table 1: Performance levels expected during the pilot physics run

Beyond this, during this phase the crossing angle would be commissioned, giving a direct measurement of the effect that this has on luminosity without the added effects of running with parasitic beam-beam encounters.

3. 75ns OPERATION

Running with 75ns bunch spacing brings several advantages compared to 25ns operation [3]:

- The reduced number of parasitic beam-beam encounters allows a relaxed crossing angle
- With increased β^* any field errors in the triplet are less critical
- The electron cloud effect is not expected to be a problem
- Total beam intensities are reduced

Since electron cloud is not expected to be a limitation, 75ns operation could begin without embarking on scrubbing, the process of using the beam to clean the surfaces of the vacuum chambers. The same may well be true for smaller bunch spacing, such as 50ns, but this creates the problem of missing collisions in LHCb.

It is therefore proposed to begin multi-bunch operation with 75ns bunch spacing with relaxed parameters. This mode would be used for luminosity production while learning how to manage multi-bunch operation. Eventually in this mode the aim would be to move to nominal β^* and crossing angle.

Table 2 shows expected performance levels under selected conditions. Column 1 shows a proposed initial target, taking the β^* and bunch intensity parameters hopefully achieved at the end of the pilot run. Column 2 shows what would be achieved if nominal β^* and crossing angle could be reached. In both of these cases the bunch current has been selected to keep the event pileup at a reasonable level. It should be pointed out at this stage that reaching nominal β^* requires to fulfil very demanding tolerances on machine stability as well as on collimator position and alignment. Should this prove to be too difficult in early operation, it may well be better to run with higher β^* (such as 1m or 2m) with correspondingly lower luminosities.

Once optimum β^* and crossing angle has been reached, the machine would be in a suitable state to switch to 25ns operation, and this move should be made as early as possible. However, if for some reason there is a limitation in the total current, it would be better to put it into fewer bunches, if the experiments could stand the event rate and subject to possible limitations imposed by staging certain equipment (see section 8). Column 3 shows what could be achieved by pushing the bunch current to 9 10^{10} protons. This is to be compared with Column 1 of Table 3, where the same total intensity is injected into bunches with 25ns spacing.

Beam energy (TeV)	6.0, 6.5 or 7.0	6.0, 6.5 or 7.0	6.0, 6.5 or 7.0
Number of bunches (per beam)	936	936	936
β* in IP 1, 2, 5, 8 (m)	2,10,2,10	0.55,10,0.55,10	0.55,10,0.55,10
Crossing Angle (μR)	250	285	285
Transverse emittance (μm)	3.75	3.75	3.75
Bunch Intensity	4 10^{10}	4 10^{10}	9 10^{10}
Luminosity in IP 1 & 5 (cm^{-2} s^{-1})	~ 1 10^{32}	~ 4 10^{32}	~ 2 10^{33}
Luminosity in IP 2 & 8 (cm^{-2} s^{-1})	~ 2 10^{31}	~ 2 10^{31}	~ 1 10^{32}

Table 2: Performance levels expected during 75ns operation

4. 25ns OPERATION

It is expected that electron cloud effects will limit the bunch intensity in 25ns operation to around 3-4 10^{10} protons until successful beam scrubbing has been performed. This is expected to take a few weeks after each long machine shutdown.

Assuming that the 75ns operation has allowed reaching all other nominal parameters, Table 3 shows expected performance levels for different bunch intensities. As already mentioned, column 1 shows a factor 3 reduction in luminosity compared to the same total current injected into 75ns bunches, and could be achieved without beam scrubbing. Column 2 could be achieved after a period of beam scrubbing. Column 3 shows nominal parameters.

Beam energy (TeV)	6.0, 6.5 or 7.0	6.0, 6.5 or 7.0	7.0
Number of bunches (per beam)	2808	2808	2808
β* in IP 1, 2, 5, 8 (m)	0.55,10,0.55,10	0.55,10,0.55,10	0.55,10,0.55,10
Crossing Angle (μR)	285	285	285
Transverse emittance (μm)	3.75	3.75	3.75
Bunch Intensity	3 10^{10}	5 10^{10}	1.15 10^{11}
Luminosity in IP 1 & 5 (cm^{-2} s^{-1})	~ 7 10^{32}	~ 2 10^{33}	10^{34}
Luminosity in IP 2 & 8 (cm^{-2} s^{-1})	~ 4 10^{31}	~ 1 10^{32}	~ 5 10^{32}

Table 3: Performance levels expected during 25ns operation

5. IP2 CONSIDERATIONS

While the ALICE experiment located in IP2 is primarily conceived for ion physics, there is also a strong interest to exploit pp operation. The preferred luminosity is initially around 10^{29} $cm^{-2}s^{-1}$ in order to have clean events (no pileup, small even size). Later, for rare processes, higher luminosities (up to 5 10^{30} $cm^{-2}s^{-1}$) are acceptable. Above 10^{31} $cm^{-2}s^{-1}$, however, ALICE has to switch off certain sub detectors for stability reasons. Finally, for extended running with luminosities above a few 10^{32} $cm^{-2}s^{-1}$, accumulation of excessive radiation becomes a concern.

IP2 luminosities during the pilot run with unsqueezed optics (Table 1) satisfy these requirements very nicely. However once 75ns operation begins with reasonable bunch intensities, the IP2 luminosity is too high with β^* of 10m. The optics in IP2 has been designed to allow adjustment for higher β^* and values of up to 200m are possible in principle. However, β^* values larger than 35m are no longer compatible with a beam separation of at least 7 sigma and are only feasible for configurations with large bunch spacing or low bunch intensities. With 25ns operation, at least with reasonable bunch intensities, the required β^* is out of range and transverse beam displacement will be needed to provide collisions at acceptable rates.

6. IP8 CONSIDERATIONS

Due to its efficient trigger, the LHCb experiment located in IP8 requires a much lower luminosity (2 10^{32} $cm^{-2}s^{-1}$) than the nominal LHC luminosity. As indicated above in Tables 2 and 3, IP8 luminosities with β^* = 10m are below this value during early operation and above this value when nominal conditions have been achieved. Therefore, in order to optimise the physics potential in LHCb, the optics in IP8 has been designed to allow adjustment over the range 1m < β^* < 30m.

Nominal IP8 luminosity will not be in range during the pilot run. However, 10^{32} cm^{-2} s^{-1} and above should be possible with 75ns operation at modest bunch intensities. For all 25ns operation, delivering nominal luminosity to LHCb should not be an issue.

7. TOTEM CONSIDERATIONS

The TOTEM experiment will measure the total pp cross-section and study elastic proton scattering, and is also interested in the study of diffractive events. This results in various run scenarios, most of which require a particular machine configuration that is considerably different from the standard configuration in IP5. The experiment suggests several runs, typically of one day duration, spread throughout the first years of machine operation. Furthermore the total-cross section measurements should begin in the initial phase of LHC operation.

While these runs are expected to be short, requiring perhaps just one substantial physics coast per measurement, the time to switch in and out of this mode of operation should not be underestimated. The experience with LEP polarisation runs shows that 2-3 shifts should be allocated for preparation and recovery each time. Furthermore, considerably longer will be needed to commission the new optics with tight beam conditions the first time it is tried on the machine, and to understand how to safely operate the Roman pots located either side of IP5.

Performance levels that can be expected under selected conditions in IP5 are summarised in Table 4. It should be noted that TOTEM would prefer to run with the lowest possible transverse emittance, and suggest a target value of 1μm for the 43 and 156 bunch operations, which will be difficult to achieve. Furthermore, there is an interest to make total cross section measurements at lower energies, if possible as low as the Tevatron beam energy of 0.9TeV.

Finally, TOTEM is presently evaluating additional running scenarios, and the conditions shown in Table 4 are not intended to be complete.

Beam energy (TeV)	6.0, 6.5 or 7.0	6.0, 6.5 or 7.0	6.0, 6.5 or 7.0
Number of bunches (per beam)	43	156	2808
β* in IP 5 (m)	1540	1540	18
Crossing Angle (μR)	0	0	285
Transverse emittance (μm)	3.75	3.75	3.75
Bunch spacing (μs)	2.025	0.525	0.025
Bunch Intensity	$3\ 10^{10}$	$6\ 10^{10}$	$1.15\ 10^{11}$
Luminosity in IP 5 ($cm^{-2}\ s^{-1}$)	$\sim 4\ 10^{27}$	$\sim 6\ 10^{28}$	$\sim 3\ 10^{32}$

Table 4: Performance levels expected during TOTEM operation

The ATLAS experiment is also likely to be equipped with Roman pots around IP1 for calibration purposes. They will require a particular machine configuration in IP1, and low emittance beams, for calibration runs. In the interest of operational efficiency, cross section and calibration runs should take place in points 1 and 5 simultaneously.

8. IONS

The ALICE experiment has requested a short run with ions "before the first long shutdown". As with TOTEM running, the time to prepare for this mode of operation should not be underestimated, particularly the first time it is tried.

The first ions runs will be made using the so-called "early ion scheme", which foresees 62 bunches per beam and a β^* of 1m in IP2. With all other parameters as nominal, the performance levels that can be expected under these conditions are summarised in Table 5.

Beam energy / nucleon (TeV)	2.76	2.76
Number of bunches (per beam)	62	592
β* in IP 2 (m)	1	0.5
Crossing Angle (μR)	0	0
Transverse emittance (μm)	1.5	1.5
Bunch spacing (μs)	1.350	0.099
Bunch Intensity	$7\ 10^{7}$	$7\ 10^{7}$
Luminosity in IP2 ($cm^{-2}\ s^{-1}$)	$\sim 5\ 10^{25}$	10^{27}

Table 5: Performance levels expected during early and nominal ion operation

9. OTHER CONSIDERATIONS

With the above evolution in mind, two key accelerator systems will be staged. Firstly, 8 out of the final 20 beam-dump dilution kickers will be installed for first beam. With this configuration the beam dump can safely deal with up to half the nominal intensity distributed around the machine, corresponding to around $5\ 10^{10}$ protons per bunch in 25ns mode. Secondly, the collimation system will be installed in phases [4]. Due to impedance issues, with phase I collimators 25ns (and possibly 75ns) beams will be unstable at bunch intensities above around 5 10^{10} protons. Furthermore, staging of the TCLI collimators will limit the injected intensity per batch to 50% of nominal.

All modes and performance levels mentioned, except nominal and possibly high intensity 75ns operation, are possible under these conditions. A shutdown of 6 months is presently estimated to allow for sufficient cool down and installation of the final configuration. This estimate needs to be refined once details of the required intervention are better known.

10. CONCLUSIONS

The LHC will be commissioned with protons with the goal of providing a low luminosity pilot physics run with few bunches and relaxed machine parameters. Once this has been mastered, attention will turn to multi-bunch operation with 75ns bunch spacing. In this mode, luminosities in excess of 10^{32} cm^{-2} s^{-1} in IP1 and IP5 should be within reach with modest bunch intensities. If the experiments could stand the event rate at this stage, 10^{33} cm^{-2} s^{-1} is possible by pushing intensities towards 10^{11} protons per bunch. Once nominal machine parameters have been reached with 75ns bunches, operation will turn to 25ns bunch spacing, with modest bunch intensities to respect the beam dump, collimator and electron cloud restrictions. Luminosities in excess of 10^{33} cm^{-2} s^{-1} are possible under these conditions. Finally, after installation of the final beam dump and collimator configurations, and after a suitable scrubbing run, nominal performance is possible with 25ns bunches of 1.15 10^{11} protons per bunch.

TOTEM and ions will be accommodated into this scheme at the appropriate times, and the time needed to set up and switch to and from these modes should not be underestimated.

11. REFERENCES

[1] R.Bailey & P.Collier, *"Standard Filling Schemes for Various LHC operating Modes"*, LHC Project-Note 323, Geneva CERN, September 2003.

[2] R.Schmidt, *"Operating the LHC Initially at a Lower Energy"*, Proc. LHC Project Workshop, Chamonix XIII, 19-23 January 2004.

[3] O.Bruning, *"Parameter Evolution for the First Luminosity Runs"*, Proc. LHC Project Workshop, Chamonix XII, 3-8 March 2004.

[4] See the LHC Collimation Project for full details.