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Options and Preferences for proton Running in 2009

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Abstract

The choice of parameters for proton operation in the LHC in 2009 is subject to constraints from beam dynamics as well as the experiments desiderata. These constraints are reviewed and the preferred operational scenarios are presented together with possible strategies to increase the performance.

OBJECTIVE FOR PROTON RUNS IN 2009

A main objective for p running this year is to deliver significant luminosity to the LHC experiments, details have been presented in [1].

In preparation of running at the highest possible performance, it is important to gain experience with the dynamics of the beams, in particular in collision and the effect of many bunches in the machine. The knowledge of this behaviour and possible limitations will help to establish and improve the procedures and to define the strategies to obtain the maximum LHC performance.

KEY PARAMETERS

The key parameters for the LHC performance (luminosity) are:

- Beam energy
- Number of bunches
- Bunch intensity
- Beam size (i.e. β^*) at the collision point.

These parameters are strongly correlated and cannot be chosen freely. A consistent set of parameter is required for possible operational scenarios.

Energy

The beam energy is largely determined by the machine hardware and the experiments desiderata. The interesting options for the beam energy in 2009 are [1]:

- 450 GeV
- 2.75 TeV (ion comparison)
- 5 TeV (or maximum)

The choice depends on the availability and hardware performance of the machine and the protection of the accelerator must be taken into account to minimize the risk of damage.

Number of bunches

The number of bunches in the LHC is a key parameter for the performance and the beam dynamics. First, only with a large number of bunches the maximum luminosity can be reached and secondly, it will affect strongly the stability of the beam, in particular through the beam-beam interaction. The choice of the bunch filling scheme depends on the availability from the injector chain and the requirement to have collisions in all four experimental interaction points. The possible filling schemes are described in [2, 3, 4]. We have to distinguish two cases: a reduced number of bunches where a crossing angle is not required since counter-rotating bunches from the two beams never share the same beam pipe. For a large number of bunches a crossing angle is required to avoid parasitic collisions. We shall study the following options:

Without crossing angle (half longitudinal spacing larger than shared beam pipe length):

- 2, 3, 43, 156 bunches per beam

With crossing angle (half longitudinal spacing smaller than shared beam pipe length):

- 25, 50, 75 ns bunch spacing (within a train of 72, 36 or 24 bunches)
- Total beam intensity depends on number of injected trains (max. 39, see later)

For the choice of the bunch filling pattern one must take into account that the interaction point in IP8 is not in the symmetry position of the ring. For multiple bunches and a bunch spacing of 25 ns or 75 ns this does not have a negative effect since the longitudinal displacement of the experiment corresponds to 37.5 ns spacing, i.e. a reduced number of bunches from the two beams still collide in the centre of the detector [5, 6]. For equally spaced bunches or a very few bunches this is not the case. Therefore it is required to shift selected bunches longitudinally to allow collisions in the LHCb experiment.

The minimum number of bunches per beam ensuring collisions in all interaction points is 2. In this case all experiments have one colliding bunch pair per turn. However, in this case the two beams are not symmetric, i.e. the bunches are distributed in different relative buckets. Adding a third bunch to each beams would make them symmetric, resulting in three interactions per turn for experiments in IP1 and IP5 and a single collision in IP2 and IP8. Another interesting aspect of this symmetric option is that the effect of missing collisions on the beam dynamics can be studied in a very simple configuration and at an early stage of the commissioning.

Optical function β^* at interaction point

For a given beam emittance (mostly determined by the injector chain) the beam size and therefore the luminosity is determined by the β^* at the interaction point. As it will be shown, the choice of β^* is strongly constrained by machine considerations and the beam dynamics. Given the constraints can be fulfilled, the β^* is chosen to optimize the experimental conditions desired by the experiments [1].

COLLISIONS WITHOUT CROSSING ANGLES

Collisions without a crossing angle are possible when two bunches never share the same vacuum chamber at the same time. This is the case for the filling schemes with 2, 3, 43 and 156 bunches per beam. The cases for 2 and 3 bunches have been discussed above and are trivial cases when bunches are injected into the correct longitudinal slots. We therefore study cases with more bunches:

- (Almost) equally spaced bunches (either 43 or 156)
- Requires shifting some bunches to allow for collisions in LHC*b*
    - Shift done by adjusting timing of SPS to LHC transfer
    - Determines possible filling schemes
    - Filling schemes can be adjusted to meet requirements from experiments

It should be noted that the TOTEM experiment with $\beta^* = 90$ m must run without crossing angle.

Bunch filling options

Starting with the filling scheme with 43 bunches per beam, a maximum number of collisions is found in IP1 and IP5 while a slightly reduced number in IP2 (due to the beam dump abort gap). Because of the shifted interaction point in IP8, no collisions occur for equally spaced beams. The required longitudinal shift to allow such collisions can be arranged at the transfer of the beams from the SPS to the LHC. The number of shifted bunches can be varied (see Tab.1) which allows to re-distribute the number of collisions between IP2 and IP8 [4]. When the shift is done symmetrically in both beams, the number of collisions in IP1 and IP5 are not affected, except that the time between collisions is not equal.

A corresponding table with 2 options for 156 bunches per beam is shown in Tab.2.

displaced	0	4	11	19
IP1	43	43	43	43
IP2	42	34	21	4
IP5	43	43	43	43
IP8	0	4	11	19

Table 1: Possible filling schemes for 43 bunches per beam.

	no bunches displaced	option 1	option 2
IP1	156	156	156
IP2	152	76	16
IP5	156	156	156
IP8	0	36	68

Table 2: Possible filling schemes for 156 bunches per beam.

Optical parameters and aperture

For a configuration without a crossing angle the limiting factor becomes the aperture. Therefore the key parameters are:

- β^*, since $\hat{\beta} \propto 1/\beta^*$
- Energy, since $\sigma_{max} \propto 1/\sqrt{\gamma}$

It is therefore necessary to determine the minimum β^* possible as a function of the beam energy. As a criterion I have used the standard definition of the aperture and require $n1 \geq 7.0$.
The result of this evaluation is shown in Fig.1 where I show the minimum β^* as a function of the beam energy E. For lower energies the minimum β^* is strongly restricted. Since some runs are foreseen at the injection energy of 450 GeV, I show the corresponding figure for low energies (Fig.2). A minimum β^* of 5 - 6 m at 450 GeV can be obtained from the data.

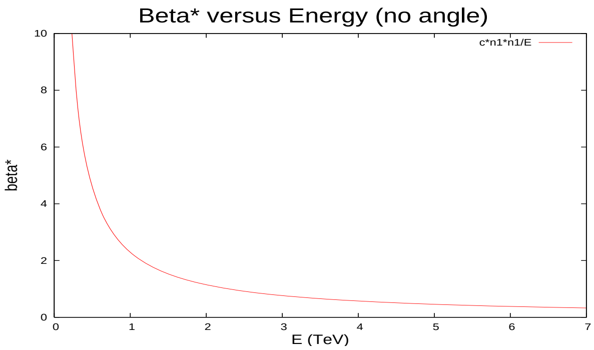

Figure 1: Minimum β^* as function of energy E.

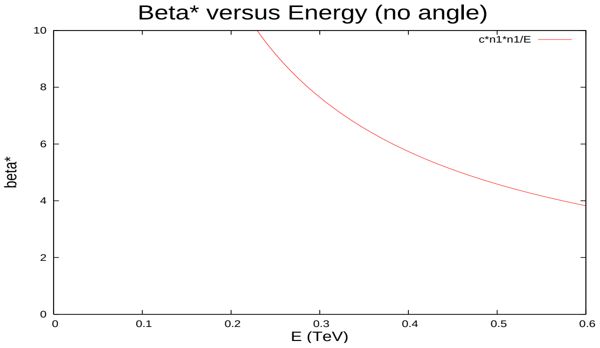

Figure 2: Minimum β^* as function of energy E.

Collisions at 450 GeV

At 450 GeV a crossing angle is not possible and collisions are only possible for a small number of bunches. The possible conditions are:

- No crossing angle: 2, 3, 43, or 156 bunches per beam
- β^* limited to $\beta^* \geq$ 6 m (may want to stay at injection value of β^* = 11 m)
- Assuming N = 0.4 10^{11}, $\epsilon_n = 3.75\ \mu$m
- Luminosity IP1/5 (43 bunches) $\approx 1.3{\cdot}10^{29}$ cm^{-2}s^{-1}
- Luminosity IP1/5 (156 bunches) $\approx 4.7{\cdot}10^{29}$ cm^{-2}s^{-1}

The luminosity in IP2 and IP8 will be smaller due to the reduced number of colliding pairs, depending on the filling scheme (see Tab.1).
Smaller emittances have been measured for the reduced intensity per bunch, but since the head-on beam-beam tune shift does not depend on γ or β^*, but only on the bunch intensity and emittance like:

$$\Delta Q \ \propto \ \xi \ = \ \frac{N \cdot r_o \cdot \beta^*}{4\pi\gamma\sigma^2} \ = \ \frac{N \cdot r_o}{4\pi\epsilon_n}$$

we cannot hope to collide bunches at a significantly lower emittances than the nominal value of $\epsilon_n = 3.75\ \mu$m.

Collisions at other energies

Under the same assumptions, (i.e. N = 0.4 $\cdot$ 10^{11}, $\epsilon_n = 3.75\ \mu$m) and with the help of Fig.1 one can derive the minimum β^* and the corresponding luminosity for the cases with 43 and 156 bunches per beam. This is summarized in Tab.3 for the three proposed energies. The β^* should be considered as a comfortable limit, but to minimize risk a larger value can be chosen.
At the corresponding interaction rates the luminosity lifetime is not determined by the loss of particles due to the collisions, but by other limitations and therefore is difficult to quantify without relevant operational experience.

Energy (TeV)	β^* (m)	$\mathcal{L}_{43}$ (cm^{-2}s^{-1})	$\mathcal{L}_{156}$ (cm^{-2}s^{-1})
0.45	6	$0.13 \cdot 10^{30}$	$0.47 \cdot 10^{30}$
2.75	1	$4.30 \cdot 10^{30}$	$15.6 \cdot 10^{30}$
5.00	0.6	$13.0 \cdot 10^{30}$	$47.0 \cdot 10^{30}$

Table 3: Luminosities for different options without crossing angle an limited number of bunches.

COLLISIONS WITH CROSSING ANGLE

Basic considerations

In case the bunches collide with a finite crossing angle, the formula for the luminosity has to be modified to include a geometric reduction factor S. The luminosity with a crossing angle α in x-plane (round beams) is then:

$$\mathcal{L} = \frac{N_1 N_2 f n_b}{4\pi\sigma_x\sigma_y} \cdot S$$

where S is the reduction factor and for small crossing angles and (Gaussian bunches) $\sigma_s \gg \sigma_{x,y}$ can be written as:

$$\Rightarrow S \approx \frac{1}{\sqrt{1 + (\frac{\alpha}{2}\frac{\sigma_s}{\sigma_x})^2}} \ = \ \frac{1}{\sqrt{1 + (\frac{\alpha^2}{4}\frac{\sigma_s^2}{\beta_x\epsilon})}}$$

The head-on beam-beam tune shift is reduced by the same factor and becomes;

$$\Delta Q_x \ \approx \ \xi \cdot S \ = \ \frac{N \cdot r_o \cdot \beta^*}{4\pi\gamma\sigma^2} \cdot S \ = \ \frac{N \cdot r_o}{4\pi\epsilon_n} \cdot S$$

The beam-beam tune shift is reduced in the plane of the crossing angle and not symmetric for the two planes, even in the case of round beams. The alternating crossing scheme [7] of the LHC partly compensates for this effect.

How many bunches should we aim at ?

Depending on the conditions, the optimum number of bunches can change. Re-writing the formula for the luminosity in terms of the total beam intensity I_{tot} instead of the bunch intensity N:

$$\mathcal{L} \ \propto \ N \cdot N \cdot n_b \ = \ I_{tot} \cdot N \ = \ \frac{I_{tot} \cdot I_{tot}}{n_b}$$

and the equivalent formula for the beam-beam tune shift:

$$\Delta Q \ \propto \ N \ = \ \frac{I_{tot}}{n_b}$$

we observe that as long as the total intensity is limited, e.g. by machine protection considerations, and the bunch intensity N is not a limiting factor, a smaller number of bunches can provide the better performance.

Bunch filling options

For a large number of bunches and in the presence of a crossing angle, the bunches are arranged in trains of 72, 36 or 24 bunches with a spacing of 25, 50 or 75 ns respectively. Two key parameters for the three options are shown in Tab.4: the distance between parasitic encounters Δs (half the bunch spacing) and the corresponding number of parasitic long range interactions per experimental area.

Bunch spacing	Δs	# long range encounters (per IP)
25 ns	3.75 m	32
50 ns	7.50 m	16
75 ns	11.25 m	12

Table 4: bunch spacing and parameters for long range encounters.

It is rather obvious that the detrimental effects of long range interactions should be strongly suppressed for the options with 50 ns and 75 ns since they largely depend on the number of long range encounters. This has been verified in a simulation of the dynamic aperture for the cases 25 ns and 50 ns [8].

Starting from the nominal filling scheme [2] and removing bunches from the nominal trains to get the desired spacing, one arrives at the number of collisions in the four experiments as shown in Tab.5. Since no collisions can occur under these conditions in IP8, the options with 50 ns was excluded although a better performance for electron cloud effects as compared to the 25 ns option is expected. However, it was revived recently [3, 4] since it allows to redistribute the collisions in the different experiments when entire trains are shifted for collisions in IP8. In Tab.6 I show 4 options (together with the not shifted case) where batches from the SPS have been shifted at the time of the transfer for injection into the LHC. In the last case (e) one train was replaced by a single bunch to minimize the collision rate in IP2. To avoid losses of collisions in IP1 and IP5, both beams are shifted symmetrically. Details of the schemes shown in Tab.6 can be found in [4].

Spacing	IP1	IP2	IP5	IP8
25 ns	2808	2736	2808	2622
50 ns	1404	1368	1404	0
75 ns	936	912	936	874

Table 5: Number of collisions for different bunch spacing.

	a	b	c	d	e
IP1	1404	1404	1404	1404	1333
IP2	1368	684	0	72	2
IP5	1404	1404	1404	1404	1333
IP8	0	655	1311	1242	1173

Table 6: Number of collisions for 50 ns bunch spacing and different options for shifted trains.

Required crossing angle

The crossing angle to avoid parasitic encounters must be large enough to minimize the detrimental effects of long range beam-beam interactions, but should not reduce the luminosity too much and should fit inside the available aperture. From simulations of the dynamic aperture a minimum separation d_{sep}can be determined and the corresponding necessary crossing angle is computed as:

$$\alpha = \frac{d_{sep} \cdot \sqrt{\frac{\epsilon_n}{\gamma}} \cdot \sqrt{\beta^* \left(1 + \frac{\Delta s^2}{\beta^{*2}}\right)}}{\Delta s}$$

where Δs is half the bunch spacing, and d_{sep} the minimum required separation in the drift between IP and Q1 (for nominal running $\approx$ 9.5)

For $\Delta s \gg \beta^*$ (and with parallel separation) we have simply:

$$\alpha = \frac{d_{sep} \cdot \sqrt{\frac{\epsilon_n}{\gamma}}}{\sqrt{\beta^*}}$$

It is clear that for small β^* and lower energy γ a larger crossing angle is required. In Figs. 3 to 5 I show the necessary crossing angle for three energies to obtain a minimum separation in the drift space of about 10 σ which corresponds approximately to the nominal case. Since for larger values of β^* the crossing angle also depends on the bunch spacing, the figures show the values for 25 ns as well as for 50 ns spacing. The steep rise of the required angle for small β^* is very visible and for all energies a minimum around 3 - 4 m for a bunch spacing of 25 ns is observed. Please note that for values of β^* less than 0.5 m the required aperture is not available and the curve does not correspond to possible scenarios.

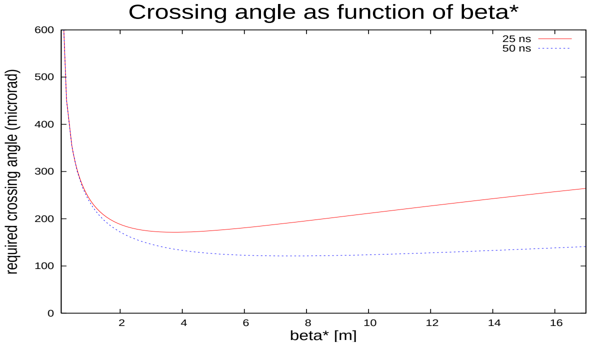

Figure 3: Minimum crossing angle for different 25 ns and 50 ns spacing as function of β^* at 7 TeV.

For the energies of 5 and 7 TeV a crossing angle of

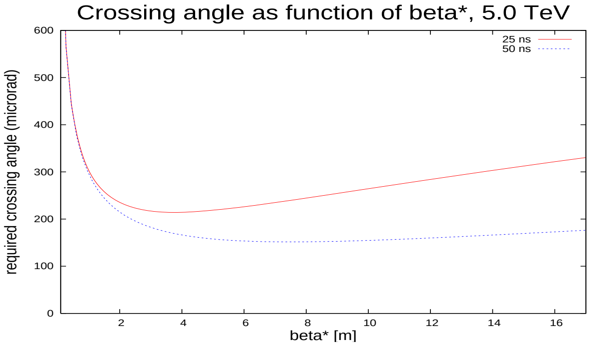

Figure 4: Minimum crossing angle for different 25 ns and 50 ns spacing as function of β^* at 5 TeV.

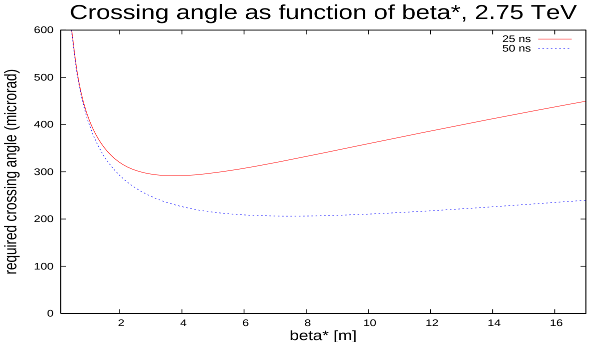

Figure 5: Minimum crossing angle for different 25 ns and 50 ns spacing as function of β^* at 2.75 TeV.

300 μrad is considered safe and with this angle and assuming a bunch intensity of $N = 0.5 \cdot 10^{11}$ protons per bunch I show the corresponding luminosities (in units of 10^{32}cm^{-2}s^{-1} for three values of β^* in Tab.7. The three possible spacings are included and the luminosity calculated for the collisions in IP1 and IP5. For the reduced number of collisions in IP2 and IP8 (depending on the filling scheme, see above) the number should be scaled, including a scaling with β^* when necessary.

Energy (TeV)	β^* (m)	$\mathcal{L}_{936}$ (cm^{-2}s^{-1})	$\mathcal{L}_{1404}$ (cm^{-2}s^{-1})	$\mathcal{L}_{2808}$ (cm^{-2}s^{-1})
5.0	3.0	0.9	1.4	2.8
5.0	2.0	1.4	2.1	4.2
5.0	1.0	2.6	4.0	8.0
7.0	3.0	1.3	2.00	4.0
7.0	2.0	2.0	3.00	6.0
7.0	1.0	4.0	6.00	12.0

Table 7: Luminosity in IP1 and IP5 for different options (filling schemes and β^*).

The luminosities can fulfill the requirements for a significant luminosity [1]. With the interaction rate per crossing the luminosity lifetime is again not determined by the interaction rate itself and a reliable estimate cannot be made.

COLLISIONS IN IP2 AND IP8

The experimental conditions in IP2 and IP8 are different from IP1 and IP5 since both experiments are not general purpose detectors and require reduced interaction rates, i.e. luminosities. Furthermore, additional complications are the large internal crossing angles produced by compensation of their spectrometers [5, 4, 6, 9]. Without any external angle (i.e. 43 or 156 bunches) no constraints on the spectrometer polarities and on their strengths (even at 450 GeV) are present, i.e. no ramping required.

The external crossing angles (if required) follow the plane given by the internal angle [7].

The case of IP8 is more complicated since it features a horizontal crossing angle and to avoid more than one crossing, a more complicated crossing scheme is required [5, 6]. As mentioned, it also requires shifted trains to allow collisions in case of 50 ns bunch spacing. The complete analysis [6] shows that an energy ramping is required for one of the spectrometer polarities in IP8. At 5.0 TeV a minimum $\beta^* \geq 3$ m (better: 4 m) is possible for both polarities [6].

STRATEGY TO INCREASE TOTAL INTENSITY

An important question is the strategy to increase the performance in the machine. While a reduction of β^* can be done with improved operational experience and taking the appropriate crossing angle, the increase of the intensity in the bunches and the entire beam current deserves special consideration.

General considerations

For the increase of the total beam current we have basically two very different options:

- Inject all (or many) bunches and in steps increase intensity per bunch
- Large (maximum) intensity per bunch and in steps increase number of bunches (i.e. trains)

The two strategies have very different effect on the beam dynamics and operational procedures. Although at this moment and without any operational experience with many bunches in the LHC it cannot be decided, a few arguments in favour of option two can be given. In the second case already at rather low total beam current we have the complete beam-beam collision schedule since the number of long range encounters depend on the number of bunches in the train and not the total number of trains (which determines the total beam current). Adding additional trains therefore does not change the dynamics since the added bunches should in principle behave like the ones already circulating in the machine, at least in the first approximation. Operationally it also does not require advanced manipulations in the injector chain since the only difference would be whether a train is injected from the SPS into the

LHC or not, in particular no adjustment of the bunch intensity in the chain is required.
Another argument comes from the experimental desiderata [1]:

- IP1 and IP5: largest possible luminosity for any configuration
- IP8: high luminosity, but 1 - 5 $\cdot$ 10^{32} cm^{-2} s^{-1} for any configuration
- IP2: low luminosity, if possible for any configuration

It can be demonstrated that the second option together with the 50 ns bunch spacing allows a control of collisions between the four experiments and simplifies to fulfill the above requirements.

Relative luminosities

I shall try to develop strategies to increase the total intensity in steps and at the same time fulfill the above request. To this purpose I start with a very few trains colliding in all four experiments and add total beam intensity by injecting further trains into the appropriate bunch slots (to allow collisions in IP8). In Fig.6 I show the relative luminosity (the effect of β^* and bunch intensity are normalized to allow a better comparison) as a function of the fraction of total beam intensity for the case of 25 ns bunch spacing.

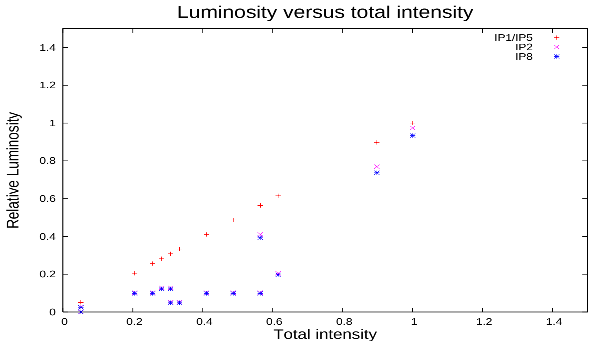

Figure 6: Relative luminosity in the four experiments as function of total beam energy for 25 ns bunch spacing.

The luminosities in IP1 and IP5 increase proportionally to the total current, while for IP2 and IP8 the relative luminosities can be kept low up to about 50% of maximum intensity and above reach values larger than desired. Since the 50 ns options allows to redistribute the colliding bunch pairs between IP2 and IP8 (see before) we can hope to get an improved scheme with this spacing. The result of an optimization is shown in Fig.7 and while IP1 and IP5 luminosities are still proportional to the maximum current (which is now half the current compared to 25 ns spacing), the luminosity can be kept small in IP2 over the full range. The luminosity in IP8 rises approximately proportional to the total current but at a lower level than the high luminosity experiments. Please note that the effect of β^* is not folded into the luminosity and the absolute value is much lower than in IP1 and IP5. The Fig.8 shows the low intensity part of Fig.7.

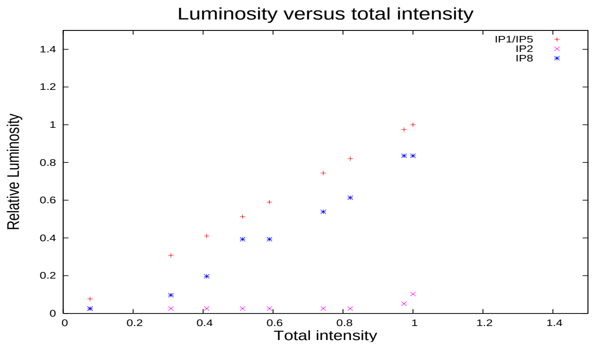

Figure 7: Relative luminosity in the four experiments as function of total beam energy for 50 ns bunch spacing.

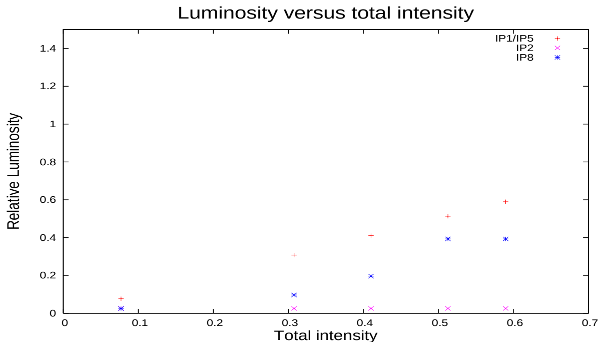

Figure 8: Relative luminosity in the four experiments as function of total beam energy for 50 ns bunch spacing.

Filling schemes

The disposition of the trains corresponding to a total current of 30% is shown in Fig.9. Doubling the intensity to 60% requires a train filling scheme as shown in Fig.10.

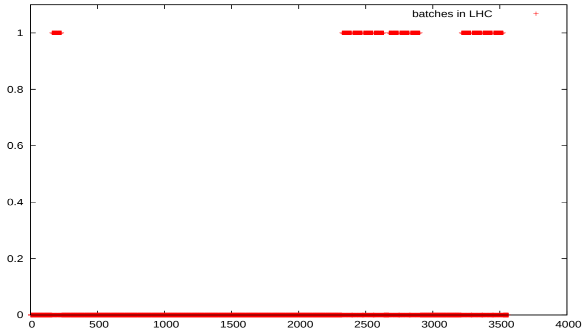

Figure 9: Disposition of 12 trains for a total intensity of 30%. Corresponds to 4 LHC injections from the SPS.

SUMMARY

In this presentation I have summarized possible options for the proton operation of the LHC in the initial stage.

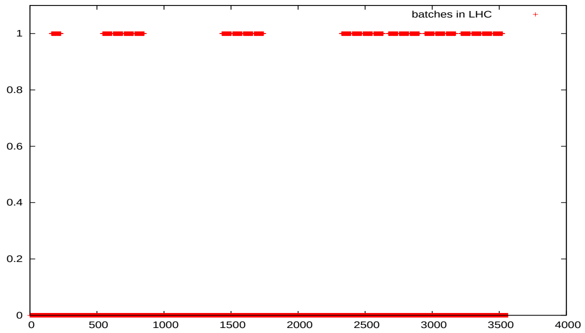

Figure 10: Disposition of 23 trains for a total intensity of 60%. Corresponds to 7 LHC injections from the SPS.

These include:

- Collisions without crossing angle at injection energy with injection optics or moderately squeezed.
- Collisions with and without crossing angle up to 5 TeV

For less than the nominal luminosity an option with 50 ns seems attractive:

- Lower total intensity
- Together with reduced β^* practically no effect from long range interactions expected.
- Adjustment of relative luminosity between the four experiments
- More flexible choice of the key parameters (β^*, crossing angle ..)

Until more solid operational experience is available, in particular concerning the dynamics of collisions, a high degree of flexibility is a strong advantage. It is feasible to reach the desired luminosity performance for the experiments [1].

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