PLANS FOR THE ION RUN IN 2016

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Abstract

The 2016 run will end with proton-lead collisions at either 4Z TeV, as in 2013, or 6.5Z TeV, still to be defined. This talk reviews the special features of operation with asymmetric collisions, and the lessons of the 2013 proton-nucleus run, as well as the 2015 lead-lead run. A new proton-filling scheme to match the lead scheme will have to be prepared in 2016. This talk also reviews the optics, the LHC operation cycle and the special requirements on various systems like RF and beam instrumentation.

FORMER ION RUNS AT LHC

Most of the LHC physics production time is spent in colliding proton beams to search for and study new elementary particles. Ten per cent of its time is dedicated, however, in colliding heavy nuclei to study the collective behaviour of deconfined hadronic matter at extreme energy densities and temperatures, the Quark-Gluon Plasma [1-4]. Moreover, since 2011, the heavy nuclei collisions are alternated with a new, more complex and almost unprecedented mode of collider operation, proton-heavy nuclei collisions recognized as a crucial component of the physics program with nuclear beams at high energies. They not only provide invaluable reference data to bench mark the Quark-Gluon Plasma studies, but also to elucidate the partonic structure of matter at low parton fractional momenta [5-7]. The list of former ion runs at LHC is shown in Table 1.

Table 1: Summary of the former ion runs at LHC.

		IP	L(ub^{-1})	β*	k_b	E_{beam} (Z TeV)
2010	PbPb	1,2,5	9.5	3	129	3.5
2011	PbPb	1,2,5	167.6, 143,149.7	1	356	3.5
2011	pPb	(Feasibility)		inj		3.5
2012	pPb	1,2,5,8	1 (Pilot)	inj	12	4
2013	pPb	1,2,5,8 LHCf TOTEM ALFA	31940 31200 31690 2120	0.8 0.8 0.8 2	296 288 296 39	4
2015	PbPb	1,2,5,8	703.7 433 600 6.81	0.8 0.8 0.8 3	518	6.37

2016 EXPERIMENTS REQUEST

Recently the LHC experiments provided their request for the 2016 ion run. Unlike earlier runs, the requirements are clearly dissimilar amongst the different experiments as summarized in Table 2. As a consequence this paper will remain as general as possible and it will summarize the potential performance in case of a heavy ion run or a proton-heavy ion run will take place at the end of 2016.

Table 2: Experiments request for the 2016 ion run.

Option	2016 E_{beam} (Z TeV)		2018 E_{beam} (Z TeV)		Comments
A	pPb	4	PbPb	4	Favor by ALICE, LHCb only
B	pPb	6.5	PbPb	4	Favor by ATLAS, CMS, LHCb, LHCf only
C	PbPb	4	PbPb	4	Favor by ATLAS, CMS only

In addition to this, ALICE requests a levelled luminosity of 1e28 cm-2s-1 during the whole run and a small amount of time at 1e29 cm-2s-1.

Last but not least, LHCb requires ten times more luminosity than in the past years requiring dedication of 4 to 5 more bunches to point 8 at the expenses of reducing the number of bunches at other interaction points (IP).

PARTICULARITIES OF pPb OPERATION

The LHC two-in-one magnet design ties the momentum of one beam to the momentum of the other. When both particles are of the same type this is not a problem. When hybrid collisions are envisaged, like protons against heavy nuclei, the equal beam rigidity condition fixes the momentum of the ion beam to be Z times the momentum of the proton beam, Z being the ion charge. Since we cannot count on the degree of freedom of two different rigidities, the system to rely on is the radiofrequency system that, in LHC, is independent for both beams.

LHC RF

Due to the different mass to charge ratio of lead ions (Z=82, A=208) compared to protons (Z=1, A=1), the lead revolution period is higher than protons, i.e. the lead beam takes longer to perform a turn around LHC than the proton beam. Since the frequency of the RF system is proportional to the revolution frequency (the inverse of the revolution period) it is straightforward to conclude that the RF cavities need to be tuned to different frequencies for each beam to allow them to run at their natural frequencies. This keeps both particle types on stable central orbits.

During the injection the RF frequencies are kept uncoupled being the difference between them of around 5000 Hz. During the ramp both frequencies approach each other as the momentum of the beam increases and once at flattop, the difference is of few tens of Hz. In particular 60 Hz at 4Z TeV and 22 Hz at 6.5Z TeV.

As long as the frequencies are separated, the encounter points between bunches of the two beams are shifting around the ring, modulating the long range beam-beam interactions. This phenomenon although severely limited the D-Au operation of RHIC, did not affect, fortunately, the proton-heavy nuclei operation at LHC.

In order to allow the beams to encounter each other at the same position every time, ideally, of course, at the IPs, both RF frequencies have to have the same value. This exercise is called RF frequency lock and cogging and takes place at flattop. Forcing both frequencies to be the same implies that the lead ion has to move to the inside of the ring to compensate for being slower, and equivalently the proton beam has to move to the outside of the ring to travel a larger distance to compensate for being faster. This brings the beams to the so-called off-momentum orbits and the amount of orbit shift depends on the energy. If one would like to do this at injection energy, each beam would move outside the reference orbit by 70 mm, clearly out of reach in LHC given the dimensions of the beam pipe. This is way this is performed at flattop where the off-momentum orbits are shifted by few hundred of micrometers, well inside the available aperture.

Running with unlocked frequencies during the injection and ramp and the cogging exercise at 4Z TeV was routinely done in 2013 and no issues are expected, consequently, in 2016. At 6.5 TeV the situation is even more favorable since the frequency difference between both beams is smaller making the off-momentum orbits shift smaller.

Beam Position Monitors (BPM)

The ion bunches have an intensity of the order of 2e10 proton equivalent charges which correspond to a proton pilot bunch. Such bunch intensity requires the Beam Position Monitors (BPM) to operate at high sensitivity giving an orbit resolution that is worse than when operated at low sensitivity with high intensity beams. But it is still acceptable and no issues were encountered in 2013 because of this.

Operating the BPMs at high sensitivity gives problems, though, to the interlocked BPMs in point 6. A considerable amount of fills in 2013 were dumped due to them. Whenever a Pb (Z=82, A=208) collides with a proton, the lead beam losses 82 charges and the proton beam only one. Therefore, the total bunch intensity decreases faster for the ion beam. When operated at high sensitivity the bunch intensity threshold for a reliable BPM measurement is around 2.5e9 – 3.5e9 proton equivalent charges. Below this value the reading is false and the interlocked BPMs dump the beams. For the time being this problem does not have a solution; therefore we have to cope with it. Still the fill length in 2013 was in average 6 hours long.

Software Interlock System (SIS) and Beam Interlock System (BIC)

In order to implement a reliable machine protection against misconfiguration of the LHC rings or particle type injection errors, the information available in the SPS and LHC was appropriately combined into a software interlock logic successfully tested in 2011 and operational in 2013 [8]. In addition, a hardware interlock at the level of the SPS extraction BIC complemented the previous one. The extraction interlock effectively ensures that the RF frequency is correct and the beam is centered. The same interlocks will be used, of course, in 2016. The only point to keep in mind is that new reference orbits will be needed in SIS for the off-momentum orbits operation.

Beam Loss Monitors (BLM)

In 2013, after repetitive dumps during the ramp and squeeze, the BLM thresholds had to be increased. A possible explanation could be that the collimator settings were set for 0.6 m β^* (tight collimator settings), but in the end the β^* stepped back to 0.8 m giving rise to an inconsistency between β^* and collimators settings. It could be that in 2016 the collimator settings are better suited to the selected optics and no losses are observed. Other wise the thresholds would have to be increased again.

In addition, luminosity losses compared to PbPb collisions in dispersion suppressors around the experiments and in IR3 are much reduced in pPb operation, which is an advantage. Bound-free pair production rate is, as well, reduced to a few percent of the PbPb rate, thus, fewer losses are expected.

INJECTION PATTERS

In 2013 the proton beam was made out of 12 trains of 24 bunches each. The bunch spacing alternated 200 ns and 225 ns. The former being the maximum bunch compression achievable in the PS at that time, the latter was imposed by the SPS injection kicker rise time. The same filling patter applied to the ion beam. In the end the total number of bunches colliding in IP1, 2, 5 and 8 were 296, 288, 296 and 39, respectively.

In the following the potential for 2016 is presented bearing in mind that other new filling schemas could be developed during 2016 with even better performances.

The first improvement comes from the PS batch compression that could achieve 100 ns as demonstrated in 2015 PbPb run. The second improvement comes from the SPS whose injection kicker rise time could be reduced to achieve 200 ns for protons. The total number of bunches per train would remain 24 for both beams, protons and ions, but more trains would fit in the LHC and it is estimated that up to 400 bunches per beam could be attained, i.e. hundred bunches more than the 2013 injection pattern.

The second possible injection pattern would be as follows. The proton beam would require two transfers from BOOSTER to PS to get six bunches at the PS flat bottom. Every bunch would undergo a triple splitting to get 18 bunches separated 100 ns. Three transfers from PS to SPS would make a 54-bunch train in SPS to be transferred to the LHC. In this case each 18 bunches would be separated by 300 ns.

The ion beam would be made out of double splitting of a two-bunch transfer from LEIR, separated 100 ns. Twelve transfers from PS to SPS would make a train of 48 bunches. Every four bunches would be separated by 200 ns. This pattern has some advantages like the filling is faster since more bunches are transferred per SPS to LHC injection. But it also has some disadvantages, like the ion bunch intensity is expected to be lower (on the other hand less space-charge effects on the SPS flat bottom) and three lead bunches per SPS batch do not collide.

On the LHC side, the 100 ns bunch separation needs beam-beam parasitic encounters studies. No issues were observed in 2015 PbPb run, but beam-beam effects could be stronger in pPb, in particular if the proton intensity is increased a factor two to 2.5 than the lead bunches as it is intended.

Machine development time will be allocated during 2016 to study the performance of all possible new filling schemas in order to retain the best one for the 2016 operation.

LIMITATIONS TO THE IP2 BETA STAR REACH

Chromatic effects due to off-momentum operation

As the allocated heavy-ion run physics time is always very short, operations capitalize on the well-established machine settings of the preceding proton run to commission as quickly as possible.

A proton-lead run, however, always requires the commissioning of a new optics with all the IPs squeezed to the minimum possible value, which brings some extra difficulties as compared to proton-proton collisions. One of them is the chromatic effect due to off-momentum operation [9,10]. Due to the off-momentum orbits there is an intrinsic beta-beat, which has to be calculated and superimposed to the usual beta-beat correction on-momentum. Amongst other effects beta beating modifies the focusing and, consequently, the tune shift; more aperture is needed because the beams are bigger, etc. The chromatic effects can bring the beta-beat up to 12%. In 2013 and with 4Z TeV per beam, aperture issues due to this effect forced the β^* of IP2 to be downgraded from 0.6 m to 0.8 m. This is, therefore, the first limitation to the β^* reach in IP2. Besides the aperture limitation issue, the beta-beat in 2013 was kept under control and therefore the tune shift remained within tolerances and dispersion beating was very small during the whole squeeze. There was only one exception: beam 1 and negative off-momentum offset which was attributed to uncorrected coupling.

This limitation could be relax if the beam energy in 2016 is 6.5Z TeV because the off-momentum orbit displacements are smaller reducing the chromatic effect.

Another interesting point to highlight is that the chromatic effects were visible only from 2 m β^* down to 0.6 m. Operating IP2 at higher β^* values would remove the chromatic consequences.

IP2 vertical displacement of -2 mm

Since LS1 the ALICE detector has moved vertically by approximately -5 mm. This is compensated in the optics by a -2 mm vertical displacement of the interaction point which will be needed in 2016 and beyond. In 2015 PbPb run at 6.37Z TeV and with a β^* of 0.8 m this vertical displacement introduced an almost aperture limitation for one of the dipole polarities (+60 µrad total half crossing angle). If operating the pPb run at 4Z TeV, as requested by ALICE, given the bigger beam sizes because of the smaller energy, there will be less available aperture and the minimum β^* will be above 0.8 m. This is the second limitation to the IP2 β^* reach for the rest of run 2, making important to point out that this should be fixed in LS2.

On the other hand, ALICE requests to run at a constant luminosity of 1e28 $cm^{-2}s^{-1}$, therefore, this restriction in β^* is not really an issue for such luminosity. However, the lower the β^* the longer ALICE could be leveled making the fills longer which favors the integrated luminosity.

The β^* limitation applies only to IP2; for IP1 and 5 the same optics used for the proton run in 2016 can be used in the pPb run, provided we run at the same energy which would bring the highest luminosity peak in those two IPs. Faster burn off is, thus, expected and, hence, less luminosity for ALICE. Luminosity sharing is going to be a difficult subject in 2016.

ALTERNATIVE SCENARIO FOR 2016

As one of the experiment requests is to run PbPb in 2016, the potential performance is discussed in this paper assuming the beam performance reached after the successful PbPb run in 2015.

First of all, the highlights of the 2015 run are summarized since lot of efforts were carried out in different fronts during the year to push the beam parameters to the maximum possible.

Starting from the source and LINAC3 several improvements were done and, after the stripper foil exchange, the extracted intensity reached a maximum.

Intensive and extensive beam studies performed in LEIR within the context of the LEIR crash program, allowed an important transmission improvement.

PS batch compression from 200 ns to 100 ns was achieved for the first time giving room for more bunches.

SPS carried out hard work to reduce the losses during the energy ramp. The average bunch intensity achieved at LHC injection during 2015 was around 2.2e8 Pb82+ (1.8e10 proton equivalent).

In parallel, the SPS injection kicker switch was replaced providing a faster rise time with less jitter allowing the reduction of the batch spacing from 225 ns down to 150 ns. This improvement, together with the PS batch compression to 100 ns, allowed to inject close to 500 bunches per beam in LHC.

And last but not least, SPS and LHC transverse damper team followed up very closely the progress as to fully guarantee the required bunch stability.

ALICE luminosity was leveled at the design value of 1e27 $cm^{-2}s^{-1}$. ATLAS and CMS got peak luminosities over 3e27 $cm^{-2}s^{-1}$. LHCb joint the PbPb run for the first time. Impressive beam availability was another ingredient of the success of the 2015 ion run. The integrated luminosities can be seen in Table 1.

POTENTIAL PERFORMANCE IN 2016

In order to calculate the potential performance for the 2016 ion run for both configurations, pPb and PbPb, the beam parameters of Table 3 have been assumed. The lead bunch intensity (NPb) is the highest average achieved in 2015. The proton intensity (Np) is aligned to the lead intensity but an MD is proposed to be able to achieved values of the order of 4 to 5e10 p+ per bunch. The normalized emittance is assumed to be the same for both beams. The run length corresponds to the value achieved in 2015 as well as the average fill length of 6 hours. The operator dumped most of the 2015 fills. The average fill length in 2013 was 6 hours as well, but dumped by the interlocked BPMs.

Table 3: Parameters assumed for the calculation of the 2016 performance.

Parameter	Units	Value
k_b		400
N_{Pb}	1e10 p+	1.8
N_p	p+	1.8
ε_n	μm rad	1.5
β*	m	0.8
$\alpha_{1/2}$	μrad	145
Run length	day	21 (1.5 fill/day)
Average fill length	hour	6

The final numbers can be found in Table 4. Those apply to the high luminosity experiments, ATLAS and CMS.

ALICE luminosity will be levelled to 1e28 $cm^{-2}s^{-1}$ with some time spent at 1e29 $cm^{-2}s^{-1}$. Studies are needed to estimate how long the levelling time will last in order to be able to calculate the integrated luminosity.

Table 4: Potential performance for 2016 in IP1 and 5. The integrated luminosity has a 10-15% uncertainty.

IP1&5	E_{beam} (Z TeV)	Peak lumi ($cm^{-2}s^{-1}$)	Fill lumi (μb^{-1})	Run lumi (μb^{-1})
PbPb	6.37	2.7e27	35	1
pPb	4	2e29	2600	77
pPb	6.5	3e29	3900	116

LHCb requests ten times more luminosity than in previous runs which means they would need four to five times more bunches, therefore less bunches for the other IPS. This is not included in the assumed number of bunches (k_b) of Table 3. The bunch sharing needs detailed filling schemas preparation.

The peak performance could be further increased by several means:

- Increasing the proton bunch intensity up to 4-5e10, the peak luminosity would increase by a factor 2.
- If running at 6.5 TeV the β* in IP1 and 5 could remain as in proton-proton, i.e. 0.5 m or 0.4 m (still to be defined); the peak luminosity would increase by a factor 1.5.

The draw back is that the higher the peak luminosity in IP1 and 5 the higher the Pb burn-off and therefore shorter fill length is expected being the integrated luminosity in those IPs higher by a factor smaller than 1.5. The higher the burn-off the less integrated luminosity for ALICE, which stays levelled to 1e28 $cm^{-2}s^{-1}$. And finally, the greater the proton intensity the more likely is to suffer from beam-beam effects on the Pb beam, but this should be carefully studied.

The best way to push the luminosity remains, thus, to find filling patterns with more bunches since there is no penalization.

CONCLUSIONS

Unlike earlier runs, the requirements for the 2016 ion run are clearly dissimilar amongst the different experiments, different colliding particles and different energies. As a consequence this paper has summarized the potential performance in case of a heavy ion run or a proton-heavy ion run at different energies. In order to calculate the performance the best beam parameters achieved in 2015 have been assumed. In any case, the calculations have focused on the high luminosity experiments. Different possibilities in order to increase the peak performance are in reach for 2016, however, those bring draw backs in what integrated luminosity for the ALICE is concerned. Luminosity sharing is going to be a critical issue to be solved for the 2016 run.

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