CHAMONIX WORKSHOP, SESSION 5 – LIU – SUMMARY

M. Meddahi and G. Rumolo

GOALS AND MEANS OF THE LIU PROJECT

The goal of the LHC Injectors Upgrade project (thereafter 'LIU') is to increase the intensity/brightness in the injectors in order to match the High Luminosity LHC (thereafter 'HL-LHC') requirements. It means for the proton accelerator complex to enable Linac4/PSB/PS/SPS to produce, accelerate and manipulate higher intensity beams (based on efficient production schemes, space charge and electron cloud mitigation measures, impedance reduction, feedback systems, hardware upgrade and improvement). For the heavy ion complex, an important upgrade of the injector chain (Linac3, LEIR, PS, SPS) is planned to produce the required beam parameters at the LHC injection that can meet the luminosity goal.

In addition, the LIU project should ensure the increased injectors' reliability and lifetime to cover the HL-LHC era (until ~2035). This part is closely related to the CONSolidation, project, and concerns the upgrade/replacement of ageing equipment (power supplies, magnets, RF…) and the improvement of radioprotection measures (shielding, ventilation…).

The timeline of the LIU project is sketched in Fig.1.

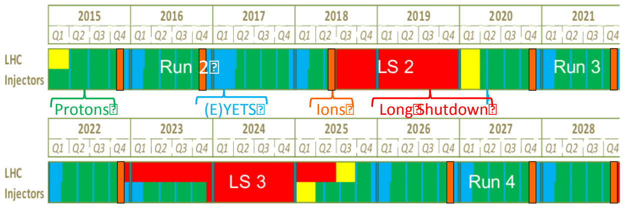

Figure 1: LHC (upper row) and Injectors (lower row) operation schedule (green: proton operation, blue: technical stops, orange: ion operation, red: long shutdown -LS)

The simulation studies, beam measurements and equipment procurement will take place during Run 2 until the start of LS2. During this time, key dates for pending decisions have been set in order to define the baseline program of all the interventions by end of 2016. All LIU installations and hardware works will then take place during Long Shutdown 2 (LS2). For some of these installation activities, it is checked if they could be anticipated to Year-End-Technical-Stop (YETS) or Extended-Year-End-Technical-Stop (EYETS).

Commissioning of LIU beams will take place in 2020 for the Pb ion beams, as the full beam performances are already needed for the 2020 ion run. The proton beam commissioning up to the LIU beam parameters will gradually be performed during Run 3 to be ready after LS3. This strategy would as well allow performing any further hardware corrective actions during the Run 3 technical stops or LS3, if needed.

LIU-IONS

The main target of the LIU-IONS can be described in a simplified form as reaching 7 times the nominal peak luminosity. This also translates into multiplying by a factor 14 the peak luminosity achieved during the 2011 Pb-Pb run. Table 1 summarises the desired versus achieved ion performance.

	L_{peak}	Beam energy
Achieved in 2011	5×10^{26} Hz/cm^2	**3.5 *Z* TeV**
LIU-IONS	7×10^{27} Hz/cm^2	**7 *Z* TeV**

Table 1: LIU-IONS beam parameters, compared to the 2011 achievements

The bunch intensity was already at the limit on the SPS flat bottom during the 2013 p-Pb run in terms of acceptable intra beam scattering and space-charge effects. It is therefore needed to accumulate a larger number of possibly slightly less intense (as compared to 2013) bunches in LHC. The targets for the p beams needed during the p-Pb runs are being defined.

The means to achieve the LIU-IONS target luminosity are the following:

- Increase the beam current from **Source & Linac3** by improving the Low Energy Beam Transport (LEBT). This requires identifying and removing bottlenecks by performing beam dynamics simulations, beam measurements, and installing new diagnostics when needed. The increase of the injection rate from 5 Hz to 10 Hz will also allow injecting more intensity into LEIR;
- Increase the beam current out of **LEIR** by both increasing the amount of injected beam (compatibly with the electron cooling capabilities) and mitigating the large beam losses at RF capture. For that, more advanced machine modelling and Machine Developments are needed;
- Use bunch splitting in the **PS** to produce 4 bunches with 100 ns bunch spacing;
- Increase the number of bunches in the **SPS**, thanks to an upgraded injection system with a 100 ns rise time, and longitudinal slip-stacking allowing the production of trains with 50 ns bunch spacing. Furthermore, mitigation of the beam degradation at flat bottom will rely on the reduction of the RF noise. The use of Q20 optics will be kept as it proved efficient during the 2013 p-Pb run.

In summary, a list of actions has been defined to achieve the target ion beam parameters at LHC injection to fulfil the luminosity goals. However, big challenges are ahead to increase the beam current into and out of LEIR (see Fig. 2), as well as to reduce the beam degradation along the chain, As the LIU-IONS beam is the first in line to be required for physics production after LS2, much effort is presently being put to solve all the related issues.

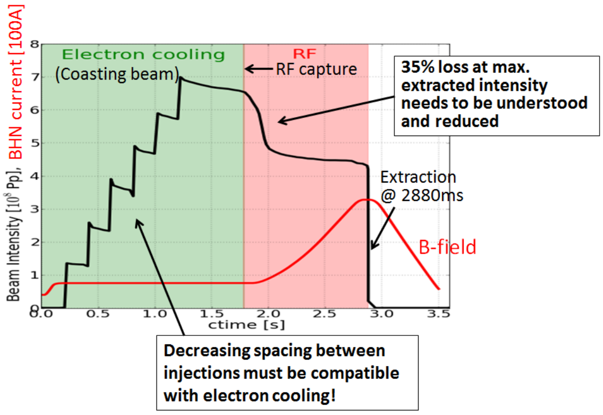

Figure 2: Open questions to improve LEIR performance to reach the LIU-IONS goals.

LIU PROTON INJECTORS

The LIU proton target is to reach the very demanding beam parameters needed by the HL-LHC project. This target is summarized in Table 2. The injectors must produce 25 ns proton beams with about double intensity and higher brightness than nowadays.

25 ns	**N (x 10^{11} p/b)**	**ε (μm)**	**B_l (ns)**
Achieved in 2012	1.2	2.6 (std) 1.4 (BCMS)	1.5
HL-LHC	**2.3**	**2.1**	**1.7**

Table 2: HL-LHC beam parameters, compared to the 2013 beam parameters

- To reach this goal, a cascade of improvements is needed across the whole injectors chain. The main items are listed below:
- Replace Linac2 with Linac4. This will allow injecting H^- into the PSB at 160 MeV and producing higher brightness beams. It implies re-designing the injection into the PSB.
- Raise the injection energy in the PS to 2 GeV to allow for higher beam brightness at the same space charge tune spread. This requires increasing the PSB magnet field, replacing its main power supply, upgrading the main PSB-RF system (C02+C04), changing the PSB-PS transfer equipment and re-designing the PS injection. The intensity out of the PS can also be increased thanks to the newly installed longitudinal feedback against the longitudinal coupled bunch instabilities and possibly the transverse feedback against the electron cloud instabilities.
- Increase the beam intensity accelerated in the SPS. This relies mainly on two actions. The first one is the RF power upgrade by adding a new 200 MHz power plant, rearranging the 200 MHz cavities, increasing the power and installing a new low-level RF for the higher harmonic 800 MHz cavity. The second one is to actively suppress electron cloud by coating with a-C the vacuum chambers in the SPS main magnets. The final decision between a-C coating versus beam induced scrubbing will be taken in mid-2015, after all the data about the SPS performance recovery after LS1 will be available and analysed.

LINAC4 STATUS

Linac4 (an approved CERN project) will be replacing Linac2, providing H^- injection into the PSB at 160 MeV, and leading to an expected double brightness for the LHC beam type out of the PSB.

The Linac4 is currently being commissioned stage by stage with a temporary source. Acceleration to 12 MeV has been successfully validated. The RFQ and chopper behave as expected and the DTL tank1 can accelerate the beam without losses. Emittance measurements agree very well with code predictions (PARMTEQ, PATH, TRACEWIN) and the phase space reconstruction methods for transverse and longitudinal emittances are also validated.

The new caesiated source (which is the baseline source) is ready for use and is projected to provide 40 mA within 0.35 μm (acceptance of the RFQ). This indicates that about 20 turns injection will be needed for the future LHC beams and simulations are ongoing to establish the future emittance vs. intensity curve. About 100 turns injection are estimated to be required for the future ISOLDE beams, having an intensity higher than present ISOLDE beams, however the attainable maximum injected intensity needs to be assessed via simulations. The source will then need to be upgraded to a magnetron, with the relative R&D program, if there is an interest to achieve the originally specified 80 mA. However, increasing the beam current will also have consequences on the attainable transverse emittance (due to the strongly space charge dominated beam transport) and will come at a significantly high cost.

A half-sector beam test is planned for June 2016 to “simulate” injection from Linac4 into PSB with the real equipment.

LIU TARGET PARAMETERS

After connecting the PSB to Linac4 and implementing all the improvements for the LIU programme, as outlined in the previous section, the beam performance reach at the extraction of the SPS at 450 GeV can be estimated as 2.0×10^{11}p/b in 1.9μm. The main limitations to these values are longitudinal instabilities/beam loading in the SPS and the PSB brightness, as illustrated in Fig.3.

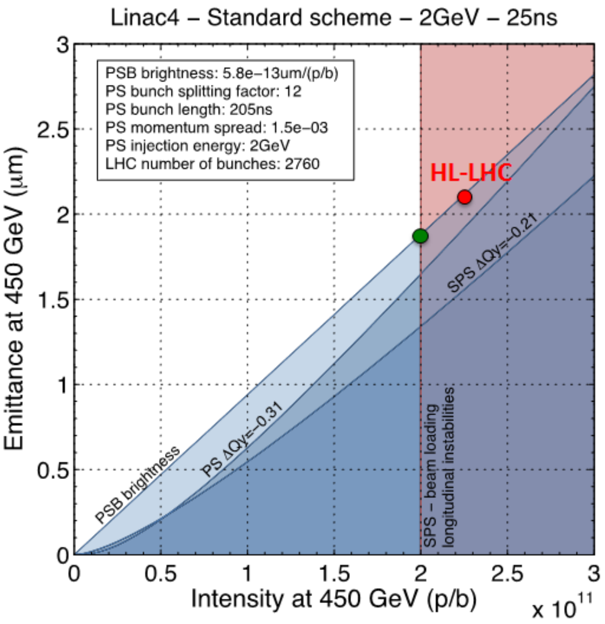

Figure 3: Proton performance reach after implementation of all the Injectors upgrades

CAN WE DO BETTER FOR HL-LHC?

The following options were discussed in the course on the LIU session:

a- Provide higher bunch current out of the SPS (larger longitudinal emittance at flat top) through the following means: using the SPS an intermediate optics (Q22), which would provide a trade-off between margin in Transverse Mode Coupling Instability threshold and constraint on RF power; reducing the ramp rate and performing bunch rotation at 450 GeV to help the CBI limitation on the ramp and the constraint on the bunch length at the SPS extraction, respectively; clearly identifying the impedance source responsible for the longitudinal limitations and suggesting techniques to reduce it. It is worth noting that the LHC could also ease this optimisation process if it becomes able to receive longer bunches from the SPS with a 200 MHz RF system. This is as well being investigated within the HL-LHC project.

b- Provide a higher number of bunches to the LHC, by injecting trains of 80 bunches into the SPS, instead of the nominal 72 bunches. The scheme is based on injecting 4+3 bunches from the PSB into the PS, with one out of 21 bunches kicked out with the transverse damper after the triple splitting at 2.5 GeV. The use of the transverse feedback to kick out a single bunch from the PS has been already validated in Machine Development.

c- Provide higher brightness beams from the injectors, i.e. using the BCMS production scheme. This results however in injecting trains of 48 bunches from the PS into SPS and requires a careful study of the potential high damage for beam intercepting devices in the SPS, transfer lines and LHC.

Concerning the SPS impedance identification and reduction, particle tracking simulations have shown that the intensity threshold for longitudinal instabilities is indeed reduced by a factor of 2 because of the impedance of the ≈550 vacuum flanges. Preliminary suggestions to reduce the impedance of the SPS vacuum flanges (requiring 15 – 30 weeks of work) are i- partial shielding and damping (a R/Q reduction factor 8 could be achieved and only half of the flanges could be modified) or ii- complete flange redesign (providing a minimum impedance, a R/Q reduction by a factor 20, all flanges could be changed, at a higher cost). This would be a major extra activity to be possibly added to the baseline project. A final decision needs no later than 2015 is needed in order to be able to prepare for LS2 installation.

Concerning BCMS beams, the performance reach is of high interest ($2.0x10^{11}$p/b in 1.4μm at 450GeV), see Fig. 4.

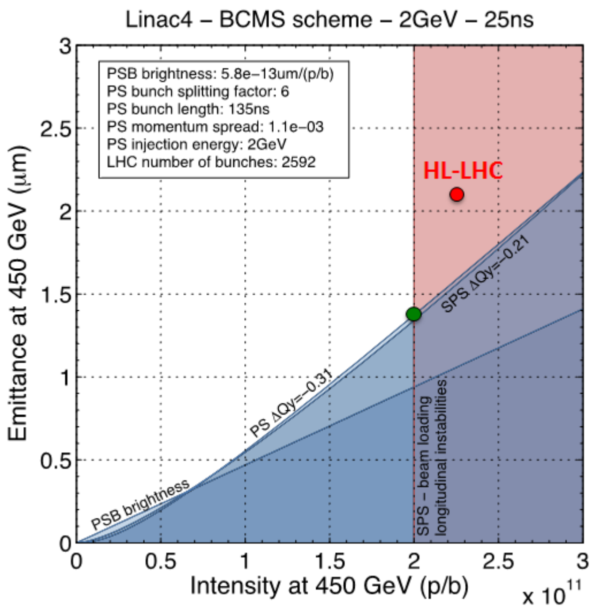

Figure 4: Proton performance reach with BCMS beams

However, high brightness beams come with larger Intra Beam Scattering rates in LHC, challenges for emittance measurement devices, fewer bunches in LHC (~5%), and less effective LHC octupoles to stabilize the beam. The added high damage risk of the protection devices in the SPS, the SPS-to-LHC transfer lines and the LHC was also stressed and the dangers further discussed. The energy deposition depends on the total intensity as well as on the spot size. It was demonstrated that the protection devices for Run2 BCMS beams and LIU beams, might need to attenuate 100-200% more than present design. The choice of material is challenging and many activities are on-going to find an appropriate material. The stresses in case of impact of high brightness beams are estimated to be beyond the strength of materials presently used in passive protection absorbers (even standard HL-LHC can pose problems). R&D is needed to possibly find suitable materials for new absorbers in post LS2 run. Beam tests in the HiRadMat facility with 440 GeV SPS beam are essential to check the material properties used as input for simulations, the robustness against 'simulated' future beams and all new promising materials -e.g. 3D Carbon-Carbon.

In conclusion, concerning the proton injectors chain, the LIU baseline program is established to ensure production of LHC proton beams with parameters close to HL-LHC request (right brightness, and for the moment ~15% lower intensity per bunch than requested). A very dense machine and simulation study program is being carried out until 2016 to further improve our parameter estimates and take decisions at the latest during 2015 for few remaining pending items. In parallel, hardware specification, design and procurement activities are being conducted and should be completed to meet the LS2 installation target. Promising options have been also identified and are under study to increase the intensity and/or brightness of the LIU beams delivered to LHC. Additional studies are planned to validate these options, after which action planning and cost estimates will have to be defined. The use of high brightness has been shown to have some disadvantages and may clash with safety of the machine protection devices. Extensive studies are being performed on this subject to ensure safe operation of the machines.

DISCUSSION

Alessandra Lombardi

LINAC 4: Progress on Hardware and Beam Commissioning

N. Holtkamp asked about the nominal value of the current at the end of the Linac4. A. Lombardi replied that, as explained in her slides, this was 80 mA and overspecified for LHC beams, since they can also be efficiently produced with lower current from Linac4. M. Vretenar said that the specification of 80 mA came specifically from the target of doubling the intensity of the high intensity ISOLDE beam. This high value of current is only necessary if the PSB needs to deliver twice the present intensity to ISOLDE. Simulations of injection of LHC beams into the PSB are presently ongoing and the target is to establish the new emittance vs. intensity curve. N. Holtkamp asked how much budget is available to improve the source. Since the future source will use the power supply and extraction system already in place from baseline, this would be in the order of 1 MCHF.

B. Mikulec remarked that the PSB will be able to accelerate 2e13p only with full Finemet upgrade, otherwise the maximum current will be limited to 1.4e13p.

F. Bordry asked how much time would be needed to set up an emergency connection to Linac4 with protons in 2015, in case of Linac2 failure. A. Lombardi replied that this will strongly depend when the request comes, i.e. what is installed at that moment, but it can be estimated to be in the order of two months. R. Scrivens added that it would be desirable to have some test run with protons in order to be ready in case of emergency connection.

E. Benedetto pointed out that the number of turns needed to inject the future LHC beams is important to determine the final beam brightness, because the degradation through the foil has an impact on the final emittance.

Giovanni Rumolo

Protons: Baseline and Alternatives, Studies Plan

N. Holtkamp asked where the assumption of twice brighter beam from the PSB after connection to Linac4 come from. G. Rumolo replied that, in absence of detailed simulations of the future injection process, the assumption is just an extrapolation from the original idea of being able to produce with Linac4 LHC beams twice as intense as nowadays but within the same transverse emittance. Therefore, double brightness becomes our working assumption to calculate the future beam parameters. Detailed simulations of the H- injection process are being carried out and the simulated intensity vs. emittance curve (similar to the one presently measured that represents the PSB performance for LHC beams) will be in the future used for improving the parameter tables.

O. Bruning asked whether a bunch intensity of 1.7e11 ppb was already achieved in the SPS with 25ns. G. Rumolo replied that presently 1.3e11 ppb is considered the maximum bunch intensity achieved in MDs at the SPS flat top with four batches, because then signs of electron cloud and longitudinal instability appeared for slightly higher intensity, which led to no increase of the extracted intensity per bunch even while increasing the injected intensity. TMCI at 26 GeV is not a limitation and is not expected to be a limitation not even for the ultimate LIU bunch intensities, because the Q20 optics has extended the acceptable bunch intensity for stability from 1.7e11 ppb to about 4e11 ppb, leaving enough margin (as is discussed in detail in H. Bartosik's talk)

F. Bordry asked whether a decision on the coating of vacuum chamber needs to be taken by mid 2015 and why coating needs to be done in LS2 and could not be postponed to LS3. G. Rumolo replied that the idea of taking the decision in mid 2015 is motivated by the fact that by that point all the information from the SPS scrubbing runs will have been collected and will be available, thus we can draw a clear picture whether scrubbing is possible and efficient also up to high intensities or a-C coating is needed. B. Goddard added that, if a-C coating turns out to be necessary, we need to be ready after LS2, so that during Run 3 we can first recover the performance and then ramp up the performance of the injectors up to the LIU targets. Commissioning of the required high intensities for the HL-LHC run cannot be done quickly after the post-LS3 restart.

L. Rossi remarked that the gain from the longitudinal feedback in the PS is clear because it allows increasing the estimated maximum bunch current from 2e13 to 3e13 ppb at the PS extraction. He asked what the gain given by the increase of the injection energy to 2 GeV. G. Rumolo showed the performance diagram that shows the gain coming from the upgrade to 2 GeV alone. It is clear that in absence of this upgrade, we would not be able to produce the necessary brightness to meet the HL-LHC request because of a strong bottleneck of space charge at the PS injection.

N. Holtkamp_asked about the logics about coating and high bandwidth feedback in the SPS. If the new feedback system is meant to damp electron cloud instabilities, it would become useless if a positive decision on coating is taken. G. Rumolo answered that, if we look at the functionality of the feedback as a damper for electron cloud instabilities, this is strictly true. However, one should not neglect that the high bandwidth feedback system could be useful also against TMCI (and allow moving to different optics with weaker constraints on the required voltage, see talks of H. Bartosik and T. Argyropoulos) and that this system has a potential interest for other machines, like LHC.

N. Holtkamp asked whether it is possible to profit from the LIU upgrades as they are implemented, possibly also already before LS2. G. Rumolo replied that this is already the case. S. Gilardoni added that also during Run 2 all upgrades that are ready are already being used on operational beams, delivering an improvement on beam quality more than on the achievable beam intensity.

Verena Kain

Concerns with Low Emittance Beams Operation

N. Holtkamp asked when and where the HiRadMat tests can be done. V. Kain replied that the experimental area uses the beam coming from SPS and the line has a tunable optics to simulate the size of the future beams.

S. Redaelli asked how many spares are available for the TCDI. V. Kain replied that there are two horizontal ones and one vertical one. He also asked about the model for properties used in dynamic simulations, i.e. whether possible variations vs. temperature and stresses are taken into account. V. Kain said that, when available, dynamic models are taken into account, but often they are not available in great detail.

R. Losito asked which are the expectations from experiments, i.e. whether they will really need in the future extra-bright BCMS beams. Lucio Rossi replied that the emphasis is anyway on producing higher intensity rather than lower emittances.

R. Alemany asked whether 1) it is possible to change the optics in the transfer line to alleviate the limitation of the TCDI with the small emittance of the BCMS beam, and 2) what happens if the TDI breaks. V. Kain replied that detailed studies have not been done for post-LS1, however the margin to increase the beta function at the TCDI is very limited. Concerning the TDI, V. Kain explained that even if it cracked, it would still attenuate the beam as it is supposed to.

M. Lamont asked whether it is possible to better tailor the BCMS emittances to remain within the specs for the protection devices (specifically the TDI). V. Kain said that probably this is possible, but then we would need a reliable transverse beam quality monitoring (BQM) system to be sure that devices are protected against accidentally low emittances.

R. Schmidt and G. Arduini inquired about the uncertainties on the material properties in these estimations. A. Lechner said that for instance Boron Nitride (BN) is supposed to become very weak at high temperature, although there are doubts on the characterization.

O. Bruning asked whether collimators with rotatable jaws from SLAC could be an option. V. Kain replied that this is being considered. Tests are foreseen in HiRadMat first, and then in the SPS.

Hannes Bartosik

Other Means to increase the SPS 25 ns Performance - Transverse Plane

M. Meddahi remarked that MDs in the SPS to test and qualify the new Q22 optics will be done during Run 2.

N. Holtkamp asked whether the new transverse feedback system could help. H. Bartosik said it should help against TMCI. G. Arduini remarked that the 80-bunch option seems very promising and he asked whether it is possible to measure the bunch by bunch emittance for beam qualification, in particular to check if the transverse damper of the PS also affects the neighbouring bunches. H. Bartosik replied that this can be done at the SPS flat bottom, as was already done also in 2012. S. Gilardoni added that in principle the bunch-by-bunch measurement of the transverse emittance is also available at the PS extraction, as the necessary hardware has been installed.

Theodoros Argyropoulos

Other Means to Increase the SPS 25 ns Performance - Longitudinal Plane

G. Rumolo asked whether the 800 MHz system could, be used for the bunch rotation at flat top. E. Shaposhnikova replied that it is already used for bunch shortening, but beyond that the available voltage will not be enough for a real bunch rotation at flat top even after the ongoing renovation.

R. Alemany asked why there are visible differences between measurements and simulations of the bunch lengthening due to microwave instability at flat top:. T. Argyropulos replied that there could be different reasons to account for this difference, for example the impedance model is not complete, or there are also errors in the bunch length measurements.

N. Holtkamp asked what is presently within the LIU baseline in terms of improvement against the longitudinal instabilities. T. Argyropoulos replied that the power upgrade of the 200 MHz system is in the baseline, while there are not yet any concrete proposals in terms of reduction of the impedance of the vacuum flanges. N. Holtkamp asked then whether the option of having longer magnetic cycles can have an impact on the power supplies. E. Shaposhnikova replied that in principle this is not the case, but this will be anyway tested experimentally soon with the doublet production.

Michael Bodendorfer

Ions: Baseline, Studies Plan and Strategy for Pending Options

M. Meddahi remarked that the LHC will be ready for the upgraded ion beam soon after LS2, therefore it is crucial that we are sure we can deliver it already before going into LS2.

J. Jowett said that we should remember that proton beams are also important for the p-Pb part of the programme. In particular, special proton beams of moderate bunch intensity should be prepared with filling schemes designed to match those of the Pb beams. This was not trivial for the 2013 p-Pb run. A scheme still has to be worked out to match the alternating 100/225 ns Pb beam in Run 2, although it might be easier for the more regular 50 ns spacing that we now expect after LS2. Moreover, it is not so easy to gain factors in integrated luminosity beyond what was achieved for p-Pb in 2013, especially if the LHC will run at the same energy, as may be requested. Therefore, it is probable that, unlike in the present schedule, to achieve the requested p-Pb luminosity goals, it will be needed to have more than 3 p-Pb runs and fewer than 8 Pb-Pb runs during the HL-LHC period. This will of course make it harder to reach the long-term integrated luminosity goal for Pb-Pb. Another way in which a substantial gain in performance could be made is to mitigate the degradation along the trains in the SPS (due to IBS, space charge and RF noise). D. Manglunki observed that some measures will be already taken in Run 2 to make progress on this front, i.e. RF noise reduction through the fixed harmonic at flat bottom and the use of the Q20 optics, which has also already helped a lot for the SPS performance. The improvement of the SPS performance will keep receiving the necessary attention.

W. Höfle asked what is needed to achieve an increased Linac3 repetition rate. R. Scrivens replied that it requires an upgrade of the RF system and some power converters. He also clarified that inside the baseline for LIU-IONS for Linac3, is an increase of the injection rate to 100ms, and a study to investigate production of higher intensity improving the low energy transport. The higher intensity is speculative and therefore not itself part of the baseline.

R. Alemany asked how long the injection time into LHC will be. A longer injection time could spoil the potential of luminosity increase with the new ion beam parameters at LHC injection due to IBS at 450 GeV. D. Manglunki replied that the LHC filling time will be between 45’ and 1 hour.

S. Redaelli asked why the target peak luminosity is 7e27 Hz/cm^2. J. Jowett replied that Michael’s focus on the peak luminosity formula was only for simplicity of presentation. In reality, it is integrated luminosity that counts and this value would probably not be reached with the beam parameters described. However, we should keep looking for ways to increase it. In any case, there is a detailed model of luminosity that takes into account the variations along the trains, injection times, luminosity evolution during a fill, etc. and this will be used to optimise the SPS train length. This will result in somewhat shorter bunch trains in the SPS and somewhat fewer bunches in the LHC (see talk at RLIUP last year).

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