REPORT FROM THE WG-2 OF THE LUMI-05 WORKSHOP SCENARIOS FOR THE LHC INJECTOR COMPLEX UPGRADE

W. Scandale, CERN, Geneva, Switzerland

Abstract

The LUMI-05 workshop was held in Arcidosso (Italy) from August 31st to September 3rd, gathering about 40 participants. The scope of the workshop was to explore scenarios for the LHC luminosity upgrade, with particular emphasis on LHC IR layouts with lower β^* and on new high energy injectors for increasing the beam intensity.

These topics were discussed by two separate working groups, the first one (WG-1) mainly dealing with the LHC IR Upgrade, and the second one (WG-2) on High Energy Injectors. This note reports about activities and conclusions of WG-2.

PHASES OF THE LHC UPGRADE

Three steps for the LHC luminosity upgrade have been identified:

- ultimate performance without hardware changes (phase 0);
- maximum performance with only IR changes (phase 1);
- maximum perform with major hardware changes (phase 2).

Phase 0 will consist in several steps with different colliding and crossing schemes, increasing the bunch population up to the beam-beam limit and increasing the dipole field up to 9 T corresponding to a collision energy of 7.54 + 7.54 TeV.

Basically, WG-1 discussed phase 1 and WG-2 discussed part of phase 2 of the LHC luminosity upgrade.

RECALL OF OUTCOMES FROM WG-1

Two main motivations are the basis for a need of an IR upgrade:

- the life expectancy due to radiation doses at the nominal luminosity of the LHC IR quadrupole magnets is estimated to be between 5 and 10 years;
- the statistical error halving time will exceed 5 years after four years from the LHC commissioning (see fig.1).

The first motivation requires new IR quadrupoles by 2015-2017. As by that time the LHC will also need higher luminosity for keeping an acceptable error halving time, it is very likely the new quadrupoles, or their integration in the LHC lattice, shall be more radiation resistant than the present ones.

WG-1 was charged to critically enumerate all possible IR solutions for the LHC upgrade.

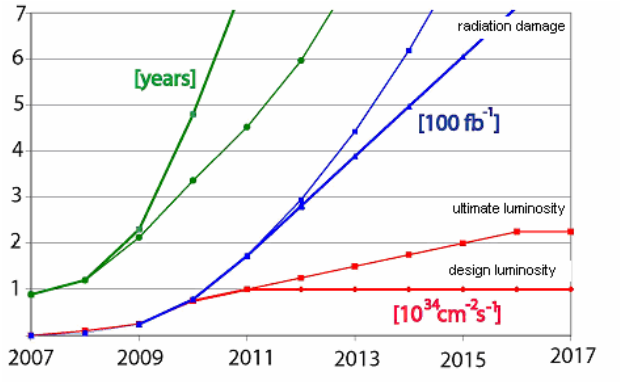


Fig.1 : time to half statistical errors (courtesy J.Straight)

Three IR layouts options have been identified:

1. dipole-first based on Nb_3Sn technology ;
2. quadrupole-first based on Nb_3Sn technology ;
3. low gradient quad-first based on NbTi technology.

In addition to these alternatives, possible early beam separation by a “D0” dipole located a few meters away from the IP was suggested by J.P.Koutchouk and schemes with different crossing angles were discussed by F.Zimmermann.

AIMS OF WG-2

The main aims of WG-2 were to discuss and identify:

- advantages of new high energy injectors for the LHC luminosity upgrade;
- optimal injection and top energy
- limitations of existing injectors;
- injection and extraction;
- transfer lines;
- R&D issues

WG-2: REPORT FROM PRESENTATIONS AND DISCUSSIONS

W. Scandale went through the different options for a possible upgrade of the injector chain.

Two main options were considered as a basis for discussion:

- the superconducting way, upgrading the PS for providing up to 60 GeV beams, and the SPS for providing up to 1 TeV beams. This alternative also requires superconducting transfer lines to the LHC.
- The normal conducting way, consisting in a refurbished PS and a refurbished SPS.

A 1.0-1.5 TeV booster ring in the LHC tunnel may also be considered, possibly using superferric magnets. In this case one of the issues would be crossing the experimental areas and the collimation and dump sections.

The luminosity upgrade through the injector chain upgrade should come from a shorter turnaround time in filling the LHC and from the increased circulating intensity and bunch population. Unfortunately it is difficult to quantify the gain in the turnaround time, as this is a loose concept strongly dependent on its definition and on operational experience.

M. Buzio presented the expected gain of higher injection energy in dynamic effects for the LHC main magnets (fig.2). After some discussion it was agreed that a tentative reduction factor of the turnaround time due to doubling the injection energy can be set to 1.5.

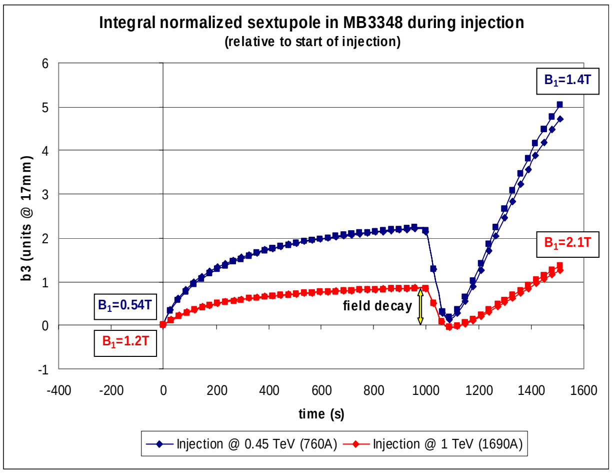


Fig.2 : normalized b3 decay during ramp (from M.Buzio)

The turnaround time was a topic of presentations reporting on the experience at Hera (M.Bieler), RHIC (R.Calaga) and Tevatron (T.Sen).

At HERA the nominal time from beam dump to luminosity should be 2.5 hours, including the setting up of both p- and e- injection. In reality a typical time from beam dump to luminosity is 5.5 hours and, taking into account that more than 11% of all ramps are lost to operational problems and 33% are lost due to hardware problems the average time from beam dump to luminosity exceeds 10 hours.

At RHIC the turn-around time is defined as the time between beam dump and next declaration of physics store. An average time of 75 minutes was achieved between physics stores, however this number does not take into account the periods of machine non-availability.

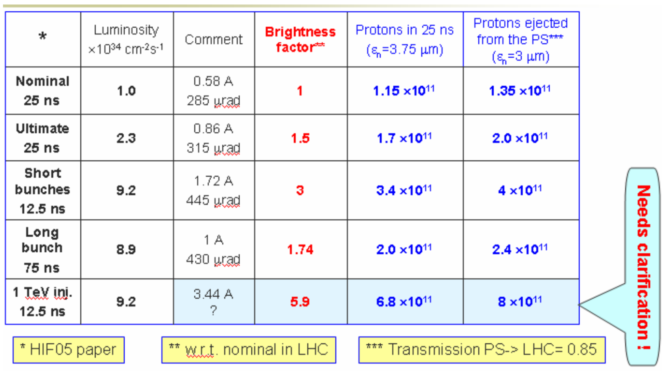
In case of the Tevatron the turnaround time is defined as the time from end of store to the start of next store. The average turn-around time is about 2 hours, without taking into account machine stops.

In addition to shorter turnaround time, the injector upgrade will allow injecting more intense proton beams with constant brightness within the same physical aperture thus increasing the peak intensity. This would yield a factor of 2 in luminosity due to the increase of bunch intensity and normalized emittance at collision energy, which adds to a factor 1.4 for shorter turnaround time.

R.Garoby presented and discussed different scenarios for generating higher brightness beams for the LHC (fig.3).

Increasing brightness in the PS can go through several options

- batch compression, sending in the SPS every 3.6 seconds a train of 42 bunches with $2.6x10^{11}$ ppb, spaced by 25 ns;
- increasing brightness in the PSB with Linac 4, sending to the SPS every 2.4 seconds a train of 72 bunches spaced by 25 ns. Feasibility of alternatives with less (48 or 24), but more intense bunches cannot be fully demonstrated;
- replace the PSB by a SPL. The injection energy in the PS would be 3.5 GeV, and a tailored train of 1 to 80 bunches with up to $8x10^{11}$ ppb, spaced by 25 ns, could be sent to the SPS every 1.5 seconds. This solution would remove the space-charge limitation in the PS.
- Replace the PSB by a RCS. As for the previous solution, to improve the space-charge limitations in the PS the injection energy to the PS would be 3.5 GeV. A train of 72 bunches with $8x10^{11}$ ppb, spaced by 25 ns, could be sent to the SPS every 1.5 seconds.



*	Luminosity $\times10^{34}$ cm^{-2}s^{-1}	Comment	**Brightness factor****	Protons in 25 ns (ε_n=3.75 μm)	Protons ejected from the PS*** (ε_n=3 μm)
Nominal 25 ns	**1.0**	0.58 A 285 μrad	**1**	**1.15 $\times10^{11}$**	**1.35 $\times10^{11}$**
Ultimate 25 ns	**2.3**	0.86 A 315 μrad	**1.5**	**1.7 $\times10^{11}$**	**2.0 $\times10^{11}$**
Short bunches 12.5 ns	**9.2**	1.72 A 445 μrad	**3**	**3.4 $\times10^{11}$**	**4 $\times10^{11}$**
Long bunch 75 ns	**8.9**	1 A 430 μrad	**1.74**	**2.0 $\times10^{11}$**	**2.4 $\times10^{11}$**
1 TeV inj. 12.5 ns	**9.2**	3.44 A ?	**5.9**	**6.8 $\times10^{11}$**	**8 $\times10^{11}$**

* HIF05 paper

** w.r.t. nominal in LHC

*** Transmission PS-> LHC= 0.85

Needs clarification !

Fig.3 : scenarios for increasing brilliance (from R.Garoby)

Starting from these scenarios, E. Shaposhnikova presented the main relevant beam issues.

The main beam challenges of a more brilliant and intense beam produced in the PS are in the SPS and concern effects related to single bunch intensity/brilliance (transverse coupling instabilities and space charge), and to multi-bunch effects (electron cloud, capture loss, coupled bunch instabilities at injection and high energy, beam loading in the 200 MHz and 800 MHz RF systems, MKE kickers heating). It was shown that in case of higher brilliance the nominal emittance cannot be reached in the SPS in the vertical plane due to electron cloud. Closer bunches, in addition to electron cloud, will also cause coupled bunch instabilities which can however be cured in the LHC by a 200 MHz capture system. Finally, beam loading can certainly be a limiting factor for ultimate intensity. Machine studies including scrubbing runs at higher intensities should be an essential program for the SPS.

A possible configuration of a new injector chain, consisting in reducing of the SPS top energy at 150 GeV and adding a new ring ramped from 150 GeV to 1 TeV was discussed.

This would allow reducing the ramp length in the SPS from 6 seconds to 2 seconds, however it would not improve longitudinal beam stability on the flat-top making more difficult the bunch-to-bunch transfer into the 400 MHz RF system in the next 1 TeV ring.

Concerning the technology of pulsed magnets, D.Tommasini has recalled that experience with AC superconducting magnets for accelerators has still to be gained. So far, few experiments were carried out typically in pulsed mode (one or few ramps). One of the most interesting is the GS001 model, made by BNL in collaboration with GSI [1,2]. The design is based on the RHIC dipole magnet with a cable modified to produce lower losses and the copper wedges in the coil cross section replaced by G11 wedges. With respect to the RHIC conductor, the filament twist pitch was reduced from 13 mm to 4 mm and the wire was stabrite coated. Furthermore, to reduce interstrand coupling losses, 2 stainless steel sheets (core) to decouple the two layers of strands. While providing a good quench performance for up to 4 T/s ramp rates, such model still showed few issues which have to be solved for use in an accelerator going from field quality to losses when cycled in AC mode (about 80 J/cycle for 3 T/s, 3T peak, corresponding to 20 W/m for a 4 seconds cycle) and, last but not least, long term stability under the cyclic operation could not be demonstrated.

OPEN ITEMS

In a discussion we identified several open issues:

- Energy swing in the injector chain. There are two relevant aspects. From one side, it is important to optimize the energy range of each ring in the injector chain, considering the possible constraints for the magnets and the RF system. From the other side, the powering network of a chain of fast ramped superconducting magnets shall be studied in all aspects, from the capacity of providing current at the required precision to the dynamic behaviour of the superconducting wires over the magnetic field swing.
- Lattice design: we should propose a realistic lattice design of a superconducting SPS and of its injector, also considering the possibility of a partial use of the present SPS ring.
- Injection optics: this issue is relevant both for the 1 TeV SPS and for the LHC itself since the space available in the extraction/injection regions is limited.
- Magnet aperture: in case of superconducting fast ramped magnets even small variants in the aperture may represent an important technological difference in the design, manufacture and reliability of the magnet.
- Correct estimate of beam losses: this is of outmost importance since it will strongly affect magnet design and cryogenic system.
- R&D on fast ramped superconducting magnets. Available experience is rather limited. To increase it a solid R&D program first on wires then on magnet manufacture and measurements is required.
- Transfer lines: increasing the injector energy means also modifying the transfer lines, in most cases needing superconducting magnets. This however should be a minor challenge, as these magnets would be operated in DC mode.
- Cryogenic system: solution should be investigated for the installation of cryogenics in the SPS tunnel.
- Consequences of higher intensity operation: they have been explored but not fully evaluated yet, and most of all not quantified.
- RF systems: the optimal choice of the RF parameters requires a full iteration both on lattice design, on the choice of the injector energy and of the ramp-rate of the magnetic cycle.
- Impedance budget: a new ring will be designed with modern criteria, aiming at minimal impedance. We should try quantifying the potential gain for an increased beam intensity operation.
- Collimation: we should propose realistic collimation scenarios allowing high intensity operation with limited losses in the cryomagnets.
- Finally, installation strategies and possible staging of the different alternatives of the LHC injectors upgrade has to be thoroughly studies also to minimise the beam down-time and may become one of the main parameters for a decision.

MAIN OUTCOMES

The main benefits on luminosity upgrade of an improved injector chain come from:

- increase peak intensity above ultimate (bunch intensity)
- increase beam normalized emittance
- decreasing the turnaround time

The workshop allowed us quantifying as much as possible the benefit and identifying the open items for a sound and staged proposal of the LHC injector upgrade.

The strategic objective is to upgrade to 1 TeV the LHC injection energy and to remove the limitations of the present SPS. These goals may require upgrading the entire injector chain with a pre-injector at about 4-6 GeV/c, a new superconducting PS at 40-60 GeV/c and a superconducting SPS at 1 TeV/c. However this path is expensive and its optimization can be matter of long investigation.

It is clear that any upgrade of the injectors system will require fast ramped superconducting magnets and the development of low losses superconducting wires. Suitable wires for a SPS upgrade are certainly in reach of present technology but require R&D for their industrialization. Wires for a PS upgrade are more challenging due to the higher ramp rate and will require a more intensive R&D for achieving filament sizes in the micrometer range with acceptable current density and stability.

CONCLUSIONS

As the LHC will reach the nominal luminosity, very rapidly an upgrade will be needed. This can be efficiently achieved, in several steps, all-relying on the outcome of a vigorous R&D programme on:

- optics, beam control, machine protection, collimation
- high gradient, high aperture radiation hard SC quadrupoles
- RF and crab cavities
- superconducting fast ramping magnets.

The activities of Working Group 2 of the LUMI-05 workshop allowed us streamlining possible alternatives and identifying the relevant open issues along this path.

REFERENCES

[1] A.Ghosh : “Cable design for fast ramped Sc magnets”, WAMS 2004.

[2] M.N.Wilson et al : “Measured and calculated losses in model dipole for GSI’s Heavy Ion Synchrotron”, IEEE Trans on appl sup0, vol. 14, June ’94.