SUMMARY OF SESSION 4: HE-LHC INJECTORS AND INFRASTRUCTURE

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Abstract

This note summarizes the fourth session of the HE-LHC workshop: HE-LHC Injectors and Infrastructure. This session was primarily concerned with the preparation and injection of the beam into the HE-LHC, but also included the issue of collimation with higher energy beams, as well as radiation issues which would arise after 20 years of normal LHC running.

Table 1: List of speakers and topics

Speaker	Topic
Roland Garoby	Optimal injector cascade for HE-LHC and possible implementations
Henryk Piekarz	Using Tevatron magnets for HE-LHC or new ring in LHC tunnel
Peter Spiller	FAIR magnets and design concepts of interest to HE-LHC
Karl Hubert Mess	Using LHC as injector and possible uses of HERA magnets/coils
Ralph Assmann	Intensity limits and machine protection
Brennan Goddard	Beam transfer and beam dump issues*
Doris Forkel-Wirth	Radioprotection issues after 20 years of LHC operation

* The speaker was unable to attend the workshop and this talk was canceled; however, the slides and the paper were ultimately published in the appropriate slot at the workshop website and are summarized in the appropriate section below.

SESSION OVERVIEW

The session on injectors and infrastructure was the fourth and last of the workshop before the summaries. The list of speakers and topics is shown in Table 1.

While this note attempts to summarize the key issues and discussion from the session, readers are encouraged to refer to the individual talks and proceedings for details.

Table 2: HE-LHC Injector Specifications

Parameter	Nominal LHC	HL-LHC	HE-LHC
Injection Energy (GeV)	450	450	>1000
Bunch Spacing (ns)	25 ns	25 ns	50 ns
Bunch Size (10^{11} p)	1.2	1.8	~1.4
Normalized Transverse Emittance (μm)	3.75	>2	3.75(H), 1.84(V), 2.59 (H&V)
Longitudinal Emittance (eVs)	1	1	?(<4)

Table 2 shows the injection parameters of the HE-LHC compared to the nominal and high luminosity LHC configurations. Most parameters are comparable or even relaxed compared to the 7 TeV LHC, and the “only” challenge is the injection energy, which will have to exceed 1 TeV[1].

Most consideration was given to solutions involving an additional new accelerator to take beam from the existing SPS and accelerate it to the HE-LHC injection energy. Most of the discussion focused on options for this accelerator:

- Super-SPS (S-SPS): a rapid cycling superconducting synchrotron which would share the tunnel with the SPS. This accelerator would have to match the ramp frequency and rate of the SPS for LHC loading.
- Low Energy Ring (LER): a synchrotron which would share the tunnel with the LHC. The SPS would inject the entire load of protons into the LER, which would accelerate them to the injection energy of the LHC and transfer them all at once. It is assumed this ring would have a single aperture and would therefore have to be bi-polar, cycling separately for each beam direction.

There were some brief discussions of other alternatives, which will be summarized shortly.

Other topics which were presented and discussed included beam transfer, injection, extraction, and dumping. In addition, collimation and machine protection were considered, as were the radiological issues after 20 years of LHC operation.

SUPER-SPS (S-SPS)

This scenario is illustrated in Figure 1. A new accelerator would be built in the SPS tunnel. This would accelerate the beam from 150 GeV to 1.0 or 1.3 TeV, depending on the injection energy which is ultimately chosen for the HE-LHC. The required maximum field strength would be 4 T or 5.2 T, respectively. Beams would be transferred to the HE-LHC using the existing TI2 and TI8 tunnels, but of course new beam lines would have to be built to accommodate the increased energy.

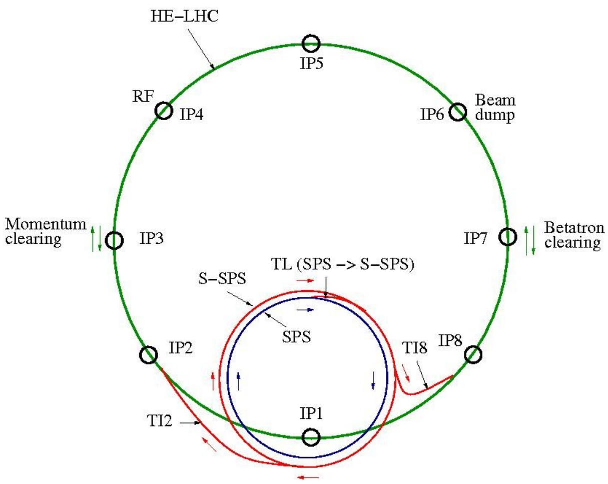

Fig. 1 Arrangement of S-SPS accelerator as an injector to the HE-LHC

The S-SPS would accelerate beam directly from the SPS and would therefore require 24 cycles to fill the LHC. In order to preserve the current fill time of 4.4 minutes, the individual transfers would have to occur in 10.8 s cycles, requiring a ramp rate of 1.3 T/s for the highest energy injections case [2].

Such high ramp rates are extremely challenging for superconducting magnet design. The most relevant recent work has been done in conjunction with the new Facility for Antiproton and Ion Research (FAIR) being built in Darmstadt, Germany [3].

FAIR is pursuing two relevant superconducting magnet R&D projects:

- SIS100: $B\rho$= 100 Tm, B_{max} = 1.9T, dB/dt=4 T/s
- SIS300: $B\rho$= 300 Tm, B_{max} = 4.5T, dB/dt=1 T/s

The latter is of particular interest, although, even in the most optimistic scenarios, the heat load on the cryogenic system from such magnets remains a significant concern.

LOW ENERGY RING (LER)

The second class of solutions to the injector problem involve a secondary accelerator in the LHC tunnel. One idea would be to use the existing LHC itself as an injector for the HE-LHC[4]; however, a cursory analysis of the tunnel layout shows that there is insufficient space for a second, higher energy ring. The only possible solution would be to re-cryostat the cold masses of the current LHC together with the magnets of the new LHC. This idea was not analyzed in any depth.

It is considered more promising to design a new, single aperture LER to share the tunnel with the HE-LHC. Figure 2 shows one proposal, based on R&D which was done for the Very Large Hadron Collider (VLHC), which was proposed in the US[2].

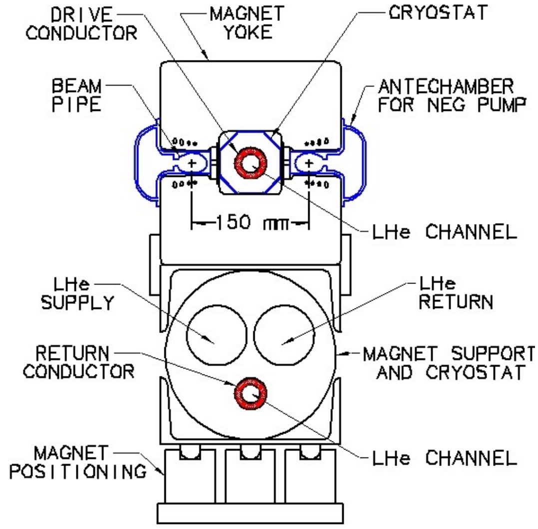

Fig. 2 Sketch of the proposed LER main arc magnet. The return conductor is inside the cryostat pipe which supports the magnet and houses liquid helium distribution lines for the LER.

A scaled down version for the HE-LHC would have B_{max}=1.76 T and a maximum ramp rate of dB/dt=6.5 T/min, although a slower ramp rate would likely be used to reduce the power load.

Of course, an LER sharing the tunnel with the HE-LHC would require a method of bypassing the interaction regions. This could be done by either designing bypass beam lines around the regions, or by switching the LER beam into the HE-LHC in those areas.

ALTERNATE PROPOSALS

New tunnels

The scenarios discussed above assume that we are limited to using existing tunnels for the new injector. It was suggested that we consider building a completely new tunnel. However, this immediately raised the question of whether it would be better to build a newer, larger tunnel for the HE-LHC itself, which would obviate the need for exotic magnets. At that point, it was decided that the discussion of new tunnels was beyond the scope of this workshop.

Completely new injector complex

It was pointed out that by the time that an HE-LHC could conceivably be built, parts of the existing injector complex would be extremely old. In light of this, perhaps it would make sense to consider a completely new injector chain, inspired by Fermilab's Project X. Straw man parameters for such a complex are shown in Table 3.

Table 3: Proposed new injector complex

Accelerator	Tunnel	Energy range	Max ramp rate
SC Linac	new	0-8 GeV	---
S-PS	PS	8-100 GeV	3 T/s
S-SPS	SPS	100 – 1200 GeV	2 T/s

BEAM TRANSFER AND DUMP ISSUES

It is assumed that the existing TI2 and TI8 will be used for transfers from the SPS tunnel to the LHC tunnel. If the beam is coming from a higher energy S-SPS, then the transfer line magnets would have to be replaced. Options for reusing magnets from existing accelerators were considered. The minimum curvature radius of these transfer lines is the same as the SPS, so the same field would be required as the S-SPS. Tevatron magnets might be sufficient for a 1 TeV injection energy, but not if the energy is higher [2]. HERA magnets have the required field, but would need significant retrofitting to fit in the tunnel and to handle the fact that the polarity is reversed relative to HERA. Also, TI2 has a large vertical slope, which would present problems for any superconducting magnets not specifically designed for it [4].

The injection, extraction and dump systems present significant challenges at increased energy; however, they do not appear to be *a priori* insurmountable [6] †.

The dump system consists of extraction kickers, septum, dilution sweep magnets, and the physical dump itself, none of which are adequate at 16.5 TeV. In addition, there are passive elements which protect the accelerator in the event of kicker misfires or beam in the abort gap, and these would also be destroyed at the increased energy.

Increasing either the length or the field of the existing extraction kickers does not appear feasible. However, one can design new kickers with smaller apertures thanks to the smaller maximum beam size that comes with the increased injection energy. These appear to present a reasonable option.

The extraction appears just feasible by using an increased number of existing B and C type septa, running at the maximum field. The total required length would increase from 73 to 136 m, and the resulting integration issues would have to be carefully studied.

† The speaker, Brennan Goddard, was unable to attend the workshop. This discussion summarizes the transparencies which he subsequently submitted.

Although the total stored energy of the beam does not increase, the energy density does, requiring an increased amplitude and/or frequency of the dilution kickers. These appear to be feasible, although more study is needed. It might be possible to amplify the effect of these kickers with quadrupoles in the dump line, but integration might be an issue.

The dump itself would have to be redesigned, likely made longer with a lower density material. However, there is room to accommodate this.

The passive protection devices in the extraction area are inadequate for the increased energy and energy density, and it's not clear that a robust solution exists to replace them. In a worst case scenario, "sacrificial" absorbers could be implemented, which would be replaced after (hopefully rare) exposure to high intensity beams.

The injection system is somewhat more challenging. This is because the existing injection kickers use all the available space, assuming that the HE-LHC magnet layout is similar to the current layout. Again, taking advantage of the fact that a smaller aperture can be used with the higher energy beams, new, higher field kickers should be feasible.

INTENSITY LIMITS AND MACHINE PROTECTION

Although the total stored energy of the HE-LHC will be roughly the same as the HL-LHC, the increased beam energy and energy density will have significant implications for the collimation system [5].

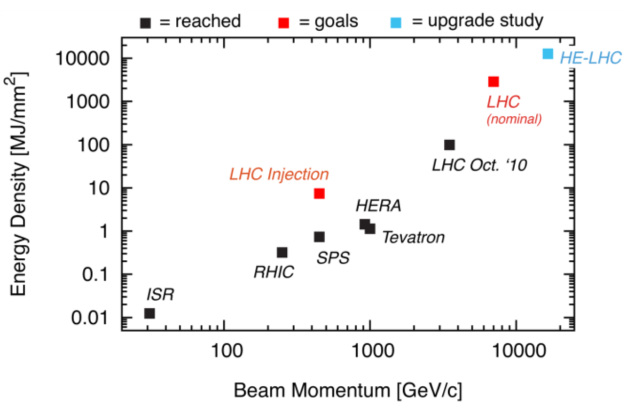

Figure 3: Energy Density of various machines, including the LHC and HE-LHC.

Figure 3 shows the energy density of various machines. As can be seen, the LHC has already exceeded all previous records in this area, but the nominal LHC will be more than an order of magnitude higher and the HE-LHC would be roughly two orders of magnitude.

Collimation inefficiency is a complex function of energy, but it is approximately proportional to the fraction of protons which undergo single diffractive (SD) scattering in the primary collimators compared to those which experience only multiple Coulomb scattering (MCS). This fraction scatters in a controlled way into secondary and tertiary collimators, while the former produce off energy protons that are lost in an uncontrolled way.

Based on this model, the collimation inefficiency will be a factor of two to three worse at 16.5 TeV than at 7 TeV. This will have a strong impact, but it is believed a solution can be found.

The other effect of the higher energy density will be the robustness of the collimators in the event of catastrophic beam loss. At the nominal brightness, the HE-LHC exceeds the currently implemented limits for collimator survival. It is possible that these limits are overly conservative, and that further simulation and tests in the HiRadMat facility might allow the limits to be raised, but this is not guaranteed. Another solution would be to decrease the brightness, but this would lead to a decrease in luminosity. It is hoped that the problem can be solved through research to find a new, more robust, absorber material.

The reduced physical beam size at higher energy will necessitate smaller collimator gaps to achieve the desired cleaning efficiency and protection of the triplet aperture. This will have implications for beam control, and will also dramatically increase the impedance of the collimation system. Detailed calculations and simulations will be required to determine the impact of these effects.

RADIOLOGICAL ISSUES

In the current plan, the HE-LHC would be built after that ~3000 fb^{-1} have been collected at the LHC and HL-LHC. Thus, radiological considerations are very important. Thought must be given to both the handling of activated components and their eventual storage and/or disposal [7].

The most radioactive areas will be the inner triplets and collimators. After 10 years of operation at HL-LHC luminosities, these could generate exposures to those working nearby of more than 1 mSv/h, respectively, after a four-month cool down. Preparation must be made for ALARA procedures, and quite likely some degree of automation will need to be employed.

Objects with this level of activation will be very difficult to dispose of and will likely need to be stored at the laboratory indefinitely.

The majority of the accelerator components will have a much lower level of activation. After four months of cooling, the dipoles will produce less than 1 μSv/h at the surfaces and less than 10 μSv/h near the interconnect areas. With care, worker exposure can be kept to a minimum.

The dipoles could potentially be disposed of at an offsite location, such as the CSTFA facility in Aube, which currently charges about 1000 Euros/m^3 for long term storage of low level waste. It is important to remember, however, that rules for handling of radioactive waste may well change in the next 20 years.

SUMMARY

While there are no obvious show stoppers for the injectors and other infrastructure required for the HE-LHC, there are significant engineering challenges. There are pros and cons to both the S-SPS and LER options for intermediate acceleration, and careful consideration must be given to injection and extraction form the HE-LHC itself.

At least at this point, it looks like little use can be made of magnets from existing machines, or indeed from the existing LHC itself. Collimation, machine protection, and radiological issues appear manageable, but certainly should not be neglected.

REFERENCES

[1] R. Garoby, "Optimal injector cascade for HE-LHC and possible implementations", presented in the fourth session of this workshop.

[2] H. Piekarz, "Using Tevatron magnets for HE-LHC or new ring in LHC tunnel", presented in the fourth session of this workshop.

[3] P. Spiller, "FAIR magnets and design concepts of interest to HE-LHC", presented in the fourth session of this workshop.

[4] K.-H. Mess, "Using LHC as injector and possible uses of HERA magnets/coils", presented in the fourth session of this workshop.

[5] R. Assmann, "Intensity limits and machine protection", presented in the fourth session of this workshop.B.

[6] Goddard, "LHC Beam Dump, Injection System, and Other Kickers", submitted to the fourth session of this workshop.

[7] D. Forkel-Wirth, "Radioprotection Issues after 20 Years of LHC Operation", presented in the fourth session of this workshop.