ACCELERATOR PHYSICS ISSUES OF A VERY LARGE HADRON COLLIDER

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Abstract

A Very Large Hadron Collider (VLHC) was proposed for the post-LHC future.[1] This paper gives a quick survey of a number of accelerator physics issues based on the information obtained from a parameter spreadsheet SSP.[2] The main technical challenges to build such a machine appear to be: the large number of events per crossing (in hundreds), enormous beam stored energy (equivalent to tens tons of TNT), ground motion (which is particularly harmful when the synchrotron frequency is in the sub-Hertz range), small dynamic aperture (due to long filling time), fast growth of the resistive wall instability (in a fraction of one turn), low threshold of the single bunch transverse instability (due to big machine size), strong synchrotron radiation (at a level close to the LEP) and short radiation damage lifetime, *etc.* Possible solutions to some of these problems will also be discussed.

1 INTRODUCTION

The VLHC is really very large in the low field approach. Although a coherent parameter list is yet to be developed, this paper will base its discussions on the following assumed "Level 0" specifications:

$$\begin{aligned} \text{Energy per beam } E &= 100 \ \text{TeV} \\ \text{Luminosity } \mathcal{L} &= 1 \times 10^{35} \ \text{cm}^{-2}\text{s}^{-1} \\ \text{Collision} &= p{-}p \\ \text{No. Detector} &= 1 \\ \text{Circumference} &= 10^6 \ \text{meters} \end{aligned}$$

Because the interaction cross section is approximately proportional to $1/M^2$, where M is the equivalent parton beam energy, the luminosity should go as E^2. Anything below 10^{35} may be difficult to justify for a 100 TeV machine.

The physics of p-p and $\bar{p}$-p is similar at multi-TeV region. But p-p is easier to reach high luminosity. Besides, $\bar{p}$ may be just too expensive to fill up a megameter ring.

Starting from these top level parameters, one can generate their derivatives by running a spreadsheet. One such program is the SSP. It was originally written for the former project SSC, but can easily be modified to serve the VLHC. The next section will discuss a number of accelerator physics issues based on the output of this program.

* Operated by Universities Research Association Inc. under Contract No. DE-AC02-76CH03000 with the U.S. Department of Energy.

2 SELECTED ISSUES

2.1 Events per crossing

The number of events per crossing has a Poisson distribution. The average number n is:

$$n = \mathcal{L}\sigma_{\text{inel}} S_b \tag{1}$$

in which σ_{inel} is the inelastic pp cross section, and S_b the bunch spacing. The value of σ_{inel} at 200 TeV center-of-mass energy is unknown. If the scaling law in the lower energy regions is employed, it could be estimated at about 150 mb. Thus, The only knob to reduce n is by reducing S_b, *i.e.,* increasing the number of bunches. But even at a 16 ns bunch spacing, the number of events per crossing could still reach about 300! This must be a serious challenge to the detector design.

2.2 Beam stored energy

This is one of the primary concerns. For $\mathcal{L}$ = 10^{35}, $S_b = 16$ ns, $\beta^* = 0.3$ m, and $\epsilon_{\text{N}}(95\%) = 24\pi$, the current is about 0.6 A per beam. The stored energy of the two beams would be about 400 GJ, which is equivalent to 90 tons of TNT! Any accidental beam loss could be a catastrophe.

2.3 Ground motion

This is another primary concern for a machine of this size. It has two effects:

1. Relative movement of the magnets:
   This may be caused by tides, seismic effects, ground water level changes, *etc.,* which could lead to mis-alignment and mis-steering and result in an aperture problem.

2. Resonance with the synchrotron frequency:
   The small slip factor (3×10^{-6}) and low revolution frequency (300 Hz) lead to a very low synchrotron frequency (fraction of 1 Hz). This would make it vulnerable to external perturbations, such as the ground motion, which has large components in this low frequency range.

2.4 Filling time and dynamic aperture

Assuming two rings in the Tevatron tunnel as the injector, each capable to deliver 2.5 TeV protons (using 10 Tesla dipoles), cycle time 200 seconds. Then the filling time would be over 9 hours!

Such a long filling time would pose a threat to the dynamic aperture at injection. The big dynamic range of the beam energy (from 2.5 to 100 TeV, a factor of 40) would imply that the field quality at injection could not be very good. Assume the error field be similar to that of the SSC magnets. Then, scaled from the SSC simulation results, the dynamic aperture would shrink to less than 1 σ!

2.5 Beam instability scaling

This has been discussed in detail in Ref. [3]. We will apply those results to the VLHC.

2.5.1 Transverse mode coupling instability

The bunch current threshold of this instability decreases as the machine size increases:

$$I_{th} \propto R^{-3/2} \quad (2)$$

in which R is the machine radius. In terms of maximum number of particles per bunch, the scaling is:

$$N_b \propto R^{-1/2} \quad (3)$$

Therefore, for large machines this instability could become an intrinsic bottleneck. This is basically because the transverse impedance $Z_\perp$ is proportional to the machine radius R and to the 3rd power of the beam pipe radius b^3. Scaled from the SSC (a presumably low impedance machine) impedance budget, the transverse impedance of the VLHC (big R and small b) could reach several hundreds MΩ/m and the beam could become intrinsically unstable. In particular in the vertical plane, where b is the smallest. Ref. [3] suggested to apply local negative transverse impedance for compensating the total machine impedance so that $Z_\perp$ would not scale with the machine size in a linear way.

2.5.2 Resistive wall instability

The growth rate (in s^{-1}) of this instability is more or less independent of the machine size. However, when expressing the growth time in terms of turn number n_w, one has:

$$n_w \propto R^{-1} \quad (4)$$

In other words, in large machines the instability could grow quickly. For the VLHC, assuming the magnet aperture is 2 cm (corresponding to 1.57 Tesla at 50 kA) and the beam pipe 2 mm thick, then the growth time at 2.5 TeV would be 0.2 turn. One needs powerful feedback systems to keep it under control, such as the so-called criss-crossing feedback and one-turn correction scheme.

2.5.3 Longitudinal microwave instability

The threshold of this one is almost an invariant when machine size increases. Therefore, it should not be a major concern.

2.6 Synchrotron radiation

2.6.1 Comparison with the LEP

100 TeV = 2000×50 GeV. This means that, apart from the machine size factor, the synchrotron radiation of a 100 TeV proton beam is in many ways similar to that of a 50 GeV LEP, as listed in Table 1. The following remarks are made:

Table 1. Comparison of 100 TeV VLHC and 50 GeV LEP

	VLHC	LEP
Synch rad (W/m)	5	55
Photons emitted ($s^{-1}m^{-1}$)	4.6×10^{16}	1.3×10^{16}
Critical energy (keV)	2.24	89.5

1. The main heat load (and the cooling requirement) would actually come from the activation of the NEG (350 W/m) instead of the synchrotron radiation. Both machines would be the same in this regard.

2. Assuming the photo-desorption coefficient has a weak energy dependence (as generally believed), the gas load of the proton machine could be close to or even worse than the LEP.

3. The radiation is hard x-ray in the VLHC (critical wavelength 5.5 Å). It could be a concern when x-ray constantly hits the superconducting cable.

4. The damping time of the transverse amplitude of the protons is about 38 hours, which may be too long to be useful.

2.6.2 The NEG

The NEG (ST707) used at the APS/ANL is about $124/m for the material. The engineering cost is several times more. (The activation temperature is 450°C. Slots are needed for accommodating the thermal expansion.) This would mean several hundreds millions dollars for the NEG.

Moreover, the NEG alone cannot produce the required vacuum. Lumped pumps (e.g., TMP) are needed to pump down to 10^{-8} torr (APS data) before activating the NEG.

2.6.3 Beam lifetime problem

In the HERA electron ring (26 GeV), poor beam lifetime was observed at 3 mA when synchrotron radiation stroke the vicinity of several sections of the antechamber that houses distributed ion pumps. When these sections were removed, the problem disappeared.

In the present sketch of the low field option, the radiation from one of the two beams would land on the wall of the antechamber housing the NEG. This makes one to worry about if the HERA problem could also happen to this machine.

2.7 Radiation damage lifetime

The SSC maximum allowable dose on the kapton was 5000 Mrad. Scaled from the SSC calculation, the radiation damage lifetime of the kapton in this machine would only be a fraction of a year.

2.8 Beam pipe

The complex cross section may exclude the use of stainless steel. The concerns about an aluminum pipe are:

1. The eddy current:
   The ramp time from 0.05 to 2 Tesla doesn't seem too bad. But the rectangular shape of the pipe could generate sizable eddy current induced sextupole field that would have to be compensated.

2. The high secondary electron yield of aluminum:
   It could cause two types of problems. One is multipactoring induced by a bunched proton beam as observed in the ISR at CERN many years ago. Another is the recently found electron cloud instability. A solution is to apply a thin Ti-N coating on the surface of aluminum, which has been adopted by LBL for the Low Energy Ring of the SLAC B-Factory. But this would mean additional cost.

2.9 Other issues

These include beam-beam, space charge, intrabeam scattering, beam heating and luminosity lifetime *etc.* They do not seem to present any major problem. The coupled bunch instability still needs some study. The issue of reliability will not be addressed in this paper.

3 CONCLUSIONS

The VLHC is an interesting yet very difficult machine to build. The primary concerns seem to be the number of events per crossing, beam stored energy, ground motion, dynamic aperture during injection and transverse instabilities *etc.* However, the key issue regarding the building of such a machine is technology, in particular the magnet and tunnelling. All other issues can only take a second seat.

4 ACKNOWLEDGEMENTS

The author would like to thank P. Limon for introducing him to the study of this interesting subject.

5 REFERENCES

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