Accelerator Physics and Technology Limitations to Ultimate Energy and Luminosity in Very Large Hadron Colliders

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The following presents a study of the accelerator physics and technology limitations to ultimate energy and luminosity in very large hadron colliders (VLHCs). The main accelerator physics limitations to ultimate energy and luminosity in future energy frontier hadron colliders are *synchrotron radiation (SR) power*, *proton-collision debris power in the interaction regions (IR)*, *number of events-per-crossing*, *stored energy per beam* and *beam-stability* [1]. Quantitative estimates of these limits were made and translated into scaling laws that could be inscribed into the particle energy versus machine size plane to delimit the boundaries for possible VLHCs. Eventually, accelerator simulations were performed to obtain the maximum achievable luminosities within these boundaries. Although this study aimed at investigating a general VLHC, it was unavoidable to refer in some instances to the recently studied, [2], 200 TeV center-of-mass energy VLHC stage-2 design (VLHC-2). A more thorough rendering of this work can be found in [3].

1. Limitations, Scaling Laws and Maximum Luminosities

Table I contains a specification of the assumed limiting parameters of a VLHC for the purpose of this study. In most cases the numbers are believed to push at the cutting edge of accelerator technology, some are those of the recently studied VLHC-2. The 10 W/m/beam peak SR power limit, though double that of the VLHC-2 study, corresponds to the ultimate power level that we believe can be handled by a beam-screen installed in a 40 mm aperture magnet, with a 20 mm beam stay-clear area [4]. The maximum stored beam energy was (arbitrarily) set to 10 GJ, which is double that in the VLHC-2 study. The beam-stability parameters represent the instabilities expected to be the most dominant in VLHCs [5], namely those of the transverse type such as the resistive wall instability, Laslett tune-shift and the fast head tail instability (TMCI). Unlike the case of the VLHC-2 study which has higher stability margins, the limiting beam-stability parameters were specified to be at the stability thresholds, assuming that counter-measures (feedback systems, ..etc.) would be in place to provide stable beams. The radiation damping time condition excludes machines that are not SR dominated. SR damping is the only way

Table I: Limiting Parameters of a VLHC.

Parameter	Limit
Peak synchrotron radiation power (W/m/beam)	10
Peak IR debris power (kW/beam)	50
Maximum number of events per crossing	60
Maximum beam-beam tune-shift parameter	0.008
Maximum peak beam stored energy (GJ)	10
Ratio of radiation damping and luminosity lifetime -peak	0.5
Resistive wall instability rise-time (turns)	1
Initial bunch intensity given by TMCI criterion	N_{TMCI}
Maximum Laslett tune-shift	0.2
Minimum luminosity $\cdot 10^{34}$ cm^{-2}s^{-1}	2

known today to achieve high luminosity. However, the beam stability limitations and the minimum SR condition are "soft". The VLHC-1 design in the study is an example of a machine that is prone to beam-instability and without radiation damping. Note, however, that the peak luminosity in this VLHC-1 is 10^{34} cm^{-2}s^{-1}. In order to permit a straight-forward formulation of scaling laws representing the limiting parameters of Table I, some parameters had to be fixed, all of which are listed in Table II. Almost all of them are similar to those in the VLHC-2 study, except for the bunch-spacing time and β^*, for which more aggressive values were chosen. The simulations assumed round beams. The scaling laws were formulated in terms of the energy per beam, the arc bending radius and the

Table II: Fixed Parameters

Parameter	*Fixed Value*
Number of IP's	2
Length of straight sections l_s (km)	10
Dipole packing factor PF	0.85
Dynamic range DR	10
Luminosity enhancement factor L_{fact}	10
Bunch filling factor F	0.9
Bunch spacing time (ns)	12
Betastar β^* (m)	0.3
Average transverse β function at injection $<\beta_{inj}>$ (m)	163
Normalized injection emittance ε_{inj} (µm)	$1.5 \cdot \pi$
Synchrotron tune at injection ν_s	0.1
Bunch length at injection l_b (cm)	8.2
Fractional tune-shift $\Delta\nu$	0.1
Beam-beam tune-shift parameter ξ, when fixed	0.008
Magnet aperture $\varnothing$ 2b (mm)	20
Beam screen temperature T_{bs} (K)	100
Beam screen coating RRR	100
Beam screen coating thickness Δ (µm)	200
Number of pumping holes in beam-screen per m n_h	120
Dimensions of pumping hole in beam-screen (mm)	1.5 x 8
Injection field in conductivity function B_{inj} (T)	1

peak luminosity. Figure 1 shows the most stringent limitations inscribed into the energy / radius plane at a stipulated peak luminosity of $2 \cdot 10^{34}$ $cm^{-2}s^{-1}$. The IR-debris T and SR-power limits restrict the parameter space toward high energy. The beam stability limitations apply to large circumference, low-beam-energy solutions. Not shown is the events-per-crossing limit, which is parallel to the IR debris limit at a higher beam energy. The TMCI limits runs just underneath the Laslett tune shift limit. The stored beam energy limit is a vertical line far outside the range of considered machine radii. The minimum radiation damping condition lies close to the beam stability lines. The beam-beam limit is implicit to all limitations shown in Figure 1. The peak luminosities within the "allowed" region (hatched are in Figure 1), were calculated, simulating accelerator operation at the various combinations of beam energy and arc bending radius, taking into account the limitations listed in Table I.

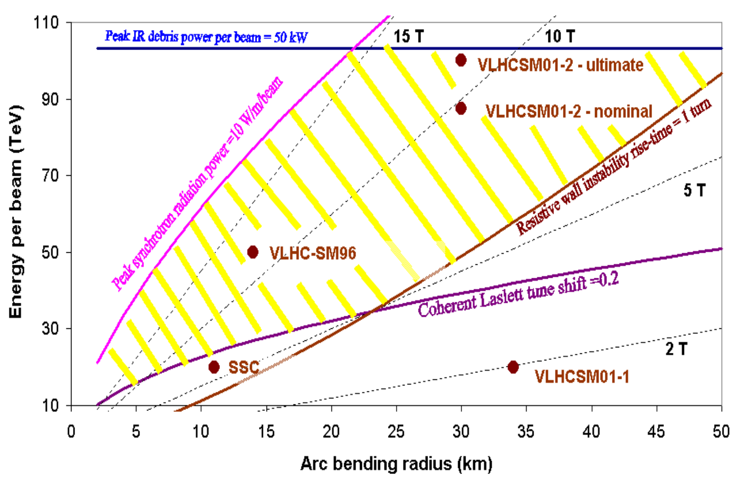

Fig. 1: Possible Particle Energy / Machine Size combinations for future hadron colliders (hatched area). In the plot only the most stringent limitations are shown, i.e. IR debris power, SR power, Laslett tune shift and resistive wall instability. The scaling laws are plotted for a minimum luminosity of $2 \cdot 10^{34} m^{-2}s^{-1}$ Shown are as well the operating points for existing VLHC proposals and the operation points for different bending fields.

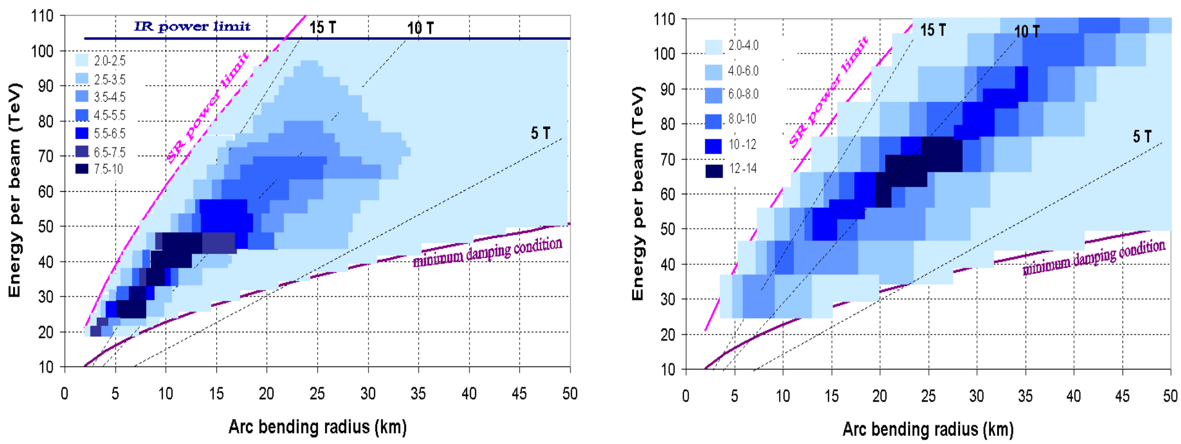

Fig. 2: Peak luminosities in possible VLHC's, in units of $10^{34}cm^{-2}s^{-1}$, accounting for: (LEFT), the Beam-beam parameter, SR-,IR-power, number of events and (RIGHT), the SR-power, and beam stability limits.

The results are shown in Figure 2. As a result of damping, the region of highest luminosity appears in the middle of the "band" delimited by the maximum SR power and the minimum radiation damping condition. The peak luminosities in the plots of Figure 2 were calculated using two different sets of limitations. In the left plot all limitations of Table I, except for beam stability were taken into account. In the right plot the IR-debris and number of events-per-crossing limits were dropped and the beam stability limits were included instead. The plot on the left shows that the high luminosities cannot be upheld in very-high-energy machines because of the IR power limit. Beam stability on the other hand, as shown in the plot on the right, sets a limit to the luminosities all along the "lower" boundary of the accelerators investigated. The regions of highest luminosity, of the order of $10^{35}cm^{-2}s^{-1}$, do not coincide in both plots, but both plots show the above mentioned "band" of highest luminosities in the region of high field machines. These results, however, are strongly tied to the set of limiting and fixed parameters chosen here. If a larger IR debris power than 50 kW/beam can be tolerated, for example, the trend of high luminosities extends toward higher beam energy in the plot on the left. A larger synchrotron radiation power limit, e.g. using photon-stops, would move the luminosity maximum toward very-high-field-rings. Relaxing the beam-stability conditions pushes the maximum luminosities toward low-field rings. A smaller beam-stored-energy condition affects the luminosity in large-circumference machines. The currently proposed VLHC in its ultimate stage with 200 TeV center-of-mass energy finds itself close to the edge of the $2{\cdot}10^{34}$ luminosity region, being primarily constrained by the IR debris power limitation. If this limit is relaxed, the luminosity could be higher, eventually limited by the SR power.

2. Summary

The main conclusions resulting from this study are that 1) the IR debris power limit of 50 kW/beam restricts the beam energy to ~100 TeV, and 2) the highest achievable luminosities are of the order of 10^{35} $cm^{-2}s^{-1}$ and they are distributed along a line going from very high fields at lower energy to moderate fields at very high energies.

As the most important result of this study appears the need for further investigation of the issue of IR debris power, since this was found to be the most stringent parameter. It affects the forward part of the detector and the IR focusing magnets.

References

[1] S. Peggs et al., "*VLHC Accelerator Physics*", BNL, C-AD/AP/49, June 2001;

[2] P. Limon et al., "VLHC Feasibility Study 2001", Fermilab TM 2194 or at www.vlhc.org;

[3] P. Bauer et al., “Accelerator Physics and Technology Limitations in High-Field, Very Large Hadron Colliders”, Fermilab, Technical Division Note, TD-01-062, Oct. 2001;

[4] P. Limon et al., “*The Influence of Accelerator Physics on the Magnet Design of a Very Large Hadron Collides*”, to be published in the Proceedings of the 2001 Magnet Technology Conference, Sept. 2001, Geneva, Switzerland;

[5] A. Chou, “Summary of the VLHC beam stability workshop at SLAC, March 2001”, SLAC PUB 8000, May 2001;