

# WHAT CAN THE SSC AND THE VLHC STUDIES TELL US FOR THE HE-LHC?

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## ABSTRACT

In the SSC and the VLHC machine designs a number of accelerator physics and technology challenges were present. These challenges and the ways they were addressed are relevant also for the high-energy upgrade of the LHC that is contemplated in this workshop. In this paper I will highlight these challenges and the mitigation strategies pursued, and I will attempt to demonstrate the commonalities and lessons for the HE-LHC.

## INTRODUCTION

### The SSC

The Superconducting Super Collider (SSC)[1, 2] was under construction when the project was terminated by US Congress in the fall of 1993. The top-level parameters of the SSC collider are listed in Table 1.

Table 1: SSC Parameters

Parameter	Unit	Value
Energy/beam	TeV	20
Circumference	km	87
Luminosity	$\text{cm}^{-2}\text{s}^{-1}$	$1 \times 10^{33}$
Intensity	ppb	$0.75 \times 10^{10}$
Trans. emittance	$\mu\text{m rad}$	1.0
Bunch spacing	ns	16.7
Stored Energy	GJ	0.4
Inj. energy	TeV	2
Dipole field	T	6.7

A diagram of the machine plus injectors is shown in Fig. 1.

Compared to the LHC the bunch intensity is more than a factor of 10 lower, with smaller beam emittance by a factor of three, while the bunch spacing is comparable. The stored beam energy is fairly similar, but in a machine almost four times the size of the LHC. The bending field of 6.7 T was at the time the highest field in any series-produced accelerator dipole magnets.

### The VLHC

The conceptual design for the the “Very Large Hadron Collider” (VLHC)[3] was a 200+ km machine with two

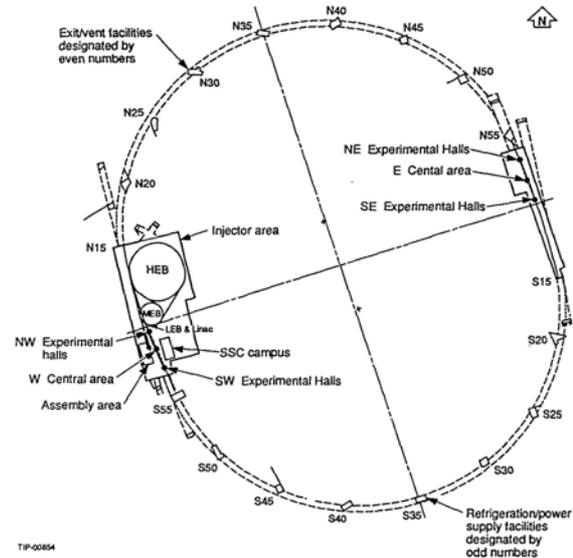


Figure 1: Diagram of the SSC Site.[2]

Table 2: VLHC Parameters

Parameter	Unit	VLHC I	VLHC II
Energy/beam	TeV	20	87.5
Circumference	km	233	233
Luminosity	$\text{cm}^{-2}\text{s}^{-1}$	$1 \times 10^{34}$	$2 \times 10^{34}$
Intensity	ppb	$2.6 \times 10^{10}$	$0.9 \times 10^{10}$
Trans. emittance	$\mu\text{m rad}$	1.5	0.04 [0.2]
Bunch spacing	ns	18.1	18.8
Stored Energy	GJ	3.0	3.9
Inj. energy	TeV	0.9	10
Dipole field	T	2	9.8

stages, a first stage for 20 on 20 TeV collisions and a second stage for 87.5 TeV on 87.5 TeV p-p collisions. For this paper, only the second stage is considered. This machine had a proposed bending field of close to 10 T, causing the machine parameters to be affected significantly by synchrotron radiation. Table 2 shows the top-level parameters for the VLHC collider, Fig. 2 shows a layout of the design.

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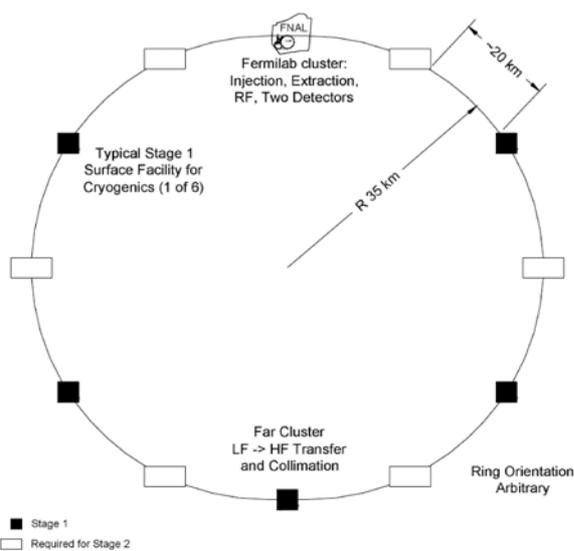


Figure 2: Diagram of the VLHC Site.[3]

## DESIGN ISSUES

### Magnet aperture

The aperture of the SSC was subject to several revisions, increasing the dipole aperture from 40 mm in the CDR[1] to 50 mm in the SCDR[2] and later increasing the quadrupole aperture to 50 mm as well. The arguments for this were based mostly on tracking studies, only late in the project the need to consider a liner in the vacuum system also affected the aperture discussion.

Fig. 3 shows the result of a dynamic-aperture study for the SSC with 40 mm dipoles. Machine acceptance for  $10^5$  turns is about 0.6 cm initial amplitude. With 50 mm this opens up significantly, see Fig 4. A different look at the

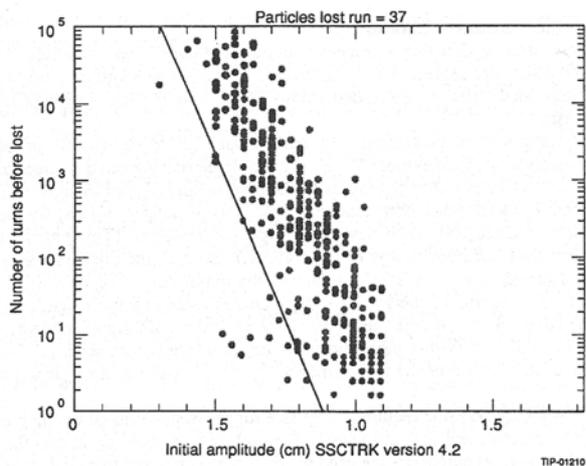


Figure 3: Survival plot for the SSC with 40 mm aperture dipole magnets.[2] Note the error on the horizontal scale (0.5 misprinted as 1.5).

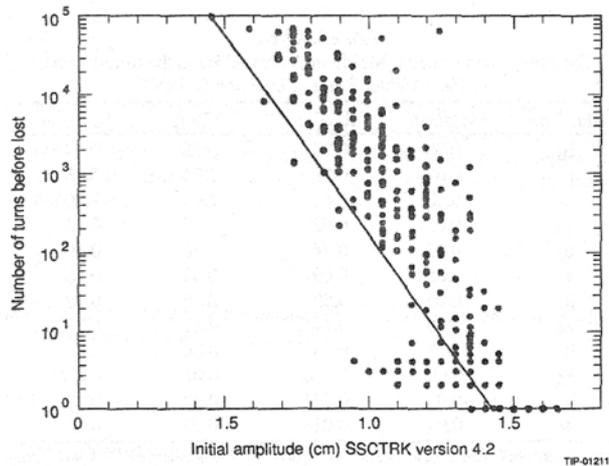


Figure 4: Survival plot for the SSC with 50 mm aperture dipole magnets.[2] Note the error on the horizontal scale (0.5 misprinted as 1.5).

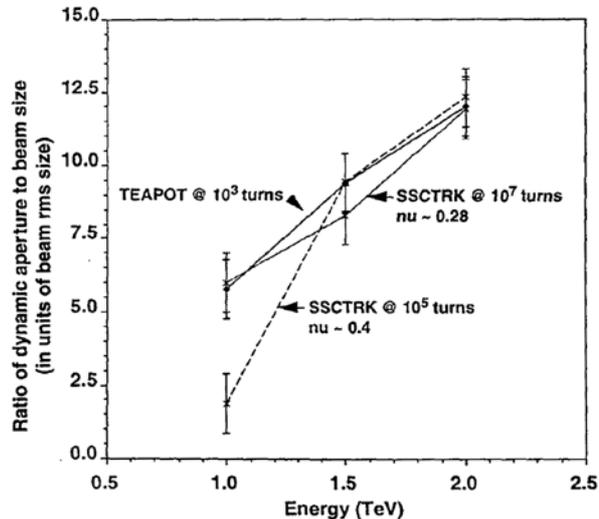


Figure 5: SSC Tracking for different injection energies. 50 mm quadrupole and dipole aperture.[4]

machine acceptance is shown in Fig. 5, with acceptance vs injection energy for the machine with 50 mm dipoles and quadrupoles. The 5 to 6  $\sigma$  acceptance at 1 TeV was considered inadequate while the nearly 12  $\sigma$  acceptance at 2 TeV was more than sufficient, leaving room to lower the HEB energy to 1.5 TeV as was considered.[4]

It is instructive to compare these with LHC tracking results. In Fig. 6 an LHC survival plot is shown, published in 1998.[5] It appears that the machine has an acceptance of about 12  $\sigma$ , which would correspond to the SSC with 50 mm aperture in dipoles and quadrupoles, and which is also consistent with the rather linear behavior the LHC has exhibited in beam commissioning in 2010. In the earlier versions of the SSC lattice with smaller magnet apertures, various field-correction schemes were devised to deal with the field harmonic at injection due to the persistent cur-

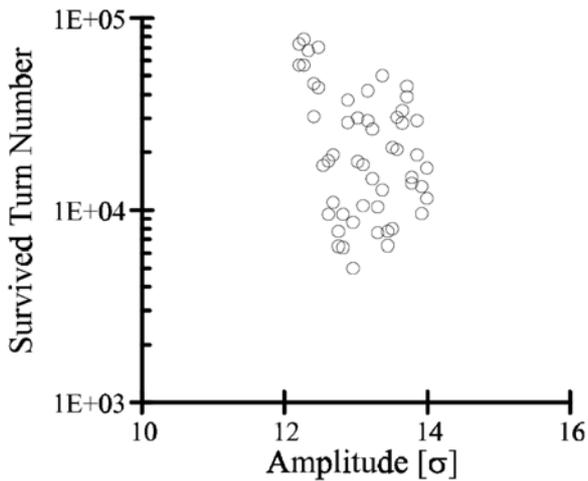


Figure 6: Survival plot for the LHC.[5]

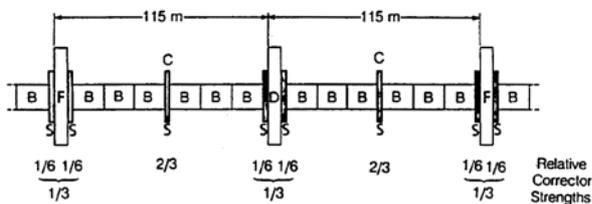


Figure 7: Mid-cell correction of dipole field errors.[6]

rents, e.g. the mid-cell corrector elements, also known as “Neuffer-Simpson” correction.[6] It consists of correctors at either end of a half-cell plus a corrector of twice the strength in the middle of the half cell, between two dipoles. This correction minimizes the introduction of extra higher-order terms arising from the correction elements, which can defeat simpler correction schemes. Sextupole and octupole correctors were foreseen. Fig. 7 shows a schematic. The 50-mm aperture design did not require these somewhat complicated mid-cell corrector packages, omitting which offset in part but not fully the increased cost of the dipoles.

The VLHC design envisaged 40 mm magnet aperture, but at a higher injection energy of 10 TeV (from the stage-1 ring in the same tunnel). At this energy the beam size is sufficiently small that the smaller magnet aperture would be sufficient (from a field-quality point of view).

### Synchrotron Radiation

Synchrotron radiation will be significant in the HE-LHC. Table 3 compares the relevant parameters for the four machines considered here. The two lower-energy machines, LHC and SSC, have s.r. power density of a fraction of a W/m and damping times of 25 to 30 hours, comparable to the luminosity lifetime. VLHC and HE-LHC on the other hand have power densities of a few W/m and damping times of a couple of hours, significantly shorter than the luminosity lifetime. Therefore the radiation damping

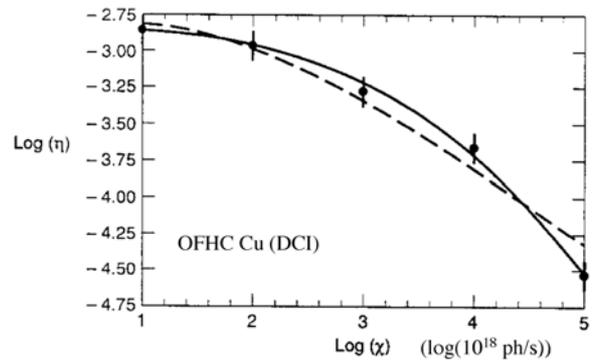


Figure 8: Photon desorption fit to data taken at DCI.[7]

dominates the beam parameters (unless specific countermeasures are taken). The power density to a certain extent is a question of effort to carry away in cooling, although reliability may suffer if the heat load on the cryo system gets too high.

In the SSC, the vacuum and cooling system were designed to absorb the power. Photon desorption became a subject of intense study as it became evident that the hydrogen frozen at the walls could cause unacceptable values of the photon-induced desorption coefficient  $\eta$  if allowed to form a monolayer or more. To this end, a diffusion model was created based on then-available photon-desorption data from BNL, the DCI collider at LAL, and BINP.[7] A fit is shown in Fig. 8 as an example, for oxygen-free high-conductivity copper (OFHC). The model in turn was used to predict the behavior of the SSC vacuum system. It was found that OFHC copper performed better than copper deposited onto a stainless-steel pipe—probably due to better surface smoothness. However, none of the surfaces as tested could be expected to clearly last longer than the 4000 hour required before a warm-up was necessary in order to boil off the hydrogen from the wall. The alternative solution of a liner (beam screen) was being considered; there would have been enough space in the 50-mm magnets.

For the VLHC with its potentially high gas load the pumping surface behind the liner still may not have sufficient capacity. To increase capacity, a getter behind the liner was considered.[8] The liner in turn has its own cooling carrying away the radiation energy. The temperature of the liner is chosen to avoid on one hand to much radiative power into the low-temperature beam pipe, to maximize on the other hand the cooling efficiency which favors a higher liner temperature. In the VLHC, 80 to 100k was anticipated. In this context the possibility of dedicated, warm photon stops was considered and even some engineering studies initiated[9]; however, in the HE-LHC context this approach does not work as the bending in each magnet is too large and the radiation fan hits the wall before leaving the magnet.

Table 3: Synchrotron radiation Parameters for the machines considered

Parameter	Unit	LHC	SSC	VLHC	HE-LHC
Energy/beam	TeV	7	20	87.5	16.5
Energy loss/turn	MeV	0.01	0.053	15.3	0.2
Radiation power/beam	kW	5.8	9	1050	255
Power density/beam	W/m	0.3	0.15	4.7	2.8
crit. Energy	keV	0.044	0.284	8.03	0.575
Transverse damping time	h	26	30	2.5	2

Table 4: VLHC IR Parameters for a flat- and a round beam

Parameter	Unit	Flat beams	Round beams
Peak Luminosity	$\text{cm}^{-2}\text{s}^{-1}$	$2 \times 10^{10}$	$2 \times 10^{10}$
Aspect ratio		0.1	1
Beam-beam parameter ( $x=y$ )		0.008	0.008
Intensity	ppb	$0.75 \times 10^{10}$	$0.75 \times 10^{10}$
Horizontal emittance	$\mu\text{m rad}$	0.161	0.082
Vertical emittance	$\mu\text{m rad}$	0.016	0.082
$\beta_x^*$	m	3.7	0.71
$\beta_y^*$	m	0.37	0.71
$\hat{\beta}_x$	km	7.84	14.58
$\hat{\beta}_y$	km	10.75	14.58
$\sigma_x^*$	$\mu\text{m}$	2.53	0.79
$\sigma_y^*$	$\mu\text{m}$	0.25	0.79
$\hat{\sigma}_x$	$\mu\text{m}$	116	113
$\hat{\sigma}_y$	$\mu\text{m}$	43	113
$\sigma_x^I$	$\mu\text{r}$	0.68	1.11
$\sigma_y^I$	$\mu\text{r}$	0.68	1111
Total crossing angle	$\mu\text{r}$	10	10
Separation distance	m	30	120
# parasitic crossings per IR		20	84

### Electron-Cloud Effect

The threshold for electron-cloud build-up was determined for the VLHC to be about  $3.5 \times 10^{10}$  ppb, later revised down to  $2 \times 10^{10}$ . [10] These values were arrived at in light of results obtained at the SPS around 1999. While there were details to be considered, the threshold appeared safely above the bunch intensity of  $0.9 \times 10^{10}$ . An SEY of 1.3 (peak, at 400 eV) was assumed in these studies, a value one might expect for a well-scrubbed stainless-steel or copper surface. With its relatively low bunch population this machine design is in a different region of parameter space w.r.t. the electron-cloud effect than the HE-LHC.

### Luminosity profile, beam dynamics, etc.

In the VLHC—as in the HE-LHC—the nominal damped emittance in all three planes is much smaller than the injected emittance. Thus luminosity and beam-beam parameter will increase as the beams damp. With a flat beam, the optical design of the IR can deviate from the antisymmetric triplet IR often used in round-beam hadron colliders

and adopt the symmetric doublet focusing scheme used in flat-beam lepton colliders. Besides simplifying the IR design, it offers the chance for a much earlier separation with a dipole as the first magnet after the IP, without causing excessive  $\hat{\beta}$ . In case of the VLHC, the separation distance for a particular set of parameters (Table 4) is 30 m for the flat-beam IR vs 120 m for the round-beam IR. As a result the number of parasitic crossings is reduced by about a factor of 4. An optical design for a flat-beam IR is shown in Fig. 9.

Once the beam-beam limit is reached, it is necessary to stop the damping process (e.g. by injection of noise in two or all three planes) and maintain the tune shift. In the VLHC this happens in the horizontal plane first, saturating  $\xi_x$ . Once  $\xi_y$  saturates as well it was foreseen to vary the crossing angle to maintain  $\xi_y$ . Figure 10 shows the resultant luminosity profile, Fig. 11, the beam-beam parameters vs time. These profiles have built-in an assumption of longitudinal heating of the beam to maintain a momentum spread of about  $0.5 \times 10^{-4}$ . The beam is left to assume a flat shape with about a 1:10 aspect ratio.

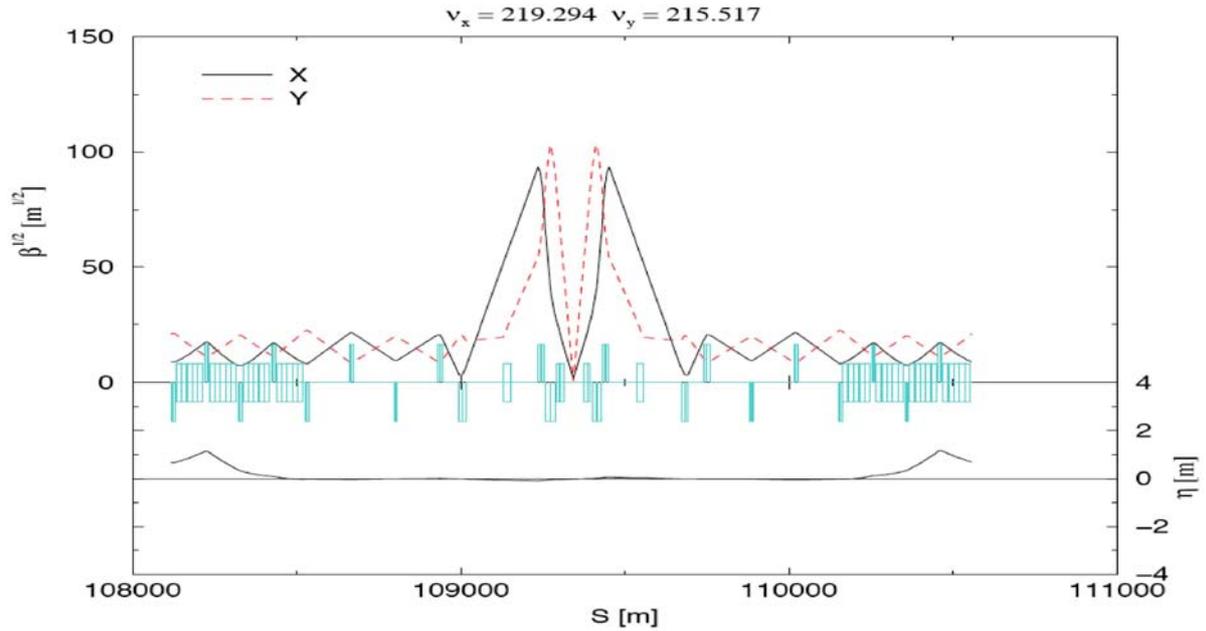


Figure 9: Optical design for a flat-beam Interaction region.[7]

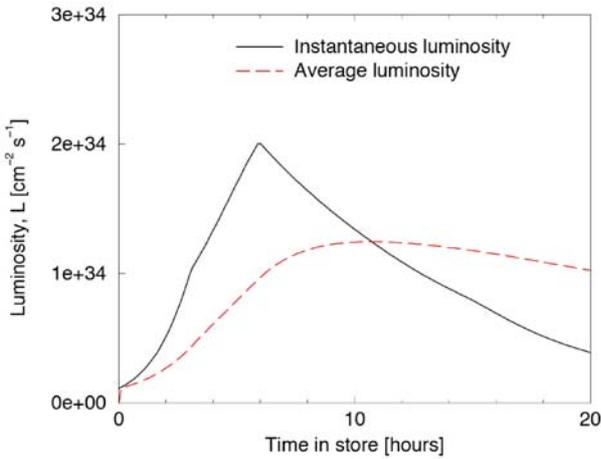


Figure 10: VLHC Luminosity vs time, flat beams.[7]

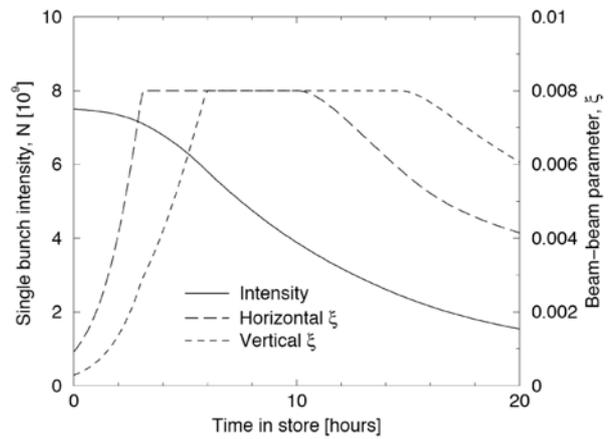


Figure 11: VLHC beam-beam parameter vs time, flat beams.[7]

With radiation damping times of about 2 hours, it may be argued that the beam-beam limit should be higher than for present-day hadron colliders. A comparative study of different machines was attempted for the VLHC and shown in Fig. 12. The exponent of  $1/3$  for the fitted equation has been found before by Assmann & Cornelis in LEP data.[11] VLHC and HE-LHC have a damping decrement of about  $10^{-7}$ , which indicates that the gain in  $\xi$  by damping will be moderate at best, on the order of 0.0025. It does have to be noted, however, that there are newer data for the Tevatron as well as the LHC, indicating that even at negligible damping the beam-beam parameter can significantly exceed the 0.006 used in Fig. 12.

### Longitudinal parameters

Table 5 gives a comparison of some of the longitudinal parameters of the machines considered here. Shorter bunch lengths can be a potential heating issue as the loss factor tends to increase with decreasing bunch length. In the VLHC II this is mitigated by the small bunch charge. In the HE-LHC, however, the combination of somewhat shorter bunches and somewhat higher bunch charge (than LHC nominal beams) may increase power loss in—or leakage through—the screen by a significant amount. Note that for VLHC and HE-LHC, a longitudinal beam-heating mechanism is assumed to keep the energy spread at a value near  $0.5 \times 10^{-4}$  in order to prevent bunches from becoming too short and/or beam instability.

Table 5: Longitudinal parameters.

Parameter	Unit	LHC	SSC	VLHC II	HE-LHC
Bunch length	mm	75	$\approx 60$	26	65
$\Delta E/E$	1	$1.1 \times 10^{-4}$		$0.5 \times 10^{-4}$	$0.4 \times 10^{-4}$
Bunch Charge	ppb	$1.1 \times 10^{11}$	$0.75 \times 10^{10}$	$0.9 \times 10^{10}$	$1.3 \times 10^{11}$
Rf frequency	MHz	40	60	55	40

Table 6: VLHC Impedance Budget.  $Z_{\perp}^{RW}$  is given for the mode with the lowest frequency

Machine	$R(m)$	$b(mm)$	$\frac{Z_{  }}{n}(\Omega)$	$Z_{\perp}^{BB}(\frac{M\Omega}{m})$	$Z_{\perp}^{LH}(\frac{M\Omega}{m})$	$Z_{\perp}^{RW}(\frac{M\Omega}{m})$
FNAL MI	529	25.4	1.6	-	26	
LHC	4243	18	0.66	28	1.5	124
SSC	13866	16.5	0.68	54	21	4200
VLHC II	36924	10	0.6	390	90	55000

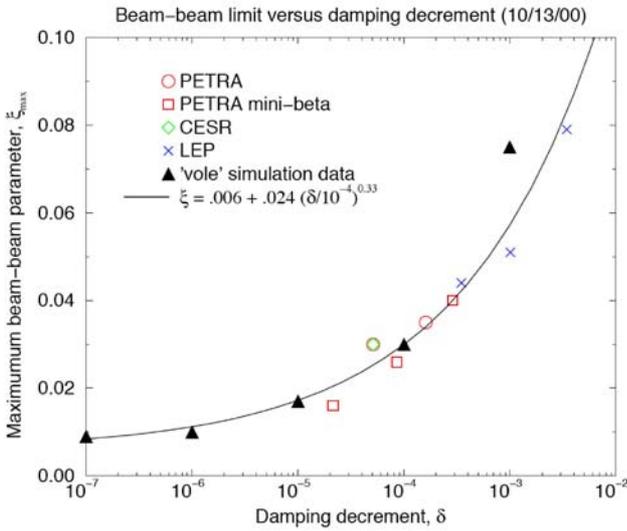


Figure 12: Fit of Beam-beam parameter vs damping decrement for various machines.[7]

### Impedance

A rough impedance budget was drawn up for the VLHC, scaled from SSC, LHC and the FNAL Main Injector, see Table 6. The longitudinal impedance for all machines is a similar  $Z_{||}/n$  near  $1 \Omega$ ; while the transverse components scale up with a certain power of the length. For the HE-LHC the impedance will be comparable to that of the LHC; however, to assess the beam stability one needs to also take into account the beam parameters, in particular bunch length, energy spread, and also the slip factor of the lattice, see Table 4. It may be argued (from scaling by  $\sigma_{x,y} \times \sigma_l$ ) that the HE-LHC (at top energy) is up-to 3 times closer to instability limits than the present LHC.

### SUMMARY

The SSC studies and the VLHC studies can give useful insight in the HE-LHC context due to the similarity in energy and—in case of the VLHC—both machines being dominated by synchrotron radiation. The possibility of flat beams may be an interesting option to explore. The aperture debate of the SSC may help in setting the right aperture for the HE-LHC, and the vacuum investigations done for the SSC should, if properly updated for the newer data available now, be useful in estimating vacuum performance and the details of the liner and pumping system needed to avoid excessive photon desorption and pressure bumps.

It may be instructive to review here the main R&D issues identified in the VLHC Accelerator Physics Report[12], given here in very abbreviated form:

1. Energy deposition in the IRs.
2. Operational aperture.
3. Instabilities.
4. Diffusion as a mechanism counteracting the radiation damping.

For HE-LHC it appears that the first and last items are the most significant ones, whereas items 2 and 3 are more-or-less addressed using operational data from the present LHC. But the radiation generated in the IRs will already be a problem at the LHC, limiting the lifetime of the IR magnets. The problem of diffusion overcoming the radiation damping at some point still remains to be studied, although the LHC, once it is operating at 7 TeV beam energy, may give an indication of the strength and even nature of such processes. In addition to these, a number of areas needing further were identified in the VLHC report:

1. Diffusion, ground motion, IBS and other mechanisms of emittance growth.

2. Lattice design incl. details of the IR.
3. Simulations and particle tracking.
4. Instabilities and the need for feedback systems.
5. Energy scaling, limits of luminosity.
6. Beam experiments designed to assess possible VLHC issues.

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