ACCELERATOR TECHNOLOGY FOR THE VLHC[*]

J. Marriner and V. Shiltsev[†]
Fermi National Accelerator Laboratory, P.O. Box 500, Batavia, IL 60510

Abstract

Accelerator Technologies useful or necessary for the construction of the VLHC (Very Large Hadron Collider are discussed. The VLHC workshop on this subject (held in February 1999 at Jefferson Lab) is summarized.

1 OVERVIEW

This paper is based on the results of a workshop held February 16-19, 1999 at Thomas Jefferson National Accelerator Facility [1]. This paper represents our summary of work done by many people. We have made an effort to refer to the original work whenever a written reference exists.

2 VLHC COSTS

The cost of the VLHC is not known. One goal of the VLHC R&D is to identify potential cost reduction strategies. For purposes of comparison a cost estimate for the SSC is shown in Figures 1 and Figure 2.

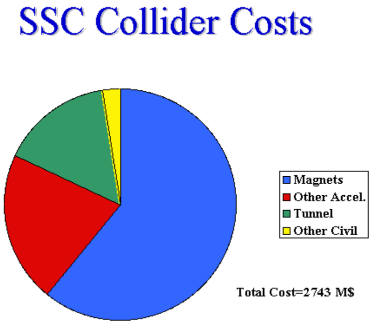

Figure 1: The total cost of the SSC collider includes all components of the large ring, but does not include the other accelerators, the detectors, or the infrastructure.

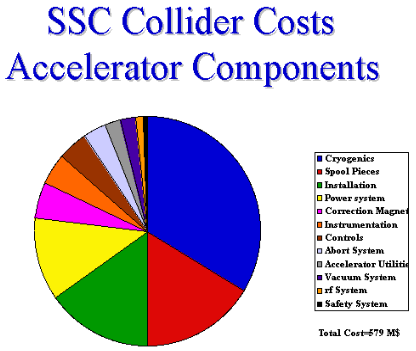

Figure 2: A breakdown of the costs of the "Other Accelerator" components shown on Figure 1.

3 CRYOGENICS

The cryogenic issues for every accelerator are:

- operating temperature
- temperature gradients
- temperature stability

From both a capital and operating cost standpoint, as well as availability, it is desirable to switch to sensible heat from latent heat systems: *e.g.*, Nb_3Sn magnets operating between 4.5 and 5.5 °K versus 4.5 and 5.0 °K. For NbTi magnets the short sample curves are such a strong function of temperature that elevated temperatures are not an option. In fact, lower temperatures are often used. For Nb_3Sn, with its much higher critical temperature, the integrated design optimization may be different. There may also be major differences between the high and low field optimizations. These optimizations are trade off between:

- Magnet short sample limit
- Cryogenic complexity and availability
- Cooling passages and cryostat sizes

One of the most important parameters that drives both the cost and availability is string length and/or recooler spacing. It must also be noted that the costs of the HERA and LHC distribution systems are very similar to the total refrigerator cost.

3.1 *Reliability and Maintenance*

System optimizations require trade-off's between efficiency and availability: the most efficient systems usually do not provide adequate availability. Scaling LHC is not an option; a simple magnet cryogenic system is required for VLHC. The Snowmass 138 km LHC scale up would have had 8000 tunnel cryogenics valves (1 valve per dipole average). These valves would more than saturate the entire cryogenic un-availability budget.

One of the continuing issues is vendor qualification: will there be any cryogenic system vendors in 15 years? In the US, the industrial cryogenic expertise has decayed over the past 20 years, due to retirements and corporate decisions that large refrigeration systems are unprofitable.

3.2 *Suggested R&D on Cryogenics*

Some R&D should probably be carried out for the VLHC:

- *Flow instabilities*. The most important for the VLHC are "Density Wave Instabilities". Numerical simulations and experiments are needed.

---

[*] Work supported by the U.S. Department of Energy under contract DE-AC02-76CH030000.
[†] marriner@fnal.gov or shiltsve@fnal.gov.

0-7803-5573-3/99/$10.00@1999 IEEE.

- *Cycle and efficiencies for sensible heat vs. latent heat systems*. Sensible heat systems typically provide system simplifications with some loss of efficiency. The relative advantages should be studied further.
- *Magnetic bearing turbines*. Highly reliable turbines that are easy to operate should be developed. Today, cryogenic turbines use either gas or oil as a bearing and also as a brake. In the future, turbines could be built with magnetic bearings and use regeneration as the brake.

4 BEAM SCREENS

The LHC beam screen system has received an enormous amount of attention and serves as an example for VLHC. The LHC primary cryogenic screen loads are Synchrotron radiation and photoelectrons, but resistive losses and nuclear scattering are not negligible. Even if the cryogenic impacts are neglected, a shield is required to prevent continual liberation of molecules adsorbed by the 1.9 °K beam tube. The regeneration interval required is much longer than a year.

Both 4.5 and 20 °K high field magnets will require a beam screen due to beam lifetimes; CERN data implies warm-ups every 50 hrs without a beam screen. LHC requires solutions for both their 4.5 & 300 °K magnets and has a major R&D effort in progress. Two options are outlined below and illustrated in Fig. 3.

1. Physical absorption
   a) shield is required
   b) absorber (e.g. metal sponge) is required
   c) tri-monthly regeneration at 20 °K
2. Chemical adsorption
   a) independent bore tube is required
   b) annual regeneration at 600 °K
   c) magnets are kept at their operating temperature
   d) finite life

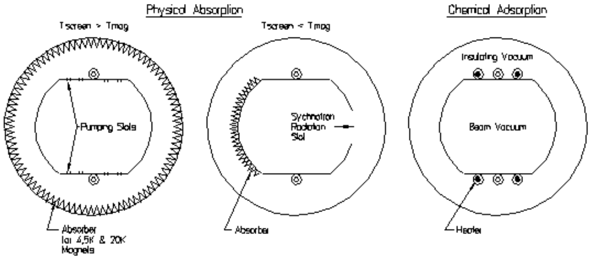

Figure 3: Concepts for a VLHC beam screen.

5 INSTRUMENTATION

There do not appear to be any VLHC devices or technologies that are especially challenging. The long distances and limited access to the tunnel require an unprecedented reliability for the VLHC instrumentation. The following design principles are suggested for the design of VLHC instrumentation.

- Placement of electronics near detectors
- Minimization of cable plant
- Use of standardized (commercial) electronics
- Placement of electronics to minimize radiation damage and monitoring the accumulated does (non-hardened electronics can typically tolerate a dose of 10 kRad)
- Achievement of reliability by redundancy
- Extensive use of self-diagnostics
- Use of modularity
- Integration of different systems, but allowing simultaneous of a variety of simultaneous maintenance activities

6 RF PARAMETERS

We have considered two options in Table 1: 478 MHz to increase the longitudinal spread in the vertices at the interaction point or 1274 MHz to give a higher momentum spread and synchrotron frequency. We assume that superconducting cavities will be used although room temperature copper cavities could be used.

Table 1: Two options for VLHC rf parameters.

f_{rf}	478	1274	MHz
Operating temperature	4.2	2.0	°K
E_{acc}	6	12	MV/m
Shunt R/Q	1000	1000	Ohm/m
Coupler	coax	waveguide	
Cells/cavity	4	7	
Volts/cavity	7.5	9.9	MV
Beam current	127	127	mA
$\cos(\theta_s)$	0.5	0.5	
Max. beam power	480	630	kW
Bucket length	21	7.8	cm
Voltage Cost	.06	.015	$/V
Cavities for 200 MV*	27	20	

*We chose a total voltage of 200 MV for the low-field case and 40MV for the high-field case so that each case has the same acceleration time of about 15 min from 3 to 50 TeV.

7 INSTABILITIES

Instabilities that may occur in the VLHC were considered at the workshop [2]. Although the low field VLHC is more susceptible to some important instabilities, none of them can be considered as a "show-stopper." Even at the current status of accelerator physics and technology there appear to be adequate tools to damp or eliminate the potential instabilities.

7.1 Transverse mode coupling instability

The frequencies of coherent bunch motion (mode 0) and head-tail motion (mode 1) are shifted by the transverse impedance towards each other resulting in the transverse mode coupling instability. Several methods of eliminating this instability have been proposed and are summarized in Table 2. Not all of the methods can be applied simultaneously, and some of them are unproven. However, it seems likely that an effective solution can be found.

Table 2: Methods for damping TCMI.

Method	Threshold Increase
Coalescing at 50 TeV	2…9
“beam shaving“	2…3
thin Cu, Ag coating	~1.3
Asymmetric beam pipe	1.5…3
RF quadrupole	2…4
AC chromaticity	~10
Feedback system	2...5...(more?)

7.2 Transverse Coupled Bunch Instability

The Coupled-bunch instability is most severe at 3 TeV and is proportional to the total beam current. It is driven by the low-frequency transverse impedance resulting from the finite conductivity of the beam pipe walls. The instability growth time in the low-field VLHC varies from 4 to 0.4 turns (depending on lattice parameters), and is about 180 turns in the high-field case. The instability can be damped with use of a distributed feedback systems [3] as shown in Figure 4.

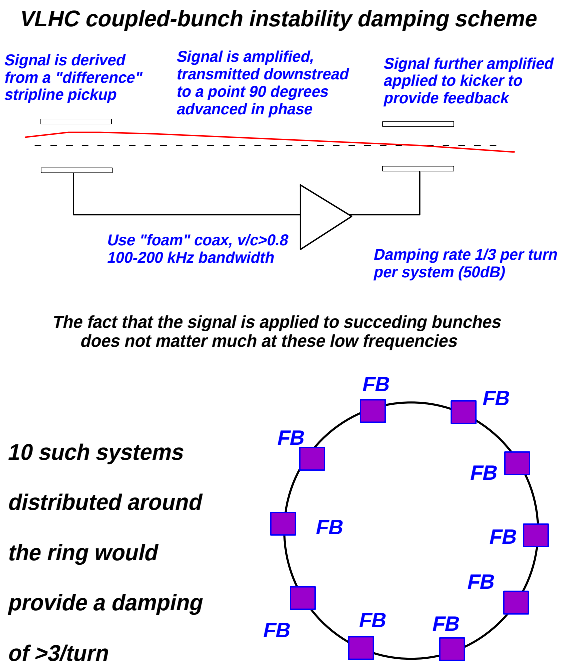

Figure 4: Proposed distributed coupled bunch instability damper system. The instability is less severe in the high field VLHC because of the smaller circumference and also because of the (assumed) higher conductivity of the cryogenically cooled beam pipe.

7.3 R&D Opportunities

There are several R&D opportunities discussed at the workshop:

- Study the TMCI experimentally, particularly in proton machines. It may be possible to excite the TMCI by a controlled increase of the Tevatron impedance with an electron beam set-up [4].
- Measure and optimize detuning wakes.
- Test a prototype rf quadrupole.
- Evaluation of different kinds of feedback systems for the TMCI.
- Simulate the distributed feedback system.
- Gain limitations in feedback systems.

A more detailed explanation of these proposals can be found in Ref. 1.

8 GROUND MOTION

Turn-to-turn dipole magnetic field fluctuations and vibration of quadrupole magnets can cause emittance growth if the resulting coherent motion is not corrected over its decoherence time (~1000 turns) [5]. Measured ground vibrations in deep Illinois dolomite tunnels are smaller than the tolerances for both LF and HF options [6]. Cultural noise level in the Tevatron tunnel is several times above the VLHC tolerances but small enough to be suppressed by the coupled bunch mode damper system discussed below. The frequency spectrum of the fluctuations in the magnetic field has not been determined, and experimental measurements are needed to determine the expected magnitude of the emittance growth.

9 FEEDBACK SYSTEMS

Table 3 lists the several feedback systems that may be necessary to avoid emittance dilution in the VLHC.

Table 3: VLHC Feedback Systems.

	System	Comments
1	Damp resistive wall coupled bunch modes and injection errors	high gain 100-200 kHz bandwidth
2	Damp high frequency coupled bunch modes	one turn delay 26 MHz bandwidth
3	Damp azimuthal mode 1 (bunch-by-bunch)	moderate gain 3 GHz carrier frequency 26 MHz bandwidth
4*	Suppress emittance growth	moderate gain 5 kHz bandwidth
5	Longitudinal feedback	

*System 1 is more than adequate to perform the function of System 4.

10 REFERENCES

[1] The conference proceedings are available via the world-wide-web at http://vlhc.org/AT_proc.html.

[2] V. Shiltsev, V. Danilov, and J. Marriner, ``Beam effects in the VLHC", these Proceedings.

[3] J. Marriner, “A Damper to Suppress Low Frequency Transverse Instabilities in the VLHC,” in *Very Large Hadron Collider Information Packet*, ed. C.S. Mishra (January 1998).

[4] V. Shiltsev, V. Danilov, D. Finley, and A. Sery, ”Electron Compression of Beam-Beam Tune Spread in the Tevatron”, FERMILAB-Pub-98/260 (1998).

[5] V. Shiltsev, FNAL-TM-1987 (1996).

[6] B. Baklakov, *et al.*, Phys. Rev. ST - Accel. Beams, **1**, 031001 (1998). See also B. Baklakov, *et al.*, these Proceedings.