The Very Large Hadron Collider

Staging Scenarios

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Second Annual VLHC Meeting
Port Jefferson, N.Y., October 16, 2000

Introduction

The Steering Committee Mission Statement establishes working parameters for a superconducting proton-proton collider of approximately 100 TeV cm and an initial 10^{34} $cm^{-2}sec^{-1}$ luminosity with possibility to go higher. The U.S. site for the vlhc is assumed to be at Fermilab due to the existence of the injector chain with required beam properties and the excellent regional geology

A **scenario** is defined as a series of **stages** that utilize a common infrastructure (tunnel(s) and utilities). At each stage a "link" is added to the "accelerator chain." Stages are spaced 5-10 years apart, not dissimilar to LEP/LHC or MainRing/Tevatron experience. This spreads costs over a long time period. A necessary requirement is that each stage leads to a world-class physics program. Thus what is proposed is a multi-decade program of energy frontier physics in the United States.

Comments on Tunneling

Tunneling is a major cost driver, so a high priority is to characterize the geology of the Fermilab region to encompass all possibilities.

The choice of tunnel size is determined by:

- lowest cost
- room for several accelerators
- sufficient room for installation and maintenance

It is expected that robotics and remote control will play a more important role in future large accelerators than with current machines. This may reduce somewhat the required tunnel size.

Two parallel R&D paths are being followed to improve tunneling and reduce its cost:
(1) Improvements in “Conventional” TBM (tunnel boring machine)/Conveyor belt tunneling;
(2) “New Approaches” to tunneling

"Conventional" TBM/Conveyor belt tunneling

Our starting point is a detailed cost model for a 34-km deep underground tunnel from the Kenny Construction Company [1] [2]. This estimate is used to understand the major cost drivers. A recent study by the Robbins Company [3] gives optimism that the cost (per meter of tunnel) can be significantly reduced from the estimate made by Kenny. Labor is a major factor so increasing the "utilization" of the TBM (the percentage of time that it is mining rock) will increase the production rate and lower the total cost of the job. In order to understand this factor more quantitatively a TBM used in a TARP Tunnel (Tunnel and Reservoir Project in Chicago) [4] [5] has been instrumented. This has been done in an informal collaboration with the Kenny Construction Company. The goal is to understand TBM system utilization with real data.

"New Approaches"

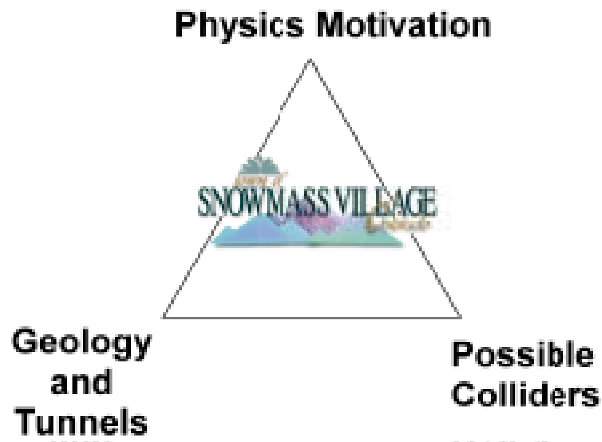
Since labor is a major cost driver having fewer people underground will reduce costs. This will also result in a safer job. A visionary goal is to have **no** people underground except during maintenance. The mining industry, which commands a much larger market than the tunnel construction industry is already moving toward totally robotic systems.

A proposal has made to modify a standard TBM with corner cutters to produce a flat floor [6] [7] [8]. Once this is done it opens the possibility of using battery operated (no diesel fumes) *autonomous* muck removal and transportation vehicles [9] [10].

What has changed since Snowmass 96?

- Low-field and high-field approaches are no longer adversarial
- There is the possibility of unity of "lepton" and "hadron" communities
- Realization (agreement) that low-field may be the most economical way to begin (yet to be shown)
- Appreciation that we need to establish a long-term physics motivated program with options for several stages to spread out funding.

VLHC Discussions at Snowmass 2001



The goal within the "vlhc community" is for Snowmass to have a "set of tools," primarily new information on magnet and tunnel costs. With these tools we can sharpen the discussion of "staging" scenarios. These will be developed for one specific scenario in the recently commissioned vlhc study to be led by Jim Strait.

VLHC documentation centralized in the Fermilab Library

Current VLHC documentation from approximately 1996 to date has been scattered in many places: papers at PAC99, papers at MT16, proceedings of vlhc workshops: http://vlhc.org, papers (VLHCPubs) that used to be accessible from a search engine on the Fermilab vlhc page http://www-ap.fnal.gov/VLHC, compilation of papers from Snowmass 96, the information packet submitted to the Gilman Panel, DPB Mini-symposia at APS Meetings, the1999 VLHC Annual Report (and bibliography).

These documents have now all been collected together and placed on the Fermilab library preprint server. To access them go to

http://fnlib2.fnal.gov/db/MARION/keyword.html and do a keyword search on "VLHC and …. "

Scenarios

	C (km)	Magnet type	Mag Field (T)	pp E_{cm} TeV	ee E_{cm} GeV	injector	E_{inj} TeV	magnet dynamic range
Single Tunnel scenarios								
A	37.58	Trans Line	2.00	6		MI	0.15	20.0
	37.58	cos theta	11.20	28		single turn	3.00	5.0
B	120	e+e- Collider			270			
	120	Trans Line	2.00	20		Tevatron*	1.00	10.0
	120	cos theta	11.20	100		single turn	10.00	5.0
C	228	e+e- Collider			360			
	228	Trans Line	2.00	40		Tevatron*	1.00	20.0
	228	RHIC type	5.75	100		single turn	20.00	2.5
D	228	e+e- Collider			360			
	228	Trans Line	2.00	40		Tevatron*	1.00	20.0
	228	high field	12.00	200		single turn	20.00	5.0
Multiple Tunnel scenarios								
E	37.58	Trans Line	2.00	6		MI	0.15	20.0
	531	e+e- Collider			360			
	531	Trans Line	2.00	100		LF	3.00	16.6
	531	high field	12.00			single turn	50.00	
F	37.58	Trans Line	2.00	6		MI	0.15	20.0
	531	Trans Line	2.00	100		LF	3.00	16.2
	100	high field	12.50	100		"topping off"	50.00	1.0
G	37.58	Trans Line	2.00	6		MI	0.15	20.0
	228	RHIC type	5.75	100		LF	3.00	16.7
H	15	high field	11.00	12		Tevatron*	1.00	5.9
	120	high field	11.00	100		HF-site filler	12.00	4.1

The rest of the talk will focus on one particular scenario: a C=228 km circumference tunnel. Four possible stages in this tunnel are:

- A "super-LEP" e^+e^- collider
- A low-field hadron collider reaching 40 TeV in the center of mass with injection from the Tevatron
- A medium-field hadron collider reaching the "nominal" Steering Committee goal of 100 TeV
- A high-field hadron collider achieving energies of 200 TeV or greater

The geology and possible siting of such a tunnel are discussed in Conroy's report at this conference. [11]

Electron colliders

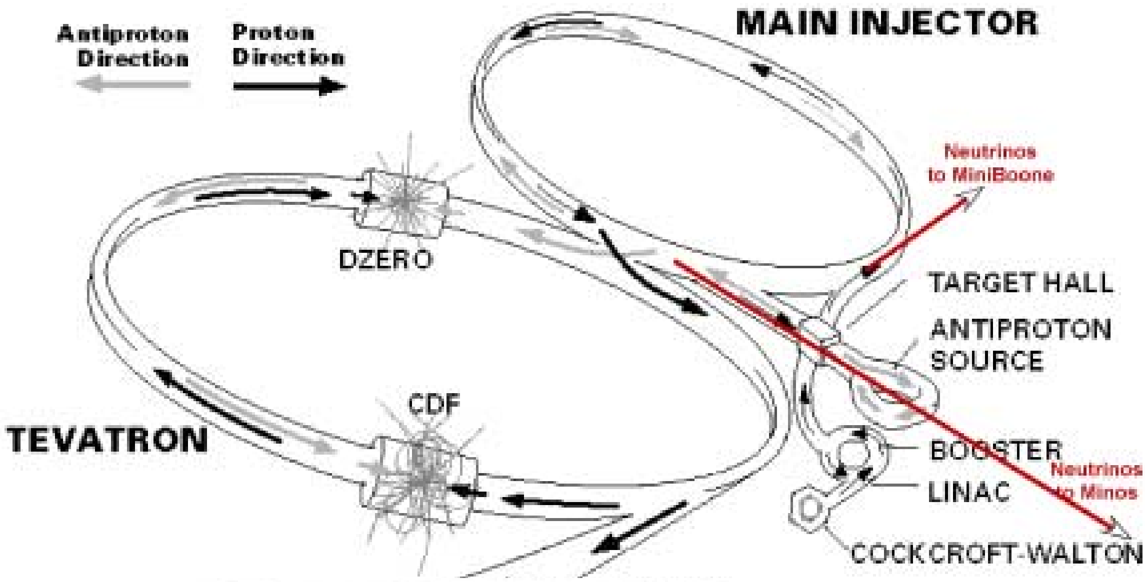
Norem et al [11] some time ago proposed parameters for a "t-tbar factory" in the C=531 km tunnel. Recently T. Sen [12] has worked out parameters for an e^+e^- collider in the C=228 km tunnel. The parameters shown in the table are chosen to be at the peak of the luminosity vs. Energy curve. In the first column are values from LEP [14]. The next two columns are for possible e^+e^- colliders, where in both cases the total synchrotron radiation power from both beams is held to 100 MW. The main difference between the two ~360 GeV colliders is the assumed vertical beam-beam tune shift parameter. More details and the design philosophy will be forthcoming.

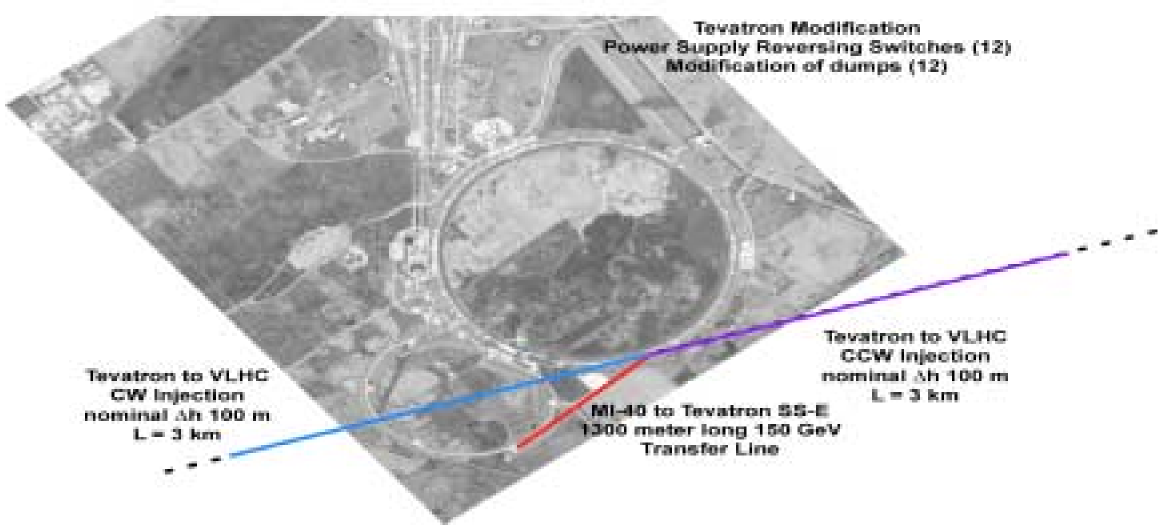
	LEP (1999)	t-t "factory"	T. Sen VLLC33
Circumference	26.65	531	228
E_{cm} (GeV)	200 ($\rightarrow$209)	360	358
ξ_y	0.079	0.03	0.1
β_y* (cm)	5	5	5
L (x 10^{32})	0.97	9.2	10
Bunches/beam	4	512	89
Total Voltage (GV)	3.05	1.6	4.46

One can trade energy for luminosity until the RF voltage becom
This needs to be examined carefully with physics goals in mind

Low field proton colliders

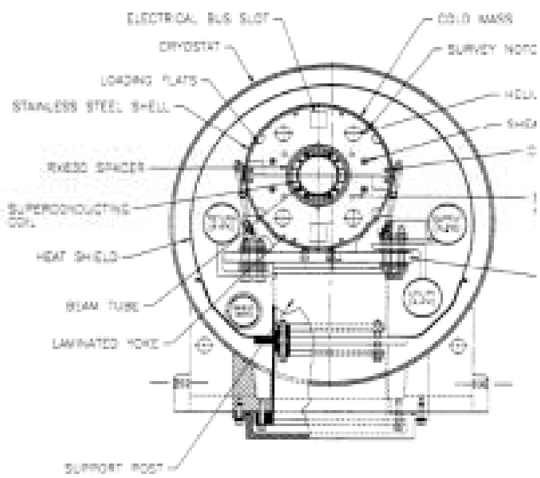
A scheme for injecting into a 20 TeV/beam low-field transmission line type collider is shown in the figures below. A new beam line from the MI-40 abort stub in the Main Injector injects 150 GeV protons into the Tevatron at Ezero counterclockwise. Two long transfer lines descending at 3% grade to the vlhc depth chosen by Conroy [11] from geological considerations bring 1 TeV protons from the Tevatron to the vlhc. The Tevatron is modified to be bipolar.





Medium field proton colliders

Eric Willen [15] has proposed a magnet extrapolation based on the successful experience with RHIC. A collider with such magnets and a filling factor = 80% would reach 100 TeV.



Single Layer cos θ Coils

NbTi

4.6 K

	RHIC	Extrapolation based on successful RHIC experience
Cable width (mm)	9.5	15
Magnet length (m)	9.45	18
Aperture (coil ID, mm)	80	40
Bores	Single	2-in-1
Field (T)	3.5	5.7

High field proton colliders

High field magnets (defined as $\geq$ 10 T and therefore constructed of material other than NbTi) have the potential to achieve 200 TeV or greater in the C=228 km tunnel. As the magnetic field (and proportionately the energy) is increased synchrotron radiation becomes more and more of an issue for the magnet and cryogenic system design. Is there a practical limit to the magnetic field? This interesting question is being addressed by Nikolai Mokhov using the MARS code. [16]

In his calculations the following assumptions are made:

- bore ID held constant at 43.5 mm
- cos θ geometry
- rescale vacuum tube and beam screen from LHC
- materials using Fermilab design
    - aluminum collar
    - "homogenized cable
    - non Cu (Nb_3Sn) : Cu 1:1
    - 3 mm Helium gap

- ignore cryostat, holes in cold mass
- "continuous" bending magnet
- filling factor = 76.5% (to get bending radius)
- 10^{14} protons

Four important quantities are calculated

1. Heat load to the cryogenics system
2. Energy density in the superconducting coils and quench stability
3. Radiation damage to coils and insulation
4. Residual dose (radioactivity; handling for maintenance)

The synchrotron radiation photons have a narrow azimuthal peak outward from the curvature of the beam. Calculations are in progress for fields of 12, 16, and 20 T with varying thickness of the beam tube/beam screen. In these calculations as the thickness of the beam pipe/beam screen is increased, the physical aperture is decreased. The quench limit in the superconducting coils is used as a guide to set this thickness. The challenge in dealing with the total synchrotron radiation power is to absorb it at as high a temperature as possible, perhaps as high as 80 K. Another interesting challenge is see if a superconducting coil geometry can be devised that allows the radiation to escape and be absorbed in discrete, spaced absorbers (as in electron machines). Results will be forthcoming shortly.

Work to prepare for Snowmass 01

The concept of scenarios leads naturally to a work list. Much of this will be done in the context of the commissioned design study. However, that study will focus on one circumference (yet to be chosen) and will exclude e^+e^- or medium field hadron colliders. In a broader context more than one scenario will be open for discussion at Snowmass. It is logical for work to proceed on three parallel, interactive paths:

- Physics: justification for each stage in a scenario
- Magnets: parameters, dynamic range, costs
- Geology and tunnels

The recently commissioned vlhc study [17] will narrow the choice of scenarios and proceed with detailed work on one of them.

Geology:

- resolve discrepancies between lampshades and sections
- investigate where additional bore holes would be useful
- look at more complex geometry -- tilts, "terrain followers"
- study alternates that may have less desirable geology but might be more desirable politically

Tunneling and Utilities:

- work on tunneling cost reductions
- study shaft spacings, linings, utilities, surface interference

Colliders:

- e^+e^- collider: define parameters, work on the injector and injection. Challenges are the low (~ 20 g) injection field and water cooling for a large deep underground ring.
- the low-field pp collider has many interesting challenges including injection from the Tevatron, bypass of the high-field ring, abort system etc.
- the medium-field pp collider may be a cost effective way to reach 100 TeV in the center of mass
- the high-field pp collider, besides the challenge of the magnets themselves has an interesting geometry challenge since in some scenarios a combined function LF collider with high packing factor will occupy the same tunnel as a HF separated function collider with lower packing factor. Injection, bypass, and detector placement also need to be worked out.

Gaining Public Support

Gaining the necessary public support for this project to go forward is a challenge at least as difficult as the tunneling and magnets. We need to learn ways on how to communicate better with our constituencies. The giant microscope metaphor may be one way.

VLHC R&D is focussed on cost reduction strategies that allow the machine to be built with technology that is already understood (e.g. increasing TBM "utilization" factor) and at the same time at other strategies require new technology, probably have longer time scales, and unknown cost implications. (e.g. HTS, new robotic tunneling techniques). Improving tunneling technologies will have real benefits to society. Significant vlhc motivated R&D can help gain the necessary public support.

Conclusions

The vlhc is <u>already</u> technically feasible. <u>THE</u> KEY ISSUE is lowering the cost measured in $/TeV.

Progress continues to be made on conceptual work on a future very large hadron collider to extend the energy frontier beyond the LHC. Innovative approaches are being proposed. R&D is underway. Proposals for future R&D are being generated

Why work on vlhc now?

Typically 10-15 years elapse from first R&D magnet to last machine magnet. So it is not too soon to be working on a post-LHC collider although construction would not begin until the first physics results come from LHC.

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