Very Large Hadron Collider

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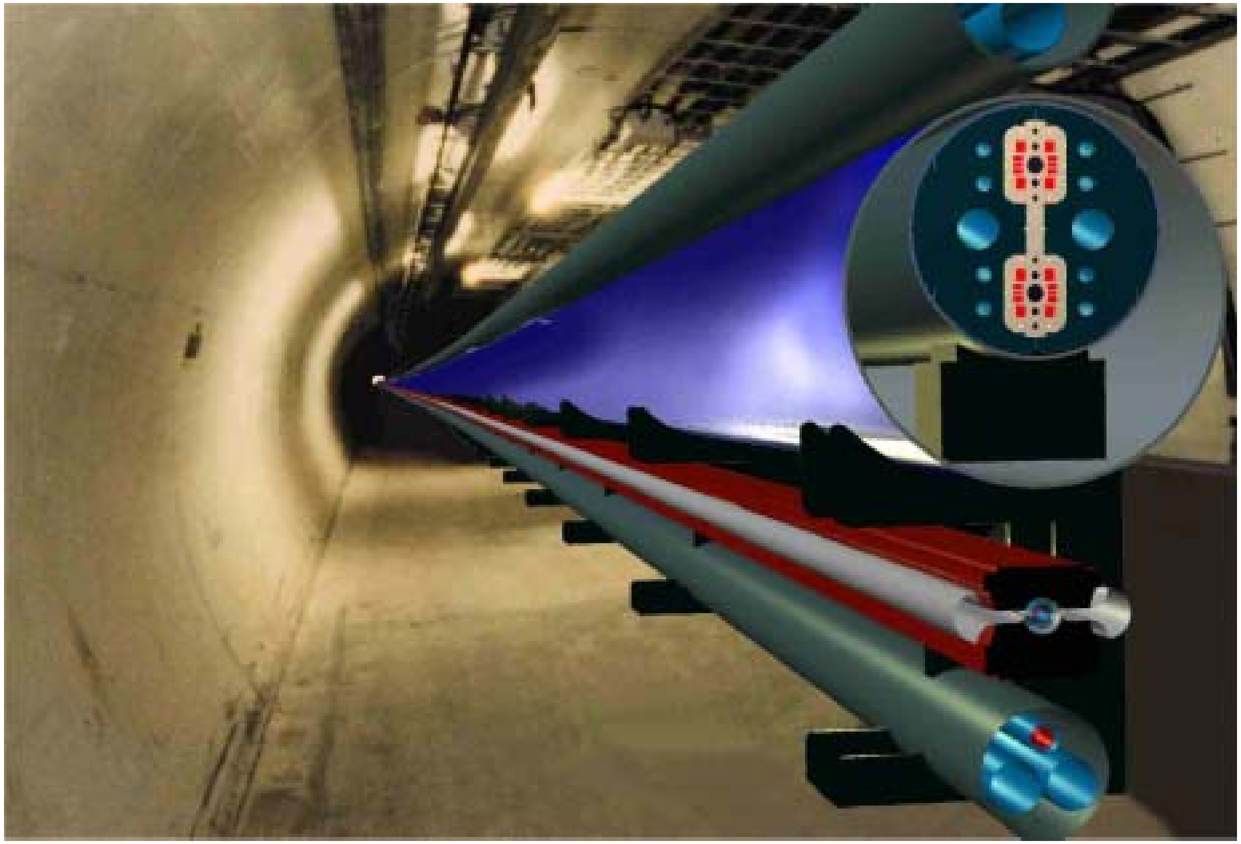
www.vlhc.org

Design Study for a Staged Very Large Hadron Collider



The Tools of High-Energy Physics

The right HEP plan should include all the necessary tools in the proper sequence, somewhere in the world, open to everyone.

- **Precision measurements**
  - **Lepton colliders make precision measurements of known spectroscopy.**
- **Special measurements**
  - **Specialized facilities, accelerators, beams, and experiments are needed to investigate neutrino mass, CP violation, particle astrophysics, etc.**
- **Big discoveries**
  - **Very-high-energy hadron colliders probe deep into the unknown and make discoveries at the energy frontier.**

The Energy Frontier

- **The most exciting physics – the Discovery Physics - is at the energy frontier.**
  - **A hadron collider is the only sure way to the next energy scale.**
  - **The technology of the VLHC is available to us now.**
  - **Our plan for a staged VLHC makes the energy frontier both affordable and achievable.**

- **The VLHC fits into and should be considered part of a worldwide high-energy physics plan that includes a linear electron collider.**

The Staged VLHC Concept

- **Take advantage of the space and excellent geology near Fermilab.**
  - **Build a BIG tunnel.**
  - **Fill it with a "cheap" 40 TeV collider.**
  - **Later, upgrade to a 200 TeV collider in the same tunnel.**
    - This spreads the cost and produces exciting energy-frontier physics at each step.
    - It allows time for the development of cost-reducing technologies and ideas for the challenging high-energy upgrade.
    - A high-energy full-circumference injector into the high-field machine solves some sticky accelerator issues, like field quality at injection.
    - A BIG tunnel is reasonable for advancing to a synchrotron radiation-dominated collider.

The Design Study of a Staged VLHC

❖ The design study showed us that:

- **A staged VLHC starting with 40 TeV and upgrading to 200 TeV in the same tunnel is completely feasible.**
- **There are no major accelerator physics or technical obstacles.**
- **The construction cost of the first stage of the VLHC is comparable to that of a linear electron collider.**
- **The existing Fermilab accelerator complex is a good injector into the Stage 1 VLHC.**
  - Using Fermilab's (or CERN's! or DESY's!) existing accelerator complex saves at least $1 billion.
  - Siting VLHC at an existing lab and using the existing intellectual and organizational infrastructure saves both time and money.

Very Large Hadron Collider

The VLHC Design Study Group

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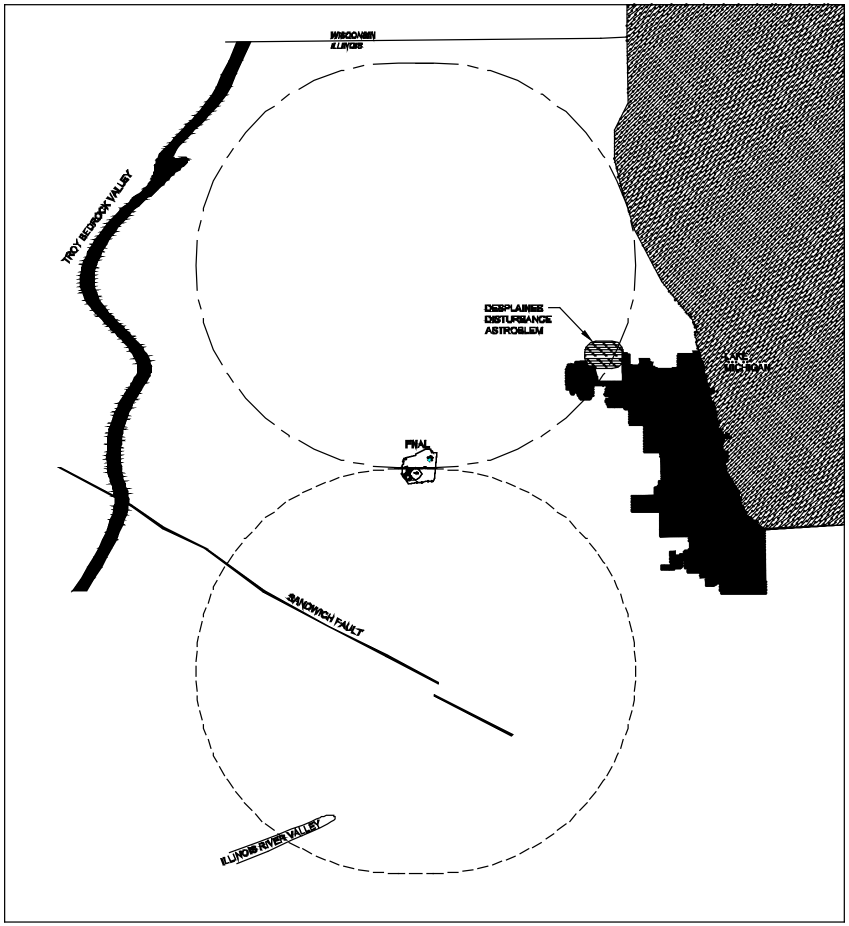
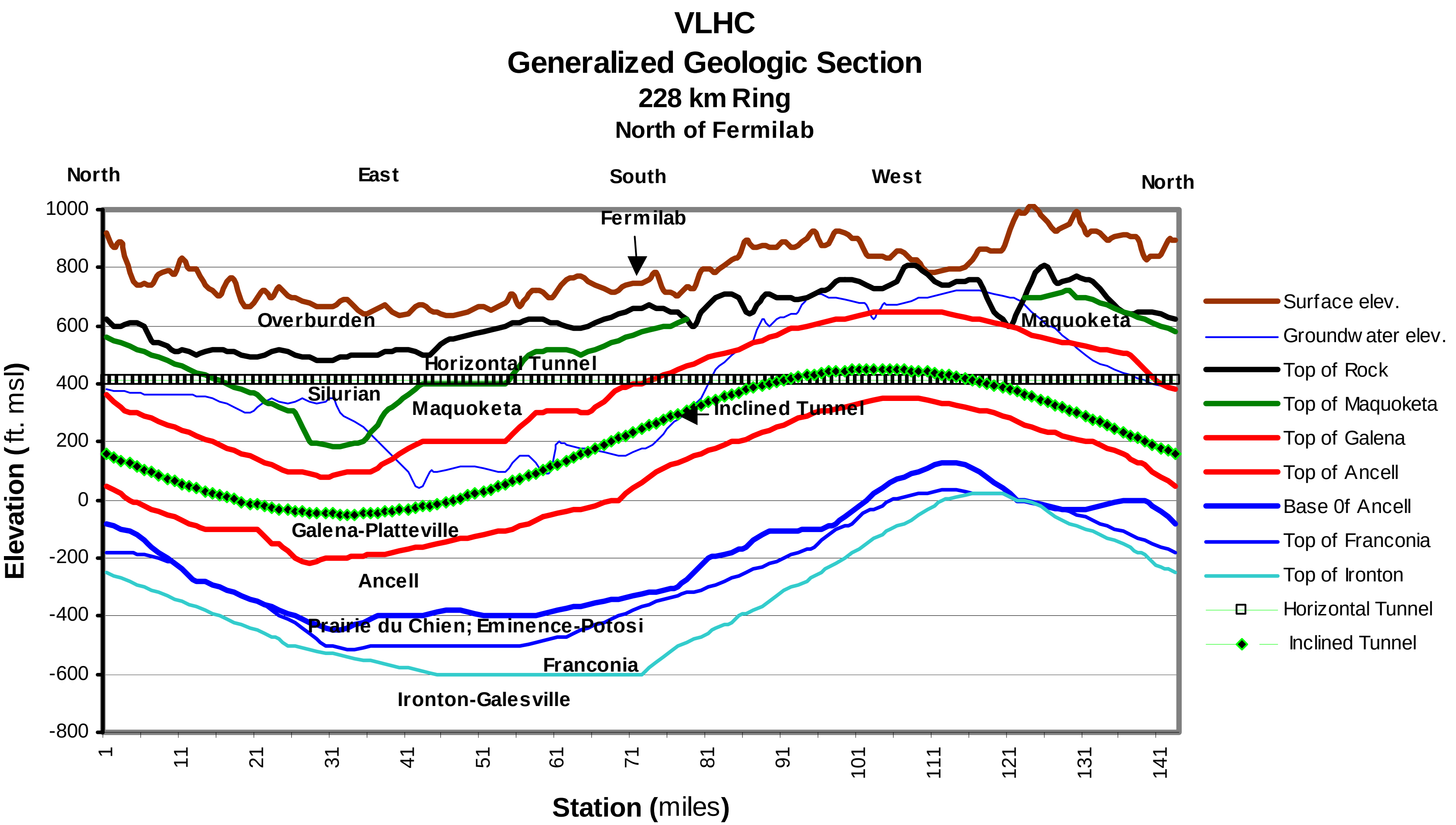
	Stage 1	Stage 2
Total Circumference (km)	**233**	**233**
Center-of-Mass Energy (TeV)	**40**	**175**
Number of interaction regions	**2**	**2**
Peak luminosity ($cm^{-2}s^{-1}$)	**1×10^{34}**	**2.0×10^{34}**
Luminosity lifetime (hrs)	**24**	**8**
Injection energy (TeV)	**0.9**	**10.0**
Dipole field at collision energy (T)	**2**	**9.8**
Average arc bend radius (km)	**35.0**	**35.0**
Initial Number of Protons per Bunch	**2.6×10^{10}**	**7.5×10^{9}**
Bunch Spacing (ns)	**18.8**	**18.8**
β^* at collision (m)	**0.3**	**0.71**
Free space in the interaction region (m)	**± 20**	**± 30**
Inelastic cross section (mb)	**100**	**130**
Interactions per bunch crossing at L_{peak}	**21**	**54**
Synchrotron radiation power per meter (W/m/beam)	**0.03**	**4.7**
Average power use (MW) for collider ring	**25**	**100**
Total installed power (MW) for collider ring	**35**	**250**

Underground Construction

- **Three orientations chosen to get representative geological samples of sites near Fermilab.**
  - South site samples many geologic strata and the Sandwich fault.
  - One north site is flat and goes through many strata.
  - Other north site is tipped to stay entirely within the Galena-Platteville dolomite, and is very deep.
- **These are not favored sites – merely representative.**
  - Cost of other sites can be built from data gained in these sites.
- **We are now investigating a west orientation.**

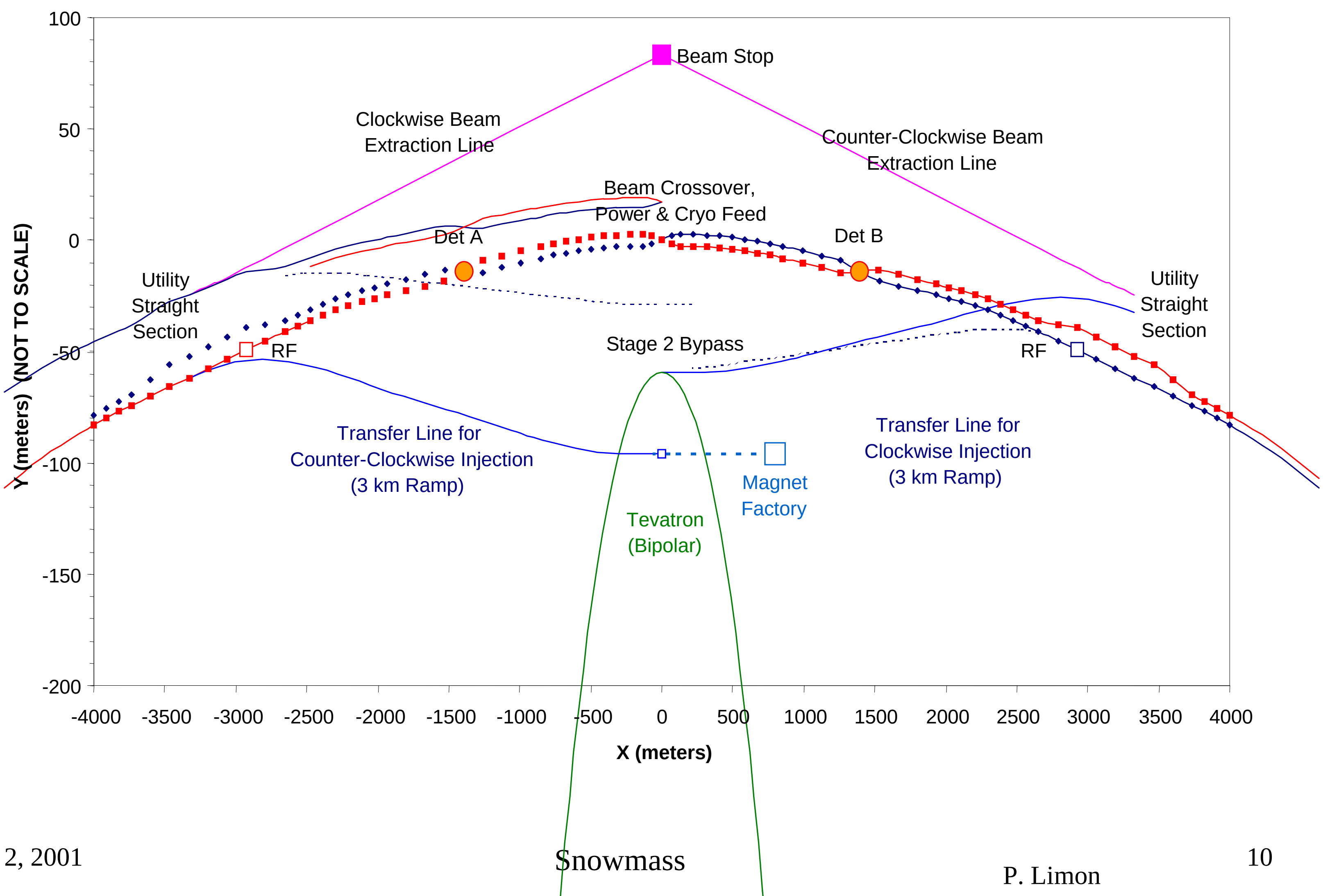


Very Large Hadron Collider

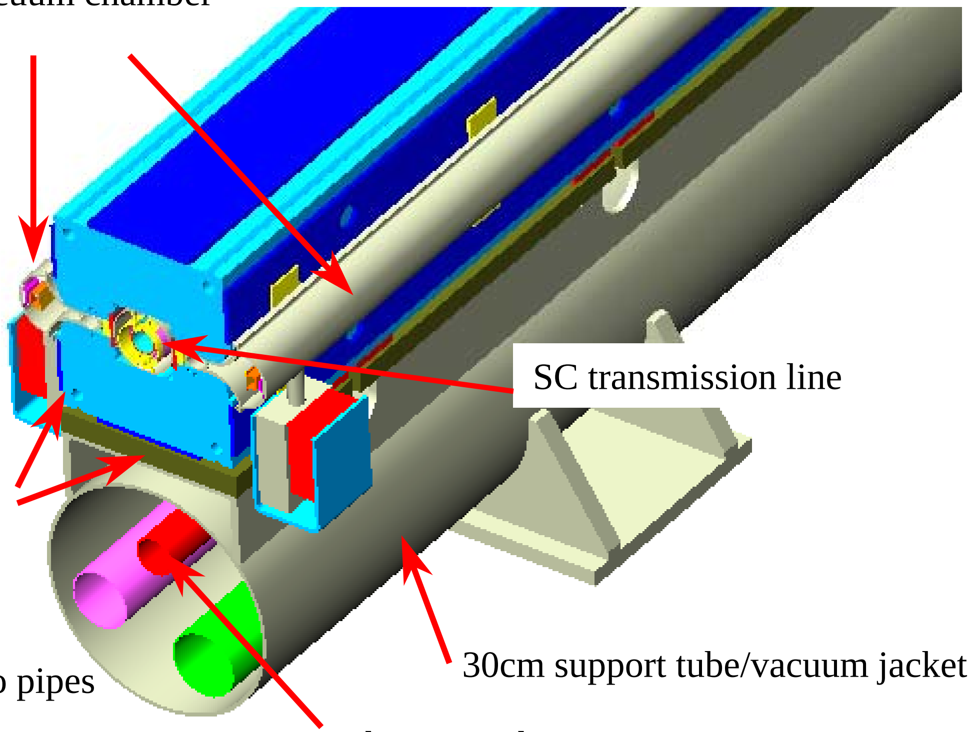


Very Large Hadron Collider

VLHC DESIGN STUDY SITE LAYOUT

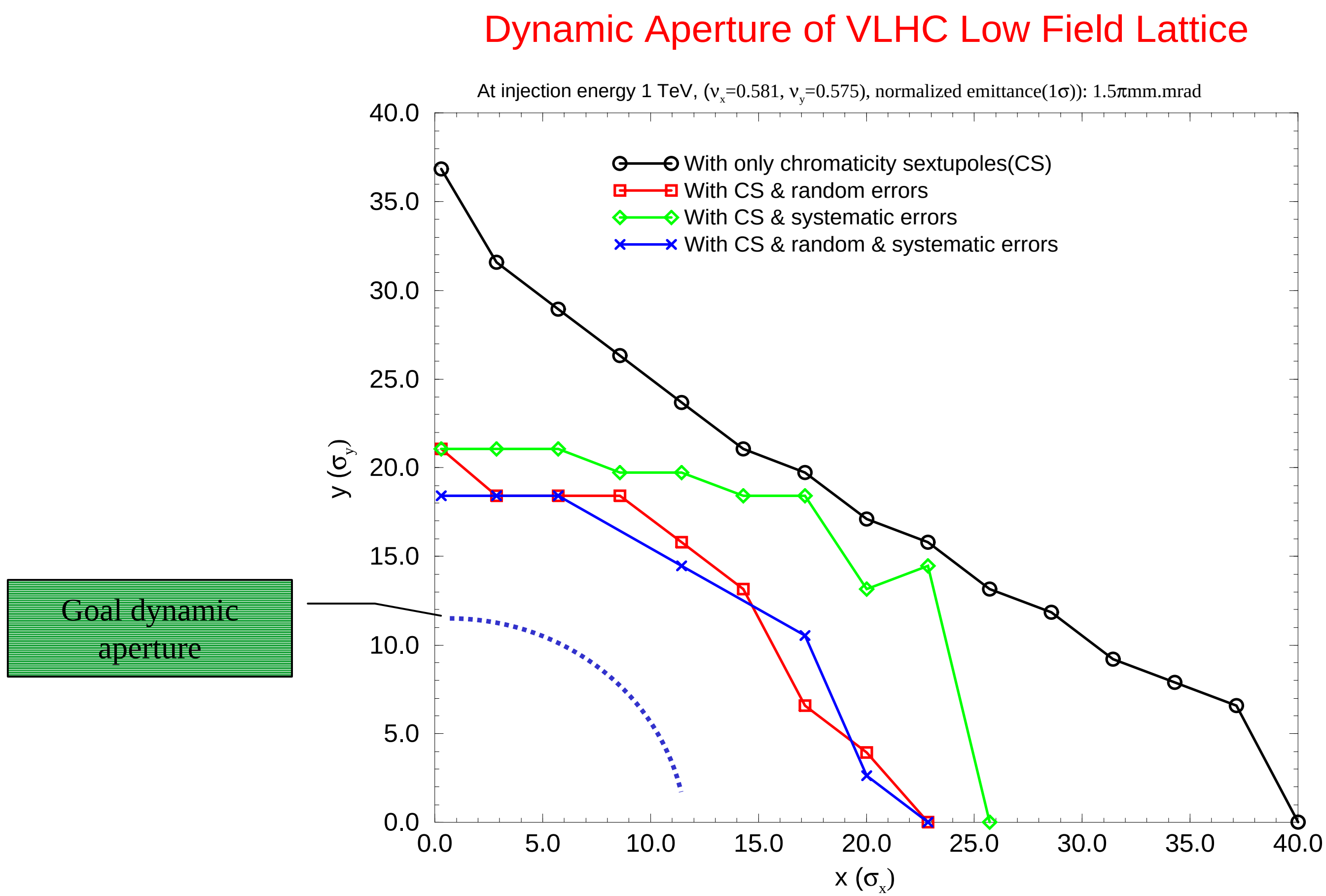


Transmission Line Magnet



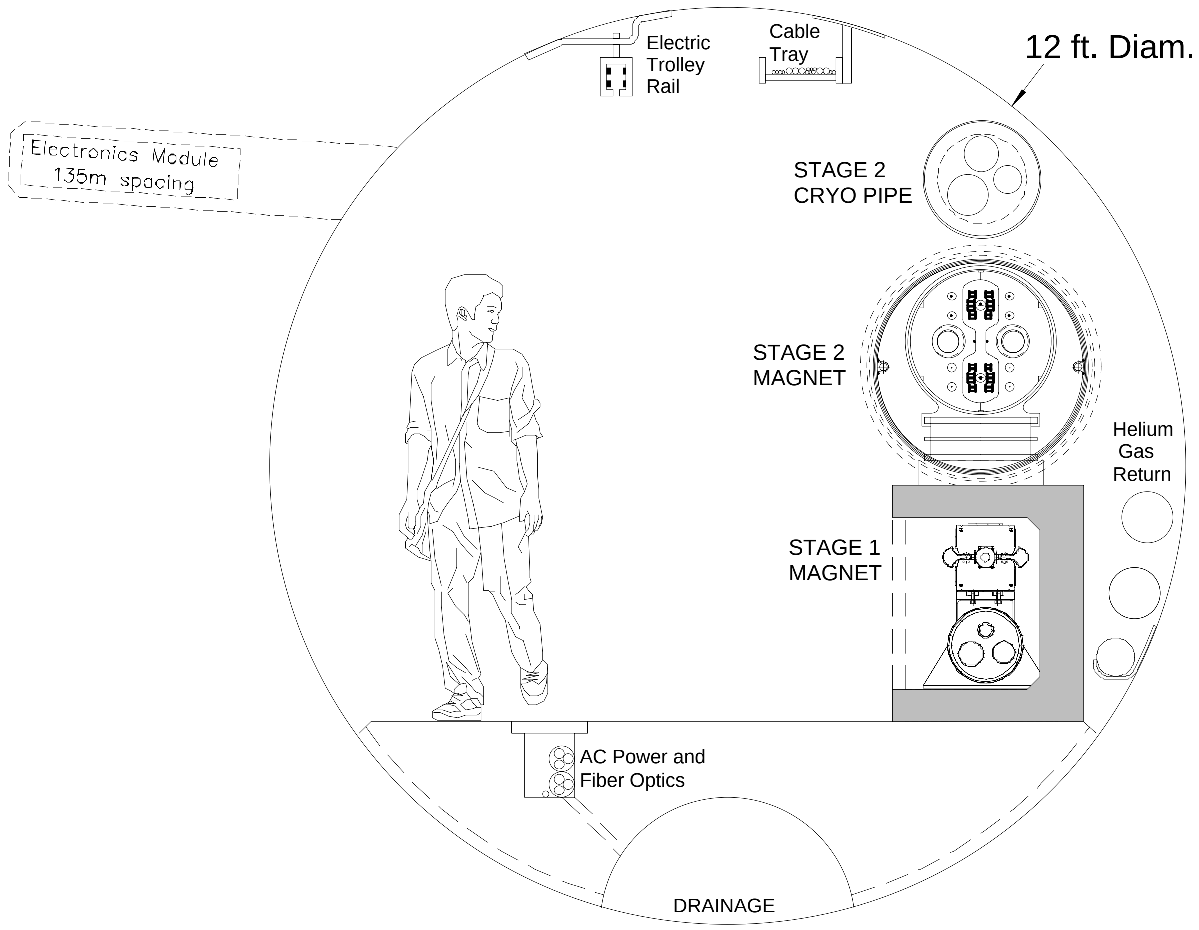
- 2-in-1 warm iron
- Superferric: 2T bend field
- 100kA Transmission Line
- alternating gradient (no quadrupoles needed)
- 65m Length
- Self-contained including Cryogenic System and Electronics Cabling
- Warm Vacuum System

Stage 1 Dynamic Aperture at Injection

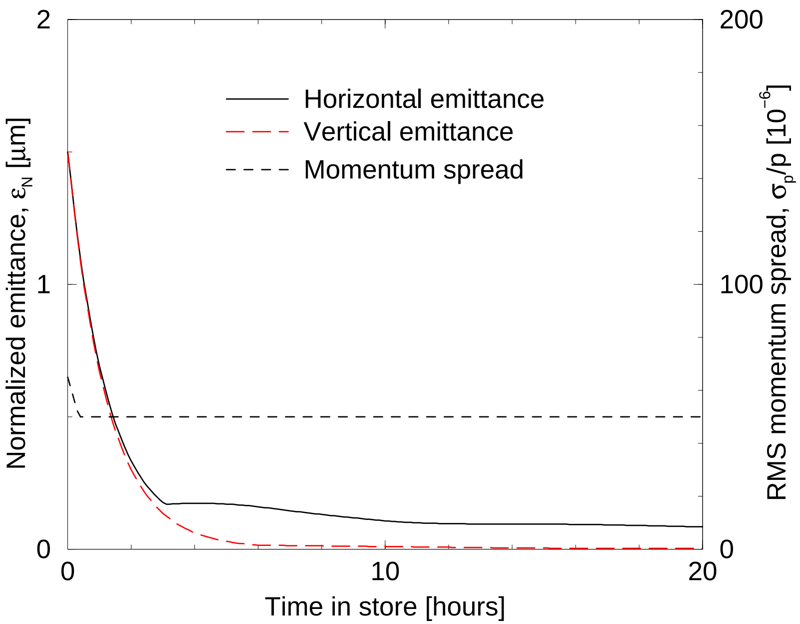


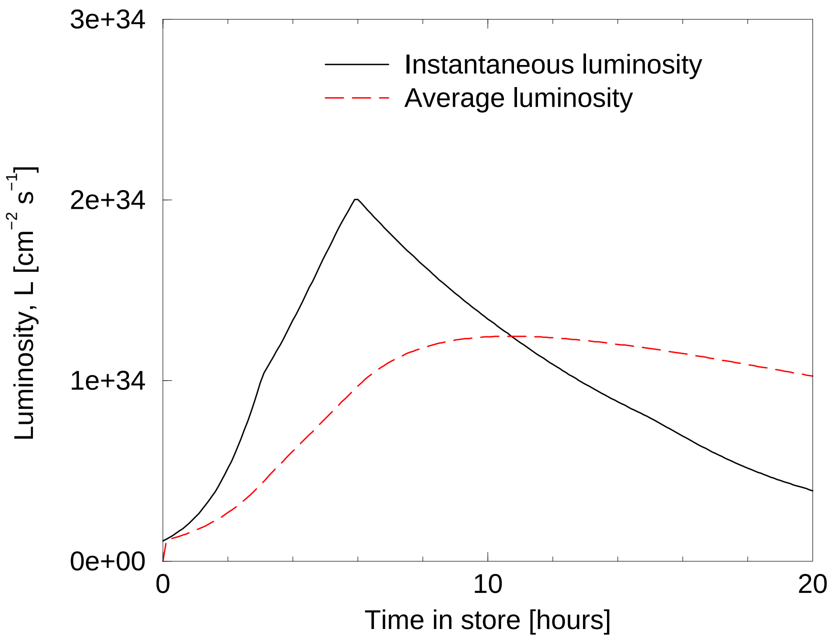
- 1000 turn data shown here
- 10000, 100000 turn data similar results
- Magnet errors scaled to MI distribution

Stage 2 VLHC Tunnel



Stage 2 Parameter Evolution due to Synchrotron Radiation





Stage 2

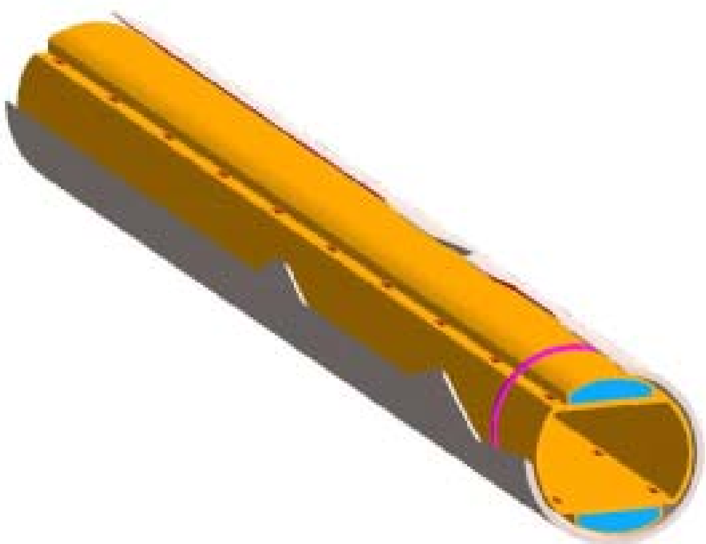
❖ It is clear that Stage 2 could get to **200 TeV or higher!**

Collision Energy (TeV)		*Magnetic Field (T)*	*Leveled Luminosity ($cm^{-2}s^{-1}$)*	*Optimum Storage Time (hrs)*
Stage 1	**40**	**2**	**1.0×10^{34}**	**20**
Stage 2	**125**	**7.1**	**5.1×10^{34}**	**13**
Stage 2	**150**	**8.6**	**3.6×10^{34}**	**11**
Stage 2	**175**	**10**	**2.7×10^{34}**	**8**
Stage 2	**200**	**11.4**	**2.1×10^{34}**	**7**

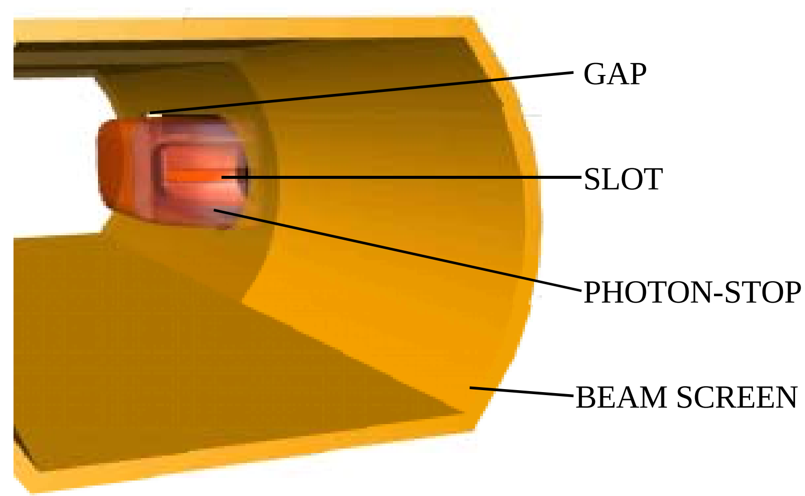
Leveled luminosity vs. energy. The luminosity is limited by one or more of the beam-beam tune shift, the synchrotron-radiation power per meter, or the debris power in the interaction region.

Stage 2 R&D – Vacuum and Cryogenics

- Synchrotron radiation masks look promising. They decrease refrigerator power and permit even higher energy



A “standard” beam screen will work up to 200 TeV and $2x10^{34}$



A synchrotron radiation “mask” will allow even higher energy and luminosity, and is practical only in a large-circumference tunnel.

Technical Conclusions of the Study

- There are no serious technical obstacles to the Stage 1 VLHC at 40 TeV and 10^{34} luminosity. There are improvements and cost savings to be gained through a vigorous R&D program.
- Making a large tunnel is possible in the Fermilab area. Managing such a large construction project will be a challenge.
- A total construction time of 10 years is feasible, but the logistics will be complex.
- The Stage 2 VLHC can reach 200 TeV and 2×10^{34} or more in the 233 km tunnel. There is the need for magnet and vacuum R&D, but no insurmountable problems. The luminosity limits are multiple interactions and IP power, not synchrotron radiation, beam-beam tune shift or operating power.

VLHC Cost Basis

- **Used only the "European" cost base**
  - No detectors (2 halls included), no EDI, no indirects, no escalation, no contingency – a "European" base estimate. This is appropriate for cost comparisons, as the factors needed to make it a "US estimate" apply to all projects in the same manner.
- **Estimated the cost drivers using a standard cost-estimating format. This is done at a fairly high level.**
  - Underground construction (Estimates done by AE/CM firm)
  - Above-ground construction (Estimates done by FNAL Facility Engineering Section)
  - Arc magnets
  - Corrector and special magnets (injection, extraction, etc)
  - Refrigerators
  - Other cryogenics
  - Vacuum
  - Interaction regions
- **Used today's prices and today's technology. No improvements in cost from R&D are assumed.**

CNA Underground Construction
Cost Estimate Summary, May 20, 2001

12 ft diameter ($1 million 2001)	North Inclined	North Inclined	South Flat
Shafts	$ 414 M	$ 263 M	$ 168 M
Caverns (incl. 2 Exp)	$ 232	$ 238	$ 243
TBM Tunnels	$ 866	$ 1,058	$ 1,166
D&B Tunnels	$ 36	$ 36	$ 36
Alignment Risers	$ 3	$ 2	$ 2
Portals	$ 2	$ 2	$ 2
Misc. (5% non-est)	$ 83	$ 85	$ 86
Subtotal	**$ 1,636 M**	**$ 1,685 M**	**$ 1,703 M**
EDIA (17.5% AE/CM)	$ 286	$ 295	$ 298
Total	**$ 1,922 M**	**$ 1,980 M**	**$ 2,001 M**

VLHC Cost Drivers

In FY2001 K$	VLHC Estimate	VLHC Fraction
Total	**3,981,159**	**100.00%**
Civil Underground	1,968,000	49.43%
Civil Above Ground	310,000	7.79%
Arc Magnets	791,767	19.89%
Correctors & Special Magnets	112,234	2.82%
Vacuum	153,623	3.86%
Installation	232,397	5.84%
Tunnel Cryogenics	22,343	0.56%
Refrigerators	94,785	2.38%
Interaction Regions	26,024	0.65%
Other Accelerator Systems	269,986	6.78%

* Underground construction cost is the average of the costs of three orientations, and includes the cost of a AE/CM firm at 17.5% of construction costs.

Cost Conclusions of the Study

- **The cost for Stage 1 is comparable to the cost of TESLA**
  - VLHC can be built for about $4 billion (European accounting, which can be compared with ~ $3 billion for TESLA using the same rules.)
  - VLHC operating cost is moderate, using only 20 MW of refrigeration power, comparable to the Tevatron.
- **Building the VLHC at an existing hadron accelerator lab saves significant money and time.**
- **There are obvious cost drivers, and obvious places to concentrate cost-reducing R&D. The major cost driver is underground construction, representing over 50% of the construction cost.**
- **From this and previous studies, we note that the cost of a collider of energy near 40 TeV is almost independent of magnetic field. Hence, the large-circumference tunnel, which permits a future very-high-energy upgrade, is not a cost penalty.**

Preliminary Review

- **A preliminary review was held April 30, May 1, 2001, as a check to see if we were way off base before releasing our report.**
  - **Review Committee:**
    - Bob Kephart, Fermilab, Chairman
    - Gerry Dugan, Cornell; Jon Ives, consultant; Eberhard Keil, CERN
    - Philippe Lebrun, CERN; Al Zeller, MSU; Erich Willen, BNL;
    - Mike Anerella, BNL
- **The reviewers made many good recommendations and observations. They found no serious insurmountable accelerator physics issues. They recognized the need for some cost- and risk-reducing R&D.**

- **Question: "Have the major cost drivers been identified and is the preliminary cost estimate for Stage 1 of the VLHC reasonable?"**

- **The Reviewers' Answer: "Although they can and will be improved through focused R&D, the basic technologies on which the Stage 1 VLHC rests are known today. The unit costs quoted to support the estimates can be deemed as rather conservative."**

Stage 1 R&D to Demonstrate Feasibility

- **Magnet field quality at injection and collision energy**
  - Produce field quality model magnets. About six months
- **Beam instabilities and feedback**
  - A combination of calculation, simulation & experiments
- **High-field quadrupoles are required for the IR**
  - Similar to 2nd-generation LHC IR quads – a Fermilab goal for LHC
- **Other R&D will be accomplished in a magnet string test that we intend to have fully operational in 3 to 4 years**
  - **Magnet production and handling**
    - Demonstrate ability to produce and handle long magnets
  - **Cryogenic behavior; possible flow instabilities due to long lines**
    - Heat leak is a critical factor
  - **Demonstrations and designs of other systems.**

Stage 1 R&D to Reduce Costs

- **Tunneling R&D: tunneling is the most expensive single part**
  - Automation to reduce labor component and make it safer
  - Improvements in reliability, utilization and logistical support
  - Careful design & coordination with AP and HEP to reduce special construction
- **Magnet production and handling; long magnets reduce cost**
  - Reduce assembly time, labor & storage; fewer devices to install
- **Vacuum; surprisingly expensive**
  - Develop getters that work for methane, or investigate cryopumps
- **Improvements in many smaller systems**
  - Complete development and designs of many accelerator systems

Further Studies

- **It is appropriate to continue the design study**
  - **Complete a second pass of the Design Study during the next two years with International Participation.**
    - Narrow the cost uncertainty
    - Improve the designs of both Stage 1 and Stage 2 VLHC
    - Develop other VLHC possibilities; parametric studies and optimization
    - Study installation and construction scheduling and interleaving
    - Begin the environmental impact studies
    - Start to study some management possibilities
  - **Physics studies**
    - Begin to understand the opportunities of the VLHC for both stages
    - Study the detector issues of both stages, and outline necessary R&D
    - Directors are discussing the possibility of ICFA sponsorship
  - **Public outreach**
    - It is not too early to start to approach our neighbors and our governments.

Public Acceptance

- We must work on public and political acceptance from the beginning.
- The old way of "decide, announce, defend" will not work.
- What are the possible public acceptance issues?
  - risk to environment, safety and health;
  - effects on property values;
  - distrust of government;
  - esthetics;
  - perceived lack of community control;
  - appropriate use of government funds;
  - community disruption during construction;
  - perceived lack of participation in decision-making;
  - trust of Fermilab.
- There is a group studying this issue at Snowmass. You are encouraged to join.

Stage 2 R&D

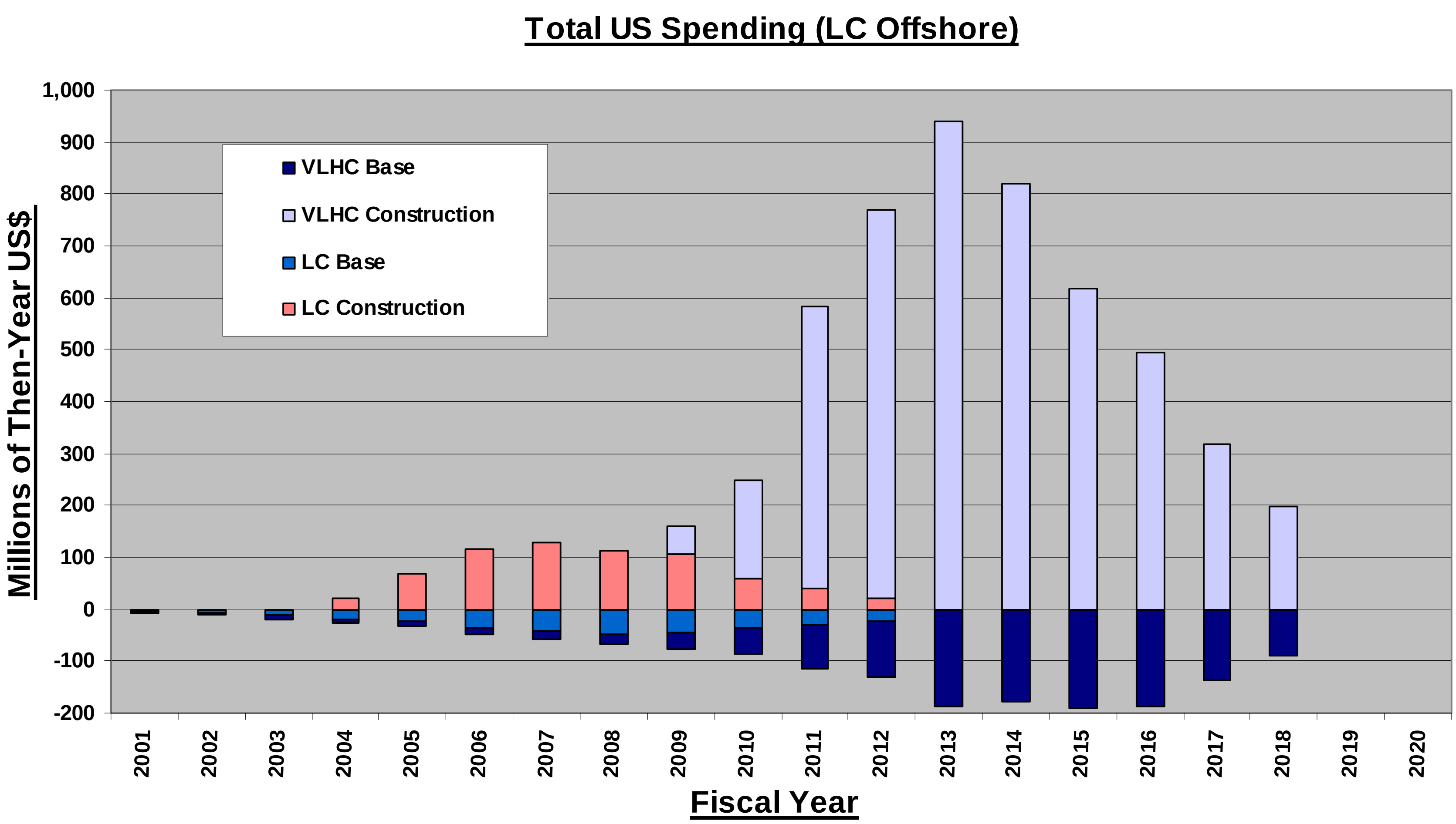
- A longer time scale
  - Magnet development
    - High-field magnets are not yet industrial products.
  - Conductor performance
    - High-field magnets need high-performance conductor.
  - Magnet and conductor cost
    - The conductor cost is mostly market driven.
  - Synchrotron radiation induced cryogenic and vacuum issues
    - Must investigate vacuum issues; requires R&D at light sources.
    - SynchRad masks will reduce refrigerator capital & operating costs.
  - Detector R&D
    - How to handle many interactions per crossing
    - High debris power in the IP. This is mostly a magnet issue, but also affects the far-forward detectors.

A Plausible Scenario for the VLHC

Let's assume that an LEC will be built starting fairly soon—but not in the U.S.

- **Given adequate resources, we could propose building a staged VLHC at Fermilab with a construction start in about five years.**
  - However, that may not be the best plan for high-energy physics in the long term, because HEP must have worldwide cooperation to accomplish its goals. Hence, the U.S. should be a significant collaborator in an LEC, no matter where it is built.
  - This might be as much as $1 billion, spread over eight years, with peak spending ~$200 million/year including lab salaries.
- **In the meantime, VLHC R&D, engineering studies and planning must continue, to be ready for the next step.**
- **When the TESLA spending profile starts to turn down, the US should begin to build the VLHC at Fermilab with collaboration from other regions.**
  - This could be about 2008/2009 according to the fastest TESLA plan

A VLHC at Fermilab



Conclusions

- **We have completed a first study of a staged VLHC. The study shows that:**
  - The VLHC is both feasible and affordable, with a cost comparable to that of a linear collider.
  - The first stage can reach 40 TeV and 1×10^{34}; the second stage can reach 200 TeV and at least 2×10^{34}.
  - There are no major technical obstacles to realizing the desired performance goals of the Stage 1 VLHC.
  - Only a modest amount of R&D is needed to prove the design and narrow the cost estimate. This work can be accomplished in five years.
- **The staged VLHC should be part of the roadmap of the future worldwide and, especially, U.S. high-energy physics.**
- **The staged VLHC should be the next major accelerator initiative in the U.S.**