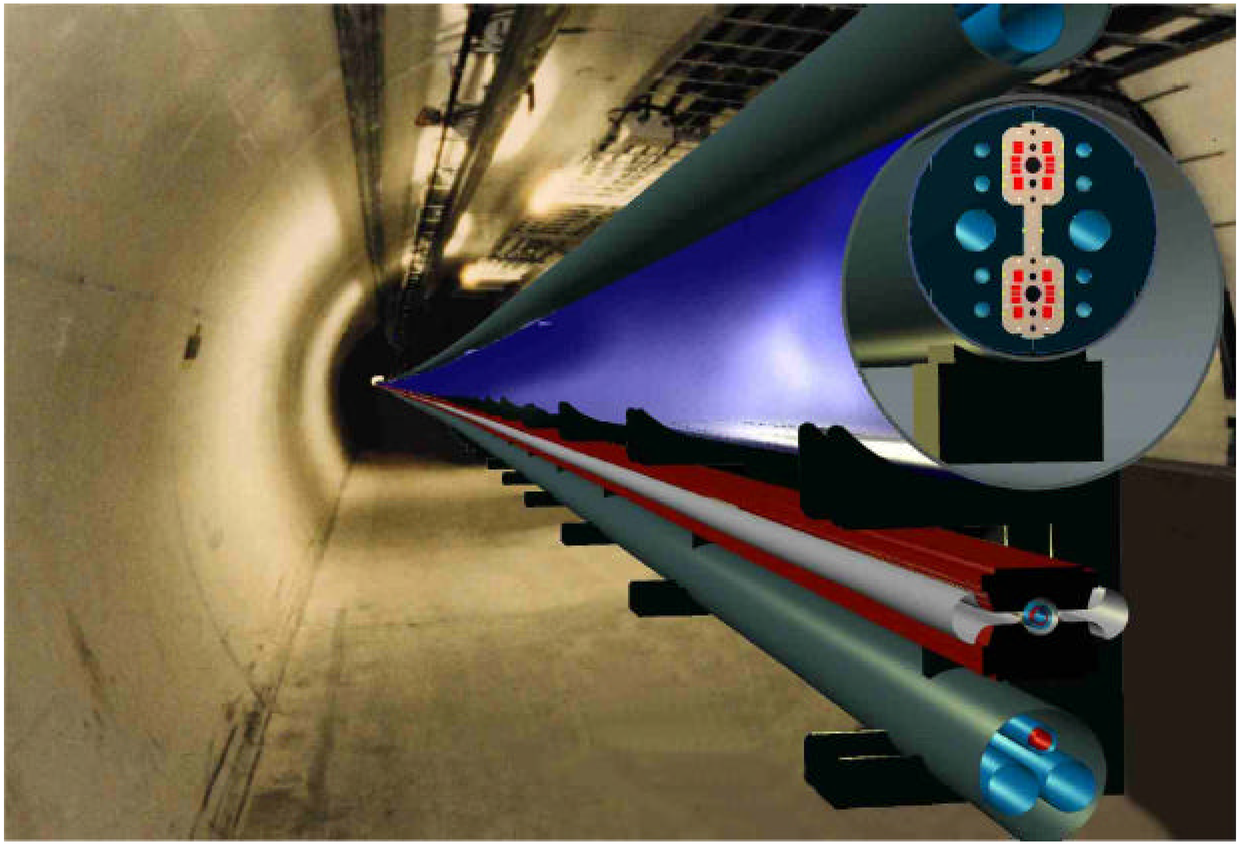
Very Large Hadron Collider

Fermilab-TM-2149
May 18, 2001

www.vlhc.org

Design Study for a Staged Very Large Hadron Collider



What Direction Should HEP Take?

✍ The best path to answer the questions of HEP

- Take the path that always works – HIGHER ENERGY
- Someone, somewhere must advance to the next energy scale!
- A hadron collider is the only sure way to the next energy scale
- The technology of the VLHC is available to us now!

What Should Fermilab Do Next?

- A staged VLHC will be the world's energy frontier collider for 50 years.
  - Stage-1 VLHC, 40 TeV collision energy is about the same cost as a linear collider at 500 GeV
  - VLHC is much cheaper per unit parton energy
  - VLHC can be upgraded to 200 TeV (C.M.)
- The VLHC is the ENERGY FRONTIER where the most exciting physics will be!
  - A linear collider may have some nice physics (we don't know that yet), but it will never be at the energy frontier
- If we can afford a linear electron collider, we can afford a VLHC
- So, what's the plan?

First, a little recent history

- After Snowmass-1996, we had the following plan
  - A VLHC of 100 TeV (center-of-mass)
  - Three different magnets – 1.8 T, 9.5 T and 12.5 T
  - Three different rings – 650 km, 140 km, 105 km

- More recently, we devised a new model for the VLHC
  - If we are willing to accept a decades-long program, low-field and high-field approaches are not adversarial - they support each other
    - This was the Main Ring/Tevatron and LEP/LHC approach, and, if the first step is appropriate, and if an upgrade path is possible, it is the best use of resources

The Concept

- Take advantage of the space and excellent geology near Fermilab
  - Build a **BIG** tunnel, the biggest reasonable for the site
  - Fill it with a "cheap" collider
  - Later, upgrade to a higher-energy collider in the same tunnel
    - This spreads the cost, and, if done right, enables exciting energy-frontier physics at each step
    - It allows more time for the development of cost-reducing technologies and ideas for the challenging high-energy collider
    - 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 a synchrotron radiation-dominated collider, and tunneling can be relatively cheap.

The first step

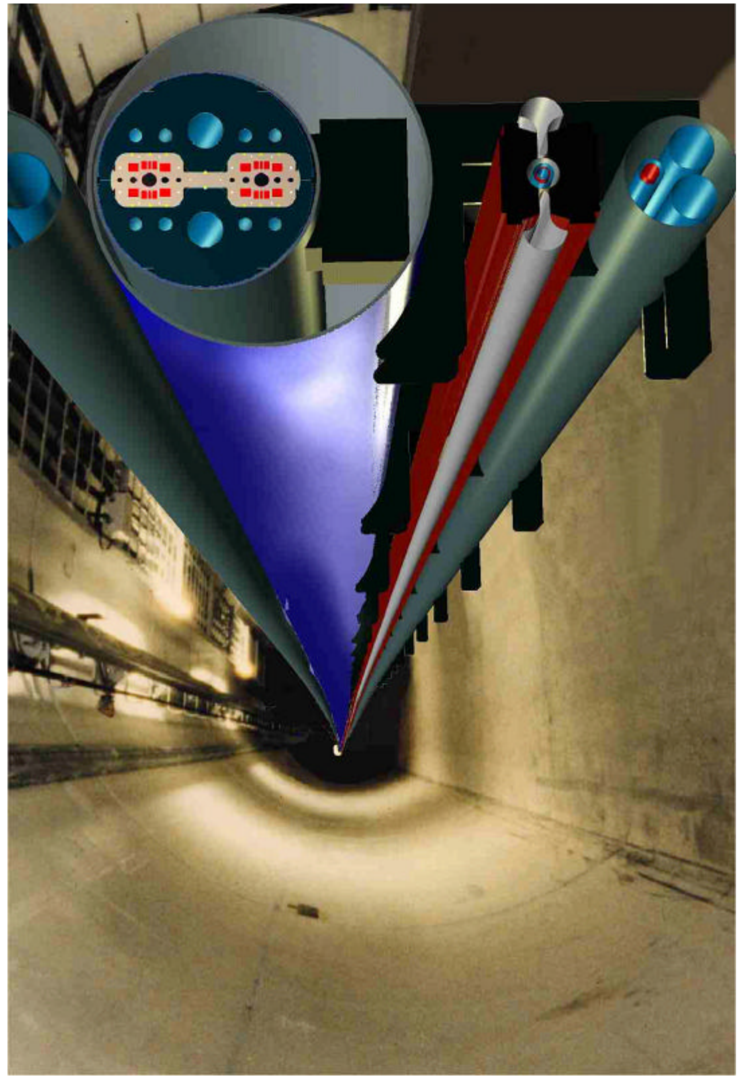
✍ A VLHC Accelerator Study

- Requested and charged by the Fermilab Director
- Based on a Staged Scenario of E_{cm}>30 TeV, Lum>10^{34} first, eventually E_{cm}>150 TeV, L_{peak}>2×10^{34} in the same tunnel
- The report is due in May, 2001.
- The Report will include estimates of the ranges of expected costs and some analysis of the major cost drivers for Stage 1. But it is not a cost estimate for Stage 1 of a VLHC!
- BNL and LBNL are involved, particularly in accelerator physics, vacuum systems and feedback
- We will have international involvement; initially as reviewers, which will be the first step toward forming an international collaboration.

Design Study for a Staged Very Large Hadron Collider

Report by the collaborators of
The VLHC Design Study Group:

Brookhaven National Laboratory
Fermi National Accelerator Laboratory
Laboratory of Nuclear Studies, Cornell University
Lawrence Berkeley National Laboratory



Very Large Hadron Collider

The VLHC Design Study Group

Giorgio Ambrosio[1], Terry Anderson[1], Nikolai Andreev[1], Emanuela Barzi[1], Bob Bauer[2], Pierre Bauer[1], Sergey Belomestnykh[3], Robert Bernstein[1], Mike Blaskiewicz[4], Rodger Bossert[1], John Carson[1], Deepak Chichili[1], Pete Conroy[5], Don Cossairt[1], Christine Darve[1], Dmitri Denisov[1], Angelika Drees[4], Alexander Drozhdin[1], Luciano Elementi[1], Dave Finley[1], Wolfram Fischer[4], Bill Foster[1], Peter Garbincius[1], Norman Gelfand[1], Henry Glass[1], Steve Gourlay[6], Ramesh Gupta[4], Mike Harrison[4], Steve Hays[1], Yuenian Huang[1], Linda Imbasciati[1], Alan Jackson[6], John Johnstone[1], Vadim Kashikhin[1], Vladimir Kashikhin[1], Kurt Kennedy[6], Jim Kerby[1], Arkadiy Klebaner[1], Glen Lambertson[6], Mike Lamm[1], Chris Laughton[1], Valery Lebedev[1], Peter Limon[1], Alexander Makarov[1], Ernest Malamud[1], John Marriner[1], Phil Martin[1], Mike May[1], Nikolai Mokhov[1], Chuck Nelson[7], King Yuen Ng[1], Tom Nicol[1], Barry Norris[1], Igor Novitski[1], Andy Oleck[1], Tom Page[1], Steve Peggs[4], Lee Petersen[7], Tommy Peterson[1], Henryk Piekarz[1], Fulvia Pilat[4], Mauro Pivi[6], Duane Plant[1], Vadim Ptitsyn[4], Roger Rabehl[1], Gianluca Sabbi[6], Phil Schlabach[1], Tanaji Sen[1], Vladimir Shiltsev[1], Jeff Sims[1], Jim Strait[1], Mike Syphers[1], Gianni Tassotto[1], Steve Tepikian[4], Iouri Terechkine[1], Jay Theilacker[1], John Tompkins[1], Dejan Trbojevic[4], Vladimir Tsvetkov[1], William Turner[6], Jim Volk[1], Masayoshi Wake[8], Bruce Wagener[7], Ron Walker[1], George Wojcik[1], Meiqin Xiao[1], Ryuji Yamada[1], Victor Yarba[1], S.Y. Zhang[4], Alexander Zlobin[1]

Editors:

H. Glass, P. Limon, E. Malamud, G.W. Foster,

P. Garbincius, S. Peggs, J. Strait, M. Syphers, J. Tompkins, A. Zlobin

Acknowledgments

The authors thank Michael Witherell, Director of Fermilab, and the U.S. Department of Energy for their support of this study.

They also thank Ping Wang for creating the web site for maintaining this document.

[1] Fermilab

[2] Illinois State Geological Survey, Champaign, IL

[3] Laboratory of Nuclear Studies, Cornell University

[4]Brookhaven National Laboratory

[5] consultant, Elmhurst, IL,

[6]Lawrence Berkeley National Laboratory

[7] CNA Consulting Engineers, Minneapolis, MN

[8] KEK, Japan

Preliminary Review

- A preliminary review was held April 30, May 1, 2001, just to see if we were way off base.
  - **Review Committee:**
    - Bob Kephart, Fermilab, Chairman
    - Gerry Dugan, Cornell; Jon Ives, consultant; Eberhard Keil, CERN
    - Philippe Lebrun, CERN; Erich Willen, BNL; Mike Anerella, BNL

- Made many good recommendations and observations. Found no serious insurmountable accelerator physics issues. 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?

- **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.

Some advantages of this scheme

- Each step yields new and interesting physics
- Stage-1 is at or close to a minimum cost for 40 TeV and its construction greatly reduces the cost of Stage-2
- Because it is sited at an existing lab, it uses the existing intellectual and organizational infrastructure, saving time and money
- There are many accelerator physics advantages
  - A superferric magnet permits injection from Tevatron
  - Injection at high energy eliminates magnetization and stability issues in the high-energy collider
  - The initial technology is straightforward, minimizing risk and necessary R&D and allowing an early start.
  - Time is made available for the R&D necessary to solve problems and reduce cost of high-energy phase
- Using the Fermilab (or CERN! or DESY!) exisiting accelerator complex saves at least $1 billion

Some disadvantages of this scheme

- It may longer to get to the highest energy – this is more a political and cost issue than a technical one
- There may be other scenarios that get to high energy sooner
  - For example, one could get to an intermediate energy, say 100 TeV, by skipping 2 T magnets and using 5 T for the first step. This might be quicker, although at Fermilab it would require a new injector.
- The initial low-energy design must predict correctly many details of the final high-energy design
- There will necessarily be a pause in the HEP program while the second collider is installed in the tunnel (five to seven years)
- The plan starts with a very big tunnel, which may have some political difficulties

Parameters for a Staged VLHC

	Phase 1	Phase 2
E_{cm} [TeV]	40	175
Peak Luminosity [cm^{-2} s^{-1}]	10^{34}	2×10^{34}
$Circ_{total}$ [km]	233	
B_{dipole} [T]	1.9	9.8
Arc packing factor	~95.0%	~83.0%
Average R_{arc} [km]	35.000	
Half-cell length [m]	135.486	
Number of half cells	1720	
Number of dipoles	3440	9728
Length of dipoles [m]	65	16
Bunch spacing [ns]	18.8	

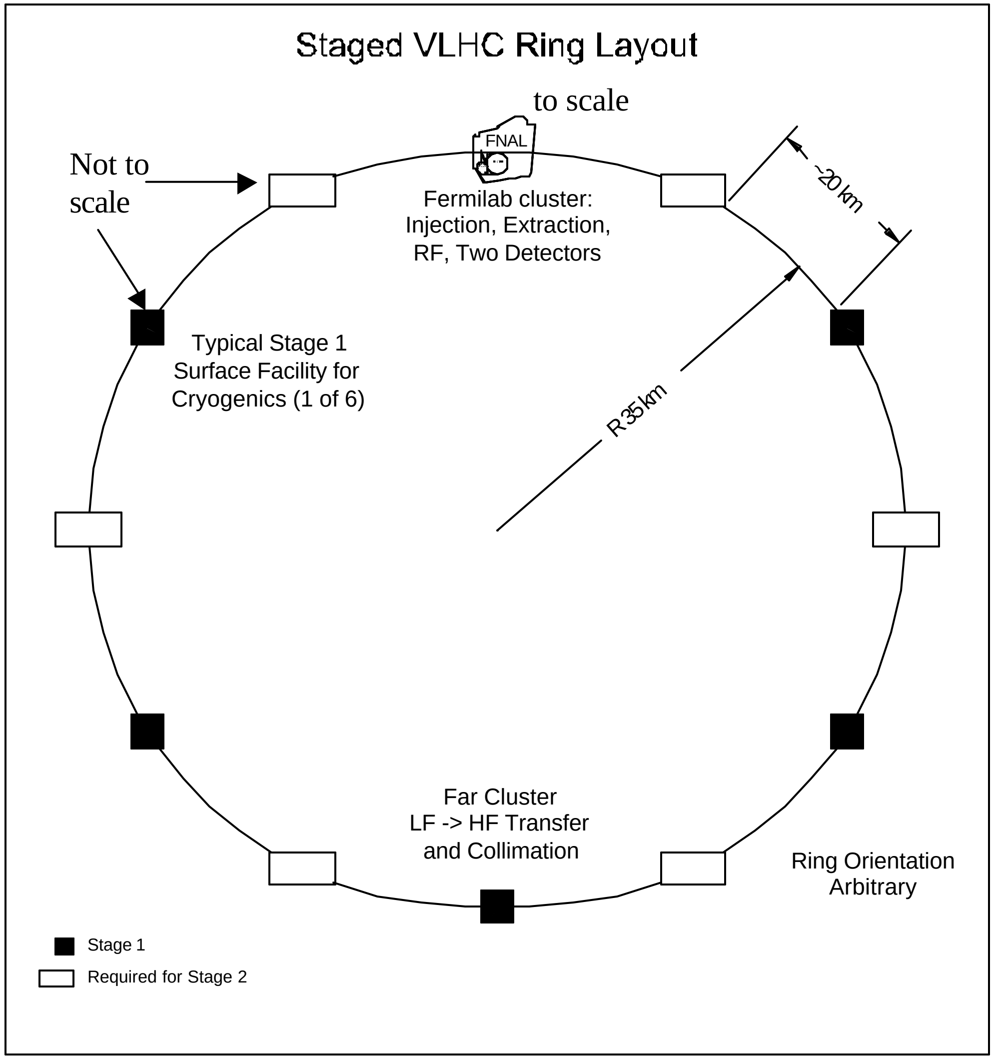
	Stage 1	Stage 2
Total Circumference (km)	233	233
Center-of-Mass Energy (TeV)	40	175
Number of interaction regions	2	2
Peak luminosity ($cm^{-2}s^{-1}$)	1×10^{34}	2.0×10^{34}
Luminosity lifetime (hrs)	24	8
Injection energy (TeV)	0.9	10.0
Dipole field at collision energy (T)	2	9.8
Average arc bend radius (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
?* at collision (m)	0.3	0.71
Free space in the interaction region (m)	± 20	± 30
Inelastic cross section (mb)	100	133
Interactions per bunch crossing at L_{peak}	21	58
Synchrotron radiation power per meter (W/m/beam)	0.03	4.7
Average power use (MW) for collider ring	20	100
Total installed power (MW) for collider ring	30	250

Stage 2

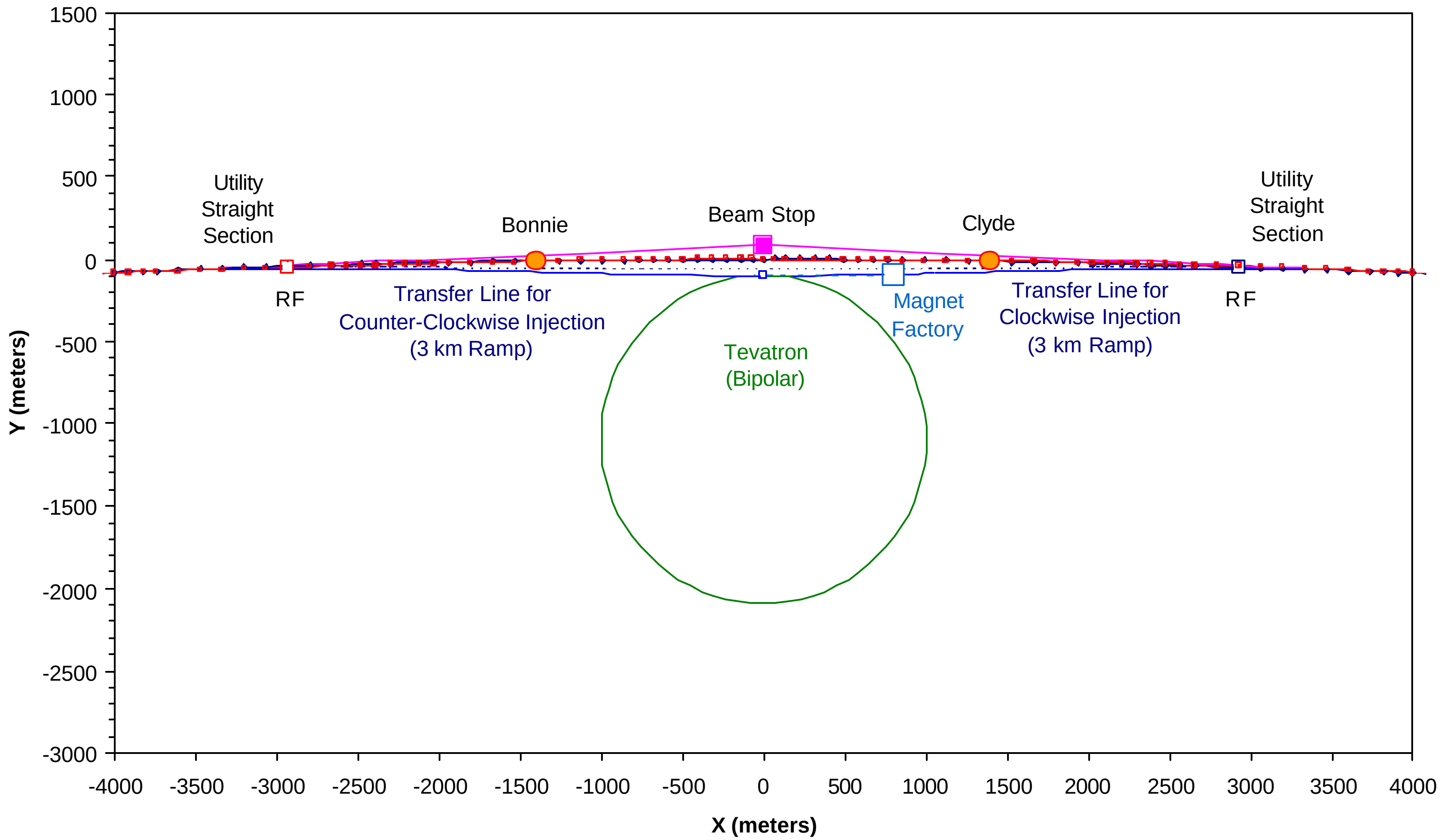
- It is clear that Stage 2 could get to 200 TeV or higher!

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**

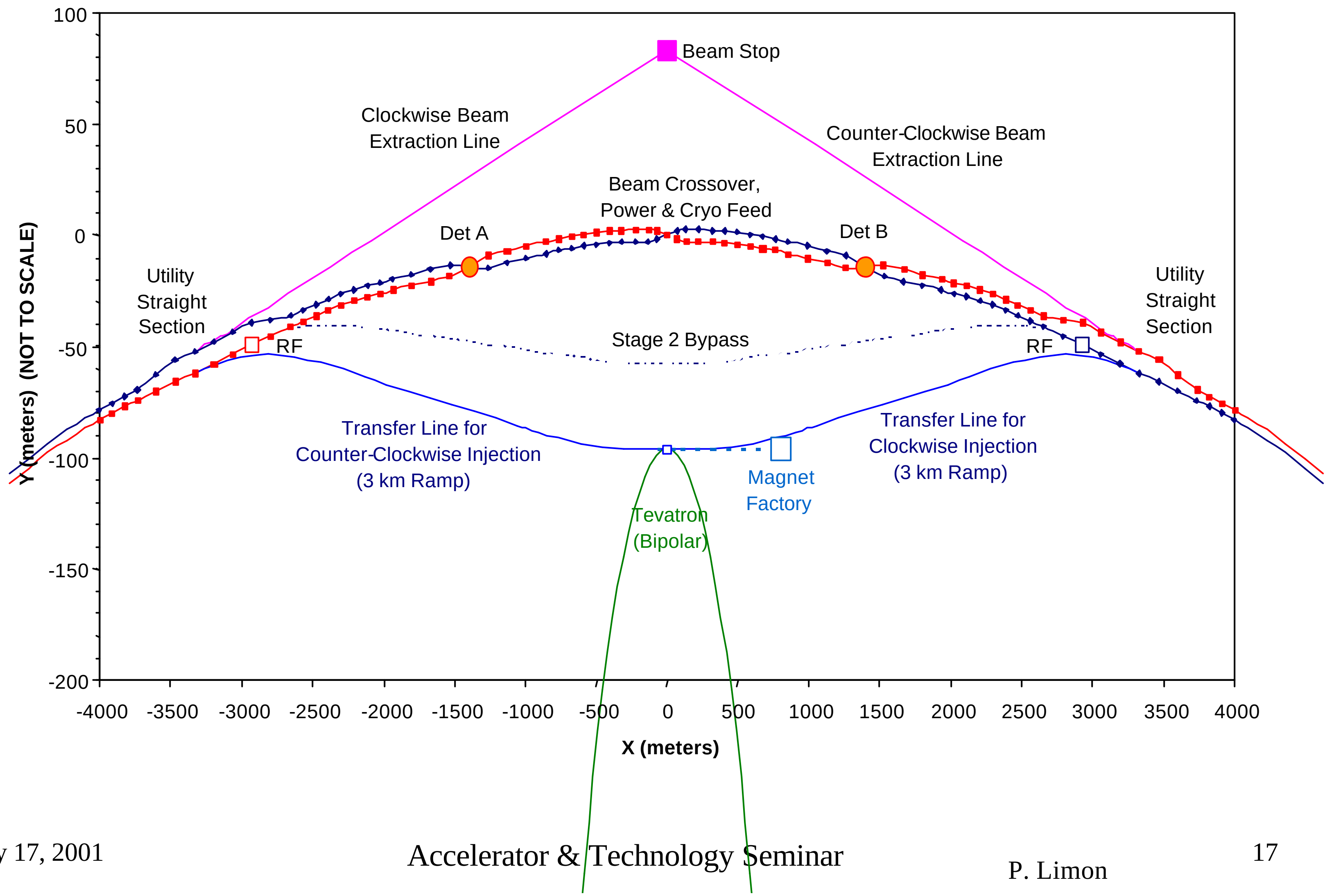
Leveled luminosity vs. energy. The luminosity is limited by one or more of the beam-beam tune shift, the synchrotron-radiation power per meter, or the debris power in the interaction region.

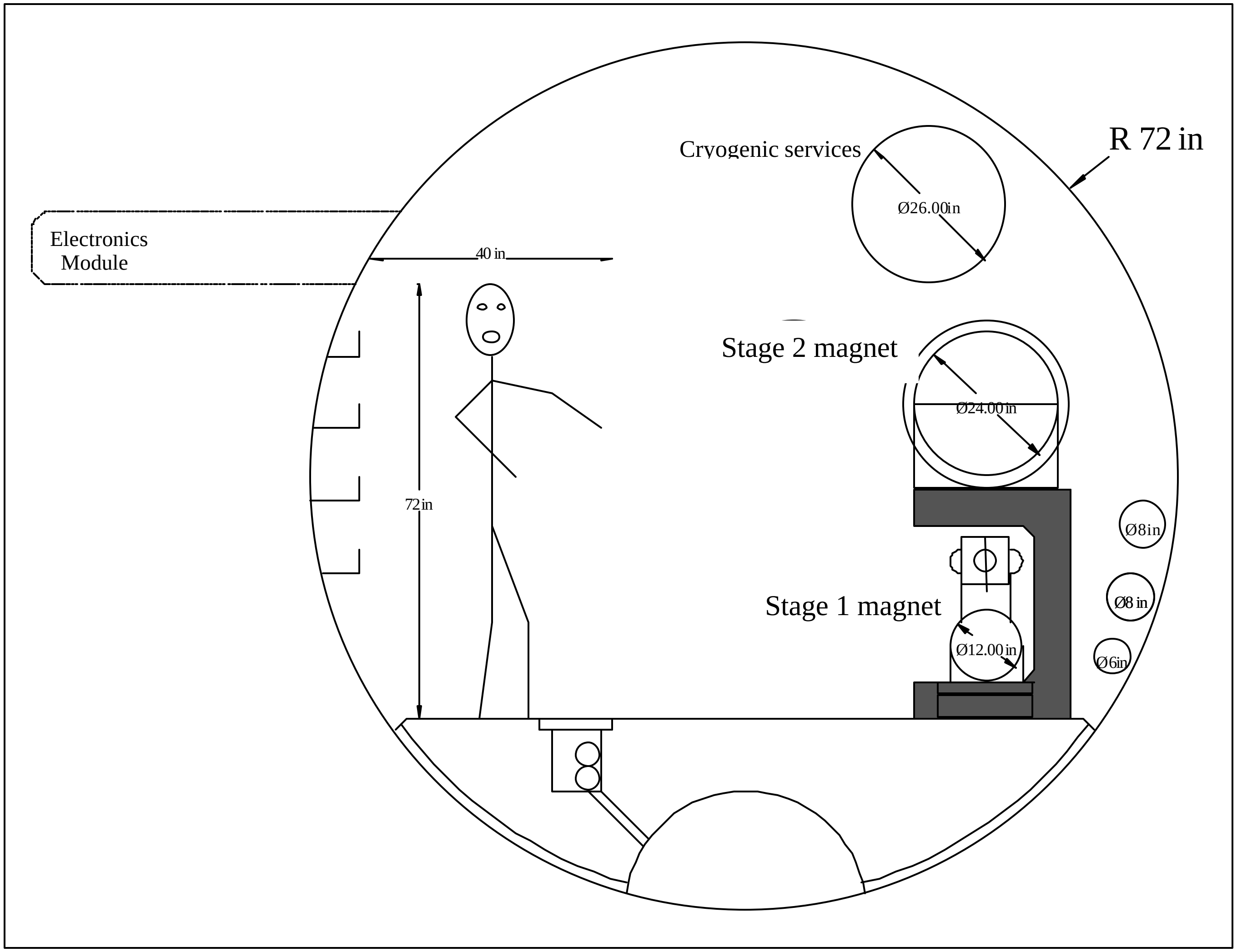

Staged VLHC Ring Layout
to scale
FNAL
Not to scale
~20 km
Fermilab cluster:
Injection, Extraction,
RF, Two Detectors
Typical Stage 1
Surface Facility for
Cryogenics (1 of 6)
R 35 km
Far Cluster
LF -> HF Transfer
and Collimation
Ring Orientation
Arbitrary
Stage 1
Required for Stage 2

VLHC DESIGN STUDY SITE LAYOUT

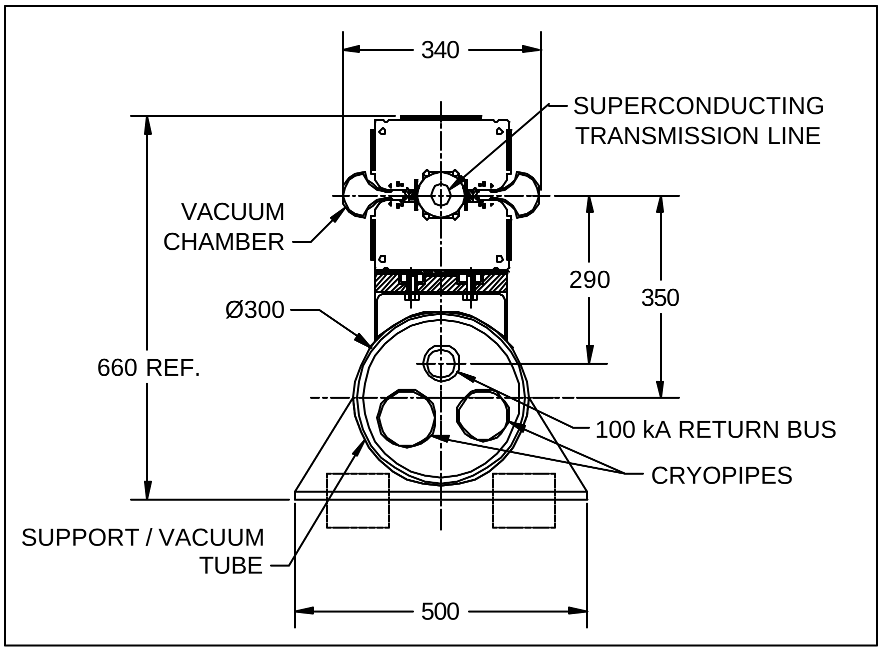


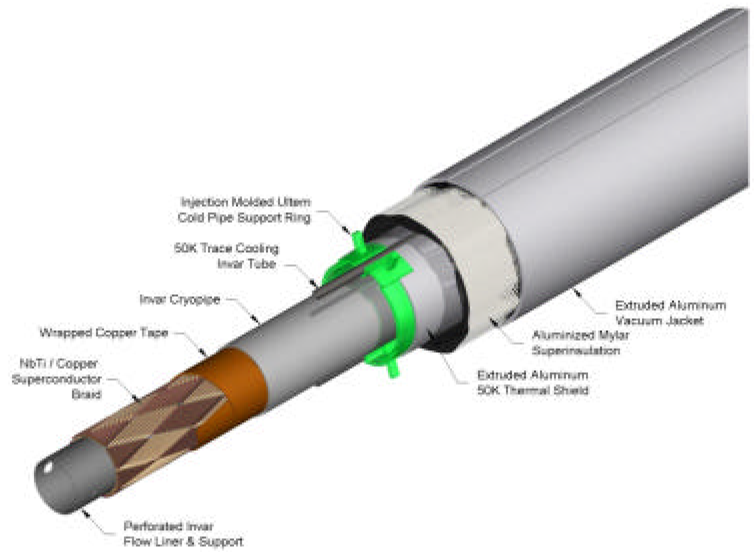
VLHC DESIGN STUDY SITE LAYOUT




R 72 in
Cryogenic services
Ø26.00in
Electronics Module
40 in
Stage 2 magnet
Ø24.00in
72in
Ø8in
Ø8 in
Stage 1 magnet
Ø12.00in
Ø6in

VLHC Stage-1 Magnet

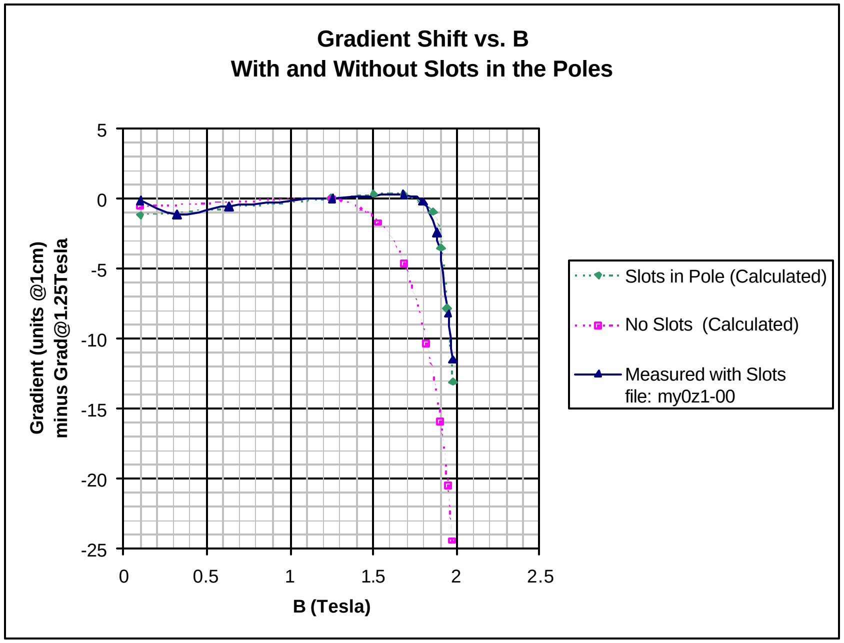


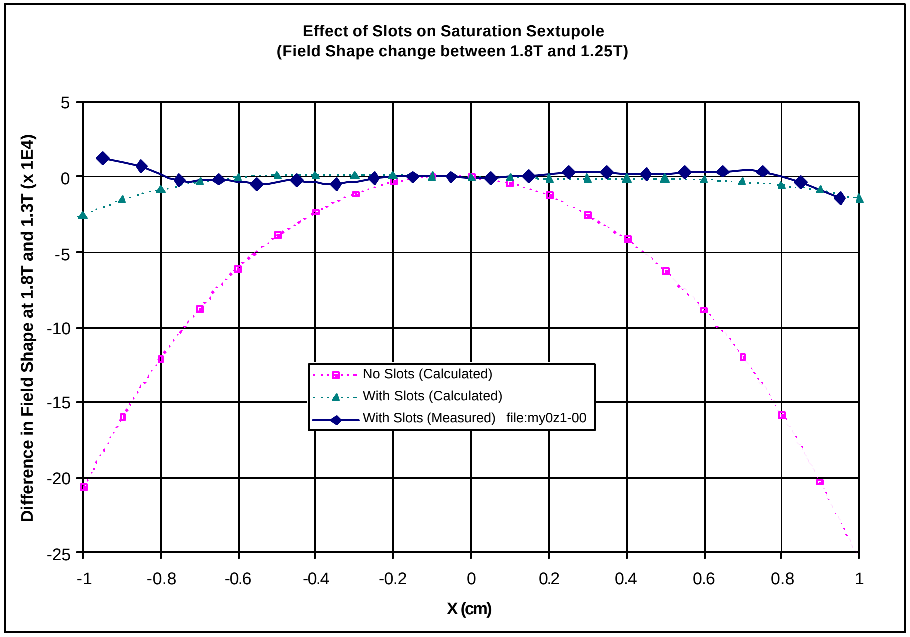


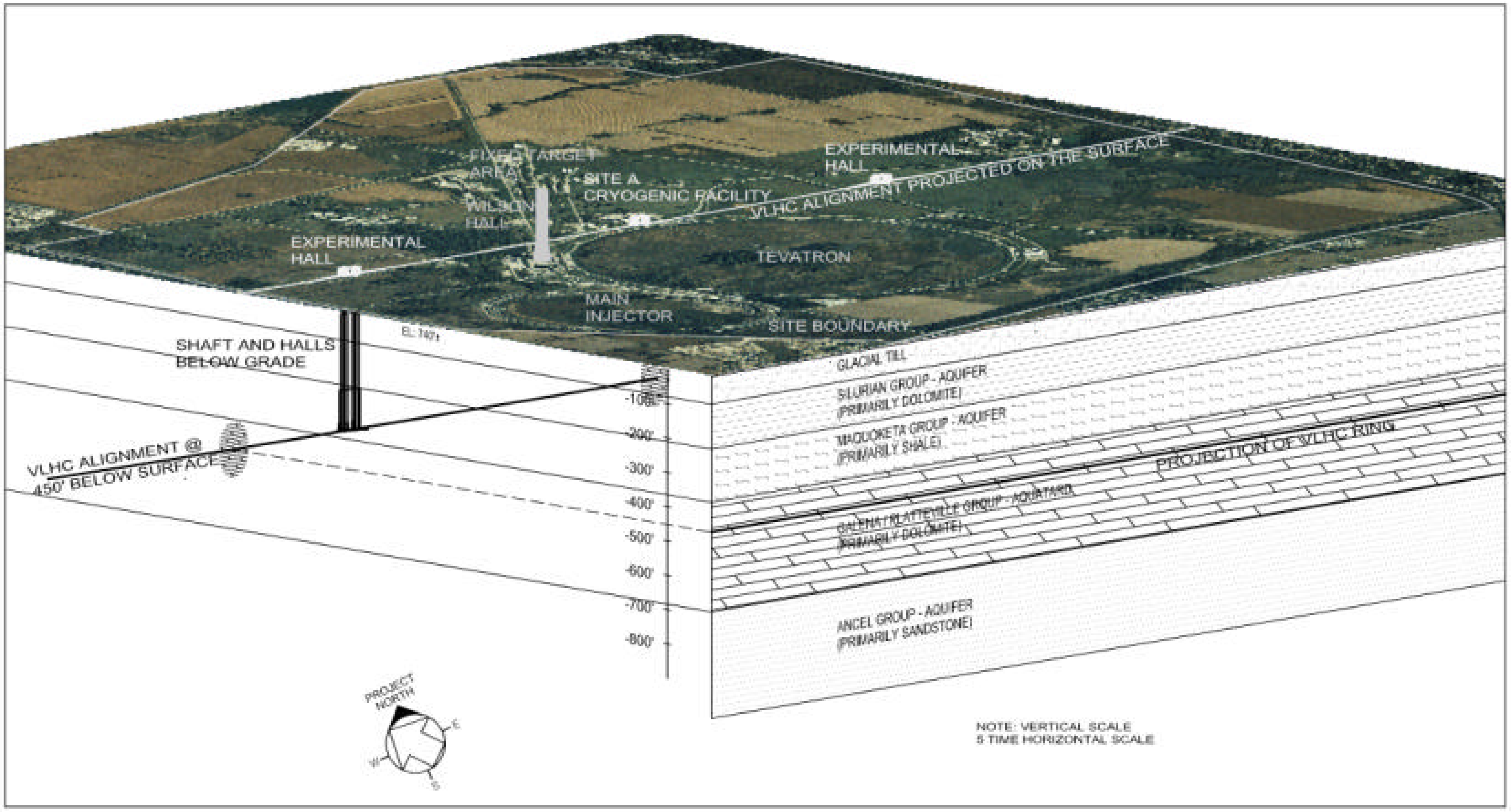
Cross-section of Stage-1 superferric magnet

100 kA superconducting transmission line

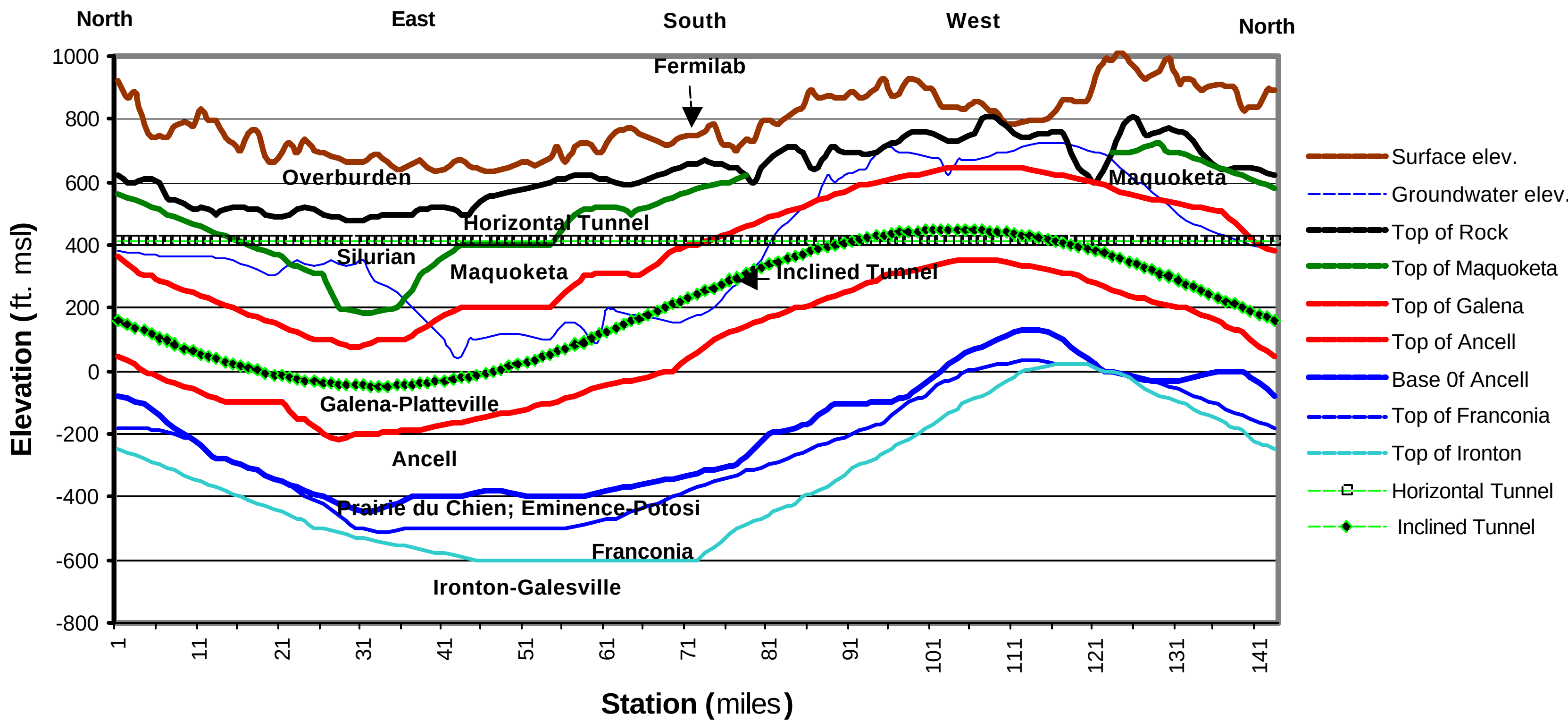
Effect of Slots in Pole on Gradient Shift in Transmission Line Magnet



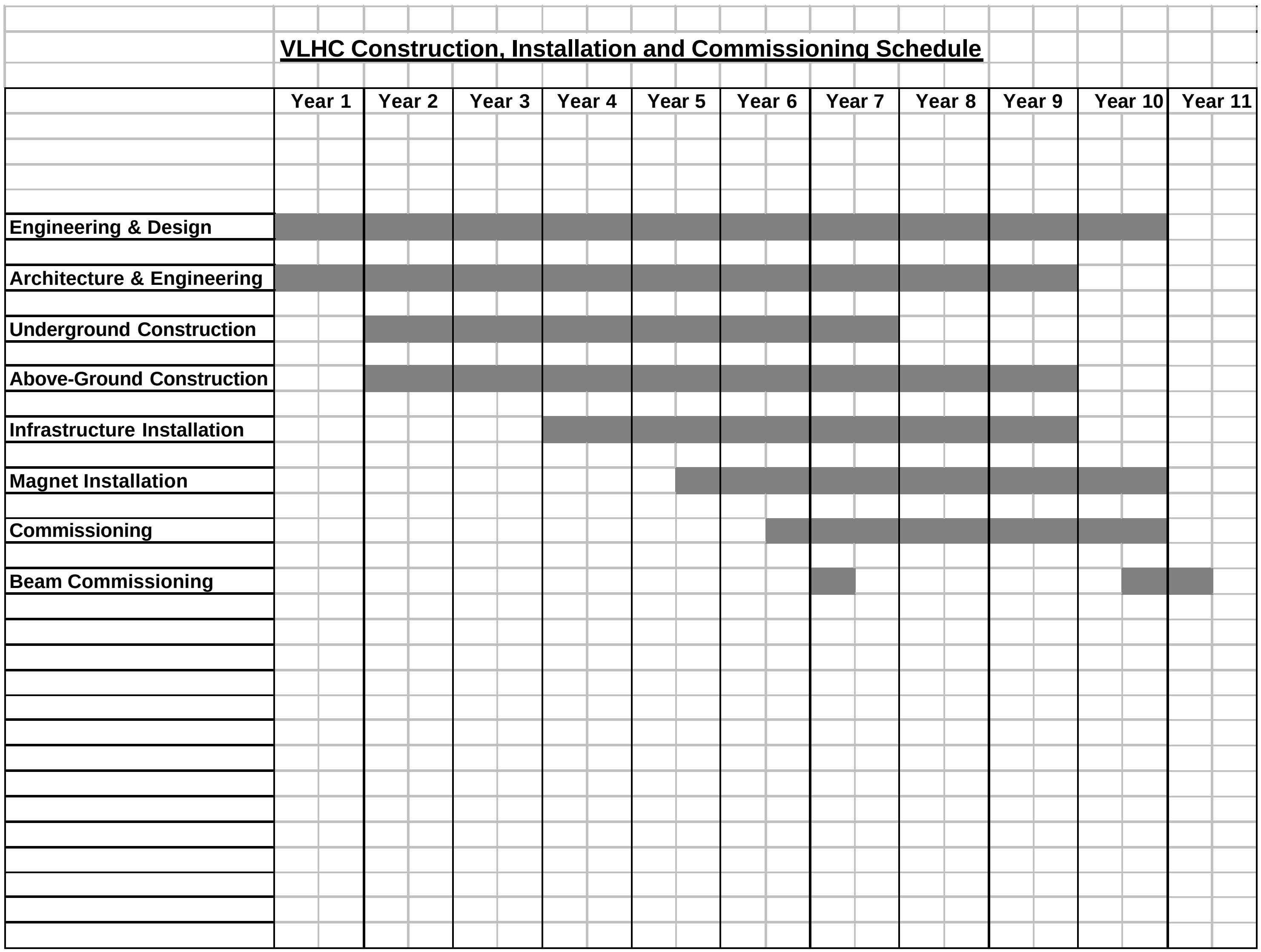



FIXED TARGET AREA
WILSON HALL
SITE A CRYOGENIC FACILITY
EXPERIMENTAL HALL
VLHC ALIGNMENT PROJECTED ON THE SURFACE
EXPERIMENTAL HALL
TEVATRON
MAIN INJECTOR
SITE BOUNDARY
SHAFT AND HALLS BELOW GRADE
VLHC ALIGNMENT @ 450' BELOW SURFACE
-100'
-200'
-300'
-400'
-500'
-600'
-700'
-800'
GLACIAL TILL
SILURIAN GROUP - AQUIFER (PRIMARILY DOLOMITE)
MAQUOKETA GROUP - AQUIFER (PRIMARILY SHALE)
PROJECTION OF VLHC RING
GALENA / PLATTEVILLE GROUP - AQUITARD (PRIMARILY DOLOMITE)
ANCEL GROUP - AQUIFER (PRIMARILY SANDSTONE)
PROJECT NORTH
E
W
S
NOTE: VERTICAL SCALE
5 TIME HORIZONTAL SCALE

VLHC
Generalized Geologic Section
228 km Ring
North of Fermilab



Very Large Hadron Collider



Stage 1 Issues

- Dynamic aperture is not an issue
- Beam stability at injection needs study. It appears that it can be controlled by straightforward methods, but experiments need to be done to verify this.
- Is this the best way to proceed? How does it compare with other staging options or a no-staging option? A subject for Snowmass
- The cost analysis results are still uncertain, but the cost is about the same as recently reported by TESLA
- What are the public acceptance issues?
- What R&D remains?

Public Acceptance

- Must work on public 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.

Technical Conclusions

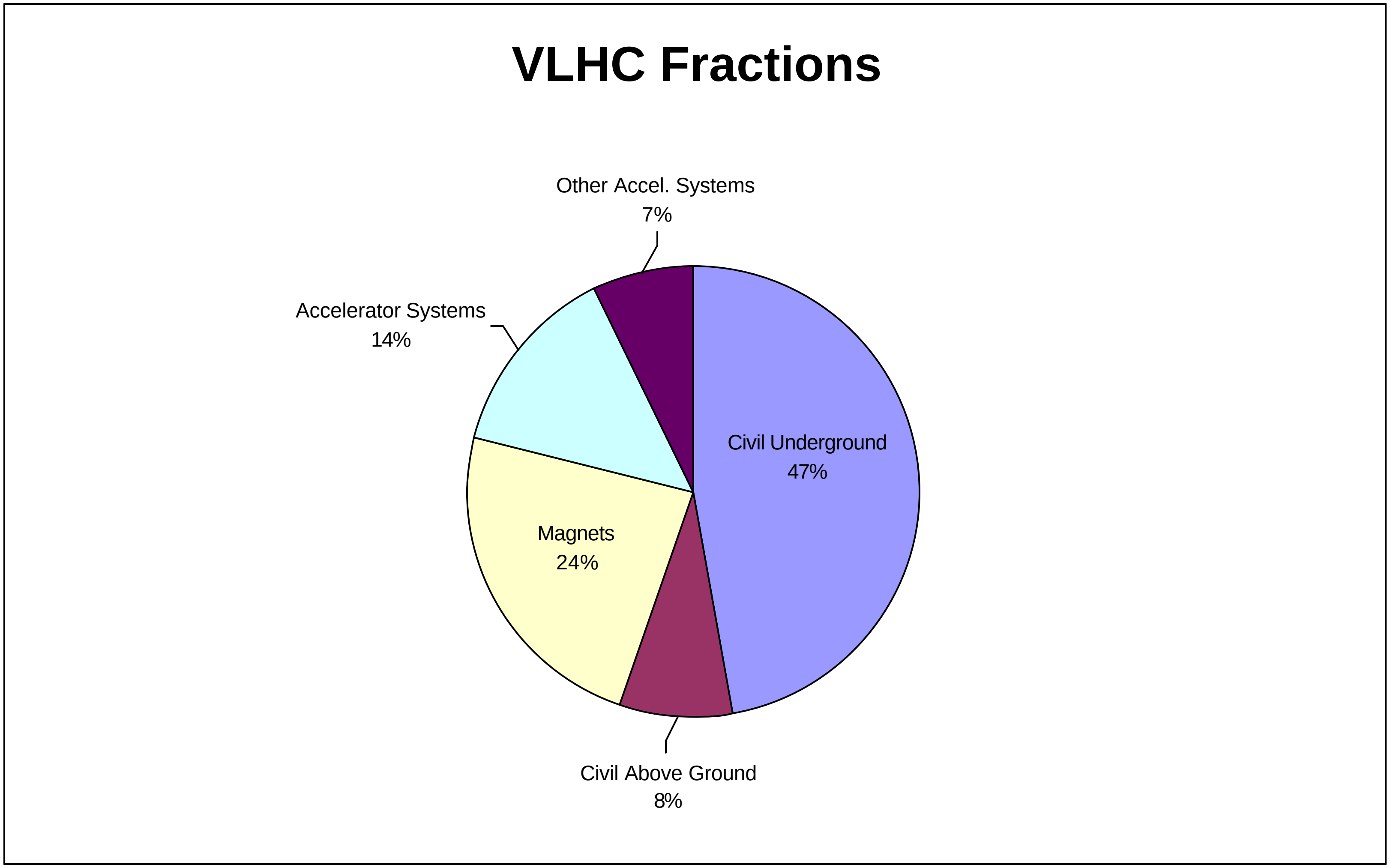
- There are no serious technical difficulties to the Stage-1 VLHC, although there are improvements and cost savings that can be gained through a vigorous R&D program.
- The Stage-2 VLHC can reach 200 TeV and 2×10^{34} or more in the 233 km tunnel. There is the need for magnet and vacuum R&D, but no insurmountable problems. The luminosity limits are multiple interactions, IP power and luminosity lifetime.
- Making a large tunnel is certainly possible in the Fermilab area. We are waiting for the final civil construction report.
- A 300 GeV (cm), 10^{34} e^+e^- collider, or a top factory (360 GeV, 10^{33}), with an affordable power cost is possible in the same tunnel.

Cost Conclusions

- The cost driver is underground construction, especially tunneling.
- The total cost for Stage-1 appears to be slightly higher, 10% to 30%, than the cost for TESLA (~ $3 billion, as recently estimated by DESY).
- The cost for the Stage-1 collider is consistent with the cost for the SSC Collider Ring inflated to 2001 dollars.
- It's absolutely necessary to build the VLHC at an existing hadron accelerator lab.
- There are some obvious cost drivers, and some obvious places to concentrate cost-reducing R&D.

VLHC 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 what we thought would be the cost drivers using a standard cost-estimating sheet. This is done at a fairly high level.**
  - Underground construction
  - Above-ground construction
  - 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.**


VLHC Fractions
Other Accel. Systems
7%
Accelerator Systems
14%
Civil Underground
47%
Magnets
24%
Civil Above Ground
8%

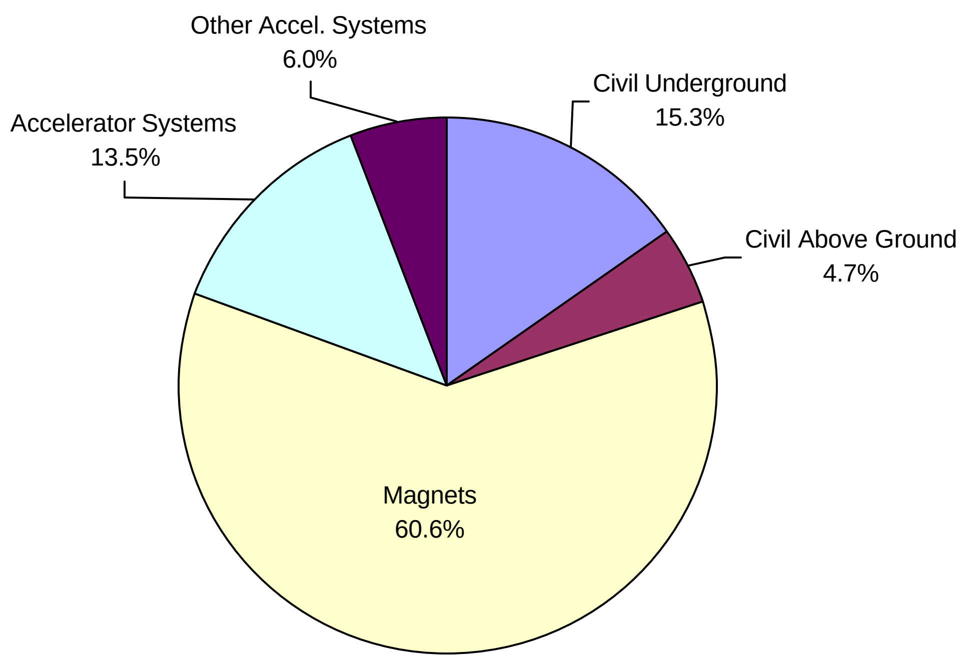
SSC Basis

- **Used July, 1990 SSC Cost Estimate – The SCDR Baseline**
  - No adjustments by reviews. The real cost increase was about $200 million; this adjustment remains to be done. (There were other adjustments not relevant to this analysis.)
- **Used only the "European" cost base**
  - Tried to strip out all EDI, indirects, escalation and contingency – a "European" base estimate.
- **Deconstructed the SSC estimate and reconstructed it into the VLHC categories and adjusted to the VLHC design.**
  - Adjusted number of detector halls, for example; moved special magnets from AccelSys to Magnet category
  - Added the "other accelerator systems" to VLHC by the SSC ratio of AccelSys/(Cryo+Vacuum+Install)
- **Escalated SSC from 1990 to 2001 by 35% (CPI)**

Comparison of VLHC and SSC Cost Drivers

	SSC	VLHC
	100.00%	100.00%
Civil Underground	15.29%	47.33%
Civil Above Ground	4.66%	7.89%
Magnets	60.59%	23.77%
Accelerator Systems	13.50%	13.91%
Other Accel. Systems	5.96%	7.10%

SSC Fractions



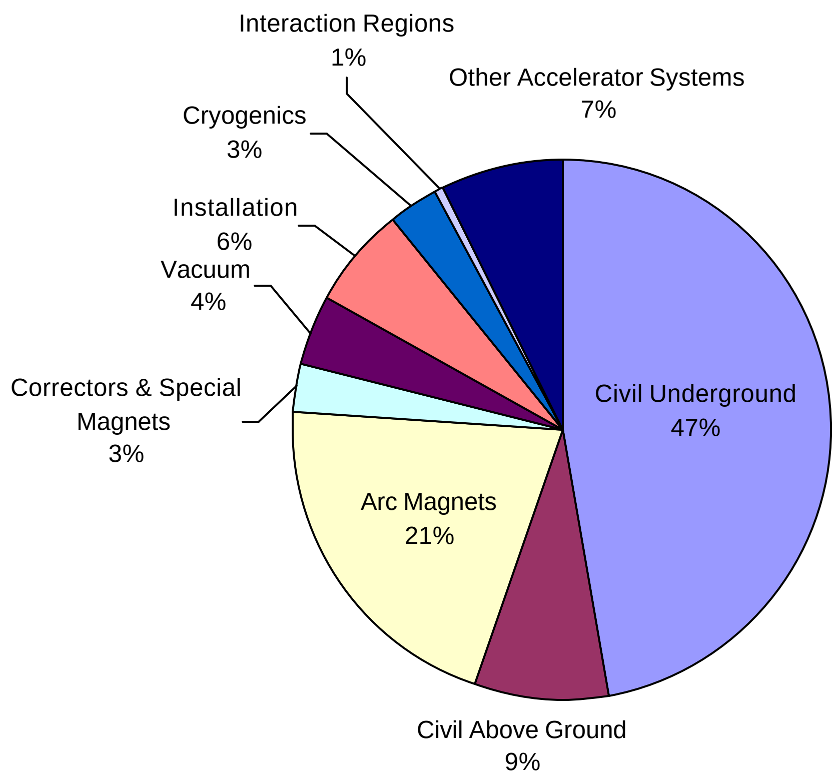
Very Large Hadron Collider

VLHC Cost Drivers

In FY2001 K$	VLHC Estimate	VLHC Fraction
Total	**3,803,159**	**100.00%**
Civil Underground	1,800,000	47.33%
Civil Above Ground	300,000	7.89%
Arc Magnets	791,767	20.82%
Correctors & Special Magnets	112,234	2.95%
Vacuum	153,623	4.04%
Installation	232,397	6.11%
Tunnel Cryogenics	22,343	0.59%
Refrigerators	94,785	2.49%
Interaction Regions	26,024	0.68%
Other Accelerator Systems	269,986	7.10%

For comparison, the SSC Collider Ring, escalated to 2001 (1.35) is $3.79 billion

VLHC Ratios


Interaction Regions
1%
Other Accelerator Systems
7%
Cryogenics
3%
Installation
6%
Vacuum
4%
Correctors & Special
Magnets
3%
Civil Underground
47%
Arc Magnets
21%
Civil Above Ground
9%

What's the Total Cost?

- The factors below apply to any and all cost estimates.
  - EDI, Engineering, Design and Inspection.
  - Overhead and G&A, or indirects
  - Escalation
  - Contingency
- Scaling from the TESLA cost estimate, we might estimate EDI + Overhead at 10,000 person-years, ~ $1 billion. This will be split among Fermilab and collaborating institutions.
  - TESLA estimated 7,000 person-years for an eight-year construction cycle; 4,000 came from DESY, based on the whole Accelerator Div. (500 people) working full time on it. The rest of the manpower came from collaborating institutions.
- In addition, there are two detectors to be costed.
- At this time, contingency needs to be high. Engineering and R&D will make it smaller

Stage-1 R&D

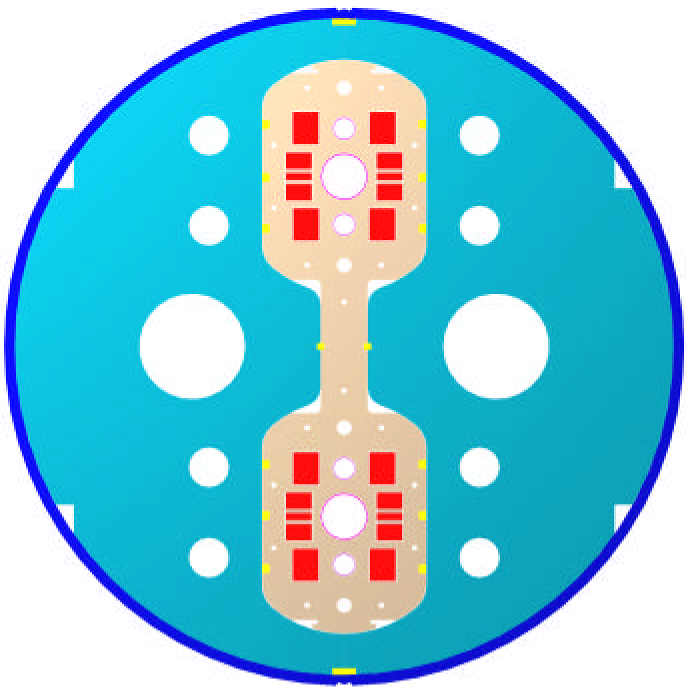
- The purpose of R&D is to reduce technical risk and cost, and to improve performance.
  - Tunneling R&D: tunneling is the most expensive single part
    - Automation to reduce labor component and make it safer
    - Careful design to reduce adits and special construction
  - Beam instabilities and feedback: the largest risk factor
    - A combination of calculation, simulation & experiments
  - Magnet field quality at injection and collision energy
    - This does not appear to be an issue, but needs more study
  - Magnet production and handling; long magnets reduce cost
    - Reduce cost of steel yokes and assembly time & labor
  - Installation; a complicated, interleaved procedure to save time
    - Handling long magnets is tricky
  - Vacuum; surprisingly expensive
    - Develop getters that work for methane, or cryopumps
  - Cryogenic behavior; possible instabilities due to long lines
    - Heat leak is a critical factor

Stage-2 R&D

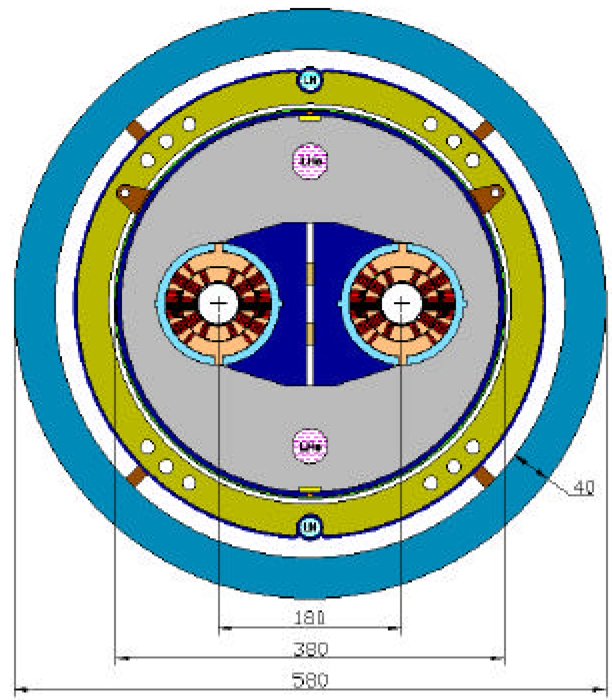
- The purpose of R&D is to reduce technical risk and cost, and to improve performance.
  - Magnet development
    - High-field magnets are not yet a state-of-the-art product
  - Conductor performance
    - High-field magnets must have high-performance conductor
  - Magnet and conductor cost
    - The 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

Stage 2 R&D - Magnets

- There are several magnet options for Stage 2.



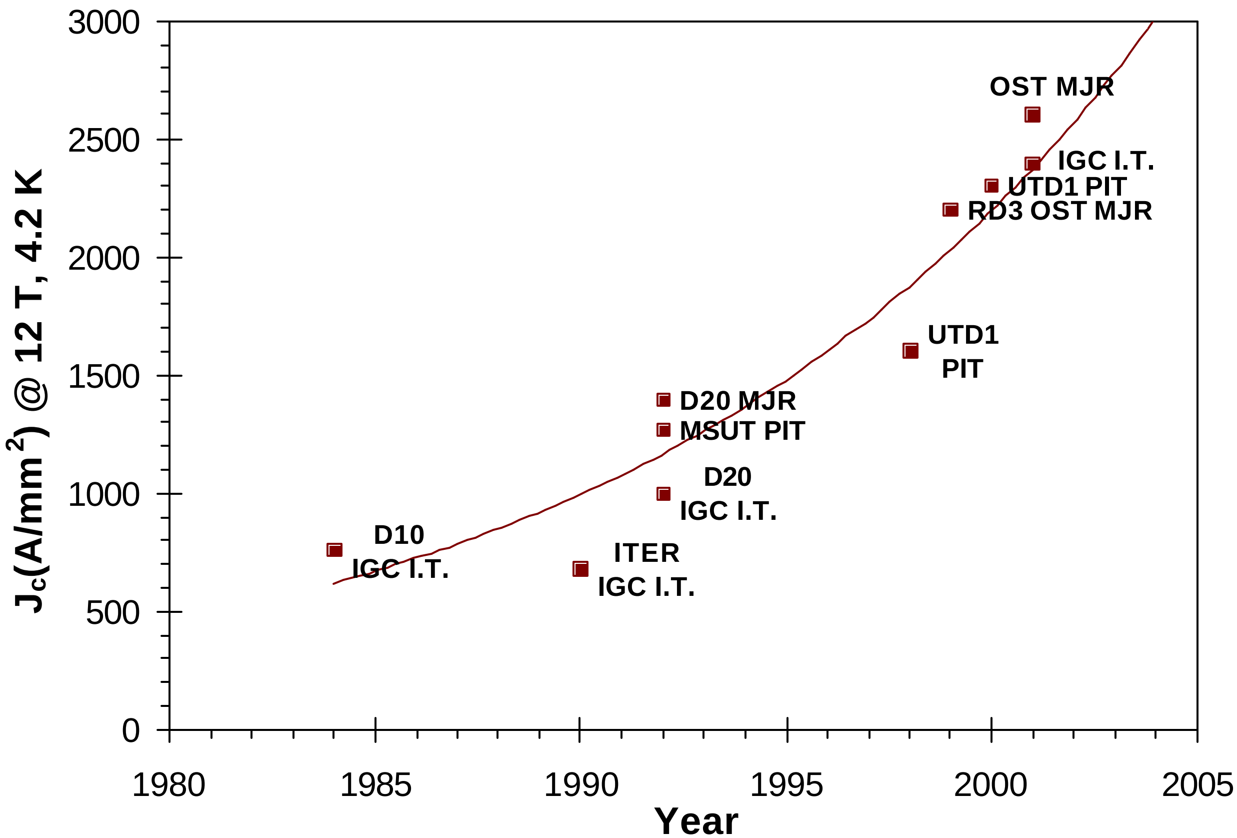
Stage-2 Dipole Single-layer common coil



Stage-2 Dipole Warm-iron Cosine ?

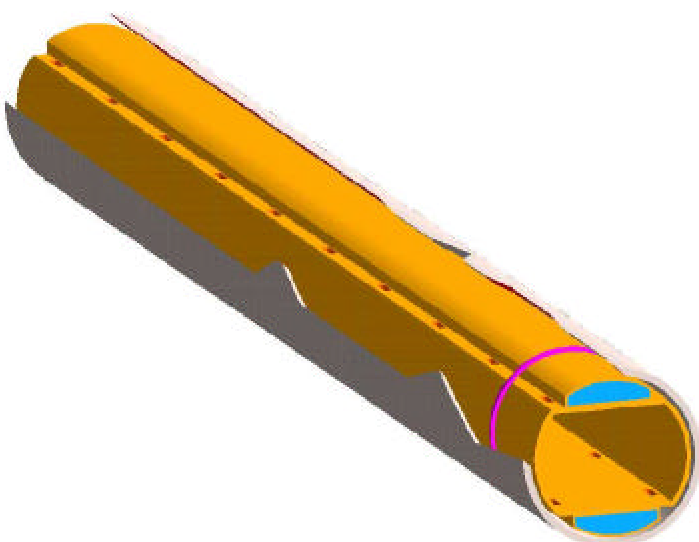
Stage 2 R&D - Conductor

- Nb3Sn conductor is continuing to improve

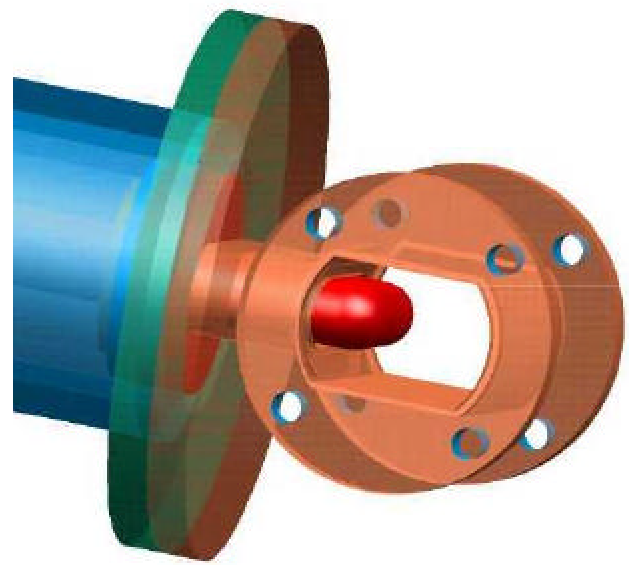


Stage 2 R&D – Vacuum and Cryogenics

- 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 $2\mathrm{x}10^{34}$



A synchrotron radiation “mask” will allow even higher energy and luminosity

What's the Plan?

- At this stage, one cannot guess what will really happen
- It's dangerous to try to predict what politicians, or even the scientific community will decide.
- There are at least one hundred reasons why any plan won't work, so the right thing to do is pick the **best plan** for HEP and for the U.S.
- The following is the best plan because:
    - It spreads the HEP investment over many regions
    - It puts every region on the roadmap at the start
    - It results in new HEP being done somewhere in a smooth sequence
    - It puts the U.S. at the energy frontier as soon as possible, and keeps us there forever!

What's the Best Worldwide Plan?

- **TESLA should be built. It is most likely to be built in Germany, but in any case, not in the U.S.**
  - The US should be deeply involved in TESLA, contibuting up to 20% of the cost, in kind. This is $700 million raw, ~$1.2 billion loaded, spread over eight years. Peak spending ~$250 million/year
  - XFELs, using TESLA technology can and will be built in many regions.
- **In the meantime, the US and others should continue to do VLHC, CLIC and MSR R&D, engineering studies and planning.**
- **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 TESLA plan

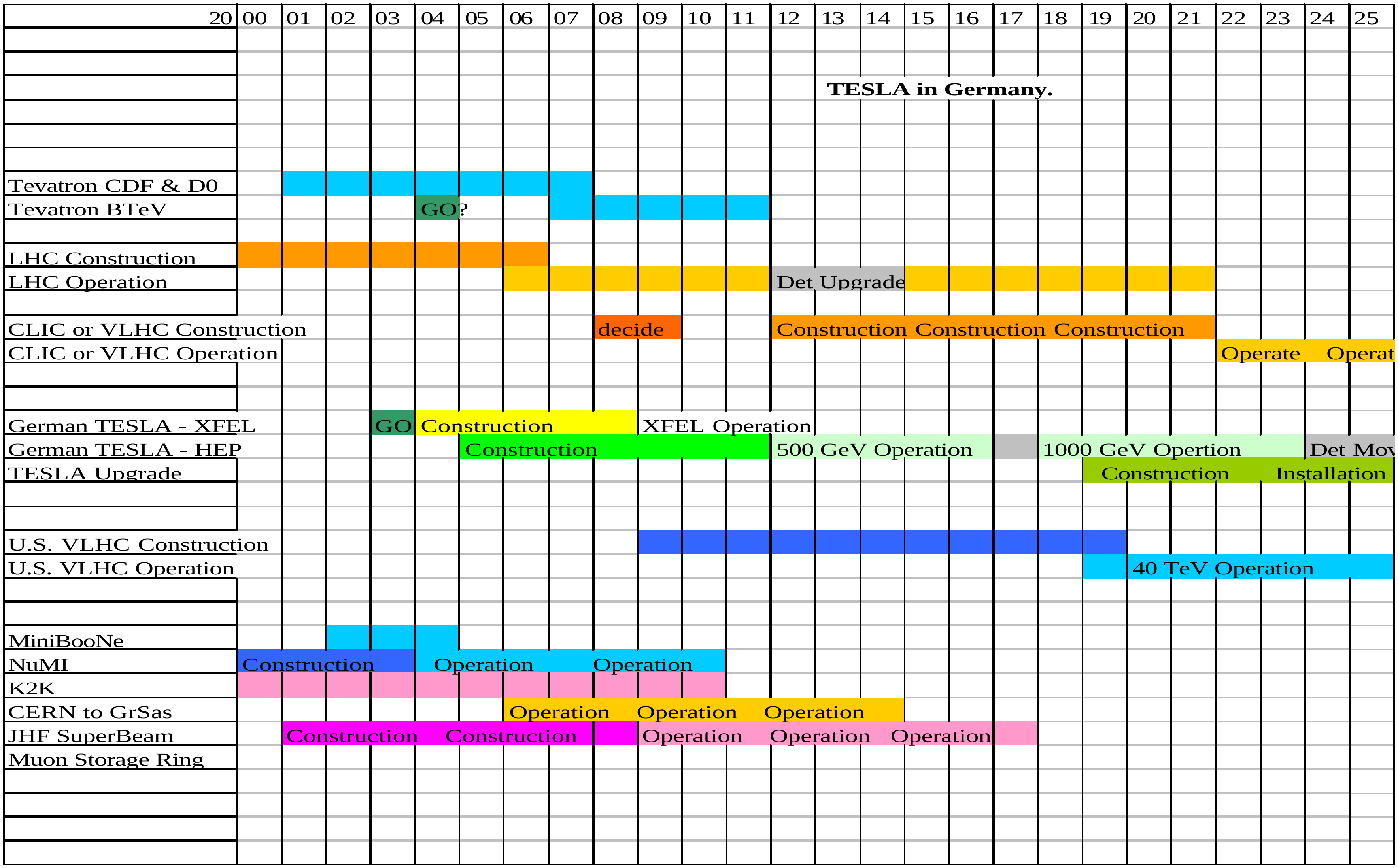
What's the Best Worldwide Plan?

- Another region might do improved neutrino physics
  - This might involve a muon storage ring if R&D is successful, or it could involve a high-power proton source.
- R&D for a third-generation lepton collider, CLIC-like, or a muon collider should continue.

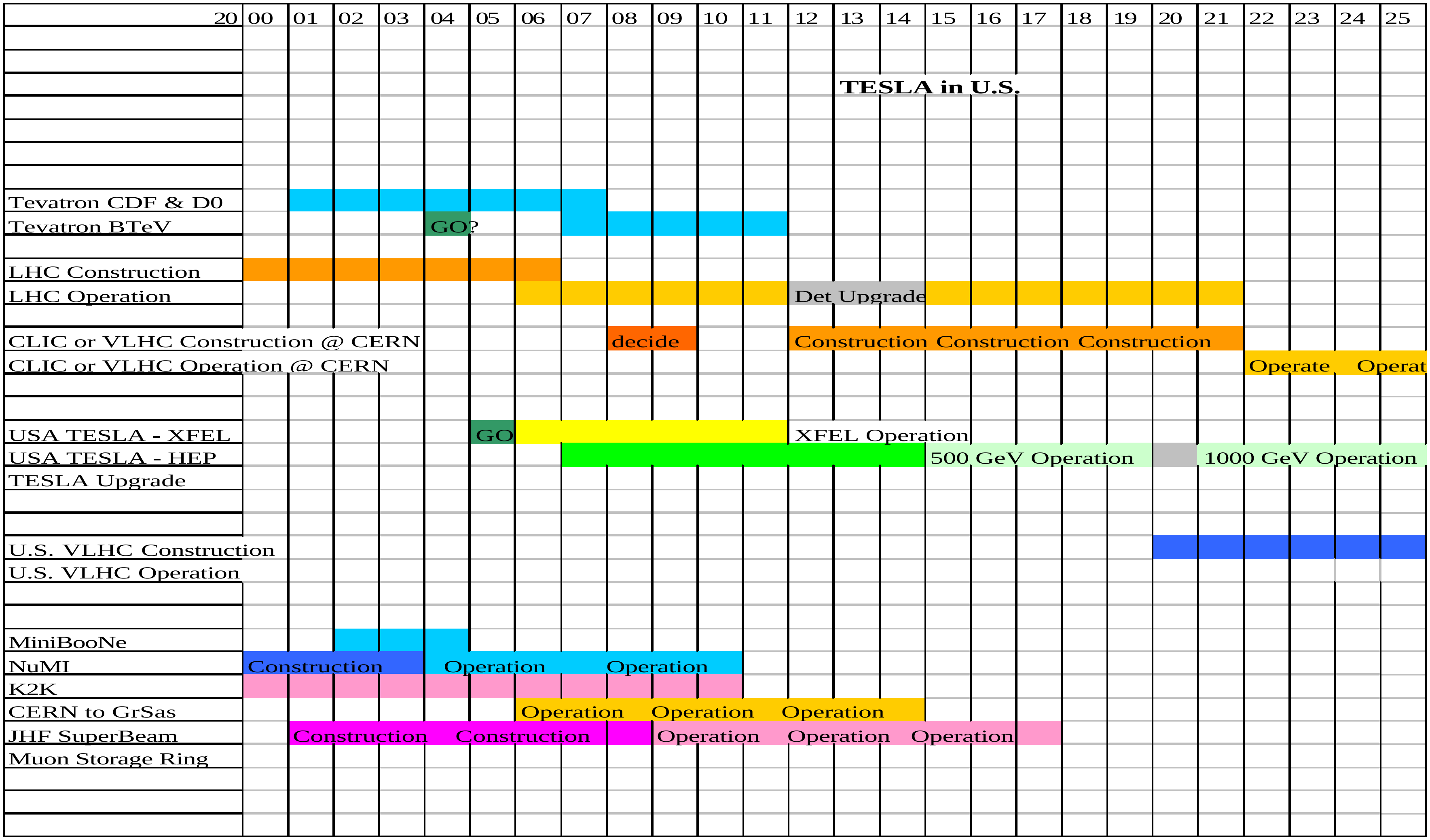
- This plan leads to a sensible program in which every region contributes, every region gets an HEP machine, and in which there are continual opportunities for HEP experiments.

- This plan is expensive. In the US, the budget should to increase by 30% in 2004 to support TESLA and R&D, and 50% in 2008 to help support the VLHC construction.

Very Large Hadron Collider



Very Large Hadron Collider



What's the Best Worldwide Plan?

- **Predicting the future is dangerous, and violates our own rules! It's hard enough to predict the past.**
- **Why should TESLA will be built in Germany?**
  - Germany can make a decision in one year to go ahead with something. The US will take much longer if it has to pay most of the cost.
  - DESY and European industry have the technology in hand or close by. The U.S. will take some years to catch up.
  - Germany does not have to decide to go the whole way. They could decide to build an XFEL, and start land procurement while searching for collaborators.
  - DESY developed the technology and stayed with it in the dark hours. Helping Germany build TESLA at DESY is the fair thing to do.
  - A linear collider should not be built in the US. It condemns the US far from the energy frontier.

How can this be done?

- **We don't really know. It will be difficult, but it might play out like the following"**
- **An international agreement is forged.**
- **This agreement contains the goals of the worldwide HEP program right from the start.**
- **The agreement contains a place and responsibilities for each region**
  - The details can change, of course, as HEP and technology advance, but the overall goal of a plan in which everyone has a place must be part of the initial agreement.
- **This is not a quid pro quo, which is an exchange-you give me this, I'll give you that. This is a worldwide HEP plan.**

What should HEP, and especially Fermilab do now?

- The purpose of R&D is to reduce technical risk and cost, and to improve performance.
  - Fermilab and others should commit sufficient resources to modestly increase the magnet and accelerator physics R&D for VLHC, and to start a serious tunneling R&D effort.

- In order to understand the engineering and physics issues of the VLHC, we need to put together an international team to complete a serious HEP and engineering design.
  - Fermilab and others should commit sufficient resources and encouragement to form a complete physics and engineering design team to study the HEP opportunities, to understand the accelerator physics issues, and to complete an engineering design and accurate cost estimate in two years

What should world HEP do now?

- Both of the above should be international efforts that require overall international guidance and management.
  - VLHC needs an imprimatur from the Lab Directors to form an international team to guide VLHC R&D, studies and engineering, with the goal of publishing a complete design and cost estimate in two years.
- The Lab Directors (ICFA?), or even better, the Lab Directors and the science ministers (who represents the U.S?) should get together to formulate a worldwide agreement and plan for high-energy physics.
  - This is different from Albrecht Wagner's goal in that the purpose is not merely to support the next machine, but to make a long-range plan. This is consistent with the charge to Snowmass and the HEPAP Subpanel.