

The
Very **L**arge **H**adron **C**ollider

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The next HADRON COLLIDER

- Is already technically feasible
- However, must be significantly lower in cost/TeV
- we need to be innovative and use new and emerging technologies to achieve this goal

The Subpanel recommends an expanded program of R&D on cost reduction strategies, enabling technologies, and accelerator physics issues for a VLHC

- Must be built at an existing lab: use the injector chain and infrastructure
- This will be a site specific talk, i.e. Fermilab based

Outline of presentation

- Why VLHC?
- History of the current effort
- Accelerator physics: high field/low field
- Tunneling issues
- The Magnet: the “heart” of the matter
- Next Steps

- New approaches are required to continue the dramatic rise in collider energies as represented by the Livingston Plot.
- Ahead are several years of intensive and challenging R&D required to fully establish feasibility and have credible cost estimates

Build on Fermilab's proven core competence:

- Operation of the world's only hadron collider user facility
- Accelerator research, design, construction, and operation
- Superconducting magnet research, design, and development
- Detector development
- High-performance computing
- International scientific collaboration

- Utilizes the multi-billion dollar investment in the current laboratory

"Snowmass '96" Parameters

(for both low- and high- field approaches)

- superconducting pp collider
- $E_{cm} = 100 \text{ TeV}$
- Luminosity $\sim 10^{34} / \text{cm}^2 / \text{sec}$
- 3 TeV "booster" fed from the Main Injector

Why VLHC?

Hadron Colliders are “Discovery Machines.” They reach farther and probe deeper than any other type of accelerator -- the only known route to the 10 TeV scale

VLHC March '97 Workshop.
(transparencies in “Yellow” book)

A few excerpts from working group summaries:
(“Turquoise” book)

New Strong Dynamics

If strong dynamics is involved in EW symmetry breaking, the physics associated with it will first appear at the 1 TeV scale. The VLHC will have the opportunity to explore it in more depth than the LHC. New strong dynamics as well as any phenomena associated with flavor physics would also give a rich structure in the 1-10 TeV range.

Supersymmetry

If SUSY is discovered at “low” energy, and is gauge-mediated, one could then expect new gauge bosons in the 10-100 TeV range.

Exotics

◆ Scalar lepto-quarks

Tev - run 2	250 GeV
LHC	1.5 TeV
VLHC	~ 7 TeV

◆ W', Z'

CDF, Dzero (now)	~ 700 GeV
VLHC	~ 25 TeV

- ◆ Compositeness scale:

LHC could see effects @ $\Lambda_c \sim 10\text{-}15$ TeV

VLHC could probe to ~ 100 TeV! $L \sim 1$ $\mu\text{fermi!}$

Detectors at VLHC

- ◆ Multiple interaction working group.

$N_{\text{av}} \sim 22$ at $\Delta t = 17$ ns. Situation will be worse than, yet comparable to the situation at the LHC. The underlying event problem will be more difficult. This should be manageable if one is searching for relatively high energy particles and jets.

- ◆ Occupancy, radiation levels grow slowly ($\sim \ln s$)

- ◆ Vast R&D effort for SSC/LHC is applicable

As often happens developments in technology may push machine & detectors to higher luminosity

History of the current effort

Local effort began ~ Nov. '95

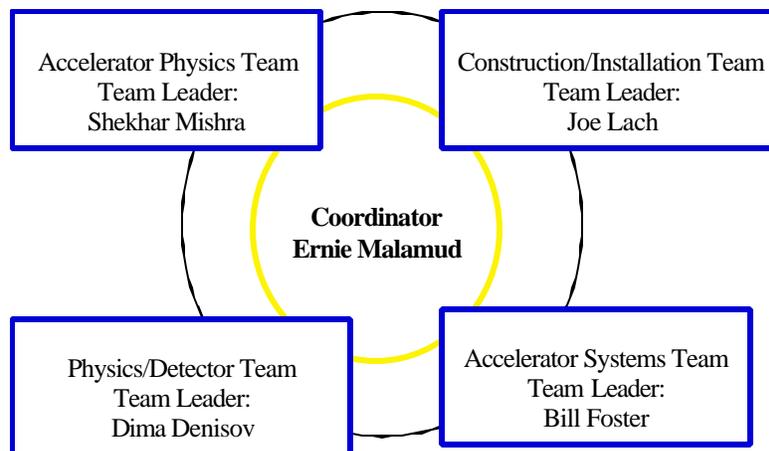
New low-cost approaches to High Energy Hadron Colliders at Fermilab
Mini-Symposium. APS Annual Meeting, Indianapolis, May 2-5, 1996
Collected transparencies.

“Pink” Book. The “Pipetron,” a low-field approach to a very large hadron collider, Selected Reports submitted to Snowmass '96.

Presentation to URA Visiting committee, February 21, 1997

“Yellow” Book. Very Large Hadron Collider Physics and Detector Workshop.
March 13-15, 1997. Collected Transparencies

Formation of VLHC Study Group:



July 22 – August 1. “Summer study.” Many of the Beams Division engineering staff were able to participate and contribute.

“Turquoise” Book. Very Large Hadron Collider Information Packet. Selected reports on the work done since Snowmass '96 on the VLHC. January 1998. (earlier version submitted to the Gilman Panel, September 1997).

Information at <http://www-ap.fnal.gov/VLHC>

The Subpanel recommends an expanded program of R&D on cost reduction strategies, enabling technologies, and accelerator physics issues for a VLHC. These efforts should be coordinated across laboratory and university groups with the aim of identifying design concepts for an economically and technically viable facility.

February 25. Fermilab-BNL-LBL meeting to discuss formation of a

National VLHC Collaboration

Accelerator Physics

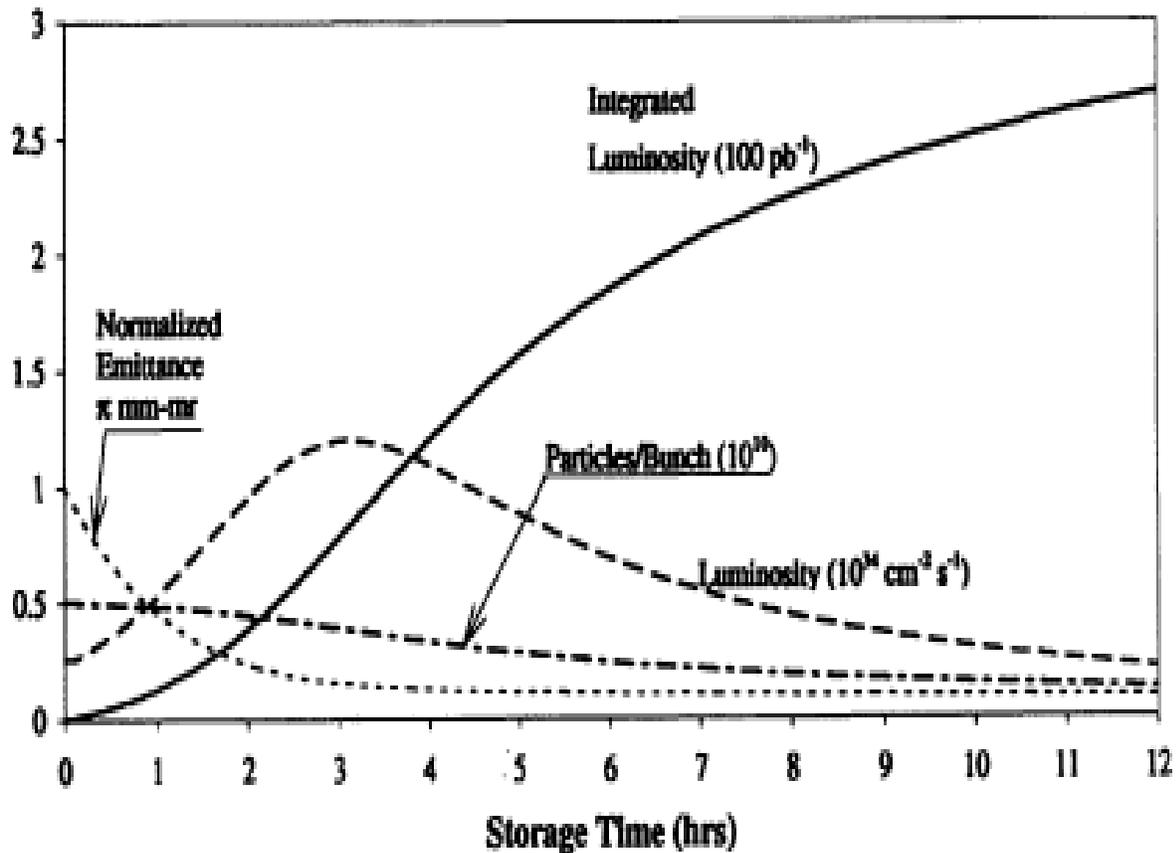
Two approaches have quite different design challenges

- Low-field 1.8 – 2.0 T
- High Field >10 T

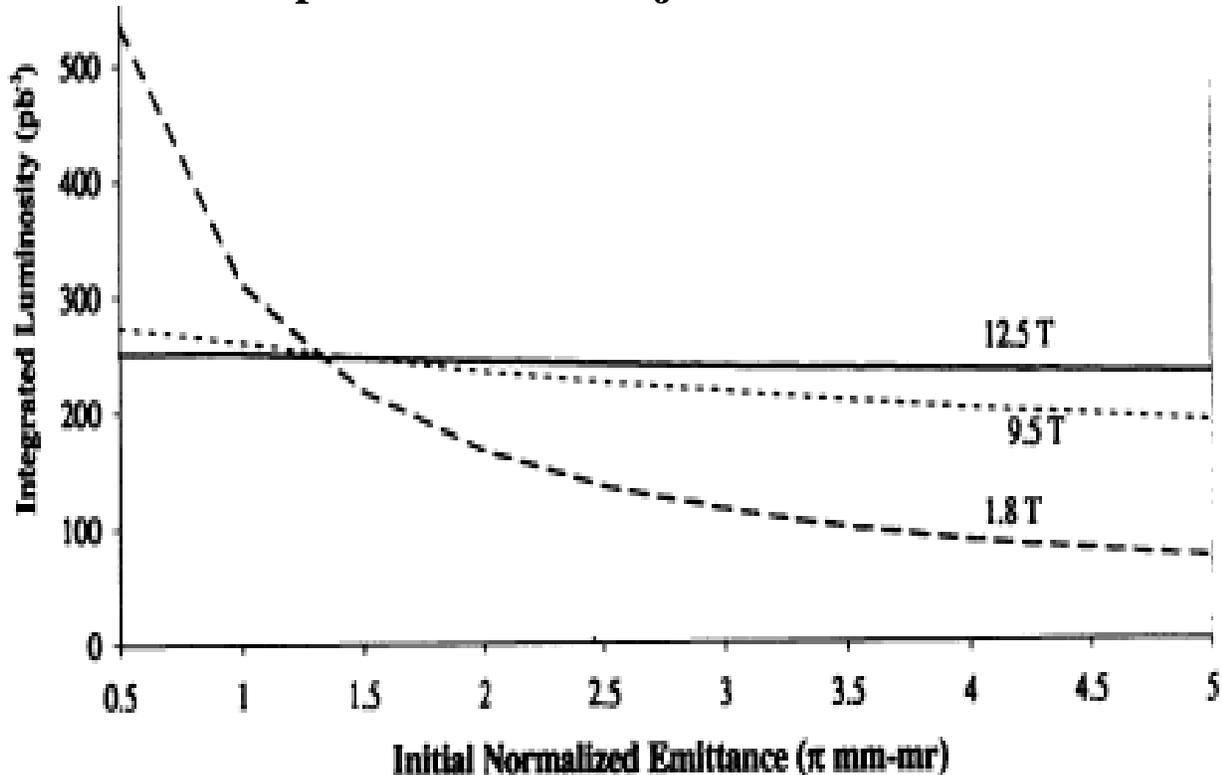
High field has the advantage of synchrotron radiation damping

B=12.5 T, 1.3 hr radiation damping time

luminosity increases after injection



insensitive to e preservation in injector chain



High Field >10 T

NbTi, Nb₃Sn

Emerging technologies: Nb₃Al, HTS

In the high-field approach, magnetic fields as low as 10 T could also be used with similar benefits over the low-field designs. These magnets would be feasible with current NbTi technology at 1.8 K. However, the cryogenic loads and the complexity of the vacuum chamber would tend to make this approach very expensive.

(Gilman Panel DRAFT p. 79)

However, one has to get rid of the power

High Field, NbTi, 1.8 K 180 MW

Nb₃Sn, 4.5 K 72 MW

HTS (e.g. BSCCO) at 25 K, 54 MW

Large operating as well as capital costs

Low-field 1.8 – 2.0 T challenges: much larger circumference

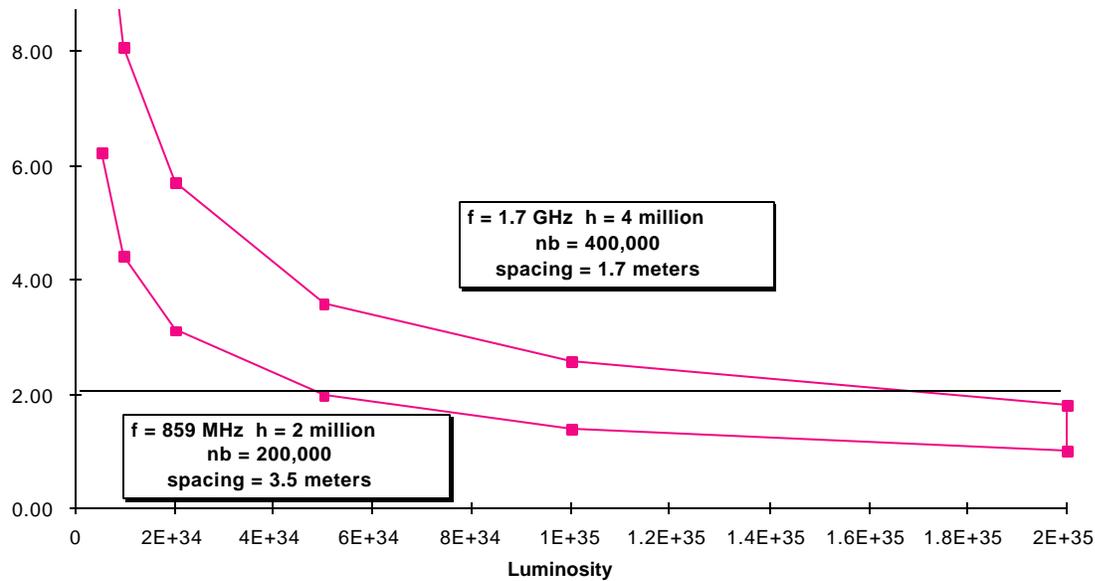
... drives potentially serious instabilities, such as the mode-coupling single-bunch instability (TMCI) and the transverse coupled-bunch instability.

(Gilman Panel DRAFT p. 79)

Transverse Mode Coupling Instability

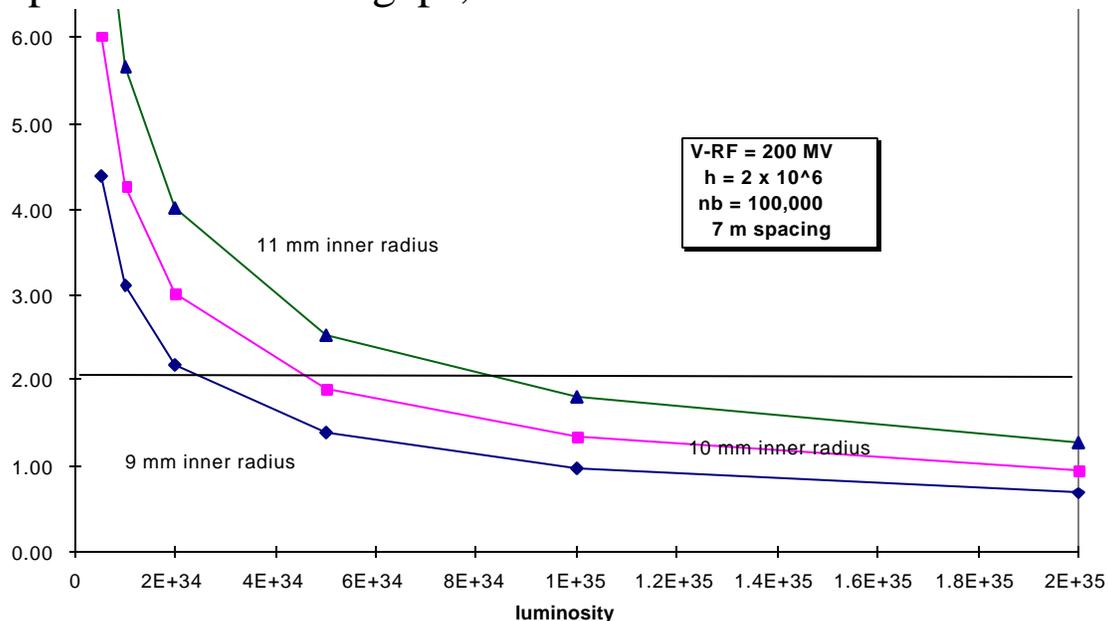
The strong head-tail instability appears due to the defocusing effect of the wake fields induced by the head of the bunch on the bunch tail particles. Synchrotron motion, i.e. exchange of particles between head and tail helps to avoid the instability. TMCI has been observed in electron storage rings but not (yet) in proton storage rings. For proton machines, there may be factors (in addition to synchrotron motion), such as incoherent tune spread due to direct space charge or beam-beam interaction, that increase the TMCI threshold.

Define SF = Safety Factor = $Z_{\text{threshold}}/Z_{\text{pipe}}$
 assume vertical half height = 9 mm (double-C magnet prototype)
 high purity aluminum on inside of vacuum chamber



coalesce at (or before) E_{coll} to achieve
 16 ns spacing; 20 int/crossing

another strategy: increase vertical gap
 pipe impedance varies as gap^3 ; increases drive current



Above considerations are for the 50 TeV low-field ring.

What about the 3 TeV low-field “booster?”

2 papers in the Turquoise book:

K-Y Ng:

2.7×10^{11} /bunch

(only necessary if the 3 TeV machine is used as for $E_{\text{cm}} = 6$ TeV collider physics while VLHC is under construction)

$Z_{\text{th}} = 6.37 \text{ M}\Omega/\text{m}$ (150 GeV injection)

$Z_{\text{ch}} = 48.0 \text{ M}\Omega/\text{m}$

V. V. Danilov, V. D. Shiltsev:

$Z_{\text{ch}} = 39.7 \text{ M}\Omega/\text{m}$.

However, they obtain $N_{\text{th}} = 2.5 \times 10^{11}$ /bunch.

Clearly more work is needed including experiments using the Tevatron.

TM-2033. V.V. Danilov. “On possibility to increase the TMCI threshold by RF quadrupole”

“...it is possible to significantly enhance the (TMCI) threshold, introducing a difference of betatron tunes for the head and the tail of a bunch ..”

Transverse Coupled Bunch Instability

John Marriner “A Damper to suppress low frequency transverse instabilities in the VLHC” (in “Turquoise” book)

- Growth time (high field) ~ 300 turns (similar to LHC)
- Growth time (low field) ~ 0.4 turns!
- This led to previous statements that this “required a feed-back system beyond the state of the art”
- One way out is the undesirable step of increasing the magnet gap since $Z_{tr} \sim b^{-3} f^{1/2}$

The important point that Marriner makes is that growth times vary as $f^{-1/2}$ so only low frequencies need to be considered (higher modes will be dealt with using a “conventional” bunch-by-bunch damper with a single turn delay).

Growth time is ~ 1 msec for lowest mode (and fastest growing)
Fastest growing modes below 100 kHz

System is not particularly challenging in any respect. The technique is not speculative and should not be controversial. A similar system was used to damp the resistive wall instability in the Main Ring.

Signal is derived from a
"difference" stripline pickup

Signal is amplified,
transmitted downstream to
a point 90° advanced in
phase



Use "foam" coax, $b > 0.8$
Bandwidth 100 - 200 kHz

1 km

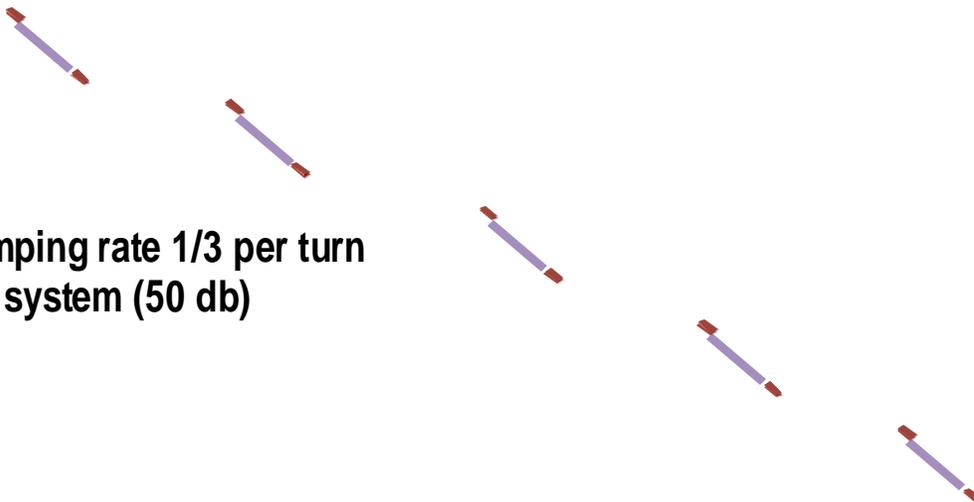
Signal further amplified
applied to kicker
to provide feedback to
stabilize the beam

The fact that the signal is
applied to succeeding bunches
doesn't matter much at these
low frequencies



Damping rate $1/3$ per turn
per system (50 db)

10 such systems distributed around the ring would
provide a damping of $> 3/\text{turn}$



Tunnels and Tunneling

Important for any version of VLHC, clearly more so for low-field
Fermilab is a member of

- North American Society for Trenchless Technology
- American Underground Construction Association

Through these connections we are keeping up with the rapidly
evolving field of TRENCHLESS TECHNOLOGY

Trenchless Technology is growing in importance as a practical solution to expansion and repair of underground utilities. This is an area where not only can VLHC benefit from the expanding technologies but can also be a catalyst to this environmentally crucial industry.

Excellence of Fermilab region geology

- predictable rock and tunneling conditions, relatively homogenous rock mass – extensive local experience in the TARP tunnels
- no settlement problems at the depths being considered
- rate of movement of groundwater in the dolomite layer we are considering for the collider is very small (aquatard)
- choose depth so that 3 TeV and 50 TeV machines in same layer of dolomite
- two long (2-3 km) transfer lines from MI-62 and MI-50. FODO lattices using permanent magnet quads

Noise

- Fermilab region is seismically stable
- vibration free environment, important to minimize emittance growth problems
- *Shiltsev et al*: recent measurements in TARP (deep tunnel project under Chicago) and Aurora Mine

Plot of PSD = Power Spectral Density ($\mu\text{m}/\text{sec}$)²/Hz

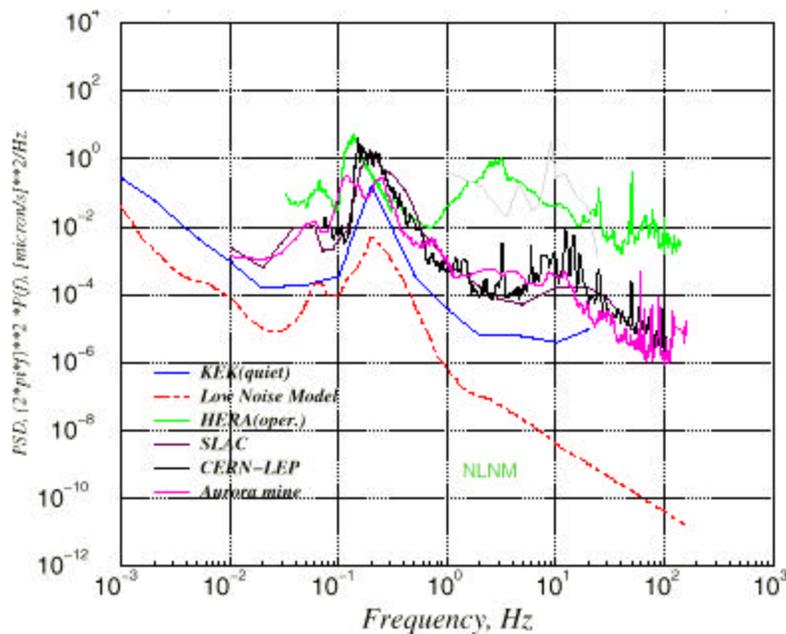


Figure 20: Ground motion spectra at different accelerator sites and the USGS New Low-Noise Model.

Alignment Orbit Stability e growth

low field $f_{\text{rev}} = 480$ Hz, $f_{\beta} = 184$ Hz (depends on choice of fractional tune)
 high field $f_{\text{rev}} = 2890$ Hz, $f_{\beta} = 1156$ Hz

some conclusions:

- **50-200 Hz** In deep tunnels of Illinois dolomite we observed vibrations below the tolerance. As the amplitudes of ground vibrations are smaller at higher frequencies, we propose to operate the machine at higher fractional part of the tune.
- It will be possible to obtain vibrations 10-100 times lower than at the Fermilab site (surface), close to what we detected in the deep tunnels.
- $> 1 - 4$ Hz correlation drops significantly at dozens of meters between points. Therefore, displacements of different magnetic elements of the accelerator can be regarded as uncorrelated
- Careful engineering of mechanical supports, of vacuum, power and cooling systems should be an important part of R&D efforts to decrease the level of vibrations.
- Comparison of on-surface and underground sites have shown that levels of vibrations are typically smaller in deep tunnels.
- Effects due to on-surface noise sources is less in the deep tunnels, though visible.

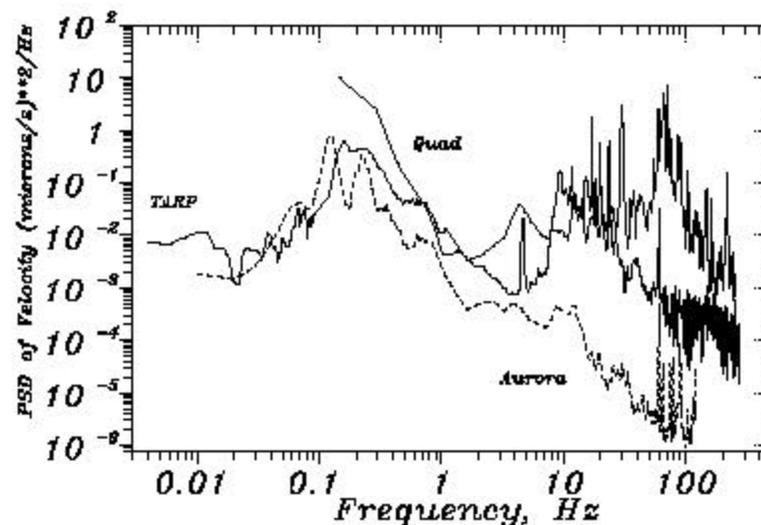


Figure 17: Spectra of ground motion in Aurora mine, TARP tunnel, and the Tevatron magnet vibrations

Choice of tunnel size

- lowest cost
- room for other machines (Fermilab & CERN strategy)

“Conventional” TBM/Conveyor belt tunneling

- ◆ using the specific siting and depth of the 34 km tunnel as a model to investigate tunnel costs
- ◆ using detailed cost model from Kenny Construction to understand how cost depends on parameters

New ideas

Safety is a major issue. The fewer the number of people underground the safer the job.

The mining industry is moving toward totally robotized systems: roadheaders and LHD's (load-haul-dump vehicle)

No people during construction, so no problem with diesel fumes. Obviously reduces labor costs. So far, they are working with softer materials, i.e. coal.

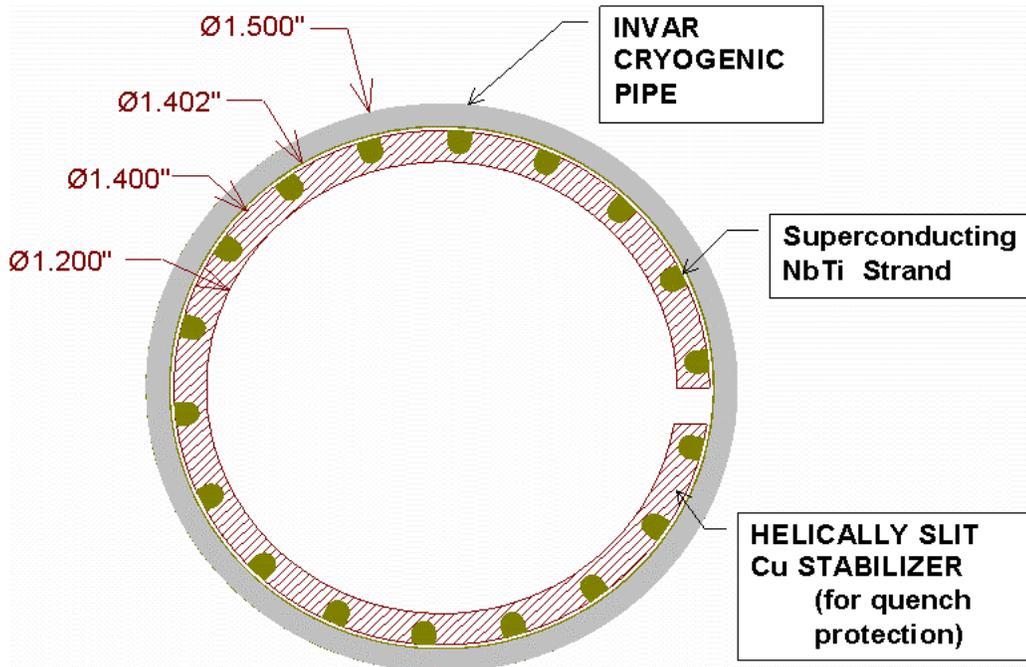
We have obtained samples (from the North Aurora mine) and sent them to two major roadheader machine manufacturers for analysis.

Pipeline capsule - capital costs higher than a conveyor, but labor costs less (and it is safer). Might be possible to build the entire 34 km tunnel with only one on-site access!

Chris Laughton, internationally respected specialist in Geotechnical Engineering, has just joined Fermilab

The Magnet: the heart of the matter

Current R&D: structure and how to manufacture

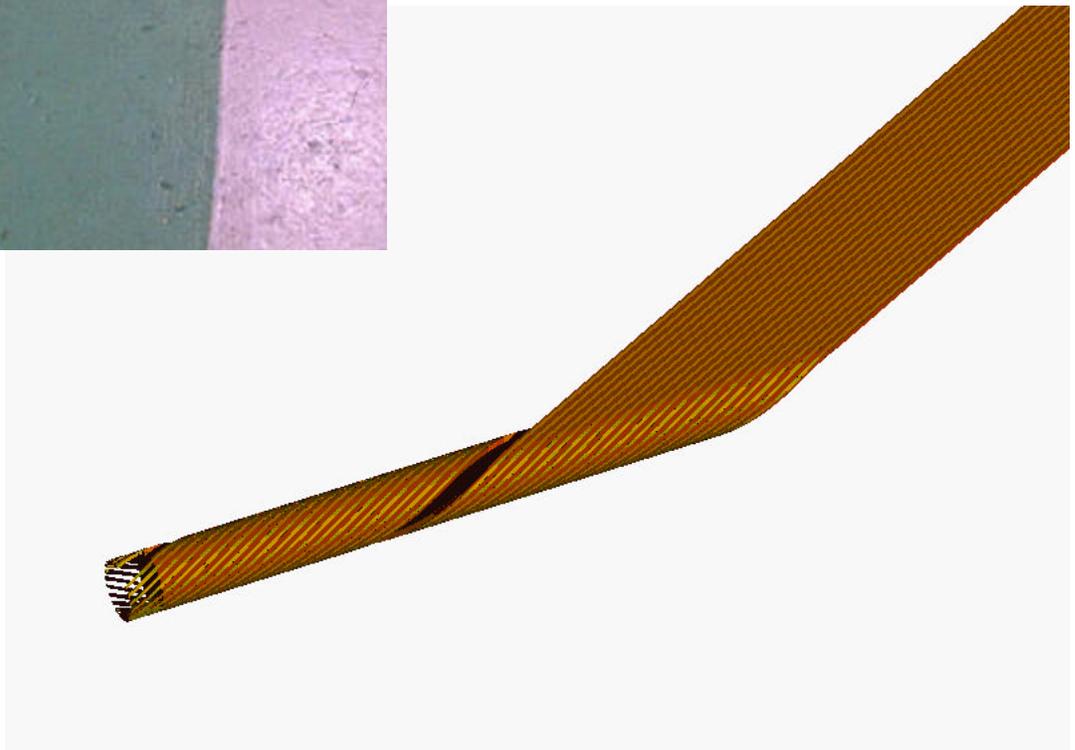


Invar known to be a difficult material to weld

Invar pipe thermal cycling experiment to test welding

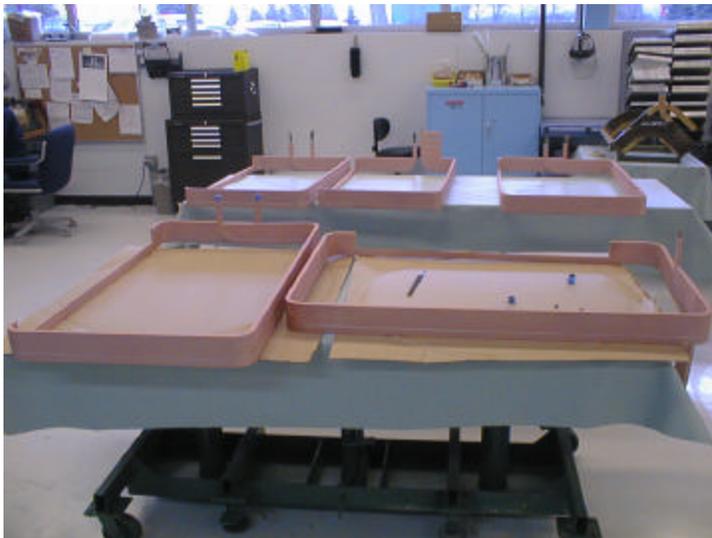
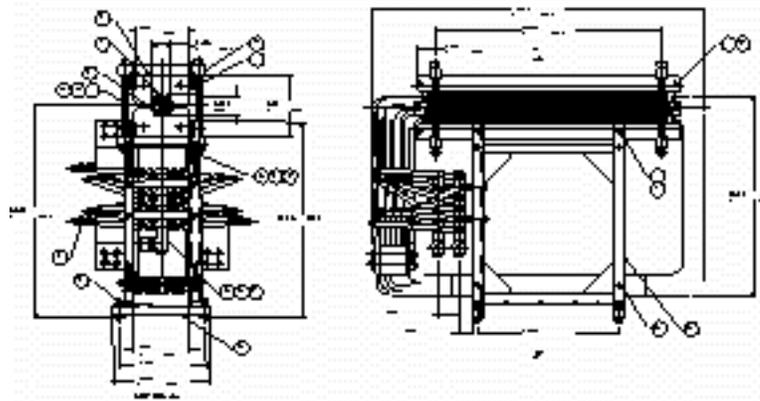


Roll forming experiments



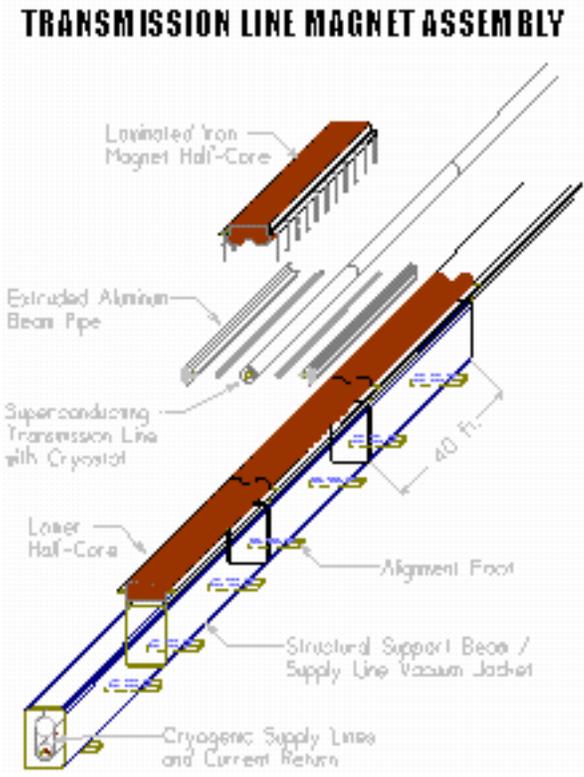
Water-cooled copper test stand for optimizing the iron shape and developing measuring techniques. Coil capable of 100 kA-turns to drive the iron into saturation.

Double-C Iron Test Fixture

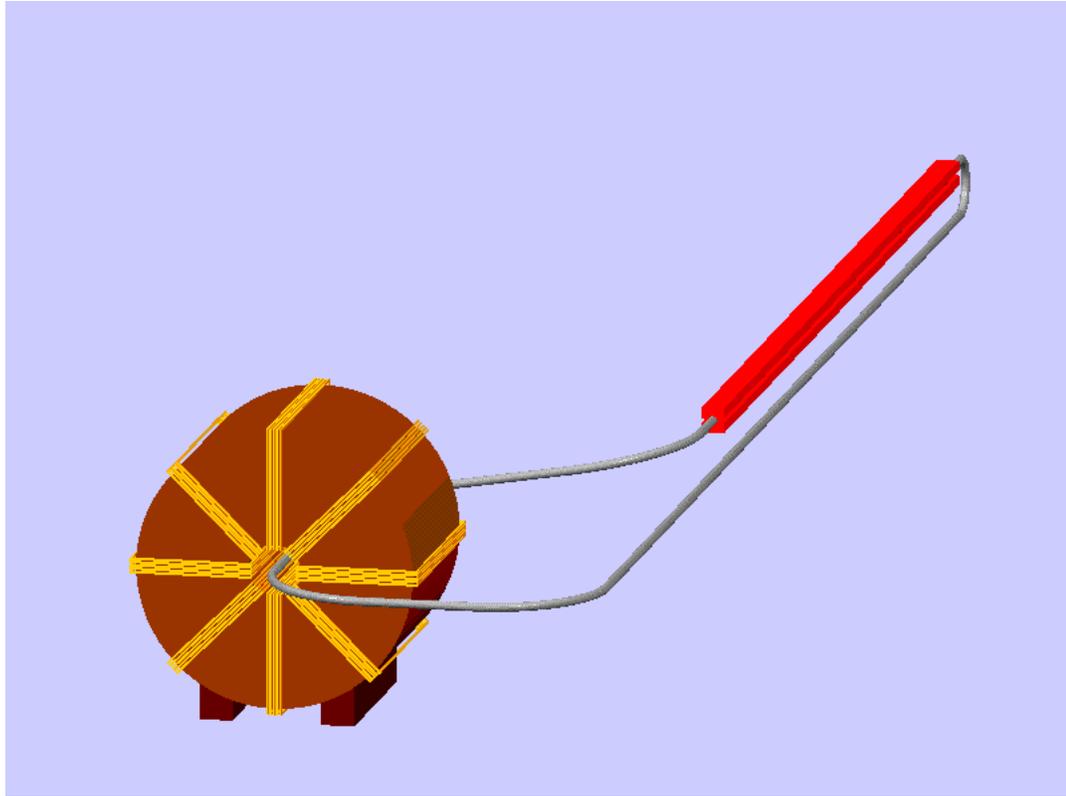


Parts ready for
assembly

How to assemble in long lengths---



Use of a surplus fixed-target toroid (in Meson Area) as a drive transformer to power the next **50-meter prototype magnet**. Will be set up in M-West.



- ◆ Now under construction
- ◆ Major length surplus SSC conductor
- ◆ Changeable test sections of transmission line

Conclusions

What's next? R&D goals:

- Produce detailed designs with cost estimates for a 3 TeV (low-field) and 3 TeV (medium field) boosters
- Find ways to lower the cost/meter of the tunnel by 2x
- Continue to develop concepts for a 100 TeV cm pp collider built in the Fermilab region using either low or high field magnets
- Begin work on a high-field dipole magnet
- Carry out prototype work on all components of the low-field machine.

The KEY issue is to lower the cost/TeV
Cost goal is < \$100 M/TeV

- This appears to be achievable
- The 3 TeV Booster can be considered as a Tevatron replacement, with higher energy, and lower operating costs
- It will test our ability to build a machine that extends off site
- It will be a rapid-cycling injector for the larger machine
- It could be a new benchmark of HEP's ability to construct machines with much lower cost/TeV