Concepts and Challenges of Long Magnet Strings

Vistas in Axion Physics: A Roadmap for Theoretical and Experimental Axion Physics through 2025

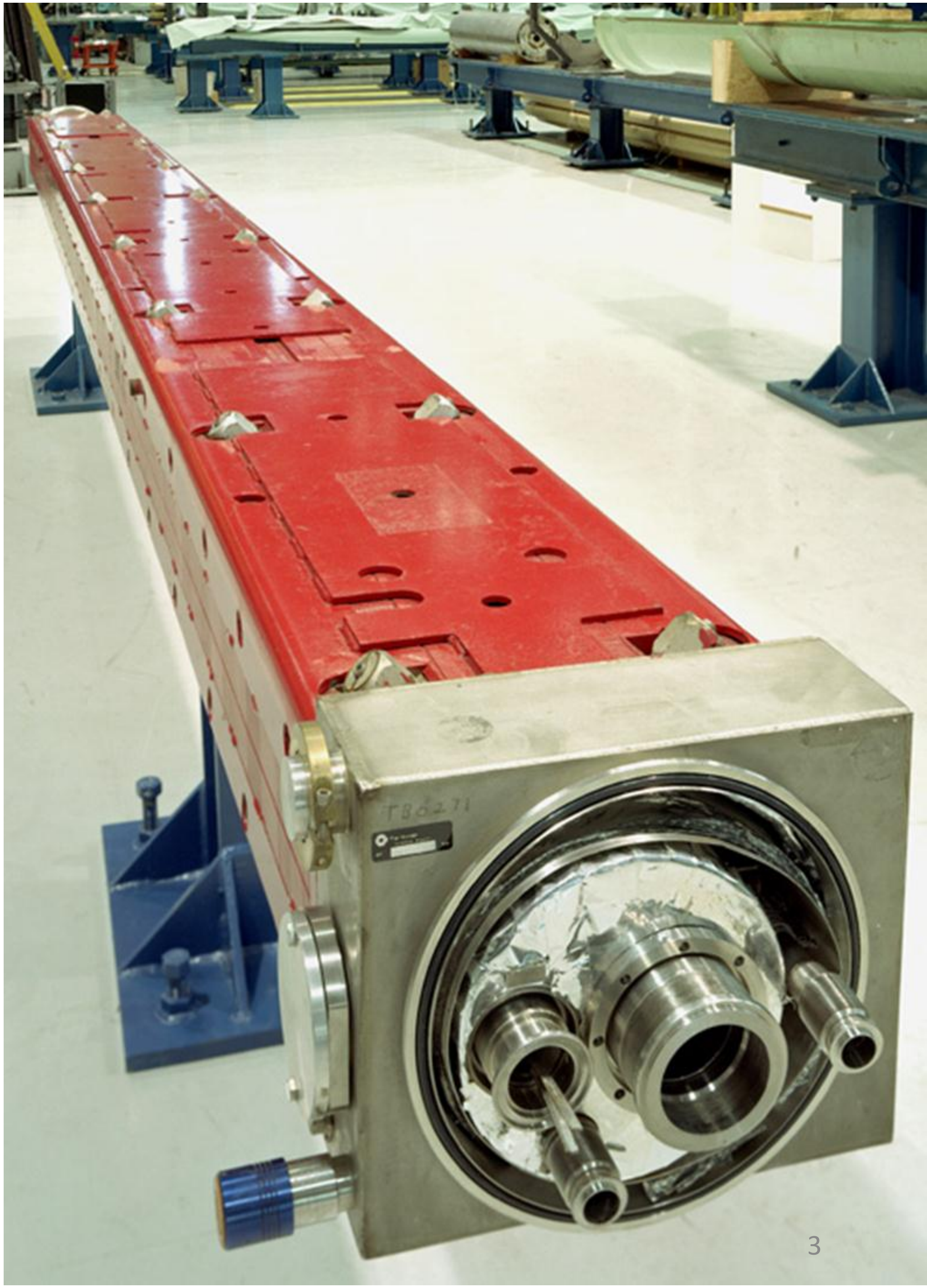
Peter O. Mazur, Fermilab

April 25, 2012

Talk Outline

- Consider long magnet strings for Resonant Regeneration experiments.
- Will use Tevatron technology as an example throughout, followed by a report from ALPS-II using HERA technology.
- Consider other available magnet technologies and possible future technologies.
- Aspects to be considered
  Magnet string layout
  Magnet details
  Cryogenic systems
  Power systems
  Safety and cultural requirements and concerns

Tevatron Dipole



Spare Tevatron Dipoles in the Magnet Storage Building

700 More Spare Tevatron Dipoles in the New Underground Magnet Storage Facility

Magnet String Layout

- Length of magnet string is limited by beam losses to be overcome. Assume a 100 kW beam and a limit of 10 ppm losses.
  - The resulting 1 W loss rate is a good limit for the optical system, based on laser size selected, for REAPR.
  - A larger laser is not a problem from a cryogenic standpoint.
- Magnet aperture is 59 mm wide with 5.6mm sagitta.
- Baseline design for this discussion: two strings of 16 magnets. (This can easily be reduced to save costs, of course.)
- I will leave the discussion of clipping losses to the Opticians.

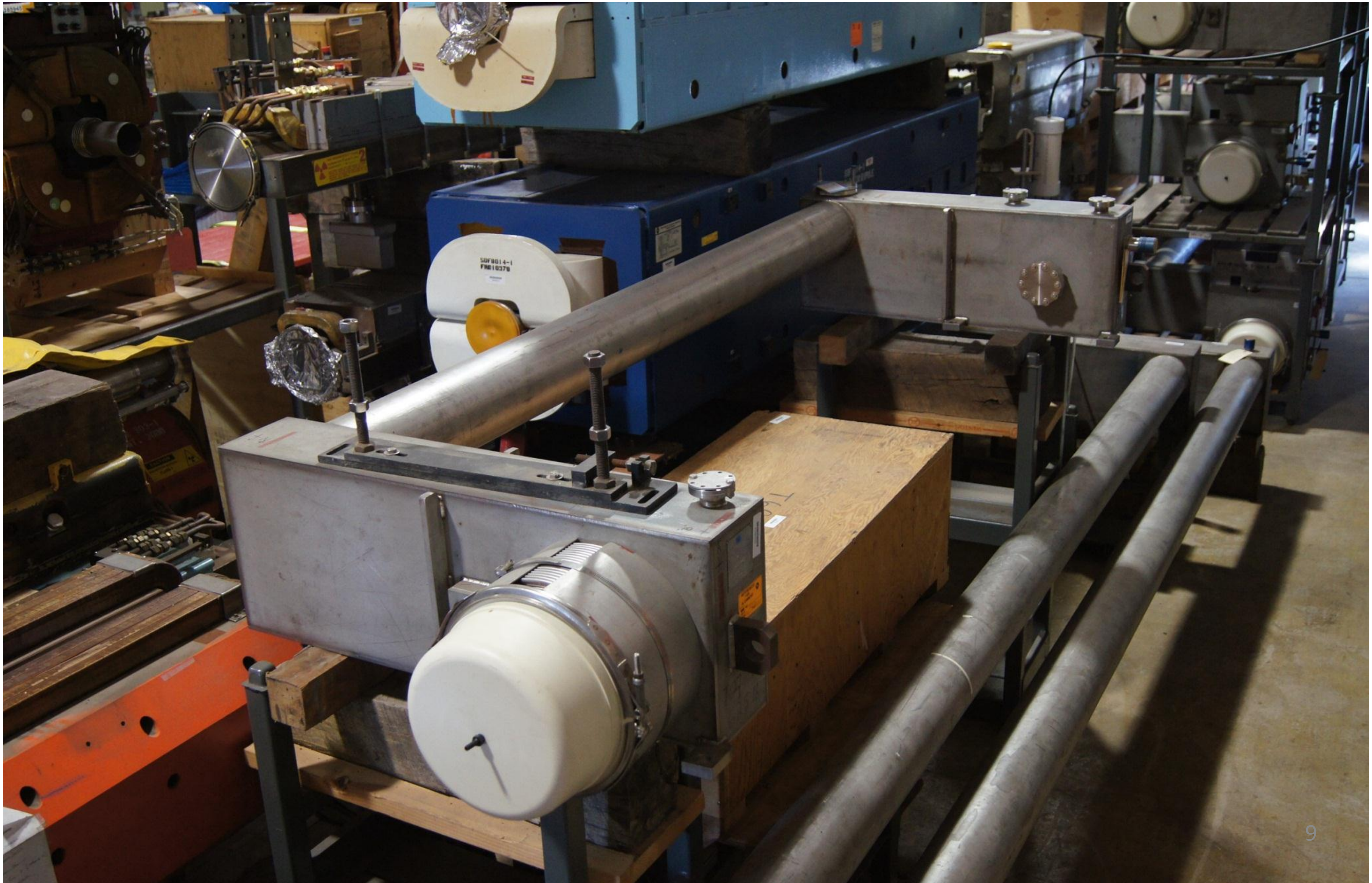
Magnetic Field

- The Tevatron ran at about 4.3 T and 4.5 K.
- The magnets built later in the construction used higher quality superconductor (higher critical current.)
- These magnets can operate at 5 T at 3.9 K.
  - Need to select magnets with late, high quality superconductor.
  - Need to train magnets to 5 T in Magnet Test Facility before installation in our string.
  - The cryogenics needs to run at 3.9 K, raising operating costs.

Magnetic and Physical Lengths

- The magnet has a magnetic length of 6.1 m and physical length of 6.4 m.
- At 5 T, this gives BL = 488 Tm per 16-magnet string.
- Power spool (power leads) at one location requires at least 2 m length.
- Feed can (device to connect cryogenics to the magnet string) to be built: Likely less than 1 m length.
- "End can" (cryogenic device at the other end of the magnet string) is available, ~ 1.1 m.
- If we add nothing else, physical length is about 105 m plus room for optical equipment between the strings.
- Bypasses to allow space between strings for optics come in many lengths, from ~1 m up to 6.1 m or even more.

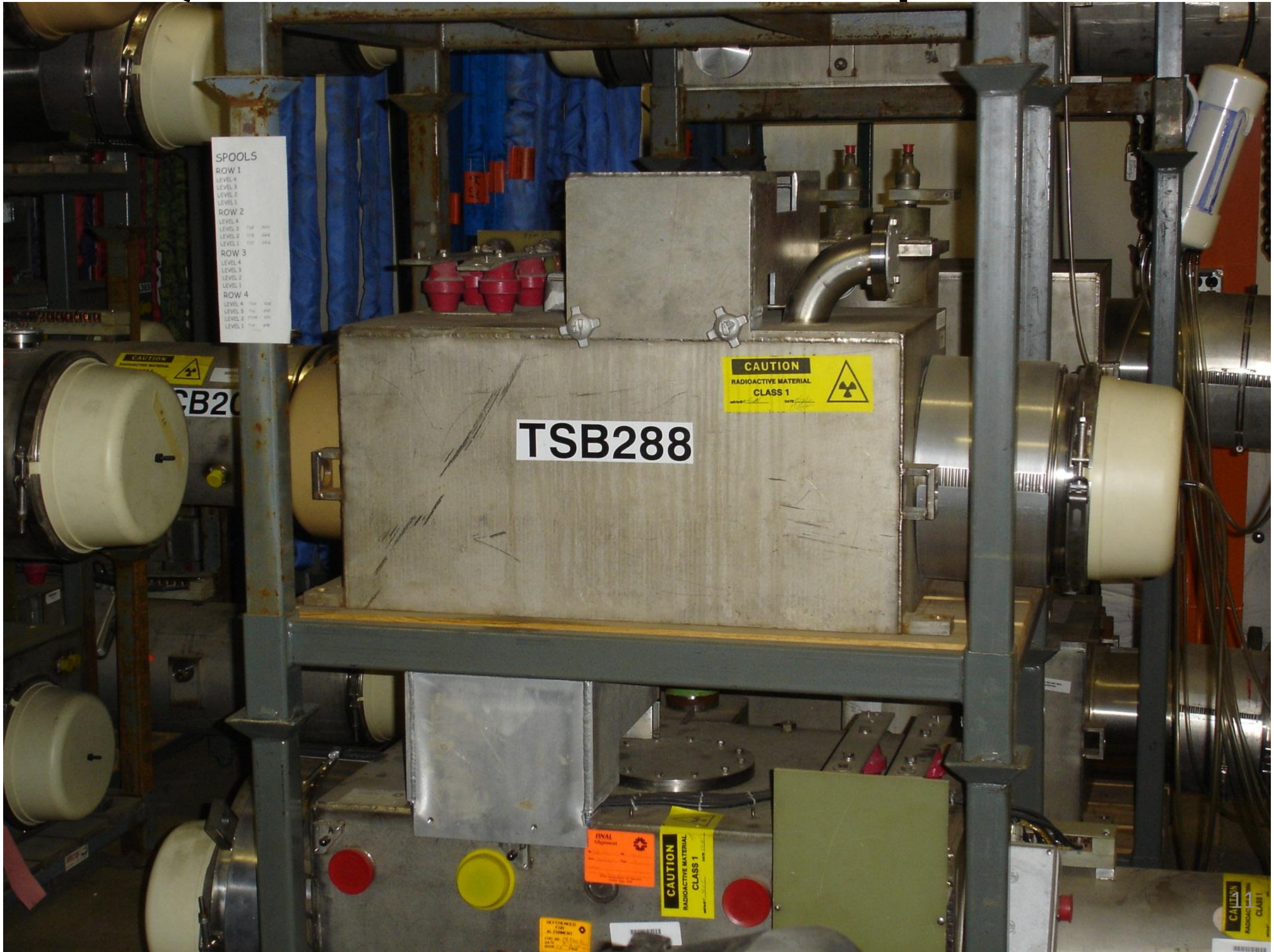
Bypass

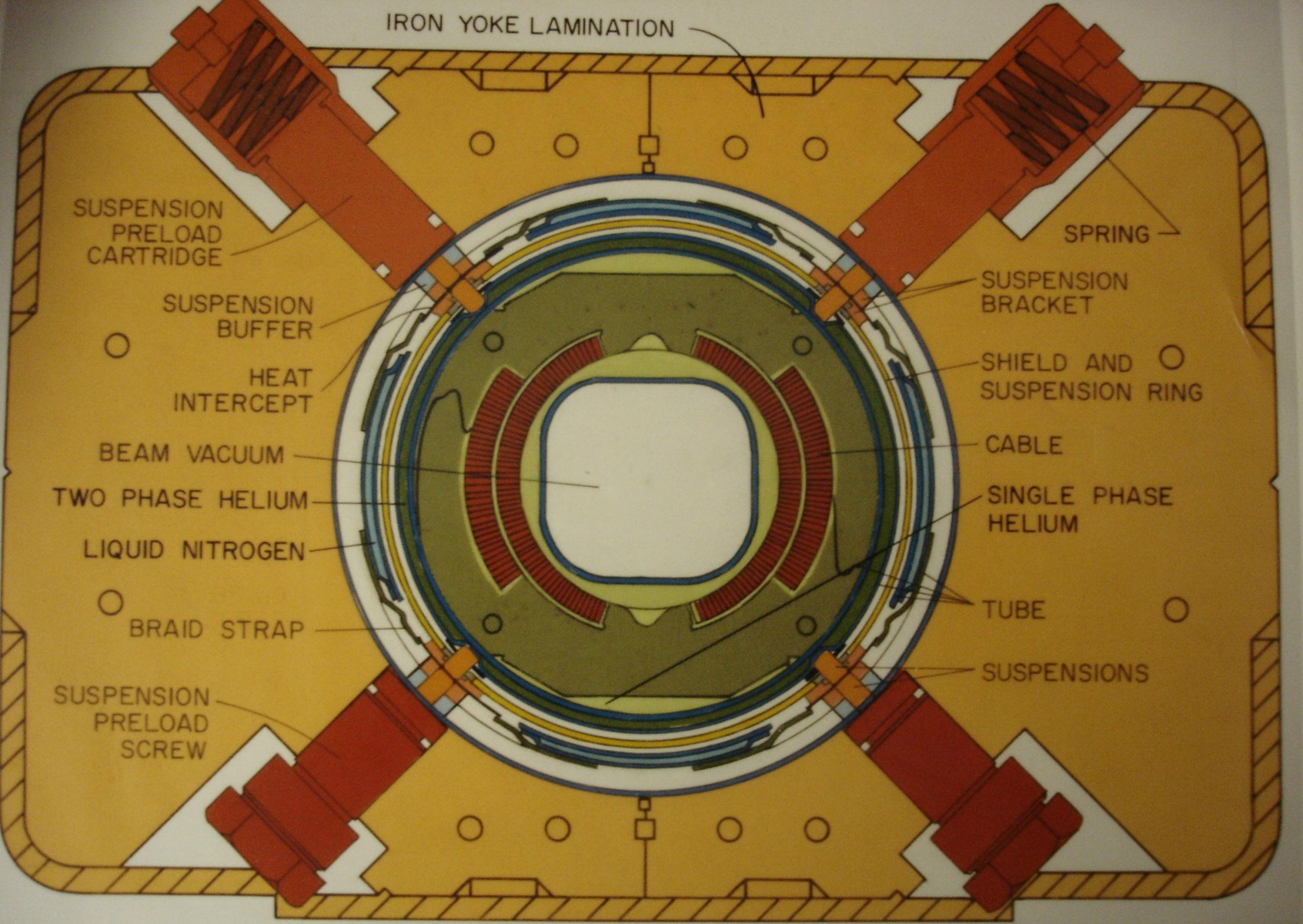


Quench Protection and String Length

- Quench protection bypass leads are required for the Tevatron every 4-5 magnets. (These leads were normally provided by quadrupole magnets in the Tevatron.) They bypass the current in the unquenched magnets around the quenched magnets so that only the quenched magnets are heated.
- So add a spool with bypass current leads every 4-5 magnets with a 1.1 m length. This adds physical length plus heat load (10 W/spool.)
- A better solution is one used for beam lines: don’t break the string up for quench protection. No spools, but entire string must be quenched at once by heaters when any magnet quenches.
- At 5 T, this gives BL = 488 T-m per string and a physical length of 105 m.

Quench Protection Spool




IRON YOKE LAMINATION
SUSPENSION PRELOAD CARTRIDGE
SPRING
SUSPENSION BUFFER
SUSPENSION BRACKET
HEAT INTERCEPT
SHIELD AND SUSPENSION RING
BEAM VACUUM
CABLE
TWO PHASE HELIUM
SINGLE PHASE HELIUM
LIQUID NITROGEN
TUBE
BRAID STRAP
SUSPENSIONS
SUSPENSION PRELOAD SCREW

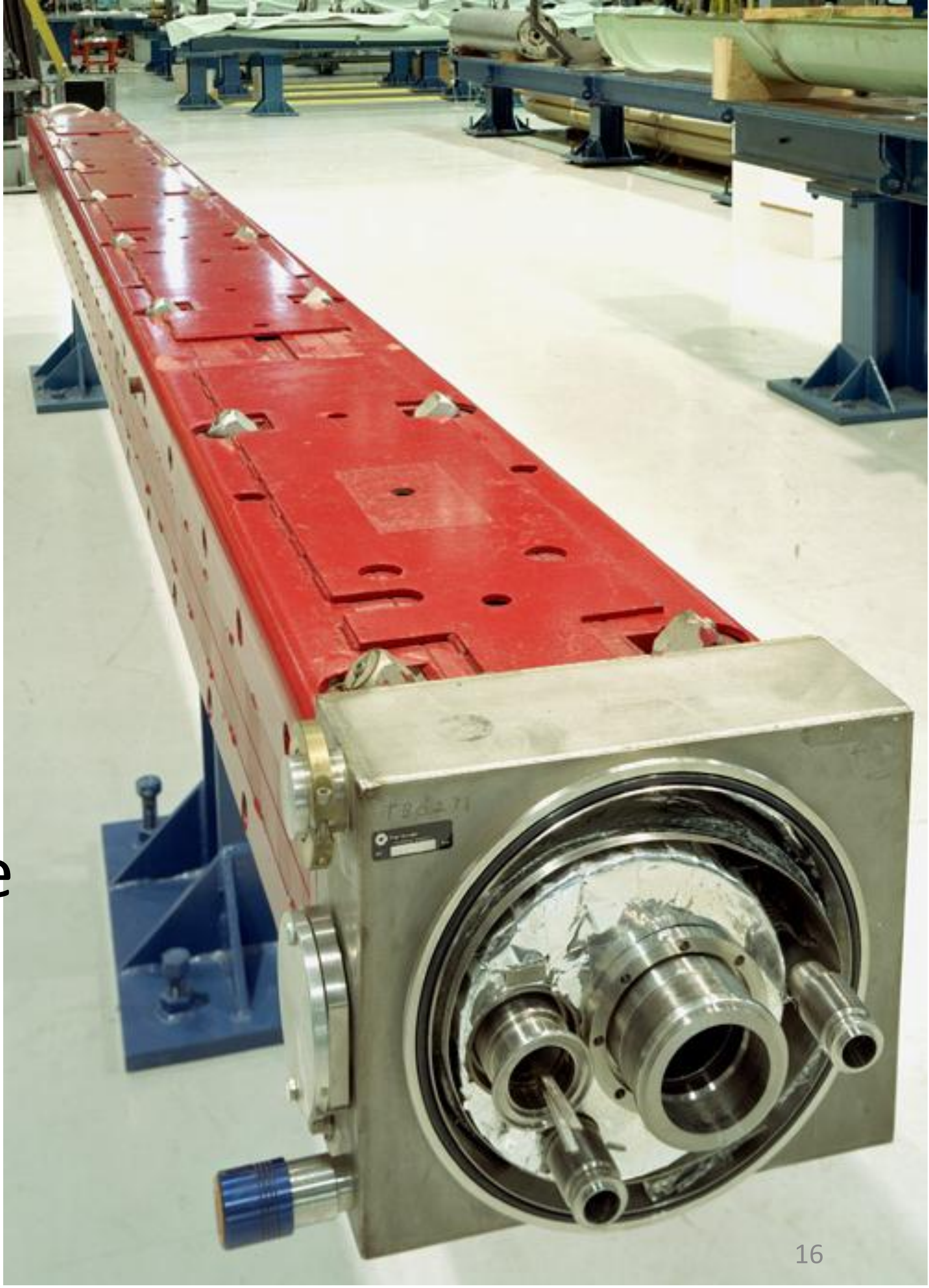
Sagitta

- 5.6 mm sagitta can be removed from dipoles if it is valuable to increase aperture to full 59 mm.
- Sagitta was originally set by installing cryostat assembly into the iron lamination yoke and welding the yoke assembly in a curved form.
- To reverse the assembly procedure:
  - Cut apart yoke by removing tie plates at top and bottom.
  - Reassemble and re-weld in straight configuration. (The tooling still exists to allow this.)
  - Retest magnet, at least for the first few.
  - Damage to magnet coil and cryostat not likely with this procedure.

Magnet Cryostat

Tevatron Dipole Iron Yoke

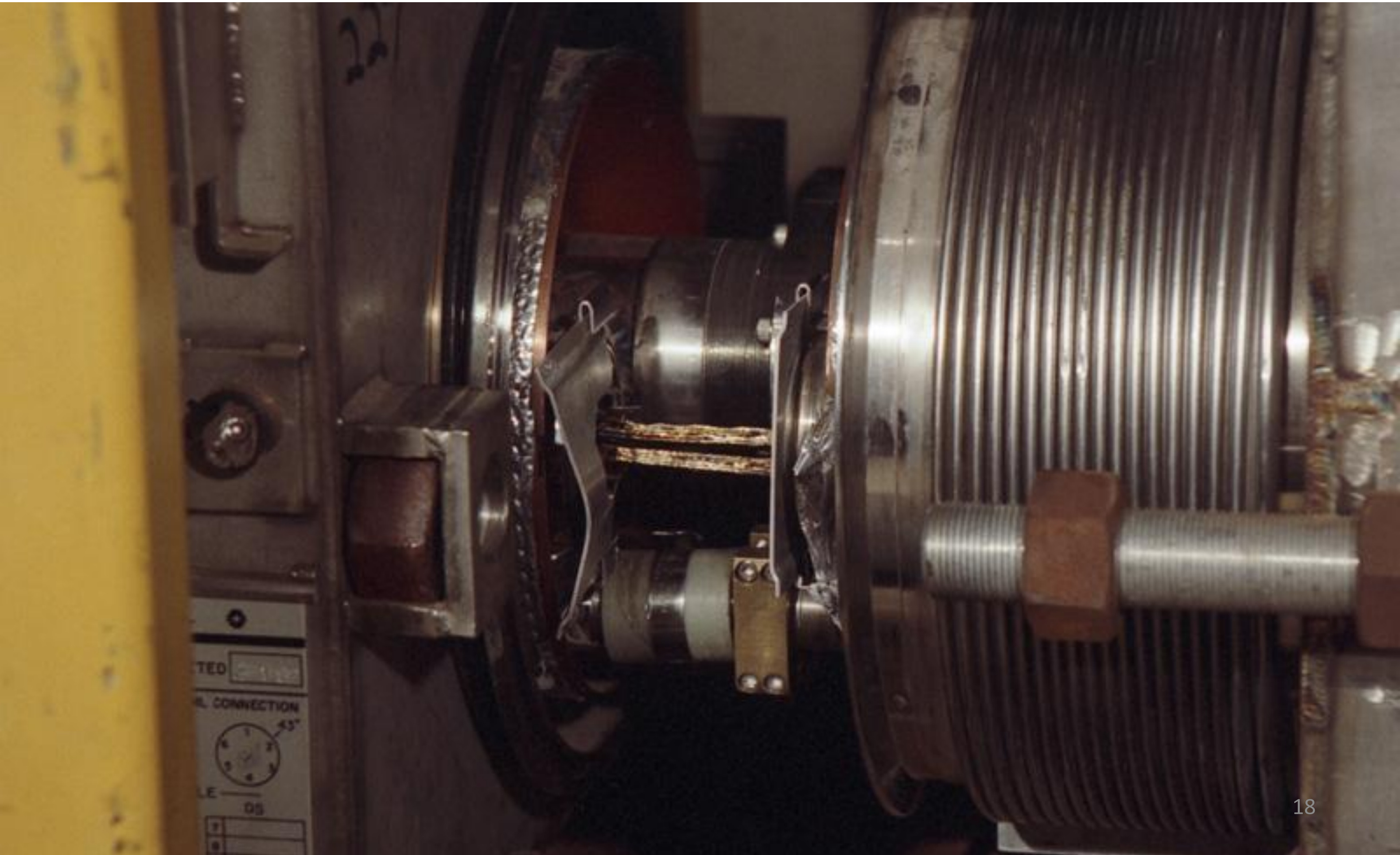
Tevatron dipoles are held together by welded tie-plates on top and bottom of the iron yoke. They can be cut off, the yoke straightened, and then the tie plates would be welded on without the sagitta. This is just the reverse of the procedure used to build the magnets.



Alternating Polarity

- Consider reversing polarity of each magnet. (See William Wester’s talk.)
- The electrical connections between magnets are in the single phase helium bellows. This is very tight.
- Superconducting cable is not annealed and is very, very stiff, making manipulation to reverse polarity in the small space available difficult or impossible.

Tevatron Cable Splice



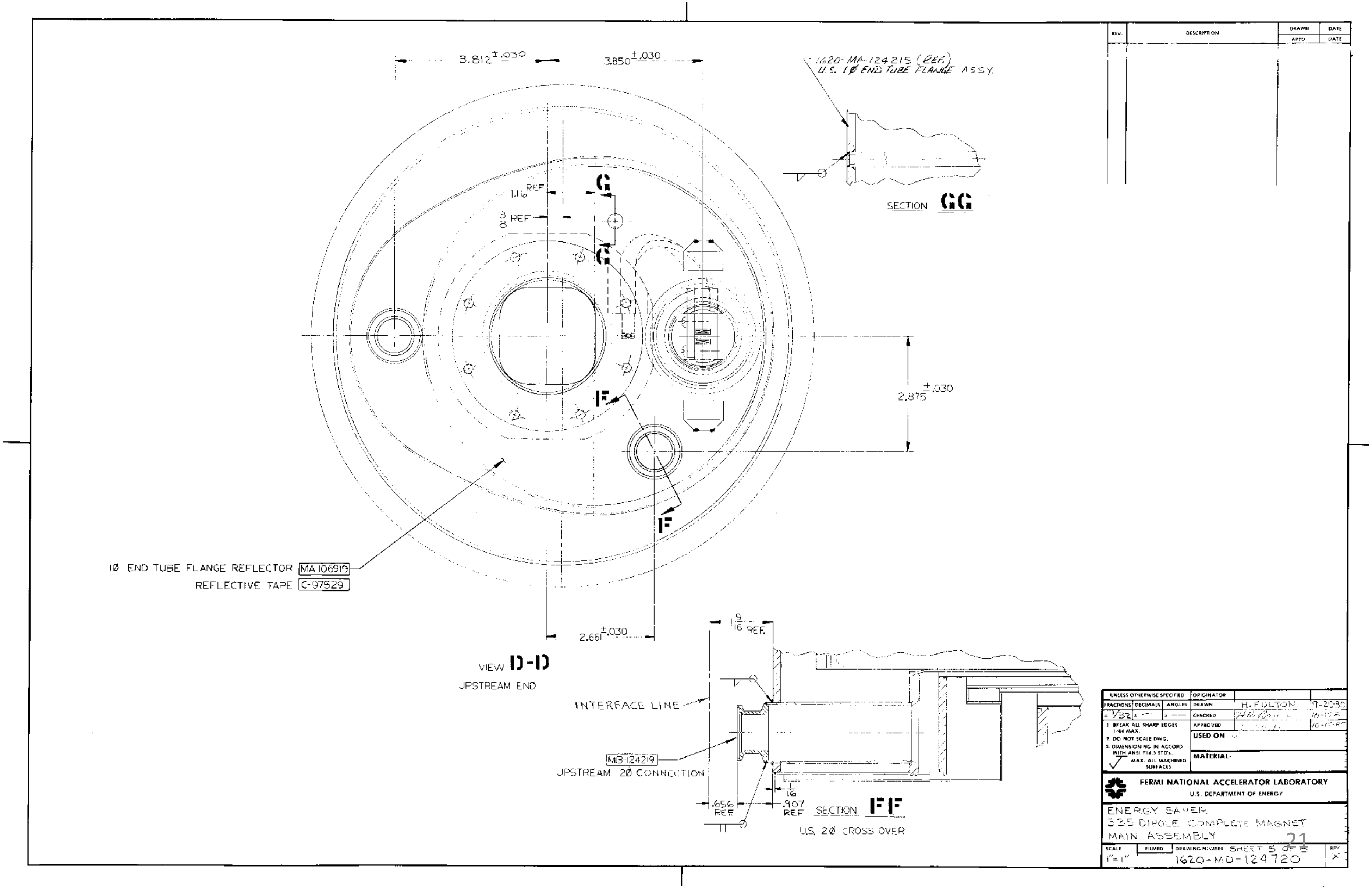
Splice Connections to Reverse Polarity

- Since we can’t bend the conductors very much, consider a different technique:
  - Solder one upper cable to one lower cable
  - Install a G-10 tube over that splice, wrap the tube with superconducting wire, and hold the remaining two cables tightly to it.
  - Wrap again with superconducting wire and solder.
  - We should be able to test this and, if it works reliably, do this for all magnets at installation.

Backup Method for Alternating Polarity

- Inside each end of the of the cryostat is a large loop of superconductor cable which can be manipulated to reverse polarity.
  - Grind off the end plate on the cryostat
  - Rearrange the cables to reverse polarity
  - Weld the end plate back on and leak check the assembly.
- We did this once in the early days of the Tevatron to many, many magnets to fix another problem so we know it can be done at reasonable (?) cost.

Superconducting Cable Inside Cryostat



Cryogenic Services

- Provided by 625 W Satellite Refrigerator. We will design conservatively for 400 W from it.
- Use a “power spool” to get power (5000 A) from room temperature to 4K environment.
- ~ 20% of refrigerator capacity goes to the power leads if conventional leads are used.
- Power lead refrigeration load can be eliminated by using High Temperature Superconductor leads, which are available at Fermilab.
- Subcooling possible with cold pump and heat-exchanger dewar.
  - Repair and borrow reciprocating cold pump from MTF, or
  - Use turbo-compressor from Tevatron with heat-exchanger dewar.
  - Could run at 5T at 3.8-3.9 K if we select the best magnets.
  - This low temperature operation would require a second refrigerator. Fortunately, there are three refrigerators in the Meson Cryo system.
  - Sub-atmospheric pressure in magnet string and instrumentation and relief lines adds risk of contamination, so special care needed to eliminate leaks.

Power Spools

High Temperature Superconductor Power Lead Spool Piece

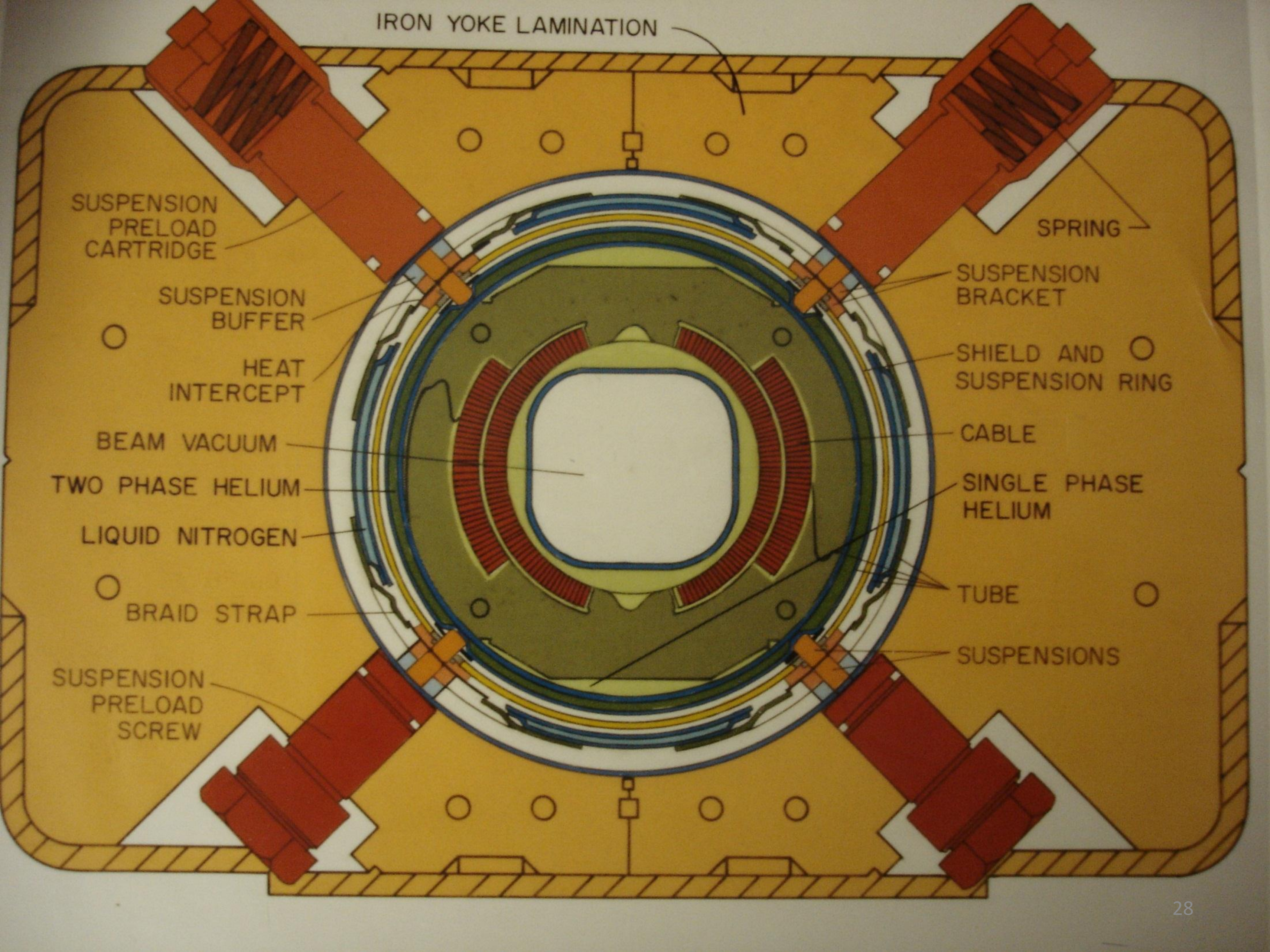
Planned Experiment Location
Downstream of Meson Detector Building

Cryogenic Transfer Lines

- There is a gap between existing cryo services and our installation.
- Need to add cryogenic transfer line, which can be expensive. We need two helium lines: liquid supply and cold gas return.
- Consider adding two transfer lines from Tevatron, since they exist, with their existing expansion/contraction systems.

Two Kinds of Heat Load

- The heat from outside is intercepted by the LN_2 shield and two-phase (boiling) helium layer.
- Heat from inside the beam tube is intercepted by the single- phase (subcooled liquid helium) region which keeps it out of the magnet coil.
- One watt of laser power dumped into a magnet raises the single phase helium temperature ~0.02K, a very small increase. So 2-3 watts per magnet would not be a problem.


IRON YOKE LAMINATION
SUSPENSION PRELOAD CARTRIDGE
SPRING
SUSPENSION BRACKET
SUSPENSION BUFFER
HEAT INTERCEPT
SHIELD AND SUSPENSION RING
BEAM VACUUM
CABLE
TWO PHASE HELIUM
SINGLE PHASE HELIUM
LIQUID NITROGEN
TUBE
BRAID STRAP
SUSPENSIONS
SUSPENSION PRELOAD SCREW

Maximum number of dipoles

The achievable power buildup of an optical cavity, the aperture of the vacuum pipe in the dipoles, and its length are correlated [see Thesis of Tobias Meier].

The table shows the maximum number of HERA dipoles, allowing for an optical cavity with a power buildup of 40000 at a wavelength of 1064 nm for different horizontal apertures, including tolerances of ±3 mm.

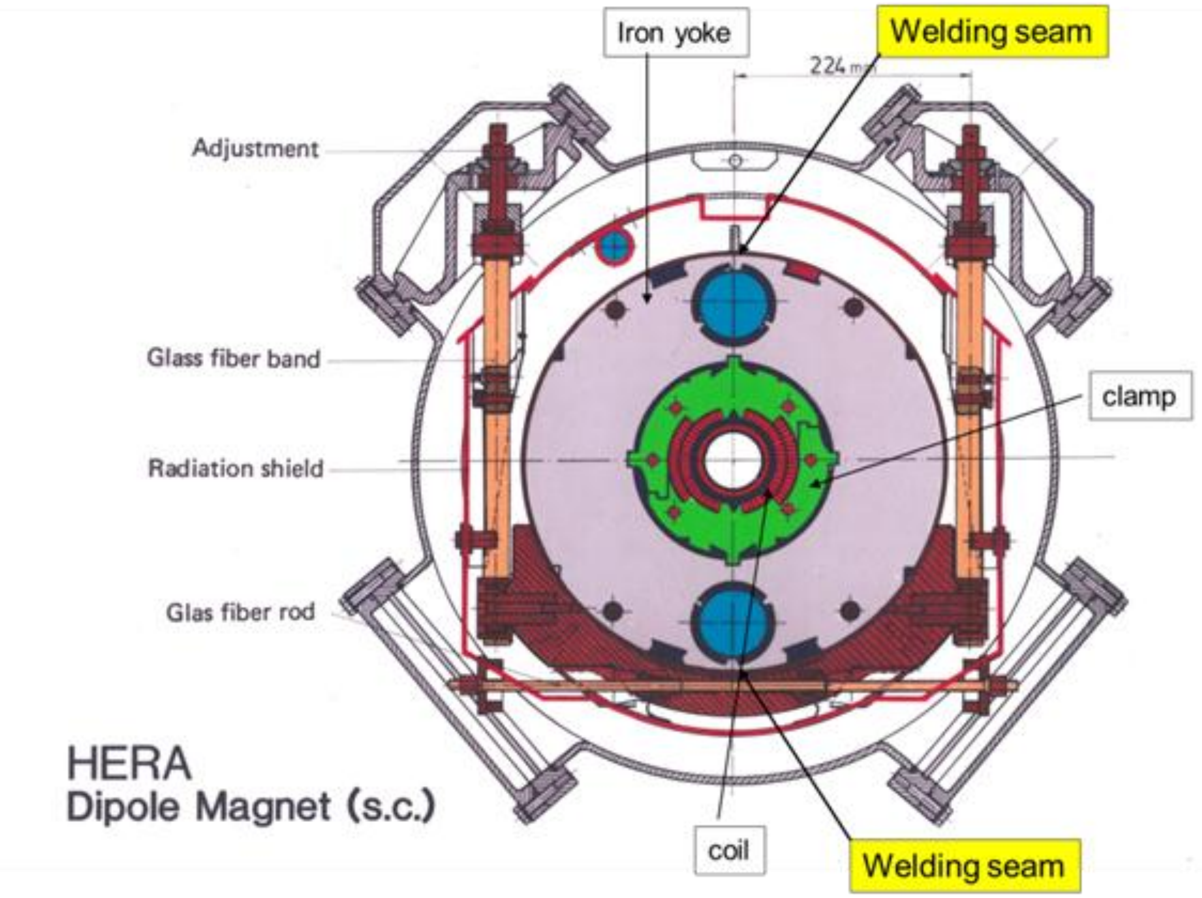
HERA	Dipole aperture [mm]	Max Number of dipoles	B*L [Tm]	Length single string plus 5 m optical setup [m]
standard	35	2*4	187	44
almost straight	50	2*10	468	103
straight	55	2*12	562	122

HERA: magnetic L 8.83 m; field B=5.3 T

For comparison ALPS I
had a B*L of 23 [Tm]

As the sensitivity for the detection of Axion Like Particles scales with B*L, the availability of straight or almost straight dipoles would lead to a substantial increase in sensitivity.

Straightening of HERA dipoles

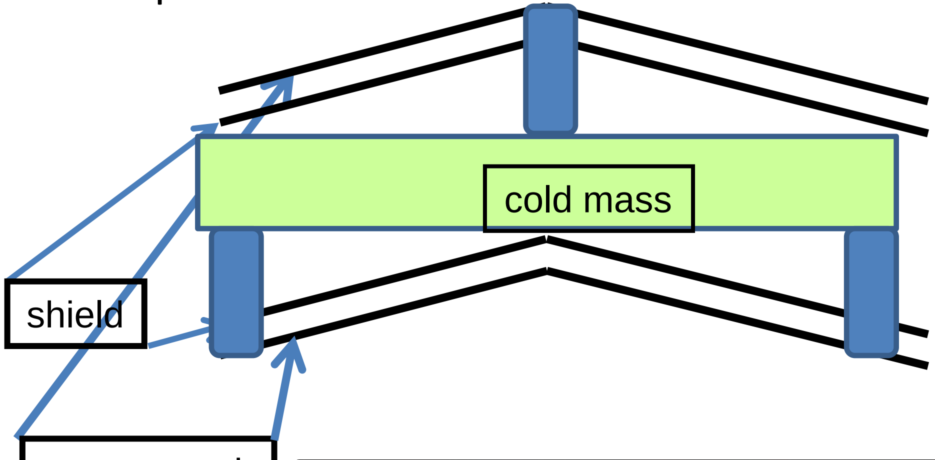


The inner diameter of the vacuum pipe in the superconducting HERA dipoles is 55 mm, however, due to the curvature of the magnet the free horizontal aperture is reduced to ~35mm.

Cutting the welding seam, straightening the yoke and welding two straight half cylinders around the yoke, would allow to obtain a straight dipole magnet.

Straightening of HERA dipoles

A simpler and thus much cheaper way of straightening the dipole is achieved by a brute force deformation with ~40 kN from the outer vacuum vessel at the 3 planes of support of the dipole

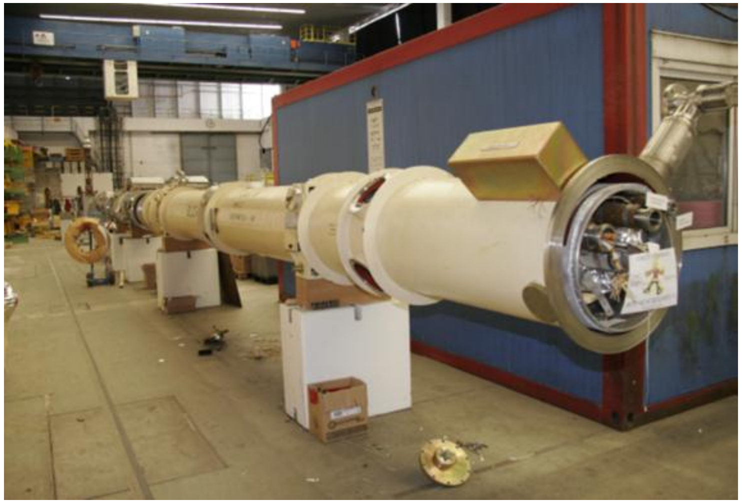


cold mass

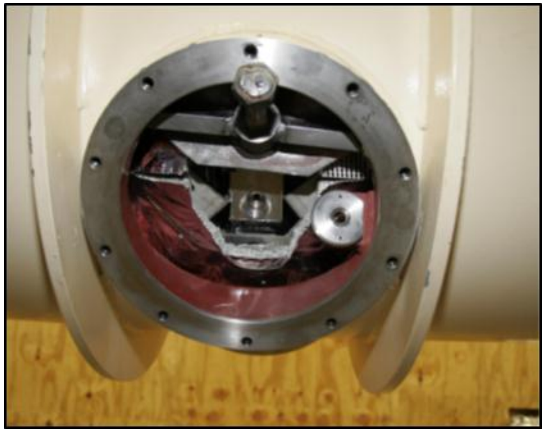
shield

vacuum tank

‘Test’ HERA Dipole

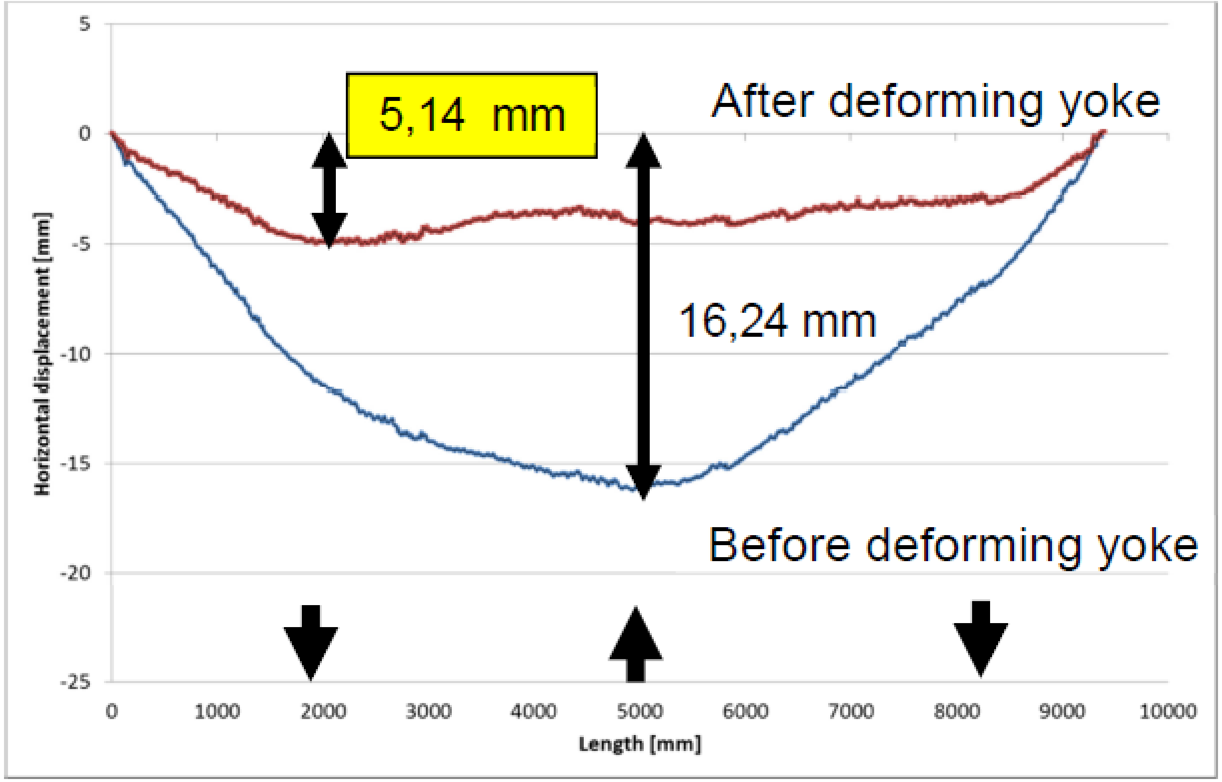


Deformation tools



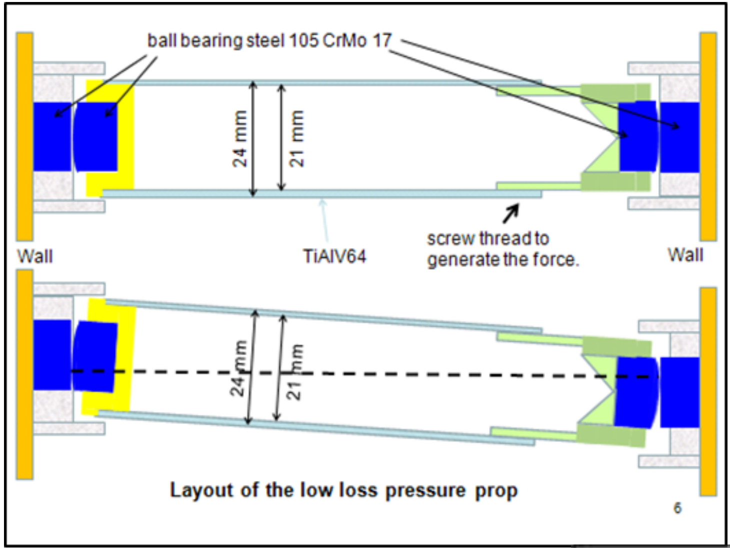
Straightening of HERA dipoles (1st attempt)

Position of Center of Vacuum Pipe along the ‘Test’ HERA dipole



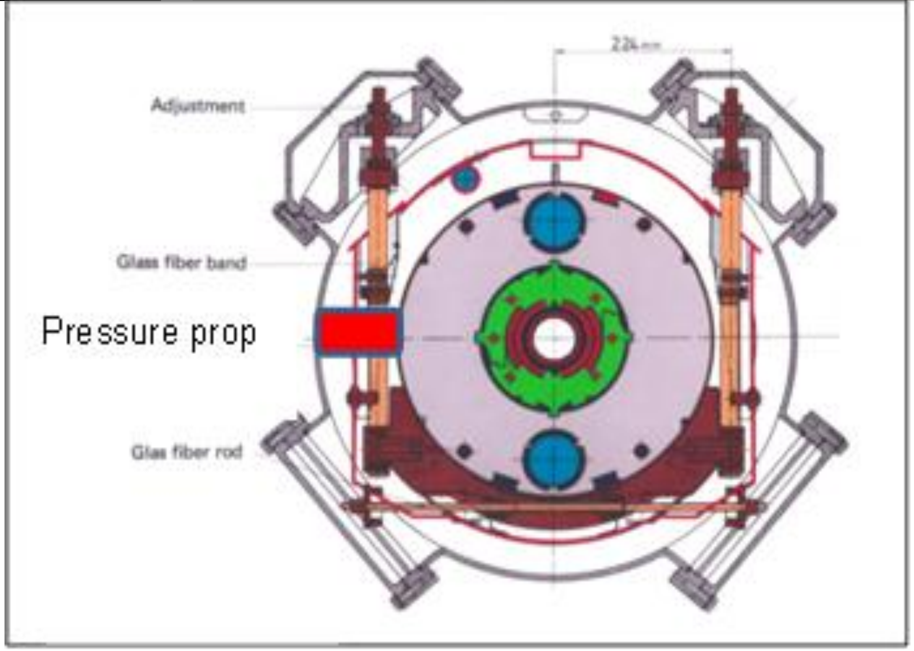
Pressure props for low thermal flow

Room temperature



4K

As the deformation of the yoke is elastic, the deforming force has to be maintained during operation at cryogenic temperatures. Therefore pressure props were built, which keep the thermal flux from the vacuum vessel at room temperature to the yoke at liquid Helium temperature within acceptable limits. The pressure props replace the deformation tools after the straightening.

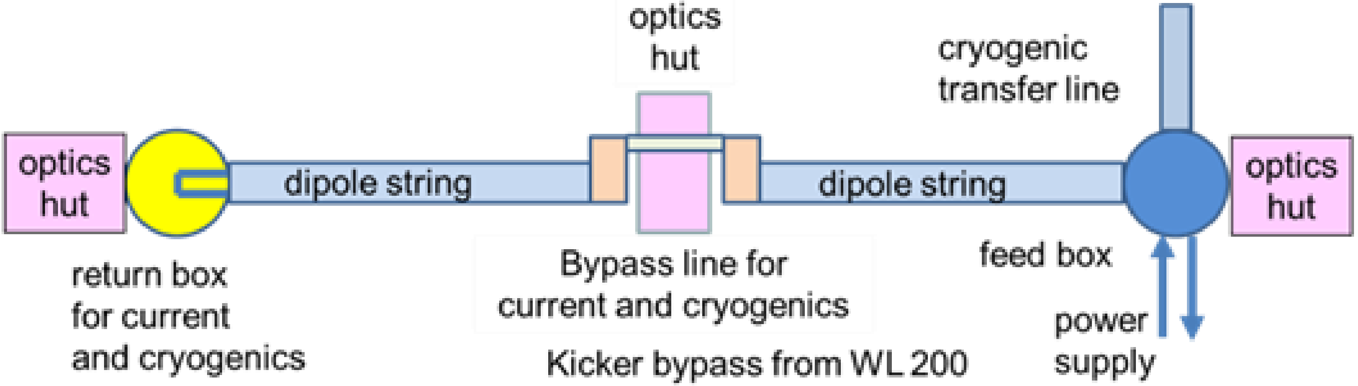


Setup of ALPS-I Experiment

Within the next weeks it is planned to straighten the HERA dipole presently at the magnet test stand, which was used for the ALPS-I experiment.

Subsequently it is planned to measure the actual thermal losses of the pressure props and assure the functionality of the magnet after the straightening procedure.

Schematic layout of ALPS-II



Kicker bypass line in HERA tunnel

The cryogenic boxes will be taken from the straight section of HERA selected for the setup of the experiment.
To pass the magnet current and cryogenics around the optical setup in the middle, the ‘Kicker Bypass’ from the HERA section WL 200 will be used.
Essential systems like the quench gas collection line, other warm Helium pipes or the dump resistors are not shown in the drawing.

Cryogenics and site selection

HERA feed box for cryogenics and magnet current

Supplying cryogenics to the ALPS-II setup is possible to any of the HERA halls in principal from the cryogenics plant on the DESY site. The effort and the cost of operation depend on the straight section chosen for the setup.

Assuming the availability of straightened superconducting dipoles, a string of 2*12 dipoles would supply the necessary horizontal aperture for the laser beam with sufficiently low clipping losses. A sufficient number of spare HERA dipoles are available. With the overall dipole length of 9.766 m and including the space required for the cleanrooms and laser huts this ask for a total length of about 260m.

The natural choice for such a setup is the straight sections of the HERA tunnel due to the principal availability of infrastructure like cryogenics. The available space in the long straight sections East and West amounts to ~320 m allowing easily for a string of 2*12 dipoles, whereas the short straight sections South and North with a length of ~220 m would allow for a string of 2*10 dipoles only.

Cryogenics and site selection

Operation cost for the cryogenics of ALPS-II deduced from the cost for the HERA proton ring

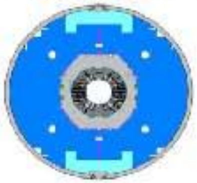
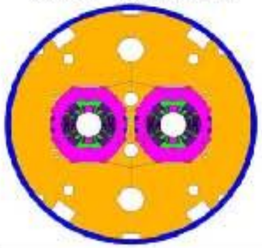
Cost	HERA	ALPS II		
		West	East	North
per month	219.000 €	16.000 €	32.000 €	23.000 €
10 month + 1 cooldown	2.471.000 €	186.000 €	337.000 €	253.000 €

Site selection

Considering the cost for installation and also the operation of the experiment, and the availability of an adequate power supply to operate and ramp the current for the dipoles of the strings, at present the straight section HERA North requires the lowest overall cost for the setup of ALPS-II with 2*10 dipoles.

11 T Nb_3Sn Dipole for LHC Upgrade

- **Nb_3Sn dipole for LHC upgrade (with CERN)**
  - 11 T at 11.85 kA, compatible with LHC lattice and main systems to replace 8.35 T MB
  - 2012: 2-m long single-aperture demonstrator
  - 2013: 2-m long twin-aperture demonstrators
  - 2014: 5.5-m long twin-aperture prototype

Parameter	Single-aperture 	Twin-aperture 
Aperture	60 mm	
Yoke outer diameter	400 mm	550 mm
Nominal bore field @11.85 kA	10.86 T	11.25 T
Short-sample bore field at 1.9 K	13.6 T	13.9 T
Margin B_{nom}/B_{max} at 1.9 K	0.80	0.81
Stored energy at 11.85 kA	473 kJ/m	969 kJ/m
F_x per quadrant at 11.85 kA	2.89 MN/m	3.16 MN/m
F_y per quadrant at 11.85 kA	-1.57 MN/m	-1.59 MN/m

IPAC2012: TUOAC03, THPPD043, THPPD044

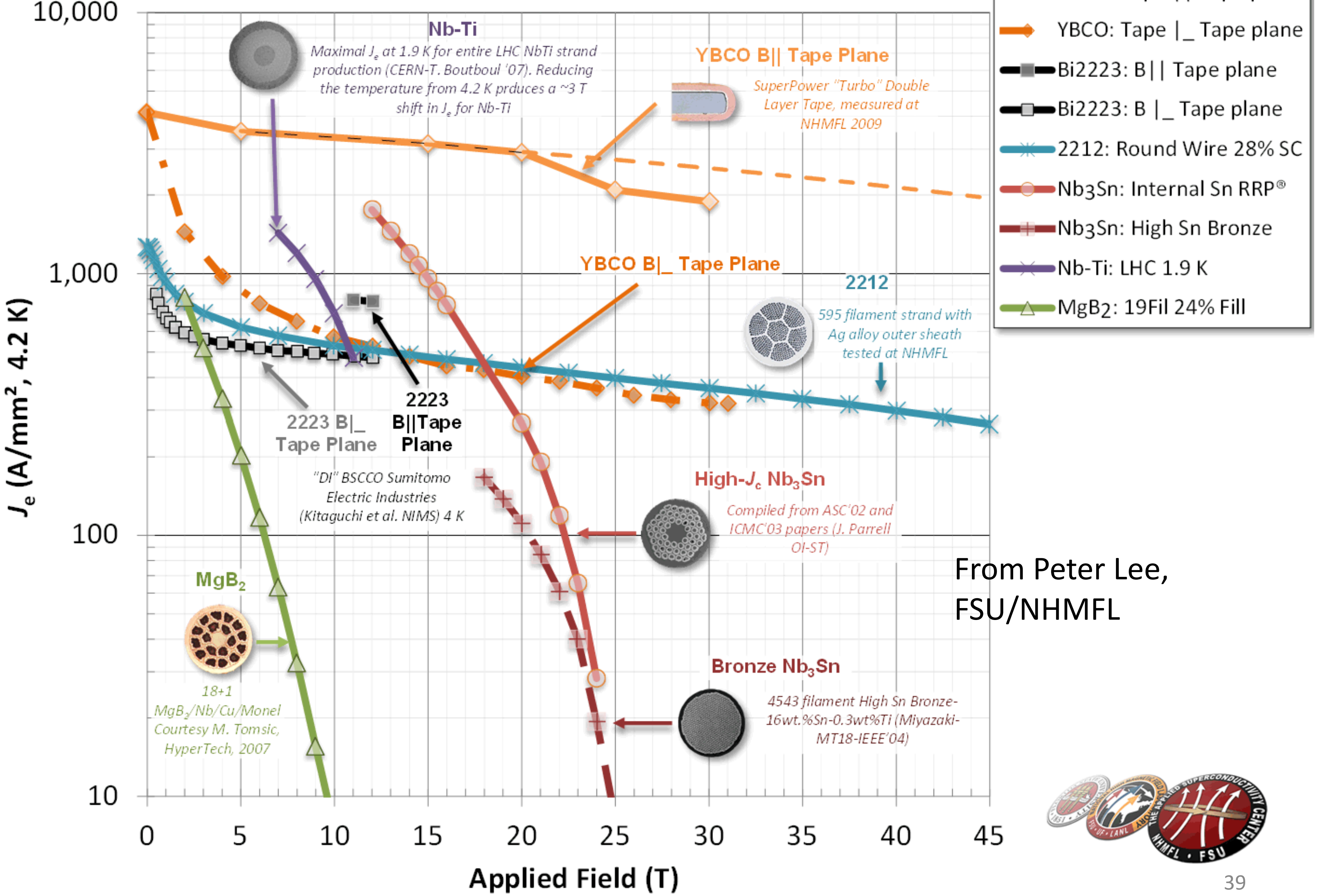
40-strand keystoned cable

Epoxy impregnated coil

Collared coil

Cold mass

Current Density Across Entire Cross-Section



Maximal J_e at 1.9 K for entire LHC NbTi strand production (CERN-T. Boutboul '07). Reducing the temperature from 4.2 K prduces a ~3 T shift in J_e for Nb-Ti

SuperPower "Turbo" Double Layer Tape, measured at NHMFL 2009

595 filament strand with Ag alloy outer sheath tested at NHMFL

"DI" BSCCO Sumitomo Electric Industries (Kitaguchi et al. NIMS) 4 K

Compiled from ASC'02 and ICMC'03 papers (J. Parrell OI-ST)

4543 filament High Sn Bronze-16wt.%Sn-0.3wt%Ti (Miyazaki-MT18-IEEE'04)

18+1 MgB_2/Nb/Cu/Monel Courtesy M. Tomsic, HyperTech, 2007

From Peter Lee, FSU/NHMFL

Far Future Magnets

- Next step in field (20 T) requires high temperature superconductor.
- A dipole with an Nb_3Sn coil (like the 11 T magnets already discussed) could have an HTS insert for 20 T.
- Needed for muon collider, possible LHC energy upgrade in ~2030.

SSC Dipole Magnets

SSC Dipole Magnets

- 50 mm aperture diameter, 17 m length
- 6.7 T field at nominal 4.35 K.
- One was tested to 9.5 T at 1.8 K, when the power supply reached its limit of 10,000 A
- Three are in (outdoor) storage at Fermilab with continuous nitrogen purge.
- Because of the “post type” support system, removing sagitta should be relatively simple.
- Connection to a cryogenic system with a new “feed can” could be expensive.

SSC Feed Can in Storage

SSC Feed Can

- Provides power leads for 10,000 A, cryogens 4.3 K to 1.8 K with internal heat exchangers.
- Designed for operation with normal helium and superfluid helium.
- Met all design, safety and documentation requirements when built in 1988.
- Would not meet documentation requirements today and could not be used.
- A replacement would likely cost in excess of $\$10^6$

Safety and Cultural Requirements

- Cryogenic safety, mechanical (pressure vessel) safety, and Oxygen Deficiency Hazard safety are all institutional requirements at Fermilab.
- Stringent requirements on safety of the design, documentation of design and fabrication, and operation exist.
- It is very difficult to have equipment “grandfathered in” just because it was built before the requirements existed.
- Example: pressure vessel, whether room temperature or cryogenic, that does not meet the ASME Code, including documentation of materials and fabrication, would generally not be permitted to operate. A possible exception might be for operation in a remote, interlocked location.

Example:
Oxygen Deficiency Hazards (ODH)

- Unless operation is shown to pose a risk of death to exposed persons less than 10^{-7}/hr special restrictions will be imposed to reduce the risk to below that level.
  - Special training, health, ventilation requirements.
  - Carry oxygen monitors and escape packs at all times.
  - Possibly two-man rule requirement.
- Operation of cryogenic magnet strings will be subject to this policy.
  - Could isolate with walls, barriers, interlocks, the magnets/cryogenics from workers, including scientists.
  - Such separation could reduce risk enough in the scientific work area to eliminate further requirements.

Cultural Requirements Example: Access to operating magnets restricted

- At the Fermilab Magnet Test Facility, people work next to operating magnets of all types.
- In the Fermilab Accelerator Department, the operating magnets were always interlocked behind closed doors and people did not have access to operating magnets.
- Operation of long magnet strings at Fermilab will likely come under the control of the Accelerator and Particle Physics Divisions and be subject to their rules (and cultural biases.)
- Design of the experiment and operations will likely require separation and interlocking of the apparatus from the scientists.
- Laser beam safety will be important, but may not be the most difficult problem for us to deal with.