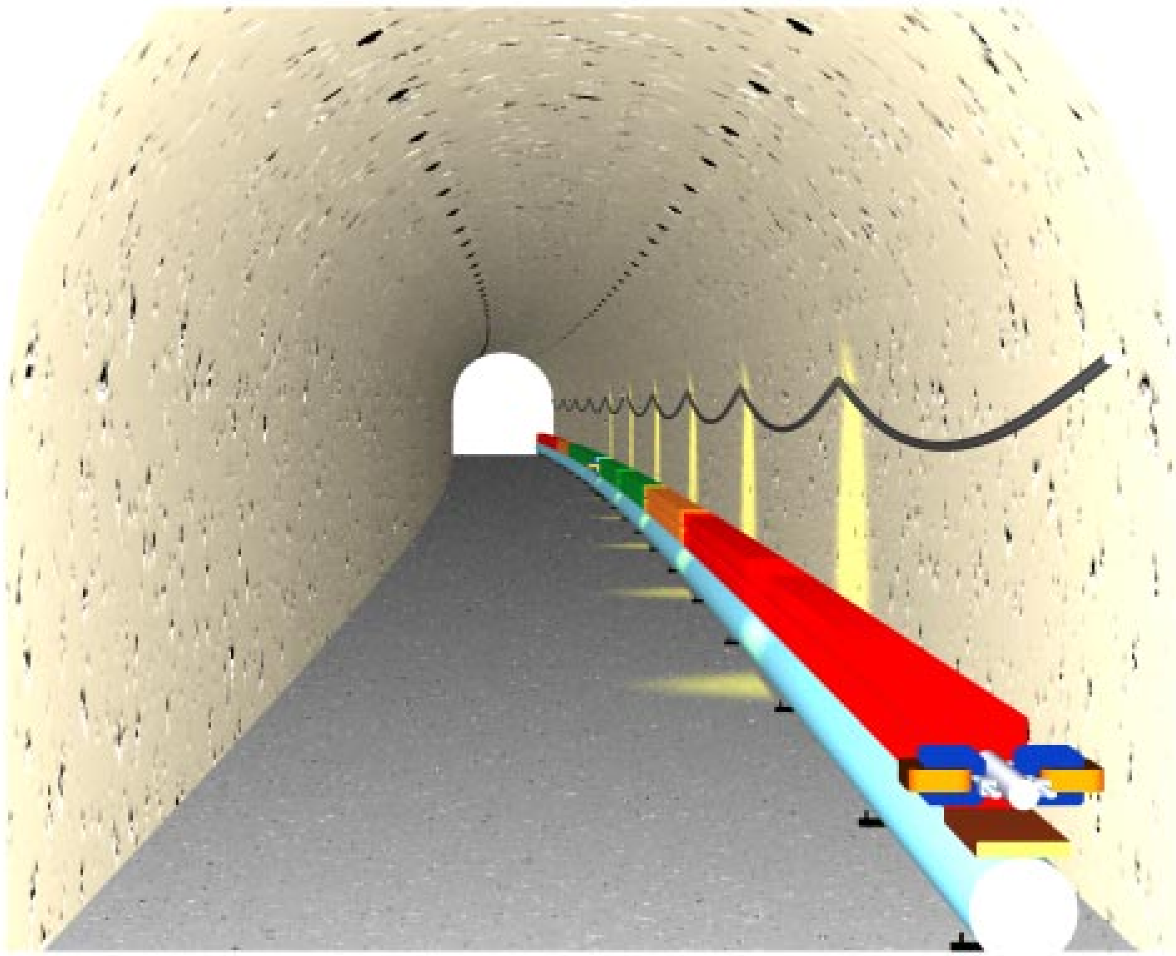
The Low-Field VLHC Transmission Line Magnet



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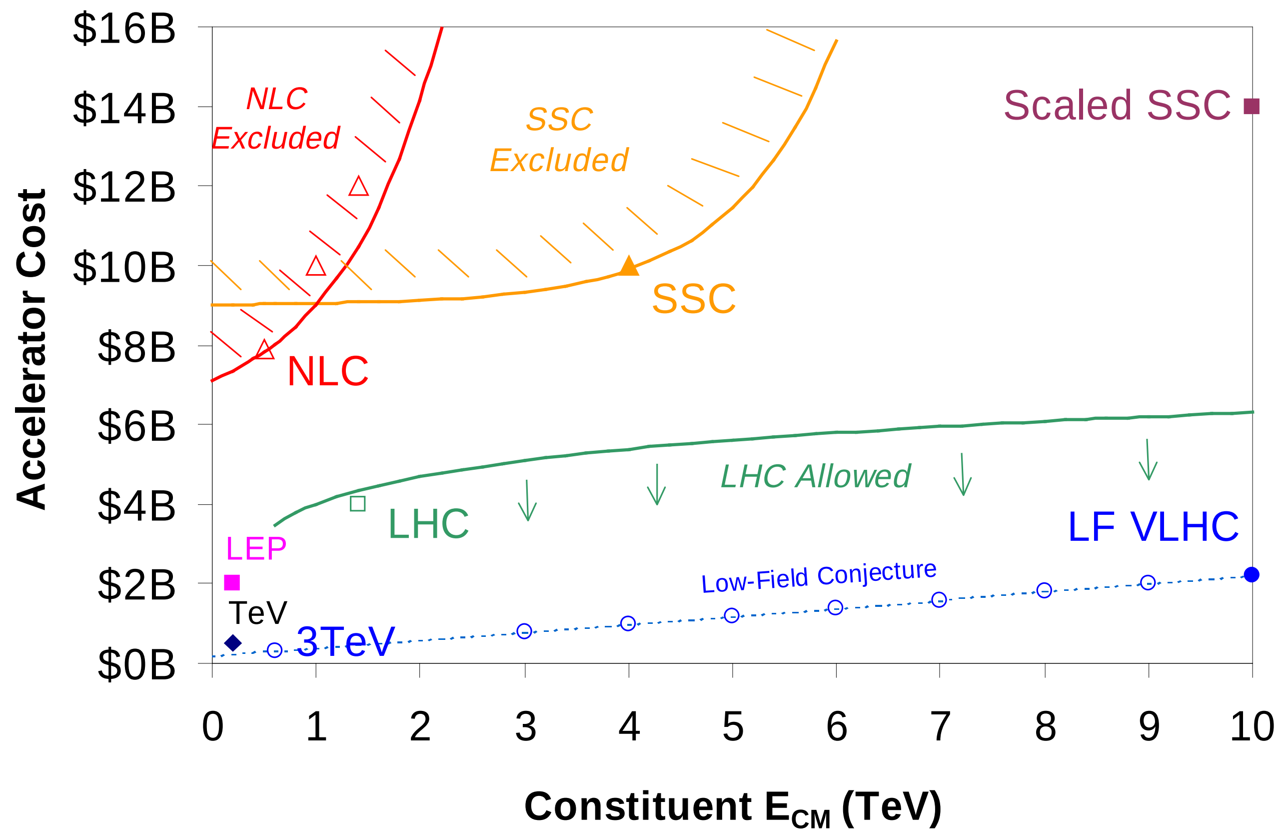
Experimental Overview

Accelerator Cost vs. E_{CM}



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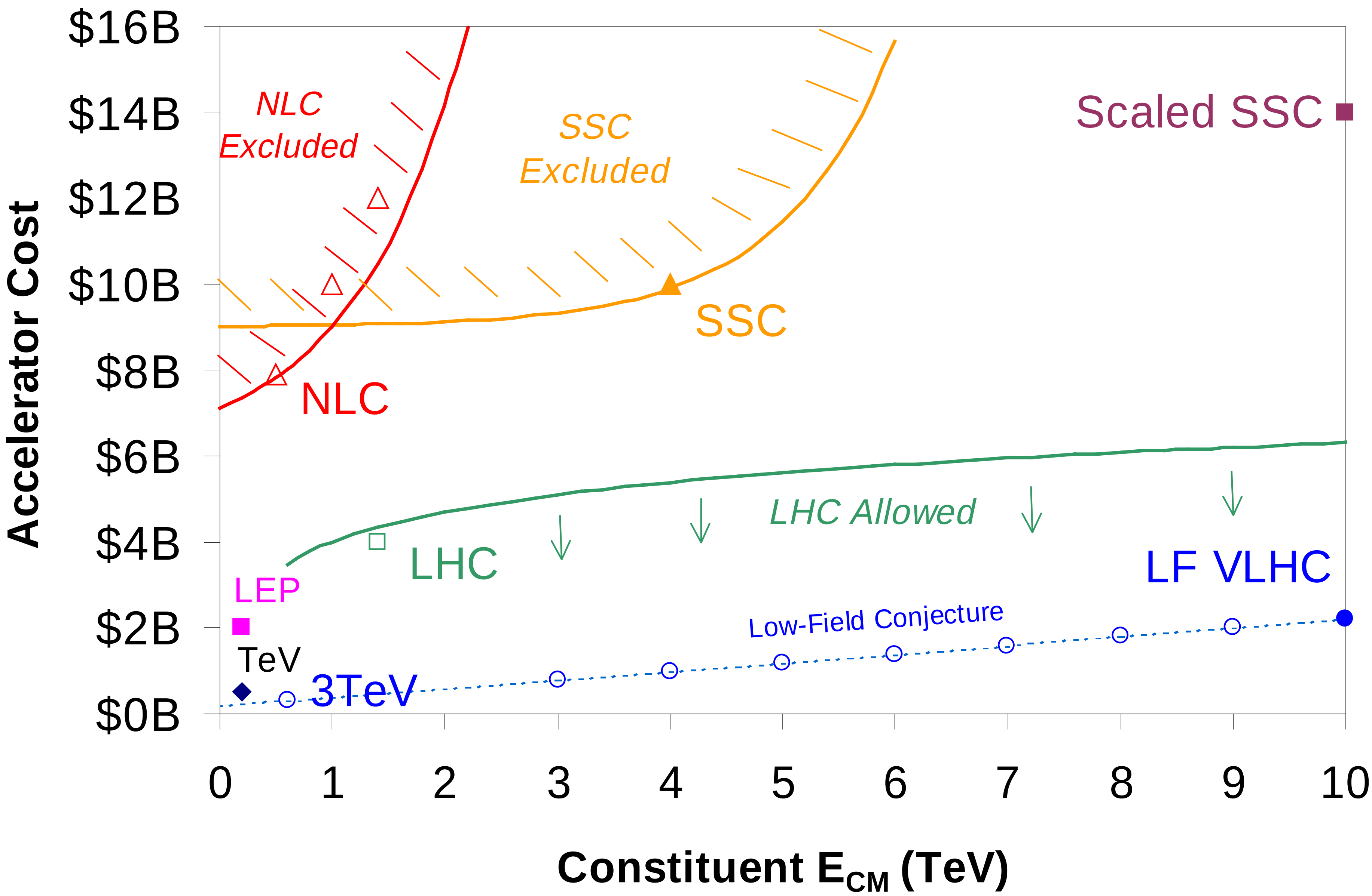
Accelerator Cost vs. E_{CM}



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Some Round Numbers

- A 2-Tesla machine requires:
  - 1 mile of radius per TeV, or
  - 10 km of circumference per TeV.
- The radius of the 50x50 TeV machine is ~100 miles.
- The circumference is 500km.

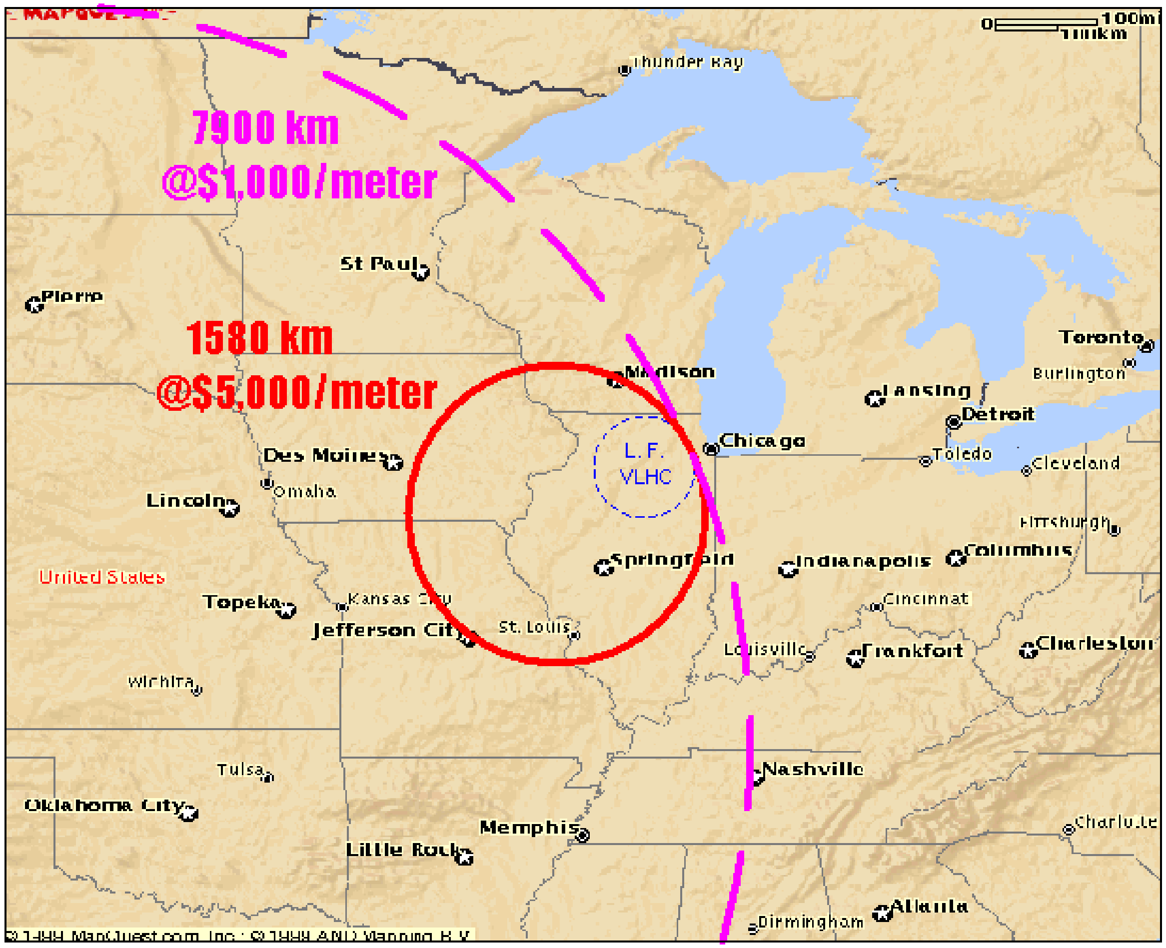
Round Numbers (cont'd)

- **IF:** the magnet costs \$1000/m
  AND: the tunnel costs \$1000/m
  THEN: the bare cost of (magnet+tunnel) is:

500km x (\$1k+\$1k) = \$1B

...and you can hope for a \$2B project.

How Much Tunnel Can You Buy for $7.9B ?



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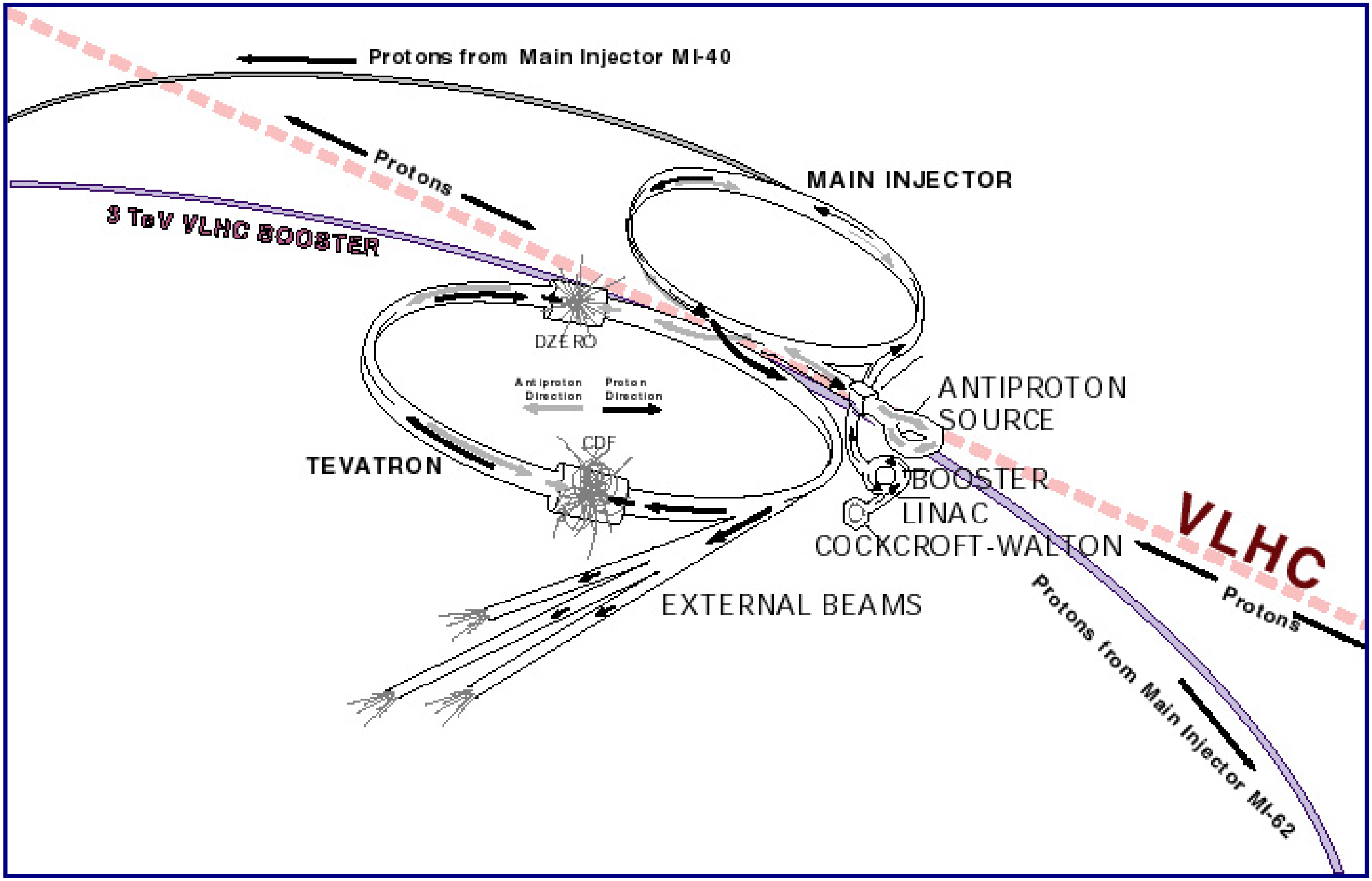
Hadron Colliders are Based on 3 Lossless Processes:

1) Recirculating protons in a magnetic guide field.
2) Superconducting current transport.
3) Exciting DC magnetization currents in blocks of iron.

- The beam energy is not thrown away each machine cycle.
- Fundamental physics makes them cheaper per TeV.

VLHC at Fermilab



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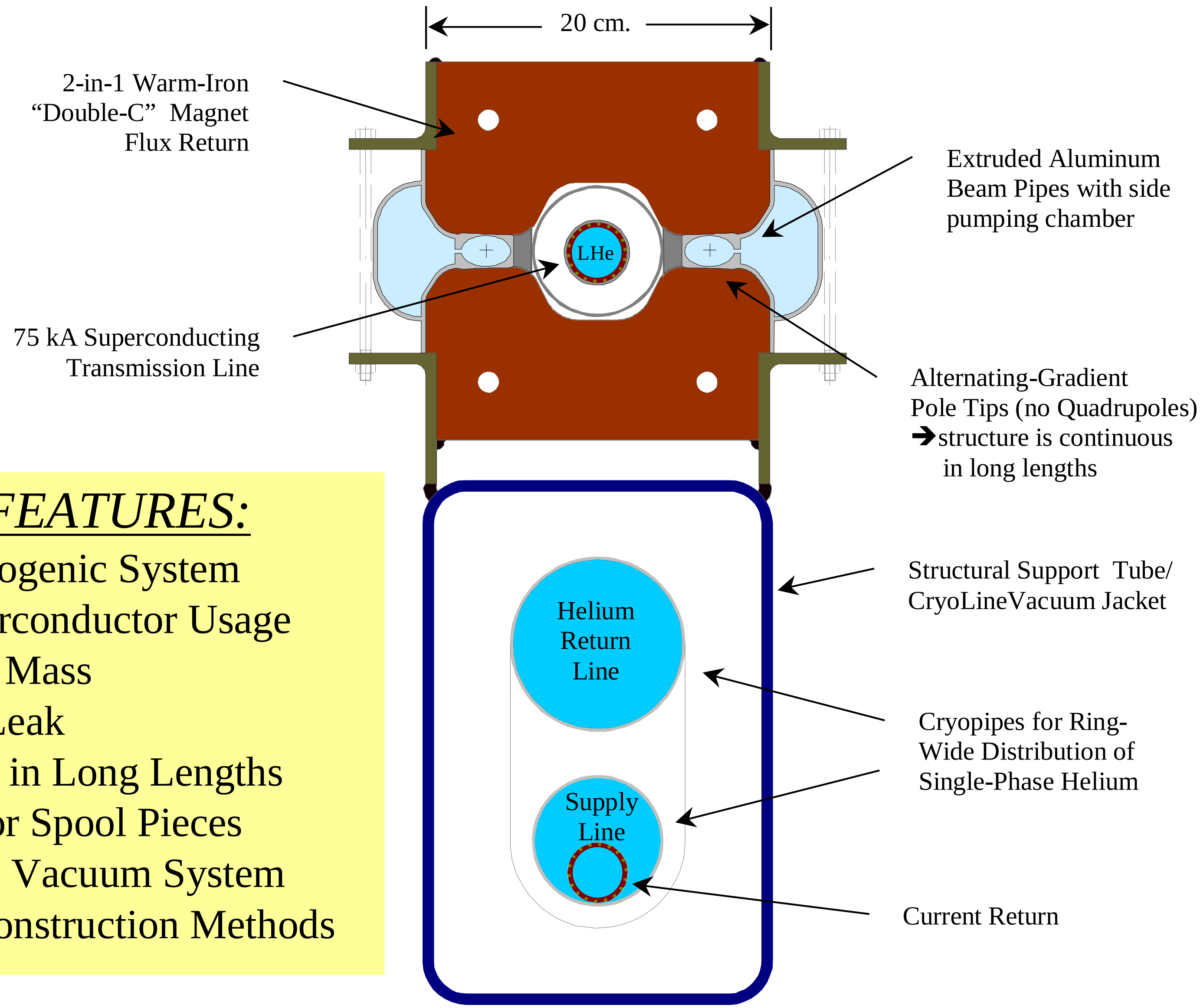
Transmission Line Magnet



KEY FEATURES:

- Simple Cryogenic System
- Small Superconductor Usage
- Small Cold Mass
- Low Heat Leak
- Continuous in Long Lengths
- No Quads or Spool Pieces
- Warm Bore Vacuum System
- Standard Construction Methods

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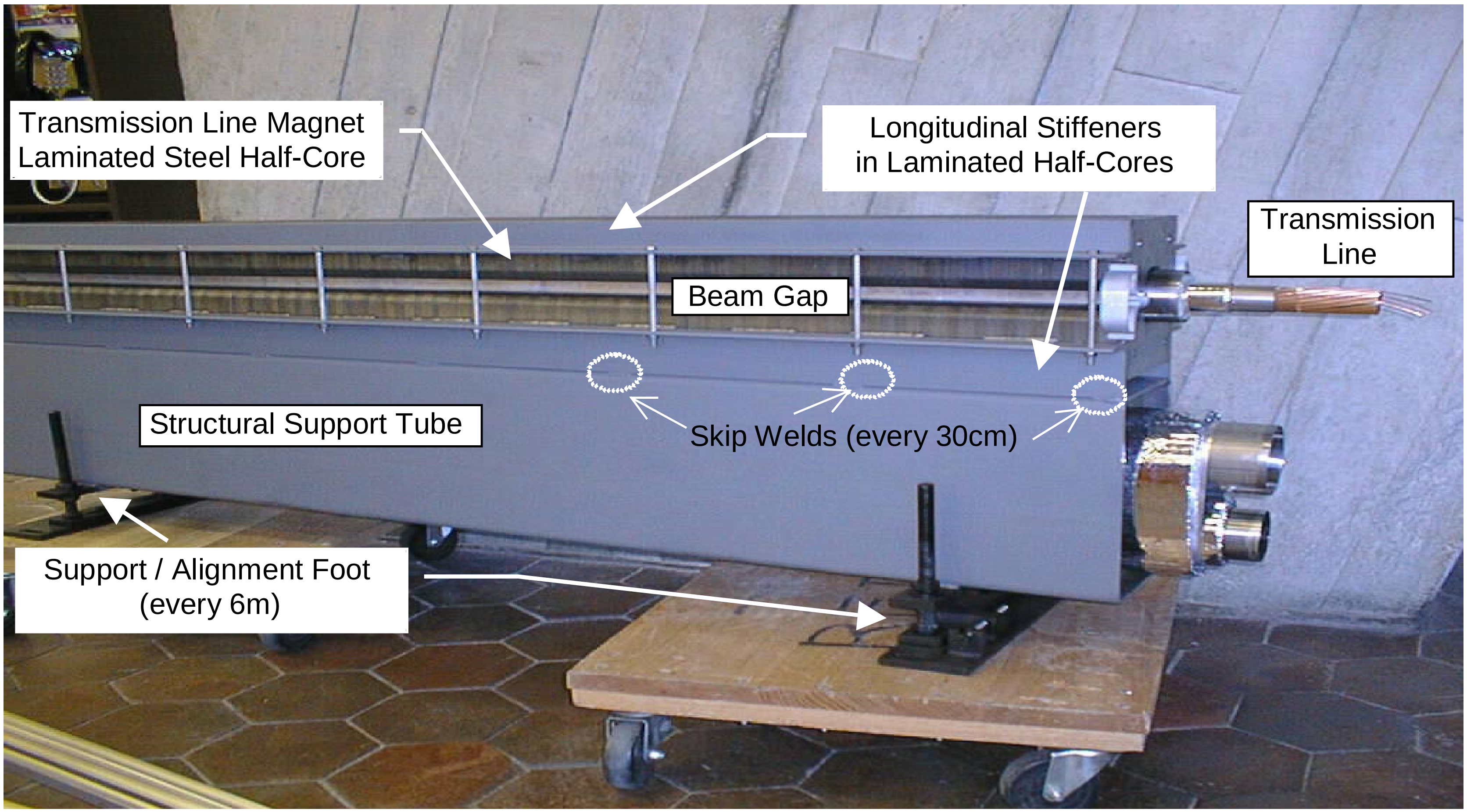
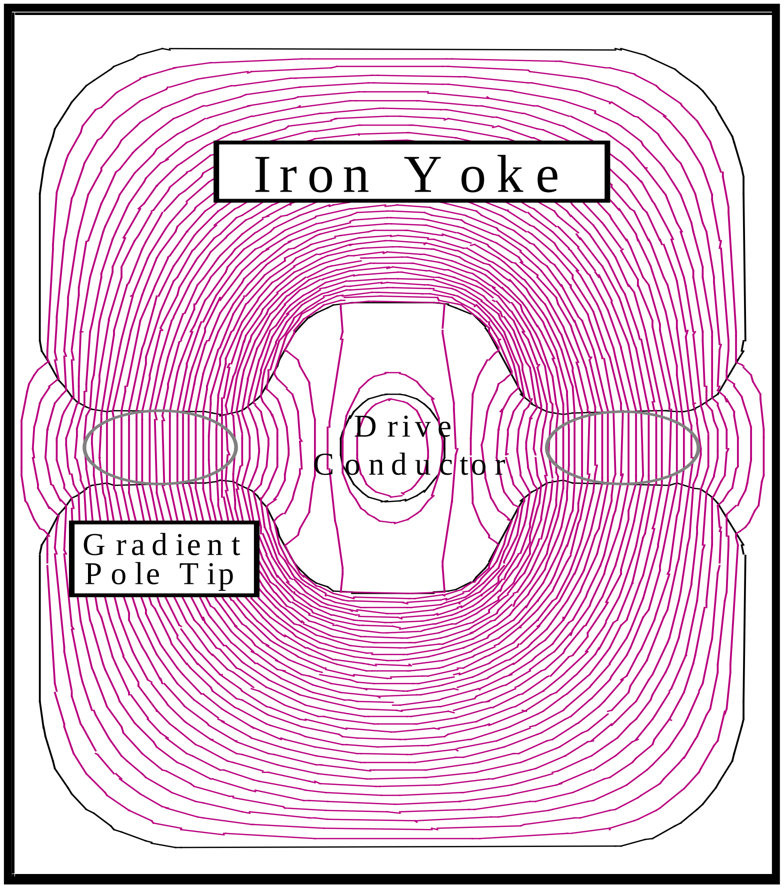
Components of the Transmission Line Magnet



“Double-C” Iron Yoke



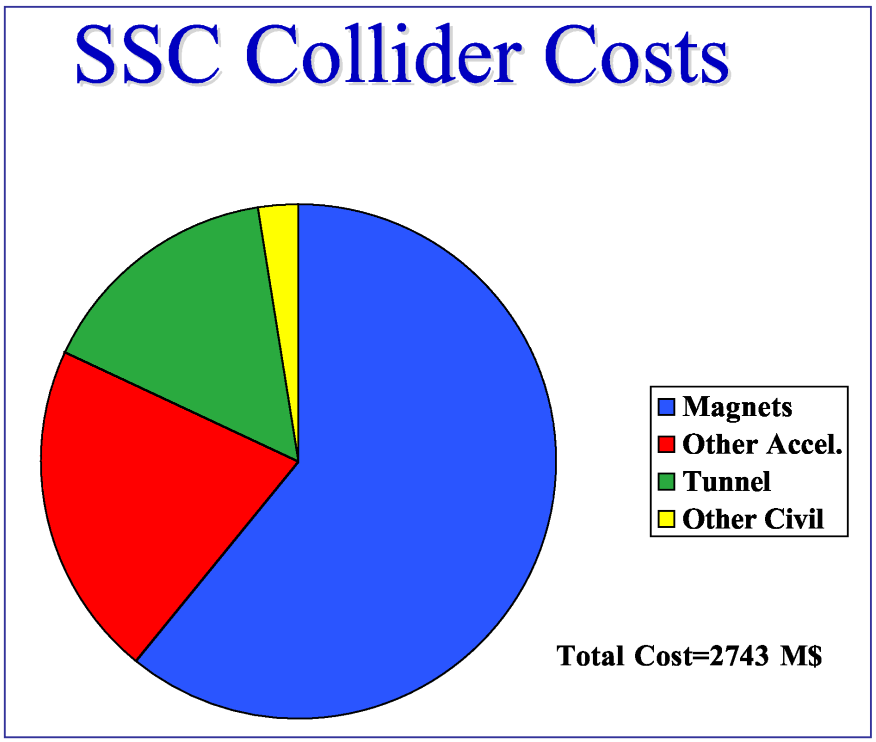
- 80-100kA current drives two beam apertures.
- Gradient Pole tips provide bend and focussing (no quads).
- Iron shapes field: superconductor position not critical.
- Iron Yoke is ~2/3 of magnet cost.

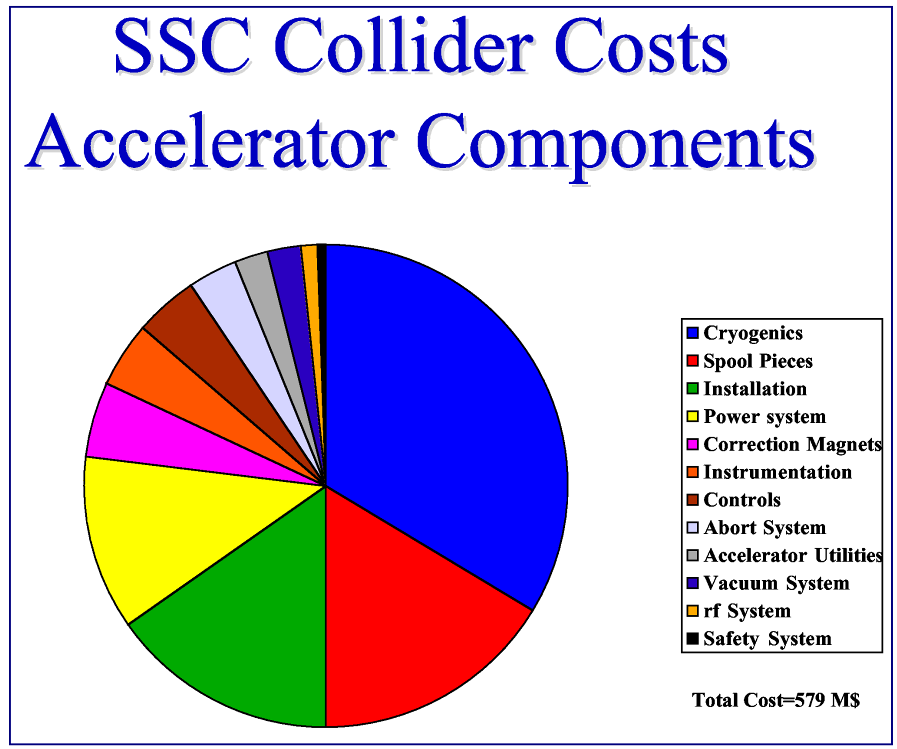
Low Field VLHC Subsystems

- Power Supplies
- Cryogenics
- Quench Detection & Protection
- Beam Vacuum
- Corrector Magnets
- Instrumentation
- Injection, Extraction, Abort

SSC Collider Costs

(J. Marriner)





Magnet Power Supplies

Are Power Supplies a big Deal?

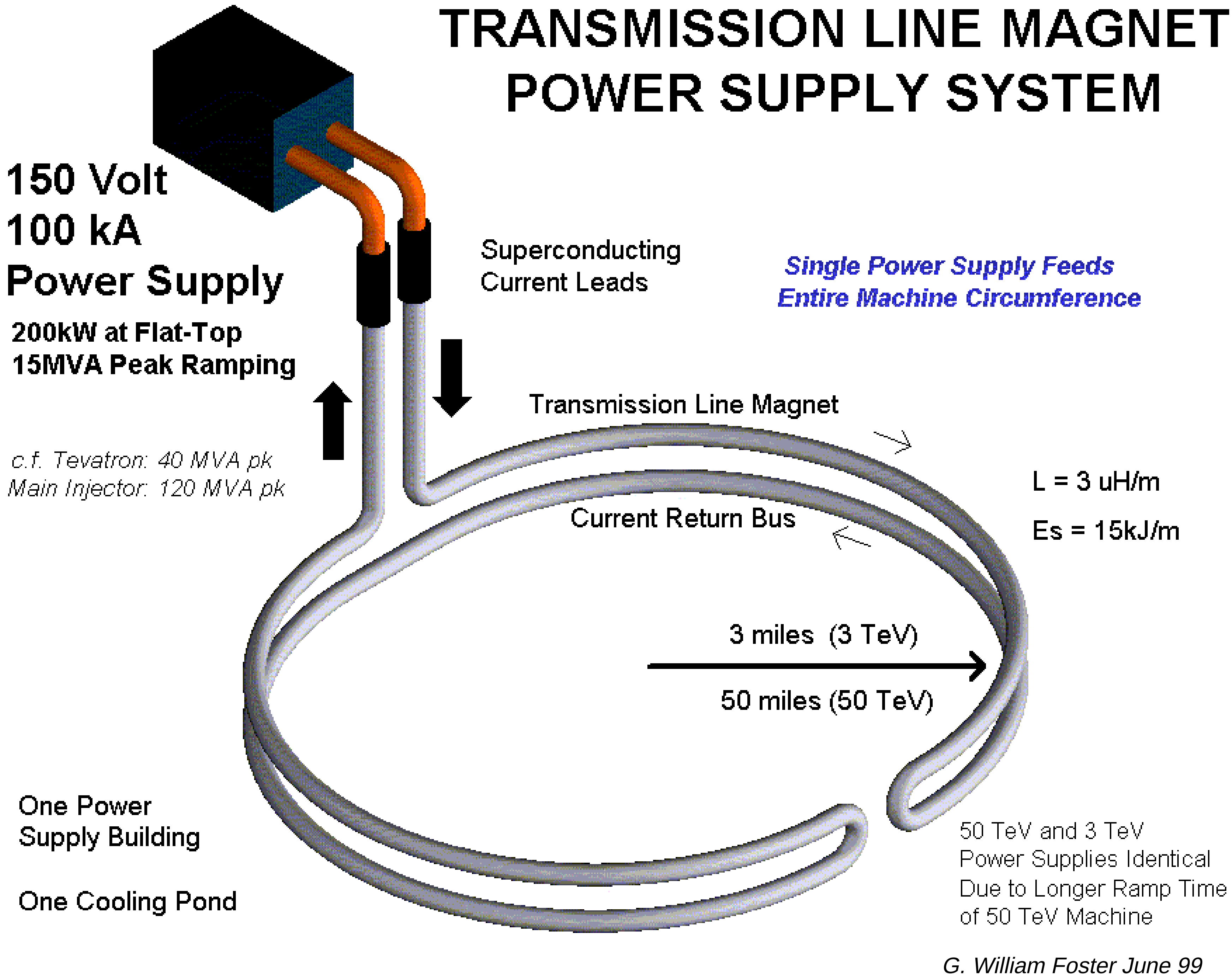
- LHC: 140 MVA Ramping Power
- SSC: 10 Power Supply Buildings around circumference of ring
- Main Injector: 90 MVA, 6 Bldgs.
- LF VLHC: Single 15 MVA Power Supply Located on-site at FNAL

Magnet Power Supplies

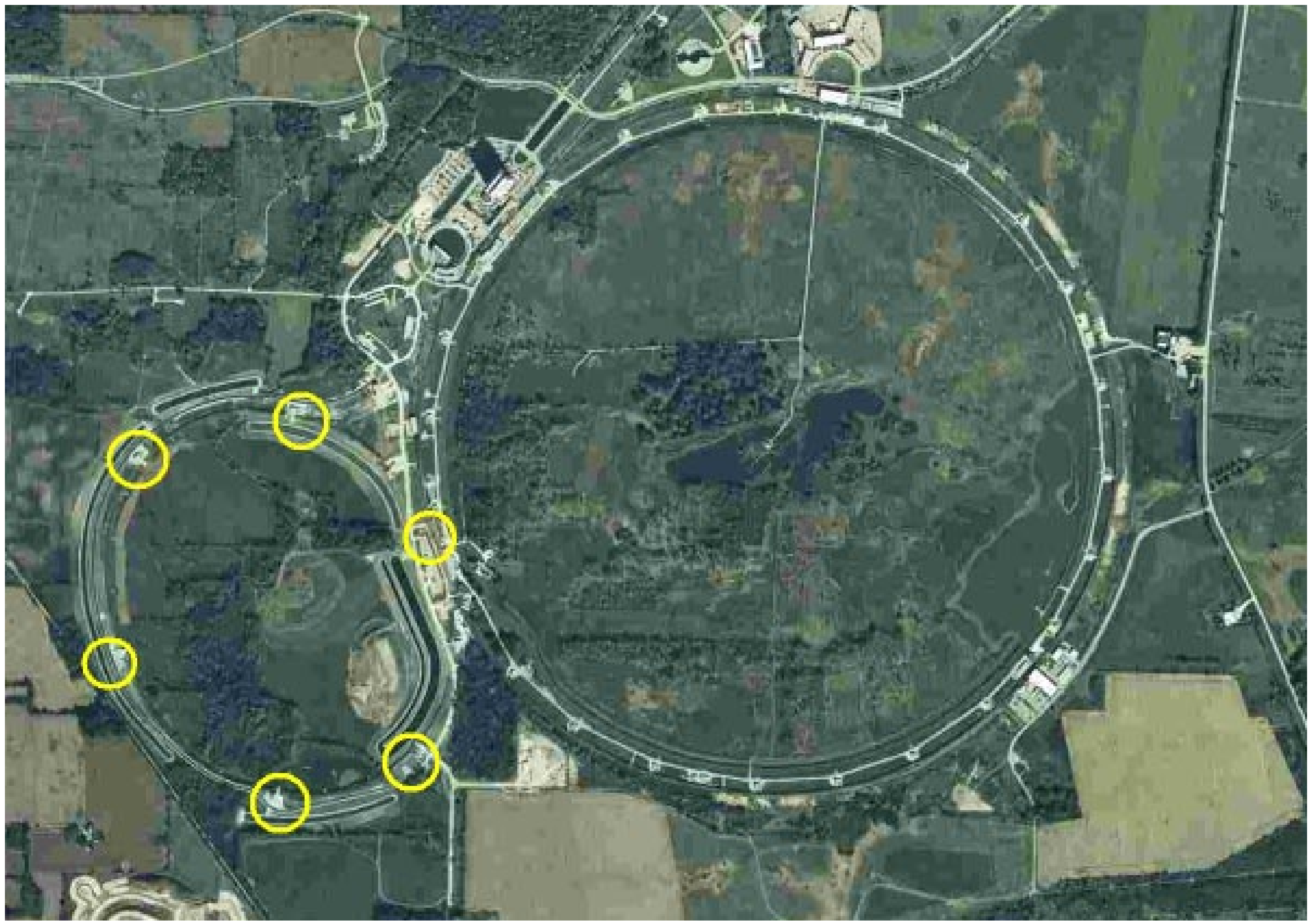
- The Transmission Line Magnet:
  - Low Inductance 3uH/m
  - Low Stored Energy 10kJ/m
  - Zero Static power during flat-top (since it is superconducting)
  - Only Requires a single set of superconducting power leads

→ significant system cost savings

TRANSMISSION LINE MAGNET POWER SUPPLY SYSTEM



Main Injector Has Six Power Supply Buildings >15MVA



What Does a 15 MVA Power Supply Building Look Like?

MI-20: One of 6 Fermilab Main Injector Power Supply Buildings

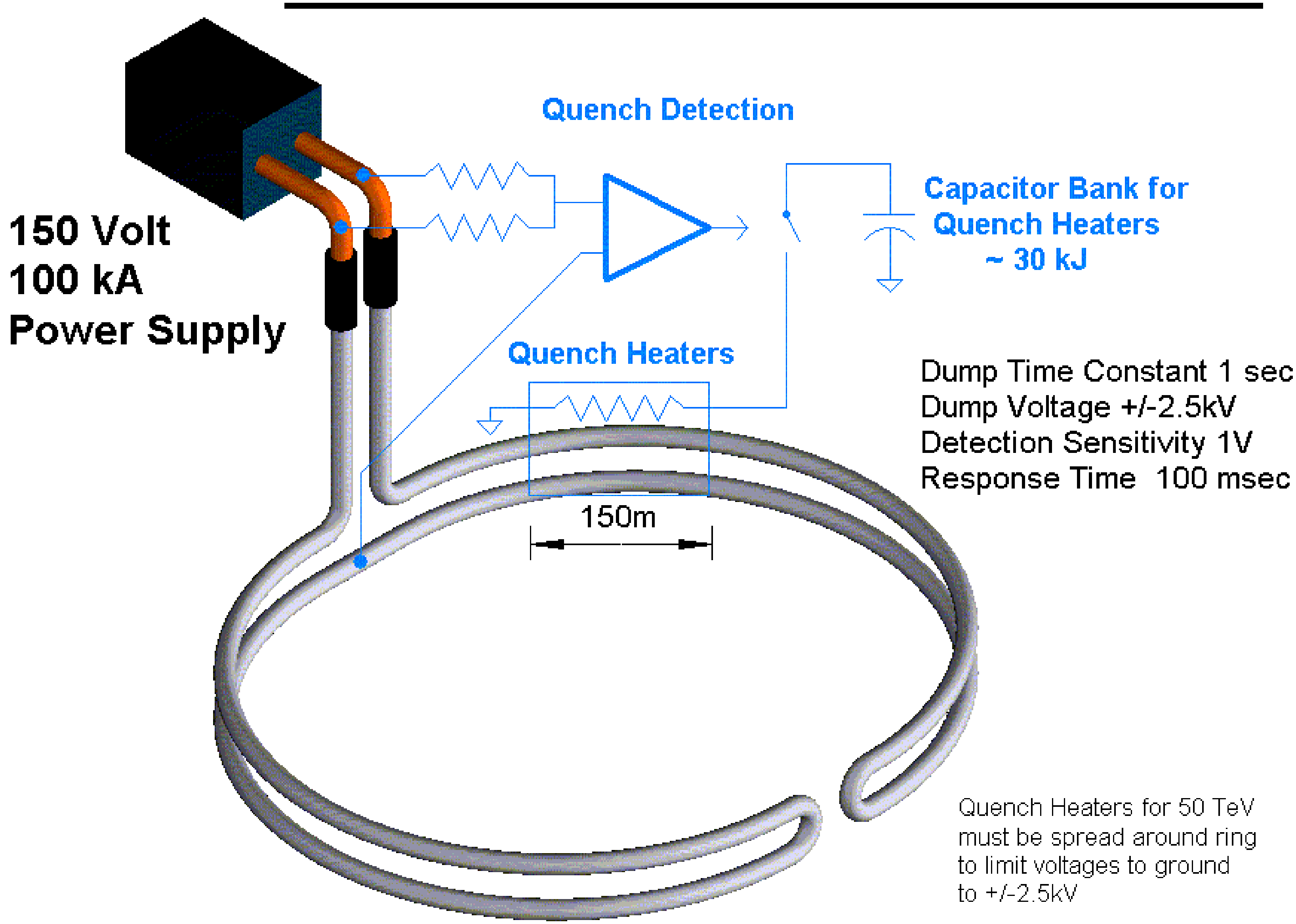
Inside the MI-20 Power Supply Building

Quench Detection

Is Quench Protection a big deal?

- **LHC: Electronics Rack under every dipole for 27 km**
- **Every dipole has 40 instrumentation leads**
- **LF VLHC quench detection via a single circuit at P.S. Terminals**

QUENCH DETECTION & PROTECTION



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Stability Against Quenches From Beam Losses

- Full shower development and energy deposition calculated *(Mokhov).*
- Warm iron design can tolerate ~50x more beam loss than conventional cold-bore magnet.
- This is good since each lost proton will carry 50x more energy than at Tevatron.

Quench Localization
(identify which magnet quenched...)

- Wait for slug of hot helium to flow down to next temperature monitoring point: drift time tells epicenter of quench.

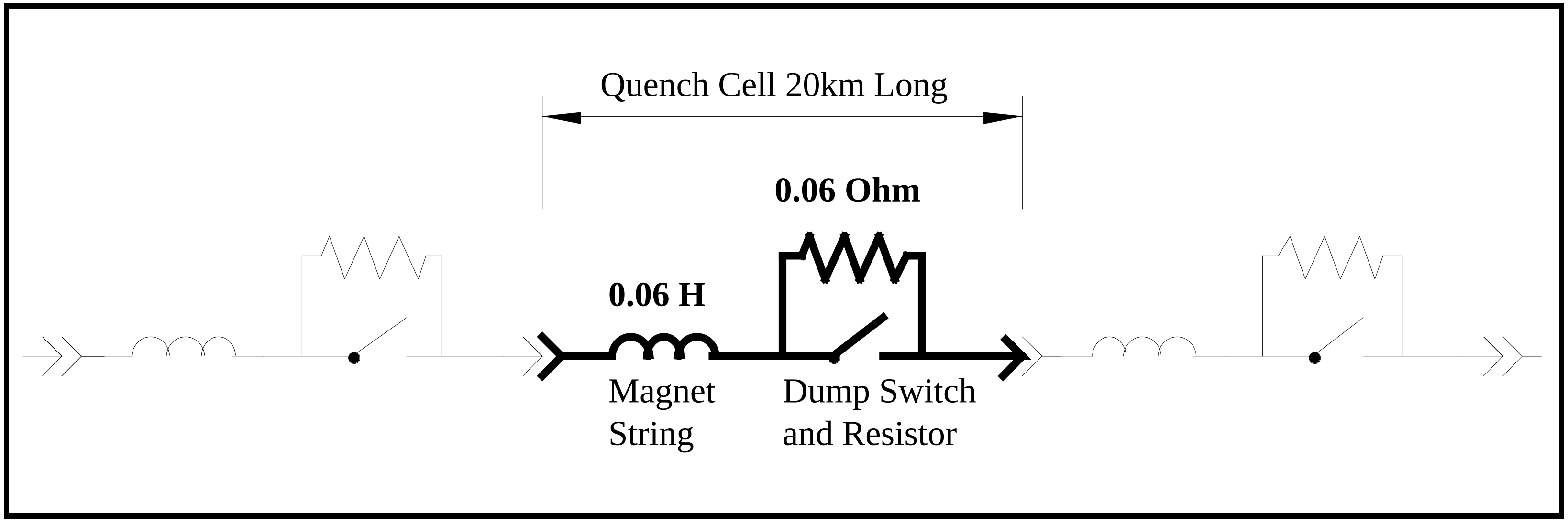
..or..

- Acoustical time-of-flight: put microphones at vacuum breaks every few km.

Magnetic Energy Dump System

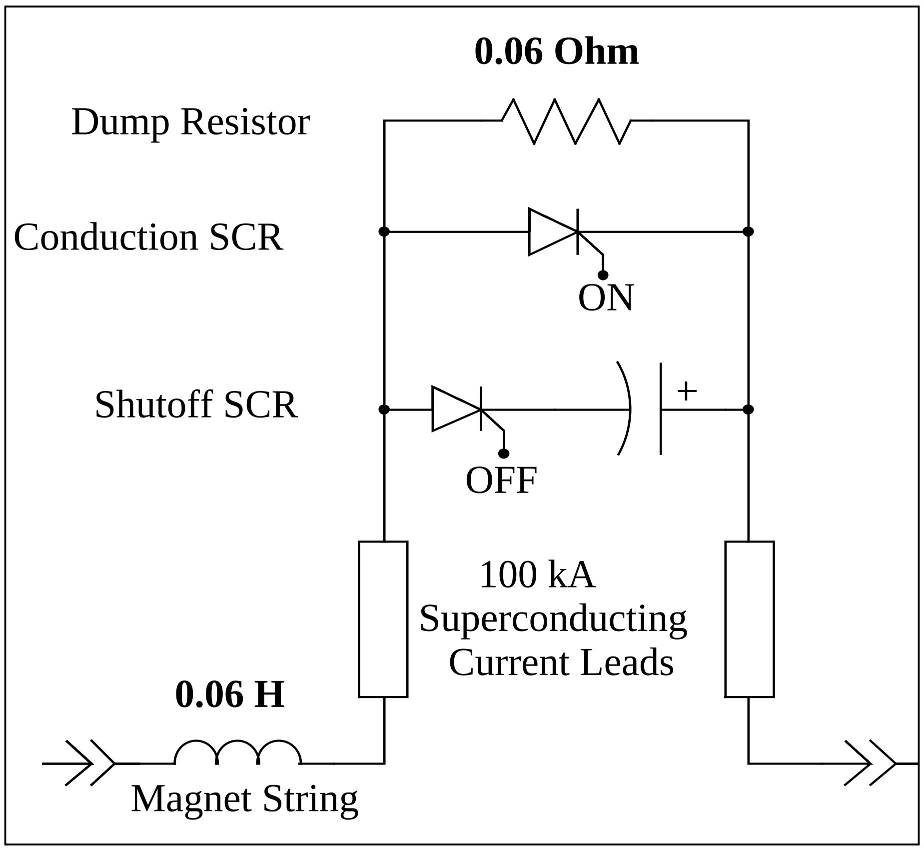
- 10kJ/m stored energy in magnet requires active energy dump.
- 5 GJ VLHC vs. 10GJ LHC
- When quench detected, current diverted to series dump resistor to extract magnetic energy.
- 1 second dump time reasonable.
- Practical limit +/-3kV to ground

VLHC Magnetic Energy Dump System



- Requires dump resistors and switches to be spaced ~20km.
- 3 TeV ring OK with 1 location.

Conventional Dump Switch



Requires:

- Pair of 100kA SC current leads
- High-current SCR or IGBT Switch
- 200kW power dissipation
- LCW system

...every 20km

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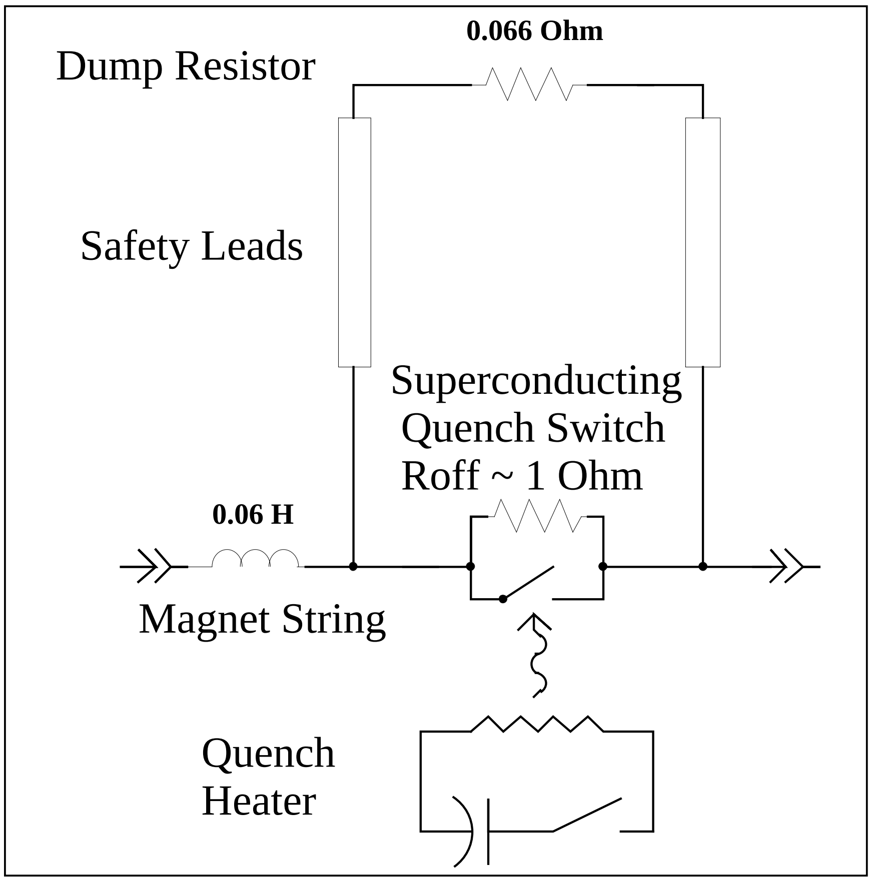
VLHC Superconducting Dump Switch



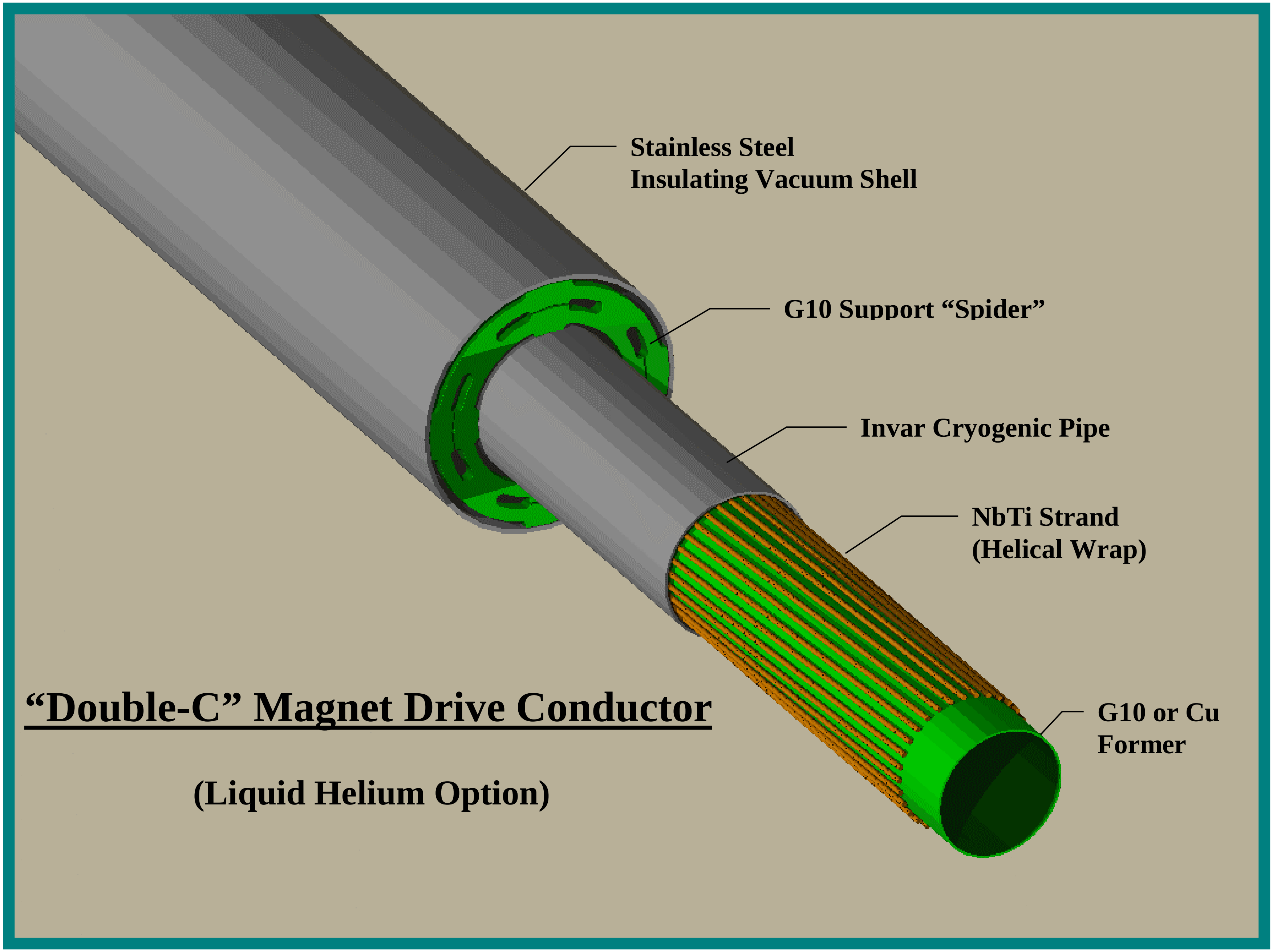
- Pass 100kA through superconducting quench switch
- Initiate quench with heater pulse
- Current bypassed to warm resistor through safety leads

Advantages of Superconducting Dump Switch

- Zero Power Dissipation.
- Small heat leak (safety leads).
- Easy to re-cool by venting He into warm gas return.
- No LCW.
- Small quench trigger power ~1kJ.
- Can be spaced far from utilities.

The Transmission Line

- 80 kA Cable-In-Conduit
- Except:
  - Zero Thermal Contraction
  - 3cm Clear Bore for Helium
  - Magnetic De-Centering Forces
  - Current Centroid $\pm$1mm
  - Need Easy Field Splice



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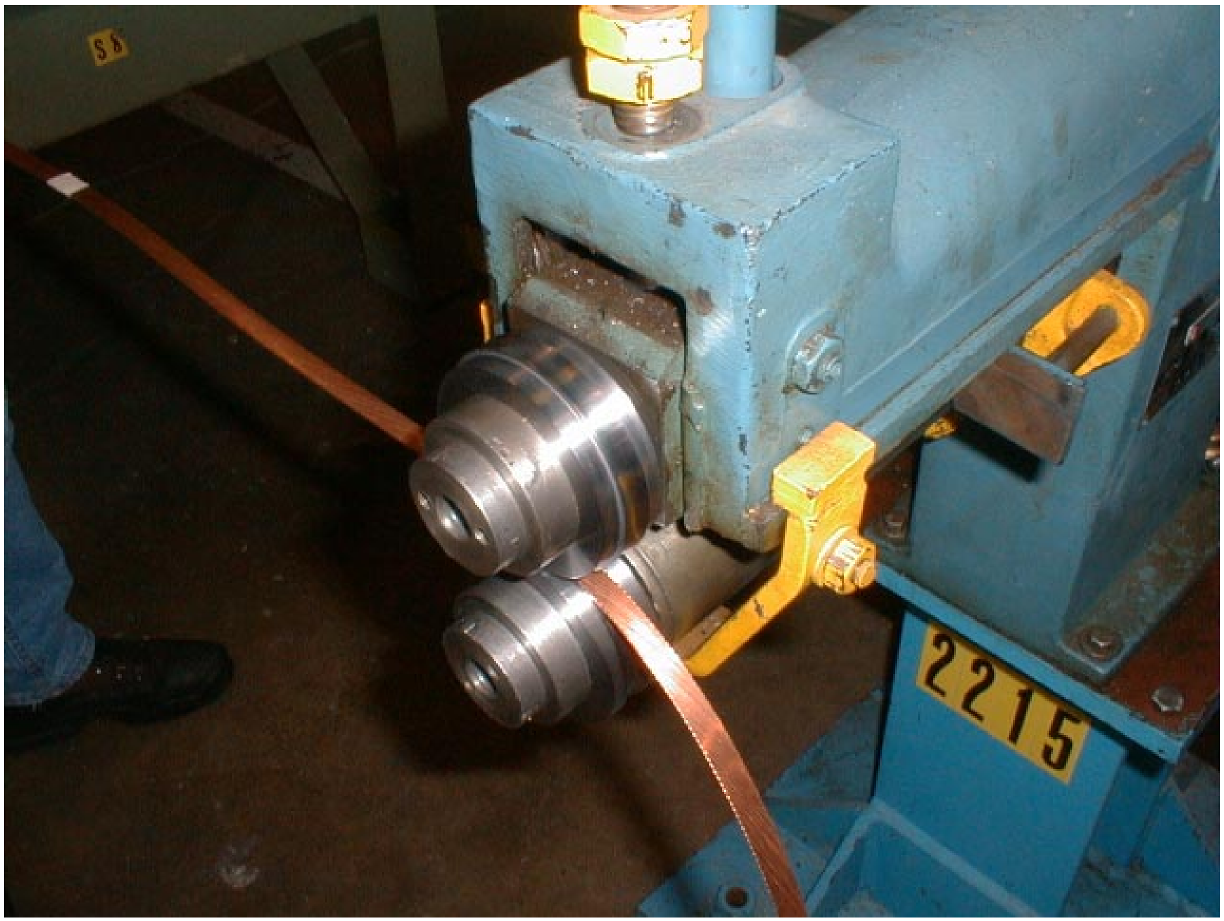
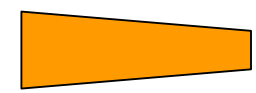
Re-Rolling SSC Conductor

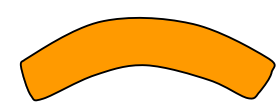
to remove keystone and form arched cross-section for transmission line



Before



After



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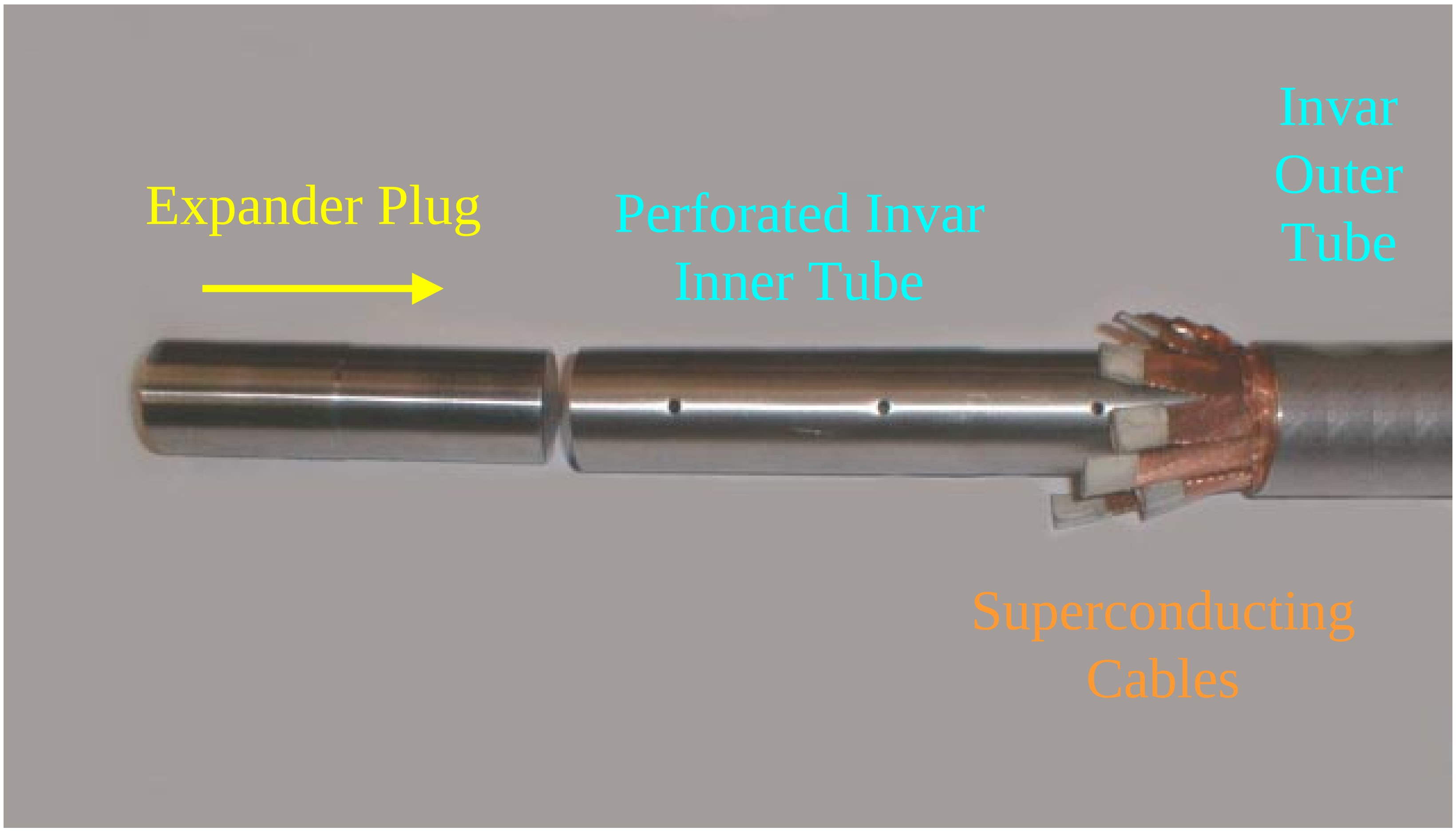
Preparation of Cables for Wrapping on Transmission Line

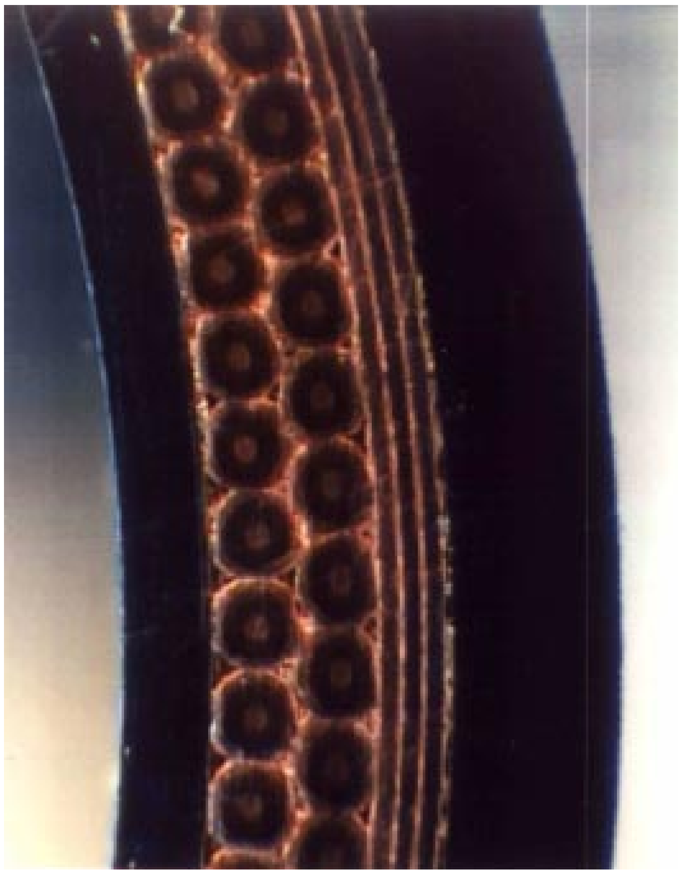
Copper Tape Wrapping of Transmission Line Conductor Using Wrapping Fixture from Tevatron and Recycler Beam Pipes

Pipe Swaging Operation to Expand Inner Invar Tube to Pre-load Conductor



Draw Bench Swaging Operation To Expand Inner Invar Tube on Transmission Line Conductor

Cross Section of Finished Transmission Line



- Superconductor clamped between inner & outer Invar pipes
- Copper tape protects during subsequent welding

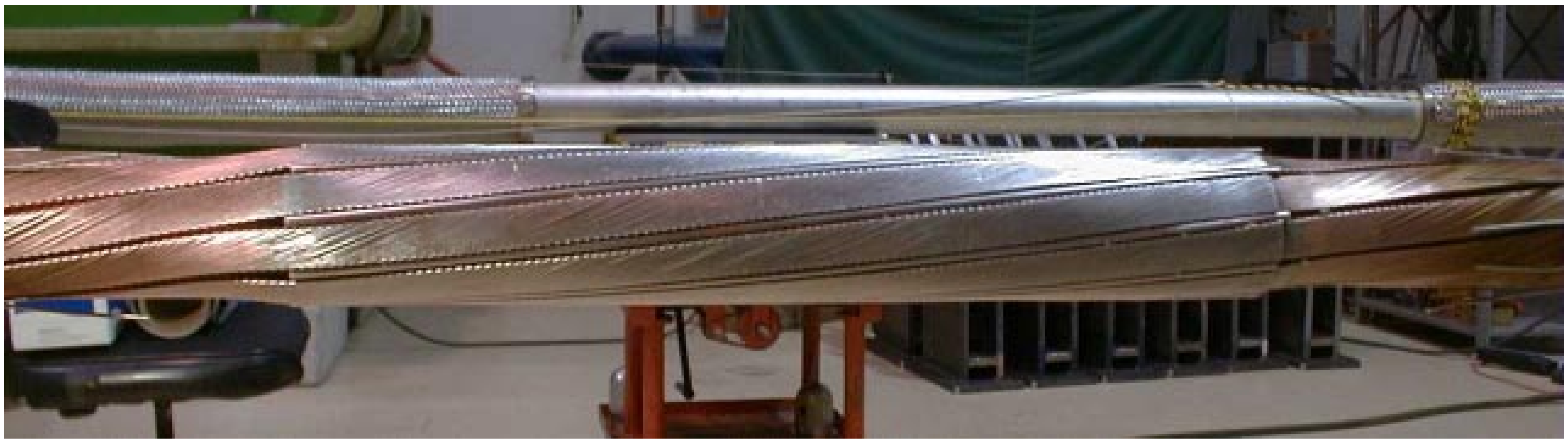
100 kA Conductor Splice (1)

1

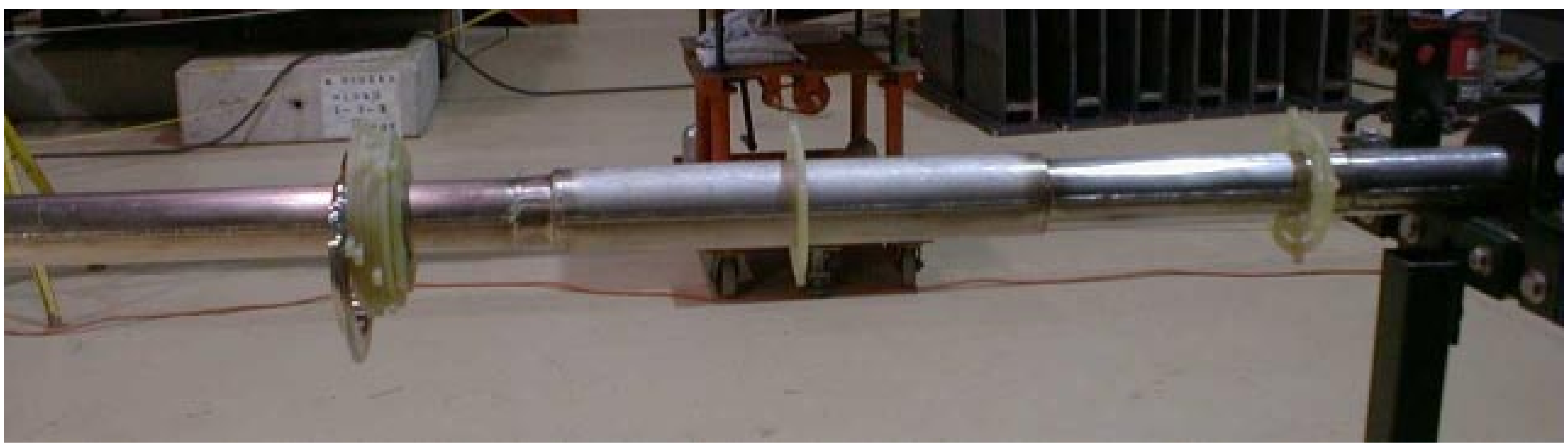
2

100 kA Conductor Splice (2)

3



4



50m Invar Cryopipe Thermal Cycling Test

Invar Pipe cut into small sections and robotically welded.

50 meter Cryopipe.

128 Robotic Welds.

1,000 Thermal Cycles with ends clamped.

Zero Leaks.
($<10^{-10}$ std cc/sec)

R. Walker

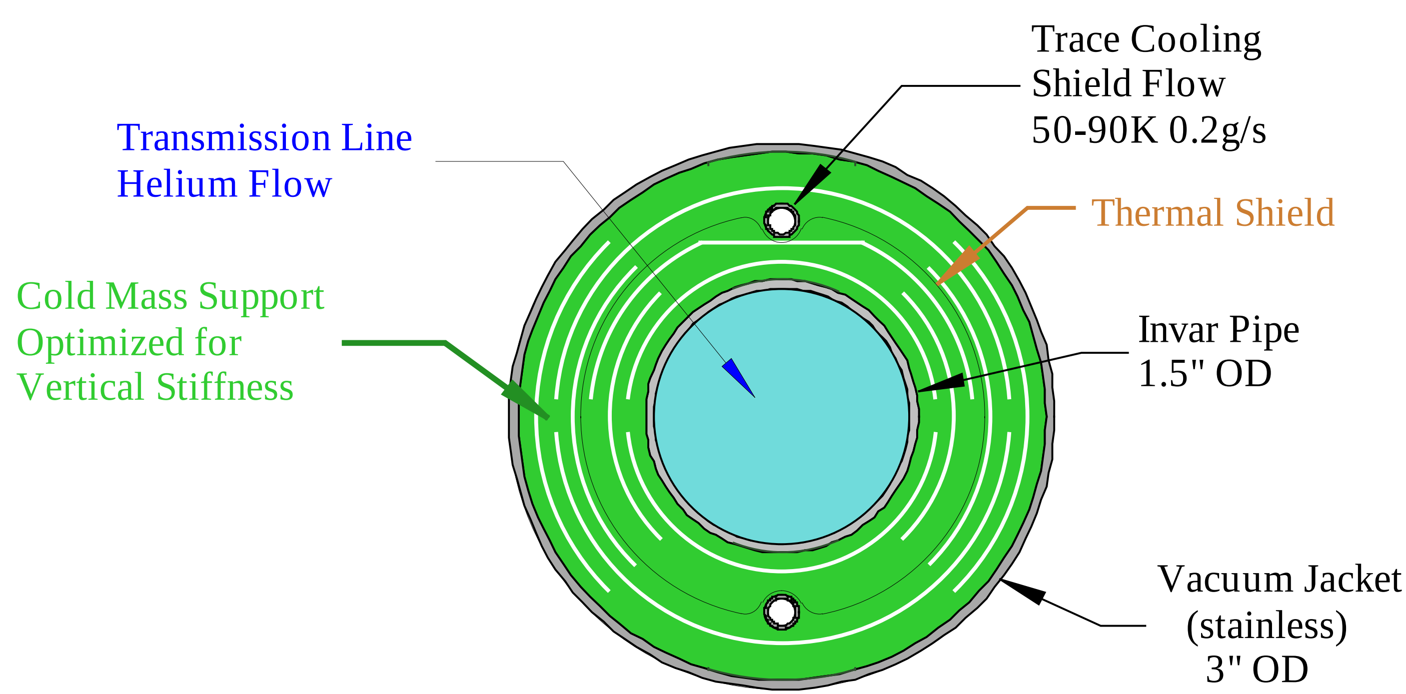
Cryopipe Support

- **Transmission Line Experiences Zero Force at Center of Yoke.**
- **Vertically off-center conductor sees decentering force:**
  - **200kgf per meter per mm offset.**
  - **Conductor is stable horizontally.**
- **Support must maintain small heat leak, high stiffness & strength.**

M. McAshan

Cryogenic Heat Leak in Transmission Line

Cold Mass Support for Shielded Transmission Line

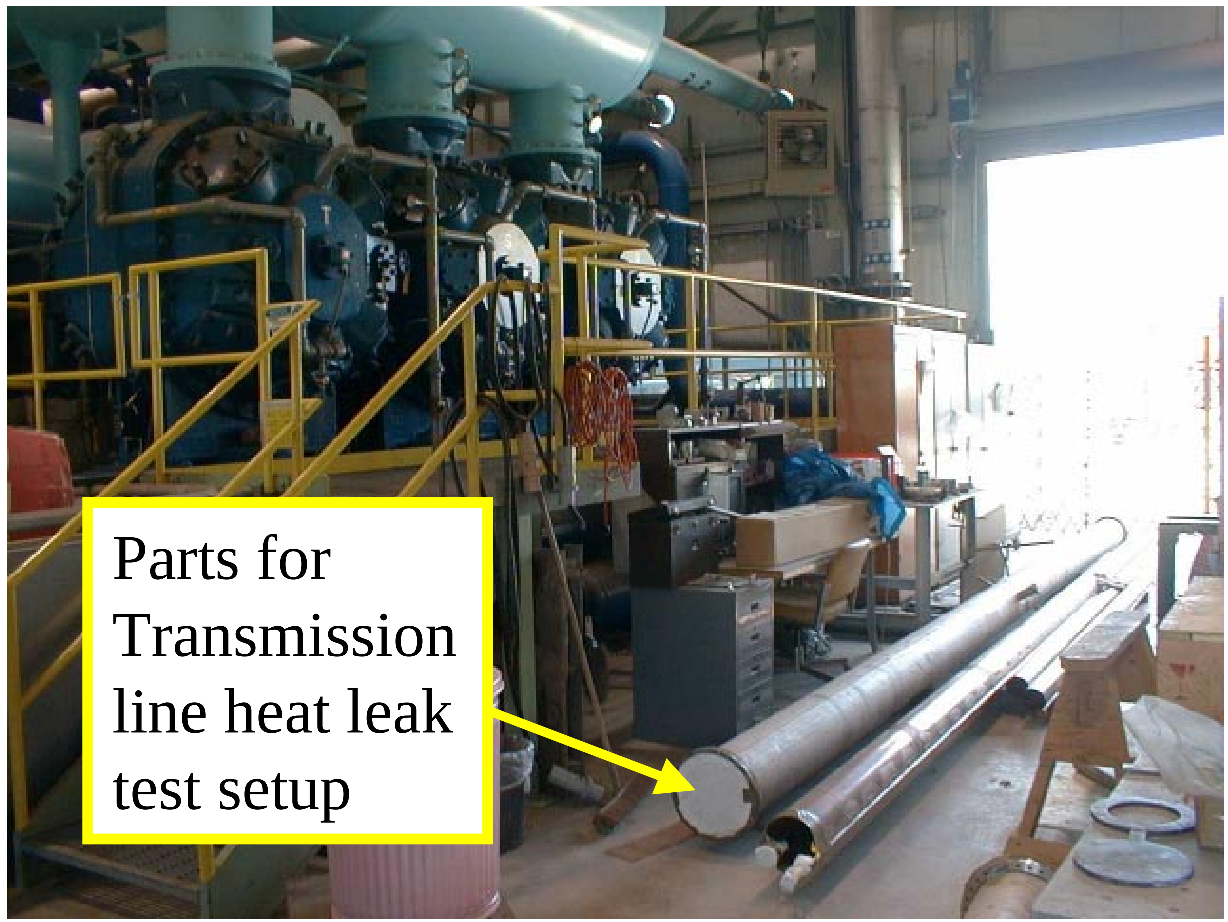


Transmission Line Heat Leak Test Setup at CHL (R.Walker)

Goal:

measure heat leaks into pipe <20 mW/m

- LN2 shield around entire assembly
- Adjustable shield to study heat leak vs. T



Cryogenic System

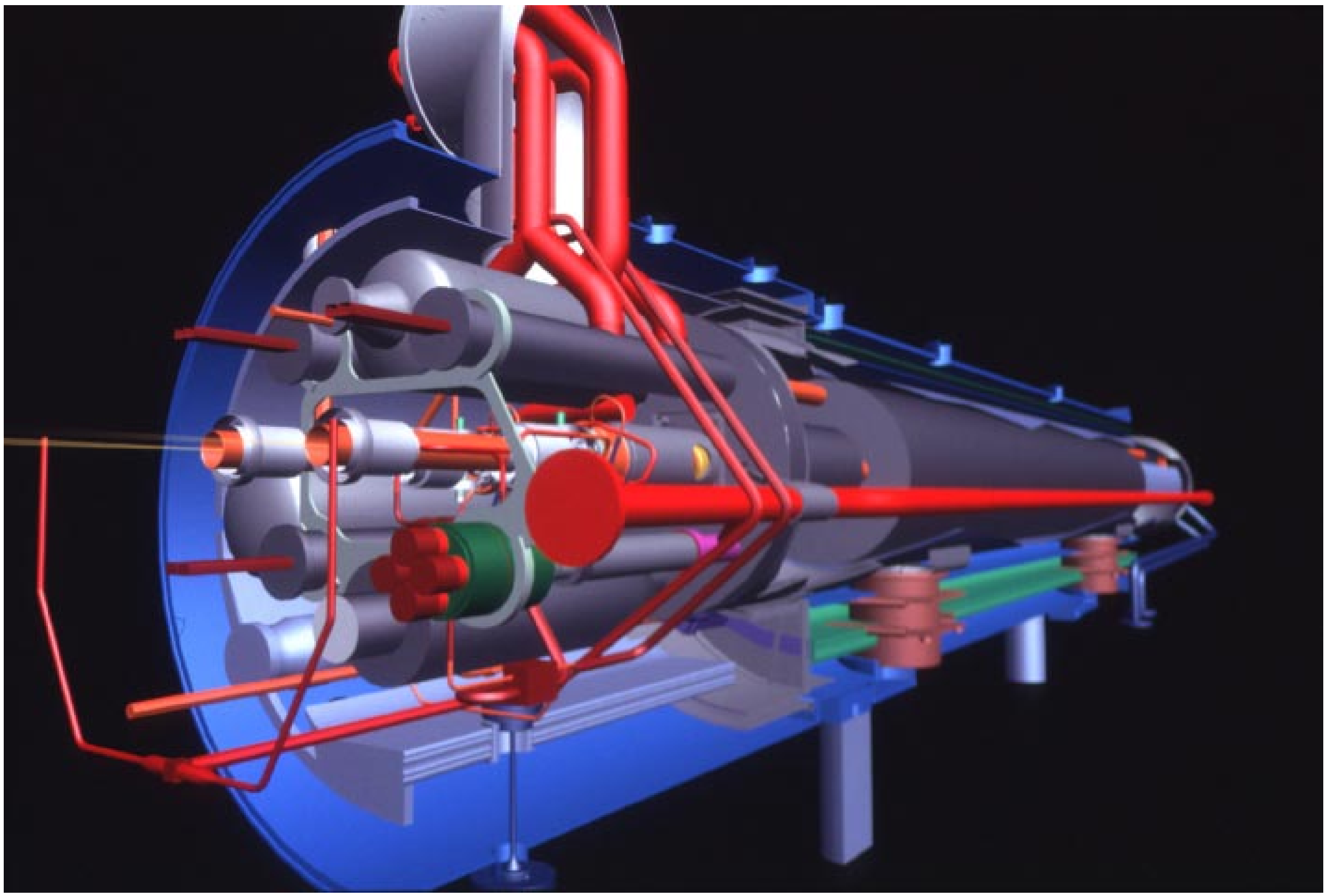
Are Cryogenics a big Deal?

- **SSC: 10 Cryo plants around ring**
  - **Wall power >40MW, cost >$200M**
- **LHC: 8 Cryoplants around ring**
  - **Wall power >40MW cost >$300M**
- **LF VLHC: Depends on Heat Leak and magnet design.**

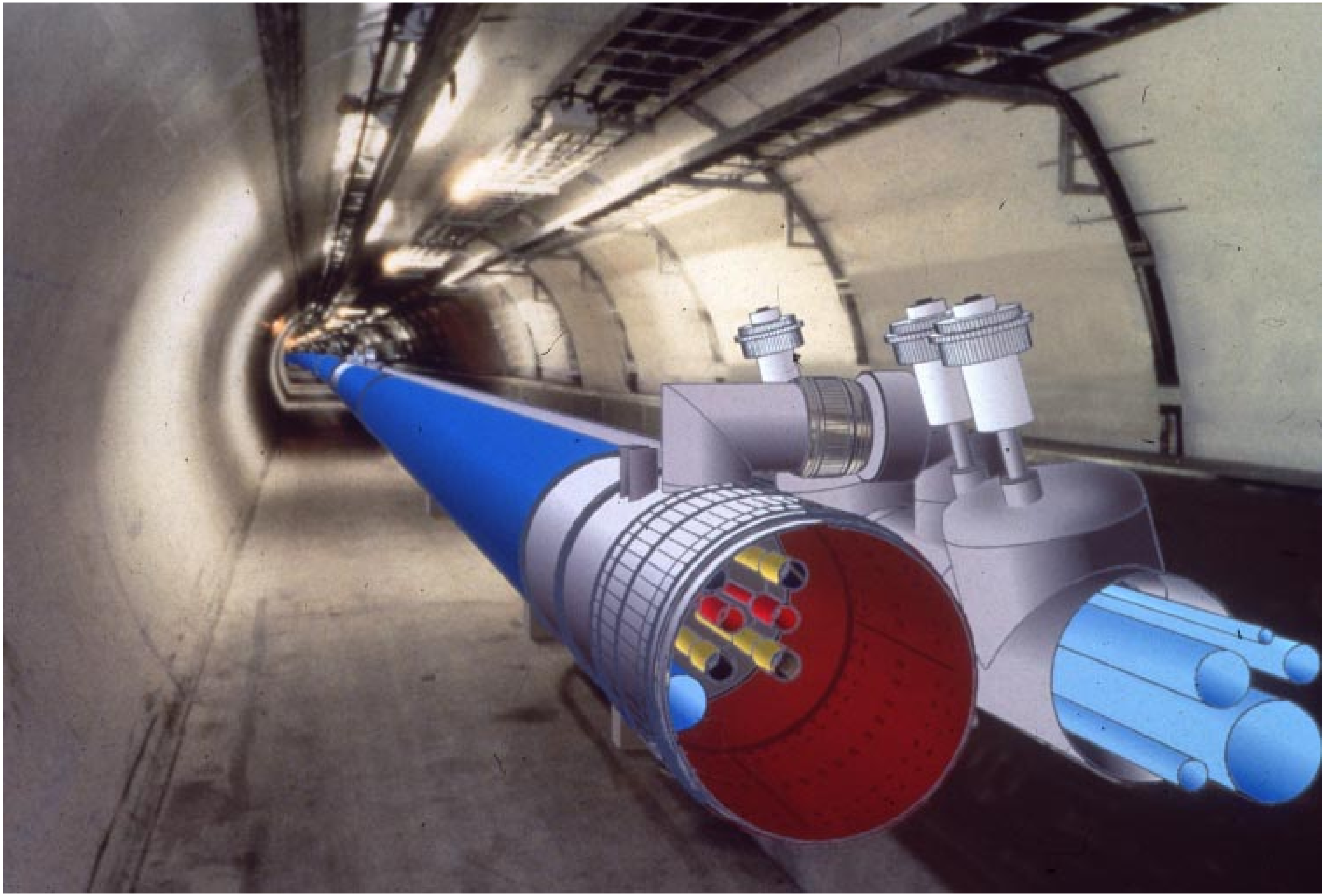
Cryogenic Tradeoffs

- Complexity
- Cost
- Power Consumption

Cryogenic Complexity



LHC Cryo Interconnect at each cell.



LHC Magnet & Cryogenic Service Pipe In Tunnel

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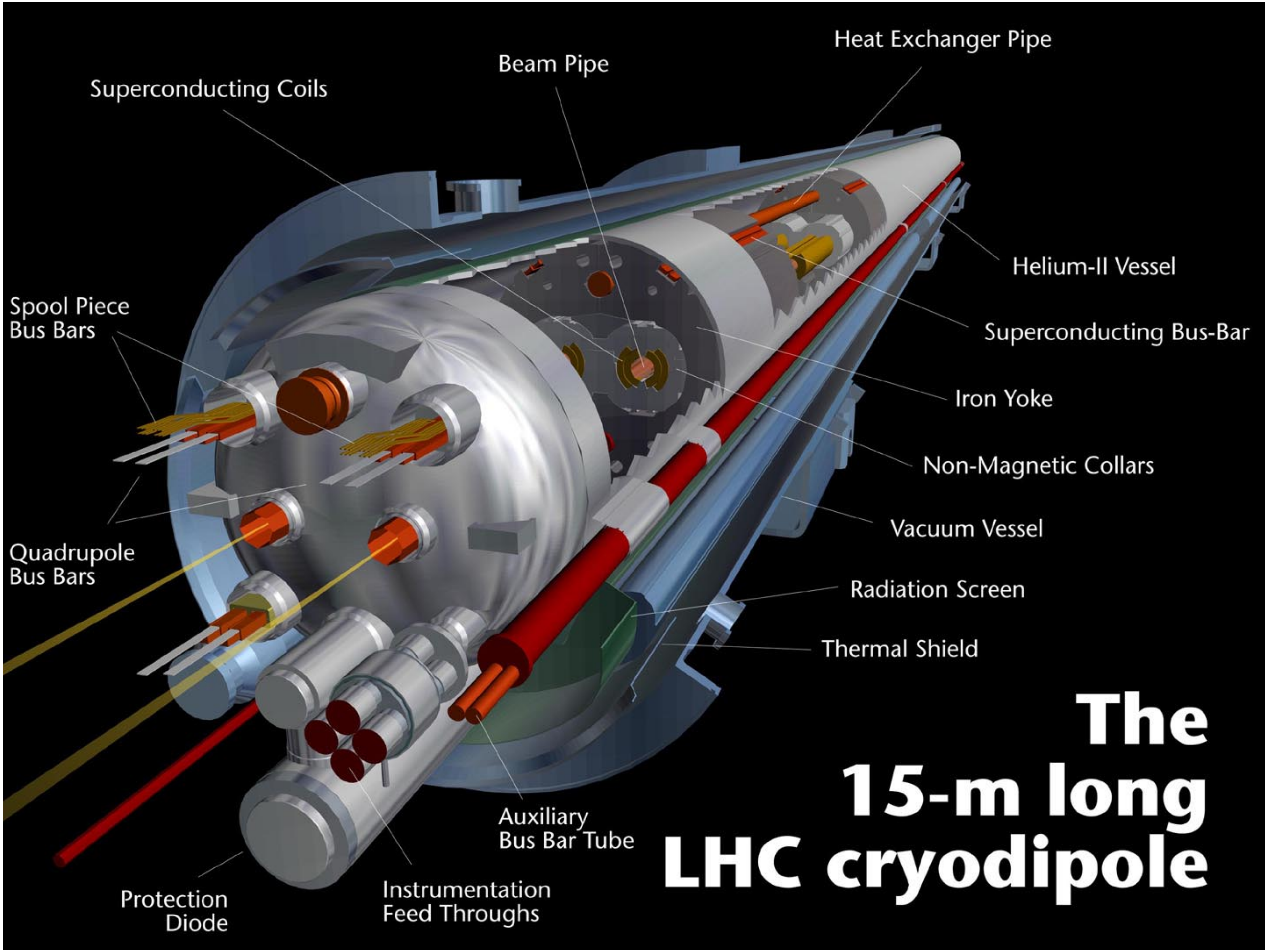
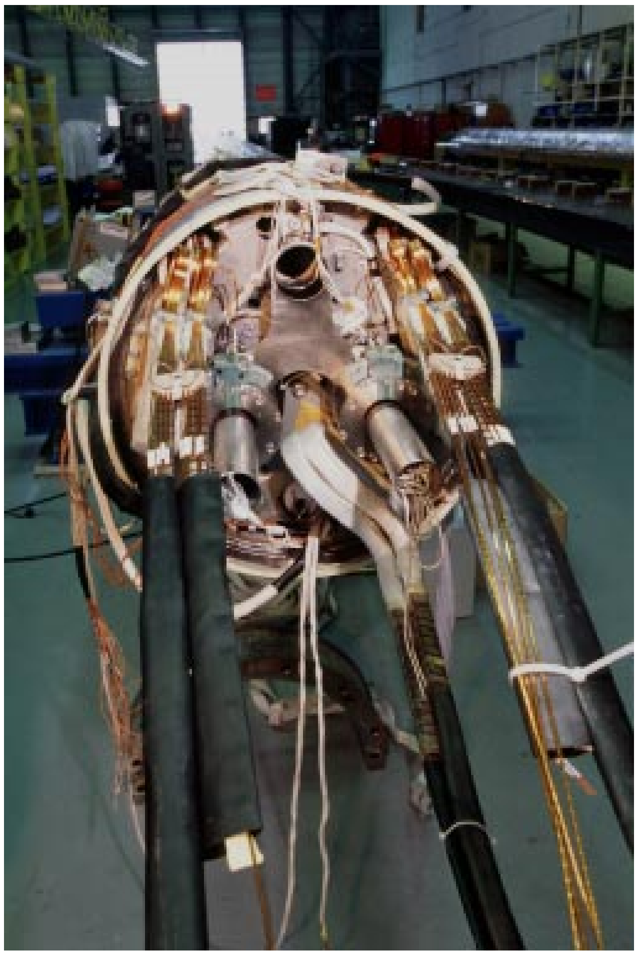
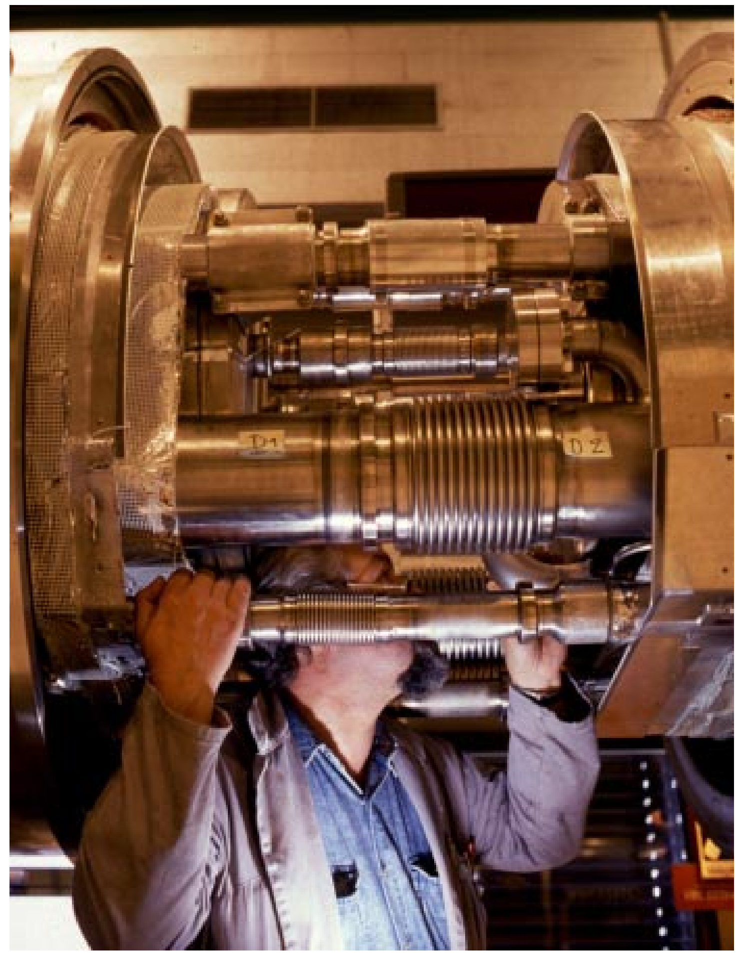
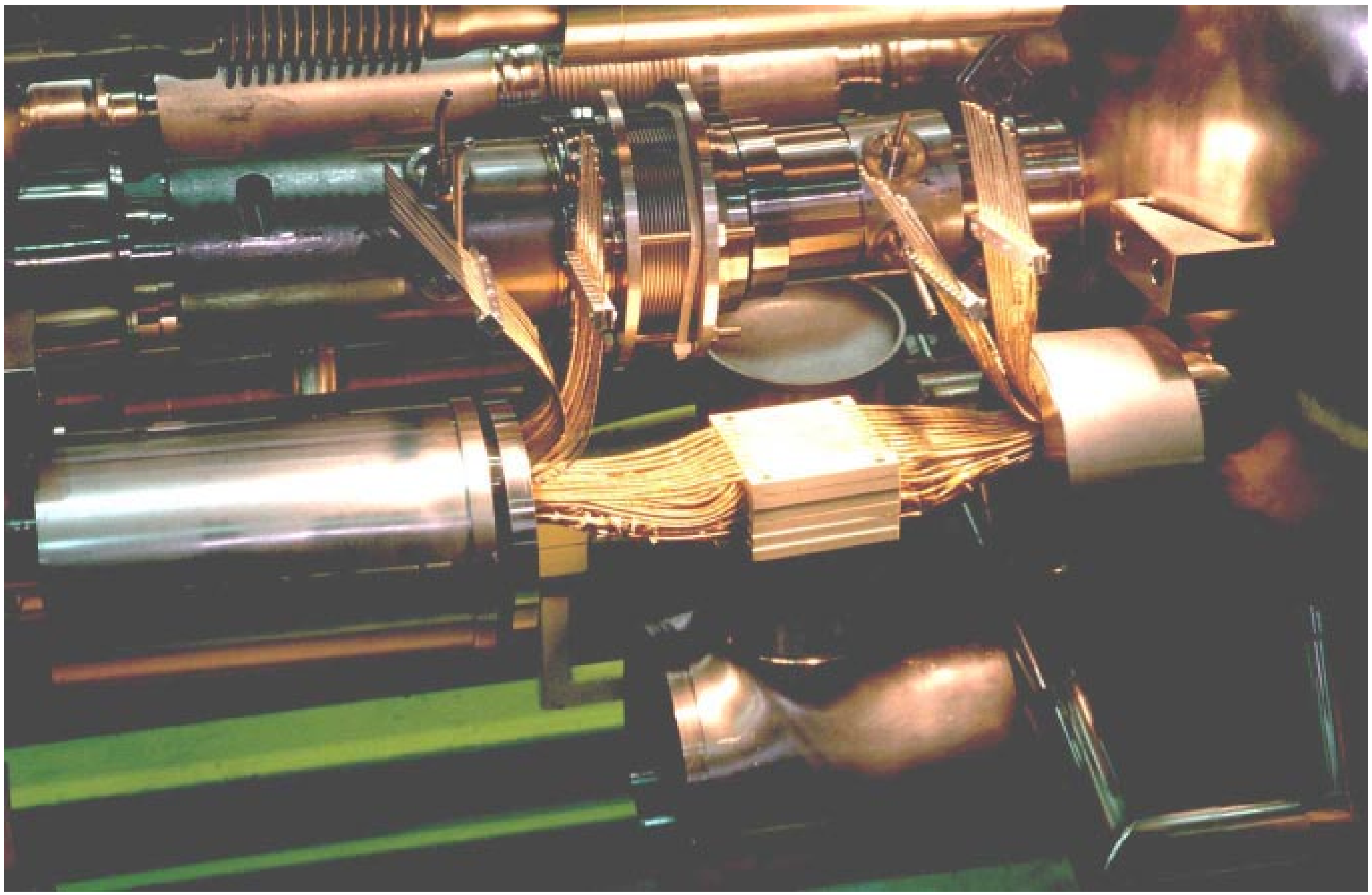

The 15-m long LHC cryodipole
Superconducting Coils
Beam Pipe
Heat Exchanger Pipe
Helium-II Vessel
Spool Piece Bus Bars
Superconducting Bus-Bar
Iron Yoke
Non-Magnetic Collars
Vacuum Vessel
Quadrupole Bus Bars
Radiation Screen
Thermal Shield
Auxiliary Bus Bar Tube
Protection Diode
Instrumentation Feed Throughs

What do the ends of 2-in-1 cold bore magnets look like?

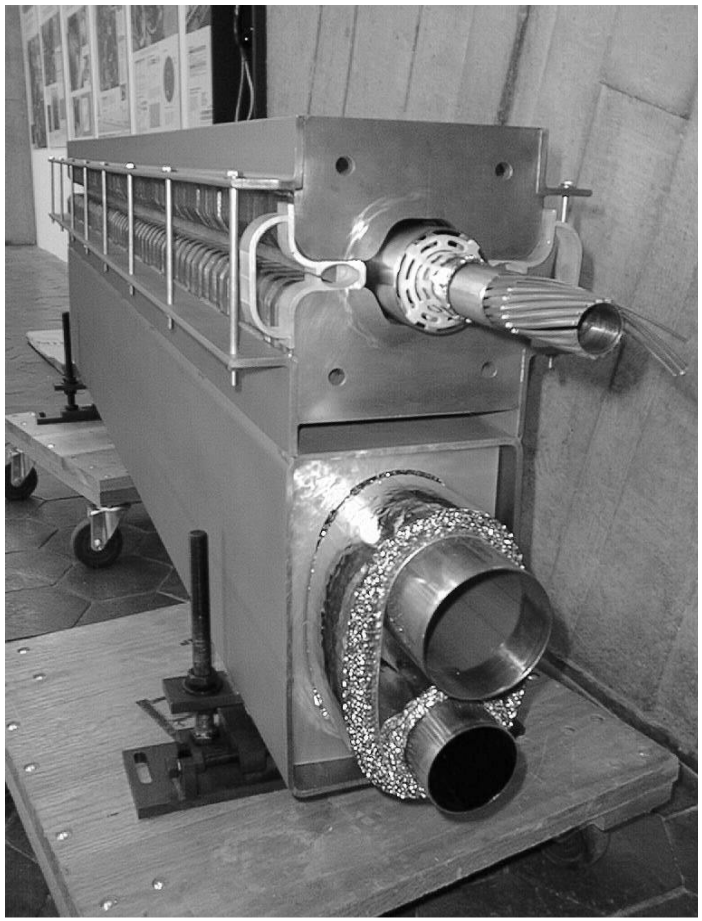




Splicing Ends of LHC Magnets



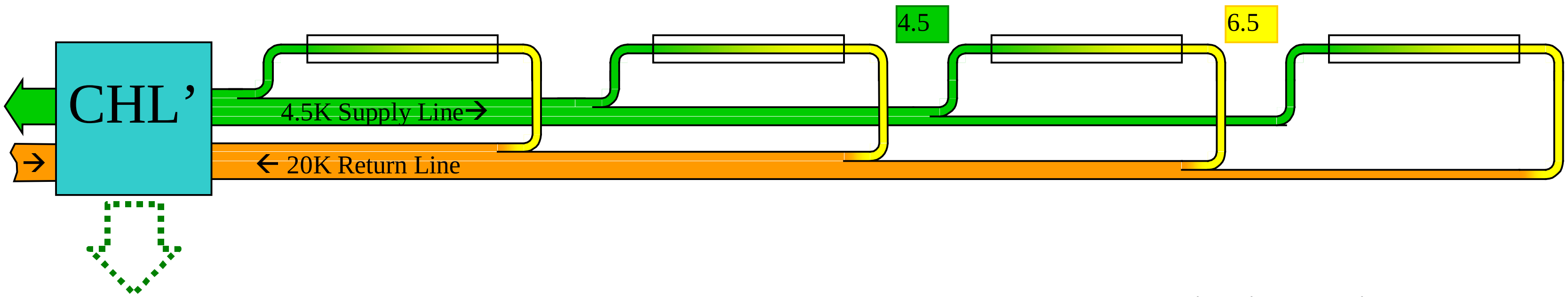
Transmission Line Magnet



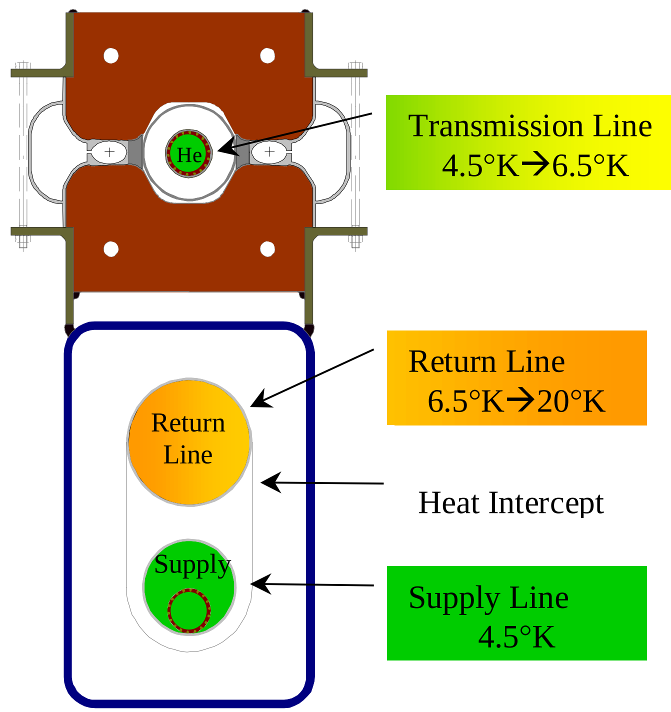
Magnet ends are simple, and far between.

3 TeV Injector Cryogenic System

← 8 x 4km Transmission Line Magnet Strings →



Transmission Line



Single Phase Cryogenic System

- Single Fluid (He at 2.5 bar)
- Low mass flow 2 x 160g/sec
- No Recoolers
- No Heat Exchangers
- Simple Control System & Piping
- Takes advantage of high Cp of Helium in critical region
- Wall Power for 3 TeV Machine < ½ of Tevatron

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3 Reference VLHC/3 TeV Cryosystems

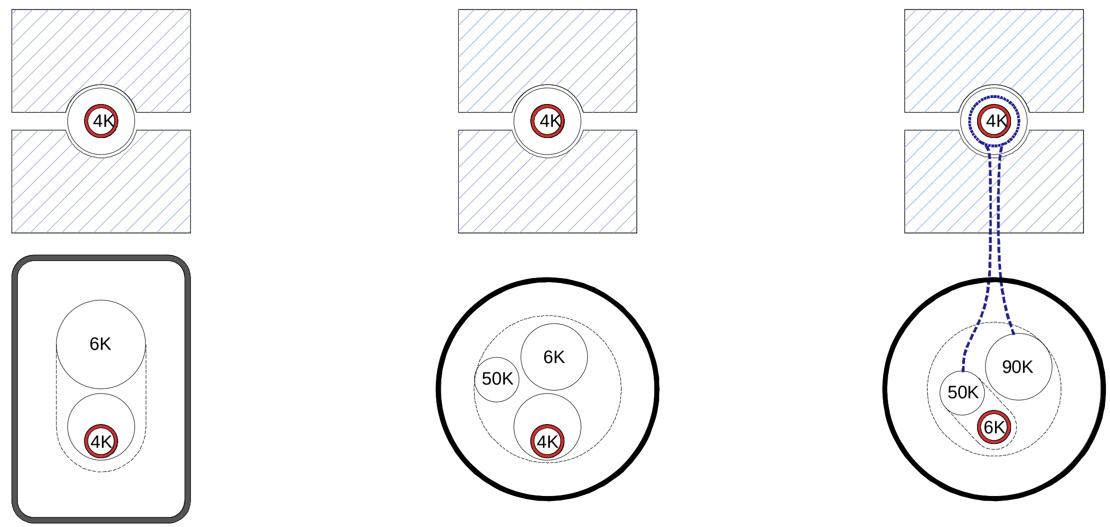
- **Unshielded**, 3 pipes, 2MW/TeV
- **Half-Shielded**, 4 Pipes, 1MW/TeV
- **Full Shielded**, 6 Pipes, 0.3MW/TeV

  =15MW for 50x50 TeV

- IR's are not negligible on this scale and must be included.

3 Cryogenic Options:
Performance vs. Simplicty

UNSHIELDED	HALF SHIELD	FULL SHIELD



3 PIPES	4 PIPES	5 PIPES
Wall Power 2 MW/TeV	Wall Power 1.1 MW/TeV	Wall Power 0.25 MW/TeV

Simplicity

Performance

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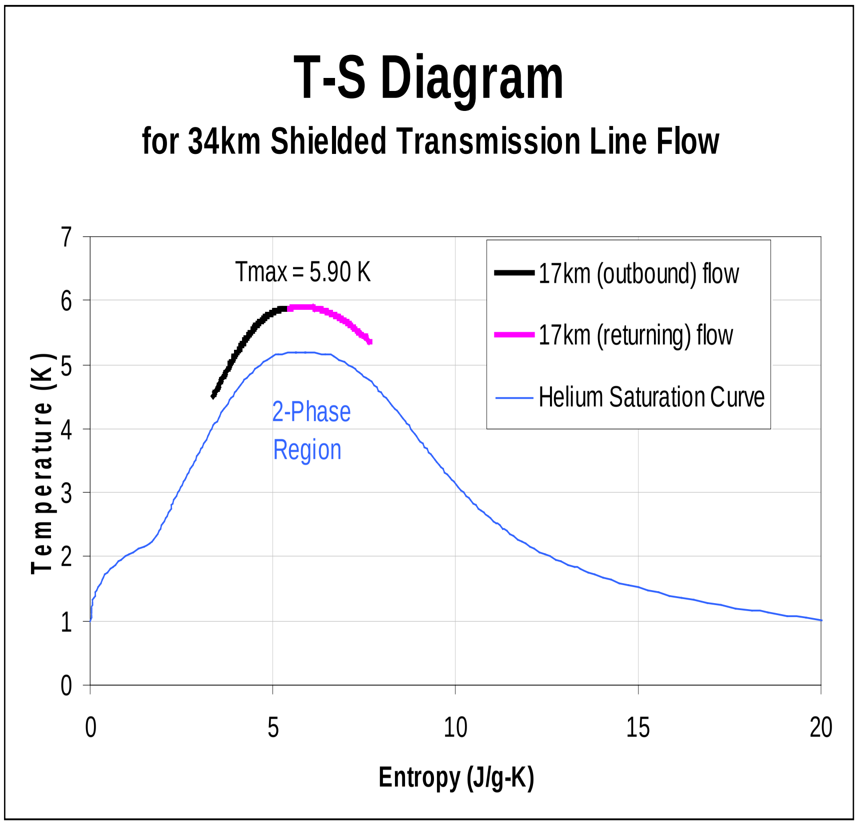
Transmission Line Flow



- Takes advantage of high heat capacity of He in critical region.
- Pressure drop in piping causes temperature drop due to J-T effect.
- No Re-Coolers.

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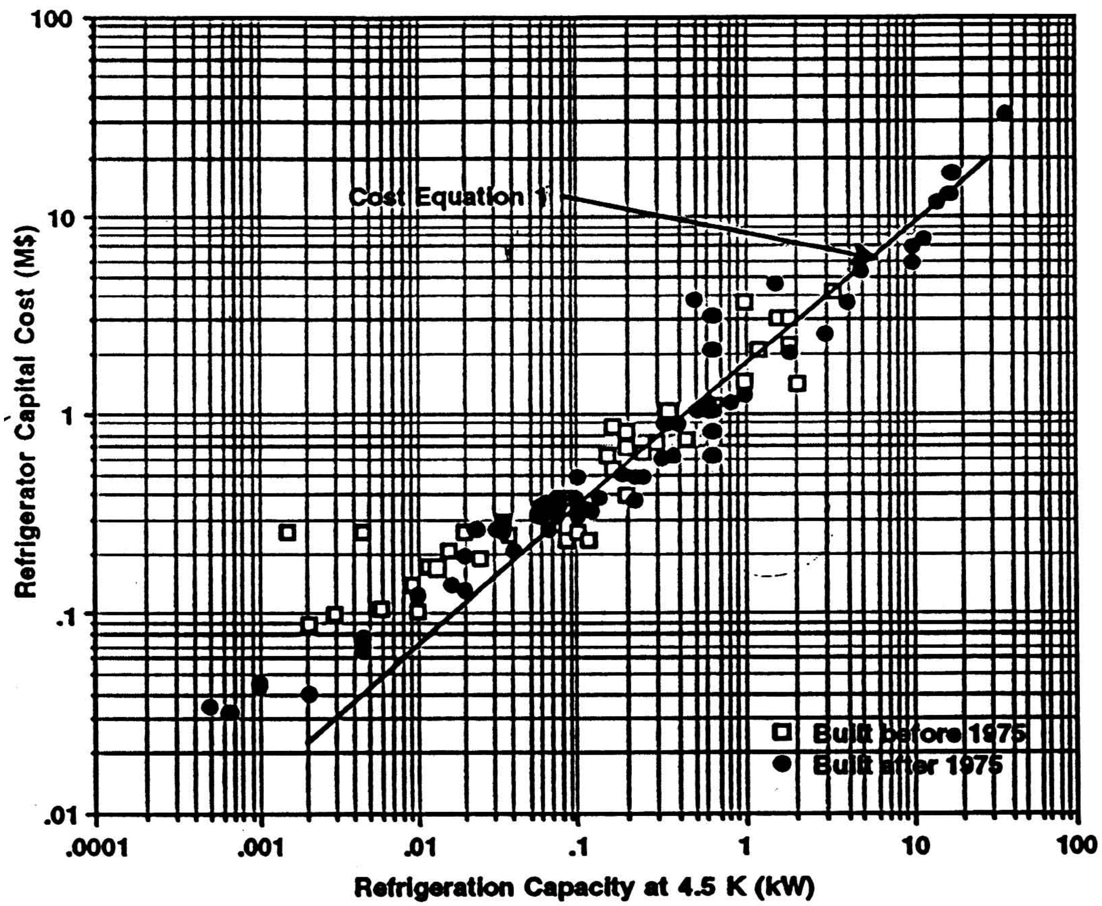
Cryogenic Reality Check: Tevatron LHe Transfer Lines

- TeV has ~8km of LN_2-Shielded Liquid Helium Transfer lines.
- Measured Heat Leak: ~300 Watts.
- Naïve scaling to 50x50 VLHC:
  - 18.75 kW (smaller than RHIC cryoplant).
  - Wall Power: ~5MW.
- VLHC is different (smaller pipes, bigger forces) but we’re in ball park.

Well Understood Cost-per-Watt of Cryoplant



- One Watt of heat at 4.5K costs about $1000
- 4 years operating cost: ~$200/W
- Total system cost ~$2K/W

What Does a 1.8kW of Refrigerator Look Like?

Fermilab Meson Lab Cryogenics (Satellite) Refrigerator

20kW are required for 100 TeV E_{CM}

Cryogenic Inventory

Is Helium Inventory a big deal?

- **SSC: 2,280 m^3 LHe**
- **LHC: 700 m^3 LHe**
- **LF VLHC**
  - **Unshielded: 2,500 m^3 LHe**
  - **Shielded: 700 m^3 LHe**

Liquid Helium Inventory for 3 TeV Machine

- 44 m^3 LHe in full-shielded line for 3 TeV
- Fermilab/CHL has single tanks this size.
- Also need gas storage...

VLHC Cryo Inventory

Fermilab’s Central Helium Liquefier

Superconductor Costs

- Historically, conductor costs are ~1/3 of magnet costs.
- Superconductor Cost =

=	Conductor Cost	($/kA-meter)
x	Magnetic Efficiency	(kA-Turn/Tesla)
x	Total Bend Field	(Tesla-meters)

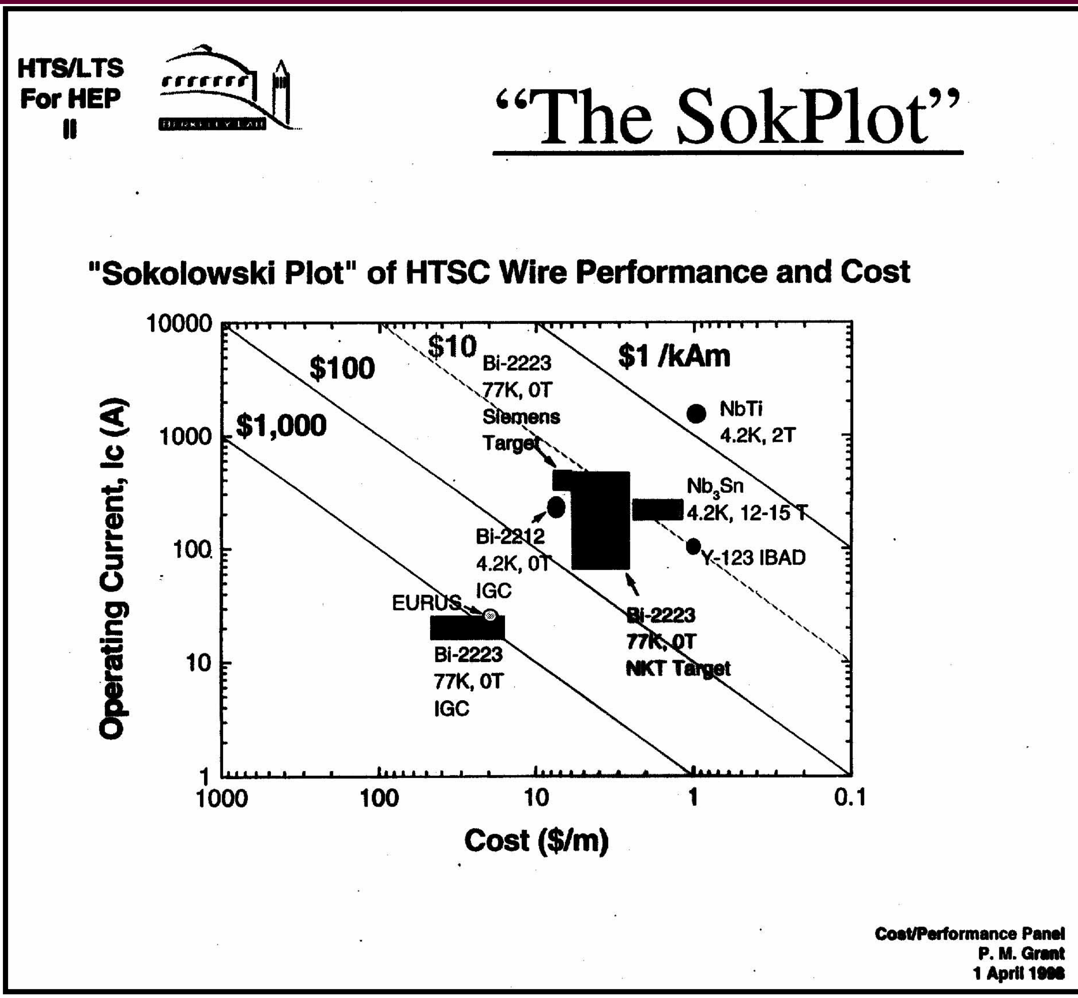
- 2M Tesla-m required for 50x50 TeV.

Superconductor Costs vs. Cryogenic Operating Temperature

As Temperature Increases:

- ➔ Superconductor costs go UP due to decrease in current density.
  - Depends on SC type, B-field, and efficiency of magnet design.
- ➔ Cryogenic costs go DOWN due to increase in Carnot efficiency.
  - Depends on heat load per TeV of magnet (including beam-associated).

Superconductor Cost



- Conventional NbTi is ~$0.50/kA-m.

  (Cheaper than Copper!)

- Nb_3Sn is 5-10x higher in cost.
- Cost <u>target</u> for High-Temp Superconductor is 20x Higher.

Conductor & Cryogenic Cost Optimization

- NbTi at 6K is cost minimum.
- Conductor costs ~$150 per meter of magnet or ~15% of parts cost.
- At today's prices, the increase in conductor costs for Nb_3Sn or HTS are not justified by their reduced cryogenics costs.

Beam Vacuum System

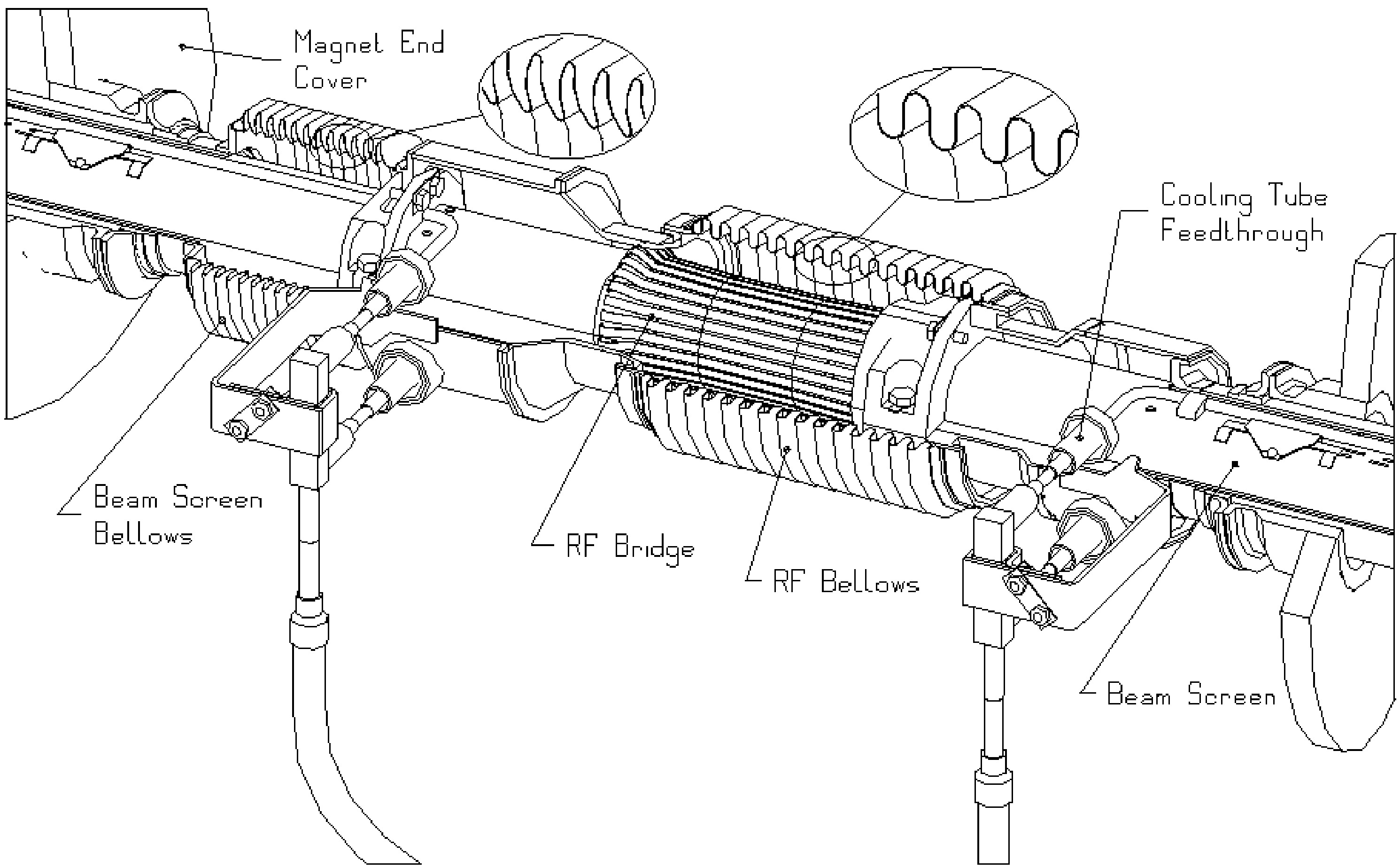
- Conventional SC Magnets have cold beam pipes with complicated interconnects and beam screens at E>20 TeV
- The Low-Field machine uses a warm bore which works at energies >> 100 TeV

  ...and is much cheaper.

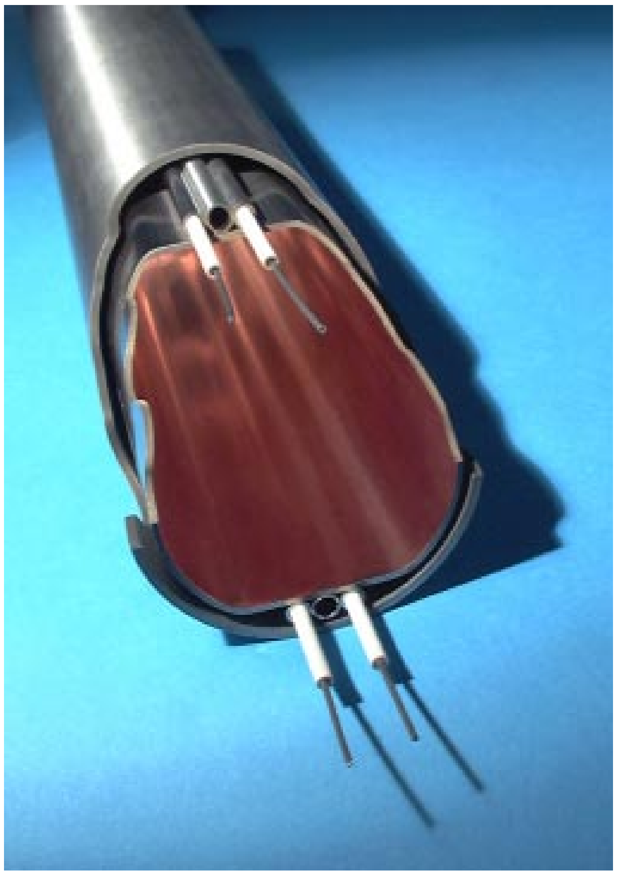
Beam Vacuum Connections

- The Vacuum Connections of a <u>Cold Bore</u> Magnet Must Deal With:
  - Thermal Contraction of Pipes during bakeout & cooldown
  - Beam Screen Cryogenic Flows
  - RF Continuity (Beam Impedance)
  - Cryogenic Instrumentation Leads
  - Warm $\leftrightarrow$ Cold Transitions

LHC Beam Vacuum Interconnects



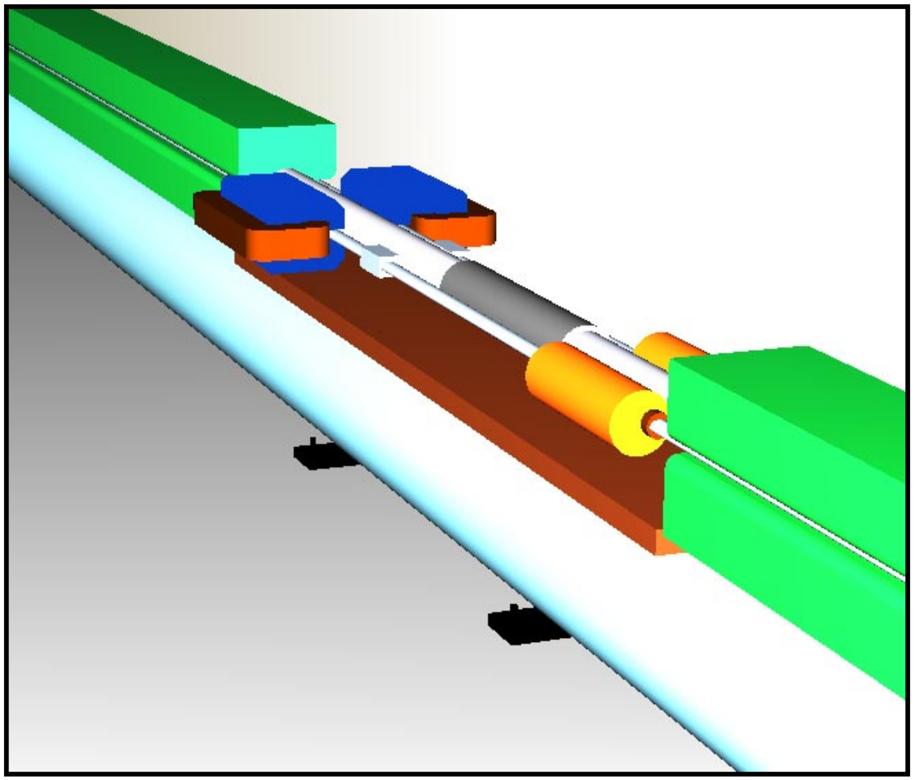
Beam Screen Needed for Cold-Bore/High Field Magnets



LHC Beam Screen Prototype

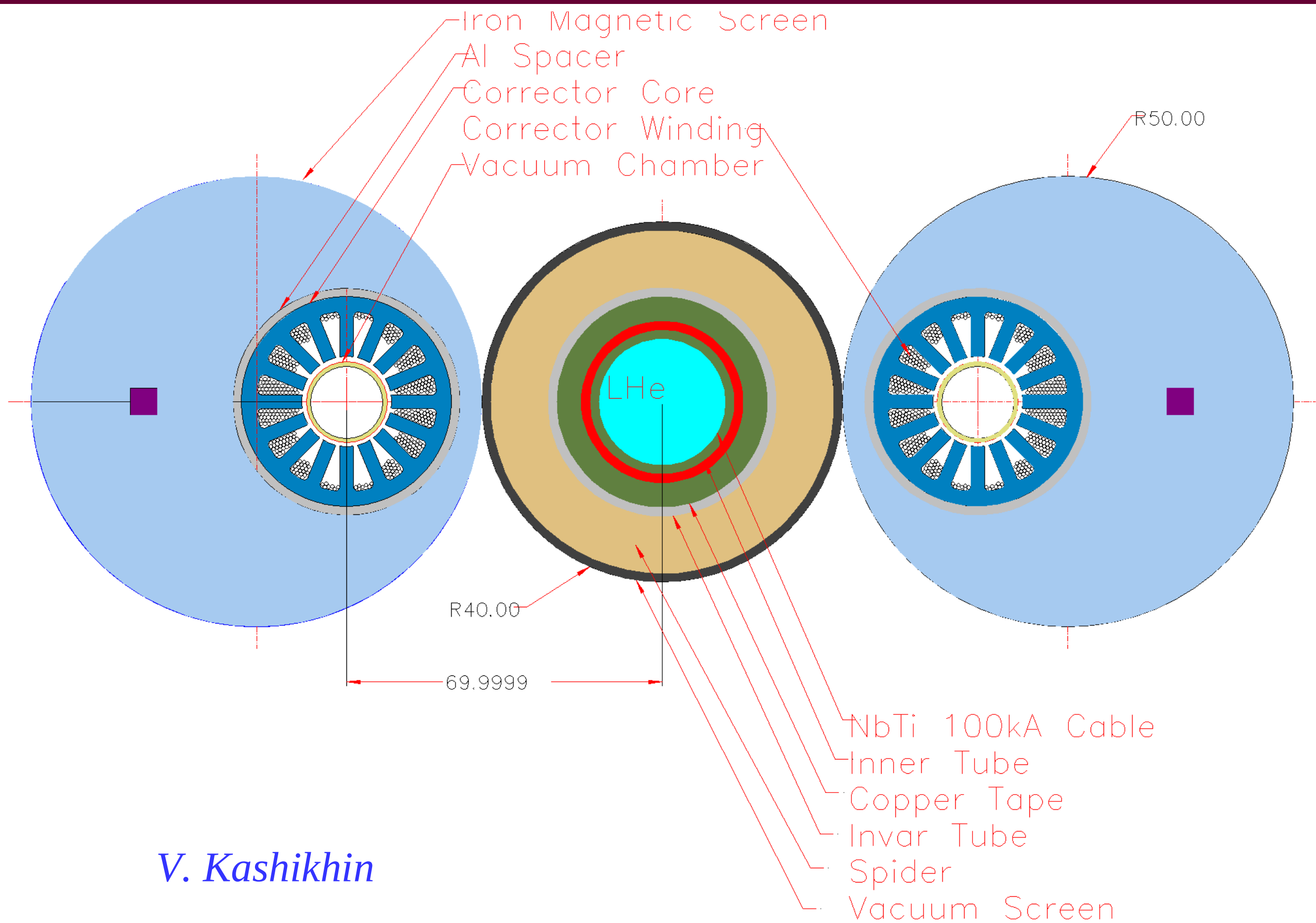
- Beam Screen needed to intercept synchrotron radiation
- Maintained at 10-30K by cryogenic trace cooling
- Electron Cloud Instabilities and H_2 Desorbtion

VLHC Beam Vacuum Interconnects



- Welded Joints in Aluminum Beam Pipe Extrusion
- Bellows-Free System Minimizes Cost & Leaks
- No Contribution to Beam Impedance

Corrector magnets



V. Kashikhin

- **Arbitrary Field Defects Corrector**
- **1kG Pole tip field**
- **~500W/meter dissipation**
- **Air Cooled**
- **No Cooling Water in Arcs**

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Corrector Magnet Example: 3 TeV Machine

- 0.1 Tesla Pole Tip Field
- 0.65m correctors every 65m cell
- Corrector Strength: (B_{CORR}/B_{CELL})
  - Injection (B=0.1T) : B_{CORR}/B_{CELL}=1%
  - Flat Top (B=2.0T) : B_{CORR}/B_{CELL}=.05%
- Expected Defects are at .01% Level at injection and few x .01% at B=2T

Corrector Magnet Power Dissipation (3 TeV)

- Average power per corrector ~200W
- Peak Power ~1kW for experiments
- 500 Correctors in 3 TeV Machine
  - 500kW Installed Corrector Power
  - 100kW average Power in tunnel
  - (heat leak into magnets (-)30kW)

System Can be Air Cooled

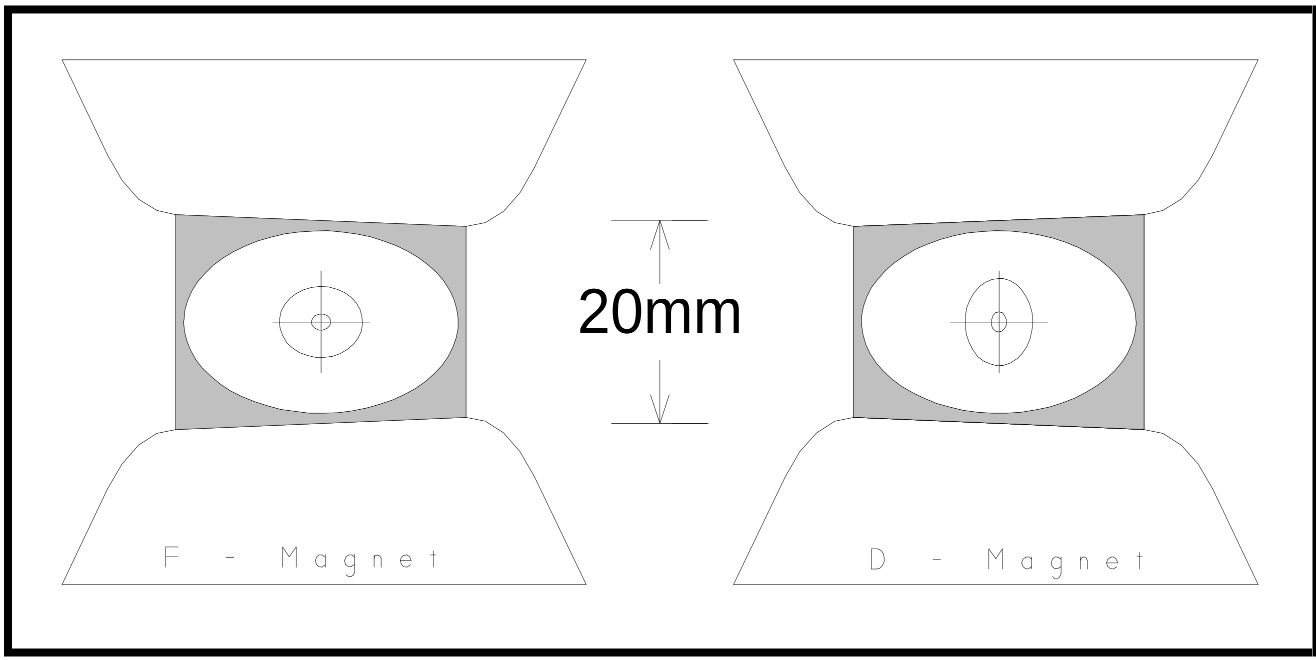
Corrector Power Supplies (3 TeV)

- Direct Cost of Power Supplies
  - Installed corrector power 500kW
  - Inverting power supplies ~$2/watt
  - Nominal Power Supply Cost $1M
- Power Distribution Wiring
  - Example: 500VDC x 100 Amps x 2 ckts
  - Allows direct DC-DC conversion
  - Requires 2-3cm^2 copper ~ $2M/ring
  - Incorporate wiring into magnets to avoid installation costs?

Other Corrector Possibilities

- Pole Face Windings
  - No Cooling Problems
- Moving Iron Blocks
  - Energized by Transmission Line
  - Automatically tracks bend field
  - Zero Power Dissipation
  - Iron Blocks have low failure rates
  - Stepping motors, manual or robotic operation

Beam Pipe Aperture



Beam Sizes in the 3 TeV Injector. The 95% beam envelopes for 15π beams (roughly the current FNAL collider emittances) are shown. The large ellipses show the beam envelope at injection energy (150 GeV). The small ellipses show the beam size at flattop (3000 GeV). The left and right pictures indicate the beam envelopes in the in the vicinity of focussing and defocusing half-cell locations. Lattice functions are β min =130m, β max = 200m, Dx = 6m. Beam sizes - 150 GeV: Rmin=3.5mm, Rmax=4.3mm; 3000 GeV: Rmin=0.8mm, Rmax=1.0mm. The magnet gap is 20mm x 30mm (h x v) and the beam pipe aperture is 18mm x 27mm. Beam sizes in the 50 TeV machine are roughly 2x smaller.

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Aperture Budget for 3 TeV Machine

	Horizontal	Vertical
15π 95% beam size @β-max, dP/P=.01%	± 4.4mm	± 4.3mm
Closed orbit distortion	± 0.5mm	± 0.5mm
Injection Steering Errs	± 1mm	± 1mm
BPM Offsets	± 0.1mm	± 0.1mm
Magnet Straightness	± 0.5mm	± 0.5mm
Magnet Settling (between realignments)	±1.0mm	±0.5mm
TOTAL	± 7.5mm	± 6.9mm
Available Aperture	± 10mm	± 9mm

Table 2 – Aperture at injection into the 3 TeV machine.

Accelerator Issues Resolved

- **Resistive wall at injection requires damper system**
  - **Similar to one already demonstrated in FNAL Main Ring (Marriner,McGinnis)**
- **TMCI more carefully calculated for low field magnet**
  - **Not a limiting factor for $L>10^{34}$ (Shiltsev et. al.)**
  - **Several means identified for further increases**

2 x 3cm warm bore supports ultimate $L > 10^{35}$

- **Aperture OK for resonant extraction for 3 TeV fixed target (Marriner).**
- **Proceeding with engineering design based on this aperture.**

100kA Transmission Line
17 meter Test Loop

Henryk Piekarz, Phil Schlabach, Phil Gallo of FNAL Tech Div.

Inductive Coupling
to avoid 100kA
Current Leads

4m Section is
Replaceable for
studying design
variants.

Use as “flux-pump”
to power long magnets.

Near -Term Plans

- Bring 17m Inductive Test loop into operation
  - Test "Leftover SSC" and Nb3Al Conductors
- Freeze Iron Cross Section & Build Long Magnet
  - Punch Iron Laminations
  - Energize with Inductive Test Loop
- Verify & Optimize Cryogenic Heat Leak
  - Key Input to Cryogenic System Design
  - Optimize Components on Heat Leak Test Stand
  - Measure Heat Leak on Long Magnet

Near -Term Plans (cont'd)

- Continue Preparations for Magnet Test String
  - 100kA DC Power Supply
  - Cryogenic Current Leads
  - Direct Connection to Meson Cyro
- Design Study for 3 TeV Injector
  - Technical Designs for all Components.
  - Evaluate progress on total system costs.
  - Identify physics opportunities for 3 TeV "bridge" program as Fixed-Target machine & Hadronic B-Factory.

Selected References for Low Field VLHC

Accelerator Physics & Instabilities

http://www.vlhc.org/tjef/wg2_summary.pdf

Accelerator Systems and Feedback

http://www.vlhc.org/lakeg/Marriner.pdf

Transmission Line Magnet Design

http://www-ap.fnal.gov/VLHC/vlhcpubs/pubs1-100/5/magnet_status.doc

Cryogenic System for Low-Field VLHC

http://www-ap.fnal.gov/VLHC/vlhcpubs/pubs1-100/87/cryo.doc

Slow Extraction from 3 TeV Machine

http://www-ap.fnal.gov/VLHC/vlhcpubs/pubs1-100/62/marr_slo.doc

Automated Tunneling

http://www-ap.fnal.gov/VLHC/vlhcpubs/pubs1-100/85/battery_tunneling.pdf

Searchable Index of VLHC Technical Papers:

http://www-ap.fnal.gov/VLHC/vlhcpubs/search.html