The Pipetron as an Engineering Model for 10 GW Electricity Transmission over 1,000 km

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In collaboration with G. W. Foster and H. Piekarz

IASS Brainstorming Workshop

Transporting Tens of Gigawatts of Green Power to the Market

12-13 May 2011, Potsdam, Germany

U.S. DEPARTMENT OF ENERGY

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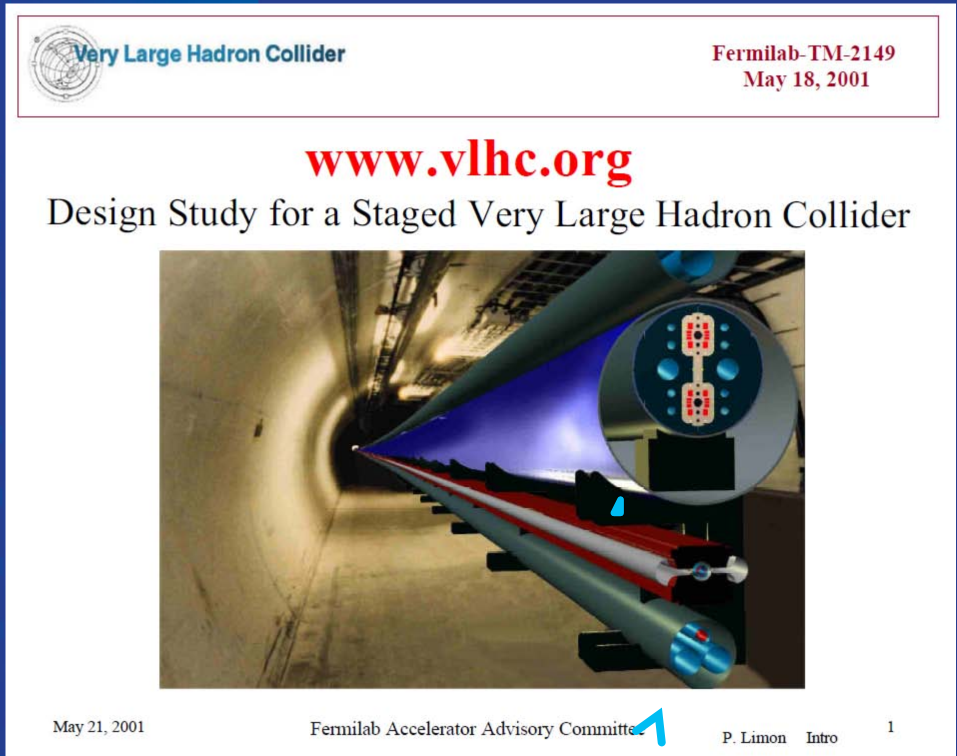
Overview of my message

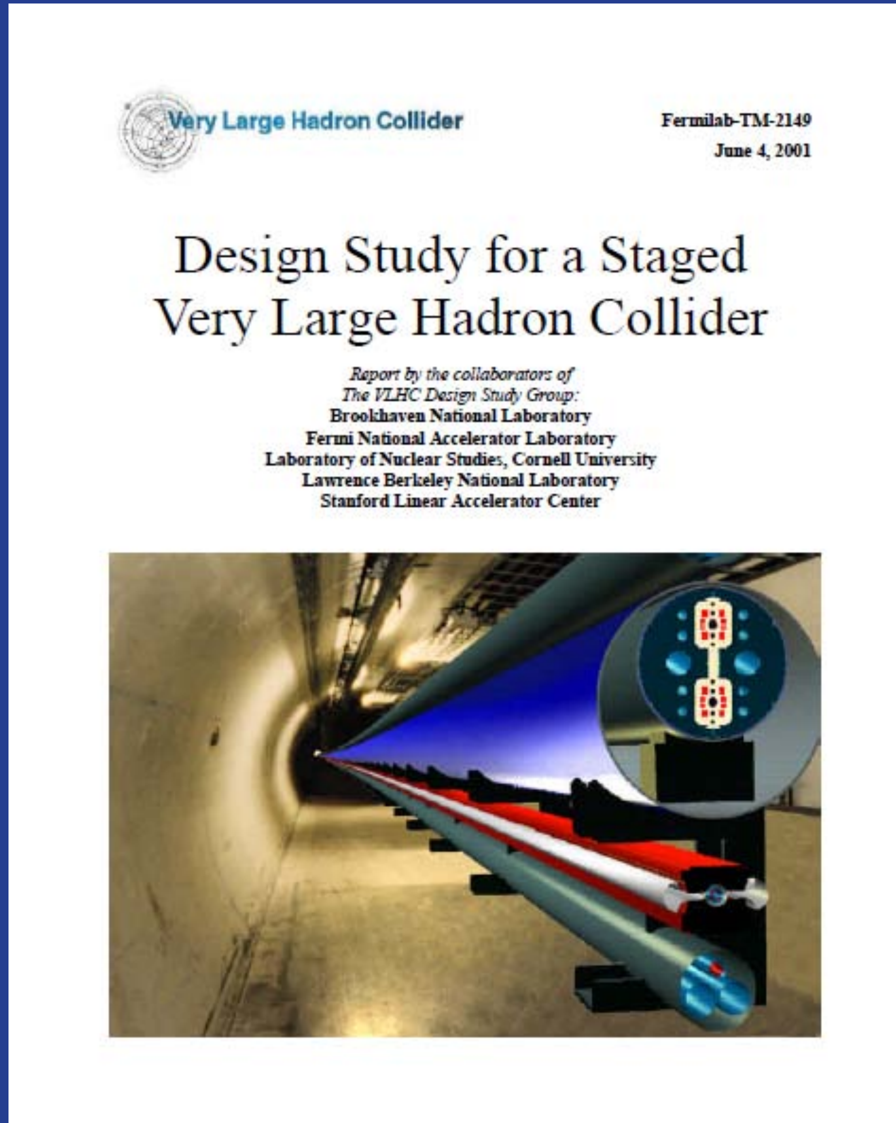
- *Accelerator concepts continue to use high-current (100 kA) DC superconducting transmission lines*
  - Fast injectors, low-energy rings
- *A 10 GW transmission line could be built today*
  - Installation like a liquefied natural gas (LNG) pipeline
  - Supercritical He cryogenics operating at ~6 K multiplies capacity and provides operating margin
    - ~10% of heat load occurs at splices
    - 100 MW over 1,000 km competes with UHVDC
  - Scale of project, including conductor procurement, is like that of an accelerator physics project
- *Long (1,000 km), high-power transmission lines are a reasonable cost for the overall renewable scheme*
  - Superconducting lines are favored at 10+ GW levels

Outline

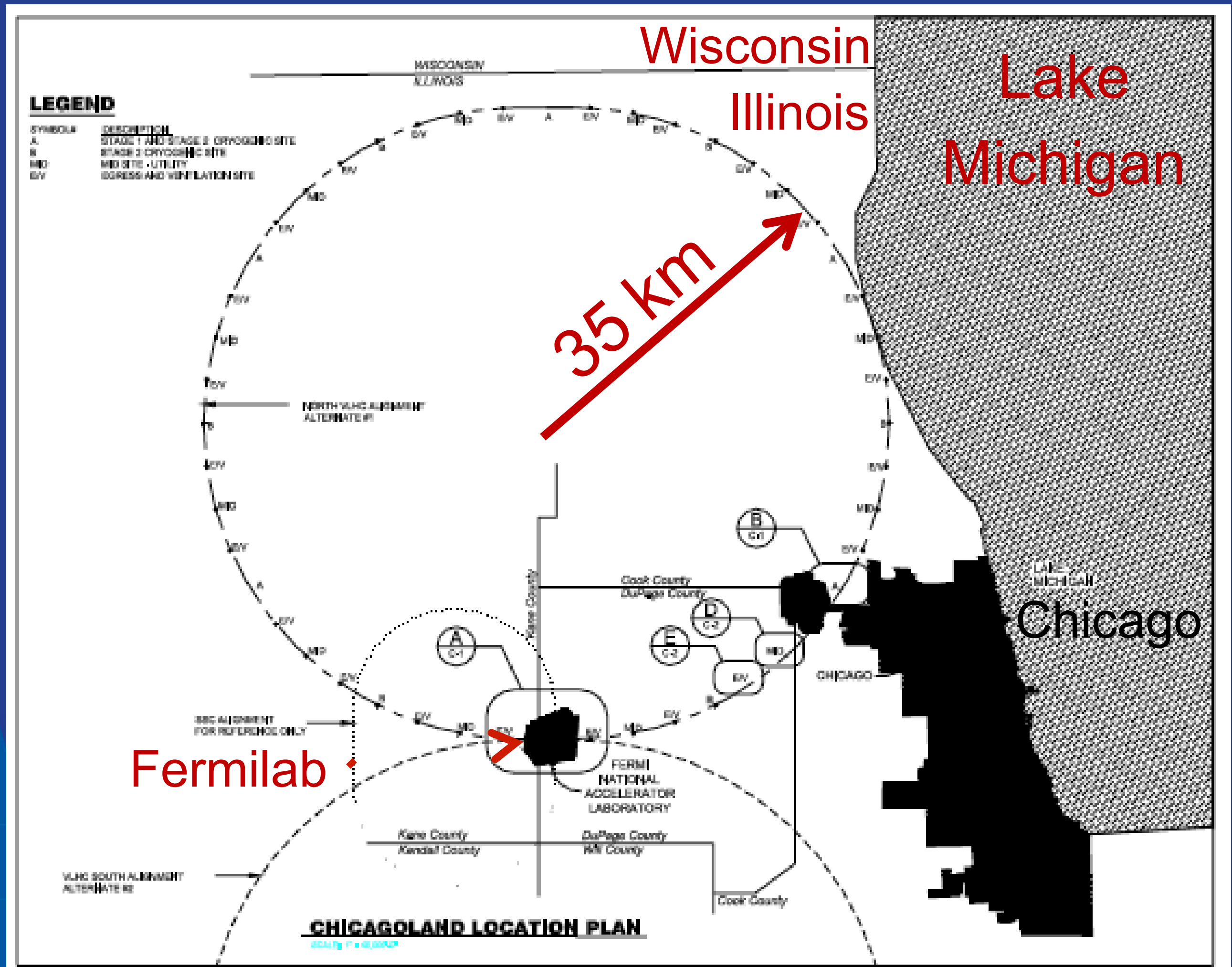
- *Review of enbineering from the Very Large Hadron Collider study (a.k.a. "Pipetron") that may be useful for the present discussions*
    - I gratefully acknowledge assistance from GW Foster and H Piekarz, as well as the rest of the VLHC team
- *Superconductor costs*
- *Considerations for a 10 GW transmission line operating at 100 kA and 100 kV over 1,000 km*



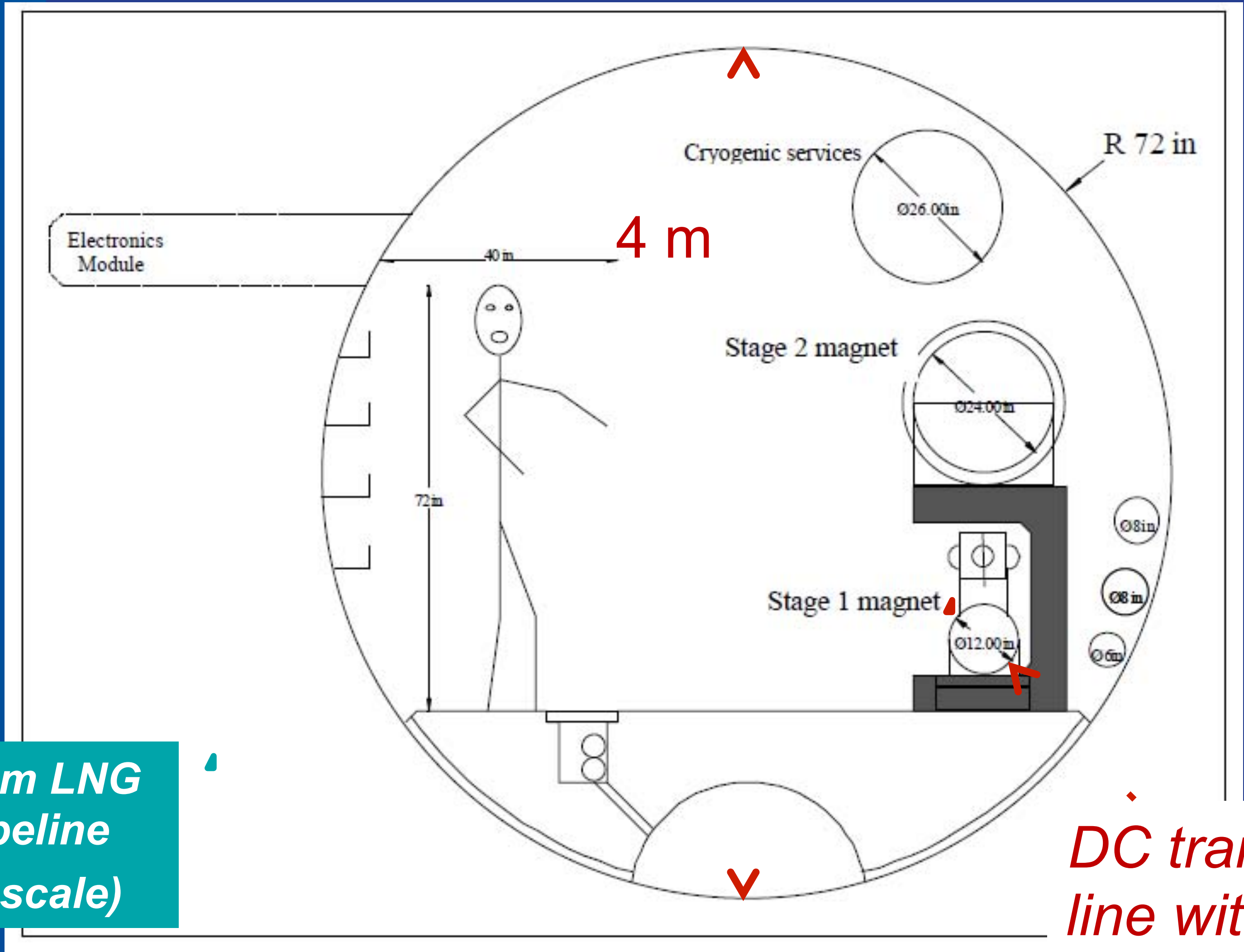
Stage 1: 40 TeV
"Transmission line" magnet
Stage 2: 200 TeV from ~11 T superconducting magnets



A big, deep tunnel was considered, 233 km around



Complexity of the design study was much greater than needed for a simple DC transmission line



60 cm LNG pipeline (to scale)

DC transmission line with cryostat

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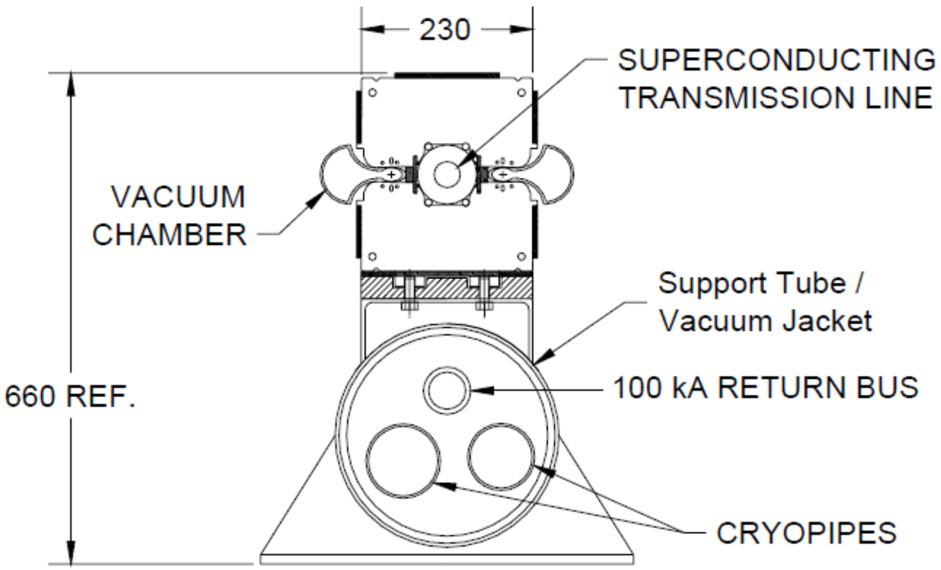
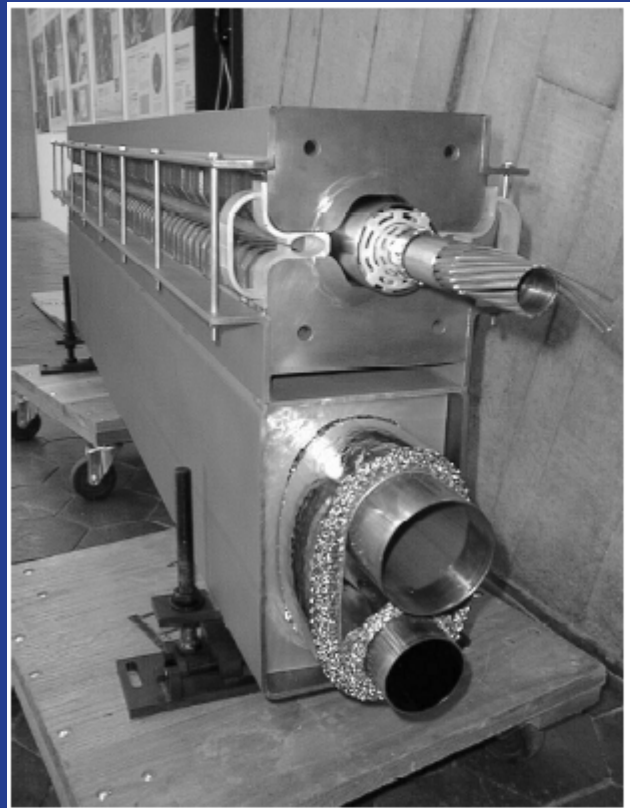
Transmission Line Magnet



- 2-in-1 warm iron warm bore superferric
- alternating gradient (no quads)
- 100kA Transmission Line
- all-piping cryogenic system

G.W. Foster AAC May 2001

GW Foster et al, Proc. PAC 1999



Transmission Line Design Requirements

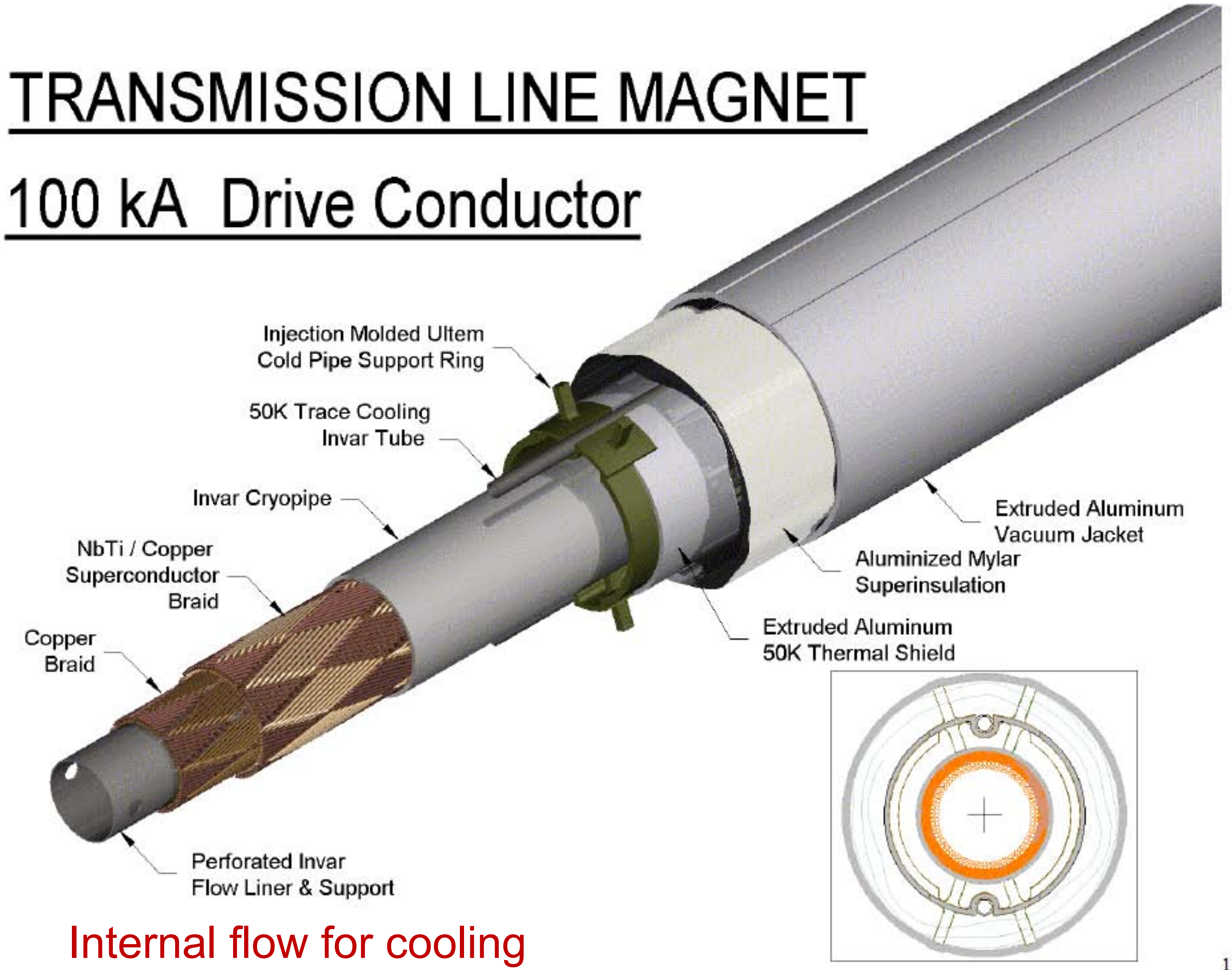
- Enough NbTi to carry 100kA at 6.5K, 1T
  - (includes margin: T_{NOM}= 6.0K, I_{NOM}=87.5kA)
- 2.5cm clear bore for He transport 9.5 km
- Enough Cu to survive quench with τ = 1 sec
- Withstand 35 Bar quench pressure
- Conductor centered +/- 0.5mm
- Low heat leak: < 50mW/m (with all the magnets)
- Survive cooldown *with ends constrained*

$\Rightarrow$ Invar™ transmission line piping

G.W. Foster AAC May 2001 12

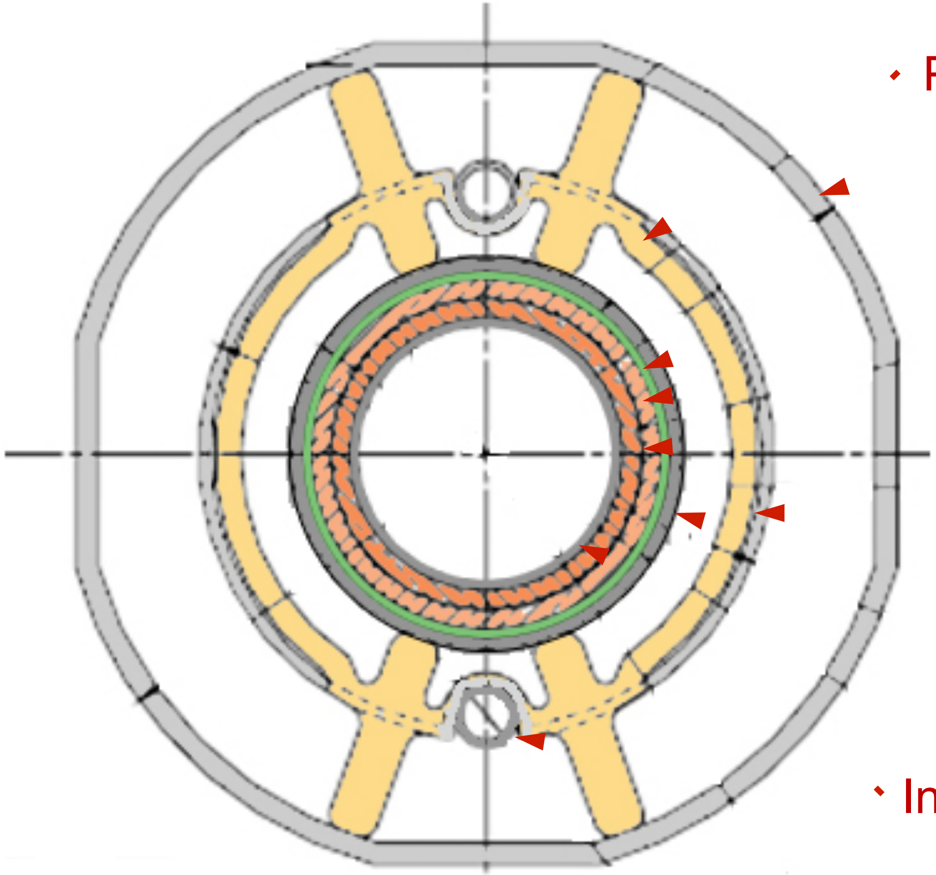
TRANSMISSION LINE MAGNET

100 kA Drive Conductor



Internal flow for cooling

Transmission Line Cryostat



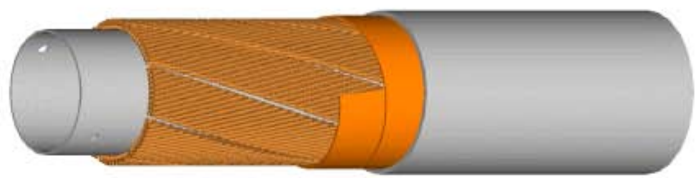
- Resist Vertical Decentering Force
- Low Heat Leak

Three Transmission Line Variants

	Drive Bus	Return Bus	Bus in Corr. Space
Cu/SC ratio in strand	1.8	1.8	1.3
Diameter (mm)	0.648	0.648	0.808
Cond. Type	Braid	Braid	9 Rutherford Cables
Number of strands	288	288	270
Cu Wire dia. (mm)	0.64	0.64	0.64
Number of wires	240	288	288
Inner Pipe ID .(mm)	25.3	36.8	36.8
Outer Pipe OD (mm)	38.1	47.1	50.1
Max working Pressure (bar)	40	40	40

BRAIDED CONDUCTOR
(Drive and Current Return)

RUTHERFORD CONDUCTOR
(Corrector Region)



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Nb-Ti cables and splices

GW Foster et al, Proc. PAC 1999

Fig. 4 – End of transmission line conductor. From right to left: Invar pipe jacket, superconducting cables, perforated Invar former, and expanding plug.

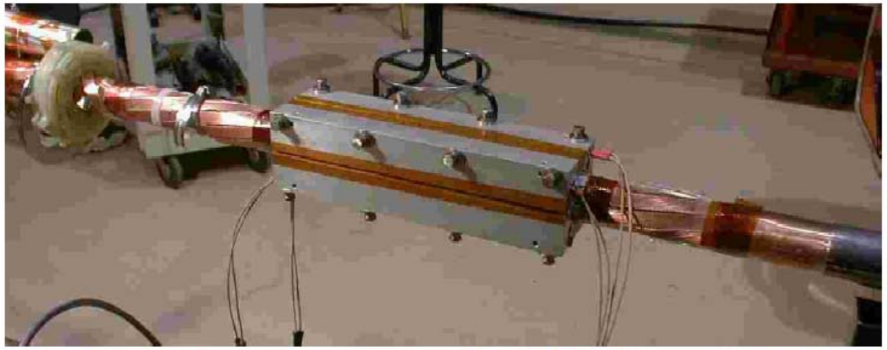
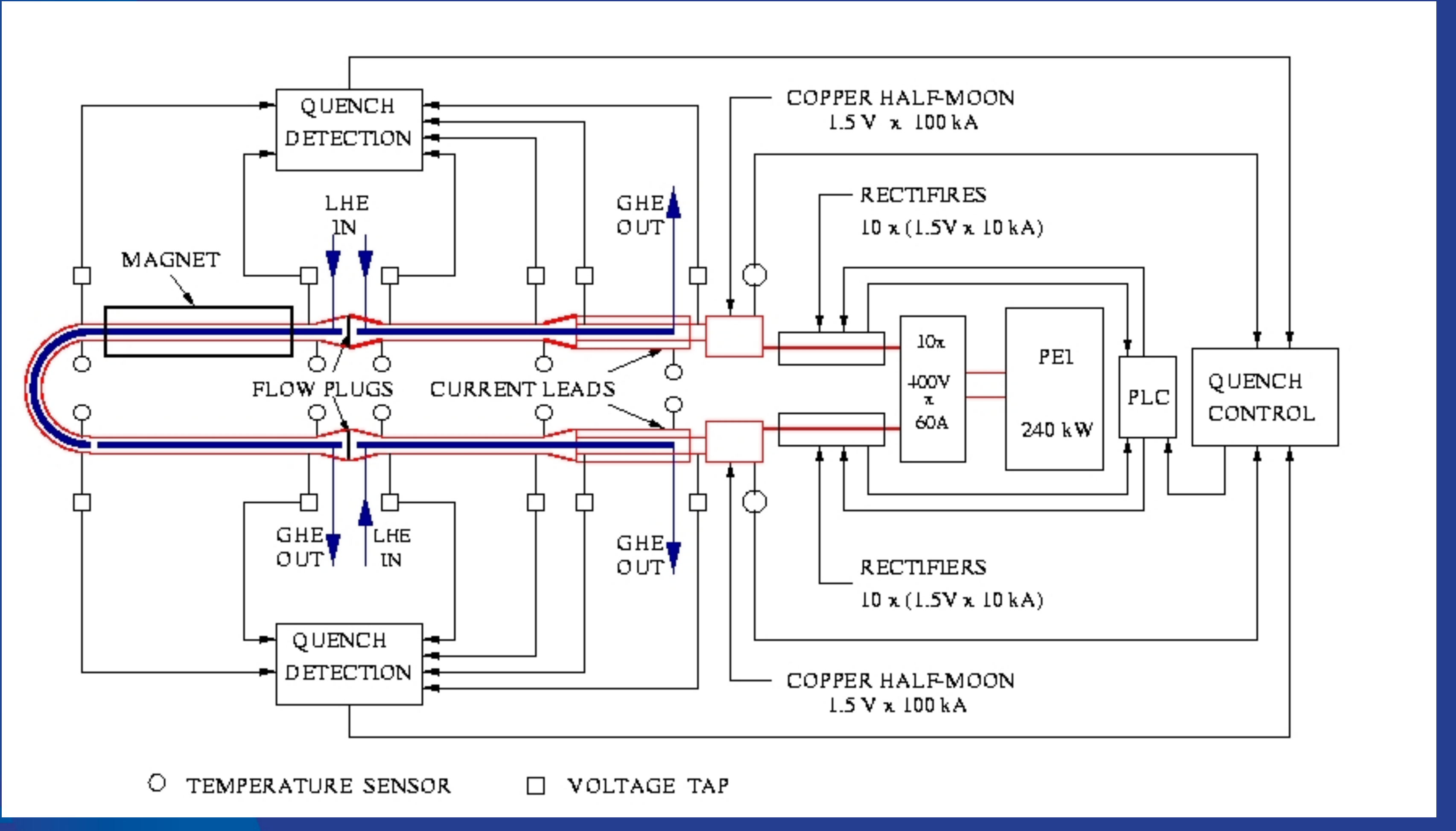


Fig 5 - Splicing technique for 100kA conductor test facility. Pre-tinned cables are interleaved and clamped in an aluminum 4-way split block with heating cartridges and temperature regulation.

Fig. 6 – Completed splice for the conductor test loop. After soldering, the conductor is wrapped in copper tape to allow clamshell welding of the helium pipe over the splice. The vacuum jacket is made up with telescoping sections over the splice region.

100 kA test schematic



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100 kA conductor test!

GW Foster et al, Proc. PAC 1999

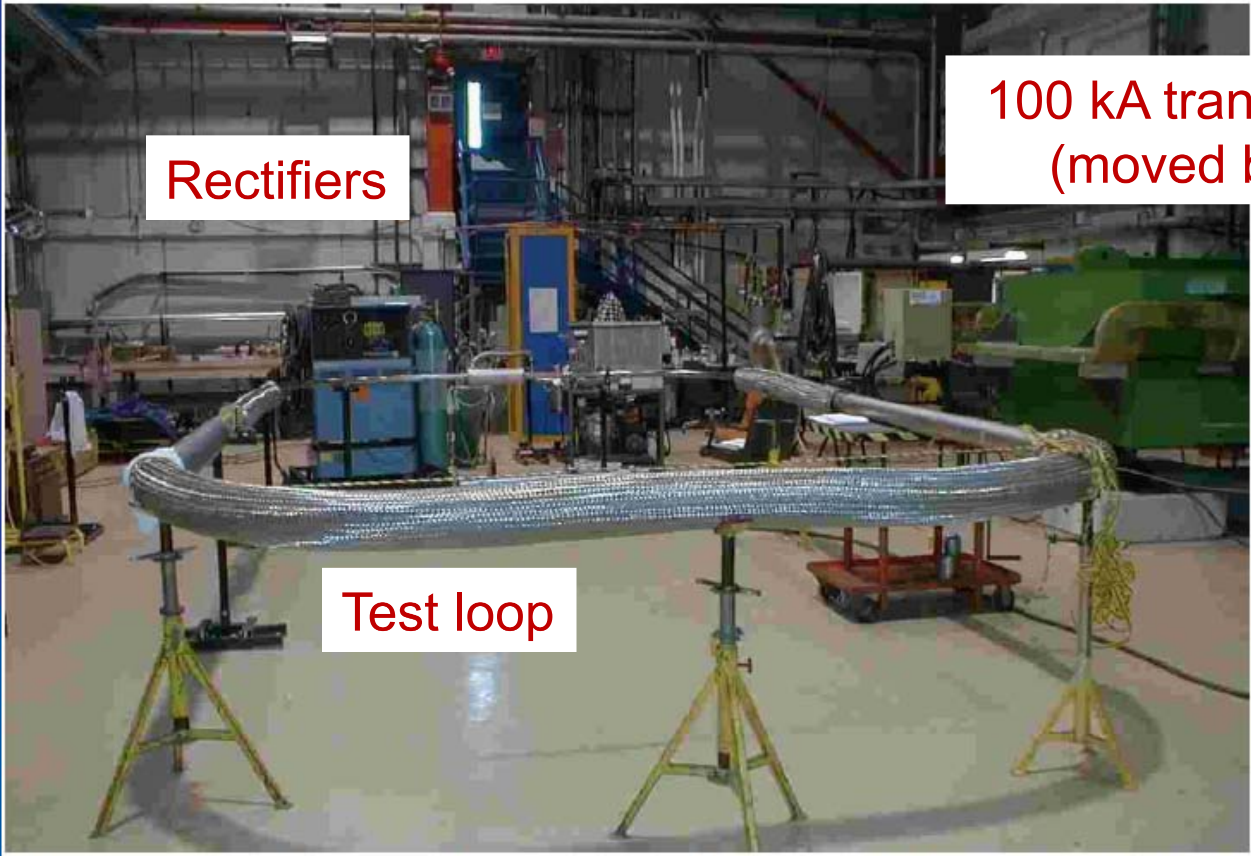

Fig. 9 – 100kA conductor test loop nearing completion. Dewar-based cryogenic system in background and drive transformer at right. The test loop contains a 4m replaceable test section of transmission line

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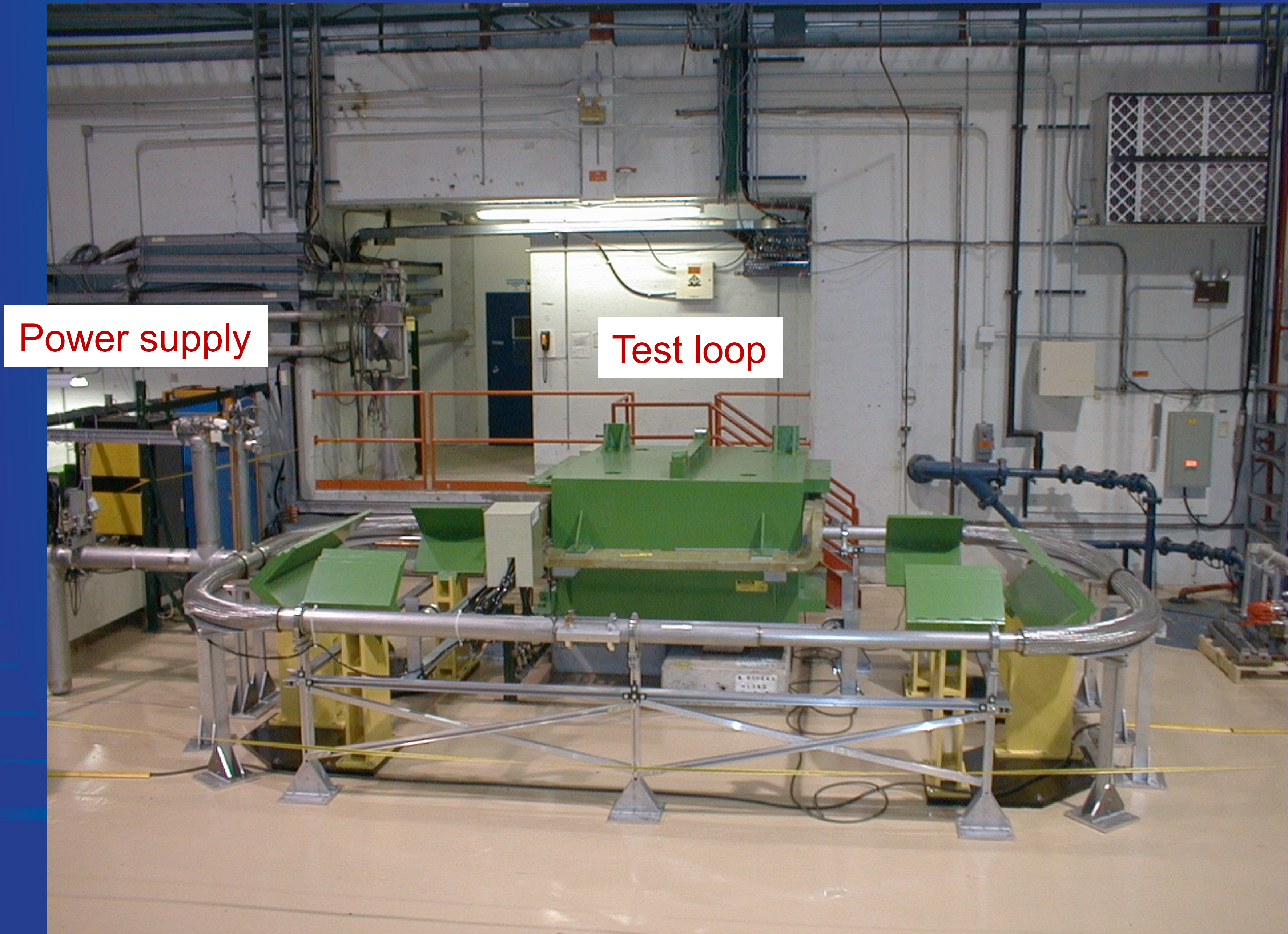
Power supply
Test loop

Rectifiers and transition at current leads

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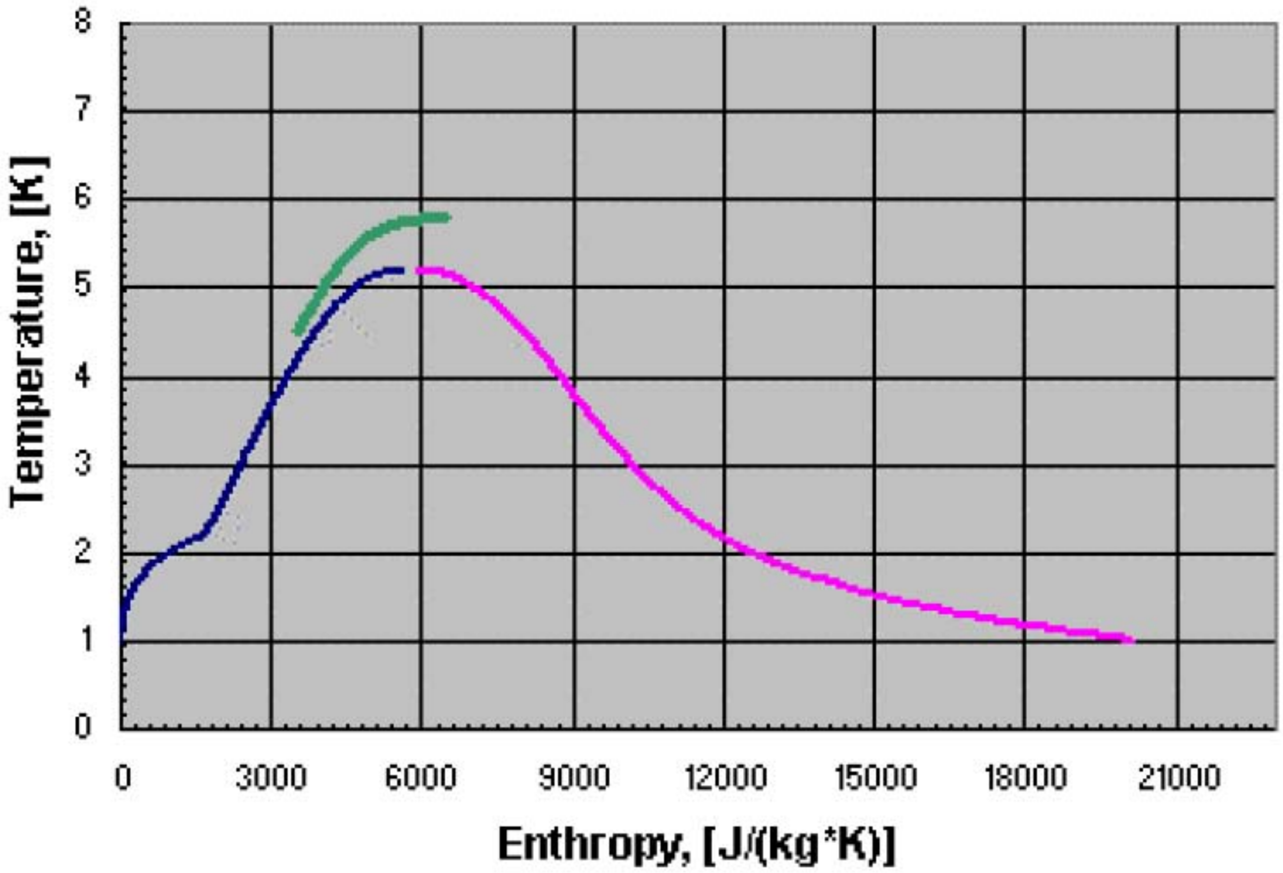
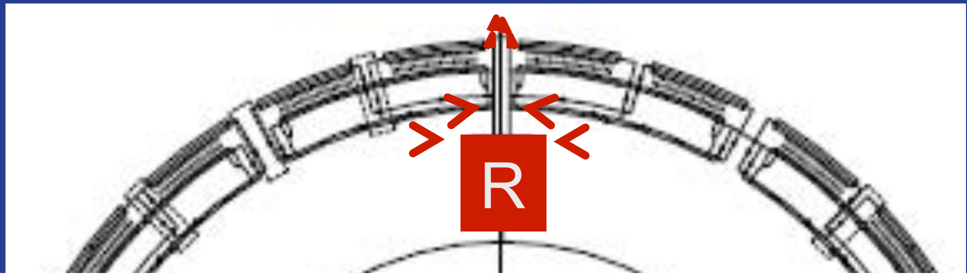
4.5K-6K Supercritical Flow



Cryogenic heat loads

"Near" and "Far" loops refer to parallel cooling loops from 1 refrigerator



		Primary 4.5K	Secondary 40K
STATIC	Carnot factors:	67	7.5
Near Loop			
Mechanical Supports,	[mW/m]	53	670
Superinsulation,	[mW/m]	15	864
		68	1534
Far Loop		X 67 = 4560	x 7.5 = 11500
Mechanical Supports,	[mW/m]	53	670
Superinsulation,	[mW/m]	13	864
DYNAMIC			
Beam Loss,	[mW/m]	2	1
Superconductor Splice,	[mW/m]	7	-

(4.56 + 11.5 = 16.1 W/m) x 233 km = 3.75 MW

3.75 MW / 28% = 13.4 MW (wall plug)

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CRYOGENICS

- Stage 1: 6 Plants, each ~10kW@4.5K equiv
  - ≤ 12 MW total wall power (17MW installed)
  - ~15% additional for SCRF option, IR's etc.
  - Installed power 150% of nominal
- Stage 2: 12 Plants, each ~43kW@4.5K equiv.
  - 85 MW total Wall Power (113 MW installed)
  - ~3.5x LHC

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What do we learn from the Pipetron?

- *Transmission line could be like a LNG pipeline*
  - (The huge tunnel was for physics, not transmission)
- *A 100 kA Nb-Ti conductor was demonstrated using cables like those for LHC, with splices*
- *Supercritical helium cryogenics with a 50 K shield*
  - 17 MW installed over 233 km (73 W/m)
  - Roughly 2/3 of the load is intercepted by the shield
- *The superconductor strand and cable must be mechanically strong*
- *Practically impossible to react the superconductor in-situ – must be pre-reacted*

Further development of the Pipetron

Henryk Piekarz, FNAL
Workshop on high-energy LHC, Malta

IEEE/CSC & ESAS EUROPEAN SUPERCONDUCTIVITY NEWS FORUM (ESNF), No. 16, April 2011
Paper selected from the Proceedings of the EuCARD - HE-LHC'10 AccNet Mini-Workshop on a "High Energy LHC"

USING TEVATRON MAGNETS FOR HE-LHC OR NEW RING IN LHC TUNNEL*

Henryk Piekarz #, FNAL, Batavia, IL 60510, U.S.A

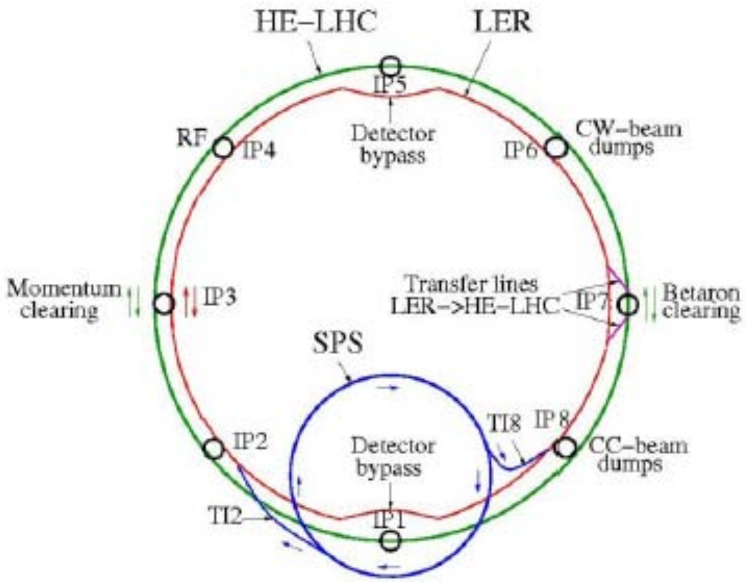

Fig. 2: LER injector Option 1 with LER beam bypassing detectors at IP1 and IP5intersection points

- *Idea: put a "low energy ring" (Pipetron) in the LHC tunnel*
- *What's new: HTS emerges in the design!*

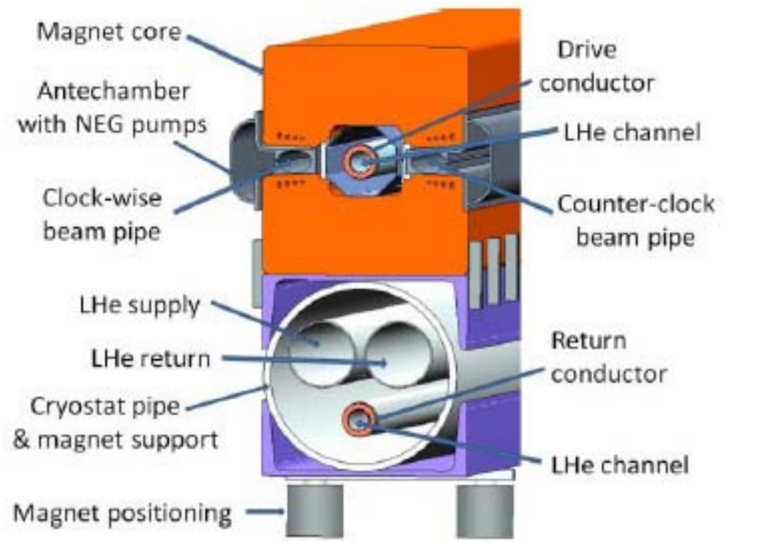

Fig. 5: LER main arc magnet position in the LHC tunnel

Fast-cycling main injector - Explicit comparison of Nb-Ti vs 2G YBCO in a Pipetron

- *Transmission line magnet ramping at 1 to 2 T/s*
  - AmSC "344" tape @ $25/m, which has nearly the same J_e (2 kA/mm^2) as Nb-Ti strand does at 5 K, 2 T
    - H. Piekarz, private communications and *IEEE Trans ASC* **20**, 1304 (2010)
- *330 MA-m of conductor @ full capacity*
  - Cable of 200 strands (0.8 mm dia) or 92 tapes (0.25 mm x 4 mm), 3.3 km circumference
  - 50 kA @ 1.4 T, operate at 50% critical current
- *HTS has 25 K margin, vs. 2 K for Nb-Ti, @ 2T*
  - Margin may be the critical deciding factor when dB/dt losses are considered, especially at splices
  - Actual Nb-Ti margin is more like 0.5 K !!

Could the fast-cycling main injector be built today?

- *Interesting trade-off revealed by MI project:*
  - YBCO critical current increases by factor of <u>20 to 25</u> when cooled with helium from 77 K to 5 K
  - Conductor cost becomes “tolerable” – see below
  - Cooling cost is (only) 3x higher when a 40 K shield is used
- *YBCO @ $25/m rated at 100 A (77K, 0.1T)*
  - 2 kA at 5 K, 2 T = $13 / kA-m
  - 330 MA-m would be about $4M of conductor
    - BUT this is 15x the total YBCO annual production
- *Nb-Ti @ $1/m rated at 1 kA = $1 / kA-m*
  - Temperature margin may not be sufficient
    - Can YBCO cover the joints?

Costs of superconductors

INSTITUTE OF PHYSICS PUBLISHING SUPERCONDUCTOR SCIENCE AND TECHNOLOGY
Supercond. Sci. Technol. **18** (2005) R51–R65 doi:10.1088/0953-2048/18/4/R01

TOPICAL REVIEW SuST **18** (2004) R51

Costs of high-field superconducting strands for particle accelerator magnets

L D Cooley[1], A K Ghosh[2] and R M Scanlan[3]

- *Costs could be scaled as multiplier "P" times raw materials content*
- *"P" decreased approximately as square root of billet mass or production run mass*
  - LHC strand: P = 3.3, 400 kg billet mass at restack
  - ITER strand: P ~ 10, 40 kg billet mass at restack
    - Recent data (600 tons) not analyzed
    - At ~4 g/m for strand, these are ~10 km piece lengths

What does the cost analysis say about other pre-reacted superconductors?

- *YBCO: $25 / m needs to be reduced to < $5 / m*
  - Main obstacle is production unit length – right now this is about 1 km pieces with a few 10 km pieces
    - P would then be 10 to 25 if this were a strand
      - Factor of 10 or higher increase in production scale is needed!
    - ($25 / m) / P = $1 to $2.5 per meter, an estimate of the "raw materials" cost
      - This is 10x Nb-Ti
      - New processes could use simpler substrate (stainless steel, not textured nickel) and layers (e.g. deposition of elements)

What does the cost analysis say about other pre-reacted superconductors?

- *MgB_2 : is \$2 / kA-m possible?*
  - (assuming the ex-situ process strand can be cabled after reaction – more from Grasso tomorrow!)
  - Analysis considered 0.8 mm strand, 25% MgB_2
  - Boron cost drives overall cost – use 97% pure not 99.9%
    - \$0.1 / m for 97% B, \$1.0 / m for 99.9%B
      - Techniques to remove oxygen have emerged – how expensive will they be in production?
    - Sneaky fact: about 2x more meters of MgB_2 per unit cost of raw Mg and B due to low densities
  - For 20-40 kg billets, P ~ 8, yielding \$1/m to \$2/m
  - J_c (H) is very similar to that of Nb-Ti at 5 K
    - 0.8 mm strand above has ~1 kA critical current at 1T, or a cost of ~\$1 to ~\$2/kA-m

A 10 GW, 100 kA, 1000 km DC power line: Conductor procurement

- *Specify 1 kA / mm² J_e @ 6 K, 1 T*
  - Nb-Ti, 2G-YBCO, maybe MgB_2, and Nb_3Sn reacted “GE” tape* can all meet this spec in a pre-reacted form
- *Supply enough conductor for 50% margin*
  - Total conductor is thus 150 GA-m
  - 150 GA-m / 1 GA m^{-2} = 150 m^3 of conductor
  - Typical strand is ~9,000 kg / m^3 = 9 tons / m^3
  - Total delivery is thus about 1,350 tons
    - Annual MRI production is ~1,000 tons Nb-Ti
    - Production for a HEP collider is ~1,000 tons
    - ITER: 600 tons Nb_3Sn and 300 tons Nb-Ti

The procurement is equivalent to that for a large physics project!

*No longer in production. GE used tape designs for several MRI projects in 1980s and 1990s, and a similar conductor was used for the BNL power transmission project 1980s.

A 10 GW, 100 kA, 1000 km DC power line: Cable

- *Deliver strand in > 10 km pieces*
  - Want splice-free cable between cryogenic plants
    - Cryogenic plants would be spaced 10-20 km
- *Cable may need additional stabilizer*
  - Flux jumps have not been analyzed here
  - Alternate model: SMES conductors – strands in channels
    - Externally cooled “barber pole” conductor
- *100 kV insulation is available – Kapton, S-glass wraps, G10 lining in helium pipe*
- *Splices must have low loss*
  - Soldered overlaps work well for Cu sheath
    - Must use low temperature solders for YBCO
    - Nb-Ti splice loss could be reduced with YBCO shunt

A 10 GW, 100 kA, 1000 km DC power line: Cryostat and cryogenics

- *Nickel-steel cryostat provides good engineering properties*
- *Heat load should be close to that of the Pipetron*
  - Less than 100 W/m installed at wall plug
  - 100 MW over 1000 km represents 1% power loss, compared to 3% for UHVDC
  - Pipetron: Cryogenic load from splices is 10% of full 4.5K load, so splice technology is a key area of attention
- *Cryogenic capacity 3 to 4 times that of LHC*

A 10 GW, 100 kA, 1000 km DC power line: Costs (meant to be thought-provoking)

- *LNG pipeline can be installed for ~$0.5M / km*
  - Can a pipe transmission line be installed for $1M / km?
  - Let's use $1B for the pipeline as a frame of reference
- *Superconductor: 150 GA-m @ $xx / kA-m*
  - Nb-Ti @ $1/kA-m = $150M, is thermal margin risky?
    - Hybrid – Nb-Ti with YBCO splice shunts?
  - 2G YBCO @ $13/kA-m = $1.95B, as much as the pipeline, excellent margin and strength, delivery in >10 years
  - GE Nb_3Sn Tape @ $5/kA-m = $750M, adds margin, not in production (but proven), properties are sensitive to strain
  - MgB_2 – possible?
- *Rights of way etc. can be $1B*
- *<u>This is a $2-4 Billion project!</u>*

Is it worth it?

- *U.S. Electricity consumption: 4000 TW-h in 2009*
  - About 0.5 TW continuous = 500 GW
- *Renewable goal: 40% within 10 years*
  - Cost of installed solar, geothermal, wind are all running at about \$2.5 to \$4 per watt
  - 200 GW renewable installed is > \$500 Billion
    - The electricity pipeline is \$few billion, or 1% of this!
- *Electricity price is ~\$0.1 per kW-h, or \$400 Billion in annual revenue*
  - \$500 billion over 10 years = \$50 billion per year, or about a 12% increase in electricity bills to pay for renewables
  - (Oil profits can buy it now – "One BP is the entire DOE"†)
  - Communities with renewable electricity sources pay ~ \$0.05 per kW-h – costs can be recovered

† Undersecretary for Science Steven Koonin, ASC 2010.

Conclusions

- *A 100 kA, 10 GW DC power transmission line 1,000 km long can be built today based on present engineering designs*
  - It is equivalent to a large physics project
  - > 1,000 tons of superconductor
- *The capacity increase may be worth the expense of helium cryogenics*
  - Buy 20 times less YBCO, 5 times less MgB_2
  - Refrigeration loss stays below losses for competing technology if the power line capacity is large (10+ GW)
    - 1% for 1,000 km, vs 3% for UHVDC
- *Planned renewable installations exceed 1 GW per site, so "Pipetricity" partnerships may be effective*
  - A 10 GW renewable cluster costs $25 to $40 B installed
  - A 10 GW power line costs 10% of this