Transmission Line Magnet R&D

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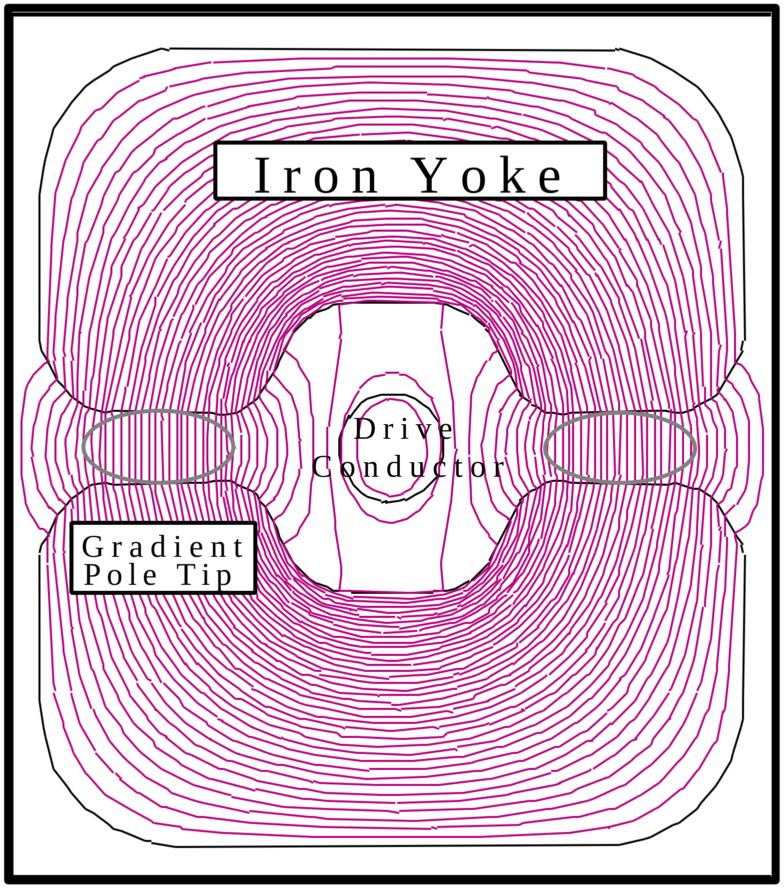
Oct. 2000

Outline

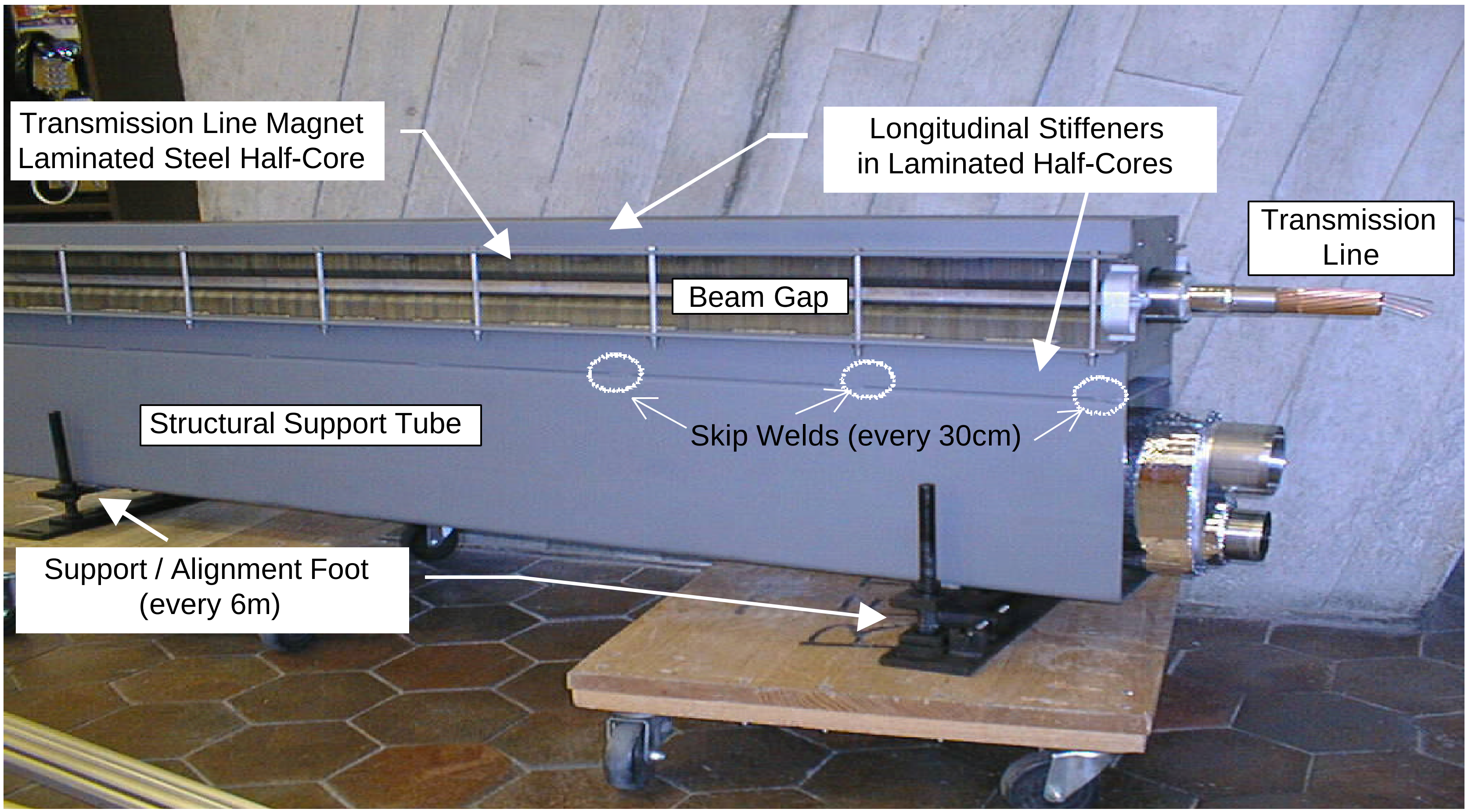
- Transmission Line Development Completed
- String Test Approved & Started
  - 100kA Power Supply & Current Leads
- Iron Design
- System Design
- Relationship w/ Upcoming Design Study

“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.

Components of the Transmission Line Magnet



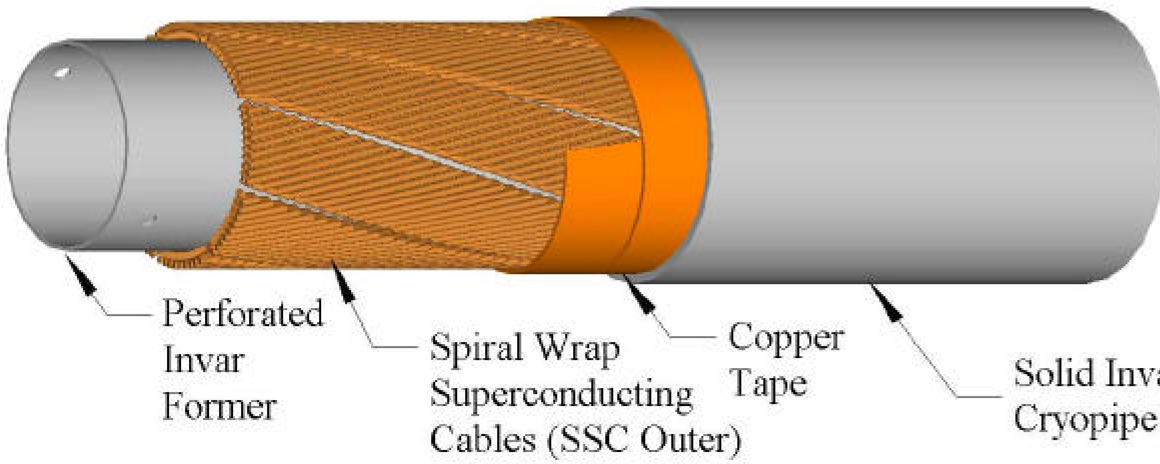
100kA Transmission Line
17 m Test Loop

Transmission Line Development Completed

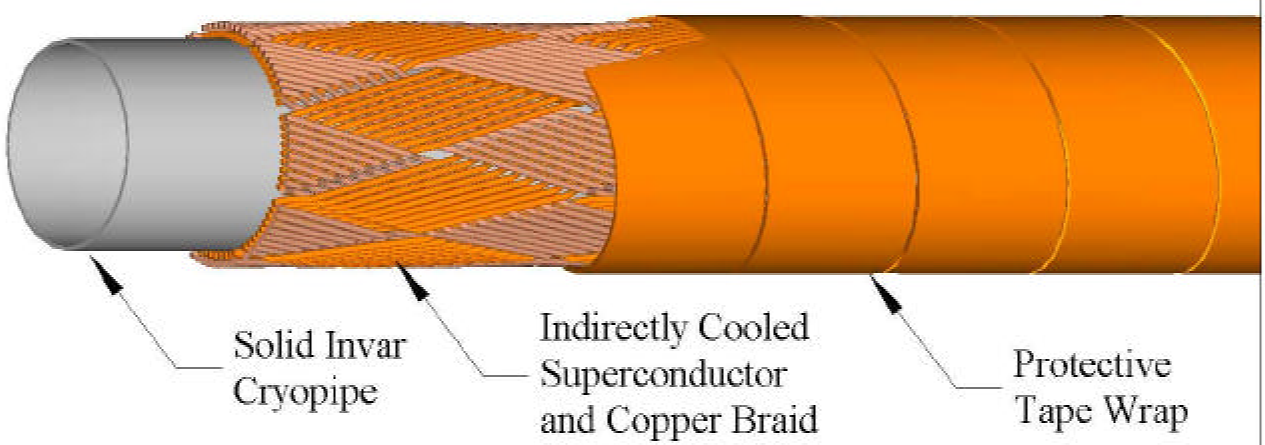
- Conductor Design meets all Requirements
  - Electrical : carries >100kA at >7K
  - Mechanical
  - zero contraction mode (Invar)
  - magnetic decentering forces 1000k cycles
  - cryogenic: shielded design, low heat leak
- Performance Verified on 100kA Test Loop
  - Loop decommissioned
- Parts in hand for extended test

TRANSMISSION LINE CONDUCTOR DESIGNS

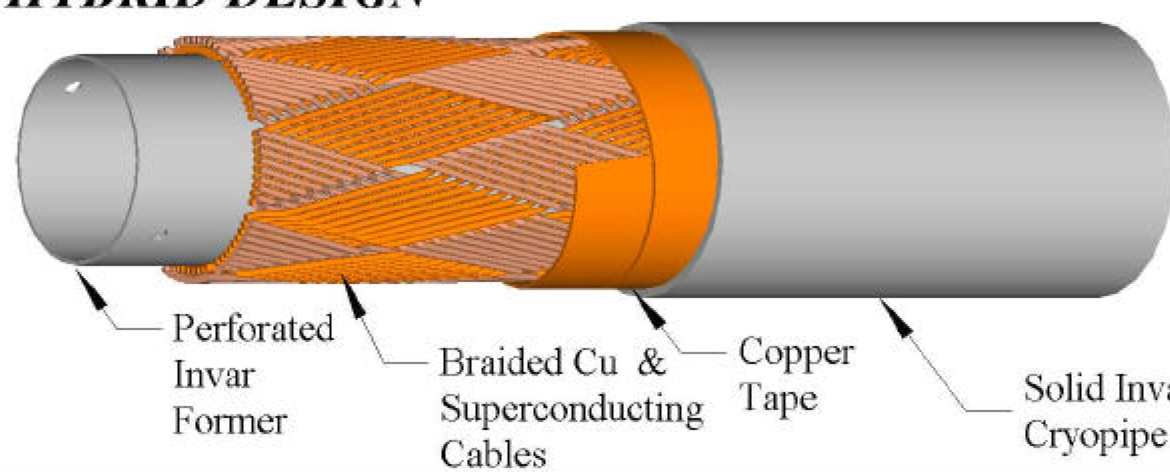
BASELINE (Rutherford Cable-in-Conduit) DESIGN



KEK (Indirectly Cooled Braid) DESIGN



HYBRID DESIGN

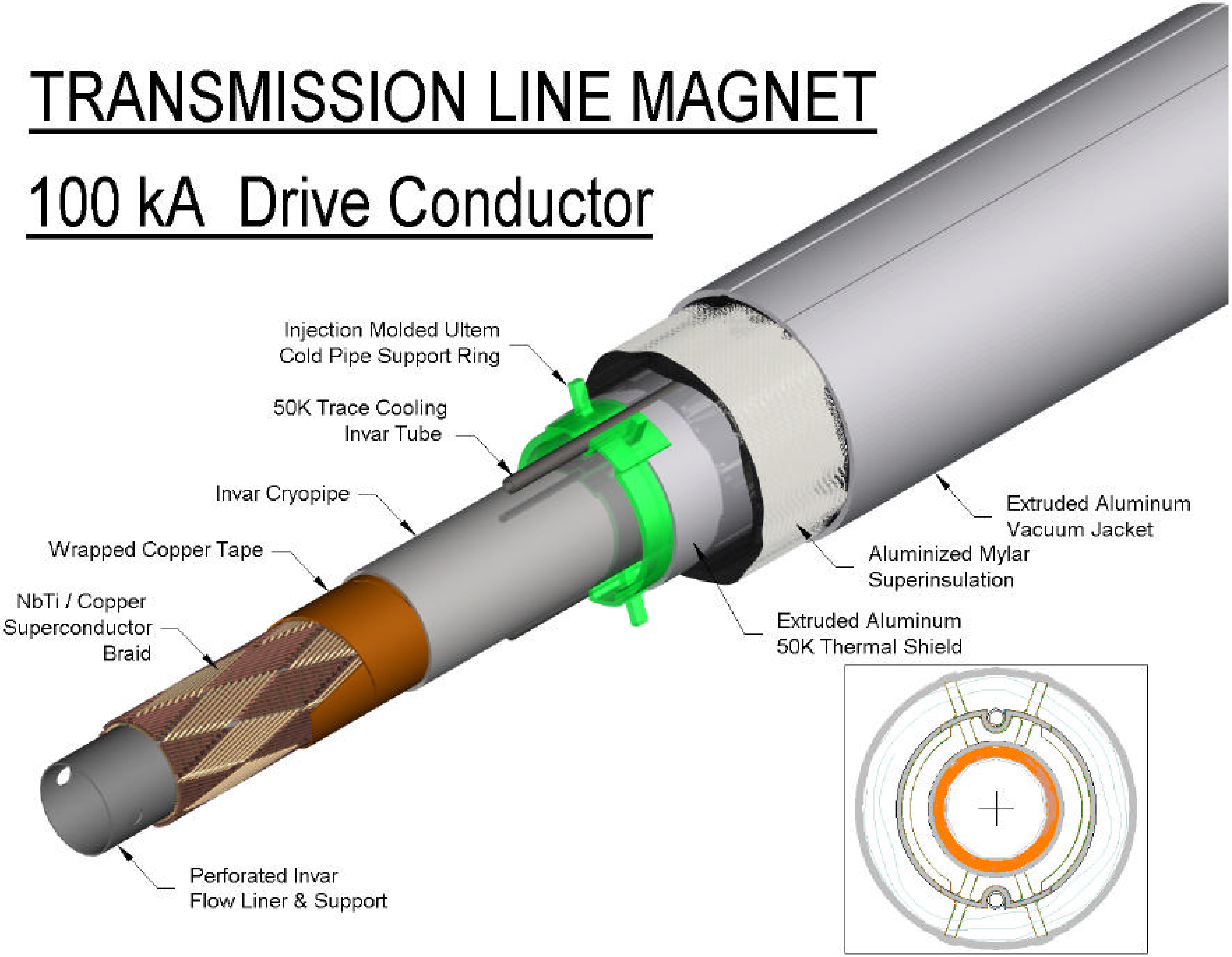


Results from 100kA Test Loop

Transmission Line Test Loop Configuration	Results
1. Test loop commissioning run.	100kA at ~8K
2. Two-layer Rutherford (8 x 2 Layer SSC Outer Cable)	100kA at 7.1K
3. Niobium3-Aluminum transmission line (Sumitomo)	35kA at 11K
4. Single Layer Rutherford (8 x Single Layer SSC Outer Cable)	100kA at 6.8K
5. Braided Nb-Ti Strand	100kA at 7.6 K

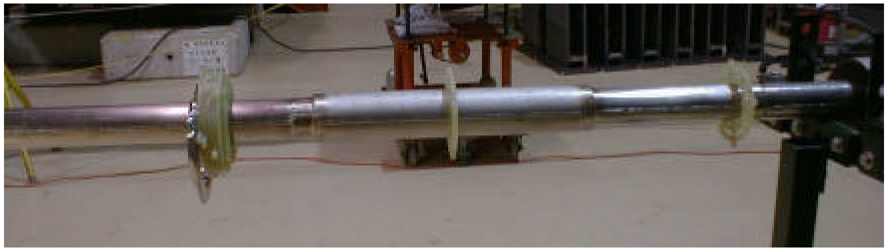
TRANSMISSION LINE MAGNET

100 kA Drive Conductor



Transmission Line Finished Design

100 kA Conductor Splice



Cold Pipe Support & Shield

- Lowest Possible Heat Leak
  - Drives Cryogenic Design
- Magnetic Decentering Forces
  - Nominally Zero
  - Design for 100kg/m to allow 0.5mm off center
  - Design lifetime ~10^5 cycles

    (50 Years at 2000 ramps/year)
- Injection Molded Ultem “Spider”
- 50K Shield

Load Testing ULTEM Spider

Injection Molded Spider Survives 100,000 Cycles to 3x Rated Load

MW8 String Test

String Test Civil Construction

Enclosure for 100kA Transfer Line from Power Supply Building to Tunnel for String Test

View of Upstream MW8 Tunnel

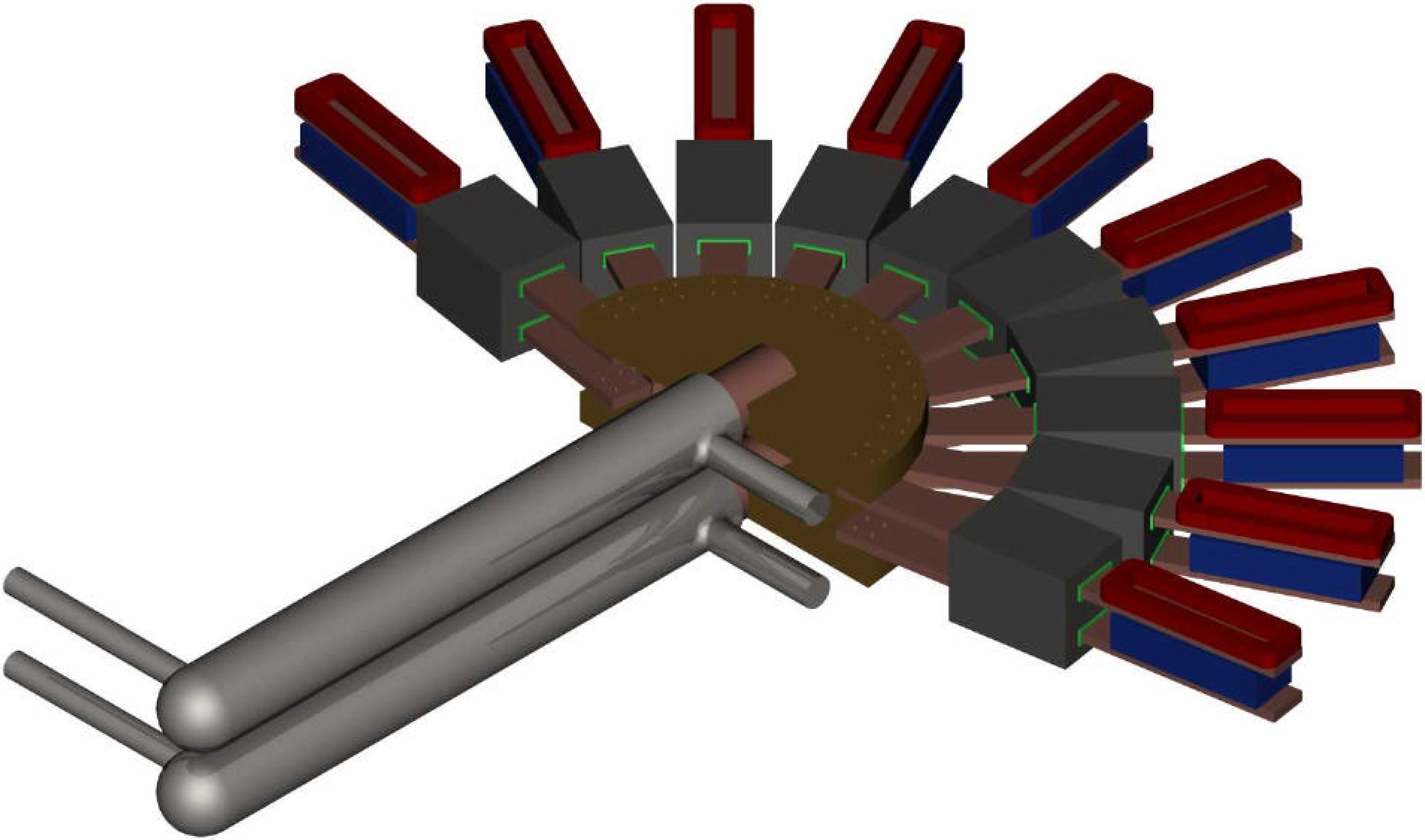
300 m
Tunnel

Cleared
Sept ‘00

View of Downstream MW8 Tunnel

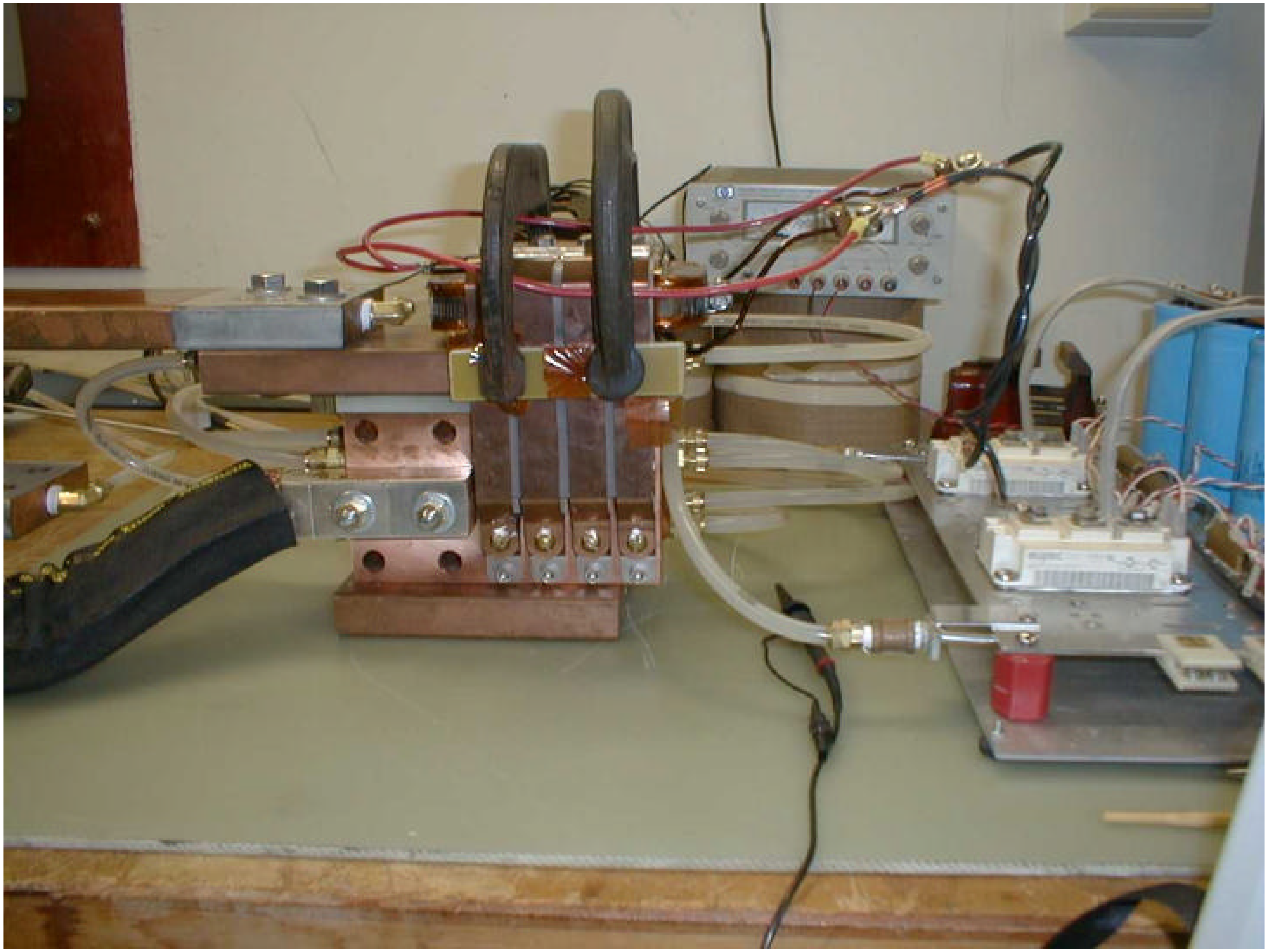
Cleared & being used for Storage for 500ft of Trans. Line Parts

100kA Power Supply & Current Leads



3kA Prototype Power Converter

2kHz Chopper / Rectifier



IGBT
Bridge
Chopper

Tape Core
Xformer

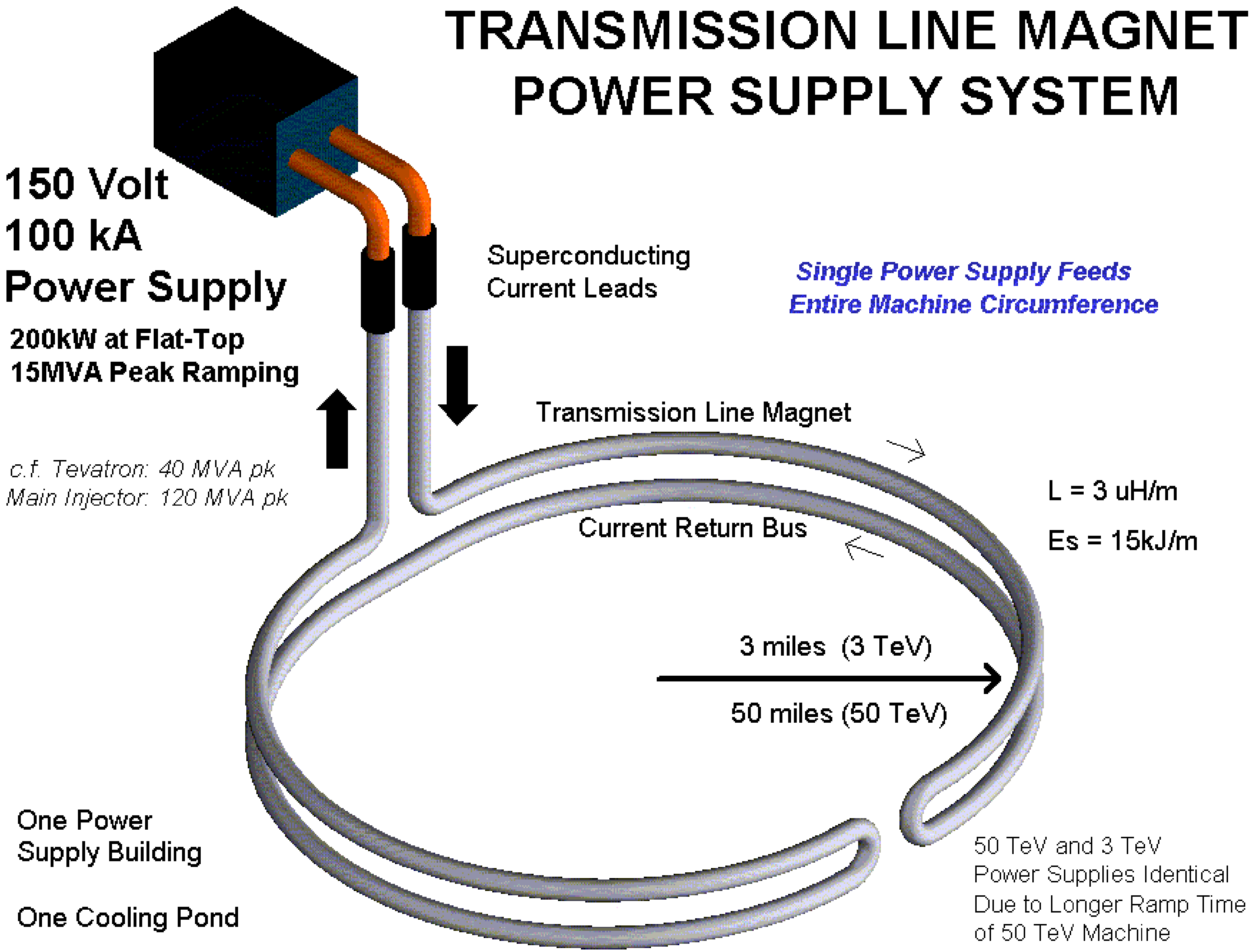
Shottkey
Rectifier

Full Size Rectifiers for 100kA

~ All Parts in hand for 100kA Supply

High Current Power Leads

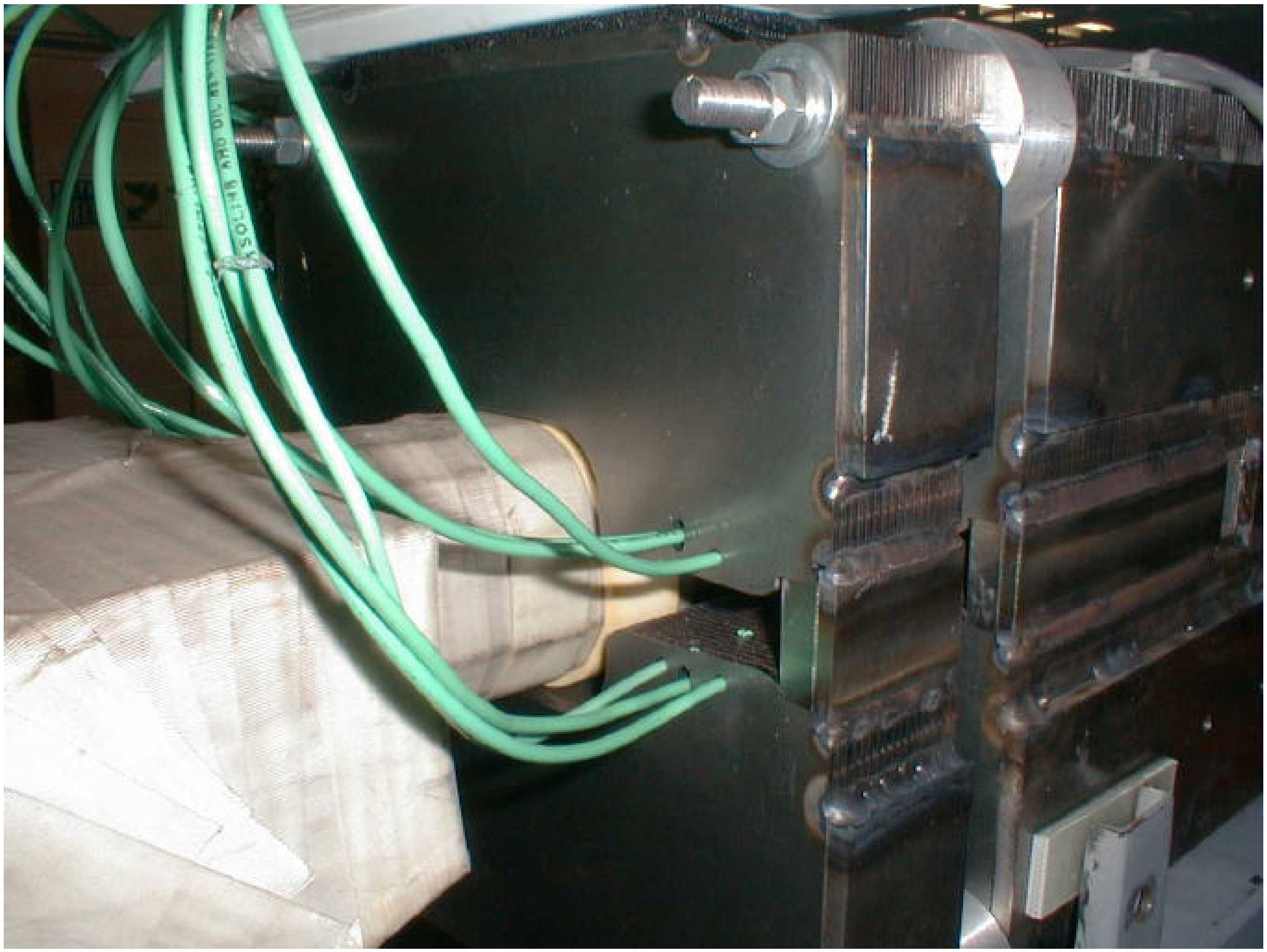
- Design Based on 1/4” ETP Copper Rods
- G10-Baffles to enforce cross-flow
- Start with 10kA prototype to debug concept and controls
- ~75% of parts in hand


TRANSMISSION LINE MAGNET
POWER SUPPLY SYSTEM
150 Volt
100 kA
Power Supply
200kW at Flat-Top
15MVA Peak Ramping
c.f. Tevatron: 40 MVA pk
Main Injector: 120 MVA pk
Superconducting
Current Leads
Single Power Supply Feeds
Entire Machine Circumference
Transmission Line Magnet
L = 3 uH/m
Es = 15kJ/m
Current Return Bus
3 miles (3 TeV)
50 miles (50 TeV)
One Power
Supply Building
One Cooling Pond
50 TeV and 3 TeV
Power Supplies Identical
Due to Longer Ramp Time
of 50 TeV Machine

Iron Design

- Laser-cut prototype Laminations to test tricks to control saturation
- Contract ready for stamping die and industrial production of magnets for string test

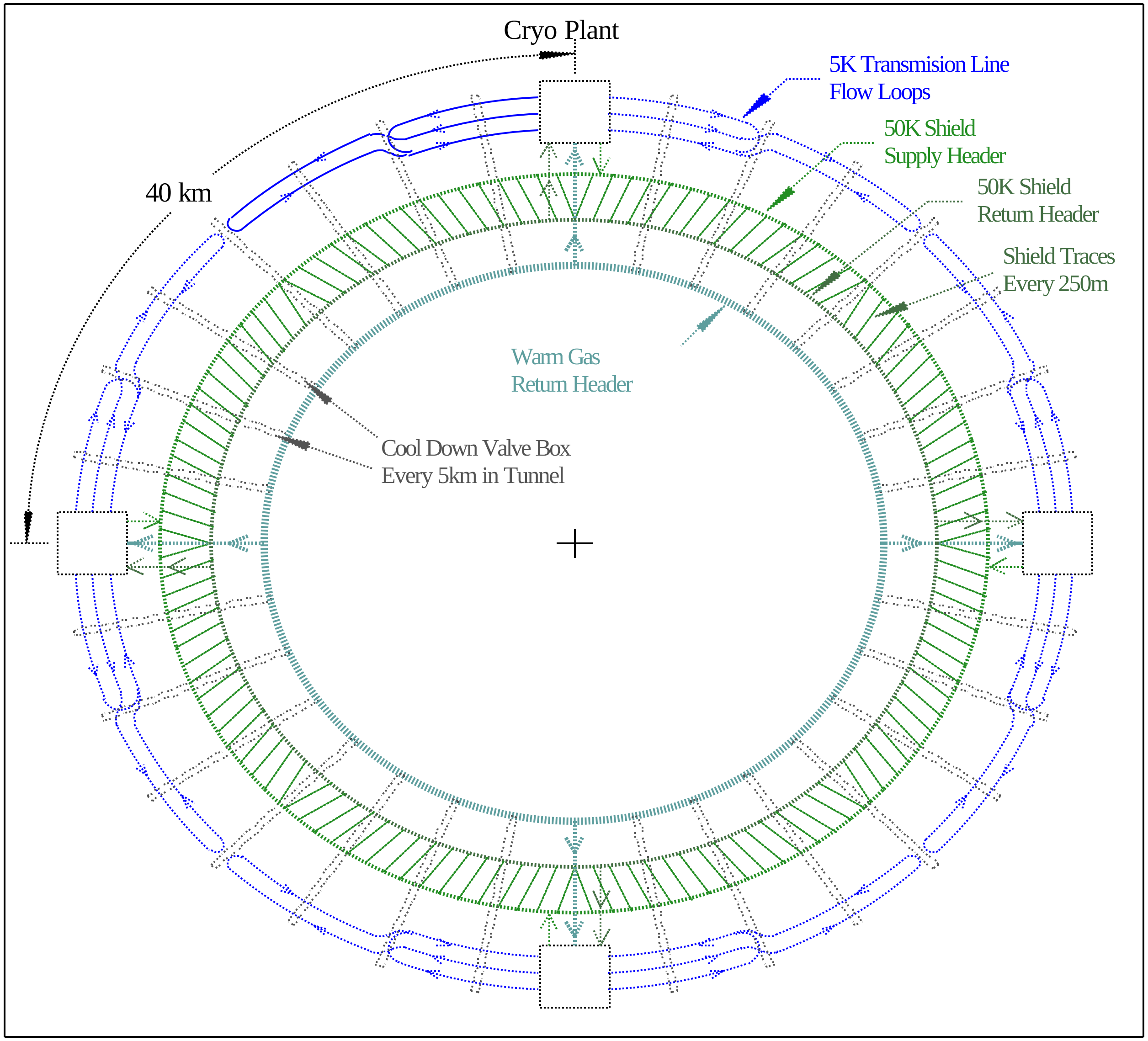
Using Wires in Holes for Low-Field Correctors



3 Circuits give control of gradient, sextupole, & Octupole.

1-5 Amps has big effect @injection

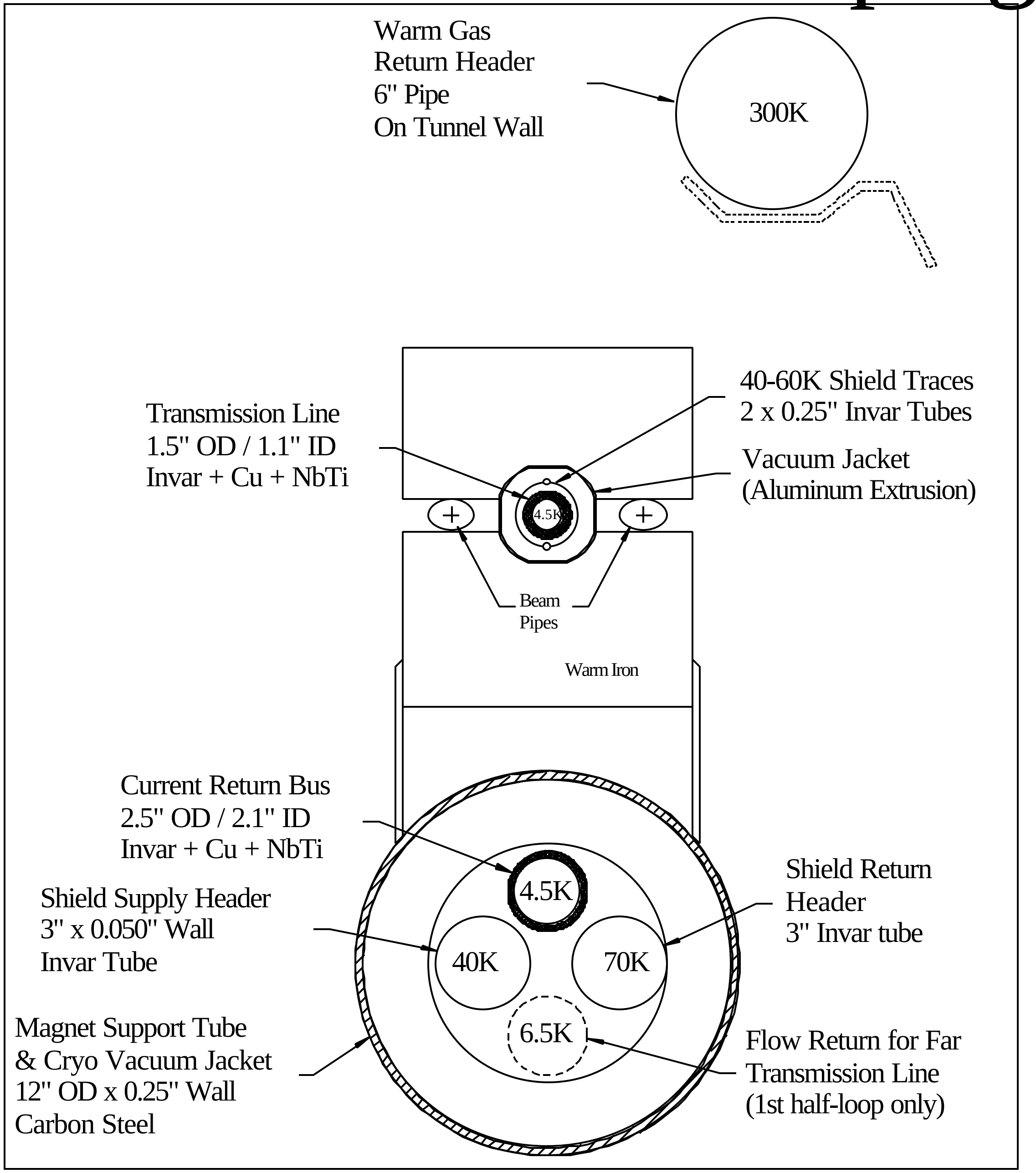
Cryogenics for 14x14 TeV Transmission Line Magnet System



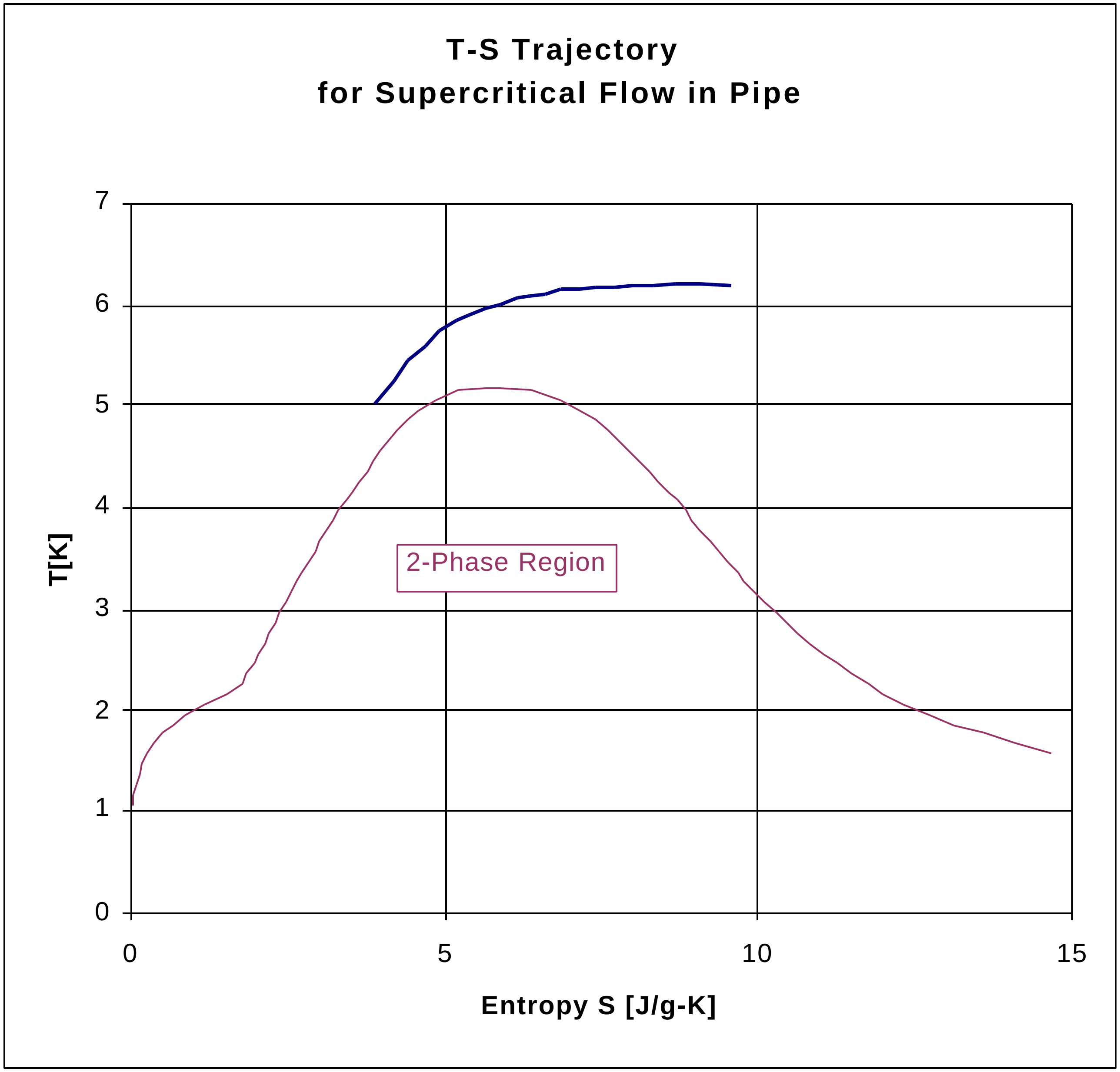
Parameters for 14x14 TeV Transmission Line Magnet System

Beam Energy	14 TeV	(Example machine 2x LHC energy)
Magnetic Field	2 T	(warm iron, warm bore 2-in-1 transmission line magnet)
Arc Circumference	160 km	
Cryogenics		
Cold Mass	4100 tons	
Superconductor Temperature	5-6.5K	
Heat load at 5-6.5K	10kW	
Shield Temperature	40-70K	
Heat Load at 40-70K	165kW	
Cryo Power @4.5K Equiv.	20 kW	(30 kW installed)
Cryogenic Wall Power	6 MW	(9 MW installed)
Helium Inventory	58 tons	(includes 100% warm storage)
Number of Cryo Plants	4	(each plant 7.5kW @4.5K equiv.)
Magnet		
Operating Current	100kA	
Number of Turns	1	
Inductance	3uH/m	(including current return bus)
Ring total	480mH	
Magnetic Stored Energy	15kJ/m	
Ring total	2400 MJ	
Ramp Time	1000 sec	
Power Supplies		
Number of Power Supplies	1	(single power supply per ring)
Maximum Current	100kA	
Ramp Voltage	48V	
Ramping Power	4.8 MVA	
Holding Power	200kW	
Cryogenic Current Leads	100kA-pair	(single pair of 100kA leads)
Quench Protection		
Quench Detection Threshold	1V	(Single circuit at power supply)
Energy Dump Time Constant	1 sec	
Dump Switch Type	cryogenic	(Dump switch is deliberately quenched section of special Transmission Line)
Dump Switch Spacing	10km	
Peak Voltage to Ground	+/- 3kV	

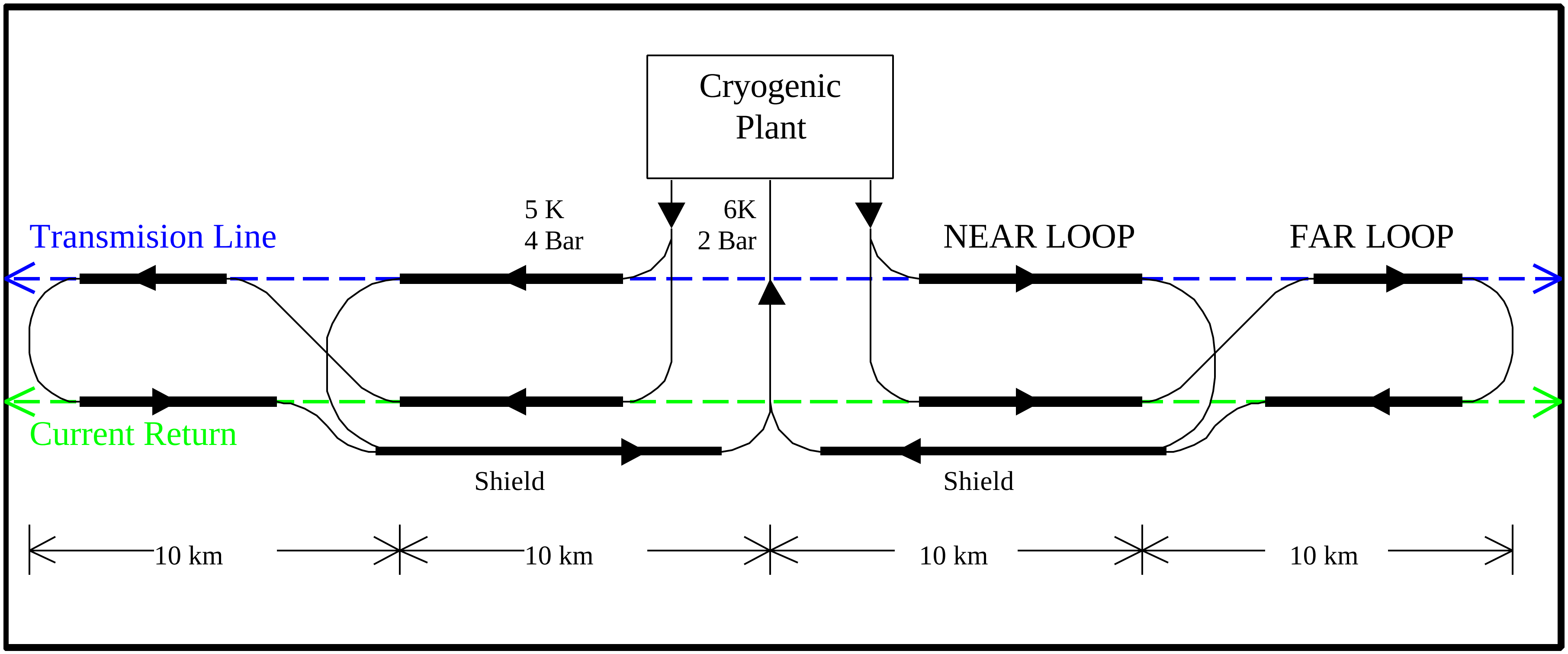
Transmission Line Piping



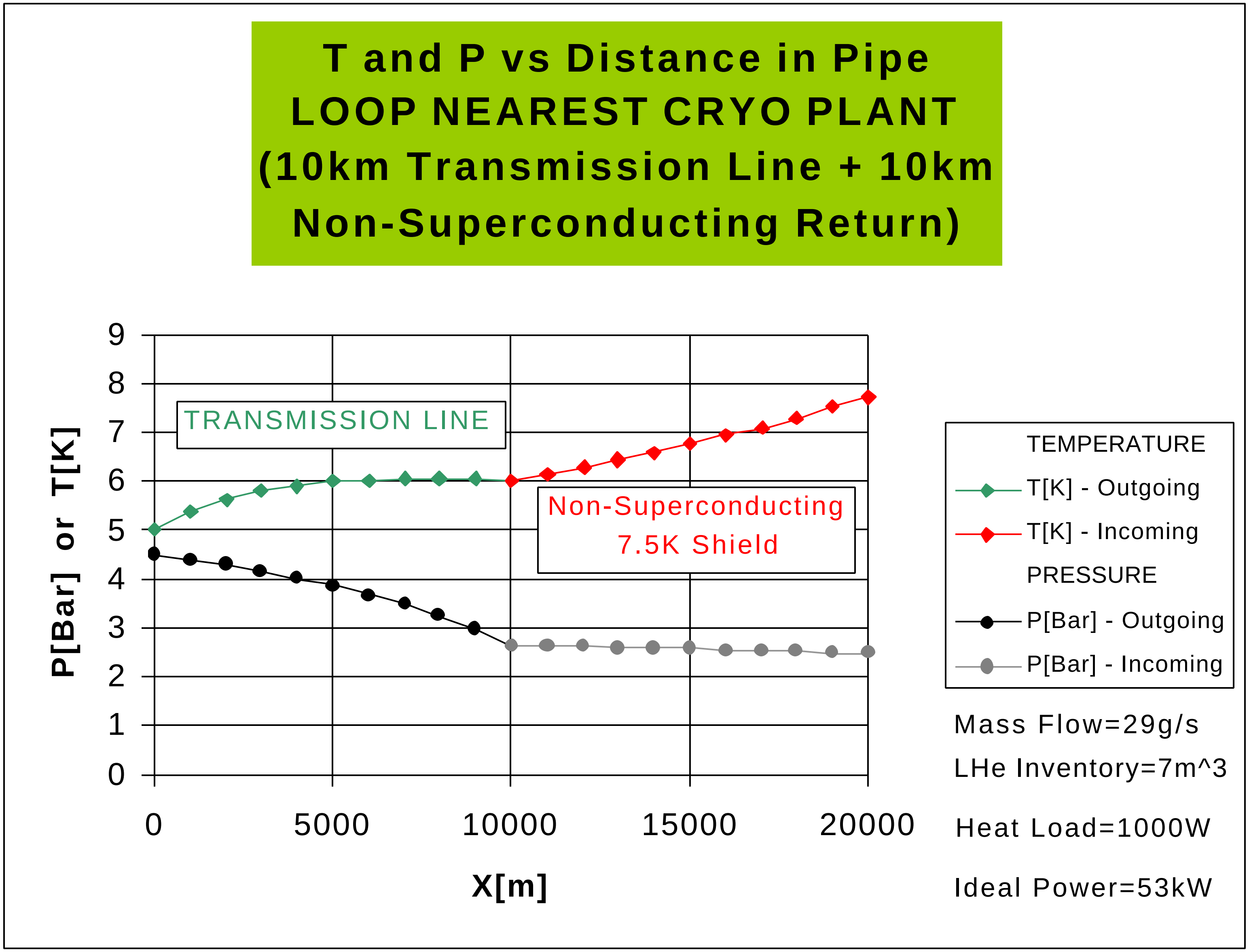
Supercritical Flow in Transmission Line



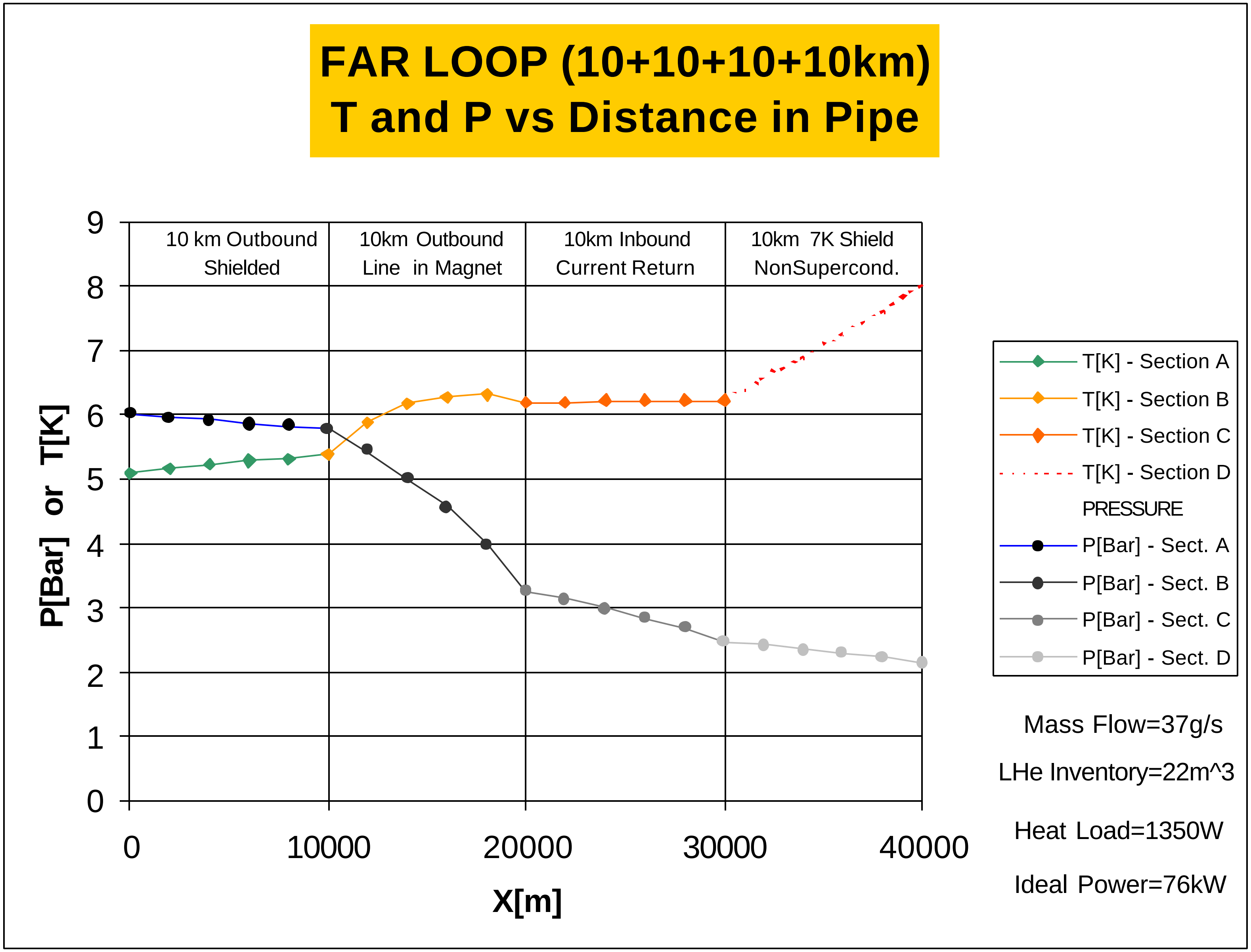
5K Transmission Line Flow



5K Supercritical Flow in Near 10km String



5K Supercritical Flow in Far 10km String



Effects of 100m Altitude Change on Supercritical Flow Conditions

	P[Bar]	T[K]	ρ [kg/m^3]	S[J/g-K]
Surface (Cryoplant outlet)	3.2	4.38	132.50	3.42
Tunnel (Magnet Inlet)	4.5	4.50	135.24	3.42
Tunnel (magnet outlet)	2.5	7.50	19.11	9.93
Surface (Cryoplant inlet)	2.3	7.25	18.23	9.93

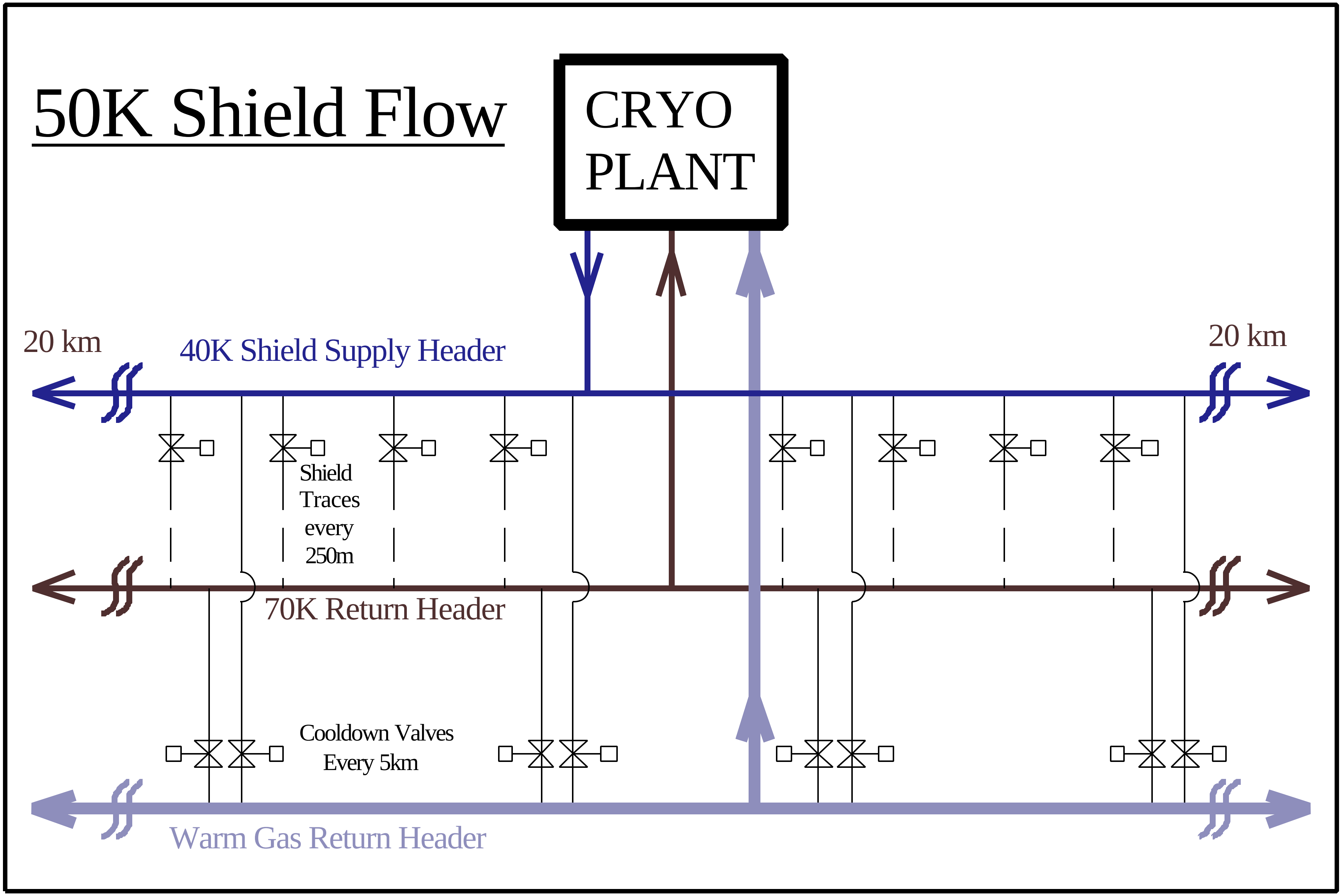
- Pressure & Temperature Changes Compensated by Adjusting Output Conditions at Cryoplant.
- Flow Stays Safely Away from 2-Phase Region.
- No Downstairs Coldboxes Needed in Tunnel.

Estimated Heat Loads in 5K Transmission Line and Return Bus

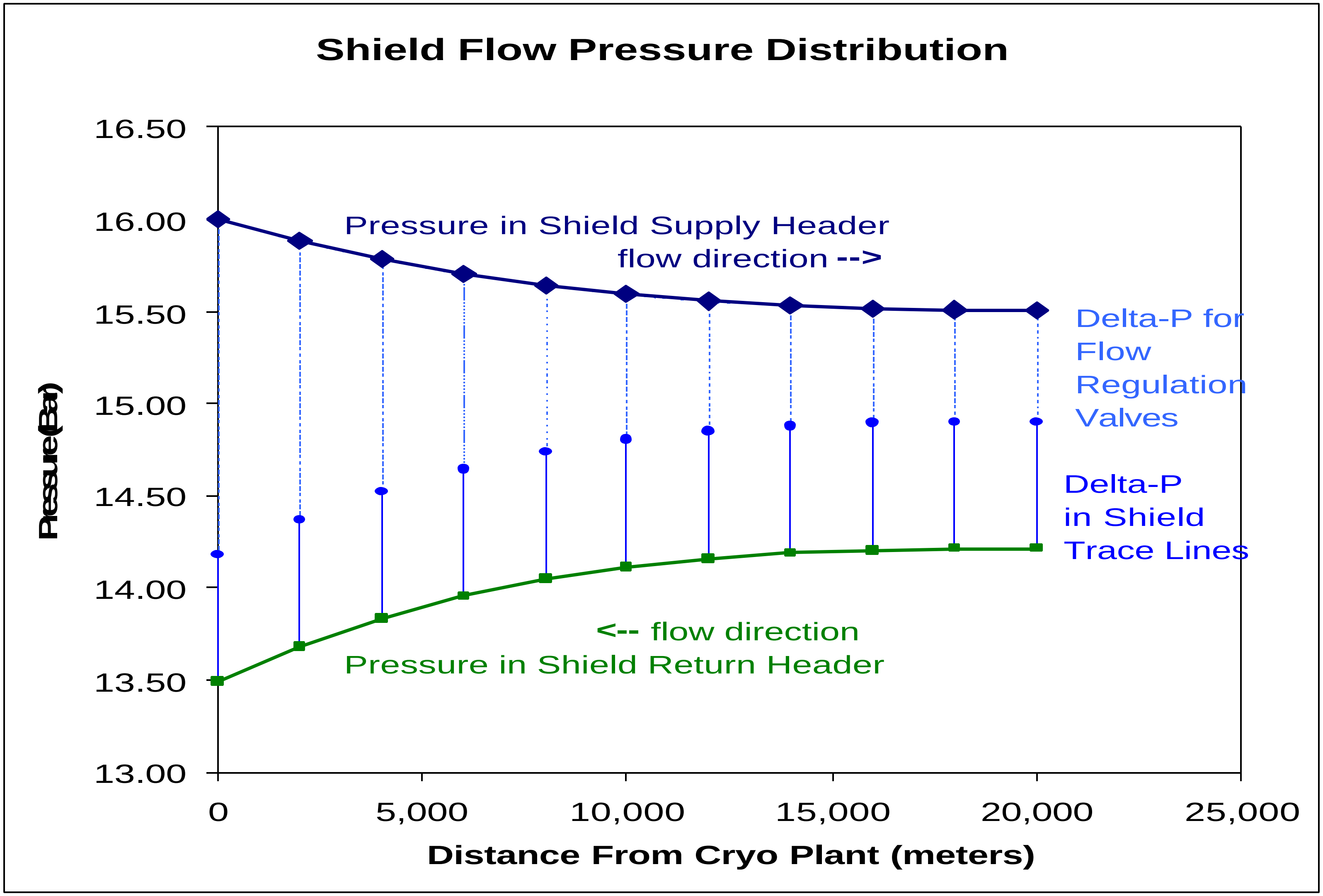
Transmission Line 5K Flow	**W/m**	**0.048**
Conduction		
Supports per meter		2
Pegs Per Support		4
Peg Length	cm	0.75
Peg Cross Sect	cm^2	0.09
Ultem TC Integral 50K-->5K	W/cm	0.042
Conductive Heat Load	W/m	0.040
Longitudinal Anchor (w/50K intercept)		
Length	cm	10
Cross Sect	cm^2	3
Conductive Heat Load	W	0.013
Spacing	m	125
Average Heat Load	W/m	0.0001
Radiation		
Emissivity		0.10
T-hot	K	50
Area per meter	m^2/m	0.08
Radiation Heat Load	W/m	2E-04
Instrumentation Leads		
Load per Tube	W	0.5
Distance between Tubes	m	250
Average Heat Load	W/m	0.002
Valve Boxes		
Heat Load Per Box	W	5
Distance Between Boxes	m	5000
Average Heat Load	W/m	0.001
Splice Power at Full Current		
Trans. Line Current	kA	100
Splice Resistance	nOhm	0.05
Voltage@full current	uV	5
Power per Splice	W	0.5
Distance Between Splices	m	125
Average Splice Heat Load	W/m	0.004

Return Bus 5K Flow	**W/m**	**0.014**
Conduction		
Supports per meter		1
Pegs Per Support		4
Peg Length	cm	2.5
Peg Cross Sect	cm^2	0.09
Ultem TC Integral 50K-->5K	W/cm	0.042
Conductive Heat Load	W/m	0.006
Longitudinal Anchor (w/50K intercept)		
Length	cm	10
Cross Sect	cm^2	6
Conductive Heat Load	W	0.025
Spacing	m	125
Average Heat Load	W/m	0.0002
Radiation		
Emissivity		0.10
T-hot	K	55
Area per meter	m^2/m	0.12
Radiation Heat Load/meter	W/m	5E-04
Instrumentation Leads		
Load per Tube	W	0.5
Distance between Tubes	m	250
Average Heat Load	W/m	0.002
Valve Boxes		
Heat Load Per Box	W	5
Distance Between Boxes	m	5000
Average Heat Load	W/m	0.001
Splice Power at Full Current		
Trans. Line Current	kA	100
Splice Resistance	nOhm	0.05
Voltage@full current	uV	5
Power per Splice	W	0.5
Distance Between Splices	m	125
Average Splice Heat Load	W/m	0.004

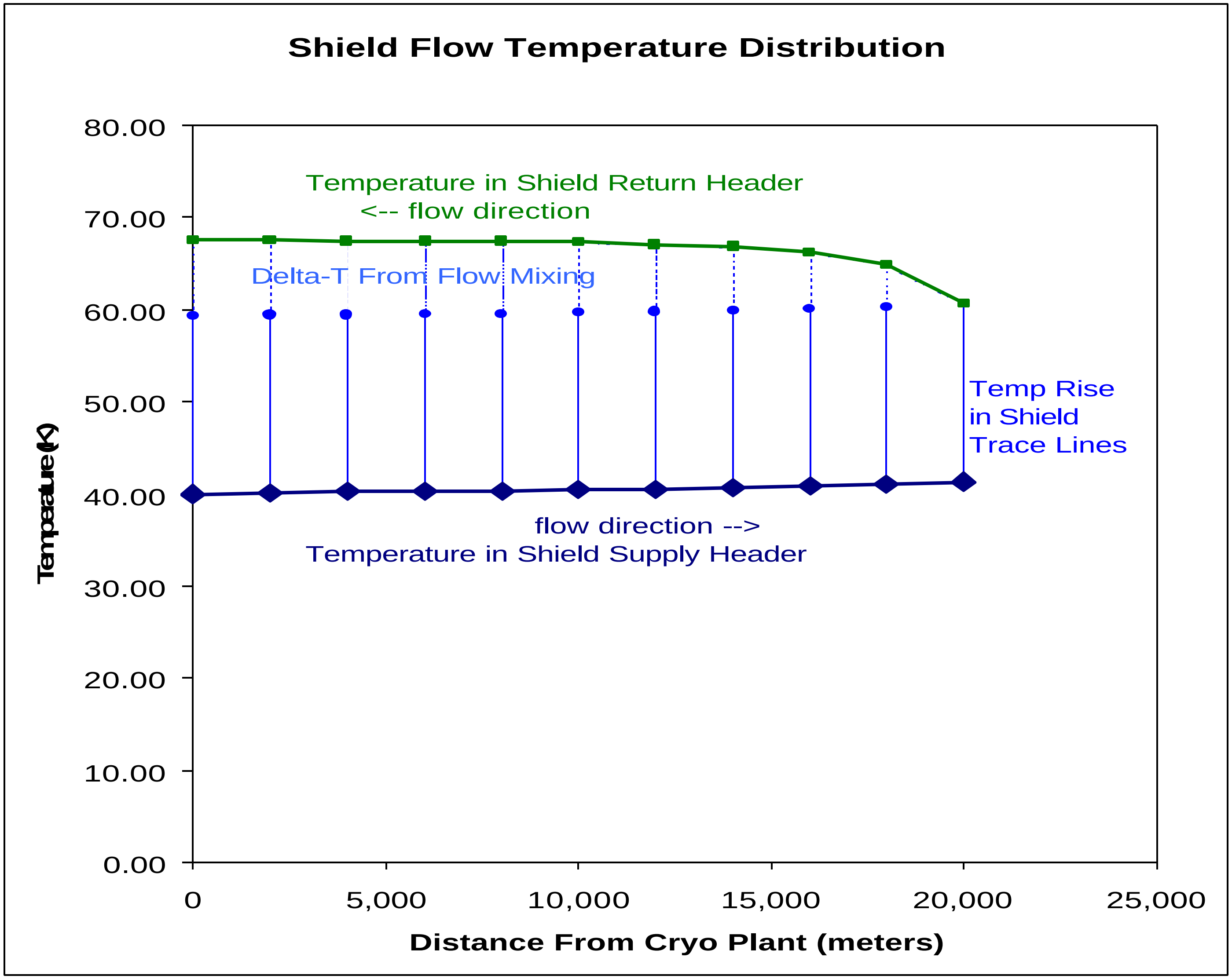
50K Shield Flow



50K Shield Flow Pressure Drops



50K Shield Flow Temperature Distribution

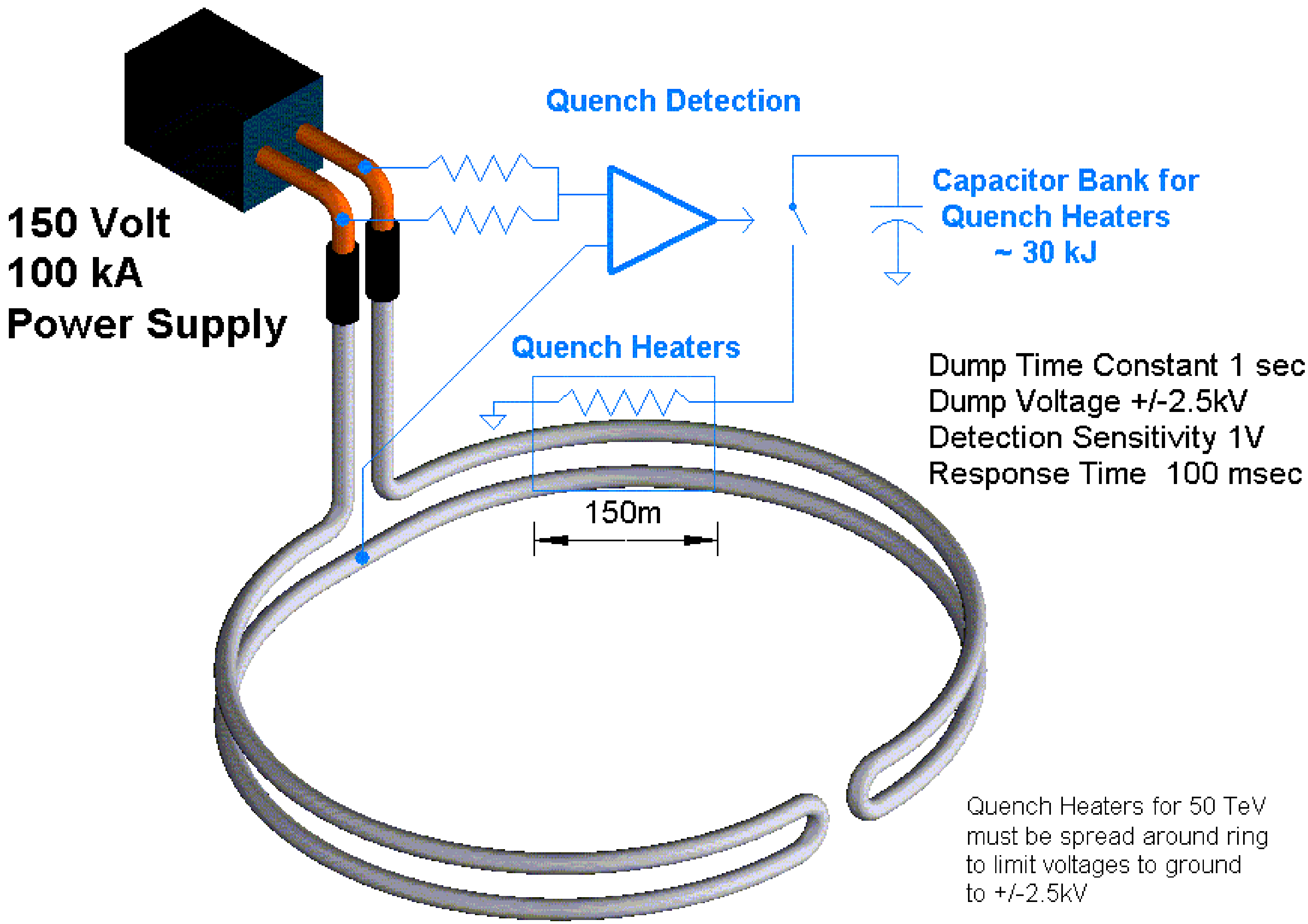


Heat Loads into 50K Shield System

Transmission Line Shield	**W/m**	**0.573**
Conduction		
Supports per meter		2
Pegs Per Support		4
Peg Length	cm	1.15
Peg Cross Sect	cm^2	0.09
Ultem TC Integral 300K-->50K	W/cm	0.69
Conductive Heat Load	W/m	0.432
Longitudinal Anchor (w/50K intercept)		
Length	cm	10
Cross Sect	cm^2	3
Conductive Heat Load	W	0.207
Spacing	m	125
Average Heat Load	W/m	0.002
Superinsulation (MLI) Leak (incl. Vacuum)		
Average Radius	m	0.04
Area per meter	m^2/m	0.22
Heat Leak Per Area	W/m^2	0.50
MLI Heat Load/meter	W/m	0.110
Instrumentation Leads		
Load per Tube	W	5
Distance between Tubes	m	250
Average Heat Load	W/m	0.020
Valve Boxes		
Heat Load Per Box	W	25
Distance Between Boxes	m	5000
Average Heat Load	W/m	0.005

Shield Return Header	**W/m**	**0.463**
Conduction		
Supports per meter		0.5
Pegs Per Support		4
Peg Length	cm	5
Peg Cross Sect	cm^2	0.72
Ultem TC Integral 300K-->50K	W/cm	0.69
Conductive Heat Load	W/m	0.199
Longitudinal Anchor (w/50K intercept)		
Length	cm	10
Cross Sect	cm^2	6
Conductive Heat Load	W	0.414
Spacing	m	125
Average Heat Load	W/m	0.003
Superinsulation (MLI) Leak (incl. Vacuum)		
Average Radius	m	0.13
Area per meter	m^2/m	0.79
Heat Leak Per Area	W/m^2	0.30
MLI Heat Load/meter	W/m	0.236
Instrumentation Leads		
Load per Tube	W	5
Distance between Tubes	m	250
Average Heat Load	W/m	0.020
Valve Boxes		
Heat Load Per Box	W	25
Distance Between Boxes	m	5000
Average Heat Load	W/m	0.005

QUENCH DETECTION & PROTECTION



Quench Protection and Cryogenic Dump Switch Parameters

QUENCH PROTECTION SYSTEM PARAMETERS		
Length of Quench Protection Cell	Km	20
Current	kA	100
Inductance	mH	60
Stored Energy	MJ	300
Energy Dump Time Constant	Sec	1
Peak Temperature in Conductor	K	250
Peak Pressure in Conductor	Bar	35
Dump Resistor Spacing	km	10
Total Dump Resistance	mOhm	60
Peak Dump Voltage to Ground	V	+/- 3000

CRYOGENIC DUMP RESISTOR PARAMETERS		
Operating temperature	K	6
Peak Temperature in Quench	K	300
Stainless Steel Pipe Cold Mass	m^3	0.42
	tons	3.37
Stainless Steel Cross Section	cm^2	17
Length	m	248
Resistance per unit length	mOhm/m	0.24
Voltage Drop per meter	V/m	24
Total Voltage Drop	V	5986.

HELIUM REQUIRED FOR RECOOLING DUMP SWITCH		
He Required for 300K-40K Cooldown	kg	192
He available in 40K supply Header	kg	1890
Helium for 40K-5K Cooldown	kg	0.06
Helium available in 5K supply header	kg	>1000

Helium Inventory

INVENTORY (4 Cryoplants)		Per Plant	4 Plants
5K Piping	m^3 LHe	54.2	216.8
50K piping	m^3 LHe	45.1	180.5
Cryoplant/Reserve	m^3 LHe	15	60
Total	m^3 LHe	114	457
WARM STORAGE (100% inventory)			
# of Propane Tanks	30,000 gal ea.	57	228
Cost @$40k/tank		$2,280,000	$9,120,000
LIQUID STORAGE (100% Inventory)			
# of LHe tanks	10,000 gal ea.	3	12
Cost @$150K/tank		$450,000	$1,800,000

During Power Failure, Transmission Line Warms Up
and He Gas Pressure "Automatically" Transfers Inventory
Into Warm Storage

Comparison with Cryogenics of other Superconducting Synchrotrons

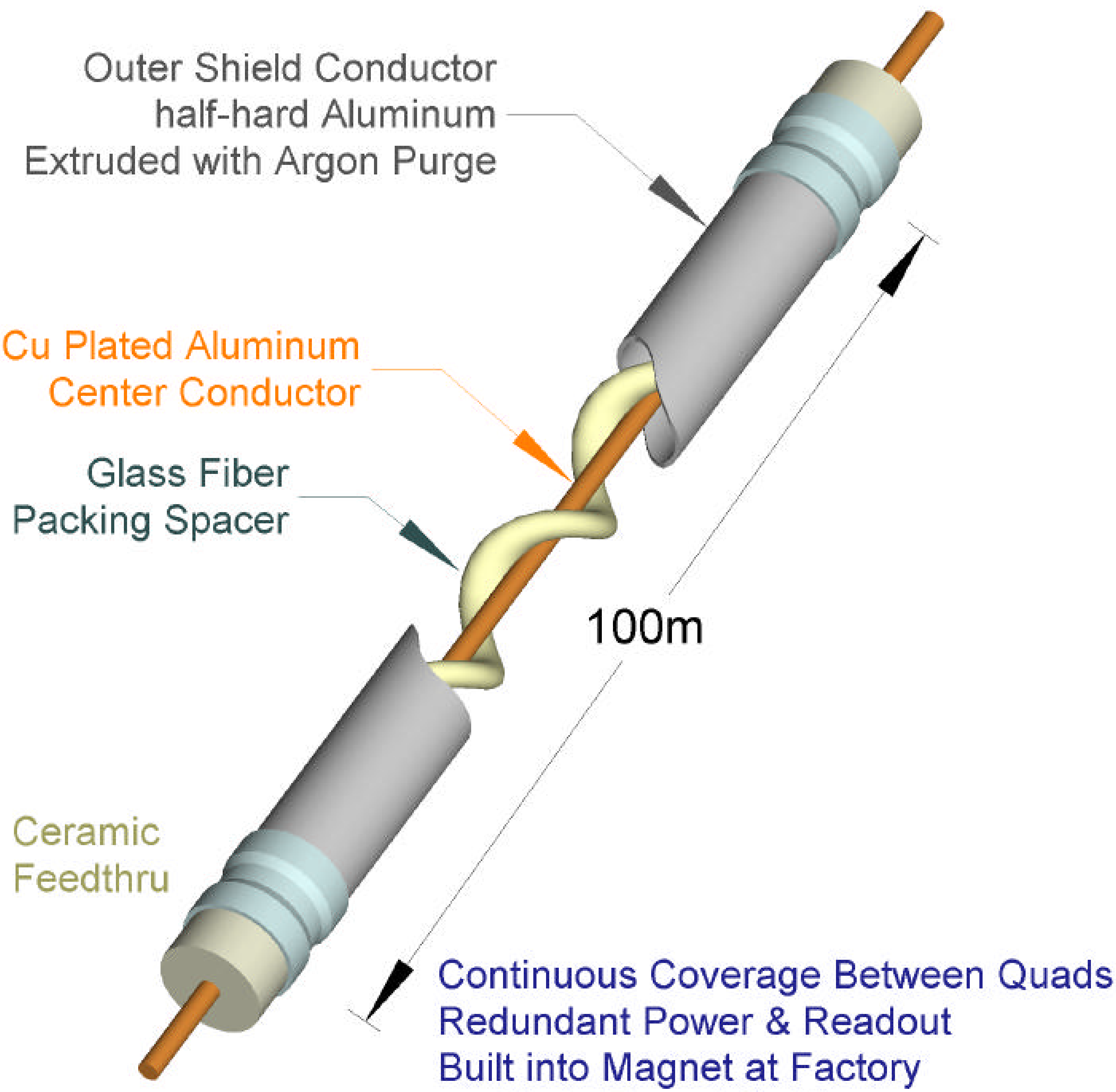
		Tevatron	RHIC	HERA	LHC	SSC	14x14
Beam Energy	**TeV**	1	0.3	0.8	7	20	14
Bmax	**Tesla**	4.4	3.5	4.7	8.4	6.6	2.0
Circumference	**Km**	6	4	6	27	85	160
Temperature	**K**	4.0	4.5	4.4	1.9	4.3	6.0
Cold Mass (approx.)	**tons**	500		4000	36,000	100,000	4,000
Magnetic Stored Energy	**MJ**	400		800	11,400	12,000	2,400
Refrigeration(4.5K eqv.)	**kW**	27	25	30	144	200	30
Specific Power	**W/W@4.5K**	440	600	270	220	270	300
Wall Power(approx)	**MW**	12	15	8	32	50	9
Helium Inventory	**tons**	12		17	96	320	57

14x14 TeV Transmission Line Collider is Cryogenically about the size of HERA.

Comparison of Cryogenics Per TeV Beam Energy

		Tevatron	RHIC	HERA	LHC	SSC	14x14
Cold Mass/TeV	**tons/TeV**	600		5000	5,143	5,000	286
Magnetic Stored Energy/TeV	**MJ/TeV**	400		1000	1,629	600	171
Refrigeration(4.5K eqv.)/TeV	**kW/TeV**	27	83	38	21	10	2.1
Helium Inventory/TeV	**tons/TeV**	12		21	14	16	4

Zero Maintenance Cable Stlye Beam Loss Monitor



Continuous Coverage Between Quads
Redundant Power & Readout
Built into Magnet at Factory
--> No In-Tunnel Cabling <--