ARIES CS MAGNETS

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ARIES MEETING
PPPL
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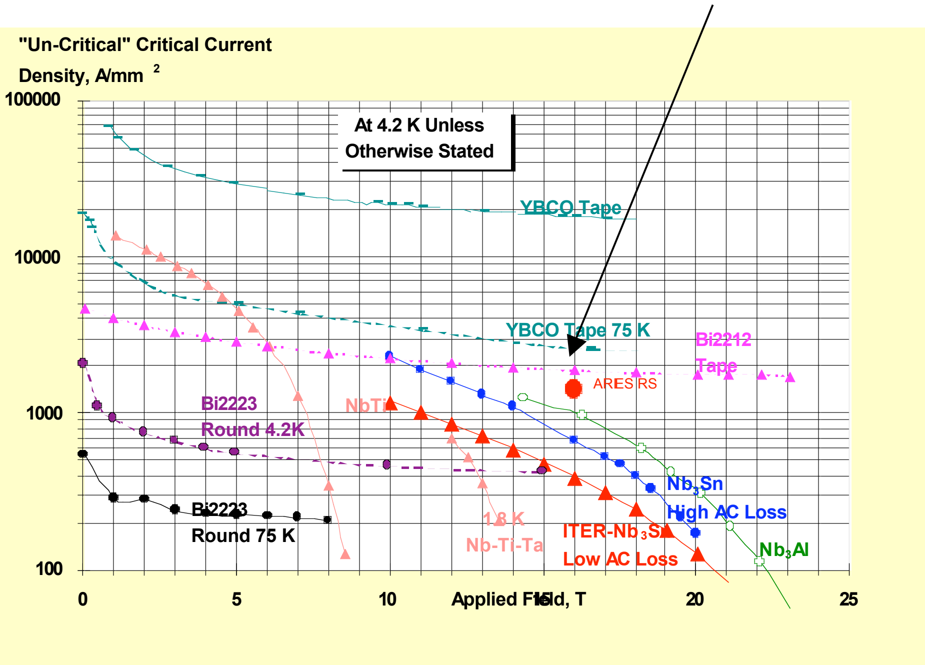
Organization of talk

- Cost of LTS and MTS magnets (wound)
- Cooling of intermediate temperature magnets (HTS and MTS at intermediate temperatures)

High temperature superconductors

- High Tc SC, with very high current density and no need for large cross sectional fraction for quench protection/stabilizer
  - Cross sectional area, therefore, determined from structural and cooling considerations
- Since structure is SC substrate, SC strain limitations of ~ 0.15 - 0.2% are comparable to limits in structure (~2/3 $\square_y$)
- Allow for ~ 20% of structural cross section for cooling



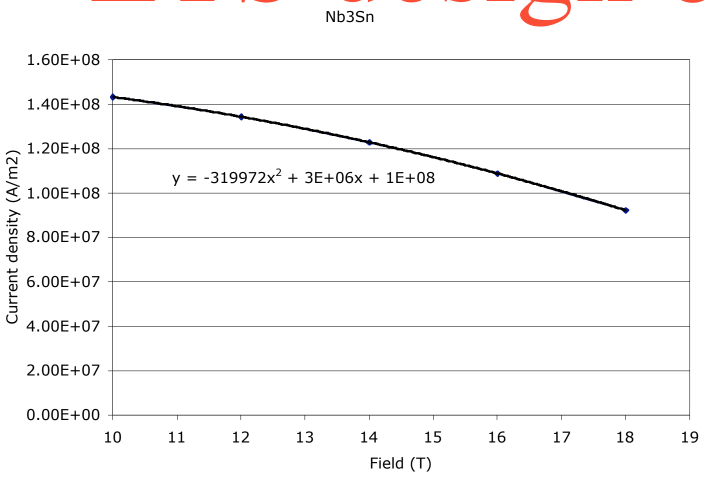
Courtesy of Lee, UW Madison

Structure

- Using simple beam theory (good for system analysis)
  - $t_{in} = \square_1 / \square_m$; $t_{out} = \square_2 / \square_m$
    - $\square_1 = A\ (R_{out} \ln (R_{out}/R_{1in}) - R_{out} + R_{in})/(R_{in}\ (R_{out} - R_{in}))$
    - $\square_2 = A\ (R_{out} - R_{in} - R_{in} \ln (R_{out}/R_{in}))/(R_{out}\ (R_{out} - R_{in}))$
    - $A = B_0^2 R_0^2 / 2\ \square_0$

  - R_{out}: outer external structure radius
  - R_{in}: inner external structure radius
- Assume that coil thickness is constant with the value determined by the outer thickness (dominates the mess of the structure)

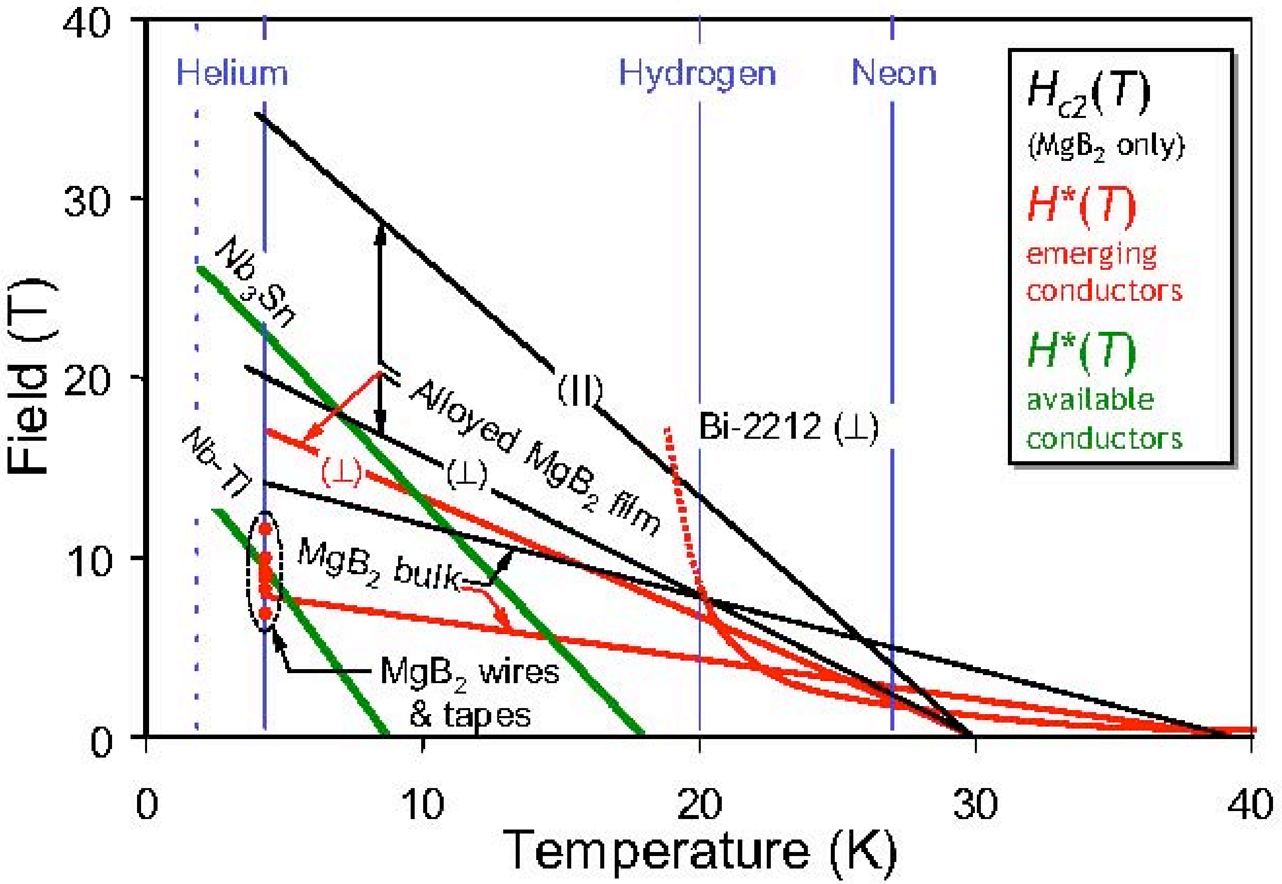
LTS design of conductor (Nb_3Sn)



- Winding pack design criteria:
  - –Use 0.7 $J_{\text{current sharing}}$
  - –Use 3:1 copper to superconductor (some laced)
  - –Use 50% packing factor (determined by pushing strands through sheath, requirement for cooling (CICC)
  - –Assume that conductor is 50% of cross section (rest is conductor sheath and insulation)
  - –Loads transferred to structure outside winding pack

Magnetic field	T	10	12
SC current density	A/m^2	4.00E+09	3.00E+09
J2 tau	(A/m^2)s	5.00E+16	5.00E+16
tau	s	2.00E+00	2.00E+00
Current density in Copper	A/m^2	2.24E+08	2.24E+08
Helium fraction		0.25	0.25
Sheathing thickness			
B^2/2mu0	Pa	3.98E+07	5.73E+07
Stress in sheath	Pa	8.00E+08	8.00E+08
Fractional thickness of sheath		4.97E-02	7.16E-02
Sheath fraction in conductor		9.70E-02	1.38E-01
Current density	A/m^2		
Current density in strands	Conductor	2.12E+08	2.08E+08
Strands + Helium	Conductor + helium	1.59E+08	1.56E+08
Strands+helium+sheath	Conductor + Helium + sheath	1.43E+08	1.35E+08

Medium temperature SC (2212 and MgB_2)



STUCTURE

- QA 2
- Uniform thickness top/bottom plates
- “educated” guesses to some dimensions and stresses

Bo	T	5.6
Ro	m	10
ASPECT		4.4
INBOARD	m	1.5
OUTBOARD	m	2.5
Rout		6.23
Rin		14.77
A		2.50E+09
S1		1.98E+08
S2		6.26E+07
sigma m	Pa	6.00E+08
sigma b		9.00E+08
tin	m	3.30E-01
tout	m	1.04E-01

- Calculate the volume of the structure (assume continuous toroidal shell to support forces)
- Multiply by specific cost (cost per unit weight)

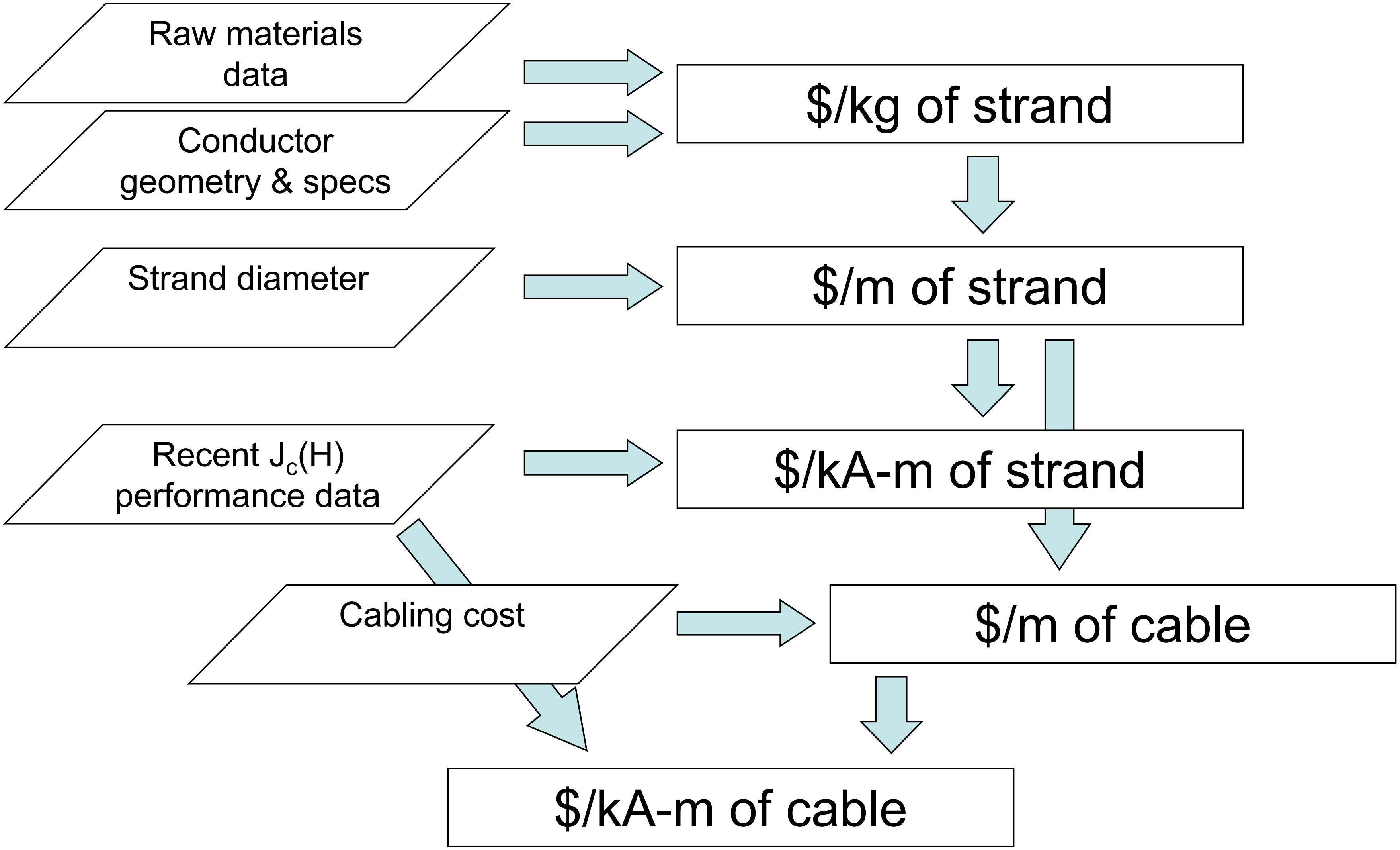
Superconductor cost comparison

Previous suggested costing of SC

- NbTi
  - Presently: 1-2 $/kA m
- Nb_3Sn
  - Today: 10-20 $/kA m
  - Expected: 2-4 $/kA m
- YBCO
  - Presently: 200 $/kA m
  - Guessed: 10-20 $/kA m
  - Expert opinion: 50$/kA m

  - Evaluation of costing using model/data from Lancey/BNL (June 2003)

Methods



Raw materials data

Conductor geometry & specs

Strand diameter

Recent $J_c(H)$ performance data

Cabling cost

$/kg of strand

$/m of strand

$/kA-m of strand

$/m of cable

$/kA-m of cable

Motivation

- On what bases should the cost of superconducting materials be compared?
  - Price per mass ($/kg) reflects raw materials purchases, billet mass
  - Price per length of cable ($/m) reflects cabling, insulation, and winding charges
  - Price per amp-turn ($/kA-m) reflects finished magnet performance

- How can intrinsic quantities (raw materials, conductor geometry, cable specs, performance) be separated from production factors?

Price = intrinsic costs x production scale factor

- Can "ultimate limits" of cost be predicted?

L.Cooley 2003

Nb-Ti

	Conventional		APC
	4.2 K	1.8 K	4.2 K
Strand raw cost, $/kg	$65.93	$65.93	$44.73
Strand raw cost, $/m	$0.27	$0.27	$0.19
Strand cost relative to LHC Nb-Ti			0.7
Production cost scaling factor	225%	225%	225%
Relative to LHC Nb-Ti			1.0
Scaled strand cost, $/kg	$148.34	$148.34	$100.64
* Recent purchase prices, $/kg	$150	$150	
Scaled strand cost, $/m	$0.60	$0.60	$0.42
Cabling cost, $/m	$3.00	$3.00	$3.00
Scaled cable cost, $/m	$24.53	$24.53	$18.06
Cable final performance index at field, $/kA-m			
5	$1.21	$0.60	$0.65
8	$2.64	$1.21	$3.88
10	$4.69	$2.11	(>Hc2)
12	(>Hc2)	$8.44	(>Hc2)
Scanlan data			
15	(>Hc2)	(>Hc2)	(>Hc2)
20	(>Hc2)	(>Hc2)	(>Hc2)

Nb_3Sn

	Bronze	Int. Sn	R&D-A	R&D-B	R&D-C	Low-Cu
	4.2 K	4.2 K	4.2 K	4.2 K	4.2 K	4.2 K
Strand raw cost, $/kg	*$146.30*	*$97.30*	*$97.30*	*$102.45*	*$94.25*	*$168.05*
Strand raw cost, $/m	*$0.67*	*$0.43*	*$0.43*	*$0.46*	*$0.42*	*$0.74*
Strand cost relative to LHC Nb-Ti	*2.5*	*1.6*	*1.6*	*1.7*	*1.6*	*2.8*
Production cost scaling factor	**450%**	**1190%**	**830%**	**830%**	**830%**	**830%**
Relative to LHC Nb-Ti	*2.0*	*5.3*	*3.7*	*3.7*	*3.7*	*3.7*
Scaled strand cost, $/kg	*$658.37*	*$1,157.87*	*$807.59*	*$850.34*	*$782.28*	*$1,394.82*
Recent purchase prices, $/kg		**$1,060**				
Scaled strand cost, $/m	*$3.02*	*$5.14*	*$3.58*	*$3.80*	*$3.47*	*$6.17*
Cabling cost, $/m	*$3.00*	*$3.00*	*$3.00*	*$3.00*	*$3.00*	*$3.00*
Scaled cable cost, $/m	*$111.65*	*$188.03*	*$132.05*	*$139.84*	*$128.01*	*$138.73*
Cable final performance index at field, $/kA-m						
5	*$3.66*	*$1.93*	*$1.35*	*$1.43*	*$1.31*	*$1.39*
8	*$6.53*	*$3.55*	*$2.50*	*$2.64*	*$2.42*	*$2.57*
10	*$9.14*	*$4.76*	*$3.35*	*$3.54*	*$3.24*	*$3.45*
12	*$12.19*	*$7.70*	*$5.41*	*$5.73*	*$5.24*	*$5.58*
Scanlan data	***$11.90***	***$7.74***		***$5.74***		
15	*$20.32*	*$14.44*	*$10.14*	*$10.74*	*$9.83*	*$10.46*
20	*$67.73*	*$57.76*	*$40.56*	*$42.96*	*$39.32*	*$41.84*

PIT(Powder_in_Tube)

		Nb_3Sn	Bi2212	MgB_2	H-Nb_3Sn	H-MgB_2
		4.2 K	4.2 K	4.2 K	4.2 K	4.2 K
	Conductor raw materials cost					
LHC-NbTi	**filament cost, $/kg**	* $170	** $400	$500	$200	$50
⇩	**stabilizer cost, $/kg**	$5	$175	$5	$5	$5
	reactants cost, $/kg	* $200	$0	$0	$0	$0
	diffusion barrier cost, $/kg	$0	$0	$5	$420	$10
	ancillary material cost, $/kg	$0	$0	$1,000	$0	$20
$66	***Conductor raw cost, $/kg***	***$83.50***	***$214.21***	***$252.59***	***$83.50***	***$19.50***
27¢	***Conductor raw cost, $/m***	***$0.35***	***$0.93***	***$1.01***	***$0.36***	***$0.06***
	Strand performance data					
	non-stabilizer J_c at field, A/mm^2					
	5	**6400**	**2400**	**1500**	**12650**	**4000**
	8	**3600**	**2200**	**500**	**6820**	**1800**
	10	**2550**	**2030**	**150**	**5100**	**1000**
	12	**1780**	**2000**	**60**	**3150**	**500**
	15	**1050**	**1900**	**2**	**1680**	**100**
	20	**200**	**1800**	**0**	**425**	**0**
	Strand raw performance index $/kA-m					
	5	***$0.11***	***$1.47***	***$0.90***	***$0.06***	***$0.03***
	8	***$0.20***	***$1.61***	***$2.69***	***$0.11***	***$0.07***
	10	***$0.28***	***$1.74***	***$8.96***	***$0.14***	***$0.12***
21¢ @ 5T	***12***	***$0.39***	***$1.77***	***$22.41***	***$0.23***	***$0.24***
	15	***$0.67***	***$1.86***	***$672.37***	***$0.43***	***$1.19***
	20	***$3.51***	***$1.96***	***>Hc2***	***$1.72***	***>Hc2***

* Reflects recent VAC/SMI bid and extruded tube quote

** Reflects recent presentation by Hasegawa at MT-18

Powder_in_tube

	Nb_3Sn 4.2 K	Bi2212 4.2 K	MgB_2 4.2 K	H-Nb_3Sn 4.2 K	H-MgB_2 4.2 K
Strand raw cost, $/kg	***$83.50***	***$214.21***	***$252.59***	***$83.50***	***$19.50***
Strand raw cost, $/m	***$0.35***	***$0.93***	***$1.01***	***$0.36***	***$0.06***
Strand cost relative to LHC Nb-Ti	***1.3***	***3.5***	***3.8***	***1.4***	***0.2***
Production cost scaling factor	**825%**	**805%**	**225%**	**225%**	**225%**
Relative to LHC Nb-Ti	***3.7***	***3.6***	***1.0***	***1.0***	***1.0***
Scaled strand cost, $/kg	***$688.88***	***$1,724.39***	***$568.33***	***$187.88***	***$43.88***
Recent purchase prices, $/kg					
Scaled strand cost, $/m	***$2.90***	***$7.49***	***$2.27***	***$0.82***	***$0.13***
			$0.50		
Cabling cost, $/m	*$3.00*	*$3.00*	*$3.00*	*$3.00*	*$3.00*
Scaled cable cost, $/m	***$107.31***	***$272.53***	***$84.71***	***$32.53***	***$7.76***
Cable final performance index at field, $/kA-m					
5	***$2.06***	***$29.82***	***$2.96***	***$0.32***	***$0.24***
8	***$3.66***	***$32.53***	***$8.88***	***$0.59***	***$0.53***
10	***$5.17***	***$35.26***	***$29.60***	***$0.78***	***$0.95***
12	***$7.41***	***$35.79***	***$74.00***	***$1.27***	***$1.91***
Scanlan data				***$1.50***	
15	***$12.56***	***$37.67***	***$2,219.94***	***$2.38***	***$9.53***
20	***$65.92***	***$39.76***	***(>Hc2)***	***$9.40***	***(>Hc2)***

Cost comparison

Previous suggested costing of SC

• NbTi	
– Presently: 1-2 $/kA m	0.6 $/kA m (@ 5T)
• Nb_3Sn	
– Today: 10-20 $/kA m	
– Expected: 2-4 $/kA m	1.27 $/kA m (@12 T)
• YBCO	
– Presently: 200 $/kA m	36 $/kA m (2212 @ 12T)
– Guessed: 10-20 $/kA m	
– Expert opinion: 50$/kA m	

- Evaluation of costing using model/data from Lancey/BNL (June 2003)

Low temperature magnet

- Use grading to decrease cost
  - Use NbTi in regions of low field (< 7 T)
  - In regions of higher field, use Nb_3Sn or equivalent
- Problem:
  - To wind stellarator magnets with Nb_3Sn, it is needed to use react and wind method
  - Magnets too complicated for applying insulation/bonding after winding (wind & react)
- Solution:
  - Use high Tc material/Medium Tc material at low temperatures
  - Use high Tc material/Medium Tc material at medium temperatures

Magnet Cooling

- Progress in YBC (HTS) materials has not been as fast as expected
- Suggestion at last meeting to develop model for use of near-term materials
  - BSSCO 2212
  - MgB_2
  - Operating at medium temperature
    - 15 K

Code development

- At 15 K, cooling options limited
  - Gaseous helium

- Question: Can gaseous helium be used for practical cooling of superconducting magnets at ~ 15K?

- Extrapolated 1-D code for the use of cooling of silver superconductors using superheated He
  - Heat conduction from gaseous to solid (ignore axial conduction in solid)
  - Pumping losses
  - Properties varying with length.

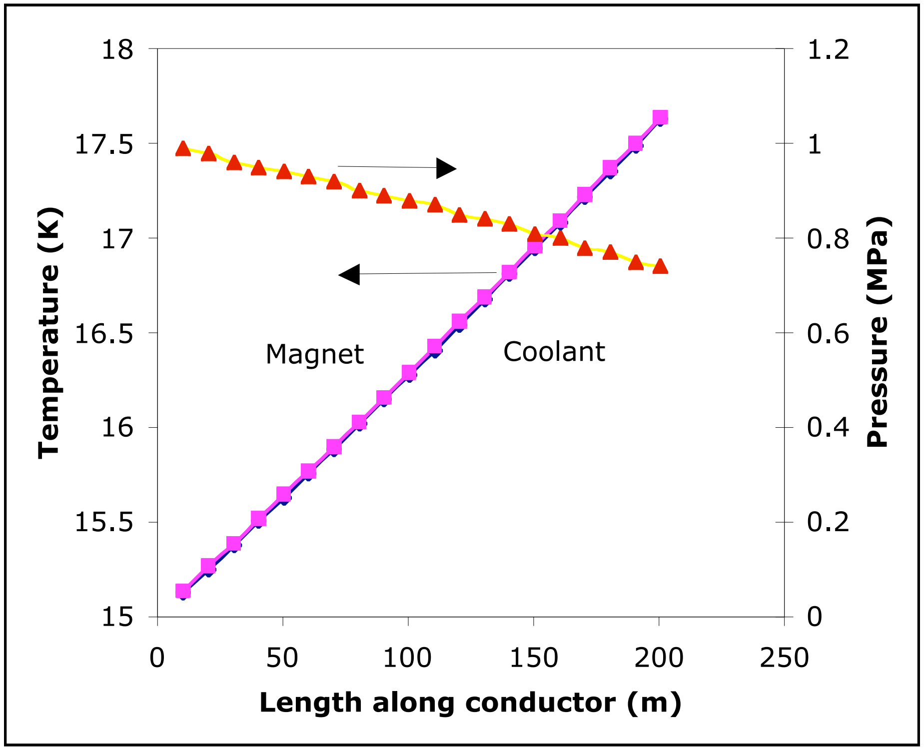
Gaseous He cooling

$q \sim 5$ mW/cm3

$T_{in} = 15$ K

$P_{in} = 1$ Mpa

20% coolant fraction



Gaseous He cooling?

- Large heating rate (5 mW/cm^3, instead of more likely 2 mW/cm^3)
- Pumping pressure drop about 2 bar in about 200 m of cooling passage
- Exit velocity ~ 5 m/s (vs about 220 m/s sound speed)
- Large Reynolds number (increases surface heat transfer coefficient, resulting in less than 0.01 K temperature difference between coolant and magnet)
- Effect of transient heat conduction (important for addressing quench protection/recovery)

- Looks good!

Summary

- Costing developed over last year summarized
- Will discuss with ORNL about implementation of costing algorithm in system code
- He-cooling at intermediate temperatures is feasible and looks attractive