A Proposal for a 50 T HTS Solenoid

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Muons Inc.
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We are not the first to be interested in 50 T Magnets for HEP

Fermilab

October 1, 1986

MEMO TO: "Super Wise Men"

SUBJECT: Wild Speculation

It is generally conceded that SSC is the last accelerator of that format (circular proton synchrotron). Since we are all genetically opposed to anything that is "generally conceded" I asked some of the experts at the Applied SC Conference whether one could build a magnet, if a new material would allow one to reach 50 T. Everyone said no. I guess the problems are: strength of materials, stored energy and synchrotron radiation. The question: are these problems more formidable than the linear collider problems at the level of 20 TeV e^+e^- collisions where beams have to be ~1A° to get luminosity? I am putting this in writing as the opening gun in the SSC upgrade program.

Alan

Tollestrup
Lundy
Kuchnir ✓
McInturff
Mantsch

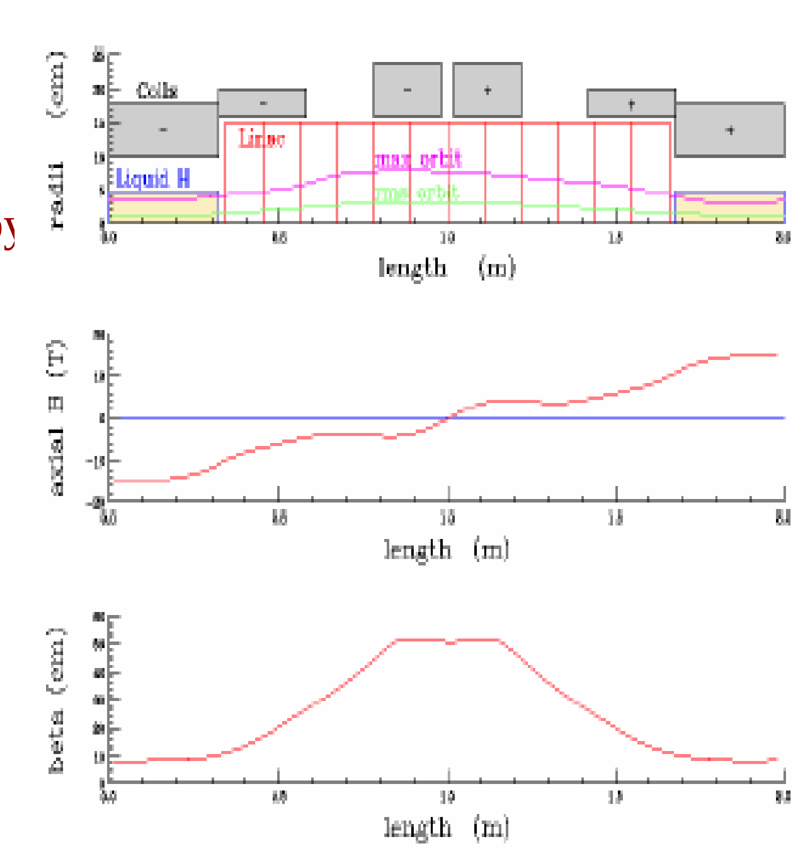
Alternating Solenoid Lattice for Cooling

- We plan to use high field solenoid magnets in the near final stages of cooling.
- The need for a high field can be seen by examining the formula for equilibrium emittance:

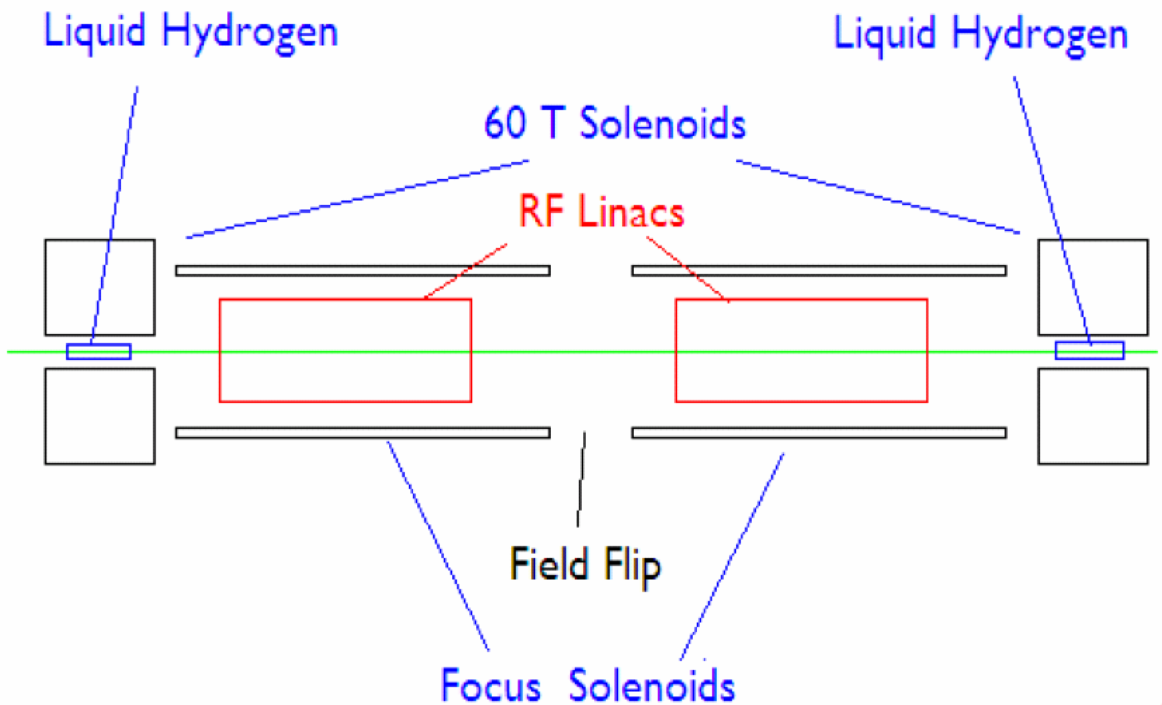
$$\min\ \epsilon_{xN} = \frac{\beta_{\perp} E_s^2}{2\beta m c^2 L_R \left|\frac{dE}{dz}\right|}$$

$$\beta_{\perp} = \frac{2 p_Z}{c B_Z}$$

- The figure on the right shows a lattice for a 15 T alternating solenoid scheme previously studied.

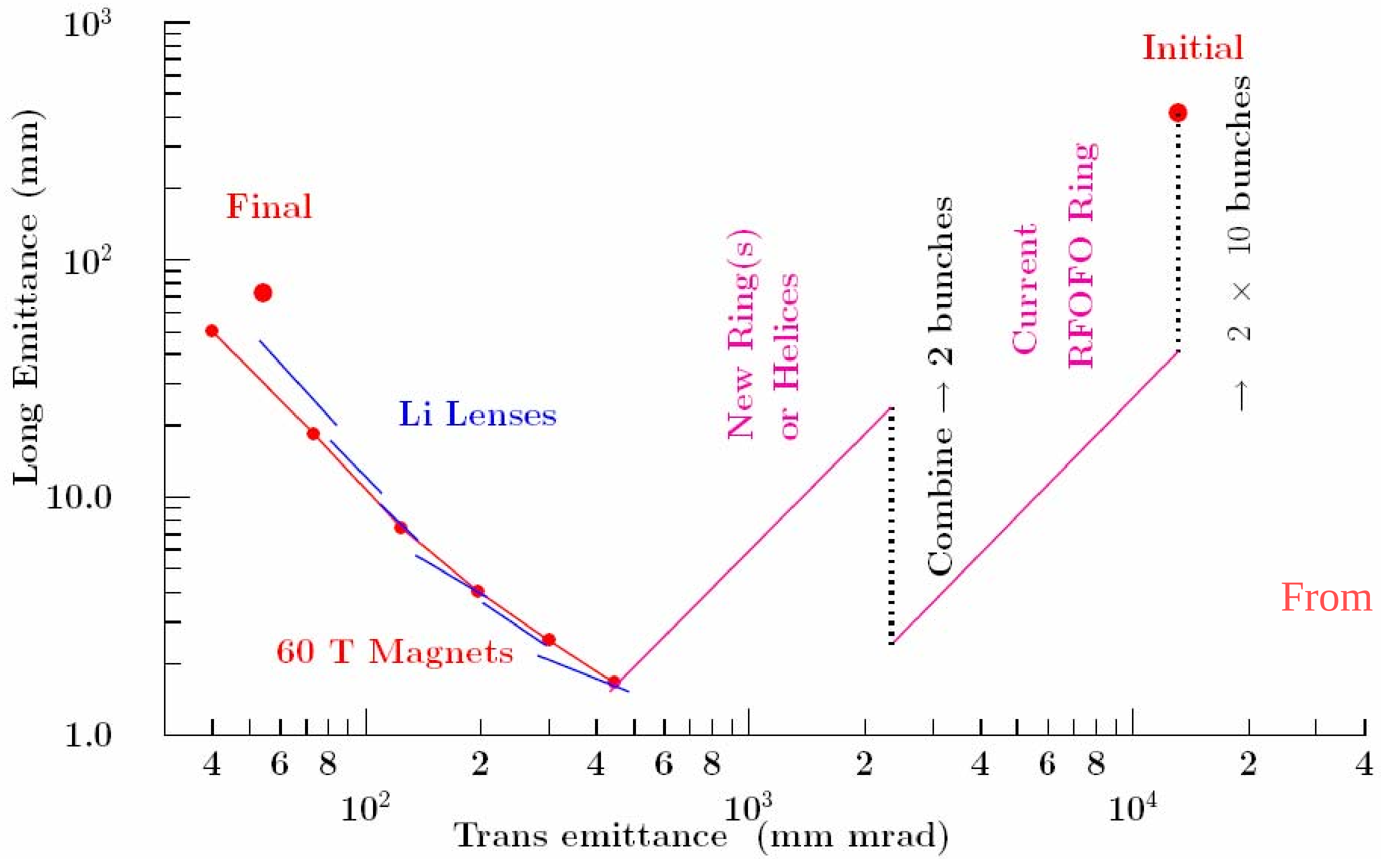


Concept of Final cooling Stages



From R. Palmer

Full System & Li Lens comparison

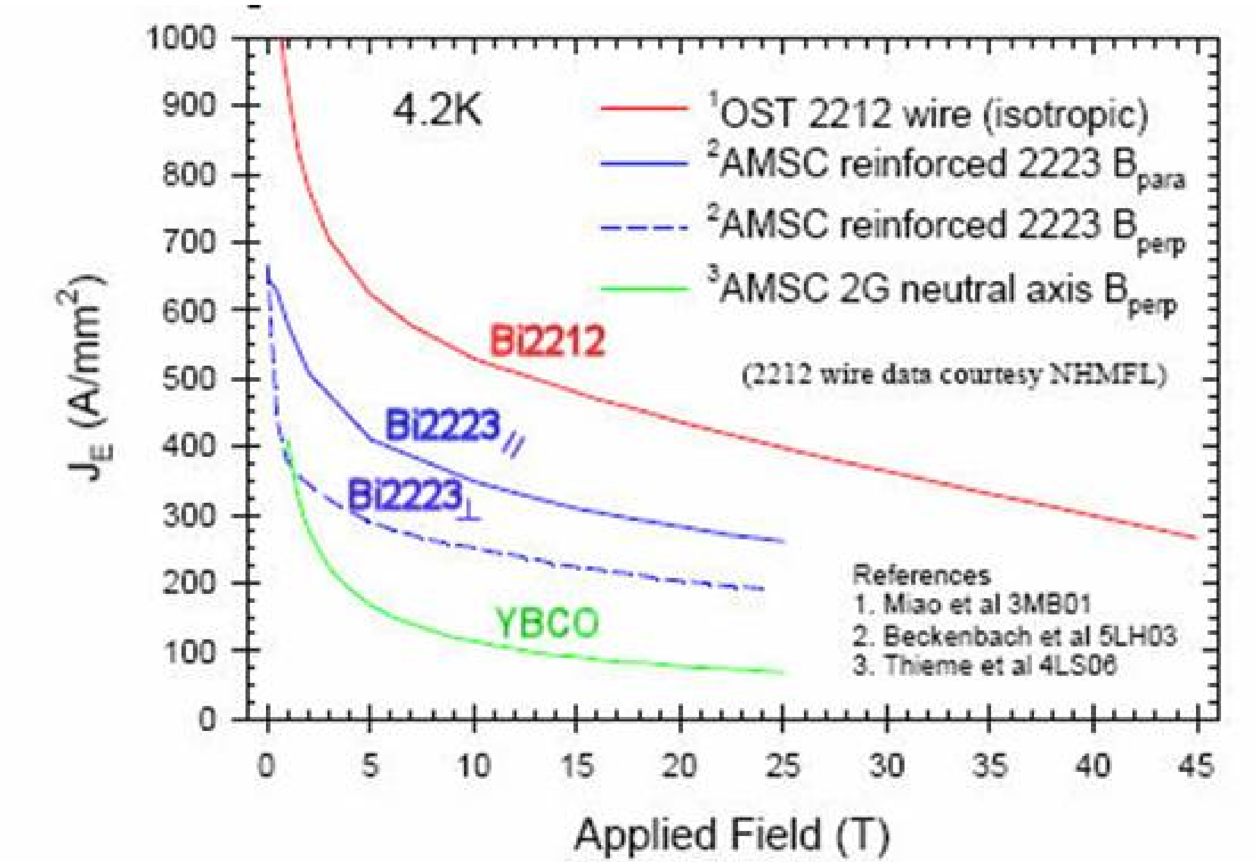


From R. Palmer

A Proposal for a High Field Solenoid Magnet R&D

- The availability of commercial high temperature superconductor tape (HTS) should allow significantly higher field that can produce smaller emittance muon beams.
- HTS tape can carry significant current in the presence of high fields where Nb_3Sn or NbTi conductors cannot.
- We would like to see what we can design with this commercially available HTS tape.

Comparison of J_E for HTS Conductors



We have chosen to use Bi2223 since it is available as a reinforced tape from AMSC

The conductor can carry significant current at very high fields. NbTi and Nb_3Sn can not.

Properties of American Superconductor's High Temperature Superconductor Wire

High Strength Tape used for calculations

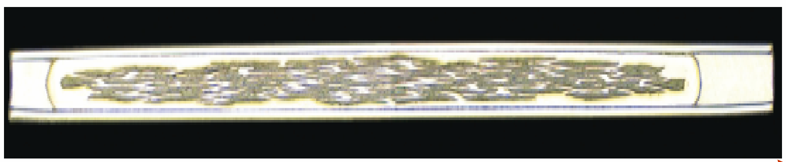
New and Improved *High Strength Plus* Tape

Parameter	High Current Wire	High Strength Wire	Compression Tolerant Wire	High Strength Plus Wire
J_e amp/mm^2	161	113	100	133
Thickness, mm	0.22	0.3	0.3	0.27
Width, mm	4	4.2	4.85	4.2
Iax Tensile Strength (77° K), MPa	65	300	280	250
Max Tensile Strain (77°K)	0.10%	0.35%	0.30%	0.4%
ıx Compressive Strain (77° K)		0.15%	0.15%	
ːin Bend Radius, mm	50	25	25	19
Max Length, m	800	400	400	400
Spliceable	no	yes	yes	yes

- 6% more current per turn
- 10 % more turns per radial space

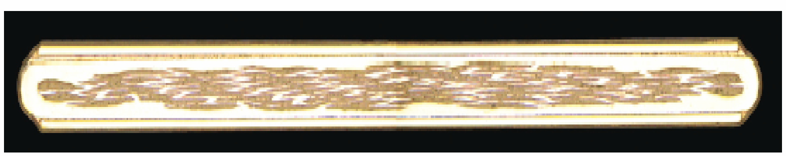
Cross Sections of HTS Tape

Bismuth based, multi-filamentary high temperature superconductor wire encased in a silver matrix and laminated with stainless steel to provide high mechanical strength.



Bismuth based, multi-filamentary, high temperature superconductor wire encased in a silver alloy matrix.

Bismuth based, multi-filamentary, high temperature superconductor wire encased in a silver matrix and laminated with stainless steel for high mechanical strength.

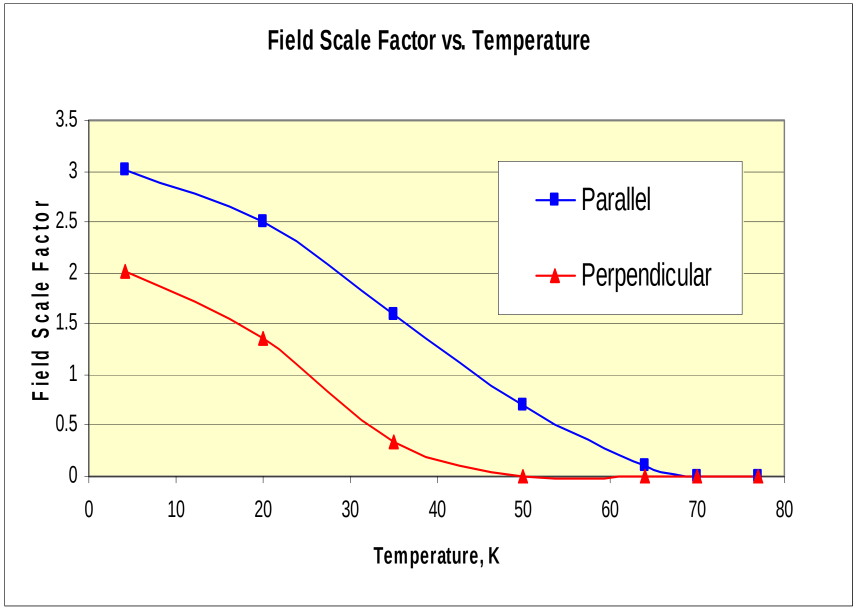


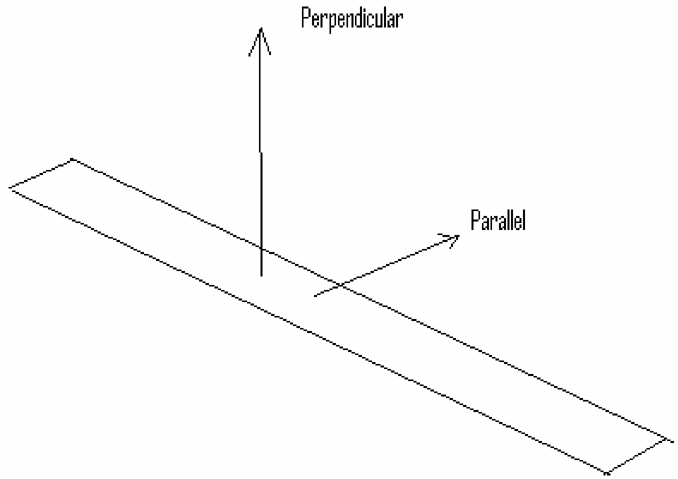
High Current Tape

High Compression Tape

High Strength Tape

Why Do We Want to Go to Liquid Helium?

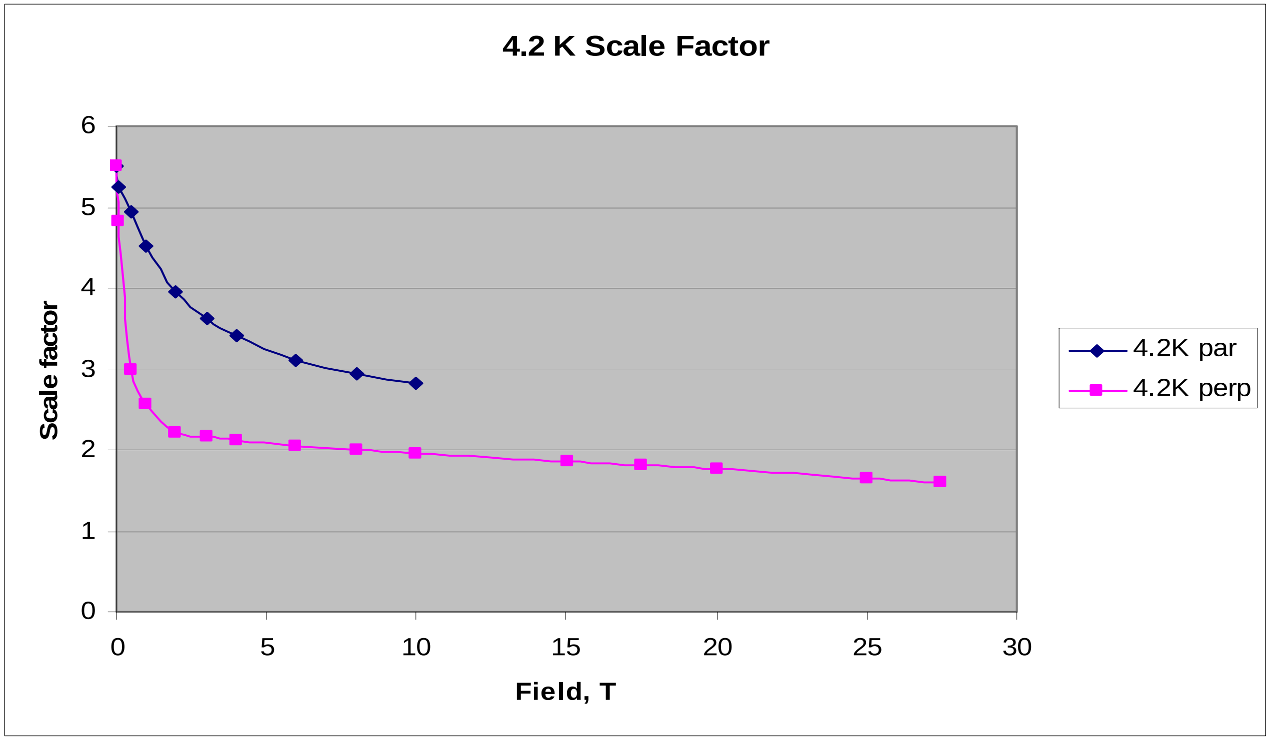




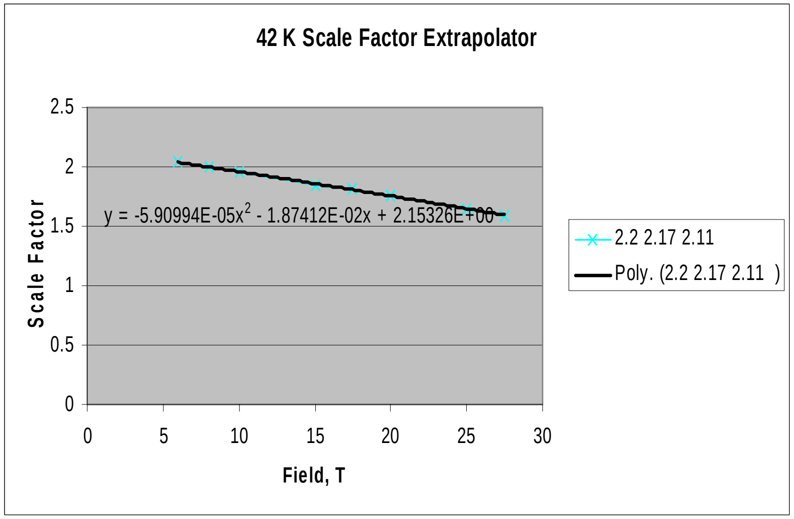
The parallel field orientation is the most relevant for a solenoid magnet.

Previous calculations had used the perpendicular field. (We can view this not as a mistake, but as a contingency).

Current Carrying Capacity for HTS Tape in a Magnetic Field
Scale Factor is relative to 77ºK with self field



Fit to High Field to Extrapolate Beyond 27 T



Field	***Quadratic***	***Linear***
30	1.5378	1.5454
40	1.3091	1.3384
50	1.0685	1.1314
60	0.816	0.9244

- We are using BSSCO 2223 which has been measured only to 27 T in the perpendicular configuration. We are using it in the parallel configuration.
  - We have to extrapolate to high field.
- We know that BSSCO 2212 has been tested to 45 T, so we *think* that the AMSC tape will work.
  - The high field measurements of BSSCO 2212 has a different falloff from BSSCO 2223.
- We certainly will need *measurements* of the AMSC tape at high field

A Vision of a Very High Field Solenoid

- Design for 40 Tesla.
- Inner Aperture Radius: 2.5 cm.
- Axial Length chosen: 1 meter
- Use stainless steel ribbon between layers of HTS tape.
  - We will vary the thickness of the SS ribbon.
  - The SS ribbon provides additional tensile strength
    - HTS tape has 300 MPa max tensile strength.
    - SS-316 ribbon: choose 660 MPa (Goodfellow range for strength is 460-860 MPa)
    - Composite strength = $\alpha_{SS}\ \sigma_{SS} + (1-\alpha_{SS})\ \sigma_{HTS}$ (adds like parallel springs).
- We use the J_{eff} associated to 40 Tesla.
  - We operate at 85% of the critical current.
- All parameters used come from American Superconductor's Spec Sheets.

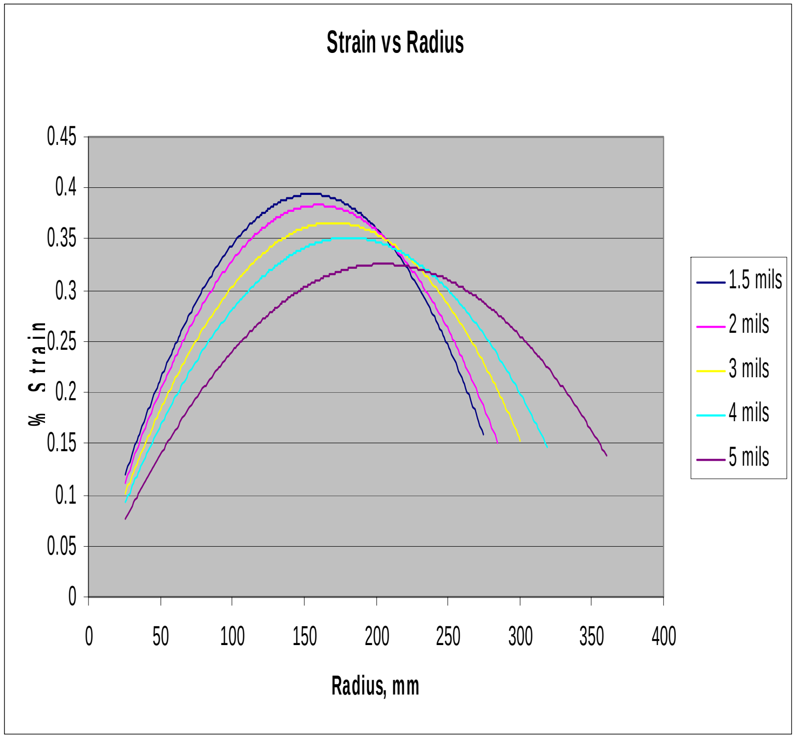
Case 3: Constraining Each Layer With A Stainless Steel Strip

- Instead of constraining the forces as a single outer shell where the radial forces build up to the compressive strain limit, we can put a mini-shell with each layer. Suggested by R. Palmer, but actually implemented previously by BNL's Magnet Division for RIA magnet. (See photo)

Fig. 3. A coil being made by co-winding HTS tape (on right) and stainless steel insulating tape (left). This is wound using a first generation winding machine that could be quickly set-up.

Case 3: Using Stainless Steel Interlayer

- The figure shows tensile as a function of the radial position for the cases of 1.5 and 2 mil stainless steel interleaving tape which will take some of the stress. These stresses are calculated for a 40 Tesla solenoid!
  - The effective modulus for the HTS/SS combination increases with increased SS fraction:
    - 90 GPa for no SS
    - 96 GPa for 1.5 mil SS
    - 98 GPa for 2 mil SS
    - 101 GPa for 3 mil SS
    - 104 GPa for 4 mil SS
    - 110 GPa for 5 mil SS
  - The maximum strain limit for this material is 0.35%.
  - With 4 mil Stainless Steel we have achieved 40 Tesla!



40 Tesla Solenoid Parameters When Varying the Stainless Steel Fraction

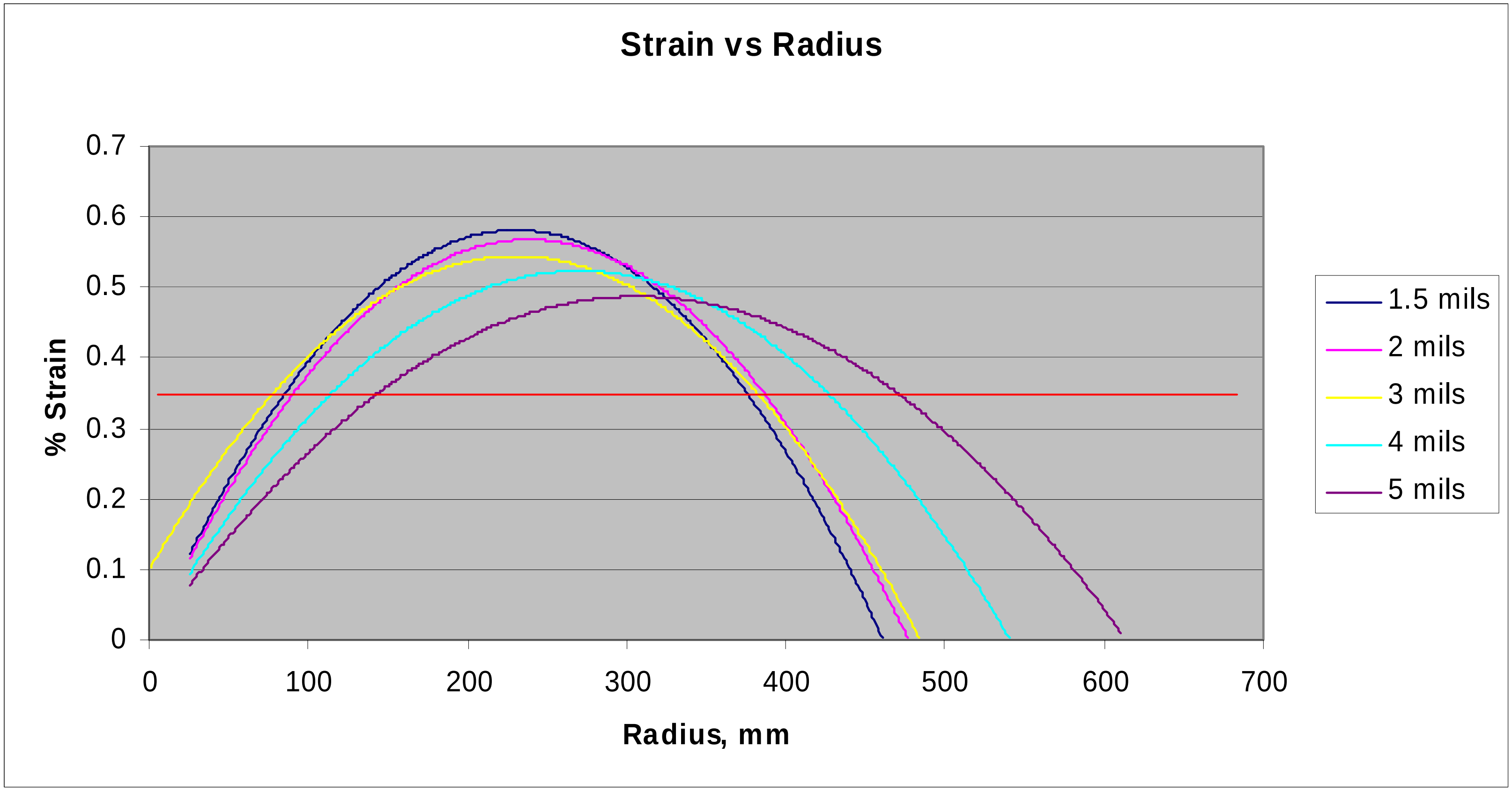
Stainless Steel Thickness	*1.5 mils*	*2 mils*	*3 mils*	*4 mils*	*5 mils*
Fraction SS	0.111111	0.142857	0.2	0.25	0.3429
Fraction HTS	0.888889	0.857143	0.8	0.75	0.6671
J_{eff}, ***amp/mm***^{2}	112	108	101	94	83
R_{inner}, ***mm***	25	25	25	25	25
R_{outer}, ***mm***	310	320	341	362	410
Max Tensile Stress	340	351	372	390	423
Max Observed Stress	378	374	370	367	361
Max Observed Strain	0.394%	0.383%	0.366%	0.351%	0.326%
Cable Length (1 m solenoid)	2.12×10^5 m	2.18×10^5 m	2.31×10^5 m	2.44×10^5 m	2.74×10^5 m
HTS Cost	4.2 M$	4.4 M$	4.6 M$	4.9 M$	5.5 M$

40 Tesla Solenoid Parameters when varying the stainless steel thickness. Used 1.31 for nominal scale factor

A Slightly More Aggressive Approach

- Bob Palmer has suggested that we can vary the amount of stainless steel interleafing as a function of radius.
  - At small radius where we have smaller stress, we could use a smaller fraction of stainless steel. (See previous slide)
  - In the middle radial region we would use more stainless where the tensile strength is largest.
- Following this approach Bob finds that he can build a 60 Tesla solenoid. (We need to check this but it seems plausible).
  - I was only able to achieve 50 T.
- A 60 Tesla solenoid will require significantly more HTS and will consequently cost more.

Case 4b: Naively Increasing The Field to 50 T



Case 5: Vary SS Thickness to Achieve 50 T

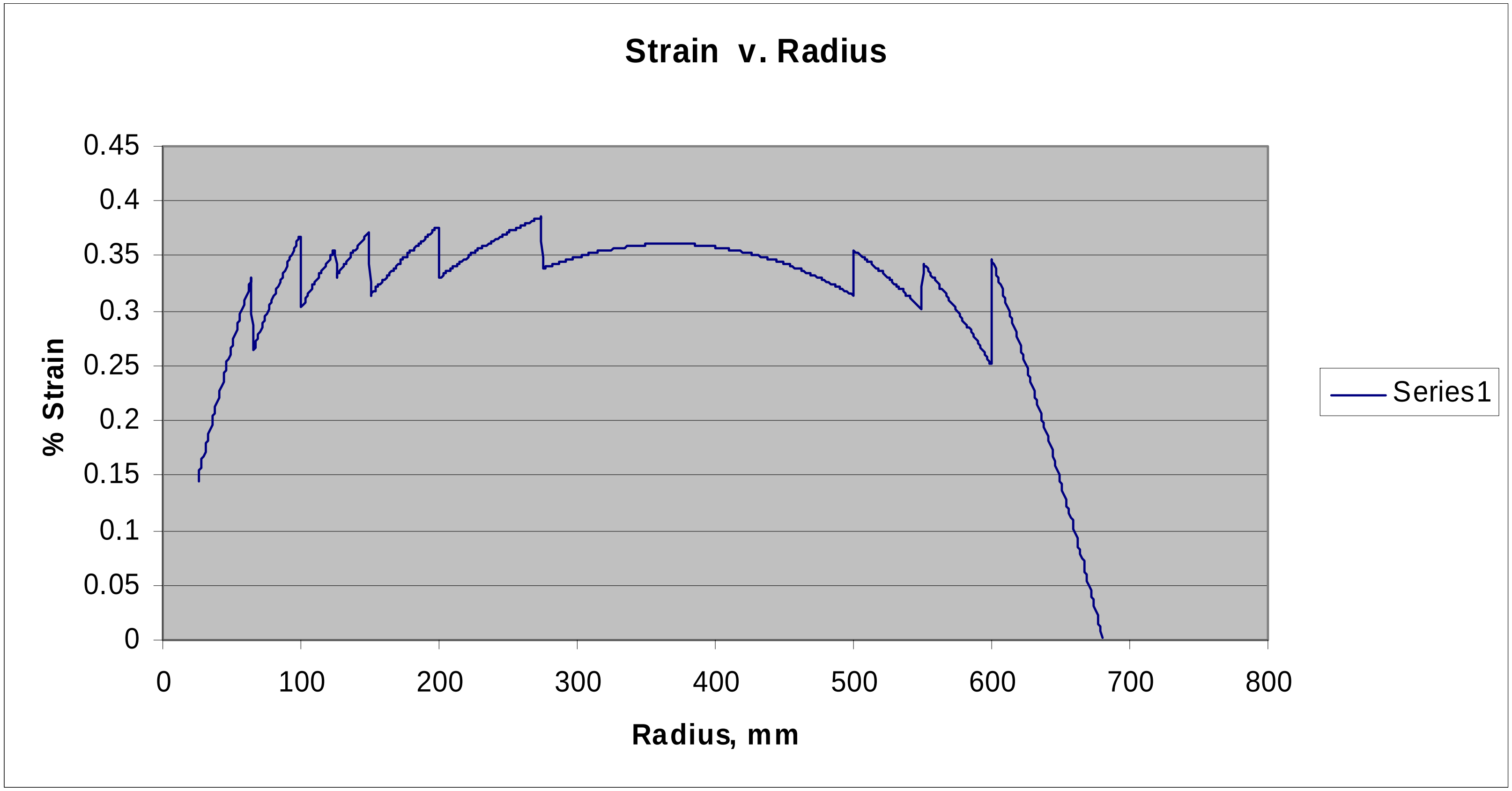
SS Thickness (mils)	*Fraction SS*	*Fraction HTS*	R_{min} *mm*	R_{max} *mm*	*E GPa*	J_{eff} *amp/mm²*
0	0	1	25	65	90	103
2	0.14286	0.85714	65	100	98	88
4	0.25	0.75	100	125	104	77
6	0.3333	0.6667	125	150	110	68.5
8	0.4	0.6	150	200	115	62
10	0.454545	0.545455	200	270	120	56
12	0.5	0.5	270	500	124	51
10	0.454545	0.545455	500	550	120	56
8	0.4	0.6	550	600	115	62
4	0.25	0.75	600	650	104	77

Note that the HTS tape includes SS in its geometry

HTS Length: 7.27×10^{5} m

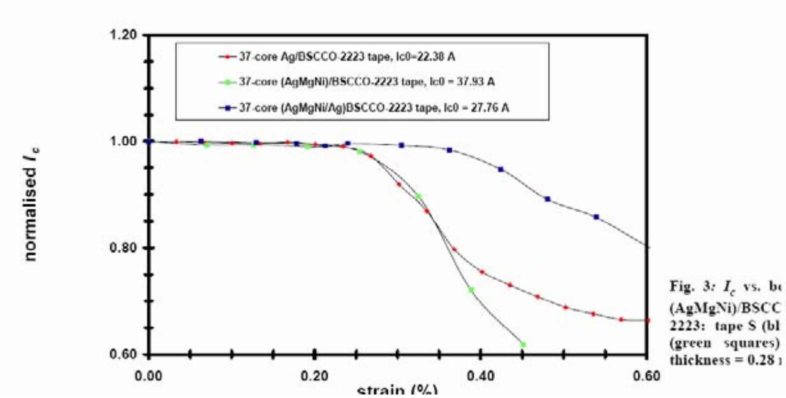
HTS Cost: M$ 14.6

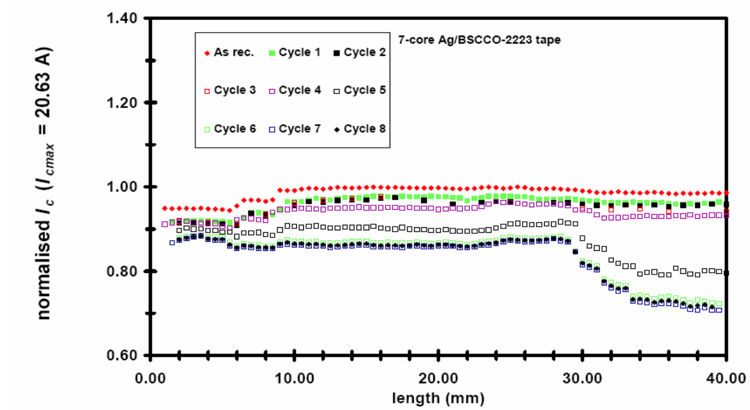
Case 5: Varying SS Thickness in Different Radial Regions to Achieve 50 Tesla



R&D Issues Associated with HTS

- Mechanical Fatigue performance is good:
  - For strain <0.1% $N_{cycles}>1.5\times10^5$ observed
  - For strain 0f 0.26% $N_{cycles}\approx4000$ have been observed
- There are *thermal cycling* issues that have been observed.
  - Figure shows degradation with cycling between LN_2 and RT.
  - ASC has solution (next transparency)





Special HTS Solutions for Special Problems

We may need to use up some of our J_e contingency by using Hermetic Wire to address thermal cycling issue

Parameter	High Strength Wire	Cryoblock Wire	Hermetic Wire
J_e amp/mm^2	113	148	85
Thickness, mm	0.305	0.21	0.40
Width, mm	4.2	4.0	4.2
Max Tensile Strength (77°K), MPa	300	50	200
Max Tensile Strain (77°K)	0.35%	?	0.30%
Max Length, m	400	Cut to specifications	800
Spliceable	yes	probably not	available

Nominal High Strength Wire used in our study

Good for Leads?

Special Reasonably High Strength Wire that prevents cryogens from contact with conductor

Possible Phase 1 R&D Program

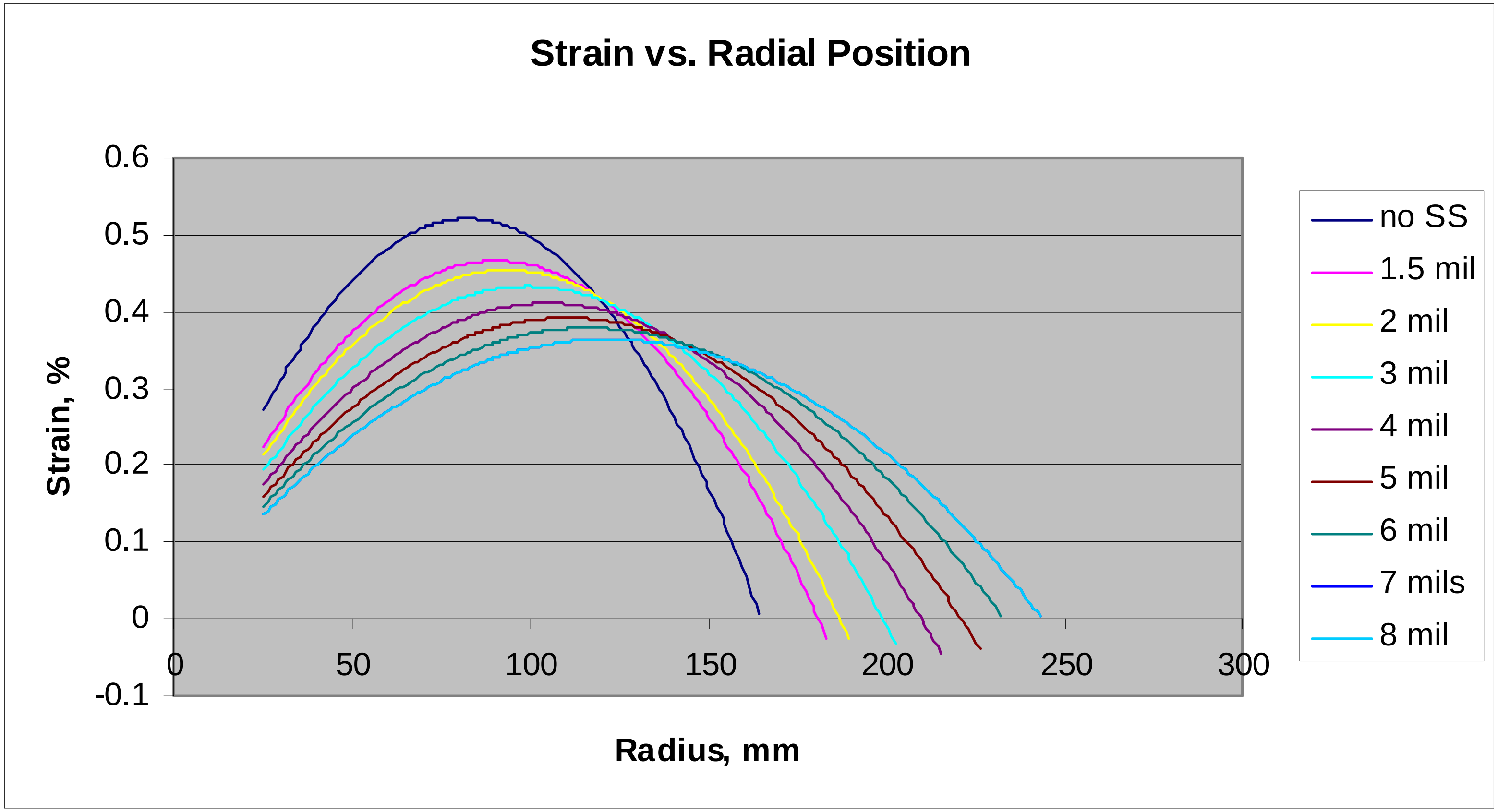
- Measure the current carried by HTS at 4.2°K and under tensile strain.
  - This measurement would be performed at a number of strain points up to and beyond the recommended tensile strain limit of 0.35-0.45%.
  - This could be done at self field.
- Measure the current carried at the HTS at 4.2°K and under 0.35% tensile strain and thermal cycle the conductor ~10 times.
  - Thermal cycling with LHe should be worse than with LN_2. LHe may get through the hermetically sealed HTS.
  - This could be done at self field.
- Wind a small number of test coils with the new *high strength plus* HTS conductor both with and without the stainless steel interleaving.
  - The dimensions should be chosen to fit into existing test solenoids:
    - 11 Tesla available at BNL
    - 15 Tesla available at FNAL
    - 45 Tesla available at NHFML in Florida. (This may need to be done in phase II.

Conclusions

- Commercially available HTS appears to make very high field solenoid magnets viable.
- These very high field magnets can permit the necessary muon phase space cooling to once again think about muon colliders.

Backup Slides

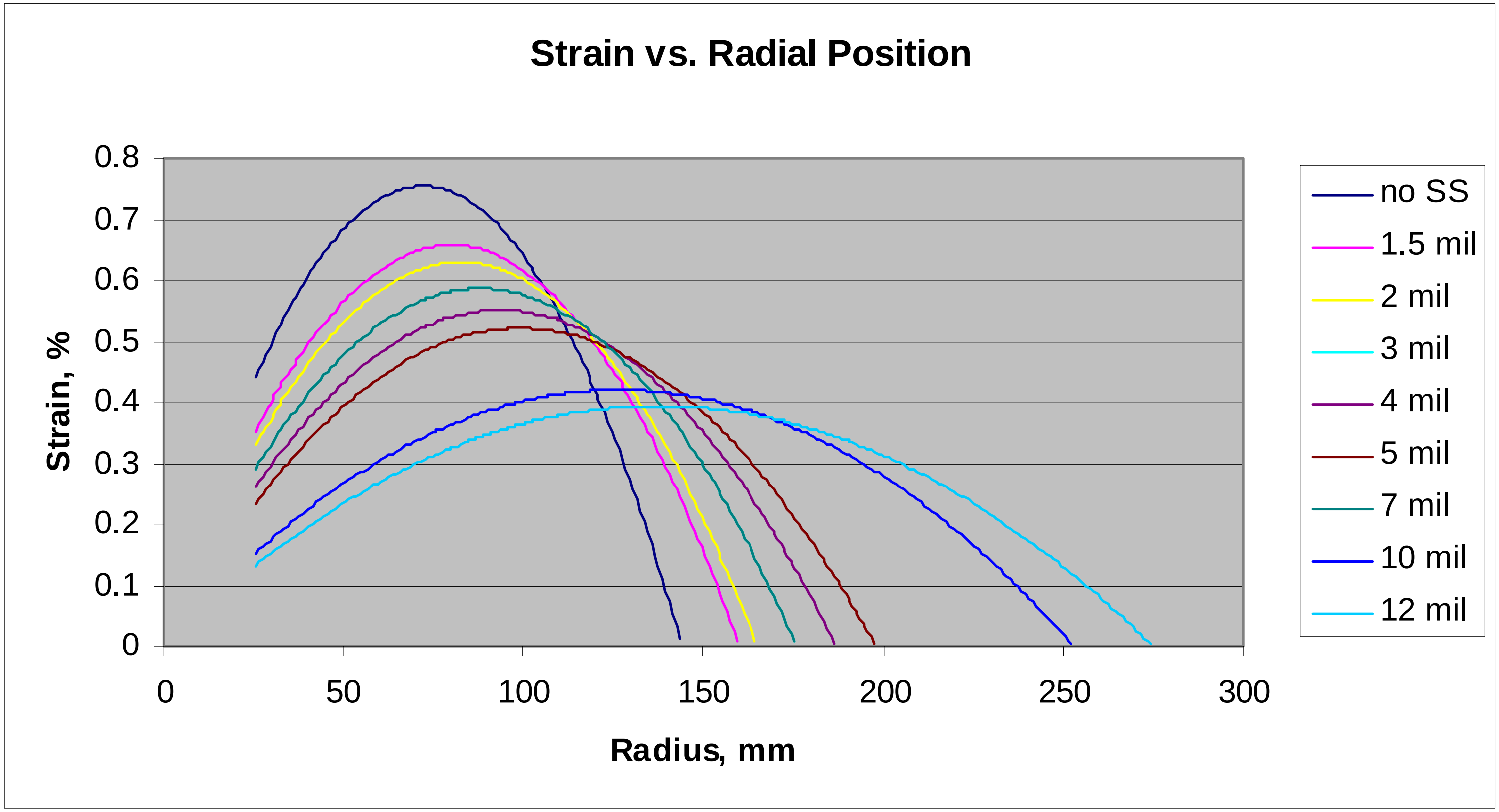
Strain Plot for High Strength Conductor Using Parallel Config



High Strength using Parallel Field Config for 40 T Solenoid

Stainless Steel Thickness	***4 mil***	***5 mil***	***6 mil***	***7 mil***	***8 mil***
Fraction SS	0.2469	0.2907	0.3297	0.3646	0.3960
Fraction HTS	0.7531	0.7093	0.6703	0.6454	0.6040
J_{eff} amp/mm^2	172	162	153	145	138
R_{inner}, mm	25	25	25	25	25
R_{outer}, mm	210	221	233	244	256
Max Tensile Observed_Strain	0.41%	0.39%	0.38%	0.36%	0.35%
Max Tensile HTS Stress	352	336	325	312	303
Cable Length, km	88.6	92.5	97.3	101.3	106.1
HTS cost	1.77 M$	1.85 M$	1.95 M$	2.03 M$	2.12 M$

Strain Plot for the High Strength Plus Conductor



High Strength Plus Conductor for 40 T Solenoid

Stainless Steel Thickness	4 mil	5 mil	7 mil	10 mil	12 mil
Fraction SS	0.2703	0.3165	0.3933	0.4808	0.5263
Fraction HTS	0.7297	0.6835	0.6067	0.5192	0.4737
J_{eff} amp/mm^2	196	184	163	140	127
R_{inner}, mm	25	25	25	25	25
R_{outer}, mm	187	198	220	253	275
Max Tensile Observed Strain	0.55%	0.52%	0.47%	0.42%	0.39%
Max Tensile HTS Stress	344	326	295	262	246
Cable Length, km	67.8	71.4	78.4	89.1	96.1
HTS cost	1.36 M$	1.43 M$	1.57 M$	1.78 M$	1.92 M$