Very High Field Solenoid Proposal

Steve Kahn

Muons Inc.

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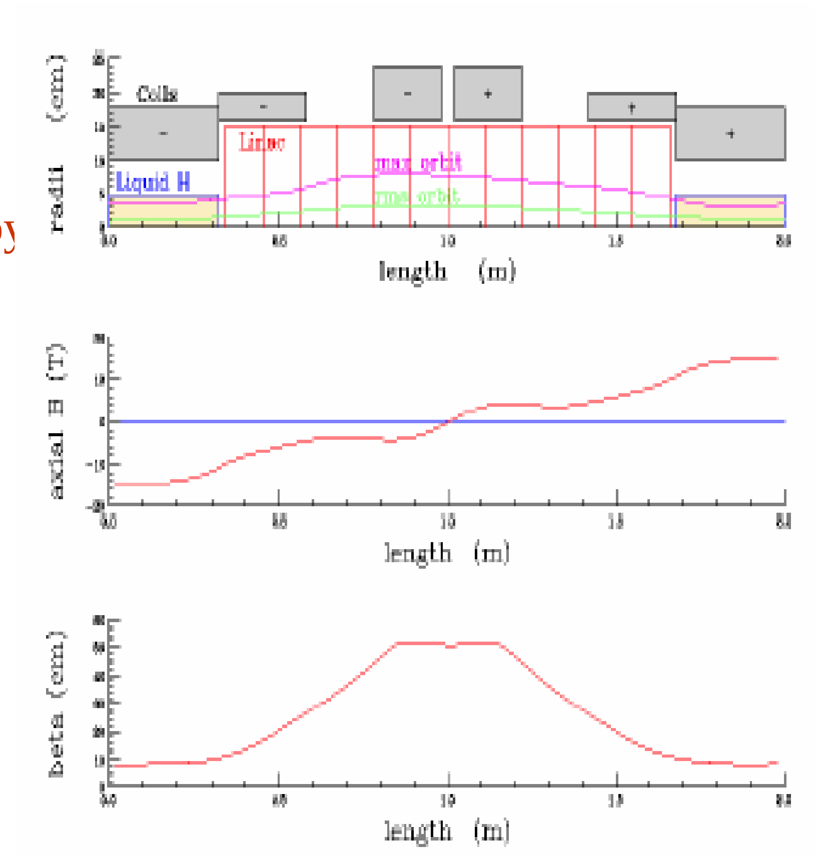
Alternating Solenoid Lattice for Cooling

- 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.



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. Consequently we have chosen what is called *First Generation* HTS.
  - Specifications for *Second Generation* HTS seem to imply that its main advantage is cost reduction not higher field. It has similar current capabilities.

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.

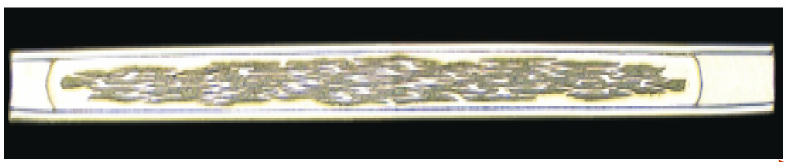
Tollestrup
Lundy
Kuchnir ✓
McInturff
Mantsch

Properties of American Superconductor's High Temperature Superconductor Wire

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

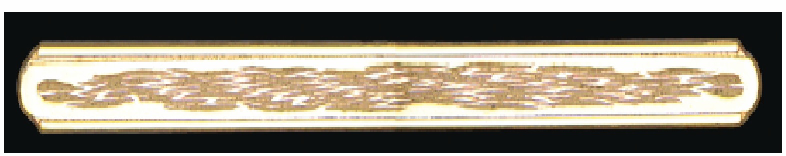
Cross Sections of HTS Tape

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.

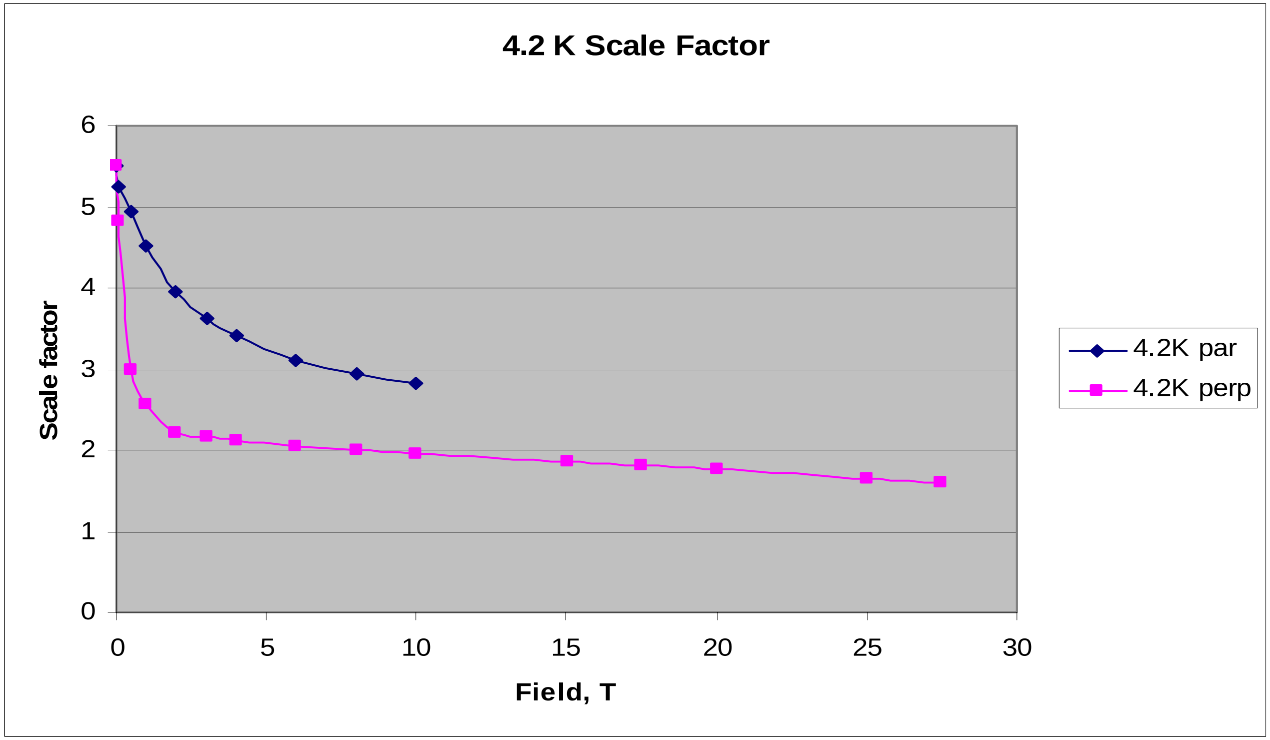


High Current Tape

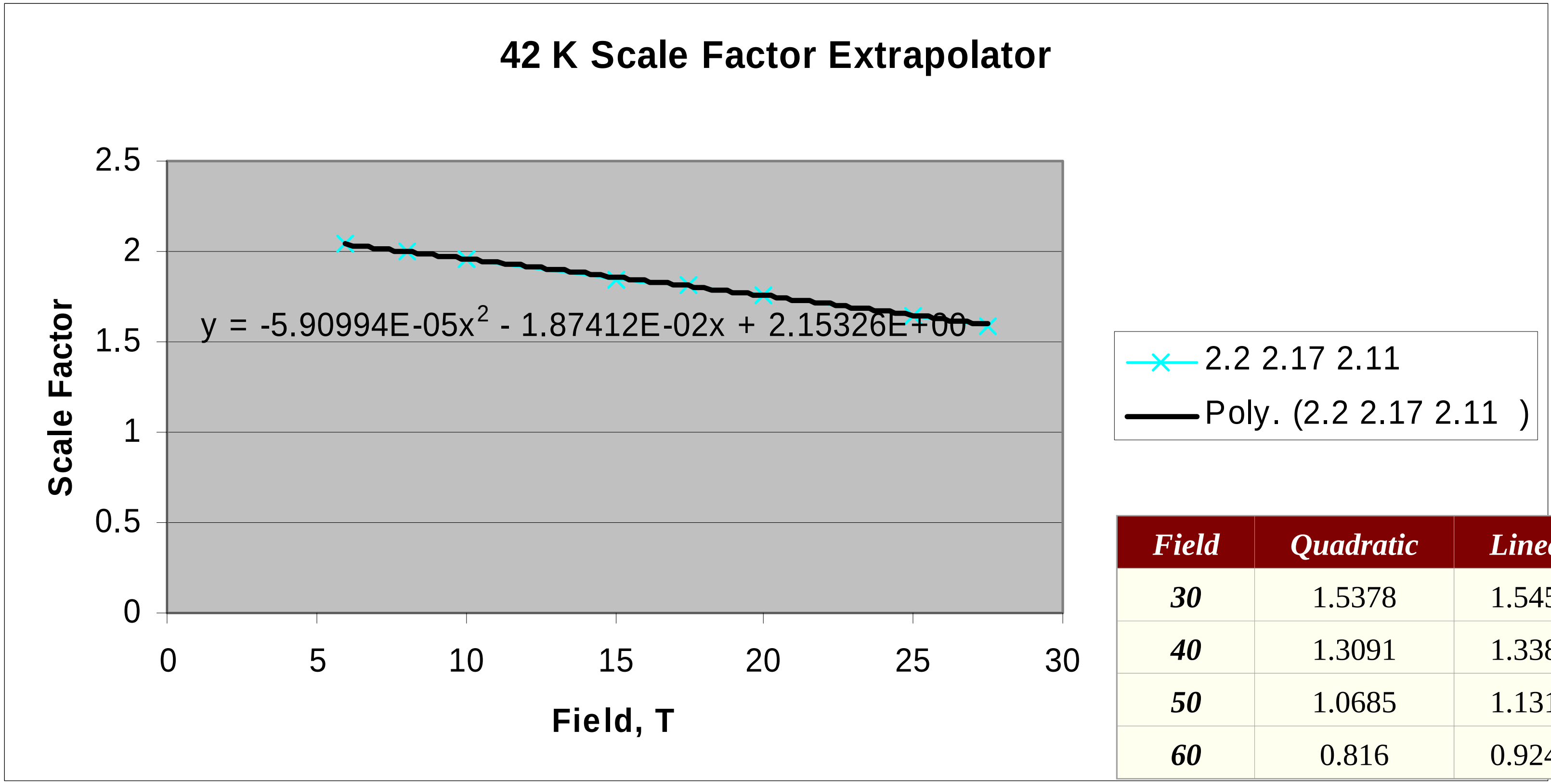
High Compression Tape

High Strength Tape

Current Carrying Capacity for HTS Tape in a Magnetic Field
Scale Factor is relative to 77°K 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

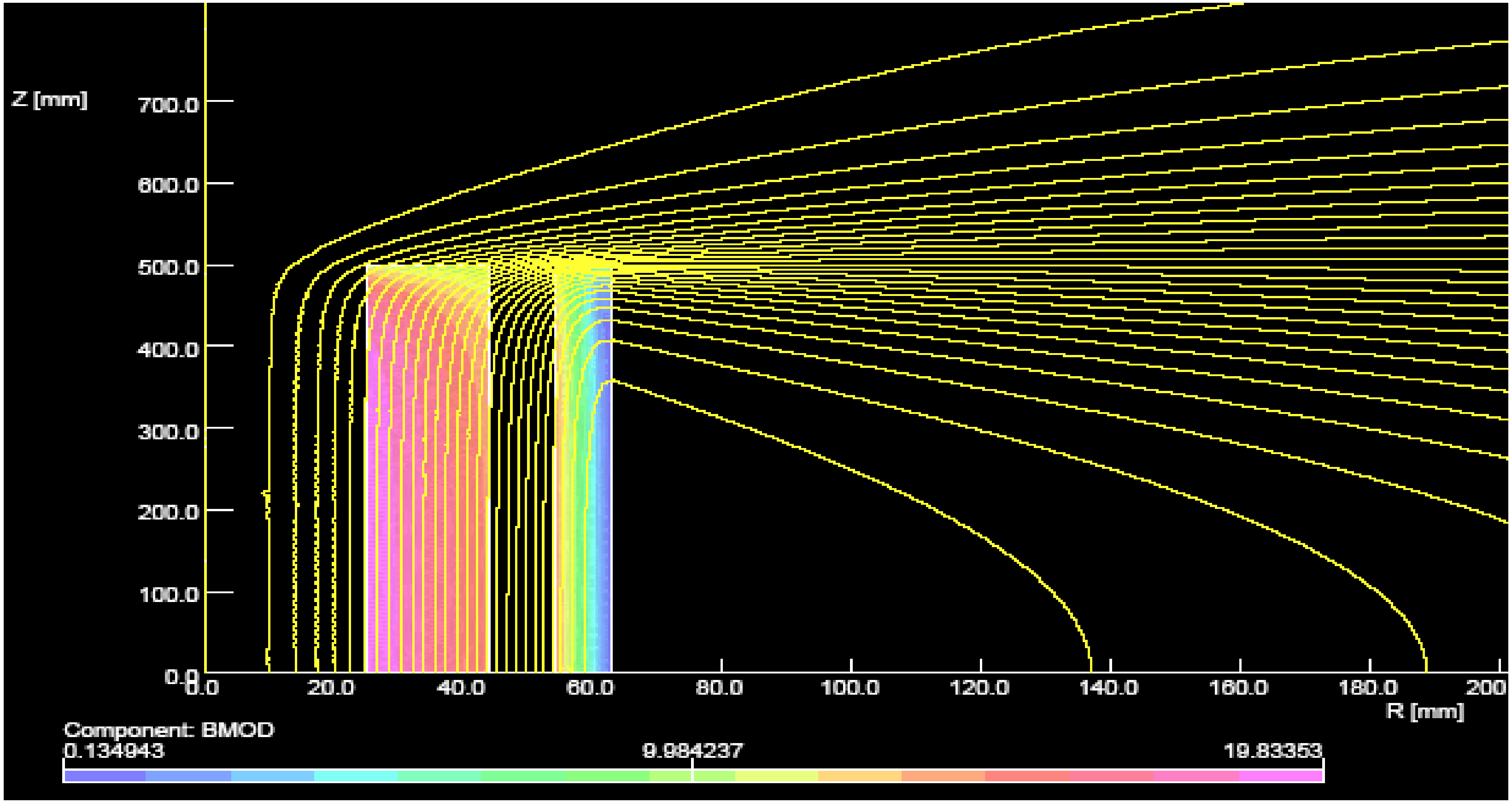
Different Approaches

- We have examined several different approaches. Each approach is tailored to a different desired field.
  - A hybrid design where a HTS insert is placed inside a Nb_3Sn Solenoid
    - The Nb_3Sn outsert provides 14 T and the HTS insert provides the last 6 T to achieve 20 T solenoid.
  - A design where HTS tape is interleaved with constant thickness stainless steel tape to mitigate strain on the HTS. We think that we can achieve 40 T with this scheme.
  - If we vary the thickness of the stainless steel tape as a function of radial position we can possibly achieve 50 T.
  - If we vary the current density as a function of the radial position we may possibly achieve 60 T.
- Examining these different approaches will be the scope of the Phase I proposal.

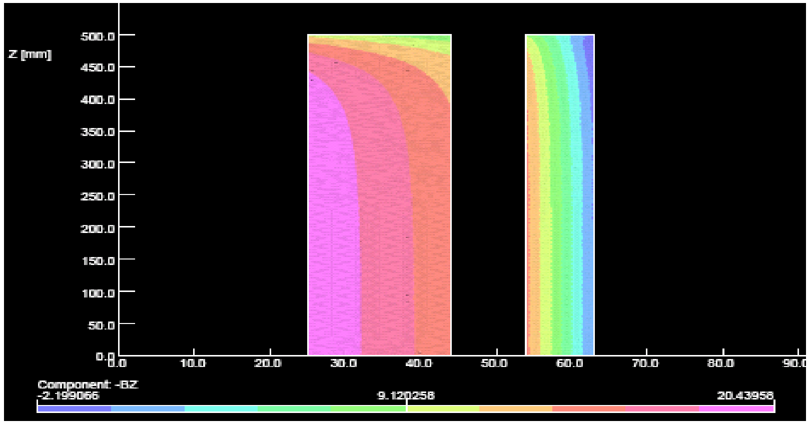
Building a High Field Solenoid from HTS Conductor

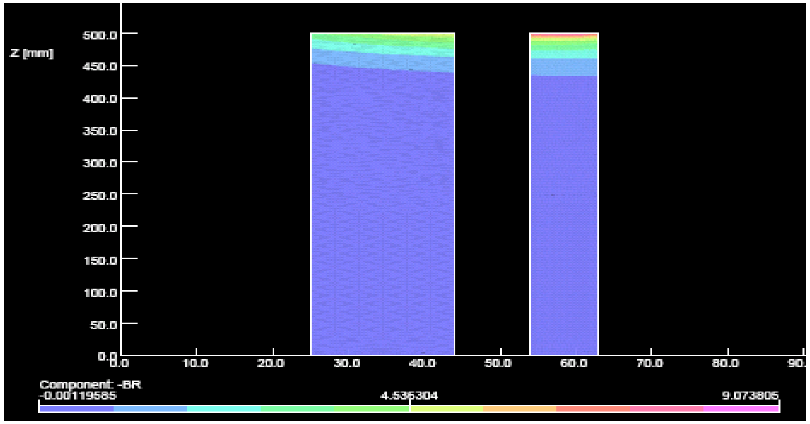
- We shall look at two examples to build a 20 Tesla solenoid.
  - One example is built entirely with HTS conductor.
  - The other is a hybrid solenoid with a HTS insert surrounded by a outsert solenoid made with Nb_3Sn conductor.
    - The hybrid design is chosen since HTS conductor is very expensive. Generating 14 T of the field with the less expensive Nb_3Sn makes the magnet more affordable.
- We have chosen the *high strength* HTS conductor.
  - The inner radius is the minimum bend radius: 25 mm
  - The current density is determined by the 20 T field needed on the inner surface: 254 amp/mm^2
  - The outer radius of the all HTS solenoid is determined by the total current necessary to make 20 T: 88 mm.
- In both these cases the radial forces are contained by an outer Stainless Steel Shell.

Case 2: Hybrid Magnet with Outer Nb_3Sn Coils and Inner HTS Coils



Hybrid Case with Outer Coils Made of Nb_3Sn and Inner Coils of HTS





- This case uses Nb_3Sn superconductor for the region where the field is less than 14 Tesla.
- The upper figure shows a contour plot of B_Z. The lower figure shows a contour plot of B_R.

Case 2: Summary of Parameters for Hybrid Magnet

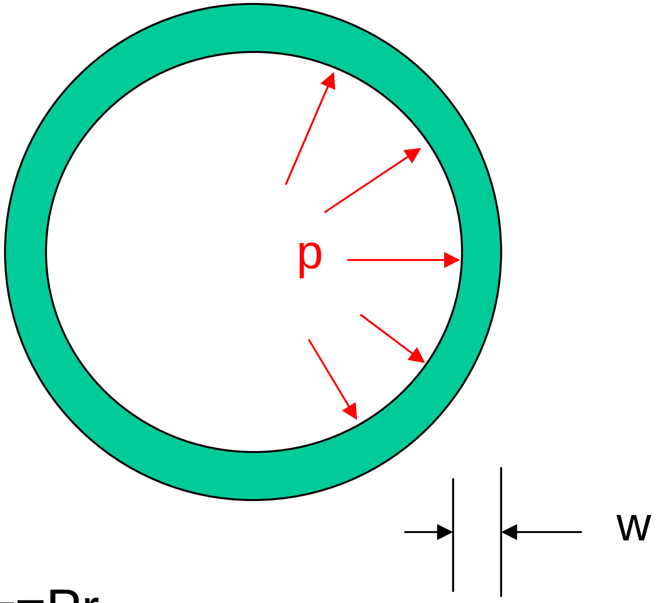
Parameter	Units	Inner	Outer	Total
Total Current	Amp-turns	4.35×10^{6}	1.154×10^{6}	1.59×10^{6}
Stored Energy	Joules	1.51×10^{5}	9.26×10^{5}	1.076×10^{6}
Radial Force	Newtons	1.52×10^{7}	2.74×10^{7}	4.26×10^{7}
Upper Half Axial Force	Newtons	-1.57×10^{5}	-9.65×10^{5}	-1.156×10^{6}
Central Field	Tesla	5.45	14.39	19.83
$B_{eff}=\int B\, dl/L$	Tesla	5.45	14.43	19.88
R_{inner}	mm	25	54	25
R_{outer}	mm	44	63	63
Length	mm	1000	1000	1000
Stress	MPa	63.7	93.5	—

Maximum Stress determined by integrating radial force density.

Note that Inner and Outer Stored Energy are that part of the total energy associated to those coils. They are not that which comes from powering the coils separately.

How Do We Constrain the Radial Force?

- Suppose we try to constrain the radial force with a stainless steel shell.
  - Stainless Steel 316 Tensile Strength: σ=460-860 MPa.
    - Choose σ=700 MPa.
  - Radial stress from superconductor: P =84 MPa
  - Superconductor outer radius: 88 mm.
  - The constraining shell needs to be at least 10.6 mm thick.
  - This is possible!



$w\sigma=Pr$

Case 2 : Hybrid Magnet Radial Containment

- Based on the radial stress from the HTS we would require a stainless steel containment shell with thickness of 4 mm.
- Based on the radial stress from the Nb_3Sn we would require a stainless steel containment shell with thickness of 8.5 mm.
- This approach is limited by the maximum compressive stress the the conductor can take.
  - We think that we can get to 27 T by this approach.
  - There are uncertainties about the material properties that might further limit this.

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)

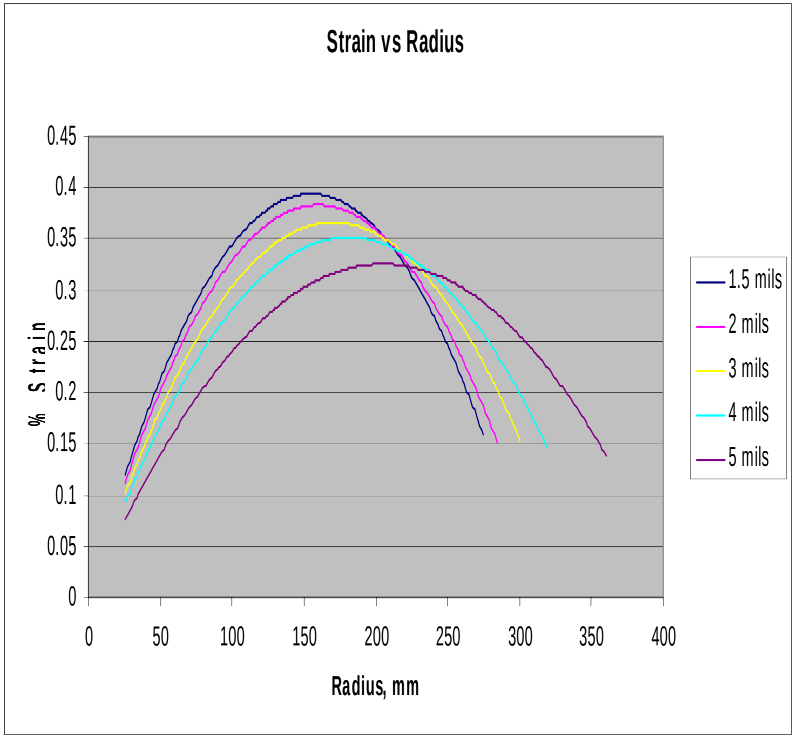
Fig. 3. A coil being made by co-winding HTS tape (on right) and stainless steel insulating tape (left). This is wound using a first generation winding machine that could be quickly set-up.

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 modulus = $\alpha_{SS} E_{SS} + (1-\alpha_{SS}) E_{HTS}$ (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: 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

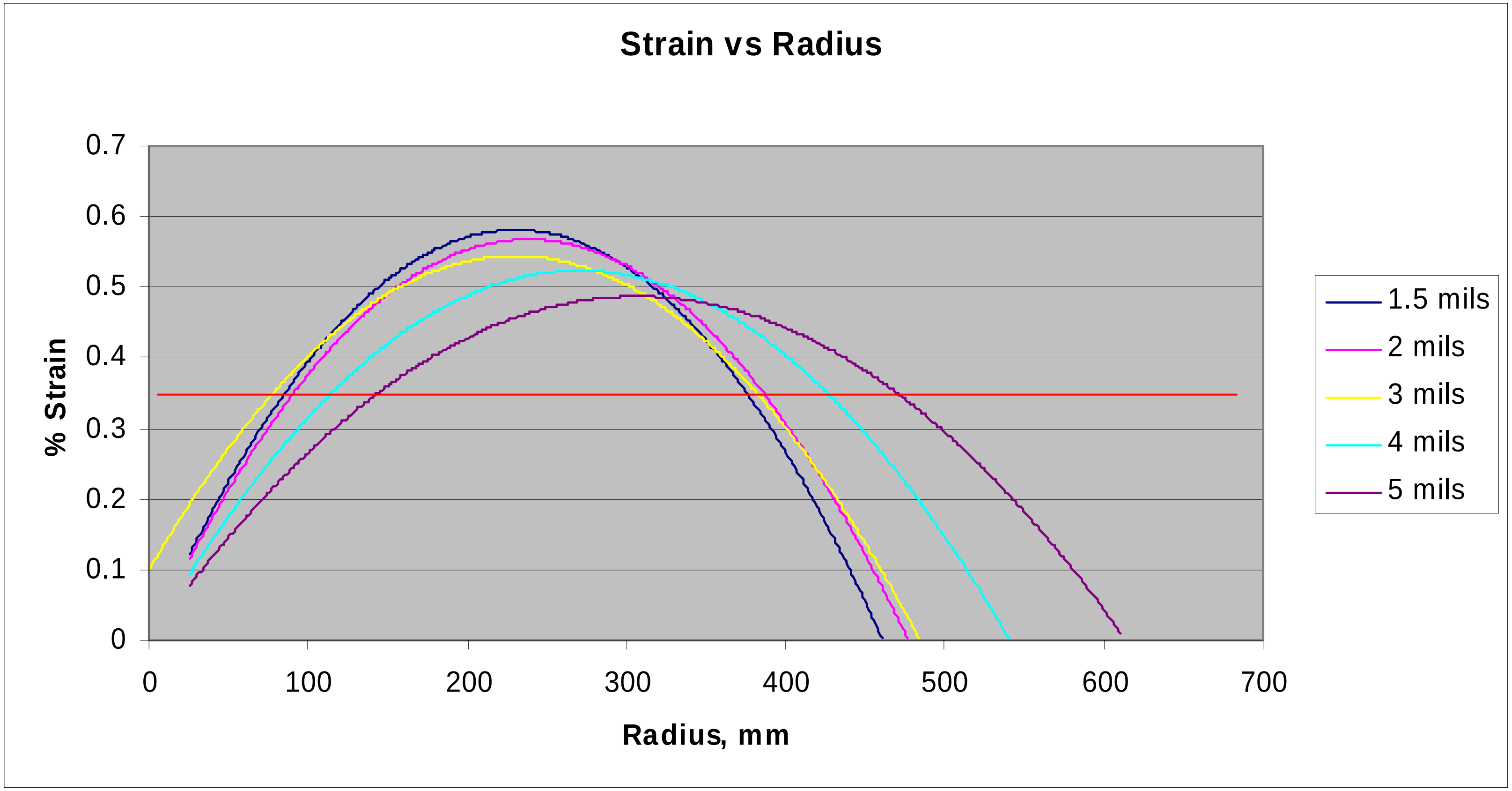
Stainless Steel Thickness	***1.5 mils***	***2 mils***	***3 mils***	***4 mils***	***5 mils***
Fraction SS	0.111111	0.142857	0.2	0.25	0.3429
Fraction HTS	0.888889	0.857143	0.8	0.75	0.6671
J_{eff}, ***amp/mm***^{2}	112	108	101	94	83
R_{inner}, ***mm***	25	25	25	25	25
R_{outer}, ***mm***	310	320	341	362	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

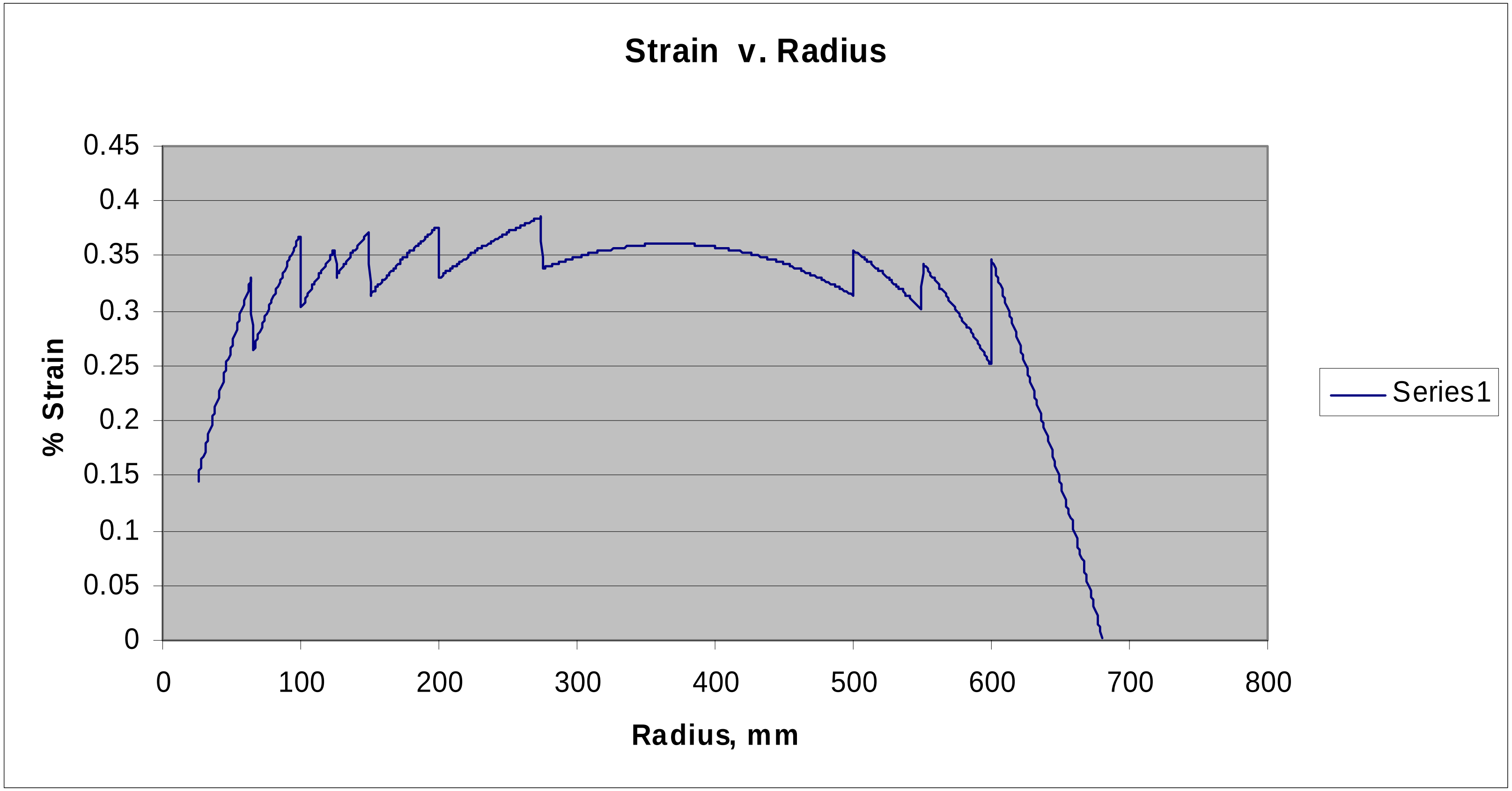
SS Thickness (mils)	***Fraction SS***	***Fraction HTS***	***R_{min} mm***	***R_{max} mm***	***E GPa***	***J_{eff} amp/mm^2***
0	0	1	25	65	90	103
2	0.14286	0.85714	65	100	98	88
4	0.25	0.75	100	125	104	77
6	0.3333	0.6667	125	150	110	68.5
8	0.4	0.6	150	200	115	62
10	0.454545	0.545455	200	270	120	56
12	0.5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



Can We Do More?

- So far we have used a constant current density in each layer.
  - This current density is determined by the field of the solenoid on the inner surface. We know that the field drops as radius in the conductor region.
  - We could put different radial regions on different power supplies and increase the current as the field drops.
    - This could increase the field of the magnet.
    - This will reduce the amount of HTS (and cost) needed.

Can We Do More (Continued)

- We could use some other material other than Stainless Steel. We are limited by the stainless steel modulus. A higher modulus would reduce the strain allowing us to increase the field.
  - Possibilities include Chromium:
    - Modulus: 279 GPa   (Stainless Steel was 200 GPa)
    - Strength: 689 MPa (for Hard Cr) (Stainless Steel was 460-860 MPa)
    - Stainless Steel is probably easier to work with than Chromium (??)
  - Iridium: Not cheap
    - Modulus: 528 GPa
    - Strength: 1200 Mpa
  - Molybdenum: Not cheap and probably not available in practical form
    - Modulus: 325 GPa
    - Strength: 650 MPa

Some Material Properties That We Need to Know

- What is J_{eff} for fields B>27 Tesla?
  - Could this be done at the NHMFL in Florida?
- What are the moduli of this anisotropic material along the three principle axes?
  - Does the American Superconductor know this or could we measure it?
- What are the compressive strain/stress limits along each of the three principle axes?
  - What are the current carrying aspects under these limits.
- What are the temperature expansivity along these three principle directions?
- Are there fatigue issues associated with repeated cycling of the magnet?
  - American Superconductor had observed cycling issues with associated with He getting into the current carrying region. This may have been addressed.
- Are there radiation issues with this material?

There Are Major Engineering Issues That We Need to Understand

- At 20 T we have 1 mega Joule of stored energy. At 60 T we have 10 mega Joules of stored energy.
  - We need to plan how to get the current and stored energy out should there be an incident (i.e., quench).
    - Can we use diodes to induce resistance? Are there diodes massive enough to take 60 T?
    - Unlike normal superconductors, heaters to induce a quench may won’t work.
  - The overall forces go up with the stored energy. We need to constrain monstrous forces.

Lattice Designs and Simulations

- We need to design a lattice for 20, 30, 40, 50, 60 Tesla.
  - The lattice must go from high field to a lower field that can encompass the large RF cavities associated with 850-1300 MHz.
- Will need simulations to verify performance.
- Need to match to upstream/downstream cooling
  - Upstream HCC parameters
  - Downstream PIC parameters

What Phase I Can Provide

- A feasibility design of a very high field solenoid.
  - We think that can be 50 Tesla.
- Some material studies:
  - Measure current carrying capabilities under strain exceeding manufacturers suggested limits.
    - At 293°K and at 77° K
  - Measure current carrying capabilities under compressive stress
  - Wind small coil with and without stainless steel interleaving to be tested in 11 Tesla magnet at BNL or 15 Tesla magnet at Fermilab.
    - Can add compressive strain with outer Aluminum band by cooling to 77 °K

Conclusion

- This is turning out to be a very exciting proposal.
- Hopefully the referees will think so!