Towards a Realistic 50 T HTS Magnet for Final Muon Collider Cooling

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Collaboration UCLA Jan 07

- Re run of work presented at NHFML in Nov 07
- But include data on angular dependence of HTS j shown there

Choice of HTS Material

1. Most of the study with BSCCO 2223 Tape

- American Superconductor "High Strength"
- Pre-reacted (like YBCO)
- Has ss cladding, strong
- Relatively cheap (20$/m)
- May not tolerate cycled strain

2. Alternative BSCCO 2212

- Can be made into Cable
- Must be reacted after winding - hard in thick magnet
- May not tolerate cycled strain

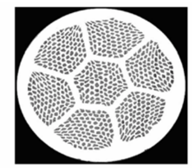
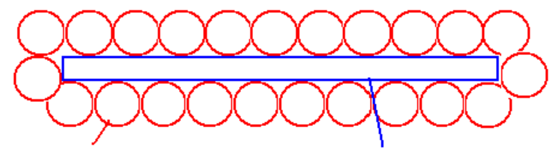


Fig. 3. Transverse cross section of an unreacted 91 × 7 filament wire at 0.8 mm diameter.



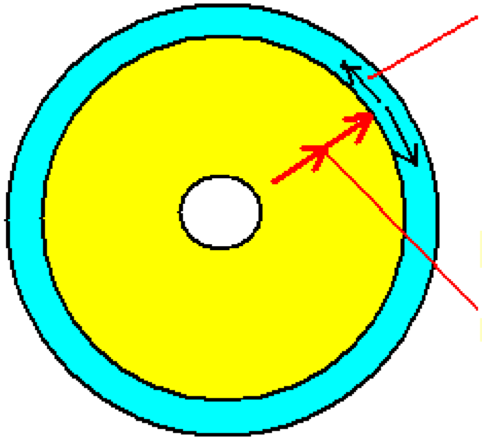
3. YBCO

- Higher density at 77 degrees
- Not known at 4 degrees
- Currently more expensive, but expected to become cheaper
- Wider, thin, bends easily, can be cycled

Radial Force Constraint

If radial forces only constrained at outer radius then maximum radial pressure:

$$P_r\text{max} \;=\; \int B(r)\; j\; dr$$



For a long solenoid:

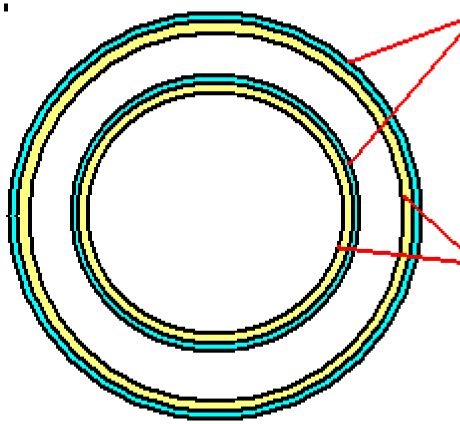
$$j \;=\; \frac{dB}{dr}\,\frac{1}{\mu_o}$$

from which:

$$P_r\text{max} \;=\; B^2\,\frac{1}{2\mu_o}$$

For B=50, and $\mu_o = 4\pi\ 10^{-7}$

$$P_r\text{max} \;=\; 995\ \text{MPa} \;\gg\; 130\ \text{MPa}$$



Radial forces must be constrained locally.

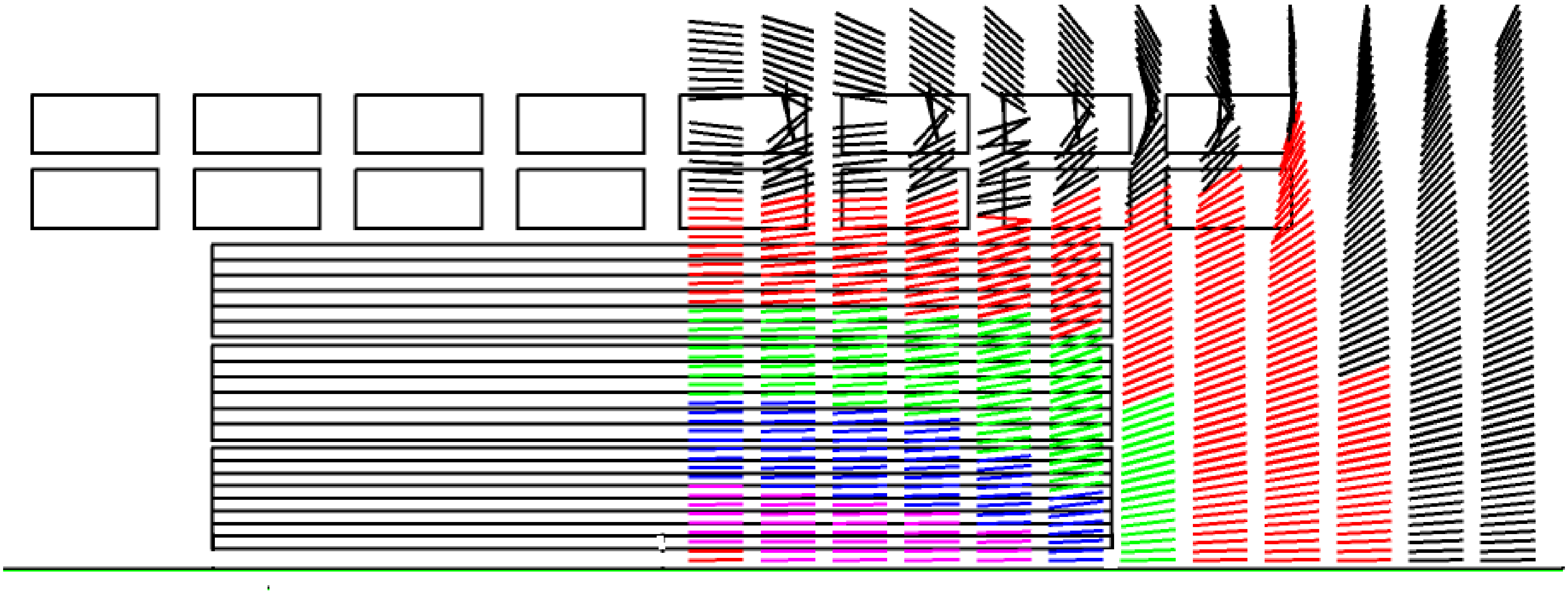
Latest Modified Design

- Adjust currents for true 50 T
- Keep sum of strain from bending and tension below specified value
- Add 25 μm insulation to each tape - for ramp down
- Lower current densities as needed to correct for field vs tape angles
- Add 1cm gaps to separate HTS into 3 blocks for support and cooling
- Break Nb3Sn and NbTi into blocks supported by ss discs & cylinders (McIntyre did this for LHC tripler, using 130 MPa limits)
  - Wind them in pancakes without ss & take radial force on outer ss rings
  - Fix their current densities at 120 A/mm^2
  - Lengthen the outer coils to lower the radial fields in the HTS by 'drawing' the field lines out
- Assume 10 different HTS power supplies (plus one each for NbSn & NbTi)
- Assume 20 different SS thicknesses

Assumed Parameters

Central Field	50	(T)
Inside radius	3	(cm)
HTS Length	1	(m)
HTS conductor width	4.3	(mm)
HTS conductor thickness	.27	(mm)
HTS Current at 77 deg	155	(A)
HTS Current used	85	%
HTS thickness for bend strain	.14	(mm)
HTS Stabilizer fraction	.66	
Conductor cost	20	($/m)
Insulation thickness	25	(μm)
Max Strain	.4	(%)
j_{sc+ins} at 77 deg	94.6	(A/mm^2)
j(4 deg)/j(77 deg) at B=0	3.0	
dfactor/dB	-.029	(1/T)
Young's modulus HTS Y$_{sc}$	85.7 ???????	(GN/m^2)
Young's Modulus SS Y$_{ss}$	192	(GN/m^2)
NbSn current density	120	(A/mm^2)
NbTi current density	120	(A/mm^2)

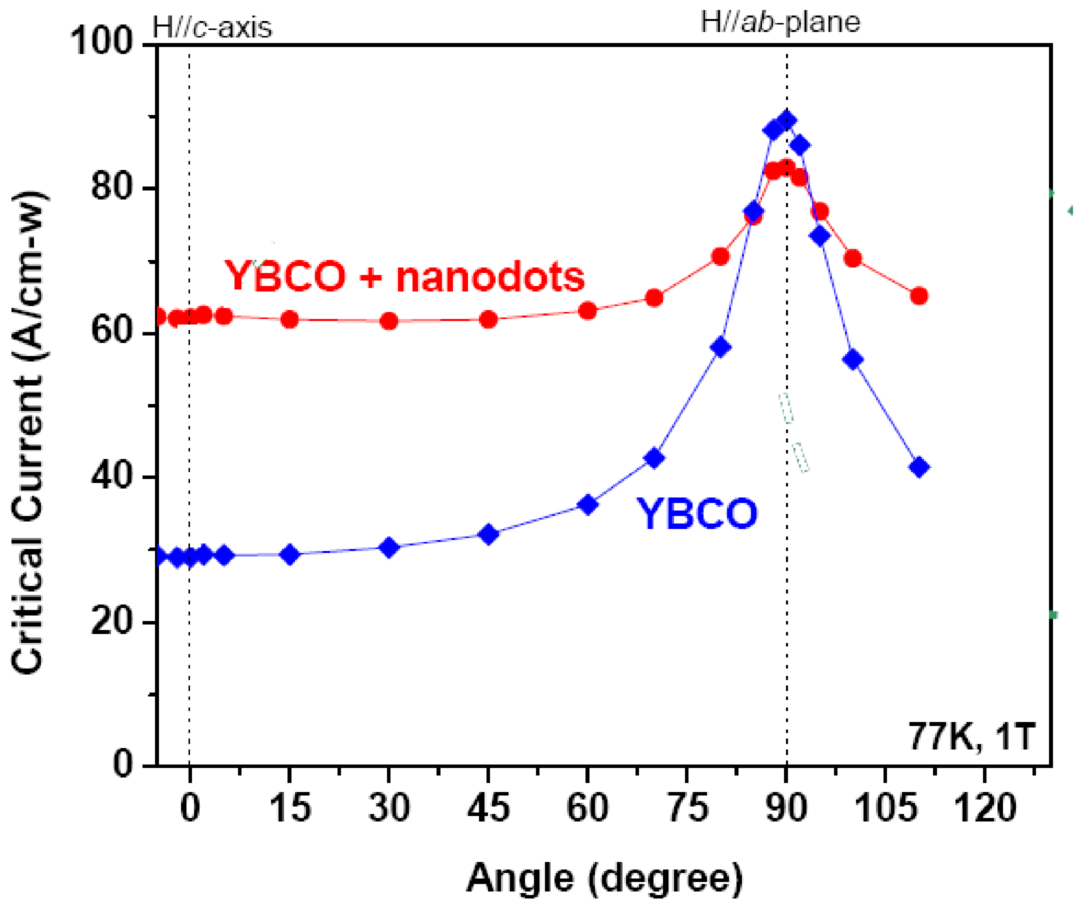
Coils and Fields



- Note fields not in conductor plane at ends of outer layers

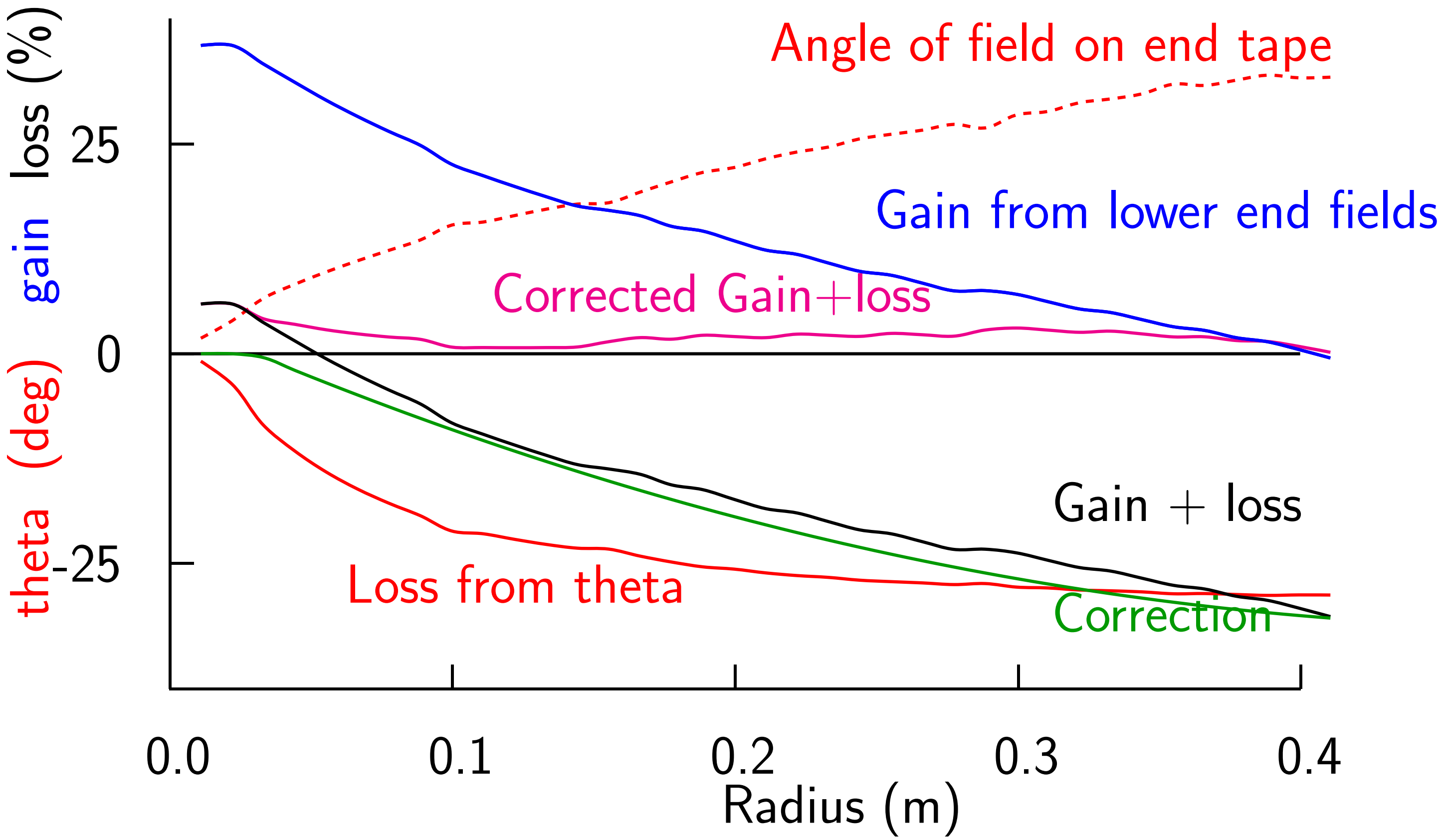
j_c vs. angle of field to tape

- Having no data on angular dependence of jc for BSCCO 2223
- Use that for YBCO with nanodots at 77 deg
- This has similar ratio of $jc_{\parallel}$ to $jc_{\perp}$



Cees Thieme (American Superconductor)

Reduction of current density for ends

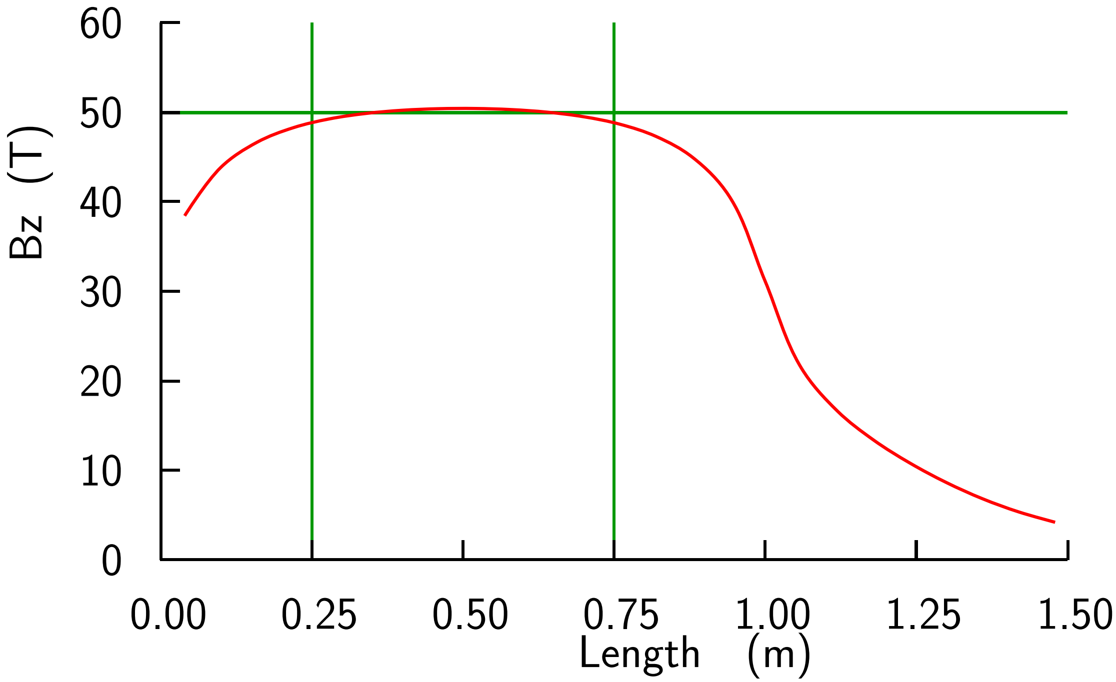


- At low radii, gain from lower fields at coil ends compensates for angles
- at larger radii current is reduced

- I had assumed loss in j_e proportional to θ
- Using the YBCO data leads to much larger required correction

Magnet parameters with new end correction

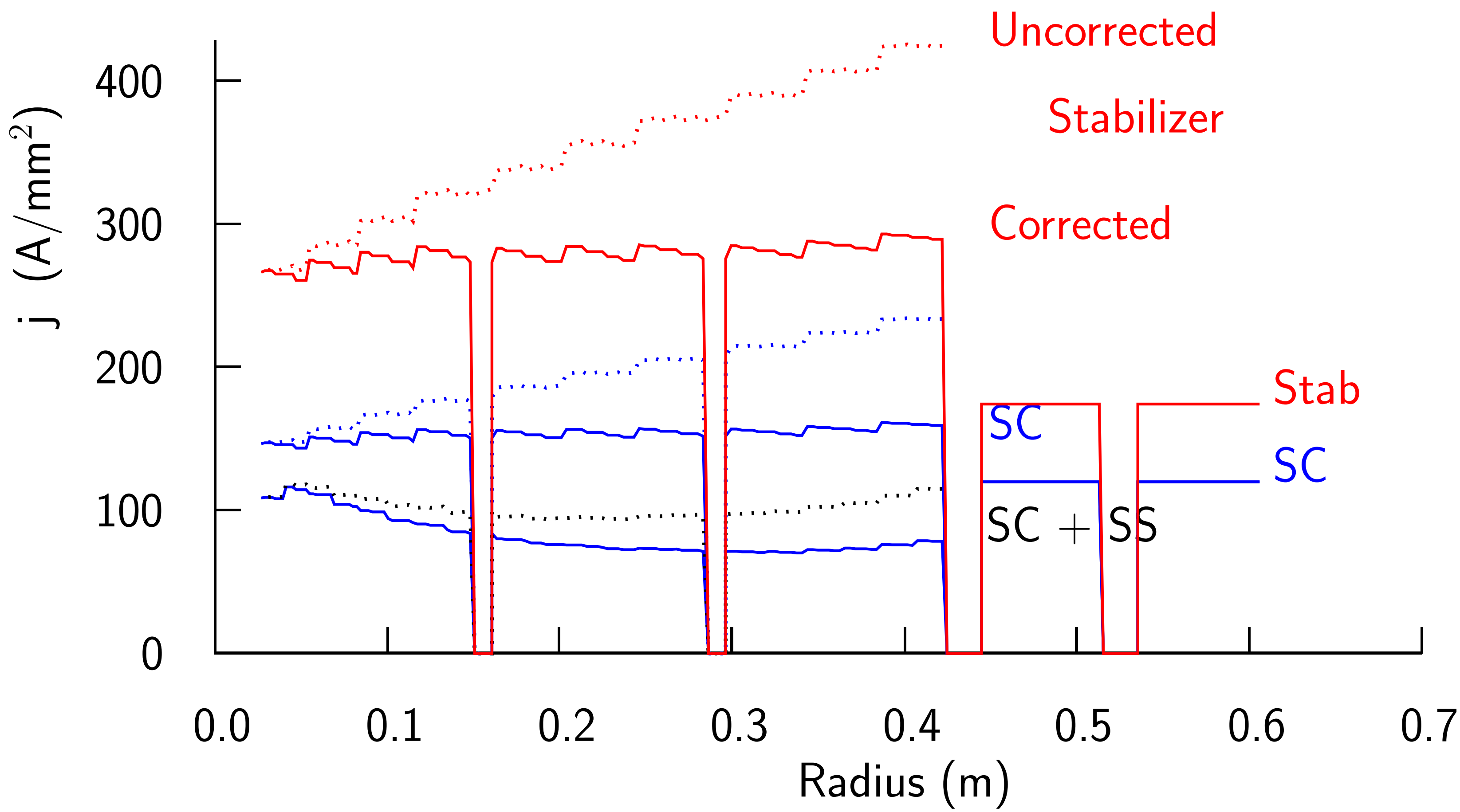
- The outer radius is now 60.6 cm   c.f. 57 cm
- The HTS radius is now 42 cm   c.f. 39 cm
- The HTS conductor length is now 189 km   c.f. 137 km
- The HTS conductor cost is now 3.8 M$ c.f. 2.7 M$
- Stored energy now 160 MJ   c.f. 140 MJ



50 cm of "good" field is required in final cooling

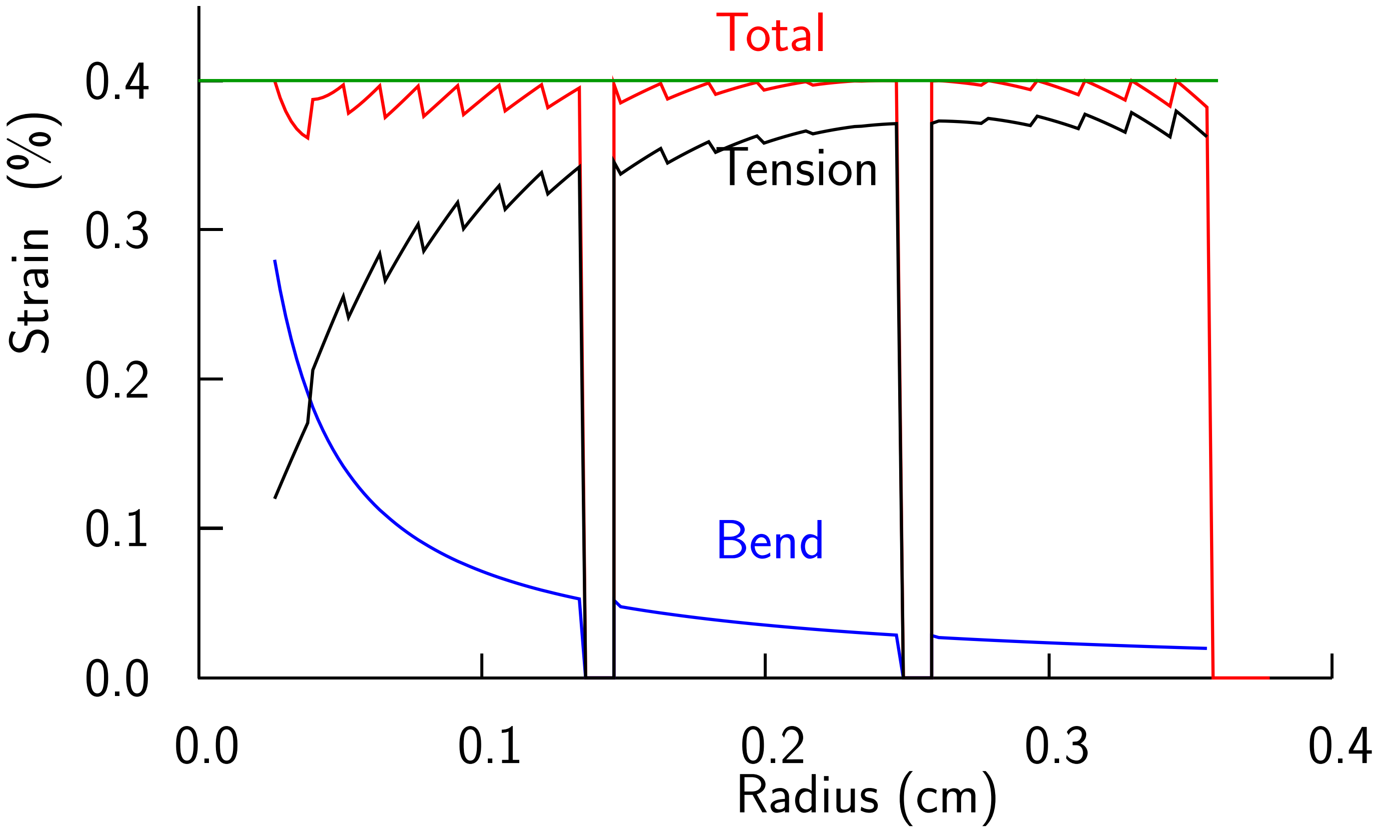
Current Densities

Assume 10 different Currents for HTS coils



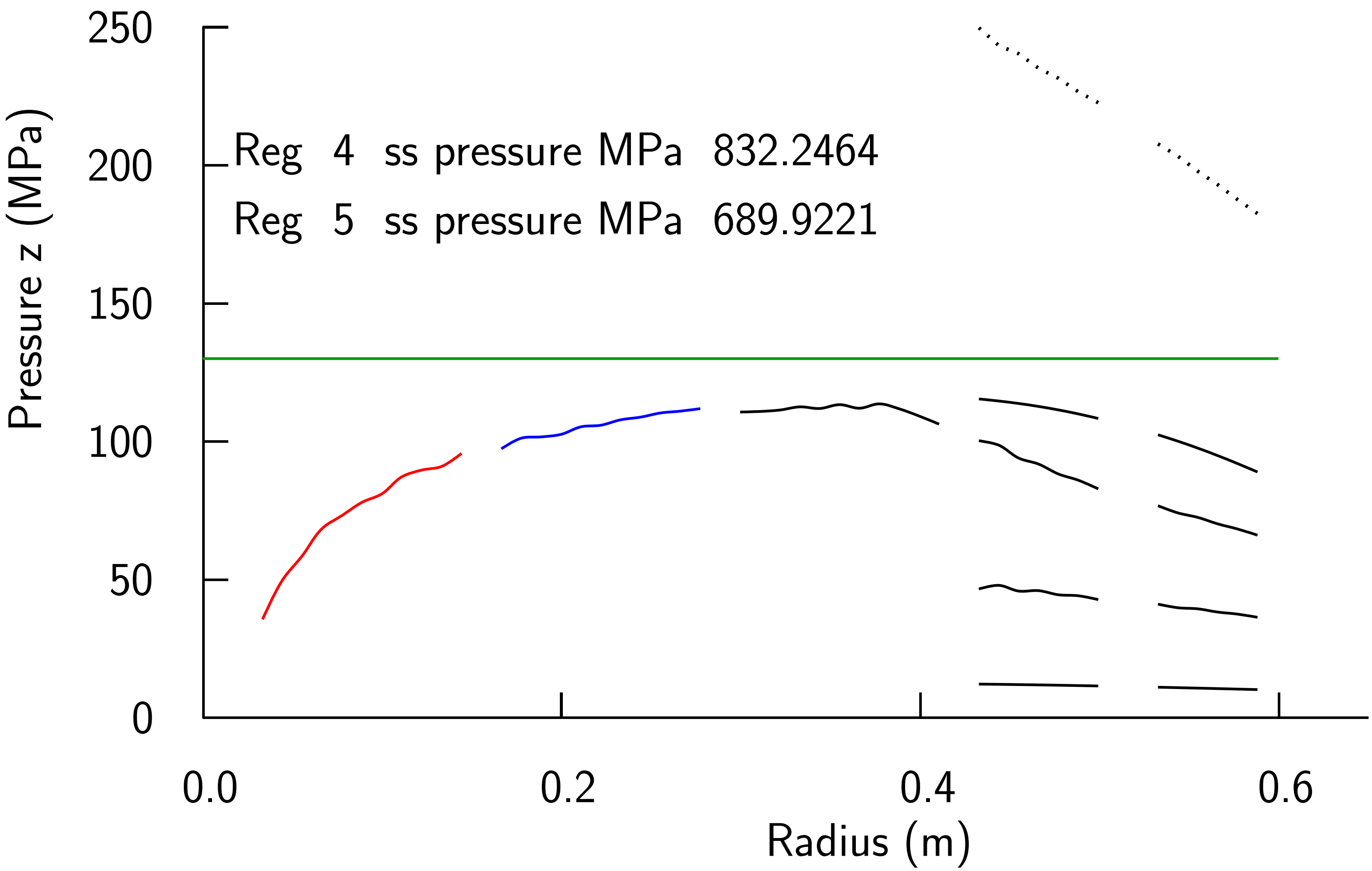
- With allowance for end angles, currents are mostly independent of radius

Strains



- Strain from bend at inner radius (3cm) is very large and significantly increases need for support material
- Wind and react BSCCO 2212 avoids this problem
- YBCO also avoids the problem because it is so thin

Axial Forces



- Dots show pressures if not subdivided
- Axial pressures are well below limit of 130 MPa

Quench protection

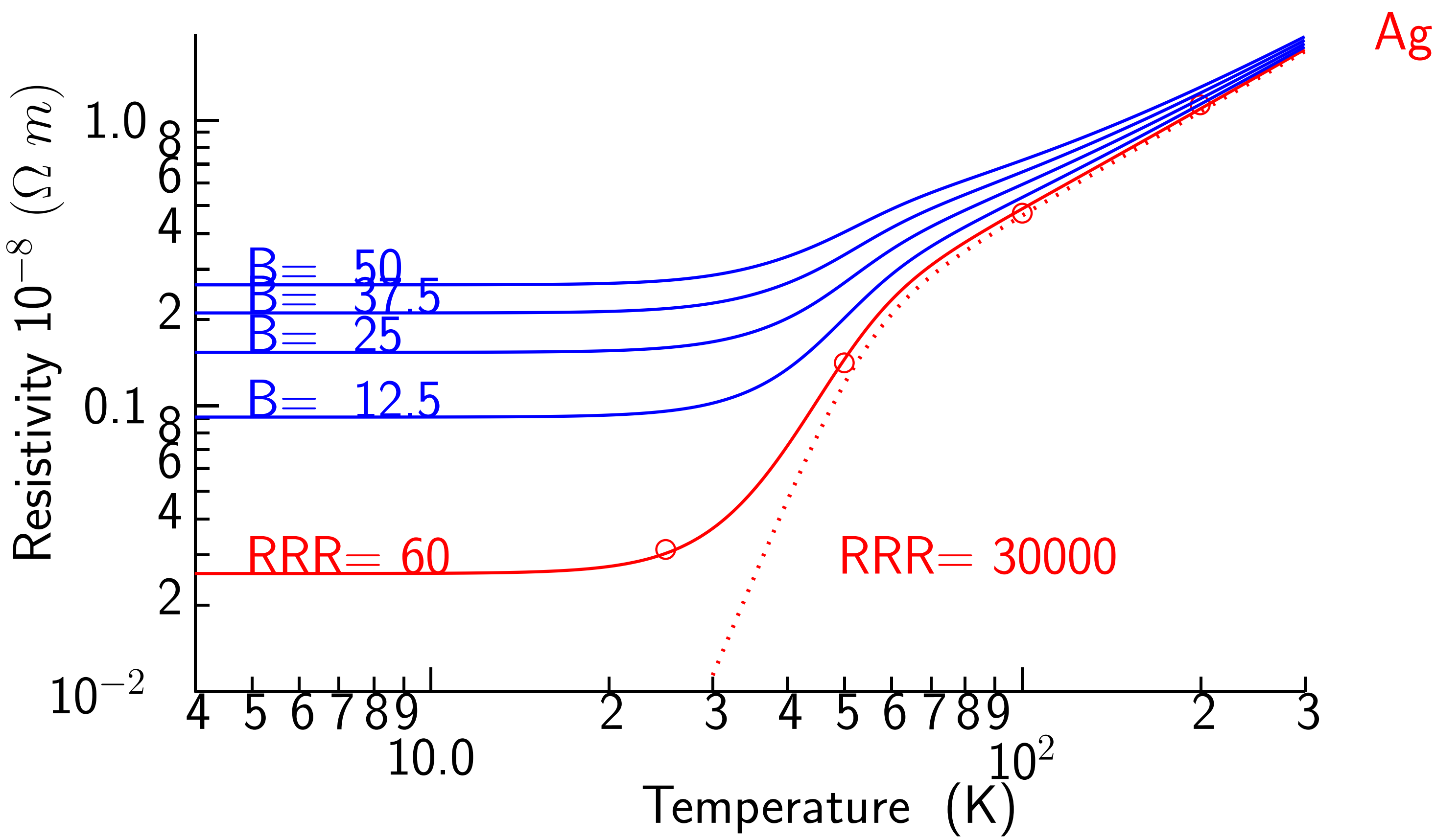
- At local spot where quench starts, ignoring heat conduction, the local heating causes temperature to rise until current is stopped.
- HTS has a low quench propagation (assumed 3 cm/sec), so the quench is hard to detect till after significant heating
- The Current must then be ramped down before the local temperature gets too high (say 200 Deg K to avoid damage)
- In a high field solenoid the inductance is so high that a rapid turn off requires high voltages and/or multiple circuits.

After a quench, all the local current will be flowing in the stabilizing material (Cu or Ag): The rate of heating depends on the stabilizing conductivity and specific heats that depend on temperature, and on the integral of the squared current density with time:

$$\Delta T \; = \; f[\int j^2_{\rm stab} dt]$$

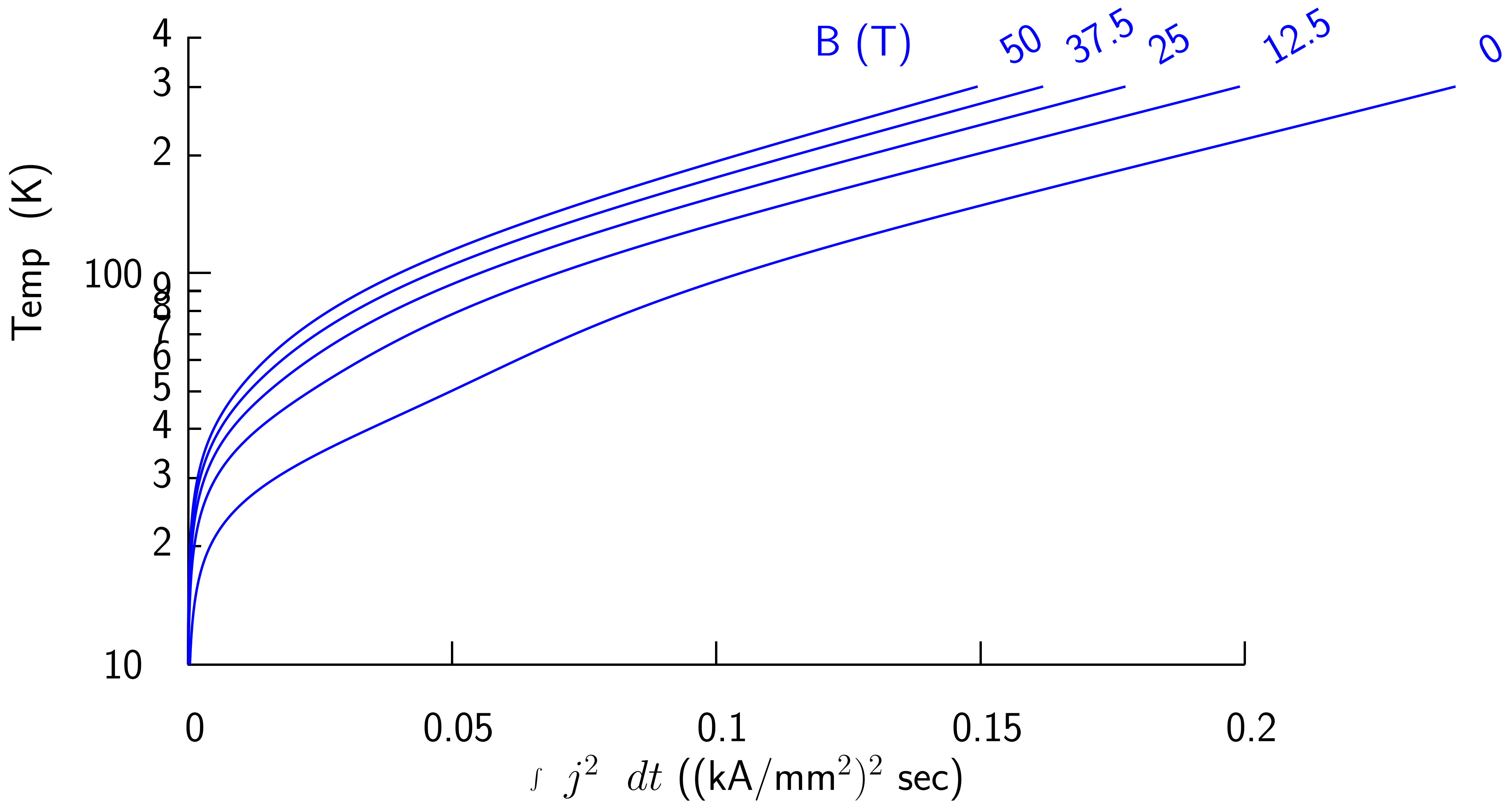
where the f is a function of the material properties and their cross sections

Stabilizer resistance



- Assuming a stabilizer RRR=ρ_{273}/ρ_4 =60
- The Magnetic Field effect is large
- Initial heating, when specific heats are low, will be rapid
- Above 80 degrees, the B effect is small

Heating vs Integral $j^2\ dt$

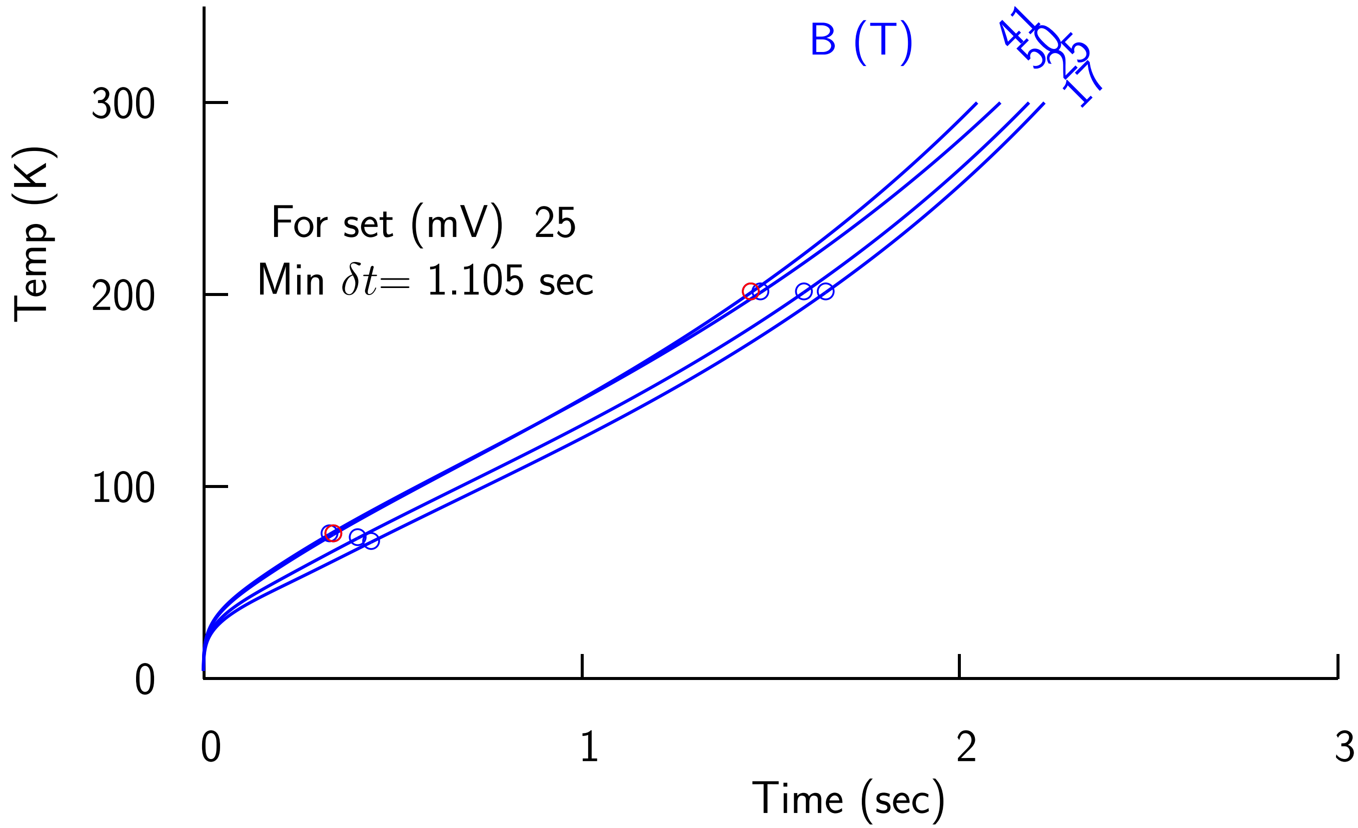


- Heating is significantly higher (per $\int j^2 dt$) at higher fields
- But for fixed HTS margin, js at higher fields are less

Heating for actual js vs. B

Assuming: Quench velocity = 3 cm/set at 85% of short sample current ?????

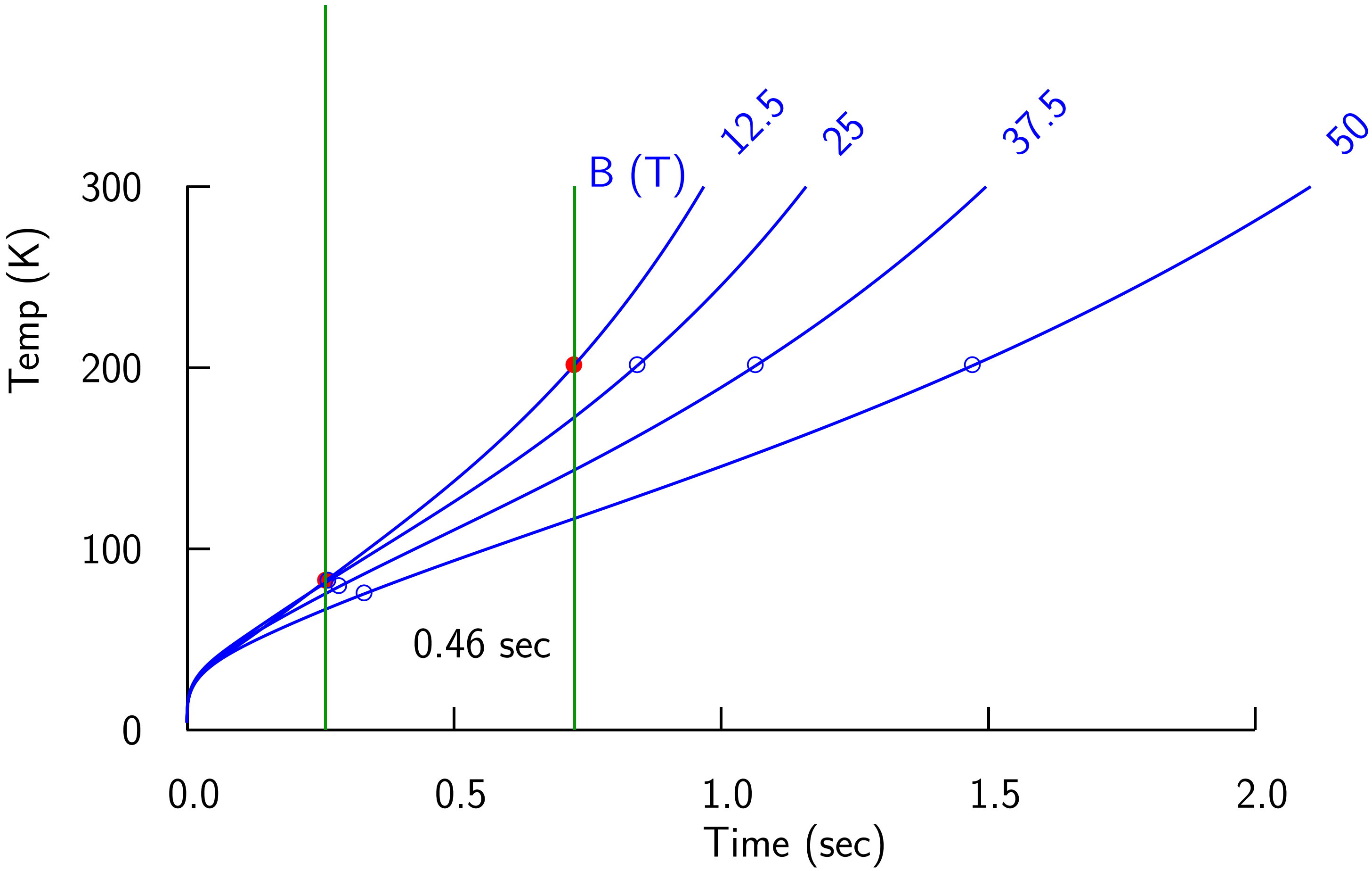
And Quench detection at 25 mV ?????



- This is more than a factor 2 slower than without end angle correction

Heating for actual js vs. B if no angle effect

e.g. for BSCCO 2212



- This is more than a factor 2 faster
- Note now worst case is at low field

Required ramp down rate

For an exponential decay of the current with a time constant τ then

$$j \;=\; j_o\, e^{-t/\tau}$$

$$\int j^2\, dt \;=\; \frac{1}{2}\, j_o^2\, \tau \;=\; j_o^2\, \Delta t$$

where $\Delta t = 1.1$ sec from above, so

$$\tau \;=\; 2\,\Delta t \;=\; 2.2 \quad \mathrm{sec}$$

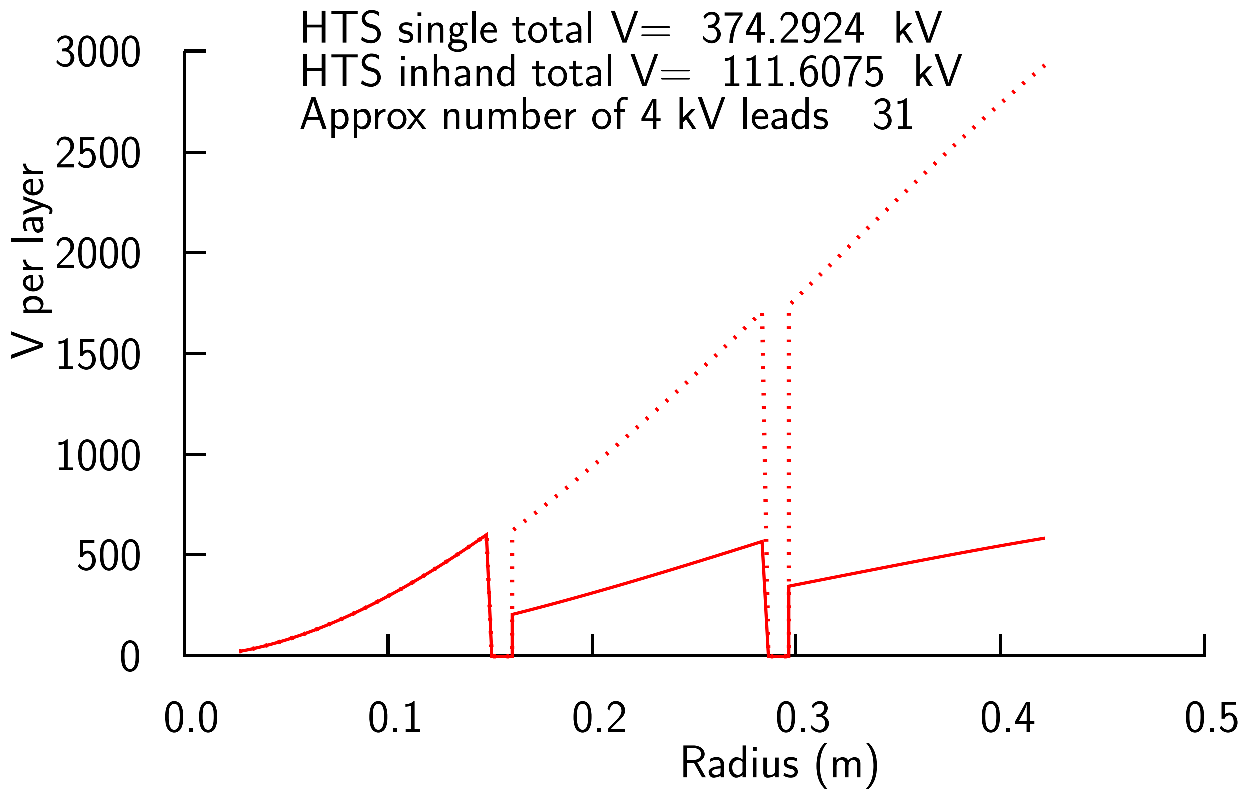
Quench Protection (Ramp Down) Methods

1. Active heaters
   Detect any quench and actively fire heaters to quench entire magnet causing rapid ramp down without large external voltages
   all the energy ends up in the magnet

2. Active Ramp Down
   Detect any quench and actively ramp down magnet
   Some technique must be employed to avoid very large external voltages
   Most energy is extracted

Layer-layer Voltage

For $w = 4.3$ mm, L=1m, τ=0.94 sec then for the HTS part (above 15 T):

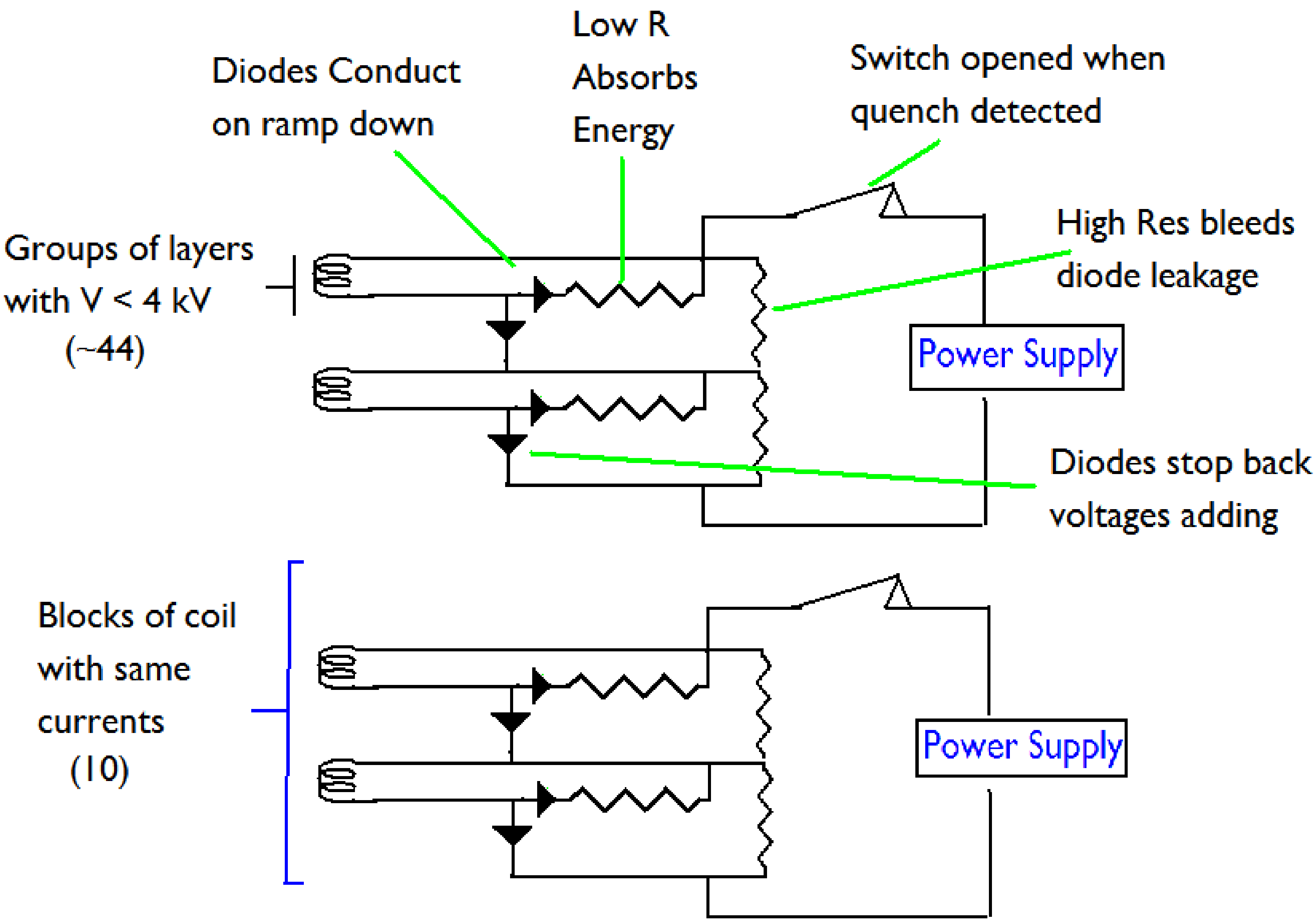


- Maximum layer to layer voltage, if simply wound, is 3 kV
- If wound "in hand", voltage/layer is ≈ 600 V prefered
- If wider YBCO then no need to wind " multiple in hand"

- If wound "in hand" or YBCO and max V<4 kV: need ≈ 30 sub-coils

High Voltage Avoidance during Active Ramp Down

Currents ≈ 180 Amps



Use of BSCCO 2212 Wind & React Cable

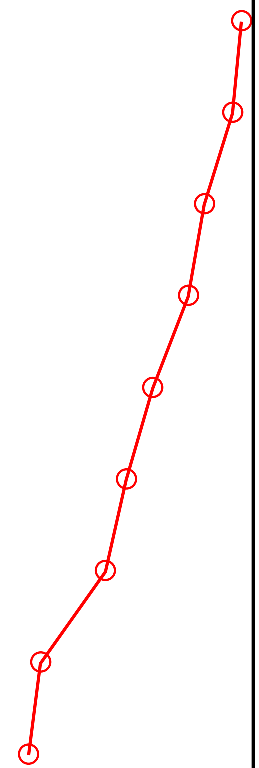
- No loss at magnet ends when B not parallel with tape
- No reduction in allowable strain from bend radius
- Can be made into cable with larger cross section:
  - Fewer turns
  - Less Voltage on ramp down
- Assuming Y=70 GPa ??????

		2223 Tape	2212 Cable
Outer Radius	cm	60	45
HTS Radius	cm	42	28
Stored Energy	MJ	181	79
Conductor length	km	189	4.4
HTS Layers		635	54

Use of YBCO tape

- Most Industry development on this material
- Will probably be cheaper and have better performance
- But very thin, requiring many layers
- Must be joined at every layer end

Radii vs Assumptions

2223 Cases	Δr (cm)	Radius (cm)
Modified Design		
	1.6	
No gaps for cooling		
	5.2	
All HTS js		
	2.7	
No fix for axial Press		
	6	
No insulation		
	4.5	
No fix for non parallel B		
	3.5 (.5)	
Ignoring Bend stress		
	11	
correction for finite length		
	2	
Infinite Starting Design		

Conclusion

- With American Superconductor react-and-wind BSCCO tapes:
  - More realistic j_c vs θ raises magnet radius from 57 to 60.6 cm
  - Concern is that cycling strains to 0.4 % may damage tape
- Use of wind-and-react BSCCO 2212 cable
  - Reduces HTS mass and stored energy
  - May be difficult to react relatively thick coils
  - Concern is that cycling strains to 0.4 % may damage tape
- Use of YBCO
  - Reduces HTS mass and energy relative to 2223
  - But still requires allowance for field angles at ends
  - Most development now on this material
  - Most likely to allow strain cycling
- These results are based on many uncertain material properties
  - Need study of strain cycling and angle dependence of BSCCO
  - Need data on YBCO at 4 degrees