Magnets for SPS +

Fast Ramping Design Issues moving towards a design.

Glyn A Kirby

thanks to
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Amalia Ballarino
Peter Limon
&
Nuria Catalan Lasheras

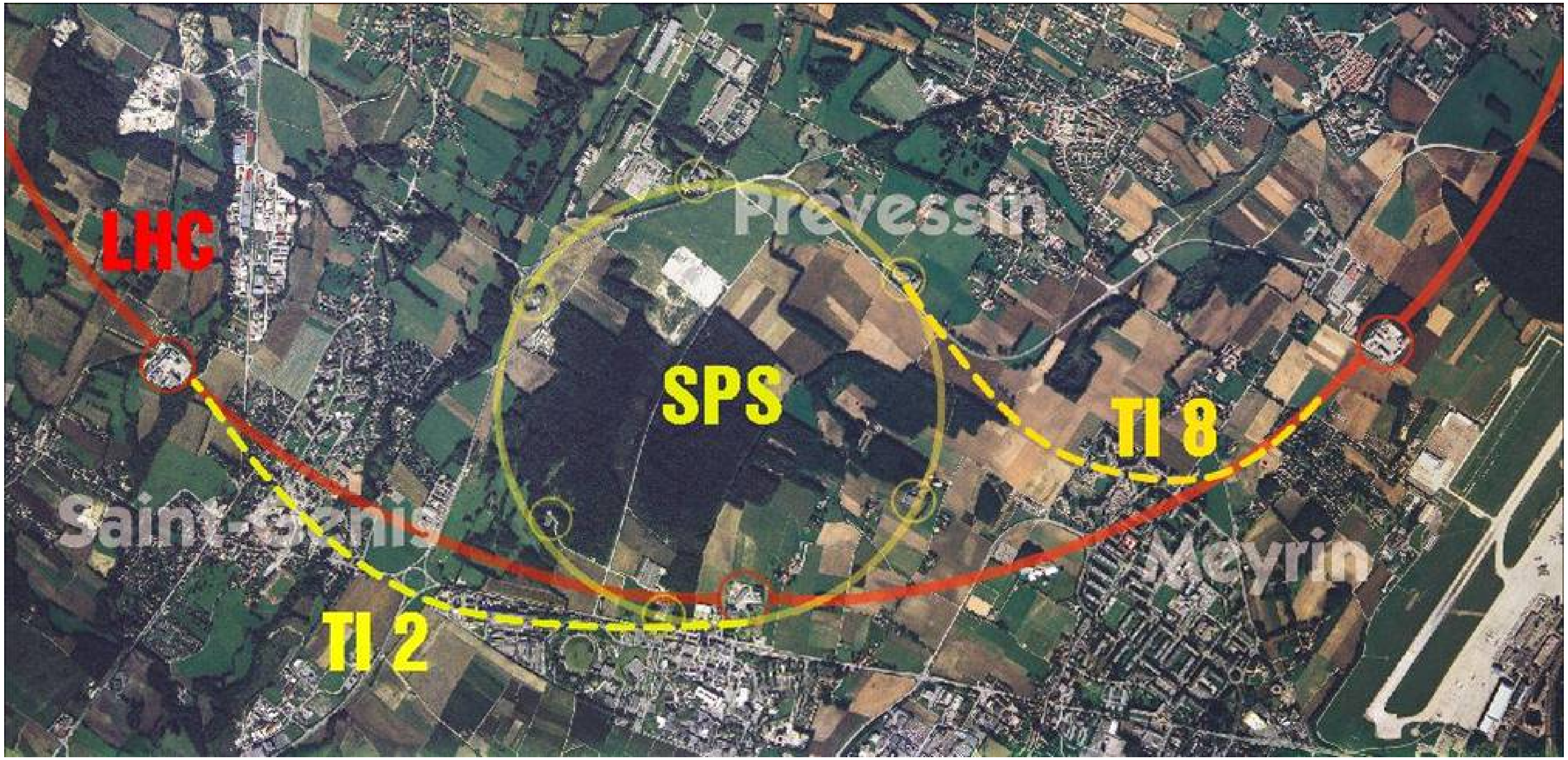
What's coming up

- GSI & possible PS & SPS upgrades.
- Strand & Cable designs.
- Changing aperture its affect on losses.
- 1 or 2 layer design.
- Temperature change during cycles.
- Longer magnet heat less / use less superconductor .
- How to get the heat out, some ideas (lots of questions).
- Warm or cold Iron hysteresis losses.
- Eddy currents in wedges select materials.
- Fatigue and some history.
- How long could it take.
- Things to do!
- Conclusions.

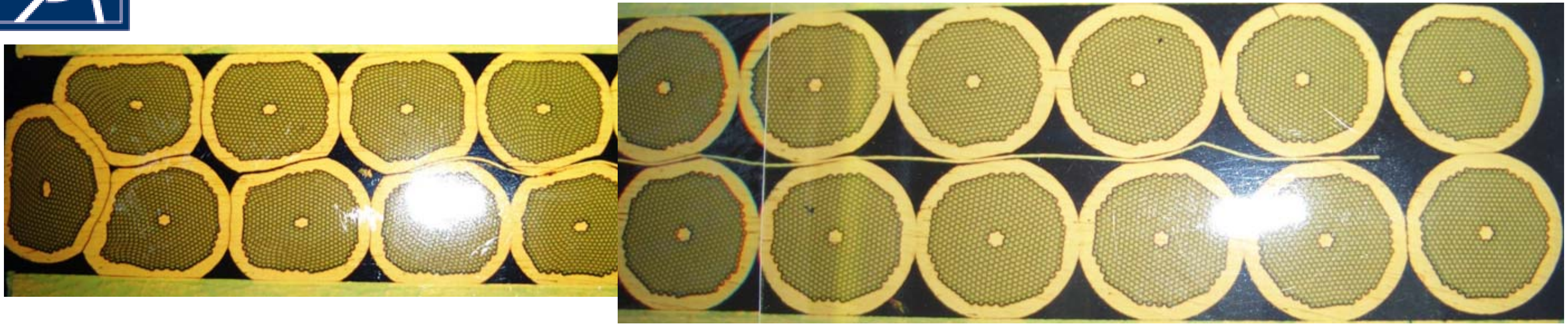
Magnet spec's for GSI & LHC possible upgrade.

	SIS 100	PS II	SIS 300	SPS II
Peak field	2T	3T	6	4.5
dB/dT [T/s]	4	3.5	1	1.5
Cycles (20 years)	200M	60M	1 M	1 M
Rad. load [W/m]	1	10	1	10
Peak load [W/m]	3	30	3	30
Magnet length [m]	2.9	4	2.9	6
No. of dipoles	108	100	108	750

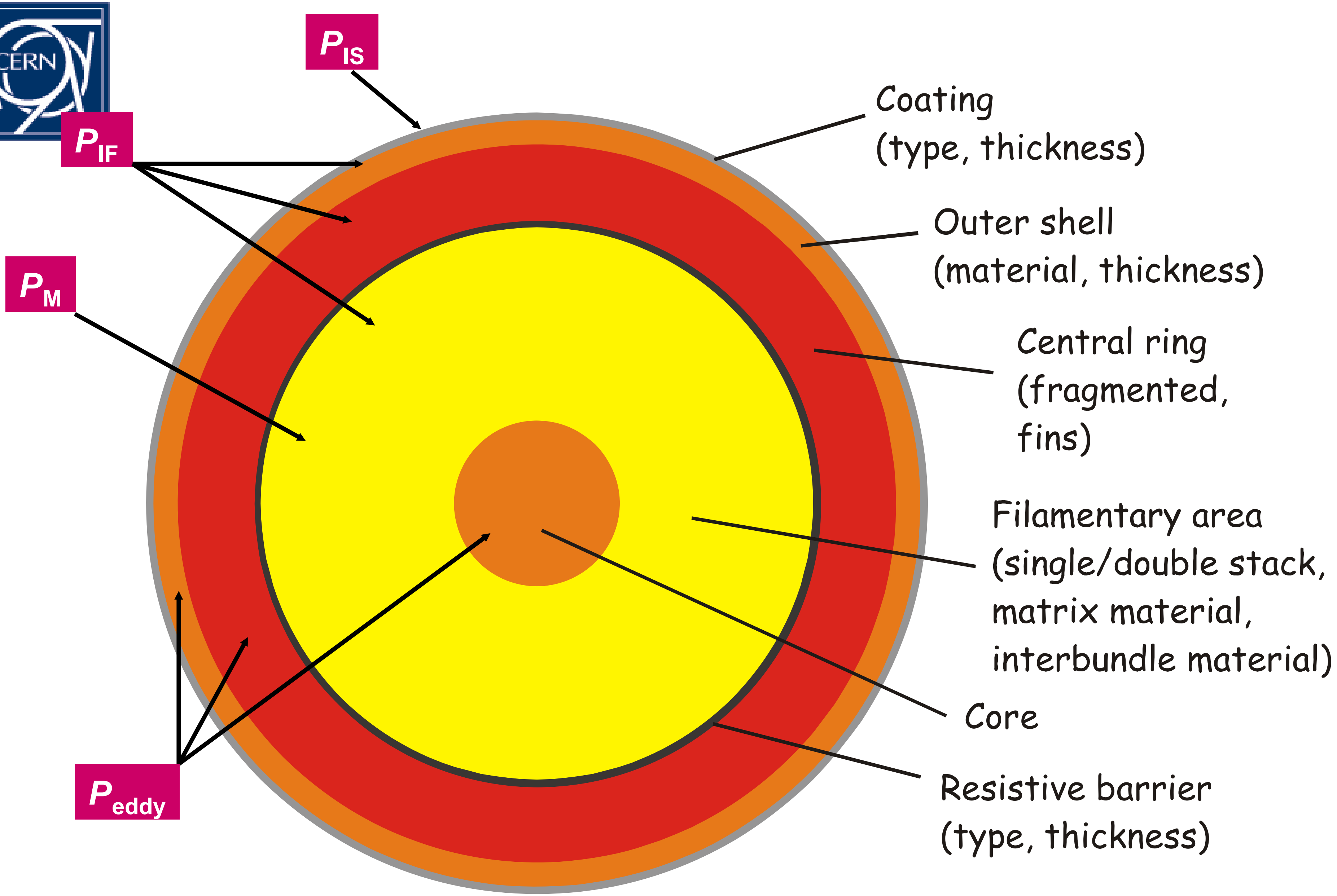
LHC INJECTION LINES : 5.6 km, about 700 to 750 Magnet's



Cable design



- Cable width : 10mm to 20mm wide
- Up to 40 Small strands: 0.5, to 1.0 mm diameter
- Filaments in resistive matrix, with Fragmented Copper core and band for protection
- Small filaments : 3 µm or 1 µm
- filament twist pitch: 6 x strand diameter.
- Cable twist pitch : 7 x cable width.
- Cable thin edge compaction: 0.78 max (but don't do it)
- Cable fat edge compaction : 0.95 min
- Foil through center of cable to control Rc
- Coating on strand to control Ra



Coating
(type, thickness)

Outer shell
(material, thickness)

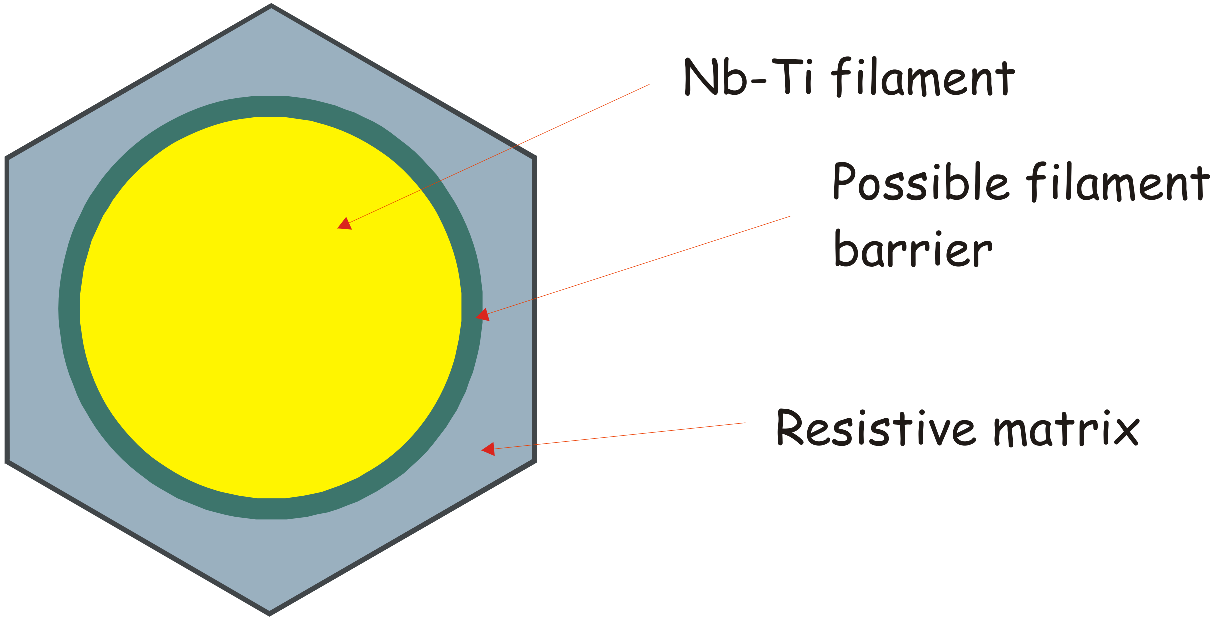
Central ring
(fragmented,
fins)

Filamentary area
(single/double stack,
matrix material,
interbundle material)

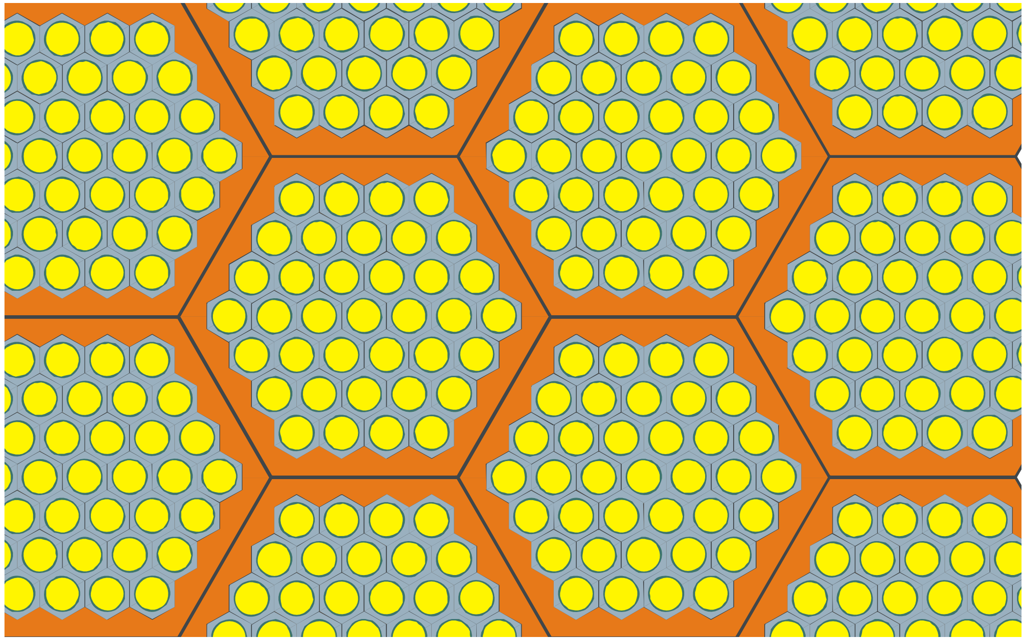
Core

Resistive barrier
(type, thickness)

Small filaments : 3 μm or 1 μm



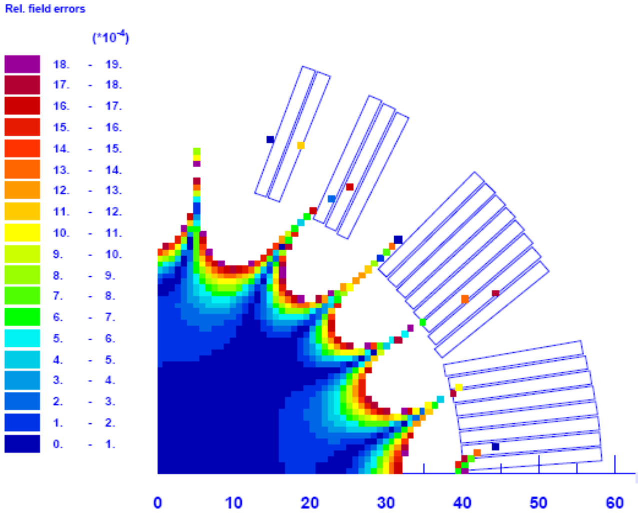
Filamentbundles with interbundle Cu



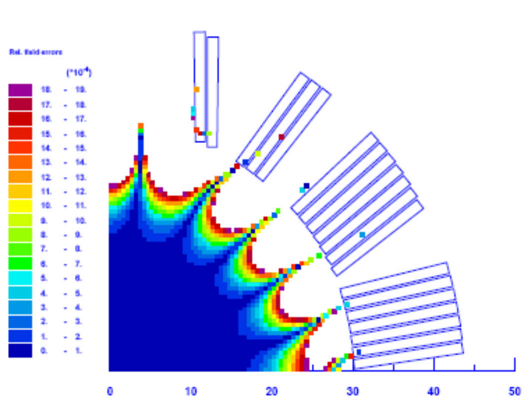
Fragmented central ring
(Cu hexagons with resistive barriers)

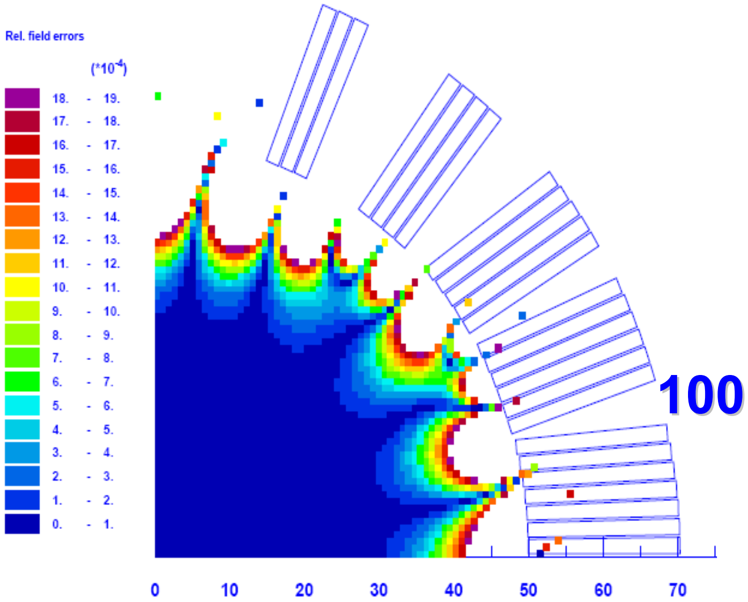
Magnet aperture

80mm

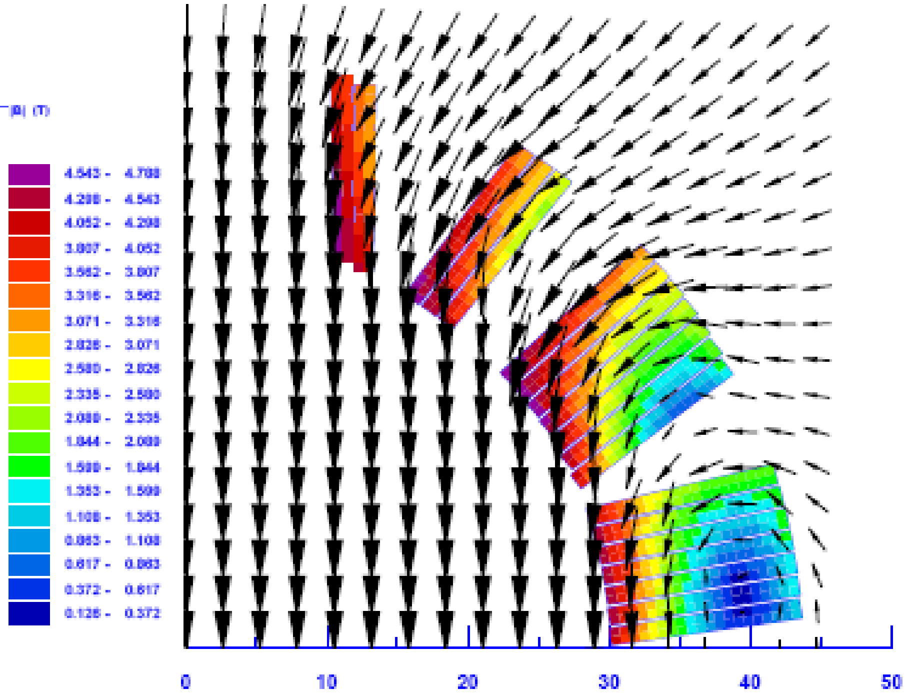


60 mm

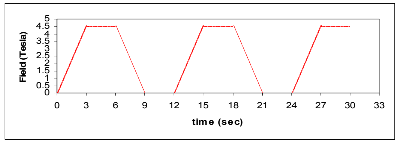


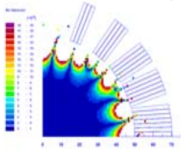


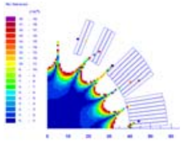
100mm

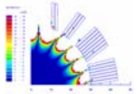


Losses for the 100, 80 & 60mm







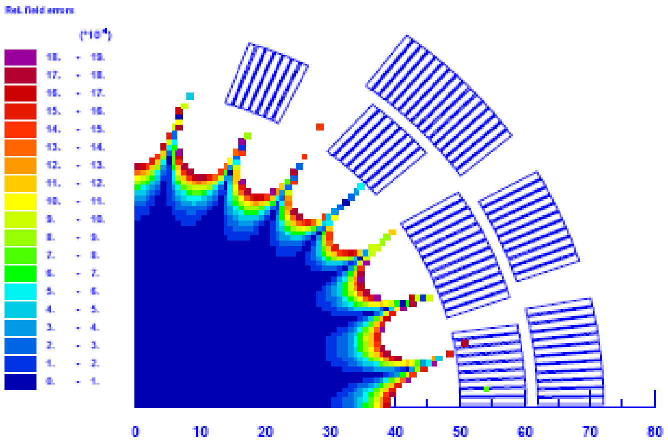


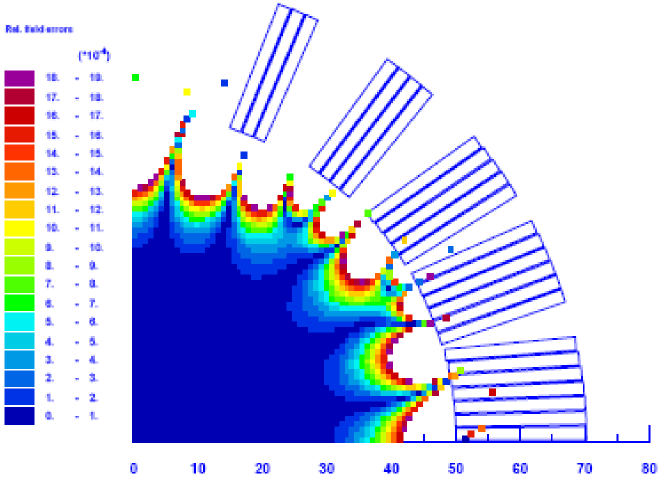
Design name		100 1layer		80 1 Layer		60 1 Layer
Number of layers	-	1		1		1
Strand diameter	mm	0.9		0.9		0.67
Current at central field	A	12414		11898		10374
Inductance	mH/m	1.602		1.1299		0.8477
Stored energy at operating current	kJ/m	123		80		46
Ramp voltage for a magnet of 6 m	V	40		27		18
Matrix		Cu	CuNi + frag	Cu	CuNi	Cu
Ra to keep P_IS_a=1 W/m	uOhm	120	120	64	64	21
Rc to keep P_IS_c=1 W/m	uOhm	9500	9500	4900	4900	1600
Average loss during field sweep in W/m						
P_M	W/m	4.79	4.79	3.85	3.85	1.93
P_IF	W/m	6.73	0.61	5.46	1.93	1.49
P_eddy	W/m	0.25	0.25	0.58	0.58	0.16
P_IS_a	W/m	1	1	1	1	1
P_IS_c	W/m	1	1	1	1	1
TOTAL	W/m	13.77	7.65	11.89	8.36	5.58
TOTAL, averaged over 1 cycle (TARGET: 5)	W/m	6.885	3.825	5.945	4.18	2.79
dT_ramp	K	1.84	0.95	1.72	0.87	1.05
P_iron, averaged over 1 cycle	W/m	2.83	2.83	1.72	1.72	1.02

1 or 2 Layer coil design?

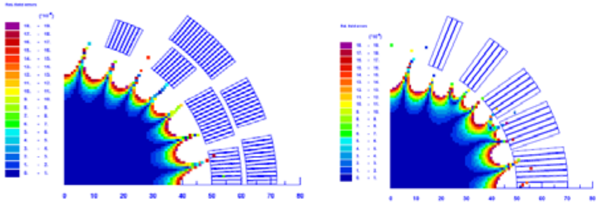
4.5 T magnets, cycling time of 12 sec

Design name		2 layer 100mm	1 layer 100mm
Bore diameter	mm	100	100
Strand diameter	mm	0.5	0.9
Number of Filament	-	11,111	36,000
Number of strands in the cable	-	40	40
Cable width	mm	**10.19**	**18.31**
Central field	T	4.5	4.5
Current at central field	A	3,879	12,414
Operating temperature	K	4.8	4.8
Inner radius yoke	mm	110	110
Outer radius yoke	mm	260	260
Inductance	mH/m	17.38	1.602
Stored energy at operating current	kJ/m	131	123
Ramp voltage for a magnet of 6 m	V	**135**	40



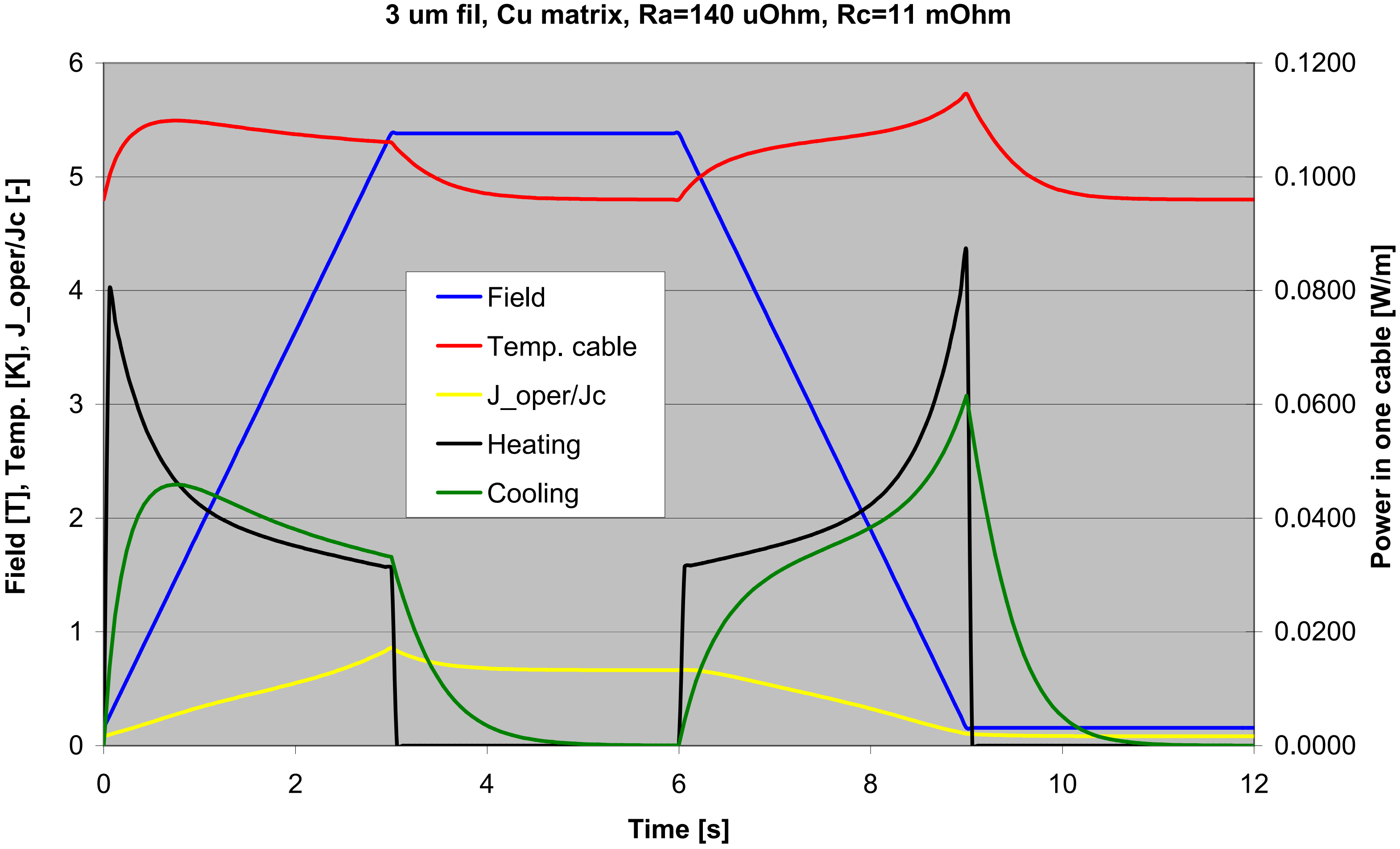


1 or 2 Layer coil design, losses



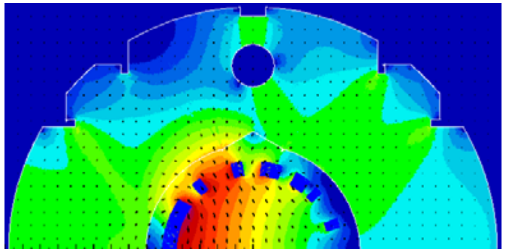
Loss parameters used		2 layer 100mm ap	1 layer 100mm ap	
Filament diameter	um	3	3	3
Matrix		Cu	Cu	CuNi
Central ring		Cu	Cu	Fragm. Cu
Ra * 1 mm^2	uOhm*mm^2	50	50	50
Rc * 1 mm^2	uOhm*mm^2	5000	5000	5000
Ra	uOhm	110	34	34
Rc	uOhm	11000	3400	3400
Jc at 4.2K, 5T	A/mm^2	2600	2600	2600
Average loss during field sweep in W/m		2 layer 100mm	1 layer 100mm	
P_M	W/m	4.68	4.79	4.79
P_IF	W/m	2.08	6.73	0.61
P_eddy	W/m	0.23	0.25	0.25
P_IS_a	W/m	1.25	3.56	3.56
P_IS_c	W/m	0.99	2.78	2.78
TOTAL	W/m	9.23	18.11	11.99
TOTAL, averaged over 1 cycle (TARGET: 5)	W/m	4.615	9.055	5.995
dT_ramp	K	0.39	2.05	0.82
J_oper/J_c at Bpeak, T=Tbath	%	60	59	59
J_oper/J_c at Bpeak, T=Tbath+dT_ramp	%	73	>100	92
P_iron, averaged over 1 cycle	W/m	2.83	2.83	2.83
J_Cu_Quench (TARGET: <=1200)	A/mm^2	827	815	1190

Temperature fluctuation during operation of 80mm 2 layer design

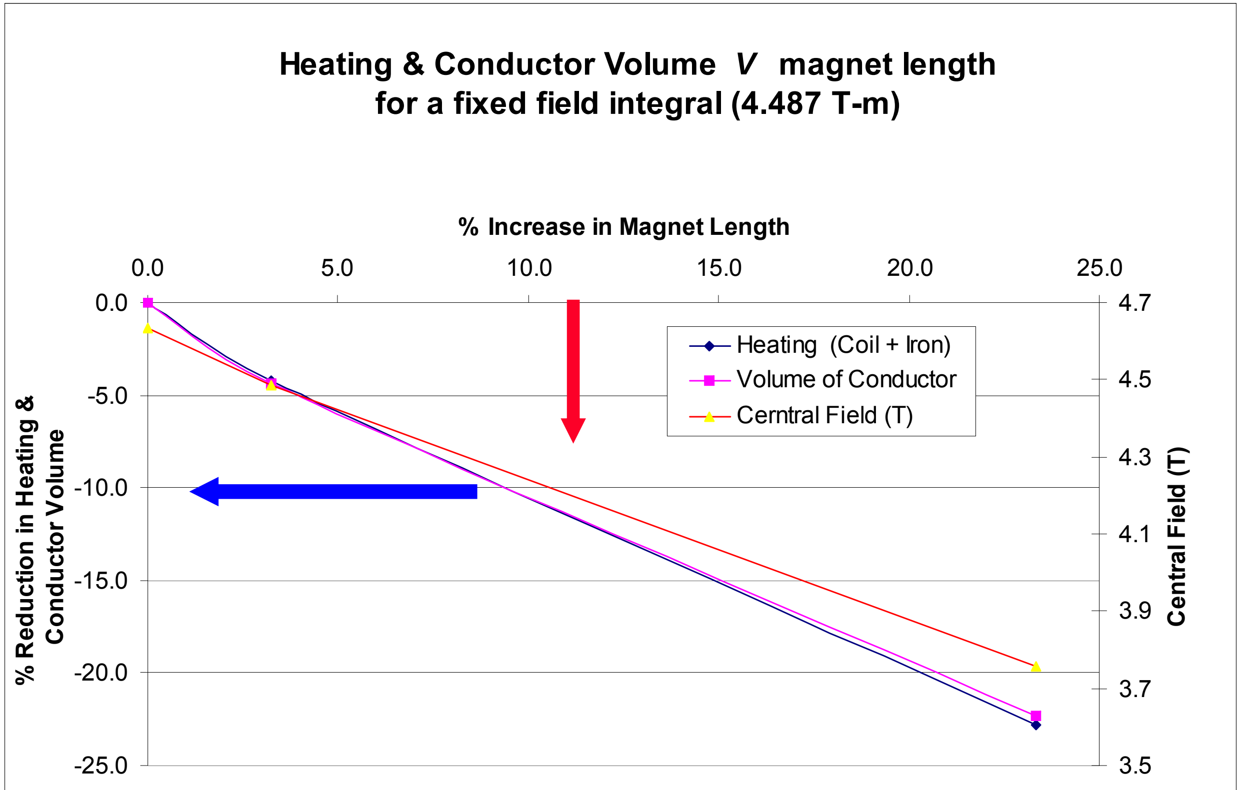


Longer Magnet Generate Less Heat and use Less Superconductor!

CFM?



Combining the Quad into the DP the effective length on the DP could be as much as 11% longer including a 5% quad corrector Without using up any more space than is currently occupied.



Results for a set of DP designs

But,But,But! Field quality of CFM, tune in SPS, Scaling is correct for DP but not yet studied for CFM.

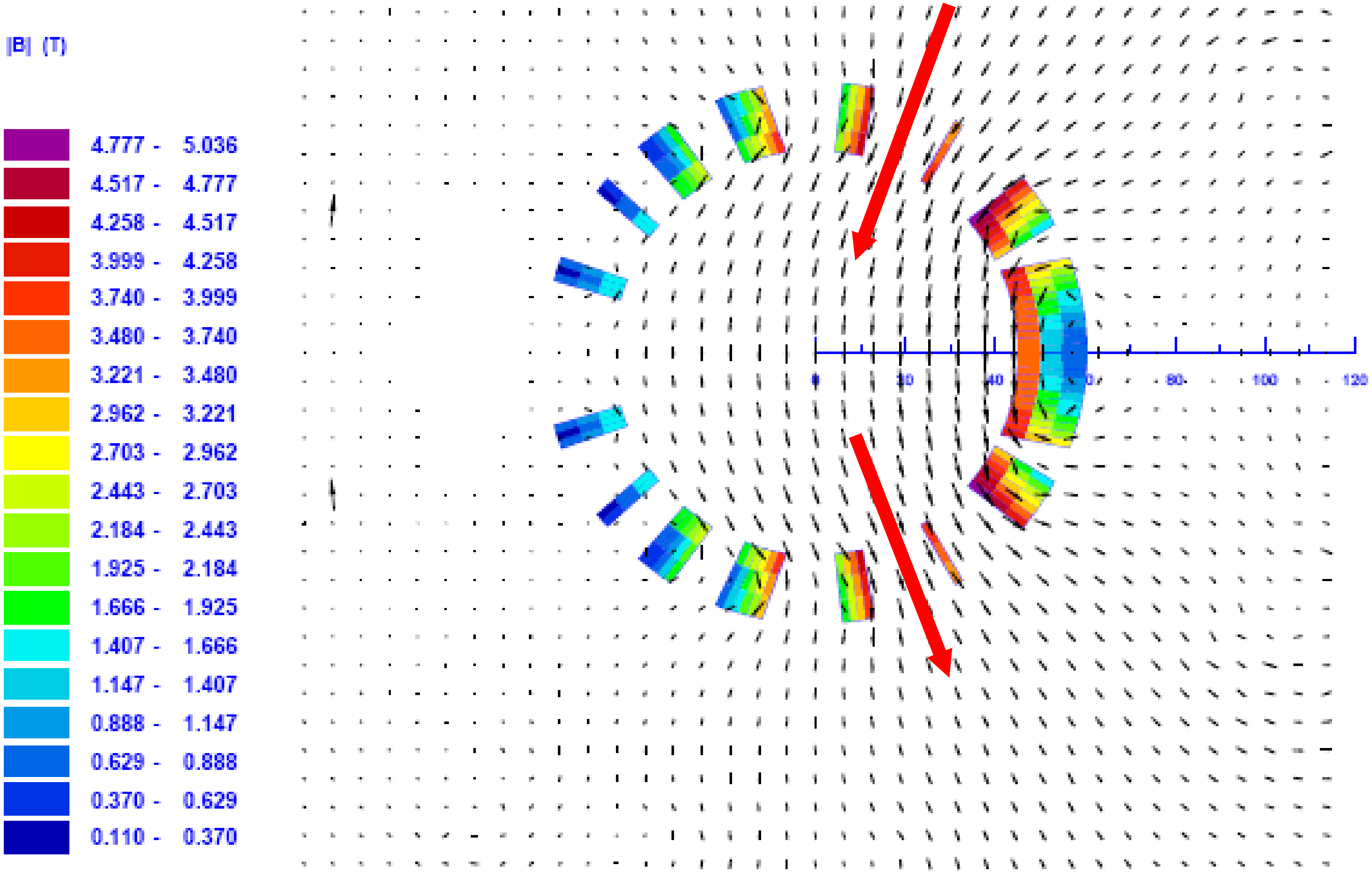
CFM

SPS + half cell at 1 Tev

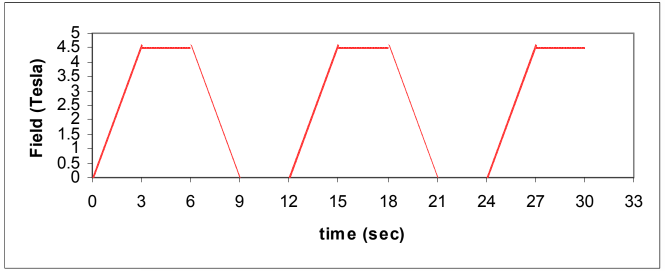
Quad	DP	DP	DP	DP
3m	6.26m	6.26m	6.26m	6.26m
48.89 T/m	4.89T	4.89T	4.89T	4.89T

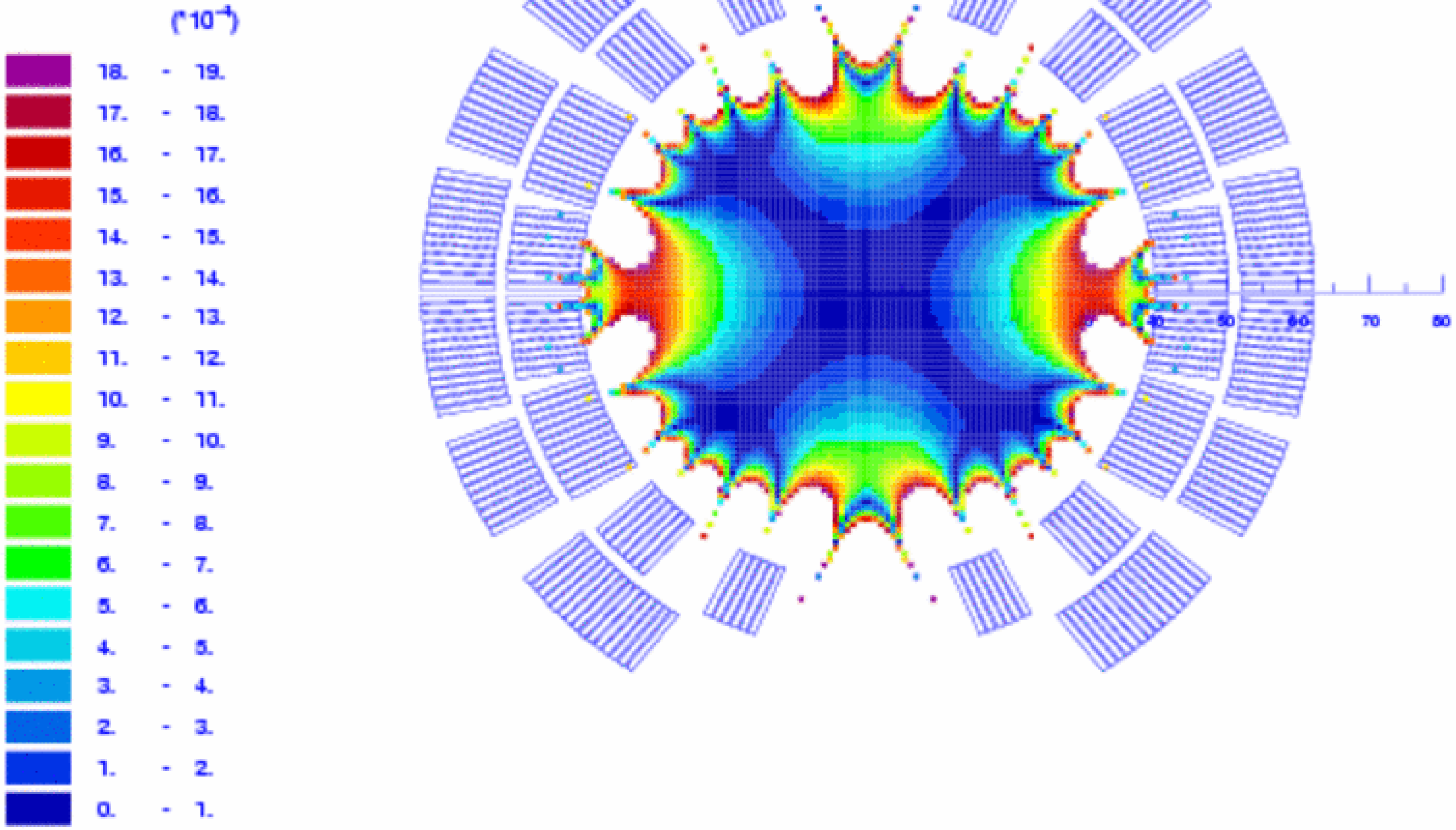
Quad corrector	CFM	CFM	CFM	CFM
0.15m	7m	7m	7m	7m
48.89 T/m	4.37T	4.37T	4.37T	4.37T
5%	5.23 T/m	5.23 T/m	5.23 T/m	5.23 T/m

CFM


|B| (T)
4.777 - 5.036
4.517 - 4.777
4.258 - 4.517
3.999 - 4.258
3.740 - 3.999
3.480 - 3.740
3.221 - 3.480
2.962 - 3.221
2.703 - 2.962
2.443 - 2.703
2.184 - 2.443
1.925 - 2.184
1.666 - 1.925
1.407 - 1.666
1.147 - 1.407
0.888 - 1.147
0.629 - 0.888
0.370 - 0.629
0.110 - 0.370
0
20
40
80
100
120

Field quality during ramping





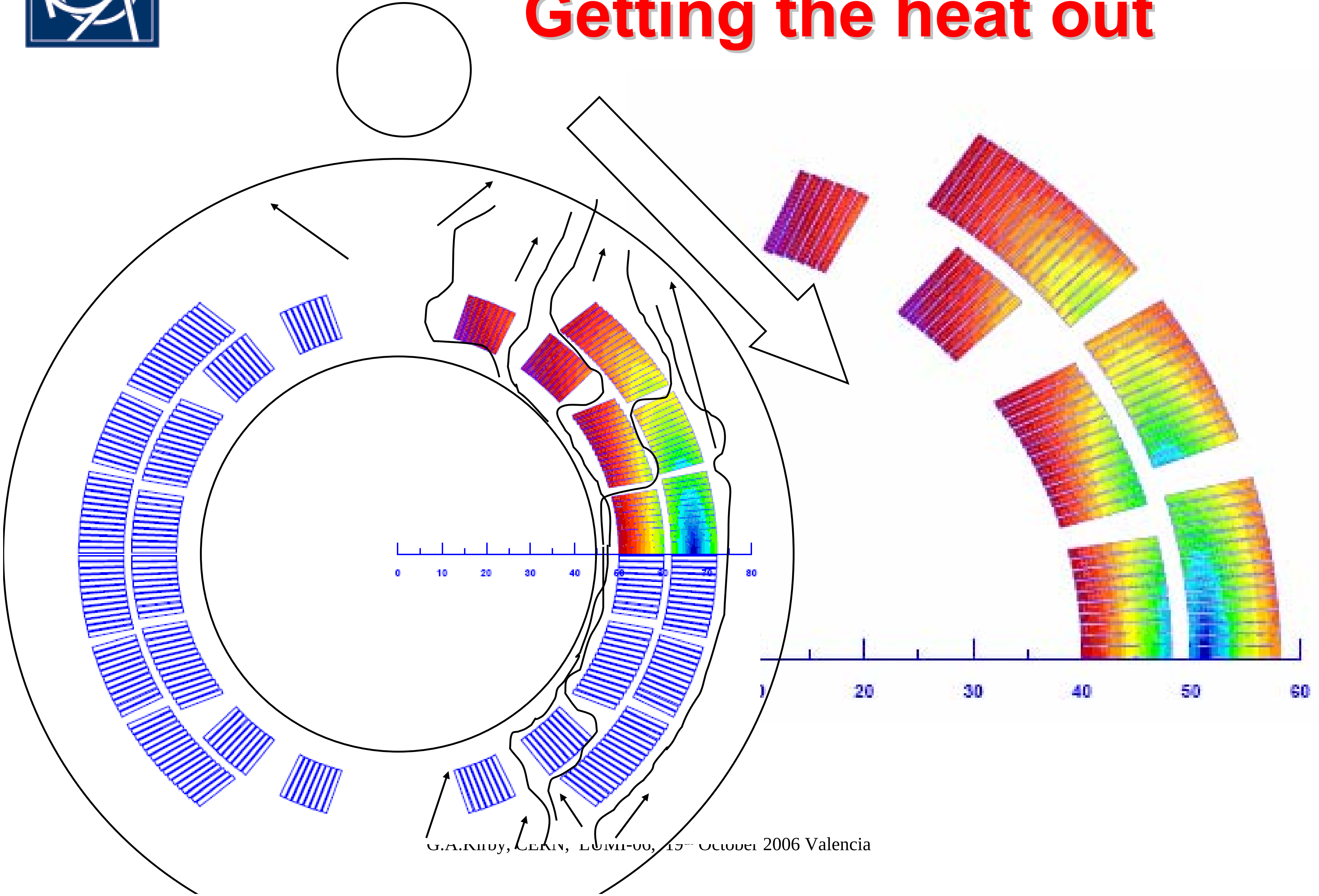
Comparison of cooling modes

- Pool boiling (~1 W/m)
- Forced convection of superfluid helium (~1 W/m)
- Static pressurized He II LHC (~1-10 W/m) <2.2K
  - LHC @ 1.9K has 10W/m with a temperature change of 0.1K so this could be a possible cooling mode.
  - However Rc & Ra are still note fixed and vary by orders of magnitude. If due to the very low Cp at 1.8k the temperature rise will be above 2.2K the system would fail.
  - More work is needed.

- **Forced convection of supercritical helium (~1-10 W/m) 2.2K to 5K**
  - **This cooling mode seems to be a safer option, but relies on pumping supercritical helium through channels in the magnet.**
  - **Easy to implement for low heat loads, Single phase Mass flows of O(W/0.1 kg/s), High heat load possible at the expense of T-margin and high ΔP, Cross-flow construction needed for high heat loads.**

- **Needs work to carefully check which mode works and the costs**

Getting the heat out

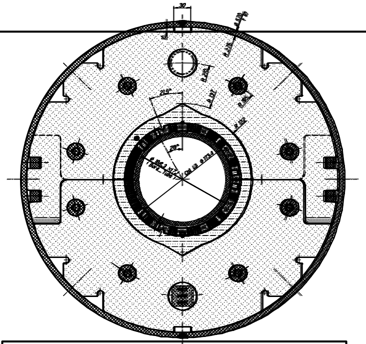


Getting the heat out

$$Q = \dot{M}.Cp.\Delta T_{Helium}$$

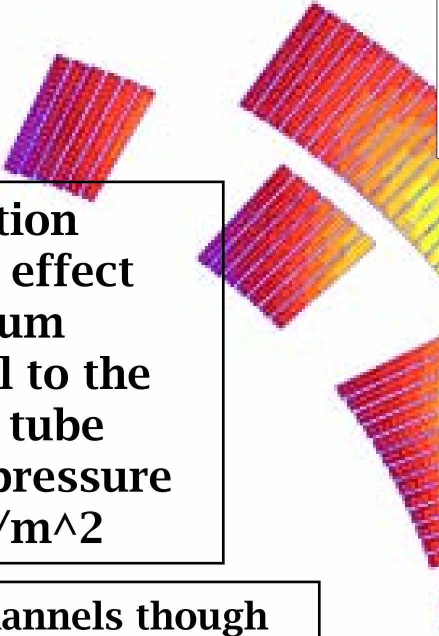
$$Buoyancy = V.(\rho_{4.8K} - \rho_{4.5K}).g$$

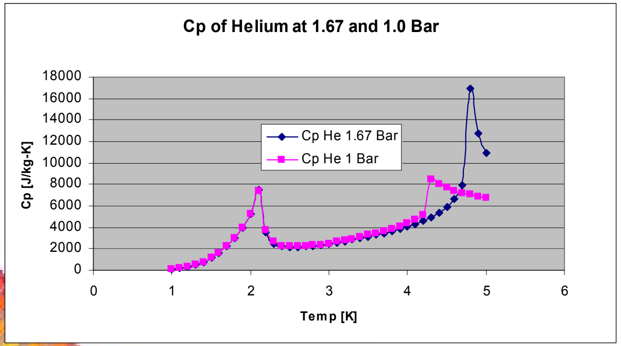
With 10 W/m we must move about 4 L/min of helium through the coil, with a bath temp 4.5K and T max 4.8K.

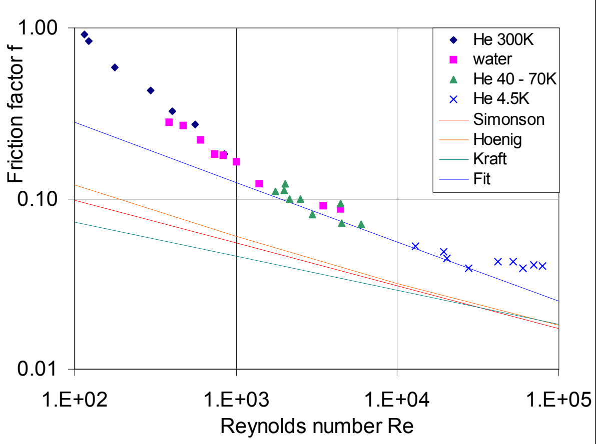


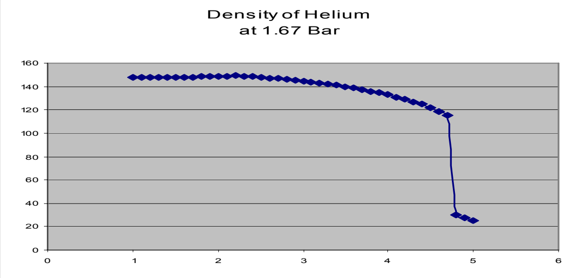
$$\dot{M} = A_h \sqrt{\frac{PD_h \rho}{2f}}$$

Natural convection Thermosyphon effect pushes the helium through the coil to the heat exchanger tube with a driving pressure of about 180 N/m^2







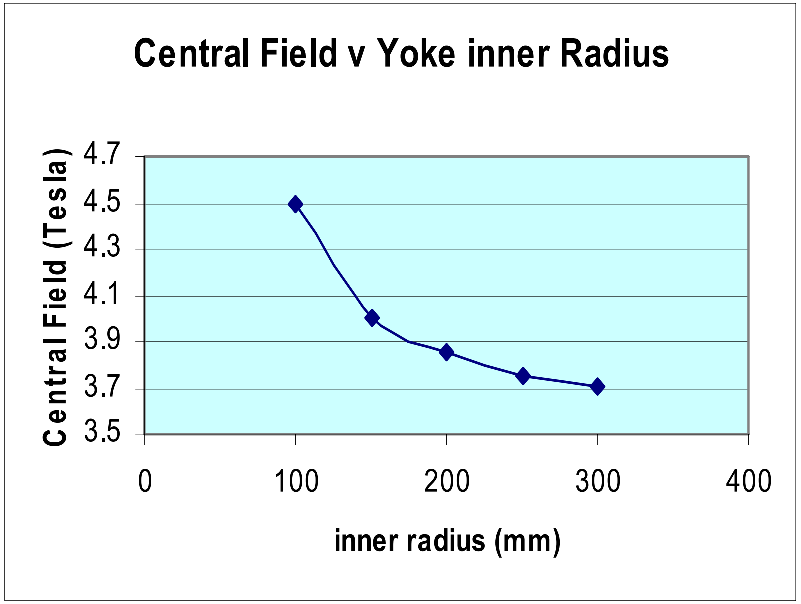


If we assume 1 mm diameter cooling channels though the coil, we will need about 2500 channels per meter to extract the 10 W/m at 4.8K. This is a tube every 3mm or 33% open magnet structure.

We don’t have such channels in our LHC magnet, needs careful design and testing!!

Yoke, cold or warm

- At 1.5 T/s the hysteresis losses averaged over 1 cycle in the iron are between 1.02 W/m for the 60mm aperture up to 2.83 W/m for the 100mm aperture. So can we eliminate this heat load?
- A warm iron inner radius design
- Collars, support tube, cryostat cold-warm support = warm iron inner radius 200mm.
- We loose 0.8 Tesla central field in the 100mm aperture design.
- To replace this lost field and maintain the same short sample % we need to add about 20% extra superconductor.
- For this design what we gain with the iron losses we loose with the Superconductor losses and cost. Plus the Rc & Ra could make a bigger diff.



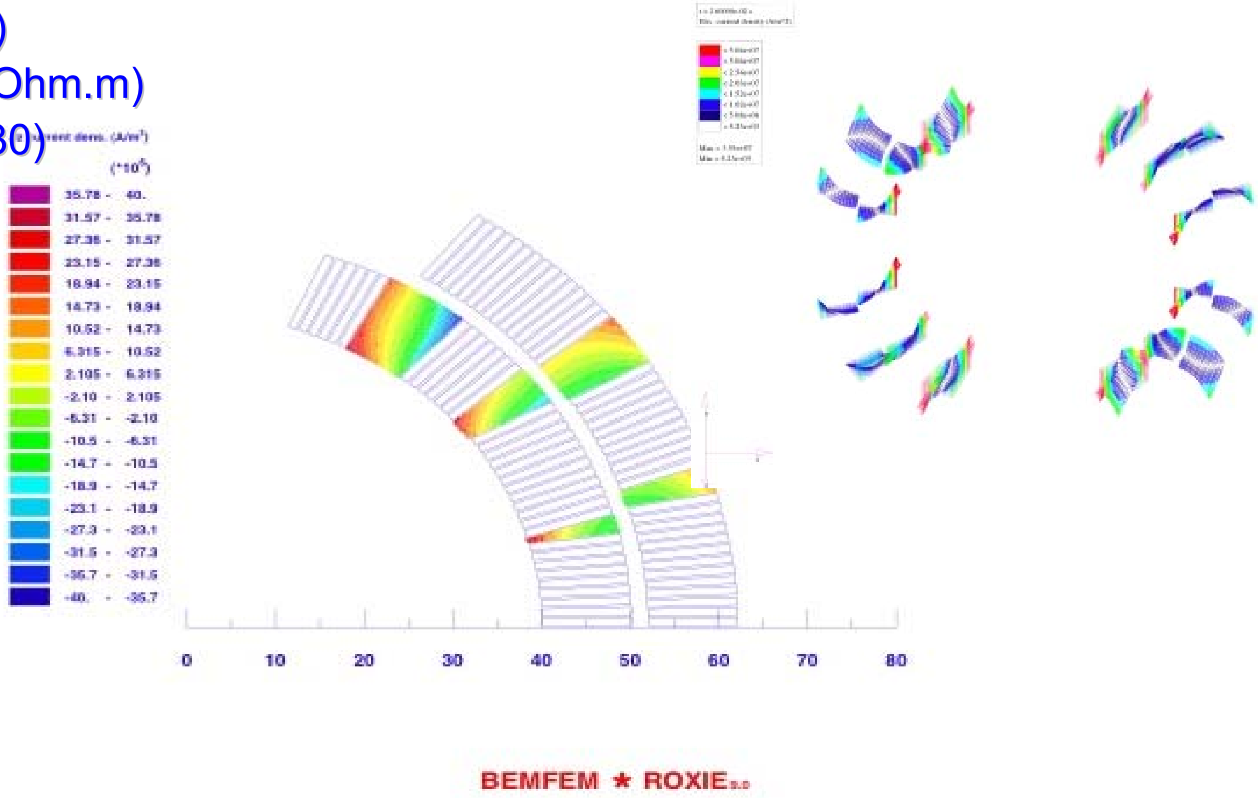
Cable losses only

		Cold Iron	Warm Iron
P_M	W/m	4.68	5.62
P_IF	W/m	2.08	3.02
P_eddy	W/m	0.23	0.33
P_IS_a	W/m	1.25	1.81
P_IS_c	W/m	0.99	1.44
TOTAL	W/m	9.23	12.21

2.9

Wedges and eddy current effect on internal heating and field quality.

- calculated losses and impact on field quality for 3 materials
- copper with 1.7e-10(Ohm.m)
- bronze with 3.0e-8(Ohm.m)
- stainless steel with 5.0e-7(Ohm.m)
- GRP very big e10 +(20 or 30)

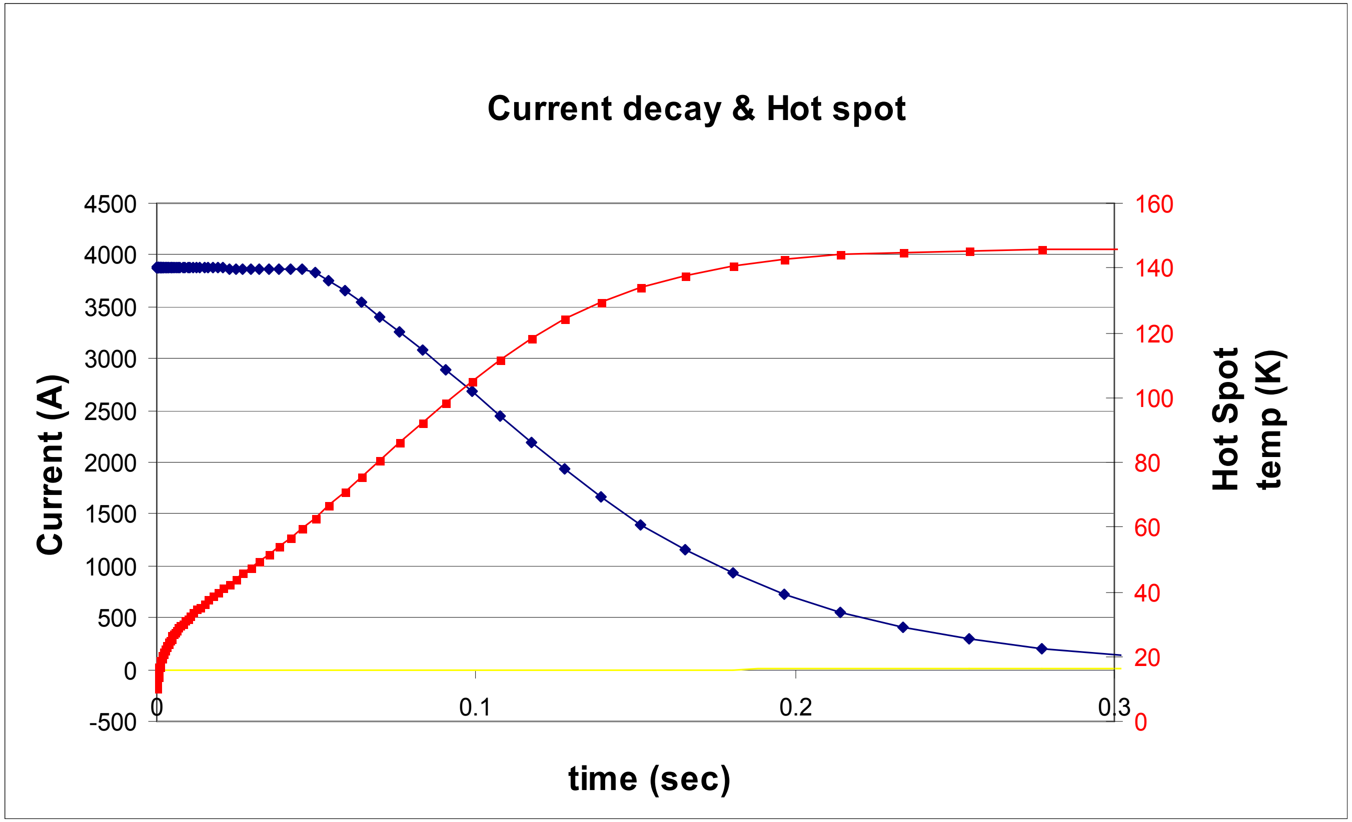


- The losses
- copper: 22.03W/m
- bronze: 0.1248W/m
- stainless steel: 7.49mW/m
- the impact on field quality is not negligible for copper. the eddy- current density is at about 1/10 of the transport current density in the cables -> delta b3 of about 2 units. For the others materials there is no effect of eddy-currents on field quality.

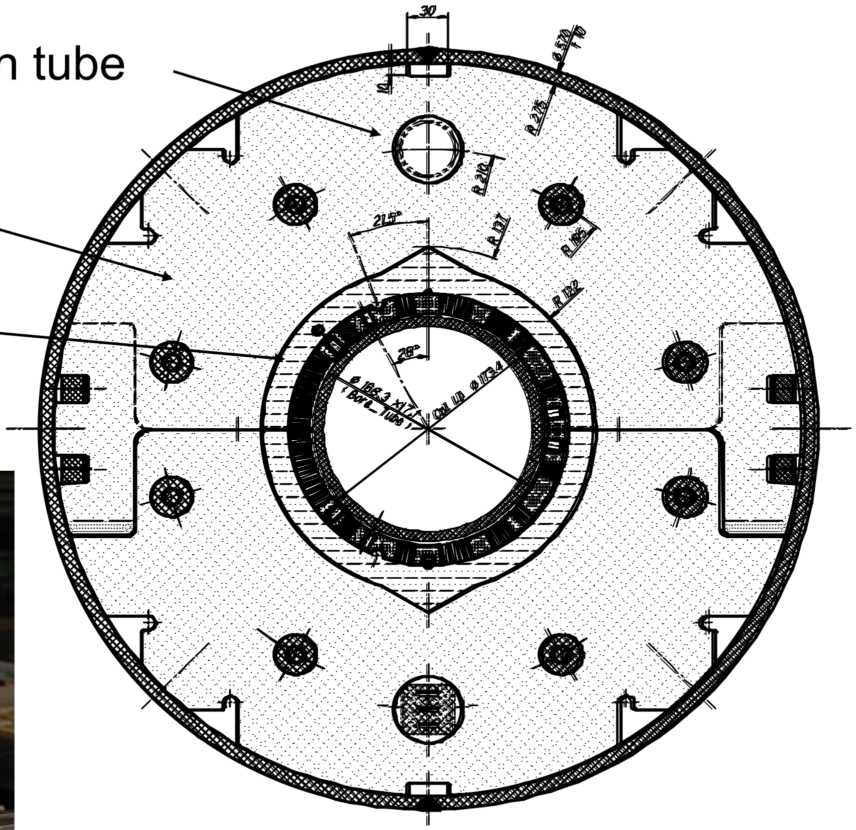
Quench simulation

- 100 mm 2 layer design
- Quench heaters only no dump
- 0.045s detection delay
- 6m long magnet
- No cooling to the bath assumed

Look very, too safe?



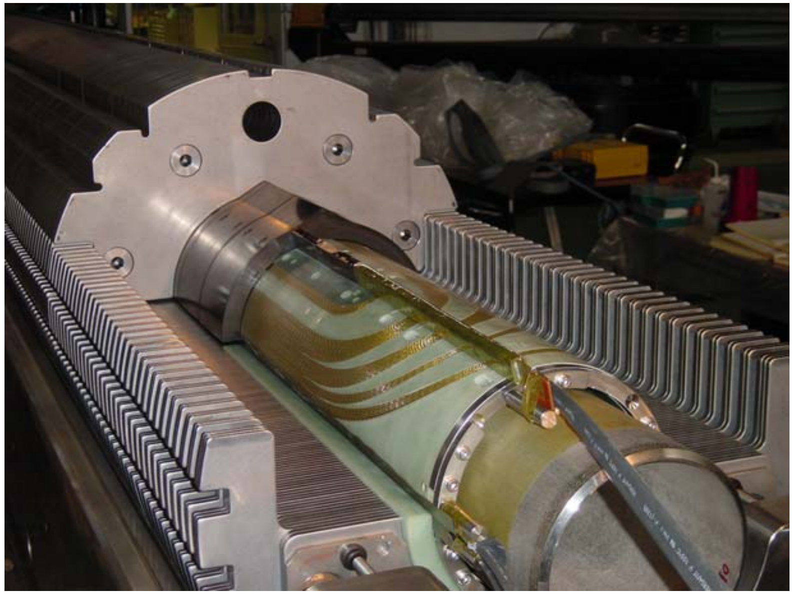
Magnet mechanical design



Heat extraction tube

Yoke collar

Plastic spacer



Photographs & sketched thanks to KEK.

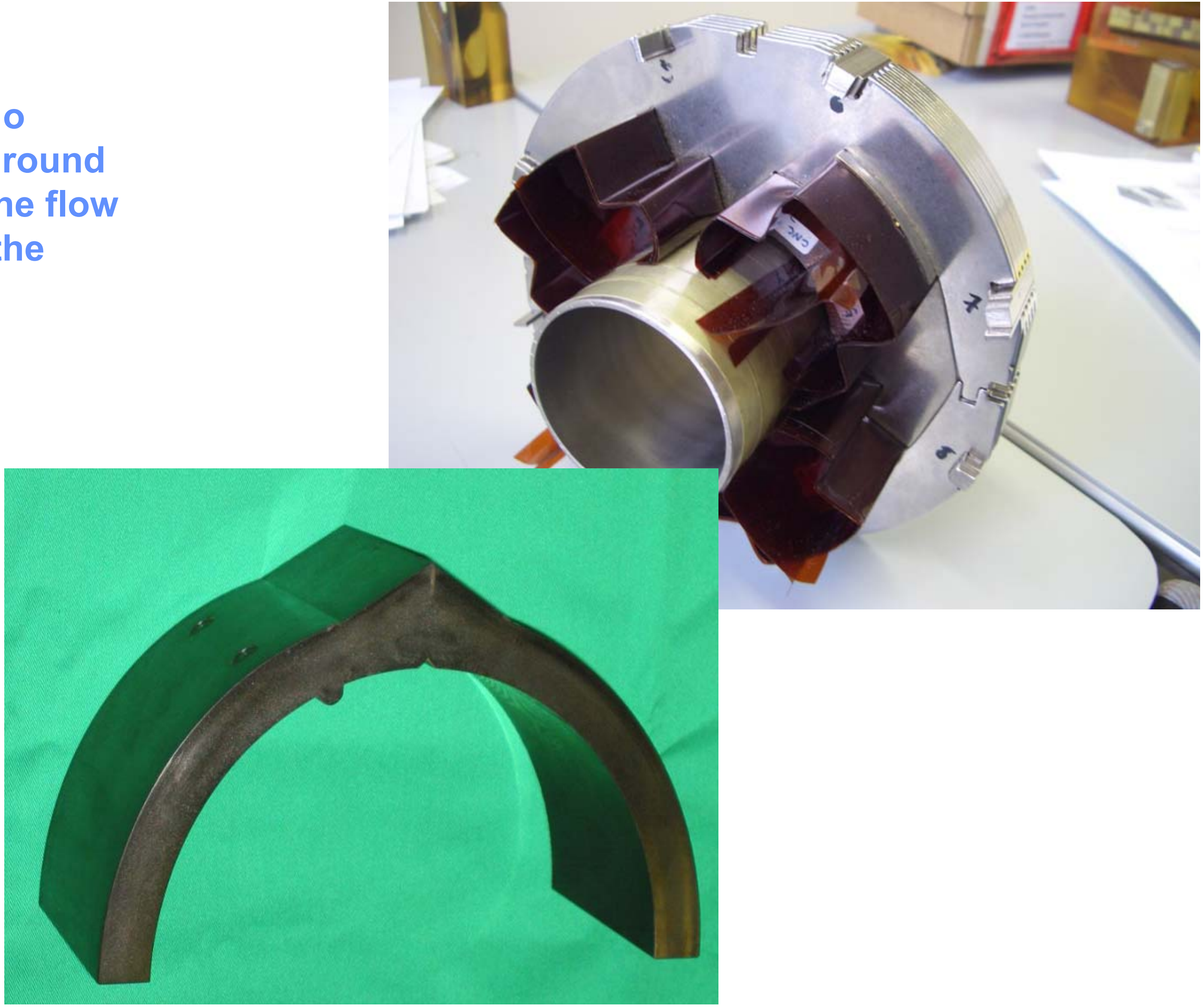
Plastic spacers

Get the heat out: No kapton sheets for ground insulation to stop the flow of Helium through the magnet.

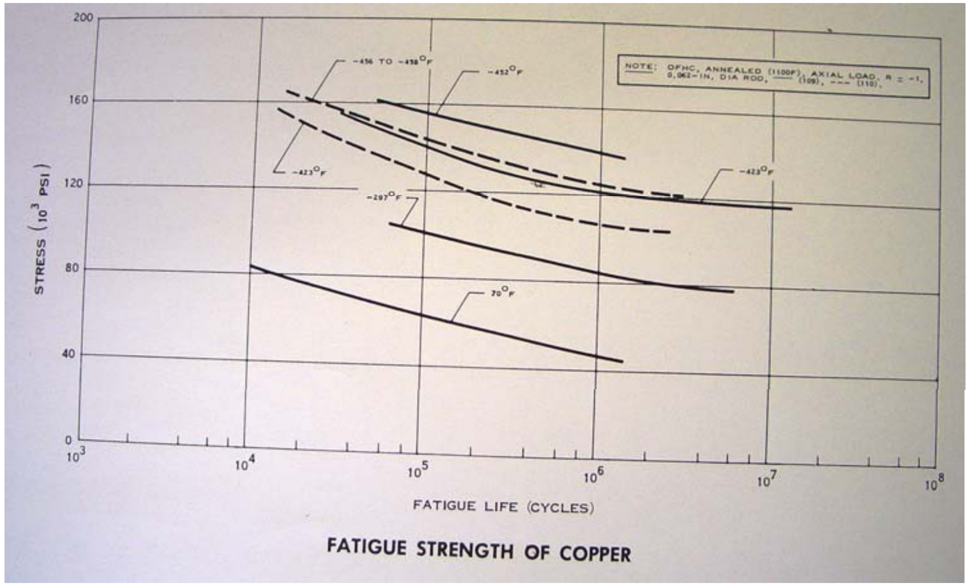
Labyrinth design will give >>5Kv to ground insulation.

Inexpensive and fast to assemble

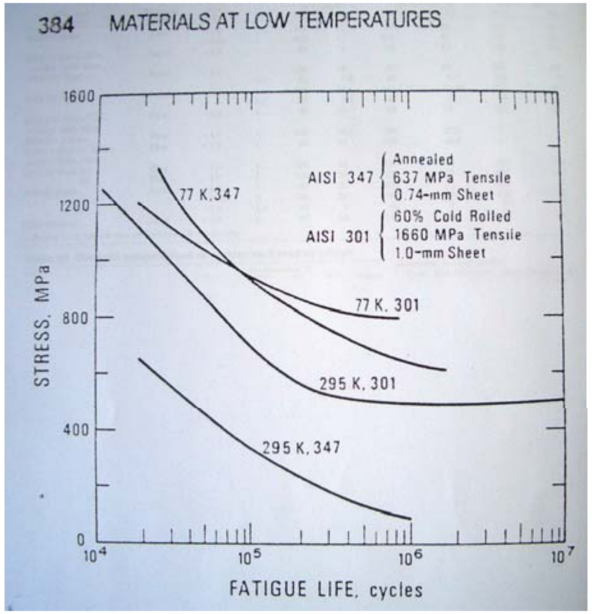
Bent apertures?



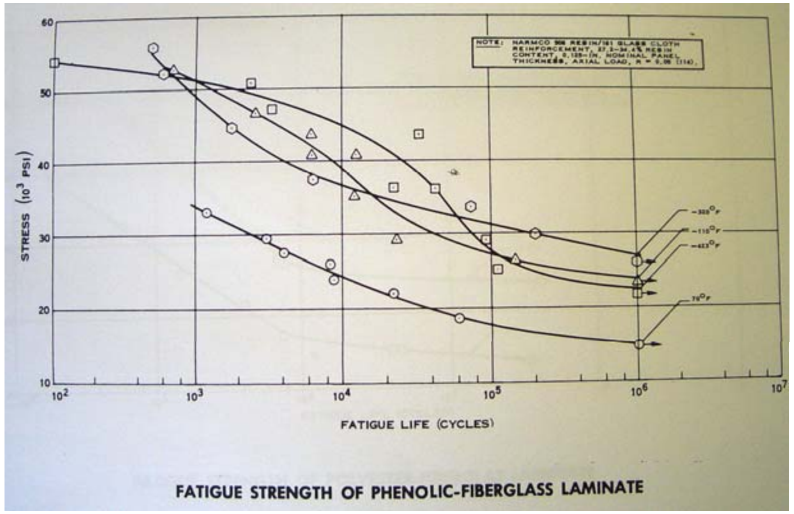
Fatigue 10^6 Cycles material data



FATIGUE STRENGTH OF COPPER



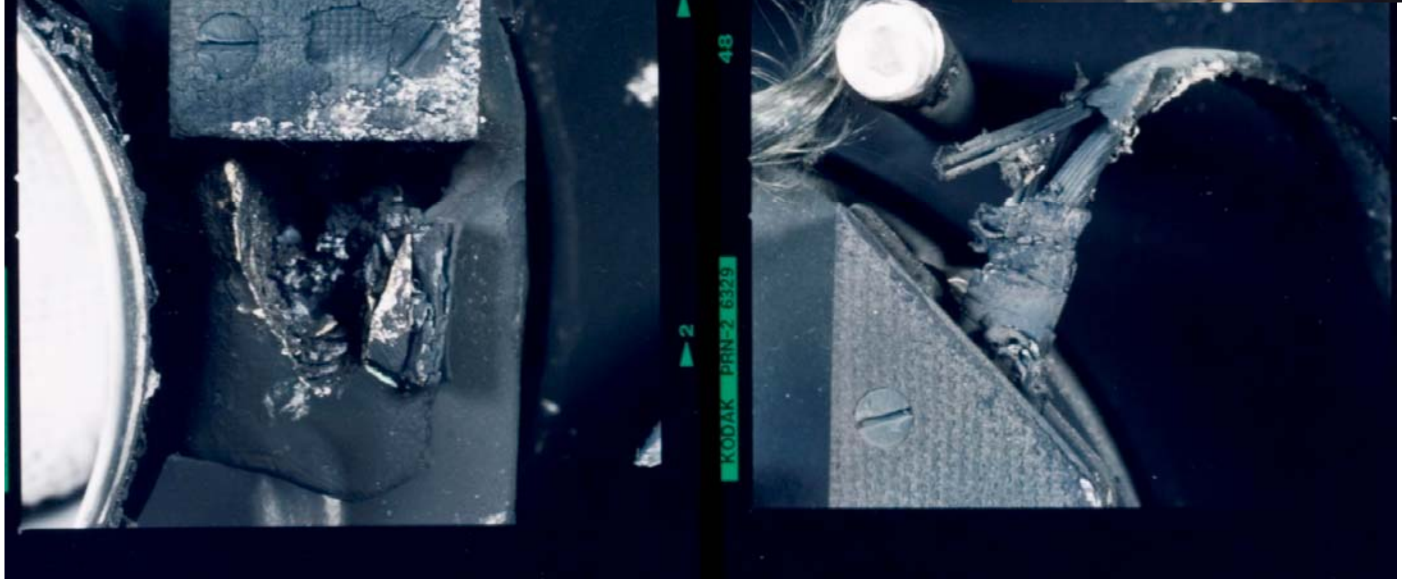
- **Some Fatigue data can be found for low temperatures.**
- **Fatigue life increases with lower temperature.**
- **77k tests not 4k are the norm.**



FATIGUE STRENGTH OF PHENOLIC-FIBERGLASS LAMINATE

Fatigue at Fermilab

- After about 10^5 cycles Fermilab repaired all the TeV magnet, after they started to fail from Fatigue due to a moving current lead.



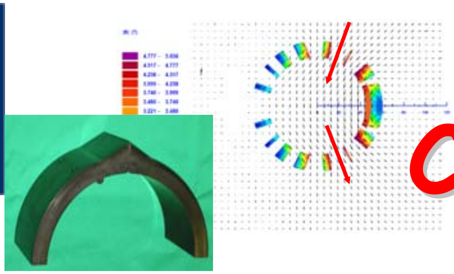
How long to develop and build the magnets

- 2 years to design and get the new strand materials for first model.
- 2 to 3 years to perform sensible fatigue and heat extraction testing with improved models.
- 3 to 4 years to build the 750 magnets.

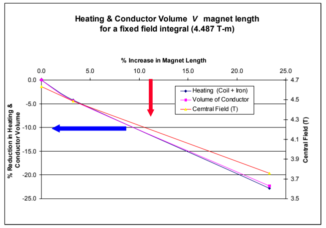
- 10 years project!   From when you start!

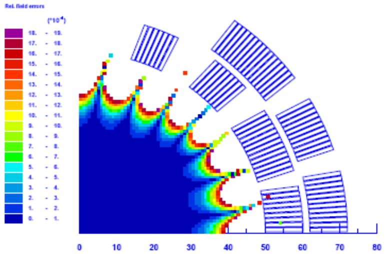
Things to do

- Study Combined Function Magnet for SPS.
- How to get the heat out of a Horizontal Magnet!! study this 4.5K or 1.8K!
- Develop an open insulation system.
- Develop a Quench heater that lets Helium through the coil at 4L/min/m.
- Get superconductor ASAP!!! CuNi or Cu and make a very short test magnet.
  - Test to find Rc & Ra values in the magnet!
  - Test heat extraction, measure temp fluctuation.
  - Fatigue test station. set up accelerated fatigue cycling tests M cycles (one or two years).

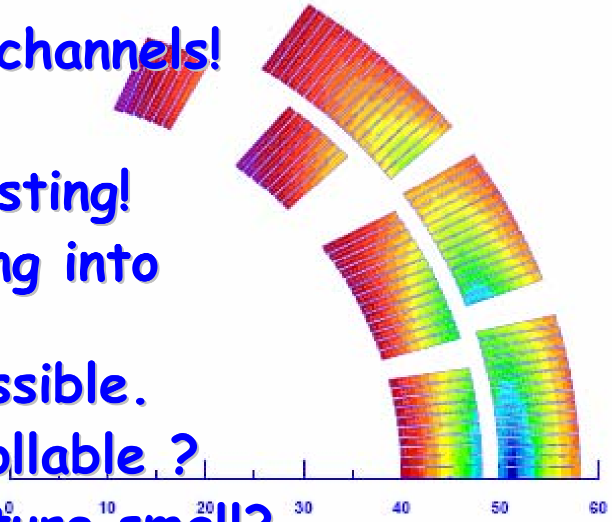


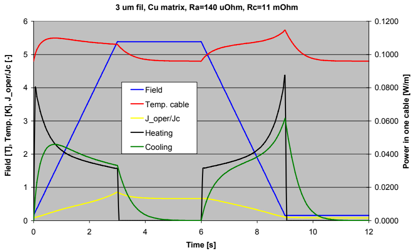
Conclusions





- 2 layer design!
- GRP or Stainless steel wedges with big channels!
- Cold Iron!
- Fatigue is important! Needs design & testing!
- Aperture keep as small as possible taking into account the beam? 60 80 100?
- Beam losses push aperture as big as possible.
- Field quality during ramping seem controllable ?
- Bend the magnet to help keep the aperture small?
- Get the heat out! Very open coil / insulation.
- Long Magnets have lower heating & less conductor! a CFM design?





Filamentbundles
with interbundle Cu