Preliminary field quality and quench margins

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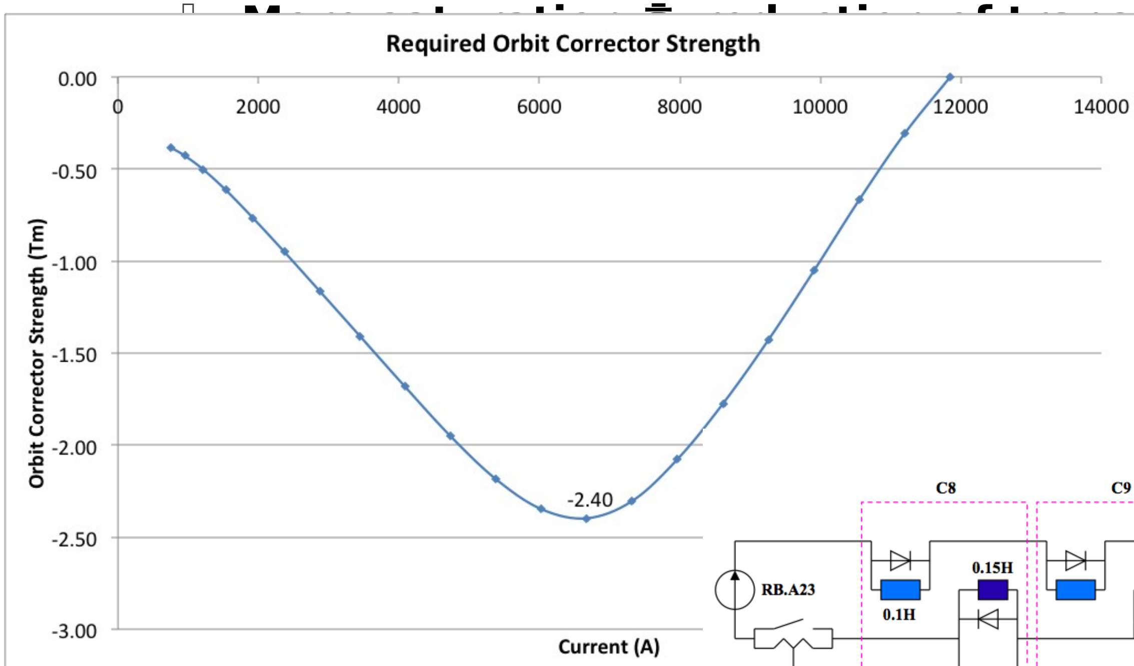
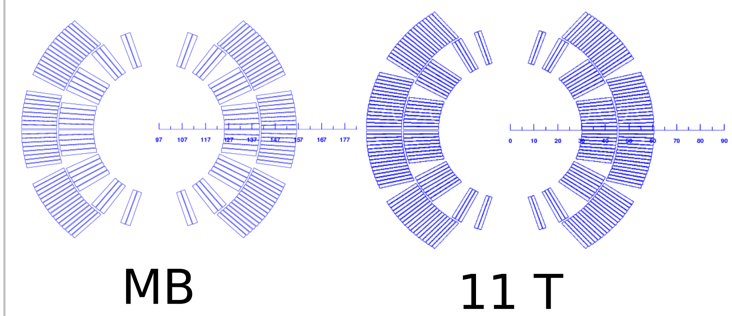
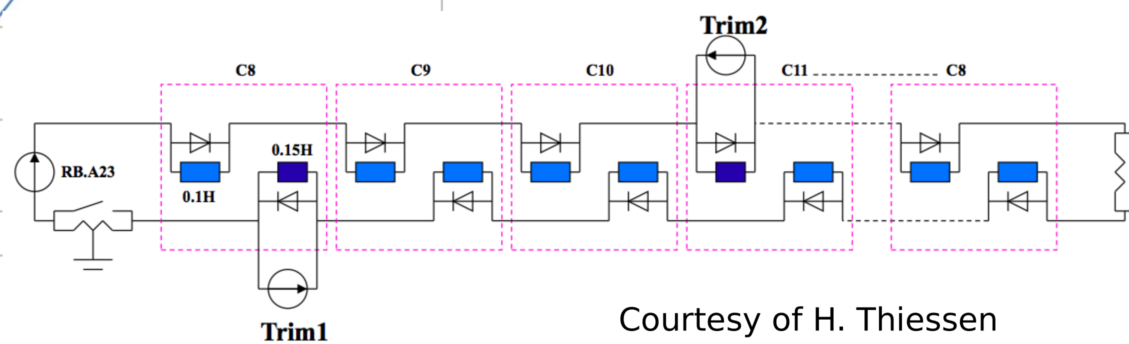
on behalf of the CERN-FNAL collaboration

Transfer Function

- **A discrepancy between MB and 11 T is inevitable:**
  - **More turns than MB (56 vs. 40) ⇒ 11 T dipole is stronger low field.**
  - **More saturation ⇒ reduction of transfer function at high field.**



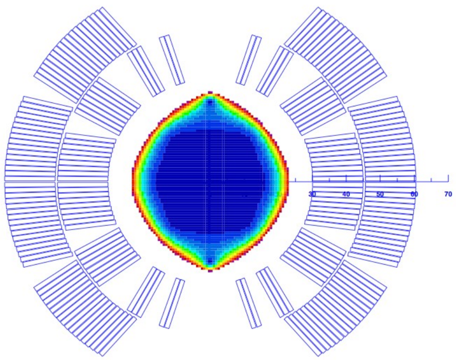


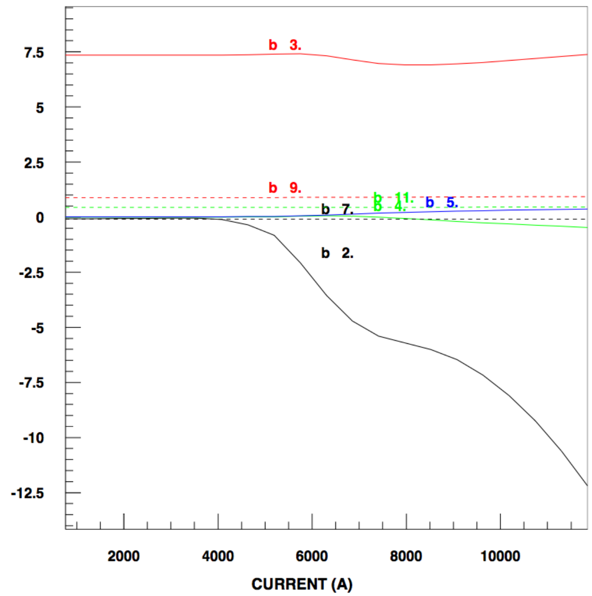


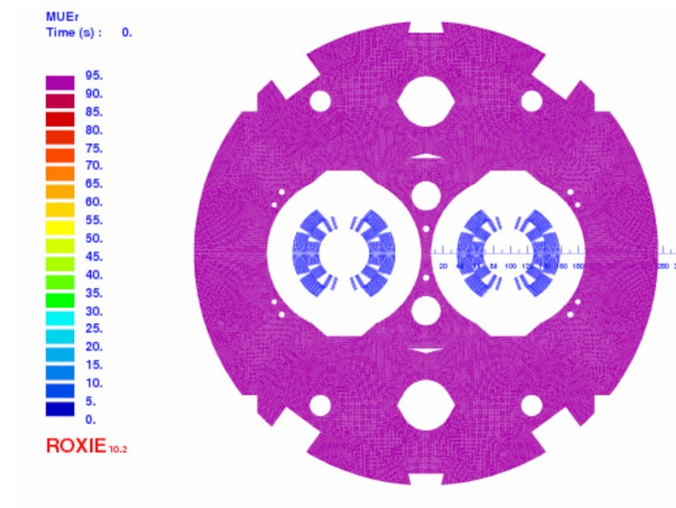
Courtesy of H. Thiessen

- **Remedy:**
  - **No space for correctors (~ 1 m MCBC/MCBY needed).**
  - **300 A trim power converter.**
    Preferred: monopolar to avoid voltage peaks that perturb QPS.

Coil and Yoke



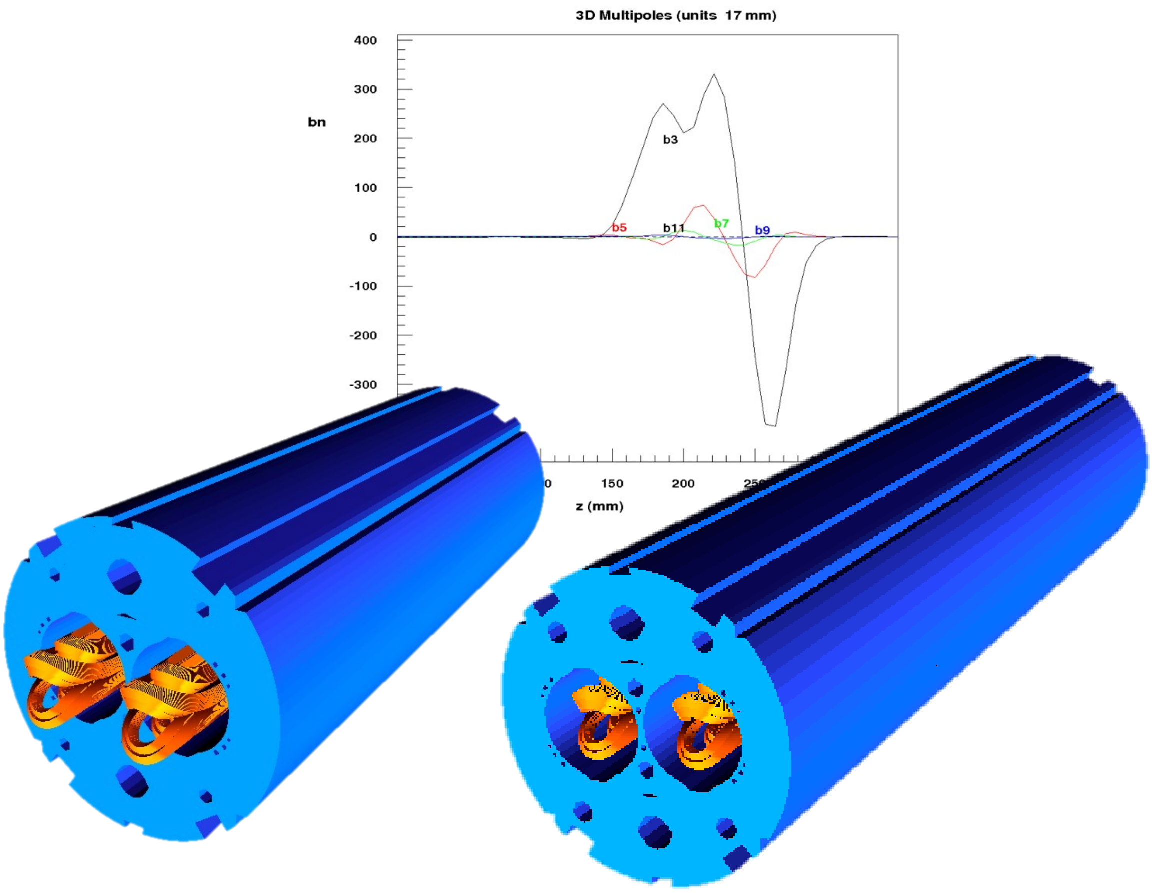




- **Coil geometric multipoles < 1 unit @ 17 mm.**
- **Yoke design**
  - **The cut-outs on top of the aperture reduce the *b*3 variation by 4.7 units as compared to a circular shape.**
  - **The holes in the yoke reduce the *b*3 variation by 2.4 units.**
  - **The two holes in the yoke insert reduce the *b*2 variation from 16 to 12 units.**
  - **Remedy for *b*2: thinner collars are being studied.**

3-D Field Quality

- **3-D integrated harmonics vs. 2-D harmonics @ *I*nom**
  - **Optimized 3-D coil design.**
  - **Extending the yoke over the ends reduces *b*2!**
  - **Need to control winding accuracy.**



	2-D	3-D	3-D
cutback	**n/a**	**yes**	**no**
***B*1**	**11.212**	**11.225**	**11.233**
***b*2**	**-14.6**	**-15.6**	**-9.4**
*b*3	7.4	9.0	9.0
*b*5	0.4	1.1	1.1
*b*7	-0.1	0.2	0.1
*b*9	0.9	0.9	0.9
*a*1	0.0	2.4	2.3

Persistent Currents

- After the ramp from the pre-cycle reset current Imin = 100 A to injection current 757 A, the change of ramp-direction has not flipped the magnetization in the entire coil.
- In this regime, the impact of persistent currents on field quality is highly non-linear w.r.t. filament size and depends strongly on the pre-cycle reset current.

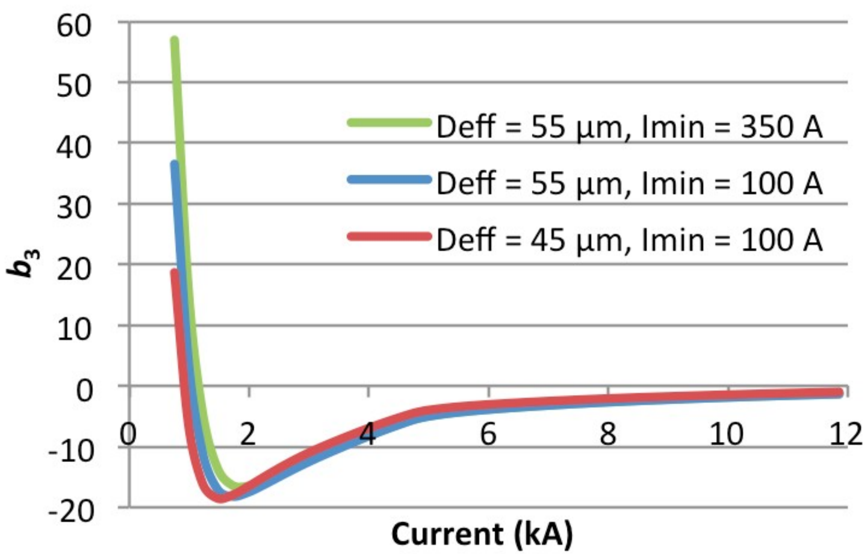


Figure 3: Transfer function with (red) and without (blue) persistent current effect.

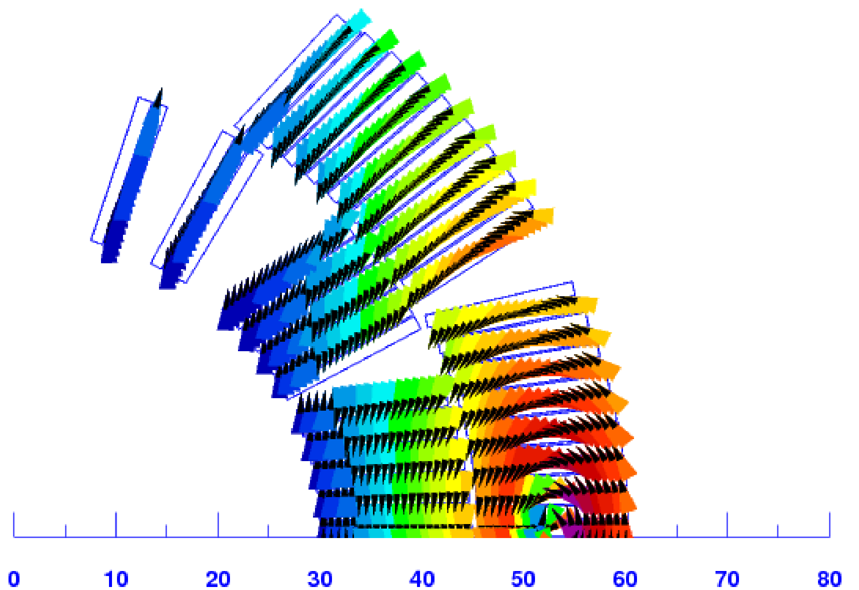


Figure 4: Persistent-current-induced coil magnetization at injection level, I = 757 A.

Sextupole Compensation

- Passive compensation schemes by means of SC strands or ferromagnetic shims are being explored.
- Compensation by SC strands is efficient once the change of ramp direction has sufficiently penetrated the coil.
- Ferromagnetic shims can shift the sextupole at low fields.
- The passive compensation reduces the aperture diam. by 4 mm.

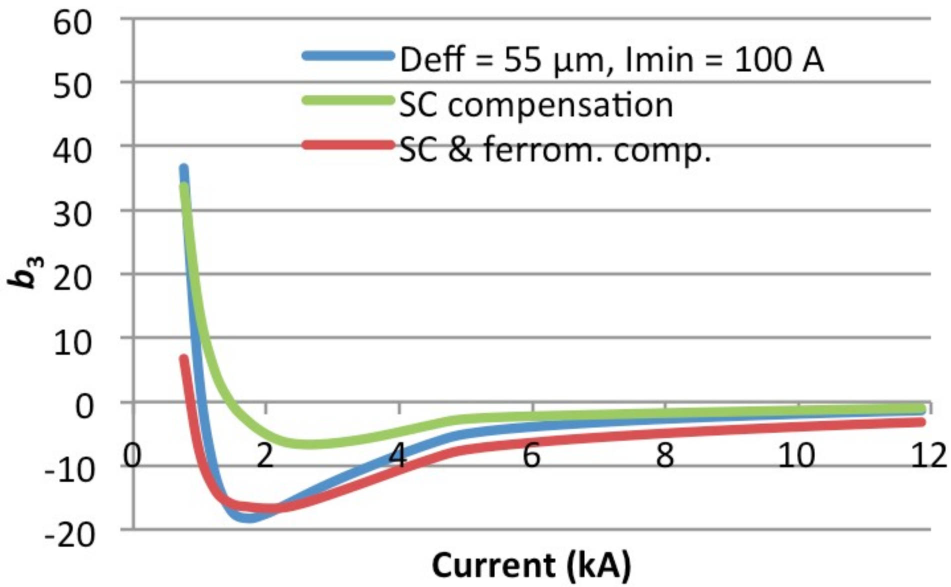


Figure 5: Impact of passive compensation measures on the sextupole component.

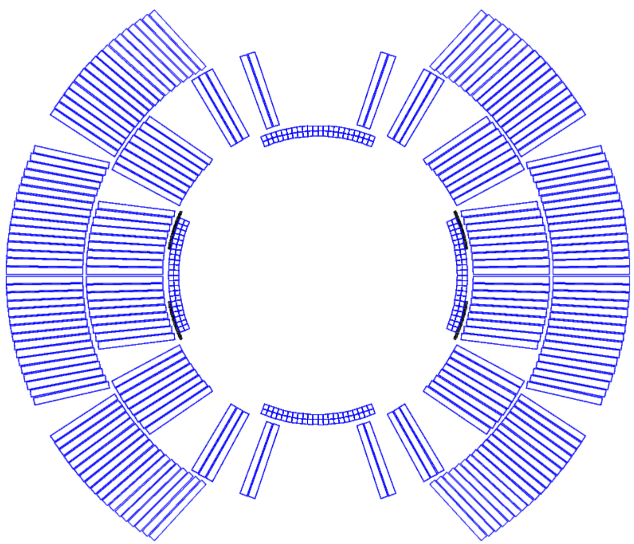
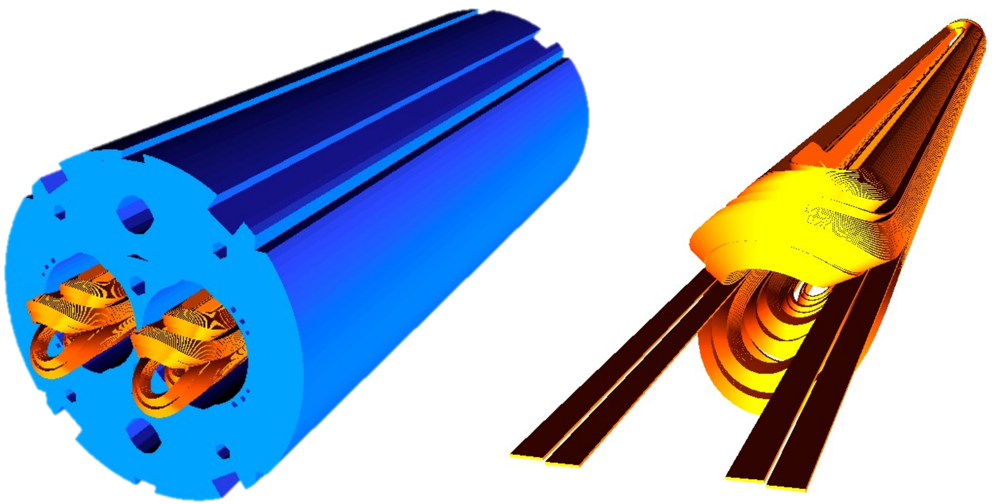


Figure 6: 4 sectors with two rows of passive strands, and 4 ferromagnetic shims near the mid-plane.

Best-Guess Error table

- **Including**
  - **Persistent currents with Imin = 100 A, Deff = 55 µm.**
  - **Skew harmonics due to cryostat.**
  - **3-D return and lead ends with 11 cm yoke cutback.**



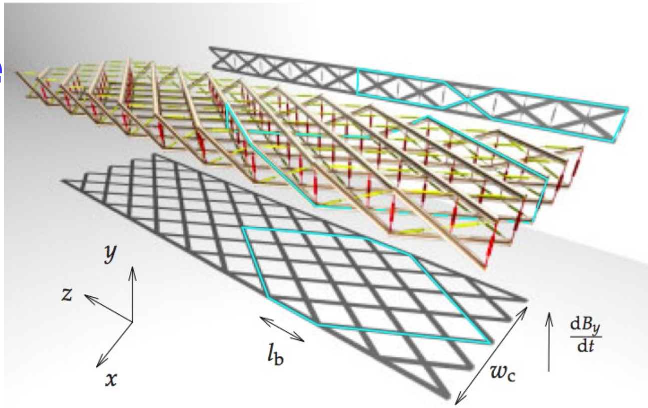
The 3-D electromagnetic model of coil and yoke. Layer-jump, block transitions, and leads are visible in the coil.

5.5 m 11 T Dipole Error Table

	Iinj	**Inom**	**Stdev**
B0	-0.758	-11.217	
B/I	-1.001	-0.947	
Lmag	5300	5300	
b2	-0.80	-14.41	1.93
b3	41.33	5.20	1.24
b4	0.09	-0.45	0.60
b5	6.90	0.51	0.31
b6	0.01	-0.02	0.18
b7	-0.10	0.10	0.11
b8	0.00	0.00	0.06
b9	1.31	0.94	0.03
b10	0.00	0.00	0.01
b11	0.33	0.43	0.01
b12	0.00	0.00	
b13	0.00	0.00	
a1	0.87	4.02	2.87
a2	-0.02	-0.26	1.66
a3	-0.11	-0.08	1.00
a4	0.00	-0.01	0.64
a5	0.09	0.09	0.38
a6	0.00	0.00	0.20
a7	0.03	0.03	0.09
a8	0.00	0.00	0.05
a9	0.00	0.00	0.03
a10	0.00	0.00	0.02
a11	0.00	0.00	0.01
a12	0.00	0.00	
a13	0.00	0.00	

Cable Eddy Currents 1/2

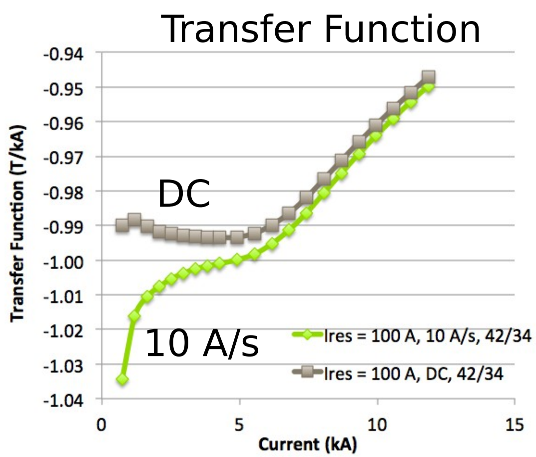
- **Dominant effects in cable without core**
  - **Inter-filament coupling negligible w.r.t. inter-strand coupling.**
  - **Cross-over resistance *R*c defines dominant mode.**

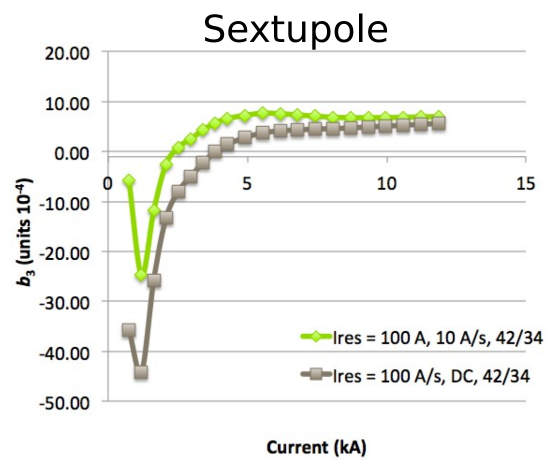


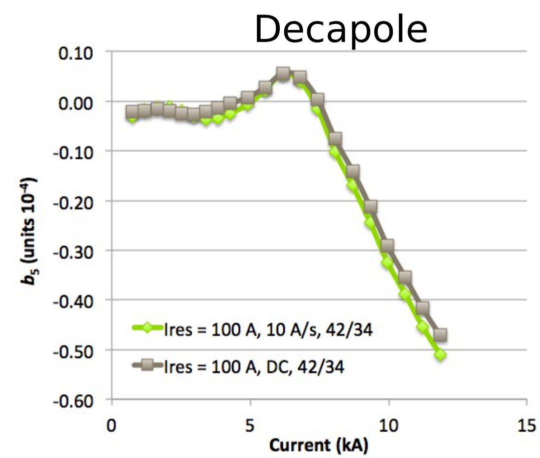
- ***R*c varies by orders of magnitude.**
  - **HFDA measurements: 4 – 500 μΩ.** [8]
  - **MSUT estimates: 1.2 μΩ. Called it *"Eddy-Current Machine"!*** [7]
  - **HQ calculations: 0.4 – 6 μΩ.**
- **Reproducibility is an issue.**
- **Decay and Snap-back**
  - **Interplay of boundary-induced coupling currents and strand magnetization.**
  - **BICCS are ISCCs on large loops,with long time constants.**

Cable Eddy Currents 2/2: 11 T

- **ISCCs in 11 T magnet**
  - **Based on *R*c = 0.4 μΩ we give presumably worst-case field quality for the 11-T dipole.**
  - **“Field advance” of ~ 4% due to ISCCs clearly visible in transfer function.**







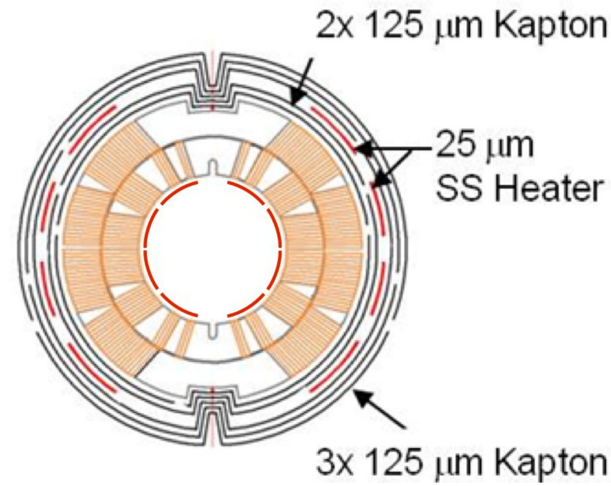
- **Probably need a cored cable to increase *R*c.**
- **Need to measure snap-back at injection with and without cored cable.**

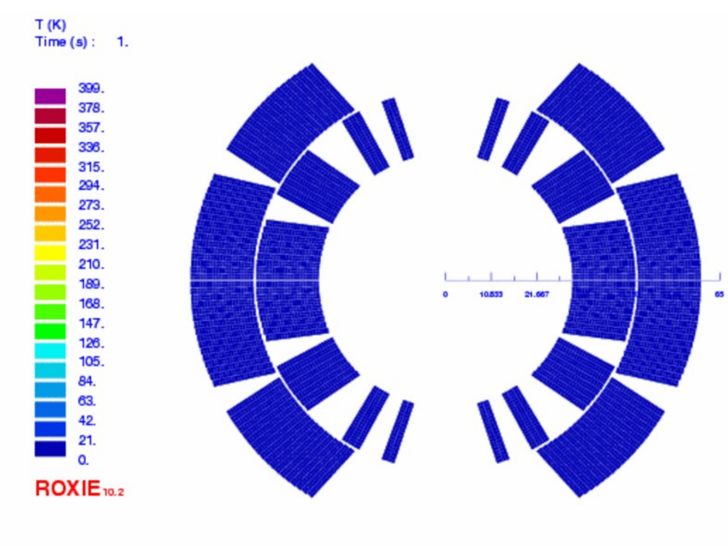
Field Quality Requirements

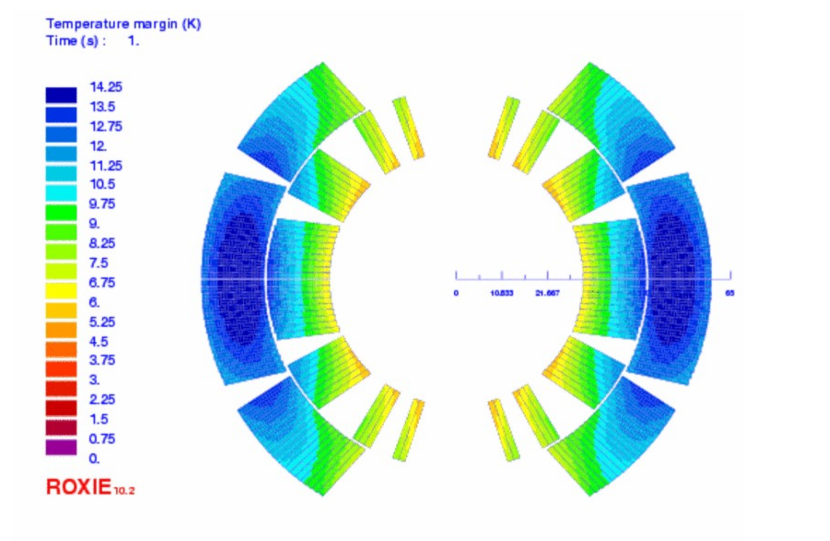
- **Beam-dynamics boundary conditions see talk by B. Holzer:**
  - ***B*1 matches MB.**
  - **|*b*3| below 20 units, correctable by spool-piece correctors.**
  - **|*b*2| below 16 units.**
  - **|*b*5| below 5 units.**
  - **…**
  - **to be confirmed by B. Holzer for updated error tables.**
- **We can deliver with**
  - **trim power converter,**
  - **part-compensation in coil geometry,**
  - **reduction of filament diameter,**
  - **passive persistent-current compensation,**
  - **adapted precycle (trim power converter),**
  - **and cored cable.**

Magnet Protection

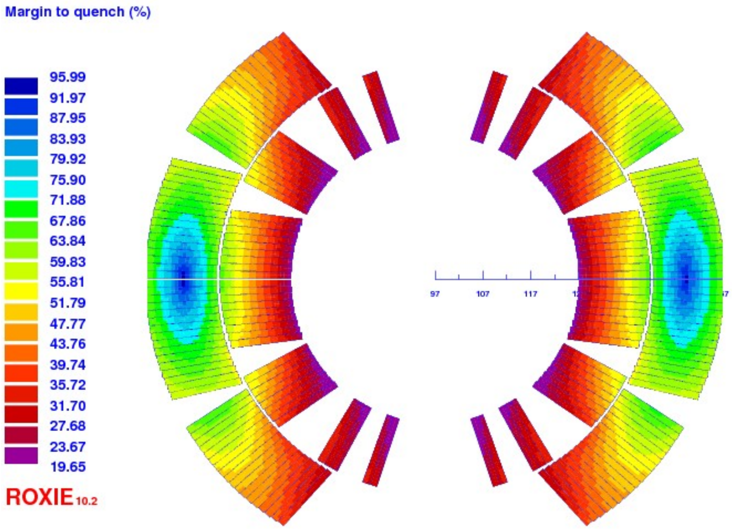
- **Design goals:**
  - **Max. 400 K (to be discussed).**
  - **Redundant heater systems.**
  - **Robust (enough) detection thresholds.**
- **Challenge:**
  - **Large temperature margin in outer layer.**



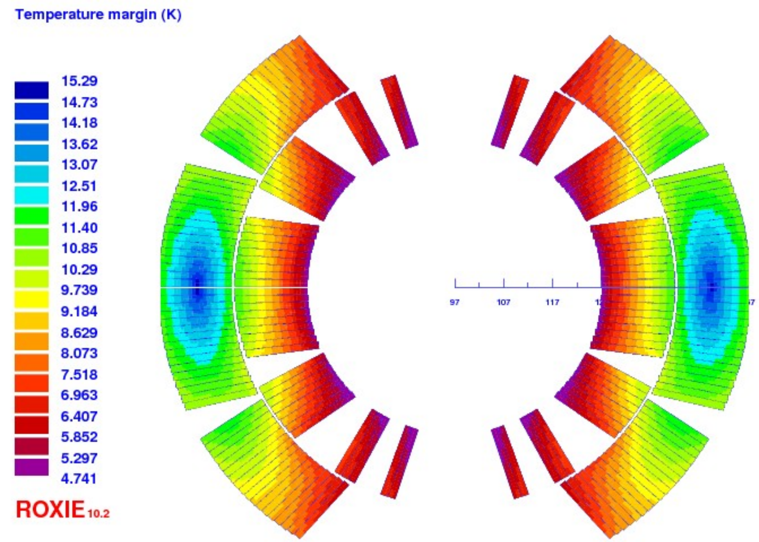




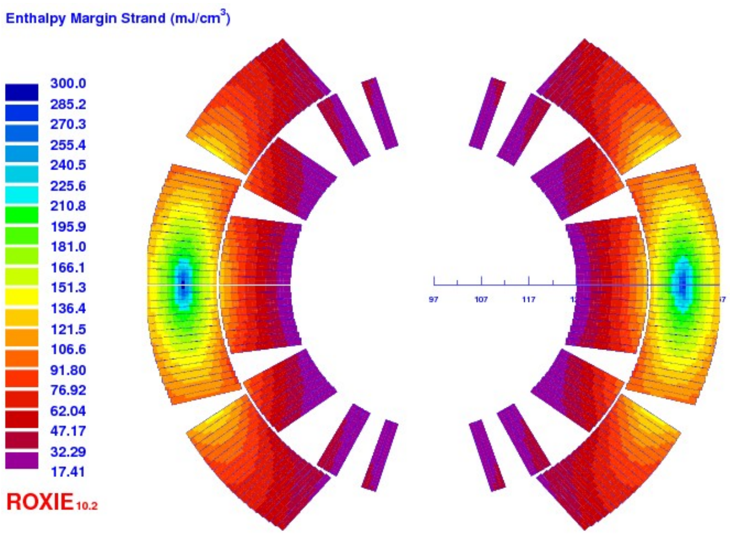
Margins to Quench



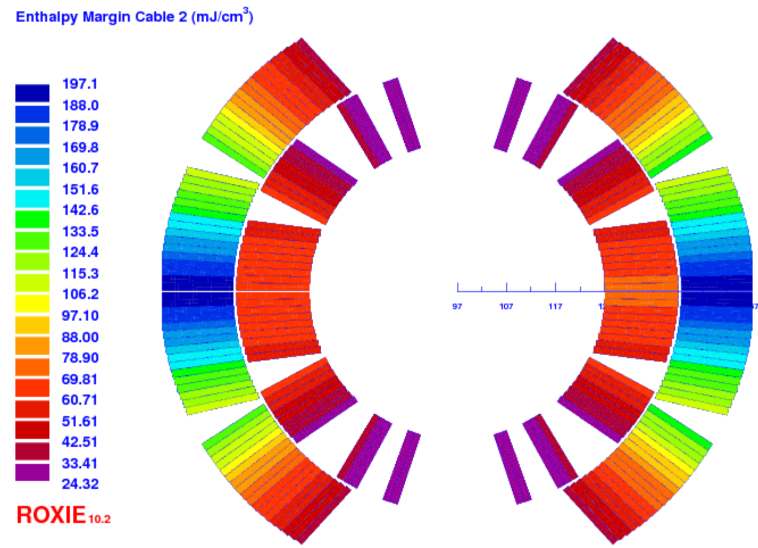
Margin on loadline



Temperature margin



Strand enthalpy margin



Cable enthalpy margin
with resin