Expected Field Quality in the 11-T Dipole

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HQ test data from

M. Marchevsky (LBL): HQ01e Quench Performance

G. Chlachidze (LBL): HQM01 Test Results

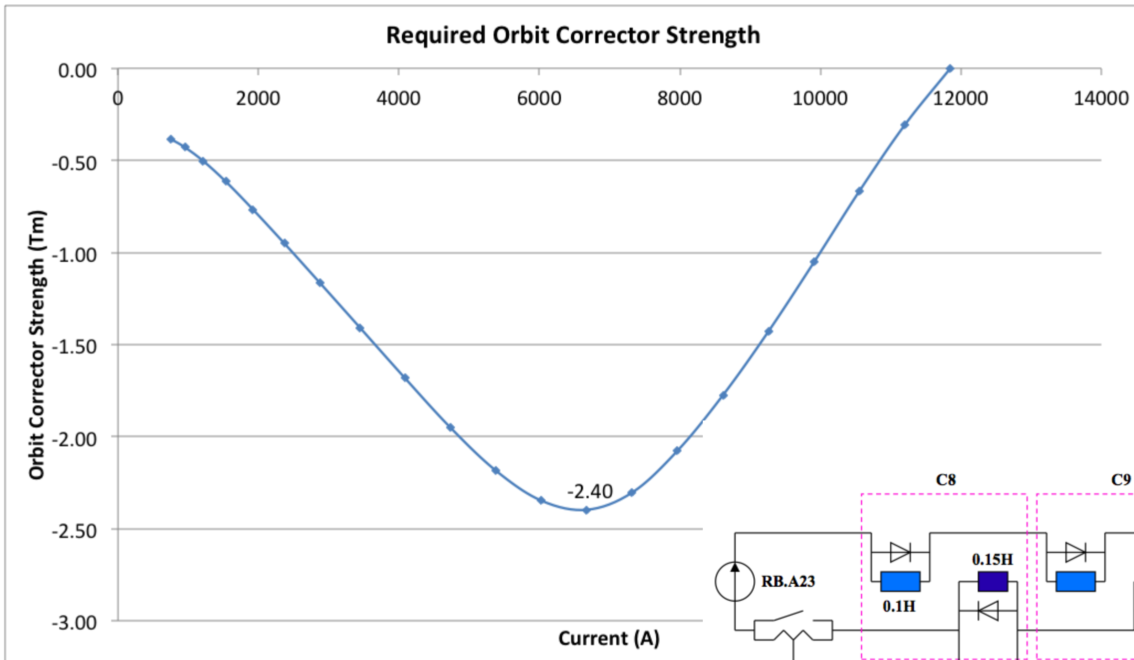
X. Wang (LBL): Summary of HQ01e Magnetic Measurements, Version 0a

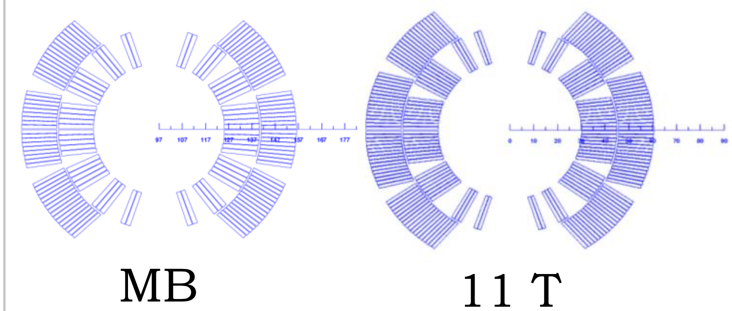
Contents

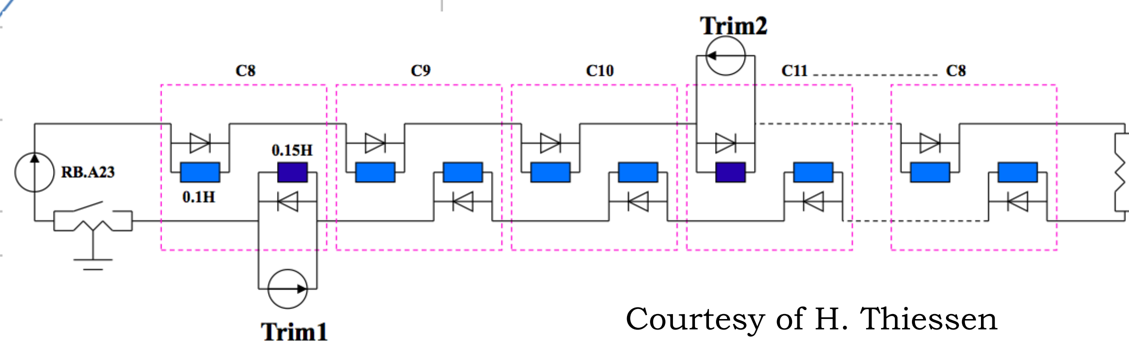
- **What are the design goals in terms of:**
  - **Transfer function**
  - **Field quality**
  - **Magnet protection**
- **What are the challenges?**
  - **Based on HQ, MSUT, HFDA experience and ROXIE simulations.**
- **How do we inted to cope with them?**
  - **Based on simulations.**

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.**







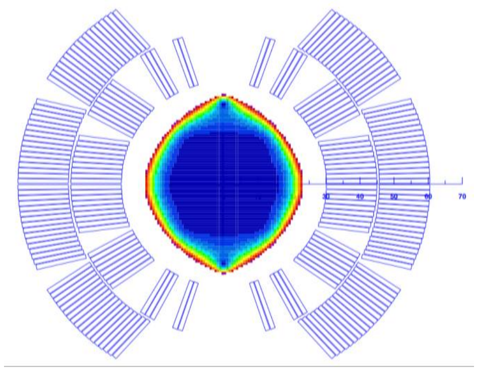
Courtesy of H. Thiessen

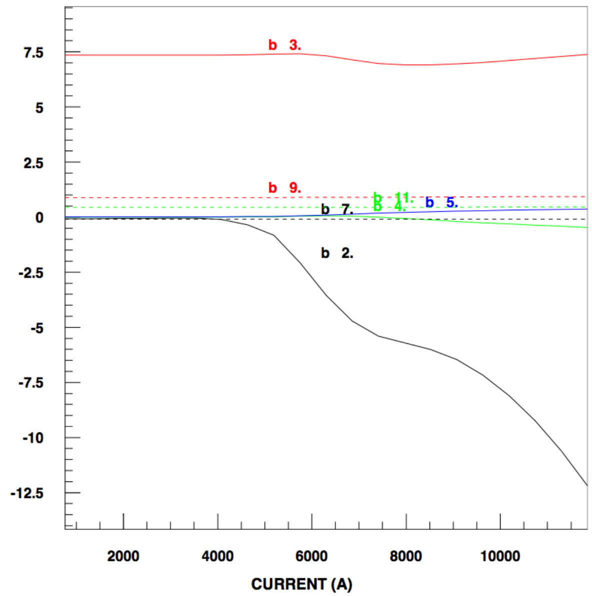
- **Remedy:**
  - **No space for correctors (~ 1 m MCBC/MCBY needed).**
  - **300 A trim power converter.**
    Preferred: monopolar to avoid voltage peaks that perturb QPS.

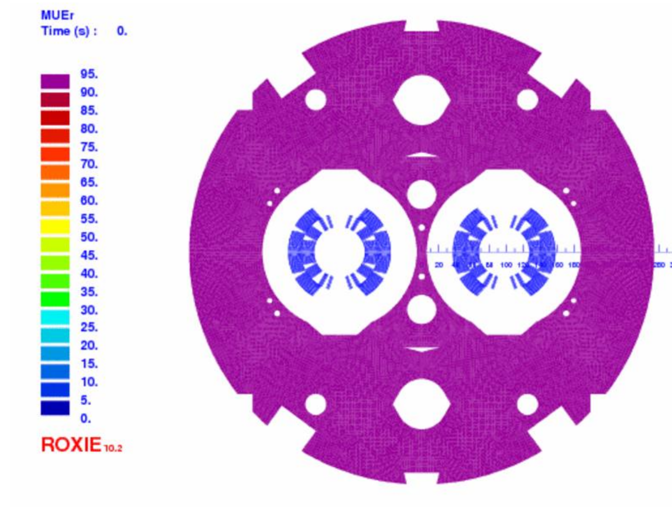
Field Quality

- **What effects need to be considered?**
  - **Geometric from coil transport current.**
  - **Yoke saturation, cross-talk.**
  - **3D field quality.**
  - **Persistent current effects.**
  - **Cable eddy currents.**
  - **Decay and snapback.**
  - **Coil deformation during assembly, cool-down, and powering.**

Coil and Yoke





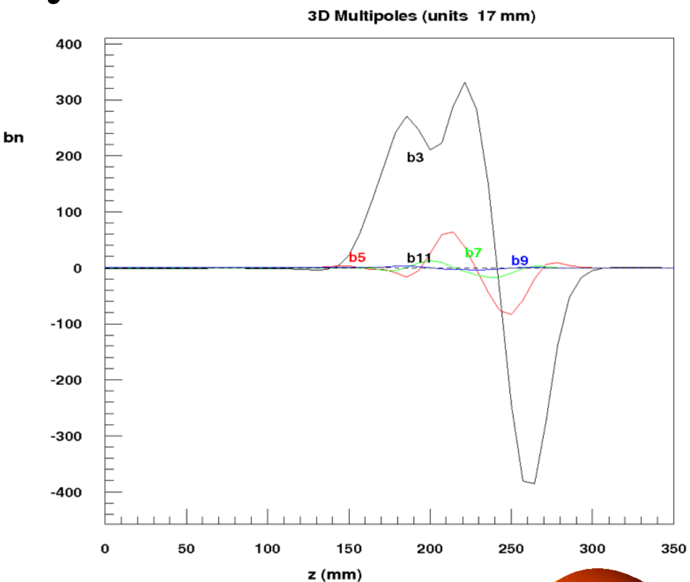


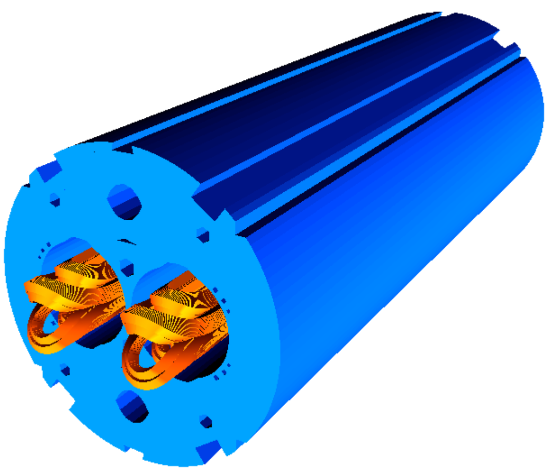
- **Coil geometric multipoles < 1 unit @ 17 mm.**
- **Yoke design**
  - **The cut-outs on top of the aperture reduce the b_3 variation by 4.7 units as compared to a circular shape.**
  - **The holes in the yoke reduce the b_3 variation by 2.4 units.**
  - **The two holes in the yoke insert reduce the b_2 variation from 16 to 12 units.**
  - **Remedy for b_2: thinner collars are being studied.**

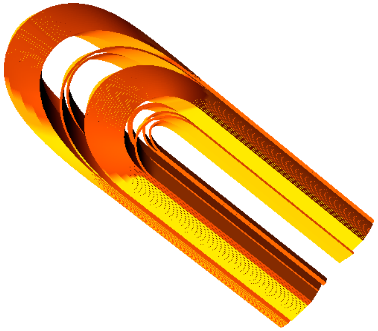
3-D Field Quality

- **3-D integrated harmonics vs. 2-D harmonics @ I_{nom}**
  - **Optimized 3-D coil design.**
  - **Cross-talk in the ends ➔ increase in b_2.**
  - **Need to control winding accuracy.**

	2-D	3-D
b_2	-12.5	-15.8
b_3	7.4	7.4
b_5	0.4	0.6
b_7	-0.1	-0.2
b_9	0.9	0.8



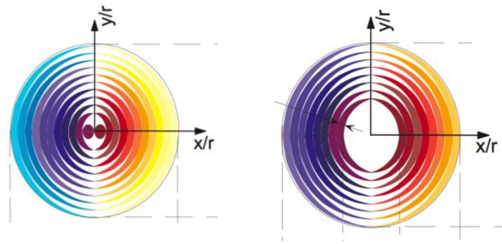


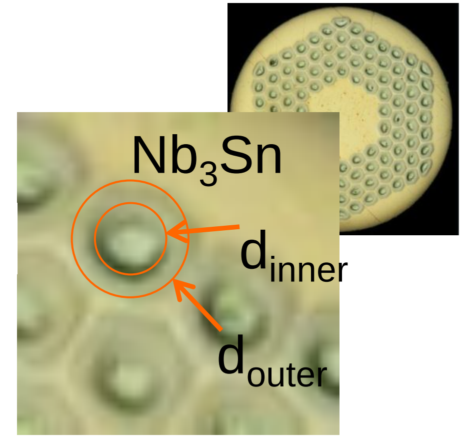


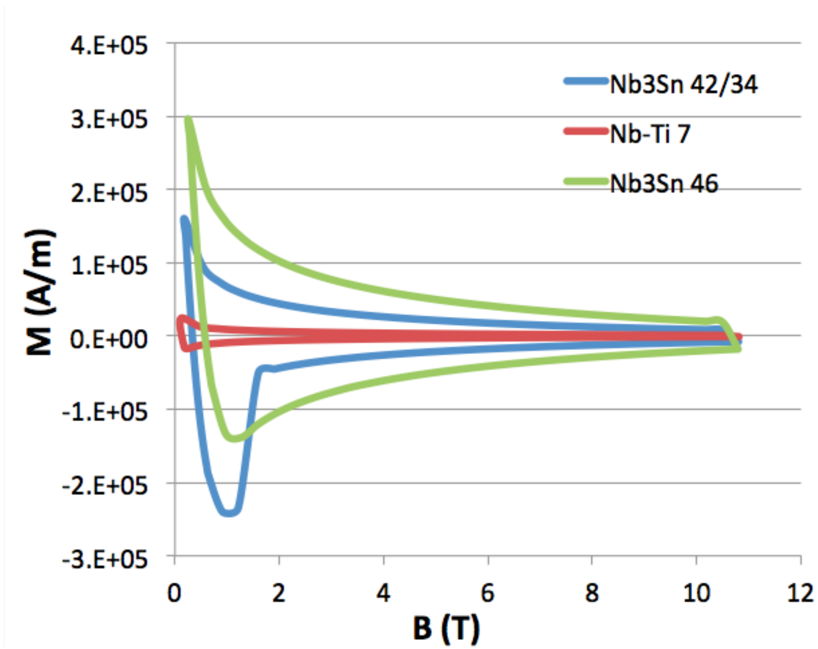
Persistent Currents 1/3: Nb_3Sn & Nb-Ti

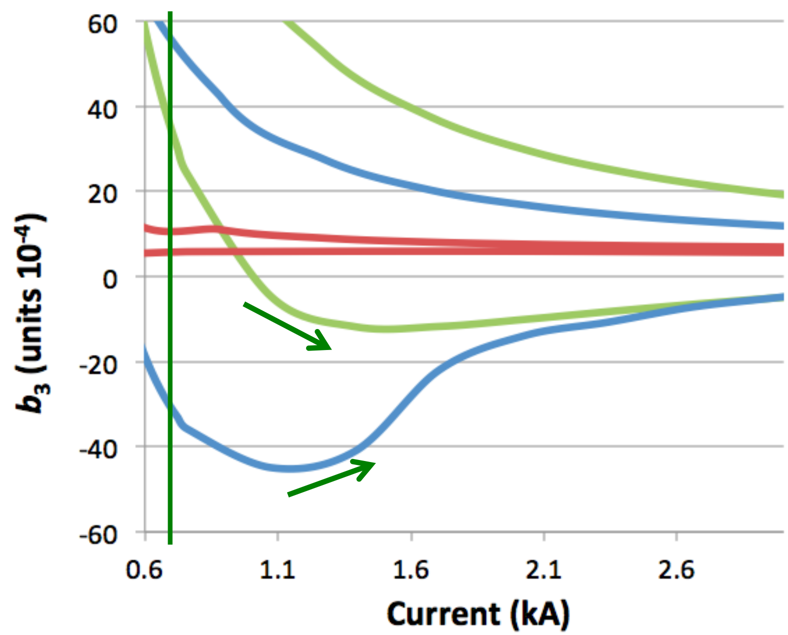
❖ Strand magnetization:

- **7µm fil. Nb-Ti**
- **46µm fil. Nb_3Sn**
- **d_{in} = 42 µm / d_{out}= 34 µm. fil. Nb_3Sn**





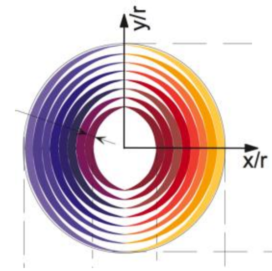


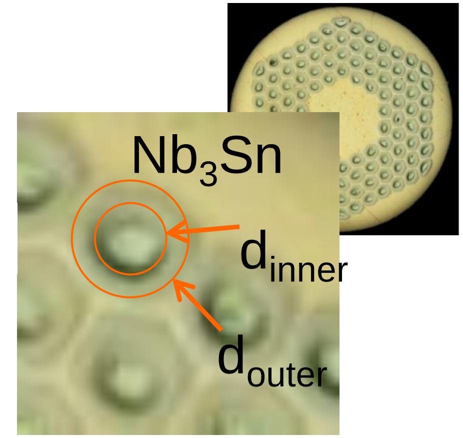


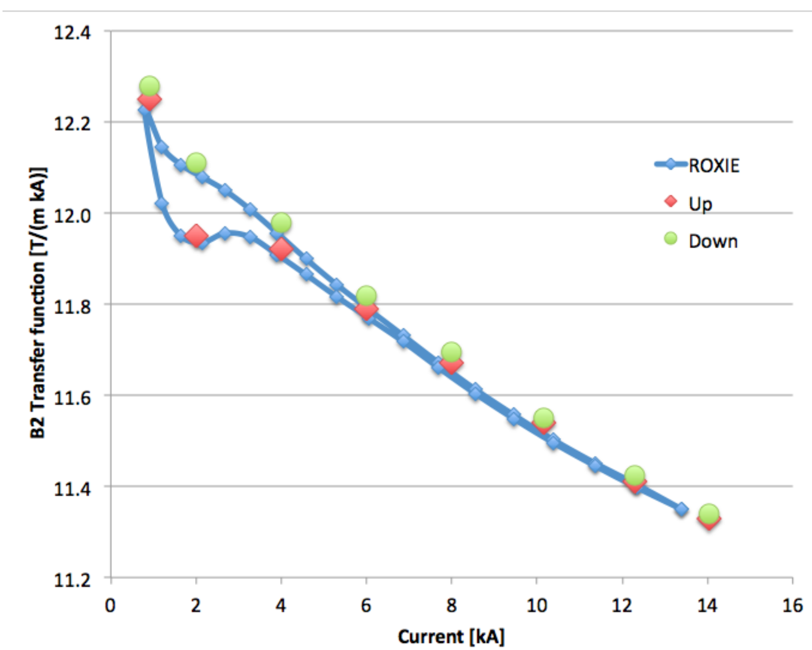
Persistent Currents 2/3: HQ

❖ HQ experience:

- 0.8 mm RRP 2 coils with 70 μm filaments and 2 coils with 52 μm filaments.
- ROXIE persistent current simulation based on LBL J_c fit and crude assumptions
  70 μm fil.: d_{in} = 58 μm / d_{out}= 46 μm and
  52 μm fil.: d_{in} = 42 μm / d_{out}= 34 μm.







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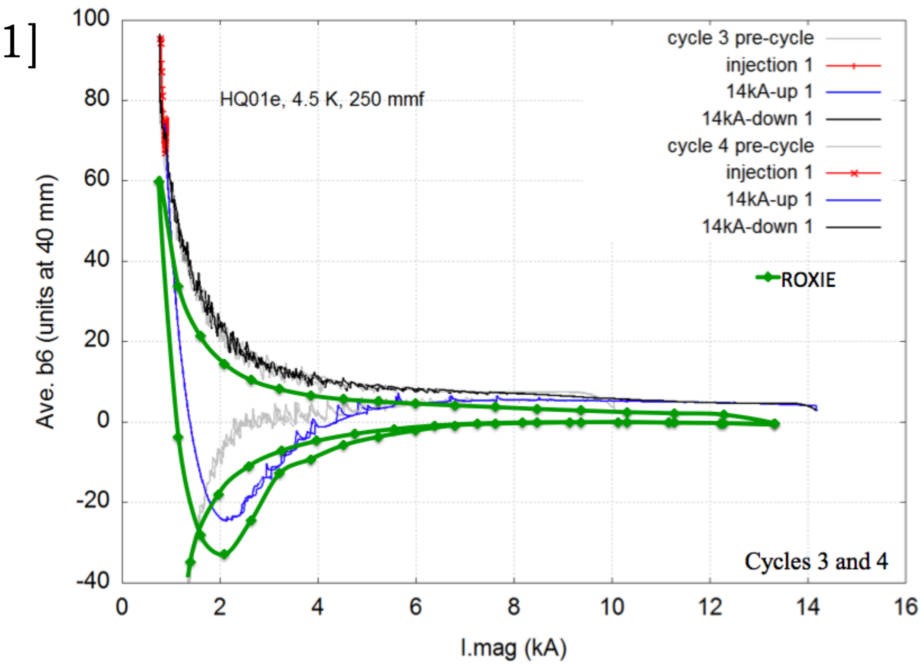
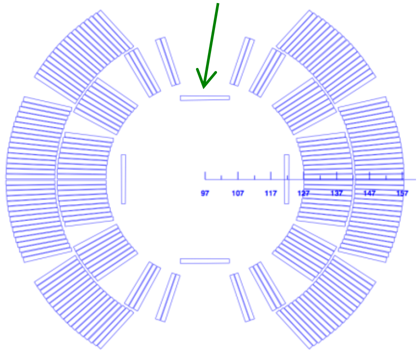
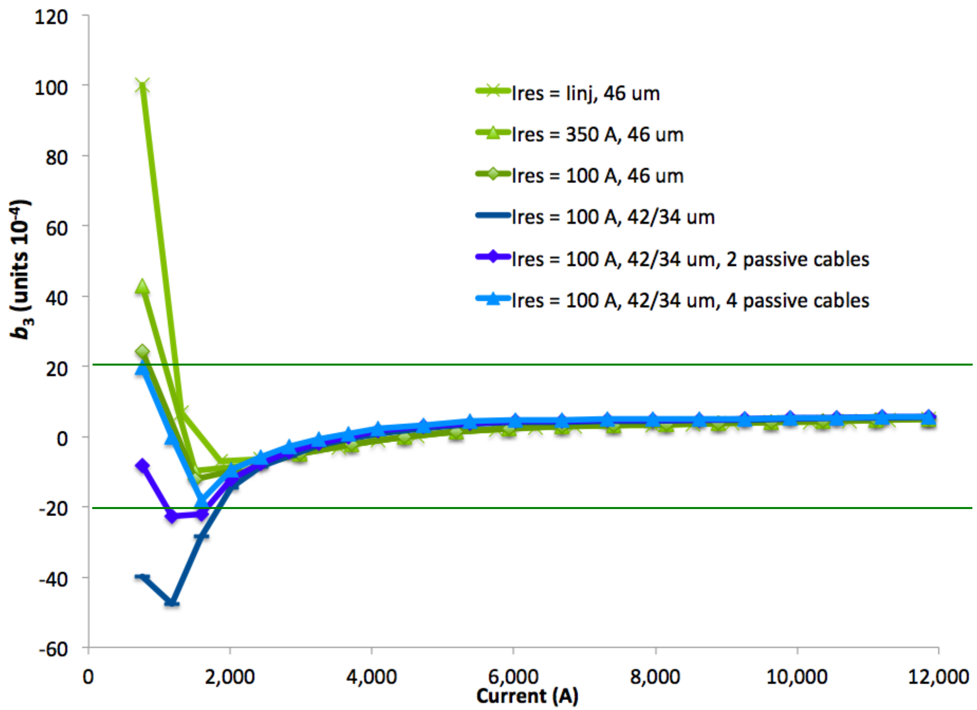


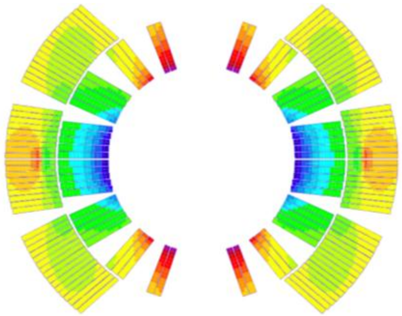
Persistent Currents 3/3: 11 T

- **Strand J_c and M characterization for 0.7 mm RRP 108/127 in preparation with B. Bordini.**
- **Expected range for 11 T:**
  - **Full filaments ➔ ok for reset current 0-100 A.**
  - **d_{in} = 42 μm / d_{out} = 34 μm ➔ passive correction, more optimization possible.**
- **Result is within reach of spool-piece correctors.**
  - **Integrated B_3 difference 11-T/MB ~ 0.03 Tm < 0.052 Tm of MCS.**

passive strands



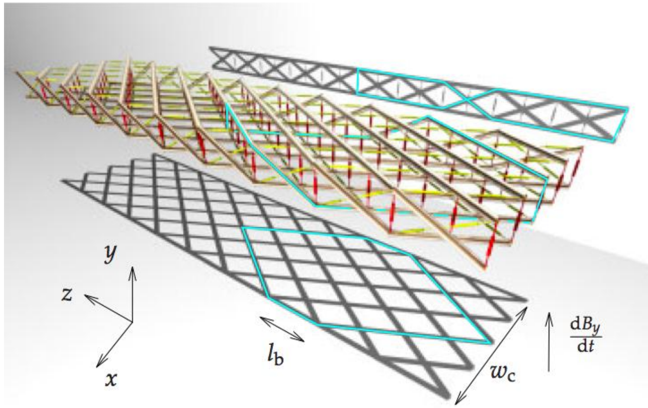




b_3 due to strand magnetization in MB

[4]

Cable Eddy Currents 1/3

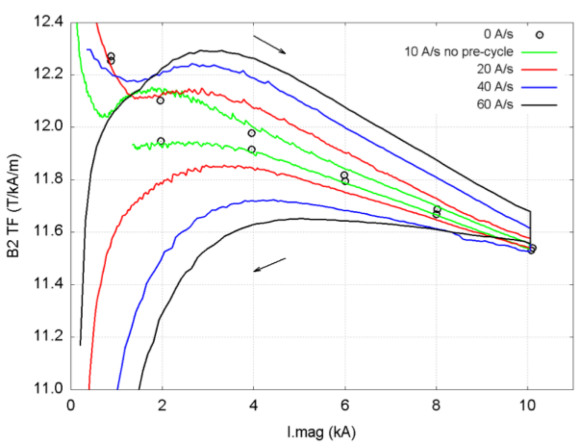


- **Dominant effects in cable without core:**
  - **Inter-filament coupling negligible w.r.t. inter-strand coupling.**
  - **Cross-over resistance R_c defines dominant mode.**
- **R_c varies by orders of magnitude.**
  - **HFDA measurements: 4 – 500 µΩ.** [8]
  - **MSUT estimates: 1.2 µΩ. Called it *"Eddy-Current 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.**

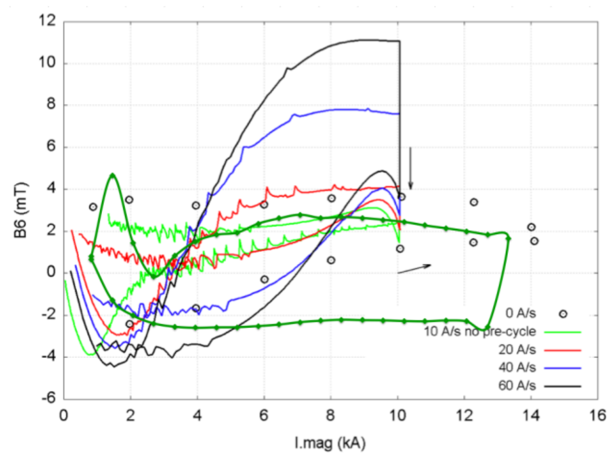
Cable Eddy Currents 2/3: HQ

❖ **HQ experience measurements.**
- o **Cannot be reproduced in simulations.**
- o **Need R_c ~ 0.4 μΩ to get similar orders of magnitude.**
- o **Large snap-back?**
- o **Should be independently confirmed at CERN soon!**

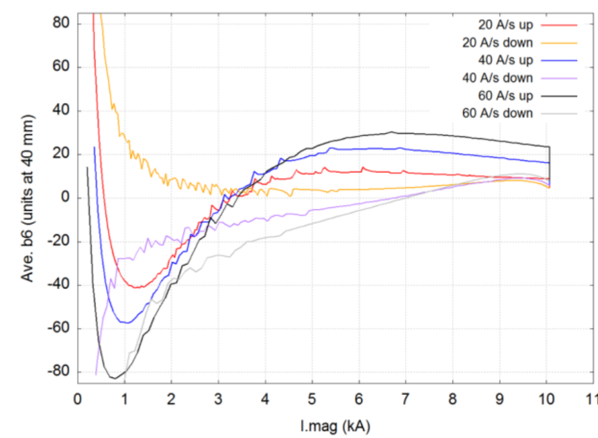
Transfer Function



Sextupole



Relative Sextupole

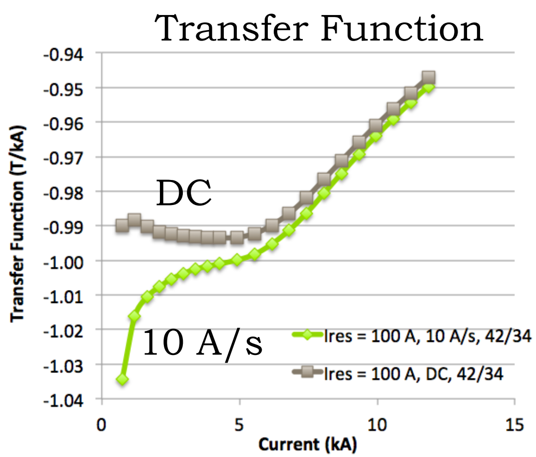


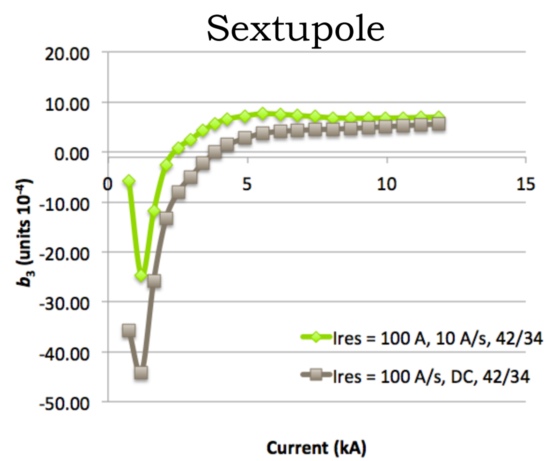
Black curve (measured) and green curve (simulated) correspond to 60 A/s ramp rate.

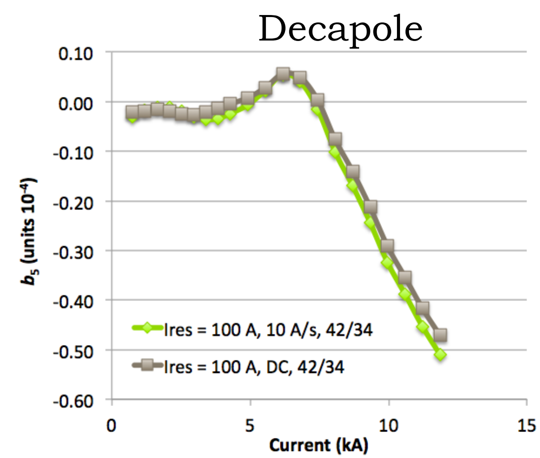
[1]

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.**







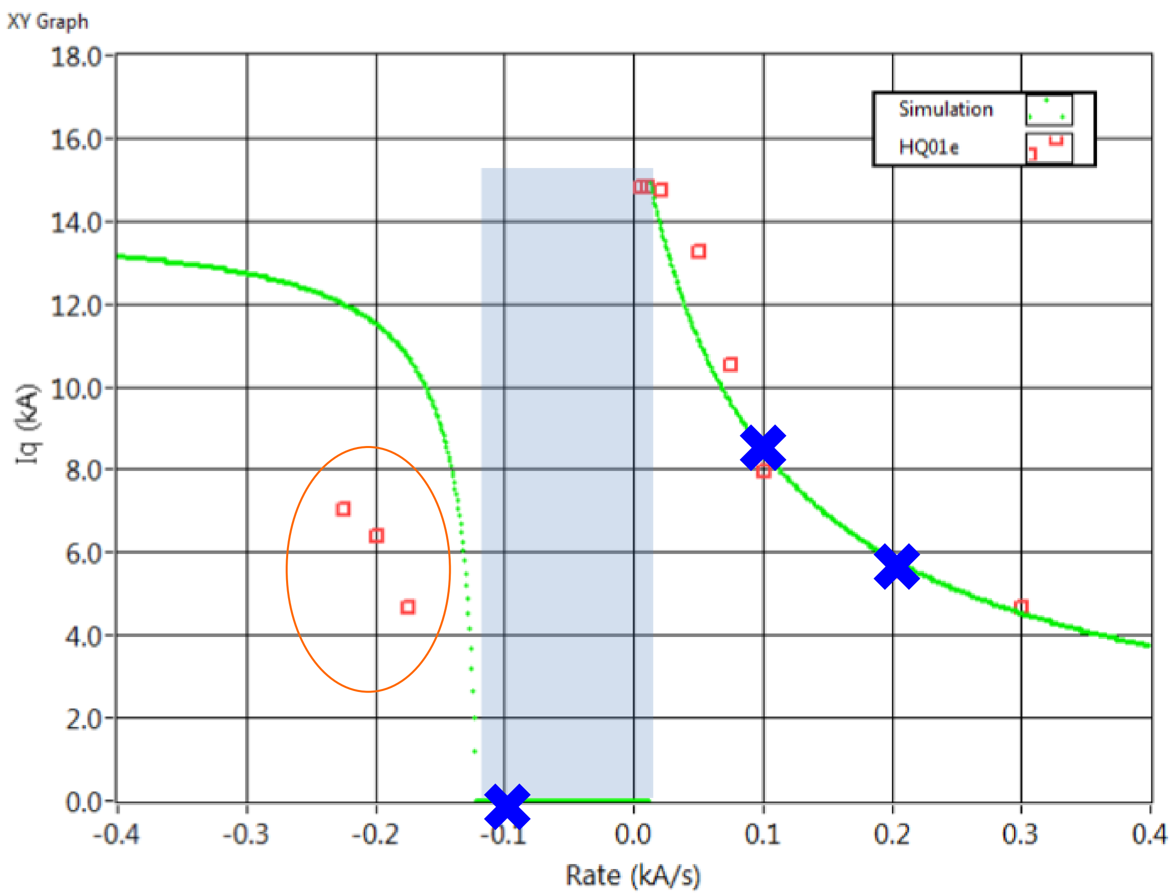
- **Probably need a cored cable to increase R_c.**
- **Need to measure snap-back at injection with and without cored cable.**

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,**
  - **passive persistent-current compensation,**
  - **adapted precycle (trim power converter),**
  - **and cored cable.**

Surviving a Fast Power-Abort 1/2: HQ

- **HQ tests by M. Marchevsky, LBL and ROXIE simulations (✖).**
  - **Positive ramps reproduced with R_c = 6 μΩ.**
  - **No cooling in the model ➔ in reality R_c < 6 μΩ.**



[2]

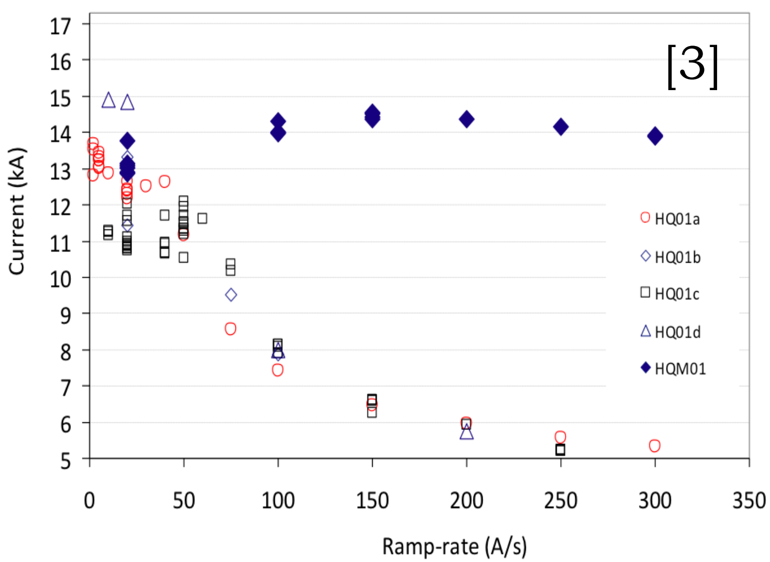
Down: 14 to 1 kA

Up: 0.5 to 15 kA

Surviving a Fast Power-Abort 2/2: 11 T

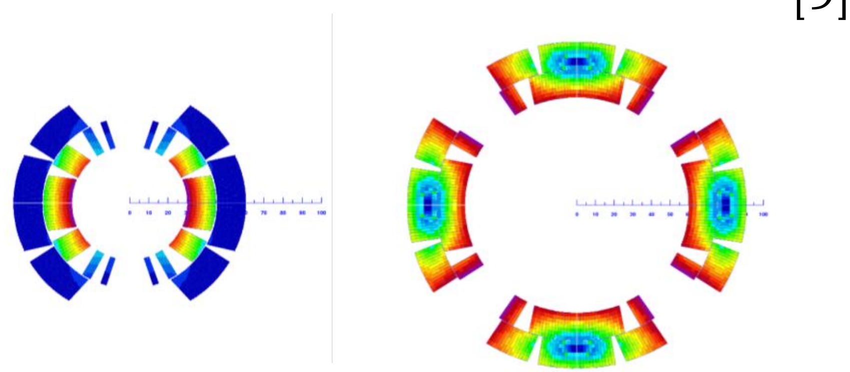
- **Higher losses and smaller heat capacity.**
- **11-T quenches in simulations already at 11 kA!**
- **Cored cable in HQM01 proved effective.**

	HQ	**11 T**
No. of strands	35	40
Twist pitch (mm)	102	90-111
R_c (μΩ)	6	7.5
Op. Temp. (K)	4.5	1.9
Losses in midplane turn (mW)	75	130



$$P_c = 8.49 \cdot 10^{-3} \frac{L_{p,s} w^2 (N_s^2 - N_s)}{R_c} \dot{B}_\perp^2 \quad [\mathrm{Wm^{-1}}]$$

[9]

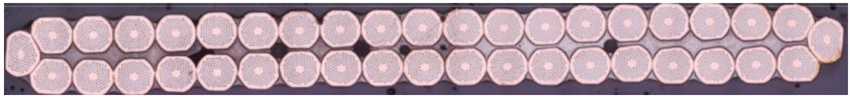


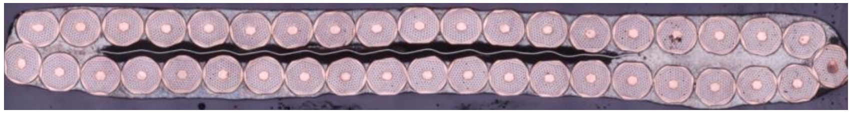
Loss distribution in 11 T and HQ cross-section

Cored Cable pro & con

- SIS300 experience with core: R_c from μΩ to mΩ!

- Successful cabling tests for cored 11 T cable with 9.5 mm x 25 μm core.

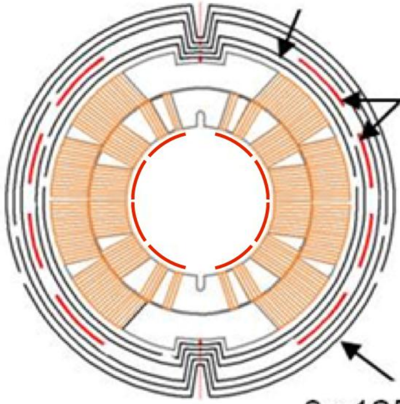




- Pros:
  - Fast-power abort stability.
  - Snap back reduction.
  - Supression of ramp-rate dependence of field quality.
  - Increased reproducibility.

- Cons:
  - Less quench back for protection.

Magnet Protection



- **Design goals:**
  - **Max. 400 K (to be discussed).**
  - **Redundant heater systems.**
  - **Robust (enough) detection thresholds.**
- **Collaboration with LARP**
  - **HQ results are being studied.**
- **Simulation results for 25 ms from quench to full heater efficiency, RRR = 200**
  - **T_{peak} = 480 K for outer-layer (OL) low-field heaters.**
  - **T_{peak} = 360 K for OL high-field heaters.**
  - **T_{peak} = 450 K for OL low-field heaters with quench-back.**
  - **T_{peak} = 300 K for intra-layer low-field heaters.**
- **Single-aperture demonstrator will help to validate the model.**
  - **Heaters between inner and outer layer should be studied, tested in short-model coil (11-T SMC).**
  - **Temperature measurements and refined thermal model to improve peak temperature estimates.**

Conclusion

- **Transfer function: trim power converter**
- **Field Quality**
  - **Yoke: thinner collars, part-compensation in coil layout.**
  - **3D: by design ok, check field quality based on real winding.**
  - **PCs: solutions exist for a range of assumptions.**
  - **ISCCs: most likely we need a cored cable.**
  - **Snap back: too early to quantify – cored cable should help.**
  - **Coil deformation: will be studied shortly.**
- **Magnet protection**
  - **Develop fast and efficient heaters, possibly between layers.**
  - **Use SMC as test bed.**
  - **With test results: determine thresholds for QPS and nQPS.**

- **Thanks to LARP for sharing data!**

Literature

❖ **Literature**

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