HQ01d magnetic measurement and next steps

LARP – CM16

Xiaorong Wang, LBNL

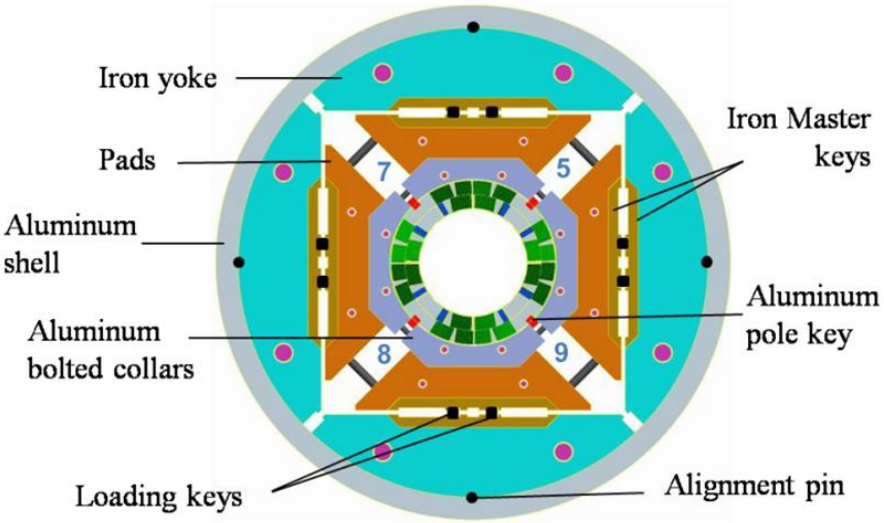
Collaboration between FNAL, BNL and LBNL

Topics

- Measurement overview.
  - Magnet, hardware and data reduction.
- HQ01d observations.
  - 70 K and 4.5 K z scan.
    - Two measurement systems used for 70 K meas.
  - 4.5 K measurement.
    - Stair-step: harmonics at 120 T/m.
    - Ramping current: ramp-rate dependence.
- Summary of the initial discussion on 5/16/11.
- Discussion on the plan for field quality study.

HQ01d magnet

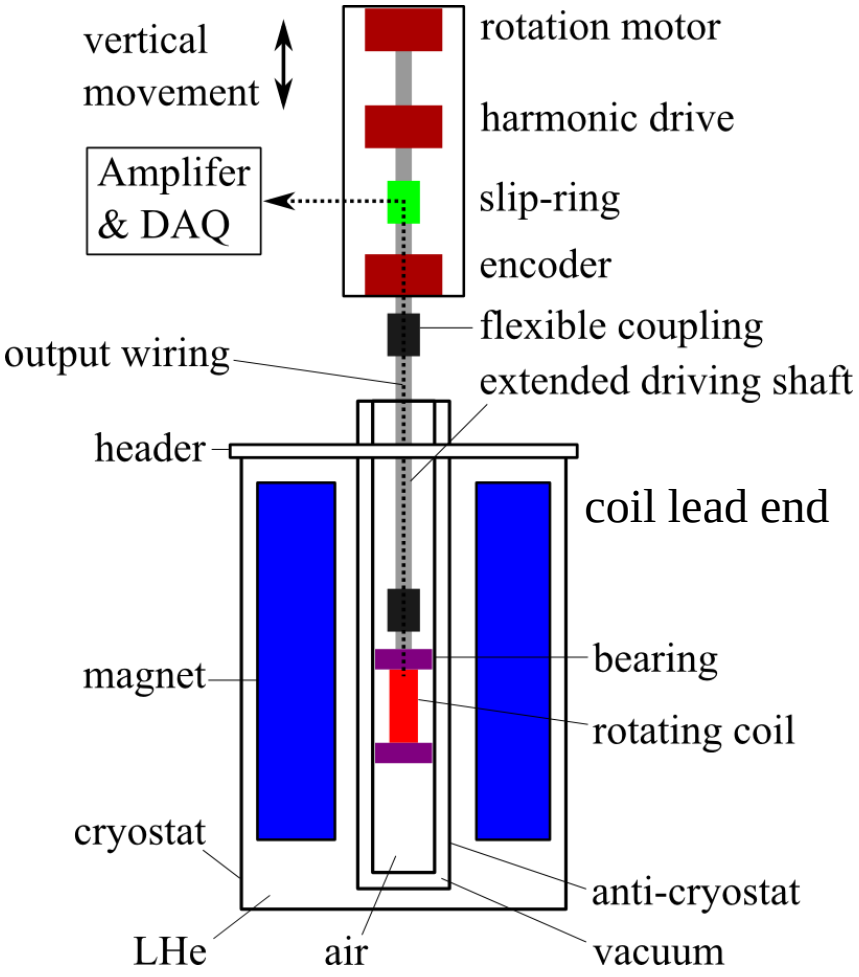
- HQ collaboration between FNAL, BNL and LBNL.
  - 1-m long, 120-mm bore.
- Alignment collars:
  - 6061-T6 Aluminum alloy (1.4 $\mu\Omega$-cm at 4 K).
  - 50 mm thick lamination.
- 4.5 K conductor limit:
  - 17.3 kA I_c.
  - 195 T/m gradient.
- HQ01d conductor *asymmetry*.



Magnet	Conductor (RRP)	d_{sub} (μm)
TQS02	54/61	70
LQS01		
HQ01d	Coil 5&7: 108/127	50
	Coil 8&9: 54/61	70

Test system at LBNL

- Magnet tested vertically.
- Probe rotating in an anti-cryostat with embedded heater.
  - 49 mm bore, 2.3 m long.
- Probe rotating in one direction (slip-ring).
  - Speed ~ 0.5 Hz.
  - 4096 positions/turn.



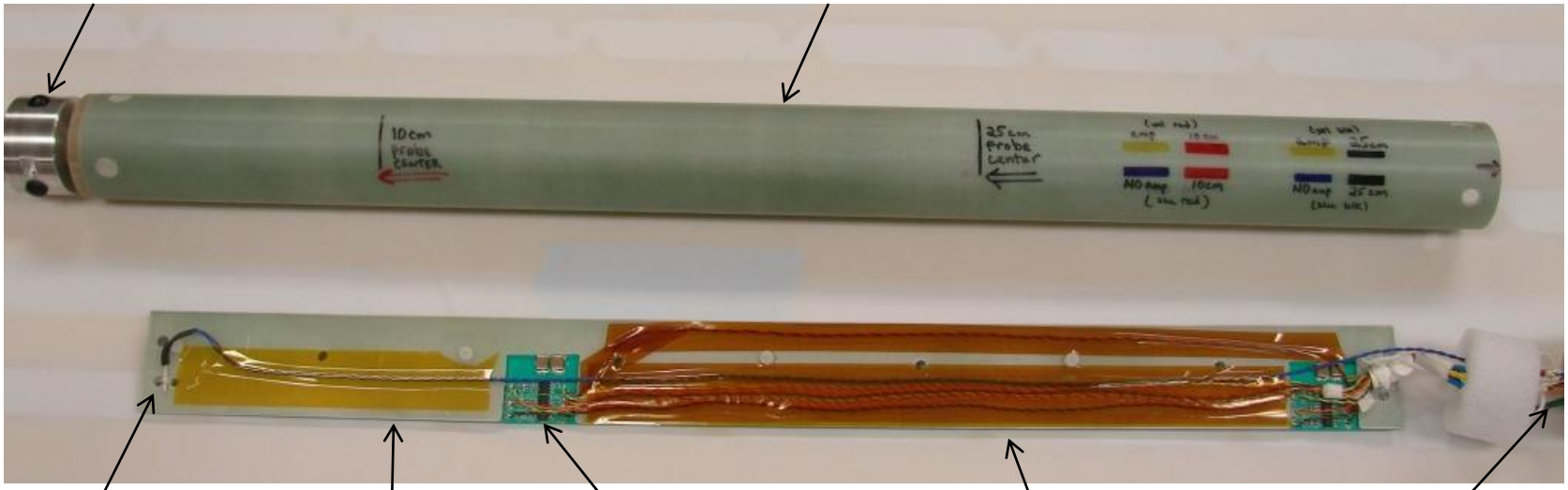
schematic not to scale

Rotating probe from FNAL

- Circuit-board probe developed by FNAL was used.
  - 2 radial coils on a circuit board, 100 mm and 250 mm long.
  - ~ 21.55 mm radius for the outermost trace.
  - More details can be found in J. DiMarco's presentation[1].

Bearing cartridge w/ buttons

G10 shell (47.6 mm OD, 0.7 mm clearance)



Temp. sensor

100 mm coil

Onboard amps

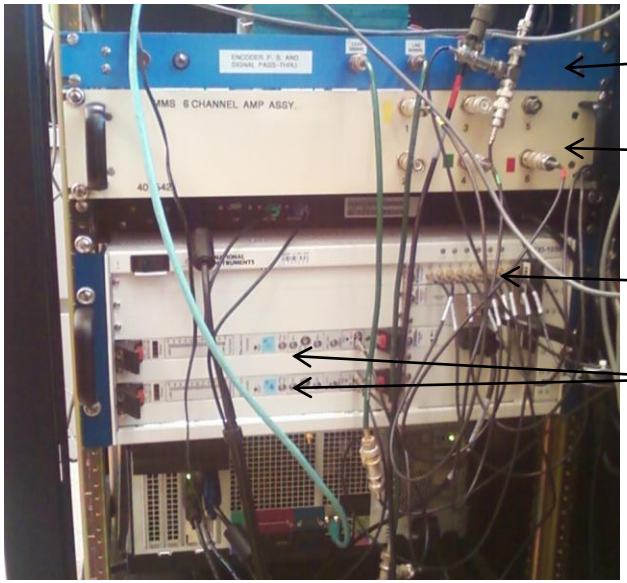
250 mm coil

Micro connector

[1]J. DiMarco, Rotating Circuit Board Probes for Magnetic Measurements, IMMW 15, FNAL, Aug. 2007. http://tdserver1.fnal.gov/immw15/

Data acquisition

- Voltage-based system
  - Probe voltage simultaneously sampled by NI 4472B.
  - Numerical integration to construct the angular flux profile.
- Hybrid system (mainly normal-state measurement)
  - NI 4472B // FDI 2056 (Metrolab).
  - Numerical vs. “hardware” integration.



Data reduction

- Flux-drift correction:
  - Amplifier offset.
  - Ramping transport current.
- Feed-down correction by zeroing the measured dipole component in the unbucked signal.
- B_2 from the dipole-bucked signal as the main field.
- Reference radius:
  - Magnetic straight section: 40 mm (2/3 magnet bore radius).
  - Coil end: 21.55 mm (radius of the outermost trace of the rotating coil, 36% of the magnet bore radius).
- Harmonic coefficients normalized to the central B_2 ($A_2 = 0$).

Topics

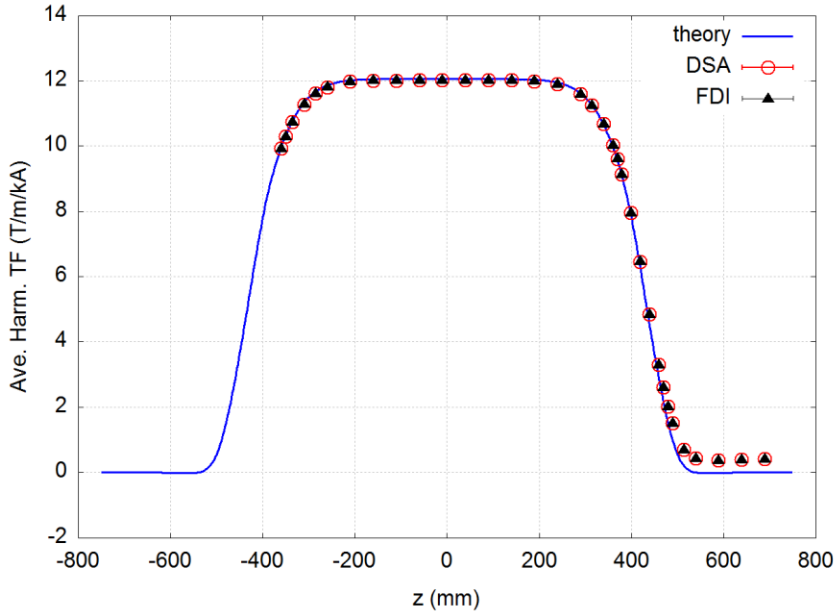
- Measurement overview.
  - Magnet, hardware and data reduction.
- HQ01d results.
  - 70 K and 4.5 K z scan.
  - 4.5 K measurement.
    - Stair-step: harmonics at 120 T/m.
    - Ramping current: ramp-rate dependence.
- Summary of the initial discussion on 5/16/11.
- Discussion on the plan for field quality study.

Z-scan measurement protocol

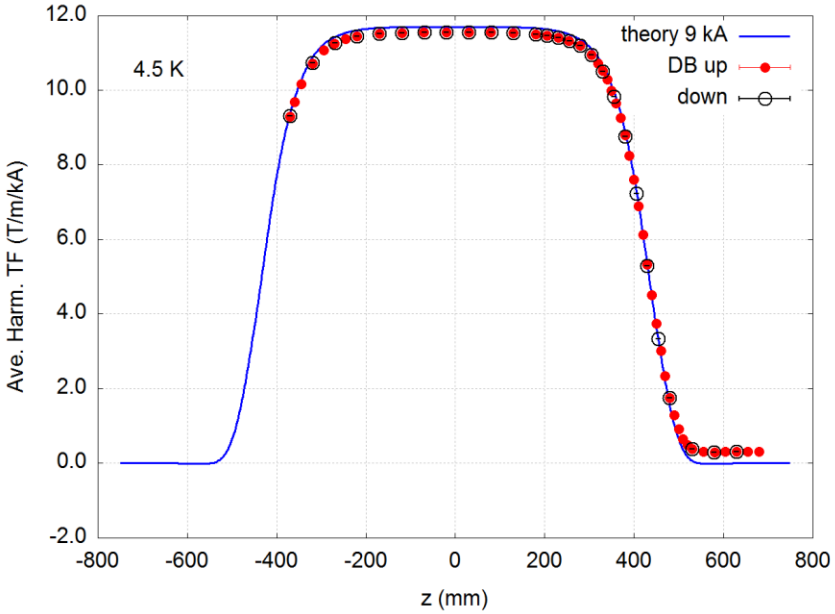
- Ramp up the current to the desired level.
  - Probe rotating in the magnetic center.
- Scan along the bore.
  - Probe moving up and down.
- Ramp down the current.
  - Probe rotating in the magnetic center.
- Five measurements (rotations) at each *z* location.
  - Averaged results reported. Error bars indicating the spread of 5 measurements.

100 mm, z-scan, transfer function

70 K, 30 A

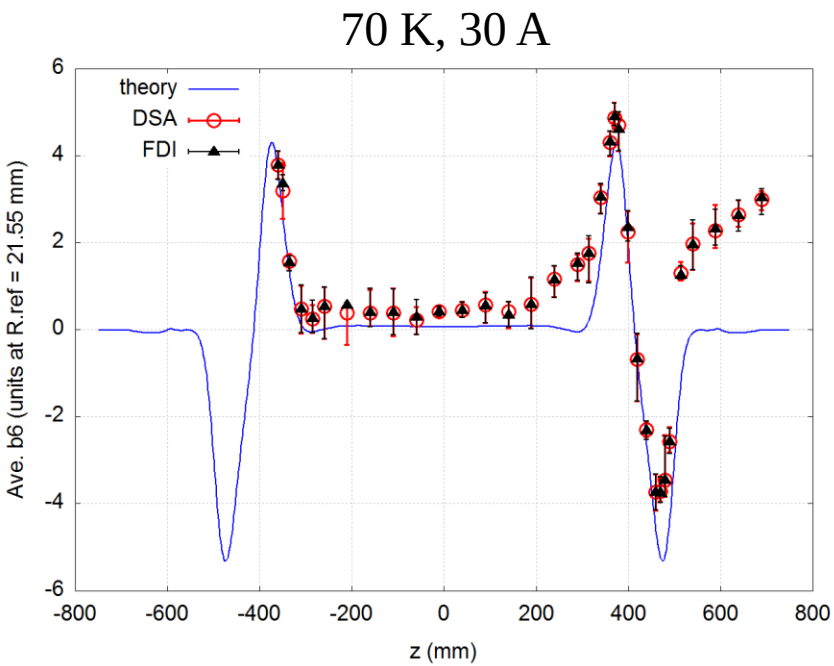


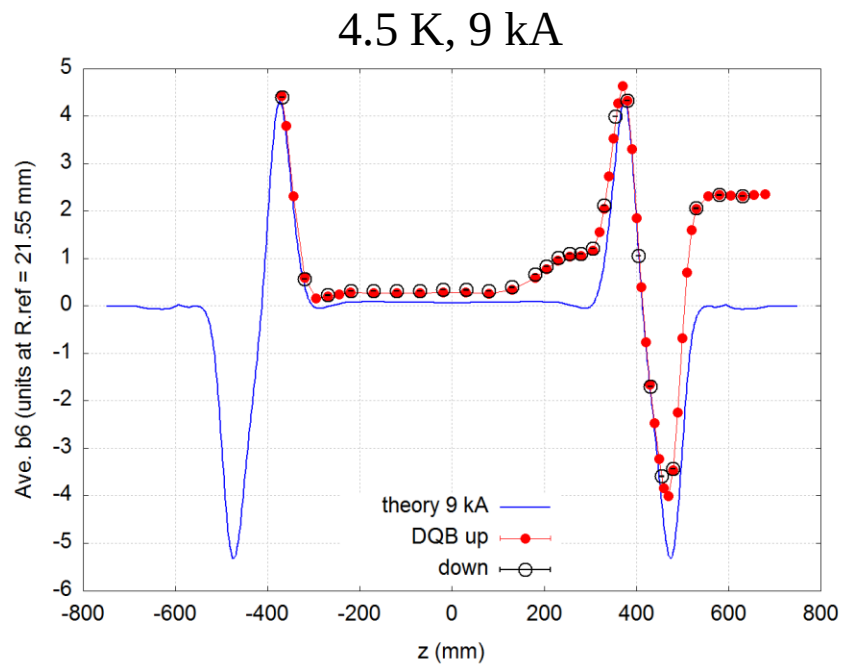
4.5 K, 9 kA



- Return end missed.
- At 9 kA: measured main field slightly lower than calculation (98.7%).
- Constant offset, 0.3 T/m/kA, for z > 500 mm (current leads/junctions).

100 mm, z-scan, b_6, R_{ref} = 21.55 mm

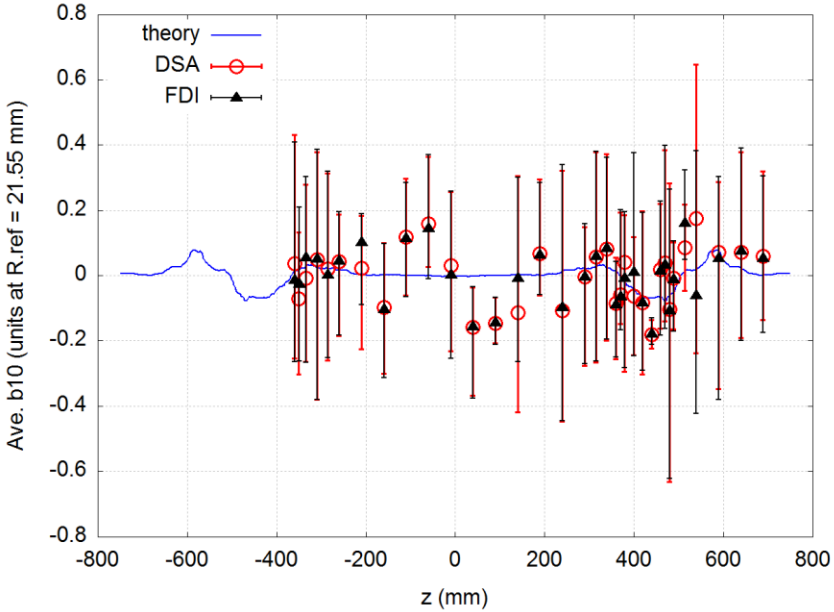




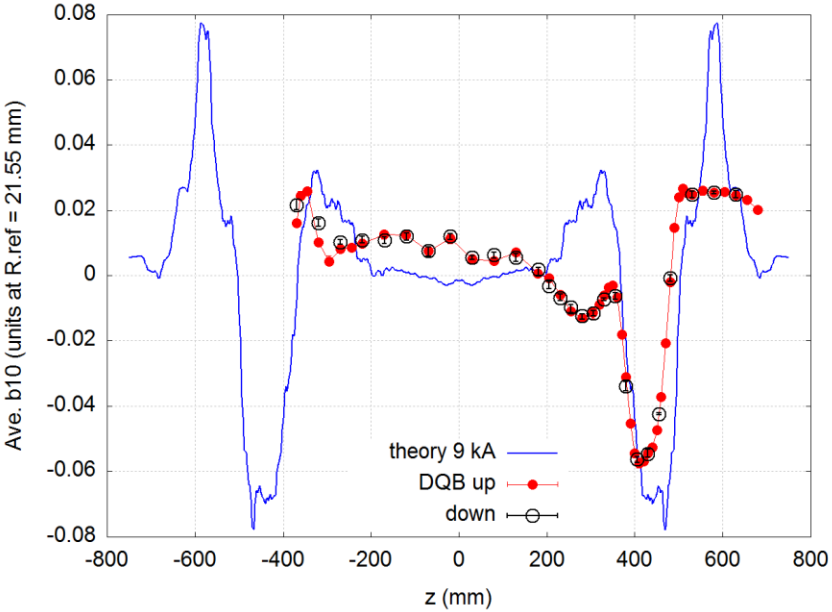
- Good agreement between FDI and NI4472B.
- 70 K: 4.76 ± 2.38 units (R_{ref} = 40 mm).
- 9 kA calculation for geometric harmonics only. Measurement performed at the up-ramp (no down-ramp measurement made).

100 mm, z-scan, b_{10}, R_{ref} = 21.55 mm

70 K, 30 A



4.5 K, 9 kA



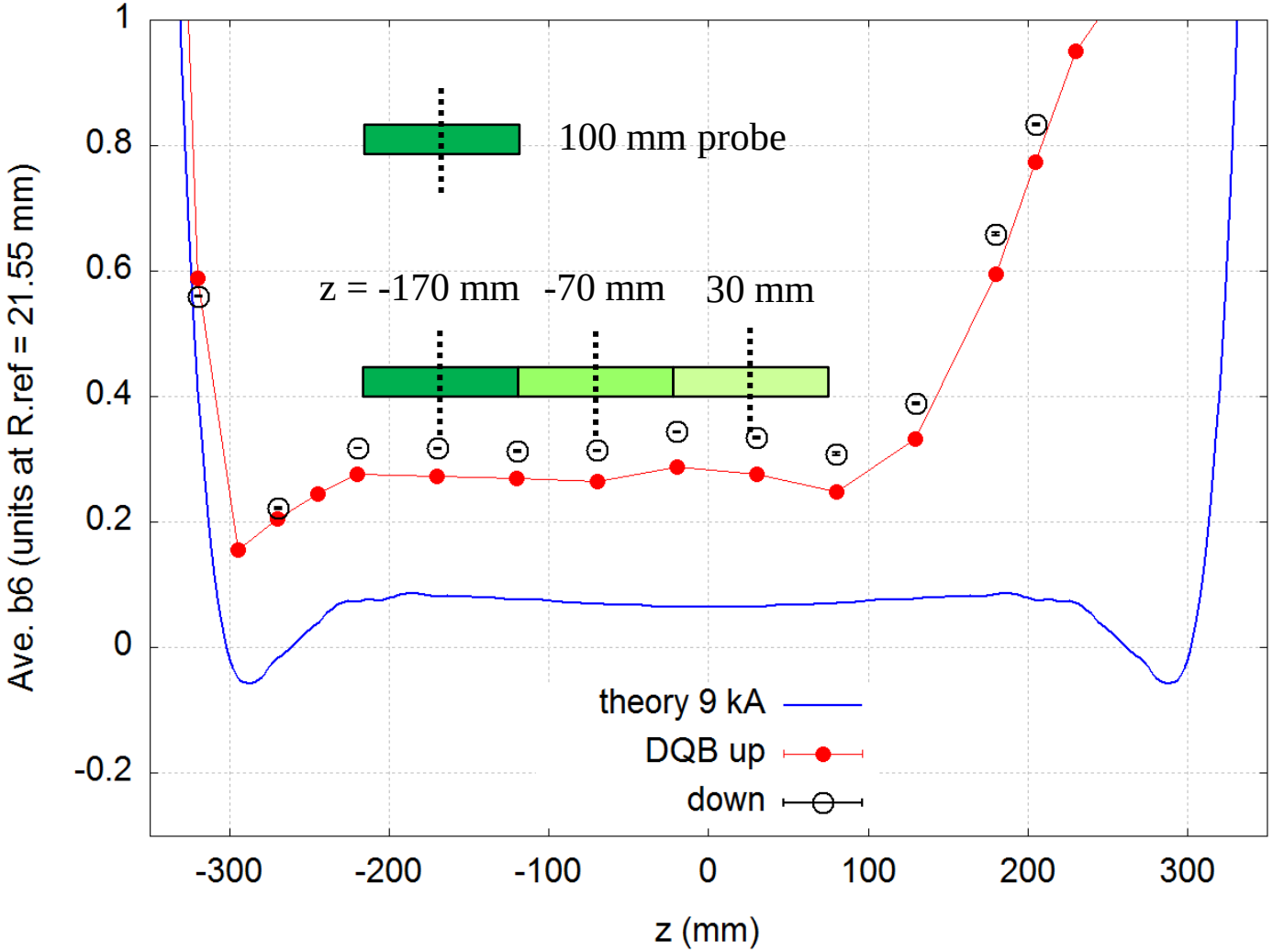
- Low signal/noise ratio at 30 A for b_{10} (current/temperature, probe).

Stair-step measurement overview

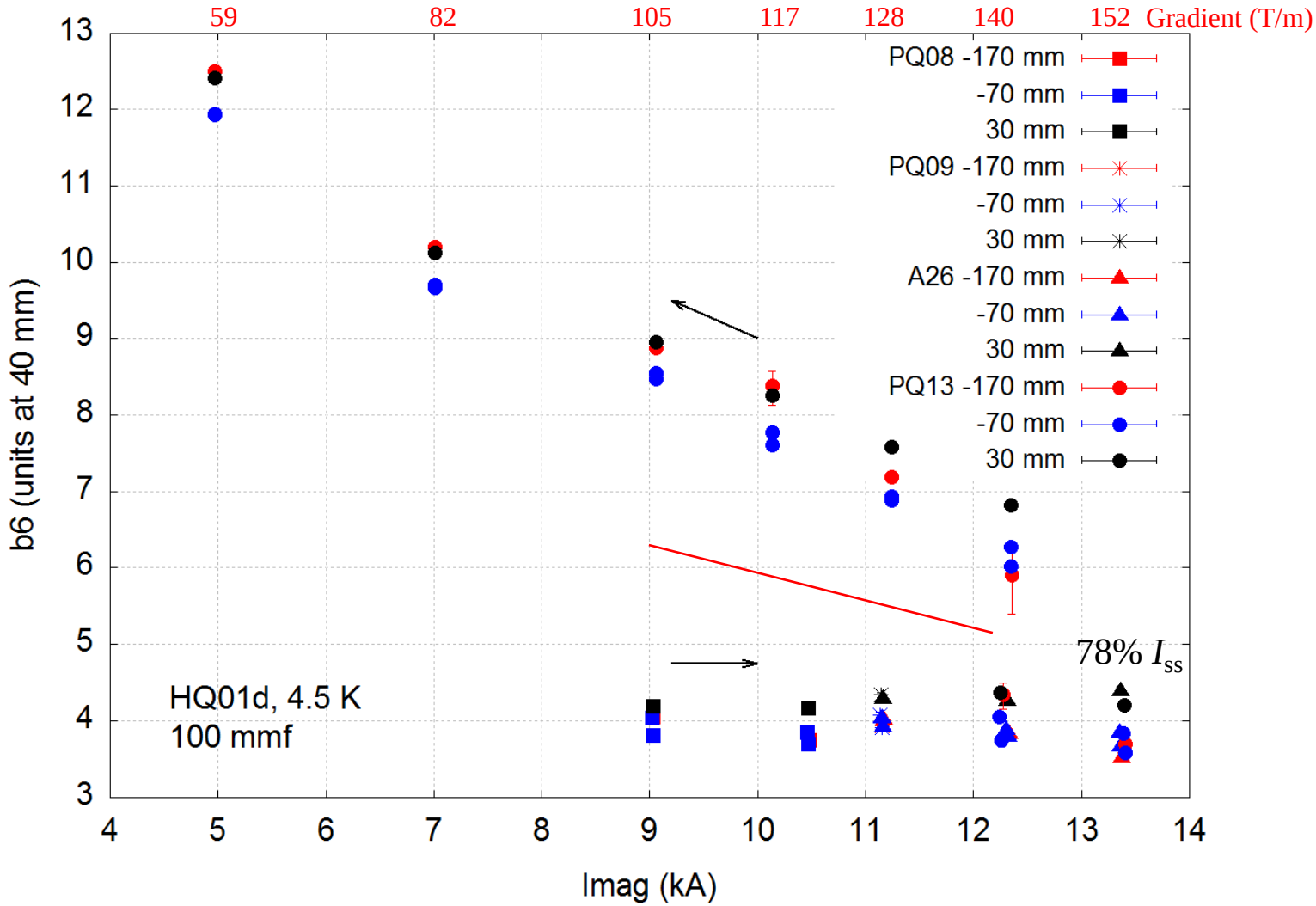
- Protocol
  - Probe rotating at the magnetic straight section.
  - Current ramp to a certain current level.
  - Hold for > ~ 120 s (still taking data).
  - Scan at the straight section: 3 locations.
  - Ramp to another current level (20 A/s).
- Four attempts for the 100 mm probe:

Test	Up-ramp target (kA)					Down-ramp target (kA)					
	9	10	11	12	13	12	11	10	9	7	5
PQ08	x	x									
PQ09			x								
A26			x	x	x						
PQ13				x	x	x	x	x	x	x	x

100 mm, stair-step scan locations



100 mm, stair-step, b_6, R_{ref} = 40 mm

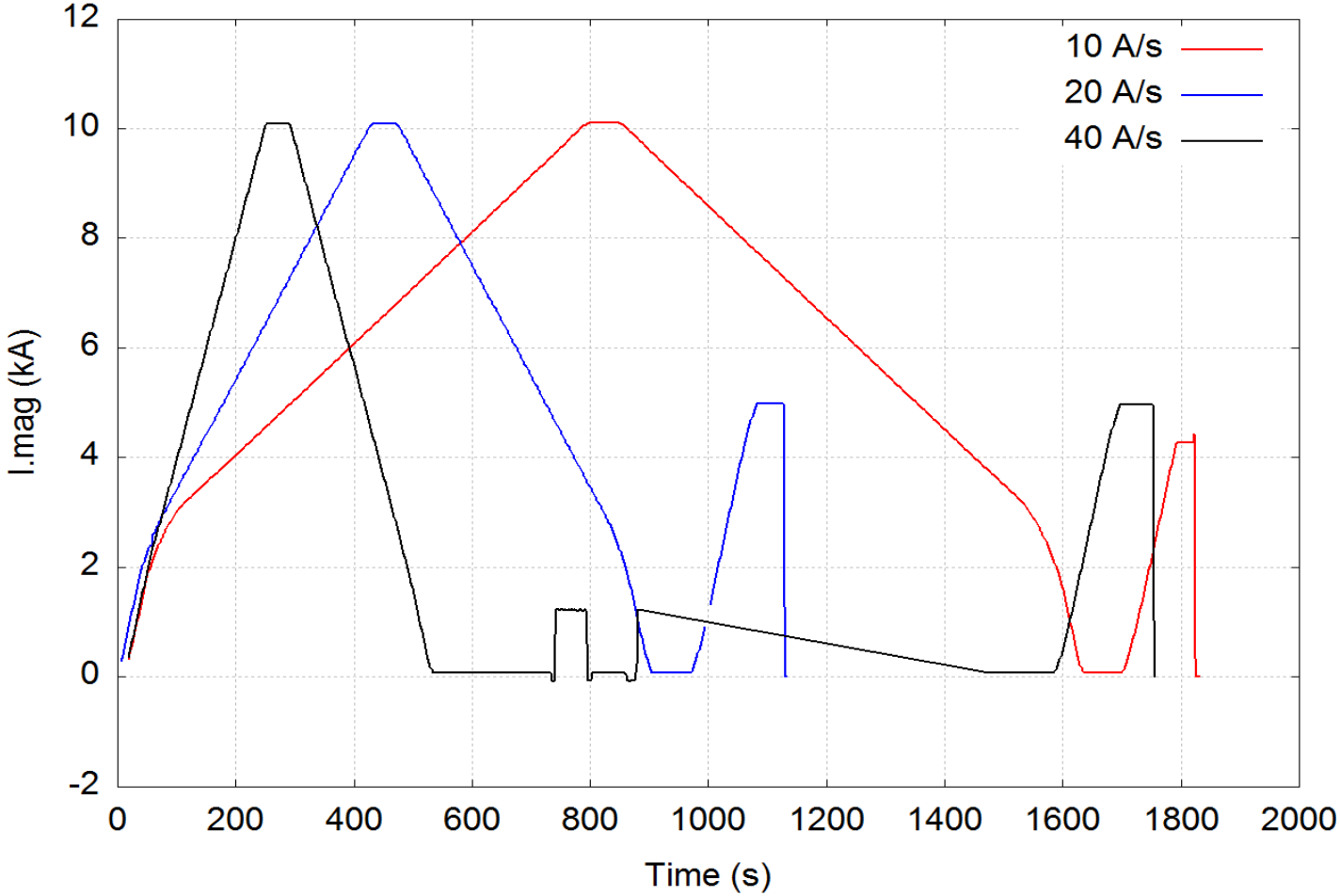


Harmonics at 120 T/m, R_{ref} = 40 mm

- Based on 100 mm coil stair-step measurements.
  - z = -70 mm.
  - Down-ramp data linearly interpolated between 10.1 kA and 11.2 kA.

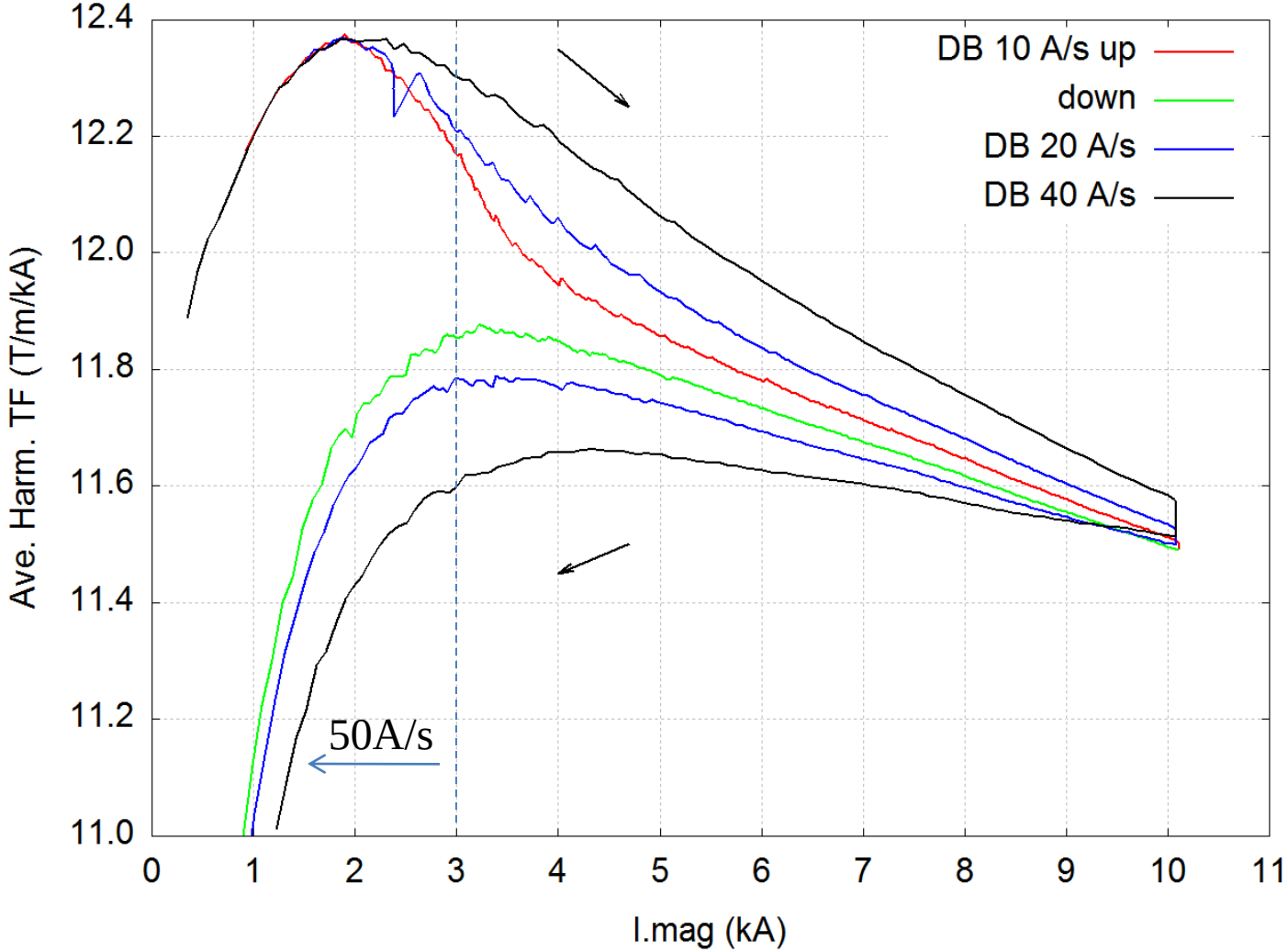
	Up-down averaged		**Up-ramp only**	
n	Normal (b_n)	Skew (a_n)	Normal (b_n)	Skew (a_n)
3	0.21	-3.17	-0.51	-3.44
4	-0.63	-4.16	-0.66	-4.30
5	0.93	0.33	1.74	0.44
6	5.61	-0.17	3.77	-0.17
7	0.96	-0.57	1.30	-0.44
8	0.44	0.02	0.26	0.39
9	-0.12	0.30	0.23	0.72
10	1.88	4.23	1.04	2.32

Continuous loop measurement

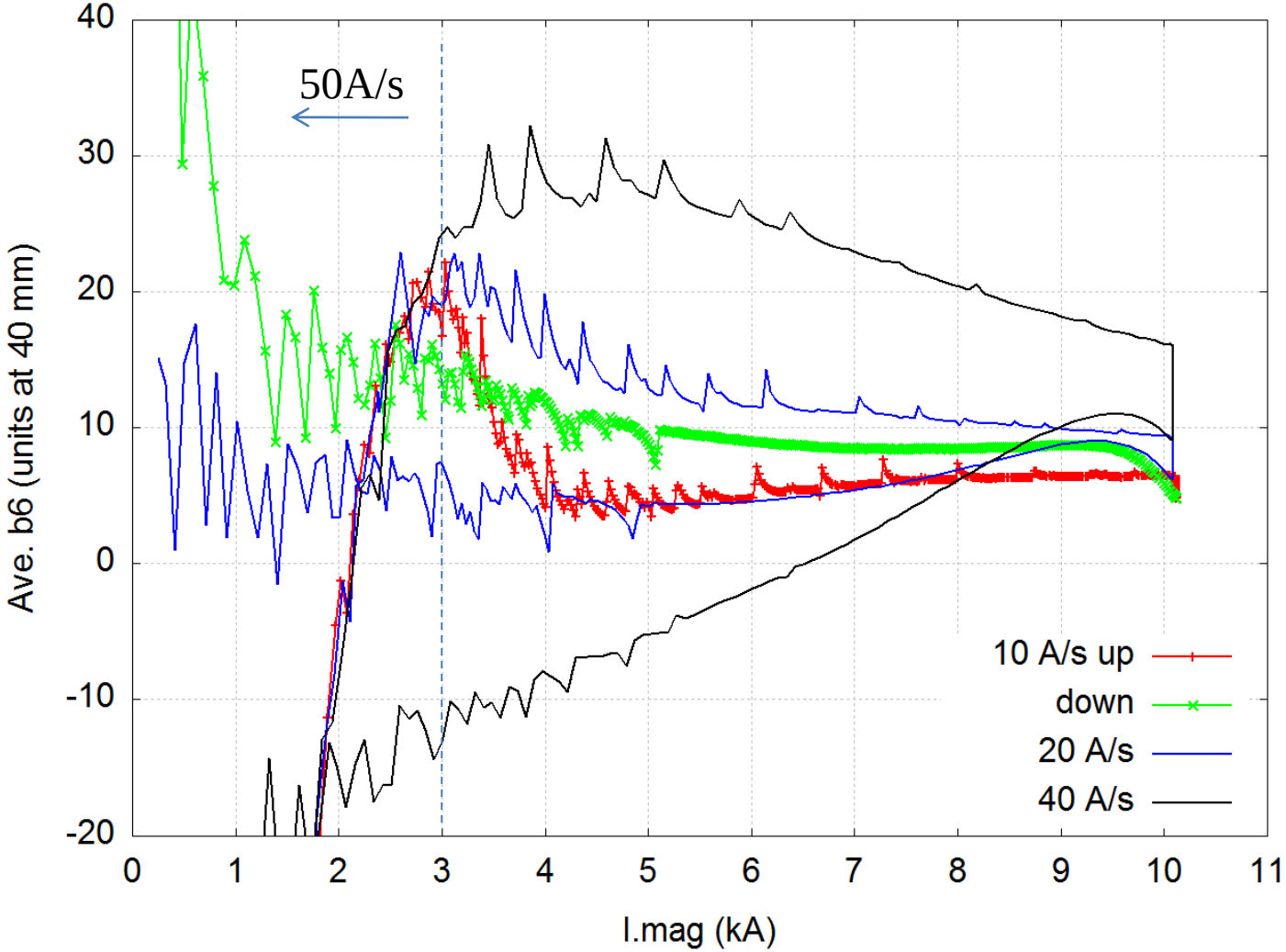


- 100 mm probe rotating at the magnetic center.
- 50 A/s below 3 kA. Quench at 5 kA before next loop. <u>No pre-cycle</u>.

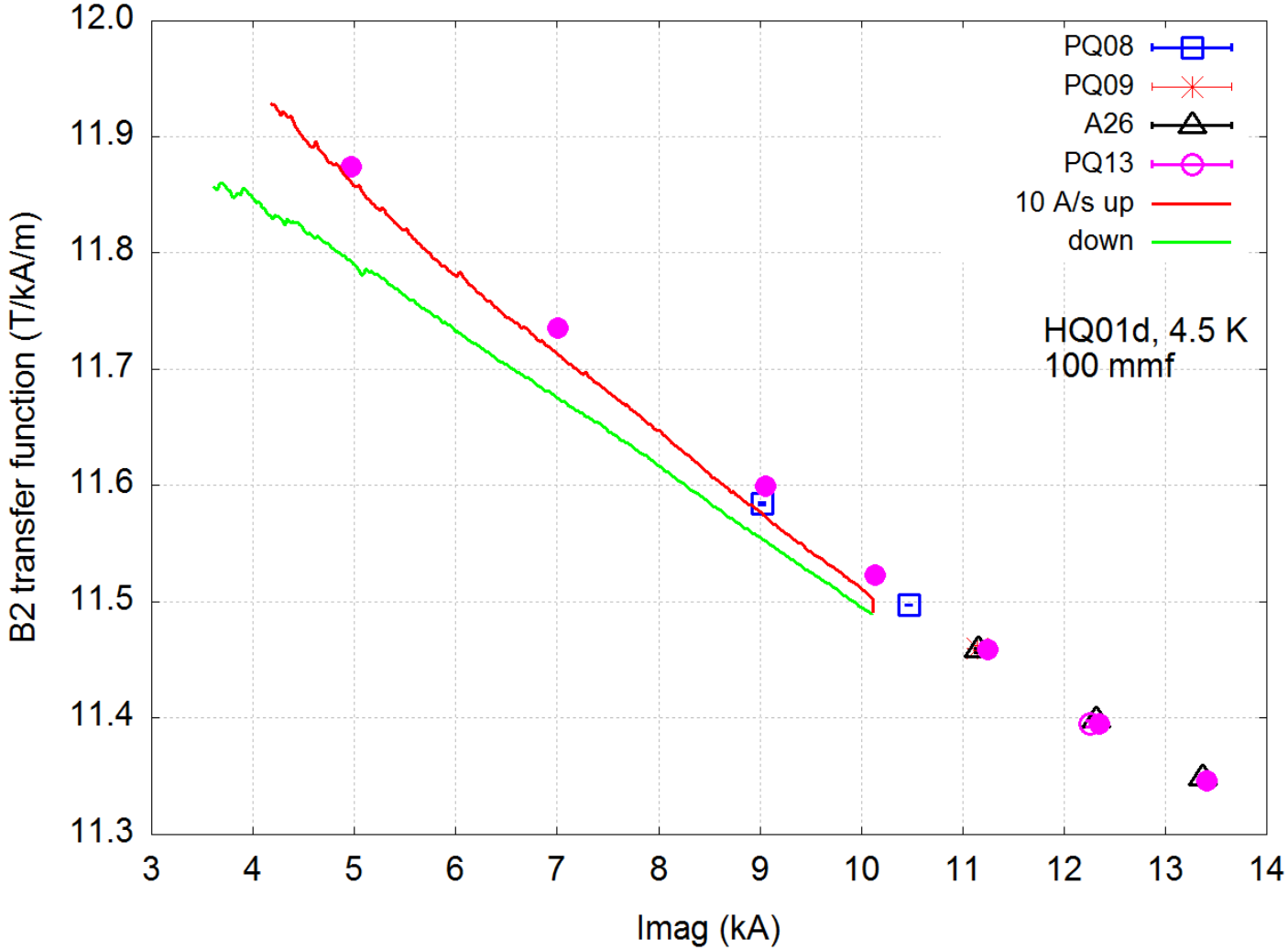
100 mm, transfer function



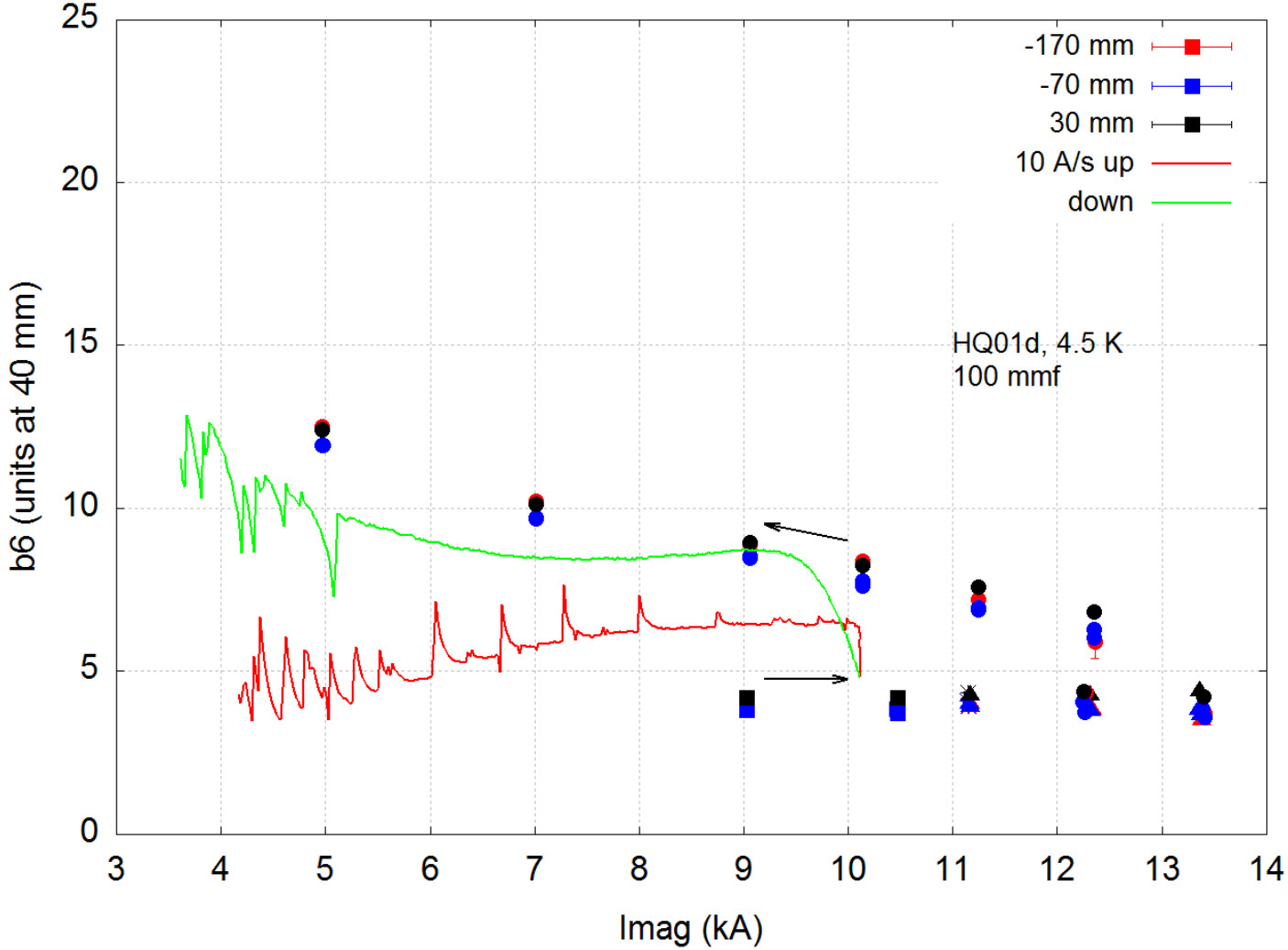
100 mm, b_6, R_{ref} = 40 mm



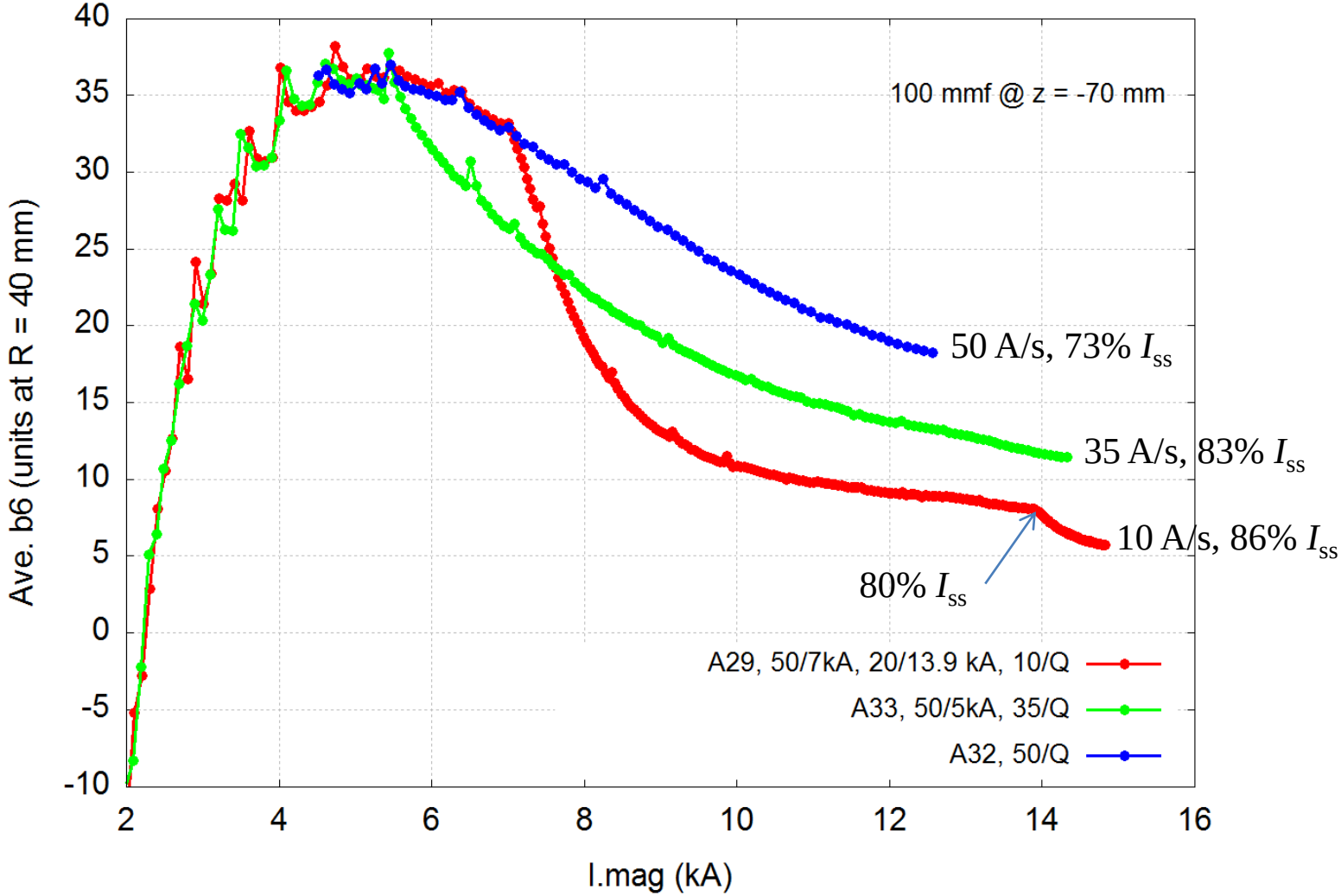
10 A/s w/o pre-cycle vs. stair-step, transfer function



10 A/s w/o pre-cycle vs. stair-step, b_6, R_{ref} = 40 mm



100 mm, up-ramp of training quenches, b_6, R_{ref} = 40 mm



- Ramp-rate dependence (seen at 80% I_{ss})

Summary of the discussion on 5/16/11

- Performance during the up ramp relevant to the operation.
  - Reproducibility of multiples @ 10 A/s. To do in future measurements.
- Probe with large diameters should be implemented.
  - Good performance of existing PCB probe.
  - Increase from 44 mm diameter (HQ01d meas.) to > ~ 80 mm.
  - Anti-cryostat modification.
  - Check/coordinate with CERN's instrumentation plan.
- HQ01d results study
  - Better understanding of dynamic effects through calculation (also for future measurements), e.g.,
    - Magnetization modeling based on strand magnetization measurement.
  - Spikes
    - More measurements at low and high ramp rates.

Discussion for future field quality study

- What are the requirements/important questions?
- What can be learned from HQ01d (and TQ/LQ)?
  - Issues that can be identified.
- What remains to be answered?
- What needs to be done (time and priorities)?
  - Mid- and long-term items.
  - Near-term for HQ01e.
    - Measurement plan.

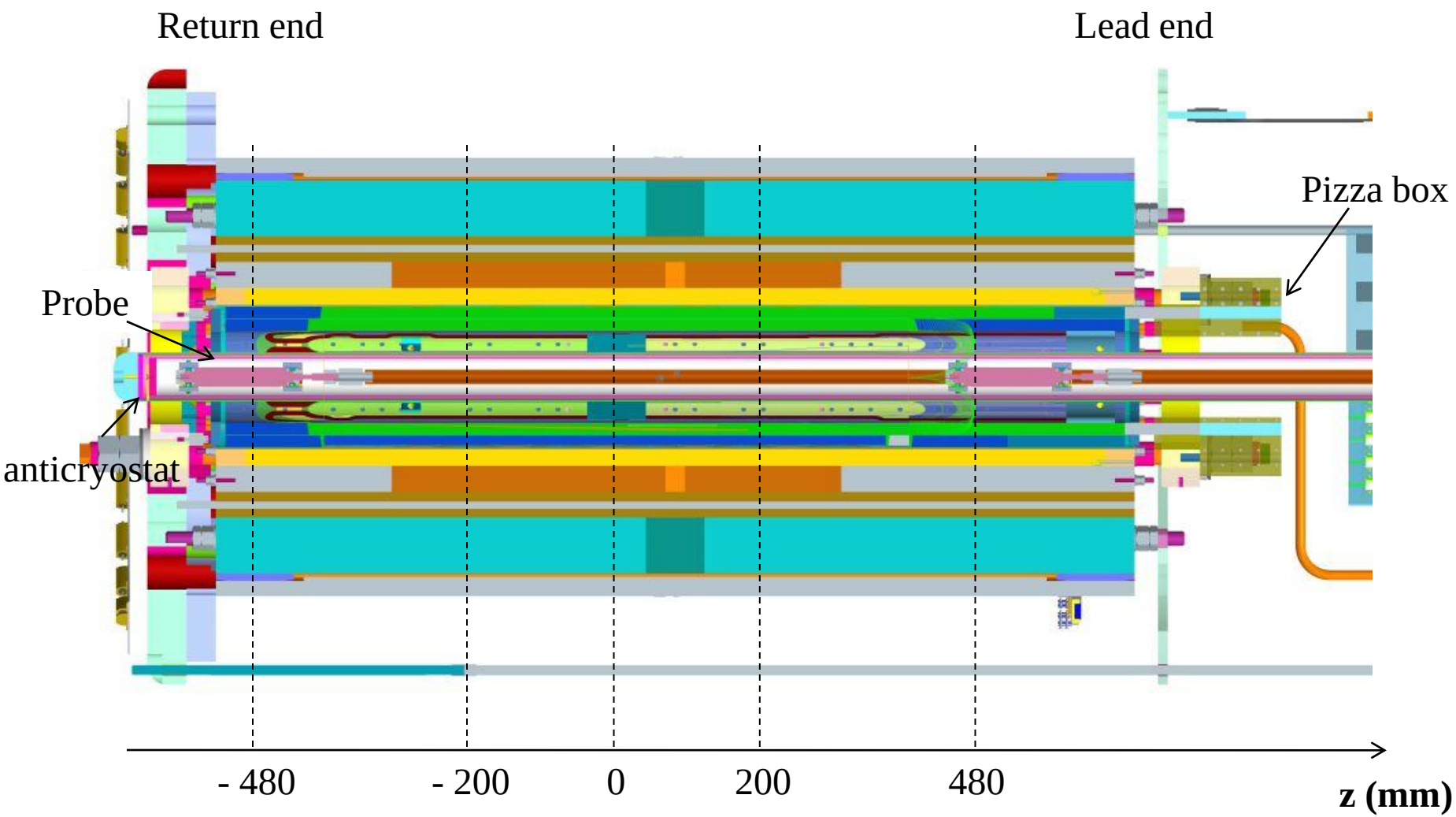
Items that should be addressed

- Experimental/hardware:
  - Large probe: what's the optimal diameter? (> 80 mm for 120 mm magnet bore, 92 mm is possible at LBL)
  - Strand magnetization measurement.
  - Anything else?
- Calculation/analysis:
  - Dynamic effect (persistent current, eddy current…)
  - Anything else?

Backup slides

- Probe location during the z scan.
- TQ/LQS results.
- Ramp-rate effects.

Probe location during the z-scan



TQ/LQS ramp-rate dependence

ΔTF of TQC and TQS

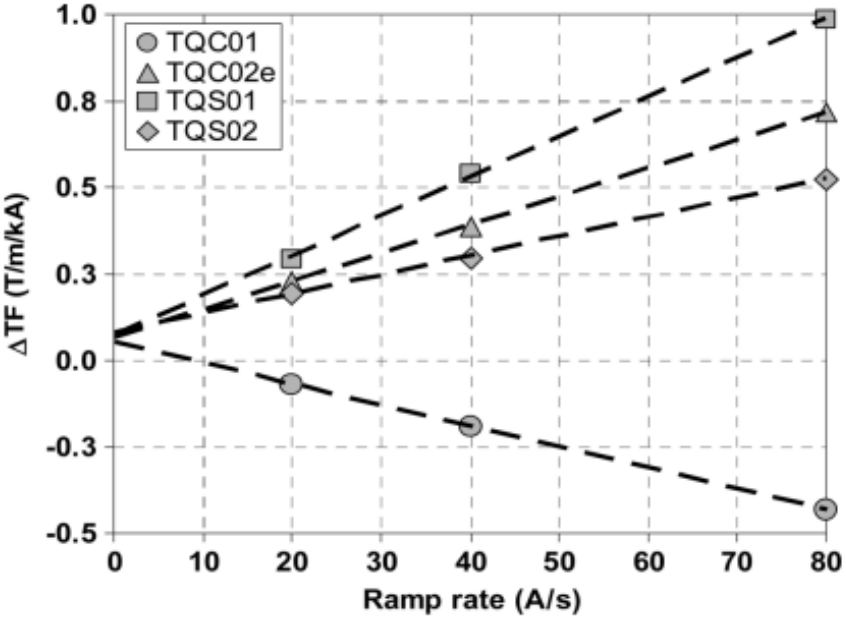


Fig. 7. Width of the transfer function loop as function of the ramp rate.

G. Velev, et al. IEEE TAS 18(2), 2008, p. 184

Δb_6 of TQC, TQS and LQS

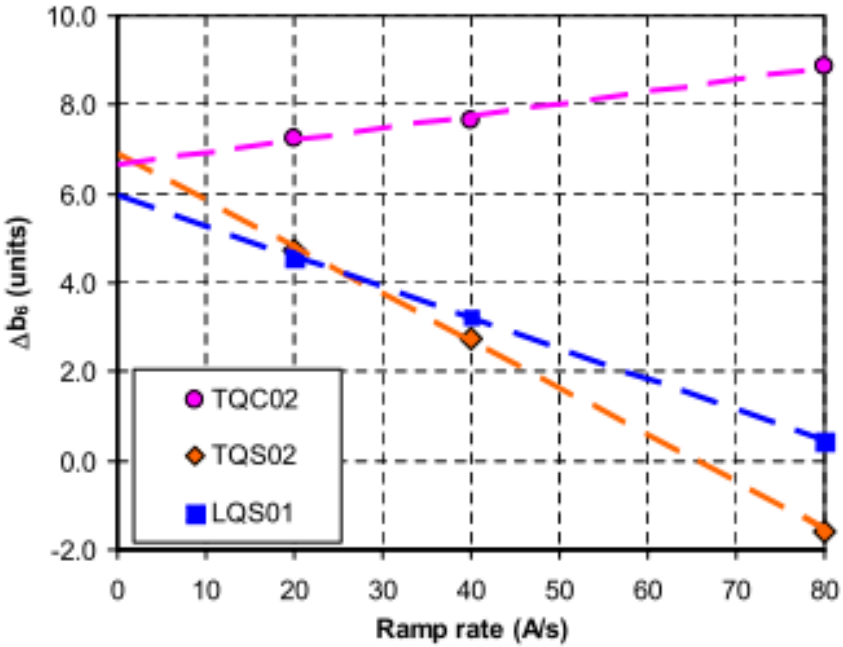


Fig. 5 Dodecapole loop width as function of the ramp rate.

G. Velev, et al. IEEE TAS 2010, in press.

Decay observed in TQS and LQS?

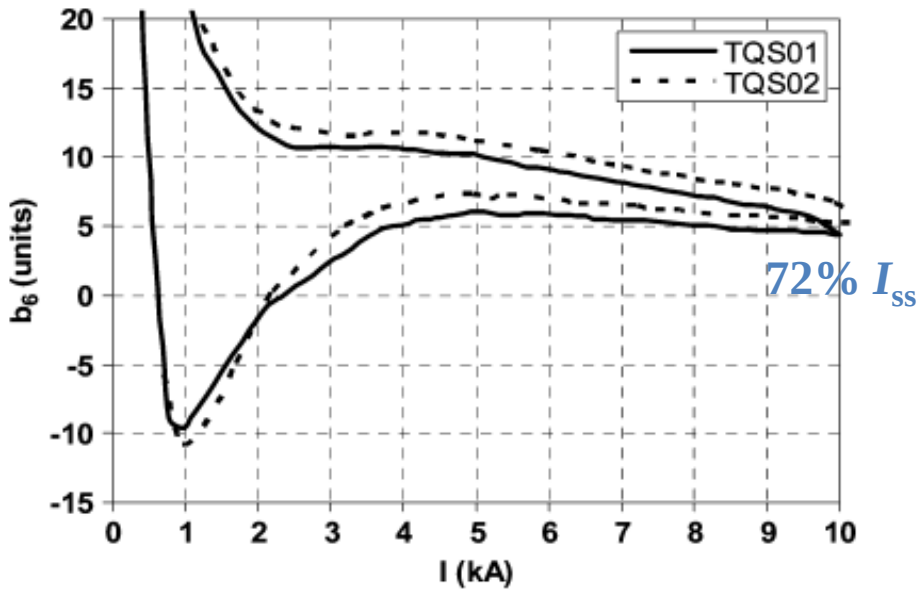


Fig. 6. Normal dodecapole hysteresis for TQS01-02 at ramp rates of 20 A/s.

G. Velev, et al. IEEE TAS 18(2), 2008, p. 184

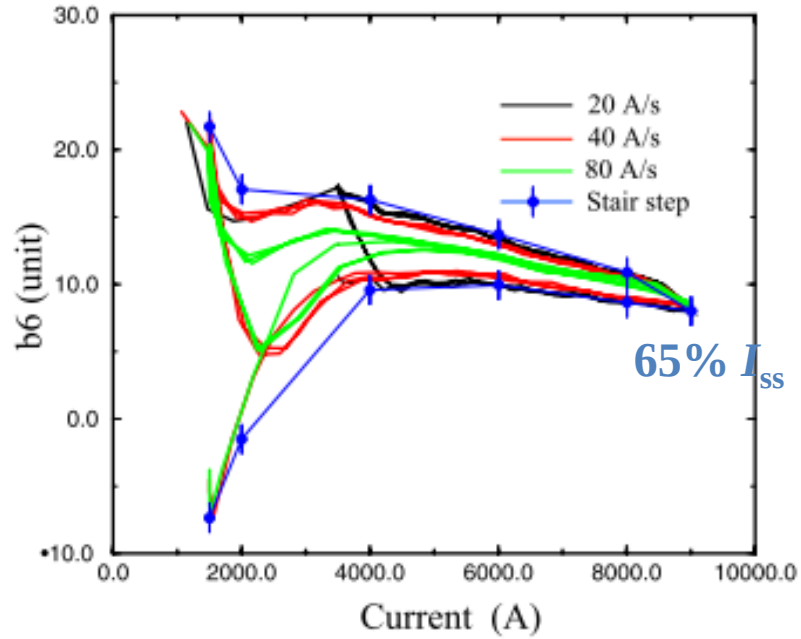
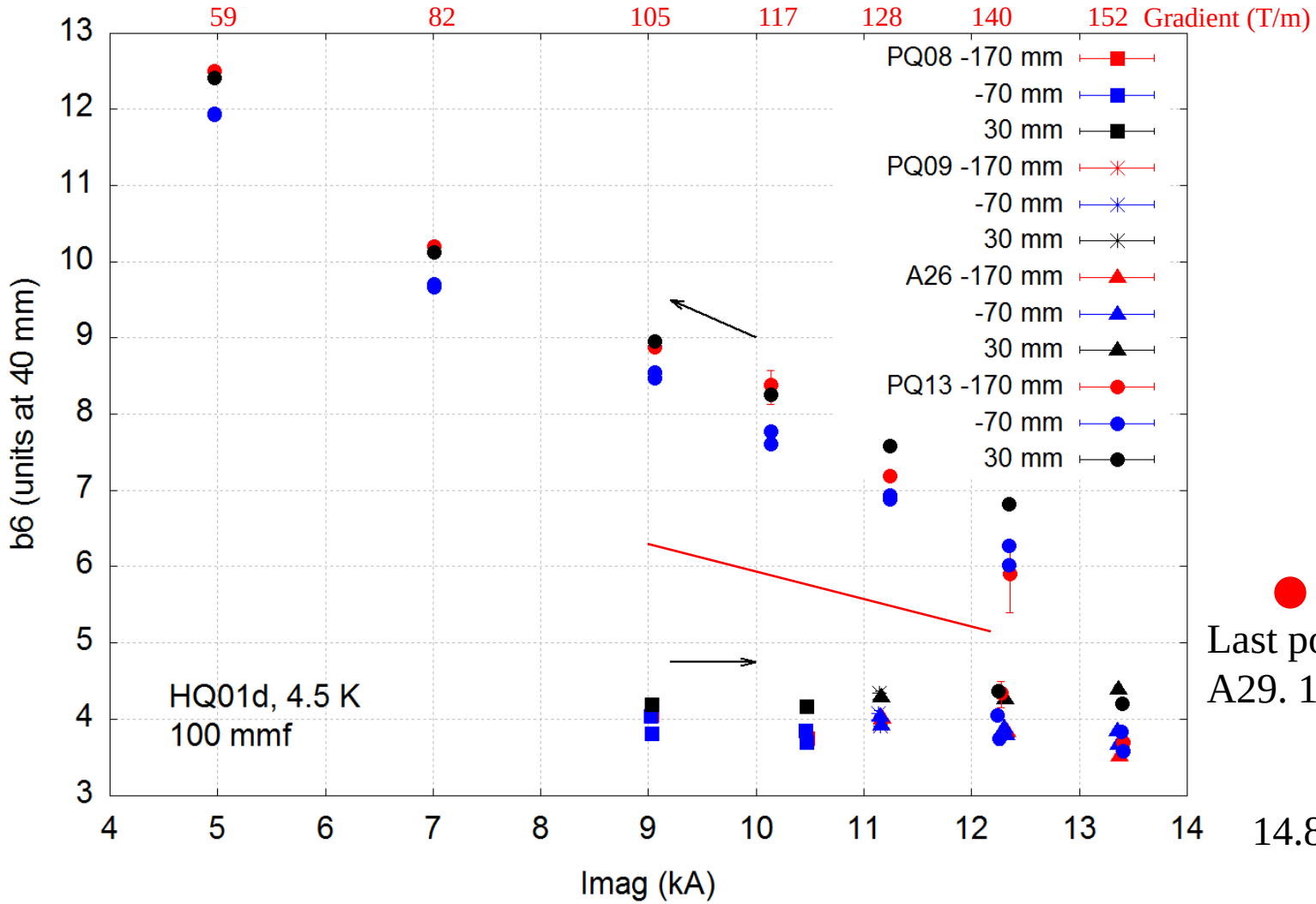


Fig. 4 LQS01 current loops executed at ramp rate of 20, 40 and 80 A/s. The points represents the "stair step" measurement described in the text. G. Velev, et al. IEEE TAS 2010, in press.

- No obvious decay/spikes observed in the results from TQS02 and LQS01.
- TQS02/LQS01: 13.8 kA @ 4.5 K; HQ01d: 17.3 kA @ 4.5 K.
- Conductor: HQ01d two filament sizes; cable widths.
- No Aluminum collars in TQ/LQ. (Collar ρ ~ 1.4 $\mu\Omega$-cm at 4 K, time constant ~ ms).

100 mm, stair-step, b_6, R_{ref} = 40 mm



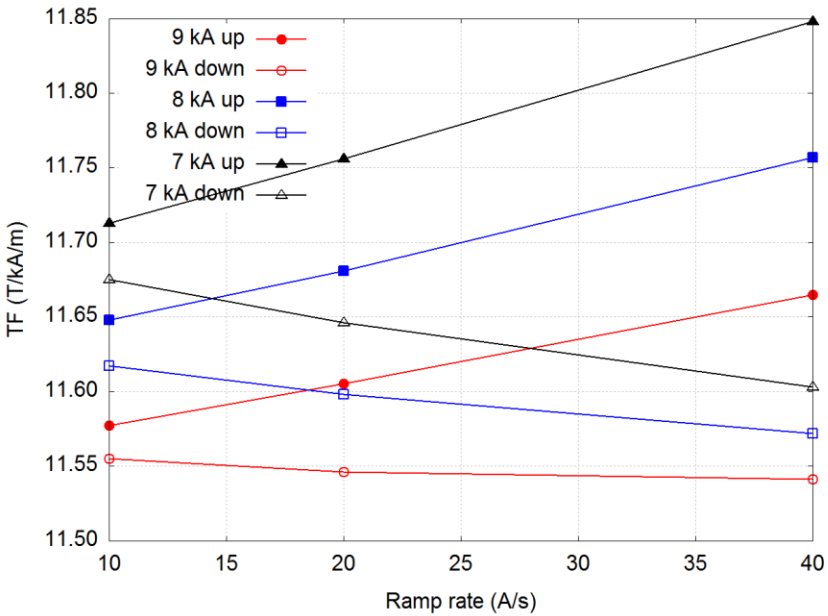
Last point in A29. 10 A/s.

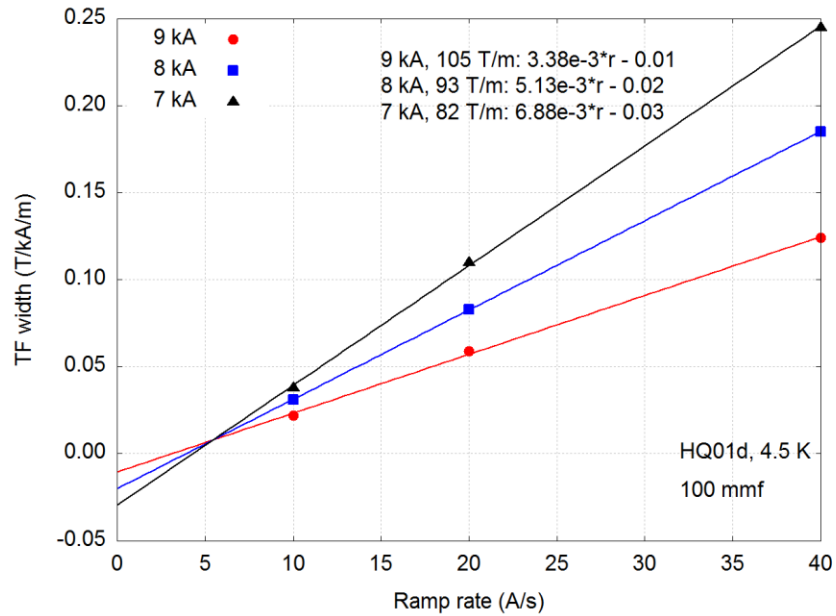
14.8 kA

Ramp-rate effect, transfer function

Sampled TF values at the up- and down-ramp

$\Delta TF = TF^{up} - TF^{down}$



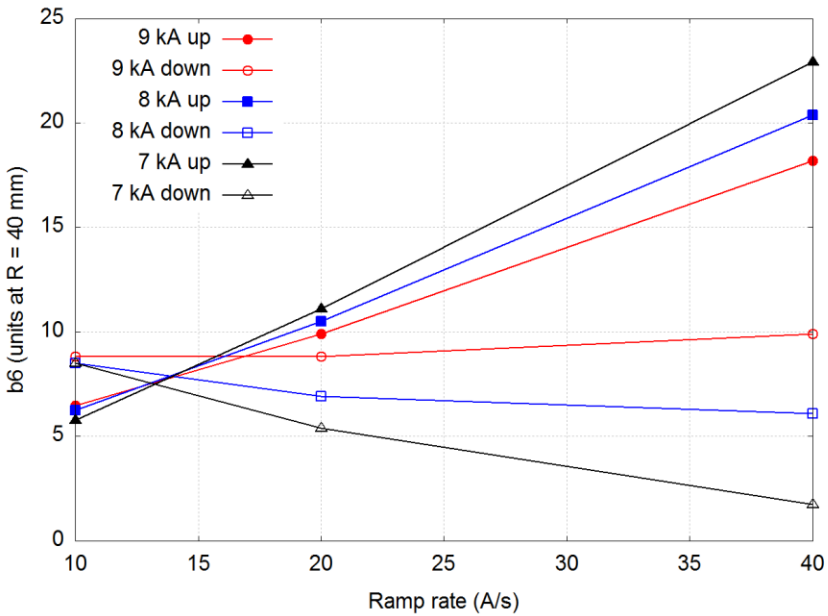


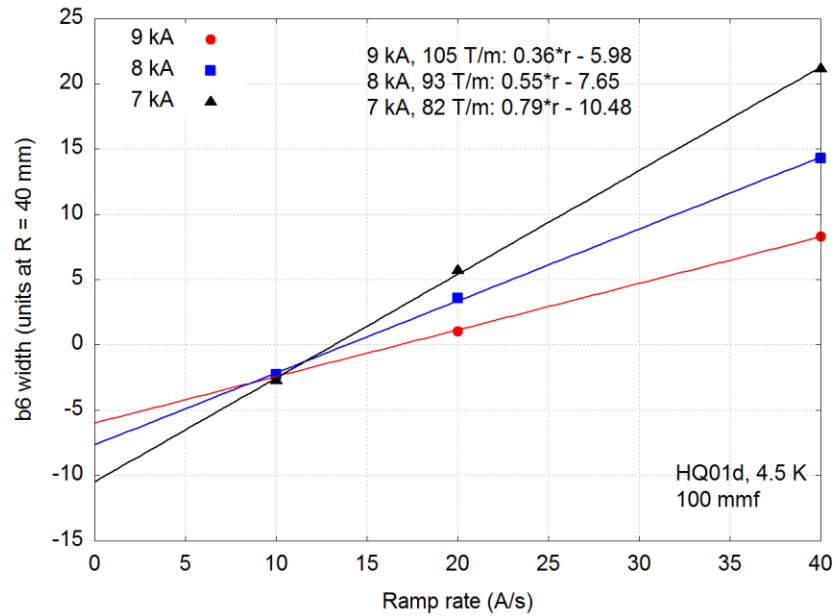
- Transfer function values sampled at 9 kA, 8 kA and 7 kA.
- ΔTF proportional to the tested ramp rates.

Ramp-rate effect, b_6, R_{ref} = 40 mm

Sampled b_6 values at the up- and down-ramp

$\Delta b_6 = b_6^{up} - b_6^{down}$





- Δb_6 proportional to the tested ramp rates.