MEMORANDUM

31th August 2007
EDMS n. xxxxxx

Subject: Correction of the MQY cold mass field quality measurements

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To: L. Bottura, L. Deniau, J. P. Koutchouk, N. Catalan-Lasheras, N. Sammut, S. Sanfilippo, E. Todesco

The issues

During the production of the MQY quadrupoles for the insertion regions an unusual spread in the transfer function measured at room temperature has been discovered. According to measurements at operational temperature the effect disappeared almost totally. This effect has been traced back to collar permeability significantly higher than specifications, as it happened for the MQ [1]. It was then decided to measure the collar permeability for all remaining apertures to be built [2]. Table I gives a summary of the MQY warm measurements after the production has ended. It shows 3 interesting features:

- There are permeability measurements for 14 out of 60 apertures. The given value represents an average for the magnet as there is some variability in the same collaring pack.
- The production information for MQY 19 in MTF [3] contain no cold mass measurements
- The production information reports that aperture that aperture 41 is present in both magnet 21 and 29

Table II gives a summary of the MQY cold measurements after the testing at CERN has ended. It shows 2 interesting features:

- 6 out of 18 cryostats have no cold field quality measurement
- 6 cryostats consist of two MQY magnets in series

If all the MQY magnets had been tested at cold conditions the warm data would not have been needed. However, it seems there are 3 good reasons why the warm data is of interest beyond the trivial case of using it for cross-checking:

- 6 cryostats need to be extrapolated at cold using a warm-to-cold correlation
- The cold measurements can only give integrals for the entire cryostat. Our AB/ABP colleagues would prefer to have the field quality information per magnet, which is the unit of resolution in the MAD-X description of the LHC accelerator [4].
- There is some calibration issue with the cold measurement system [5] concerning the transfer function, and the warm data is used for finding the correct offset.

The remaining of this memo deals with the correction of the warm measurements affected by the elevated permeability, following the approach developed for the MQ. A more elaborated analysis has been developed in [6] taking into account the effect at cold.

Table I. Summary of MQY “warm” measurements

family	m	ap	apid	μr	warm meas	role
MQY	1	1	1		x	Q4L8
MQY	1	2	2		x	Q4L8
MQY	2	1	3		x	Q4L8
MQY	2	2	4		x	Q4L8
MQY	3	1	5		x	Q5R8
MQY	3	2	6		x	Q5R8
MQY	4	1	7		x	Q5R4
MQY	4	2	8		x	Q5R4
MQY	5	1	9		x	Q4R2
MQY	5	2	10		x	Q4R2
MQY	6	1	11		x	Q5R8
MQY	6	2	12		x	Q5R8
MQY	7	1	13		x	Q4L1
MQY	7	2	14		x	Q4L1
MQY	8	1	16		x	Q4R2
MQY	8	2	15		x	Q4R2
MQY	9	1	18		x	Q5L6
MQY	9	2	17		x	Q5L6
MQY	10	1	19		x	Q6L4
MQY	10	2	20		x	Q6L4
MQY	11	1	21		x	Q6R4
MQY	11	2	22		x	Q6R4
MQY	12	1	23		x	Q4L5
MQY	12	2	24		x	Q4L5
MQY	13	1	26		x	Q5L4
MQY	13	2	27		x	Q5L4
MQY	14	1	25		x	Q4R5
MQY	14	2	28		x	Q4R5
MQY	15	1	29		x	Q4L6
MQY	15	2	30		x	Q4L6
MQY	16	1	31		x	Q4R6
MQY	16	2	32	1.011	x	Q4R6
MQY	17	1	33		x	Q5R6
MQY	17	2	34	1.015	x	Q5R6
MQY	18	1	35	1.016	x	Q4R1
MQY	18	2	36	1.016	x	Q4R1
MQY	19	1	37	1.016		Q4R8
MQY	19	2	38	1.014		Q4R8
MQY	20	1	39	1.013	x	SPARE
MQY	20	2	40	1.008	x	SPARE
MQY	21	1	41		x	SPARE
MQY	21	2	42	1.008	x	SPARE
MQY	22	1	43		x	Q4R8
MQY	22	2	44		x	Q4R8
MQY	23	1	46		x	Q4L2
MQY	23	2	47		x	Q4L2
MQY	24	1	48		x	Q4L2
MQY	24	2	49		x	Q4L2
MQY	25	1	51		x	Q5L2
MQY	25	2	52		x	Q5L2
MQY	26	1	50		x	Q5L2
MQY	26	2	53		x	Q5L2
MQY	27	1	54		x	SPARE
MQY	27	2	55	1.011	x	SPARE
MQY	28	1	56	1.011	x	SPARE
MQY	28	2	57	1.010	x	SPARE
MQY	29	1	41		x	SPARE
MQY	29	2	58	1.010	x	SPARE
MQY	30	1	61		x	SPARE
MQY	30	2	60	1.009	x	SPARE

Table II. Summary of MQY "cold" measurements

cryoid	family	m1		m2	cold meas	role
607	MQY	1	MQY	2	x	Q4L8
608	MQY	5	MQY	8		Q4R2
609	MQY	3	MQY	6		Q5R8
621	MQY	7			x	Q4L1
622	MQY	18			x	Q4R1
633	MQY	10			x	Q6L4
634	MQY	13			x	Q5L4
635	MQY	4			x	Q5R4
636	MQY	11			x	Q6R4
647	MQY	12			x	Q4L5
648	MQY	14			x	Q4R5
658	MQY	9				Q5L6
659	MQY	15			x	Q4L6
660	MQY	16			x	Q4R6
661	MQY	17			x	Q5R6
670	MQY	25	MQY	26		Q5L2
671	MQY	23	MQY	24		Q4L2
672	MQY	22	MQY	19		Q4R8

The warm measurement data

Plots of the original warm data are shown in Fig. 1 to 4.

The normalised *G/i* in Fig. 1 is based upon the assumption that the measurement current was 1.5 A for aperture 1 and 3.0 A for the others (the current is not recorded in the data). The G/i are constant for apertures 9 to 17. When we compare these values to the integrated *G/i* we see a variation as expected and assumes that the measurement system records the G/I dl integral correctly, but the natural variation in G/i has wrongly been attributed to the magnetic length for apertures 9 to 17. Since these apertures have no associated permeability measurement, they will not complicate the treatment in this memo.

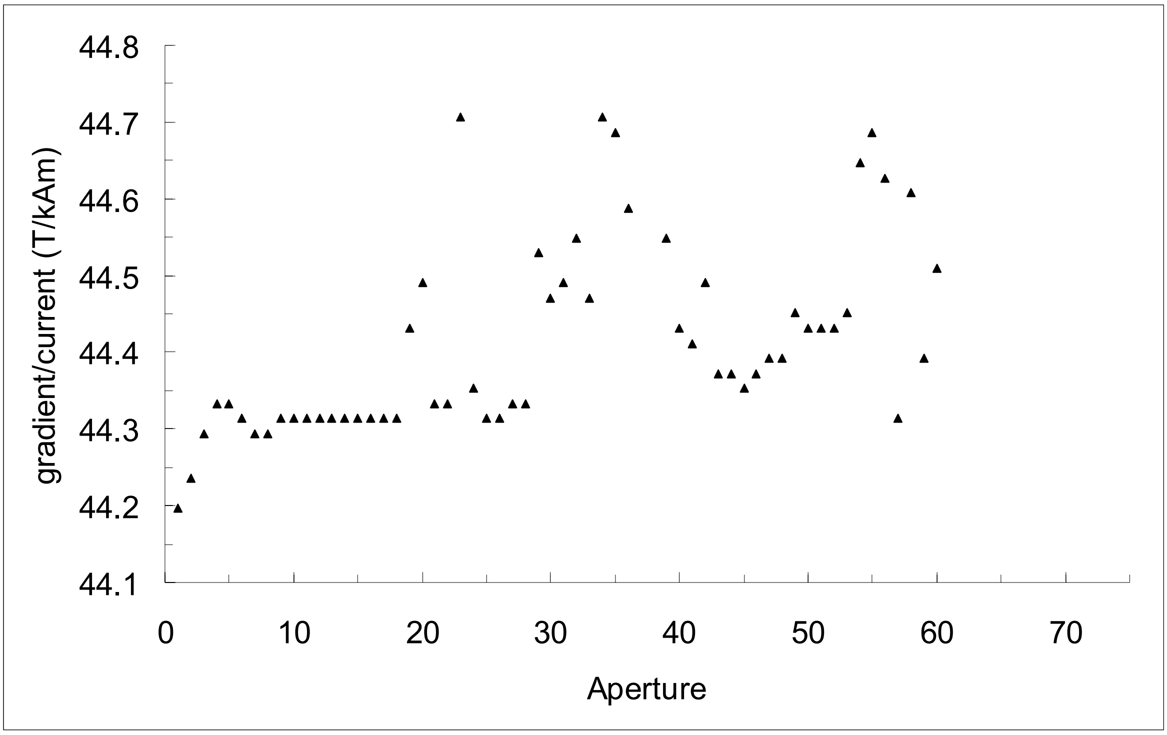

Fig. 1. Measured *G/i* in the cold mass

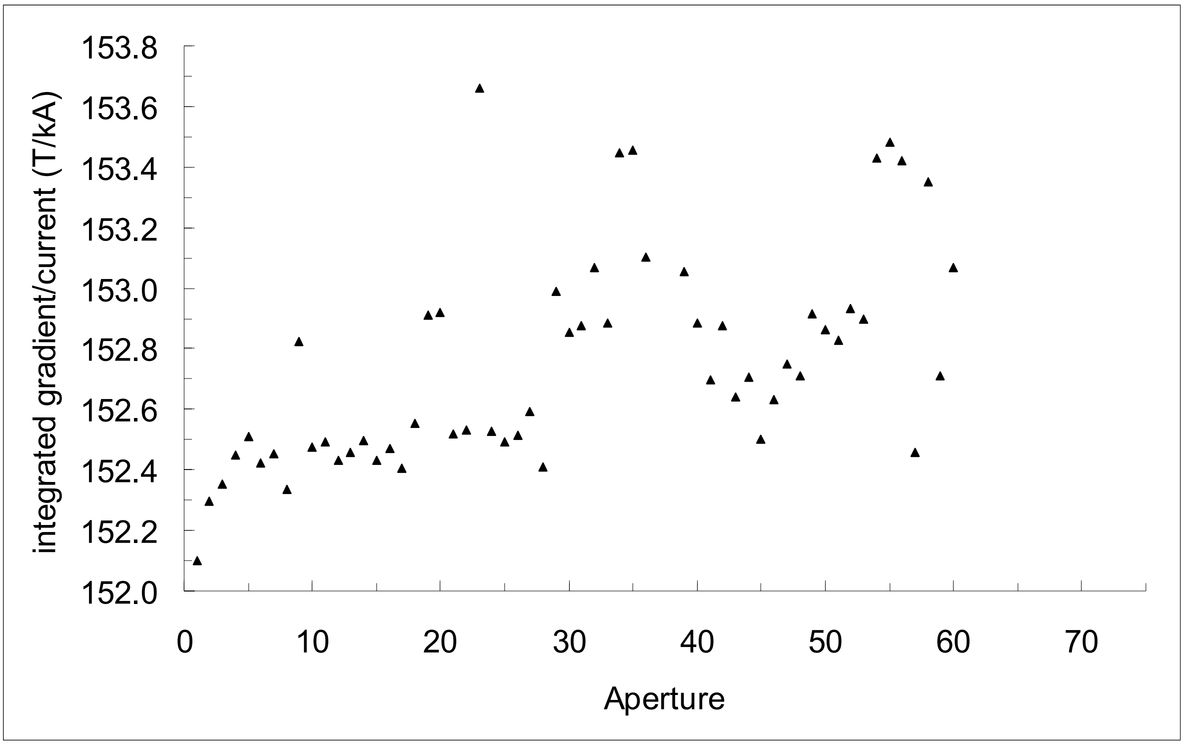

Fig. 2. Measured integrated *G/i* dl in the cold mass

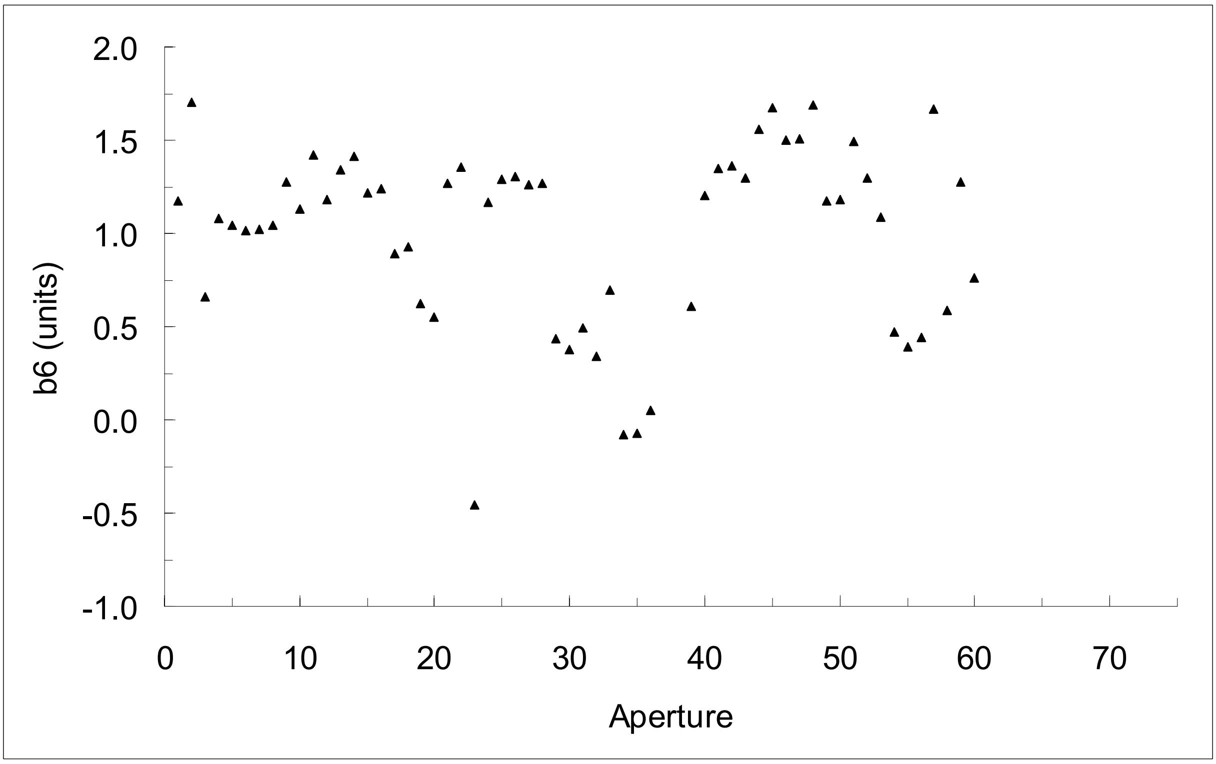

Fig. 3. Measured b_6 in the cold mass

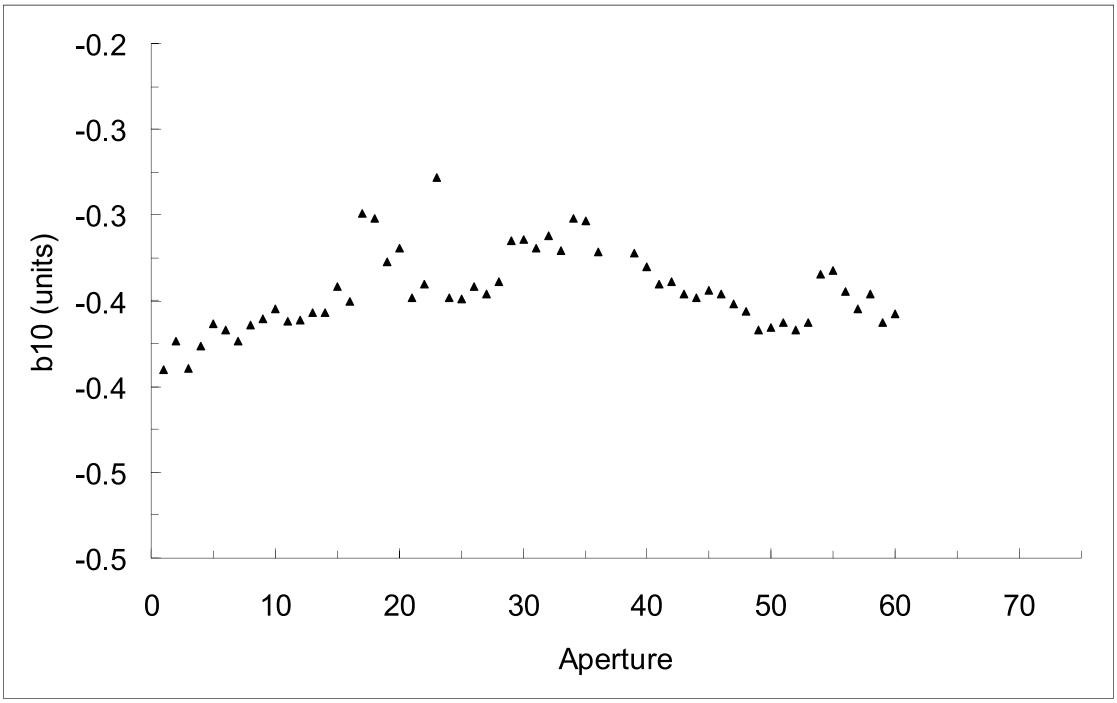

Fig. 4. Measured b_{10} in the cold mass

The average and standard deviation of the data in Fig. 1 to 4 is shown in Table III. The spread of the *Gdl/i* being smaller than the spread of the *G/i* confirms the previous working assumption that *Gdl/I* was the quantity actually measured, but not always correctly split between magnetic length and normalised gradient. Judging the spread of the integrated transfer function against other similar magnet families like MQ and MQM we would expect a value between 10 and 15 units. The 23 units observed is indeed a significant quantity.

Table III. Summary of MQY “warm” statistics

	mag len (m)	G/i (T/kAm)	Gdl/i (T/kA)	b6 (units)	b10 (units)
ave	3.439	44.413	152.750	1.00	-0.34
sigma (units)	7.7	28.1	22.9	0.5	0.0

The permeability sensitivity

We assume that the elevated permeability changes the transfer function and allowed harmonics as linear functions as shown in Eq. 1 and 2 where *S* are signed sensitivity coefficients.

$$\mathrm{G/i'}_{\mathrm{cm}} = \mathrm{G/i}_{\mathrm{cm}} + S_g \cdot \mu_r \tag{1}$$

$$\mathrm{b_n}'_{\mathrm{cm}} = \mathrm{b}_{\mathrm{n\,cm}} + S_n \cdot \mu_r \tag{2}$$

The *S* coefficients should normally have been computed from the magnetic model input to BEM-FEM code [7]. The S coefficients that were available did not match the observed effect. Therefore we pursued the idea of guessing the sensitivity permeability using the magnets where the permeability was measured, together with the room temperature magnetic measurements. Plots of the original warm data versus permeability, and linear fit, are shown in Fig. 5 to 7.

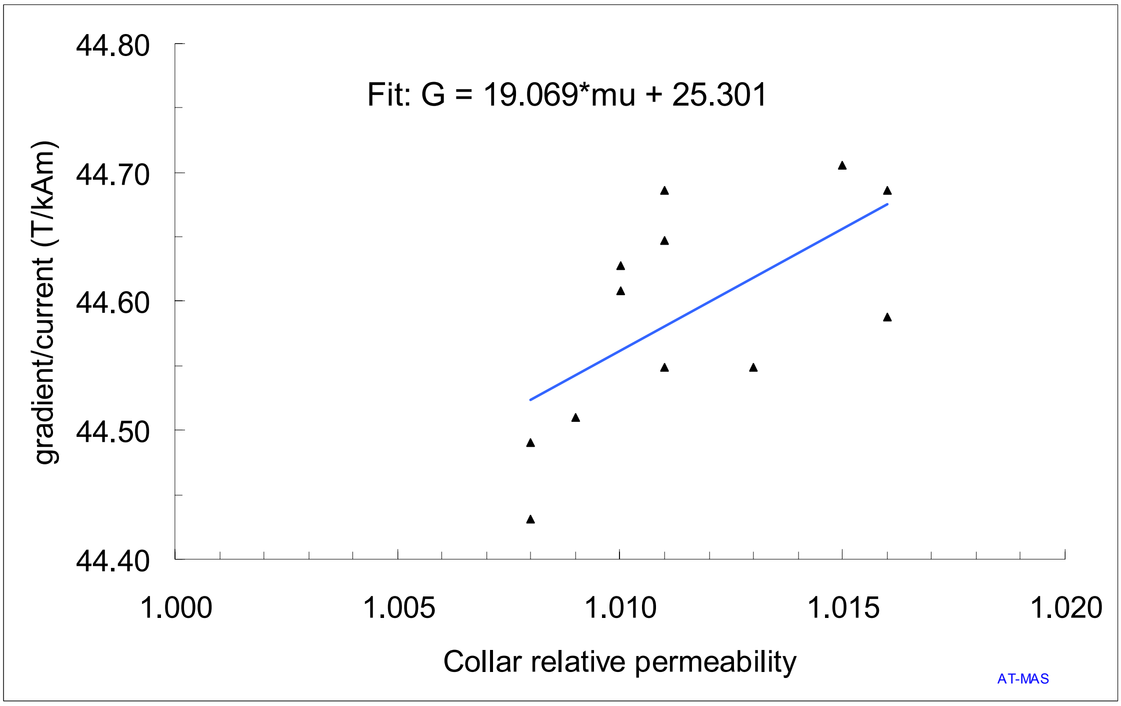

Fig. 5. Measured *G/i* in the cold mass vs measured relative permeability

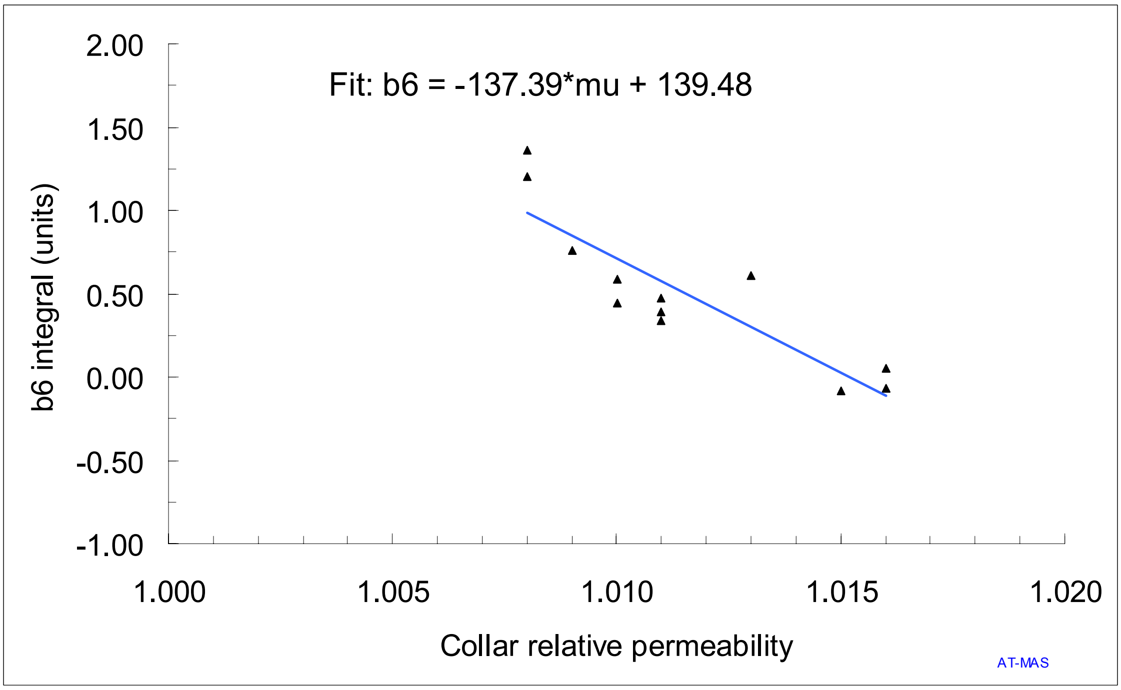

Fig. 6. Measured b_6 in the cold mass vs measured relative permeability

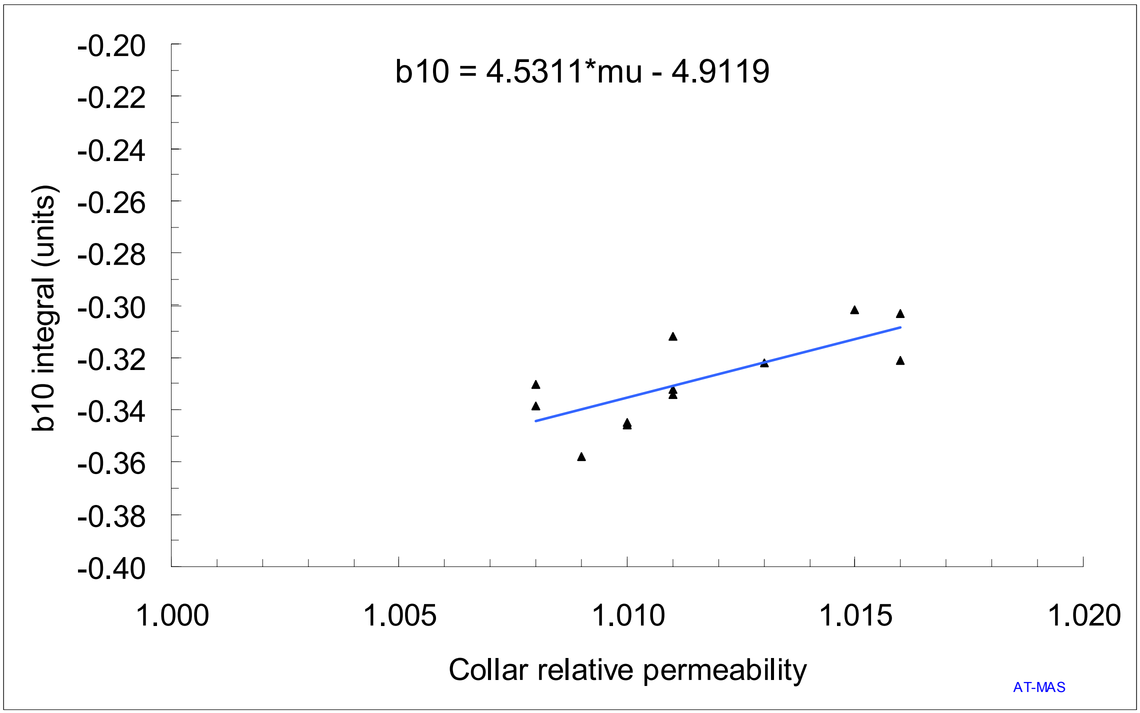

Fig. 7. Measured b_{10} in the cold mass vs measured relative permeability

Table IV. Sensitivity table constructed from linear fits

S sensitivity (units)		
G/i	b6	b10
4274.81	-137.39	4.5311

The *S* coefficients in table IV are to be understood as follows. If the relative permeability change with $\Delta\mu_r$ = 0.01, then the normalised gradient will increase by almost 43 units, and b_6 will decrease with -1.4 units and b_{10} of 0.045 units.

Permeability estimates

The value of the permeability can be guessed from the magnetic measurements by selecting a reference set of magnets characterized by an average focusing strength b_2^{ave} and an average permeability μ^{ave}, and assuming that the difference between the measured focusing strength b_2^{meas} in one magnet and the average one b_2^{ave} is only due to the permeability. Therefore one can estimate the permeability as

$$\mu_{b2} = \frac{b_2^{meas} - b_2^{ave}}{s_2} + \mu^{ave} \qquad (3)$$

where s_2 gives the effect of the variation of permeability on the focusing strength. One can have two other independent estimates based on b_6 and b_{10}:

$$\mu_{b6} = \frac{b_6^{meas} - b_6^{ave}}{s_6} + \mu^{ave} \qquad (4)$$

$$\mu_{b10} = \frac{b_{10}^{meas} - b_{10}^{ave}}{s_{10}} + \mu^{ave} \qquad (5)$$

where s_6 and s_{10} gives the effect of the variation of permeability on b_6 and b_{10} respectively. To understand which estimate is more reliable, we compare the impact of a permeability variation on field quality to the standard deviations of b_2, b_6 and b_{10} in room temperature measurements. If the sensitivity to permeability is much larger that the natural spread, the estimate is reliable, whereas if it is much smaller, its signal will be covered by the noise and the estimate will be not precise. For b_2, a variation of 0.01 of permeability gives 43 units, i.e. 2.1 times the natural standard deviation (23 units). Likewise we compute weights for b_6 and b_{10}. Therefore, we give the best guess for permeability as the weighted average of the three

$$\mu^e = \frac{w_{b2}\mu_{b2} + w_{b6}\mu_{b6} + w_{b10}\mu_{b10}}{w_{b2} + w_{b6} + w_{b10}} \qquad (6)$$

where w_{b2}=1.9, w_{b6}=2.9, w_{b10}=2.0

The remaining difficulty is to add a constant offset we do not know precisely, namely the nominal μ_r representing the normal permeability for the unperturbed collars. We estimate this value by using a quadratic error function formed by the sum of the ε between permeability measured and guessed. This function has a global min around 1.003 as shown in Fig 8. This is a value that confirms with typical values measured for the MQ magnet family. Table V gives the comparison between known and guessed μ_r.

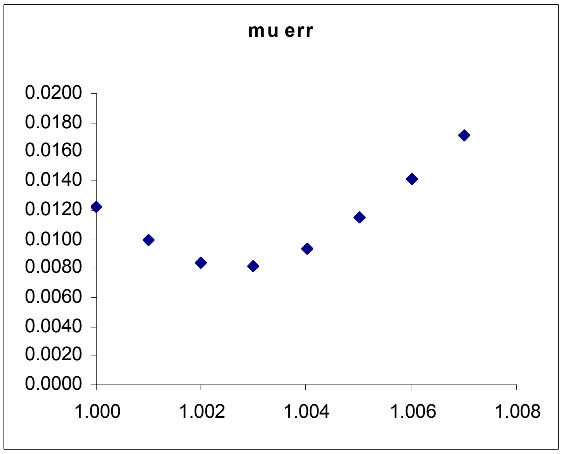

Fig. 8. “Global” relative mu error as function of nominal relative mu

Table V. Known mu compared to guessed mu

apid	known μr	μr guess
32	1.011	1.010
34	1.015	1.015
35	1.016	1.014
36	1.016	1.011
39	1.013	1.009
40	1.008	1.005
42	1.008	1.005
55	1.011	1.010
56	1.011	1.011
57	1.010	1.009
58	1.010	1.009
60	1.009	1.006

Correction of the cold mass measurements

The last part of the exercise is to correct the cold mass measurements for the perturbed permeability. We know that the effect should almost or mainly disappear at cold so we just use the sensitivity table to adjust the warm data by removing the estimated effect. The treatment is straightforward and the results are shown in Fig. 9 to 11 using the same scale on the vertical axis as in Fig. 2 to 4 and plotting both uncorrected and corrected series. The spread in the integrated transfer function has dropped from 23 units to 12 after the correction (see Table VI). This spread is similar to the ones known for the MQM and MQ magnet families. This is another cross-check that the result of the correction is been reasonable.

Table VI. Summary of MQY "warm" statistics (corrected for elevated μ)

	mag len (m)	G/i (T/kAm)	Gdl/i (T/kA)	b6 (units)	b10 (units)
ave	3.439	44.378	152.630	1.26	-0.35
sigma (units)	7.7	13.0	11.7	0.3	0.0

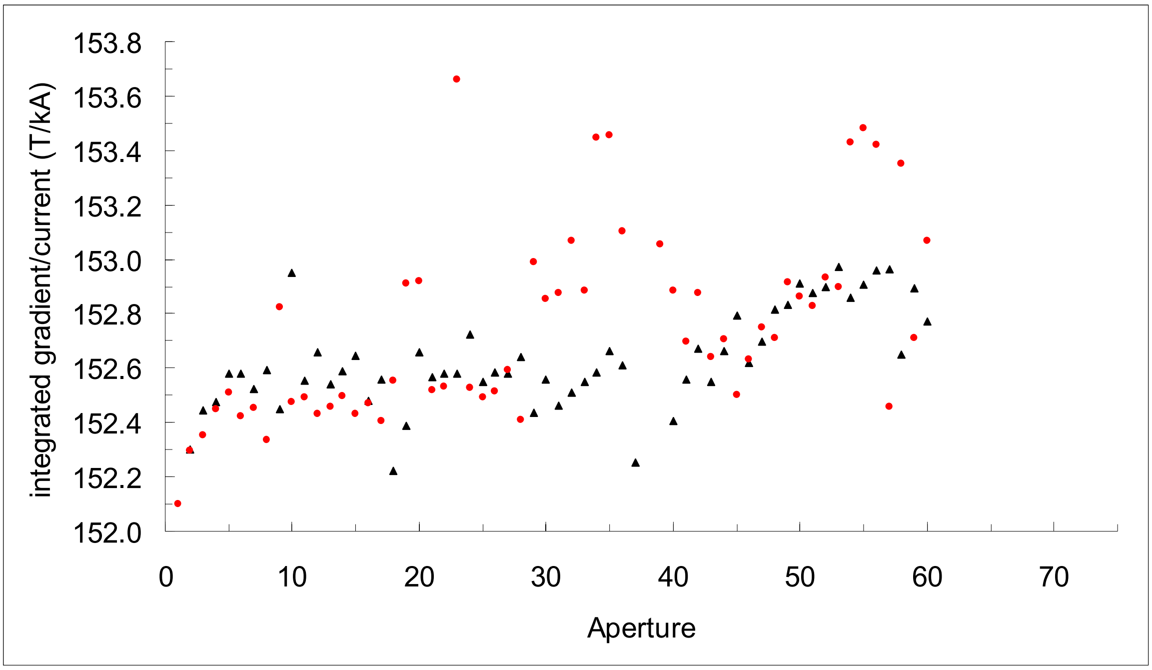

Fig. 9. Measured integrated *G/i* dl in the cold mass (red dot = original value, black triangle = μ corrected)

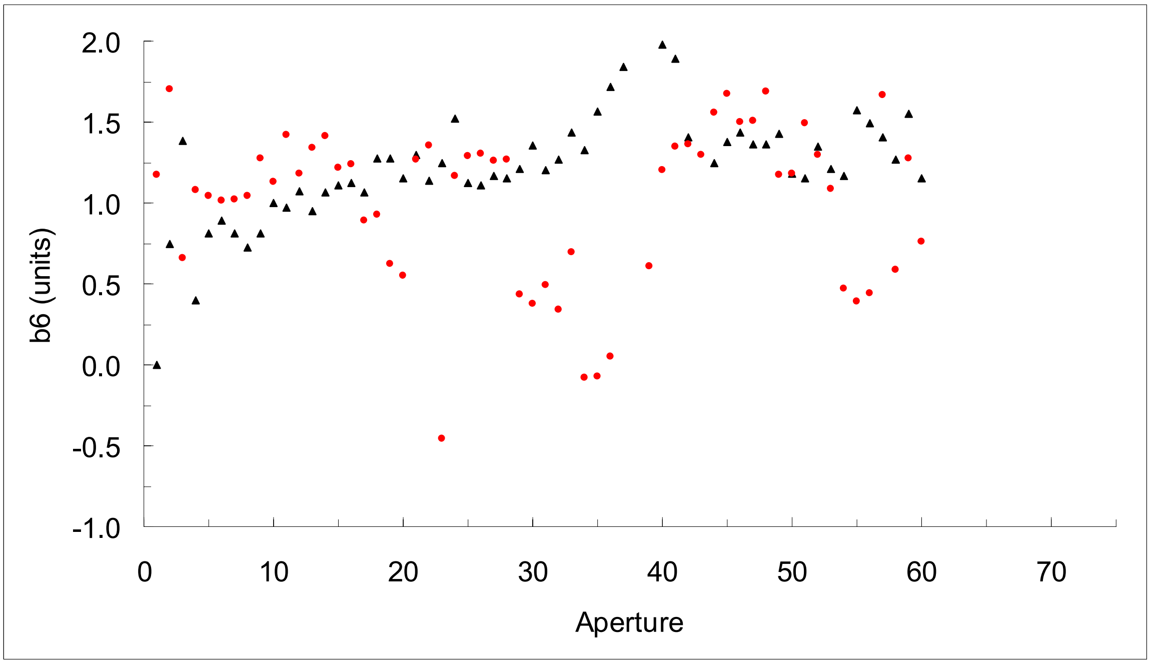

Fig. 10. Measured b_6 in the cold mass (red dot = original value, black triangle = μ corrected)

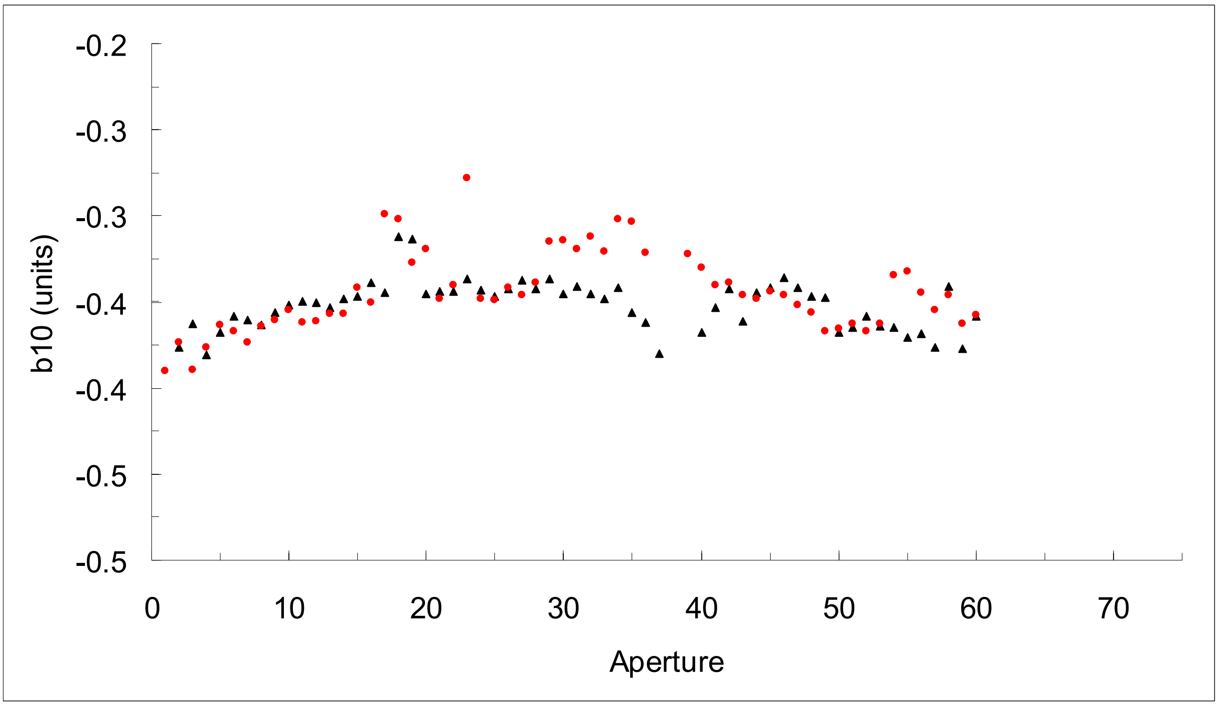

Fig. 11. Measured b_{10} in the cold mass (red dot = original value, black triangle = μ corrected)

The "warm to cold" correlation

The most interesting feature of the "warm" data is how they can be used to predict the field quality at "cold" operational conditions. The following figures (Fig. 12 to 19) show the plots of warm-cold correlation before and after the data has been corrected for elevated μ. The plots have not changed significantly but the spread in the horizontal axis (warm) is reduced. This is most clearly visible in Fig. 19.

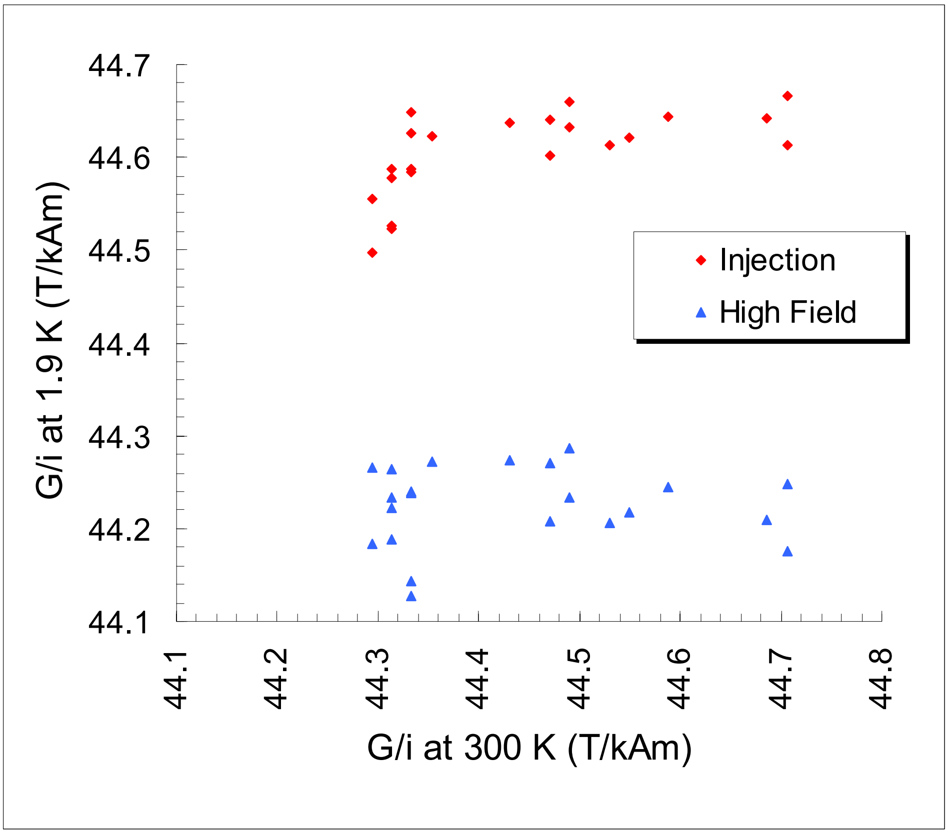

Fig. 12. *G/i* correlation for "warm to cold"

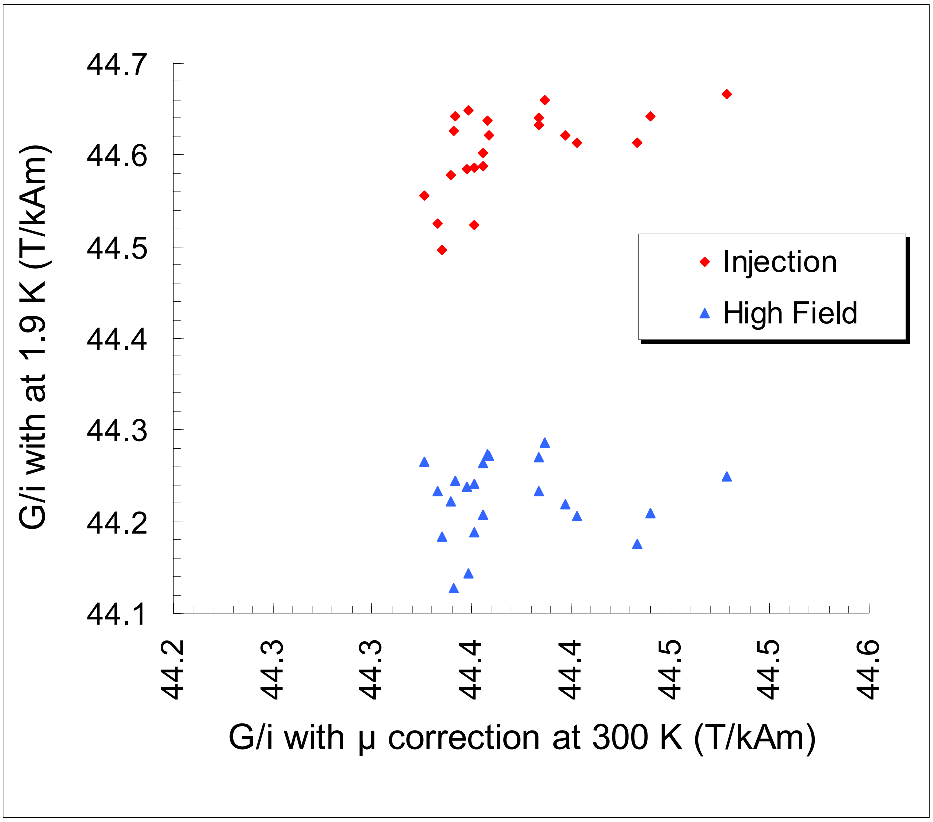

Fig. 13. *G/i* correlation for "warm to cold" (corrected for elevated μ)

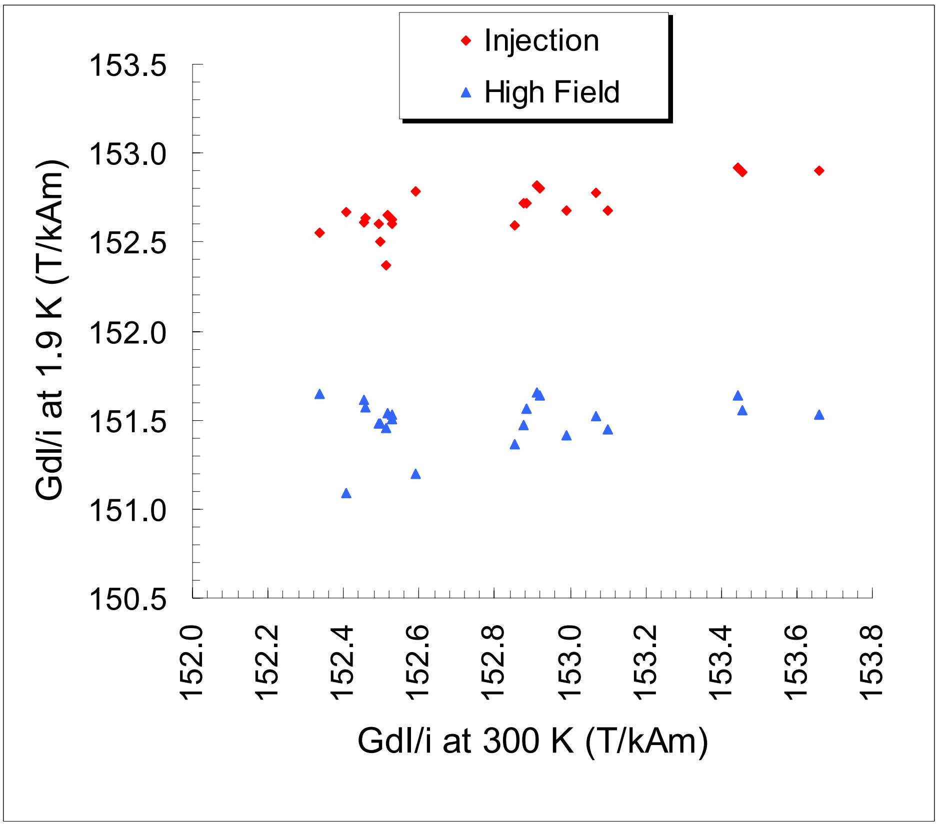

Fig. 14. *G/I dl* correlation for "warm to cold"

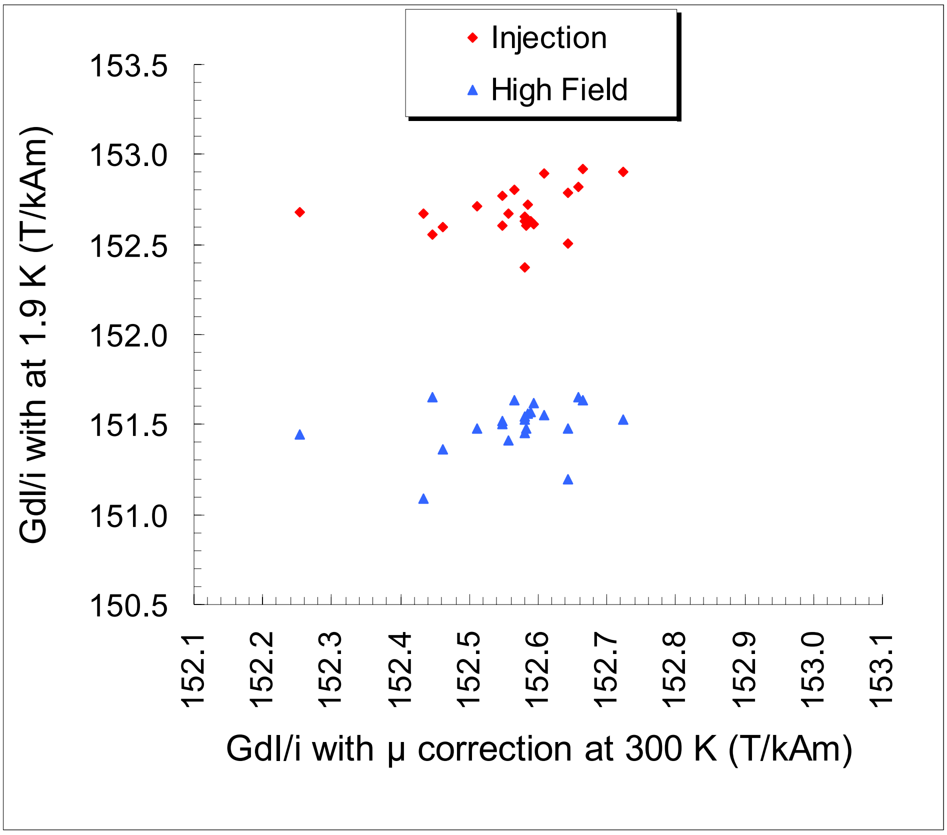

Fig. 15. *G/i dl* correlation for "warm to cold" (corrected for elevated μ)

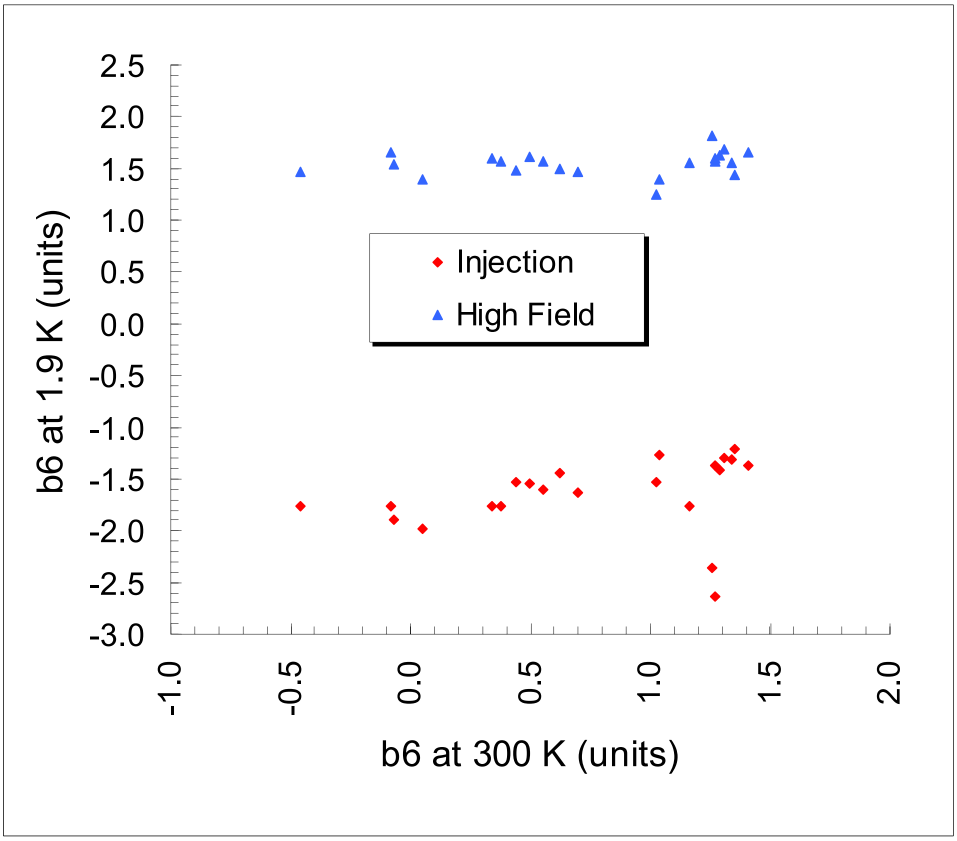

Fig. 16. *b6* correlation for "warm to cold"

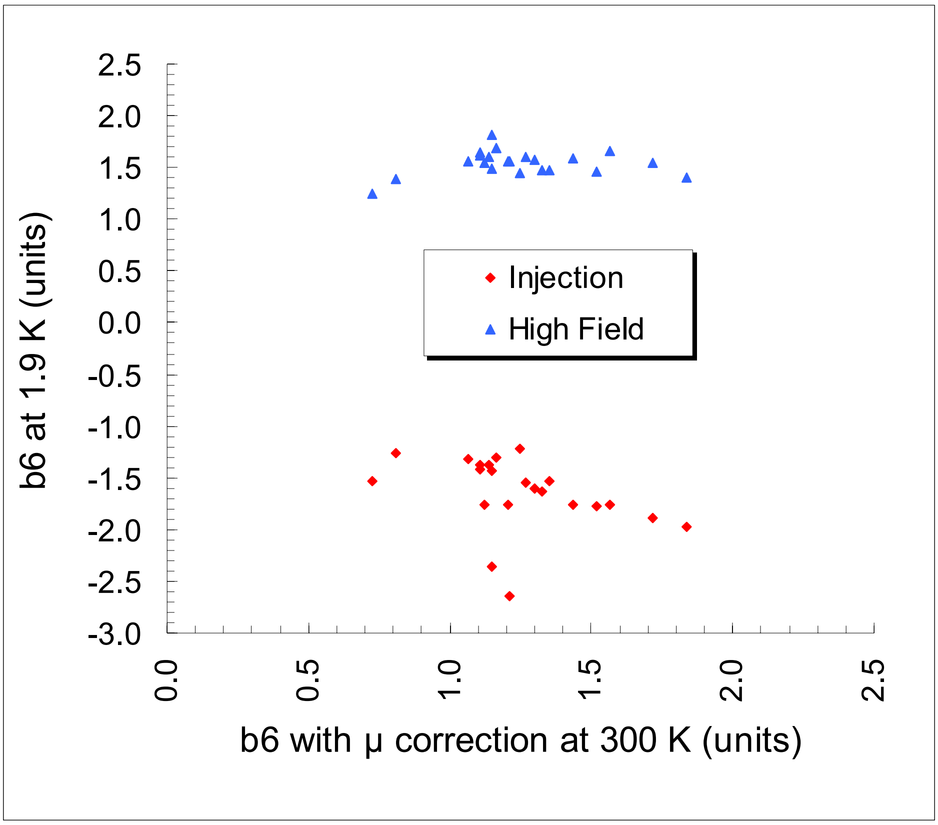

Fig. 17. *b6* correlation for "warm to cold" (corrected for elevated μ)

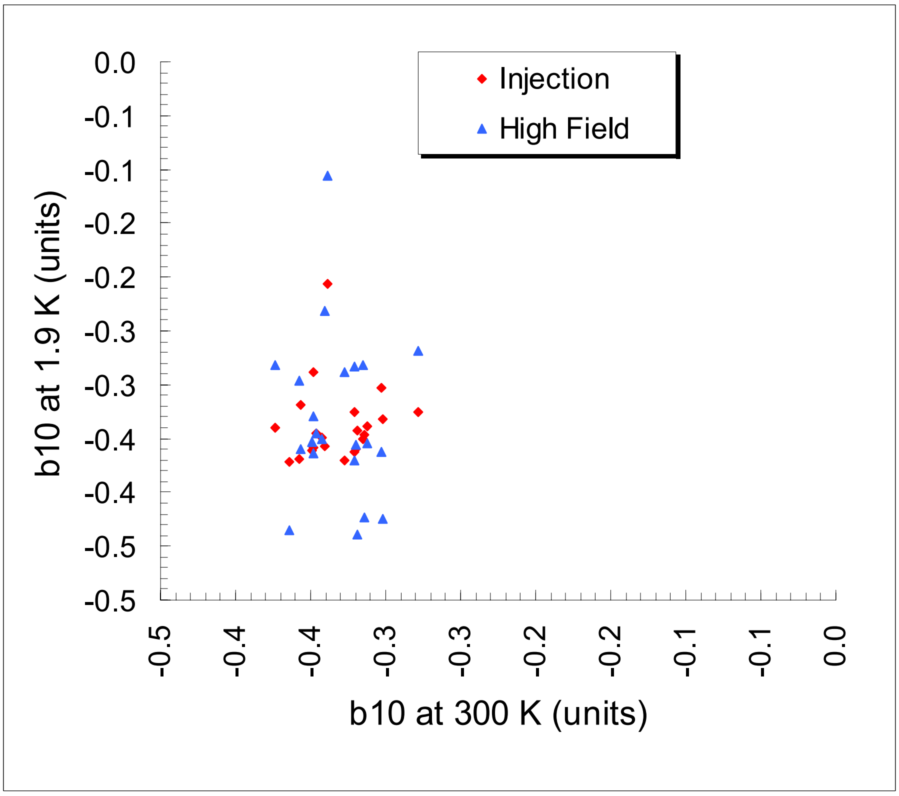

Fig. 18. *b10* correlation for "warm to cold"

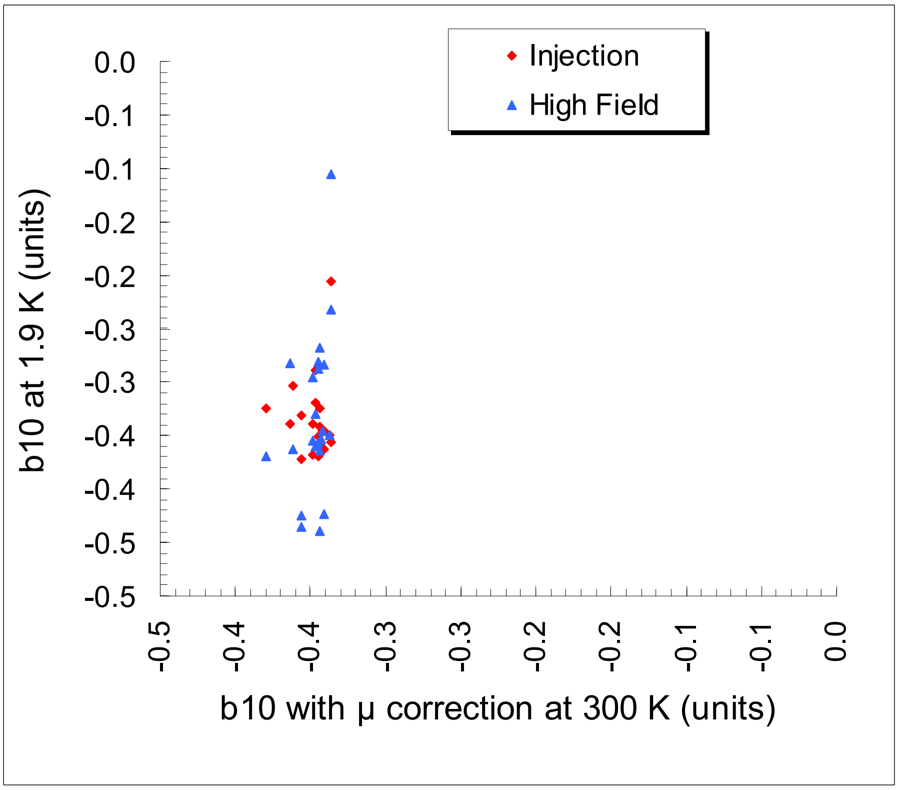

Fig. 19. *b10* correlation for "warm to cold" (corrected for elevated µ)

Conclusion

Table VII shows the cold-warm offsets before and after correction. The µ-correction seems to be effective although the *b6* at injection did not improve much, but the improvement in the *G/I dl* is significant (a factor two) and similar to the one found for the MQM and MQY magnet families.

Table VII. Average and standard deviations for cold-warm offsets, before and after µ-correction

		injection			high field		
		ΔGdl/i (T/kA)	Δb6 (units)	Δb10 (units)	ΔGdl/i (T/kA)	Δb6 (units)	Δb10 (units)
before	**ave**	-0.108385	-2.41	-0.01	-0.108385	-2.41	-0.01
	sigma (units)	18.6	0.6	0.0	18.8	0.6	0.0
after	**ave**	0.125279	-2.90	0.01	-1.066033	0.29	0.02
	sigma (units)	9.1	0.5	0.0	9.5	0.3	0.1

Acknowledgements

We wish to thank our colleagues in AT and ABP for pointing out the anomalies in the magnetic measurements and subsequent discussions.

References

[1] P. Hagen, E. Todesco, "Impact of magnetic permeability of the collars on magnetic field in the LHC main quadrupoles and warm-cold correlations", LHC Project Report 868
[2] R. Ostojic, private communication
[3] MTF. Manufacturing and Test Folders Travellers, url **https://edms.cern.ch/asbuilt/plsql/mtf.home**
[4] M. Giovanozzi and F. Schmidt, private communication
[5] E. Todesco, private communication
[6] N. Lasheras, "Effects of Collar Permeability on the Field Quality of the Large Aperture Quadrupoles for the LHC", presented at MT-20 (2007 IEEE Magnet Technology Conference) , Philadelphia, USA
[7] S. Russenschuck, "ROXIE: Routine for Optimization of Magnet X-Sections, Inverse Field Calculation and Coil End Design", CERN Yellow Report 99-01