Present Status and Trends of Cable Properties and Impact on FQ

Workshop on Field Quality Steering of the Dipole Production
20-21 March 2003

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Goal during production and follow-up

Restrict field errors (average and random) due to the superconductor by:

- **proper specification,**
- **good process control in the firms,**
- **good quality assurance in the firms,**
- **good quality control of the s.c. at CERN.**

(all errors in this presentation at injection in units of 10^{-4} at 17 mm)

Superconductor related effects that have an impact on FQ

	'Persistent' error	'Ramp induced' error	'Geometric' error	Decay and snap-back
Filament magnetisation	Yes			Yes
Inter-filament coupling currents		Very small		
Inter-strand coupling currents		Yes		
Boundary induced coupling currents		Sinusoidal		Yes
Redistribution of the transport current			Sinusoidal	Yes
Cable geometry			Yes	

Filament Magnetisation (M)

Caused by 'persistent' currents within the filaments, (partially) screening the interior of the filaments for a change in applied field.

SPECIFICATION	Cable 01	Cable 02
Magnetisation width at B=0.5 T, T=1.900 K.	< 30 mT	< 23 mT
Maximum spread around the average value for a given manufacturer.	±4.5%	±4.5%

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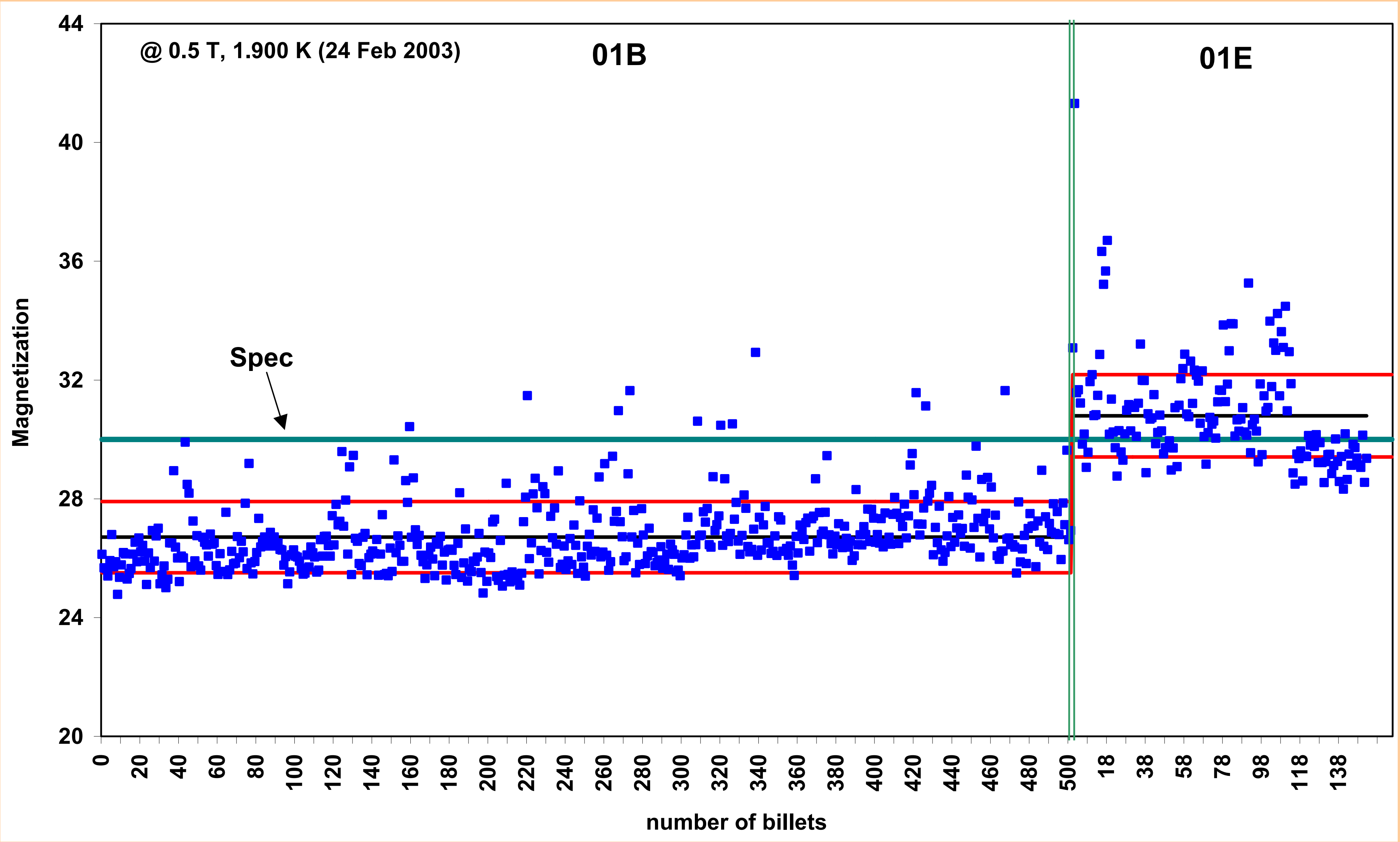
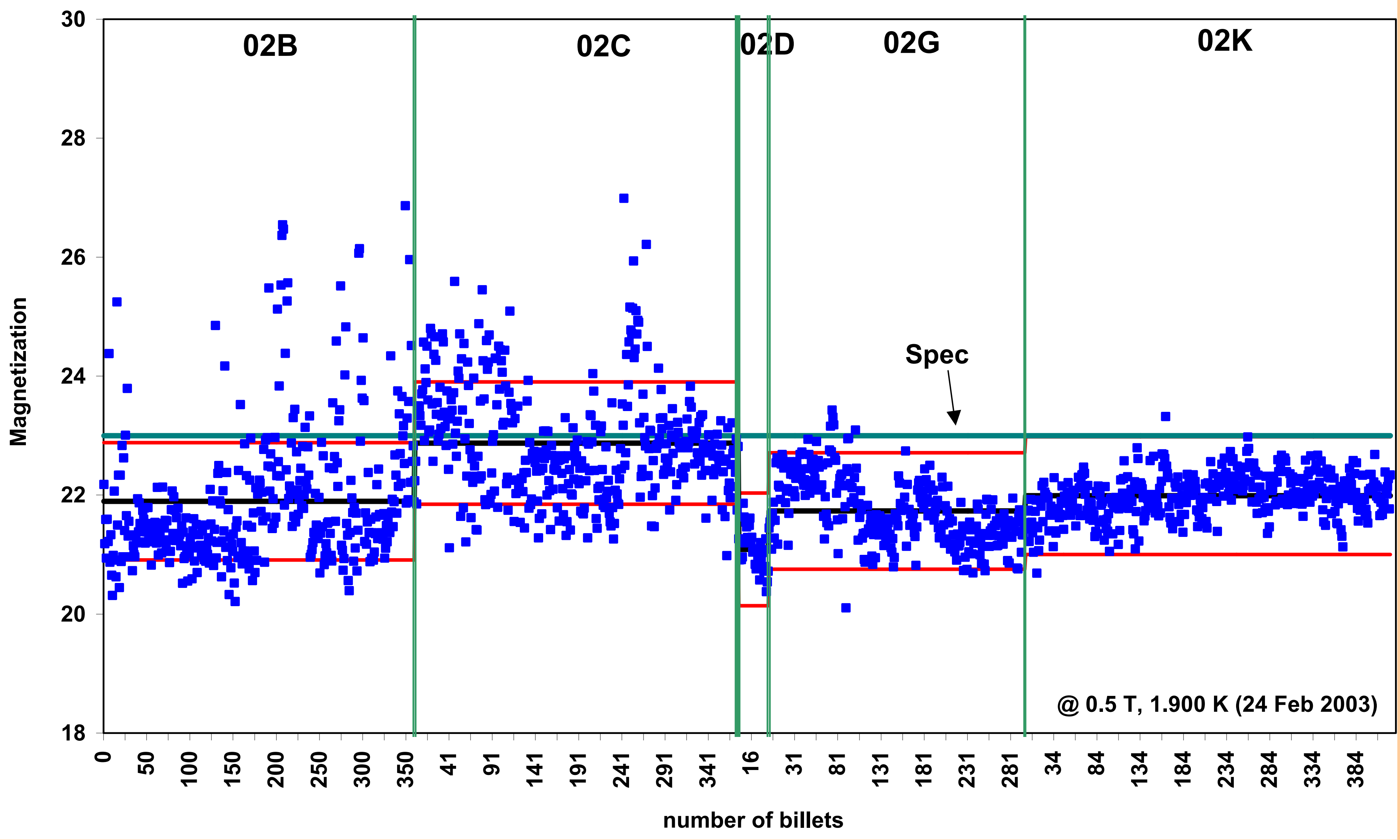
M: measurements strand 01



Data provided by S. Le Naour

M: measurements strand 02



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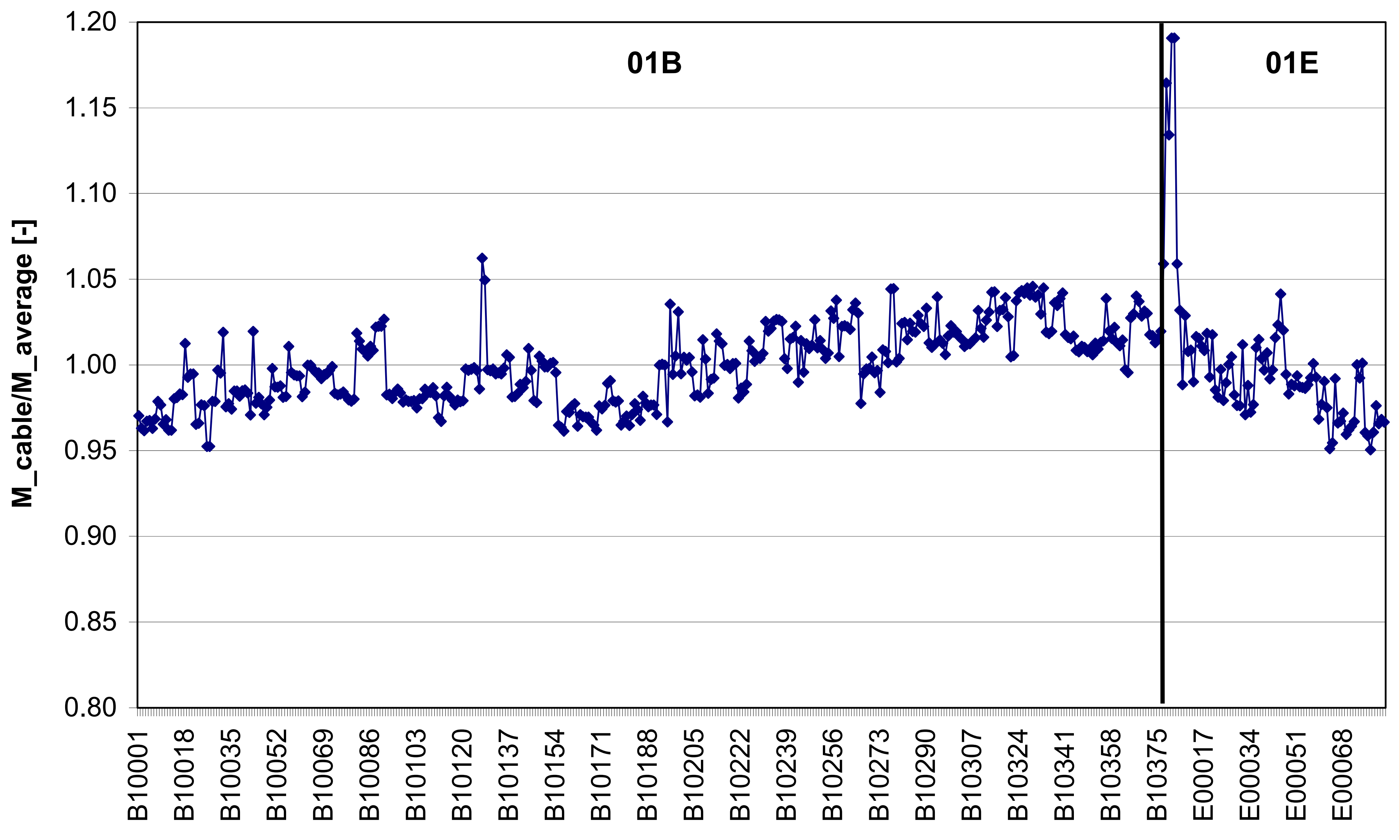
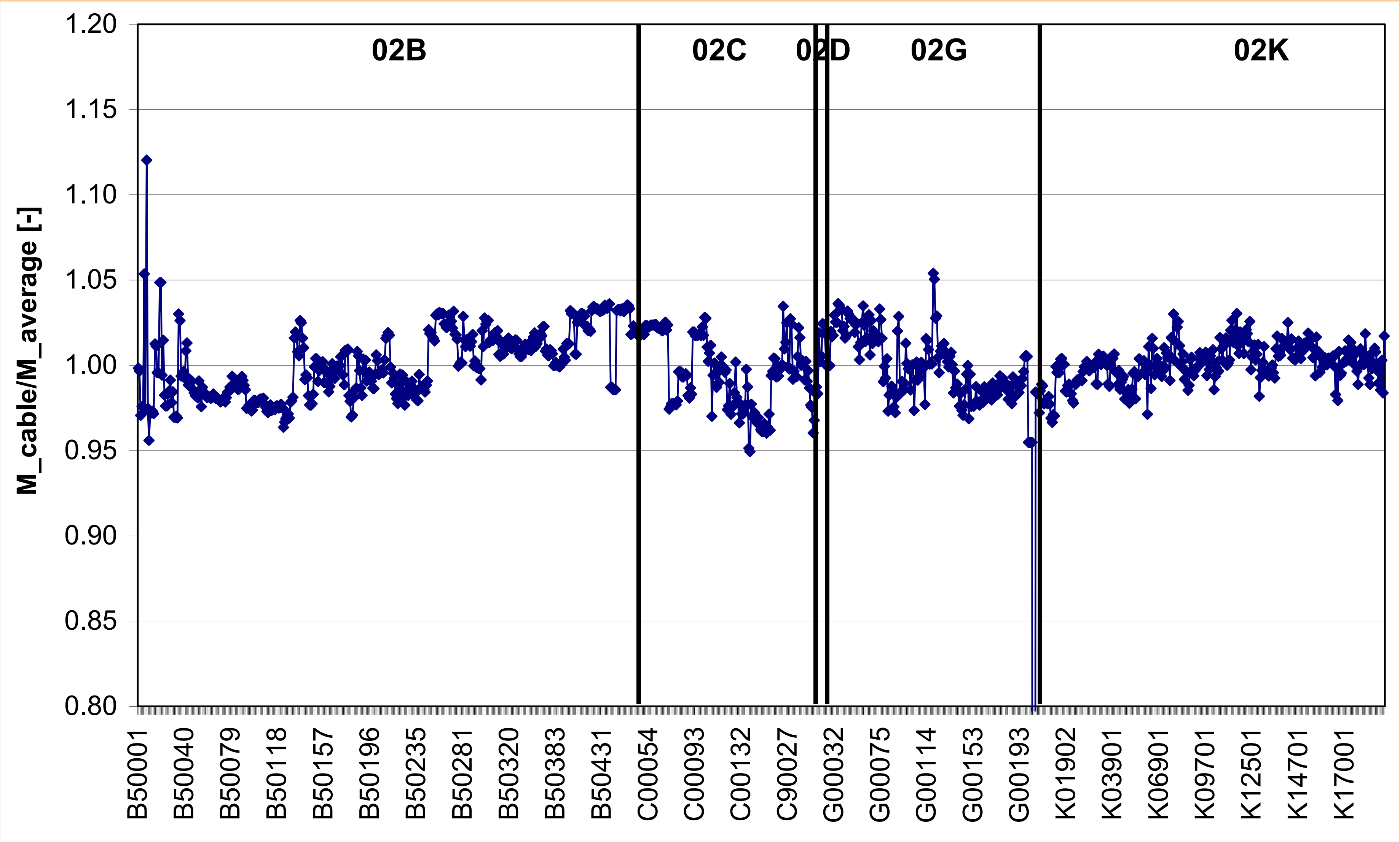
M: cable 01



M: cable 02


02B
02C
02D
02G
02K
M_cable/M_average [-]
1.20
1.15
1.10
1.05
1.00
0.95
0.90
0.85
0.80
B50001
B50040
B50079
B50118
B50157
B50196
B50235
B50281
B50320
B50383
B50431
C00054
C00093
C00132
C90027
G00032
G00075
G00114
G00153
G00193
K01902
K03901
K06901
K09701
K12501
K14701
K17001

M: statistics

Type	Contract size (# oct.)	Produced strands (# oct.)	Average M at 0.5 T, 1.900 K [mT]	Strand σ [%]	Cable σ [%]
01B	5	1.76	26.7	4.4	2.2
01E	3	0.68	30.8 (29.4 *)	5.9 (1.9 *)	4.5
02B	3	0.87	21.9	5.4	2.0
02C	2	0.56	22.9	4.1	2.3
02D	1	0.08	21.1	1.6	1.0
02G	1	0.60	21.7	2.6	1.9
02K	1	0.95	22.0	1.7	1.2
01	8	2.44	27.5		7.0
02	8	3.06	22.0		2.9

* : Recent trend

M: Impact on FQ

Systematic errors for different combinations of inner and outer cable.

Error	01B-02B	01B-02C	01B-02K	01E-02B	01E-02C	01E-02K	All	Target/ Spec.
b_1	-7.1	-7.9	-5.6	-5.2	-5.9	-3.6	-6.3	-8.6
b_3	-8.3	-8.5	-7.6	-8.7	-8.8	-7.9	-8.3	-11
b_5	0.96	1.04	1.03	1.20	1.28	1.27	1.10	1.19
b_7	-0.39	-0.38	-0.39	-0.48	-0.47	-0.48	-0.42	-0.49
b_9	0.18	0.18	0.18	0.22	0.22	0.22	0.20	0.23
b_11	0.031	0.031	0.031	0.038	0.038	0.038	0.034	0.035

Data provided by R. Wolf

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M: Impact on FQ

Random errors

Error	Same cable type per octant (σ=1.7%)	Complete mixing of cable types per octant	Target / Spec. random
b_1	0.33	1.37	8
b_2	0.14	0.14	0.7
b_3	0.11	0.49	1.4
b_4	0.023	0.023	0.5
b_5	0.021	0.13	0.5
b_6	0.003	0.003	0.1
b_7	0.007	0.046	0.2
a_1	0.32	0.32	8
a_2	0.42	0.42	1.9
a_3	0.056	0.056	0.7
a_4	0.065	0.065	0.5
a_5	0.007	0.007	0.4
a_6	0.036	0.036	0.2

Data provided by R. Wolf

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M: Mixing

Mixing strands in a cable:

Large M-variations in the strands result mainly from strong deformation of the filament cross-section (form factor and increased coupling), which does not necessarily affect Ic.
Proper mixing of strands in the cable reduces the M-variations in the cables considerably.

Mixing cables in a magnet:

The 4 inner and 4 outer cables in each dipole will be made by the same manufacturer and if possible produced during the same cabling run (in order to avoid the skew errors).

M: Mixing

Mixing cables in an octant:

The use of the same cable type per octant gives the smallest random field errors, but this is not really required since even for complete mixing the errors are small as compared to the target.

However, for reasons of cable handling, geometry and RRR it is recommended that octants are made of the same cable type, and that the cable type sent to each of the 3 CMA's changes as less as possible.

	ALS	ANS	NOE
Magnets 1-52	01B / 02B	01B / 02K	01B / 02K
Magnets 53-104	01B / 02B	01B / 02K	01B / 02G

Superconductor related effects that have an impact on FQ

	'Persistent' error	'Ramp induced' error	'Geometric' error	Decay and snap-back
Filament magnetisation	Yes			Yes
Inter-filament coupling currents		Very small		
Inter-strand coupling currents		Possibly		
Boundary induced coupling currents		Sinusoidal		Yes
Redistribution of the transport current			Sinusoidal	Yes
Cable geometry			Yes	

Inter-Strand Coupling Currents

- Inter-Strand CC's are currents in and between the strands coupled through the electrical contact resistances (Rc) between the strands, and are generated during a field sweep.
- Typical time constants are about 0.1-1 sec.
- Variations among cables depend mainly on Rc.
- Field errors due to these coupling currents are linear to 1/Rc.
- Target for Rc is >20 $\mu\Omega$ (inner cable) and >40 $\mu\Omega$ (outer cable).
- High Rc not desirable for current redistribution issues.

Rc control

Rc is controlled by oxidation of the thin SnAg coating on the strands.

Process	Parameters	Measurement
Strand tinning	Speed, temperature, tinning die	Coating thickness
Cabling and cleaning		Rc measurement
Cable oxidation (heat treatment)	Duration, temperature	Rc measurement
Storage		
Coil winding & curing		
Magnet assembly		(Rc measurement)

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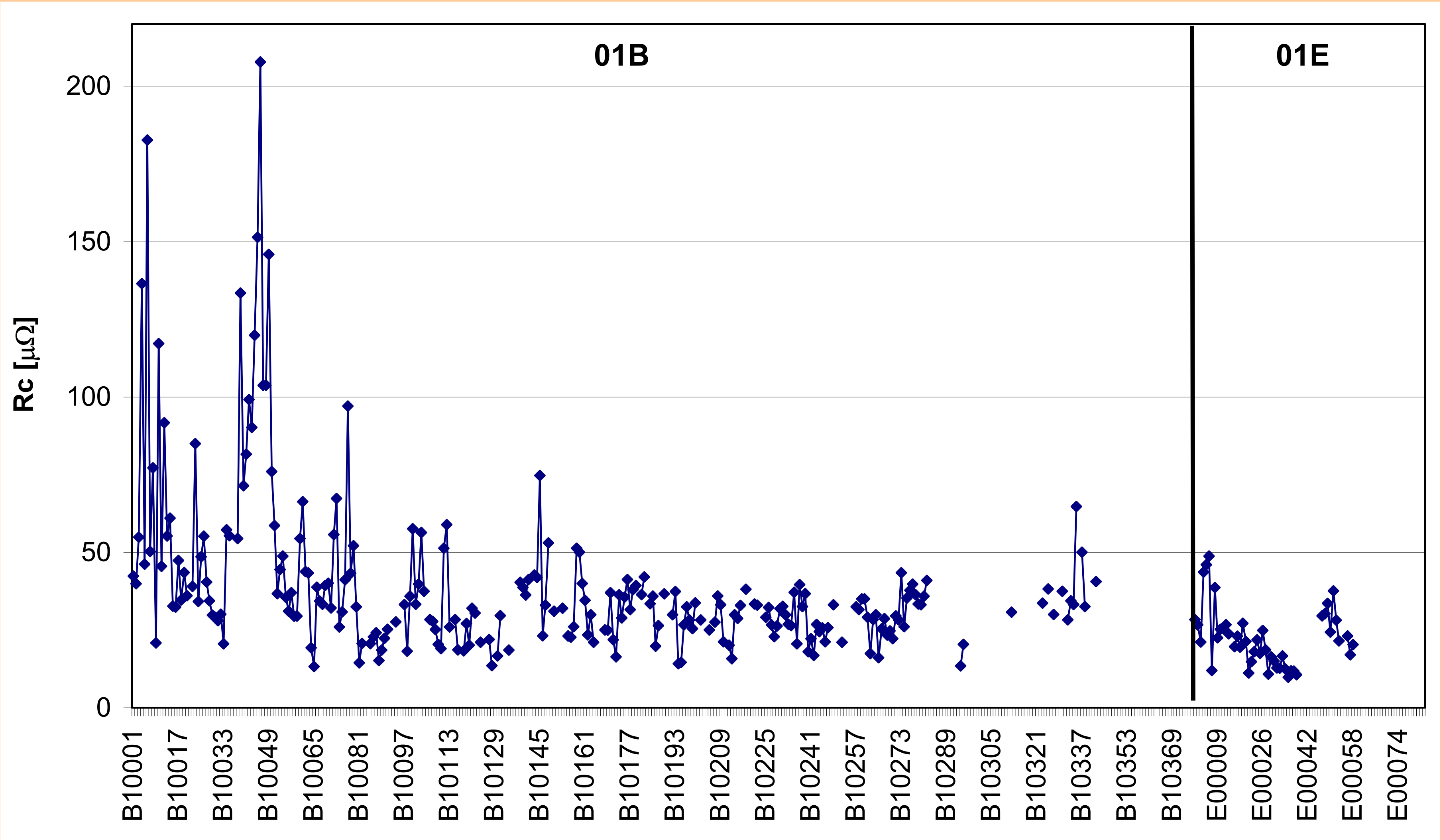
Rc: measurements cable 01



Data provided by D. Richter

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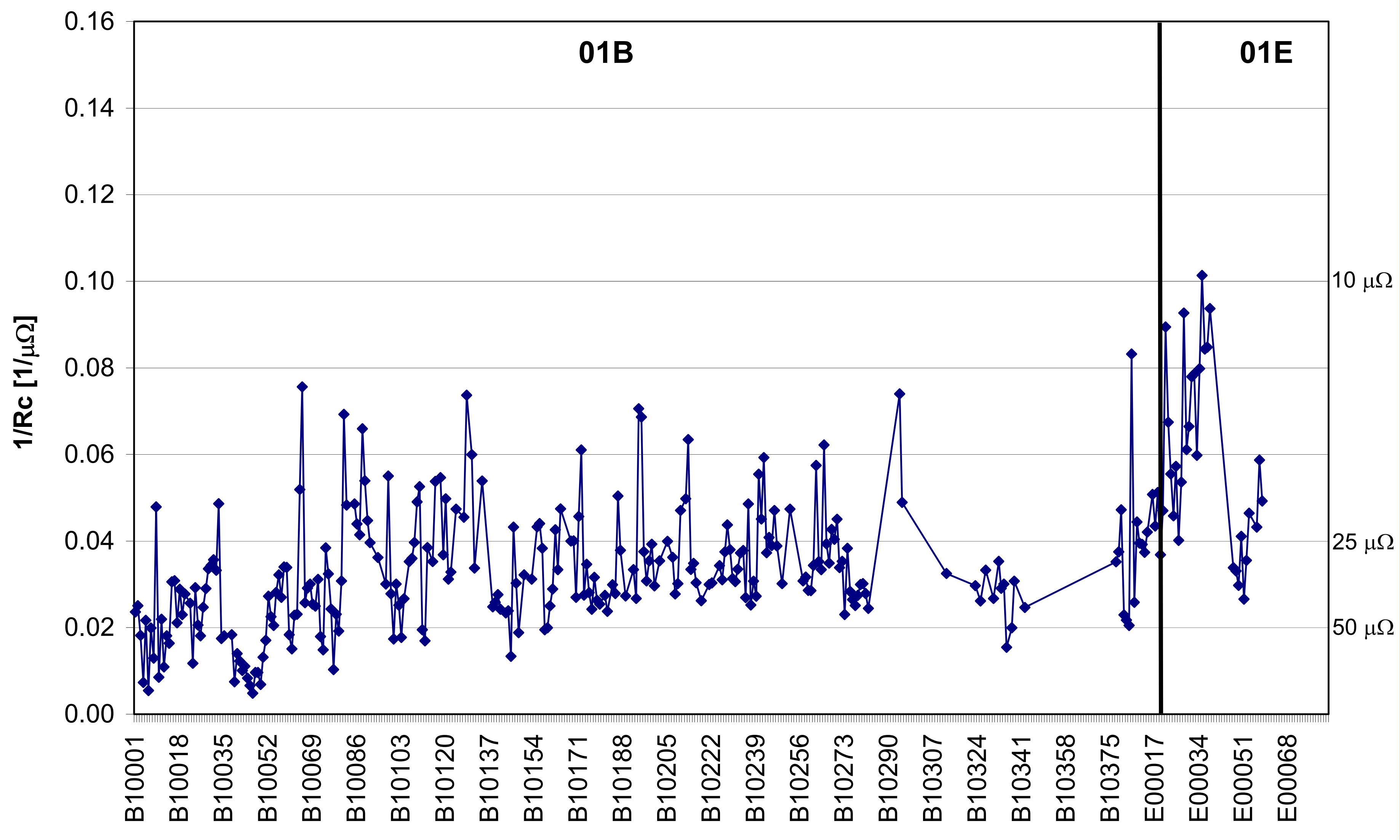
Rc: measurements cable 01



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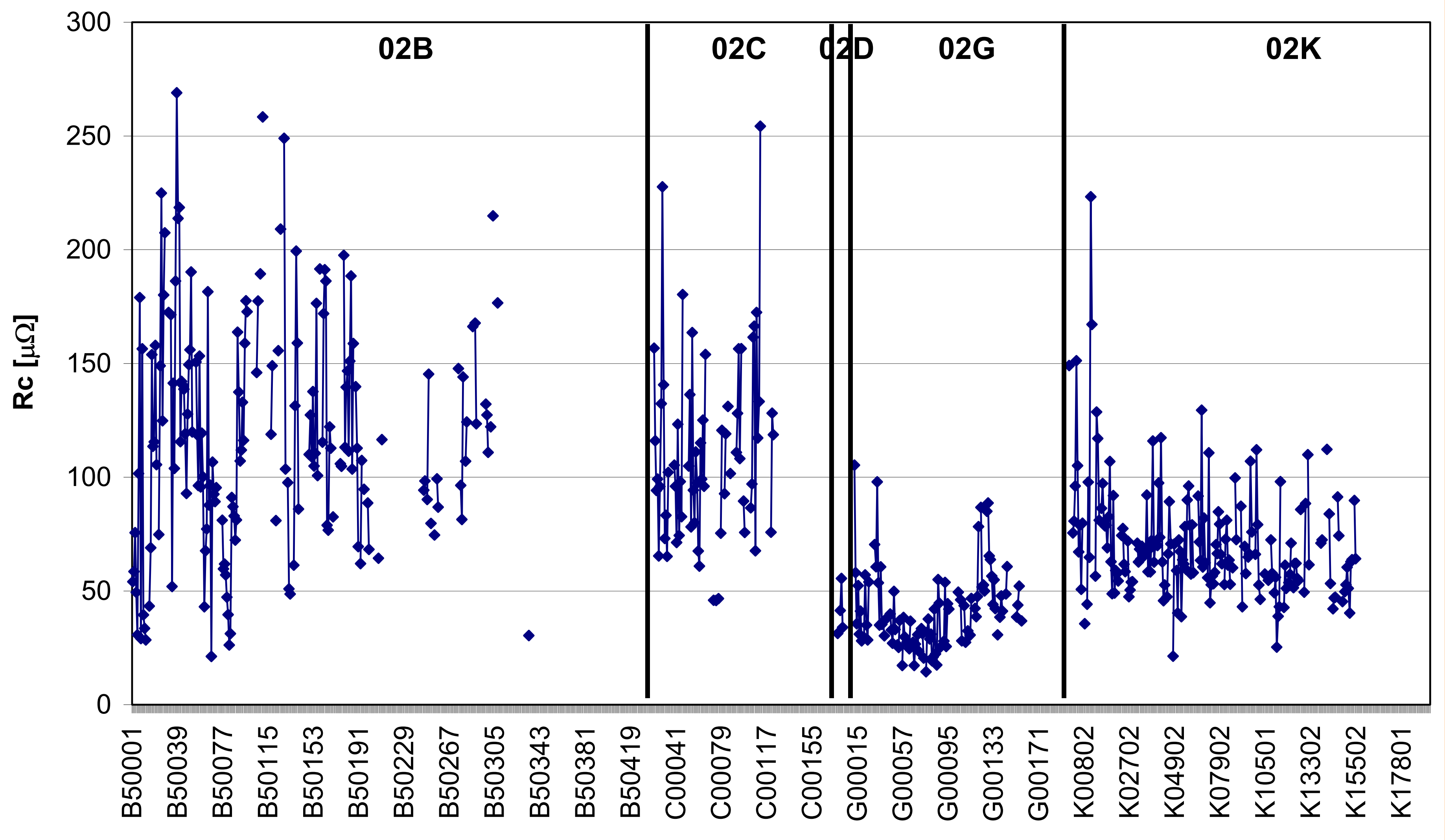
Rc: measurements cable 02



Data provided by D. Richter

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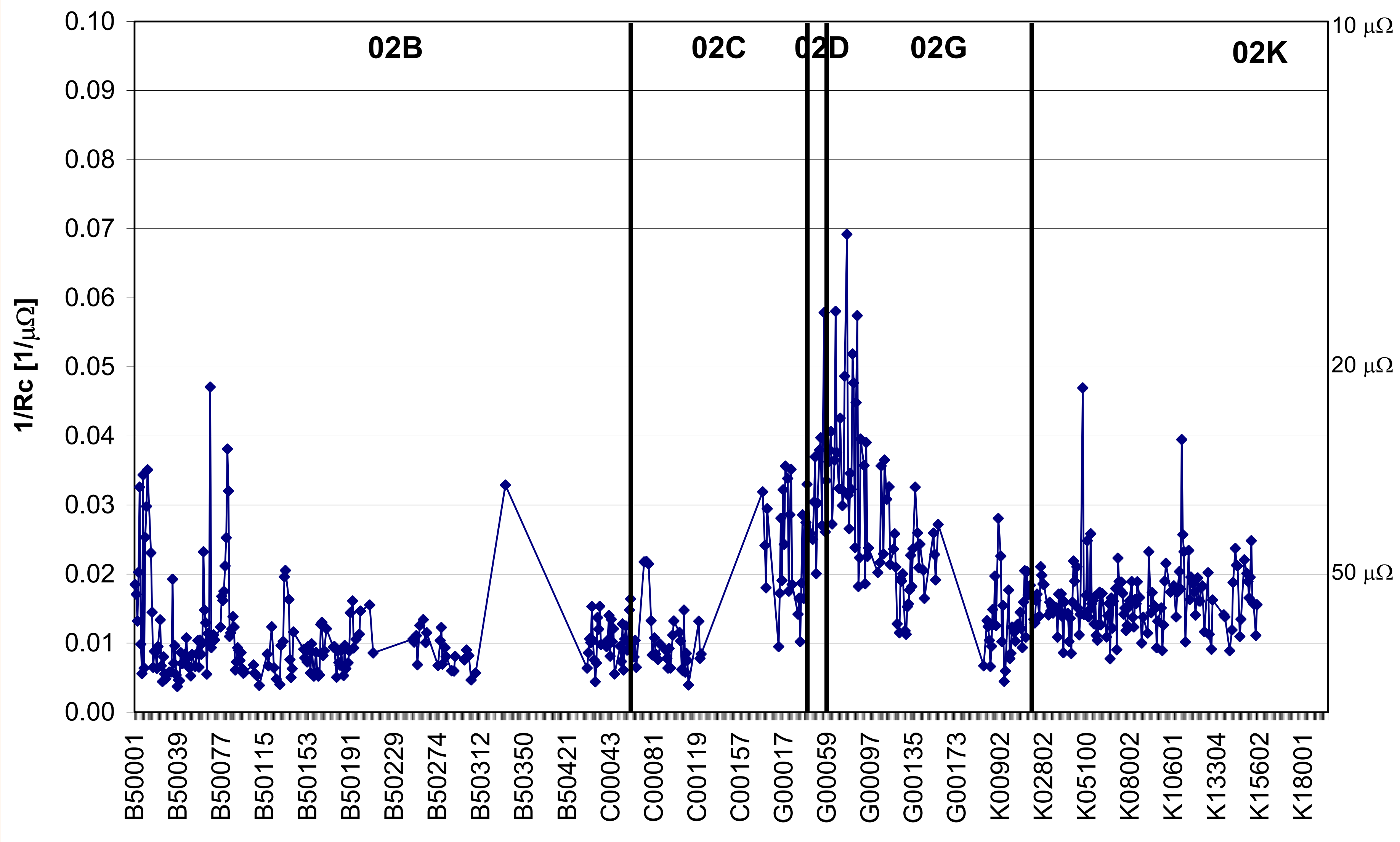
Rc: measurements cable 02



Data provided by D. Richter

Rc: Statistics

Type	Average Rc [μΩ]	σ Rc [%]	Average (1/Rc) [μΩ]	σ (1/Rc) [%]
01B	39	67	0.032	42
01E	22	42	0.053	41
02B	118	43	0.011	65
02C	110	36	0.010	37
02D	41	27	0.026	24
02G	42	42	0.028	40
02K	71	36	0.016	33

Rc: Impact on FQ

Rc=15 $\mu\Omega$ with σ=50%   dB/dt =6.6 mT/s

Error	Average	Random	Target / Spec. average	Target / Spec. random
b_1	5.25	2.0		8
b_2		0.78	1.4	0.7
b_3	0.47	0.58	11	1.4
b_4		0.38	0.2	0.5
b_5	-0.11	0.25	1.1	0.5
b_6		0.13		0.1
a_1		0.52	6.5	8
a_2		1.87		1.9
a_3		0.62		0.7
a_4		0.62		0.5
a_5		0.22		0.4
a_6		0.15		0.2

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Rc: Impact on FQ

Several random errors are close to the target values for a linear ramp of 6.6 mT/s.

But:

With the projected exponential type of ramp all ramp induced errors will be reduced by a factor of 5.

Conclusion:
Actual Rc and σRc values are well under control and cause errors much smaller than the target values.

Superconductor related effects that have an impact on FQ

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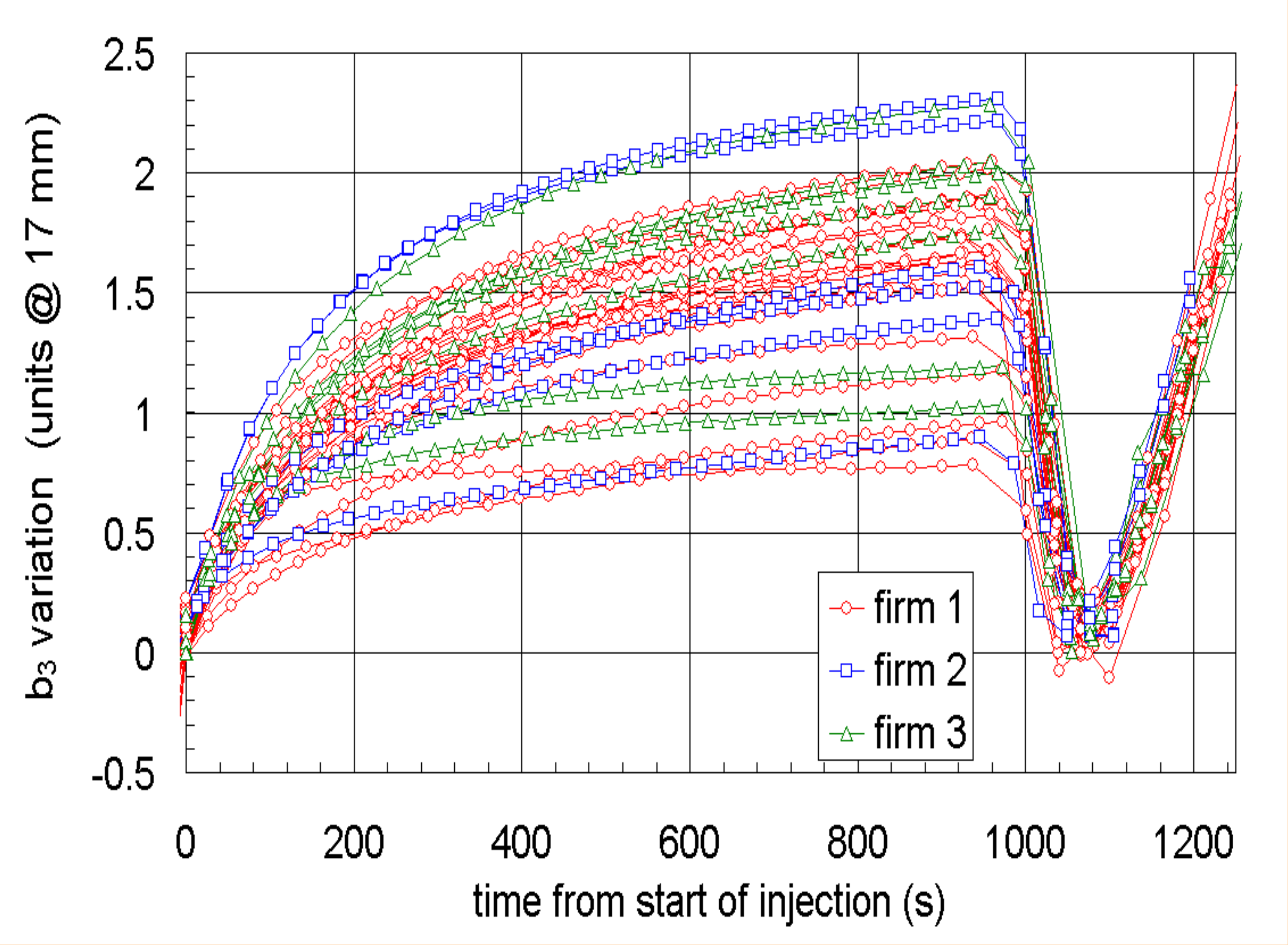
Magnetisation decay and Snap-back



Courtesy: S. Sanfilippo

Magnetisation decay and Snap-back

- The main origin is a change of the local field inside the windings, caused by:
  - Boundary-Induced Coupling Currents, provoked during a field sweep, and slowly decaying after the field sweep.
  - Redistribution of the transport current, mainly provoked by non-uniform joints (also with very long characteristic times).
- Additional origin is possibly some fluxcreep.
- These effects cannot be avoided.
- Decay and snap-back can be non-reproducible at each insertion cycle.
- Maximum decay linked to M.
- Spread not dominated by M-variations and no clear correlation with Rc observed (but also not expected).

Conclusion

With about 30% of the total amount of superconductors for the LHC produced, good statistics is now available, which will be representative for the entire production.

"Persistent" errors:

Random field errors much smaller than target random errors.

"Same cable per octant"-scenario not required (for magnetisation reasons) but favourable (especially for handling, geometry and RRR issues) and will probably be possible if the cable will be produced according to the actual projection.

"Ramp-induced" errors:

Rc is well controlled and the average and spread are such that the ramp-induced errors are much smaller than the target in case of an exponential type of ramp.

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Conclusion

Decay and Snap-back:

Origin: redistribution of the transport current and Boundary-Induced Coupling Currents.

Both effects cannot be predicted quantitatively.

Small statistics at present show no clear correlation with Rc and/or the cable type.

It is likely that the actual scatter will also be present for the rest of the production.

In order to deliver the proper cables to the CM assemblers, it is important that it is clarified how the magnets & cables of the different manufacturers should be distributed over the 8 octants.