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LHC Project Report 99

Summary of the LHC Workshop on Dynamic Effects and their Control

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Abstract

A brief overview is given of the discussions and recommendations formulated during the "LHC Workshop on Dynamic Effects and their Control". The workshop took place at CERN from 5 to 7 February 1997 in order to discuss the required performance for the control of the LHC beams and the accuracy, reproducibility and stability of various key equipment in the presence of the expected dynamic effects of the LHC superconducting magnets.

*CERN / AC
Reported on behalf of the workshop organizing committee (J.P. Koutchouk, P. Proudlock and R. Schmidt) and the Dynamic Effects Working Group.

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1. Introduction

The workshop took place in the LHC auditorium on the CERN Meyrin site from 5 to 7 February 1997 and was opened with a short welcome given by the LHC Project leader L. Evans. The workshop consisted of four plenary sessions, a morning devoted to break-away groups and a final summing-up session as follows:

		Session title	Chair
Wednesday 5 February	am	Scene setting and requirements	R. Saban
	pm	Experience from other machines	J. Gareyte
Thursday 6 February	am	Magnet system	C. Wyss
	pm	Beam observation and feedback	R. Bailey
Friday 7 February	am	Break-away discussions	
	pm	Summing-up	P.Proudlock

This report will not give an account of each session but rather endeavour to sum up the main points, conclusions and recommendations of the workshop. It also contains some background thinking formulated during the sixteen meetings of the Dynamic Effects Working Group (DEWG) which took place before the workshop. The names of the members are given in Annex 1.

A complete set of all transparencies presented during the workshop is available at the workshop secretariat (CERN Building 30/6-031) and more information can be found on the WWW; access from the LHC project welcome page.

The workshop was attended by 115 participants (not necessarily full-time) and a list can be found in Annex 2. These included representatives from DESY (HERA), Fermilab (Tevatron) and BNL (RHIC).

2. Aims of the workshop

The aims of the workshop were to establish the required performance for the control of the LHC beams and the expected accuracy, reproducibility and stability of various key equipment. From this it was hoped to set a possible scenario for the operation of LHC in the presence of the expected dynamic effects of superconducting magnets and thus establish, where possible, the equipment needs as well as the necessary development programmes.

3. Dynamic Effects in superconducting machines and the LHC

All accelerators are confronted with the problem of taking a beam(s) from injection energy to top energy in the presence of non-linearities, differing response times and transfer functions (some varying with time) of equipment without detriment to the parameters of the beam dynamics.

In machines using superconducting magnets these problems are made worse by large variations in the field and field errors not only at the start of ramping but even at injection when the persistent currents decay causing field changes of several units [1] even with stable current. The ramp induced errors, caused by coupling currents within the superconducting cable, are now better understood and are expected to be reproducible as a result of controlling and limiting the spread on the inter-strand contact resistance of the cable. However, the understanding and prediction of persistent current behaviour is less evident. The decay at stable current and "snap-back" (Fig. 1) of the fundamental and multipole components depend very much on the previous powering history of the magnet and are not, at present, easy to predict [1].

The LHC suffers from its size and certain constraints imposed by the use of the existing infrastructure of LEP. The very large electrical stored energy has resulted in an electrical segmentation of the machine into eight sectors requiring tracking amongst sectors as well as families of magnets. The sectors will be equipped with magnets from the same manufacturer. Many parameters, such as tune and chromaticity, have relatively large numbers which means that tolerances are tight. For instance, the sextupole component of the persistent current amounts to about 500 units of chromaticity while this needs to be corrected to a few units. Exact know-ledge of the correction to apply under all operating conditions will be a considerable challenge.

In general, safety margins are strictly limited since they are very costly in a machine of this size and this gives rise to tight tolerances on many parameters.

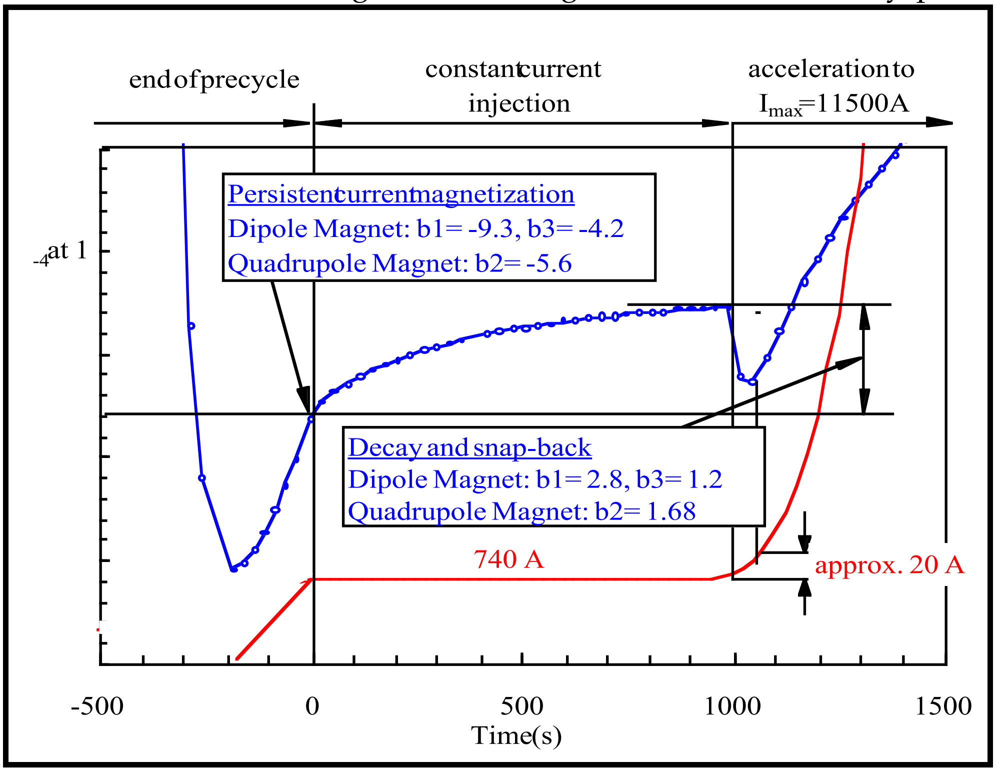

Figure 1 Example of persistent current decay and snap-back

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[1] One unit is defined as 10^{-4} of the main field at 10 mm.

4. Beam dynamic tolerances

The beam dynamic tolerances were presented and discussed. They will be published in another report [2]. These were presented for several stages of the machine's development from initial commissioning through to regular operation. Tolerances are reasonable during the commissioning stage but became very tight (e.g. $\Delta Q= 0.003$) once high performance is required operationally which is particularly difficult during injection and the start of acceleration. This means that, while accuracy was not an important issue, reproducibility and short term stabilities were. The tolerances were considered acceptable but it was noted that a larger acceptance of momentum spread was necessary at injection (increase $\Delta P/P$ accept-ance from 1 to $3x10^{-4}$). In general, the LHC will require a very good control of beam parameters which is normally only obtained after several years of operation.

5. Current cycle in the main magnets

There is every interest to start the acceleration very slowly so as to minimise the transients in the field and field errors particularly during the "snap-back" of the persistent current decay. It was shown that the estimated errors produced by the main dipole, with a constant dV/dT (and therefore parabolic current waveform) until full voltage is reached after 500 seconds, would require corrections during snap-back about once every second. However, it could well be prudent to pass through the region of snap-back before allowing the boost voltage of the dipole supply to turn on, and a revised cycle with a reduced rate of voltage at the beginning of the cycle will be studied and published shortly. *(Action: DEWG)*

In order to achieve these slow rates as well as for fine adjustments, the power converters will need a monotonic resolution of 1ppm of maximum.

It was suggested that by using a continuous slow ramp at injection the decay of the persistent currents (and therefore the snap-back) could be avoided but this would imply either injecting with an increasing momentum from batch to batch or correcting the increasing field and field gradients with correctors (the correctors have a considerable strength at injection). Although not immediately attractive, it is probably worth studying these possibilities further. *(Action: DEWG)*

Because of the large hysterisis in the dc magnetisation curves it is important that the overshoot (and undershoot) is zero or at least kept below 5 ppm of maximum at injection. Further, it is desirable, particularly at the beginning of machine operation, that a ramp can be stopped at any point. *(Action: SL/PS/CO)*

The main dipole magnets can be ramped-down at a constant -10A/sec, but because the power converters of the main quadrupole circuits can only supply a very small negative voltage, they will follow an exponential descent with an initial rate of -30A/sec. *This means that deceleration (at nominal rate) would not be possible but no requirement has been identified.*

6. Reference magnets

The present layout of the LHC foresees a set of reference magnets (one dipole and one quadrupole) connected in series with each of the main power converters of the eight separately powered sectors of the machine (Fig. 2). Because of the lack of space and the need to place them close to the start of the arcs (cryogenic and electric feeds), they will need to be housed in enlargements of the existing tunnel. This represents an expensive installation and the workshop was asked to consider alternatives both in terms of the number needed and the location.

This issue was considered, in particular, by the groups on "Experience from other Machines" and "Magnetic Systems" both of which came to a similar conclusion.

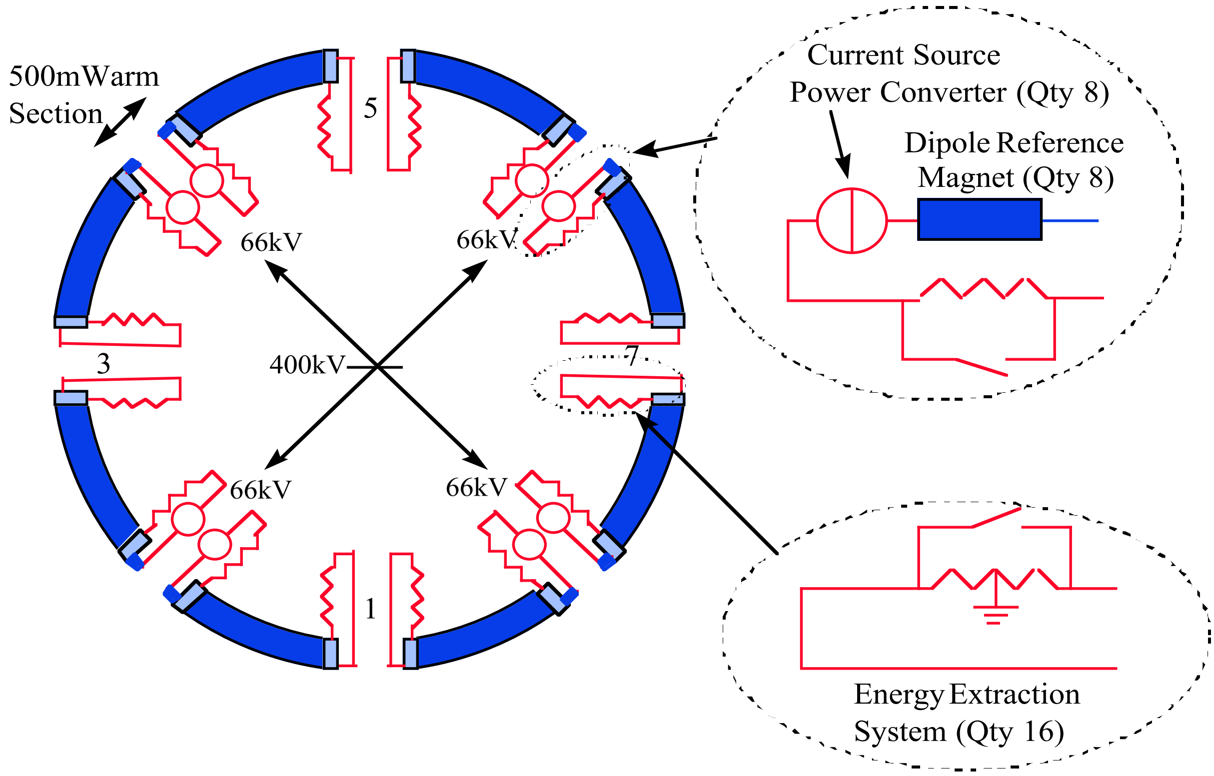

Figure 2 Segmentation of main dipole circuits (reference magnets in tunnel)

Since LHC will use less than eight dipole manufacturers, past powering history and power converter tracking were identified as the only reasons for the choice of eight in-series sets of reference magnets. However, it is not necessarily the case that an in-series reference magnet would always give a true reflection of the integrated fields of a sector. The effect of a quench, for instance, of one (or several magnets) in a sector would not be observed by a reference magnet. (At HERA they do not quench the reference magnets after a machine quench.) However, an in-series reference magnet would experience the rapid discharge current (TC = 100 sec). Recent improvements in power converter performance (see Power Converters) means that tracking should no longer be an issue.

Therefore, taking into consideration:

- *the better understanding of the behaviour of superconducting magnets;*
- *the expected performance of the power converters;*
- *the operating principle of correcting all dynamic effects with correcting magnets;*

it is recommended that reference magnets, with comprehensive instrumentation, be installed remotely in building SM18 and that there should be one per type of dipole and one per type of quadrupole. The reference magnets can either be driven individually, using the power converters of the magnet measurements, or driven in series for each family giving a simplified operational scenario but perhaps requiring a special power converter for the dipole chain because of the increased inductance. (The latter has become known as the "9th sector" of LHC.) This can better be decided once we have an idea of the series magnet performance and the exact number of reference magnets needed.

However, so as to allow additional verification within the machine, these remote reference magnets should be complemented by flux-loops measuring the fundamental fields of the dipoles and quadrupoles of the machine magnets of each sector. It is not clear yet whether these should be fitted in some or all of the magnets and also whether the reference magnets should be chosen from magnets equipped with flux-loops. The flux loops can only make dynamic measurements during tracking and they are not useful for multipole control (unless, as may be the case, a correlation with the fundamental exists).

This solution has several advantages:

- SM18 would become a calibration and standards centre for the LHC as far as current and field measurements are concerned and their relationships with respect to dynamic effects.
- The reference magnets could be developed with, or out of, the magnet test benches used for the series measurements thus concentrating resources.
- The reference magnets themselves would not need the enlargements and would be accessible at all times.
- Such an area could be on-line to assist with machine operation or off-line for new developments, depending on the state and use of the machine. The area would also be much more flexible and accept changes more readily than a tunnel solution.

The disadvantages are associated with recovery from a failure of the power–ing or cryogenics systems in SM18 and the fact that the infrastructure of SM18 becomes important to machine operation until such time as it is not needed on-line. Scenarios for recovery from these failures, as well as a sector quench, need to be investigated in theory and practice. (The first indications are that, following a quench, a sector will need to be cycled once to top-energy and remain there for typically 15 minutes before re-injection [1].) This will also define in part some of the measurements needed during the series measurements. *(Action: DEWG)*

It was also suggested that one reference magnet could be placed in one of the sectors to allow comparison and that this could be a short model. This needs further study. *(Action: DEWG)*

7. Beam instrumentation

It was generally accepted that LHC will need comprehensive beam instrumentation from the start-up. Fast orbit acquisition and good correction software will be needed already at the commissioning stage. A clear request for pick-ups reading in both planes at each quadrupole aperture has been made [3]. (This is more realistic both technically and financially now that it has been decided to install electronics in the LHC tunnel.) On-line orbit stabilisation with local feedback is needed in general but especially for the cleaning insertions. New techniques to observe coupling, tune and chromaticity need to be investigated with a view to using these signals for on-line corrections should they prove suitable. HERA was about to make some interesting machine developments on this subject and following the workshop some very encouraging results were obtained.

8. Power converters

A reasonable, although tight specification for the main ring power converters was agreed upon as follows:

Resolution	*1 ppm of maximum*
Short-term stability and dynamics	*±3 ppm of maximum*
Reproducibility and tracking between sectors	*±5 ppm of maximum*
Accuracy	*±10 ppm of maximum*

The requirements, expressed in terms of maximum current, come from the needs at injection. These are 15 times less severe when expressed with respect to the actual current at injection.

It was therefore suggested, both for magnet measurement and for the machine, that the possibility of a second low-level current measurement should be investigated since this could give improved sensitivity around the critical operating region. (Action: SL/PS)

Current ripple specifications need further work and the exact requirements for the insertions have not yet been fully considered. *(Action: LHC/ICP, SL/AP, SL/PS)*

The powering system and its performance are important to the success of the machine. It is therefore essential that the work achieved to date on precision and digital aspects (predictive regulation) continues and that a close collaboration is maintained between magnet testing and power converter specialists.

9. Controls

Although it is not clear today which parameters require or eventually will use on-line control, *it is recommended that the machine is prepared to accept slow feedback as far as the control, power converter and RF systems are concerned*. Best estimates suggest a rate up to a few Hz, but this will depend, for instance, on the exact magnet ramping speed. Likewise field and beam instrumentation should be suitable for inclusion in such a feedback system.

10. Development programme

Beam instrumentation and controls pilot projects were proposed on the SPS and LEP. For beam instrumentation these will concern mainly studies on tune and chromaticity. These could, as well as being important for LHC, eventually benefit these machines. HERA is also developing new techniques and these should be followed closely. (See earlier statement under beam instrumentation.)

SM18 will become an important centre for magnet, power converter and controls evaluation. Work will start as soon as possible using the test benches to understand just how well tracking and correction can be achieved either by prediction or feedback. This will be further developed once the full powering scheme of String 2000 becomes available.

The SM18 reference magnet system for the machine will also be developed in parallel to the magnet measurement programmes and could hopefully utilise a large part of its hardware. The first reference magnet for the sector 8 to 7 could be available and participate in the sector tests of 2003.

11. Operation

Although it may seem early days, it was considered worthwhile to discuss possible operational scenarios in order to verify or specify requirements and the workshop looked at this.

A principle of operation [4] was outlined using predefined tables (corrected by feed-forward) to drive all eight (and the reference magnets in SM18) families of main dipoles and quadrupoles. Verification of field and field error settings would be made from measurements on the reference magnets in SM18 representing each type of magnet. In particular b3 and b5 correction would be made using the associated correctors in each sector of the machine. Injection of a pilot pulse and capture can be achieved as long as reasonable reproducibility is achieved (one to two units on the main field). Once injected, correction of local orbit, coupling, tune and chromaticity would be made using various correctors but not the main fields. (Such corrections could be fed-forward to up-date the tables for the next cycle.) LHC is anyway a very slow electrical machine with large time constants in the main circuits (23000 seconds for the dipoles) meaning that correction will be difficult with the main circuits and any “fast” adjustments will have to use the corrector circuits.

Already at the commissioning stage, it is felt that acceleration will need on-line correction of the orbits (very good control of the closed orbit (~0.2mm) is necessary in order to minimise the effects of non-linearities) and feedback from the reference magnets will be needed for the main dipole spool-pieces (b3 and b5 correctors). As well as using the reference magnets, verification of the performance of the main fields in the machine would be made using the flux-loops, probably in a post-mortem mode. Later, but still early in the life of the machine, as the machine progresses and increased performance is needed, on-line correction of coupling, tune and chromaticity will be needed.

12. Miscellaneous

Other points were raised during the workshop some of which are not strictly related to dynamic effects. Some of these have already been mentioned, e.g. ripple specifications.

Interference from the SPS pulsing on LHC operation (as seen at LEP) was thought to be insignificant due to the much greater field levels of LHC. However, this should be quantified since, apparently, the exact coupling mechanism is still not fully understood. *(Action: DEWG or PLC)*

The temperature tolerance of the cryo-magnets is not yet specified and this could be important for the remote reference magnets. *(Action: LHC/MMS)*

References

[1] L. Bottura, LHC Project Note in preparation.

[2] JP. Koutchouk, LHC Project Note in preparation.

[3] J. Miles, LHC Project Note 76.

[4] R. Schmidt, Slides from Summary Session available on the WWW.

Annex 1

List of Members of DEWG

R. Bailey/SL
F. Bordry/SL
L. Bottura/LHC
P. Burla/SL
K. Henrichsen/LHC
J.P. Koutchouk/SL
R. Lauckner/SL
R. Parker/ SL
J.G. Pett/SL
P. Proudlock/AC
H. Schmickler/SL
R. Schmidt/LHC
L. Walckiers/LHC
R. Wolf/LHC

Annex 2

List of Registered Workshop Participants

Ang	Zhengting	LHC	Henrichsen	Knud	LHC
Annala	Jerry	FNAL	Herr	Werner	SL
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Bailey	Roger	SL	Hofle	Wolfgang	SL
Barnett	Ian	SL	Holzer	Bernhard	DESY
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Beetham	Gary	SL	Ijspeert	Albert	LHC
Billan	Jacques	LHC	Jeanneret	Bernard	SL
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Bordry	Frédéric	SL	Jensen	Steen	SL
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Catalan Lasheras	Nuria	SL	Lauckner	Robin	SL
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Collier	Paul	SL	Lüttge	Cristoph	DESY
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De vries	Jannes	SL	Myers	Stephen	SL
Dehning	Bernd	SL	Oberli	Luc	LHC
Di Maio	Franck	PS	Parker	Robert	SL
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Fernqvist	Gunnar	SL	Rausch	Raymond	SL
Fischer	Claude	SL	Reichel	Ina	SL
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Schmickler	Hermann	SL
Schmidt	Rudiger	LHC
Schmidt	Frank	SL
Schmüser	Peter	DESY
Schneider	Michael	LHC
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Vanden Eynden	Marc	SL
Verdier	André	SL
Verweij	Arjan	LHC
Vos	Luc	SL
Wagner	Udo	LHC
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