An Alternative to Classical Real-time Magnetic Field Measurements using a Magnet Model

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Abstract

Longitudinal and transverse beam control in circular accelerators depends critically on a reliable real-time knowledge of the magnetic bending field. Traditionally this is achieved with a long-measurement coil placed in a reference magnet. In the CERN PS Booster, such a measurement generates a 1 Gauss step-size train with an absolute precision of 0.1%. Modern magnet control can be done with a precision of 0.01%. Consequently, a synthesised magnetic field train based on a reliable magnet model could potentially yield a 10 times better result. The PSB will become a part of the injector chain for the future Large Hadron Collider (LHC). Therefore the main power supply of the PSB has been upgraded to full cycle $L\frac{di}{dt}$ control. This has made it possible to follow the entire magnetic cycle with a refined model, and to synthesise a real-time magnetic field train from a newly developed programmable pulse generator. We will discuss the general design concepts and the first results.

1 Introduction

Precise knowledge in real-time of the magnetic field in the main bending magnets in synchrotrons as a function of time is important for longitudinal and transversal beam control. In addition, many measurement applications depend critically on such information for the correct evaluation of acquired data. The demand on precision and resolution varies with application and machine. The PS Booster (PSB) has 4 superimposed rings using 4-gap bending magnets. In this machine, the most severe demand on the B-field measurement comes from the digital longitudinal beam control system which requests 0.3 Gauss precision and 0.1 Gauss resolution.

The magnetic field in the PSB bending magnets is currently measured with a long coil in a reference magnet that is powered in series with the main dipoles. The data is distributed in real time with an incremental pulse train with 1 Gauss resolution (B-train). Any system in need of this real-time information simply has to count the number of pulses from a timing signal marking the start of the magnetic cycle. A pre-burst before the start of the field increase assures that all counters initially are set to an offset corresponding to a low field reference formed from the field at bottom current and the remanent field.

Within the LHC project, the main power supply of the PSB is being renovated. The accelerator operator can now define the complete magnetic cycle with an application program in physical units. The Main Power Supply (MPS) control unit receives a vector array with $L\frac{di}{dt}$ as a function of time, and executes the cycle with a precision of 0.01 %. A theoretical magnet model has been developed which makes it possible to predict the magnetic field throughout the machine cycle from the available $L\frac{di}{dt}$ vector array with twice the measured precision of the present long coil B-train generation system. This information is distributed through software channels to provide magnetic field information directly in application programs and to create a synthetic B-train.

2 Mathematical model magnet of the PS Booster

The feedback loop of the PSB main power supply control (Fig. 1) determines the current to be supplied to the magnets based on the $L\frac{di}{dt}$ functions programmed by the cycle editor application program, and the bottom current value I_{bottom} with a precision of 0.01% (10^{-4})

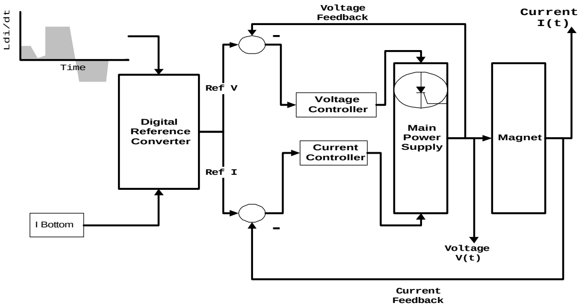

Fig. 1: Main Power Supply control feedback loop of the PS Booster

Small correction functions are used to ensure that the integral of the magnetic field around the machine $\int Bdl$ seen by the beam is the same in each of the four PSB rings. As the geometry and relative permeability μ_r of the magnets are nearly constant, and no significant core saturation occurs, even at the highest field value (0.8 T), then a linear relationship between current I and the resulting field B can be assumed. In this case the simple model illustrated in Fig. 2 [1], which models the resulting $B(t)$ function from $\left(\frac{dB}{dt} \propto L\frac{di}{dt}\right)$ and $\left(B_{bottom} \propto I_{bottom}\right)$, is a useful approximation.

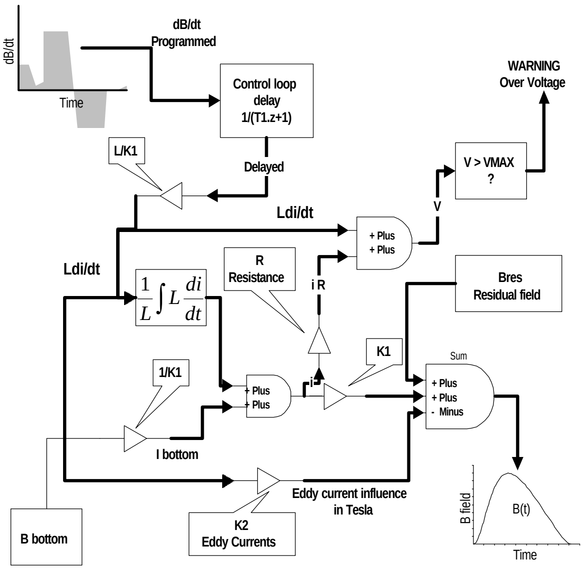

Fig. 2: Mathematical magnet model

$$K1 = \frac{\mu_0 * N}{gap} \times \frac{\Re gap}{\Re gap + \Re core}$$

$$\Re \;\Rightarrow\; Magnetic\ Reluctance$$

$$T1 \Rightarrow Time\ constant\ lag\ of\ regulation\ loop$$

An ideal magnet and power supply respond perfectly to the $L\frac{di}{dt}$ control function in zero time. This model takes such an ideal $\frac{dB}{dt}$ function and the bottom field value B_{bottom} programmed from the cycle editor as input. It uses a first order recursive filter to calculate the delayed function $L\frac{di}{dt}$ and the bottom current I_{bottom} which represents the MPS control loop response to the ideal.

$$L\frac{di}{dt} = \frac{dB}{dt}^{delayed} \times \frac{L}{K1}\text{, and } I_{bottom} = \frac{B_{bottom}}{K1}$$

The control voltage that must be applied to the magnet is given by $V_{(t)} = L\frac{di}{dt} + Ri_{(t)}$ which must be checked not to exceed the maximum voltage limit V_{max} that the power supply can deliver.

The first order eddy current influence appears as a time lag of the final field that can be expressed as the adjustment value $B_{eddy} = -K2 \times L\frac{di}{dt}$

3 Calibration

Over a period of a few hours, the magnet parameters may drift significantly enough to make it necessary to re-calibrate the model. The needed calibration data is obtained from two Nuclear Magnetic Resonance (NMR) probes operated in “*peaking strip mode*”. [2]. In this mode, the probes are operated with fixed radio frequencies corresponding to two chosen fixed field values close to the bottom and top field values (Fig. 3). During the cycle ramp as the field passes these NMR set points, the resulting resonance signal triggers the production of timing pulse events. The time at which the NMR produces these field crossing events is compared with the model prediction, and if the mean of the difference exceeds a pre-set threshold value, new offset and scale factors are calculated.

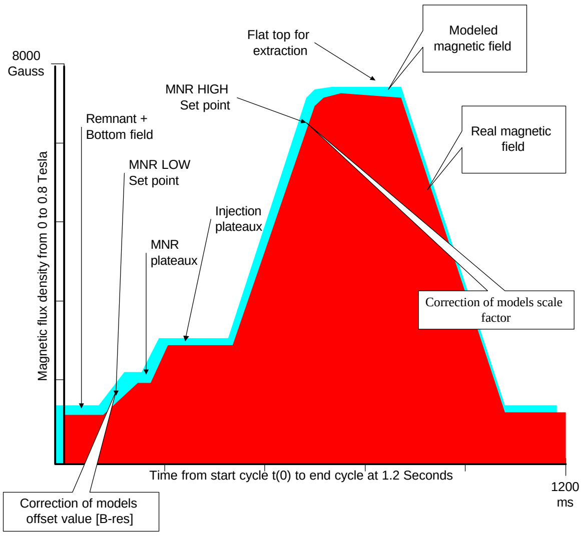

Fig. 3: Calibration using NMR low and high markers

This adaptive model can thus be described as a guided interpolation through the NMR set points, based on the control function and the magnet and control loop parameters. These NMR set points are *point like* measurements made in the central field region of the reference magnet, and correspond to the chosen high and low fields with a precision of better than 0.1 Gauss. This NMR precision limitation is a consequence of using it in the *peaking-strip mode* [2] There may also be small differences between the field in the reference magnet, located outside the beam tunnel and without the beam pipes, compared with those bending the beam.

4 Hardware and software layout

Fig. 4 shows the layout of the measured and synthetic B-Train components. The maximum ramp $\frac{dB}{dt}$ obtainable from the MPS is limited by the maximum driving voltage

(V_{max} = 4000 Volts), implying 4 T/s. A 0.1 Gauss incremental B-Train thus requires a maximum grid frequency of 400 kHz.

Each time a PSB cycle $L\frac{di}{dt}$ function is modified, the model must be run again. The resulting $B_{(t)}$ function is converted into two bitmaps, B-up and B-down, in which each bit represents a 0.1 Gauss increase or decrease in field, on a time grid of 1/400ms. The bit maps are loaded into two specially developed VME pulse generator modules [3], which produce the synthetic B-trains. These modules are shift registers clocked at 400KHz, and started at the beginning of the cycle. The two resulting output bit streams are the synthetic B-Trains, B-up, and B-down, and the value in an up-down counter clocked by these trains is the value of B at each instant in the cycle.

The measured B-train derived from a long coil in the reference magnet produces only a 1 Gauss resolution B-up train, which is useful only if the field during the first half of the cycle continually increases with an error less than 1 Gauss. A B-value counter clocked by the measured B-Train is sampled at a frequency of 1KHz, by a Dual Port RAM (DPRAM) VME module [4], and the samples are kept in memory. The contents of the DPRAM thus represent the sampled magnetic profile of the cycle $B(t)_{measured}$, which can be compared with the model. Any unexpected differences (Fig. 5) between the two estimates of the field profile indicate problems either with the MPS control or with the measurement system.

5. Comparing the measured and synthetic B-trains against the NMR at the high field value set point

The measured B-train system has been improved by triggering the start of the measurement from the NMR low field event. The initial burst offset value is set to correspond to the NMR low field set point. Comparisons were made of the variation between the measurement with and without NMR triggering against the synthetic train at 0.6849 T near the flat top of the proton acceleration cycle (Fig. 6). The deviation of the synthetic train from the NMR is caused by the control loop error.

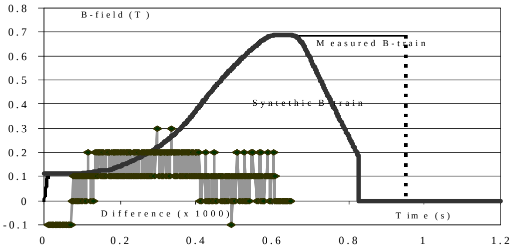

Fig. 5: Typical difference between the measured and synthetic field estimates

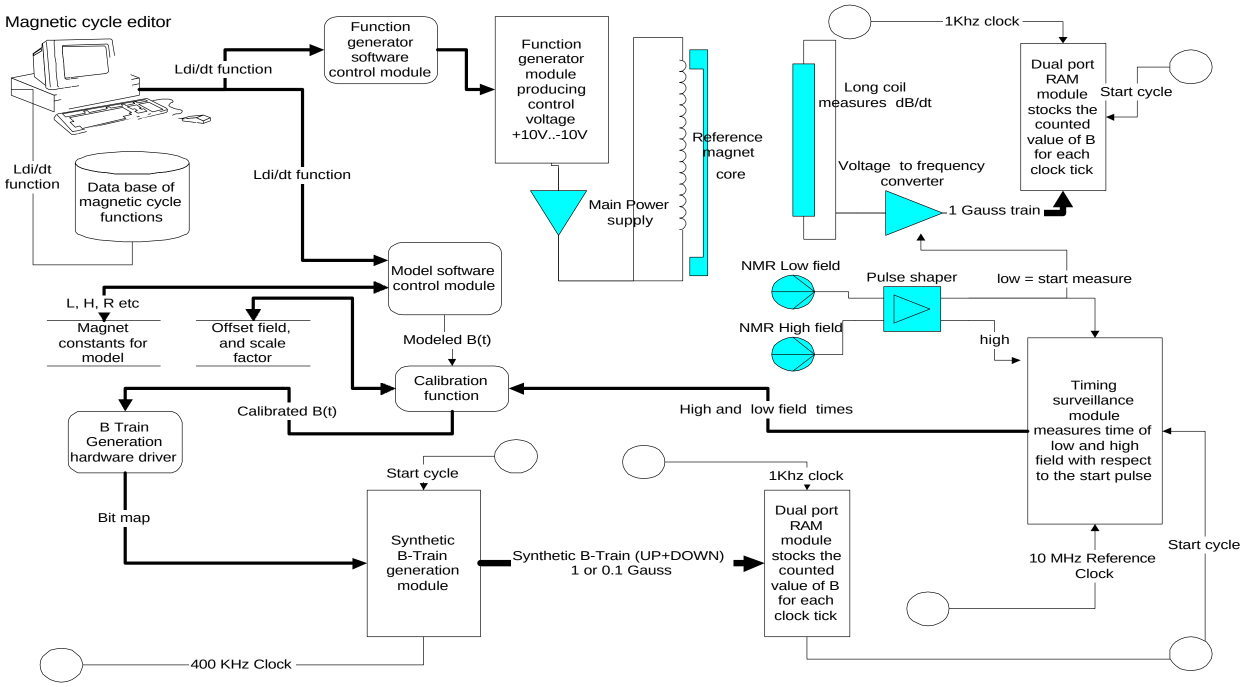

Fig. 4: Hardware and software layout

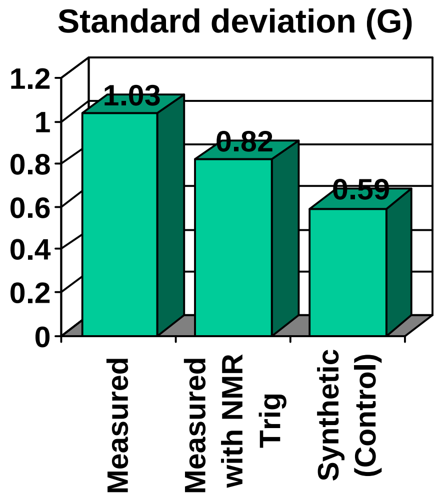

Fig. 6 : Comparison of the measured and synthetic

6 Conclusion

It is simpler to maintain a model of the magnetic field than to perform the corresponding real measurement. In providing a synthetic B-train, the control loop itself is the limit on precision, the model assumes the control works. Nevertheless, a measurement is essential because there can be cases when the control is incorrect, and hence the difference function between the synthetic and measurement trains [Fig. 6] is a very useful diagnostic. The repeatability and lack of noise of the synthetic train often simplifies hardware and software processing of the field data. The adaptive model following the NMR set points is able to follow slow drifts such as those induced by temperature changes.

7 Acknowledgements

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8 References

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