MAGNETIC FIELD CORRECTION IN NORMAL CONDUCTING SYNCHROTRONS

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Abstract

While ramping the magnets in a synchrotron the magnetic fields deviate from their set values. Especially the field errors in dipole and quadrupole magnets result in different problems during operation. At the Heidelberg Ion Therapy Center HIT a measuring system with extremely high precision has been developed. It can measure in real time integral magnetic fields with a precision of better than $5 \cdot 10^{-5}$ in a reproducible way. A feed-back control system for the magnetic fields is being installed and will be operational in May 2010. This control loop lets the magnets reach the nominal field much faster and thus shortens the dead time in a synchrotron cycle. The cycle can be reduced by 30% and more patients can be treated.

INTRODUCTION

In synchrotron accelerators it is characteristic that the time-dependent magnetic fields of the dipoles differ from their set values. The field errors lead to a deviation in the position of the beam corresponding for example to mismatched optics and energy drift of the extracted beam. In Fig. 1 the integral magnetic field during a synchrotron cycle is shown with the measured deviation of the magnetic field from its set value in (red). After reaching the extraction flattop at t=1s the currents in the dipoles are kept constant for 6 seconds and then brought back to zero for the next cycle.

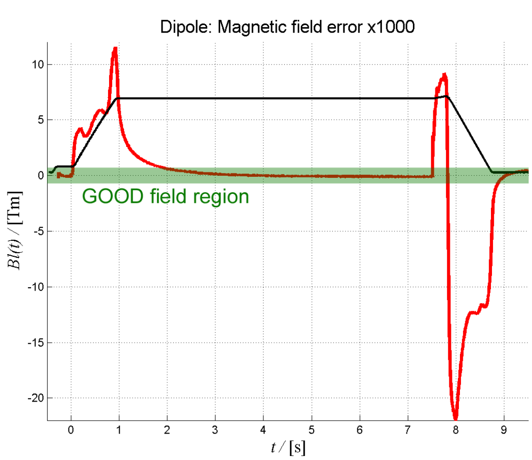

Figure 1: Magnetic field of a synchrotron dipole (black) with the magnetic field deviation x1000 (red).

In Fig. 2 the radial position of the beam at one location in the synchrotron is shown. It is measured with the beam position monitors. The injection of the beam is at t=0. From t=0.1s to t=1s one can see radial deviations during the acceleration of the beam. After reaching the flattop at t=1s the beam has a deviation up to 16mm. The set orbit is then approached exponentially within about 1 second. This effect is caused by eddy currents which decay in time. At the beginning of the flattop the energy is a few percents too high. To minimize the energy deviation of the extracted beam an unwanted holding time of 0.7 seconds is added to the synchrotron cycle before extraction. In this figure the extraction starts at t=1.7s.

During therapy operation beams with different energies are requested from cycle to cycle. Therefore the flattop current changes cycle by cycle. Hysteresis effects of the magnets cause crosstalk between cycles. To avoid these effects a so called "chimney" at the end of each cycle is introduced where the magnets are driven to maximum current in order to force well defined starting conditions for the next cycle.

In the synchrotron cycle approximately 30% of time is needed to let the eddy currents decay and to avoid hysteresis effects. Accounting for these effects would reduce the energy consumption and improve the patient throughout.

The power supplies of the magnets are operated by predefined settings. Our novel approval is to control the power supplies using a feedback of the magnetic field as an additional input signal. Field deviations due to hysteresis effects and eddy currents can thus be compensated and will no longer disturb the beam quality. The deflection of the ions is given by the integral of the field along the beam path. Therefore the so called integral field has to be measured.

MEASURING THE MAGNETIC FIELD

The requested accuracy of the magnetic field measurement is determined by the maximum allowed deviation from the nominal orbit during extraction flattop and the required field accuracy during the injection of the synchrotron.

At extraction flattop level the deviation of the beam from the nominal orbit can be estimated in the following way: The bending angle of the dipoles is proportional to the magnetic field and therefore there is also a linear relation to the radius of the circulating beam. At the Heidelberg Synchrotron with a circumference of 65m a field deviation of $2 \cdot 10^{-4}$ leads to a radial beam deviation of about $1mm$ which corresponds to an acceptable deviation of the beam energy. The absolute accuracy should thus be in the range of $2 \cdot 10^{-4}$ of the maximum field value. Furthermore it has to be secured that the measuring coil integrates the same field as the beam particles.

For the application of the magnetic field control in the

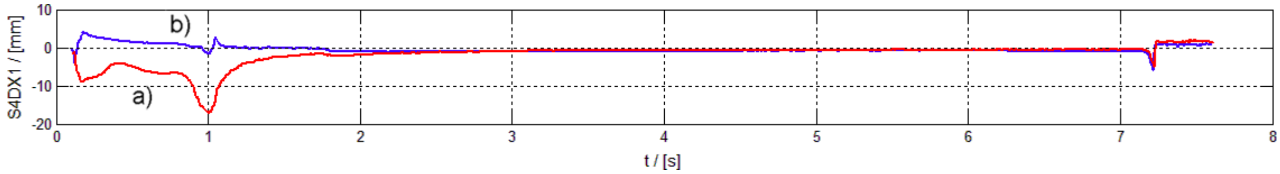

Figure 2: Radial deviation of the beam position without field control (a) and with field controlled (b) magnet currents.

clinical routine operation further requirements are reproducibility and reliability over long time schedule.

Implementation of Measuring Sensors

A pickup-coil with a low number of windings is placed along the vacuum chamber through the gap of the magnet. The magnetic flux through the pickup coil and the vacuum chamber is idenical. The temporally varying magnetic flux $\Phi(t)$ induces a voltage $U_{ind}(t) = -d\Phi(t)/dt$ in the coil. By integrating the induced voltage the integral magnetic field can be calculated.

$$\Phi(t) - \Phi(t_0) = -\int_{-t_0}^{t} U_{int}(\tau)\, d\tau \qquad (1)$$

For determining the start value $\Phi(t_0)$ a hall sensor is used which measures a reference value B_0 of the magnetic field at one point in a homogeneous area of the field during a phase when it is constant in time. It was shown that in a time-independent small magnetic field the start value $\Phi(t_0)$ and the measured reference value B_0 are proportional. The reference value is taken every cycle at the same time, this can be e.g. on the injection flattop.

Thus the measuring system consists of two probes: the pickup coil for the dynamic field measurement and the hall sensor for the determination of the initial reference value. By controlling the magnetic flux in real time the magnetic field can be adjusted to its set value and the non linear effects from eddy currents and saturation will be compensated.

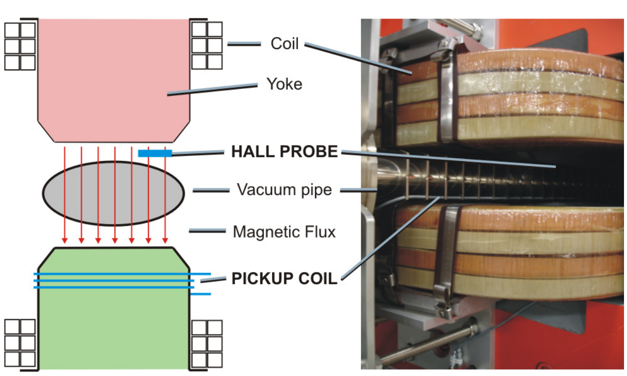

Figure 3: Sensors in a synchrotron dipole.

Analysis of The Sensor Signals

The accuracy of measurements with hall probes are generally 10 to 100 times worse than the needed accuracy of $2 \cdot 10^{-4}$. Recent investigations have shown that only a few commercial sensors are available which reach the necessary accuracy under lab conditions. The noise of these hall probes are in the range of 10^{-4}. The temperature drifts are compensated and the noise of the sensor is filtered.

The voltage of the pickup coil has a resolution in the range of a few micro volts and is integrated during the whole cycle. Offsets in the range of micro volts lead to relevant errors which can be seen in the integrated signal as a drift. To avoid such small offsets the electronic device is built redundantly and recalibrates every 30 seconds. The measurement of the pickup signal are very demanding to the electronics.

Determination of The Integral Magnetic Field

By placing the pickup coil next to the beam the magnetic flux through the coil is equal to the flux in the vacuum chamber seen by the beam. It has been shown that it is also good enough to place the pickup coil around the joke.

The integral magnetic field is calculated from

$$\begin{aligned} U_{field}(t) =& g_{hall} \cdot (U_{Hall}(t_0) - U_{HallOffset}) \\ & - g_{ind} \cdot \int_{-t_0}^{t} U_{int}(\tau)\, d\tau \end{aligned} \qquad (2)$$

where $(U_{Hall}(t_0) - U_{HallOffset})$ denotes the hall voltage corrected for possible offset and $U_{int}(\tau)$ is the induced voltage of the pickup coil. An offset and gain calibration is introduced to consider different probes and electronic tolerances. The parameters results from an in-situ calibration. $U_{HallOffset}$ reflects the zero field value of the hall probe. g_{hall} and g_{ind} are the scale factors of the two different sensors.

The calculations are done in an FPGA (field programmable gate array) based hardware solution and solved in real-time. The digitized measurement signal $U_{field}(t)$ is transmitted to the control system of the power supplies.

CONTROL SYSTEM OF THE DIPOLE MAGNET POWER SUPPLIES

The control system of the power supply is divided in two parts. The first part is the standard current control part.

It uses a PI controller with a set value from the accelerator control system and an actual current value detected by a DCCT (direct current to current transformer). For the field control a second part is introduced which overlays the current control loop. The accelerator control system calculates an additional set value for the B-field. The difference between this set value and the measured magnetic field is the magnetic field deviation. It is used as a steering signal added to the current control loop (Fig. 4).

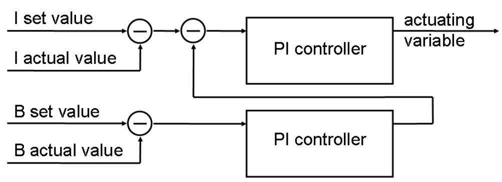

Figure 4: Block diagram of the overlay control loop.

DIFFERENT RAMP RATES

Systematic studies at the SIS 18 dipoles at GSI with different ramp rates in the range of $1.5T/s$ to $9.5T/s$ have shown that the maximum field error is reached at $7T/s$. The maximum field error occurs at the end of the acceleration phase on the extraction flat top (Fig. 6 at 1s). Eddy currents generated by dB/dt can no longer rise and decrease in first approximation exponentially. At a ramp rate of $7T/s$ two eddy current effects are balanced. On the one hand the field error increases with higher dB/dt. On the other hand the faster ramp is too short to develop the full amount of eddy currents because of a given diffusion time constant in the order of one second. In Fig. 5 the maximum field error at different ramp rates is shown.

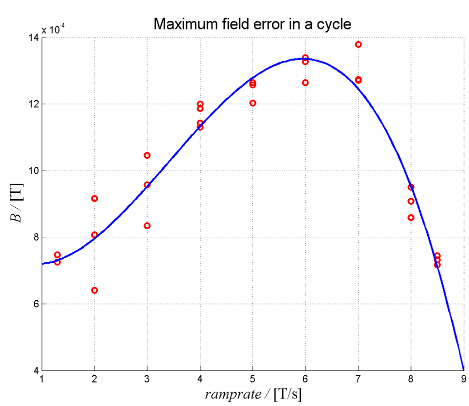

Figure 5: Maximum field error at the end of the ramp. Line is to guide the eye.

RESULTS

The first results using the initial method described above to control the magnetic field in the Heidelberg have already shown that large time savings are possible. In Fig. 6 the current controlled operation mode and its field deviation (a) is compared to the field controlled mode and the remaining error (b).

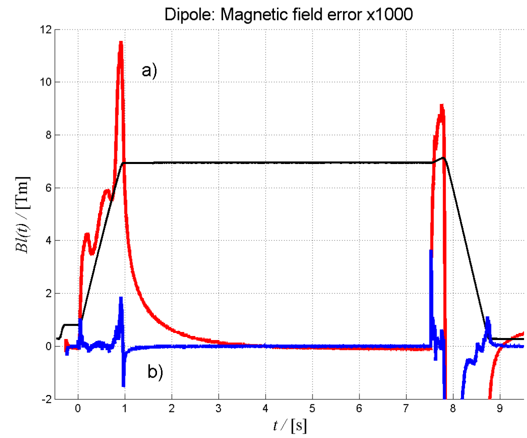

Figure 6: Magnetic field and deviation x1000 (red) without (a) and with field control (b).

The field deviation during acceleration between $t = 0$ and $t = 1s$ is reduced to almost zero and also the exponential decay in the flattop region $(t > 1s)$ disappeared. The deviation of the B-field during the flattop time is below the required tolerance so that the extraction with the correct beam energy can start right after the acceleration phase.

The radial beam deviations measured by the beam position monitors in the synchrotron are shown in Fig. 2 (a) for the uncontrolled and in Fig. 2 (b) for the field controlled operation mode. The beam position confirms the results obtained from the field measurements. In the field controlled mode the structure at the acceleration ramp $(t = 0.1 - 1s)$ and also the exponential decay of the radial deviation during the flattop are corrected. Already 0.1 seconds after the acceleration the needed field accuracy is reached and thereby the energy deviation is acceptable.

As the beam energy (beam position) is the ultimate quantity that has to be controlled this proofs the successful operation of the new field control loop. For this reference cycle the cycle time can be shortened by about 30%. This implies a corresponding saving in power consumption and increase of patients to be treated per year.

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