MAGNETIC FIELD CONTROL IN SYNCHROTRONS

Andreas Peters[1#], Eike Feldmeier[1], Christian Schömers[1,3], Rudolf Steiner[1], Hartmut Eickhoff[2], Thomas Knapp[2], Carsten P. Welsch[3]

[1]Heidelberg Ion Therapy Center (HIT) [2]GSI, Darmstadt [3] MPI for Nuclear Physics, Heidelberg

Abstract

Hadron beams delivered by normal conducting synchrotrons are highly attractive in various fundamental research experiments as well as in the field of tumour therapy. These applications require fast synchrotron operation modes with pulse-to-pulse energy variation and magnetic field slopes up to 10 T/s. The aims are to optimize the duty-cycle and to minimize treatment times for the patients as well as to provide extremely stable properties of the extracted beams, i.e. position and spill structure. Studies performed at the SIS18 synchrotron at GSI proved that the ring quadrupoles contribute to the deterioration of the slowly extracted beam as well as the dipoles. An attempt has been made to measure the magnetic fields in the synchrotron magnets with high precision and speed comparable to the current measurement with a DCCT used in the power supplies. Adding magnetic field monitoring into the current control feedback loop suppresses the unfavourable dynamic effects from hysteresis and eddy currents. The presentation describes this approach and the results obtained at the HIT [1] synchrotron will be discussed.

THE SYNCHROTRON-CYCLE

Two major effects in contradiction to high-performance operation like therapy requirements occur in normal conducting magnets:

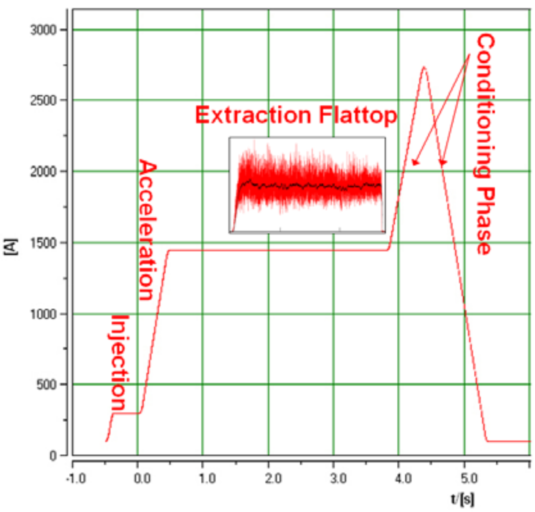

Figure 1: Cycle of main dipole current at HIT, with conditioning phase at the end.

- Hysteresis, which can only be handled by adding a conditioning phase at the end of each synchrotron-cycle. This means driving all magnets into saturation to create well defined initial conditions for the next injection, see Fig. 1.
- Eddy currents appear due to fast ramping (in case of HIT: 1.5 T/s). After the acceleration it takes about 1s until the magnetic field reaches the nominal value and the beam attains an orbit sufficiently stable for the extraction process , e.g. by RF Knock-out. The relative magnetic field measurement in a high energy cycle, displayed in Fig. 2, shows the strong effect.

The standard magnet-by-current control cannot deal with these both effects, time and energy consuming processes are necessary. Magnetic field control would eliminate these processes, improving the efficiency up to 30% as compared to the present HIT operation. Fig. 1 shows that the waiting phase at the beginning of the extraction flattop as well as the conditioning phase at the end leads to only 50% duty cycle concerning the spill-on-time.

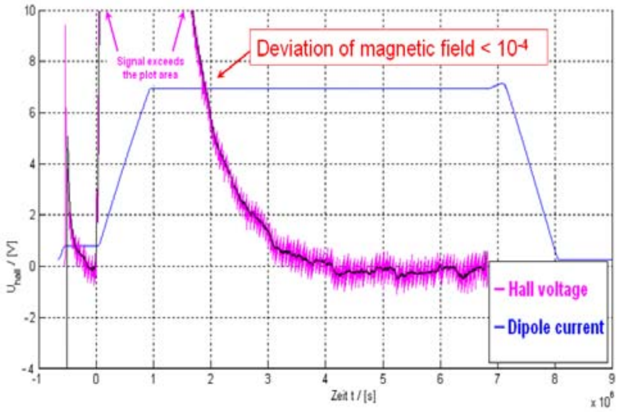

Figure 2: The plot shows the highly attenuated signal of the Hall probe mounted in a HIT dipole; the Hall voltage represents the difference of the reference value and the actual measurement, scaled by a factor of 10,000.

EFFECTS ON THE BEAM

Due to the deviation of the magnetic field from the reference value caused by eddy currents after the acceleration phase the beam position in the synchrotron is also strongly affected, resulting in an orbit, which differs considerably from the reference orbit, see Fig. 3 for an example measurement. As the magnetic field stabilizes after about one second, the beam follows in the same time to reach a radial position, which allows starting the extraction process with always equivalent conditions.

#andreas.peters@med.uni-heidelberg.de

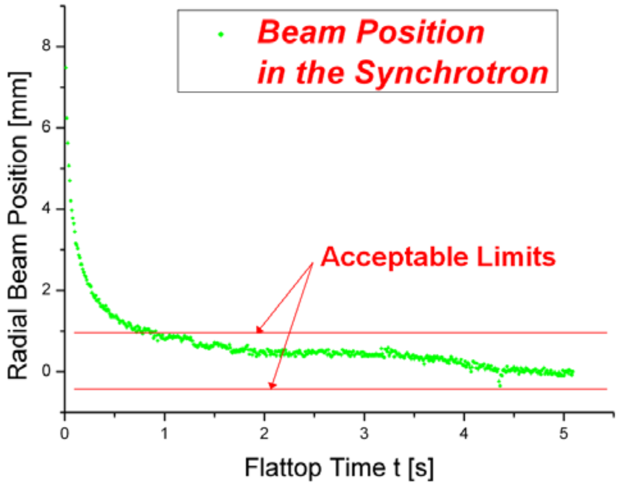

Figure 3: The (offset-corrected) beam-position in the synchrotron after acceleration deviates from the reference orbit due to the effect of eddy currents on the magnetic field.

The same effect on the beam can be observed in the High Energy Beam Transport (HEBT) line, as shown in Fig. 4. The acceptable position variation at the measurement location of +/– 1 mm corresponds to less than +/– 0.5 mm beam displacement at the treatment position, which is within the specified limits.

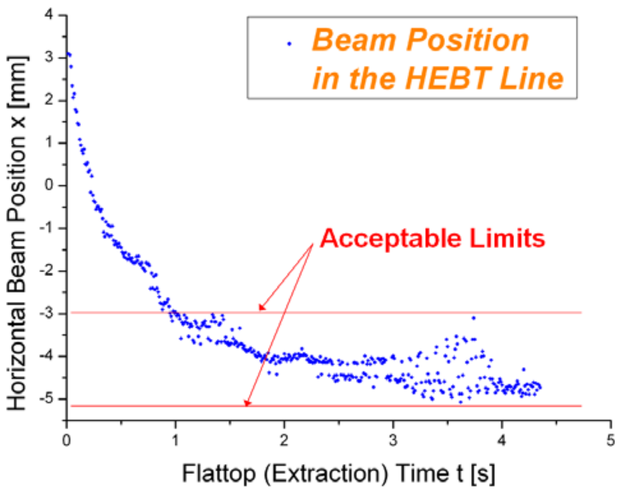

Figure 4: The measured beam position in the HEBT line when extracted without waiting for the decay of the eddy currents in the synchrotron magnets.

THE PROPOSED SET-UP

High precision magnetic field online measurement systems are successfully in operation, using normally reference dipoles and NMRs, e.g. [2, 3]. Our proposed set-up [4] for a magnet-by-field control covering both dipoles and quadrupoles is the following combined system: To measure an absolute magnetic field strength at the beginning of the synchrotron cycle an initial value B_0 is determined by a Hall probe, while the dynamic field change dB/dt during acceleration is detected by a pick-up coil via induction and online integrated electronically:

$$B(t) = B_0 + \int \frac{\partial B}{\partial t}\, dt$$

A relative accuracy of the actual magnetic field measurement B(t) in the range of 10^{-4} (or better) is necessary for a stable operation, especially in synchrotrons used for therapy.

The performance of the main components was studied in detail, whether it is possible to fulfil the criteria. The critical points are the accuracy of the Hall sensors and the position of the pick-up coils.

The Hall Probe

Since NMRs cannot be used – those do not work in inhomogeneous field of quadrupoles – Hall sensors as the next best magnetic sensors have been chosen, although they have disadvantages like temperature gradients, non-linear transfer functions, and aging effects. If the Hall probe is used to exclusively measure the magnetic field B_0 on the injection level at the beginning of the synchrotron cycle, it can be optimized to achieve the demands.

A selection of commercially available sensors has been tested [5] to find out the one with the best performance (see Table 1). Relative accuracy in the range from 50 – 200 mT, which covers all injection levels at the HIT-synchrotron, was the main criterion, the listed values were obtained at 100 mT.

Table 1: Performance results of selected Hall sensors

Probe	**Company**	**Signal@0.1 T** [mV]	**Accuracy** [relative]
KSY 44	Siemens	110.385 +/- 0.055	5.0E-04
CYSJ 1011	ChenYang	110.000 +/- 0.230	2.0E-03
CYSJ 411	ChenYang	218.150 +/- 0.048	2.2E-04
CYSJ 422	ChenYang	220.000 +/- 0.097	4.4E-04
CY P3A	ChenYang	114.000 +/- 0.117	1.0E-03
CY P15A	ChenYang	100.000 +/- 0.117	1.2E-03
HGT 2100	MagnetPhysik	24.220 +/- 0.039	1.6E-03
HGT 2010	MagnetPhysik	18.419 +/- 0.023	1.2E-03
HGT 1010	MagnetPhysik	8.364 +/- 0.031	4.0E-03

The needed accuracy is hardly to achieve, nevertheless one sensor from ChenYang Technologies [6] nearly fulfils the requirements and is under further tests now.

The Pick-up Coil

As there are no external reference magnets at HIT, the pick-up coil has to be mounted inside the synchrotron magnets. Fig. 5 shows the proposed set-up in a schematic view as well as the built-in pick-up coils in one of the HIT synchrotron dipoles. Due to saturation effects, the yoke geometry and the inhomogeneities of the iron the positioning of the coil is not arbitrary.

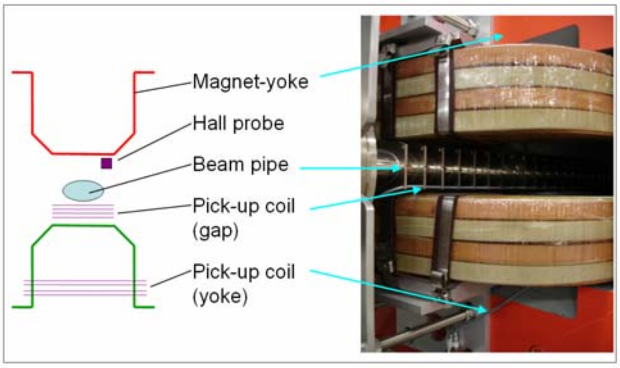

Figure 5: Schematic view and built-in set-up at a HIT synchrotron dipole

To quantify the distinction of two geometrical differently mounted coils the following measurement has been performed, see Fig. 6:

- The plot below shows a dipole-cycle, indicated by the Hall signal on the top.
- The magenta trace represents the induced voltage of a coil, which is located closely to the vacuum-chamber and therefore representative for the integral field seen by the beam. This is always the coil location, if a reference magnet is used.
- The blue trace displays the same signal for a coil wound around the bottom of the yoke. It surrounds almost all field-lines, including the fringe fields.
- Green trace: the difference of those two signals, scaled with 5,000 → deviation is small enough for the necessary relative accuracy of 10^{-4}!

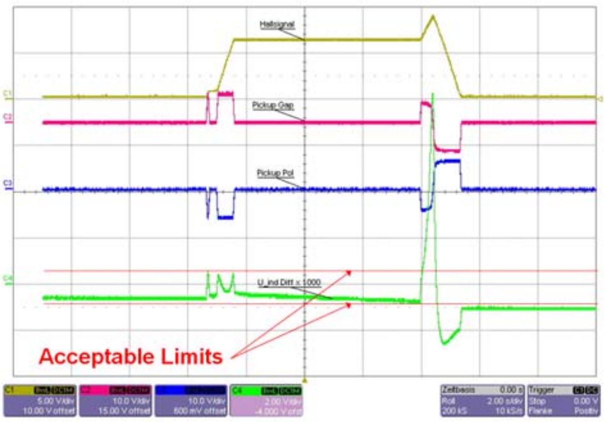

Figure 6: Measurement comparing two geometrical differently mounted coils (see text)

From this measurement it can be deduced that it is possible to use a coil wound properly around the yoke instead of the standard position at the beam pipe in case of space constraints near the vacuum chamber.

OUTLOOK

To achieve a fully functional magnet-by-field control system further development steps have to be undertaken, thus the following road map was defined:

- Enhanced pick-up coil and Hall probe measurements concerning their relative position at a reference quadrupole with free access (at GSI).
- Further qualification of chosen components and linked electronics for the magnetic field measurement: Acquisition of characteristic maps concerning temperature dependency, studies of long-term stability (e.g. drift effects), aging and radiation effects.
- Closing the control loop - different combination of DCCT current measurements at the power supplies and magnetic field measurement system in the dipoles and quadrupoles have to be studied and compared.
- At last, integration of the magnet-by-field control system in the accelerator control system for routine operation with special emphasis on the safety aspects in case of a therapy facility.

REFERENCES

[1] H. Eickhoff, Th. Haberer, B. Schlitt, U. Weinrich, “HICAT - The German hospital-based light ion cancer therapy project”, EPAC 2004, Lucerne, Switzerland.

[2] H.K. Kuhn and J.D. Pahud, “The Control Systems for the CERN Super Proton Synchrotron Ring Power Supplies“, PAC 1981, Washington D.C., USA.

[3] G. Franzini et al., „Measurements on an A/D Interface used in the Power Supply Control System of the Main Dipoles at CNAO“, EPAC 2008, Genoa, Italy.

[4] Patents DE102008020445.5 and DE 102008057815.0 (pending).

[5] C. Schömers, „Untersuchungen zur Magnetfeldregelung an normal-leitenden Synchrotronen“, diploma thesis, see http://edoc.mpg.de/421795.

[6] http://www.cy-sensors.com/.