

THE FIRST MAGNETIC FIELD CONTROL (B-TRAIN) TO OPTIMIZE THE DUTY CYCLE OF A SYNCHROTRON IN CLINICAL OPERATION

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Abstract

In December 2011 the Heidelberg Ion Therapy Center started to use the magnetic field feedback control for its clinical operation. Therewith the magnetic field deviation of the ramped magnets in the synchrotron depending on eddy currents and hysteresis are no longer in effect. Waiting times on the flattop and the "chimney" in the recovery phase of the synchrotron cycle are no longer necessary. The efficiency of the accelerator is increased by more than 20% and the treatment time shortens accordingly. The core of the magnetic feedback system is a real time measuring system of the magnetic field with extremely high precision.

INTRODUCTION

At the Heidelberg Ion Therapy Center HIT a system has been developed to measure the integral magnetic field of a ramped magnet with extremely high precision. The main component is the HIT Integrator to process the voltage from a pickup coil combined with a hall probe system as shown in Fig. 1. At the beginning of a synchrotron cycle a reference value from a hall probe is taken. The local magnetic field $B(t_0)$ is used as the initial value to start the integration process of the voltage obtained from a pickup coil covering area A . The voltage of the coil in a homogeneous field is according to Stokes' law $U = -A \cdot dB/dt$ induced by the time-dependent B-Field. By integrating the voltage over time the system can measure magnetic fields in real time with a precision better than $2 \cdot 10^{-5}$ of B^{max} in a reproducible way. For a 1.5T magnet a resolution of 0.3 Gauss over 10 seconds is reached.

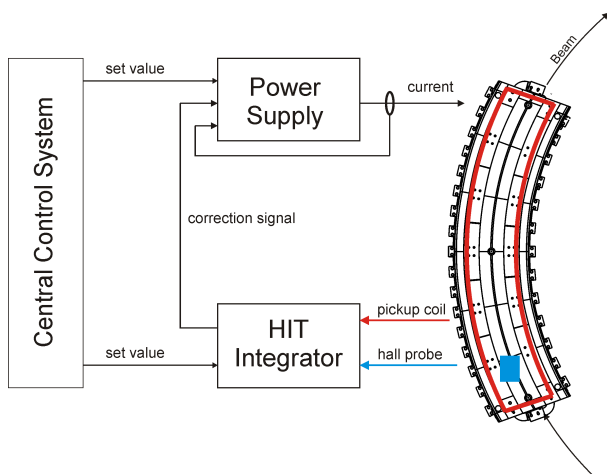


Figure 1: Field control system of a dipole with the pickup coil (red) and the hall probe (blue).

The difference between the measured field and the set value from the global control system is the magnetic field deviation. It is used as a steering signal added to the current control loop of the power supply of the magnet. The system was introduced on IPAC10 [1]. The specifications of the HIT Integrator are shown in Table 1.

Table 1: Specification HIT Integrator

Parameter	Units	
Integrator		
Resolution	20	Bit
Resolution LSB	10^{-5}	Vs
Output Range	± 5.24	Vs
Pickup Coil Voltage up to	± 4.8	V
Integrator Stability @ 1σ		
10s	$2 \cdot 10^{-5}$	Vs
	3.8	ppm

In Fig. 2 the magnetic field integrated along the beam path ($Bl(t)$) and its deviation ($\times 1000$) is compared for the current controlled operation mode (a) and the field controlled mode (b).

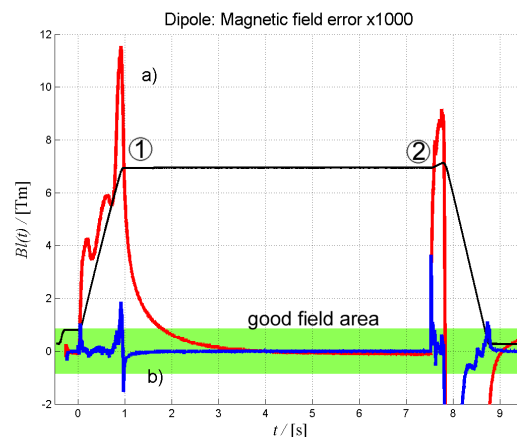


Figure 2: Magnetic field and deviation $\times 1000$ (red) without (a) and with field control (b).

The acceptable limits for the magnetic field deviation are $10^{-4} \cdot B^{max}$, shown as the good field area in Fig. 2. In the normal operating mode one can see that a waiting time ① is needed for the decay of eddy currents before extracting the beam. In the field controlled mode the field deviation is within the acceptable limits immediately after acceleration. There is no need for a waiting time ① anymore. To reduce hysteresis effects a so called "chimney" is in-

roduced in the recovery phase ② to drive the magnet to a maximum current, which is the same for each cycle and generates identical preconditions for the following cycle. Without the chimney the magnetic field at the beginning of the next cycle depends on the last cycles of the synchrotron.

With the field feedback system the magnetic field is measured and corrected in real time, so that the chimney is no longer needed. The reduced cycle is shown in Fig. 3 (red).

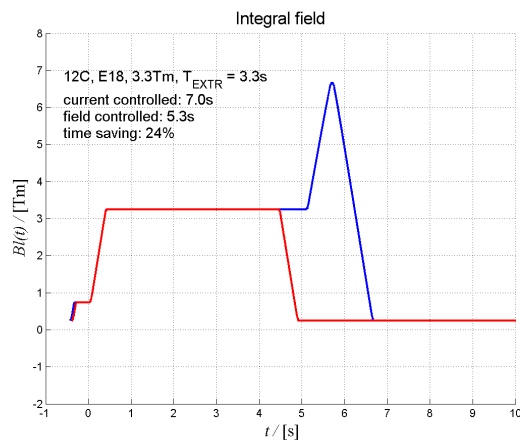


Figure 3: Synchrotron cycle in normal operating mode (blue) and reduced cycle in field controlled mode (red).

The field is only measured in one of the 6 equal dipoles of the synchrotron and the steering signal is used for all of them. The field feedback system for the 12 quadrupoles divided into 4 groups is arranged in an analogue way. It has been shown that the difference of the field deviation of two different magnets from the same type is small enough to accept this concept.

MAIN CONTROL SYSTEM

The global control system of the therapy accelerator calculates with the given bending angle and the stiffness of beam the needed integral magnetic field the magnets have to provide. The set value for the current in the magnet is calculated with respect to the calibration curve of the magnetic survey. In normal operation without field control, only the set value for the current is used for the power supply. For the field controlled mode an additional set value for the integral magnetic field is needed. The integral magnetic field is defined as the integral of the magnetic field along the beam path and is called Bl . The field controller generates with the set value for Bl a steering signal which is added to the current control loop.

For the medical accelerator 45900 different virtual accelerators for each ion species with different parameters are predefined. This large amount of parameters are the combinations of 255 energies, 15 extraction rates (intensities), 4 foci and 3 target places. For the synchrotron only the 255 different energies are relevant. This means that 255 different ramps per ion species are used with the field feedback system. The needed accuracy at extraction flattop for each

ramp has to be smaller than $10^{-4} \cdot B^{max}$ in a reproducible and reliable way.

IN SITU CALIBRATION

To achieve this accuracy of the field measurement system a so called in situ calibration is done for each of the predefined settings. Second and third degree errors resulting from the fringing fields, the non-linearities of the integrator etc., require a new calibration curve. It represents the dependency of the measured integral field on the current in the magnet after relaxation. To obtain the desired quality of the extracted beam, the calibration values refer to the end of the extraction flattop. To cover the whole current range, ramps with low and high currents are used. Thus the calibration includes all effects caused by power supply, cables, different fringing field, pickup coil, hall probe or measuring electronics.

OPERATION

The measurements at the HIT synchrotron show that the quadrupole behavior is mainly dominated by hysteresis effects while the eddy currents are very small and can be neglected. For the dipoles however the eddy currents show a big effect on the field.

The introduction of the field feedback system was therefore divided in two phases. In the first phase only the 6 ring dipoles are switched to the field controlled mode because the eddy current effect at the quadrupoles are acceptable. The cycle is already shortened by skipping the waiting time.

In order to eliminate the "chimney", the quadrupoles will be operated in the field controlled mode in the second phase of the project.

The launch in two phases has the advantage that the medical risk analysis is less complicated. For phase 1 only one field control system has to be tested and certified. In Phase 2 four more control systems for the quadrupoles are installed. The risk analysis is done in phase 1 only for the dipoles and in phase 2 only for the quadrupoles. Furthermore the operating team becomes acquainted with the new equipment step by step.

After introducing phase 1 the field feedback system reduced the waiting time by 700ms per cycle. This is 8% of the cycle time which used to be 8.7s in normal operating mode. For a fixed extraction time in a cycle of 5 seconds the duty cycle (ratio between beam on and beam off) is increased from 57% to 63%.

In phase 2 the chimney is also eliminated which reduces the cycle time by 0.95s on average. This corresponds to an added saving of 12% of the already reduced cycle time from phase 1.

Overall the complete reduction of cycle time due to the field correction is on average 1.65s per cycle, which is 19% of the standard cycle time and a new duty cycle of 71% results for the synchrotron. The total cycle time is reduced from 8.7s to 7.05s for a beam extraction time of 5s.

In normal therapy operation the extraction time is rarely 5 seconds, because an iso energy slice is filled much faster and a new synchrotron cycle with a new energy is requested. Therefore the time saving is even bigger. In Fig. 4 the average cycle time of all therapy beams per week are shown. In 2011 the synchrotron operated in normal mode. The average cycle time in week 42 to week 51 is approximately 7 seconds with an extraction time of 3.3s. In the field controlled mode these cycles would be reduced by 1.65s. The cycle time would be 5.35s, which corresponds to a saving of 24%. In real operation the real saving is much higher because the average extraction time is shorter.

In 2012 the clinical operation used the field controlled mode with phase 1 and one can see the reduced cycle time in Fig. 4. From week 2 to week 15 it is in average 6.34s. This shows the saving of 0.7s. This corresponds to 9.4%, which is again higher than the estimated value of 8% for a fixed extraction time of 5s.

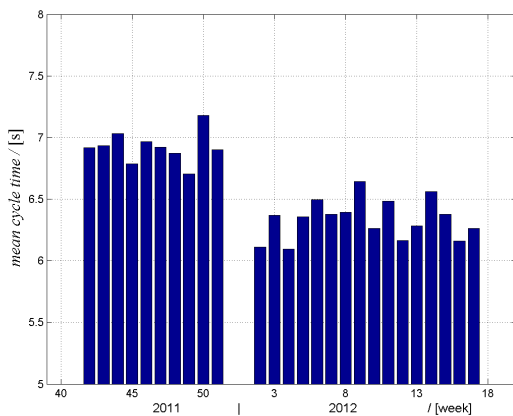


Figure 4: Reduced cycle length due to the field control system in 2012.

RISK ANALYSIS

A revision procedure was launched to investigate the possible impacts on the medical treatment system and to prove the preservation of the accelerator compliance with the EU directive for medicine products. This resulted in an accreditation of the field control system for medical operation at HIT.

The main focus was on the beam quality, but also technical and safety issues are considered. The risk for patients, coworkers and third party people were investigated. Furthermore scenarios of possible technical failures up to the total damage of the field feedback system and the roll back to normal operation mode had been reviewed.

To reduce the risk of a deviation in the magnetic field and a corresponding wrong beam energy the condition was issued to use an additional redundant field measuring system to control the operating one. The intervention threshold for the synchronism of the two systems are set to $10^{-4} \cdot B^{max}$. For the dipoles with a maximum field of 1.5T the limit is

set to 1.5 Gauss (three times the geomagnetic field). The HIT Integrator has a precision of 3.8ppm over 10s, thus an accuracy of 0.06 Gauss in a laboratory environment can be reached. The field measuring system in the working accelerator with all disturbances has a overall accuracy of 0.3 Gauss.

In Fig. 5 the field deviation of the two field control systems are displayed. One can see a slight difference between the two systems during acceleration phase ① and a much smaller one in the extraction phase ②. This is caused by the different locations of the two pickup coils in the magnet measuring a slightly different magnetic field.

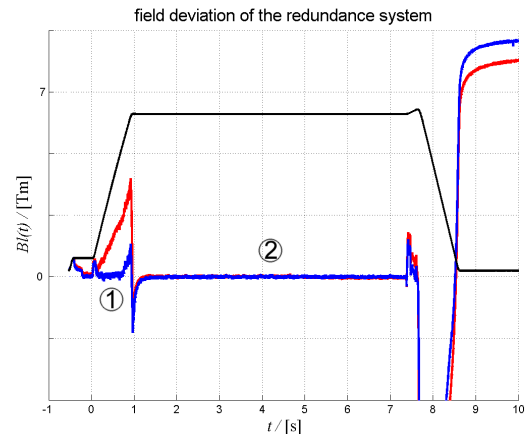


Figure 5: Field deviation x1000 of the field control system (blue) and the monitoring system (red).

To complete the revision process a huge part of the given beam library of 45900 different settings has been tested with the treatment control system. The beam quality in normal operating mode and in the field controlled mode had been compared. It had been shown that the field feedback system has no influence on the beam quality.

BENEFIT FOR THE THERAPY

The field feedback system reduces the time for a treatment session up to 30%. This means a shorter duration for the patient in the uncomfortable fixation during the treatment. As the irradiation of each patient is shorter, more patients can be treated per day with the same costs for the accelerator, energy and employees. A single synchrotron can serve more treatment rooms in parallel.

REFERENCES

- [1] Feldmeier E., Haberer T., Peters A., Schömers Ch., Steiner R., Heidelberg Ion Therapy Center (HIT), Magnetic field control in normal conducting synchrotrons, Proceedings of IPAC 2010, Kyoto Japan, 2010.