DEVELOPMENT OF A HIGH PRECISION INTEGRATOR FOR ANALOG SIGNALS TO MEASURE MAGNETIC FIELDS IN REAL-TIME

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Abstract

For the Magnetic Field Control of the synchrotron at the Heidelberg Ion Therapy Centre the magnetic fields are measured with a pickup coil along the beam pipe. The induced pickup voltage, corresponding to changes in the magnetic field, has to be integrated in real-time to determine the actual integral field. A high precision integrator has been developed to measure magnetic fields with an accuracy of 4ppm over 10 seconds. This new integrator has a very low drift and calibrates during the measurement. It is the fastest and most accurate integrator for integrating analog voltages in real-time.

INTRODUCTION

Since the opening in 2009 the Heidelberg Ion Therapy Center HIT has treated successfully 1500 patients with carbon ions and protons. To reduce the treatment time and to increase the number of patients per year, the accelerator and the therapy system are constantly enhanced.

To shorten the time of an acceleration cycle a magnetic feedback control [1] for the synchrotron magnets has been developed that measures the integral magnetic field of a ramped magnet with extremely high precision. Its main component is the "HIT Integrator" which processes the voltage from a pickup coil in combination with a hall probe system as shown in Fig. 2. At the beginning of a synchrotron cycle a reference value from a hall probe is taken. This 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 which encloses an area A. The voltage of the coil in a homogeneous field is according to Faraday's 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

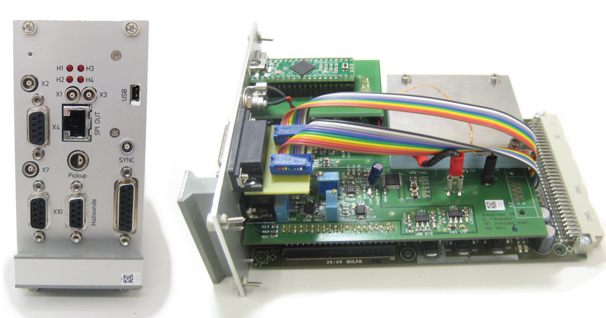

Figure 1: The HIT Integrator combines the novel high precession real-time integrator and the hall probe electronics.

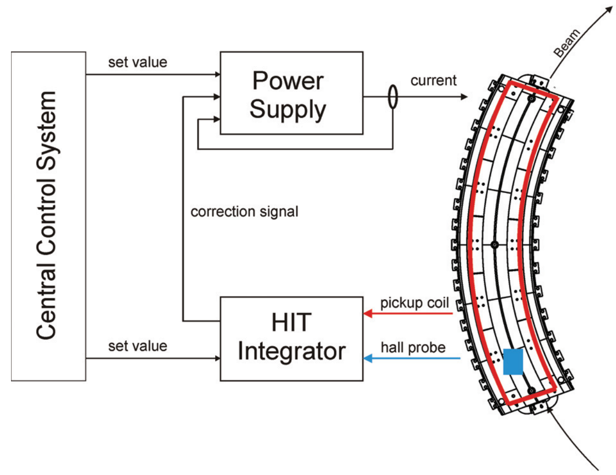

Figure 2: Field control system of a dipole with the pickup coil (red) and the hall probe (blue) [1].

1.5 T magnet a resolution of 0.3 Gauss over 10 seconds is reached [1].

The requirements for the integrator are: high precession, real-time ability, automatic calibration, continuous measurement, temperature insensitive and high availability.

For the therapy synchrotron a precession of the magnetic field feedback system better than $2{\cdot}10^{-5}{\cdot}B_{max}$ is required. In units of the integrated voltage this means a resolution of 10^{-4} Vs with a full range from -5 Vs over a measurement time of 10 s.

The signal from the integrator is used for a real-time correction of the magnet current. Real-time means that measurement and signal processing is faster than the change of one bit in the integral.

During acceleration the integrator has to provide a continuous measurement and online calibration.

The HIT Integrator fulfills the requirements by using new techniques.

HIT INTEGRATOR

In Fig. 3 the block diagram of the integrator is shown. The integrator path is doubled for simultaneous calibration and measuring. While one path is measuring the input signal the other path is in calibration. For the integration a commercial synchronous voltage-to-frequency converter (VF converter) from analog devices is used. The frequency of the output pulses is proportional to the input voltage. By counting the pulses one gets the integral of the input voltage. The number $N(t, t')$ of counts given in the time

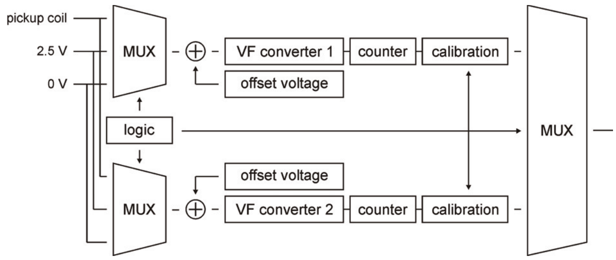

Figure 3: Block diagram of the HIT Integrator.

interval from t' to t and is described by

$$N(t,t') = \frac{1}{\Delta\Omega}\left(\int_{t'}^{t} V_{IN}(\tau)\,\mathrm{d}\tau + \delta N\right) , \qquad (1)$$

with $\Delta\Omega = R_{\mathrm{IN}} I_{\mathrm{REF}} T_{\mathrm{clk}}$ a property of the VF converter. The mean output frequency in the time interval from $t_{n2} - t_{n1} = (n2 - n1)T_{clk}$ during $(n2 - n1)$ clock cycles is

$$f_{out} = \frac{N(t_2, t_1)}{t_{n2} - t_{n1}} \pm \delta f_{out} , \qquad (2)$$

with an inevitable discretization error $\delta f_{out} = 1/(t_{n2} - t_{n1})$.

With ideal electronics, the change of the magnetic flux, enclosed by the pickup coil is a linear function of $N(t,t')$:

$$-\Big(\Phi(t) - \Phi(t')\Big) = \int_{t'}^{t} U_{\mathrm{ind}}(\tau)\,\mathrm{d}\tau \qquad (3)$$

$$= \Delta\Omega\,\Big(N(t,t') - N_{\mathrm{offset}} \pm 1\Big) . \qquad (4)$$

With

$$\Delta\Omega = R_{\mathrm{IN}} I_{\mathrm{REF}} T_{\mathrm{clk}} = 10^{-5}\,\mathrm{Vs} \qquad (5)$$

the smallest measurable change of the magnetic flux as a property of the setup.

Offset

To integrate positive and negative voltages U_{ind} from the pickup coil, an offset voltage $U_{\mathrm{offset}} = 5\,\mathrm{V}$ is added to get the input voltage V_{IN} for the VF converter

$$V_{IN}(t) = U_{\mathrm{ind}}(t) + U_{\mathrm{offset}} . \qquad (6)$$

which shifts the measurement range for U_{ind} from 0 V – 10 V to -5 V – +5 V.

Calibration

The novel concept of calibration is that during repeated short time intervals two consecutive calibration measurements determine N_{offset} and $\Delta\Omega$. Thus, all possible errors on the path from the pickup coil input (U_{ind}) to the output of the VF converter are corrected.

The intervals should be short enough to react to environment changes but long enough to keep the discretization error sufficially small.

For the calibration, instead of the pickup coil, two known voltages with a high accuracy (0 V and 2.5 V) are connected with fast analog switches to the integrator path. During the first 2 seconds of the calibration time

$$N^{cal}_{\mathrm{offset}} = N^{[0V]}(2\,s, 0) \qquad (7)$$

is measured and during the next 2 seconds the value of one pulse is determined as

$$\Delta\Omega^{cal} = \frac{5\,\mathrm{Vs}}{N^{[2.5V]}(4\,s, 2\,s) - N^{[0V]}(2\,s, 0)} . \qquad (8)$$

These two values are then used in the subsequent measure time.

The deviation from the expected value for $N_{\mathrm{offset}} = f_{clk}/4 \cdot 2\,\mathrm{s} = 500000$ is corrected in real-time by adding negative pulses to the counter. The pulse generators can only generate frequencies which are a fraction of the FPGA clock $f_{\mathrm{FPGAclk}} = 80\,\mathrm{MHz}$. To increase the accuracy, the negative pulses are divided to a fixed pulse generator and a variable pulse generator. For the fixed pulse generator working at the expected pulse rate $f^{max}_{out}/2$, no calculations are necessary.

$$f_{\mathrm{offset\_fixed}} = f^{max}_{out}/2 \qquad (9)$$

The frequency of the flexible pulse generator is set to the difference between the measured and the expected value.

$$f_{\mathrm{offset\_variable}} = N^{cal}_{\mathrm{offset}}/2\,\mathrm{s} - f^{max}_{out}/2 \qquad (10)$$

with the period length of

$$t_{\mathrm{offset\_variable}} = \frac{f_{\mathrm{FPGAclk}}}{f_{\mathrm{offset\_variable}}} . \qquad (11)$$

The value of one pulse $\Delta\Omega^{cal}$ from the VF converter or the pulse generators are calculated by the second calibration measurement, equation 8. The theoretical value for the given setup is $\Delta\Omega = 10^{-5}\,\mathrm{Vs}$.

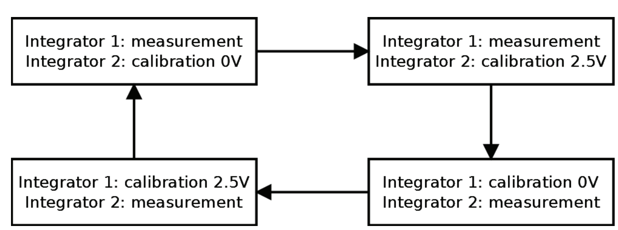

Figure 4: The four possible calibration states of the integrator are changed in the shown sequence every $t_{cal} = 2\,\mathrm{s}$.

Timing

The calibration of the two integrator paths (Fig. 3) is done in 4 states that change every 2 seconds, as shown in Fig. 4. Each integrator paths is half of the time in calibration mode and half of the time in measuring mode. Therefore a continuous measurement can be guaranteed.

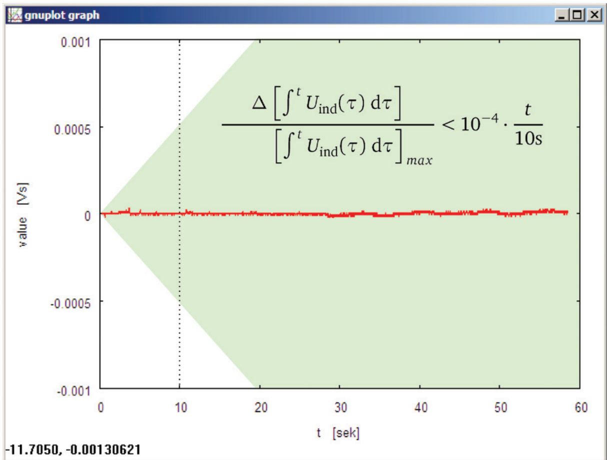

Figure 5: The integral of a short circuit (0 V) shows the accuracy of the integrator. The green area describes the required accuracy for the feedback system in the therapy accelerator for the clinical use.

Error Estimation

Because of the discrete clock times and the integer values for $N(t + t_{cal}, t)$, a relative error $\delta f/f$ of $1/N(t + t_{cal}, t)$ is unavoidable. If this error should be smaller than 10^{-6}, $N(t + t_{cal}, t)$ has to be bigger than 10^6. For an offset frequency $f_{\text{offset\_fixed}} = f_{clk}/4 = 500000$ Hz, the discretization error in $\delta f_{\text{offset\_fixed}}$ is

$$\delta f_{\text{offset\_fixed}} = 10^{-6} \frac{f_{clk}}{4} . \qquad (12)$$

From this follows that a calibration time of $t_{cal} > 4/f_{clk} \cdot 10^6 = 2$ s is needed.

Analysis have shown, that a longer calibration time, which would decrease the discretization error, increases on the other hand the error caused by environment changes especially temperature fluctuations. The optimal calibration time $t_{cal} = 2$ s is used.

The error caused by the switching between the two integrator paths one pulse ($\Delta\Omega$) in maximum. The average value is zero.

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

MEASUREMENTS

The voltage signal of the pickup coil, shown in Fig. 6, is positive at the rising part ramp and negative at the falling part of the ramp. The signal is overlaid with noise of about the same magnitude. Due to the continuous integration process the integral of the noise is zero with insignificant deviations. The integral of the pickup coil voltage (blue) shows the integral magnetic field of the dipole $BL(t)$ with an overall acurracy of $2 \cdot 10^{-5} BL_{max}$.

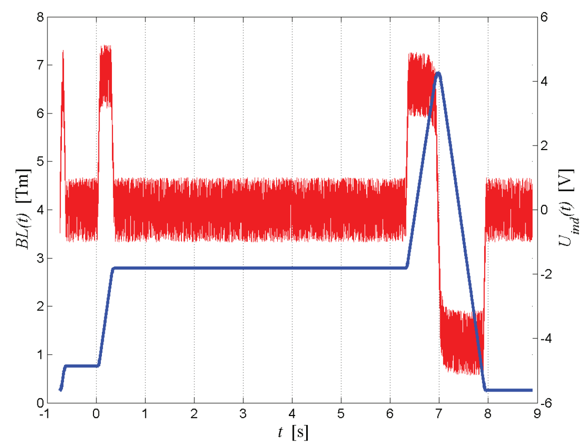

Figure 6: The induced voltage of a pickup coil in the synchrotron dipole during an average synchrotron cycle (red). The integrated voltage of this pickup coil (blue).

SUMMARY

The HIT Integrator is the first integrator for real-time applications with an accuracy specified in Tab. 1. In Fig. 5 the measured integral of a short circuit (0 V) over 20 s is shown. The deviation from zero is smaller than $4 \cdot 10^{-5}$ Vs. The integrator is drift compensated and calibrates during the measurement. Therefore it depends no longer on temperature changes and guarantees a continuous measurement.

It is used for the field feedback system at the Heidelberg Ion Therapy Center since January 2012 in the clinical routine and has the feasibility to save up to 25% of the cycle time. The irradiation time of each patient is reduced accordingly and more patients can be treated.

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[1] Feldmeier E., T. Haberer, M. Galonska, R. Cee, S. Scheloske, A. Peters, Heidelberg Ion Therapy Center (HIT). The first magnetic field control (B-Train) to optimize the duty cycle of a synchrotron in clinical operation. In Proceedings of IPAC 2012, *N*ew Orleans, *U*SA, 2012.

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