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INVESTIGATION FOR THE APPLICABILITY OF A HALL PROBE MEASUREMENT IN B-FIELD CONTROL FOR SYNCHROTRON DUTY CYCLE OPTIMIZATION

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Abstract

MedAustron is a state-of-the-art synchrotron-based accelerator complex that provides irradiation with proton and carbon ion beams. The implemented DCCT feedback based control of the current provides good results for magnets of the accelerator in terms of precision and accuracy. However, since the B-field of the main ring dipoles is not directly controlled, parasitic, time consuming effects cannot be compensated. Hence, the implementation of a B-Field control system offers a significant opportunity for enhancing operation. This contribution presents the measurement chain of the proposed solution which is centered around a Hall probe located in the so-called B-train magnet. This approach requires an assessment of the applicability of local Hall probe measurements for this purpose, including the development of a model for relating the respective local measurement to the integral field. Ultimately, the Hall probe has shown characteristics of high accuracy and a measurement uncertainty that is below the overall field error target of 2 units (U). The model was tested under laboratory conditions and an accurate estimation of the integral field has been observed in the scope of simulations.

INTRODUCTION

The conventional measurement approach for the implementation of a B-field regulation systems in synchrotrons includes the utilisation of a combined so-called field marker and a search coil [1, 2]. Nuclear magnetic resonance spectroscopy (NMR) probes or Hall probes are the most commonly used field marker systems. On the other hand, search coils are usually inserted into the magnet such that their measurement range covers the relevant beam trajectory in order to measure the integral B-field, BL (i.e., the field the beam integrates while it is traversing the magnet aperture). In contrast to that, the measurement chain for MAPTA (MedAustron Particle Therapy Accelerator) is centred around a Hall probe located inside the B-train magnet aperture and any coil-based measurement is completely renounced. Therefore, the proposed measurement only provides a local B-field, B. Hence, a major challenge of the proposed implementation is a sufficiently precise estimation of BL. To this end an extensive feasibility study has been conducted at MedAustron for the purpose of evaluating the usability of the proposed Hall probe [3] as an instrumentation candidate. Furthermore, synchrotron performance improvement opportunities are based on the compensation of parasitic magnetic effects evaluated and depicted in Figure 1(a) and (b). The former shows the impact of eddy currents on the stability, which ultimately impacts the usability of the flattop BL. For certain extraction methods such a B-field characteristic is not acceptable and requires an operation of the machine with a wait time of up to a few seconds (≈ 3 s in case of carbon at 402 MeV/u). The second parasitic effect to be mentioned is observable in Figure 1(b), which can be assigned to remanence magnetism and has to be accounted for by cycling to a dedicated maximum field. It is desired for the synchrotron duty cycle improvement to remove both time consuming effects.

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MEASUREMENT SETUP

The core idea of this investigation is to characterise the behaviour of the sensors including stability and accuracy in operating conditions. A major part of this assessment includes evaluating the long term stability and cycle-by-cycle reproducibility of the B-field measurement. Another analysis campaign is based on comparing the reproducibility performance of the Hall probe and search coil measurements for various flattop energies in case of protons as well as carbon ions. The measurement setup is centred around the so called B-train magnet, as shown in Figure 2. It can be deduced from the lack of a beam pipe that this magnet is not directly part of the synchrotron. Instead this bending dipole is located close to its power supply. All 17 bending dipoles (16 in the main ring + 1 B-train magnet) are powered in series. Therefore, the B-train magnet is expected to deliver a representative field with respect to (w.r.t.) the magnets located in the synchrotron. Furthermore, the image shows the inserted fluxmeter coil on one end. The Hall probe is centred inside the aperture of the magnet close to its pole edge [4]. The measurement campaign has been conducted by means of the development and prototype converter regulation boards (CRB).

The later implements two sigma delta (Σ-Δ) ADC's for a total of eight measurement channels. The signal processing and regulation is implemented in a Zynq7000 based system on chip (SoC), with multistage down-sampling and filtering for a resulting sampling frequency t_s of 2 kHz. The SoC

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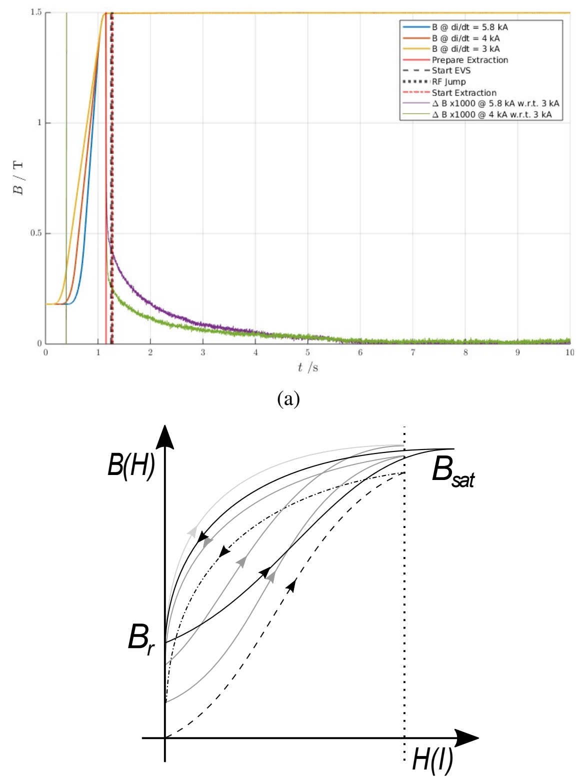

(a)

(b)

Figure 1: Parasitic effects to be compensated by means of the B-Field regulation. (a) Different ramp rate study to evaluate the parasitic effects of eddy currents on the field stability on flat top for carbon at 402 MeV/u. (b) Illustration of the remanence field impact on reproduce-ability of B on flattop.

Table 1: Measurement Setup Parameters Including Magnet and Power Supply (PS) Specifications

Property	Description	Value
R_m	Mag. R (17 Dipoles)	86.55 mΩ
L_m	Mag. L (17 Dipoles)	194.29 mH
V_{max}	PS maximum voltage	1.5 kV
I_{max}	PS maximum current	3 kA
$\frac{\Delta I}{\Delta t}$	PS max. ramp rate	$7\,\frac{\text{kA}}{\text{s}}$
B_{max}	Bending dipoles B	≈1.6 T @ 3 kA
B_{range}	Hall probe full scale	±2 T
BW_{Hall}	Hall probe bandwidth	2.5 kHz
t_s	Sampling rate	2 kHz
ΔB_{max}	Max. B error at flattop	2 U (1 U = $\frac{\Delta B_{max}}{B_{max}}$)

is ultimately also responsible for the communication with other parts of the machine (i.e., power converter controller, beam diagnostics system, RF system, etc.). The specific t_s has been chosen in order to come as close as possible to the actual operating conditions, since this frequency is the typical regulation and data acquisition frequency of generic power converters in the scope of MAPTA.

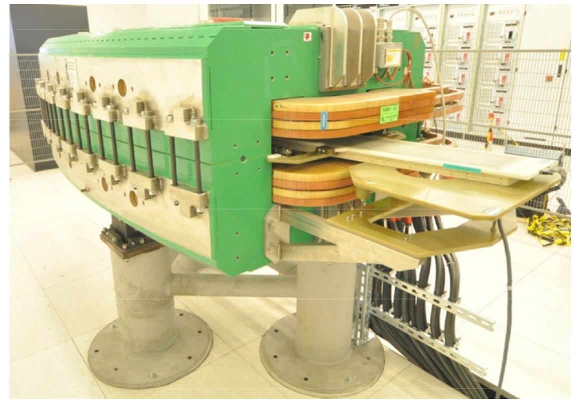

Figure 2: MedAustron's B-train magnet.

MEASUREMENT METHODOLOGIES

All measurements have been performed parasitically during dedicated shift times with a maximum extraction time of 10 s. Typically, various energies have been played for carbon ions and protons to cover scenarios also encountered during clinical operation i.e., ramp rates, treatment energies, etc. First, comparative measurements have been conducted. In this case both, fluxmeter and Hall probe were used for parallel data acquisition. However, after the analysis of those measurements, only the Hall probe was used for all subsequent experiments. The different measurement scenarios are summarized in Table 2. The methods are sorted in chronological order in the way they have been applied.

Table 2: Measurement campaign methods. Note: The energies E were used with protons and carbon ions, therefore, the particle type is not explicitly stated.

Meth.	E, $\frac{\Delta I}{t}$	Meas. Devices
#1	various E, $6\,\frac{\text{kA}}{\text{s}}$	Hall, Fluxmeter
#2	E (min., max.), $6\,\frac{\text{kA}}{\text{s}}$	Hall
#3	E (max.), various $\frac{\Delta I}{\Delta t}$	DCCT, Hall
#4	various E, $6\,\frac{\text{kA}}{\text{s}}$	DCCT, (Fluxm.), Hall

RESULTS

The results obtained in the first measurement campaign are illustrated in Figure 4. The energy deviations at injection, extraction, as well as at maximum hysteresis level as a result of B errors are depicted for various energies in case of carbon. The figure includes two chronologically separated measurement campaigns. It is evident in all cases, that when measuring with the fluxmeter coil a larger energy error is obtained.

A result of the second measurement setup is shown in Figure 3. The Hall probe has proven to be almost drift-free with measurement uncertainties in the range of 6 μT (in case of proton 198 MeV). This is well below the uncertainty target stated in Table 1.

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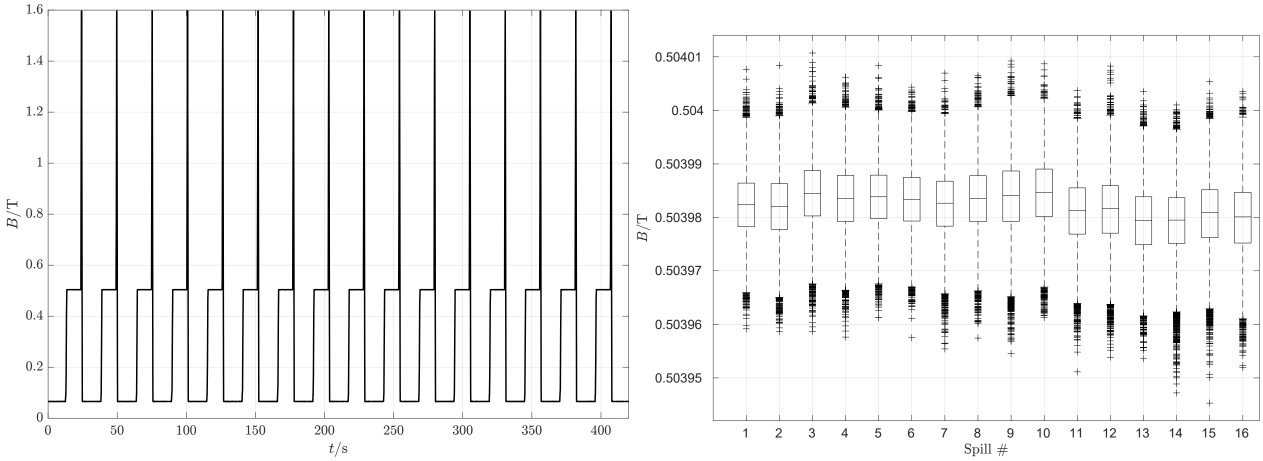

(a) (b)

Figure 3: Reproducibility B-field measurements with proton at 198 MeV flattop energy and multiple subsequent cycles. (b) Box-plots analysis of the corresponding 10 s flattop sections.

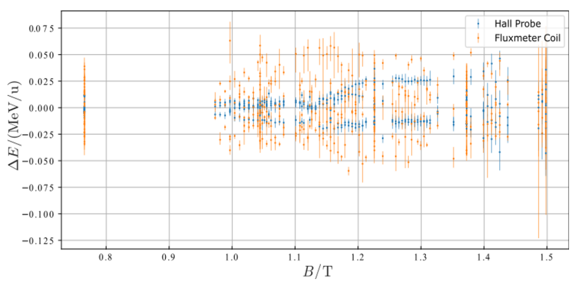

Figure 4: Energy error comparison between fluxmeter coil and hall probe at injection, flattop and maximum hysteresis level. For carbon energies between 120 MeV/u and 402 MeV/u. The analysis is based on a post measurement calculation.

The third measurement campaign lead to the results already presented in Figure 1(a). As already mentioned, the result shows the necessity for a wait-time at flattop start. This is especially true with higher ramp rates and energies.

The last setup from Table 2 is used for the estimation assessment shown in the next section.

CONCLUSION & OUTLOOK

The utilised Hall probe has proven its usability for B-field regulation in the scope of an extensive measurement and analysis campaign. A point still under investigation and one of the main aspects to be foreseen is the estimation of the effective magnetic length of the dipole magnets that can usually be expressed as a function of current and time. As it can be observed by the analysis performed by means of Figure 5, the estimation margin (red) of the integral length is depicted. Based on this requirement, the B-field regulation is currently in the feasibility study phase for the live-system (i.e., with the machine during dedicated shift times). Proposed techniques include an estimation based on a function estimation network. Based on correlated measurements of the integral and the locale field a transfer function is obtained. For this reason, an algorithm is trained and tested on this set of measurements. Another option could be an in-situ mapping of all relevant flattop currents with their corresponding B-field. The later option would require an extensive amount of measurements and hence shift time, which is rather undesired. Furthermore, sensor fusion by means of Kalman filtering is considered in the scope of the feasibility study.

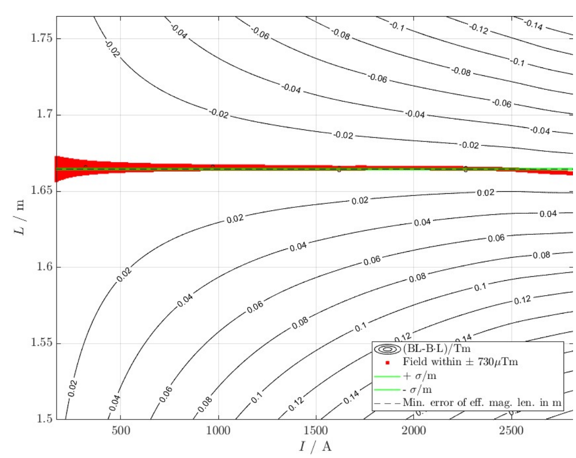

Figure 5: *BL* error between estimated integral field and actual measured integral field by means of a search coil. The effective magnetic length and the magnet current are varied.

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