I.FAST

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MILESTONE REPORT

Engineering design of improved power supply current measurement and RF-amplifier layout

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ABSTRACT

This report concerns technical investigations to mitigate beam current fluctuations on the 100 µs time scale for beams slowly extracted from a synchrotron, referred as spill microstructure. During the first 24 months of the IFAST WP5.3, the engineering design for two technical systems were performed. The first device concerns the measurement of the magnet power supplier ripples (refers to remaining AC current I_{AC}) in the presence of a strong DC current I_{DC}. It comprises a combination of current transformers, and a resolution of almost $\Delta I_{AC}/I_{DC} = 1x10^{-7}$ is reached within a bandwidth of 10 Hz to 40 kHz. The second topic contains the control electronics and power amplification chain for the knock-out extraction. A preliminary yet detailed specification of technical parameters was prepared, while the beam-based experiments were performed. The main observation in the experiments was that spill microstructure depends strongly on the signal shape and excitation bandwidth. The technical design of the power chain was modified to the required power level and bandwidth; and the basic layout was elaborated. For the control, a versatile Software Defined Radio technology can be used; its applicability was demonstrated.

For more information on IFAST, its partners and contributors please see https://ifast-project.eu/

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	Name	Partner	Date
Authored by	Matthias Barthel Eike Feldmeier Peter Forck Florian Kühteubl Philipp Niedermayer Dale Prokopovich Marco Pullia Claus Schmitzer Rahul Singh Andrzej Stafiniak Frank Stulle Laurent Dupuy Miguel Cerqueira Bastos	Barthel HF Technik HIT GSI MedAustron GSI MedAustron CNAO MedAustron GSI GSI Bergoz Instrumentation Bergoz Instrumentation CERN	28/04/2023
Reviewed by	M. Vretenar [on behalf of Steering Committee]	CERN	31/05/2023
Approved by	Steering Committee		31/05/2023

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Executive summary

Resonant slow extraction from a synchrotron is exclusively used at all ion medical facilities as well as at GSI and CERN for fixed target experiments. The beam extraction is performed by creating a 3rd order, non-linear resonance condition and increasing horizontal betatron oscillations. The extracted particles are referred to as "spill". Even slight tune variations, caused by current variations of the quadrupole magnets, lead to a burst-type extraction of the beam particles; forming temporal microstructure in the spill. The goal for IFAST-REX is an improvement of those beam current fluctuations by applying appropriate mitigation schemes.

This report concerns the technical design of novel or improved hardware: Firstly, an extremely high dynamic range measurement of the magnet current fluctuations is in testing phase. Secondly, an optimized and common realization of the beam excitation components for the knock-out extraction at all partner facilities is considered. Precursor beam-based investigations were required to establish a solid specification for knockout extraction, which were recently completed. Some components in this second system are fully developed while some components are now in design process.

Magnet current measurement: The determination of the magnet current fluctuations concerns the AC part with a bandwidth from 10 Hz to 40 kHz, as the high-quality switching mode of typical power suppliers covers this frequency range. The measurement system comprises two current transformers: Firstly, an AC transformer covers the entire bandwidth of the AC current I_{AC} *with a sensitivity of* $\Delta I_{AC}/I_{AC} = 5\text{x}10^{-5}$ *to be able to monitor fluctuations. To prevent the saturation of the AC transformer, a compensation of the DC current is required. Hence, as a second technical device, a DC current measurement transformer comprises a split-core transformer core and a Hall probe. The achieved properties of this novel device are discussed below; the functionality in terms of proof-of-principle fulfils the specification.*

Knock-out extraction hardware: Besides the variation of the magnet current, the signal spectrum of the transverse knock-out excitation significantly influences the spill microstructure. This is caused by the diffusion of the particles toward the unstable area and the excitation strength during the movement in the unstable region. Detailed experiments were recently performed at HIT and other IFAST-REX facilities to investigate the dependence. Based on simulations, it is verified that excitation at multiple bands of the betatron frequency is very beneficial. Those impressive improvements are summarized in this report as they significantly influence the specification and technical realization of the rf power chain. To control the low level rf input signal, an innovative solution was realized, comprising commercial hardware (known as Universal Software Defined Radio) operated by the mature and widely used freeware GNU Radio. The suitability to generate multi-band signals is discussed. To enable multi-band operation, the amplifier's rf bandwidth must cover 0.5 to 15 MHz with an output power of 500 W; those values are larger than initially anticipated. A precursor amplifier with a slightly lower bandwidth was successfully tested; however, a bandwidth extension is possible and will be realized in accordance to the deliverable plan. A matching network between amplifier and electrodes for the beam excitation is required to adapt the impedance from the 50 Ω amplifier output to the capacitive load of the electrodes. Detailed design considerations for a transformer-based adaption are ongoing, and it is expected to achieve the required bandwidth and power requirements.

1 Introduction

Slow extraction from a synchrotron is used at all medical ion therapy centres in Europe and is the primary delivery type for fix-target experiments at GSI and FAIR. Similarly, at CERN, slow extraction is increasingly used for beams from PS and SPS. Other accelerator centres in Asia and America use slow extraction as well. The basic procedure of slow extraction consists of exciting a 3rd order resonance created by sextupole fields and a slow, typically several seconds duration extraction by feeding the beam particles into this resonance. Two methods are frequently realised in most accelerator facilities: In the first method, referred to as tune scan, the transverse emittance growth is performed by driving the machine tune toward the 3rd order resonance by means of quadrupole scan. While in the second method, the transverse emittance expansion is driven by an external rf-field with frequency components correlated with the beam spectra. The resulting diffusion process drives the particles outside the stable phase space, and this method is referred to as knock-out extraction method.

The temporal quality of slowly extracted beams from the synchrotron is crucial. At the medical ion centres, it significantly influences the patient treatment time and safety requirements; for the physics experiments at GSI and CERN, the maximum count rate is significantly influenced. Within the project IFAST-REX work-package 5.3, we aim to develop tools and technologies, which aid in significant improvement of the spill microstructure, i.e. fluctuations on the 100 µs time scale. Generally, the cause of the fluctuations is related to technical imperfections such as power supplier ripples with the main contributions from the quadrupole power supplier as they result in a variation of the particle tune. In a knock-out extraction, the stochastic excitation signal forming the diffusion process is the primary influence in the spill microstructure. Within IFAST-REX, mitigation strategies are developed to achieve a more uniform beam extraction to increase the treatment capability and fix-target count rate. The investigations comprise beam dynamics simulations to mitigate the beam sensitivity to device imperfections, developing state-of-the-art technical devices with exceptional parameters and beam-based experimental verifications.

This deliverable concerns two novel technical systems that are currently developed in association with industrial partners within IFAST-REX.:

- A current measurement system for a high dynamic range determination of the power supplier ripples, i.e. small current fluctuations ΔI_{AC} in the order of $\Delta I_{AC} / I_{DC} < 10^{-6}$ with respect to the DC current I_{DC}. It consists of an active AC current transformer with at least 40 kHz bandwidth. A precise compensation of the DC current is required to prevent magnetic core saturation due to the strong magnetic fields induced by the DC current. It is realised by a split ring core DC field measurement and compensation circuit. The technical functionality for typical power supplies was successfully demonstrated using a prototype (see below). A prototype realisation for current fluctuation measurements applicable to all involved facilities is the project goal of IFAST-REX. In the future, such a system will be used as a feedback or feedforward system for power supplier stabilisation.
- The second technical system concerns the knock-out extraction scheme and its hardware realisation comprising a generator capable of generating custom excitation waveforms, along

with high-performance amplifiers and matching networks as a common design for the installation at the participating facilities. As a first step, the required parameter for an optimised knock-out extraction scheme was investigated in detailed beam measurements at HIT in cooperation with GSI and SEEIIST. A high-performance commercial digital-analogue conversion module based on Software Defined Radio principles was used for the low-level rf-signal generation in the first step. Complex waveforms adequate for an improved extraction scheme can be generated using the software GNU-Radio; see below. The goal is to develop rf-amplifiers and matching networks with specified parameters, such as bandwidth, output power, and other technical constraints.

This report concerns the conceptual design, technical realisation for both technical systems, and a summary of related component tests. The IFAST-REX project aims for current ripple mitigation methods and optimised knock-out operation, which can be implemented with minor modifications at the partner facilities.

2 High Dynamic Range Current Measurement System

2.1 AIM AND GENERAL LAYOUT

To achieve the required stabilisation of the magnet power supplier currents, a current sensor is being developed to detect current fluctuation $\Delta I_{AC} / I_{DC} < 10^{-6}$ with respect to the full-scale DC current. Within this project, the detection system is developed; later, it will be incorporated into the power supplier control chain. Table 1 summarises key specifications established at the beginning of the IFAST-REX project. The prototype, subject to this report, was specified for DC currents up to 5 kA.

Parameter	**Abbreviation & condition**	**Value**
DC current	I_{DC}	10 kA (5 kA for prototype)
AC current	I_{AC}	$\leq 1\% \, I_{DC}$
Measurement resolution	$\Delta I_{AC}/I_{DC}$ for full bandwidth	$\sim 10^{-7}$
	$\Delta I_{AC}/I_{AC}$ for $10\text{Hz} < f < 40\text{kHz}$	$\sim 10^{-5}$
Measurement bandwidth	$\Delta f = f_{max} - f_{min}$	10 Hz – 40 kHz
Measurement accuracy	u_i/I_{AC}	<1%

Table 1: Key specifications of the high dynamic range current measurement system.

The requested resolution with respect to the DC current is challenging to achieve. However, knowing that the AC current remains below 1% of the DC current allows to adapt the challenge by splitting into two full-scale measurement ranges: For signals in the frequency range DC to 10 Hz, the measurement range must reach up to I_{DC}. For signals in the frequency range to 40 kHz, the measurement range must reach up to 1% I_{DC}. Consequently, the required resolution with respect to the AC current is only $\Delta I_{AC}/I_{AC}$ $(f > 10\text{ Hz}) = 10^{-5}$, which is a reasonably relaxed requirement and is in principle achievable.

Absolute AC measurement accuracy is specified to $u_i/I_{AC} < 1\%$. Such a level is easily reachable with standard calibration techniques. Long-term stability and temperature dependence of electronics are good enough to remain within specification.

Despite emphasising performance of AC current measurements and leaving DC current measurements mostly unspecified, DC currents of the required strength must be addressed. Their magnetic fields easily saturate any neighbouring magnetic materials. Thus rendering, for example, the use of normal current transformers impossible. A viable solution is to add to the current transformer a DC compensation winding, which is driven by feedback electronics using a DC magnetic field sensor as schematically depicted in Figure 1. Such a DC compensation loop implies a highly accurate DC current measurement even surpassing specification of the AC measurement accuracy. That means, an accurate DC measurement will be available despite not being strictly required within this project.

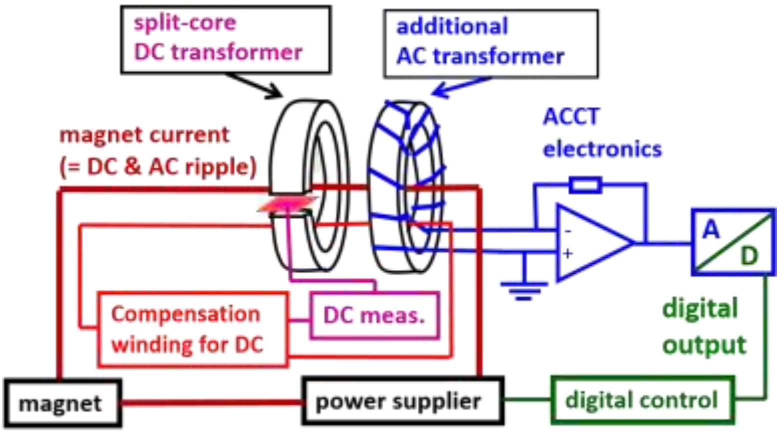

Figure 1: General scheme for the combination of a DC transformer and an AC transformer to determine the AC component of the magnet current.

2.2 PROTOTYPE DEVELOPMENT

The prototype acts as a proof-of-principle at high DC currents. As such, it shall come close to the specifications of the high dynamic range current measurements system. However, it is allowed to only partially fulfil these specifications. A maximum DC current of 5 kA is considered sufficiently demanding to highlight the benefits and possible shortcomings of the tested solution.

A measurement scheme which has proven to be capable of highly accurate DC current measurements even in the multi-kA range is the closed-loop fluxgate DC current transformer (DCCT). However, since this project emphasises AC measurements, a somewhat different approach has been chosen.

The ACCT combines a passive current transformer with active electronics. It is widely used in particle accelerators for average current measurements of macro-pulses or chopped DC beams [1-3]. It has a measurement bandwidth of 1 Hz to 1 MHz and a resolution of about $\Delta I_{AC}/I_{AC} = 5\text{x}10^{-5}$. Assuming a uniform noise spectrum, reduction of the ACCT bandwidth to the required 40 kHz limits noise to the specified $\Delta I_{AC}/I_{AC} = 1\text{x}10^{-5}$ due to the scaling of the noise amplitude proportional to the square root of the measurement bandwidth Δf, i.e. $I_{noise} \propto \sqrt{\Delta f}$. To such an ACCT, a DC compensation winding shall be added, driven by feedback electronics. A commercial DC magnetic field probe (standard Hall sensor Honeywell SS495A1) is used to detect the strength of the magnetic field induced by the magnet power supplier current. A sketch and a photograph are shown in Figure 2. The DC and AC transformers are each equipped with a 1500-turn winding.

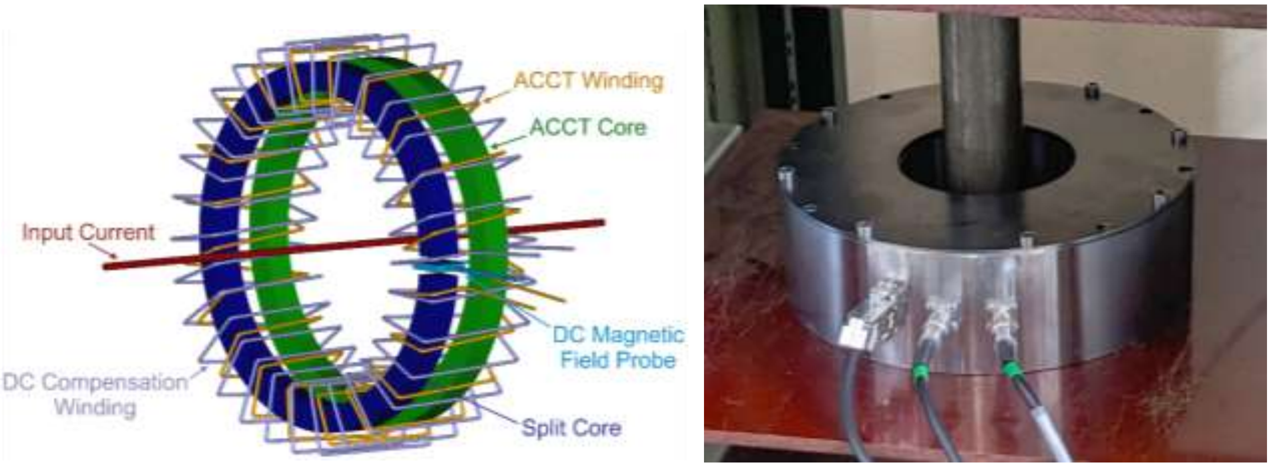

Figure 2: Sketch of the current sensor (left) and prototype on a test stand at CERN (right).

The DC magnetic field probe is placed in the gap of a split ring core. A closed ring core is added to improve inductive coupling between primary and secondary currents. One coil is used for the DC feedback, and one for the ACCT electronics.

The envisaged solution may seem simple and straightforward. However, achieving the required performance is challenging. The sensor resembles a three-winding transformer where the current to be measured acts as the primary winding. DC and very low frequency signals shall circulate only in one secondary winding, higher frequencies only in the other. The transition between the two must be limited to a narrow frequency band to avoid that ramping of the DC current has a negative impact on the AC measurement. The ACCT output signal must be fed back into the feedback electronics to avoid resonances in this frequency region. Figure 3 shows the schematics of the solution.

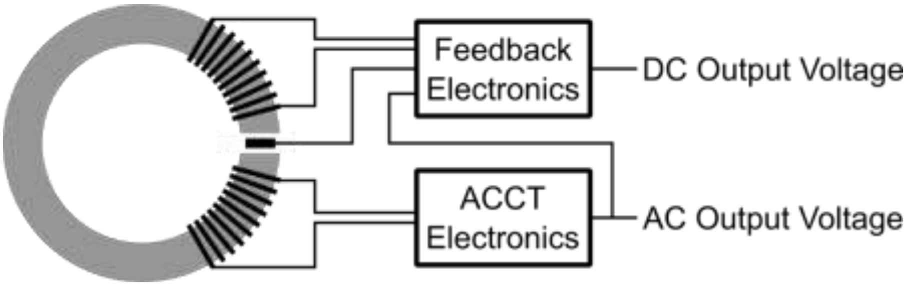

Figure 3: Schematics of sensor and related electronics.

Furthermore, it is favourable if the frequency transition and phase relation of the two signals allow reconstituting a signal spanning the entire frequency range of DC to 40 kHz:

$$I_{\mathrm{DC-40kHz}} = g_{\mathrm{DC}} U_{\mathrm{DC-10Hz}} + g_{\mathrm{AC}} U_{\mathrm{10Hz-40kHz}}$$

g_{DC} and g_{AC} are the calibration factors required to relate the output voltages $U_{\mathrm{DC\text{-}10Hz}}$ and $U_{\mathrm{10Hz\text{-}40kHz}}$ to the corresponding input current.

The ACCT electronics is a copy of standard ACCT electronics [3], only adapted to fit current and frequency ranges. The feedback electronics was newly designed. The number of transformer winding turns is a compromise between, on the one hand, limiting feedback current and power loss in the coil and, on the other hand, limiting parasitic capacitance and high-frequency signal deformations. Models of transformers and electronics were created using Pathwave Advanced Design System (ADS) and the Quite Universal Circuit Simulator (QUCS). Time-domain and frequency-domain simulations were performed to verify the characteristics and stability of the system.

2.3 PROTOTYPE MEASUREMENTS

At Bergoz Instrumentation (BI), measurements are possible for currents up to 20 A_{rms} and a bandwidth of up to 200 kHz. Using several primary turns allows to increase the effective primary current at the expense of bandwidth. The reachable current levels are sufficient to measure the specified AC current range. But only at low DC current levels. Tests under more realistic conditions were performed on a test stand at CERN which can provided 6 kA_{DC}. Figure 4 shows frequency responses measured at CERN for three different DC currents (0 A_{DC}, 2500 A_{DC} and 5000 A_{DC}).

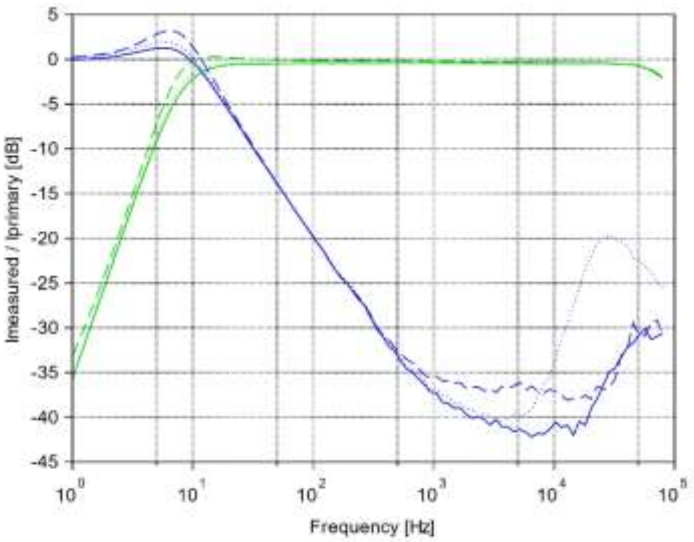

Figure 4: Feedback (blue) and ACCT (green) frequency responses at 0 A_{DC} (solid), 2500 A_{DC} (dashed) and 5000 A_{DC} (dotted).

While the measured frequency responses are close to expectation and bandwidth is within specifications, some unwanted dependence on the DC current is visible. After these tests, it was recognized that a reference voltage on the feedback electronics was slightly wrongly set. This led to a slight feedback current error and, thus, to an insufficient compensation of the primary current. Due to this, even without DC current the transformer core would always remain magnetically saturated.

Figure 5 shows frequency responses measured at BI without DC current before and after correcting the reference voltage. After correction, measurements agree well with simulations. Results above a few kHz strongly depend on transformer coupling factors, and simulations were tuned to match measurements.

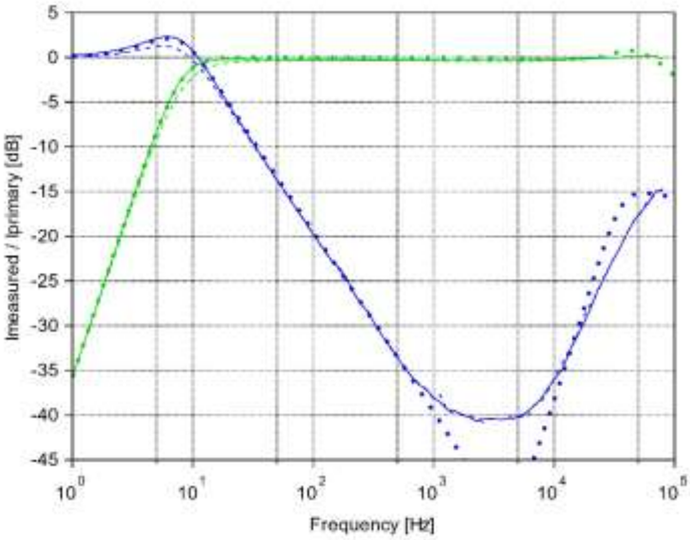

Figure 5: Feedback (blue) and ACCT (green) frequency responses measured at BI without DC current, before (dashed) and after (solid) correction of a reference voltage. Simulation results are shown by the dotted line.

The feedback response was measured for several DC currents up to 5 kA_{DC} as depicted in Figure 6. At high currents the measurement error was about 2%. However, as explained above, all measurements at CERN were performed with a small voltage regulation error, and the feedback could not correctly compensate for the primary current.

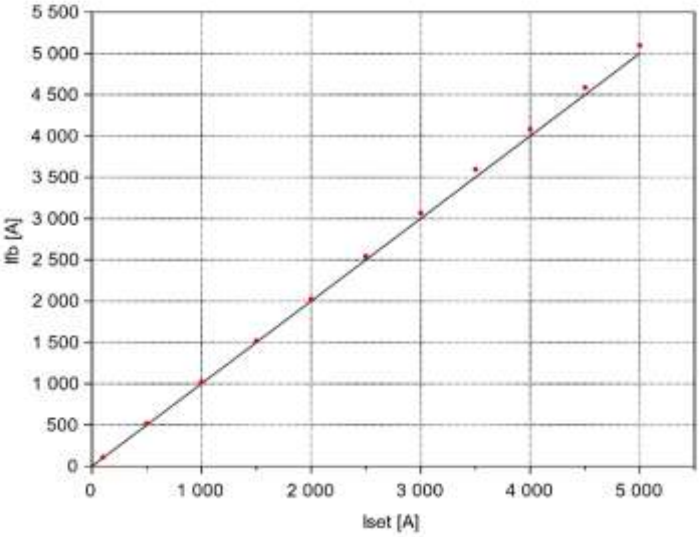

Figure 6: Current measured by feedback (red dots). The black line marks the set current.

The ACCT noise was determined under various conditions. When the feedback is switched off, the ACCT noise is ~50 µV, i.e. ~$5x10^{-6}$ with respect to the full-scale voltage of 10 V, which is better than required. However, when the feedback is switched on, the ACCT noise increases to ~$5x10^{-5}$, slightly higher than required.

Data taken at CERN shows that ACCT noise is higher by about a factor 6 when a strong DC current is present. Figure 7 shows spectral amplitudes calculated from 100 A_{DC} and 5 kA_{DC} data. At frequencies above 10 kHz, both data sets contain contributions induced by the ACCT power supplier and the primary current DC power supplier. On the other hand, strong harmonics of 300 Hz are visible only in the 5 kA_{DC} data set. This data set also has a higher 150 Hz content. A closer analysis of the available data shows the presence of many 50 Hz harmonics up to the kHz range. Further efforts are required to understand the related origin. Compared to the DCCT noise, which was determined to be ~30 mA_{rms}, the ACCT noise remained at least a factor 2 lower, i.e. <15 mA_{rms}.

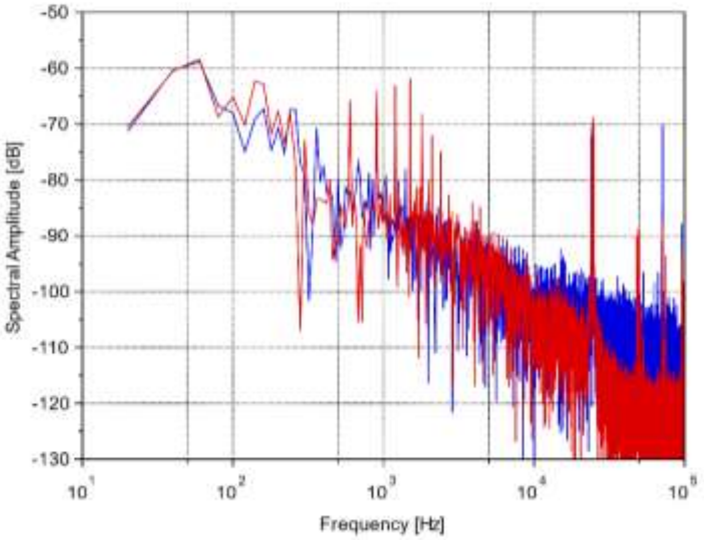

Figure 7: ACCT spectra at 100 A_{DC} (blue) and 5000 A_{DC} (red).

2.4 CONCLUSION FOR HIGH DYNAMIC RANGE CURRENT MEASUREMENT SYSTEM

The first prototype of the high dynamic range current measurement system with 40 kHz bandwidth was built and tested with DC currents up to 5 kA_{DC}. This novel arrangement comprises an AC transformer with a bandwidth of 10 Hz to 40 kHz and a DC measurement sensor to control the related compensation current and prevent the transformer cores from magnetic saturation. The results show that the prototype partially fulfils specifications, namely the measurement bandwidth and AC ripple resolution $\Delta I_{AC} / I_{AC} = 1\text{x}10^{-5}$ at low DC current levels. It comes close to specifications in the presence of a strong DC current up to 5 kA_{DC}. Though the results also reveal some deficiencies. Investigation and correction of these deficiencies have started. Further tests with high DC currents will be scheduled when the required improvements are implemented. It is clearly expected to achieve the requirements within the time frame of the IFAST project.

3 RF Signal Generation for knock-out Extraction

3.1 STATUS OF KNOCK-OUT SIGNAL GENERATION

HIT and MIT use a knock-out extraction scheme exclusively. At the same time, the other medical facilities, CERN [4] and GSI can operate the extraction by knock-out, tune scan or longitudinal beam manipulations. For knock-out extraction, the influence of the exciter signal spectrum on the spill microstructure is investigated at most facilities using beam dynamics simulations and beam-based measurements.

In the following Section 3.2, we summarise recent experimental findings from HIT [5]. These beam-based investigations are precursors for accurate specifications of the signal generation methods, rf-amplifier parameters and the potential need for matching network parameters. Detailed physics understanding towards optimal excitation spectrum for various beam conditions is still under investigation from the experimental and beam dynamics simulation side with other sub-packages in the IFAST-REX. Comparable campaigns are executed at the facilities of the European consortium members, e.g. [6,7], providing an intense exchange of results and related interpretation. Similar contemporary developments e.g. [8,9] show the relevance of excitation signal induced spill microstructure for all synchrotron worldwide,

The low-level control and signal generation methods were recently developed in relation to the versatile signal shapes required for the experimental investigations. Methods for generating complex signal shapes are part of the IFAST-REX project, and initially, only custom build digital modules were foreseen. At the beginning of the project, also high adaptive commercial hardware was available and could be controlled with versatile software. IFAST-REX participants commonly examined the capability for various signal generation methods that are now in operation. This task is one branch of the IFAST-REX project; it was realised ahead of time and acts as a performant technical solution for beam tests and some final installation. Section 3.3 describes the technical setup for this hardware and the software capabilities.

We are still in the experimental phase to determine the optimal signal shape and its properties concerning bandwidth and power requirements; hence, the final specification of the rf-power amplifier and matching network is still pending. Nevertheless, a preliminary design of these devices was started such that the realisation will be executed efficiently. The final achievements within IFAST-REX, i.e. the manufacture of an optimised rf-power branch knock-out extraction, will be reached within the project duration of IFAST-REX. Section 3.4 summarises the actual design investigations and technical solutions.

The beam excitation system being developed has immediate applications beyond slow extraction such as beam parameter measurements [10], transverse dampers [11] and advanced diagnostic tools [12].

3.2 BEAM-BASED INVESTIGATIONS FOR SIGNAL GENERATION SPECIFICATION

Slow knock-out extraction of several seconds duration is a multi-step process comprising the following procedures:

- In the first step, the horizontal machine tune is transferred close to a 3rd order resonance, i.e. the fractional part of the tune is close to 1/3 or 2/3. By the action of sextupole fields and the related non-linear dynamics, the beam motion is unstable above a certain amplitude for a given tune in the horizontal plane. The border between the unstable region and stable region is formally referred to as separatrix.
- A transverse excitation is applied to randomly drive the particles' betatron amplitude from the beam core towards the separatrix in a diffusion process.
- When particles cross the separatrix, their betatron amplitudes grow exponentially. The increase continues until the particles reach the extraction septum where an additional kick results in the passage through the extraction channel. The duration between the separatrix crossing and the arrival at the extraction septum is referred to as transit time.
- Any power supplier ripple leads to a variation of the separatrix or the beam's closed orbit, resulting in a burst of particles or a break of the extracted beam current. Moreover, the knock-out signals' properties strongly influence the particle motion during the diffusion process and the separatrix crossing. Both processes can cause significant fluctuations in the spill microstructure.

Extensive beam dynamics simulations are required to model and interpret the various steps and the sensitivity of the beam to external excitations. Those simulations are an integral part of the IFAST-REX project and are performed by all collaboration partners; however, the achievements are not the subject of the current report but will be included in the final delivery report.

For the specification of the rf signal spectrum for knock-out excitation, a detailed understanding of the extraction process is required; simulation must be verified experimentally. To achieve a better insight, an experiment was executed to determine the tune distribution with a machine setting under extraction conditions, i.e. for a beam close to a 3rd order resonance at HIT [13,14]. The beam response to a sequential excitation by a frequency chirp (similar to a beam transfer function measurement) is depicted in

Figure 8 [14]. Contrary to regular beam settings without sextupoles and external excitation, where a continuous tune distribution is expected, several visible peaks were observed. Figure 9 visualises this for a single particle coordinate evolution in the phase space in the presence of non-linear forces created by sextupoles and external dipolar rf fields [10]. It can be seen that particles oscillate in amplitude which translates into multiple peaks in tune space. More details on the experimental and theoretical details are described in [10,13,14]. In this report, we note that the phase space motion of the particles follows complex trajectories leading to a complex tune distribution evolution during the extraction.

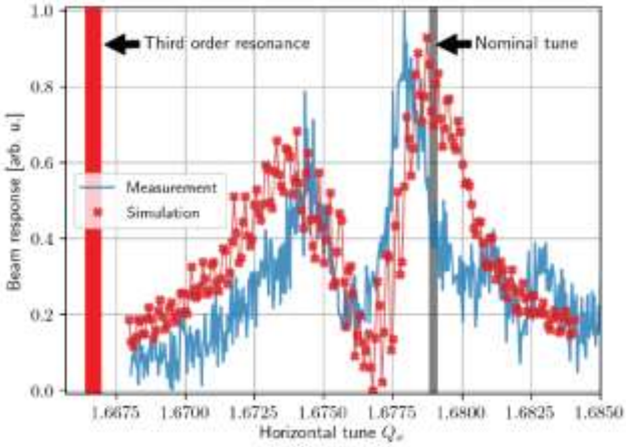

Figure 8: *Horizontal beam transfer function measurement at HIT for a 124 MeV/u C^{6+} beam with a nominal machine tune setting close to a 3^{rd} order resonance under extraction conditions compared to tracking simulations; reproduced from Ref. [14].*

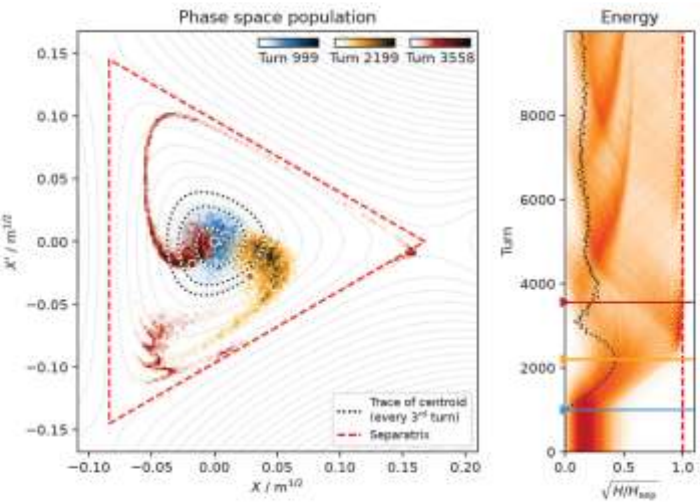

Figure 9: Particle beam dynamics during sinusoidal excitation with frequency $f_{ex} = 0.6641 \cdot f_{rev}$ of the revolution frequency. The excitation with strength $\mathcal{K} = 10^{-4}$ $m^{-1/2}$ starts in turn 1000. The colour shading represents particle density; the dotted black line is the centroid motion, and the red dashed line is the separatrix. Left: Phase space image for three distinct turns and a centroid trace in between. Right: Energy distribution calculated by a non-linear Hamiltonian; see in Ref. [10] for more details.

Based on the theoretical studies, the knock-out excitation must be adapted to the aforementioned complex phase space distribution to ensure a smooth diffusion and separatrix crossing and, consequently, an acceptable spill microstructure. For demonstration, we cite recent experiments performed at HIT [5,13,14], where multi-frequency excitation spectra close to the betatron frequency and its harmonics were investigated in combination with coasting and bunched beams. These studies use excitation signals from the recently implemented signal generator refers as KO DDS v2 [15]. The device can produce signals with up to four frequency bands. One or three of which were used for the experiments. Two exemplary spectra are shown in Figure 10, top. Each band is generated by random binary phase-shift keying (BPSK), a phase modulation technique in which a random binary sequence is encoded on the carrier frequency. For a time window of 1 s, Figure 10 shows the achieved spill microstructure for both signals for a coasting beam; a significant improvement is visible for the multi-band excitation. Longitudinal bunching further improves the extraction.

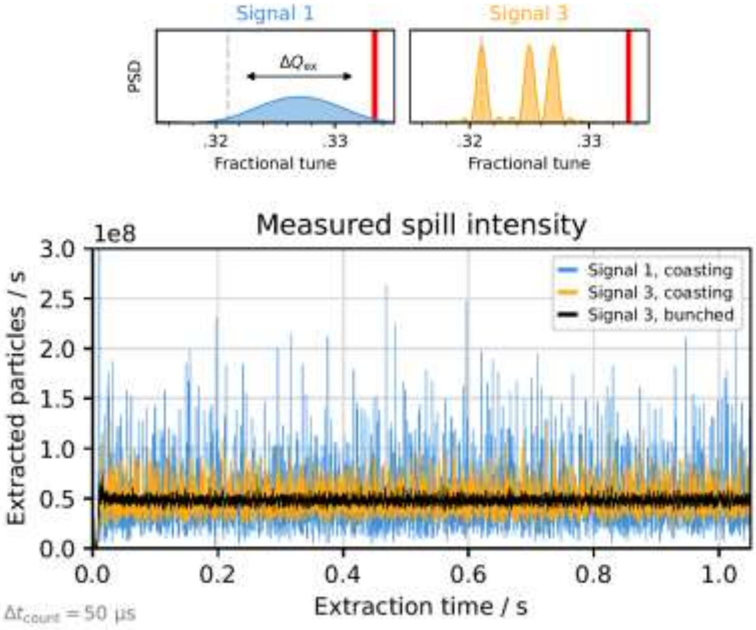

Figure 10: Top: Spectra of excitation signals transformed to baseband. The grey dashed line marks the machine tune Q_x *= 1.679; the bold red line is the resonance. Bottom: Spill intensity during the first second of extraction at HIT for two excitation signals, coasting and bunched beam recorded with a readout time* $\Delta t_{count} = 50$ *µs; reproduced from Ref. [5].*

Figure 11 summarises the improvement of the spill microstructure for three exemplary signal spectra as a function of the longitudinal bunching voltage. The spill quality is characterised by the coefficient of variance $c_v = \frac{\sqrt{\langle N^2 \rangle}}{\langle N \rangle}$ (left vertical axis) or the duty factor $F = \frac{\langle N \rangle^2}{\langle N^2 \rangle} = \frac{1}{1+c_v{}^2}$ (right vertical axis) with $\langle \ldots \rangle$ denotes the mean over an evaluation interval much larger than the readout time $\Delta t_{count} = 50$ µs. A clear improvement for the multi-band signals is visible for coasting and bunched beams up to medium bunching voltages; larger bunching voltages do not lead to an additional improvement. Further signal spectra are applied to confirm the correctness of the experimental results. Beam dynamics simulations support the related findings; and further detailed results are described in the cited publications. In general, these measurements and initial simulations confirm that a tailored excitation spectrum is required and there is a tendency of improvement where higher harmonics of the betatron frequencies are added [8,9].

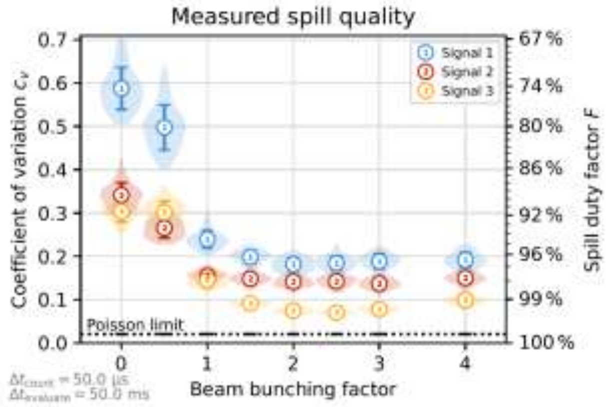

Figure 11: Violin plot for the spill quality for different excitation signals and bunching factors evaluated over $\Delta t_{evaluate} = 50\ ms$ *intervals; reproduced from Ref. [5].*

Extensive theoretical and experimental studies concerning the excitation spectrum's influence on the spill microstructure are presently performed by IFAST-REX consortium members to find the optimal signal spectrum for a given synchrotron and beam parameters. As it is an ongoing process, the exact technical specification for the rf-amplifier and matching network, such as power, bandwidth and impedance have been updated. However, the technical design of the rf power chain was started based on a preliminary version, see Section 3.4 and will be updated accordingly.

3.3 RF CONTROL TECHNICAL SOLUTION

As an integral part of IFAST-REX, a low-level signal generator for the transverse knock-out excitation was developed for prototyping at HIT [15] and later commissioned with a larger diagnostic scope at GSI SIS-18 and GSI-ESR [16] and MedAustron [6,17]. A novel approach for accelerators is taken using a software-defined radio (SDR) system and the open-source GNU-Radio software. The transceiver technology implements digital signal processing in software, thus allowing for a low-cost yet highly flexible setup for creating customisable and tuneable excitation spectra. The GNU-Radio software is used for the graphical design of signal processing flow graphs and control of signal parameters. Due to its open-source nature, it has the potential for long-term maintainability and integration into the accelerator environment at several facilities. It can serve as a general solution for knock-out extraction, when custom build DDS are not available. Furthermore, this opens up the possibility of sharing algorithms for generating waveforms across accelerator facilities.

SDR is widely used in radio communication systems but has potential applications in many fields. An SDR typically consists of a frontend with ADCs and DACs, and a backend performing the digital signal processing (DSP). A universal software radio peripheral (USRP) was used as an off-the-shelf frontend to generate the RF signals. For the implementation of the DSP, the open-source GNU-Radio framework [18] was chosen, which allows a graphical design of the signal processing flow graphs. The extensive flexibility and low modification efforts make the device a natural choice for prototyping [6,15,16], experiments, and also regular use in the accelerator environment.

Figure 12 depicts the working principle of the signal generator meeting these requirements in the context of a custom tune measurement system. The USRP digitises the revolution frequency reference signal (sine with frequency $f$rev) and receives the trigger (TTL pulse) via the general purpose input/outputs (GPIOs). It streams the data via Gigabit Ethernet to an industrial PC, where GNU-Radio performs the DSP. The generated signals are streamed back to the USRP and delivered via a Digital Analogue Converter (DAC) at the two RF ports. The Ettus model N210 with the low-frequency daughter boards were used. In principle, the installed DACs provide sampling rates of up to 400 MS/s with 16-bit resolution. In practice, however, this is limited by the data processing rate to about 10 MS/s, allowing to handle and generate frequencies up to 5 MHz. A higher performance Ettus USRP X310 is purchased, providing more extensive data processing and higher analogue bandwidth. Moreover, the latency between the trigger and shaped excitation signal could be reduced to the 1 ms time range with dedicated effort [10]. This model will be used to control the knock-out extraction amplifier in future at GSI. MedAustron will use the same control hardware with a slightly different setup, see [6] for more details.

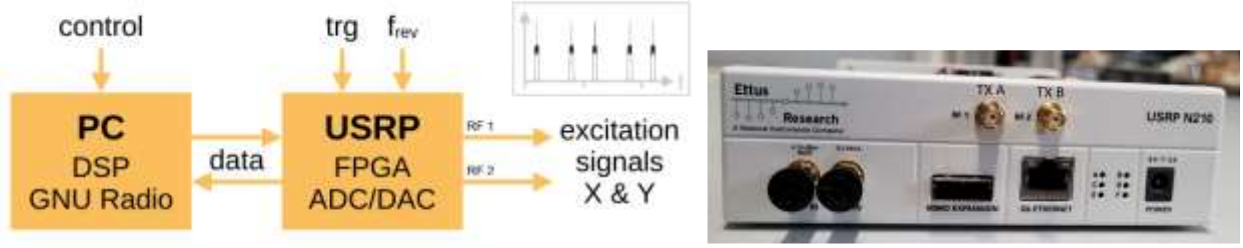

Figure 12: Signal generation scheme (left) and universal software radio peripheral hardware (right); reproduced from Ref. [16].

To show the capability of the GNU-Radio software and programming style, Figure 13 (left) depicts a basic example of the generation of excitation signals. Three basic signal types have been implemented for this example: Firstly, a binary sequence randomly flipping between ±1, which yields a random binary phase-shift keying (BPSK, top left box) modulation; secondly, a band-filtered uniform white noise (middle left box); thirdly, a sinusoidal frequency modulated sine resulting in a frequency chirp (lower left box). The baseband signal is up-sampled, and the frequency is shifted to the betatron frequency, i.e. the desired sidebands of the revolution frequency $f$rev. The latter is determined from the supplied RF reference signal utilising a phase-locked loop (PLL) to follow the frequency ramp during acceleration or can alternatively be specified manually by the connected Graphical User Interface. Since the excitation bandwidth Δf is constant, the relative width $\Delta q = \Delta f / f$rev decreases during acceleration, increasing spectral power density. This compensates for the increasing rigidity of the beam. Figure 13 (right) shows the resulting frequency spectrum of these three signals centred around the betatron frequency.

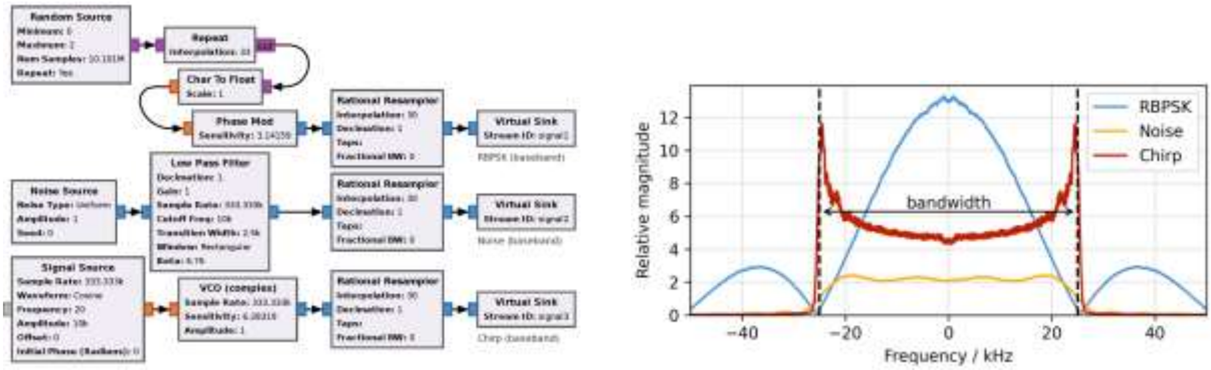

Figure 13: GNU Radio flow graph for the generation of a knock-out signal at baseband (left) and the frequency spectrum for three excitation types generated by the branches of the flow graph (right); reproduced from Ref. [16].

More complex signal chains can be created comparably with reasonable effort and were realised for the experiments mentioned above at HIT and beam diagnostics purposes at GSI; more details are described in [10,13-16]. As GNU-Radio is open software, a custom out of tree (OOT) block related to decreasing a trigger delay has been added to the GNU-Radio repository by the IFAST-REX collaboration members.

To control the extracted particle rate, the amplitude of the excitation signal must be changed during the spill, as particles must diffuse from the beam core to the periphery. The required rf-amplitude control can utilize by the same hardware and software. Considerations are started for realising a software-controlled feedback loop to ensure the uniformity of the extracted current on the 1-10 ms time scale in terms of a feedback system in connection to an extracted beam current measurement detector as the regulation input, as it is implemented in the HIT's medical accelerator [16] since 2013. The RF signal chain acts as the input for the rf power amplifier, which provides sufficient bandwidth and power as required for the knock-out extraction. In principle, the described control solution for the knock-out extraction could be adapted for all facilities of the IFAST-REX consortium.

3.3.1 The new Knock-Out Direct Digital Synthesis (KO DDS v2) at HIT

For the medical accelerator at HIT a new version of Knock-Out Direct Digital Synthesis (KO DDS) was developed to fit into the central control system, fulfil the requirements for the fast switch off medical interlock system and to increase the availability and reliability compared to a PC software solution.

The design of KO DDS v2 is based on the outcome of a recent master thesis [20] and substantial parts of which has also been published in [13,14]. As depicted in Figure 14, the KO DDS v2 generates an RF signal with up to four different frequencies, each of which can be broadened in the spectrum with a PRN-PSK. For each of the four frequencies an amplitude can be specified. The four frequency paths operate independently and are added together. An RF switch turns off the RF signal under certain conditions.

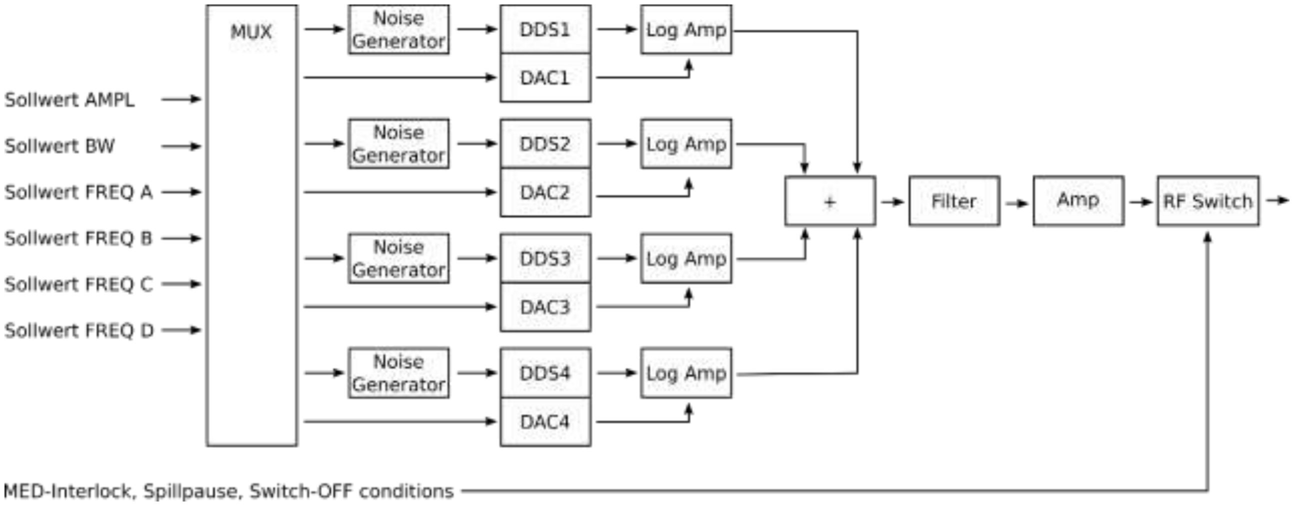

Figure 14: Block diagram of the KO DDS v2. Each of the four DDS paths consists of a noise generator, a DDS, a DAC and a logarithmic amplifier. The four signals are combined in a sum amplifier, filtered and amplified. An RF switch at the end can switch off the signal in case of an external interlock.

The KO DDS v2 consists of two boards, the motherboard with FPGA for communication with the control system and the daughter board with the RF front end and the interlock system. The KO DDS v2 daughter board has four independent DDS (AD9835), four logarithmic amplifiers (LMH6502), one combiner, two amplifier stages. Furthermore, for patient treatment safety regulations, there is a fibre optic interlock circuit for spill pause and external medical interlock on the board, which drive a fast RF switch. An example for a generated signal is shown in Figure 15 and Figure 16.

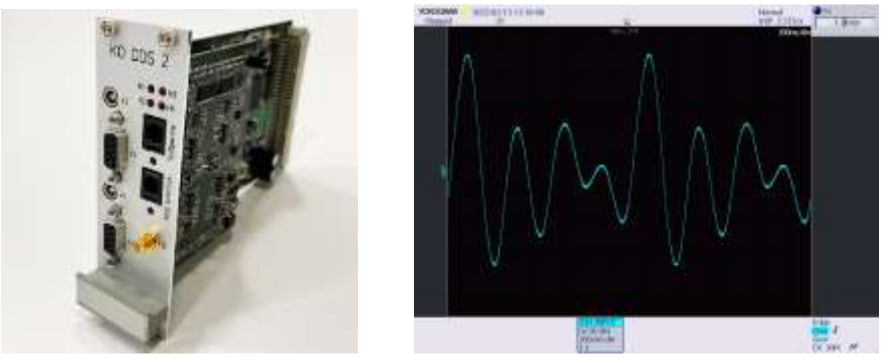

Figure 15: KO DDS v2 hardware produced for HIT (left) and an example for a signal with three frequencies (right).

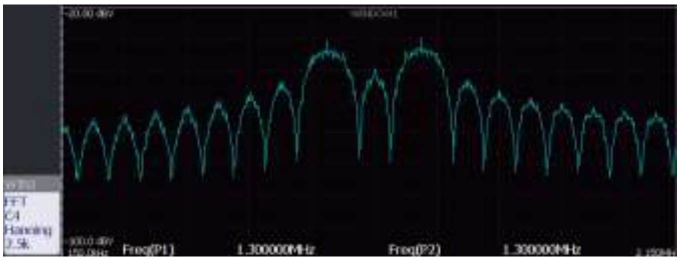

Figure 16: Example for a spectrum of the KO DDS v2 with two frequency bands.

3.4 RF AMPLIFIER DESIGN

Due the above described recently concluded beam-based investigations, the specification for the RF power amplifier was preliminary; moreover, the demand at the IFAST-REX facilities differs. Recently, the consortium agreed on the amplifier specification as collected in Table 2. Two 500 W amplifiers with a bandwidth of 0.5 to 15 MHz are planned with two termination schemes, a) Directly into a 50 Ω termination, b) via a matching network in the capacitive load of the exciter electrodes.

Parameter	**Value**
Frequency range	0.5 … 15 MHz
Output power	≥ 400 W, cw operation
Gain	57 … 60 dB
Gain flatness	Lower than 3 dB
Input impedance	50 Ω
Input reflection VSWR	< 1.2:1
Amplifier output impedance	50 Ω
Capacitive load of exciter electrodes and transformation ratio for matching networks	50 pF and voltage transformation ratio of 1:5
Output reflection VSWR	< 3:1
Cooling and acoustic noise	Air, < 70 dBA
Mechanics	19" rack mount

Table 2: Basic specifications for the power amplifier

Before the technical parameter was exactly specified, we started with preliminary considerations for the power chain of the knock-out extraction. An amplifier covering a bandwidth of 30 kHz to 10 MHz with an output power of 400 W was considered. Figure 17 shows a related network analyser measurement. The gain decreases slightly at both bandwidth peripheries. However, the electronics can be optimized to achieve the anticipated bandwidth from 500 kHz to 15 MHz. The gain stability (gain as a function of input power) is shown in Figure 18; it shows the broadband operation of the amplifier. The optimization will be addressed in the next design iteration.

Concerning the output power capability we refer again to Figure 17: The gain for an input power of -2 dBm is a bit higher than for an input power of -15 dBm which indicates that the circuits have sufficient power margin for a 500 W operation. Hence, it shall be possible to optimize the circuits for an output power of 500 W. As a result of the next technical iteration process, we are confident of reaching the specification demands.

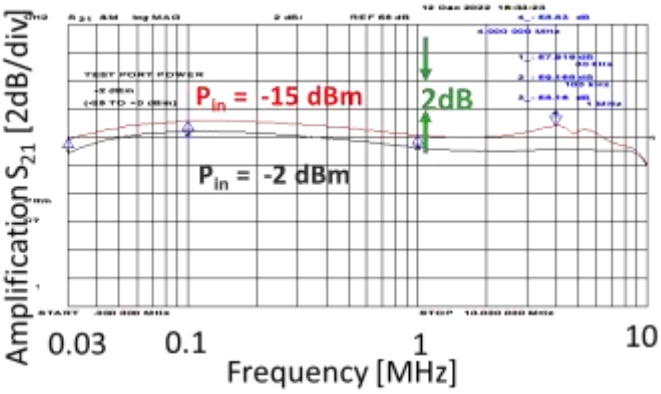

Figure 17: Scattering parameter S_{21} (transmission measurement) for the precursor amplifier in the range from 30 kHz to 10 MHz with two different input power levels.

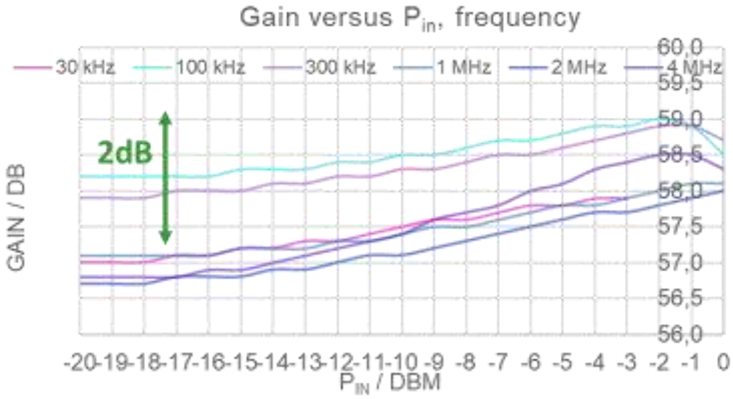

Figure 18: Gain stability for various input frequencies determined with the precursor amplifier for a 50 Ω (gain in units of dB, input power in units of dBm).

While discussing the overall setup, it became apparent that an additional matching network is required to transform the amplifier 50 Ω output impedance to the capacitive load of the knock-out electrodes. The matching is based on a multi-step transformer setup and detailed design considerations were started. The challenge for this matching network is the extremely wide bandwidth range from 0.5 to 15 MHz providing a sufficient flat transmission characteristic as the matching conditions depends on the capacitive load by the electrodes. For this bandwidth interval, the power absorption by the ferrite cores is frequency dependent, leading to a temperature change and, hence, a permeability modification. Moreover, it is challenging to prevent for backward reflections towards the amplifier as it is required for a safe operation at high output power levels.

3.5 CONCLUSION CONCERNING RF-CONTROL AND AMPLIFIER DESIGN

Due to its high relevance, slow extraction improvements are executed by all consortium members. Detailed beam dynamics simulations for the non-linear extraction process are required. For their verification, relevant beam-based investigations were performed at the consortium facilities. The final goal is tailoring the optimal excitation spectrum for a smooth diffusion and a uniform separatrix crossing. A large spread in the transit time contributes to the mitigation of fluctuations as well.

Due to the ongoing theoretical and experimental investigations, the detailed specifications for the rf-amplifier and matching network were only in the preliminary stage and are recently updated. However, the technical design for this power electronics was already started considering various options. With the developments so far, current knowledge and clear specifications, the production and experimental verification within the IFAST-REX project duration is clearly expected.

For the generation of complex signal spectra, an adequate solution was found by using a high-performance commercial product with versatile and user-friendly software control. The engineering design for this branch is finished.

4 Future plans / Conclusion / relation to other IFAST work

The two technical devices are summarized above and are here only repeated in brief:

- A current transformer system was developed capable of detecting residual AC fluctuations of current from a power supplier with a resolution almost down $\Delta I_{AC}/I_{DC} = 10^{-7}$ which was never realized before. The AC part determines fluctuations $\Delta I_{AC}/I_{AC} = 10^{-5}$ for a bandwidth of 10 Hz $< f <$ 40 kHz on a high level of DC current up to I_{DC} = 5 kA_{DC}. The device was realized at the company Bergoz Instrumentation and tested in-house and at CERN. Further tests are foreseen at other facilities; particularly, in connection to the determination of the spill microstructure. Presently, it is a test device with full functionality. Some improvements and further tests are required to finalize product development which will be realized within the IFAST duration.
- The system design for the knock-out extraction control, amplifier and matching network are progressing. As a first step, versatile experiments were executed to determine the influence of the transverse excitation signal with respect to the spill microstructure. Significant insight into the excitation process was achieved and is accompanied by detailed beam dynamics simulations. The specification of the bandwidth and power requirements were elaborated for the entire signal chain. For the signal generation and control, the applicability of the commercial Software Defined Radio was clearly demonstrated. Basic considerations of the power amplifier were started. It is demanding to produce an amplifier with a bandwidth of 500 kHz $< f <$ 15 MHz and at least 500 W output power which can be connected to a capacitive load of several 50 pF. A matching network is required to handle the capacitive load's reflections and achieve sufficient voltage for the beam influence. The design and realization will be done in close collaboration between IFAST-REX members. HIT will serve as the first choice for the beam-based test of the entire system, followed by tests at further IFAS-REX facilities. A functional system will be provided within the IFAST project duration.

Both technical systems have many applications at accelerators: The system of current transformers can be applied at any magnet power supplier to monitor the residual AC part and its usage as the input of a feedback system. The method of beam excitation can be used not only for slow extraction but for many measurements, such as tune, chromaticity and within a regulation loop for beam stabilization. In this sense, the development will contribute to an improved operation of accelerator facilities in future and have a strong connection to several work packages within IFAST. In particular, a strong relation to the WP5.2 (Pushing Accelerator Frontiers) exists.

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