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Abstract. Resonant Schottky cavity pickups have applications in the measurements of beam parameters in a storage ring. Apart from that they can be used in non-destructive in-ring decay studies of radioactive ion beams. In order to obtain the results of an experiment suitable Data Acquisition System (DAQ) is necessary. Several DAQs were used at Experimental Storage Ring (ESR) at GSI based on the different hardware and software solutions such as TCAP or NTCAP. The goal of this work is to design a prototype of a DAQ using open hardware and open source software defined radio (SDR) and conduct the test measurements at ESR.

1. Introduction

Studying the rapid neutron capture process (r-process) in stellar environments, that leads to the creation of elements heavier than 56-Fe, remains one of the fundamental questions of modern physics and therefore an active field of research within nuclear astrophysics [1]. Apart from other key measurables like neutron capture cross section and decay lifetimes, nuclear masses are of outmost importance for pinpointing the r-process using theoretical and experimental approaches. Exotic nuclides which participate in the r-process due to their low production yield and short half-life can be efficiently investigated in storage rings [2, 3]. In such facilities non-destructive methods of particle detection are often used for in-flight measurements based on frequency analysis [4]. Due to the low signal level the detectors should be very sensitive and fast because of short lifetime of the particles. Resonant Schottky cavity pickups fulfill such requirements [5]. Apart from their applications in the measurements of beam parameters, they can be used in non-destructive in-ring decay studies of radioactive ion beams [4]. The goal of this work is to design a prototype of a DAQ using SDR.

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2. Schottky analysis

Resonant Schottky cavity are highly sensitive non-destructive beam position and intensity detectors. Schottky mass spectrometry is a method for precision nuclear mass spectrometry based on the measurement of the revolution frequencies of cooled ions in storage rings performed by frequency analysis of the beam noise, the well-established Schottky diagnosis technique. The method has been applied at the Experimental Storage Ring ESR at GSI observing electron cooled highly charged ions up to bare nuclei at relativistic energies around several hundred MeV/u [6]. Schottky mass spectrometry can be done in the standard mode of a storage ring or it can be done in so-called isochronous mode. In the standard mode all particles can be cooled in order to decrease their momentum spread. For example the momentum spread at ESR after cooling $\frac{\Delta p}{p} \leq 10^{-4}$. In this mode particles flies through the detector with different frequencies but with almost the same momentum. Cooling process can take up to several seconds which is an inappropriatly long time for performing the mass measurement of exotic nuclides whose lifetimes could be in the order of miliseconds. In order to work with such nuclides the isochronous mode could be used. This mode is specially designed for in-ring high precision mass measurements of exotic nuclei which have the half-life time as short as several tens of microseconds and the production rate as low as one ion per day [7]. Usually the Schottky noise of an ion beam in a storage ring is non-interceptively coupled by a pickup, followed by amplifications, and finally analyzed in frequency domain by means of the Fourier transformation [8].

3. Previous data acquisition systems at ESR

Obtaining results of an experiment is impossible without having a suitable DAQ. In order to monitor the status of a storage ring, expensive broadband DAQs such as frequency analyzers are widely used. But in case of the Schottky measurements frequency range of interest is relatively narrow. The maximum necessary bandwidth is equal to the particle revolution frequency in a storage ring due to the repeating frequency spectrum pattern. For example at ESR typical particles revolution frequencies are between 1-2 MHz. To obtain data from this bandwidth one can use a simple DAQ with the local oscillator (LO) to mix down the signal of interest. One of the first systems which has been devoted to acquire the data from resonant Schottky cavity was the TCAP [9]. It had a fixed bandwidth of 500 kHz and sampling rate of 642 kHz. Later on a New TCAP (NTCAP) was developed [10]. It has the maximum bandwidth of 50 MHz and the maximum sampling rate 70 MHz, which allows more than 10 harmonics of the ion beam to be recorded simultaneously [11]. In addition to it NTCAP offers a possibility to change the bandwidth and the sampling rate. Inspite of their advantages, DAQ systems based on TCAP and NTCAP are resource intensive and bound to used hardware. To overcome all these restrictions an idea of using an SDR has been proposed. The main reason of using the SDR is its versatility and scalability. One of advantages of the SDR is that the

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DAQ based on it can be easily scalable just by adding a new SDR where it is needed. Open source philosophy of SDR allows to connect it to any modern computer and have no problems with updating of the drivers. The main script which has control over the SDR settings is stored centrally on the PC, which means that all of the SDRs can be set in the same way from one master device. Such a system can be easily synchronized with one master clock which gives the same time stamps for all acquired data. LimeSDR has been chosen due to its open software and open hardware which allows to configure not only the high-level parameters such as sampling rate and sampling frequency, but also to conduct the fine FPGA configuration or change the format of the output data file.

4. Description of the used SDR

LimeSDR is a device which has input and output ports, LO, radio module which is responsible for analog signal digitizing and processing and an FPGA which can be programmed to adjust the radiomodule settings, start reading data etc. In this work we store the data as raw binary files. LimeSDR has two channels for data sending/receiving, every of them is divided to low frequency(below than 1.5 GHz), broadband and high frequency(higher than 1.5 GHz) antennas. Signals from all those antennas are then processed by the radiomodule LMS7002M with 12-bit ADC, which is guided by the FPGA Altera Cyclone IV EP4CE40F23. LimeSDR has USB 3 connector as data transceiver and IPX male RF connectors. It can be powered with USB 3 cable or with external 6-12V DC power supply using LimeSDR jack and pinheader. There are several possibilities to program LimeSDR using SoapySDR library and C++ or Python. FPGA firmware can be changed using VHDL programming language and JTAG interface.

5. Method of measurements

Measurements were conducted at ESR using signals from the resonant Schottky cavity with resonant frequency of 245 MHz[4]. At first one has to initialize the LimeSDR, set all preferences and setup the data streams. During the initialization process and stream setup board will calibrate itself according to its LO which has constant frequency 30.72 MHz. During the initialization several settings have been set. We chose channel 1 as data receiver, used low frequency signal antenna because our frequency of interest was 245 MHz which is below the 1.5 GHz, and set all the amplifiers to 0 dBm. Afterwards, we had to allocate the data buffer (or two buffers in case of simultaneous signal receiving from both channels 1 and 2) according to the amount of data one wants to process. In Python we chose a numpy array to write data and then gave this array to LimeSDR stream as a parameter. When this array is filled the stream closes. The size of the array is the sampling rate multiplied by the measurement time. Then this array is converted using numpy array routines from ADC values to 64 bit complex numbers each for future offline processing.

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6. Results

We measure the signal for 5 seconds at a center frequency of 244.3 MHz with 1 Ms/s and a bandwidth of 500 kHz. The cavity has been tuned to 244.7 MHz. A beam of $^{40}Ar^{18+}$ has been injected at ESR at the energy E of 245.7 Mev/u and cooled. Momentum compaction factor α_p was 0.16 and transition Lorentz factor γ_t was 2.4 with beam current of 550 uA, number of particles was 1.12×10^8. A spectrum of the recorded data shown in the Figure 1.

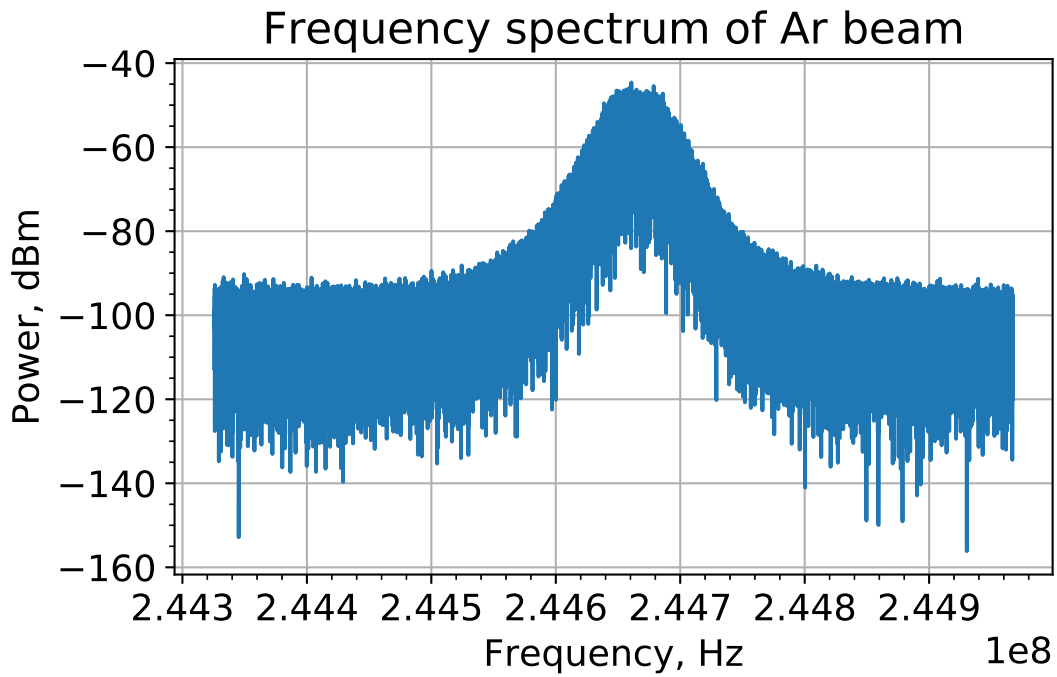**Figure 1.** Signal of the $^{40}Ar^{18+}$ beam recorded by LimeSDR. Center frequency is 244.7 MHz, width at -3 dB point is 40.79 kHz

Taking into account that we had one species of $^{40}Ar^{18+}$ we can calculate Lorentz factor as

$$\gamma = \frac{E + m_0c^2}{m_0c^2} \tag{1}$$

where m_0c equal to 938 MeV/u. Momentum spread can be calculated as

$$\frac{\Delta p}{p} = \frac{\Delta f}{f}\left(\frac{1}{\gamma^2} - \frac{1}{\gamma_t^2}\right) \tag{2}$$

where f is the peak frequency, Δf is full width at -3 dB point. Using equation (1) and equation (2) we can calculate the momentum spread using parameters of the peak and the result is $\frac{\Delta p}{p} = 3.7 \times 10^{-3}$.

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7. Conclusion and outlook

LimeSDR is a small, relatively affordable versatile device for the Schottky analysis in storage rings. It can be easily programmed using high-level programming languages. Adjustments of a particular setting can be done using simple commands from SoapySDR library. We have an opportunity to save data in a preferable format. Tests on the beam at ESR showed that LimeSDR is sensitive enough to detect the beam signals from the resonant Schottky cavities. Further investigations will be conducted to test the sensitivity, signal degrading with frequency, gain efficiency and other important parameters for precision isochronous mass-spectrometry.

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