DESIGN OF A NEW SUPER-HETERODYNE MICROTCA.4 BPM AND LLRF REAR TRANSITION MODULE (RTM) FOR THE EUROPEAN SPALLATION SOURCE

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Abstract

The 5 MW European Spallation Source (ESS) is a long pulsed source based on a high power superconducting LINAC. In order to achieve this high level of performance, the beam position measurement system needs to measure the beam position, phase and intensity in all foreseen beam modes with a pulse rate of 14 Hz, duration of 2.86 ms and amplitude ranging from 5 mA to 62.5 mA. We have designed a general purpose Beam Position Monitor (BPM) front-end electronics that has a dynamic range of 70dB. The front-end uses the MicroTCA (Micro Telecommunication Computing Architecture) for physics platform that consists of a 16-bit 125 MSPS ADC module (SIS8300L/2 from Struck) that uses the Zone 3 A1.1 classification for the RTM. This paper will discuss the design of this new RTM that includes eight channels of super-heterodyne receivers, two channels of DC-coupled inputs to measure klystron voltage and current, one vector modulator that modulates the LLRF output. The RTM communicates with the AMC FPGA using a QSPI interface over the zone 3 connection.

INTRODUCTION

The Beam Position Monitor (BPM) system of the ESS linac will use BPM sensors of different sizes and types. It is planned to use small-aperture stripline BPMs in the low-energy linac including the Medium Energy Beam Transport (MEBT) and Drift Tube Linac (DTL) sections. The BPMs of the cold linac including the Spoke, Elliptical and the downstream sections such as LogLeg, Dumpline and Accelerator-to-Target (A2T) may be of electrostatic button or stripline type. These two types are currently being studied in terms of performance, cost, space requirements etc. before a decision will be eventually taken on which type to use.

Most of the BPMs will belong to the Linac Warm Units (LWUs) that will be installed in between each two successive cryomodules. The LWU will include two quadrupoles, and in the current design, there is a BPM close to each quadrupole [1]. The BPM number per LWU may however be decreased to one in the next revisions that is mainly due to space limitations. The other alternative would be to use two longitudinally-short BPMs with welded feedthroughs to resolve the space limitation issue.

In order to minimize potential disturbances from nearby RF sources, BPM signal processing will be done

at opposite frequency with respect to RF. This means the second harmonic (i.e. 704.42 MHz) of the BPM signal will be processed in the Spoke and upstream sections while the fundamental harmonic (i.e. 352.21 MHz) will be processed in the sections downstream to the Spokes. A direct consequence of this is that for beam phase measurements, the BPM and Low Level Radio Frequency (LLRF) systems will need phase reference signals with opposite frequencies.

The BPMs need to have an overall accuracy of +/-200 um and a resolution of 20 um with the nominal beam current of 62.5 mA and pulse width of 2.86 ms. The BPMs also need to successfully measure the beam position (possibly with a lower S/N ratio) under off-optimal conditions such as with a debunched [2] and low-current beam of 6.25 mA and pulse width of 10 us that is foreseen for linac commissioning. Calculations show that under the worst-case scenario, the BPM voltage with the off-optimal beam can be lower than the nominal voltage by three orders of magnitude.

The BPM button voltage is expected to decrease to less than one-half from the beginning to the end of the linac [1]. This is due to the beam velocity increase and the changes in the BPM size and type. Despite these voltage level variations, the electronics of all the BPMs will be based on the "ESS centralized design". The BPM electronics and firmware of the low-energy linac will however be slightly different from those of the high-energy linac because of the RF frequency jump at the end of the Spoke section.

The BPMs will also be used to measure the absolute and relative beam phase. The phase information will be needed for RF tuning as well as beam energy measurements based on the beam Time Of Flight (TOF).

As the LLRF and BPM systems have somewhat similar requirements, an effort is being made to maximize synergy by using same/similar electronics and firmware for both systems.

ESS BPM/LLRF FRONT-END REQUIREMENTS

Both the BPM and LLRF front-end designs are based on down-mixing to Intermediate Frequency (IF) and sampling in In-phase / Quadrature-phase (I/Q) or near-IQ to measure the amplitude and phase of the RF input signal. These signals will then be FPGA processed to calculate the beam position, phase and intensity (BPM system) or to control/regulate the cavity voltage (LLRF system). A clock frequency of 88.0525 MHz (this is one-

forth of the bunch frequency and it is locked to RF) is already available from the ESS timing system. Therefore, for I/Q sampling, the IF frequency needs to be 22.013125 MHz. With respect to near-IQ sampling, a clock frequency of 110.065625 MHz may be used at later stages of the development.

The ADC clock and the LO for down-mixing will be generated and synchronized to RF using a new MTCA.4 module that is currently under detailed design. The LO generator, the RTM and the digitizer will be all hosted by the same MTCA.4 crate.

Both the BPM and LLRF designs are based on a RTM/digitizer with 10 ADC input channels. In the case of BPMs, 9 AC-coupled inputs will be needed to measure signals from two successive BPMs, being 8 for the electrode signals plus one for the phase reference. In the LLRF case, 8 AC-coupled inputs will be needed to measure the cavity/waveguide field in each RF plant, and 2 DC-coupled inputs will be needed to measure the modulator current and voltage. Moreover, the LLRF will need one Vector Modulator (VM) output on the RTM to control the RF amplifier.

The RF input channels need to be optimized for 352.21 MHz or 704.42 MHz depending on location in the linac.

As there is a possibility that the final BPM/LLRF systems will use a combination of off-the-shelf and custom-made RTMs, care should be taken to have -to the extent possible- same connectors on both RTM types. That will then facilitate RTM connection to other modules and reduce cost as well. Also, the input voltage range of the two RTM types need to be similar. Assuming that the RTM is configured for 0 dB net gain/attenuation, then the maximum input needs to be about +/- 1 V_{peak} (i.e. 10 dBm).

The overall gain/attenuation of the front-end card needs to be controlled over a wide range of typically larger than 30 dB. This is mainly to adapt the BPM voltage level to the ADC input range. Also, in order to improve the S/N ratio with a weak BPM signal, it might be useful to amplify the electrode voltage before the mixer, because the mixer has a large Noise Figure of 16 dB.

Both the BPM and LLRF systems have stringent requirements on S/N ratio. Current version of the LLRF requirements mandates that the amplitude and phase of the RF voltage in the superconducting cavities be stabilized to 0.1% and 0.1 degree over the pulse length (these stability requirements are 0.2% and 0.2 degree with the normal-conducting cavities). Also, in the BPM case, the position and phase need to be measured with a resolution of 20 um and 0.2 degree respectively. In order to achieve these, the S/N ratio and the channel-to-channel isolation need to be better than 70 dB.

Shafer equations [3] have been used to calculate the button voltage. This is estimated at 170 mV$_{peak}$ at high energy with the nominal beam being at the centre of the beam pipe. Considering cable attenuation, thermal noise and the RTM noise figure, the expected S/N ratio at the

input of the digitizer is about 67 dB at 352 MHz. Using Eq. 1, the resultant BPM resolution will be about 10 um that meets the requirements.

$$\sigma_X = \frac{b}{2} \cdot \frac{\sqrt{2}\sigma_V}{2V} = \frac{b}{2\sqrt{2}} \cdot \frac{1}{\sqrt{SNR}} \qquad (1)$$

Also, it is foreseen to provide the BPM/LLRF electronics with clean LO, phase reference and clock signals. Additive jitter (10 Hz – 10 MHz) of these signals will be significantly better than 1 ps.

SUPER-HETERODYNE RTM DESIGN

Super-heterodyne RTM design as illustrated in Fig. 1. The design of the super-heterodyne was chosen because the ADC input bandwidth would attenuate the 352MHz by 10dB thus effecting the signal to noise ratio. The super-heterodyne circuit uses two programmable attenuator one to prevent saturation at the input and a second attenuator after the amplifier to prevent saturation of the mixer. The output of the mixer is converted to single ended to amplify the signal and filter mixing harmonics. The specification of the LTC5577 requires that the heterodyne be a "High-Side" mixer. This means that the f_{lo} is greater than $f_{rf.}$ [4]. This mixer has a broad range of operating frequencies (300MHz -6GHz). To insure that the mixer appears to be 50 ohms at 352MHz a matching circuit for the RF has been carefully tuned. The output of the mixer is a 100 ohms differential. A 2:1 transformer was added to provide gain and IF filtering. An ADC matching circuit was added to provide known impedance over the zone 3 connection. The design of the LO distribution is a simple design using 90^0 hybrids. This was done so that any reflection would be terminated in the isolation port. In the next version a full PLL circuit would be added to derive the LO from the master RF.

To communicate with the RTM a QSPI interface was chosen to provide good noise isolation and an easy way to write and read back attenuator, board health and switch values. This interface has been used on the Pohang, LCLS BPM system [5]. Figure 2 shows a photo of the fabricated RTM.

Figure 2: Photo of the RTM.

RTM TEST PLAN

As the 352 MHz super-heterodyne RTM is a new and complex design, it may need to go through a test procedure before it is installed in a crate that is populated with other modules and used for some RF signal measurements. The RTM was designed with a way to test some active components (power supplies, opamps, amplifiers) by using a header to supply 12V. This will also be used to measure the current of the board and calculate power of the module. The test procedure should typically start with checking the power lines and also verifying that the design and manufacturing is free from any errors.

The parameters that are of significant importance for both BPM and LLRF include those that have a large influence on resolution and accuracy. This includes ex. S/N ratio, channel-to-channel cross-talk, and third-order intercept using two-tone measurement technique. These measurements check dynamic range, noise from adjacent channels, and linearity and temperature dependencies on each channel. Also, it is important to make sure that the RTM can be successfully operated within its attenuation range, and the LO, clock and trigger sources configured as desired. In order to verify these, an FPGA code and a software driver will be needed. These are basically to control the two on-board attenuators as well the RF switches.

It is also foreseen to test the RTM later on a BPM test bench that is already available at ESS. An RF signal generator will then be used to generate a 352.21 MHz sinusoidal current going through a wire that will emulate the beam. The induced voltages on a prototype BPM will then be band-pass filtered and fed into the RTM. These signals will get down-mixed to 22 MHz in the RTM, and then digitized and FPGA processed in the digitizer card to calculate position, phase and intensity.

Similar tests will be done in parallel by the LLRF group using a LLRF prototype connected to a mock-up pillbox cavity.

FUTURE RTM MODIFICATIONS

Due to the RF frequency jump at the end of the Spoke section, and as the BPM and LLRF requirements are slightly different, 4 variants of the RTM will be ideally needed for the ESS linac. These are summarized in Table 1 (current design is variant 3).

Table 1: Summary of BPM/LLRF RTM requirements

	Var.	Freq. [MHz]	No. of AC inputs	No. of DC inputs	No. of VM outputs
BPM	1	352	10	0	0
	2	704	10	0	0
LLRF	3	352	8	2	1
	4	704	8	2	1

After the performance of the current RTM has been verified, a decision may be taken to proceed with the other variants as well.

SUMMARY AND OUTLOOK

Over the past two years, SLAC and ESS Beam Instrumentation group have made a successful collaboration to design a new super-heterodyne front-end RTM for the ESS BPM and LLRF systems. The design has been done by SLAC based on the ESS requirements. A pre-series of the RTM has recently become available, and preliminary tests are being planned before using the RTM for RF signal measurements on BPM and LLRF systems. The current RTM is in principle an ideal choice for the LLRF systems of the low-energy linac in terms of frequency and the number of the AC- and DC-coupled input and vector modulator output ports. After the RTM performance has been successfully verified in practice, a decision may be taken to go ahead with other RTM variants, thus fulfilling both the BPM and LLRF requirements in the low-energy as well as the high-energy linac.

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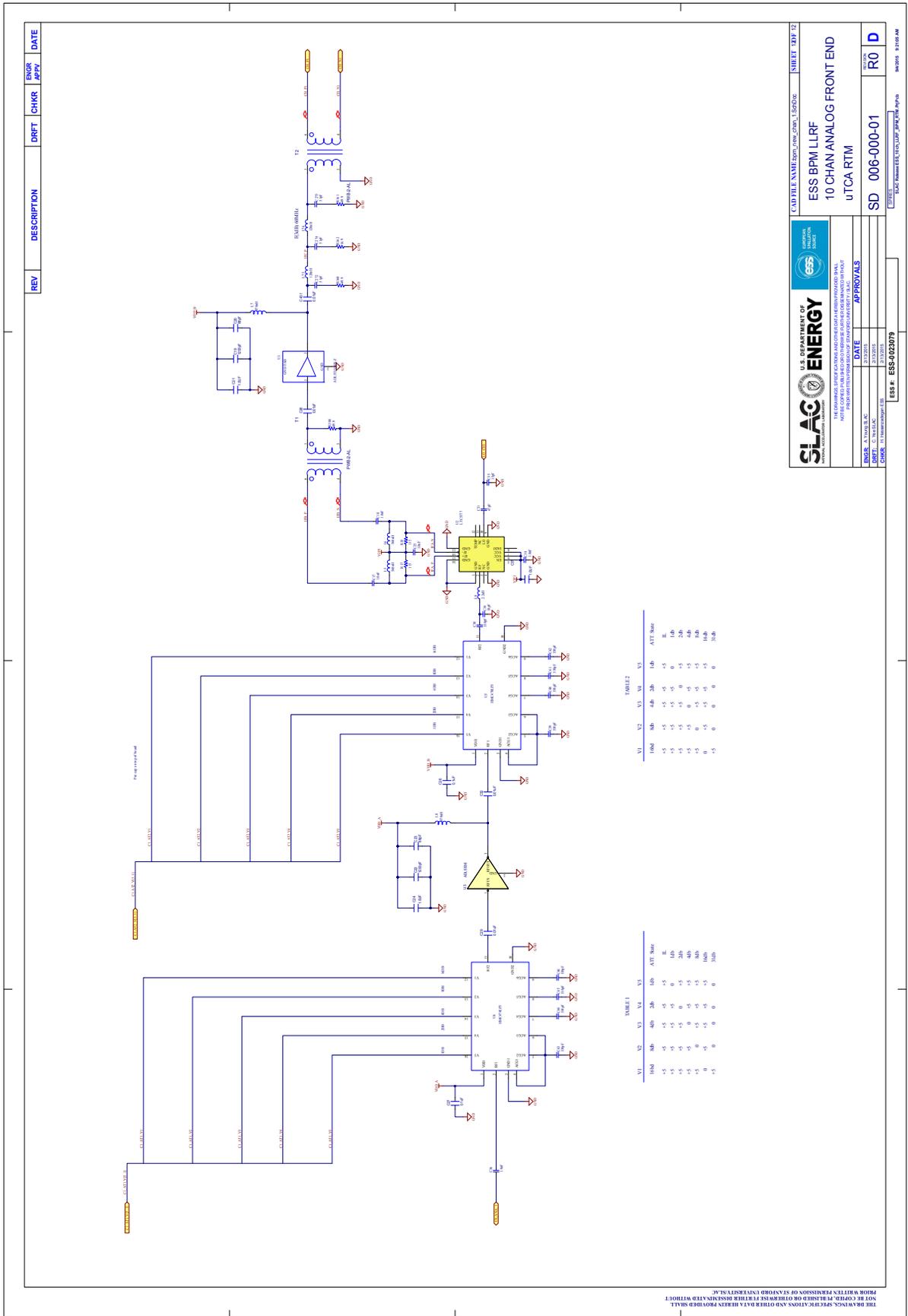
Figure 1: Super-heterodyne circuit.