TUPB051

Design of a New Super-Heterodyne MicroTCA.4 BPM and LLRF Rear Transition Module (RTM) for the European Spallation Source

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Background

The BPM system of the ESS linac will use BPM sensors of different sizes and types. Most of the BPMs will belong to the Linac Warm Units (LWUs) that will be installed in between each two successive cryomodules. The BPM button voltage is expected to decrease to less than one-half from the beginning to the end of the linac due to the beam velocity increase and the changes in the BPM size and type. In order to minimize potential disturbances from nearby RF sources, BPM signal processing will be done at opposite frequency with respect to RF. 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 will also be used to measure the absolute and relative beam phase. These will then be used for RF tuning as well as beam energy measurements based on the beam Time Of Flight (TOF). For linac commissioning, it will be needed to successfully measure the beam position (possibly with a lower S/N ratio) under off-optimal conditions such as with a low-current beam of 6.25 mA and pulse width of 10 us. As the LLRF and BPM electronics have somewhat similar requirements, an effort is being made to maximize synergy by using same/similar electronics and firmware for both systems.

BPM voltage under nominal conditions

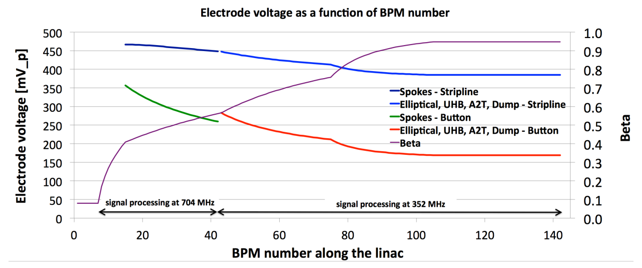

Figure 1: Calculated electrode voltage as a function of BPM number for button and stripline pickups.

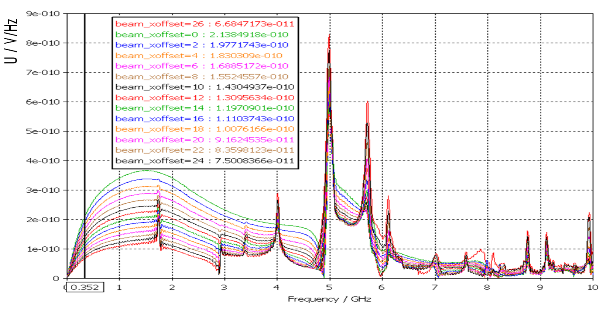

Figure 2: CST simulations showing the button voltage in frequency domain with the beam moving horizontally in 2 mm steps to the edge of the measurement area. Courtesy of D. Lipka (DESY)

BPM voltage under off-optimal conditions

Off-optimal refers to conditions such as short pulse-width or low-current or de-bunched beam. During linac commissioning, the beam may need to be steered over several hundred meters (with no longitudinal focusing) to a tuning dump while the RF cavities are being tuned. Simulations show that with no powered cavity after the spokes section, the longitudinal beam size will increase by 100 mm approximately within each 150 m of the Linac length as shown in Fig. 3. Table 1 shows expected BPM resolutions with a debunched beam pulse of 6.25 mA, 10 µs as a function of distance from the spokes section.

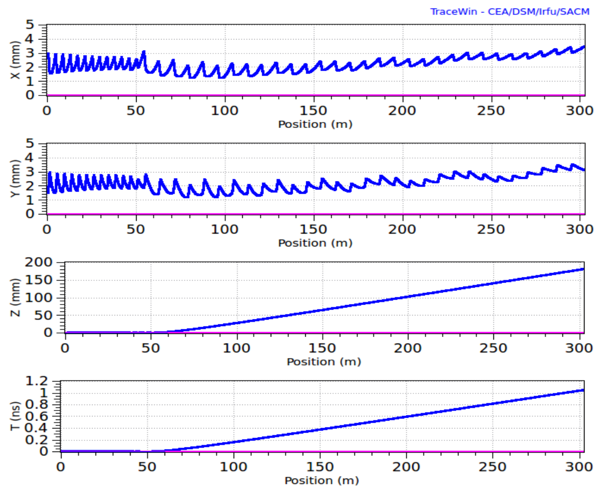

Figure 3: Simulated longitudinal bunch length growth with no powered cavity after the spoke section. Courtesy of R. Miyamoto (ESS, Beam Physics group)

Table 1: expected BPM resolution with a debunched beam of 6.25 mA, 10 µs at 217 MeV

Distance from the spokes [m]	Bunch length [ns]	Button BPM resolution without averaging	Button BPM resolution with averaging	Stripline BPM resolution with averaging
150	0.4	439 µm	38 µm	34 µm
200	0.6	728 µm	63 µm	57 µm
250	0.8	1423 µm	123 µm	110 µm
300	1	3320 µm	286 µm	258 µm
350	1.2	1 cm	858 µm	773 µm
400	1.4	3.7 cm	3.2 mm	2.9 mm
450	1.6	15 cm	1.3 cm	1.2 cm
500 (target)	1.8	83 cm	7.1 cm	6.4 cm

Super-heterodyne RTM design

The super-heterodyne RTM design is illustrated in Fig. 4. This 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.

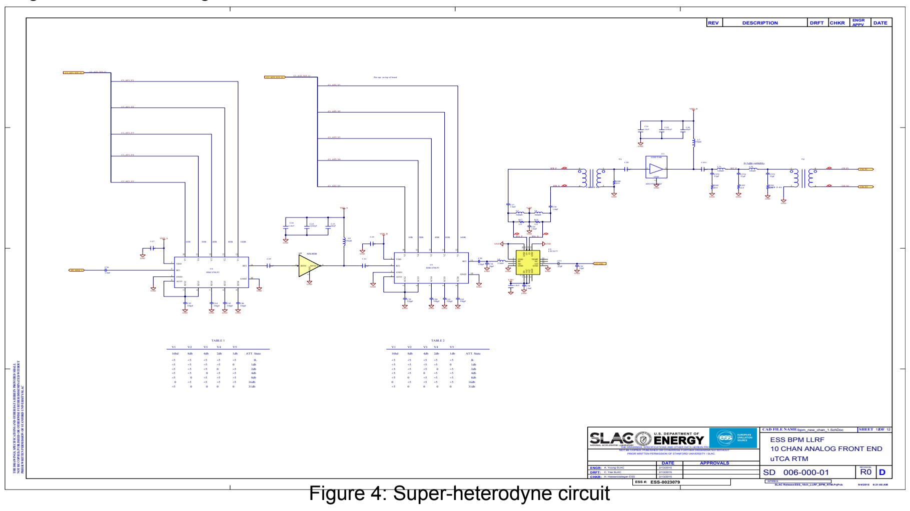

Figure 4: Super-heterodyne circuit

As there is a possibility that the final BPM/LLRF systems will use a combination of off-the-shelf and custom-made RTMs, care has been 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.

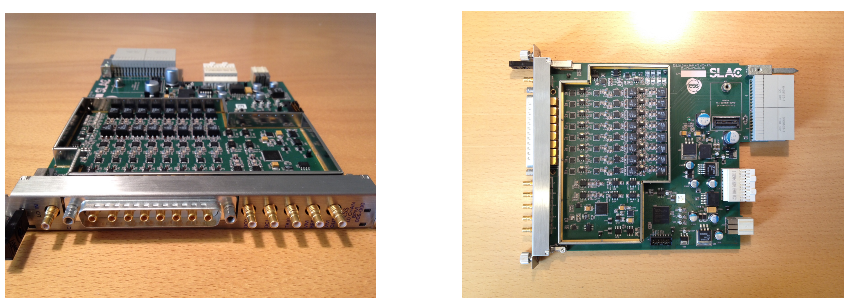

Figure 5: Front (left) and top (right) views of the RTM

BPM/LLRF front-end requirements

Both the BPM and LLRF front-end designs are based on down-mixing to IF and sampling in IQ or near-IQ to measure the amplitude and phase of the RF input signal. 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.

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/LLRF voltage level to the ADC input range.

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.

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, op-amps, amplifiers) by using a header to supply 12 V. 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, 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. Similar tests will be done in parallel by the LLRF group using a LLRF prototype connected to a mock-up pillbox cavity.

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.