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, BPMs need to have an overall accuracy of ±200 µm and a resolution of 20 µm 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. There will be RF stations on which RF tuning may be done in a test cell before they are installed in a crate that is populated with other modules and used for some RF signal measurements.

Both the BPM and LLRF systems have stringent requirements on S/N ratio. Current version of the LLRF will use 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 levels 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 ±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 µm 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.

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. These includes e.g. 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 necessary 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 pit box cavity.

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 connections 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.

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 voltage with respect to RF. The BPMs need to be measured to ensure the linearity and stability of the RF output. The BPMs require to be tested on an RF signal generator 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. These includes e.g. 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 necessary 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 pit box 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 validated in practice, it will be used in the ESS RTM in its different variants, thus fulfilling both the BPM and LLRF requirements in the low-energy as well as the high-energy linac.