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A REPORT ON DEVELOPMENTS OF THE BCM AND BPM PICKUPS OF THE ESS MEBT

S. Varnasseri, I. Bustinduy, A. Ortega, I. Rueda, A. Zugazaga, A. Conde, J. Martin
ESS-Bilbao, Bilbao, Spain
R.A. Baron, H. Hassanzadegan, T. Shea
European Spallation Source - ERIC, Lund, Sweden

Abstract

In the framework of the Spanish In-Kind Contribution (IKC) to the construction of the European Spallation Source (ESS-ERIC), ESS-Bilbao is in charge of providing some key systems for the accelerator. In this paper, design and pre-delivery measurements of two non-interceptive devices of Medium Energy Beam Transport (MEBT) (e.g. Beam Position Monitor pick-ups, shielded ACCT and FCT) are reported. Overall there are eight (8) BPMs distributed in MEBT, seven (7) of them are used for the beam position and phase measurements and one BPM is used for the fast timing characterization. The latter is used mainly to characterize the partially chopped bunches and rise/fall time of the Beam Chopper. Furthermore, there are two ACCTs, one just attached to the beam dump and the other at the end of the MEBT. One FCT combined with the second ACCT gives the complementary information on the fast timing characteristics of the beam pulses.

INTRODUCTION

ESS MEBT (Medium Energy Beam Transport) with energy of 3.62 *MeV* is part of the European Spallation Source (ESS) which is delivered recently and to be operational at Lund, Sweden early 2020 [1]. In order to monitor and characterize the beam parameters, various beam diagnostics instruments including the position, phase and intensity measurement devices have been incorporated in the MEBT. In this paper, the developments of stripline beam position monitors (BPM) and beam current transformers are reported. The processing frequency for the BPM readout is the 2nd harmonic of RF frequency. Furthermore, the bunch length (rms) varies from 60 ps to 180 ps during its passage across MEBT, which introduces slightly varied signal amplitudes on BPM pick-ups. Table 1 shows the related beam parameters of the MEBT.

Table 1: MEBT Various Beam Parameters

Parameter	Value	Unit
Beam energy	3.62	MeV
Beam current (avg.)	62.5	mA
Particles/bunch	1.1e9	
Readout frequency	704	MHz
RF frequency	352	MHz
Bunch length (σ_z)	60-180	ps
Pulse length (max.)	2.86	ms
Repetition rate	14	Hz

There are eleven (11) quadrupole magnets within the MEBT, eight (8) of them housing BPM pick-ups inside. Thus, the main mechanical restriction for the BPMs was the quadrupole magnets yoke profile and overall spaces, including the space for the BPM feedthroughs. BPMs are designed and installed in eight out of eleven quadrupole magnets of the MEBT. Seven of the BPMs are used for the beam position and phase measurements and one of them is used for the fast timing characterization of the beam. It is specifically used for the beam chopper rise/fall time measurements.

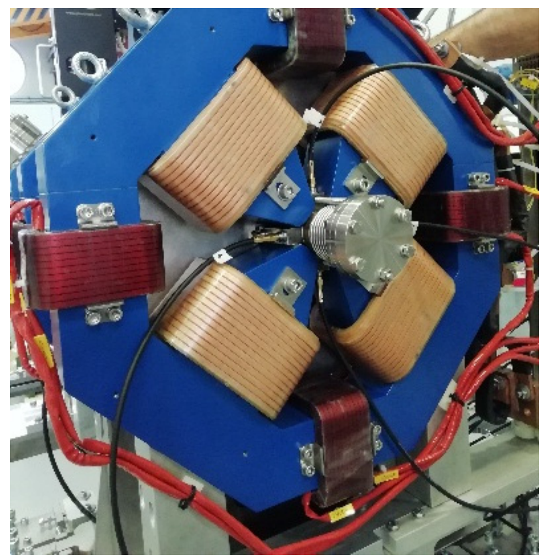

Figure 1: A BPM installed inside quadrupole before integration into the MEBT.

For the beam current with slow and fast timing characteristics, two ACCTs and one FCT are installed in the MEBT. Due to mechanical space limitations, the FCT is combined with one ACCT and located at the end of the MEBT.

BPM DESIGN

Electromagnetic design and various choices of the BPMs are explained in a previous paper [2]. Each BPM has four pick-ups, one pair in horizontal and one pair in vertical planes. The BPM pick-ups are of stripline type which are embedded inside quadrupole magnets (see Fig. 1). The main reason is due to lack of mechanical space within compact MEBT to install the BPMs in the dedicated spaces outside magnets [3,4]. The BPM sensitivity to displacement, voltage signal level, frequency response, impedance matching, and mechanical restrictions are the main factors in the design of stripline. The 3D models of several types including button type, short-end stripline and matched stripline are analyzed for low-β beam (see Fig. 2).

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In the analysis (Fig. 2), the BPM opposite pick-up distance is 37.6 mm and the pickup width, is 7 mm and 7.6 mm respectively for the stripline and button. The typical λ/4 striplines for the relativistic beams, does not produce the same signal power as for the low-β beam. Therefore, the length of the strips is reduced to a value which the beam induced and returned signal in the stripline coincides in a positive way, increasing the output signal power of the pick-ups. Transfer impedance is defined as the $Z_t(f)=V_{PU}(f)/I_{beam}(f)$ and extracted from the analysis. The transfer impedance depends on the geometrical dimensions, type of the pick-up, readout frequency and beam energy.

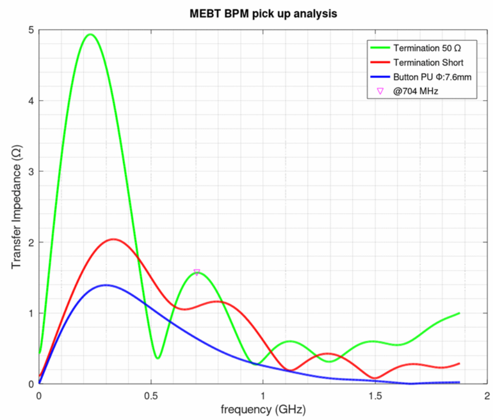

Figure 2: Transfer Impedance for various types of BPM pick-ups for low-β beam.

The design of stripline pick-up is based on transmission line with 50 Ω characteristics impedance matching to the cables and front-end electronics. The electromagnetic analysis has been introduced for low-β beam of MEBT and optimization is found based on the electrical and mechanical restrictions. The internal diameter of BPM is 37.6 mm. At the entrance of the BPM set, the internal diameter is reduced to 36.8 mm, in order to reduce the risk of stripline hit by passing beam. The outer diameter is 40 mm, leaving 0.5 mm radial gap between the quadrupole yoke and BPM outer surface for installation and alignment purposes (Fig. 3).

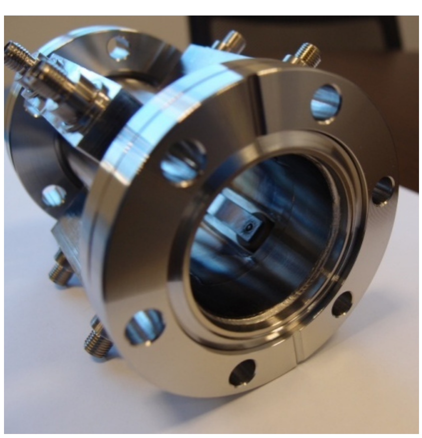

Figure 3: A fabricated BPM3 without bellows before installation in the MEBT quadrupole.

In order not to interfere with quadrupole magnetic field, the non-magnetic weldable SMA feedthrough with outer diameter of 9.48 mm, internal diameter of 7.72 mm and pin radius of 2.36 mm is used as the signal port. The design of final production of the BPM sets for the MEBT is based on 50 Ω terminated stripline which is an optimum solution at interested frequency of 704 MHz. The transfer impedance at the frequency of 704 MHz is 1.6 Ω for the 50 Ω terminated stripline.

BPM FABRICATION

After finalizing the electromagnetic simulation and mechanical drawings, several fabrication processes have been studied. We finally came out to precisely machine some parts including strips, RF rectangular boxes, ceramic spacers and BPM central tubes. The spacers material is alumina >95% Al2O3 and machined in the local company *Steelceram* [5]. Furthermore, the metallic parts are machined with tolerances of around 10 µm in the local company *Inmepre* [6]. In the second step, the e-beam welding process of various parts has been performed in ESS-Bilbao welding facility. The main welded parts include welding the feedthroughs to RF box and strips, welding the RF boxes to the central tube, welding the bellows to the central tube, welding the flanges to the central part and bellow. Two welding methods have been studied as e-beam welding (electron beam) and TIG welding (Tungsten Inert Gas). Due to in-house capabilities, the e-beam welding is chosen for the welding all parts of the BPM sets. During the welding process, through RF and vacuum leak checks have been carried out. The RF measurements played a vital role in the process of the fabrication. The idea was to group the RF boxes in families of 4 units, in order to have the four RF boxes of one BPM set, as similar as possible in terms of the impedance matching and losses. The final step was to weld the RF boxes, bellows and flanges to the central BPM tube. The final checks of UHV and RF and magnetic checks were performed before installation of the BPMs inside quadrupoles. Before the fabrication and welding of the final BPMs, several prototypes have been manufactured to check the metrology, vacuum and RF compatibility.

All the MEBT BPMs have DN40 CF flanges on both sides, except the last BPM which connects the MEBT to DTL and has a DN63 CF at the exit side. For the installation of BPM, the upper half of the quadrupole has to be removed and after placement and rough alignment of the BPM, the upper part of quadrupole is returned to its place. The final BPM alignment will be performed with Beam Based Alignment (BBA) method. By design, the BPMs longitudinal center (i.e. centre of RF box) are on the longitudinal centre of quadrupole magnets. Patch panels have been installed on the MEBT support, in order to facilitate the access to the BPM outputs and interchange the 120cm-long, small diameter coaxial cables with SMA connectors to 50m-long, large diameter coaxes with N connectors. The short cables have been assembled with electrical length difference of less than 10 ps, in order to keep the phase variation of BPM pick-ups in the required

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limit. The coaxial cables are fire resistant, halogen free and have the LSZH PE jackets. The patch panels include the SMA-N adaptors and attached to the MEBT support in several locations.

BPM MEASUREMENTS

During the process of welding and fabrication of the BPMs, several checks including the vacuum leakage, RF, electrical and metrology checks were carried out. The final RF and vacuum checks have been performed just before installation of the BPMs inside quadrupoles and after installation in the MEBT, connecting the BPM cables to the patch panels. Fig. 4 shows the measured return loss (brown), adjacent strip pick-ups coupling (blue) and opposite strip pick-ups coupling (purple) for the BPM3. In the Fig.4; S11 graph is set off to the reference, in order to show all the graphs in window. The measurements show a return loss of less than -21 dB and coupling of around -50 dB for adjacent strip pick-ups (e.g up and left) for all the BPMs at the frequency of 704 MHz. The coupling of opposite strip pick-ups (e.g up and down) is around -58 dB at frequency of 704 MHz. The measured bandwidth (3dB) of the BPMs is ~3 GHz.

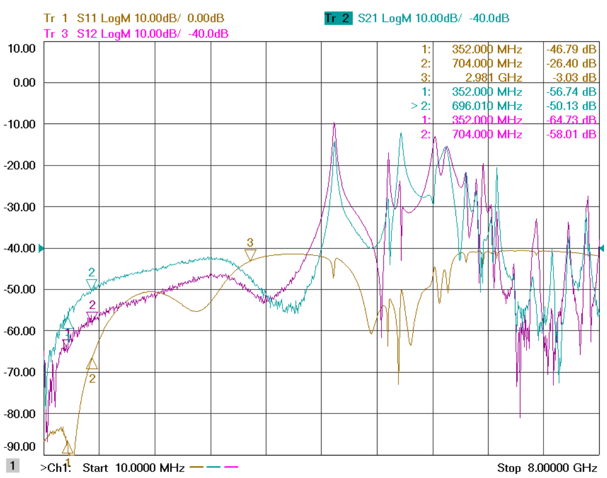

Figure 4: Measured return loss and couplings for BPM3.

In order to characterize and test the whole MEBT BPM system before installation and operation with beam at ESS, One BPM together with the front-end and readout electronics from ESS have been installed in IPHI CEA-Saclay and tested with the proton beam of 3MeV [7]. Furthermore, the electrical off-set of the BPMs strips have been identified with two methods. The first method uses a rigid wire antenna allocated precisely in the center of the BPM tube (around 50µm error). An RF signal of 704 MHz are passing through the antenna and the signals on the stripline pick-ups are measured with spectrum analyser. From the difference between pick-up signals and by introducing the sensitivity values, the x/y planes offsets have been identified. The other method is the so-called "Lambertson" method which measures the electrical off-sets from the s-parameters of the stripline pick-ups. It is based on the simultaneous measurement of BPM four pick-ups with network analyser and analysing the data in order to identify the x/y planes off-sets. The measurements in both methods show an off-set of smaller than ±175µm in x/y planes. Due to integration of the BPMs inside quadrupoles and the critical importance of the inner/outer surfaces and dimensions, 3D metrology measurement with CMM machine for all BPMs have been realized at a local centre for advanced fabrication- *CFAA* [8]. In that measurements, the linear dimensions, angles, flatness and distances of critical parts of the BPMs have been measured. From the measurement data, the mechanical off-sets of x/y planes are found smaller than ±150µm. The fine alignment of the 8 BPMs of the MEBT will be realized based on Beam Based Alignment method (BBA) using the corresponding quadrupole magnets.

CURRENT TRANSFORMERS

For the purpose of beam current measurement (BCM) in terms of slow and fast time resolution, two ACCTs and one FCT are placed in two locations of the MEBT. In addition, machine protection features of the ESS linac using the BCM system is reported in [9]. Various measured specifications of the current transformers are shown in Table 2. Due to limited space, the second ACCT and FCT toroids have been combined in one housing namely Combo.

Table 2: Measured BCM Specifications

Parameter	**Value**
ACCT 1,2 Bandwidth (3dB)	1 MHz
FCT bandwidth (3dB)	620 MHz
ACCT1,2 rise time	< 346 ns
FCT rise time	< 550 ps
ACCT 1,2 Droop	< 1.16 %/ms
FCT Droop	4.3 %/µs
Electronics full scale range	±10 V
Full scale ACCT 1,2 current	±80 mA

The ACCT1 is an In-Air toroid installed in a groove at the downstream of the beam dump (Fig. 5). The electrical gap has been introduced with EPDM gasket (Tombo 1050-EP, EP-176 from *NICHIAS*). In this solution, the bypass current is routed via the outer part of the flange to body of beam dump vessel.

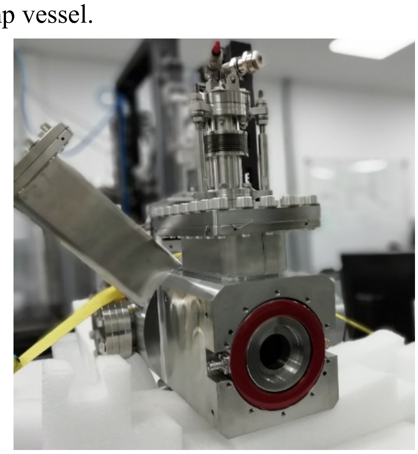
Figure 5: A view of the ACCT1 installed in the groove downstream of the beam dump vessel.

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The Combined BCM (Combo) is located between two adjacent quadrupoles with an external magnetic field as high as 60 mT for longitudinal fields and 20 mT for transverse fields in the location of toroids. Several thin (~1 mm) mu-metal shields and one thick (5 mm) soft iron enclosure have been employed, to produce magnetic shield against external fields. Fig. 6 shows the Combo installed in magnetic shield housing during the measurements under quadrupole magnetic fields.

Combo design is based on the Bergoz® in-flange CTs, which the two toroids of ACCT and FCT are surrounding its vacuum pipe. The 6 mm electrical gap is realized with the Al2O3 brazed with Kovar to the vacuum pipe in both sides. For the integration purposes, the flanges on both sides of the Combo are DN40 CF which are connected to the adjacent BPMs in MEBT. The outer diameter of the Combo is 271 mm and the flange-flange length is 100 mm. Both ACCT1 and ACCT2 have calibration windings for the automatic calibration after installation.

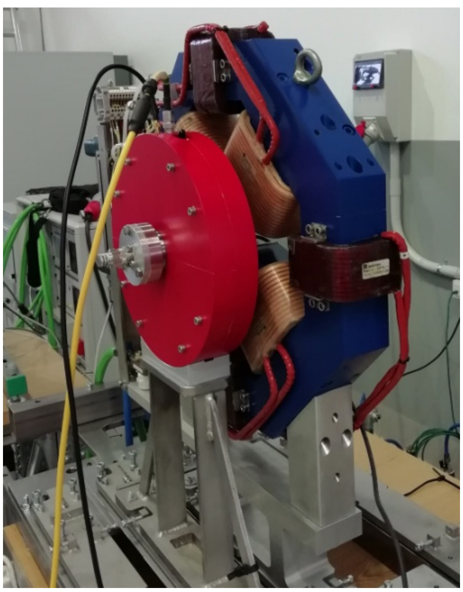

Figure 6: COMBO (color red) on its stand during the measurements before installation in MEBT.

For the Combo, the helium leak tested to 1.10^{-9} mbar.l/s and showed no detectable leak. However, in the first attempt of the fabrication, a leak suspected in the brazing has been detected, so the fabrication of the defective parts was repeated. The final measurements of vacuum and electrical specifications showed the satisfactory values before and after installation within MEBT.

CONCLUSION

The acceptance measurements of the BPM pick-ups and BCMs are performed at ESS-Bilbao before delivery to Lund and installation in the tunnel. Due to high demand of precision, there has been some challenges during the fabrication of the parts. The main challenge was the welding process of the BPM parts keeping the mechanical integrity and precision and high frequency characteristics of the pick-ups. After producing some prototypes and improving the fabrication and welding process, it was possible to reach the required specifications of the pick-ups. The BPMs and BCMs have been installed in the MEBT and are ready to be used as part of the beam diagnostics devices during the commissioning and operation of the MEBT in the early 2020.

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