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TECHNICAL REVIEW OF BEAM POSITION BUTTON DESIGN AND MANUFACTURE

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Abstract

A workshop in May 2019, hosted by Diamond Light Source (DLS) (UK), reviewed both the design and the manufacturing aspects of beam position monitor (BPM) pick-up buttons with an integrated ultra high vacuum (UHV) feedthrough and coaxial connector. The UHV feedthrough technology (e.g. ceramic brazing vs glass-sealing), the limits on mechanical tolerances, reproducibility and material choices for high reliability were examined by more than 20 users of these devices and a number of reputed manufacturers. Calibration techniques and tools and methods for inspection and testing were also assessed. This paper will present the outcome and conclusions of this workshop and identify challenges and opportunities for future BPM manufacture.

INTRODUCTION

The procurement of beam position monitor buttons was highlighted at Diamond after manufacturing issues were discovered for the buttons made for the single cell DDBA upgrade [1]. A proposed machine upgrade to Diamond-II will require around 1000 buttons to be made [2]. There seemed to be a lack of manufacturers capable of making these devices.

The aim of the workshop was to bring together representatives from the accelerator community along with potential button manufacturers, as well as system integrators who install the buttons into the accelerator vacuum chambers. In total there were seven manufacturers, two system integrators, and representatives from ten facilities.

All the attending manufacturers have made buttons for at least one accelerator facility. However the scale was usually small numbers of prototypes for testing, or small machine upgrades. Based on this new information on the manufacturing base, the workshop focus changed from identifying a manufacturer able to make buttons, to determining which manufacturers would be able to provide buttons at the scale of full machine upgrades.

Three distinct groups of attendees came to the workshop. In order to satisfy all their requirements, the workshop had a slightly different structure than usual. The aim was to have as open a dialog as possible, but the facility representatives also wanted to be able to ask manufacturers deep technical questions. The manufacturers quite understandably did not want to disclose too much information in front of their competitors. As a result, although the majority of the workshop was open at all participants there were also closed sessions for individual manufacturers where the other manufacturers were excluded.

Because of the closed sessions the manufacturers were able to the be very open about their processes. The delegates were able to understand the companies processes for designing a button. Detailed discussions were enabled on the limitations of the various techniques and various technologies the manufacturers had at their disposal. The facility representatives also got a feel for the strengths of the various companies, and how each would approach the button fabrication challenge. Some manufacturers viewed it more as a collaboration while other companies were more comfortable with the facilities doing the design and then the company stepping in to do the manufacturing. It was clear that all the companies present were keen, engaged, and interested in this type of problem. They all enjoyed the technical challenge presented, however, the scale of the number of buttons when added up across the various upgrades made it a much more interesting proposition for the companies in general. They realised that the customer demand in the next decade was not just 10s but 1000s of units.

What follows is a summary of the presentations and discussion at the workshop itself. This is designed to give the reader a summary of the main outcomes from the workshop. For more details the reader is directed to the workshop web page [3]. For a previous summary on the complete beam position monitor system readers are directed to [4].

The topics for the workshop fell into two broad categories: design and fabrication.

DESIGN

Smaller chamber dimensions are a common thread for all the machine upgrades. Smaller chambers lead to a smaller button, which has a good effect of having a lower wake loss, but at the cost of signal level.

In order to reduce the signal interference from one bunch to the next the ringing of in the button structure needs to be reduced. Such a reduction can be obtained with careful impedance matching through the design, and is helped by the use of a lower permittivity insulator.

One particular feature of concern is a trapped mode which exists between the button head and the fitting hole or housing. There were various approaches demonstrated to alleviate the effects of this unwanted mode.

There has been a general move away from having a skirt around the button. Originally it was included to simplify installation, and to mitigate against relatively poor installation tolerances. It has been found that this feature can be unhelpful in terms of wake loss and heating and so is not featuring in many of the newer designs as tolerancing improvements have made its utility questionable. Figure 1 shows an example of a skirted and non-skirted design.

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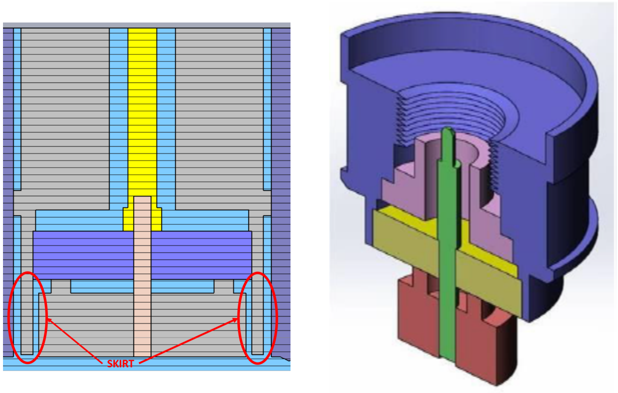

(a) The original Diamond buttons are a skirted design [5].

(b) A non-skirted design from ESRF [6].

Figure 1: Skirted and non-skirted button designs.

Another general point of interest was curved buttons. Buttons with a profile on the inner face to match the curvature of the beam pipe. This is rarely implemented in light sources, however, CERN buttons are curved [7] as are those used in the CADS proton linac [8]. There are small benefits to be had, but at the cost of more complex manufacturing and installation. Up until now curving the button faces has not been viewed as being worth the added complexity, but with smaller beam pipes and the much tighter curvatures, this is now being re-evaluated.

During discussions, ALBA showed results from simulation for their skirted design. From their thermal modelling most of the heating is happening on the button. This is now expected from a skirted design. A non-skirted design would tend to heat up the block. However the wake loss factor is very low, there is very little power trapped in the structure. Details on the original ALBA design can be found in [9]. In this design the gap between the button and the skirt is 300 µm. Newer designs aim to reduce that gap significantly. From discussion 100 µm was not seen as a problem, 50 µm was challenging while 25 µm may be possible but would require much more investigation.

Dealing with the Trapped Mode

A large subset of the design work presented was concerned with the trapped mode around the button. This has historically been identified as a source of heating and wake loss [5]. By moving the resonance frequency of the trapped mode to a higher frequency where there is less power in the beam, this heating and wake loss can be reduced.

The LNLS group achieved this frequency shift in two ways: by reducing the volume of the ceramic in the cylindrical booster ring design, and by changing the button shape for their storage ring design. Both approaches worked, with the conical storage ring button design shifting the trapped mode frequencies higher, and thus having a stronger wake loss reduction [10].

This sparked a discussion on the pros and cons of the conical vs cylindrical design. It was more complex to insert the ceramic into a conical design, and the capacitance of the button was now sensitive to the button height, but in general varying the button shape was viewed with strong interest.

The BESSY group's approach to reducing the impact of this problem resonance was to improve the impedance matching of the geometry, and also to switch to a ceramic with a low dielectric constant [11].

The geometric changes alone successfully move the trapped mode to higher frequencies. The addition of the lower dielectric constant of the fused silica moves the lowest resonance higher still. Simulation results showed the trapped mode to be confined around the button and much less in the ceramic than the original BESSY button. The mode in the fused silica design was also shown to decay away much faster than the Aluminium oxide design.

Rather than moving the resonance to higher frequencies, the team at PSI damped the problem resonance by making the buttons asymmetric. There is still a circular hole, but the placement, or shape of the button is asymmetrical. The 11 GHz target mode was successfully damped using several different geometrical designs. Non-centering the buttons, or having a cut in the buttons would all act to have a strong damping effect.

From these three investigations, we can see that there are several different approaches to evolving the button design. They are not mutually exclusive. It is possible to have the improved impedance matching and lower dielectric constant along with the asymmetric buttons, and those buttons could be conical rather than cylindrical.

Cautionary Tale

The DESY group presented the evolution of the design for the ESS buttons [12]. There was a working design in 2014. In 2016 there was a request to change the button diameter. That changed the resonance of the system so that it very nearly matched a harmonic of the machine, which could have been a significant problem. As it turned out, the decay of this resonance is short enough that it does not interfere with performance. However, it was a salutary reminder that small changes can have large impacts on such a design.

MANUFACTURING

Material Quality

The ESRF summarised the work which has been done trying to understand button failure issues [13]. These are now known to be leakage through micro-channels formed within the bulk steel. Diamond has also seen these microchannels, but luckily has had no button failures due to them. The steel quality problem was also seen at DESY where they noticed a reduction in the quality of the steel they used for knife edge flanges.

There have been many changes in the steel market over the last ten years and it seems that the material quality for a given grade is not as good as it once was. Facilities need to be much more involved in the selection of the material. Much more consideration is needed to be given to both the exact type of steel required and the preparation steps used to obtain the specified grade.

Sealing Technology

In the represented synchrotron light sources there is a significant level of experience with ceramic braising, but not so much with glass sealing. However in the wider community, there is significant level of glass sealing expertise and experience. PSI have used glass for the feedthroughs for the SwissFEL cavity BPM [14, 15], and are also looking at making some prototype capacitive buttons using borosilicate glass to start testing its capabilities. DESY over the last 30 years have made many feedthroughs with glass ceramic.

In terms of RF matching, the lower dielectric constant of the glass makes it an attractive proposition. In terms of design, glass needs to have a larger volume which can lead to longer pins, however it is generally seen as being easier to scale to smaller diameters. The fact that all the new designs of machines are moving towards smaller buttons means there was significant interest in glass sealing technology.

Automated Assembly

Irrespective of the sealing technology used, the assembly process has many manual steps. The question was asked as to whether the assembly of the buttons could be automated. The conclusion from the assembled manufacturers was not for our application because everything was fairly bespoke, and the runs were quite small.

Welding

The welding of buttons, especially if the button has a glass seal rather than a ceramic braised seal was discussed. A distributed welding process was suggested, as was the use of copper collars and active cooling to reduce the heat getting to the seal. Moving the weld further away from the seal by design was another option. The manufacturing ideal for glass sealing was for the weld to be more than 30 mm away from the seal, but with large heat sinks and active cooling various facilities stated that it was possible to safely get reliable welds 15 mm away from the seal.

Tolerancing

In order to obtain the tolerances needed for the newer smaller designs continuous communication all the way through the process of design and manufacture is key. One has to talk with the company to make sure they really understand what it is wanted. Face to face communication was also considered very important, at least in some parts of the process.

This also touched on navigating different company cultures. One company may be much happier to try new things out, another may not want to bid if they are not sure they have the capability to achieve the desired results. Also, often, facilities are coming back to a company after ten years or more. There is no guarantee that a company today, can match its past achievements. People have moved on, or the company has changed their focus, for example.

Great care had to be taken when the design moved from one group to another. Translating between electrical designers, mechanical engineers, and the people on the floor doing the machining was given as an example. The facility had to ensure all groups understood what was needed. For example, that the requirement was not just a constant diameter to 20um but also to be cylindrical all the way down. DESY in particular said that they had previous good experience sending STEP files to suppliers as the tolerancing information can be included, and it is possible to have a golden reference design for a CNC machine.

It was noted that tightening up the tolerances might reveal a difficulty. Currently the variation in the manufacturing allows the resonances of a group of buttons to be scattered over a larger frequency range, with each button having a slightly different frequency to it neighbours. By tightening all the tolerances up, this effect is reduced and the buttons may start to appear as a distinct resonance in the machine. However, some of the design work demonstrated earlier shows there are solutions available for dealing with these resonances at the design stage.

In House Testing

The guiding principle to testing is that any specifications placed on the drawings, need to be able to be measured.

Institutes have implemented various approaches to in house testing. Some facilities do full checks of the devices themselves. Others rely on documentation from the supplier and do cross checking on a small subset. Some facilities will do checks of certain aspects as the units come in. Another option that some have used is a pass / fail test setup.

There will need to be more in-house testing than there has been in the past, and many facilities will need to improve their capability to do such testing moving forward. One improvement which was identified was that each button must have a unique identifier on it. This would allow tracking through the manufacturing, testing and installation processes. Laser marking is a technology being investigated by several facilities for this purpose.

One of the problems which has been highlighted with in-house testing has been metallic particles shorting out the button electrodes. Some particles can be removed with dry nitrogen jets but if not, these obstructions can be dealt with by passing a small current through the button to burn away the debris. Permanently spot welding and short circuiting the button is a known but low risk.

With the increase in the use of NEG coated chambers there was a concern that this type of problem would become more frequent.

CABLES AND CALIBRATION

Much effort is put into the electronics and button design, but without a commensurate improvement in the cabling the system performance will not improve as much as desired.

Dependent on what user requirements one should not necessarily push for the ultimate stability. Each facility has to be somewhat careful about what they consider to be stable, and over what timescales they need to be stable over.

However, with the general requirement for the new BPM systems to have higher performance, the cabling behaviour over time is becoming more important. Static offsets can be compensated for, but it was noted by many facilities that system performance over time changes as cables change. In Diamond there is a known sensitivity to humidity, CERN no longer does cable calibration as the work required to maintain such calibrations can no longer be justified. LNLS have mitigated environmental cable variation by using four cables within one sheath, which means that all four cables for a beam position monitor system tend to respond to the environment in a very similar fashion. ESRF are currently working on an improved cable testing system, which is undergoing lab tests.

From experience from Diamond and CERN the advice was not to use foam dielectric cables. Neither of these facilities are able to use the commonly used halogen-based cables due to fire regulations. In the past the foam dielectrics have been an attractive halogen free low loss cabling option. However for this type of application, where long term stability in the face of environmental variation is an increasing requirement, they are no longer considered suitable.

There was a desire to have some form of in situ online calibration in the next generation of systems.

One way of tracking long term changes, which has been used in several facilities, is measuring the Q factor of the BPM system. Equations (1), (2), and (3) show the various signal combinations in order to obtain horizonal position X, vertical position Y, and Q factor. This Q factor is particularly sensitive to changes in individual button signals, and is insensitive to horizontal and vertical beam offsets. The signals from individual buttons are denoted A, B, C, and D. An example button configuration is shown in Fig. 2.

Diamond discovered their sensitivity to humidity by observing the changes in the Q factor.

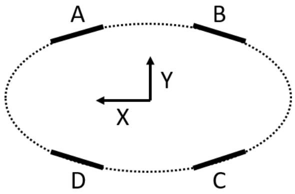

Figure 2: An example buttons geometry.

$$X = k_x \frac{(A+D)-(B+C)}{A+B+C+D} \quad (1)$$

$$Y = k_y \frac{(A+B)-(C+D)}{A+B+C+D} \quad (2)$$

$$Q = \frac{(A+C)-(B+D)}{A+B+C+D} \quad (3)$$

In the future more of the electronics will be closer to the pickups themselves. As this can have an improvement of the noise figure on the system and open the door to other signal processing and calibration techniques. There were some concerns about the effect of the radiation environment on the equipment, and how much of the system was prudent to move into the tunnel, but several facilities either already have or are planning to have some of the BPM system electronics in the tunnel.

Pilot Tone Calibration

Both Diamond and Elettra are looking into the use of a pilot tone as a way of eliminating the need to rely on the stability of the cables. Because there is a known signal combined with the picked-up signal it can be used to calibrate on the fly. By tracking changes in the pilot over time it should also be possible to track long term changes in the hardware. Further reading on the Elettra system can be found here [16, 17].

SUMMARY

New button geometries and lower dielectric constant ceramics are all independently improving button design, but these could also be combined for further benefits.

Facilities need to take far more care over specifying the materials and making sure they are getting what they expect, and what sort of processing is done on the materials.

More in house testing was identified as a general requirement moving forward and in order to aid that, each button must have a unique identifier.

There will be more electronics in the tunnel, which will improve signal to noise, and allow new techniques to be implemented, however at some increased risk of damage due to the radiation environment.

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