BPM Button Design and Manufacturing Workshop

2nd - 3rd May 2019

This document records the Q&A following the presentations and the dedicated discussion sessions.

Talk: Experience with UHV leaks at ESRF – K. Scheidt (ESRF)

Q: Steel grade?

- A: 316. See Kees' slides for steel certificates.
- Audience: "Russian level steel". Usually it is 360L (or 316L).

Q: You use a temporary seal when leak testing the buttons, but don't carry out baking? Can you distinguish between 10-9 and 10-10 vacuum without baking the button? Surface contaminants may obstruct cracks or voids, invalidating the test.

- A: Yes. Buttons are clean and handled in a clean way. Test is a "differential test", using a helium flow on the "outside" of the vacuum, and observing the helium quantity that makes it through to a leak detector. So, you don't see button "outgassing" on the detector. …. From audience: But moisture or carbons or a fingerprint could still "block" voids or cracks, so you can't see the leak. This could cause issue later. From Kees: we didn't observe this, CT scans showing "bad" buttons corresponded to those where we detected leaks.

Q: Why do you close them?

- A: These are protective caps. At that time, we expected the leak to come from the corners.

Q: There is a risk that the steel may be inferior if not explicitly specified to be UHV compatible and to use UHV compatible melting techniques.

- A: Yes, this is true, we do specify this for the vacuum vessels but perhaps we should have stated this more explicitly in the BPM specifications.

Talk: Design, Development and Manufacturing experience for Sirius Button BPM

– H. de Oliveira Caiafa Duarte (Sirius)

Q: How did you measure the capacitance when sorting buttons? What was the tolerance?

- A: TDR. (refer to Beam Capacitance slide)

Q: Simulations for finding electrical centre... did you consider the Lambertson method (I.e. using a Network Analyser) for finding cross-talk / offsets between buttons?

- A: No, we didn't do this.

Q: Are the booster buttons the same (as on storage ring)?

- A: No, step shaped large diameter buttons are used on the booster.

Q: Did you say there were leaks on buttons after a period of time?

- A: No, no leaks! Only microcracks.
- Audience: Was this from stress build-up in the production of the button?
- Henrique: We couldn't find an explanation for these. I don't know.

Q: Input flange and output flange are not fully welded on the vacuum chamber?

- A: We considered welding the bellows to the BPM but in the end it was decided to use flanges to avoid having to discard the entire block should the bellows fail in the future. It was preferred to decouple problems of the bellows from problems with the BPM block.

Q: Yellow body shown image on slide 20 is titanium, how is this attached to button body?

- A: Screwed in and then welded... Didn't need to weld it, it's just held in place, screwed in place and held using the SMA connector. This is enough.
- Audience: Is there a thread on the inside and on the outside as shown in this image?
- Henrique: Yes.

Q: Power capacity- how is this assessed?

- A: Comparing the simulations.

Talk: BPM flange vacuum sealing aspects – M. Krupa (CERN)

Q: From Speaker to Audience: Is Titanium a good choice?

- A: (Not answered)

Q: From Speaker to Audience: Light sources seem to be opting for reverse polarity connectors: can you provide some pros/cons? Besides the mechanical aspect, are there other reasons to do this? Because we have to use special radiation-hard cabling at CERN non-standard connections become much more costly.

- A: Mechanical benefit of reverse polarity at Diamond. Easy to obtain cables (Sirius).
- Speaker: Concern that having to use new cables could drive up cost.
- Audience: if the fabrication of reverse polarity connectors is an issue then maybe the supplier could change just a small portion of the connector design. Changing just the connector pin shape on the cable would be beneficial and would stop damage to the BPM button spring fingers.
- Diamond: When we later baked out the chambers the Beryllium-Copper would darken. We had to clean these mechanically with variable results.
- DESY: Long-term (30 years) bad experience using male feedthroughs

Q: Conflat is good, well understood, old technology. Why use anything else?

- A: Price. Economics. Replacing many Conflat seals was expensive. We previously didn't have any experience of how Conflat seals behaved whilst cold, while spring-seals were well understood. Now, we have more understanding of cryogenics, and better handle of temperatures. We have more experience with Conflat flanges in cryogenic situations and are happy that they work. Thus, we're now moving away from spring-seals and towards Conflat.

Talk: BPM and glass ceramic feedthrough design – F. Marcellini (PSI)

Q Speaker to Audience: NEG coating of buttons. Is this a problem? Are there precautions that are needed depending on geometry (depth & width of the slit to the dielectric, …)?

- A: Concerning the NEG coating of the buttons, I never would have considered coating them because we cannot ensure the coating is homogeneous, so the conductivity may vary. (DESY)
- A: Tests of Titanium coated buttons in-situ, didn't see any problems with short circuits or in the performance of the buttons. (CERN)
- A: MAXIV have NEG coated buttons <1um. More worried about the adhesion and material choice of the coating. (Diamond)
- A: Found problems on one chamber where the NEG coating was too thick which resulted in short circuits on all 4 buttons. These could be burned away, and the NEG flakes removed by blowing nitrogen. Vacuum group who are responsible for the coating at the ESRF have revised their processes due to these concerns. Plan to coat 20% of all BPMS at ESRF.

Q from speaker: NEG particles from coating don't reach the ceramic insulation, from the gap between button and vessel?

- A from Audience: No, negligible danger here.

Q Speaker to Audience: How to avoid synchrotron radiation hitting the button? Retract the button? How much? Experience? Impact on BPM signal if button not retracted?

- A: (Not answered)
- Comment from the audience: offset buttons shown look a good idea!

Q: Have you modelled the tapered flange that you show on slide 13? The wake losses can be an issue here.

- A: No. Not modelled, but not thought to be an issue.

Q. Any experience of inserting / welding in the buttons after the NEG coating has been completed?

- A. No, no experience of this in the room. The "holes" for the buttons must be plugged before NEG coating can happen. Audience member asks if NEG coating could be done with "blanks" in the holes. There is no experience doing this.

Q: All light sources use ceramic sealing whereas CERN use glass technology?

- A: Glass sealing has been used at light sources in North America but with varying results. More experience of this technology is needed.

- A: CERN comment that they have not had problems. FELs confirm that no problems with glass sealing have been identified.
- A: Sirius could never consider glass sealing with 1mm thickness.
- A: Miniature, k-type, less than 1mm in diameter glass sealing is commercially available.
- A: Inner pin 0.3mm hanging on a cone of 2g, but not extensively tested... One of these feedthroughs is more than 2000Euros. (DESY)
- A: Some facilities comment that they have equipment to do in-house brazing but not the expertise.

Q from speaker to audience: NEG coating process involves high temperatures, >100 degrees C. Is there a glass feedthrough that can cope with these temperatures? Are there any issues?

- A from Audience: Microcracks in ceramics have caused us concern, so we decided not to NEG coat some vessels as we were afraid of damaging the ceramics by taking them up to the NEG activation temperature of ~180 degrees C.
- A from Audience: Another commenter said that the temperature doesn’t need to be that high.
- A from Speaker: We did some tests up to 150 degrees C, and this seemed okay…

Talk: Design considerations for Button BPMs from DESY – D. Lipka (DESY)

Comment from Audience: in principal you could simplify the design as much as possible, reduce the buttons down to just three components: the “vessel”, the button, and the pin.

Q: Which sealing method did you use? Conflat sealing?

- A: Standard sealing is using Conflat gaskets. Alternative is to use the knife edge aluminium gaskets.

Q: Slide 10, Quality Controls… what kind of non-destructive vacuum check can you do on a bare button to check down to 10^{-10} mbar?

- A: We checked a leak test similar to ESRF, using rubber seals. We screwed the button into a test chamber. We check each and every button at Factory, then check again on arrival, then check again after welding. Each button takes 5-10 minutes to test.

Talk: Heating concerns from BESSY-II BPMs and concerns for new BPM design for BESSY VSR – A. Schalicke (HZB)

Q: Will you have different electronics to see different parts of the orbit?

- A: Yes, to some extent. Perhaps we separate odd/even bunches.

Q: Ringing coming from ceramic, is there any resonances in the pickup? 2GHz due to octagonal chamber?

- A: Some very high frequency ringing. 15GHz or so. Not sure about 2GHz from the vessel though, will talk about it over coffee.

Q: Reduce the button gap to 30um?

- A: No not the gap between the buttons but the insert (see slide 12).
- A from audience: Everything is pushed into higher frequencies because of this, but there looks to be decent modelling. Some of the higher frequencies have the potential to be a little scary.

Q: Have you started the prototype?

- A: Yes, we have ordered 10 buttons (Aluminium Oxide). They are already in house and we will test two BPMS this summer.

Q: Silicon Oxide. Every few years there's a new ceramic. SiO_2 has low dielectric constant, but is it being used anywhere?

- A: Yes, and it's possible to use.

Talk: Considerations for PETRA IV – G. Kube (DESY)

Audience Comment on photos in last slide: Aluminium oxide ceramic damage is unusual; it's been observed at DESY though. The ceramic cracked, looked slightly grey. There's so much power that the temperature reached over 600 degrees and the material starts to "sputter" away. Similar observations on stripline in HERA. Another audience member: I observed a mistake in a vessel, resulting in a certain resonance occurring, resulting in a high induced power. A stripline was damaged.

Q: How small should the offset be in the BPM to ensure injection is possible in PETRA IV?

- A: <30um

Q: Broader question about the Lambertson Method. Who has used it on their machine?

- A: Soliel, no, you may determine the offsets from the block very well but this is pointless if the offset from the block to the nearest quadrupole is unknown; ESRF, yes some results will be shown later; DESY, yes; Diamond, yes; Alba, yes but noisy;

Discussion session: Feedthrough technology- Chair: S. Vilcins-Czvitkovits

Material problems

- Chair: Problems of 316LN in air. The quality of this material has changed over the years. Damage has been seen on the knife edge. An "orange skin" was observed on the knife edge. The knife edge is damaged during the assembly. This is established as after assembly a good vacuum was never achieved, the system was re-opened, and the knife-edge damage was observed. Not just one edge, a couple of different flanges had problems. However, DESY nor CERN have a satisfactory explanation for this change and their observations. This failure is extremely costly.
- Audience: Was the hardness and LN specified?
- Chair: Yes. These things were explicitly stated.
- Audience: Can you provide more details of this damage?
- Chair: Discolouration and surface scratches on the knife edge. After brazing, the knife edges were fine. Damage was observed during the assembly.
- Audience: Hardness was measured before or after the brazing?
- Chair: Both. 174 was measured and matched the spec.
- Audience: Did you send a sample of the material away for analysis to check the spec?
- Chair: We have checked the grain size. Specification grain size was bigger than 2 or 3. We got them at 3 and now they're 2.
- Audience to manufacturers: Have you seen this behaviour from 316 LN ESR before?
- No manufacturers here have seen this before. Best theory is that the steel quality is just not as good as it was 10 years ago.
- Chair: Perhaps we must specify > 200 hardness (currently getting 150), nitrogen 1.7, grain size between 4 and 5 (currently 3).

Ceramic or Glass sealing technology

- Audience: Majority of experience is from ceramic and brazing. Minority experience using glass. What's wrong with ceramic? What are the advantages of glass over ceramic?
- CERN: Physics is the driver for leaving ceramic, the dielectric constant is better with glass. A "foamed glass" with epsilon 1 would be best!
- Sirius: Glass sealing feedthrough requires a longer pin which is not ideal for fabrication. Thus, ceramic is used.
- A glass sealing would require in practise double the volume to achieve the same thing.
- Glass sealing requires two materials, one for vacuum sealing and the other for mechanical stiffness.
- Manufacturer: There are pros and cons to using glass and ceramic. Glass can show irregularities thus machining is required.
- Manufacturer: glass should be good for gong to smaller sizes than ceramic. Smaller sizes also help glass as there are fewer stresses.
- FEL uses both technologies.
- DESY: For the FEL we have used both ceramic and glass technologies. Tolerancing of these materials for the cool down and heat up processes have been very relaxed. Microcracks have been observed in both.
- ESRF: From previous experiences, manufacturers seem reluctant to share fabrication info which could be useful to the community for designing new buttons.
- Manufacturer: To some extent this is true regarding the exact details however you are welcome to come to the factory and observe the process. In any case, glass is simpler than using ceramic. There is no metallisation with glass. More tooling is required for glass since it liquifies in the fabrication process. We can get a lot more pins per unit area using glass. Ceramic to metal is a sintering process. Although glass is a simpler process the cost is roughly the same as ceramic.
- ESRF: that making a BPM button is a very manual operation, lots of issues come from this manual, labour intensive operation. Any way to reduce the manual labour is good. Glass or ceramic, whichever reduces the labour will reduce problems.
- Supplier: glass manufacturer is easier, it's a compression seal. Much simpler to do than ceramic to metal. The critical part is the thermal profile in the oven as the glass melts, and cools into place. The price is roughly the same.
- Audience: Can the "painting" [for the ceramic assemble] be automated?

- Supplier: probably not. We have similar applications where we *can* automate in other markets, but no in this market, everything is too bespoke.

Smaller beam pipes

- Diamond: Regarding smaller beam pipes and the number of components, can we just make a glass feedthrough pick-up?
- DESY: This has been discussed. It would require significant effort to develop. Another alternative could be 3D printing BPM buttons- this obviously has its own challenges. Combined metal and glass printing is *possible*... not been done for this purpose though.

Cryogenic temperatures for glass vs ceramic?

- DESY: Can we comment on glass sealing feedthroughs at cryogenic temperatures?
- DESY: Did 10 cycles of cool down and warm ups in a cryostat but did not leak check after each cycle. There was a 10% failure in HERA.
- CERN: Glass ceramic performed best at low temperatures. 10 years of using these now, no problems.
- PSI: Can the heating from the welding process damage the glass? This has been experienced in the BPMS at PSI and a special technique had to be developed.
- Chair: Yes, this is known. You have to use a distributed welding process to avoid this problem.
- Diamond: Glass tech is used extensively at CERN, but it seems it is always with a flange. Should we avoid welding near glass?
- Manufacturer: Yes, it is best to avoid welding near glass. This should be considered in the design.
- Chair: Welding 1cm away from the glass ceramic or using copper cooling can help to resolve this welding problem in close proximity to the glass ceramic.
- PSI: With the new welding technique the glass feedthroughs do not show any problems. Note that the welding is almost 1cm away from the glass ceramic. In the welding process, cooling is required to prevent cracking of the glass.
- Manufacturer: Tig (distributed) welding is important to avoid cracking glass ceramics.

Welding design vs flange design?

- Audience: There is not enough space to use a flange design. (Electron machines)
- Audience: How much is the gasket for these small flanges?
- Chair: 10 Euros, there is a company in Luxembourg.
- SOLEIL comment that the tolerances in positioning with a flange is too large.
- DESY: 10 minutes needed to measure and align each BPM. Tolerances in the linear accelerator is less than 20um on the outside.
- ESRF: comment that 20mm aperture flanges is much too large. Even the small flanges are CF25 which is still too big.
- Ah, these flanges that DESY are talking about are square, and there is a rectangular bar that's used to seal it.
- DESY: What is the button diameter?
- Chair: 1.6mm
- Audience: This is too large for light sources.
- CERN: Does anyone have experience with conflat feedthrough on cryogenic machines?
- DESY: Yes, we do.
- Some special welding considerations are needed as very small button blocks and ceramic / glass insulation could be damaged. What do glass suppliers say to welding near a glass seal?
- Supplier: "The further away the better! Do no weld near the glass. 30mm away."
- DESY say 15mm away, or use some large metal heatsink/ring to keep the temperature okay. They welded many, 1500, and developed a technique for doing it with some cooling air flow to avoid cracks of the glass.

Discussion session: Mechanical tolerancing- Chair: G. Schneider (CERN)

Chairs summary

How and how many mechanical tolerances are checked?

There is no absolute answer to this. The amount of tolerances to be checked depends on the criticality of the item. Gerhard stated that for beam instrumentation objects which are mounted on the beam lines, a 100% check of mechanical tolerances is required. Usually, this is done by 3D fully automated touch measurement systems.

Alternatives can be a go/no-go gauge which guarantees the assembly of the components, e.g. BPM electrodes.

DESY has experience with sending a STEP file to the suppliers with median mechanical tolerances. This can possibly save cost, if the CNC machines with controlled tools are used. The electrical performance is tested independent of this.

Discussion if tomography and endoscopes could be used to measure hidden mechanical tolerances. To be followed up.

How can cultural differences between companies when promising tolerances be faced and in the same context, how can it be assured that companies do not forget their know-how?

Both problems are regularly seen by the institutes as shown in the discussion. In order to minimise bad surprises, companies should be challenged to see if they can supply the tolerances and other design parameters by showing a sample or a similar assembly. Ultimately, after checking the ability of the company, a certain level of trust is unavoidable. In order not to be cornered in with one company and possibly find alternatives, early contract placement is desirable. Reality shows, however, that early contract placement is rather wishful thinking than reality.

What should be checked and where?

Ideally, all requirements as tolerances, leak tightness and electrical performance are checked and documented on an asset-based approach. Some institutes follow this approach, others go for more global checks.

In-house testing can be reduced to cross checks if the documentation of the company can be trusted. This compensates the additional cost of the quality checks in the producing company.

Follow-up of mechanical tolerances on drawings, checks and supply.

A full understanding of the design intention, which then results in symbolic mechanical tolerances according to a design standard, is necessary. It is a well invested effort to verify the correct interpretation of the symbols used by the producing company – both towards the manufacturing and the quality *control department of the producing company. The loop between the design intension and the production must be closed.*

Only dimensions which can be checked should figure on a drawing.

Stringent temperature control is required both for the measurement environment and for the part to be checked.

Session notes

Chair: From the discussions so far today, it does not seem that mechanical tolerance issues is a primary concern.

- Diamond: Concentricity issues of DDBA buttons delivered at Diamond. There was no quality assurance test station available at Diamond to check these parts.
- CERN: we pay for 100% checks that the parts match the specified tolerances e.g. 20um diameter tolerance. Yes, it is expensive, but it is worth the money. It is also very important that everyone involved at each stage understand the mechanical tolerances and the real meaning. For example, you don't just want a constant diameter to 20um tolerance, you also want it to be cylindrical all the way through. Communication is key.
- Diamond: Variability of responses from companies when they assess the feasibility of the button designs. **Do facilities measure every button that is delivered?**
  - CERN: No, we do not measure every button in-house as this would be a huge demand on the workshop. Instead we request detailed reports from the company which we review in detail. We specify details to the company which should be included in this report. However, you must pay for this additional reporting.
  - CERN: First discuss with the company "how good are their measurements?" Be careful when "translating" between electrical designers, mechanical engineers, suppliers, manufacturers, etc. Take your time to ensure that what is on the design is what the client wants at the end! If you want it all measured, you must ensure that the person on the shop floor doing the measurements understand what the requirements are.
  - Audience: How do you check at CERN that the company actually makes these measurements correctly?
  - CERN: regular reporting of the company's measurements, ensure each button has a reference number. Company measures the button, then CERN checks a subset of them. Ensure that what CERN measures is what the company stated. Accountability in all steps in the manufacturing process.
  - ESRF: Instead of having a detailed report, an alternative would be to make a test rig to check each button fits. Thus, each button receives a pass or fail based on this test rig. Obviously, the test rig that is used as the standard reference must be exact.
  - DESY: We have experience with these milling machines. The mechanical tolerances are attainable. Making a reference button and test rig like the ESRF is recommended.

    - DESY: Good CAD files include tolerances in an unambiguous way. Good CAM machines can read these tolerances and will machine the piece accordingly! Have one button as a "reference button", compare all other buttons to this.
    - CERN: Communication and correct interpretation of mechanical drawings is the key to success.
    - CERN: Make sure that the company you're working with *really* understands what you want.
    - DESY have had some issues with a company being very inconsistent.
    - CERN: That's why you need the company to do the quality-check regularly, and regularly report back. Ensure they're using the right materials and the right procedures. Then make additional in-house cross-checks.
- DESY: Previously a company provided good buttons, then five years later they could not reproduce the buttons at the same quality and performance. So even when you find a reasonable supplier, they may lose the expertise and quality.
    - CERN: This is the advantage of always doing in-house checks on a random sample of the received order.
    - DESY: Personal face-to-face communication with these companies is important before placing large orders.
- Audience: what tools does CERN use for their in-house checks?
    - CERN: It does not make sense to define anything on the drawing if you cannot check it later. CERN have a large metrology lab for this purpose (Feeler gauges, optical methods, the full monty). This becomes even more important if you dispute that the company has not fulfilled the order.
    - DESY: To check 20um tolerances you need to ensure that the room is temperature stabilised otherwise the results will vary and be unreliable.
    - ESRF: Do you use endoscopic tools to verify the internal dimensions?
    - CERN: We use an endoscope but not to verify the dimensions?
    - Diamond: X-ray tomography

Discussion session: Design Considerations- Chair: D. Lipka (DESY)

Chairs summary

- "Bare buttons": produces lower induced power, the impedance budget is smaller; otherwise you can get a variation of resonances around the button holder with strong induced heat.

- curved vs flat buttons: the wake loss will be lower with curved buttons, but the button needs a guide to find the correct orientation. The specialist's opinion is that a guide can be add easy to the button and at least for flanged version the screws will give a guide. Should be considered certainly.

- accuracy: the alignment of a BPM body in the synchrotron can be provided with a precision of 30 µm (some synchrotron experts pointed it out), therefore the Lambertson method would be applicable to correct an offset. But need to consider the cable influence: use of 4 wires in one cable will help.

- round or conically button: question: does need the conically button an extra piece: answer no. Variation of the button deepness will influence the capacity of the conically button larger because the area with the distance to the holder will change more. But advantage of conically is the better transmission line, resonances are shifted to higher frequencies.

- would an additional pair of buttons to a 4 button BPM help: more information will be provided which can be used to increase the range

Session notes

Chair: **Please can the audience provide the definition of “bare buttons”?**

- Audience: Bare buttons do not have a skirt.
- DESY: Pros/cons of bare buttons?
- ESRF: There is not a clear benefit to having a skirt.
- DESY: It improves your impedance budget.
- Diamond: We can show an example of a bare button. Skirts tend to have problematic heating on the button itself. A bare button heats the block, but this is preferred.
- Skirts help ensure “concentricity”, but concentricity maybe isn’t entirely needed (see earlier talk showing offset buttons). Offset buttons can be compensated for with Lambertson method. At Diamond we measured our whole machine impedance, and we found no contribution from the BPMs, at least, nothing large compared to the collimators. Helpful note: all buttons are slightly different, it can’t be helped, manufacturing isn’t perfect - this helps avoid resonances!
- With manufacturers claiming tolerances of 20um a skirt isn’t necessary.

Chair: **The concentricity of the button is important.**

- Diamond: If we know the offset or asymmetry of the button, we can account for this when we orientate the button in the block relative to the beam.
- PSI: But this will change the gain of each button.
- Diamond: Yes, but this is a systematic error that could be measured using the Lambertson method (network analyser). Furthermore, it is important not to overestimate the risk of the impedance of hundreds of buttons in the machine. Remember that the buttons will differ slightly so you may not observe resonance.

DESY: We do extensive tests to align the buttons and BPM block during production. But sometimes the installation of the BPM blocks in the accelerator is not completed to the same accuracy.

- Sirius: We have a vice to ensure that all components are locked and aligned when they are installed.

CERN: **How do synchrotrons align/terminate the cables?** If the mechanical tolerances are so tight, surely applying different cables will “pull” the buttons one way or another rendering these nice mechanical tolerances pointless. Also how is thermal stability managed?

- Sirius: We have one single cable that has 4 cables inside.

Chair: **Any experience with curved buttons?** Typically, only flat buttons are used.

- DESY: Limed experience:
- Sirius: It depends on the ratio of the button diameter to the vacuum chamber diameter.
- Diamond: Curved buttons are harder to align; how do you check this?
- Soleil: We ensure to include alignment marks or a mechanical guide to ensure that misalignment is not possible. In this way internal checks are not required.
- Diamond: We did a short study on this just before we did DDBA, we found the curved button gave us slightly better performance, and slight reduction in wake field, but the small DDBA buttons introduce very little wake field anyway. It was a very marginal improvement, not worth the extra trouble. It does in principal reduce the wake loss though, which is maybe helpful in smaller chambers with buttons closer to the beam, in machines with more BPMs. However, future synchrotrons are going for longer bunch lengths, which reduces wake losses anyway.
- CERN: In the LHC, the buttons are curved. But they operate in a very different regime.
- Audience: We agree for the electron ring upgrades we will need to consider using curved buttons given the small vacuum pipe diameter and longer bunch lengths.

Sirius: Only way to measure the gap size in a non-destructive way is by measuring the capacitance.

Chair: **Any preference between a stepped cylindrical vs a conic shape?**

- Diamond: It’s an impedance transformer. A cone is better than a step.
- Chair: But nobody uses this conic design.
- Audience: True, but perhaps this is just because it is different and thus poses some unknown risk.
- Sirius: It can be more difficult to insert the ceramic in a conic design, rather than a cylindrical design.
- Diamond: Advises the audience to look to Sirius and their new button design.

ESRF: **Where do you put 4 buttons on a hexagon beam pipe?** On the flat top surface or on the tilted sides? Using the sides means the buttons would be very far away from the beam and the signal would be correspondingly low.

- We considered a 6-button BPM. Note that this unfortunate beam pipe geometry was imposed by the magnet design. We chose not to use this in the end. Impedance, wake loss, complications and failure possibilities. Might (maybe) be useful for first turn operation... Normally though the dynamic aperture is so small that these complications are not needed.

Discussion session: Testing and Inspection- Chair: A. Olmos (ALBA)

Chairs summary

Electrical testing:

Angel (ALBA) started the discussion session summarizing the different tests they did regarding the electrical check of the buttons.

Buttons were measured with a TDR after manufacturing in order to check the buttons and sort them afterwards according to their capacitance value. Buttons were arranged in groups of 4 similar capacitance and then welded into the BPM block. After the welding + baking process, buttons capacitance was measured again, and it showed that the capacitance was shifted towards lower values.

Before the installation of the vacuum vessels in the tunnel, the buttons were measured using the Lambertson method in order to get their electrical offset. Measurement turned to be too noisy to have a good electrical offset value. Even knowing that, the obtained offsets were used on the first days of commissioning (firsts turns). Once the beam was stored, the BBA routine was used to set the final BPM offsets, including then the effects of cables and misalignments.

Short-circuit problems:

Then Kees (ESRF) explained some problems they had with dust and metallic particles placed in the button's electrodes. Problem appeared first as buttons short-circuits in NEG coated chambers. Blowing high pressure dry nitrogen initially solved the problems. Then the issue also showed up in other vessels, not NEG coated. The final solution applied was to perform batteries discharges into the buttons to fuse/melt any particle creating the short-circuit. Note: short-circuits means : anything not Hi-Z, i.e. 65ohm or many Kohms etc.

Audience asked if such discharges could potentially damage any welding and in which phase of the manufacturing/installation process ESRF realized about the short-circuits. Kees, and colleagues from other facilities who also applied the same procedure, confirmed that they had no welding problems after such treatment. At ESRF they detected the problem right after the chambers were delivered and again after other installation phases.

The audience then asked if the chambers had an ultrasonic cleaning after the buttons welding and Kees confirmed that it was not case at ESRF.

Production documents:

Discussion then moved to the useful production documents. Audience agreed that a proper marking (laser, edge) of the buttons is necessary in order to track them and essential if one wants to do some kind of sorting of buttons before installation.

Visual inspection:

FMB did some endoscopy movies after welding the ESRF chambers, but no quantification of buttons retraction or detailed misplacements could be done with such method. At DESY they developed some sliding tools in order to guide the endoscope closer to the buttons while not touching any part inside the vessel. Companies can perform detailed measurement of the positioning of the buttons after welding using special mechanical tools. At DLS they had experience with bad positioning of buttons. Guenther claims that the Lambertson method should work for the detection of such issues. For the new machines, with smaller electrodes but smaller chamber diameters (closer buttons) the measurement should be possible. They will do tests soon, maybe enhancing the precision by introducing an amplifier between the BPM and the VNA.

Session notes

Slides on sorting and Lambertson method at ALBA

- Soleil: Sorting before welding on the BPM block? You can do it because you have a feedthrough with a skirt, yes?
- ALBA: Yes
- Diamond: If you have bare buttons there is no point sorting before welding.
- ALBA: Hyperlabs is the company we've used for these tests.
- ALBA. We also use the Lambertson method at ALBA, but the results were quite noisy. And we use Beam Based Alignment to then include the complete BPM (buttons, cables, etc).
- Diamond: We recommend that you don't sweep through the frequencies you don't need. You should set the VNA at 500 MHz and this will improve the signal to noise ratio.
- DESY: Support this recommendation, the problematic noise is probably just due to not optimising the setup rather than a limit of the Lambertson method.
- DESY: More precise measurements could be obtained at higher frequencies. (2GHz)
- Audience: But we care about what happens at our operational frequency (500MHz). It would be risky to assume that the same response is obtained at 500 MHz and 2GHz as we know there are parasitic effects.
- Audience: We must also stay away from the cut-off frequency. This is clear.

Slides of Lambertson method at ESRF

- ESRF: Observations have shown that NEG coating can cause problems. Blowing these flakes away can resolve the buttons which have short circuits. We expect this to be a reoccurring problem in the future.
- Diamond: It's not simply a 12V battery. How did you settle on using this capacitor to "clean" the buttons? Are you worried about spot-welds?
- Audience: CERN, Soleil and the ESRF report that they have all tried this and not suffered from accidental spot-welding.
- Diamond: Is this all due to the NEG coating?
- ESRF: No, we have not confirmed this "dust" is actually NEG coating. We have requested the vacuum group to analyse the debris, but this has not been done yet.
- Diamond: At what stage of the process is this debris settling on the buttons?
- ESRF: It seems like it can happen at any time, assembly, transport etc., especially if you are moving the equipment.
- Audience: Similar observations have been made at Diamond and Sirius.
- Sirius: It is possible to damage the buttons if cleaning or higher voltages are needed.
- ESRF: This debris is definitely conductive. Therefore, we tried to move the particles and see if the impedance changes to verify whether the debris is ferromagnetic as this would be a real problem. So far, we cannot confirm whether the debris is ferromagnetic.
- DESY: When do you do the ultrasonic bath cleaning? If the path is "dirt" you risk contamination.
- ESRF: Welding is the final step before baking.
- Manufacturer: Confirm that this debris cannot be from the supersonic bath.

Diamond: **It is important to number individual buttons to keep track of the performance. Do any facilities do this?**

- Audience: CERN yes. Generally, no.
- Audience: We all agree that etching or using laser marking should be included in all button designs and manufacture in future.

ESRF: From FNB we are given movies for internal inspection of the BPM. We can improve this internal inspection. Endoscopy can be improved. Concentricity could be checked during welding.

- Diamond: Is there a risk of creating dust in doing endoscopy with NEG coated chambers?
- ESRF: Yes, there is a risk, you should avoid sliding the endoscopic probe through the beam pipe. However, at the ESRF we do the NEG coating in-house so we can to the endoscopy prior to coating.
- Audience: It is difficult to check concentricity after welding. It really depends on whether dimensions are accessible.

Have we seen significant performance issues directly caused by a concentricity offset or other tolerance offsets?

- Diamond: Yes, but this was really due to our previous design where the buttons could be seated too far in. If we incorporate a shoulder in the design, then we would not see this problem.
- Audience: The Lambertson method could address this. We may need additional amplification, but this is all feasible.
- Diamond: We plan to do tests using the Lambertson method this year.

Sirius: TDR measurements are very sensitive to the environment. We have had to do our measurements in a temperature controlled room. We also kept the instrument turned on and waited half a day for the instrument to warm up. We could not repeat measurements after welding due to time constraints and additional equipment overhead.

Discussion session: Calibration Techniques and Methods- Chair: N. Hammond (Diamond)

Chairs summary

Prepared questions:

1. *The Lambertson method is now often used to Characterise the BPM block with its 4 buttons Is this method itself 100% validated, or backed up, by other techniques in parallel*
2. *In some reports I find that complex measurements (phase and amplitude) are done with network analysers. Is this adding anything to the quality of the calibration, or can a calibration with only amplitude factors be just as good?*
3. *What calibrations have people found useful:*
    a. *For acceptance tests*
    b. *For performance optimisation*
    c. *For fault finding.*

Question 3 was used to initiate discussion. The initial response was 'Can we define what is meant by calibration?'. Discussion proceeded on the bases that calibration is based on a fully installed system rather than as a quality check for individual units.

Generally, there seemed to be a large overlap between this session and the previous one on 'Testing and Inspection', which was to be expected since both are linked.

Never-the-less discussion flowed well and was helped greatly when B-K S took the floor to present and discuss some of their work. It was illustrated that the Lambertson method could detect anomalies, such as a retracted button.

A question was asked concerning the use of a stretched wire from BPM to adjacent quadrupole. Lambertson method.

Question 1 generally it was agreed that this method was 'tried and trusted' more than any other. Representatives from the ESRF confirmed that they have used this technique to check the Lambertson method.

Question 2 was not specifically addressed but covered in the general discussion.

Session notes

What calibration techniques have people found useful? In addition to the Lambertson method that we have discussed.

- Diamond: Can we clarify what we mean by calibration? Geometric response of the BPM or the alignment of the electrical centre to the magnetic centre?
- Audience Geometric response
- Diamond: Can we calculate this? The k response?
- Soleil: Antena measurement is done to measure the offset, it's an alternative to Lambertson. It also measures the position of the four buttons relative to the housing.
- Diamond: If we use the stretched wire and reference to the fiducials, and so on, this becomes quite complex as you accumulate the errors. Could we simplify this, with some electromagnetic principle? Such that the we know the offset between the electrical centre and magnetic centre before doing a BBA. MAX VI got around this problem partly by using the integrated magnet design. However, no other machines seem to be copying this, so we all plan to assemble and align individual components which might be problematic since the tolerance will be reduced in the new machines.
- Diamond: Once you have stored beam you could use the xBPMs. This isn't really useful for initial commissioning.
- Soleil: Differences of 100um observed.

Diamond: Should we be surprised by this as there are many causes that result in a measured offset.

- Audience: No. We agree it is very difficult to compare offsets.

- ESRF: Propose to use a device in the tunnel to perform Cross RF transmission measurements in BPM blocks (Lambertson method) to obtain these calibration values and hence remove the varying button sensitivity. It is important to measure offset and coupling.
  - ESRF: Where there are mechanical misalignments the Lambertson method shows this. BBA can be used to compensate for X, Y misalignments of electrical centre of buttons, but not X, Y coupling.
  - Diamond: It is not unfeasible to remove this coupling using a 2x2 matrix in the BPM analysis. Therefore, this coupling can be removed for the stored beam as these coefficients will remain constant at a fixed position. It is a systematic error. LOCO gives you this measurement.
  - Diamond: Do the cable connections introduce reflections? As this will directly impact on the precision of the calibration method. Unfortunately, good quality connections become very expensive.

  - Question to ESRF: What specifically do you evaluate with Lambertson? What if there are differences between connectors? Cables?
  - ESRF: We always use the same 600mm cables, but indeed it's difficult to be precise in determining how much of the differences between buttons that we measure is due to cables / connectors.
  - DLS: When you look at the spectrum on the network analyser the response is usually quite different if the connector is damaged. Newer network analysers have even better diagnostics for testing if the connectors or cables are causing differences.
  - Audience: Did you try connecting / reconnecting and retesting the same buttons?
  - ESRF, yes, get some differences.
  - Diamond: By repeating measurements, disconnecting and reconnecting the cables, it is possible to identify which signals are related to the connector rather that the BPM button. Doing a thorough analysis with a high spec VNA in time and frequency domains also provides additional information for distinguishing what is from the connector and what is from the button.
- **Measure the EBPM cables themselves with a network analyser.**
  - Diamond: Yes, very important! We have done this with all of our cables. Electrical DC contact may be fine and tested by the contractors that installed them, but RF performance might be different.
  - Audience: Agreement that cable lengths must be equal to within a few millimetres.
  - Audience: Cables lengths might change over years! Due to someone stepping on them, temperature, stress, cables age asymmetrically, etc, RF performance may change. The epsilon doesn't need to change much to change the delta.
  - DESY: Recommend checking cables and connectors post-installation with a VNA.
  - Diamond: We have done this and had to replace many cables and connectors. It also helped us find cables that had been damage due to other installation activities.
  - DESY: You can also check the length. You can think to combine the length and BPM offset. In effect you know the systematic offset to include this.
  - Diamond: 1mm change on a 30m cable is not unfeasible. Perhaps we should more regularly check the cable length.
  - CERN: We experience that cables age differently. They react to humidity differently.
  - Diamond: Personal opinion is to put more trust in the VNA rather than other methods.
  - ALBA: This is reasonable given the investment and testing from the telecommunications industry.
- ESRF: **Are there any other techniques for verifying the Lambertson calibrations?**
  - Diamond: Front end XBPMs on stepper motors can be some use, but only once you have beam!

ESRF: **Is phase useful from the Lambertson method.**

- Audience: We currently don’t know.
- Diamond: We don’t have enough experience to say for certain. Though, there’s a whole industry of vector network analysers and I trust that industry! They must be useful for something, as their results are extremely useful and well understood. They have excellent self-calibration methods, but better than a Libera Spark for example!
- Sirius: Instead of TDR we measure the group delay using a VNA. This allowed us to find faulty detector cables.

Discussion session: Cables and Cable Technology- Chair: M. Ferianis (Ellectra)

Chairs Summary

It appeared, from previous discussion sessions, that cables and connectors play a central role in a BPM system. After a short introduction by MF, the discussion rapidly focused onto calibration issues, as cables over time vary physical characteristics. CERN reported that even cables routed closely together in the same envelope exhibit variations, over medium time scale (years). Clearly, cable calibration shall not be conducted on a daily basis, but rather on a summer-winter time scale. Measuring the Q factor could help in monitoring cable degradation or variations. At ESRF, Kees report (shows a few slides) they are calibrating cables using a semi-automatic custom-made RF injector emulating the real button pick up signal such that in one day shut-down they can easily calibrate them all. On large (long period) machines, like at CERN, one could also in principle think about time multiplexing the signals from the four buttons over a single high-quality long run cable.

Another interesting discussion has been how to "get rid" of (long) cables, by moving the electronics closer and closer to the BPM pick-ups. At the X-FEL there is plenty of electronics in the tunnel, few meters away from the beam axis. Guenther proposes to move the front-ends directly to the tunnel.

Several labs report they are using in-tunnel short PEEK (Polyetheretherketone) cables with very good results. Though, these shall be replaced every second year. Alun brought in the issue of SiO_2 as cable dielectric, as SiO_2 provides unparalleled phase and attenuation stability over a wide temperature range significantly improving system accuracy and reliability in all critical situations (ref. MEGGIT).

Also, the idea of bringing in cable dispersion and attenuation variations into position computation has been proposed.

Session notes

Chair: We have already touched on some issues for discussion relating to cables in BPMs already. These include performance, calibration, maintenance and radiation hardness. The advantages of reverse polarity. The choice of operation frequency and how this impacts performance etc. The dream for electron machines would be to locate the electronics close to the buttons, so that the uncertainties introduced by long cables are supressed entirely.

Perhaps we can first begin with the importance of cabling for stability and resolution.

- Diamond: We should future proof cable stability. It is not enough to assume 5dB stability forever, these cables will age. If we cannot replace the cables, we must at least regularly calibrate them. There are various methods, we can approach this with switching, or pilot tone approaches.
- CERN: We used to calibrate cables every year in the SPS, but the calibration of these 250m cables would only be valid for a week. Therefore, it wasn't worth the calibration effort. We are investigating time multiplexing.

  - Diamond: Could we look to developments to the telecommunications industry for ideas? They have experience maintaining long cables. I assume calibration is required as well.
  - Diamond: There are differences between telecoms and our applications, it's definitely worth looking for ideas and transferable developments.
  - ESRF: Why not monitor Q? We've been monitoring it for a year now.
  - DLS: Yes! We always monitor Q. Relative humidity impact was identified at Diamond from regular Q-factor measurements.
  - SOLEIL: Yes, we monitor Q, but we see no changes.

  Location of frontend electronics

  - Sirius: We aiming to bring all of the electronics close to the BPM. To within 1m of the BPM.
  - Ellectra: In the XFEL we try to move electronics nearby, but this will still be approx. 30m cables.
  - PETRA: We are very reluctant to do this; we know we have quite a "dirty" machine.
  - Diamond: Another advantage of front-end electronics in the tunnel in addition in the ability of sending a pilot tone is also that amplification is done as close to the source as possible. You can gain 15dB noise figure.
  - CERN: The amplifier would also need to be calibrated.
  - Diamond: The amplifier would sit after the pilot tone. So, we will know if the amplifier has broken.
  - ESRF: The pilot tone method operates at a different frequency, is it valid for the operating frequency of the BPM.
  - Diamond: This has already been solved with the filters commercially available.

- Ellectra: We should include in the electronics some in-situ calibration of the BPM to makes these checks as easy as possible. If testing and calibration is simple, it is then feasible to perform the calibration on hundreds or thousands of BPMs routinely. Any calibration tool would evidently need to be maintained.
  - Diamond: The pilot tone calibration method is almost ready to fulfil this demand.
  - ESRF: Could beam based alignment be integrated in these regular checks?
  - For light sources we should keep in mind the stability requirements of the users. For example, a typical user is only running their experiment for 3 days and they need to realign the beamline for each sample tested during the 3 days. Therefore, we shouldn't

focus on long term (months and years) stability but rather the shorter (weeks) term stability.

  - ESRF: For us micrometre stability is not required over weeks or months. Just weekly alignment would be fine.
  - Diamond: Longer periods of stability are better
  - Soleil: If we agree the cables are moving over months, won't the calibration equipment in the tunnel also suffer the same aging or drift? These pilot tone injection schemes aren't perfect either. The filters might drift over time just as much as the cables
  - Diamond: Active devices like switches may fail. However passive devices like couplers are less likely to fail. A coupler is a much more intrinsically stable device, there are no semiconductors. They are very stable over these pilot tone frequencies.
- ESRF: **How to check cable degradation?** 4-way splitter relies upon an ideal splitting scenario. We propose it would be better to send 4 equal reference signals. How to cope with standing waves in the cable due to non-perfect 50Ohm termination at the electronics end and an almost perfect reflector at the button end. Constructively interfering standing waves could cause an issue. ESRF has a "calibrator tool" with four equal RF signals (these themselves are calibrated in a lab) that can temporarily be installed in the tunnel.
  - Audience: Have you run any long-term tests using your calibrator tool? ESRF: No! Not yet.
  - Diamond: So, you are using the BPM electronics? These might drift. We propose you leave this calibration box connected for a week.

Chair: Is there a preferred type of cable?

  - Soleil: We have tried this using LMR and 10cm PEEK cables in the tunnel. We have observed radiation damage and had to replace them. Note that in this region we have Aluminium vessels. Therefore, care must be taken using Aluminium vessels in light sources. This radiation damage is from the emitted synchrotron radiation.
  - PETRA has a 4m "patch cable" that we use that is made from PEEK.
  - Radiation damage to cables near the vessel will become a bigger problem as we all get thinner copper vacuum vessels.
  - Audience: since the PEEK cables are radiation tolerant, why not have a longer (~1-2m) PEEK cable? Or silicon dioxide cables?
  - Audience: cost is the biggest problem.
  - DESY get their PEEK cables from a supplier that no longer has them available in small quantities.
  - Diamond: Silicon Dioxide cables are radiation hard but very expensive. CERN use these.
  - DESY: We have cables from "Megit" that sell cables at a more reasonable cost.
  - CERN: They might not want to sell these cables in such small quantities.

  - Audience: We agree it would be good idea to identify a supplier for Silicon Dioxide cables.

- Diamond: **Any experience with foam cables?**
  - CERN: Foam cables should be avoided as they often introduce more issues. We chose them as they're very low loss, but this isn't really an issue. We don't lack for signal.
  - Humidity affects them
  - signals vary over time.
  - Diamond: We can confirm that we've also seen performance issues with foam cables. It would be better to use Teflon. Safety regulations do not allow us to use many of the other high performance, commercially available cables.
  - CERN: We are also restricted by the same fire safety regulations.

Discussion session: Future Trends (smaller pipes etc.)

Smaller vacuum vessels, smaller BPMs, smaller buttons, what else should we expect?

- Bakeout, we typically bakeout to 200 degrees C. We currently need in situ bakeout, so we might need to bakeout for lower temperatures for a longer period of time for DLS-II. This is due to magnet tips being so close to the vessel. It’s also a problem for cables as the bakeout must take place with the cables connected. PEEK cables should be fine for bakeout at ~200 degrees C. Kapton is a poor choice as it has very poor RF characteristics.

Sirius: As mentioned yesterday, microcracking can occur from applying too much torque. Thus, the choice of connector and attaching cables important.

ESRF: **Why do we limit ourselves to 4-buttons only?**

- Diamond: More buttons could impact the impedance budget, but if this is designed properly it should not be an issue. More buttons provide more information.
- Diamond: We are limited to 4 buttons because this is the minimum needed for XY position measurements and each button has a unit cost. Moving to 8-buttons will increase the cost significantly.
- More buttons Would give you additional analysis options.
- Losses might come into effect with a small beam pipe, but probably not so much. Biggest issue might be stability.
- Why not just have a few extra buttons in a few places. ESRF has a few places with extra BPMs / buttons. Say, eight buttons, might allow you to do interesting calibrations.

Diamond: **Do we need to be careful in future machines since the beam pipes are smaller and thinner?**

- Diamond Vacuum group concerned by how accurately they can position these.
- Diamond: The BPM block must still be adequately supported. This should not be overlooked and hopefully nobody is proposing freestanding BPMs on flimsy beam pipes. But perhaps stability could become an issue.
- Diamond: We already encountered some of these problems during the girder construction for DDBA.
- Diamond: Perhaps this would be a motivation for the integrated magnet design seen at MAX VI. At MAX VI, "floppy" copper vessels are supported by the magnets.
- Soleil: We must support the BPMs.
- HZB: The alternative is to measure the position of the BPMs while they "float".
- Diamond: We think that alternative is not worthwhile. Especially for a storage ring with top-up.

With smaller numbers of components in the button, could we integrate buttons into other components? Additive Manufacturing?

- Yes, we could go down this route.

How long does beam based alignment take?

- At Diamond approx. 8hours.
- Audience: Ranges from a few hours to approx. 8hours.

HZB: **How long do you need to wait for equipment to thermally stabilise?**

- Diamond: For beamlines its 1-2 hours. Sometimes as little as 40minutes.

BPMs inside the dipole. How can this be done?

- Diamond: Our idea would be to develop some optical BPMs. This could use Synchrotron Radiation (perhaps limited to 1D) or non-invasive polarisation radiation for 2D position sensitivity (Cherenkov-Diffraction Radiation). Another alternative would be to implement X-ray projection monitors with specially designed thin windows for extraction of SR from the lower field dipole magnets.
- Synchrotron radiation pickups?
- Fluorescent screens behind absorbers?
- Might not be as fast as turn-by-turn, but possibly 10kHz FOFB.

Soleil: **They have water cooled BPMs. Is there another way?**

- Diamond: We had to implement air cooling due to the double-skirt on some BPMs.
- Soleil: We've tried running during commissioning without it and can clearly notice the difference. We just have a very slow flow, with little vibration. Have not seen any turbulence issues with the water cooling on their BPMs.
- Sirius: We do not have water cooled BPMs. The temperature of the button block reaches some 35 degrees C, some 15 degrees different from ambient, this will take some time to thermally stabilise. We considered attaching a larger heatsink / fins to help with cooling. One idea we have is to put a groove in the BPM stand and fit a copper channel later if cooling is needed.
- ESRF: The BPMs at EBS will not be cooled. They are fixed to the girders for support. Heating is more due to radiation rather than RF, unlike Diamond.
- DESY: At PETRA we have cooled chambers, but we do not cool BPMs.
- Diamond: We must avoid incident SR on buttons as this will cause inhomogeneous heating of the BPM. Therefore, bumps to shadow the buttons may be needed. Perhaps in the new machines with the longer bunch lengths these RF heating issues will be avoided. We should also try to suppress the heating by designing the BPM buttons suitably.

- **SMA connectors? Should we switch to SMC?**
  - Yes, it might well be sensible.
- **Male or Female connectors?**
  - DESY: Female better as they're harder to damage. Having short PEEK cables helps here, as you have to rotate the cable to connect it to the button!
  - Future BPMs may have some strange not-quite-standard connectors: male collar, female pin.
  - Sirius: We had an issue from microcracks introduced by too much torque when connecting our cables to our BPMs. We now have a very light-touch approach.

ESRF: aluminium BPM body, titanium button body, welded together. Titanium looks like it has problems with radiation damage and poor elasticity.

- Looks similar to the effect Diamond saw with pinholes "furring up", (Tungsten/aluminium). Might be the same thing though. Resolved by nitrogen gas with pinholes, but difficult to implement for 300 BPMs around the machine.