**Design Choices for the cold LHC- BPMs**

Christian Boccard, CERN AB/BI

**Abstract**

The 3\textsuperscript{rd} half day of the CARE workshop was dedicated to special mechanical design and cold technology. This presentation is not a complete and global review on the LHC BPMs design and fabrication. The goal is more to pinpoint particular aspects or technological issues to be carefully taken in account during each step of the design and fabrication process. It is also a chance to give other experts feedback on the experience gained during these years of development, design, fabrication, testing and final installation.

**Outline**

- Design parameters and choice
- BPM types in the LHC
- BPM Integration
- Components
- Bodies
- Buttons
- Striplines
- Cold Cables
- Cryostat feedthroughs
- BPM installation and Tests

**Design parameters and choice**

A lot of parameters have to be taken in account during the design phase leading to technology and material choices. Here are some examples:
Some of these parameters will change during the development phase of the accelerator. I found it very useful that many of these parameters were summarized in a single working document. For the LHC, this document was stored under EDMS number 100513.

Early choice

One of the first choices to do was: Button or Striplines electrodes?
Arguments retained in favor of Buttons were:

- A welded Button electrode on a feedthrough is simple and robust.
- When fitted on a flange with a gasket, it is removable from outside the vacuum chamber and so can be replaced in case of leak or short-circuit.
- A diameter 24mm Button BPM is less cumbersome in longitudinal space compared to 120mm striplines.
- It is well adapted to short LHC bunches.
- Has little effect on longitudinal impedance.

On the other hand striplines were:

- More expensive to build.
- Less reliable due to the numerous small assembled parts.
- Requiring a precise machining or gap adjustment.
- More sensitive. However, this was not an advantage in the case of the cold LHC BPMs because of the power to be extracted from the cryostat and the heat load generated with the nominal beam current.

Given these pro and cons, the final choice (made in 1996) was for button electrodes for the arc BPMs with of course some directional striplines couplers around the experimental areas were directivity is needed. One can also state that this kind of choice is also greatly influenced by good or bad experience of people having already worked with each kind of technology.
**BPM types in the LHC**

How many types of BPM do you think we need in a machine like the LHC?

The first studies were concentrated on the standard cold BPM, 860 of them being needed for the arcs and dispersion suppressors. Then came the time to adapt to enlarged vacuum chambers; rotated aperture beam screens; experimental areas (with striplines). Some combined pick-ups were also designed to be shared with RF systems. The cold family was then completed with some other special cases requiring a particular integration.

With the warms areas, the number of BPM types was inflated drastically since the initial design due to the ever changing environment and parameters in these regions. The family was not completed until this year, with the special BPMs required for the beam dumping system and transverse diagnostics (long striplines, Tune and chromaticity measurements and wideband pick-ups).

At the end, it was necessary to construct, install and maintain a family of more than 30 Equipment codes and 1090 monitors. This diversity greatly increased the workload, as it was nearly as much work to launch and integrate a series of 5 BPMs as it was for the larger series of hundreds of monitors.

**BPM Integration**

The LHC BPMs are housed in the technical service module (QQS) on the connection side of the Short Straight Section (SSS), upstream of the beam 1 quadrupole. This is a crowded area shared with many other systems, leading to severe installation constraints. Given the number of components, people involved and interfering functions, every change done in the QQS during the development phase had to be well documented and made aware to all involved. This was done with the help of Engineering Change Request Procedures.
Given the restricted space, the BPM was since the beginning designed to be the input point for the cooling capillaries feeding helium to the Beam Screen. So once welded to the 5m long Beam Screen, the BPM is considered as a Vacuum component.

On the upstream side, the BPM flange is used to interconnect the SSS to the neighboring dipole magnet and at this end therefore has to satisfy the requirements of an interconnect component.
Exceptions to this standard integration scheme required even more work than the standard layout. The most difficult one to integrate was the directional coupler, named BPMS, situated in front of the Q2 magnet in the Q1-Q2 interconnect. Not only were these magnets designed by US collaborators, making integration of any CERN component more difficult, but given the proximity of surrounding bus bars, the BPM had to be rotated by 45 degrees in order to make it even possible to connect the coaxial signal cables.

Having learned with this first experience, (tooling development for the first arc BPMs was lengthy and costly) the integration concept was changed for the Enlarged BPM (BPMY). Here the monolithic arc BPM evolved to a modular concept with the aim of producing standardized components that could be adapted to other locations without the need for special tooling. It also took advantage of existing vacuum components such as the dipoles plug-in modules.

Components
Let's now review the system components and see some particular aspects or technological issues that have to be carefully taken in account during the fabrication process.

Bodies

Mechanical tolerances
Given the functional specification, usually requesting measurements in the micron range, it is usual to specify tight mechanical tolerances during the mechanical design stage. This is promising but:

- Be sure to maintain these tight tolerances all along the production chain.
- Do not over-specify your design as tight tolerances immediately impact the cost of machining.
• Do not forget that the 3 axis metrological controls are long and expensive.
• Do not forget to take into account mechanical deformations (see below).

Simulations
In the same manner as Microwave Studio is useful in the design of electrical parameters, Ansys 3D proved to be very valuable in determining the expected mechanical deformations under pressure constraints or to show the thermal gradients along components.

Material
Up to now, 50 leaks have been found in the LHC machine due to bad material (but not yet on BPM bodies). They were discovered after the welding of interconnect components. The reason behind these leaks was found to be due to macro-inclusions found in one batch of the forged austenitic stainless steel of type AISI 316LN used in the LHC.

Picture from A. Gerardin
Leaks appeared around these inclusions due to the final stress applied on the material during welding. Such macro-inclusions can produce leaks on material thicknesses up to some millimeters. To avoid this, a new material specification with an enhanced forging procedure is being issued to replace the current one issued in 1999 (CERN 1001-Ed. 3-02.08.1999).

**Copper**

The electroplated inner copper layer of 0.1mm thickness is mandatory to maintain the LHC longitudinal impedance. It also equalizes the temperature over the length of the BPM body. Nickel being excluded due to its magnetic properties, gold is used as a strike between the steel and copper. Perfect cleaning is the key for strong adherence. Witness samples were requested all along the fabrication to check process quality and copper RRR. Poor adherence leads to blisters forming on the copper layer during the bakeout. It is important that such an eventuality is discovered well before the end of the fabrication process.

![Figure 1: Photoelectron survey spectra of the 316LN samples 626-1 (left plot) and 626-2](image)

**Welding**

Welds should be re-qualified regularly during production even with automated orbital welding machines. The internal welding surface should be such that the weld does not affect the copper plating.
**Buttons**

The curved BPM Buttons are the only non welded cold components of the LHC vacuum chamber. The component was designed to be exchangeable, fitted on a flange with a Helicoflex® type gasket.

**Feedthrough technology**

Classical Ceramic Seal

Glass-Ceramic Seal

For the UHV coaxial feedthrough, glass metal technology was preferred to brazed ceramic after checks and analysis done on prototypes.
A close collaboration with the supplier allowed the design and fabrication steps to be optimized before the series production got underway.

The following systematic tests were carried out by the supplier:
- Mechanical measurements,
- 5 thermal shock cycles in liquid nitrogen
- Electrical checks,
- Leak test after bake out at 150 degrees for 15 hours.

Electrical tests and the pairing of buttons were carried out at CERN. To measure the amplitude response and capacitance, a synthetic pulse from a Vector Network Analyzer is sent to the antenna of a test bench. A reference button is used to cross check the VNA calibration.

Button measurement test bench.

Pairing on amplitude response.
**Striplines**

The design consists of two parts:

1. Installed from inside the vacuum chamber, two coaxial assemblies are used to mechanically attach the electrode to the body.
2. Fitted from outside, glass ceramic to metal UHV feedthroughs (same technology as for the buttons) with a Helicoflex® gasket gives the vacuum seal and electrically connects the electrodes to the N connectors on the outside of vacuum chamber.

The insulator used for the coaxial assemblies inside the vacuum chamber must be UHV and cryo compatible, radiation resistant, mechanically stable and have low losses. Ultem was our material of choice.

On one side, a sliding contact allows for the thermal contraction of the electrode. A Rhodium – Gold contact was used for this as it has been shown not to stick at cryo temperatures.

The whole fixture is Electron Beam welded. The small weld on the 2mm diameter pin was finally done at CERN.

The electrode gap is not easy to trim with this design. After 3D metrological control of key points in the body, the spacer (2) is adapted in height and the electrode washer (5) welded. The achieved directivity with this design is 28 dB with a high cut-off frequency of 70MHz.

Electrical tests using a TDR were carried out in a cryogenic environment during the development to measure the contact resistance and impedance variation with temperature. External inputs of the Vector Network Analyzer S Parameter set were used to switch the different instruments during temperature cycles.
**Cryogenic Signal Cables**

**A strong specification**
The cold semi-rigid coaxial cables have to meet some tough specifications:
- The cables must be compatible with a cryogenic environment, have high radiation resistance, be mechanically preformed, have a low heat transfer coefficient and VSWR, and most important, have good electrical stability under all these conditions.
- The electrical length difference was specified to be less than 10ps for the 4 cables associated with a single BPM

The dielectric materials under consideration included silicon dioxide, magnesium oxide and ultem (polyimide). The contract was finally awarded to KAMAN (US) for 4250 units in 2001 with the choice of a silicon dioxide foam (SIO2) dielectric. However, MEGGITT (US) took over KAMAN before the start of production.

A “Gold length cable reference” was used all along the fabrication to ease the pairing of cables, which helps the logistics on the CERN side as all cables of a particular type are now replaceable by any other of the same type.

**Integration is a challenge**
It was not possible to mount the first prototype in the QQS! A new integration design with a groove in the thermal shield was required to finally be able to mount the cables and eventually to allow their removal if one of them breaks.

Forming was not found to be as accurate as was specified.
Other configurations

The design of 5 different forming configurations was required to fit to all the BPM types. The cabling of the directional coupler in front of the Q2 magnet is the worst, requiring in the tunnel during the interconnection process. This kind of configuration should be avoided for the safety of these fragile and expensive components.

Cabling of the directional coupler in front of the Q2 magnet.

Finally, in order to avoid that the connector becomes unscrewed with thermal cycling, the connector nuts are locked in place by a twisted wire.
**Cryostat feedthroughs**

This warm component used to extract signal from the insulation vacuum has to withstand radiation and have a low VSWR.

Use of a DN100 flange with 4 N tight connectors with NBR (Nitride Rubber) gaskets in place of welded ceramic feedthroughs allowed us to gain a factor 10 in price.

To detect any crossed cables during installation, a simple wiring test was included in the assembly work package.

**BPM installation and Tests**

BPM installation is part of a work package that is sub-contracted for the 480 SSS magnets.

**Procedure:**

- Weld the 5 m long beam screen to BPM body (contract)
- Select pairs of button feedthroughs for mounting (BI)
- Mount button feedthroughs (contract)
- Perform leak test (VAC)
- Insert BPM/beam screen assembly (contract)
- Spot weld BPM to support (contract)
- Measure and adjust position and tilt of BPM (Survey)
- Weld BPM to support (contract)
- Measure position and tilt of BPM (Survey)
- Install and connect BPM cables (contract)
- Mount warm feedthrough on cryostat (contract)
- Perform electrical test of BPM system (BI)

**Worries:**

The contract started slowly in December 2003 and technology transfer had to be repeated many times as the personnel changed regularly.

Magnet installation cannot wait! As this work package is one of the last before installation any non-conformities have to be treated rapidly.
Summary

- **Schedule**
  All hardware has now been received after years of development (some of it just in time!) Installation is now nearing completion (840 cold BPMs from a total of 956 are now assembled)

- **Budget**
  We are currently within budget, but the original cryogenic cable budget was greatly underestimated.

- **Design**
  Experience from previous machines at CERN and similar machines around the world proved to be extremely valuable in making some of the technical choices.

- **Specification**
  Many of the issues related to materials could have been avoided if a timely global material purchase had been made at the project level. As it was, competition between different project engineers to order tons of material at the same could lead to delivery delays of up to 8 months.

- **Integration**
  We learn all along the project ….
  “What I would change if I would do it once again”

- **Construction and Installation**
  Everything was slower than planned partly due to the large scale of the project and the limited manpower available.