ADAPTIVE COLLIMATOR DESIGN FOR FUTURE PARTICLE ACCELERATORS*

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Abstract

The function of collimators in the Large Hadron Collider (LHC) is to control and safely dispose of the halo particles that are produced by unavoidable beam losses from the circulating beam. Even tiny proportions of the 7TeV beam have the stored energy to quench the superconducting magnets or damage parts of the accelerator if left unchecked. Particle absorbing Low-Z material makes up the active area of the collimator (jaws). Various beam impact scenarios can induce significant temperature gradients that cause deformation of the jaws. This can lead to a reduction in beam cleaning efficiency, which can have a detrimental effect on beam dynamics. This has led to research into a new Adaptive Collimation System (ACS). The ACS is a re-design of a current collimator already in use at CERN, for use in the HL-LHC. The ACS will incorporate a novel fibre-optic-based measurement system and piezoceramic actuators mounted within the body of the collimator to maintain jaw straightness below the 100µm specification. These two systems working in tandem can monitor, and correct for, the jaw structural deformation for all impact events. This paper details the concept and technical solutions of the ACS as well as preliminary validation calculations.

INTRODUCTION AND COLLIMATOR DESIGN

The current energy stored in nominal LHC beams is two times 362MJ [1]. For the High-Luminosity LHC upgrade (HL-LHC), this is expected to be higher than 700MJ [2]. As little as 1mJ/cm^3 at 7TeV of deposited energy can quench the super-conductive magnets or cause more major damage to other sensitive areas of the accelerator complex [3]. In efforts to counter this, the LHC collimation system is designed to intercept and safely dispose of the halo particles that are produced from the unavoidable beam losses generated from the circulating beam core.

Broadly speaking, the collimation system comprises of primary, secondary and tertiary collimators presented in a variety of geometrical configurations, working in union to clean the circulating beam. Each collimator consists of three main areas: the jaw assemblies, the actuation system, and the vacuum tank, shown in figure 1.

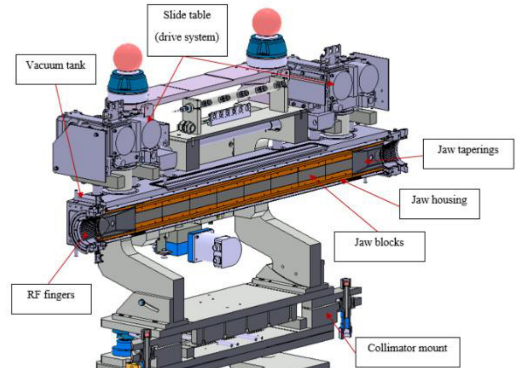

Figure 1: Section view of a typical horizontal secondary collimator.

The main component of the jaw assembly is the active absorption area. In primary and secondary collimators, this is made up of several blocks of low-Z material, such as a graphite composite or carbon reinforced carbon, to ensure low electrical induced impedance whilst maintaining mechanical robustness. These blocks are then clamped to a dispersion strengthened copper (Glidcop®) housing. The blocks are clamped to the housing rather than being rigidly fixed as this is not easily achieved. This is also to ensure a certain amount of slippage as the thermal expansion of Glidcop® is far greater than the thermal expansion of the low-Z blocks. Within the Glidcop® housing is also the jaw cooling system. The cooling system is designed to be able to evacuate the high heat loads generated by loss absorption (up to 47kW for HL-LHC cases) in an effort to minimise thermal deformations, which may be induced [4]. The cooling pipes are sandwiched between the block-housing stiffener on the front and an intermediate stiffener on the back then vacuum brazed together to ensure a good thermal conductivity, as shown in figure 2.

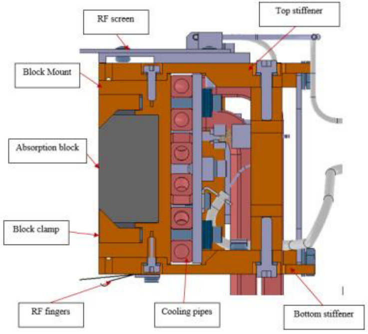

Figure 2: Cross section of current HL-LHC jaw assembly.

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The jaws are then housed inside an electron beam welded vacuum tank. To ensure compliance with the vacuum requirements for the LHC the collimator tank must be leak tight to ultra-high-vacuum (UHV) standards with static pressures in the range of 10^{-9} Pa to ensure beam stability and suitable beam lifetime [5]. In addition, the tank has several Conflat® knife design flanges to allow electrical feedthroughs currently servicing the beam position monitors and temperature sensors.

Finally, mounted outside the vacuum tank and connected to the jaws through a series of flexible UHV bellows is the actuation system. The actuation system allows the jaws to be moved precisely both laterally and angularly in relation to the beam. The system can laterally position the jaw within 10µm and angularly within 15µrads [6].

However, whilst the actuation system can position the jaws precisely with respect to the beam axis, the geometric form of the jaws must be kept to a very high precision. Key to the jaws cleaning efficiency is the straightness of the collimator jaw with which the beam interacts. Transverse deformations in the jaw can significantly change the jaws interaction with the beam in terms of cleaning efficiency and deposited thermal loads. The transverse deformation can vary over the length of the jaw due to the flatness of the jaw blocks, angular misalignment, mechanical error or thermal deformation. For secondary collimators, like the design the ACS is based upon, the maximum admissible straightness deviation is 100µm [7].

Whilst angular misalignment can to some degree be corrected by the actuation system, and flatness and mechanical errors can be reduced during assembly, thermal deformations are difficult to monitor and are inherent due to the nature of the beam dynamics.

LOSS EFFECTS ON COLLIMATOR JAWS

The robustness of collimators is fundamental to their operation within the LHC. They must be able to deal with a multitude of beam loss scenarios all of which can have a detrimental effect on jaw straightness, whether it is steady state losses from varying beam dynamics and differing variations in the LHC, or from accidental cases caused by machine failure. For this investigation, the loss scenarios that have been reviewed and used as the basis for this design study are as follows [8] [9]:

- Slow losses-
  - Steady state – 1h beam lifetime (BLT), $1.68\text{x}10^{11}$p/s at 7TeV leading to a 9.38kW energy deposition on the most loaded jaw.
  - Accidental state – 0.2h BLT, $8.34\text{x}10^{11}$ p/s at 7TeV leading to 46.9kW on the most loaded jaw.
- Dynamic Losses
  - SPS injection error – 288 bunches at 450GeV
  - Asynchronous beam dump – 8 nominal LHC bunches at 7TeV.

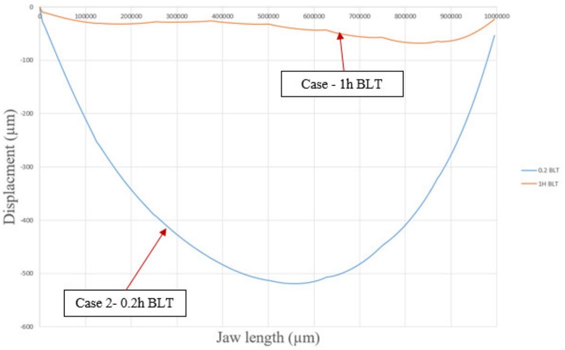

Figure 3: Jaw thermal deformation due to energy disposition from slow losses.

In terms of straightness error and deformation, cases one and two produce slow retarding elastic deformations that will return to their nominal positon over time. Shown in figure 3 is jaw deflection due to quasi-static losses outlined in cases one and two. For the 1h BLT case the maximum deflection is about 65µm. However this value is only indicative of the thermal load on the jaw combined with its own self weight. If a mechancial tolerence of 40µm is also taken into account then from Equation 1, the quadratic average of the deflections the overall deflection increases to 76.3µm.

$$s_{total} = \sqrt{s_{thermal}^2 + s_{mechanical}^2} \qquad \text{Eq 1}$$

Whilst this is below the acceptable deviation limit for this style of collimator, it is potentially very close.

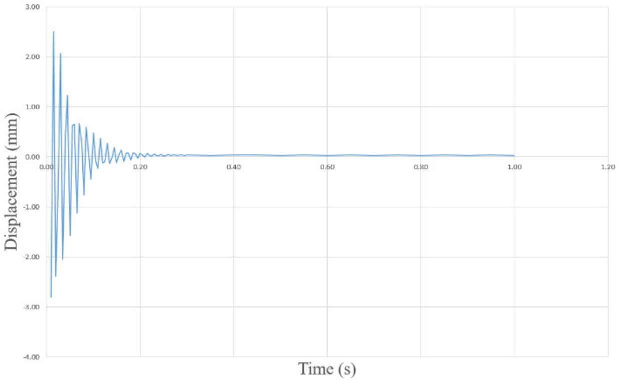

Figure 4: vibrational response of jaw after simulated SPS injection error.

In case two, the 0.2h BLT the maximum deformation is about 500µm, clearly exceeding the 100µm tolerance limit.

Whilst these losses cause slow elastic deformations, direct beam impacts will have an intensely more violent effect. Simulating an injection error with 288 bunches ($6.4\text{x}10^{13}$ total protons) at 440Gev, has the energy to plastically deform the Glidcop® housing [10] and will induce an underdamped dynamic flexural response, seen in figure 4. This response can have a period in excess of 120Hz in accordance with the first natural modal frequency [11], combined with a large amplitude potentially over 2mm. Note: the above cases are based upon the TCSPM secondary collimator design utilising molybdenum-graphite blocks [12].

ADAPTIVE COLLIMATION SYSTEM

In an effort to correct the thermal deformations induced on collimators, an adaptive collimation system is proposed. The ACS is a closed loop approach to monitoring and correcting the straightness errors in collimator jaws, consisting of real-time measurement and integrated actuation. The base design is that of the current secondary TCSPM collimator, under deployment at CERN[13]. The TCSPM has been re-designed to allow to the integration of the measurement and actuation systems into the jaws and the necessary services that they require. Figure 5 shows the new TCSPM ACS jaw layout.

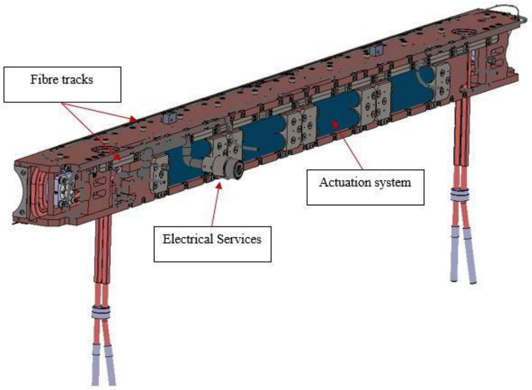

Figure 5: ACS Jaw design.

Measurement

The measurement system is a fibre based dispersed reference interferometry (DRI) measurement system, shown in figure 6. The DRI system *[14]* utilises several fibre-based probes mounted in the jaw to monitor the deflection. A fibre-based system was chosen due to space constraints inside the vacuum tank, and because optical fibres are more resilient to radiation than electrical based sensors, even when considering susceptibility to fibre darkening. Whilst fibre darkening is an issue when using optical fibres in high radiation environments, the DRI system can operate on as little as four percent returned light.

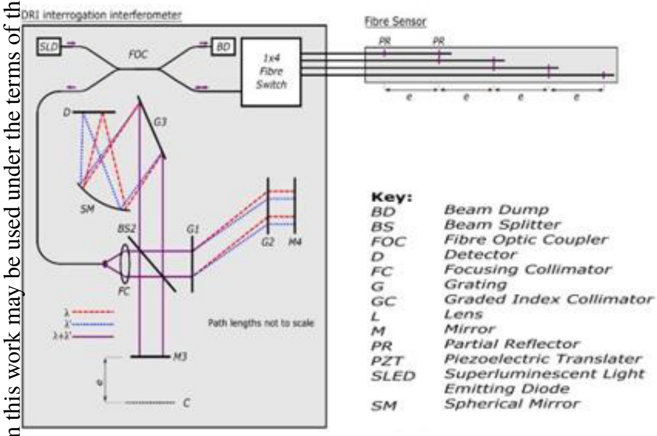

Figure 6: DRI system layout.

The system consists of twelve probes split into two groups, with six mounted on the front of the jaw and six mounted on the rear side. Mechanically clamped to the jaw the probes will elongate as the jaw deforms, providing a deduced value of strain. The differentiation between the strain values at the front against the values at the back, in corresponding probes will allow the deduction of displacement direction and magnitude.

Of the six probes in each track, only five will be used for strain measurement. The sixth will be unclamped allowing it to elongate freely. By doing this the expansion of optical fibres due to temperature in the jaw can be observed and extrapolated against the actual values of expansion due to jaw displacement.

As glues and other adhesives are generally not permitted in LHC components due to issues with out-gassing, the optical fibre probes will be clamped in purpose built mounts (figure 7) that will be fixed to jaw housing that will run the full length of the jaw.

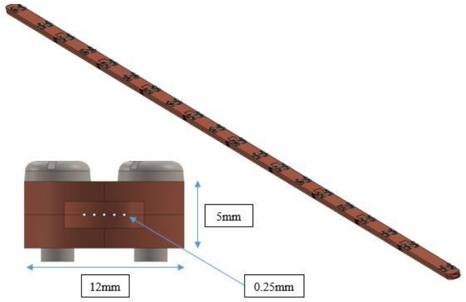

Figure 7: Fibre mount and cross section.

Table 1 shows the summary of the DRI measurement system.

Table 1: DRI Summary

No of measurement arms	2
Measurement cavities intervals	200mm
No. of cavities	6 per arm (12 per jaw)
Optical Resolution	850nm at 50nm bandwidth
Strain resolution	±0.417 με
Rate of acquisition	4KHz
Temperature range	10-300°

Actuation

The actuation system for the ACS jaw comprises a series of high-powered piezo-ceramic (PZT) stack actuators (figure 8). The current design of the TCSPM jaw makes it inherently stiff, requiring large amounts of force to manipulate it. One of the reasons PZT actuators were chosen is for their high force generation. Each actuator in the ACS has a blocking force of 14000N and a maximum displacement at 0N of 120μm at 1000V. The number of actuators required to manipulate the jaw was determined by their proximity to the jaws neutral plane. Due to space constraints inside the vacuum tank, the actuators have to be placed unavoidably close to the jaws neutral plane. This decreases the moment and therefore requires a higher force to deform the jaw to the desired amount, thus leading to the use of eight actuators currently in the design. Fewer could have been used, reducing the cost and complexity, if it had been possible to locate them further from the neutral plane. Because of this, the actuators are embedded in what would traditionally be the back stiffener of the collimator. They are mounted on universal semi-spherical mounts to avoid the undesirable exertion of external lateral forces and torques on the actuators.

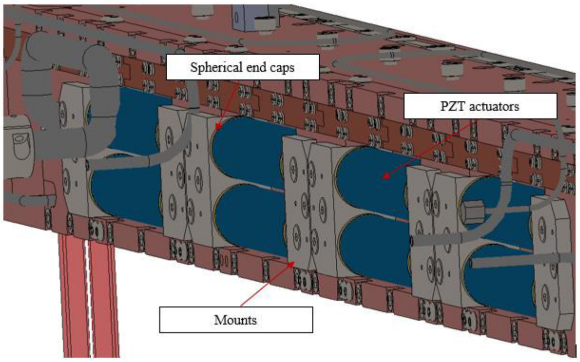

Figure 8: Piezo mount.

It is envisaged that the actuation system will be operated in two distinct modes. One, the actuators will expand at constant rate to reverse the effects of the slow elastic thermal deformation in order to keep the jaw's straightness value below the specified limit. This scenario has been run in an FEA simulation, which shows the current design configuration can achieve the correction of a 500μm displacement, the same as that caused in a 0.2h BLT. The results of this are shown in figure 9.

The second mode of operation will be a vibrational response capable of acting as an active damping system designed to respond to the events caused during a direct beam impact. By pulsing the actuators out of phase with the frequency caused by a beam impact the two frequencies should interfere with each other destructively thus reducing the amplitude. This still has to be proved analytically, but in theory the actuators expansion speed can easily match the resultant frequency caused by a beam impact.

The theoretical speed at which the actuators can expand is governed by the actuators resonant frequency f_o and given by:

$$T_{min} = \frac{1}{3 \cdot f_o} \qquad \text{Eq 2}$$

If the electrical supply were not taken into account this would give a rise time of 33ns. However, the rise time is governed by the current supply, which due to the UHV electrical feedthroughs is capped at 3A. This gives a rise time even of 0.86μs, given by:

$$I = C \cdot \frac{dV}{dt} \qquad \text{Eq 3}$$

where C is the capacitance of the actuator. This would give a frequency response in the KHz range, easily capable of matching the jaws first order natural frequency.

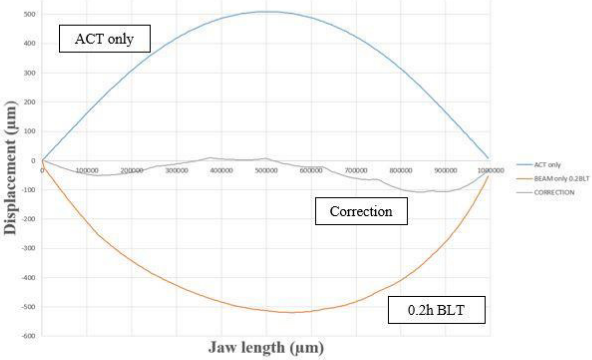

Figure 9: 0.2h BLT displacement and actuated correction.

CONCLUSION

The design of the ACS and its integration into a current collimator design poses serious challenges. A large amount of additional hardware must be added into a compact space that cannot be altered. The fundamental parts of the collimator design, cooling system, active area etc. cannot be radically redesigned in fear of altering the collimators primary function. This leads to further difficulties in regards to integrating the ACS. Whilst the fundamental parts that make up the ACS have been used separately and with high degrees of success, combining them and making them fit for purpose for operation in the LHC is still uncertain. However, initial FEA simulations show promising results concerning the current hardware specification. In addition to FEA, several test rigs have been planned to facilitate the final design. Chief among these was a dedicated line in HiRadMat 36 [15] [16] at CERN. The results for the ACS line in the "Multimat" experiment will be published in due course. In addition to this a 1/3 scale jaw has been developed to review the design intents of the ACS as well as the relationship between the measurement and actuation systems, and the controls that links the two. The ACS will continue to develop over the next fifteen months with a full-scale working collimator ready for the end of 2019.

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