DESIGN OF A ROTATABLE COPPER COLLIMATOR FOR THE LHC PHASE II COLLIMATION UPGRADE*

Jeffrey Claiborne Smith†, Eric Doyle, Lewis Keller, Steven Lundgren, Thomas Walter Markiewicz
(SLAC, Menlo Park, California), Luisella Lari (CERN, Geneva; EPFL, Lausanne)

Abstract

The Phase II upgrade to the LHC collimation system calls for complementing the robust Phase I graphite collimators with high Z, low impedance Phase II collimators. The design for the collimation upgrade has not been finalized. One option is to use metallic rotatable collimators and this design will be discussed here.

The Phase II collimators must be robust in various operating conditions and accident scenarios. Design issues include: 1) Collimator jaw deflection and sagitta due to heating must be small when operated in the steady state condition, 2) Collimator jaws must withstand transitory periods of high beam impaction with no permanent damage, 3) Jaws must recover from accident scenario where up to 8 full intensity beam pulses impact on the jaw surface and 4) The beam impedance contribution due to the collimators must be small to minimize coherent beam instabilities.

INTRODUCTION

The principle function of LHC collimation system is to protect the superconducting magnets from quenching due to particle losses. The collimation system must absorb upwards of 90 kW in the steady state operating condition (1 hr beam lifetime) and withstand transient periods where up to 450 kW is deposited for no more than 10 seconds. The maximum energy deposited on any one secondary collimator is 23 kW for the steady state and 115 kW for the transient condition [1]. The system must also be robust against an accident scenario where up to 8 full intensity bunches impact on one collimator jaw due to an asynchronous firing of the beam abort system imparting 1 MJ over 200 ns [2]. In the steady state condition the maximum deformation of the jaw toward the beam should be no more than 25 microns relative to the 7σ initial aperture. When fully inserted the minimum half gap is 0.5 mm which corresponds to 7 sigma. The jaws must also move in parallel ±5 mm back and forth at full insertion in order to follow the beam centroid. Additionally, when the jaw are fully retracted, the minimum aperture must be 45 mm.

For the phase I collimation system, it was decided to use graphite, a low Z material, which can withstand the accident scenario with no damage. But due to the same low Z properties, the graphite collimators cannot absorb enough beam halo for the LHC to operate at design beam intensities. The plan is to upgrade the phase I collimators with up to 30 high Z phase II collimators. The high Z material of the phase II collimators will not withstand the impact of the 8 full intensity bunches in the accident scenario without permanent damage, so a rotatable jaw has been designed which will be recoverable. Composed of two cylindrical jaws, if a beam happens to hit a jaw it can be rotated to introduce a clean surface for continued operation. Over the course of the lifetime of the LHC it is estimated that any one collimator will experience the accident scenario no more than 20 times, so 20 flat facets on the cylindrical jaw surface is sufficient.

MECHANICAL DESIGN

The most critical issue in the design of the collimator is the thermal deflection of the jaws due to beam heat load. A variety of materials were investigated to determine which had the appropriate thermal and Z properties to sufficiently absorb the beam yet not rise above the melting point. Ultimately, copper was chosen as a balance between collimation efficiency, thermal deflection and manufacturability [3].

Each jaw consists of a molybdenum shaft and concentric glidcop jaw joined only at the center via a glidcop hub as illustrated in Fig. 1. This layout was dubbed the Jaw-Hub-Shaft concept. Between the shaft and outer jaw is a 2mm gap. This allows the jaw ends to deflect mostly away from the beam during heating, reducing the jaw deflection toward the beam. The use of molybdenum for the central shaft is to increase structural rigidity. The heat load on the central shaft is minimal so good thermal conductivity is not an issue.

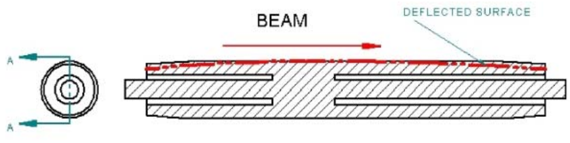

Figure 1: Jaw-Hub-Shaft concept to minimize the jaw deflection toward the beam.

The jaw must be water cooled. This introduces an obstacle to the rotation of the jaws. Any type of sliding seal was deemed impractical so instead a single long copper tube of length 16m is formed in a helix within the jaw, with straight tails extending through the center of the shaft. This eliminates any vacuum to water joints and allows for the copper tube to be twisted as the jaw rotates. The final jaw design is illustrated in Fig. 2 showing the inner shaft and mandrel

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[*] Work supported in part by the U.S. Department of Energy contract DE-AC02-76SF00515

[†] js344@slac.stanford.edu

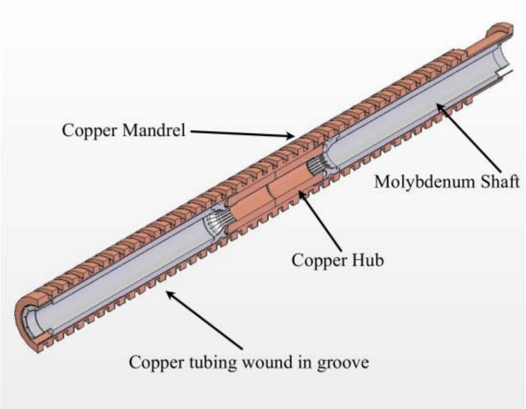

Figure 2: Cutaway of jaw showing inner moly shaft and mandrel.

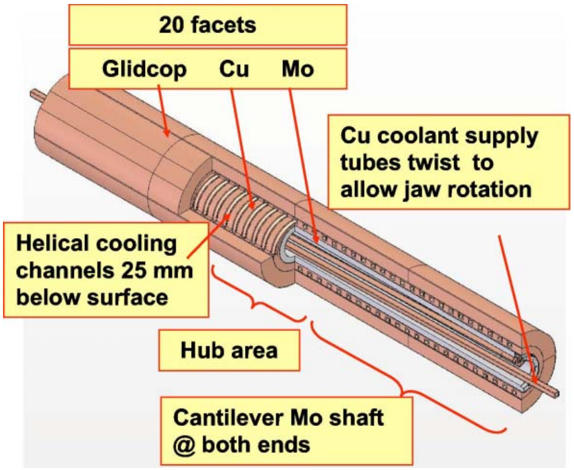

Figure 3: Cutaway of Jaw showing outer jaw surfaces and cooling tube routed through the center of the molybdenum shaft.

and Fig. 3 with the jaw surfaces added. The overall Jaw specifications are given in Table 1

Jaw Heat Flow

Extensive simulations have be performed in FLUKA [6] and ANSYS [7] to determine the maximum heating and deflection of the jaws under steady state and transient conditions and are summarized in Table 2. “Effective Length” refers to the length of the jaw that is deflected less than 100μm compared to the maximum defection point – essentially giving the length of the jaw that is still within the beam path under heating conditions. The jaw must then be retracted slightly to meet the 25 micron deflection toward beam spec under steady state. Further simulations where performed to estimate the damage due to the accident scenario. The analysis found a energy deposition of 0.27 MJ in 200 ns with a peak jaw temperature of 57,000 C, sufficient to vaporize the copper. The full extent of the melting is about 5 mm, well within the facet width of 21.54 mm. It is therefore anticipated that the damage will not reach past the exposed facet and rotating the jaw will display a new clean facet to the beam. It was found, however, that this accident case results in a permanent concave deformation of the jaw of 54 microns. This may limit the performance of the collimator after recovering from a collision.

Table 1: Jaw Dimensions

Component	dimension	units
Jaw OD tangent to facet faces	136	mm
Jaw number of facets	20	
Jaw ID	66	mm
Jaw length, including edge taper	930	mm
Mo Shaft OD	64	mm
Mo Shaft ID	44	mm
Cooling tube ODxID (square)	10x7	mm
Embedded helix - center radius	80	mm
Helix - number of turns	47	
Total cooling tube length	16	m
Flow per jaw	9	l/min
Water velocity	3	m/s

Table 2: Jaw heating and deflection characteristics for Steady State (SS) and Transient (TR) conditions

Component	SS	TR	units
Max jaw temp	70.6	224	C
Max deflection toward beam	105	365	μ m
Surface Sagitta	226	880	μ m
Effective length	0.67	0.33	m
Water temp rise	20.3		C
Water pressure drop	2.4		bar

Thermal tests have been performed on a prototype jaw with 9kW of heating and have been found to agree with ANSYS simulations. The results are reported in a separate paper [4]. A further study would be to impact a jaw with a beam representative of the accident scenario however such a test has not yet been devised but is considered for the future.

Jaw Motion

An internally actuated drive has been designed that utilizes a ratchet attached to a “Geneva Mechanism,” or “Maltese Cross,” which translates a continuous rotation into an intermittent rotary motion, allowing for the precise rotation of the jaw in increments of 1/20th of a revolution, or one facet face. The mechanism effectively guarantees against the accidental over-rotating of the jaw because the jaw only begins to rotate after the 8th ratchet past the last rotation. The ratcheting is performed by over-retracting the jaw whereby the ratchet hits a “hammer” attached to the chamber wall. Successive over-retracting rotates the jaw with a total of 512 ratchets resulting in one facet rotation when using a tri-lobed geneva driver. The jaw shaft is supported on each end by a 0.5mm thick molybdenum diaphragm which acts as a universal joint. It allows for jaw deflection due to gravity sag, thermal load and a skewed jaw orientation. The diaphragm also ensures proper alignment of the Geneva Mechanism. The shaft support is shown in Fig. 4.

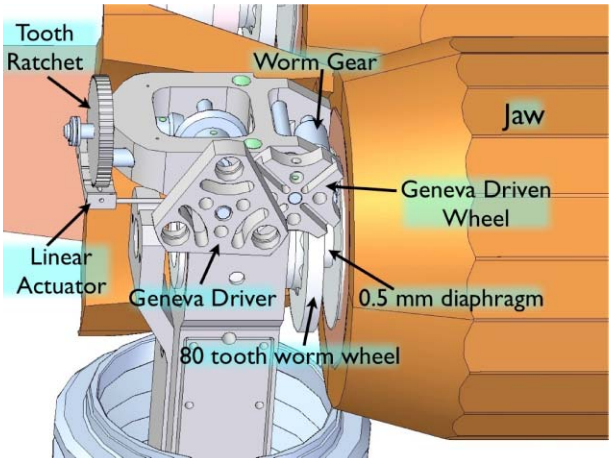

Figure 4: View of the shaft support showing the Geneva Mechanism for precision jaw rotation and universal joint diaphragm.

The mechanism for positioning the jaw in the beam path is to be adapted from the LHC Phase I Collimator design [2]. Given the heavier jaws in the rotatable jaw, modifications may be needed to the mechanism to support the greater weight. A phase I graphite collimator assembly has been obtained from CERN and is being used for designing the mechanism in the Phase II design. We expect to have to make only small changes to accept our heavier and larger jaws.

The overall design is illustrated in Fig. 5. The principal outstanding design issues relate to RF shielding. The design concerns, measurements and simulations related to RF shielding are discussed in a separate paper [5]

PROTOTYPE CONSTRUCTION

Extensive R&D went into the design and fabrication of the first jaw prototype. Numerous braze joint tests were performed until a satisfactory method was developed. In particular, the joint attaching the molybdenum shafts to the central glidcop hub proved to be rather troublesome, mainly due to the different thermal expansions of glidcop and molybdenum. The solution was found by cutting fingers along the end of the molybdenum shaft as can be seen in Fig. 2. This setup allowed for the molybdenum to expand with the glidcop as it heated. Upon dissecting and examining test pieces under a microscope the braze joints were found to be very good. Numerous other braze tests have been performed with post-brazing examinations to determine the successful methods to use.

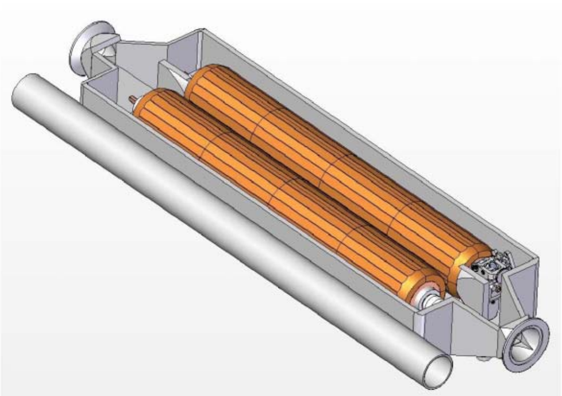

Figure 5: Full layout of the rotatable collimator showing its placement next to the beam pipe for the counter-rotating beam.

The winding of the copper tube around the mandrel was also an area of concern. As the square tube is wound it begins to keystone resulting in a gap larger than can easily be filled in with brazing alloy. Good thermal contact is required between the mandrel and cooling tube so we are currently investigating different methods to fill in the gap. One potential solution is to fill the coil with water then freeze the water. The expansion of the water as it freezes pushes out the outer wall of the coil decreasing the gap. This method has been shown to work well.

ACKNOWLEDGMENTS

Ralph Assmann and the entire LHC collimation team at CERN has been a great resource. Sharing of their experiences designing the Phase I collimators have been invaluable. Also, the SLAC klystron department has extensive experience in brazing techniques and has helped us greatly in our endeavors.

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