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RECENT PROGRESS ON THE DESIGN OF A ROTATABLE COPPER COLLIMATOR FOR THE LHC COLLIMATION UPGRADE*

Jeffrey Claiborne Smith†, 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 30 high robust Phase I graphite collimators with 30 high Z Phase II collimators. 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 due to heating and sagitta 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. This paper reports on recent updates to the design and testing.

THE COPPER ROTATABLE COLLIMATOR DESIGN

The principle function of the 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 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. The high Z material of the phase II collimators provides better collimation efficiency compared to the low Z graphite phase I collimators but 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. 20 flat facets on the cylindrical jaw surface is sufficient to last the lifetime of the LHC. Details of the jaw design and construction can be found in [1] and [2]. The final jaw design is illustrated in Fig. 1.

Recent design changes can be seen in Fig. 2 which shows the jaw end, cylindrical vacuum chamber and transition pieces. The Jaw is now supported by a thin stainless steel bar that can flex and take up the thermal expansion of the jaw without the need of a universal joint. The use of a cylindrical vacuum chamber simplifies the design and construction and facilitates the use of thinner chamber walls compared to a rectangular design. A temperature probe is positioned near the end of the jaw and there is now a design for implementing a BPM button into the transition RF foil. These BPMs will be used to align the jaw relative to the beam with a resolution of 25 microns or less. Alternatively, the Higher Order Mode excitations in the chamber could be driven and picked-up with the buttons for determining the beam position. This method is currently being investigated [3].

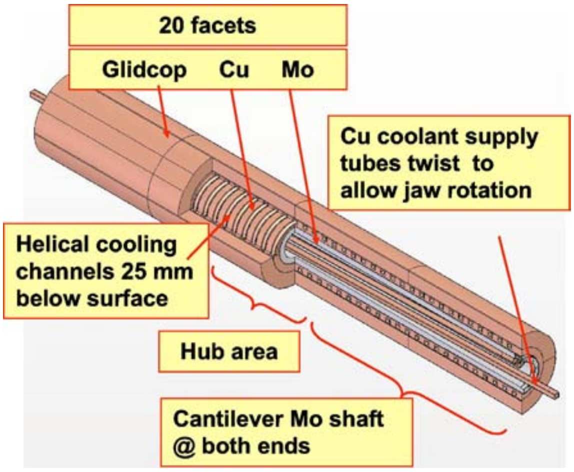

Figure 1: Cutaway of Jaw showing outer jaw surfaces and cooling tube routed through the center of the molybdenum shaft.

RF DESIGN AND IMPEDANCE MEASUREMENTS

The rotatable jaw results in the need for a sliding contact 11 mm away from the beam axis when the jaw is fully inserted as a RF contact for the image current. A sliding RF contact with very low contact resistance must be chosen that will hold up to the ∼20 year operational lifetime of the collimators without serious degradation. Rhodium coated 1 mm stainless steel ball bearings will be used as the sliding contact. A bare SS ball pressed against Cu would quickly cold-weld so appropriate coatings are necessary. Following the investigations conducted by Calatroni *et al.* [4], the most desirable ball bearing coating is rhodium. Ideally, a gold or silver coating would also be placed on the jaw and

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[†] js344@slac.stanford.edu

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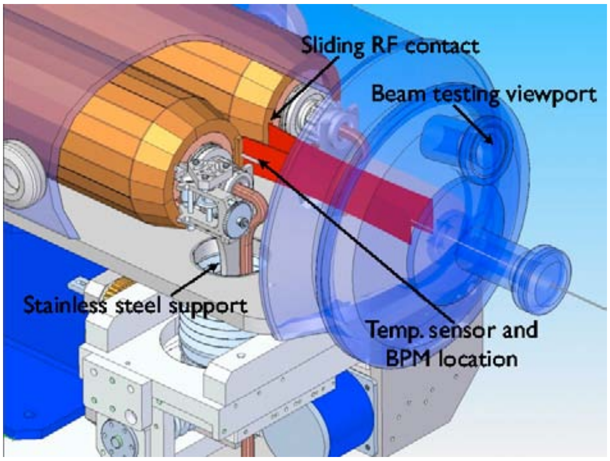

Figure 2: Jaw end showing RF transition pieces and rotation mechanism.

transition piece in contact with the balls but bare copper is also acceptable since rhodium will not cold-weld to copper. The end of the jaw and transition pieces are illustrated in Fig. 2. The use of flexible coils and springs were also investigated but it was concluded that they would not be durable enough for the 20 year lifetime of the device. A ball bearing contact is also easier to manufacture and assemble. No RF seals have been found to be necessary longitudinally along the top and bottom of the jaw.

To test this design, a copper jaw end mock-up was constructed and a groove was machined in the end to accept the balls. Three sets of 3 mm balls were tested: bare stainless steel, rhodium plated (2 microns) and gold plated (4 microns). Several different weights were placed on top of the setup in order to apply different contact loads. The results are shown in Table 1. Gold plating resulted in the smallest resistance as expected. However, using gold plating would require also plating the jaw end with rhodium, otherwise there is a risk of cold welding. Rhodium plated balls would require no such extra plating and the difference in contact resistance is only about a factor of three. With a practical load of 10 pounds, the measured resistance was 0.55 mΩ with the Rhodium plating – within acceptable resistance levels. Using smaller balls of only 1 mm diameter will decrease the impedance by a factor of three. The SS ball bulk resistance is small at 0.005 mΩ net for all balls and so they need not be made from a more highly conductive material.

Table 1: Measured Contact Resistance about Ball Bearing Contacts in mΩ

Plating	no Load	1 lb	3 lb	10 lb	26 lb
Bare	10000				500
Rhodium	4	1.7	1.1	0.55	0.33
Gold	1.1	0.51	0.33	0.19	0.1

Continuing on from previous studies of bench-top impedance measurements [5] a study was performed to compare the geometric and resistive wall components of the collimator. Since no copper rotatable collimator is yet available these measurements were performed on a LHC graphite phase I collimator obtained from CERN. We accurately know the comparative resistive wall impedance of graphite versus copper as verified in the previous measurement so this measurement also gives the geometric component of the impedance for a copper collimator. Five configurations were measured: 1) The wound coil in air (Reference). 2) The wound coil in two copper plates (Reference). 3) The wound coil in the design collimator setup with silver coated BeCu fingers. 4) The wound coil in the collimator with fingers removed. 5) The wound coil in the collimator with the fingers replaced with copper foils similar to those that will be used for the rotatable collimator. These five configurations allows for the determination of the component of the wakefield due solely to the transition pieces.

It was found that the difference in total geometric component between no transition and the silver finger transition is less than $3 \times 10^4\,\Omega/\mathrm{m}$. Theory predicts a geometric impedance of $2.2 \times 10^3\,\Omega/\mathrm{m}$ for a 12 degree taper of similar dimensions. For a right angle (90 degree) taper the theory predicts $1.66 \times 10^4\,\Omega/\mathrm{m}$. The difference between these numbers is $1.4 \times 10^4\,\Omega/\mathrm{m}$ which is close to the measured difference. The geometric impedance was measured to be purely imaginary and mostly independent of frequency which is also in agreement with theory. Measurements therefore agree well with theory and it is concluded that although the transition pieces are required to carry the image current, their geometry is of little consequence to the overall transverse impedance of the collimators. Details of the RF contact and bench-top impedance measurements can be found in [6].

THERMAL BAKE-OUT TESTS AND METROLOGY

The successful thermal tests as previous reported [7] demonstrated that the thermal deflection of the first jaw prototype, or RC0, agreed with ANSYS simulations and was at acceptable levels. The jaw then underwent bake-out vacuum tests to confirm that the desired vacuum is achievable. The jaw was first hydrogen fired in a brazing furnace at 850 °C before bake-out to help clean all surfaces after a large amount of handling during the thermal tests and to accelerate the bake-out process. The standard PEP-II Beamline bake-out sequence was then used to characterize the vacuum quality. It was inserted into the vacuum vessel and baked at varying temperatures for a total of 14 days. The final measured pressure was 8.8×10^{-10} Torr after several days of cool-down but had not yet fully bottomed out. The LHC vacuum spec is 7.5×10^{-10} Torr.

The ion pumps used in the bake-out test had a pumping speed of 400 l/s which is similar to the expected pumping rate of the LHC beam pipe so comparisons can be made with the LHC spec. Expecting the internal surface area of the bake-out vacuum chamber to be similar to the full collimator chamber and that a total of two jaws will be in the chamber, our estimated full collimator pressure is 1×10^{-9} Torr. This is slightly above spec but very close. A longer bake-out time may be adequate to reach the spec. An RGA scan was performed near the end of the run. The main potential concern would be the presence of any hydrocarbons but no molecules larger than carbon dioxide were detected. All efforts were taken to minimize the RC0's exposure to hydrocarbons by using only alcohol as the cutting fluid and maintaining clean working environments. Our efforts were a clear success.

After all thermal and vacuum tests where completed the RC0 jaw was placed in a Coordinate-Measuring Machine to measure the flatness of the jaw facets. 5 nonconsecutive facets were measured for overall flatness with three survey lines per facet totaling 99 points per facet. The worst facet flatness was measured as 43 microns and the others were at 33 microns or less. Overall, the flatness is above the spec of 25 microns but several factors including the facet machining method contributed to the overall shape. The support for the facet in the milling machine was not as well aligned as possible and due to potential off center indexing and misalignment of the milling head with respect to the mill table and jaw the facets were probably not machined purely square. The jaw was supported by the ends of the molybdenum central shaft and gravity and the force of the mill head on the part probably contributed to the overall bowed shape. Difficulties in brazing such a large object could also have resulted in non-concentric indexing and an overall conic shape to the jaw surface. It has been concluded that none of the deformed shape of the jaw is due to the vacuum bake-out. Movement due to overheating would have caused asymmetrical warping. Instead, the shape as measured must be due to the machining method. In summary, the RC0 facets are close to the flatness specification. This is in spite of several factors that contributed to non-ideal facet machining. It is fully anticipated that an improved machining and brazing method will remove most of the error in flatness and the specification will be met for production models. See [8] for details of all tests performed on the RC0 prototype jaw.

FLUKA ENERGY DEPOSITION STUDIES

A new set of FLUKA energy depositions studies have been conducted integrating new design features into the model and also comparing the rectangular to cylindrical vacuum chambers. Results for the most loaded collimator (TCSM.A6L7) are shown in Table 2. The cylindrical chamber results in lower heating because the wall thickness is less. The other components have roughly the same heating, as expected, and no components are seen as receiving excessive heating. Results of Higher Order Mode beam heating are presented in a separate paper [3].

Table 2: Net Energy Eeposition in Watts for Rectangular vs Cylindrical Vacuum Chambers for 1.0 h Beam Lifetime

Component	**Rectangular**	**Cylindrical**
2 Jaws	22000	22000
Vacuum Chamber	1516	1067
4 Moly supports	38	40
4 SS Supports	12	11
4 Copper Foils	23	25

TT60 BEAM TESTS

Beam tests are planned in the TT60 beam irradiation test facility to be constructed at CERN. A major unknown factor in the performance of the jaw is the extent of damage during a direct beam hit. Fluka and ANSYS results [2] predict the damage to not extend past one facet. Any vaporized material is expected to hit the opposing facet and the top/bottom chamber walls and quickly freeze. Some material will only melt and bead, but the extent to which that material will drip in unknown. The only definitive answer will be by experimentally hitting the jaw with a LHC-intensity beam. Diagnostic equipment including laser displacement sensors and infrared cameras are being investigated to facilitate the real time measurement of the damage during the tests. Removable plates are envisaged to measure the amount of material deposited on exposed surfaces. Figure 2 shows several viewports integrated into the vacuum chamber which will allow access for the diagnostic equipment.

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