CONSTRUCTION AND BENCH TESTING OF A PROTOTYPE ROTATABLE COLLIMATOR FOR THE LHC

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A second generation prototype rotatable collimator has been fabricated at SLAC and delivered to CERN for further vacuum, metrology, function and impedance tests. The design features two cylindrical Glidcop jaws designed to each absorb 12 kW of beam in steady state and up to 60 kW in transitory beam loss with no damage and minimal thermal distortion. The design is motivated by the use of a radiation resistant high Z low impedance readily available material. A vacuum rotation mechanism using the standard LHC collimation jaw positioning motor system allows each jaw to be rotated to present a new 2 cm high surface to the beam if the jaw surface were to be damaged by multiple full intensity beam bunch impacts in an asynchronous beam abort. Design modifications to improve on the first generation prototype, pre-delivery functional tests performed at SLAC and post-delivery test results at CERN are presented.

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Abstract

A second generation prototype rotatable collimator has been fabricated at SLAC and delivered to CERN for further vacuum, metrology, function and impedance tests. The design features two cylindrical Glidcop jaws designed to each absorb 12 kW of beam in steady state and up to 60 kW in transitory beam loss with no damage and minimal thermal distortion. The design is motivated by the use of a radiation resistant high Z low impedance readily available material. A vacuum rotation mechanism using the standard LHC collimation jaw positioning motor system allows each jaw to be rotated to present a new 2 cm high surface to the beam if the jaw surface were to be damaged by multiple full intensity beam bunch impacts in a asynchronous beam abort. Design modifications to improve on the first generation prototype, pre-delivery functional tests performed at SLAC and post-delivery test results at CERN are presented.

ROTATABLE COLLIMATOR DESIGN

The first generation prototype rotatable collimator [1]-[3] was found to have a leak in its cooling circuit and a decision was made to construct a second generation prototype. After determining that the cooling tubes were damaged during machining operations to bring the surface of the coil wrapped inner mandrel to the tolerance required to braze them to Glidcop cylinders that comprise the jaws of the collimator, the mandrel's cooling coil groove depth was increased to allow protective shims to be brazed atop the tubing as part of the mandrel to coil braze cycle. As for the first prototype, the five ~20cm long Glidcop cylinders were flash-coated with copper and had their inner surface loaded with braze wire. They were stacked over the ~1m long inner mandrel with sheets of Cu-Au material between them and brazed. Twenty symmetric facets were then machined on the outside of the jaws, equidistant from the rotation axis and flat to a precision of 25 μm.

Tests of the first prototype had indicated a number of areas where relatively minor design modifications could improve performance. The main rotation bearings, previously formed by a split molybdenum housings and 1mm diameter ceramic ball bearings, were replaced by commercial bearings comprised of caged ceramic balls constrained in stainless races after evidence of binding between the balls and wear on the molybdenum axle were observed. A new restraint clip was added to keep the bearing housing locked to the axle, as differential thermal expansion between the jaw supports and collimator during vacuum bakeout had caused bearing slippage in the first prototype.

So-called RF bearings on the outer ends of the jaws, allow, despite jaw rotation, BeCu foils to be held fixed in place to provide a smoothly varying low impedance path for image current to pass from the collimator jaws to the vacuum tank. The first generation design used split rings and 1mm Rhodium coated stainless balls; balancing the pressure required in the race to achieve low resistance with the resulting friction to rotation was problematic. The present design uses captured ceramic balls in stainless races. Rather than relying on the balls themselves to provide a low impedance path, a rhodium coated BeCu corrugated sheet is placed between the foils and the jaw.

The jaw is rotated through a ratchet and pawl mechanism, which is driven by a claw engaging the ratchet when the jaw over-travels. Eight full revolutions of the 48-teeth ratchet are required to rotate the jaw by one facet, which corresponds to $1/20^{th}$ of a revolution. A full rotation requires approximately 1.5 hours to be completed. Several changes were made to the rotation drive mechanisms. The Geneva drive wheel was replaced with a pair of gears to minimize the peak torque required for rotation. A robust pawl was introduced to prevent backlash of the drive gear. Finally, a vertical flexure screw-driven adjustment was added to the claw actuator. The adjustment screws are accessible through the beam port so that the separation between the claw actuator and drive gear can be adjusted even after the collimator is sealed in its vacuum tank. This feature was employed after welding the vacuum tank cover caused the collimator base plate to distort and after me-

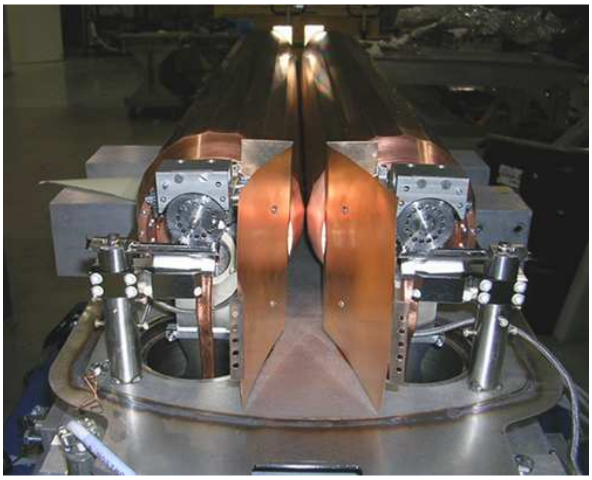

Figure 1: Photo of the upbeam, rotation drive, end of the RC before the vacuum tank cover is installed and welded.

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chanical shock during transport to CERN caused the claw actuator to change position.

The collimator uses the same stepping motor drive system as the installed LHC Phase I collimators. Motors A&C on the upbeam and downbeam corners of the left (beam's eye view) and right (B&D) collimator jaws translate each corner independently. The upbeam and downbeam jaw gaps are noted as AB and CD, respectively. The rotation actuator engages the drive wheel only when a jaw is rotated beyond any position where it may be used in normal operation (>5mm past the beamline).

QUALIFICATION TESTS DONE AT SLAC

As described in the earlier references [1]-[3], when the collimator jaws are to be mounted for the final time on their supports, each cooling tube stub is given a 90° bend so that it can project through and be brazed to a copper vacuum feedthroughs at the base of the bellows that is driven by the stepping motor system. The tube winding has been arranged so that each tube end leaves the mandrel at the end of the jaw opposite to where it exits via the feedthrough. The resulting $\sim$1m of free length, carried in the hollow mandrel support cylinder, provides the flexibility to allow the copper tube to twist the 360° required to expose each of the 20 jaw facets to beam.

Before the tubes were so constrained, the rotation drive mechanism was qualified and RF foil contact resistance measured. After verifying that each jaw could freely rotate without friction on its bearings, and that each of the two rotation drives functioned as designed, an artificial torsional load of $\sim$30 N-m was applied and the drives retested for a facet rotation (18°) under load. Coil twisting tests indicated that this was 10x the torque required to twist 1m of tubing 1 full turn and 4x the torque required to put 4 full twists into the tube.

The two jaws of the first prototype had each been measured on a coordinate measuring machine (CMM) to verify facet flatness, angular accuracy and diameter consistency. Those installed in the second prototype had flatness and diameter verified on a granite table with dial indicators. After setting the upper facets to be parallel, it was verified that the facets facing the beam were also parallel for each rotational position of the jaws. As the jaws were rotated, a 4-wire resistance bridge was used to verify that the contact resistance between each end of each BeCu foil and the jaw surface was 1-2 mOhm. Before sealing the collimator in its vacuum tank a CMM measured the jaw positions relative to external tooling balls.

For this prototype, two $\sim$2cm wide 2mm thick flanges had been welded to the vacuum baseplate and to the cylinder shaped vacuum cover. Welding was first mechanically simulated by clamping these flanges together. Upbeam-to-downbeam foil resistance and length, thermistor functionality, and proper movement of the foils during the rotation operation were verified; these tests led to the installation of the height adjustment system for the actuator. Any redesign of the RC should include a simpler rotation drive with larger gears, less gear reduction and an angular readback of each jaws angle.

The vacuum seal was achieved by edge welding the two wide flat flanges together and by brazing the copper water cooling tubes to their feedthroughs. The edge weld can be easily ground away if access to the tank interior is later desired; the flange is wide enough that several rewelds are possible. Vacuum processing included leak testing, the finding and sealing of several pinhole leaks and, in lieu of baking, several hours of cleaning with O_2 and H_2 plasmas. The end vacuum result showed an acceptable Residual Gas Analysis (RGA) scan and 3E-8 Torr at the RGA input.

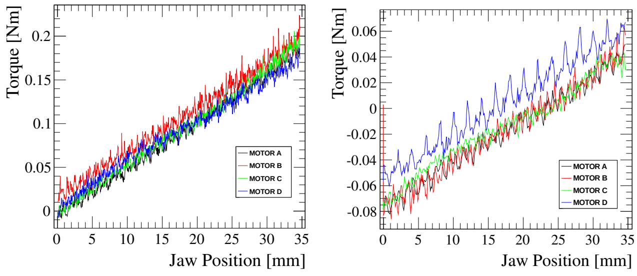
A correct full facet rotation of each jaw was verified after the tank was welded and a second full facet test rotation of each jaw was verified in vacuum. Given the damage to the cooling tubes seen in the first prototype, each tube was leak checked after every assembly procedure of this device. No leak could be seen at the 1E-13 torr-l/sec sensitivity of the tester. LHC-style water fittings were brazed to the tube ends and flow and pressure tests made. At 3.5 bar operating pressure, flow is 8l/min with a pressure drop of 2.8bar. Each tube was subjected to a static pressure test of 24 bar. Finally, the tubes were blown try and again leak tested. ABS plastic parts from a 3D printer, to block the jaws for air transport, were made, cleaned, vacuum pumped, wrapped in foil, and blocked in place to prevent jaw movement during air transport to CERN.

QUALIFICATION TESTS DONE AT CERN

The rotatable collimator was received from SLAC in an overall good state. Indeed, a first inspection of the barely opened collimator only revealed some scratches and some dust due to the friction between the packing pieces and the jaws. Later on, a torn RF foil due to excessively tightened anti-buckling fixations was also found. Thus, a cleaning of the collimator preceded qualification tests similar to those done for standard collimator before installation in the LHC.

Leak-tightness tests

The leak-tightness test consists of two steps: during a first step, a pumping system creates a vacuum inside the collimator after which, in a second step, some nitrogen in sprayed locally around the sensitive parts of the collimator in order to check for an eventual leak. This test is usually carried out right before the bake-out and residual gas analysis test but it was decided to anticipate it in order to further assess the collimator's good condition and at the same time take advantage of it to test some spare parts (mainly spare flanges) that had been shipped separately from the collimator. Thus several possible configurations of the collimator were tested. The 6" plain flanges were replaced by some BPM flanges that were installed with some helicoflex® seals and the collimator was tested with two types of 2.75" flanges: plain flanges and windowed flanges. Both configurations succeeded the tests as no leak was detected and they both reached a vacuum level in the order of



(a) Static torque (b) Dynamic torque (IN to OUT)

Figure 2: Static and dynamic torque measurements for the four jaw motors.

1.0×10^{-9} mbar. Finally the configuration with windowed flanges was selected for the later bake-out and out-gassing test as it is the favourite candidate for the installation.

RF impedance tests

A first series of impedance tests were then performed. The collimator was measured with single wire and probe measurements. Although the results are only preliminary, the observed modes (between 90 MHz and 200 MHz) are in good agreement with the previously computed ones [4]-[5]. A new set of measurements to better characterize these modes has been planned but not yet performed. Thus at this point it is still not possible to know whether the collimator will meet either the SPS or LHC standards for installation.

Drive mechanism tests

Several jaw translation movements were performed to measure LVDT calibration, mechanical play, and the motor torque. The collimator was connected to a controls test stand equipped with a PXI chassis. Torque measurements were done via an automatic scan procedure, and are plotted in Fig. 2. The dynamic torque was measured by performing jaw movements from the inner to the outer switches, while the static torque was measured through 50 μm jaw step movements. The maximum torque (∼0.4 Nm) compares well to the LHC requirement of 0.5 Nm [6].

Measurements of the mechanical play are shown in Fig. 3. The values compare well to the LHC specifications of 10 μm. The built-in non-linearity of the LVDTs was measured as shown in Fig. 4. The non-linearities are due to the way the internal coils are wired inside the LVDT, and is acceptable up to 0.2% over the jaw movement range. For operational purposes, a look-up table obtained from metrology measurements will be used to calibrate the LVDT readings.

In addition, in the event of a power cut to the motors, the collimator jaws are designed to automatically retract to parking positions to prevent beam damage. This was tested successfully by switching off the controls test stand connected to the collimator.

Jaw rotation tests

In the prototype, no automatic readout of the jaw rotation is available. Hence, the rotation of the wheel and number of steps executed were verified visually by lifting the RF foil. A less precise, though less invasive indication of the jaw rotation can be had by observing inscribed lines on the jaw surface, which are visible through portholes. An imaging system will be set up for beam tests to observe the rotation. At CERN, one full facet rotation of both jaws was performed successfully. The claw needed to be tightened to prevent the ratchet from missing steps mid-way through the facet rotation.

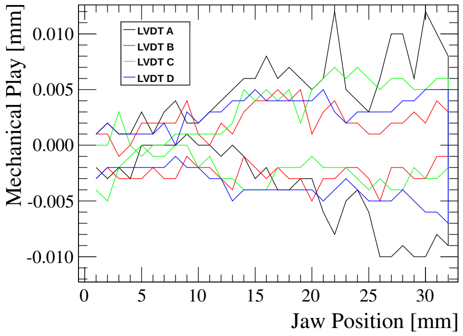
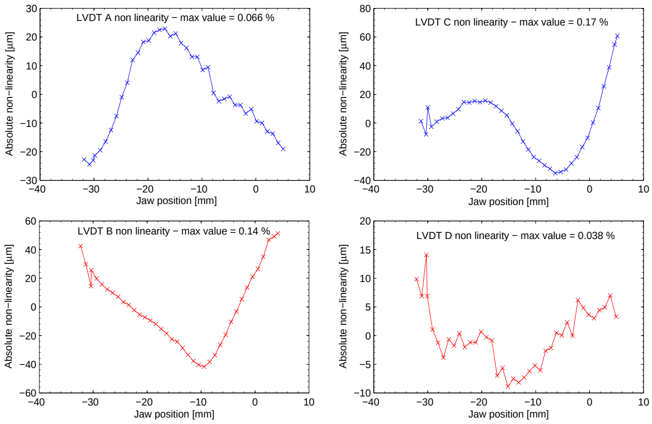


Figure 3: Mechanical play as measured by the LVDTs.



(a) Non-linearity A and B (b) Non-linearity C and D

Figure 4: Non-linearities in the LVDT measurements.

FUTURE WORK

The collimator will undergo an outgassing test cycle, including bake-out ramped up to 180^o and a slow cooldown. After bake-out, additional rotation tests will be performed, followed by metrological controls and impedance tests. Based on the outcome of the tests, a decision whether to install the collimator in the CERN SPS for alignment precision verification, impedance tests and readout from the BPMs, or at the CERN HiRadMat facility [7] for accidental beam impact tests related to LHC injection error scenarios.

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