DEVELOPMENT OF ULTRA-HIGH QUALITY SURFACE FINISH UNDULATOR VACUUM CHAMBERS FOR THE FERMI@ELETTRA PROJECT

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Abstract

The FERMI@Elettra project at the ELETTRA Laboratory of Sincrotrone Trieste (ST), currently under construction, will be comprised of a linear accelerator and two Free-Electron-Laser beamlines (FEL1, FEL2). In order to deliver high-intensity VUV and soft X-ray pulses, permanent magnet undulators with 10 mm minimum variable gap will be used. The adopted vacuum chambers will have a 7 by 25 mm^2 elliptical internal cross-section. While manufacturing the vacuum chamber in aluminum helps reducing the resistive wall wakefield effects, the chamber inner wall surface quality is strongly correlated to the surface roughness wakefield component. We report on the results of the study to improve the wall surface finish and lower the roughness periodicity. The chamber manufacturing status and its alignment mechanism is also presented.

INTRODUCTION

Fermi@Elettra is a light source linear accelerator operating two Free-Electron-Laser (FEL) beamlines covering the wavelength range from 100 nm (12 eV) to 10 nm (124 eV).

In order to reduce the resistive wall wakefields, all the undulator vacuum chambers were made of aluminum. There are three chamber lengths. The 3560 mm long chamber type is installed in the only FEL-1 modulator and in the first FEL-2 modulator. All of the eight FEL-1 radiators and nine of the eleven FEL-2 radiators mount a 2732 mm long chamber type. The third chamber type, 2550 mm long, is installed in the second FEL-2 modulator and in one of the FEL-2 radiators. All three vacuum chamber types share the same elliptical internal cross section, 25 mm wide and 7 mm high. The minimum chamber wall thickness is 1 mm. The overall chamber cross section is 320 mm wide and 15 mm high at its supports.

The surface roughness wakefield component can be minimized by achieving the best possible surface finish within the chamber aperture. Given the parameter [1]

$$AR = \frac{\text{roughness wavelength}}{\text{roughness max peak}} \qquad (1)$$

in the hypothesis of a sinusoidal surface roughness profile and for a medium electron bunch length, AR must be greater or equal to 80.

Under the same hypothesis, the root mean squared surface profile derivative Z'_{RMS} in the longitudinal direction (i.e. the electron beam direction) can be expressed as

$$Z'_{RMS} = \frac{\pi}{AR} \qquad (2)$$

Hence, for $AR \geq 80$ we have that $Z'_{RMS} \leq 40$ mrad.

For a generic surface finish, though no mathematical relation exists between Z'_{RMS} and the average surface roughness R_A, experience suggests that values of R_A ~160 nm are a good indication that equation (2) is likely met. Incidentally, a high quality surface finish reduces the residual outgassing and improves vacuum inside the chamber. This is particularly important in our case, with a close to zero conductance and ion pumps located only in the intra-undulator sections, i.e. spaced about 4 meters apart.

The chambers were produced by extrusion and abrasive flow polishing was applied to meet the surface specifications given by equation (2). The manufacturing steps, the cleaning, the vacuum performance and the chamber alignment system are presented.

MANUFACTURING

Abrasive flow polishing (AFP) is a standard industrial process commonly used with a maximum depth-to-aperture ratio of about 8 to 1. Others [2] have successfully applied the abrasive flow polishing technique improving such process to ~700/1 depth-to-aperture ratios, though with very long flowing times (~50 hours).

Starting from a more favorable depth-to-aperture ratio (~600/1), our goal was to make the process more cost effective reducing the polishing times. Clearly that also had a beneficial effect on procuring times.

Aluminum 6060-T6 was chosen for its very good extrudability and good weldability.

Extrusion

The extrusion die (see Fig. 1) was polished to a mirror-finish surface (R_A~300 nm). Thanks to that, prior to any polishing, the extrusions surface finish was remarkably good. The average longitudinal R_A was 304 nm and the transverse R_A was 393 nm. Z'_{RMS} averaged 64 mrad and its transverse counterpart, X'_{RMS}, was 86 mrad.

Each extrusion was made longer (4 meters) than the actual chambers in order to have extra material from both ends for sampling and inspecting the bore surface finish throughout all of the manufacturing steps. Rial Vacuum did the first preliminary roughness measurements with a profilometer. ST performed the 3D optical interferometry surface measurements at its Metrology Laboratory (using a Zygo Newview 5032, 10X) and calculated the relevant variables. The sampling area measured 1.35 mm (longitudinal) by 1.81 mm (transverse) with 5.6 µm step increment (240 x 320 matrix). Profilometer and optical interferometry measurements were in disagreement from 30 to 50%, with the former providing better, hence less conservative, results.

In order to connect the chamber to the alignment system the chamber section was designed not symmetric with respect to the beam axis (see Fig. 2). Despite the longer extrusion process development, this simplified the support system and virtually no welds were required.

Figure 1: The extrusion die.

Abrasive Flow Polishing

AFP technique was attained flowing an abrasive medium through the vacuum chamber aperture. The AFP medium was comprised of a viscoelastic polymer, the paste, plus abrasive silicon carbide grit.

The medium was flowed at a pressure of 70 bar and all operations were performed at room temperature (~20ºC), i.e. extrusions were not heated. Since the AFP was performed before machining, in order to withstand the high flow pressures the extrusion cross-section was generously oversized. Through finite element modeling, the minimum wall thickness was increased from 1 mm to 4.5 mm. Fig. 2 shows the extrusion cross-section with AFP medium flowing off the chamber bore.

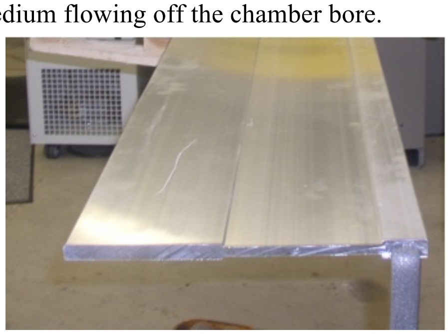

Figure 2: AFP medium flowing off the chamber bore.

A special fixture was designed to ease the connection of the extrusions to the press and to provide a better guidance to the medium flow into the chamber aperture (see Fig. 3).

The abrasive grit was used only in step 1 and step 2, passing from a coarser to a finer grain. Step 3 was accomplished flowing the paste loaded with highly-refined mineral oils, added as lubricant, and no grit. This last operation was intended for freeing up the chamber duct from the abrasive particles. Since the medium was removed by blowing high-pressure air, the abrasive particles would have damaged the polished surface causing erosion and grit embedment.

Figure 3: AFP press.

Three pre-production chambers, where step 2 was omitted (i.e. with only 160 minutes flow time and the coarser grit), were cut and accurately measured to verify the surface finish in the center of the extrusion. The average Z'_{RMS} was 24.5 mrad and R_A in the longitudinal direction was 124 nm. At the moment the production chambers have not been measured yet with the 3D optical interferometer microscope. As we have seen, profilometer measurements are too optimistic and cannot be assumed quantitatively conclusive. However, such preliminary results show a surface finish improvement of about 3 times and that is confirmed by qualitative visual checks.

Table 1 summarizes the AFP parameters. It is clear how the remarkably good surface finish attained straight from the extrusion process greatly helped reducing the AFP time.

Table 1: AFP parameters

	AFP medium	Vol. flow rate	Total flowed volume	Total flow time	Flow
STEP 1	SiC grit, size 60 EM24640	6.82 cm^3/sec	2000 in^3/side	160 min	2 cycles/ side
STEP 2	SiC grit, size 120 EM24644	11.2 cm^3/sec	1000 in^3/side	50 min	1 cycle/ side
STEP 3	Visco-elastic base P54	As necessary		5 min	one side only

Machining and welding

To achieve a higher magnetic field, the undulator pole gap is narrowed down to 10 mm. The chamber height in the bore region is 9 mm with a 500 µm clearance throughout the length between chamber and undulator magnets. It is clear that precise machining of the wall thickness was paramount to guarantee the chamber structural and vacuum integrity. In order to remove the extra material allowed for the AFP pressures, development of special milling fixtures was required. Flatness and bore symmetry were well within the 50 µm tolerance over the entire chamber length.

Rounded stress-relieving slots were cut out to allow the chamber to comply with the possible deformations induced by the alignment system (see Fig. 7). Several hole patterns for support and fiducialization purposes were machined as well.

The ConFlat® DN 40 end flanges were manually welded to the chamber body. Such bimetallic flanges, made of AISI 316L – Al 6061 T6, were provided by Atlas Technology.

Some weld samples are shown in Figure 4 and a complete undulator vacuum chamber is presented in Figure 5.

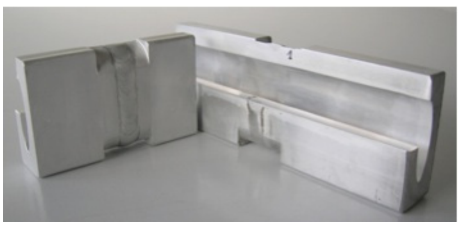

Figure 4: Weld samples.

Figure 5: An undulator UHV chamber.

CLEANING AND VACUUM PERFORMANCE

One of the challenges connected with AFP was to successfully remove all residual medium from the chamber inner wall without damaging the surface quality. Ultrasonic bathing, though universally used, is a cleaning technique posing intrinsic issues to aluminum (considerable erosion, frayed edges, surface deterioration). It was intention of the authors to avoid it.

Proper selection of the AFP paste allowed for a relatively easy removal thereof by blowing high-pressure air. The chambers were then flushed with Detersol UHV solution and high pressure rinsed with de-ionized water. Finally the chambers were purged with nitrogen gas and dried.

Given the poor chamber vacuum conductance and the aluminum outgassing levels, a test was intended in order to understand the vacuum quality at locations far from the pumping ports. After bake-out, with a 2.5 m long chamber pumped at one end by a 55 liter/sec ion pump, the pressure was 6.7×10^{-10} mbar at the pump's side and 4.5×10^{-8} mbar at the opposite end, in agreement with theoretical predictions. Room temperature was 21ºC.

Finally, RGA scans showed no mass peaks above 44 amu. The test setup is shown in Figure 6.

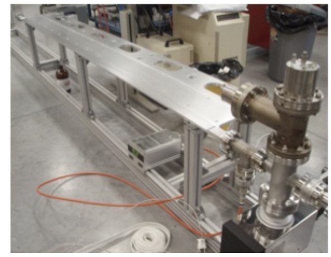

Figure 6: A chamber during RGA scan and vacuum test

THE ALIGNMENT SYSTEM

The alignment system ensures the proper chamber straightness throughout its length. Pairs of threaded rods, spaced apart 310 mm, permit the relative rotation among sections and the fine tuning of their vertical position.

The alignment system sits on a Π shaped support structure. Adjustment screws allow for longitudinal and transverse motion together with rotation around the vertical axis.

The top portion of the structure is in AISI 304 L stainless steel (SS). To reduce potential friction and material galling, bronze pads and aluminum bronze screws were used wherever SS to SS interfaces occurred.

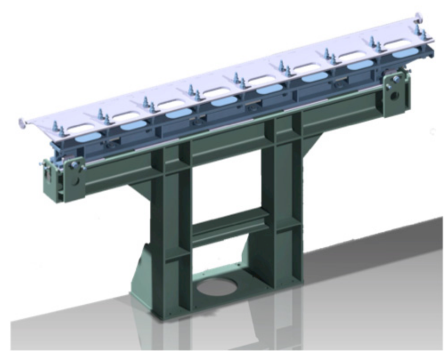

Figure 7: The alignment system.

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