Characterisation of additively manufactured synchrotron radiation absorbers for FCC-e^-e^+ manufactured by green laser based powder bed fusion

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INTRODUCTION

FCC-ee is a proposal for 92 km circumference twin ring which would generate a synchrotron radiation (SR) power of 50 MW/beam. Design studies call for the SR fan to be intercepted every ~5m with localised absorbers. Compared to the continuous design (when the synchrotron radiation absorber (SRA) channel is located all around the ring), this design is advantageous due to faster conditioning of the vacuum chambers, lower material and manufacturing costs. The proposed design uses turbulent water flow to remove generated heat. The use of additive manufacturing (AM) was chosen due to the ability to achieve complex structures in shorter time and with lower material consumption, making it ideal for SRA production.

HELIUM LEAK TIGHTNESS TEST

In order to validate a new technology for ultra-high vacuum (UHV) environments, which is present in accelerators, helium (He) leak tightness test (or equivalent) needs to be conducted. He leak tightness test uses a vacuum pump with a "sniffer" mode, which can detect specific particles (He in this case) which in fail condition penetrate through material.

The SRA needs to be fitted very tightly to the machine port and ensure cavities are sealed. Because of this they are made from known He leak tight material – usually stainless steel. The LPBF of Cu has already been tested for it and passed for detection of less than $1{\cdot}10^{-10}$ mbar·l·s^{-1} for widths of up to 0.5mm [1]. Considering the walls in contact with vacuum will be thicker the results for SRA testing should validate the design of SRA as well.

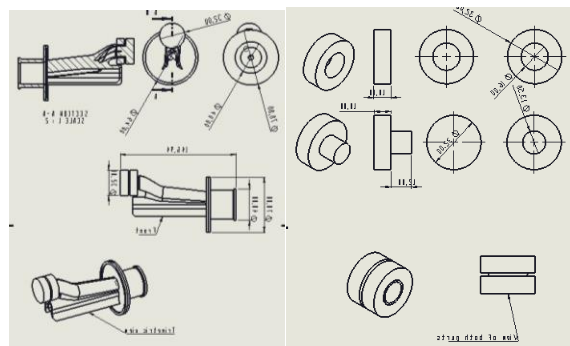

Figure 1. He leak tightness test fittings

The fittings (Figure 1) were designed using Solidworks software, considering previous designs for testing by TE-VSC team members and characteristics of the SRA.Figure 1. He leak tightness test fittings

HEAT TRANSFER TEST SETUP

The purpose of SRA is to transfer the heat from the chamber to the outside environment, therefore testing of heat transfer capabilities is essential step in the validation process. The design used for experimental setup was inspired by previous studies which aimed to experimentally confirm the results achieved theoretically [2, 3].

The setup consists of water pump connected to a water tank, through which water recirculates, ball valve, which allows to control flow rate, several thermal and pressure sensors, flow meter and the test subject. The difference in temperatures between

Figure 2. Thermal transfer test setup in progress

To verify the setup a straight copper pipe calculations was made. It used calculation formulas for both laminar and turbulent flow with speed that is equivalent to that proposed for the SRA [4, 5]. Futrther testing for verification of setup and thermal transfer tests with SRA itself are necessary.

Table 1. Experimental results of thermal transfer test with copper pipe

Flow rate l/min	Voltage, V	1	2	3	Inlet	Outlet	Speed, m/s	Mass flow rate, kg/s	h, W/m2K
20	0	27	28	29	32.6	32.8	0.701323917	3.327E-01	-1.53E+03
20	20	28	29	30	33	33.1	0.701323917	3.327E-01	-8.90E+02
10	40	30	31	32	33.4	33.5	0.350661958	1.663E-01	-7.35E+02
5.6	60	34	33	36	33.9	34.1	0.196370697	9.315E-02	6.05E+03
3.3	80	37	36	40	34.3	34.5	0.115718446	5.489E-02	3.64E+02
3.3	100	41	39	43	34.4	34.7	0.115718446	5.489E-02	2.77E+02
3.3	120	51	45	52	34.9	35.3	0.115718446	5.489E-02	1.67E+02
3.3	140	62	52	60	35.6	36.1	0.115718446	5.489E-02	1.34E+02
20	140	61	52	58	36	36.2	0.701323917	3.327E-01	3.45E+02

DENSITY TESTING

Density is an important feature of material, especially during AM material evaluation. The density of AM material ideally should be 100% of the conventionally manufactured material. The higher density means material does not posses internal flaws such as pores and cavities, which can compromise the integrity of finished part [6, 7].

For density testing several variants of Archimedes density testing method were used. First a Mettler Toledo analytical scale and when a precise volumetric flask and scale (Figure 3). The results were confirmed by measuring a piece of traditionally manufactured copper.

The results were consistent with previous tests for LPBF Cu and showed increased density to previous trials [8, 9, 10]. It is likely that the fluids penetrated into the pores and thus showed the density of copper and not the density of the cube. This is why the numbers obtained using water are likely more accurate.

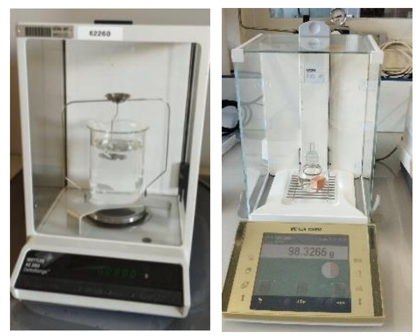

Figure 3. Left - analytical scale, right - volumetric flask

Table 2. Density testing with water/

Sample	Trial	Air,g	Water, g	Density calculated, g/cm^3	Density percentage of pure copper, %
1	1	11,0646	9,7868	8,62	96,43
1	2	11,0637	9,7882	8,64	96,61
1	3	11,0633	9,7821	8,60	96,18
	Average	11,0639	9,7857	8,62	96,41
2	1	10,8750	9,6105	8,56	95,78
2	2	10,8764	9,6140	8,58	95,96
2	3	10,8743	9,6100	8,56	95,80
	Average	10,8752	9,6115	8,57	95,85
3	1	10,7441	9,5141	8,70	97,28
3	2	10,7437	9,5170	8,72	97,55
3	3	10,7429	9,5143	8,71	97,40
	Average	10,7436	9,5151	8,71	97,41

4	1	11,0396	9,7655	8,62	96,47
4	2	11,0392	9,7751	8,70	97,26
4	3	11,0388	9,7644	8,63	96,48
	Average	11,0392	9,7683	8,65	96,74
Total average				8,64	96,60

Table 3. Density testing with ethanol

Sample	Trial	Air, g	Ethanol, g	Density calculated, g/cm^3	Density percentage of pure copper, %
1	1	11,0651	10,0860	8,87	99,26
1	2	11,0648	10,0867	8,87	99,24
1	3	11,0647	10,0855	8,86	99,13
	Average	11,0649	10,0861	8,8696	99,2125
2	1	10,8762	9,9048	8,79	98,34
2	2	10,8760	9,9038	8,77	98,14
2	3	10,8758	9,9041	8,78	98,19
	Average	10,8760	9,9042	8,7813	98,2250
3	1	10,7443	9,7971	8,91	99,63
3	2	10,7441	9,7962	8,89	99,44
3	3	10,7440	9,7956	8,89	99,39
	Average	10,7441	9,7963	8,8939	99,4841
4	1	11,0406	10,0577	8,81	98,59
4	2	11,0404	10,0563	8,79	98,36
4	3	11,0403	10,0566	8,80	98,40
	Average	11,0404	10,0569	8,8015	98,4510
Total average					98,84
Cu	1	6,4258	5,8620	8,95	100,10
Cu	2	6,4256	5,8624	8,95	100,14
Cu	3	6,4256	5,8623	8,95	100,13
	Average	6,4257	5,8622	8,95	100,12

HARDNESS TESTING

Material hardness is a good indicator of other mechanical characteristics of a material, thus testing material hardness can be a good way to evaluate a material [6]. The hardness test for cuboid AM Cu samples was done twice. The first trial was unsuccessful due to the high roughness of surface which did not allow to measure the indentations correctly (see Figure 4).

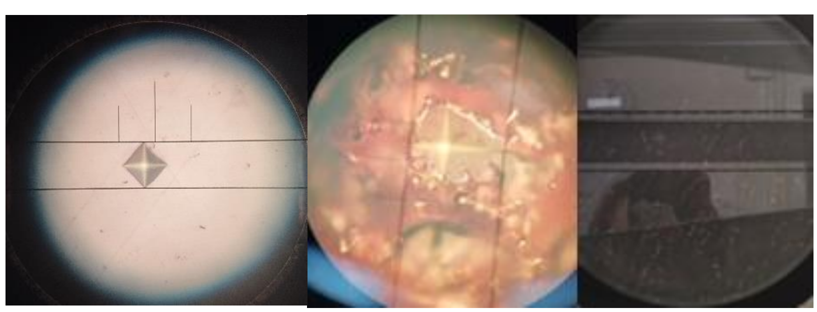

Figure 4. Left - micro hardness test, Middle – unsuccessful test due to uneven axis, right – unsuccessful test due to lighting being insufficient for rough surface

2nd trial was conducted after sample was cast in resin and polished. measurements were taken with Micro-hardness Tester 402 MVD Zwick Roell (10 gf - 2 kgf) with 0.1kgf setting. The values of copper hardness vary (60-120 HV0.1) depending on treatment. 72 HV0.1 is similar to cold worked 1/8 hard 10100 copper [11]. It should be noted that previous studies found similar results, and that it is likely that increase in hardness could be observed using bigger loads due to stress created by surface deformation during indentation process [6, 12].

Table 4. Hardness testing results

No.	Top	Side
1	70,4	73,8
2	67,7	69,2
3	75,2	59,4
4	69,2	60,4
5	73,0	80,5
6	71,1	78,1
7	71,8	74,9
8	71,4	74,3
9	71,2	73,4
10	72,0	72,5
11	72,4	72,3
12	69,9	71,1
13	75,3	80,6
14	70,8	76,7
15	71,0	74,3
Average	71,5	72,8
SD	1,9	5,9
Range	7,6	21,2
Mean	71,2	73,8

3D SCANNING

The 3D scan of the part was done by J. P. RIGOULD (EN/MME/MM) and the report can be found in EDMS 2924563 [13]. The scan was done using Handy SCAN BLACK ELITE CREAFORM scanner. The conformity analysis was done using GOM Inspect software. For fitting the distance selected was chosen as 20mm due to many artifacts present in file. The 3D scan was able to measure the outside surface topology, however the inner surface measurement was very rough. There are missing sections where scanner was not able to reach and form complete image. The 3D scan confirms the visual analysis – the sharp and rough edges can be seen very clearly. Majority of the surface falls within 0.3 mm of deviation (see histogram in Figure 5).

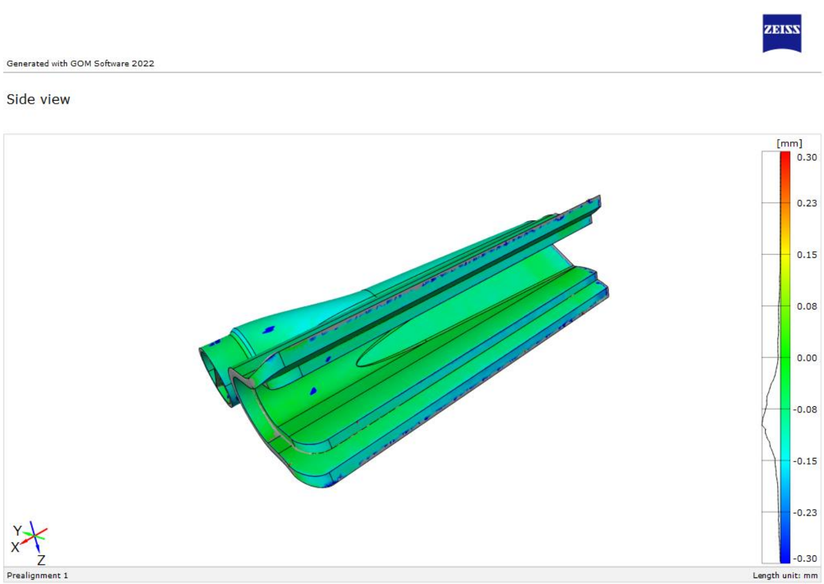

Figure 5. 3D scan and CAD comparison

OTHER TESTS

In addition to tests which were performed by author, other measurements were done by EN-MME sections. Their results can be found in EDMS files:

- Micro computed tomography test EDMS 2931607 – found that the channel vein is intact.
- Roughness measurement EDMS 2924563 – the manufactured part in deviates on average around 0.3 mm, average roughness is 18 µm.
- Tensile and SEM tests EDMS 2922640 - the yield strength is 100 MPa and Young's modulus is 137, GPa, material exhibits properties consistent with as built AM process.

CONCLUSIONS

- The AM process produced a part, which reflects CAD geometry within approximately 0.3mm according to 3D scan inspection. CT scan verified the inner vein is approximately 0.5mm in width. Shrinkage is seen, thus this should be accounted for when preparing blueprints for manufacturing.
- The tested Cu samples have yield strength of 100 MPa, which is below that required of design, and similar to 1/8 hardened copper, this is consistent with other mechanical characteristics and to the measured hardness of approximately 72HV0.1.
- The piece exhibits high density >95%, which decreases the risks of mechanical failures during exploitation.
- He leak testing and thermal transfer tests will be undertaken to validate the part for UHV environment and to determine it's heat transfer capabilities, which are essential parts for fully evaluating the design and manufacturing method of the part.
- Final decision about design and manufacturing method cannot be made until all tests are finished.

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