Construction concepts and validation of the 3D printed UST_2 modular stellarator

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Abstract. High accuracy, geometric complexity and thus high cost of stellarators tend to hinder the advance of stellarator research. Nowadays, new manufacturing methods might be developed for the production of small and middle-size stellarators. The methods should demonstrate advantages with respect common fabrication methods, like casting, cutting, forging and welding, for the construction of advanced highly convoluted modular stellarators. UST_2 is a small modular three period quasi-isodynamic stellarator of major radius 0.26 m and plasma volume 10 litres being currently built to validate additive manufacturing (3D printing) for stellarator construction. The modular coils are wound in grooves defined on six 3D printed half period frames designed as light truss structures filled by a strong filler. A geometrically simple assembling configuration has been concocted for UST_2 so as to try to lower the cost of the device while keeping the positioning accuracy of the different elements. The paper summarizes the construction and assembling concepts developed, the devised positioning methodology, the design of the coil frames and positioning elements and, an initial validation of the assembling of the components.

1. Introduction
Advanced stellarators are geometrically complex and simultaneously require high accuracy. Such requirements imply difficulties during fabrication and assembly, resulting high cost and long fabrication periods. The development of new enhanced manufacturing methods and assembling configurations may contribute to accelerate the advance of the stellarator research line.

Additive manufacturing is becoming cost-effective for direct final manufacturing of relatively small, geometrically complex parts when few identical items or single customized items are required. Fusion devices, particularly stellarators, are suited to such conditions, except for the size. Therefore, developing and validating 3D printing methods, particularly developed for fusion device manufacturing, may be useful. The use of additive manufacturing for stellarators has been previously proposed, [1].

Moreover, assembling and positioning the different stellarator components last long, contributing to the final cost and long construction period. The development of improved simpler positioning methods is essential for a faster assembling of advanced highly convoluted modular stellarators.

In this framework, the paper describes the construction concepts developed and the devised positioning methodology applied to the manufacturing of the UST_2 modular stellarator.

UST_2 is a small modular three period quasi-isodynamic stellarator based on the last closed flux surface (LCFS) of an optimised Quasi-isodynamic stellarator of 3 periods, [2]. The original LCFS is modified to obtain some enhanced engineering features. The torsion of the LCFS at the middle of the 3 straight mirror sections of the stellarator is eliminated and the torsion is increased in the remaining
sections. A re-optimization process is carried out, starting from the original optimized magnetic configuration [2], to keep a reasonable neoclassical confinement, magnetic well in vacuum and lack of islands from low order rationals. Therefore, the coils at the middle of the straight mirror sections can be designed as non-circular planar coils and located far from the plasma, figure 1. Thus, the straight sections of the stellarator may contain wide ports for easy, fast and wide in-vessel access, and large volume for possible future divertors. The system is a combination of concepts somewhat similar to the ones proposed in Refs. [3].

Figure 1. Concept and design of UST_2 stellarator.

A combination of 3D printing and moulding is used for the construction of the coil frames. The coil frames (figure 1 and figure 2) are the structures supporting the convoluted coils of the stellarator. The 3D printed piece for each coil frame is designed as a truss structure enclosed in a thin external surface. The internal volume of the 3D printed piece is filled with a material able to solidify, like resin or a low melting point metallic alloy. This method reduces 3D printed costs and increases the strength of the component. The method is currently applicable to small stellarators since large and accurate 3D printers are unavailable. However, it may be applicable to middle size or large stellarators in a next future.

The work is the continuation of the study and development of construction methods applied for UST_1 stellarator. UST_1 is a small stellarator designed and built by the author by a special toroidal milling machine developed on purpose, [4].

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2. Coil frame construction concept
Each coil frame (figure 2) of the stellarator is devised as a 3D printed light hollow structure filled with a material able to solidify.
The 3D printed hollow structure is defined as a truss structure covered by a 3D printed thin closed surface equipped with upper filling openings (figure 3) for fast and easy filling process. Four curved beams (figure 3) define the edges of each winding pack and are parallel to the respective filamentary coil definition. The thin external surface envelops the curved beams to generate twisted grooves where the copper conductor is wound. Reinforcement bars are defined among the curved beams of the same coil and of consecutive coils. The result is a complex three-dimensional structure automatically generated by a VisualBasic Automation code for CATIA. The coil frame is divided in two halves to allow the introduction of the vacuum vessel in the coil frame. Legs are also part of the 3D printed piece in order to simplify the assembling process. Legs are designed to rest on horizontal surfaces located at different heights.

Diverse materials may be used as fillers depending on the design requirements, i.e. casting resins (epoxy, acrylic, polyurethane, etc.), fibre reinforced casting resins, low melting point alloys, type III or IV hard plasters, or fibre reinforced cements and plasters. The hollow volume is designed to allow satisfactory gravity flow of the filler as in conventional moulding or reinforced concrete buildings. The 3D printed hollow structure, acting as a mould, remains as part of the final component since the pieces are geometrically complex and only one or few identical items are produced of each piece. Producing and manipulating a mould that would allow extraction of such complex pieces would result more expensive. Consequently, the still costly 3D printing material and process is minimised and the strength of the component is supplied by the relatively low cost strong filler.
3. Assembling and positioning concepts

A series of coil frames are assembled contiguous (figure 1) and located on a mechanised circular base to form a full toroidal coil frame. All the coil frames of the torus are identical due to stellarator symmetry on condition that the legs are located both at the top and at the bottom of the coil frame, figure 2. One halfperiod coil frame of a stellarator period is rotated 180° with respect a horizontal axis and located on the respective legs to achieve stellarator symmetry, figure 6.

The positioning strategy for UST_2 coil frames is somewhat similar to the remote handling techniques used in JET and ITER. Thus, the assembling is fast but UST_2 is assembled hands-on. The inboard of the coil frame is equipped with two 3D printed positioning stops, figure 4. The stops contact on a central circular ring located in the central torus hole at the equatorial plane of the stellarator. Each coil frame is located on two tables (figure 2) of different height so as to accommodate the large vertical excursion of the magnetic axis of UST_2. Each table is formed by two flat trapezoidal horizontal plates located at the top and at the bottom of the table legs. Each table lays on a flat smooth circular base of slightly larger diameter than the external diameter of the torus, figure 1. The circular base is free of obstacles hindering the horizontal movement of the tables on the base. The coil frame, located on two contiguous tables, moves freely on the circular base until the positioning stops contact with the central circular ring. At this position, the coil frame has only one turning degree of freedom defined by the stops on the central circular ring. The position of the each coil frame is finally completely defined when all the coil frames are located around the central circular ring by successive horizontal movement of the coil frames. This assembling procedure is facilitated if straight mirror sections and planar coils between periods are designed, as in UST_2 stellarator.

Several particular features are implemented for UST_2. The central circular ring (figure 4) is formed by several bolted pieces to allow the vertical extraction of the central ring to facilitate inboard access on the coil frames. The central ring contains three positioning extensions since UST_2 is a 3 period stellarator, and it has two different diameters because the UST_2 magnetic axis viewed from the top is triangular, very different from a circle. One positioning stop contacts with the larger diameter circle of the circular ring and the other stop contacts with the smaller circle.
4. Validation of the construction and assembling

Several components of the stellarator have been produced. Two halfperiod coil frames have been 3D printed and one has been filled with resin. The base and the central circular ring have been respectively milled and laser cut. The central circular ring has been installed on a provisional base. The vacuum vessel is still being designed and tested.

4.1. Construction and assembly of the coil frame

The first halfperiod coil frame has been produced in the company Shapeways by Selective Laser Sintering in Polyamide 12. Polyamide 12, a type of nylon, has reasonable mechanical properties and relatively low cost for Selective Laser Sintering. Tensile strength is 46 MPa and deflection temperature 177 °C. Selective Laser Sintering has been selected against Fused Deposition Modeling (FDM). FDM is less appropriate for very hollow pieces since the abundant support material required must be printed and extracted from the interior of the piece. The cost in such cases is higher than for SLS. The SLS manufacturing cost of one UST_2 halfperiod was 700 €. Many holes of 6 and 3 mm diameter (figure 2) are designed on the external surface of the coil frame in order to allow the extraction of the nylon powder from the inside of the hollow piece. The laser melting process of the SLS manufacturing method tend to produce thermal warping. The two halves of each coil frame are 3D printed as a sole piece joined by small bars which are cut after filling both halves with the filler material. This strategy reduces the thermal warping.

Twenty small specimens 3x1.5x0.6 cm have been tested: hard plasters (Exaduro and Duro-6 plaster brands from Hëbor), cement, epoxy casting resin, polyurethane casting resin, glass fibre reinforced polyurethane resin, pita fibre reinforced hard plaster (Exaduro plaster). Viscosity, moulding operation simplicity and speed, fracture bending strength and effect of fibre reinforcement were compared. Casting acrylic resin moulds easier (less leaks, tools cleaned with water) than epoxy and polyurethane casting resins and it was selected to mould the first halfperiod coil frame. The first halfperiod of UST_2 stellarator was gravity filled with acrylic resin, brand Jesmonite, type ACw300. The tensile strength of this resin is 20 - 25 MPa and the expansion on set 0.15%. Expansion on set is low and it was favorable since the 3D printed piece resulted slightly smaller than designed. The small bars joining the two halves of the coil frame were cut after settling.

4.2. Results from the construction of the coil frame
The deviation between the drawing dimensions and the real dimensions is lower than 0.3%. The deviation among different coil frames would be lower than 0.3% if the same 3D printer and position of the piece were used. 0.1-0.2% deviation among coil frames might be achieved. Therefore, Selective Laser Sintering with Polyamide 12 is preliminarily considered satisfactory for small stellarator construction.

Nylon powder remained in the legs and other nooks inside the first 3D printed halfperiod. The powder was removed by drilling new holes on the surface of the halfperiod and using air compressed to extract the powder. Holes were added to the design where needed and the second 3D printed halfperiod did not contain internal nylon powders. Internal remaining nylon powders are undesirable since the casting resin does not fill the whole internal volume and strength is lower.

Moulding the halfperiod coil frame was easy and fast. Filling the 3D printing piece lasted only 5 minutes. However, preparation of the 3D printed piece, tools and resin, and final cleaning of the components lasted about 2 hours. Preparation the 3D printed piece includes closing the powder extraction holes, leak testing of the closed volume to prevent resin leaks and, attaching the filler feeding basin to the filling openings, figure 5.

Figure 5. 3D printed coil frame prepared for moulding with resin

4.3. Results from the assembly

Figure 6 shows the current assembly status. The base is still the pre-assembling base though the definitive base has been mechanised and received. Collisions among components have not been found. Bolting standard bolts for all the coil frame legs was feasible and simple for most of the bolts. Bolting the bolts for the short table (figure 6) was more difficult than for the tall table, as expected, but the table design allowed bolting from the inside of the table. The distance between the positioning stops and the central circular ring (figure 4), at design position, has not been accurately measured since the base is not the definitive one. Coplanarity of the two or three legs corresponding to the same horizontal level is acceptable. Before moulding with resin, slight thermal warping of the coil frame legs was observed. Shim gauges of 0.2 mm can be inserted among certain coil frame legs and the table. This issue can be partially corrected if the leg bolts are attached to the moulding base (figure 5) while moulding. On the whole, the assembly of the central circular ring, tables and the two halfperiods have been satisfactory and the same design will be kept for the two remaining periods.
5. Results and conclusions

Additive manufacturing combined with moulding for the construction of fusion components has been conceived and tested. Coil frames for UST_2 stellarator are being produced to validate the construction methods developed. Each coil frame is devised as a 3D printed light hollow structure filled with a material able to solidify. The hollow structure is conceived as a truss structure covered by a 3D printed thin closed external envelop surface.

One coil frame has been moulded with acrylic resin. Filling the internal hollow volume of the coil frame with the filler was satisfactory. The issue of remaining nylon powder inside the hollow volume of the coil frame was solved for the second 3D printed halfperiod. Resin leaks did not occur.

The use of the still expensive 3D printing material is minimised, resulting a 3D printing cost for one UST_2 halfperiod of 700 €.

The assembly of UST_2 coil frames corresponding to one stellarator period has been feasible, simple and fast. The validation of the full stellarator assembly still remains.

Completion of the vacuum vessel and two periods remains for a future work.

The construction of small stellarators by 3D printing appears feasible. The feasibility will be determined by e-beam field mapping experiments after completion of the construction.

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