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New concept for cryogenic gaseous hydrogen-cooled lightweight electric engine

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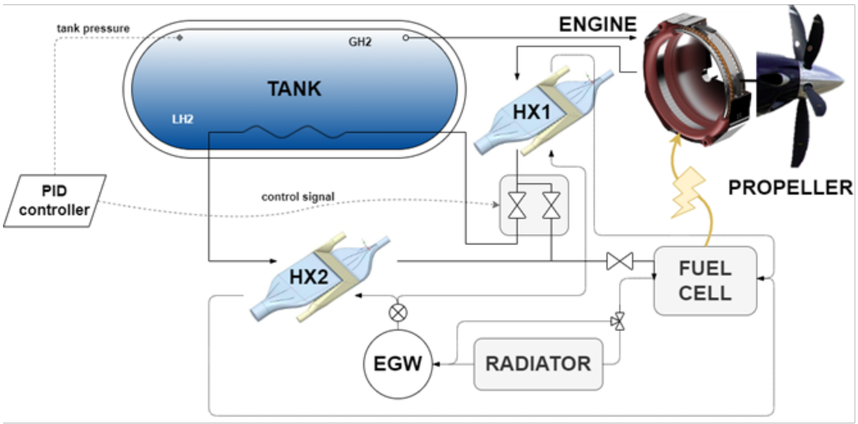
Abstract. This paper presents parts of the engineering design process and the resulting concept for an electric engine for aviation purpose. Based on the requirement classes mentioned in [1], the concrete requirements resulting from flight operation and the approach of cooling with cryogenic gaseous hydrogen are first compiled. Then, the selected electrical concept of a 500 kW engine is presented, which serves as a basis for identifying the required components and their arrangement. Compared to conventional electric motors, additional components are required. These include hollow coils, structures to distribute the cold gaseous hydrogen to the coils and elements to support the stator laminations with the coils. Materials are then selected for these components with the aim of minimizing weight, and their geometries are predimensioned using analytical approaches and numerical methods. Finally, the individual concepts are synthesized into an overall concept. The result is a compact design for a cryogenically cooled electric motor with a power density of more than 10 kW/kg and a mass of less than 50 kg.

1. Introduction and concept of the powertrain

Electric propulsion is one way of making low emission flying possible. To do so, they must be particularly lightweight and have a high efficiency, at least as good as current systems such as gas turbines or turboprop engines. To reduce the impact of global transport on the environment and pollutant emissions, a revision of current systems is necessary and expedient. Because of its high energy density, cryogenic liquid hydrogen can be used in combination with fuel cells both as an efficient supplier of energy and for effective cooling of the electric motor. The development of this system concept is the subject of the "AdHyBau" research project, of which the authors are part of the consortium. The basic system architecture of the hybrid electric powertrain was presented by partners here [1]. A DAHER TBM850 was used as a reference. This application scenario results in extremely different temperatures in different areas of the electric motor at different operating points. In addition, electrical contact and the flow of gaseous hydrogen pose special challenges. Not to be forgotten are the mechanical demands on the motor in terms of power, torque and speed. After the development of the concept for the rotor was presented here [2], the development of the concept for the stator is discussed here.

The concept of the powertrain is displayed in Figure 1. The liquid hydrogen in the tank will be heated to become gaseous and to get pressure into the system. The gaseous hydrogen flows with about 35 K into the motor, came out heated up depending on engine power between 240 and 325 K. Now the gaseous flows into the first heat exchanger (HX1). Here he will warm up to 300 K, when the temperature is too low. In this condition it will partially be used for heating the tank further and for electrolysis in the fuel cell. The hydrogen that was used for further heating of the tank will go after that into a second heat exchanger (HX2) to get heated up again to 300 K and goes then also into the fuel cell. A second circuit of ethylene glycol water mixture, a radiator and a controller manage the temperatures of the hydrogen circuit and can be used for cooling of additional electrical devices, like the controller of the motor.



electric propulsion engine	
Total mass	50 kg
Nominal power	500 kW
Max. torque	2000 Nm
Max. speed	3000 rpm

LH2 Liquid hydrogen
GH2 Gaseous hydrogen
HX Heat exchanger
EGW Ethylene glycol water mixture

Figure 1. Concept of hybrid-electric powertrain (left); main data of the motor (right)

The key facts of the motor are displayed in Figure 1 on the right side. The goal is, to achieve a total mass for the motor of 50 kg, a nominal power of 500 kW with a maximum torque of 2000 Nm and a maximum speed of 3000 rpm.

2. Concept of the stator

To develop the concept of the stator of the motor, the same procedure was used like in [2]. The start were the same mandatory requirements like for the rotor. The variable requirements are slightly different, because the stator will be more complex, due to the hydrogen circuit and the wider range of operating temperatures. There were also evaluated in an AHP-matrix. The results are displayed in Table 1. The main important variable requirement here is low mass with a value of 40 percent.

Table 1. Variable requirements, evaluated

Variable requirement	Value
Low mass	40%
Manufacturing effort	27%
Service life	13%
Low volume	11%
Time-to-market	9%

The electrical design is made by SIEMENS. The motor is a permanently excited synchronous machine with an operating voltage of 1500 V, 78 Coils in the stator and 52 magnets in the rotor. The outer diameter of the sheet metal package of the stator is 560 mm and its length measures 50 mm. The air gap between stator and rotor is 3 mm at room temperature. The allowed minimum is 1 mm.

The area classification begins with the known parts from the electric design. It's pictured in Figure 2. The main parts of the stator are the sheet metal package made from iron and the coils made from copper. They are the sources for heat. So, they were designed hollow, to guide the cryogenic gaseous hydrogen through the coils. To shorten the path through the coil, we put the intake in the middle of the coil and then the two outtakes at their ends. At the ends are also the electrical connections of the coil (see the little yellow arrow in the figure). To get the hydrogen to the coils and away from them, distributors are needed. On the cold distributor also, a thermal insulation is placed. For the joints between the Coils and the distributors, a kind of coupling is necessary. For mounting these parts and the bearing of the rotor, a housing structure is used. It also provides the mounting to the aircraft. Finally, a cover on the open side will be installed.

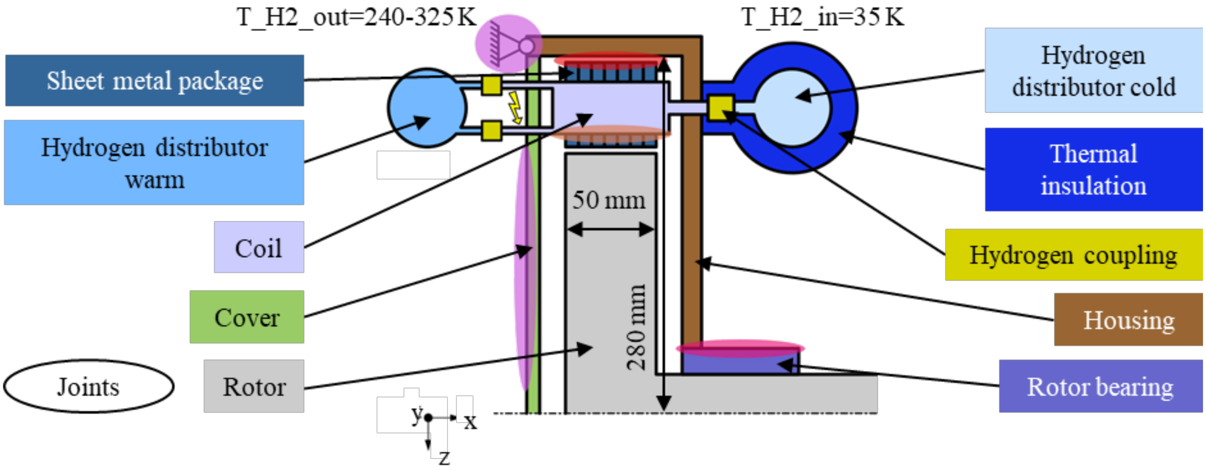


Figure 2. Concept of the motor, detailed rotor design is shown in [2]

3. Concepts for several components of the motor

In this part of the paper, two examples for some single parts were described. First example is a component. The second example is one of the joints between two components.

3.1. Hydrogen coupling

The first example is the hydrogen coupling. The main requirement is to get a sealed joint for cryogenic gaseous hydrogen. The second requirement is an electrical insulation, because the hydrogen distributor will be made from titanium with additive manufacturing, and a short circuit between the coils must be avoided. The large number of connections and that there is only a little space for assembly, because the single coils are very close to each other, are challenging. Commercial products like the isolators from CERAMTEC don't match with all of the requirements [3]. The concepts are drawn in Figure 3.

The first concept (Figure 3, left) is to overmold the two connectors and an electric insolation with thermoplastic material in a moveable mold, maybe with HDPE or PP. Due to the higher thermal expansion coefficient of the plastic compared to titanium and copper, the contact pressure of the sealing could raise during the cooling with the hydrogen and supports the sealing.

The second concept (Figure 3, middle) is like a screwed connection from SWAGELOK® [4], but smaller and with an electric insulation inside. For this concept it is necessary that the nut (dark blue color) and the first sealing (light yellow color) is placed on tubular connector from the hydrogen distributor (light blue color) before is later connected to the distributor due to the undercut.

The third concept (Figure 3, right) have an elastomeric element between the two connectors for sealing and insulation [5]. A metallic sleeve will be placed around and squeezed for contact pressure to support the sealing.

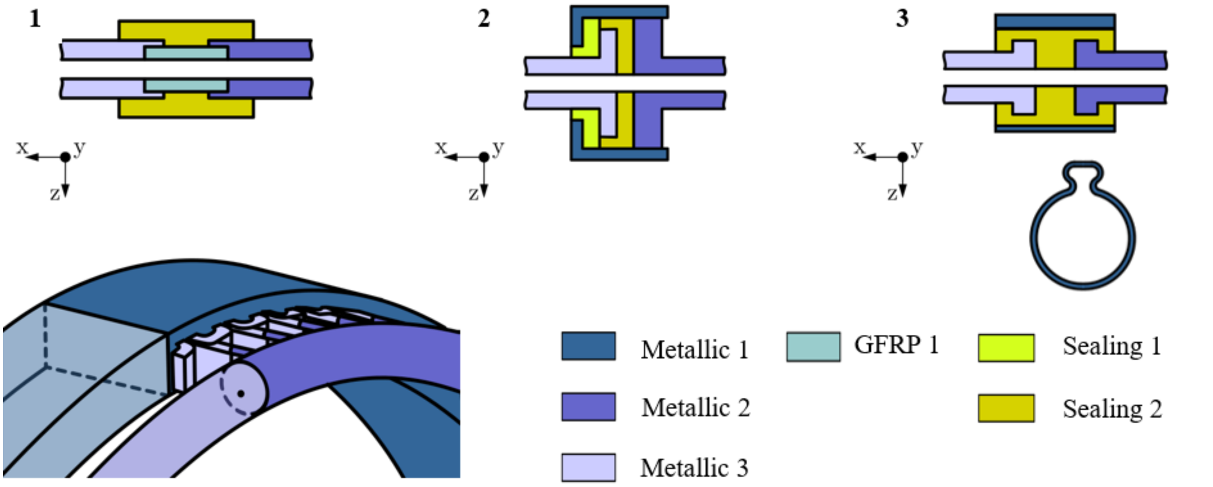


Figure 3. Concepts for the hydrogen coupling

To get a basic measurement for electrical safe distances between the two connectors the Paschen's law is used [6]. For hydrogen atmosphere and a maximum pressure of 10 bar, 0,24 mm should be necessary. For a better handling and with a safety factor of 4, 1 mm distance is chosen. For calculation of permeation, an allowable permeation rate of 4,6 ml/(h*L) and formulas for the length of permeation paths are assumed by [7]. For LDPE 0,43 mm and for PP 1,78 mm were calculated. In Table 2, the evaluation of the concepts is displayed.

Table 2. Evaluated concepts for the hydrogen coupling (bigger values are better)

Variable requirement	Value [%]	Concept 1	Concept 1	**Concept 3**
Low mass	40	7,5	4,3	**10,0**
Manufacturing effort	27	8	1	**10**
Service life	13	0	10	**5**
Low volume	11	10	10	**10**
Time-to-market	9	10	10	**5**
Sum	100	7,1	5,3	**8,9**

Concept number 3 gets the most points, so this concept is chosen for the motor.

3.2. Stator bearing

The main requirement to the stator bearing is to compensate the displacement of the sheet metal package (see Figure 4, dark blue color part), caused by the cooling of the coils (see Figure 4, green color arrows). The result of a simulation shows around 0,5 mm maximum displacement in radial direction when there is no suspension boundary condition and cooling down from room temperature to -100 °C, what was a calculated value for the sheet metal package, when the coils were cooled. The second requirement is the transmission of forces to the housing (see Figure 4, brown color part), caused by torque of the motor (see Figure 4, red color arrows) and by the mass of the rotor due to the acceleration from flight maneuvers (flying a curve or climbing flight, see Figure 4, blue color arrows). Here, the standard document set's a value of 3,8*9,81 m/s² [8]. This means that a structure is needed with a low stiffness in radial direction and a high stiffness in tangential direction. A possible geometry could be a leaf spring and their arrangement in different directions around the stator sheet metal package. The suggested quantity is 4 pieces. To design lightweight structures, it makes sense to make load paths as short as possible, so here are the mounting points from the leaf springs at the housing are located at the same place as the joints of the motor to the aircraft.

- Preliminary design
- Thickness for the leaf spring: steel 0,5 mm, titanium 1 mm, CFRP (canvas fabric) 3,5 mm
- Buckling analysis shows no problems for the investigated lengths of the leaf springs

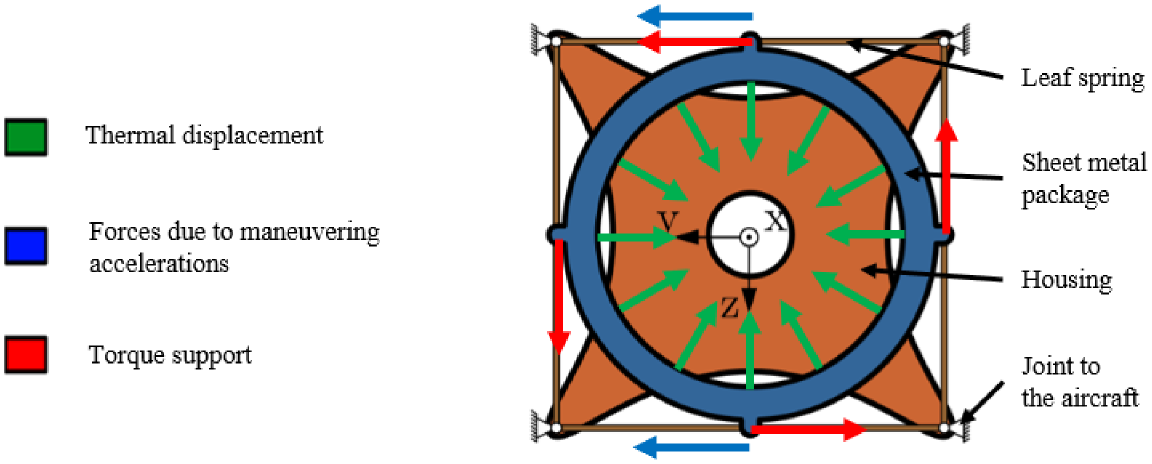


Figure 4. Concept for the joint between stator sheet metal package and housing

For the preliminary design, the leaf spring is first assumed as a bar (50 mm width, unknown thickness), with a load combined from torque-depending tension load and additional force from a maneuver in y-direction (see Figure 4, upper leaf spring). This leads with the yield strength for titanium, steel and carbon fiber reinforced plastic (CFRP, unidirectional fiber orientation, T300, epoxy, fiber volume content 60 %) to minimum thicknesses under 0,1 mm. The second load case is the maneuvering force in x-direction. Here the leaf spring is roughly assumed as a beam (300 mm length) under bending load. For a given maximum displacement of 0,1 mm in x-direction, thicknesses from 0,5 mm (steel), 1 mm (titanium) and 3,5 mm (CFRP) are necessary. In a last step, the influence of the strain, according to the thermal displacement is investigated for a leaf spring with a very short length of 50 mm. For steel, an additional tension load of 56 N/mm² is calculated. For longer leaf springs and materials with lower Youngs modulus the additional tension load is still much smaller. These loads are therefore manageable.

In a next step, the needed length for the leaf springs is investigated, depending on the deviation from the cylindrical shape of the sheet metal package, when it is fixed only on four points. In Figure 5 the geometrical setup and the results of the variation of the length of the leaf spring from 50 to 300 mm

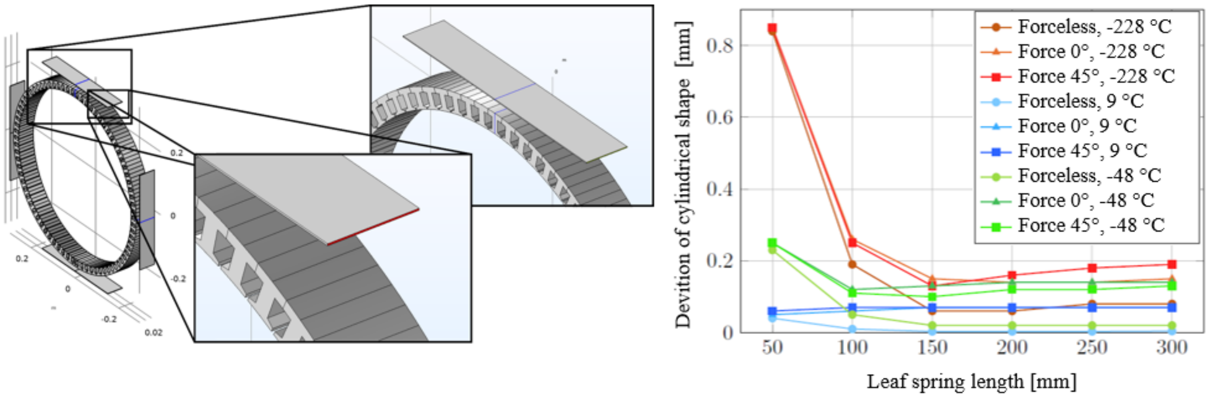


Figure 5. Investigation of the length of the leaf spring

at different load cases and temperature conditions is shown. At a length of 150 mm a minimum for the deviation of under 0,2 mm can be achieved. This should be manageable. A buckling analysis shows no problems for the investigated lengths and materials of the leaf springs.

In Figure 6 the area classification for a hybrid leaf spring is shown, made from CFRP in the free area and aluminum for the load introduction areas. The single concepts were also evaluated with the variable requirements from Table 1 like in Table 2. The best evaluated concepts are highlighted.

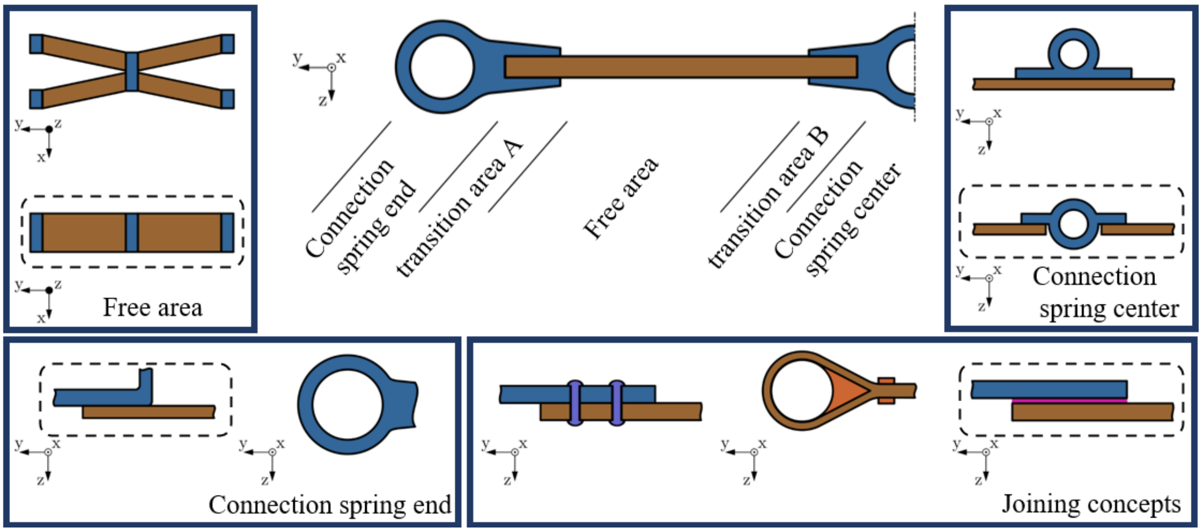


Figure 6. Area classification and concepts for the areas of the hybrid leaf spring

For a more detailed numerical design of the leaf spring, first a model is built up (see Figure 7 a)). There are fixed bearing conditions at both ends, a stack of ten plies CFRP (0,35 mm thickness, unidirectional in y-direction, T300 fibers, epoxy, fiber volume content 60 %) and a load introduction element, made of aluminum, in the middle. In Figure 7 b) the results for tension stress in the plies are displayed for different load cases (maneuver force: 250 N, shrinkage: 0,84 mm, torque induced force: 1800 N). The stresses are very low compared to literature values [9]. The higher stresses may also be due to the structure of the model, since mesh mating was used here, which can cause stiffer behavior. The reason for the higher stresses at the plies in the middle can be the Forces due to the torque support. In Figure 7 c) a picture of the shear stress distribution due to maneuvering forces in the x-direction of the first ply is shown. The values are also manageable. In a next iteration, the estimated thicknesses of the leaf spring due to the preliminary design can be reduced for a lower mass of the component.

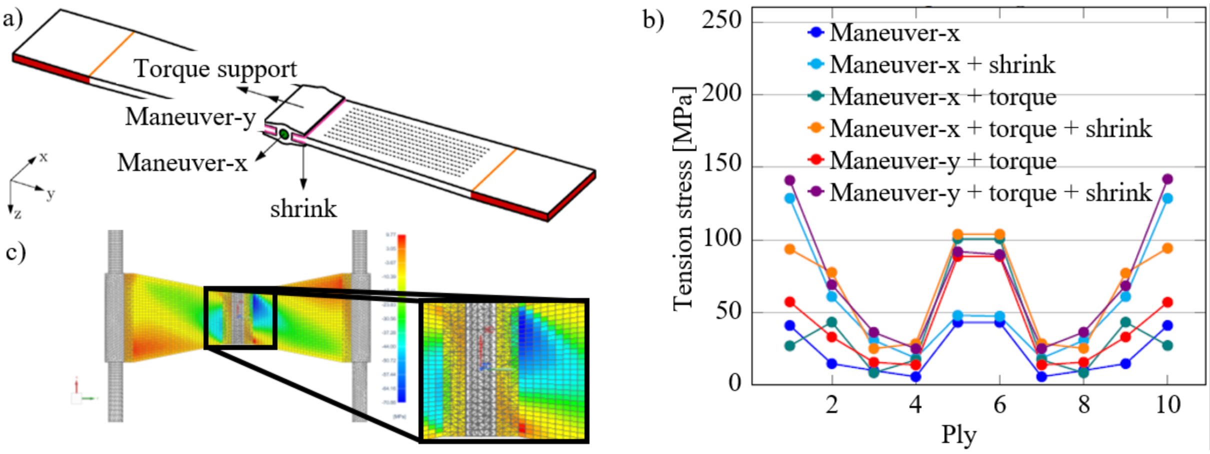


Figure 7. Detailed numerical design; a) model; b) tension in plies; c) numerical result

4. Concept of the stator and Summary

The last two sections describe only small parts of the design process of the new concept for a cryogenic gaseous hydrogen-cooled lightweight electric engine. The other components and joints were calculated in the same way, except the given electric components like the sheet metal package and the hollow copper coils. In Figure 8 the summarized concept of the stator is shown. The housing will be made from thin-walled aluminum with ribs on the front side to stiffen the bearing area. The hydrogen distributor will be made from titanium with a thermal insulation of polyurethane foam. The hydrogen coupling will be manufactured from elastomer with a metallic squeezed sleeve for support of the sealing. Finally, the leaf spring will have plain ends for a bolted connection, a bonded metallic element in the middle for load distribution and CFRP in the free areas.

The heaviest components with possibilities for weight saving are the sheet metal package with about 10 kg and the copper coils with 7,1 kg. All the other parts of the stator summarize to 2,5 kg. That's exactly how it is with the rotor. There are around 11 kg for the electrical needed parts and only 1 kg for the other components. So, the total estimated mass for the motor is approximately 32 kg. So, we achieve a power density of around 15 kW/kg for this part of the power train.

The next step is the detailed design of the motor. This will certainly increase the mass of the components somewhat due to the higher TRL level.

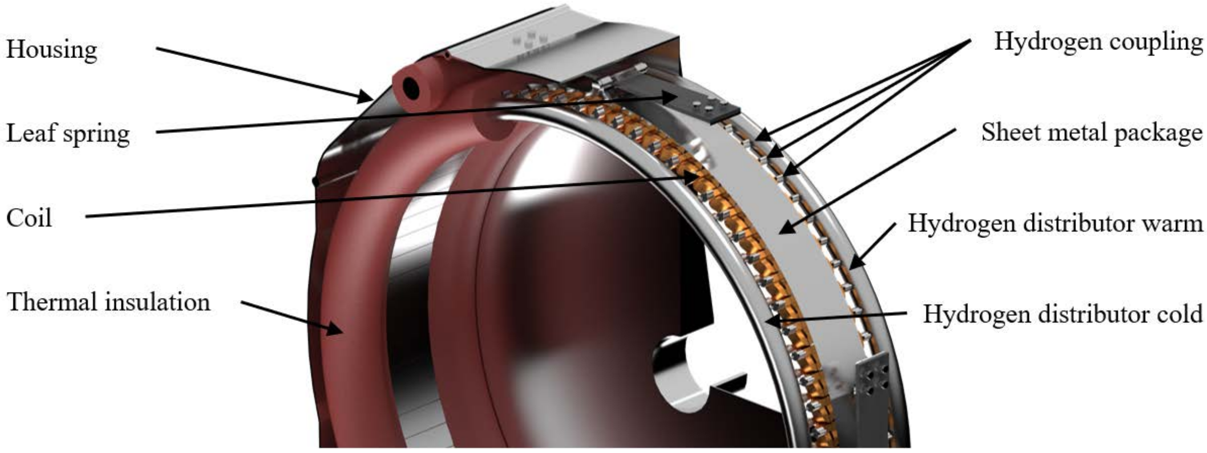


Figure 8. Summarized concept of the rotor of the motor

5. References

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