CGEM mechanical design upgrade

July 2nd, 2019

1. Investigation on the mechanical issues of Layer 1 and Layer 3

L1 construction has been completed in June 2017 in Frascati. After that, it has been tested in Ferrara at nominal values. In 2018 this detector has been used to start the tests with electronics.

In May 2018, L3 construction was completed. During final gluing operations, an incident occurred to the detector that felt down its support. Measurements of the entity of this damage were performed and there was no big external deformation of the detector. It was then moved to Ferrara, where electrical issues were found at the very beginning while powering on the detector. Until September 2018 we were able to turn it on and keep it at the nominal values with few disconnected HV channels.

In early November 2018, both layers, together with L2 have been used in Ferrara to test the assembly procedure. Two days were needed for the assembly and dis-assembly the detector and everything went smoothly.

After this test, the detectors have been prepared for the shipping to Beijing. L1 and L2 were shipped fully equipped with the electronics, while L3 only had electronics board on one side due to the assembly test.

At IHEP the boxes have been placed directly in the clean room to prepare them for the gas flow. In this phase two main problems have been noticed:

→ L1: from one side of the detector, the screws of the mechanical support fell down. This implied that the detector was hanging from one side and vibrating on his support on the other side. Already in the box, the detector has been placed back in the proper position.

→ L3: big gas leakage was found on one side, close to a Permaglass ring.

Afterward, each layer has been placed on its mechanical support for stand-alone tests.

L1 was powered on at nominal values without problems. This made us consider the incident of the shipping without consequences. A setup with cosmic tests has been prepared to start testing the electronics for the full month.

L3 has been cured for the leakage with gluing on both sides and equipped again with HV boards. Unfortunately, all the test performed to power on the detector were never successful. The detector needed more investigation.

In the meantime, it has been decided to assemble L1 and L2 together to move on with electronics tests and cosmic acquisition. Once they were together L1 showed problems on one electrode on the HV side. We decided to dis-assembly the detectors and check L1 status. Even back again on its stand-alone support the detector didn’t recovered. The assembly procedure has been deeply investigated in all his part to be sure that it was not the responsible of bad stress to the detector like compression or distortion while connecting the two layers together. No issues were found and all the operation were safe and performed with the necessary precision.

The investigation moved back to the shipping. It has been decided to perform a computing tomography of the layers, thanks to the support of IHEP. This test started with the prototype: it always worked and it has been shipped in the same ways as the other detectors. It could have been a good reference point. Than we performed the CT scan on all the others detector.

L1 showed differences between its two ends inside as shown in picture: on the left it is shown the part that fell down during the shipment, while the right report the side bouncing during the shipment. The three layers in the middle are the three GEMs and it possible to see that the gap between them is not the requested one. This confirmed the HV issued and we were able to address the problem to the fall during the shipping.

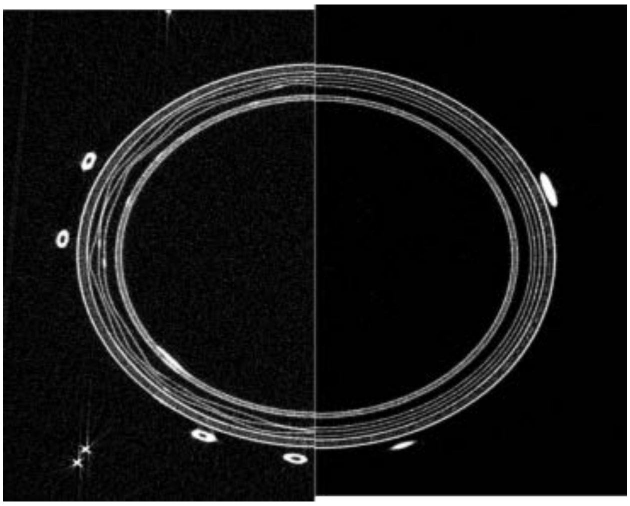

Figure 1 – CT scan for Layer 1.

Knowing the problem that affected L1, it has been decided to keep it to continue the tests of electronics and it was assembled together with L2 for a cosmic stand.

For Layer 3, the CT scan showed a similar situation to the picture on the left shown before all along the detector. We than decided to proceed with opening the detector to have a look inside. The procedure foreseen to remove one layer at time starting from the anode, then the GEM foils and finally the Cathode. This way we learned that the damage that occurred during the construction reached also the GEM and there were several defects probably due to the amount of vibration during the shipment. The picture below shows the detector were on the top half there is the GEM 3 damaged.

Therefore, we can conclude that the most of the damages for Layer 1 and Layer 3 happened during the shipment due to an excess of vibrations that have been transferred by the external supporting structure to the GEM foils. We can also conclude that the Kapton-Rohacell sandwich is not enough rigid to prevent inner damage from unexpected events.

Figure 2 – The Layer 3 opened. The damage to the GEM foil is visible.

2. Improving mechanical robustness of the CGEM

For the reasons described in the previous paragraph, we decided to improve the mechanical rigidity of the detector. Simulations have been performed to compare different structure configurations in order to find the one that maximizes the robustness of the detector while keeping the material budget within the limit of 1.5% of a radiation length.

Fig. 3 shows the maximum deformation for simulated planar samples. Each sample is 70x10 cm^2 and is composed of a filling material (either Rohacell or honeycomb) and two skins (made of either Kapton, fiberglass or carbon fiber). On top of each sample a homogenous force of 10 N is applied and the maximum deformation is reported.

The following configurations have been simulated:

- KH_2mm → Cathode of kapton and honeycomb (2 mm)
- KH_4mm → Anode of kapton and honeycomb (4 mm)
- KR_2mm → Cathode of kapton and honeycomb (2 mm)
- KR_4mm → Anode of kapton and honeycomb (4 mm)
- FGH_2mm → Cathode of fiberglass and honeycomb (2 mm)
- FGH_4mm → Anode of fiberglass and honeycomb (4 mm)
- CFH_2mm → Cathode of carbon fiber and honeycomb (2 mm)
- CFH_2mm_1 → Cathode of carbon fiber and honeycomb (2 mm) with only one skin of carbon fiber
- CFH_4mm → Anode of carbon fiber and honeycomb (4 mm)

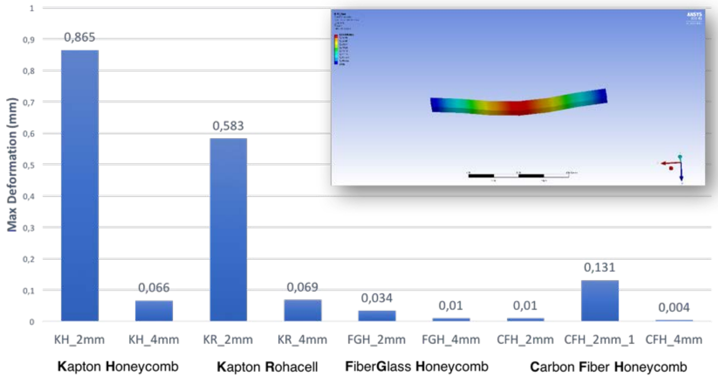

Figure 3 – Simulation of planar samples

Real samples have been assembled and tested in lab as shown in Fig. 4 in order to compare and tune the simulations. Results are reported in Fig. 5.

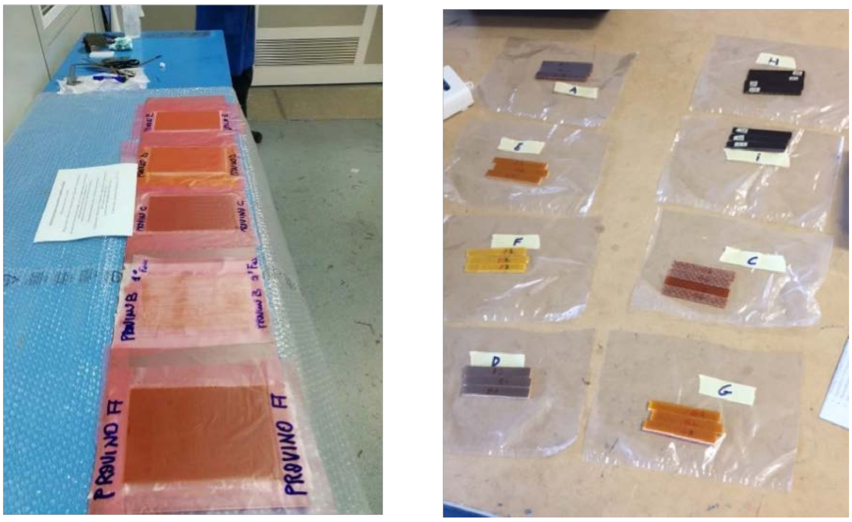

Figure 4 – Planar samples preparation

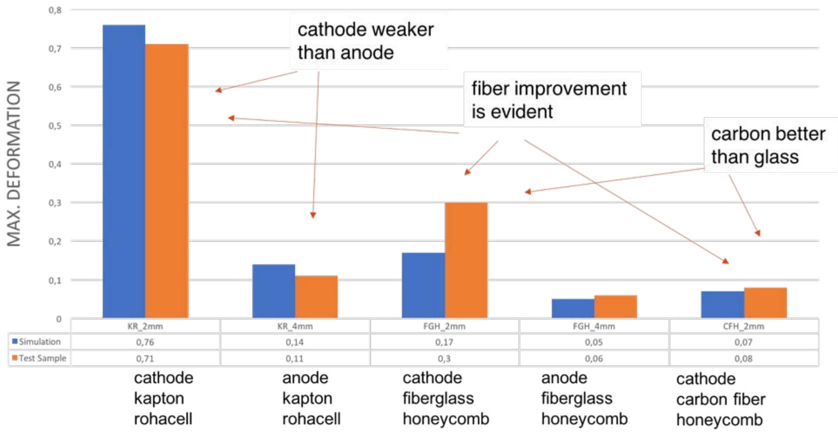

Figure 5 – Comparison between test and simulations

The main features are:

- Rohacell and honeycomb have about the same rigidity;
- The anode is more robust than the cathode (anode thickness is 4 mm and cathode is 2 mm);
- Fiber glass or carbon fiber are a big improvement with respect to Kapton-Rohacell or Kapton-Honeycomb sandwiches;
- Carbon fiber is better than fiberglass (and also lighter);
- Using two skins is better than one skin.

3. Cylindrical simulations

Then, we simulated cylindrical GEMs; only cathode and anode are simulated, since they are the structural element of the detector. To evaluate the deformation, the CGEM is fixed on one side and a force of 10 N is applied on the other side orthogonally w.r.t. the cylinder symmetry axis.

Fig. 6 shows the comparison between a Rohacell based CGEM and a CGEM made of honeycomb and carbon fiber; the deformation in case of carbon fiber is ten times smaller with respect to the old BESIII design. Fig 7 instead shows the maximum deformation for the new layer 1 and the new layer 3 (both with carbon fiber) when the same force of 10 N is applied on one side. Maximum deformation is much smaller than 100 um, which is the tolerance of the mechanics for construction and assembly of the detector. During the vertical assembly, for instance, the GEM foils are free to move within the tolerances and such a displacement is not harmful for their integrity.

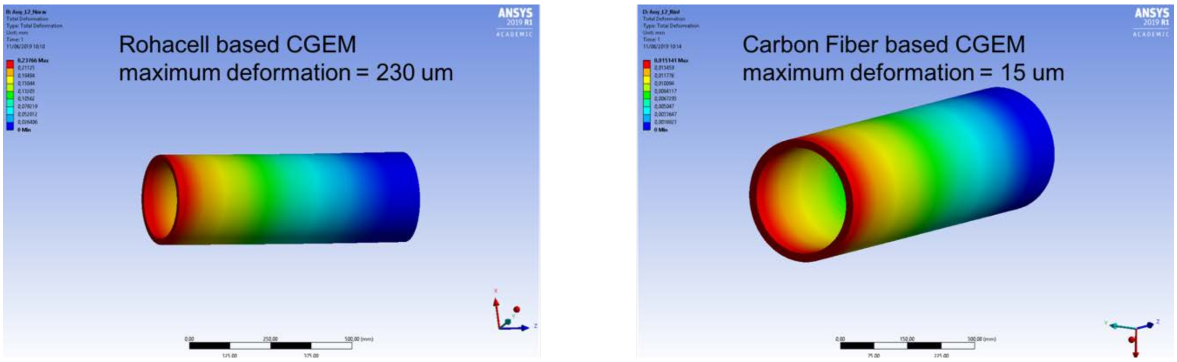

Figure 6 – comparison from Rohacell based CGEM and the new design

Layer 1 with carbon fiber

Layer 3 with carbon fiber

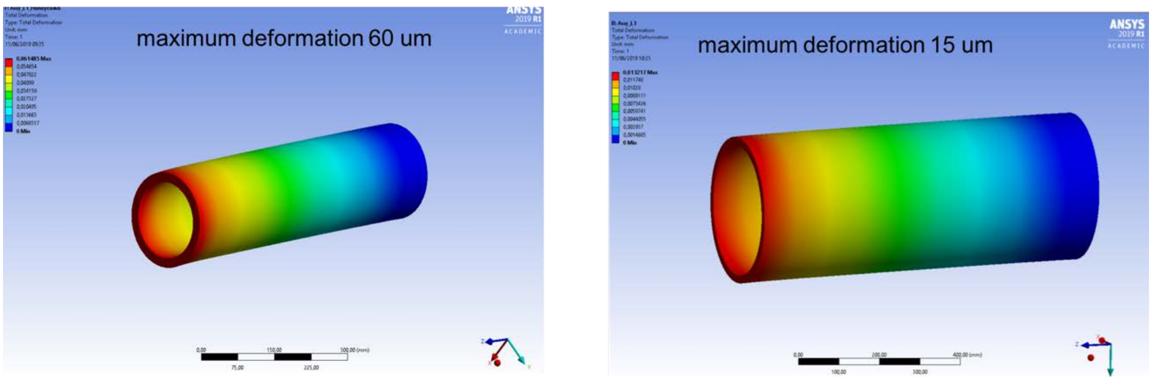

Figure 7 – Cylindrical simulation for the new layer 1 and 3.

4. Proposed layout and material budget

Here is the proposed layout for each layer

- Layer 1
    - add 2 skins of carbon fiber (70 microns each) to the anode;
    - use honeycomb[1] instead of Rohacell as “filling material” for anode and cathode
    - the cathode has the faraday cage on its internal part

- Layer 2
    - it will remain as it is
    - carbon fiber reinforcement will be added to the external structure, outside the active area, between the rings and the Rohacell

- Layer 3
    - add 2 skins of carbon fiber (70 microns each) to the anode
    - add 1 skin o carbon fiber (70 microns) to the cathode
    - the anode has the faraday cage outside the ground plane

And here are the tables we used to calculate the material budget

Material	**Rad. Len.**	**unit**
copper	1.43	cm
kapton	28.6	cm
rohacel	1425	cm
honeycomb	1250	cm
epoxy	33.5	cm
carbon fiber	28	cm
fiberglass	16	cm

[1] Honeycomb is preferred to Rohacell since the former needs less epoxy for the gluing. The Rohacell sandwich in addition is made of two layers which need a kapton foil with additional epoxy in the middle. The strength of the detector will be ensured by the carbon fiber.

	Cathode	only honeycomb		
	material	thickness	fill factor	% of X0
faraday	copper	3	1	0.021
cage	kapton	50	1	0.0175
	epoxy	15	1	0.0044
	honeycomb	1800	1	0.0144
	epoxy	15	1	0.0044
cathode	kapton	50	1	0.0175
circuit	copper	3	1	0.021

TOT Layer 1	0.50985233

GEM			
material	thickness	fill factor	% of X0
copper	5	0.77	0.02695
kapton	50	0.77	0.013475
copper	5	0.77	0.02695
		Tot GEM1	0.067375
		Tot 3 GEM	0.202125

	Anode			
	material	thickness	fill factor	% of X0
ground	kapton	50	1	0.0175
plane	copper	5	1	0.035
	epoxy	15	1	0.0044
	carbon fiber	70	1	0.024997
	epoxy	15	1	0.0044
	honeycomb	3800	1	0.0304
	epoxy	15	1	0.0044
	carbon fiber	70	1	0.024997
	epoxy	15	1	0.0044
anode	kapton	25	1	0.00875
circuit	epoxy	25	1	0.00733333
	copper	5	0.87	0.03045
	kapton	50	0.2	0.0035
	copper	5	0.2	0.007
			Tot Anode	0.20752733

Figure 8 - Layer 1 stratigraphy.

Cathode			
material	thickness	fill factor	% of X0
kapton	12.5	1	0.004375
epoxy	15	1	0.0044
rohacel	1000	1	0.007
epoxy	15	1	0.0044
kapton	12.5	1	0.004375
epoxy	15	1	0.0044
rohacel	1000	1	0.007
epoxy	15	1	0.0044
kapton	50	1	0.0175
copper	5	1	0.035
		Tot Cathode	0.09285

Tot Layer 2	0.45448333

GEM			
material	thickness	fill factor	% of X0
copper	5	0.77	0.02695
kapton	50	0.77	0.013475
copper	5	0.77	0.02695
		Tot GEM1	0.067375
		Tot 3 GEM	0.202125

Anode			
material	thickness	fill factor	% of X0
kapton	50	1	0.0175
copper	5	1	0.035
epoxy	15	1	0.0044
rohacel	2000	1	0.014
epoxy	15	1	0.0044
kapton	12.5	1	0.004375
epoxy	15	1	0.0044
rohacel	2000	1	0.014
epoxy	15	1	0.0044
kapton	25	1	0.00875
epoxy	25	1	0.00733333
copper	5	0.87	0.03045
kapton	50	0.2	0.0035
copper	5	0.2	0.007
		Tot Anode	0.15950833

Figure 9 - Layer 2 stratigraphy.

Cathode	honeycomb + carbon		
material	thickness	fill factor	% of X0
carbon fiber	70	1	0.024997
epoxy	15	1	0.0044
honeycomb	1800	1	0.0144
epoxy	15	1	0.0044
kapton	50	1	0.0175
copper	3	1	0.021
		Tot. cathode	0.086697

TOT Layer 3	0.51734933

GEM			
material	thickness	fill factor	% of X0
copper	5	0.77	0.02695
kapton	50	0.77	0.013475
copper	5	0.77	0.02695
		Tot GEM1	0.067375
		Tot 3 GEM	0.202125

Anode			
material	thickness	fill factor	% of X0
copper	3	1	0.021
kapton	50	1	0.0175
copper	5	1	0.035
epoxy	15	1	0.0044
carbon fiber	70	1	0.024997
epoxy	15	1	0.0044
honeycomb	3800	1	0.0304
epoxy	15	1	0.0044
carbon fiber	70	1	0.024997
epoxy	15	1	0.0044
kapton	25	1	0.00875
epoxy	25	1	0.00733333
copper	5	0.87	0.03045
kapton	50	0.2	0.0035
copper	5	0.2	0.007
		Tot Anode	0.22852733

Figure 10 - Layer 3 stratigraphy.

The total material budget for the entire CGEM-IT is about 1.48% of X_0, with an increment of only 0.04% of a radiation length.

6. Shipping

The original system used a box with 4 springs on both sides of the detector connected to a central axis in order to smooth the possible vibrations and deformation during the travel. This choice was taken in order to prevent any part of the shipping box touching the detector. A test of this shipping concept has been successfully performed with the cylindrical prototype. During the final shipment, while the large part of the vibrations was absorbed by the springs, the full system featured a too high rigiditiy, that prevented to smooth some crucial vibrations that damaged the detectors.

A new design for the shipping box has been discussed with the IRC and the experts from KLOE-2 (Vincenzo Valentino – INFN Bari) and from other experiment (Fabrizio Raffaelli – INFN Pisa). The new solution foresees the use of a polyutherane foam (commercial name APSOPUR) in which the detector will be immerged. A sketch of the system is shown in Fig. 11.

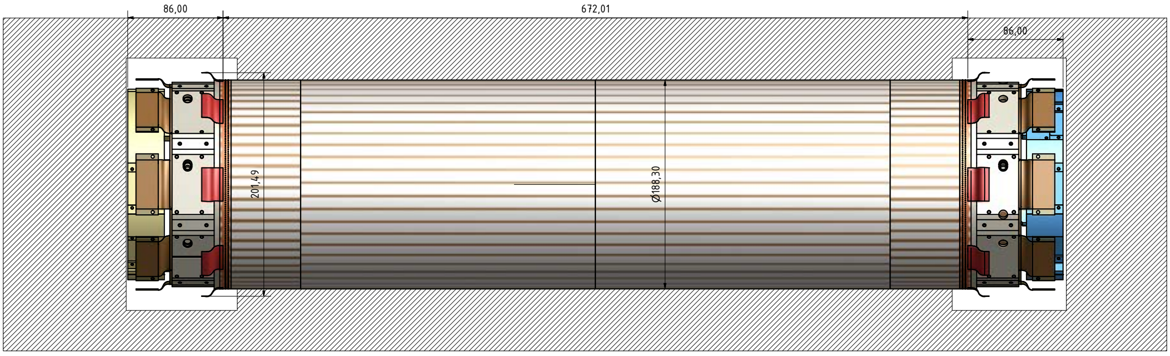

Figure 11 – scheme of the shipping foam envelop.

The use of this foam has been discussed with Angst+Pfister, an international supplier for technical material. The foam will be stratified: from the part closest to the detector towards the external part the foam density, and thus the rigidity, will increase. The detector will be fully immerged in the foam. The outside box will also provide a small compression to further decrease the mobility.

In order to fully validate the box before any shipping, a full test on a vibrating machine that is available in Engineer Department of Ferrara University will be carried out. This machine can operate in the full 3D space and thus provide a complete characterization of the vibration profile of the box. A photo on the machine in Ferrara is shown in Fig. 12.

Figure 12 – vibrating machine.

Even if the airplane transportation remains very susceptible of very long and unpredictable vibrations, it remains the only feasible solution compatible to the present schedule. The reduced dimension of the box, compared to the original design, will allow the transportation inside the passengers' cabin: this is a large improvement compared to previous case, in which the box could have received additional vibrations due to the operation of loading and unloading from the cargo. Moreover, with the possibility to bring the box as a cabin luggage, it comes the possibility to have full monitor of the vibrations with active sensors, that cannot be placed in the cargo hold, due to safety constraints. Last, but not the least, the time dedicated to the custom clearance will be reduced, since the box can pass directly to the custom as a standard item and not wait for a week as in the case when it was transported in the airplane cargo hold. We are investigating right now the various declarations that have to be prepared for such transportation with the IHEP agency that helped during the previous shipments.

7. Conclusions

A highly-renewed design, shipping method for new layer 1 and new layer 3 has been presented in the previous paragraphs. In re-engineering the system, three guiding principles were followed:

- increase mechanical robustness, since the former scheme of a double kapton-rohacell sandwich was observed not rigid enough;
- keep as low as possible the material budget, in order to keep it below 1.5% of X_0;
- provide a suitable schedule with respect to the life of the project. For layer 2, that now is successfully operating in IHEP clean room, a small modification is also foreseen to go in the direction of a better structure.

The carbon fiber skins with the honeycomb will reduce modification of a factor ~10 with respect to the previous Kapton-Rohacell structure, with a maximum deformation from cylindrical simulation that is smaller than the mechanical tolerances for the assembly. The results are extracted from simulation which have been validated with planar prototypes.

The material budget increase does not follow the trend of the rigidity. In fact, the total increase is of 0.04% of X0 per each of the two new layers, with a total material budget for the full detector of about 1.48% of X0, including the faraday cage. The original Rohacell+Kapton structure was chosen in order to maintain the material budget within the limits, while no carbon fiber with thickness below 100 microns was available.

The shipping procedure has now a renewed scheme, with the foam suspension instead of springs. The design of the box is done in collaboration with Angst+Pfister, an international firm specialized in shipping technical materials. The box will be also characterized in its vibration profile thanks to a vibrating machine that can operate in the 3D space.

The schedule (shown in Fig. 13), therefore, shall take in consideration a series of tests for the new anode and cathode materials, and for the shipping box, material procurement for both Layer 1 and Layer 3, while providing enough time to safely assembly the detector and to commission the detector in IHEP. It's of paramount importance to start the assembly of Layer 1 at the beginning of July in order to complete the construction before the holiday closure of the LNF lab, that would add further delay to the project.

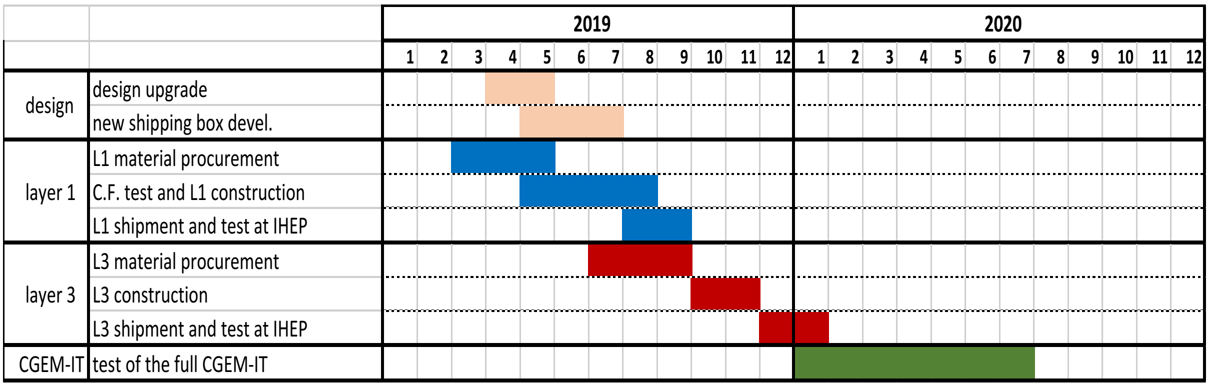

Figure 13 – construction schedule