ATL-GEN-2002-002
15 October 2002

Proposal of a Self-baking Single-wall Design for the VI Section of the ATLAS Beam Pipe

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0. Scope

This short note is meant to propose a new option for the VI section of the ATLAS beam pipe and to discuss its implications in terms of thermal performances with respect to the current baseline. The other implications (structural, integration, material, activation, cost) will not be addressed here, as the thermal performances during the bake out are the most severe design load case having the largest impact on the design.

1. Introduction

The practicability of a self-baking beam pipe design, which could go through the bake out process with the B-layer in place, has led to a significant improvement and simplification of the pixel B-layer installation procedure.
The current baseline of the VI section of the beam pipe consists of a double-wall coaxial Be tube. There is a kapton heater on the outer surface of the inner tube. The heater is used to heat up during the bake out process the inner tube to approximately 250 °C, which is the typical bake-out temperature. The gap in between the two walls is vacuum pumped during the bake-out in order to provide an effective thermal insulation, thus minimizing the heat flux to the pixel system and the temperature of the outer wall. These in fact are of a major concern for the integrity of the B-layer.
Current design parameters for the double-wall design are:

- Max outer temperature: 40 °C
- Max dissipated heat flux to the pixel volume: 100 W/m

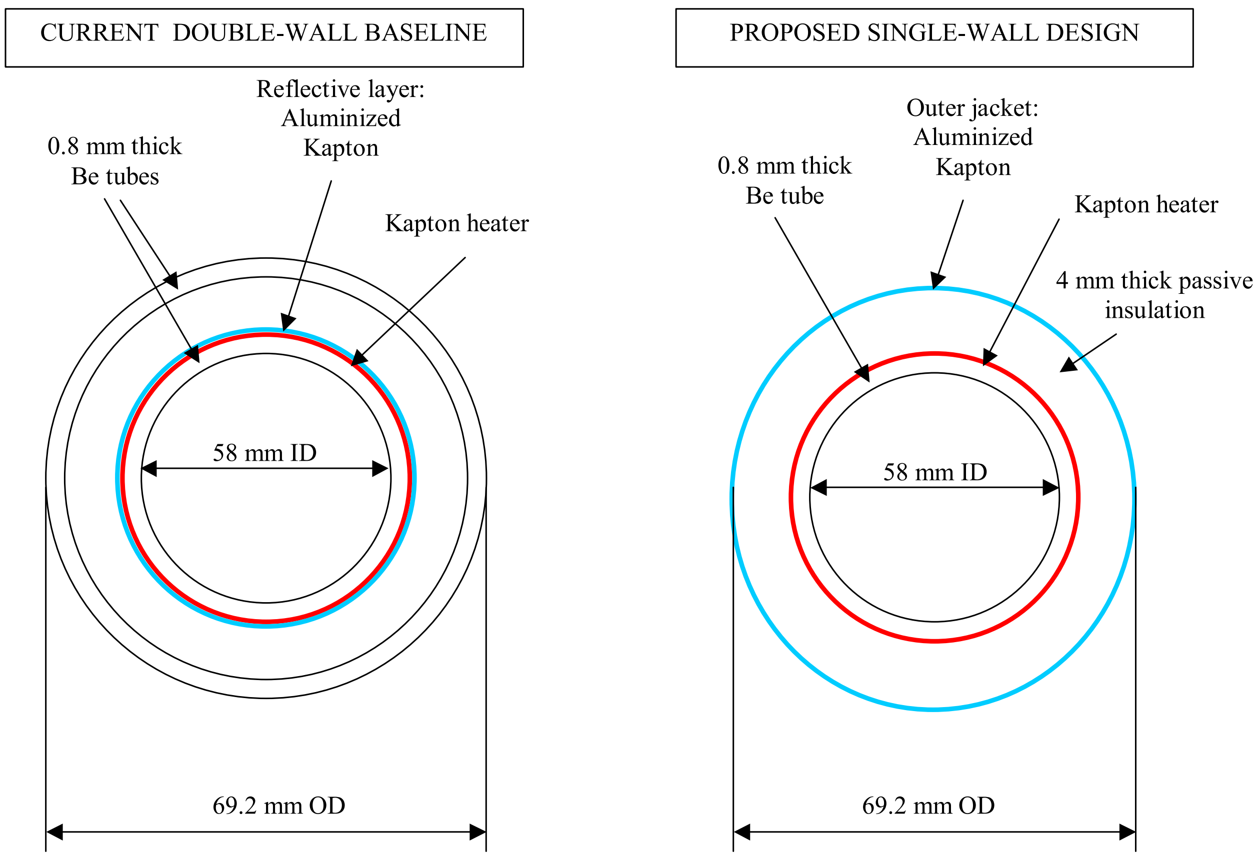
An extensive prototype work has proven that these two specifications can be met.

2. Self baking single wall beam pipe design

Although a proven self-baking baseline beam pipe design exists, it is rather complicated, it requires additional services to keep the vacuum insulation in the gap and it is also very expensive. The thermal performances, in terms of thermal insulation of the double wall construction are far the best, no doubt, due to the efficient vacuum insulation of the gap.
The alternative beam pipe design here proposed consists of a single wall Be beam pipe with a kapton heater all around and on top a layer of passive insulation with the same thickness as the gap of the double wall baseline.

Geometrically these two designs have the same envelopes.
The single wall design has lower thermal insulation wrt the baseline design, however we want to prove that these worse thermal conditions on the outer surface (higher heat flux and temperature) are not affecting the B-layer safety and that there is still a large safety margin with respect to a possible B-layer thermal damage.
In addition to that it will be proven that, in case of failure of the vacuum insulation system, the double wall design is significantly worse than the single-wall design.

The geometry of the current baseline [1] and the new proposed design is shown in the following picture.



3. Calculation assumptions and boundary conditions

The calculation of the heat transfer in the gap between beam pipe and the B-layer has been carried out taking into account all the three heat transfer mechanisms (conduction, convection, radiation).
The B-layer has been assumed as a cylinder with inner diameter of 96 mm.
The B-layer cooling system is assumed to be ON and the surface temperature of the B-layer module has been conservatively assumed uniform at 0 °C, which is the maximum module temperature in stand by-mode.
The conductive and convective heat transfer has been evaluated using the Kuehn and Goldstein correlation [2] valid for cylindrical concentric annuli.
The average heat transfer coefficient and temperature on the outer surface of the beam pipe insulation have been determined.
The convective heat transfer coefficient and hence the temperature of the outer beam pipe surface are not uniform in phi, however, a simplified analysis on average values is enough, at this stage, to allow an overall comparison of the performances of the two designs.
The analysis has been carried out only for concentric annuli, which is the nominal case with the beam pipe and the pixel B-layer coaxial.
Although a possible eccentricity of these annular region due to the beam pipe offset wrt the B-layer axis would give a different distribution of the local Nusselt number, for the Rayleigh number range of interest for our geometry, this would imply a variation of the average heat transfer coefficient not bigger than about 10%, which is small and does not justify a more complicated analysis.
The most difficult contribution to be evaluated is the heat flux due to radiation.
The formulation for coaxial cylinders is simple, but the estimation of the emission/absorption coefficients of the facing surfaces is not easy.
This is in particular true for the B-layer module, which are a mixture of different components and different materials with different emission/absorption properties.
On the contrary the properties of the outer jacket of the beam pipe are better known and, in case, can tuned as needed; here we assume to have an aluminized kapton layer which has a very low emission coefficient: 0,05.
Due to this uncertainty and to the fact that the heat flux by irradiation is, in our case, the most important contribution to the heat transfer, a sensitivity study has been carried out changing the emission properties of the B-layer surface.

In addition the following assumptions have been taken:

- Gap Blayer-beam pipe: N2 gas filled at atmospheric pressure
- Negligible contribution of the forced convection of the environmental gas through the B-layer gap
- The transverse thermal impedance of the Be walls and of the kapton heater is very small compared to the other impedances and hence has been neglected: no temperature change through thickness has been assumed
- Passive insulation material: nanoporous silica aerogel in a quartz fiber carrier (from Aspen Aerogels, Inc; trade name: Pyrogel- UQS); average thermal conductivity in the temperature range 100 – 250 °C: 0,02 W/mK
- Bake out temperature = heater temperature = 250 °C

4. Analysis

As general remark, the temperature of the B-layer modules, for a given coolant temperature, is not affected by the beam pipe outer temperature, but it is a function of the incoming heat flux to the B-layer.
The larger this heat the larger the temperature gradient across the B-layer module to take it out.
Now if the heat flow during the bake-out process is small compared with the heat load of the modules during operation, the associated temperature gradient through modules will be small and the temperature of the modules will stay close to the coolant temperature.
However in principle the coolant temperature can be brought as low as -25 °C to have more head room, but the lower the B-layer temperature, the higher the heat to be dissipated through the modules and correspondingly the higher the temperature gradient across the modules.
So the process is not linear and this intrinsic feedback phenomenon leads to a smoothing effect, which reduces the positive effects associated with a lower coolant temperature.

4.1 Thermal conditions for the proposed single-wall option

On the basis of the assumptions previously described the equilibrium temperature of the outer surface of the insulation and corresponding out coming heat flux have been calculated in two extreme cases corresponding to no radiation and to maximum radiation (B-layer surface = black body) through the gap. The calculated parameters are given in the following table:

		Out coming heat flux (W/m)				**Temperature on the outer surface of the beam pipe insulation (°C)**
		conduction	**convection**	**radiation**	**total**	
A.1	No radiation	64	74	0	**138**	**116**
A.2	Max radiation	62	70	10	**142**	**112**

Note that the real conditions are in between the two extreme cases for the radiation heat flux. However the contribution of the radiation is small due to the low emissivity of the aluminized kapton surface.
The following considerations can be drawn from these results:

1. the maximum heat flux which the B-layer would have to dissipate is small and far below (about 7%) the nominal B-layer cooling capacity. Therefore this shouldn't have any significant impact on the B-layer modules thermal conditions.
2. the maximum calculated outer temperature of the beam pipe (116 °C) won't be of any problem for the B-layer, whose corresponding thermal condition will be even better due to the lower incoming heat flux (5% of nominal cooling capacity)

4.2 Thermal conditions for the double-wall baseline design

The normal operating conditions of the baseline beam pipe design have been calculated by the beam pipe group [3] assuming simplified boundary conditions on the outer surface of the beam pipe.
The analysis shows that with a pumping line of 40 mm ID and 15 m long the expected heat flux through the gap is about 60 W.
The corresponding temperature of the beam pipe outer wall can be calculated combining the analysis carried out by the beam pipe group with the detailed model of the outer gap adopted in the present study.
This gives a temperature in the range 30-55 °C as function of the contribution due to radiation through the outer gap.
This is just to provide a rough estimation; a more refined calculation merging the detailed model of the two gaps would give a better approximation.
It is clear that the thermal performances of the double-wall beam pipe are superior to those of the single-wall option, but, on the other end, they are also significantly affected by the ultimate vacuum in the gap (see next section).

4.3 Failure conditions for the double-wall baseline design

Thermal conditions, due to a failure of the vacuum insulation system for the gap of the current beam pipe baseline design have been studied with the same approach as for the proposed single-wall design.
Combined conduction, convection and radiation heat transfer through the double-wall annular gap have been calculated assuming the gap at atmospheric pressure and the following emission coefficient of the gap facing surfaces [3]:

- inner gap surface: 0.05 (kapton heater coated with a reflective film)
- outer gap surface: 0.1 (Be with reflective coating)

This analysis has been carried out for the two extreme hypotheses of the radiation heat flux through the outer gap (B-layer/beam pipe), like for the single-wall calculations.
The results of the analysis are reported in the following table:

		Heat flux through the gap Blayer-beam pipe (W/m)			**Heat flux through the beam pipe gap (W/m)**				**Temperature on the beam pipe outer surface (°C)**
		Conduction	**convection**	**radiation**	**Conduction**	**convection**	**radiation**	**total**	
F.1	No radiation	78	98	-	157	-	19	**176**	**141**
F.2	Max radiation	75	93	15	165	-	18	**183**	**136**

The contribution of the convective heat transfer through the beam pipe gap is negligible, due to the reduced gap thickness.
The same general comments, regarding the heat flux and temperature of the outer surface of the beam pipe, as for the single-wall thermal analysis, are applicable.
What is interesting to note is that, while in normal bake-out conditions the maximum expected heat flow through the gap is about 60 W, in failure mode this is at least 3 times bigger and approximately 20% higher then the worst case heat flow of the single-wall option.
Although this is still manageable by the B-layer, it is clear that this possible working scenario in failure mode would be more severe for the B-layer than the operating conditions of the single wall option. On the other hand the single beam pipe design, does not have a similar failure mode, since it consists only of passive components.

5. Conclusions

A self-baking single-wall beam pipe design is presented and its thermal performances in terms of thermal insulation are discussed and compared with the current baseline double-wall design.
Although the proposed alternative design has poorer thermal insulation performances compared to the baseline design, the thermal analysis shows that the impact on the B-layer modules is very small and the power load which the B-layer cooling system is requested to dissipate is a small fraction of the available cooling capacity.
The thermal analysis also shows that from the thermal insulation point of view the current baseline design, in case of failure of the insulation vacuum, is worse than the single-wall design.
The single-wall design is quite attractive as it is simpler, less expensive and does not require an external vacuum pumping system with the additional complication of the pumping lines.
However there is at least a drawback associated with this proposed new design, consisting in larger axial displacements during the bake-out process due to the higher temperature of the beam pipe surface which the VI supports are attached to. This has an impact on the beam pipe wire supports an on the design of the Inner Detector end plates-to-beam pipe flexible gas seals.
In spite of this drawback, which we believe is not a showstopper, there are several good reasons making the implementation of this alternative design worth to be seriously considered.

6. References

[1] Drawing of ATLAS Beam Vacuum Chamber of Inner Detector (VI): no. LHCVC1I_0003

[2] P.Teerstra and M.M.Yovanovich, "Comprehensive Review of Natural Convection in Horizontal Circular Annuli", AIA/ASME Joint Thermophysics and Heat Transfer Conference, Vol 4, ASME 1998

[3] Beam pipe thermal calculations presented by Sebastien Blanchard at the informal meeting held at CERN on January the 23rd 2002.