ELECTRO-MAGNETIC OPTIMIZATION OF A QUARTER-WAVE RESONATOR*

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Abstract

A new cryomodule is being designed for the ongoing ATLAS efficiency and intensity upgrade. The cryomodule consists of 7 Quarter-Wave Resonators (QWR) with $ß_G$=0.075 and 4 SC solenoids to replace the existing split-ring cavities. To reduce the resonator frequency jitter due to microphonics we choose a frequency of 72.75 MHz instead of 60.625 MHz. At 72.75 MHz, the cavity is shorter by about 20 cm. The choice of the design ß was based on the beam dynamics and the actual performance of ATLAS cavities. To reach a record high accelerating voltage of 2.5 MV per cavity or higher, the EM design was carefully optimized. The main goal of the optimization was to minimize the peak magnetic and electric fields while still keeping good values for the stored energy, the shunt impedance (R/Q) and the geometric factor (Rs*Q). The cavity height was also another important parameter. The optimization has lead to a final shape which is cylindrical in the bottom and conic on the top keeping a high real-estate gradient. The optimization also included the internal drift tube face angle required for beam steering correction.

ATLAS EFFICIENCY AND INTENSITY UPGRADE

The efficiency and intensity upgrade of ATLAS was recently approved by DOE. The upgrade will increase the intensity of stable beams by a factor of 10 to make ATLAS the most intense low-energy stable ion beam source in the world. It will also double the efficiency for the transport and acceleration of exotic beams produced by the recently commissioned Californium Radioactive Ion Beam Upgrade (CARIBU) facility [1]. Figure 1 shows the ATLAS layout before and after the upgrade. The main new components are a Radio-Frequency Quadrupole (RFQ) and a cryomodule with state-of-the-art superconducting cavities.

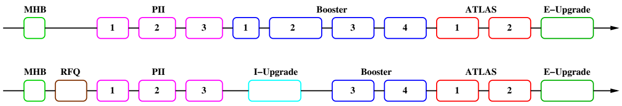

Figure 1: Layout of the existing ATLAS (top) and the proposed efficiency and intensity upgrade (bottom).

The replacement of the first two or three Booster cryomodules is essential to increase the intensity of ATLAS. These modules contain aging split ring cavities which are the most responsible for the present intensity limitations due to excessive beam steering and losses.

The fundamental frequency of the ATLAS linac is 12.125 MHz. The proposed RFQ for the intensity upgrade project will operate at the 5th harmonic (60.625 MHz). The natural choice of the frequency for the upgrade cryomodule would be also 60.625 MHz, however, to reduce the resonator frequency jitter due to micro-phonics we have chosen a frequency of 72.75 MHz. At 72.75 MHz, the cavity is shorter by about 20 cm.

The choice of the design velocity β was optimized based on the beam dynamics and the actual performance of ATLAS cavities, especially the PII injector which is operating at more than 50 % higher voltage of its original design. It was found that a β of ~ 0.075 is most appropriate. Figure 2 shows the effective voltage per cavity as a function of β for a 1/7 charge-to-mass ratio. The 7 points at ~ 2.5 MV corresponds to the proposed intensity upgrade cryomodule and the last 7 points to the newly installed energy upgrade cryomodule. Due to the fast acceleration (2.5 MV) at such low velocity (β ~ 0.075), the focusing period will consist of 2 cavities and 1 solenoid to avoid excessive emittance growth.

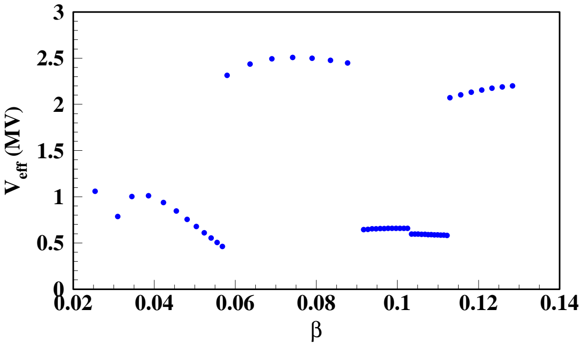

Figure 2: Effective voltage as function of β for existing ATLAS cavities and the proposed intensity upgrade cryomodule (7 points at ~ 2.5 MV).

The new cryomodule will house seven $β_G$=0.075 QWRs and four SC solenoids, it takes advantage of the recent ATLAS Energy Upgrade (AEU) cryomodule developments [2] and superior technology of fabrication and surface treatment of superconducting cavities at Argonne [3]. Figure 3 shows a 3D engineering design of the new upgrade cryomodule which will provide beams up to ~ 6 MeV/u.

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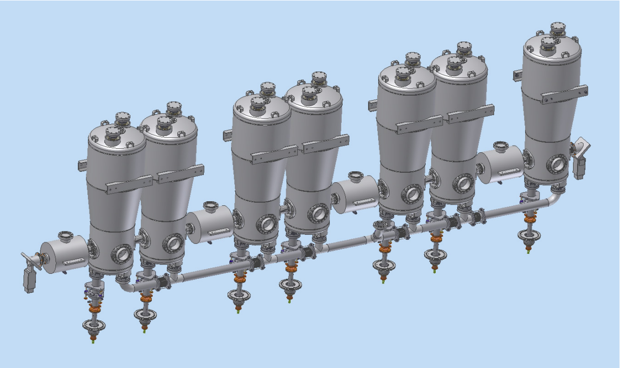

Figure 3: 3D engineering design of the new upgrade cryomodule.

ELECTRO-MAGNETIC CAVITY OPTIMIZATION

To reach a record high accelerating voltage of 2.5 MV per cavity, the EM design was carefully optimized. The most important design parameters to optimize were:

1) The peak surface electric field E-peak, which should be minimized to limit field emission
2) The peak magnetic field B-peak which should be minimized to maintain superconductivity
3) The ratio $R/Q = V^2/\omega U$ where V is the voltage, ω the resonant frequency and U the stored energy. R/Q should be maximized to produce more accelerating voltage with less stored energy in the cavity volume.
4) The geometry factor RsQ should be maximized because it measures the cavity's effectiveness of providing accelerating voltage due to the influence of its shape alone excluding specific material wall loss.

A selected number of cavity geometry parameters were used during this optimization; they are shown on figure 4 and listed below:

1) The cavity diameter (CavD)
2) The cavity top diameter (TopD)
3) The stem top diameter (STTD)
4) The stem bottom diameter (STBD)
5) The drift tube outer diameter (DTOD)
6) The drift tube gap width (DTGW)

The optimization also includes two major constraints; they are the cavity height to keep reasonable cryomodule size and good mechanical stability and the cavity dimension along the beam line to keep relatively high real-estate gradient. Starting from a 25 cm diameter cylindrical cavity and varying the geometry parameters one at a time we were able to establish the general dependence of the important design parameters on the geometry parameters summarized in table 1. The table shows the effect of increasing each parameter separately; a (+) means a positive effect, a (-) corresponds to a negative effect and (0) a neutral effect on the corresponding quantity. It also means that to improve a given quantity the parameter should be increased if (+) or decreased if (-). We clearly notice that the design parameters to optimize are more sensitive to the parameters on the left of the table, namely, CavD, TopD and STTD. In addition to the general dependence, figure 4 shows the quantitative dependence in %.

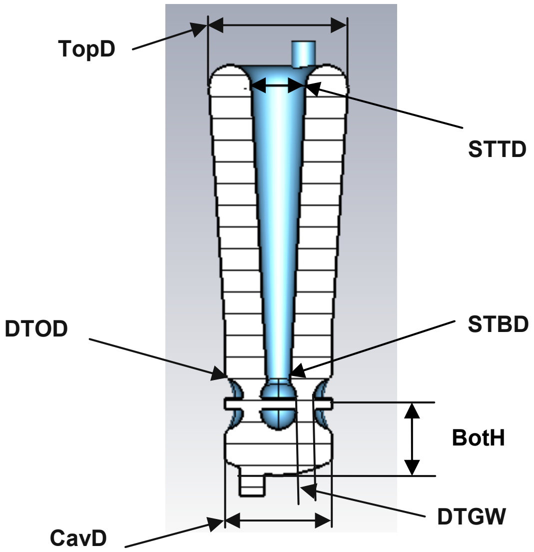

Figure 4: Parameters of the cavity geometry used in the electro-magnetic optimization.

Table 1: General Dependence of the Cavity Design Parameters on a Selected set of Geometry Parameters

	CavD	TopD	STTD	STBD	DTOD	DTGW
E_{PEAK}	+	-	0	0	0	+
B_{PEAK}	+	+	+	+	-	0
R/Q	+	+	-	-	-	-
R_SQ	+	+	-	0	0	0

Increasing the cavity diameter to 30 cm, we notice a significant improvement in all the parameters of interest, especially a ~ 15 % reduction in the peak magnetic field. Beyond 30 cm we begin to sacrifice real-estate gradient. By varying the top diameter while keeping the same diameter for the bottom section at 30 cm, we also notice an improvement in almost all the parameters. More importantly, the cavity height is reduced by about 6% for a top cylinder diameter of 40 cm. At 40 cm, the effect on the real-estate gradient is not significant because we take advantage of the space required for cavity interconnections and solenoids. Based on this, the final cavity design will have a cylindrical shape on the bottom and a conic shape on the top. Table 2 lists the parameters values before and after the EM optimization and table 3 summarizes the final design parameters.

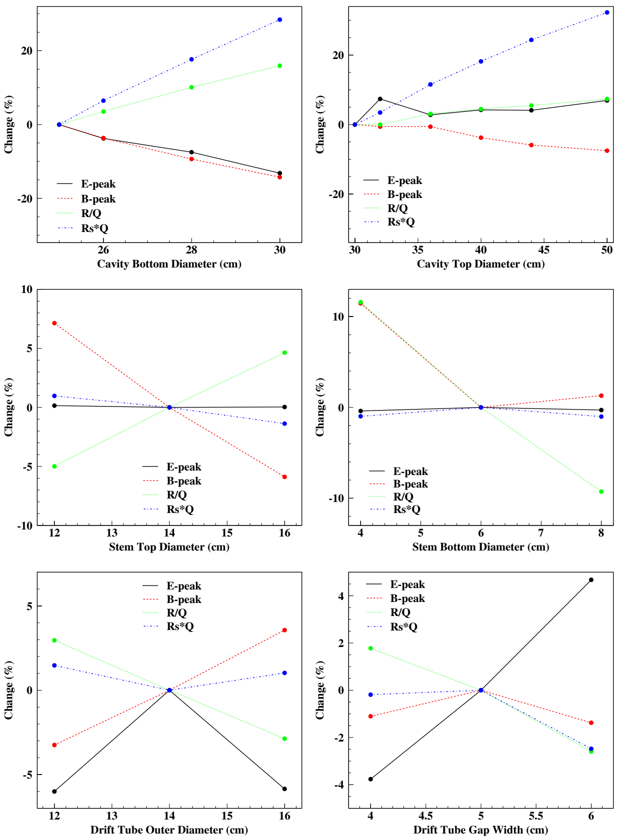

Figure 5: Quantitative dependence of the design parameters in % as function of the geometry parameters.

Table 2: Parameters Values Before and After Optimization

Parameter	Start Value	End Value	Units
CavD	25	30	cm
TopD	25	40	cm
STTD	7	8	cm
STBD	3	3	cm
DTOD	7	7	cm
DTGW	5	4.2	cm
Height	123.3	116.5	cm
E_{PEAK}	3.7	3.2	MV/m
B_{PEAK}	64	48	Gs
R/Q	515	575	Ohm
R_SQ	16.8	26.4	Ohm

STEERING ANGLE OPTIMIZATION

The optimization also included the internal drift tube face angle required for beam steering correction [4]. The asymmetry in the QWR geometry w.r.t. the horizontal plane leads to asymmetric field and beam steering in the vertical plane. To compensate for the steering, the drift tube face is tilted by a small angle as shown on figure 6-right. Adjusting the angle we can find the value that corrects the beam vertical angle centroid <y'>. In this case the optimum steering correction angle was found to be ~ 2.5 deg.

Table 3: Final Design Parameters of the New QWR

Parameter		Value	Units
Frequency		72.75	MHz
β value		0.077	
Stored energy @ 1 MV/m		0.152	J
B_{PEAK}	@ 1 MV/m	48.0	Gs
E_{PEAK}	@ 1 MV/m	3.25	MV/m
R/Q		575	Ohm
R_SQ		26.4	Ohm
Design voltage		2.5	MV
Effective length		20	cm
Design Q_0	@2.5 MV	2×10^9	

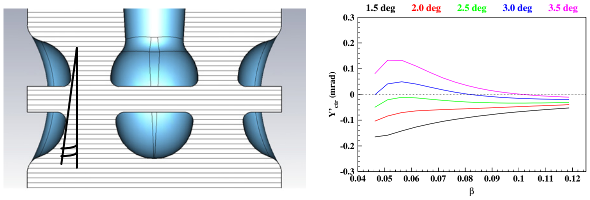

Figure 6: Right: steering correction angle definition. Left: optimization of the steering angle to correct the vertical beam angle centroid <y'>.

SUMMARY

We have successfully optimized the geometry of a 72.75 MHz - β ~ 0.075 Quarter-Wave Resonator. The optimization has led to significant improvements in all the important parameters, namely, a 25% reduction in the peak magnetic field, a 13% reduction in the peak surface electric field, a 10% increase in the R/Q ratio and more than 50% in the geometry factor Rs*Q. The final cavity has a cylindrical shape on the bottom and a conic shape on the top. It is shorter than the original cylindrical design by about 6% with 20% larger diameter

REFERENCES

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