STATUS OF THE DESIGN OF 650 MHZ ELLIPTICAL CAVITIES FOR PROJECT X

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Abstract

Project X is a proposed high-intensity proton accelerator complex that could provide beam to create a high-intensity neutrino beam, feed protons to kaon- and muon-based precision experiments and for other applications still under investigation. The present design of the proton accelerator foresees a section with 650 MHz β = 0.61 and β = 0.9 elliptical cavities.

Prototypes of single-cell cavities and five-cell β = 0.9 cavities are being designed and procured at Fermilab as part of the R&D process for Project X. This paper summarizes the design status of the β = 0.61 and β = 0.9 single-cell prototype cavities, and also addresses the design effort focused on the five-cell β = 0.9 cavities.

INTRODUCTION

The proposed design of the 3 GeV CW Project X superconducting Linac consists of 3 sections with the following types of cavities [1]:

- 3 families of 325 MHz single spoke resonators, to cover the 2.5-160 MeV range
- 2 families of 650 MHz elliptical cavities, with β = 0.61 and 0.9, to cover the 160 MeV -2 GeV range.
- ILC type 1.3 GHz elliptical cavities covering the high-energy section (above 2 GeV)

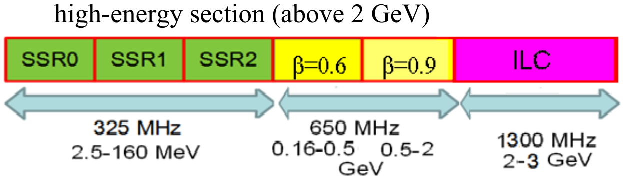

Figure 1: Layout of the Project X superconducting Linac.

An R&D program is ongoing at Fermilab to develop the cavities required for the proposed Linac design, focusing in particular on the 650 MHz family, never used before in any accelerator at Fermilab.

This R&D program includes the design and production of a few β = 0.61 and β = 0.9 single-cell prototypes, prior to the production of the five-cell cavities.

CAVITY RF DESIGN

The cavity shape was optimized in order to decrease the field enhancement factors (magnetic and electric) and to improve the interaction between the beam and the cavities. The cavity aperture was set to be as small as possible with the following limitations: (i) field flatness, (ii) beam losses, (iii) mechanical stability, and (iv) reliable surface processing.

For a given relative error in the frequencies of the cavity cells, the field flatness is determined mainly by the distance between the operating frequency in π mode and the frequency of the neighbouring mode $\pi(n-1)/n$, as follows from linear perturbation theory [2], or by the coupling k between the cavity cells and the number of cells:

$$\delta E/E \sim f_\pi/|f_\pi - f_{\pi(n-1)/n}| \equiv f_\pi/\delta f \approx 1/kn^2.$$

Thus, for a required field flatness $k\sim 1/n^2$, a cavity with a smaller number of cells allows smaller coupling k. For 9-cell ILC cavities one has $\delta f/f_\pi$ of 6e-4 (k=1.87%). For 5-cell cavities one can take the same $\delta f/f_\pi$ at least, that gives k > 0.6%. For comparison, the cavity aperture for the 805 MHz high-energy part of the SNS proton linac, which is similar to the Project-X linac in average current, is 83 mm for the low-β section, and 100 mm for the high-β section.

It is possible to use approximately the same apertures that allow the same beam losses.

Table 1: RF Parameters of the 650 MHz Cavities

B	0.61	0.9
R/Q, Ohm	378	638
G-factor, Ohm	191	255
Max. gain per cavity, MeV (on crest)	11.7	19.3
Gradient, MeV/m	16.6	18.7
Max. Surface electric field, MV/m	37.5	37.3
E_{pk}/E_{acc}	2.26	2
Max surf magnetic field, mT	70	70
B_{pk}/E_{acc}	4.21	3.75

Note that a small cavity wall slope gives more freedom to decrease the field enhancement factors. However, the slope is limited by surface processing and mechanical stability requirements. For β=0.9 we selected a slope of 5°. For β=0.61 it is a problem to get a considerably low field enhancement factor for this slope, and we reduced it to 2°, which appears still acceptable. Both the β = 0.61 and β = 0.9 cavity RF design were optimized based on the above mentioned constraints. Figure 2 shows the layout of the β = 0.9 cavity [3]. Table 1 and 2 show the parameters of the RF design.

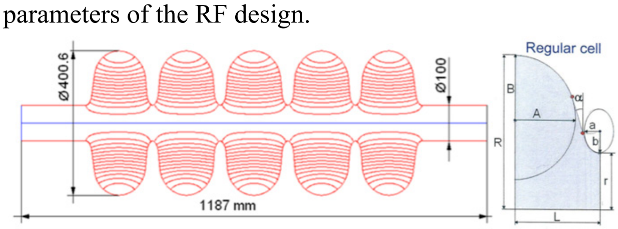

Figure 2: Layout of the β = 0.9 five-cell cavity.

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The cryogenic losses in the cavities are determined by the R/Q value, the G-factor and the surface resistance, that in turn is a sum of the residual resistance and the BCS resistance.

Table 2: RF Parameters of the 650 MHz Cavities (see Figure 2 for legend)

Dimension	β = 0.61		β = 0.9	
	Regular cell	End cell	Regular cell	End cell
r, mm	41.5	41.5	50	50
R, mm	195	195	200.3	200.3
L, mm	70.3	71.4	103.8	107.0
A, mm	54	54	82.5	82.5
B, mm	58	58	84	84.5
a, mm	14	14	18	20
b, mm	25	25	38	39.5
α,°	2	2.7	5.2	7

SINGLE-CELL CAVITIES

A few prototypical β = 0.61 and β = 0.9 single-cell cavities are being built to prove the cavity design and acquire experience in working with these new types of elliptical cavities (larger and heavier than the 1.3 GHz cavities).

Mechanical Design and Analysis

The single-cell cavity and the beam pipe have a wall thickness of 4 mm. The choice of 4 mm material arises from many different factors: (i) a thicker cell reduces deformations of the cell profile during preparation and operation; (ii) the mechanical analysis shows that a 4 mm cavity can withstand the required operational pressure without permanent deformations, (iii) the same thickness has been used in similar designs, and (iv) the material is more easily available, since the same thickness has been used for spoke resonators.

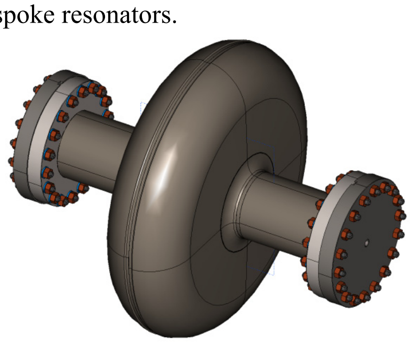

Figure 3: Layout of a β = 0.61 single-cell cavity.

The beam pipe flanges have an Aluminum diamond seal scaled from the seal used for the 1.3 GHz cavities.

The single cell cavities will be tested in a vertical cryostat; where the cavities will be operated at a working pressure of 1 bar, but will be required to withstand a maximum pressure differential of 2 bar, that can happen during cool down and warm up operation or in case of an accident.

Therefore, a series of finite element mechanical analyses were performed to verify the maximum allowable working pressure and the plasticity limit of the cavities.

According to these analyses, the β = 0.61 and β = 0.9 single-cell cavities do not show any permanent plastic deformation up to the working pressure of 1 bar (the model foresees constraint end flanges during handling and vertical test). At the safety pressure of 2 bar, the β = 0.9 cavity does not see any plastic deformation, while the β = 0.61 cavity may experience some permanent plastic deformation. The collapse pressure was estimated to be 7 bar for both the cavities.

BETA = 0.9 FIVE-CELL CAVITIES

A design effort is undergoing at Fermilab to develop the first prototype of a β = 0.9 five-cell cavity. Parallel studies are in progress to investigate the following aspects of the design:

- optimize the design for a CW operation reducing the sensitivity of the cavity to pressure fluctuations;
- clarify the need for HOM absorbers;
- study the vibrational behavior of the cavity to avoid excitation of low frequency modes during operation;
- design the coupler area;
- guarantee the mechanical stability during testing, operation and final installation in a cryomodule.

Figure 4 shows the present design of the cavity including a preliminary design of the titanium vessel. The cavity cell and beam pipe thickness is 4 mm.

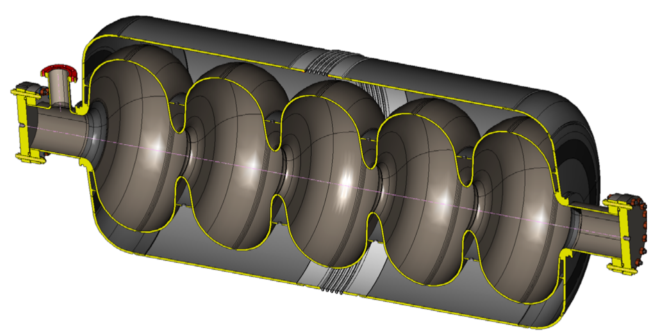

Figure 4: Layout of a β = 0.9 five-cell cavity with vessel.

RF and Mechanical Analysis: df/dP Estimation

In CW operation, an important contribution to the cavity detuning arises from microphonics vibrations, mechanical vibrations transmitted to the cavity from the surrounding environment or generated by pressure fluctuations inside the liquid helium.

Table 3 lists the requirements in terms of cavity maximum detuning allowed while keeping the cavity frequency within the bandwidth limits.

The frequency shift due to pressure fluctuations (df/dP) can be predicted with a combined mechanical/RF simulation and can be reduced with an appropriate design.

With the present cavity and helium vessel design, preliminary calculations show that a df/dP of about 36

Hz/torr can be reached. Various designs are being proposed to reduce this contribution, but the final solution is still under discussion.

Table 3: Tuning Requirements

	β = 0.61	**β = 0.9**
He pressure fluctuations (torr)	±0.1 (±0.2)*	±0.1 (±0.2)*
Bandwidth (Hz)	33	35
Microphonics amplitude (Hz)	15	15
dP contribute to mph's	50% (90%)*	50% (90%)*
Maximum df/dP (Hz/torr)	75 (135)*	75 (135)*
MAWP, warm (bar)	2	2
MAWP, cold (bar)	2.5	2.5

* Parameter under discussion

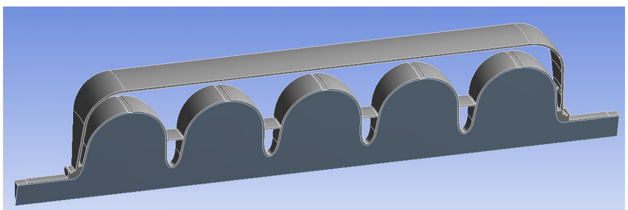

Figure 5: An RF/mechanical model to assess the df/dP.

For example, from the point of view of df/dP, the optimal design requires a finely tuned external diameter of the end cap to avoid length change of the overall cavity. The deformation of the cells due to the pressure is compensated by the force the pressure exerts on the end cap surface [4]. However, this design requires a bellow at the end cap, forcing the use of an end tuner, unfavourable in terms of tuning efficiency and space usage (it increases the coupler to coupler length).

Modal Analysis

A modal analysis was performed to investigate the natural vibration modes of the cavity. This analysis demonstrated the need for stiffening rings between the cells and between the end cells and the end caps.

Table 4: Modal Analysis Results

	No rings	**Present design**
Mode 1 (Hz)	35	84
Mode 2 (Hz)	75	84
Mode 3 (Hz)	80	130
Mode 4 (Hz)	105	217
Spring constant (N/µm)	0.8	4

Determining the radius of the stiffening rings was also a goal of this study. Different ring positions were simulated and a compromise between the cavity stiffness, the lowest mode frequency, and the ease of the welding procedure was reached to choose the final configuration.

Table 4 compares the frequency of the first modes for the present configuration and the free cavity.

Thermal Analysis

The proposed end cap design, as seen in Figure 4, simplifies the welding and assembly of the cavity and the welding of the cavity to the helium tank. Compared to the 1.3 GHz cavity end ring, it has a thicker wall that might create a thermal gradient between the external surface (at liquid helium temperature) and the inner wall where the RF power is dissipated.

A thermal analysis was performed to assess the thermal gradient created in that area: as Figure 6 shows, the power deposited on the wall during operation increases the inner wall temperature of a negligible amount.

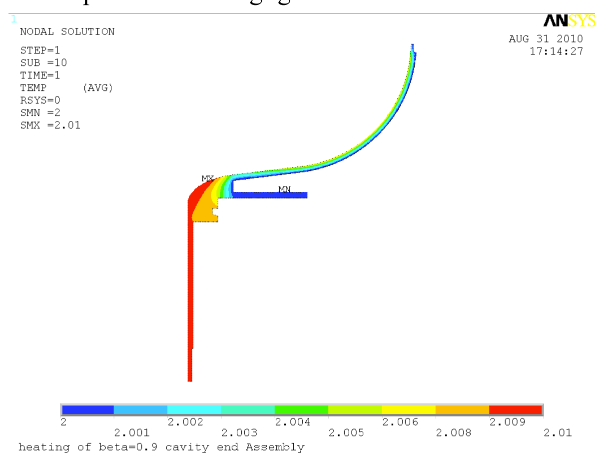

Figure 6: Thermal distribution at the end cell.

CONCLUSIONS

The design of β = 0.61 and β = 0.9 single-cell 650 MHz cavities has been finalized and several cavities will be fabricated.

The design for the β = 0.61 and β = 0.9 five-cell 650 MHz cavities is ongoing and will soon allow the first order of cavities of this kind. Some design issues are still under discussion, but no major problems have been encountered so far in the cavity development.

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