

CONCEPT EM DESIGN OF THE 650 MHz CAVITIES FOR THE PROJECT-X*

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Abstract

Concept of the 650 MHz cavities for the Project X is presented. Choice of the basic parameters, i.e., number of cells, geometrical β , apertures, coupling coefficients, etc., is discussed. The cavity optimization criteria are formulated. Results of the RF design are presented for the cavities of both the low-energy and high-energy sections.

INTRODUCTION

The Project-X, a multi-MW proton source, is under development at Fermilab [1]. It enables a world-leading program in neutrino physics, and a broad suite of rare decay experiments. The facility is based on a 3-GeV 1-mA CW superconducting linac [2]. In a second stage, about 5-9% of the H^- beam is accelerated up to 8 GeV in a SRF pulsed linac to the Recycler/Main Injector. The main portion of the H^- beam from the 3 GeV linac is directed to three different experiments. The basic configuration of the 3-GeV CW linac is shown in Fig. 1.

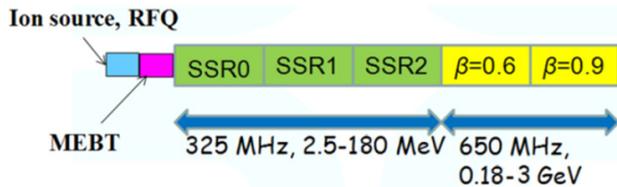


Figure 1: Configuration of Project X based on CW linac

The beam originates from a DC H^- source and then is bunched and accelerated by a CW normal-conducting RFQ up to 2.5 MeV. From 2.5 MeV to 3 GeV the H^- bunches are accelerated by the CW superconducting (SC) linac. The CW linac consists of a low-energy 325 MHz SRF section containing three different families of single-spoke resonators, and two families of 650 MHz elliptical cavities [3].

An initial proposal for the Project-X linac was based on the concept of an 8-GeV pulsed SC linac [4], where a 9-cell, $\beta=1$ ILC-type acceleration structure was used. However, at the beam energy range below 3 GeV the ILC cavity does not work effectively, because the transit time factor depends strongly on beam velocity β . The transit time factor dependence on β is shown in Fig. 2 for different numbers of cells in a cavity. One can see that in order to improve the transit time factor, and thus, increase the accelerating gradient for given RF fields in a cavity, one should use cavities containing a smaller number of

cells. Another way is to use a family of cavities with different geometrical β , which is impractical. If one uses a 5-cell cavity, it gives the possibility to improve the transit time factor and, thus, reduce the number of cavities significantly. In order to keep a reasonable cavity length, the same length as for an ILC cavity, and about the same energy gain per cavity, one should use two times lower frequency, or 650 MHz.

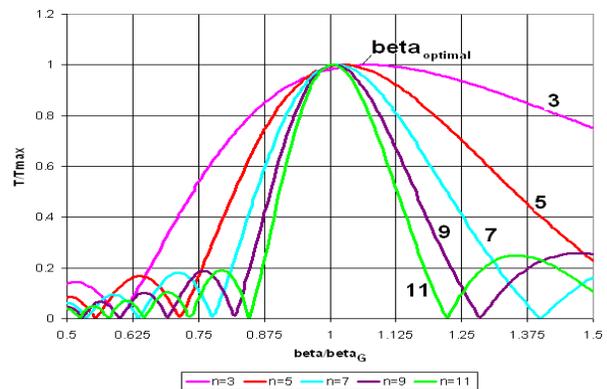


Fig.2: Transit time factor versus a ratio of beam velocity β to geometrical β for different number of cells in a cavity, n . Geometrical β is a ratio of the cavity period to half-wavelength (the cavity operates in CW π -mode).

The transition from the front end operating at 325 MHz based on single-spoke cavities [5] to the 650 MHz section based on elliptical cavities is chosen at the H^- energy of ~ 160 MeV, because for lower energy elliptical cavities are not efficient. It is inefficient to accelerate H^- from 160 MeV to 3 GeV using the same type of a cavity. In order to achieve good acceleration efficiency, two families of 650 MHz cavities may be used.

Optimization was made for the transition energy between the two families and their geometrical betas assuming a linear dependence of the field enhancement factors versus beta [6]. Optimal geometrical betas for the two sections are 0.61 and 0.9, respectively. The optimal transition energy is about 500 MeV, where the gain per cavity is equal in both sections. In Table 1 the numbers of cavities (C), focusing elements (FE) and cryomodules (CM) in each section are shown for all the sections for the recent version of the linac [2]. One can see that the actual transition energies for the section are a bit higher, because they are defined by optimization of longitudinal beam dynamics and technical requirements. (One accelerating unit is a cryomodule.)

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GENERAL

The goal of the cavity shape optimization was to decrease the field enhancement factors (magnetic and electric) to improve the interaction between the beam and the cavities. In order to do this, the cavity aperture should be as small as possible. One has the following limitations for the cavity aperture: (i) field flatness, (ii) beam losses, (iii) mechanical stability, (iv) and reliable surface processing. For a given relative error in the frequencies of the cavity cells, field flatness is determined mainly by the distance between the operating frequency and the frequency of the neighboring mode $\pi(n-1)/n$, following from linear perturbation theory [7], 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 the coupling is proportional to $\sim 1/n^2$, i.e., the cavity with a smaller number of cells allows smaller coupling. For the 9-cell ILC cavity one has $\delta f/f_{\pi}$ of $6e-4$ ($k=1.87\%$). For the 5-cell cavity one can take the same $\delta f/f_{\pi}$ at least, which gives $k=0.6\%$. For the 650 MHz cavities an aperture of 83 mm for $\beta=0.61$, and 100 mm for $\beta=0.9$ were selected, which gives the coupling values of 0.68% and 0.75%, respectively. The apertures are about the same as for the cavities of the high-energy part of the SNS proton linac, which is close to the Project-X linac in average beam current. Thus, it is reasonable to use about the same apertures expecting about the same beam losses. These apertures allow relevant surface processing.

Table 1: Parameters of the linac sections.

Section	Freq, MHz	Energy MeV	# of C/FE/CM	component type
SSR0 $\beta=0.11$	325	2.5-11.4	18/18/1	Single-spoke cavity, Solenoid
SSR1 $\beta=0.22$	325	11.4-43	20/20/2	Single Spoke cavity, Solenoid
SSR2 $\beta=0.4$	325	43-179	44/24/4	Single Spoke cavity, Solenoid
LB 650 $\beta=0.61$	650	179-559	42/28/7	5-cell cavity, doublet
HB 650 $\beta=0.9$	650	559-3000	152/38/19	5-cell cavity, doublet

Simulations of cavity sag caused by the cavities' weight, which were made for the ILC cavity and for both 650 MHz cavities, show [6] that maximal sag of the ILC cavity is 120 μm for a 2.8 mm wall thickness. In order to have the same sag for a 650 MHz cavity having 100 mm aperture, the wall thickness has to be ~ 4 mm. Note that a smaller 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 $\beta=0.9$ we selected the slope of 5° .

For $\beta=0.61$ it is a problem to get a considerably lower field enhancement factor for this slope, and we reduced it to 2° , which looks still acceptable. Based on the constraints mentioned above, optimization of the cavities for both values of β , 0.9 and 0.61, was made. In Figure 3, layout of the cavities is shown. Parameters are shown in Tables 2 and 3. Multipacting (MP) analysis [8] was made using four different codes including CST code [9], which takes into account not only true secondary emission (as the other codes which were used also: Multipac [10], Fishpact [11], and Analyst [12]), but re-diffused and backscattered electrons as well, which influences the simulation results. Simulations show, however, that the MP near the equator area of the 650 MHz cavities is not stronger than in the ILC cavity. However, it is shown that utilization of convexity near the cavity equator may suppress the MP in this area completely, see Fig. 4.

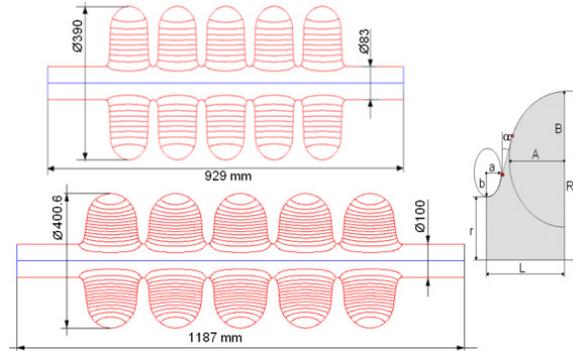


Figure 3: Layout of 650 MHz cavities. $\beta=0.61$ (top) and $\beta=0.9$ (bottom).

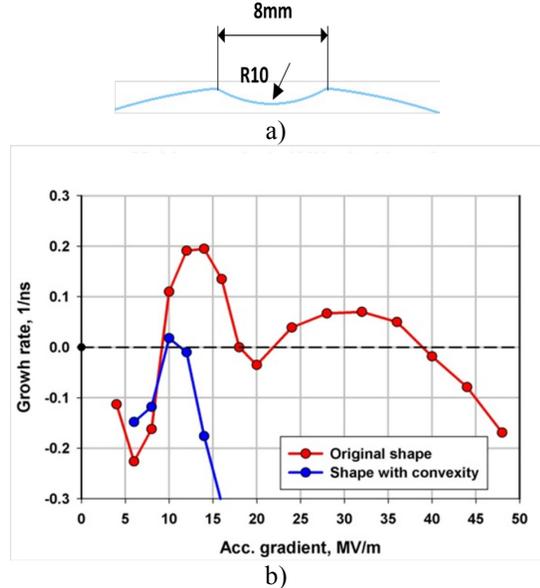


Figure 4: (a) Convexity near the cavity equator to suppress MP; (b) MP growth rate in the $\beta=0.9$ cavity. There is no MP if the growth rate is negative.

JLab is working on an alternative design for the $\beta=0.61$ cavities [13]. Tests of a single-cell prototype are expected this spring.

Cryogenic losses in the cavities are determined by R/Q value, G-factor and surface resistance which in turn is a sum of residual resistance and BCS resistance. Modern surface processing technology may consistently provide a residual resistance below 5 n Ω , see [14]. Assuming an operating temperature of about 2K, the BCS resistance may be calculated from BCS theory using numerical algorithms (e.g., SRIMP [15]), and for 650 MHz and T=2K one has ~ 3 n Ω for BCS and, thus, ~ 8 n Ω total. Assuming medium field Q-slope at the peak field of 70 mT is about 30% [14], that gives the target for the Q range of the 650 MHz cavity of $\sim 2 \times 10^{10}$ and losses < 25 W/cavity, or < 200 W/cryomodule at the operating gradients of ~ 17 MeV/m.

Table 2: Dimensions of the 650 MHz cavities.

Dimension	Beta=0.61		Beta=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

Table 3: RF parameters of the 650 MHz cavities.

Geometrical β	0.61	0.9
R/Q, Ohm	378	638
G-factor, Ohm	191	255
Max. gain per cavity, MeV(on crest)	11.7	17.5
Gradient, MeV/m	16.6	16.9
Max. surf. electric field, MV/m	37.5	33.7
E_{pk}/E_{acc}	2.26	2
Max surf. magnetic field, mT	70	63
B_{pk}/E_{acc} , mT/(MeV/m)	4.21	3.75

The feature of the linac is small beam loading and thus, a narrow cavity bandwidth. The bandwidth of the matched $\beta=0.9$ 650 MHz cavities for a gain per cavity of 17.5 MeV, and the beam current of 1 mA is 20-25 Hz, which creates problems with microphonics. In order to fight microphonics, the following means are typically used:

(i) Cavity over-coupling in order to increase the bandwidth; which leads to input power overhead. For the high-energy part of the CW linac of the Project X, 30 kW IOTs are supposed to be used. Taking into account 16% overhead caused by losses and control requirements, it gives a power reserve of about 7.5 kW per cavity. This reserve gives the possibility to increase the bandwidth up to 40 Hz, which mitigates, but does not eliminate the problem with microphonics.

(ii) Utilization of an active microphonics compensation using fast piezo tuners. Practical experience gained at Fermilab [16] shows that this approach is feasible for the cavities of the Project X CW linac. The work on active microphonics compensation in the Project X cavities is in progress.

(iii) Increase the cavity mechanical stability versus He pressure fluctuations, i.e., decrease the value of df/dP as much as possible (f is the cavity resonance frequency, P is He pressure). The cavity and He vessel mechanical optimization were made for the 650 MHz cavities which allows an expected df/dP of 6 Hz/Torr [17].

(iv) Decrease He pressure fluctuations, through careful design of the cryomodule and cryogenic system.

Analysis shows [18,19] that HOM dampers may not be needed, and experience [20] shows that having HOM dampers can create operational problems. The cavity impedance dependence on the proton velocity, the spread of the resonance frequencies of HOMs of the cavities and their fluctuation caused by microphonics (which may exist even when the frequency of the operating mode is stabilized by the tuner), and the possibility to detune the HOM frequencies by the operating mode tuning-detuning [21] may allow removal of the HOM dampers in the 650 MHz sections of the CW linac of the Project X.

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