MULTI-CELL REDUCED-BETA ELLIPTICAL CAVITIES FOR A PROTON LINAC*

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Abstract

A superconducting cavity has been designed for acceleration of particles traveling at 81% the speed of light ($\beta = 0.81$). The application of interest is an 8 GeV proton linac proposed for a Fermilab upgrade; at present, the cavity is to be used from 420 MeV to 1.3 GeV. The cavity is similar to the 805 MHz high-β cavity developed for the Spallation Neutron Source Linac, but the resonant frequency (1.3 GHz) and beam tube diameter (78 mm) are the same as for the $\beta = 1$ cavities developed for the TESLA Test Facility. Four single-cell prototype cavities have been fabricated and tested. Two multi-cell prototypes have also been fabricated, but they have not yet been tested. The original concept was for an 8-cell cavity, but the final design and prototyping was done for 7-cells. An 11-cell cavity was proposed recently to allow the cryomodules for the $\beta = 0.81$ cavity and downstream 9-cell $\beta = 1$ cavities to be identical. The choice of number of cells per cavity affects the linac design in several ways. The impact of the number of cells in the 8 GeV linac design will be explored in this paper. Beam dynamics simulations from the ANL code TRACK will be presented.

INTRODUCTION

A high-intensity superconducting (SC) H$^-$ linac is under development at Fermilab with the primary mission of increasing the intensity of the Main Injector for the production of neutrino superbeams. The linac is designed to deliver $1.56 \cdot 10^{14}$ protons to the Main Injector in typical pulse lengths of 1 msec, leading to an average beam current of 25 mA per pulse. At the final kinetic energy of 8 GeV, with a repetition rate of 10 Hz, the average beam power is ~2 MW. A schematic layout of the linac is presented in Figure 1. The 50 keV H$^-$ beam from the ion source is bunched and accelerated to 2.5 MeV by a Radio-Frequency Quadrupole (RFQ) operating at 325 MHz. Downstream of the RFQ, a Medium Energy Beam Transport (MEBT) section provides the space for a fast chopper that eliminates the unwanted bunches and forms an optimal beam time structure for multi-turn charge-exchange injection into the 53 MHz Main Injector with minimum uncontrolled losses. The chopper decreases the average current over the 1 msec pulse from 45 mA to 25 mA. From 2.5 MeV to 10 MeV, the beam is accelerated with 16 room-temperature cross-bar H-type (CH) cavities. Further acceleration to $\sim$ 420 MeV is provided via two types of SC Single Spoke Resonators (SSR1, SSR2) and one type of SC Triple Spoke Resonator (TSR). After the TSRs, a frequency transition is made to 1.3 GHz and the beam is accelerated to 8 GeV with "Squeezed ILC" cavities (S-ILC, $\beta_G = 0.81$) and International Linear Collider (ILC, $\beta_G = 1.0$) cavities [1]. Superconducting solenoids are used between the RFQ and the TSR sections. Above $\sim$ 100 MeV, focusing is provided by FODO quadrupoles since $\sim$ 6 T solenoids can produce stripping of the H$^-$ ions. The design of the linac is described in detail in Reference [2]. The beam is transfered from the linac to the Main Injector by a $\sim$ 1 km long high energy transport line.

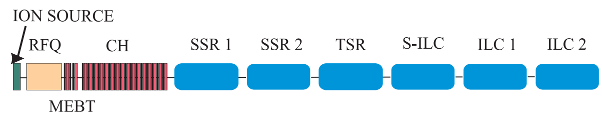

Figure 1: Schematic layout of the FNAL 8 GeV SC Linac.

In the current design of the FNAL 8 GeV linac, the S-ILC section consists of 7 cryomodules, each containing 8 cavities and 4 quadrupoles. The length of the focusing period is 6.1 m for a total length of the S-ILC section of ~84.5 m. The cavities are of 8-cell type and accelerate the beam from $\sim$ 420 MeV to $\sim$ 1.2 GeV. Two other reduced-β elliptical cavities are under consideration for the S-ILC section: a 7-cell cavity and a 11-cell cavity. These three different cavity types are described in the next section.

DESIGN STATUS

The design of the 7-cell and 8-cell cavities was done by Michigan State University (MSU) and Fermilab [3]. An alternative 11-cell cavity design was developed recently by Fermilab [4]. The cell shapes are compared in Figure 2a. The electric field lines of the 7-cell, 8-cell and 11-cell $\beta_G = 0.81$ cavities calculated by SuperLANS [5] are also shown in Figure 2. Selected cavity parameters are given in Table 1. RF parameters of the 11-cell cavity were calculated with SuperLANS and reported in [4]. Those of the 7-cell and 8-cell cavities were calculated with SUPERFISH [6], with the 7-cell parameters having been already reported previously [3].

As indicated in Table 1, the 7-cell and 8-cell structures

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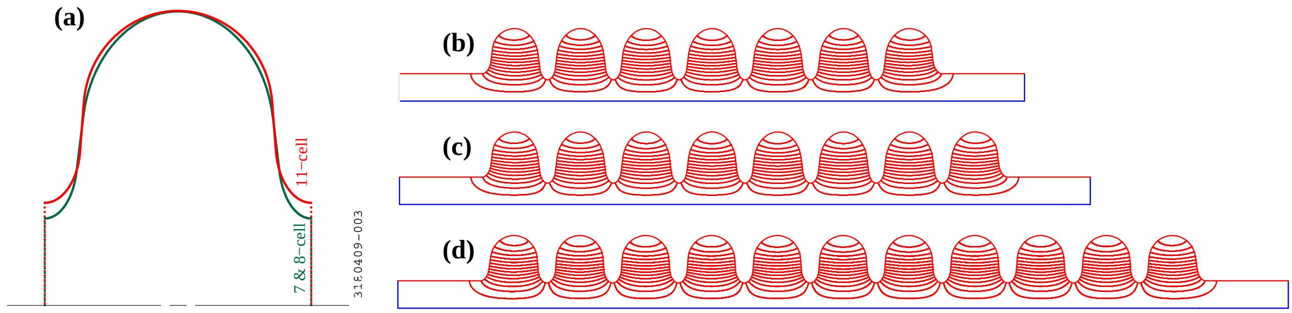

Figure 2: (a) Comparison of the cell shape for the 7-cell cavity, 8-cell cavity and 11-cell cavity. Electric field lines for the π-mode of the (b) 7-cell cavity, (c) 8-cell cavity, and (d) 11-cell cavity.

Table 1: Parameters for the three S-ILC multi-cell $\beta = 0.81$ cavities; E_p = peak surface electric field, E_a = accelerating gradient, B_p = peak surface magnetic field, c = speed of light, k_c = cell-to-cell coupling, R = shunt impedance, Q = quality factor, G = geometry factor.

Item	units	7-cell	8-cell	11-cell
Number of cells		7	8	11
wall inclination	[deg]	7	7	4.3
E_p/E_a	[-]	2.19	2.20	2.41
cB_p/E_a	[-]	1.41	1.41	1.50
k_c	[%]	1.6	1.6	2.47
R/Q per cavity	[Ω]	554	639	750
G	[Ω]	227	226	228
Iris Ø	[mm]	61	61	72
Beam pipe Ø	[mm]	78	78	78
Active length	[mm]	653.8	747.2	1028.1

have similar RF parameters; these cavities differ only in the number of cells. The resonant frequency is 1.3 GHz and the beam tube diameter cavities matches that of the 9-cell ILC-type $\beta = 1$ cavity [1]. The cell shape is similar to that of the 805 MHz high-β 6-cell cavities in operation at the Spallation Neutron Source (SNS) linac at Oak Ridge [7].

The purpose of the 11-cell cavity [4] is to thwart the time and expense of developing of a new cryostat to house the 7-cell or 8-cell cavities. The 11-cell cavity was designed to match the length of a 9-cell ILC type $\beta = 1$ cavity in order to fit inside a Type-4 ILC cryomodule without any major changes (same coupler, vacuum vessel, tuner, etc.). This option allows the Type-4 ILC cryomodules to be used for the entire 1.3 GHz section of the FNAL 8 GeV SC linac. As shown in Figure 2a, the 11-cell cavity has a larger aperture than the 7-cell/8-cell cavity for the sake of higher cell-to-cell coupling (see Table 1). The 11-cell cavity was designed to have good field flatness (necessitating higher k_c than the 7-cell or 8-cell cavity) and maximal accelerating gradient. At the design field, the maximum surface magnetic field is the same as for the 9-cell ILC cavity and the maximum surface electric field is below that of the ILC cavity [4].

The transit time factor $T(\beta)$ is defined as

$$T(\beta) = \frac{\left| \int E_z(r=0,z) \exp\left(\frac{i\omega z}{\beta c}\right) dz \right|}{\int |E_z(r=0,z)|\, dz} \qquad (1)$$

where the integrals of the longitudinal component of the electric field E_z along the longitudinal coordinate z are over the path of the beam traveling through the cavity on axis ($r = 0$), including the evanescent portion of the field in the beam tubes; ω is the angular RF frequency. The transit time factor is a useful indicator of a cavity's acceleration efficiency for a given beam velocity. Figure 3 shows the $T(\beta)$ for the three cavities. As one would expect, the cavities with fewer cells can be used for acceleration over a wider velocity range.

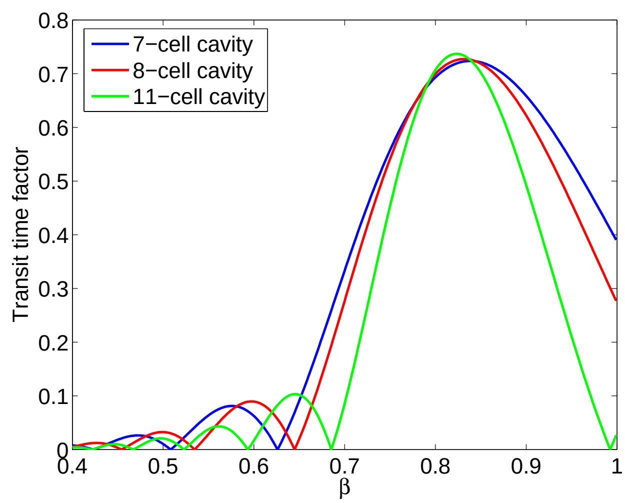

Figure 3: Dependence of the transit time factor on β for the three different types of $\beta_G = 0.81$ cavities.

PROTOTYPING STATUS

Four single-cell prototypes (with the same cell shape as of the 7-cell and 8-cell cavity, see Figure 2a) have been fabricated and tested. Two of these cavities were formed from large-grain niobium (Nb); the other two were formed from the traditional fine-grain Nb (grain size of $\sim 60\ \mu$m). The single-cell cavity fabrication and testing have been reported previously [8, 9]; surface preparation and RF testing was done in collaboration with Jefferson Laboratory. Similar gradients were reached in all four cavities ($E_a \simeq 25$ MV/m) after Ti treatment. An additional low temperature bake-out of the large grain cavities further improved the high-field performance to $E_a = 28$ MV/m, corresponding to $E_p = 62$ MV/m and $B_p = 128$ mT. This RF performance is satisfactory for the FNAL 8 GeV linac [9].

Two 7-cell cavities have been fabricated in 2007 by MSU [9], one from fine-grain Nb and the other from large grain Nb. The measurement of the RF performance of these two cavities has yet to be done. The prototyping of the 11-cell cavity has not yet been done.

BEAM DYNAMICS

Simulations with the ANL code `TRACK` [10] were performed along the S-ILC section (from $\sim$ 420 MeV to $\sim$ 1.2 GeV) at zero current for each of the 3 cavity types. The baseline lattice of the S-ILC section (described in the introduction) was used in all 3 cases, i.e 1 quadrupole followed by 2 cavities. The evolution of the kinetic energy is shown in Figure 4a: the 8-cell cavities were simulated with $E_p = 44.5$ MV/m (as defined in the current linac design), the 7-cell cavities with $E_p = 49.9$ MV/m (to match the energy gain of the 8-cell cavities) and the 11-cells with $E_p = 46$ MV/m (as defined in [4]). The energy gain per cavity for 11-cell cavities is higher, leading to a shorter S-ILC section: only 46 cavities are needed to reach 1.2 GeV (instead of the 56 cavities of type 7-cell or 8-cell). Figure 4b shows that, in all cases, there is no significant transverse or longitudinal emittance growth.

CONCLUSION

Three reduced-β cavity structures are currently being considered to accelerate the beam from $\sim$ 420 MeV to $\sim$ 1.2 GeV in the FNAL 8 GeV H^- linac. The 7-cell and 8-cell cavities differ only by the number of cells and have the advantage of efficiently accelerating the beam over a wider energy range compared to the 11-cell cavity. The cell shape for the 7-cell and 8-cell cavities has also demonstrated, in single-cell RF tests, a performance that matches the requirement for the FNAL proton driver; two prototype 7-cell cavities have been fabricated and are ready for RF testing. The 11-cell cavities have the advantage of being compatible with a Type-4 ILC cryomodule.

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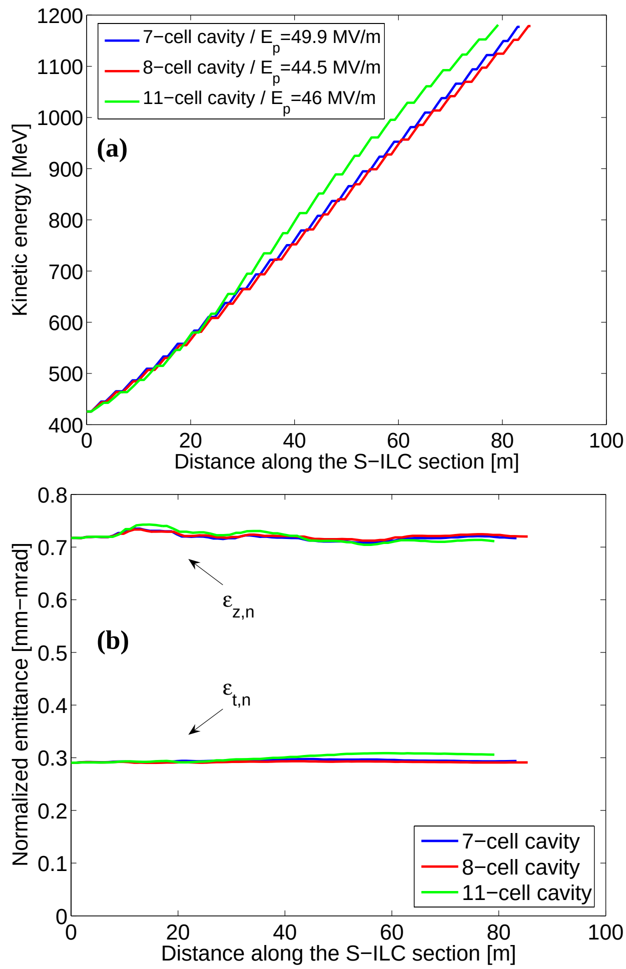

Figure 4: `TRACK` simulations of (a) the kinetic energy and (b) the transverse and longitudinal normalized RMS emittance along the S-ILC section of the FNAL 8 GeV linac at zero current for the three different types of S-ILC cavities.

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