**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-$\beta$ 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 Fermilab Upgrade 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 $1.56 \times 10^{14}$ 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 $\sim 2$ 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 transferred from the linac to the Main Injector by a $\sim 1$ km long high energy transport line.

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 $\sim 84.5$ m. The cavities are of 8-cell type and accelerate the beam from $\sim 420$ MeV to $\sim 1.2$ GeV. Two other reduced-$\beta$ 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...
Table 1: Parameters for the three S-ILC multi-cell $\beta_G=0.81$ cavities; $E_p = \text{peak surface electric field}$, $E_a = \text{accelerating gradient}$, $B_p = \text{peak surface magnetic field}$, $c = \text{speed of light}$, $k_c = \text{cell-to-cell coupling}$, $R = \text{shunt impedance}$, $Q = \text{quality factor}$, $G = \text{geometry factor}$.

<table>
<thead>
<tr>
<th>Item</th>
<th>units</th>
<th>7-cell</th>
<th>8-cell</th>
<th>11-cell</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of cells</td>
<td></td>
<td>7</td>
<td>8</td>
<td>11</td>
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<td>Wall inclination [deg]</td>
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<tr>
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<td>750</td>
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<td>$G$ [\Omega]</td>
<td></td>
<td>227</td>
<td>226</td>
<td>228</td>
</tr>
<tr>
<td>Iris (\phi) [mm]</td>
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<td>Beam pipe (\phi) [mm]</td>
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<td>Active length [mm]</td>
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<td>747.2</td>
<td>1028.1</td>
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</table>

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-$\beta$ 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

$$T(\beta) = \frac{\int E_z(r = 0, z) \exp \left( \frac{i\omega z}{c} \right) \, dz}{\int |E_z(r = 0, z)| \, dz}$$  (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; $\omega$ 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 $\beta$ for the three different types of $\beta_G = 0.81$ cavities.](image)

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 (\( E_a \approx 25 \, \text{MV/m} \)) after Ti treatment. An additional low temperature bake-out of the large grain cavities further improved the high-field performance to \( E_a = 28 \, \text{MV/m} \), corresponding to \( E_p = 62 \, \text{MV/m} \) and \( B_p = 128 \, \text{mT} \). 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 \( \sim 420 \, \text{MeV} \) to \( \sim 1.2 \, \text{GeV} \)) 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 \( E_p = 44.5 \, \text{MV/m} \) (as defined in the current linac design), the 7-cell cavities with \( E_p = 49.9 \, \text{MV/m} \) (to match the energy gain of the 8-cell cavities) and the 11-cells with \( E_p = 46 \, \text{MV/m} \) (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-\( \beta \) cavity structures are currently being considered to accelerate the beam from \( \sim 420 \, \text{MeV} \) to \( \sim 1.2 \, \text{GeV} \) 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.

**ACKNOWLEDGMENT**

The authors thank M. Hodek (MSU) for his assistance with the transit time factor calculations.

**REFERENCES**