UPGRADE OF THE DRIVE LINAC FOR THE AWA FACILITY DIELECTRIC TWO-BEAM ACCELERATOR*

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Abstract

We report on the design of a seven-cell, standing-wave, 1.3-GHz rf cavity and the associated beam dynamics studies for the upgrade of the drive beamline LINAC at the Argonne Wakefield Accelerator (AWA) facility. The LINAC design is a compromise between single-bunch operation (100 nC @ 75 MeV) and minimization of the energy droop along the bunch train during bunch-train operation. The 1.3-GHz drive bunch-train target parameters are 75 MeV, 10–20-ns macropulse duration, and 16 × 60 nC microbunches; this is equivalent to a macropulse current and beam power of 80 A and 6 GW, respectively. Each LINAC structure accelerates approximately 1000 nC in 10 ns by a voltage of 11 MV at an rf power of 10 MW. Due to the short bunch-train duration desired (~10 ns) and the existing frequency (1.3 GHz), compensation of the energy droop along the bunch train is difficult to accomplish by means of the two standard techniques: time-domain or frequency-domain beam loading compensation. Therefore, to minimize the energy droop, our design is based on a large stored energy rf cavity. In this paper, we present our rf cavity optimization method, detailed rf cavity design, and beam dynamics studies of the drive beamline.

INTRODUCTION

The Argonne Wakefield Accelerator (AWA) facility is dedicated to the development of new rf accelerating structures capable of producing gradients in excess of 100 MV/m, on the basis of electron-beam-driven wakefield acceleration [1]. The current facility uses a 1.3-GHz rf photocathode gun and rf cavity to produce 15-MeV single bunches of 100 nC or bunch trains of up to 4 × 30 nC. The maximum gradient generated at the current facility, 100 MV/m, was achieved in a short dielectric structure. In order to reach higher acceleration gradients (up to 300 MV/m), a facility upgrade is under way to increase the drive beam kinetic energy to 75 MeV and the total charge in the drive bunch train to 1000 nC.

The format of the drive bunch train is dictated by our current understanding of high-gradient breakdown. While breakdown is not well understood, it is clear that structures powered by short rf pulses sustain higher fields. On this basis, the AWA is now pursuing a short-pulse wakefield acceleration scheme [2]. Two modes of operation are envisioned. In single-bunch mode, a high-charge (~100-nC) drive bunch excites wakefields in a dielectric or metallic structure. In bunch-train operation, a 1.3-GHz drive bunch train will deliver approximately 1000 nC of total charge to the structure, distributed in bunch trains ranging from 8 × 100 nC to 32 × 30 nC. We describe the design procedure for the upgraded rf cavity and present preliminary simulations of a drive beamline.

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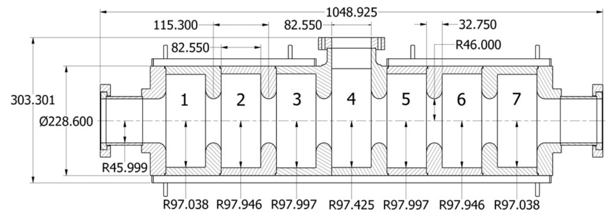

Figure 1. Cross section of the AWA rf cavity.

DRIVE LINAC DESIGN OBJECTIVES

The drive beam required for the AWA upgrade is an extremely high-charge, short-pulse beam. Approximately 1000 nC of charge located in a 10-ns bunch train must be accelerated up to 75 MeV. This means that the rf cavities must deliver 75 J in 10 ns, or 7.5 GW of beam power. Due to limited space, we only explain the design choices that were most relevant to our application.

2D Design Procedure

The design procedure was to tune the first six parameters of Table 1 to optimize those of Table 2, while minimizing cost. Optimization was subject to the usual constraints that the rf cavity (Fig. 1) be tuned and balanced.

Table 1: Optimized Iris-Loaded RF Cavity Parameters

Parameter (unit)	**Value**
iris radius, a (mm)	46.000
iris thickness, t (mm)	32.755
iris tip length to $t/2$ ratio	1.16
number of cells, N	7
mode	π
cell radius, b (mm)	97.039 to 97.997
cell length, L (mm)	115.305
gap, $g = L - t$ (mm)	82.55

RF Power

The first constraint imposed on the rf cavity design is the rf power budget. As part of the AWA upgrade, the facility is acquiring three additional klystrons capable of delivering 64 MW of 1.3-GHz power. We chose to divide this power between six rf cavities powered by approximately P_{in} = 10 MW each, for a voltage gain of 11.8 MeV. In addition, the coupling beta was optimized to 1.27 to maximize the stored energy for a 9-μs rf pulse.

Primary Design Objectives

The considerations that drove the rf cavity optimization were low cost, high single-bunch voltage gain (V), and low multibunch beam loading (ε, defined below).

Low Cost Fabrication costs were minimized by making the cell geometry simple and the number of cells few. This led us to choose a π-mode, iris-loaded cavity with as few cells as were consistent with the other design objectives. In addition, a z-slot rf coupler was used (due to its simplicity to machine), and the width of the rf coupler equalled the width of standard WR650 waveguide (to eliminate taper).

Multibunch Beam Loading Due to the very short bunch train (10 ns) of the AWA drive beam, the usual method of beam loading compensation is not feasible [3]. Therefore, we rely on the stored energy in the rf cavity to minimize the beam loading, although we will consider a ΔF method in the future [4]. The single-bunch voltage gain is $V = \sqrt{ZT^2 * P * L}$, the stored energy in the rf cavity is $U_0 = Q_o * P/\omega$, and the energy extracted is $U_b = Q_b V$, where Q_0, P, ω, Q_b, ZT^2, and L are the unloaded Q, power, angular frequency, bunch charge, effective shunt impedance per unit length, and length, respectively [3]. An energy droop across the bunch train occurs because the first bunch sees the full stored energy U_0, while the last bunch sees a reduced stored energy U_0-U_b. (There is no way to replenish this energy in the time frame of our 10-ns bunch train.) A conservative estimate of the ratio of the energy removed to the initial stored energy assumes that all the charge is in a single bunch and is given by

$$\varepsilon = U_b/U_0 = Q_b * \left(\omega/\sqrt{P}\right) * \left(\sqrt{r}/Q_0\right) \quad (1)$$

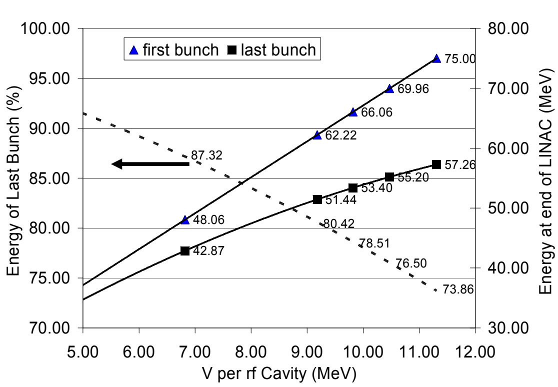

Figure 2. Energy droop (dash) vs. single-bunch energy gain (or shunt impedance) for Q_b = 1 μC.

where Q_b = 1000 nC. Since the $\omega = 2*\pi*1.3$ GHz and P = 10 MW are fixed, ε can only be minimized by raising Q_0 or lowering the shunt impedance, ZT^2*L. The figures of merit V and ε are primarily sensitive to structure parameters N and a (Table 1). The scan found that Q_0 was not very sensitive for the π-mode (~25,000), and therefore the only way to minimize ε is to reduce ZT^2*L. This means that there is a trade-off between the single-bunch energy gain and the energy droop of the bunch train. For the case of N = 5 (Fig. 2), we find V is approximately 7 MeV per cavity and the droop is only 13%, while near 11 MeV the droop rises to 27%. We chose to operate at V = 11 MeV per cavity and a droop of 27% (Table 2).

Secondary Design Objectives

Once the design was optimized to meet the major objectives, the usual rf cavity parameters were calculated to ensure they were satisfactory.

Dark Current And Pulsed Heating Dark current is minimized and breakdown is avoided when E_{surf} is less than twice the Kilpatrick limit. The Kilpatrick field at 1.3 GHz is 32 MV/m and the maximum field in the cavity is 33 << 64 MV/m. In addition, the peak surface magnetic field was calculated [5] to have a pulsed heating temperature rise of only 1.5°C.

Wakefields Single-bunch longitudinal wakefields will reduce the mean energy of the beam (μ_E) and increase its energy spread (σ_E). The code ABCI [6] was used to simulate the wake function. For the case of Q_b = 100 nC and σ_z = 2 mm (Table 2), the fractional energy loss was μ_E/V = 3%, which reduces the total energy gain from 78 to 76 MeV. In addition, σ_E/V = 1.3%, which is less than the space-charge-induced energy spread. Both are within acceptable limits.

Mode Separation The seven TM-010-like modes of the rf cavity must be separated widely enough to avoid overlapping of modes. The natural width of π mode is Δf = f/Q = 0.05 MHz. Due to the large irises of our rf cavity, the intercell coupling constant is large, k = 0.0532, and the mode separation of the π mode can be estimated with [3],

$$\frac{\Delta f}{f} = k\left(\frac{\pi}{2N}\right)^2 \quad (2)$$

For N = 7, Eq. (2) yields Δϕ = 3.5 MHz. In addition, by coupling rf into the center cell, the 5π/6 mode can be suppressed and the mode separation can be further increased to 14.7 MHz. This separation is wide enough for stable operation.

Power Flow Phase Shift Due to the energy flow in the cavity, a cell-to-cell phase shift occurs. The total phase shift from the drive cell to cell N [3, 7] is given by,

$$\Delta\phi = \frac{(N-1)^2\sqrt{1-k}}{kQ_0} \quad (3)$$

from which we have $\Delta\phi = 0.17^o$, which is negligible.

3D DESIGN

Accurate numerical simulations were carried out with Omega3p [9] in order that the cavity could be machined to its final dimension in a single step. The 3D rf cavity is shown in Figure 3.

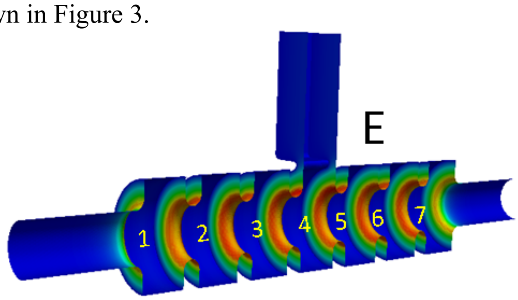

Figure 3. E field on the rf cavity inner walls.

Table 2: RF Cavity Figures of Merit

Parameter (unit)	Value
unloaded voltage gain, V (MV)	11.8
$\varepsilon = U_b/U_0$ @ 1 μC (%)	43.15
μ = mean energy loss due to wakes[1] (keV)	394
σ = rms energy spread due to wakes[1] (keV)	159
energy droop along beam[1] (%)	27
E_{surf} (MV/m)	33.5
H_{surf} (kA/m)	58.8
pulsed heat temp. rise (^{o}C)	1.5
Q_0	24320
U_0 (J)	27.49
coupling parameter, β	1.28
mode separation (MHz)	14.7
power flow phase shift (^{o})	0.17

[1]For P_{in} = 10 MW and Q_b = 100 nC, σ_z = 2 mm.

PRELIMINARY SIMULATIONS

Simulations of the drive beamline were made using Impact-T [8] to make preliminary estimates of ability of the upgraded drive beam to deliver bunch trains through small-diameter, long dielectric-loaded-accelerating (DLA) structures. The single-bunch result (Fig. 4, 10.00-MeV beam) shows that we can deliver a 40-nC beam through a 1.2-mm-diameter, 1-m-long structure.

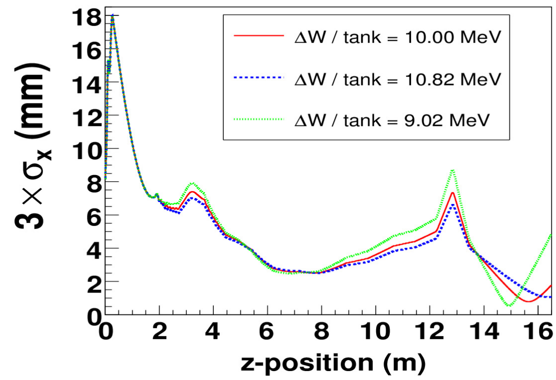

Figure 4. 3*RMS beam envelope along the beamline.

As mentioned above, the major difficulty with passing the high-charge drive bunch train through a small-diameter DLA structure is due to energy droop across the train. The bunch-train result (Fig. 4) shows that we can deliver a 10 × 40 nC train through a 2.6-mm-diameter, 1-m-long structure. The first bunch gains the maximum energy (10.82), and the last bunch gains the least (9.02).

FUTURE WORK

The simulations and mechanical design of the rf cavities are complete. The cavities have been sent out for bids on both the machining and brazing processes to local vendors. The rf cavities are expected to be completed in mid-2011.

CONCLUSION

Efforts to upgrade the AWA drive beam are under way. A seven-cell, π-mode rf cavity has been designed to accelerate the extremely high-charge (1000-nC), short-pulse (10-ns) AWA drive bunch train. Due to the short pulse duration of the bunch train, the energy droop across the beam is minimized using the stored energy in the cavity. The cavity will be fabricated by local shops and is expected to be delivered in mid-2011.

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