ENERGY COMPRESSION SYSTEM RADIO FREQUENCY DESIGN AT THE CANADIAN LIGHT SOURCE*

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Abstract

The Canadian Light Source (CLS), Canada's only synchrotron light source, is considering a linear accelerator (LINAC) upgrade. As a result, the radio frequency (RF) structure in the downstream Energy Compression System (ECS) needs to be redesigned. In this paper, we describe the design process followed to determine the geometry of the RF structure cells and coupler.

INTRODUCTION

As part of a potential LINAC upgrade, the CLS requires a redesign of its existing ECS which consists of a three-dipole magnet chicane and a travelling-wave accelerating structure. An ECS is required to inject beam from the LINAC into the booster ring without the beam being lost due to the high dispersion in the booster. Reduction of the relative energy spread of a particle bunch begins by introducing an energy chirp into the longitudinal phase space by passing the beam through a magnetic chicane which causes the low energy particles to follow a longer path than the high energy particles of the bunch. The chirped bunch passes into a travelling-wave RF accelerating structure that reduces the energy-spread of the electrons by operating off-crest.

RF STRUCTURE DEVELOPMENT

Single-cell Design

Design of a travelling-wave constant impedance accelerating structure began with the single-cell design (Fig. 1). The cell length was determined using [1]

$$L_{cell} = \frac{c\phi}{2\pi f_0}, \tag{1}$$

with $f_0 = 3\,000.24$ MHz and $\phi = 2\pi/3$. Models of fixed iris aperture a, with circular iris of radius 2.5 mm, were simulated with multiple b to determine the outer radius b required to establish a TM_{01} eigenmode of the cell at f_0. This was done by using the combination of CST Studio Suite's [2] parameter optimizer and Eigenmode solver.

The cell geometries found to resonate at 3000.24 MHz in CST were simulated in SUPERFISH and Omega3P to determine the cells' RF parameters. The lack of a periodic boundary condition in SUPERFISH required $\frac{1}{2}, 2, \frac{1}{2}$ cells be simulated with Neumann (PEC) boundary conditions on the upstream and downstream surfaces [3]. The resonant frequencies and shunt impedances were calculated in SUPERFISH (see Table 1). The group velocity was calculated using [4],

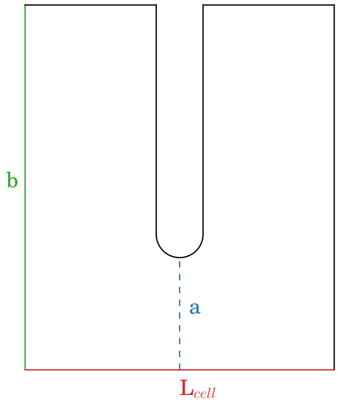

Figure 1: Geometry of a single cell of ECS RF structure with cylindrical symmetry.

$$v_g = \frac{P}{U} = \frac{\frac{1}{2}\int E_r H_\phi \, dS}{U} = \frac{\pi \iint E_r H_\phi r \, dr d\phi}{U}, \tag{2}$$

where P is the power flowing through a surface perpendicular to the beam axis, U is the energy stored per unit length, E_r is the radial component of the electric field, H_ϕ is the azimuthal component of the magnetic field which are extractable using the SF7 post-processing tool. To verify the SUPERFISH results, the single-cell models were simulated in Omega3P using Master-Slave boundary conditions on the upstream and downstream surfaces with an imposed phase advance of 120°. After it was verified Omega3P had found a TM_{01} mode whose E_z had a $2\pi/3$ phase advance, the models' quality factor Q, shunt impedance R_{sh}, and group velocity v_g were computed (see Table 2). The group velocity was computed twice: directly using Omega3p post-processing and using the dispersion diagram [1]

$$v_g = \frac{dw}{dk} = \frac{2\pi\Delta f}{2\pi/\Delta\lambda} = \Delta f \Delta\lambda = \frac{2\pi\Delta f L_{cell}}{\Delta\phi}, \tag{3}$$

where Δf is the change in frequency for a change of imposed phase advance $\Delta\phi$.

Curves were fit to R_{sh} vs. a and v_g/c (%) vs. a plots. The fit equations were used to interpolate R_{sh} and v_g/c (%) for intermediate a values. The shunt impedance and v_g/c values were used to calculate the filling time t_f, attenuation coefficient τ, and voltage across a structure consisting of 16 cells, V using Eqs. (4-6) [1]. The number of cells in the

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structure, N_{cell} was determined by measuring the available space for the accelerating structure in the ECS and dividing the available space by L_{cell}.

$$t_f = \frac{L_{\mathrm{cell}}c}{v_{\mathrm{g}}/c}, \tag{4}$$

$$\tau = \frac{2\pi f_0 t_{\mathrm{f}}}{2Q}, \tag{5}$$

$$V = \sqrt{2\tau}\left(\frac{1-e^{-\tau}}{\tau}\right)\sqrt{PR_{\mathrm{sh}}L_{\mathrm{cell}}}\cos(59.15°), \tag{6}$$

P in Eq. (6) refers to the input power available from the source, in our case 2 MW from a klystron amplifier. An approximate average Q of 13,550 was chosen for the attenuation coefficient calculation.

Table 1: Results of 3000.24 MHz Single-cell SUPERFISH Simulations

a (mm)	**R$_{\mathrm{sh}}$ (MΩ/m)**	**v$_{\mathrm{g}}$/c (%)**	**t$_{\mathrm{f}}$ (ns)**	**τ (Np)**	**V (MV)**
11	58.19	1.41	128.03	0.089	1.64
11.5	56.23	1.64	109.66	0.076	1.50
12	54.32	1.90	94.82	0.066	1.38
12.5	52.47	2.18	82.70	0.058	1.27
13	50.67	2.48	72.70	0.051	1.18

Table 2: Results of 3000.24 MHz Single-cell Omega3P Simulations

a (mm)	**R$_{\mathrm{sh}}$ (MΩ/m)**	**v$_{\mathrm{g}}$/c (%)**	**t$_{\mathrm{f}}$ (ns)**	**τ (Np)**	**V (MV)**
11	60.40	1.41	128.03	0.0891	1.67
11.5	58.89	1.64	109.66	0.0763	1.54
12	57.38	1.90	94.82	0.0660	1.42
12.5	55.87	2.18	82.70	0.0575	1.31
13	54.35	2.48	72.70	0.0506	1.22

The reference energy of the electron beam at the end of the LINAC is 250 MeV with a relative energy spread of 1%. To reduce the energy spread of a bunch, the accelerating structure needs to be able to achieve a V of 1.25 MV at the head and tail of the bunch which correspond to phases of 59.15° and 120.9° respectively. The smallest iris gives the largest total voltage however, in general, it also introduces noticeable wakefield effects. An iris aperture of $a = 12$ mm was chosen.

Coupler Design

A slot coupler design was chosen to transfer power from wr284 waveguide to the ECS accelerating structure (see Fig. 2). To determine the slot geometry required for efficient power transfer, i.e matching, it was decided the slot would have a fixed length of 14.153 5 mm, the length of half a cell without the iris section. The distance between the matching cell and the wr284 waveguide was constant, $h = 12.5$ mm. The slot width w, and the radius of the matching cell r, were variable parameters.

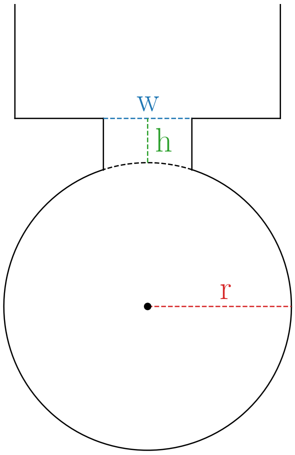

Figure 2: RF coupler geometry from wr284 waveguide to accelerating structure matching cell.

To match the coupler to the structure a method described in [5, 6] was used by varying the matching cell radius and coupling slot width of two models shown in Fig. 3 and simulating in CST Studio Suite's frequency domain solver. The objective of matching was to find the parameters w and r such that

$$S_{11} < -20 \text{ dB}, \tag{7}$$

at $f_0 = 3\,000.24$ MHz where S_{11} is the scattering parameter that quantifies the amount of power reflected back to the input coupler port for the 1-cell and 2-cell models. The geometry satisfying condition (7) needed to also provide

$$S_{21} \simeq 0 \text{ dB}, \tag{8}$$

at $f_0 = 3\,000.24$ MHz where S_{21} is the scattering parameter defining the power from the input present at the output coupler.

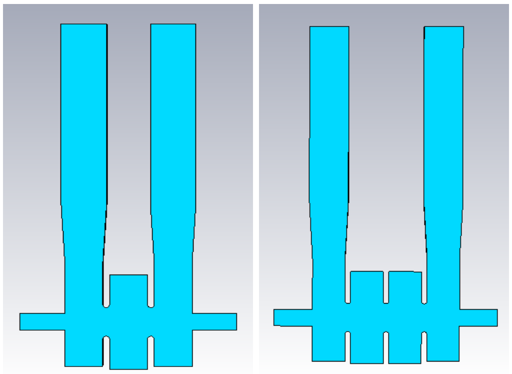

Figure 3: The first model included the input, output waveguides, tapers and matching cells with a single cell between the couplers. The second model was the same as the first but with two cells between the couplers.

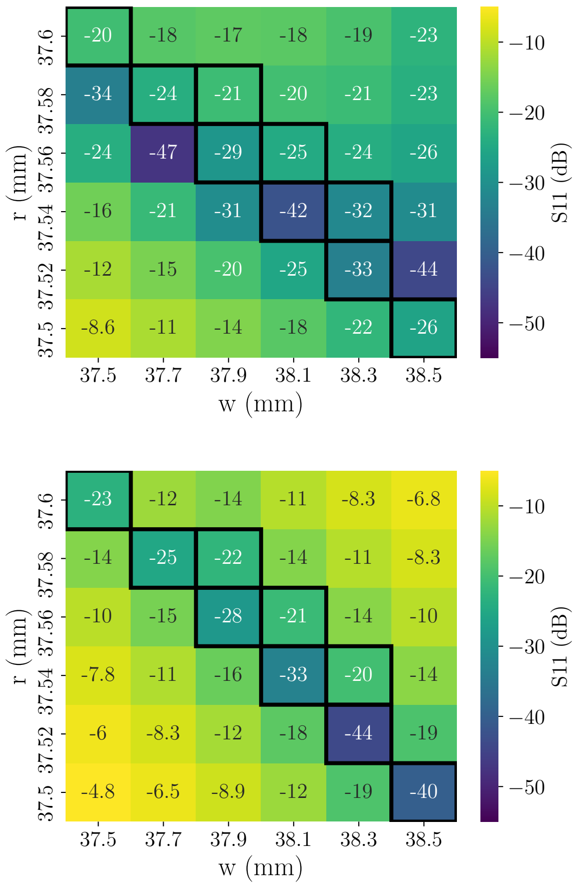

Figure 4: Heat map of 1-cell model parameter sweep (top). Heat map of 2-cell model parameter sweep (bottom). Geometries that satisfy conditions (7- 8) are highlighted with black borders.

A given w and r needed to simultaneously satisfy the Eq. (7) constraint for two different models to avoid S_{11} being artificially low due to two reflected waves from the input and output couplers being 180° out of phase [7, 8]. The reported S_{11} of a particular coupler geometry is the S_{11} with the smallest magnitude from both models [6]. The results of the CST parameter sweep are shown in Fig. 4. Possible solutions have black boxes surrounding the S_{11} values. These solutions also satisfy Eq. (8) for the 1-cell and 2-cell models.

To perform coupler parameter sweeps in S3P, an automation script was implemented in Python to produce models with fixed coupler geometry, mesh the models, prepare S3P input files, prepare slurm job files and create a directory structure for the simulations. The files were uploaded to Compute Canada's Cedar cluster where the Cubit .gen mesh files were converted to .ncdf type and the simulation jobs were submitted using a second script. A final script retrieved the computed S11 values for coupler geometries with 1 and 2 intermediate cells. The S3P S_{11} results agreed with the CST scans.

CONCLUSION

A constant impedance travelling wave linear accelerator was designed to operate off-crest as part of an energy compression system. The single cell iris aperture was selected based on the net voltage seen by the head and tail of the CLS LINAC bunch. Power coupler matching was accomplished by varying the matching cell radius and slot iris until of coupler models with 1 and 2 intermediate cells until the S_{11} was less than -20 dB while S_{21} remained high.

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