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Design of the Detuned Accelerator Structure*

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Abstract

This is a summary of the design procedure for the detuned accelerator structure for SLAC's Next Linear Collider (NLC) program[1]. The 11.424 GHz accelerating mode of each cavity must be synchronous with the beam. The distribution of the disk thicknesses and lowest synchronous dipole mode frequencies of the cavities in the structure is Gaussian in order to reduce the effect of wake fields[2]. The finite element field solver YAP calculated the accelerating mode frequency and the lowest synchronous dipole mode frequency for various cavity diameters, aperture diameters and disk thicknesses. Polynomial 3-parameter fits are used to calculate the dimensions for a 1.8 m detuned structure. The program SUPERFISH was used to calculate the shunt impedances, quality factors and group velocities. The RF parameters of the section like filling time, attenuation factor, accelerating gradient and maximum surface field along the section are evaluated. Error estimates will be discussed and comparisons with conventional constant gradient and constant impedance structures will be presented.

I. ACCELERATING MODE

The accelerator structure is a disk loaded waveguide driven at 11.424 GHz. The phase advance per cell is chosen to be $\phi = 2\pi/3$. In order for the accelerating mode to maintain synchronism with the beam the phase velocity must be $v_\phi = c$, thus the cell length is $l = 0.8748\,\text{cm}$.

Synchronism with the beam is a constraint on the dimensions of a cell. The dimensions are the disk aperture $2a$, the cell diameter $2b$ and the disk thickness t. The inner edge of the disks are round with full radius, not flat. The RF parameters of a cell can be computed by treating the cell as part of a periodic structure. Let $f_o(2a, 2b, t)$ be the accelerating mode frequency at $\phi = 2\pi/3$. Then the synchronism constraint is

$$f_o(2a, 2b, t) = 11.424\,\text{GHz}. \qquad (1)$$

This can be considered an implicit formula for $2b(2a, t)$ for the cells of the accelerator structure. That is, given the parameters $2a$ and t of a cell, solve (1) for $2b$.

The finite element field solver YAP[3] was used to compute the accelerating mode frequency f_o for various cell dimensions covering the range $0.7493\,\text{cm} \le 2a \le 1.1684\,\text{cm}$ and $0.1016\,\text{cm} \le t \le 0.2540\,\text{cm}$. The range of cell diameters was $2.0828\,\text{cm} \le 2b \le 2.3622\,\text{cm}$. For a given set of dimensions ($2a$, $2b$ and t) meshes for one cell of a periodic structure were constructed using triangular elements. The

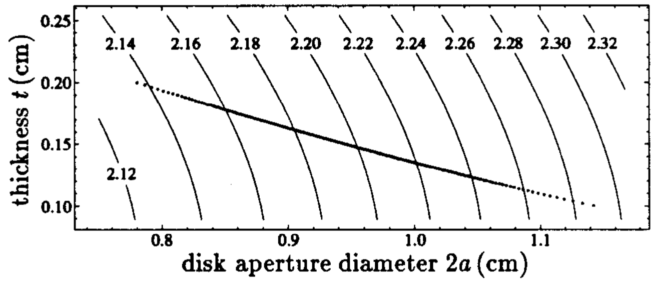

Figure 1. The cell diameter $2b$ (in cm) which yields synchronism with the beam ($v_\phi = c$). The dots are the 206 cells of the detuned accelerator structure. The rightmost dot is the first (input) cell and the leftmost dot is the last (output) cell.

number of elements and the topology of the meshes are independent of the cell parameters, so the mesh depends smoothly on the cell dimensions. Then discretization error can be considered a systematic error when comparing two cells with slightly different dimensions.

The accelerating mode frequency f_o was calculated by YAP using four successively refined meshes composed of quadratic elements. The estimated relative accuracy of the frequency calculation for the finest mesh is $\sim 10^{-6}$. Further accuracy was obtained by extrapolating the four calculations to zero element size (an infinitely refined mesh). Conservative error estimates for the extrapolated f_o range from 5 KHz for large t cases to 30 KHz for small t cases.

The calculations were fit to the polynomial

$$f_o(2a, 2b, t) = \sum_{i=-1}^{1} \sum_{j=0}^{2} \sum_{k=0}^{4} \bar{f}_{ijk} (2b)^i (2a)^j t^k. \qquad (2)$$

Only 165 calculations with $|f_o - 11.424\,\text{GHz}| < 150\,\text{MHz}$ were included in the least squares fit for the 45 parameters. The polynomial approximates the calculations with residual errors $< 80\,\text{KHz}$. The polynomial can be used to solve (1) for the cell diameter $2b$ with an error $\sim 1\,\mu\text{m}$. This error is comparable to the skin depth in copper at the operating frequency and about an order of magnitude smaller than available machining tolerances. A contour plot of $2b(2a, t)$ is shown in Figure 1.

II. DIPOLE MODE

In order to reduce the effect of wakefields it is useful to detune or spread out the frequencies of the undesired modes. A Gaussian distribution of the modes leads to very good cancellation of the wakefield effects. The wakefield decoheres in a time comparable to the reciprocal of the width of the frequency distribution of the modes.

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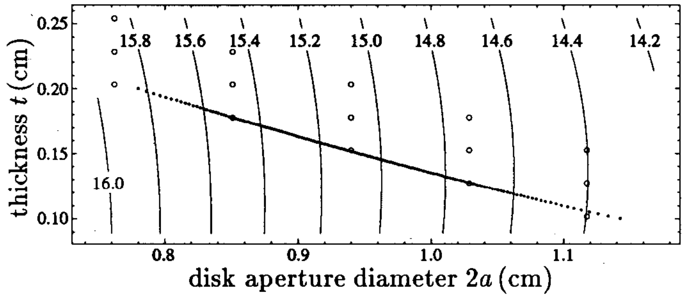

Figure 2. The lowest synchronous dipole mode frequency f_1 (in GHz). The cell diameter $2b$ is determined from the synchronism condition. The open circles are the dimensions at which f_1 was computed. The dots are the 206 cells of the detuned accelerator structure.

The largest wakefield by far comes from the lowest dipole mode. Higher dipole modes have less effect and can be effectively detuned by varying the disk thickness t along the structure such that the distribution of thicknesses is nearly Gaussian[4]. The disk thickness t has little effect on the lowest dipole mode, so the aperture diameter $2a$ is varied along the structure such that the distribution of lowest synchronous dipole mode frequencies f_1 is nearly Gaussian. While the synchronous dipole mode frequencies of the cells are not the same as the dipole mode frequencies of the structure, the distributions of the frequencies are similar according to equivalent circuit models of the structure[5].

A Gaussian distribution with rms width $2\sigma = 0.7\,\text{GHz}$ provides decoherence of the wakefield effects by the time the following bunch arrives (1.4 ns). To obtain good cancellation of wakefield effects over the whole bunch train (perhaps 90 bunches) it is necessary to have a good distribution of modes. Beam dynamics simulations[6] for the NLC indicate the tolerance for systematic relative frequency errors is approximately 10^{-4}, hence accurate calculations of f_1 are important for the design of detuned accelerator structures.

The lowest synchronous dipole mode frequency f_1 was calculated using YAP[7]. The cell diameter $2b$ was fixed using the beam synchronism constraint (1), so two parameters remain for the dipole mode calculations: $2a$ and t. Frequencies at two phase advances ϕ close to the synchronous phase and 0.02 radians apart were computed for 15 cells. Calculations on three successively refined meshes were extrapolated to zero mesh size, with conservative error estimates ranging from 120 KHz for large t cases to 400 KHz for small t cases. Then the lowest synchronous dipole mode frequency and phase advance were obtained using linear interpolation. The frequencies were fit to a polynomial quadratic in $2a$ and t. The estimated error of the fit is 600 KHz. The fit is shown in Figure 2 and is expected to be good only near the region encompassed by the 15 calculated points.

The Gaussian distributions for t and f_1 for 206 cells were truncated at $\pm 2\sigma$. The range of the disk thickness t was chosen to be 0.1 cm to 0.2 cm. This is sufficient to specify t for all cells. The relative range of f_1 was chosen to be 10.1%. With this information only one free parameter for the whole structure remains. In practice the parameter was the aperture diameter $2a$ of the first cell, but the average lowest synchronous dipole mode frequency is also a viable free parameter. In either case the free parameter determines f_1 for each cell. Given f_1 and t for a cell the aperture diameter $2a$ was found using the quadratic polynomial approximation to the lowest synchronous dipole mode frequency. Then the cell diameter $2b$ was obtained from $2a$, t and the synchronism constraint (1).

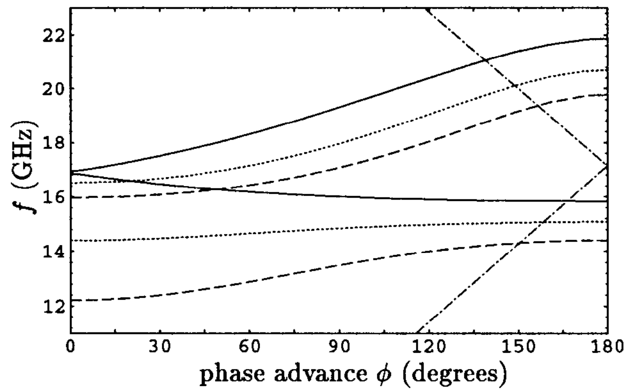

Figure 3. Dispersion diagram for the two lowest dipole modes of three differenct cells of the structure. The dashed line is the first (input) cell, the dotted line is the middle cell and the solid line is the last (output) cell. The dot-dash line is the velocity of light line.

III. STRUCTURE RF PARAMETERS

RF parameters like the shunt impedance, quality factor Q, group velocity v_g and peak surface field to accelerating gradient ratio $E_{s,\max}/E_{\text{acc}}$ were computed for the accelerating mode by SUPERFISH[8] for a few of the cells. While the code calculates RF parameters for periodic structures, the calculations are still valid locally for the detuned structure since the cell dimensions vary slowly. A polynomial fit was used to obtain the RF parameters for the remaining cells. The filling time of the structure was computed from

$$T_f = \int_0^{1.8\text{m}} \frac{dz}{v_g(z)}. \tag{3}$$

The free parameter (e.g., the aperture diameter $2a$ of the first cell) of the structure was varied to achieve $T_f = 100\,\text{nsec}$. The corresponding cell dimensions are plotted in Figures 1 and 2.

Dispersion curves for the two lowest dipole modes of three cells (first, middle and last) of the structure were computed using YAP and are shown in Figure 3.

The accelerating gradient along the length of the structure was computed[9] by first finding the attenuation $\tau(z)$ along the structure,

$$\tau(z) = \int_0^z \frac{\omega\, dz}{2Q(z)\, v_g(z)} \tag{4}$$

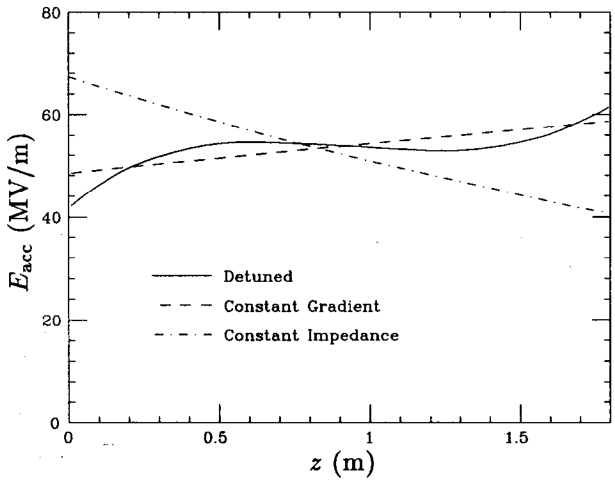

Figure 4. Accelerating gradient along the length of the structure for 100 MW input power and various structure types.

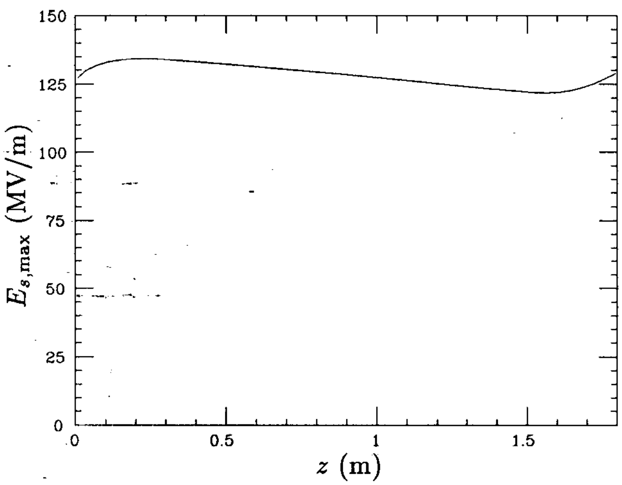

Figure 5. Peak surface gradient along the length of the detuned accelerator structure for 100 MW input power.

where $\omega = 2\pi f_o$ is the angular frequency. Then the power flow $P(z)$ in the structure is

$$P(z) = P_{\rm in} e^{-2\tau(z)} \tag{5}$$

and the accelerating gradient is

$$E_{\rm acc}(z) = \sqrt{r(z)\frac{dP}{dz}(z)} \tag{6}$$

where $r(z)$ is the shunt impedance per unit length. The gradient is shown in Figure 4 along with gradients for a conventional constant gradient structure and a constant impedance structure. All three structures in Figure 4 have the same attenuation constant τ.

It is noteworthy that the peak surface field $E_{s,\rm max}$ on the disk edges varies little along the structure as shown in Figure 5. The first cell has a thin disk and large aperture, so $E_{s,\rm max}/E_{\rm acc}$ is high ($\cong 3$) but $E_{\rm acc}$ is small due to the low shunt impedance and high group velocity. For the last cell the situation is just the opposite. Other RF parameters are listed in Table 1.

Table 1
Structure RF Parameters

Section length	1.8 m
Phase advance per cell	$2\pi/3$ radians
Iris aperture:	
radius	5.72–3.91 mm
normalized radius	0.218λ–0.149λ
Group velocity	$0.12c$–$0.03c$
Filling time	100 ns
Unloaded time constant	207–186 ns
Attenuation constant	0.517 nepers
Shunt impedance	67.5–88.0 MΩ/m
Elastance	853–946 V/pC/m
For 50 MV/m average gradient:	
Peak input power/(1.8 m)	48.1 MW/m
Peak power per feed	86.5 MW
Average power dissipation for 250 ns pulses, 180 pps	1.4 kW/m

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