DESIGN OF HIGH AVERAGE POWER LINEAR ELECTRON ACCELERATOR SECTIONS

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The design of electron travelling wave linear accelerators is a well covered subject. In particular, R. Neal[1] developed an analytic formulation of beam loading for such periodic structures, treating them as continuously variable in description. His work assumed a constant shunt impedance. It is a straightforward generalization to allow for varying shunt impedance and to treat the problem as discrete cavities and do the integrals in a step-wise fashion.

Up until the advent of high average power RF sources, the need to design linacs with significant heat removal capability was non-existent. Linac cooling systems were in fact more a temperature bath than a heat removal system. The copper structures were more or less iso-thermal and the tuning maintained by regulation of the temperature of the copper.

When heat removal becomes significant, so do the thermal gradients, mechanical distortion and frequency de-tuning. The preservation of synchronism is accomplished by reducing the water temperature to maintain some target thermocouple at the tuning temperature. Placement of this target thermocouple is at a point that when kept at the original tuning temperature the structure will maintain synchronism (at both isothermal and full gradient conditions). For structures with which we are familiar, this is typically somewhere in the disc, roughly half-way in. The existence of such a point is certain.

Whether or not the design is viable depends on the accumulated phase error the electron sees traversing the structure. This phase error, with control of the water temperature, should be kept to only a few degrees of phase to insure high beam quality as well as the energy of the centroid. The per cell contribution to phase error is inversely proportional to the group velocity of the mode.

In practice, using computer analysis programs for thermal response and mechanical distortion (We prefer ANSYS which has both built in and is only a few hours per run), we input the heat loads from cavity analysis programs like URMEL or SUPERFISH. Then, the distorted cavity shape is analyzed for frequency shift using the Slater perturbation theory.[2] The target thermocouple is located where the frequency change is negligible.

A first approach would be to make a machine which is constant gradient, use a ridiculously high flow rate of cooling water and ignore different 'target' locations for different beam hole sizes. Usually the designer is handed a few constraints; in the case of the High Average Power L-band Accelerator,

1) number, frequency, peak and average power of sources

2) schedule of I(n/m), r(Mohm/m), and v_g .vs. hole size

3) required kinetic energy at operating current

4) maximum length (minimum gradient)

A design with constant gradient at full current would start with the theory of Neal, which assumes a constant shunt impedance. The attenuation schedule of such a machine is given by,

$$I = I_0/(1-\alpha z)$$

$$;\ \alpha = \frac{\eta}{L}\left(1 + \frac{\eta}{L}\left(\frac{P_0}{i^2 r}\right)\right)$$

$$I_0 = \frac{i^2 r + 2\alpha P_0 - i\sqrt{i^2 r^2 + 4\alpha r P_0}}{4P_0}$$

$$\eta = \frac{iL}{P_0}\sqrt{2 I_0 P_0 r} \quad \text{efficiency}$$

There are a number of reasons to modify the approach to a design which has a constant gradient at a lower current than the operating current. This approach means that the heat can be concentrated at the input (high v_g) end of the machine, where thermal detuning is of little consequence. We also get much higher conversion efficiency. We have to be very careful to design the water system to warm up downstream cavities that get very little RF heat.

In the design of these structures, we have allowed for the changing shunt impedance with a model which discretely integrates the energy flow equations.

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A sample plot of I,r,v_g .vs. beam hole size is shown for our 3pi/4 structure.[3] The cavity period is 8.65 cm at 1300 MHz. Cavity tuning errors translate into phase slip errors. They are inversely proportional to the group velocity. It is paramount that we keep the group velocity as high as possible, since this will greatly minimize the accumulated phase error over the length of the section. This is clear since 1) phase error is inversely proportional to the group velocity, 2) Heat is inversely proportional to the group velocity, and 3) Smaller holes (low group velocity) tend to distort more yielding larger frequency de-tuning. Alternately, we want to minimize the average attenuation of the section.

For the Boeing High Average Power Linac we have settled upon the design, shown in Figure 1, which is constant gradient at 0.1A. Our structures are tuned at room temperature and air pressure. They are then in tune under vacuum, when elevated to 45 degrees C. Performance under various operating conditions is shown in Figure 2.

The temperatures shown for various cavities are the operating temperatures at the "target" location. Deviations from the tune temperature are errors and the cumulative phase error relates to the same.

The other part of the structure that must be modified for high average power is the waveguide power coupler. The TE_{10} waveguide mode couples to the H-field in the accelerator TM_{01}-like fundamental mode. The cavity wall is allowed to be near a knife edge at the coupler. Analysis has shown that at 2.5% duty factor, the temperatures at the edge go dangerously high. Our approach is to make these knife edges (1/32") go to at least 1/8". This improves heat conduction away from the coupler to the cooling passages nearby.

<u>References</u>:

1. R.B.Neal, "Theory of Constant Gradient Linear Electron Accelerator", R.B.Neal, Stanford Microwave Laboratory Report No. 513, May 1958

2. J.C.Slater, <u>Microwave Electronics</u>, D. Van Nostrand, New York, 1950 p.80

3. T.Buller, et. al., "Boeing Travelling Wave Structure Electrical Performance", proceedings this conference.

Figure 1, HAP cavity schedule

cav	beam hole(in.)	r(Mohms/m)	I(nepers/m)	Vg/c
1	2.784	36.0	.05	.0120
2	2.773	36.1	.051	.0117
3	2.768	36.2	.0515	.0116
4	2.762	36.3	.052	.0114
5	2.751	36.4	.053	.0111
6	2.746	36.5	.0535	.0110
7	2.740	36.6	.054	.0108
8	2.729	36.7	.055	.0106
9	2.724	36.8	.0555	.0104
10	2.718	36.9	.056	.0103
11	2.707	37.0	.057	.0100
12	2.702	37.1	.0575	.0099
13	2.696	37.2	.058	.0098
14	2.685	37.3	.059	.0096
15	2.674	37.4	.06	.0095
16	2.669	37.5	.0605	.0094
17	2.663	37.6	.061	.0093
18	2.652	37.7	.062	.0092
19	2.641	37.9	.063	.0091
20	2.630	38.0	.064	.0090
21	2.621	38.1	.065	.0089
22	2.611	38.2	.066	.0087
23	2.602	38.3	.067	.0086
24	2.593	38.5	.068	.0085
25	2.574	38.7	.07	.0082
26	2.565	38.8	.071	.0080
27	2.556	38.9	.072	.0079
28	2.546	39.0	.073	.0077
29	2.537	39.1	.074	.0076
30	2.528	39.3	.075	.0074
31	2.509	39.5	.077	.0071
32	2.494	39.7	.079	.0069
33	2.482	39.8	.081	.0068
34	2.476	39.9	.082	.0067
35	2.471	40.	.083	.0066

Figure 2, HAP performance

i=0.29A, Po=10MW, 2.5% duty factor, 25gpm, 25 deg C inlet temp.

cav	P(MW)	Heat(kW)	Gradient(MV/m)	MeV	T(@target)
1	10.	2.16	6.0	0.52	44.5
4	9.3	2.09	5.92	2.07	44.9
7	8.6	2.01	5.83	3.59	45.2
10	7.9	1.92	5.72	5.09	45.4
13	7.3	1.82	5.60	6.55	45.5
16	6.6	1.74	5.49	8.00	45.6
19	6.0	1.64	5.36	9.39	45.6
22	5.4	1.55	5.23	10.8	45.5
25	4.9	1.47	5.13	12.1	45.5
28	4.3	1.36	4.95	13.4	45.2
31	3.8	1.26	4.79	14.6	44.9
35	3.1	1.12	4.54	16.3	44.4

change in phase length of structure < 3 degrees
synchronous phase error -0.4 to +2.4 degrees

i=0.2A, Po=10MW, 2.5% duty factor, 50gpm, 25.5 deg C inlet temp.

cav	P(MW)	Heat(kW)	Gradient(MV/m)	MeV	T(@target)
1	10.	2.16	6.0	0.52	45.0
4	9.4	2.12	5.97	2.07	45.2
7	8.9	2.07	5.92	3.62	45.4
10	8.3	2.01	5.86	5.14	45.4
13	7.8	1.95	5.79	6.66	45.4
16	7.2	1.89	5.73	8.15	45.4
19	6.7	1.83	5.66	9.62	45.3
22	6.2	1.77	5.59	11.1	45.3
25	5.7	1.73	5.56	12.5	45.4
28	5.2	1.65	5.45	13.9	45.1
31	4.7	1.58	5.37	15.3	44.9
35	4.1	1.48	5.23	17.2	44.5

change in phase length of structure < 3 degrees
synchronous phase error +0.0 to +2.4 degrees

i=0A, Po=10MW, 0.5% duty factor, 100gpm, 40.5 deg C inlet temp.

cav	P(MW)	Heat(kW)	Gradient(MV/m)	MeV	T(@target)
1	10.	.433	6.0	0.52	44.4
4	9.74	.438	6.06	2.09	44.5
7	9.47	.443	6.12	3.68	44.6
10	9.21	.446	6.17	5.27	44.7
13	8.94	.448	6.21	6.88	44.8
16	8.67	.454	6.27	8.51	45.0
19	8.39	.458	6.33	10.1	45.1
22	8.12	.464	6.40	11.8	45.2
25	7.84	.475	6.52	13.5	45.4
28	7.55	.477	6.56	15.2	45.5
31	7.27	.484	6.65	16.9	45.6
35	6.88	.494	6.76	19.2	45.8