ARDB Tech Note No. 63

Scalings for the Ring-Linac

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In this note we set down the basic design scalings for the ring linac, absent tuning errors. Breakdown threshold is also discussed. A best estimate is set down for the timeline for the preparation for this experiment.

Scalings for a Tuned Structure and a VSWR=1 Ring

The picture is that of Fig. 1, consisting of a constant impedance structure of length L to be determined, with the output coupled, through a phase-shift, ϕ, and an attenuation, A, back to the structure input.

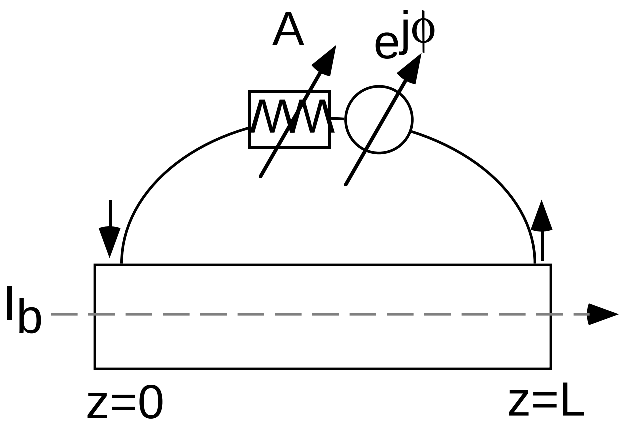


Fig.1 Idealized picture of the constant impedance structure embedded in a resonant ring.

The gradient induced by the beam in steady-state is

$$G_b(z) = rI_b\left(1 - e^{-\alpha z}\right),$$

with r the shunt impedance per unit length, and α the attenuation per unit length. The gradient produced by an input signal may be represented as

$$G_{in}(z) = G_{in}(0)e^{-\alpha z}.$$

The gradient experienced by the beam is the sum of these two,

$$G(z) = G_b(z) + G_{in}(z) = G_{in}(0)e^{-\alpha z} + rI_b\left(1 - e^{-\alpha z}\right).$$

The microwave power flowing through the structure at a point z is

$$P(z) = \frac{|G(z)|^2}{2\alpha r},$$

and thus the gradient at z=0, may be expressed in terms of the gradient at the structure exit according to

$$G(0) = \tilde{A}G(L),$$

where $\tilde{A} = Ae^{j\phi}$. This permits one to solve for

$$\frac{G(0)}{rI_b} = \tilde{A}\left(\frac{1-e^{-\tau}}{1-\tilde{A}e^{-\tau}}\right),$$

where $\tau=\alpha L$ is the attenuation parameter, with L the structure length. At any point z in the structure, one then has,

$$\frac{G(z)}{rI_b} = 1-\left(\frac{1-\tilde{A}}{1-\tilde{A}e^{-\tau}}\right)e^{-\alpha z}.$$

Note that

$$\frac{G(L)}{rI_b} = \frac{1-e^{-\tau}}{1-\tilde{A}e^{-\tau}}.$$

Evidently the gradient increases toward the end of the structure, except in the case $\left|\tilde{A}\right| = 1$ Integrating this gradient over the structure, we obtain the net voltage,

$$\frac{V}{RI_b} = \frac{1}{RI_b}\int_0^L dz\, G(z) = 1-\left(\frac{1-e^{-\tau}}{\tau}\right)\left(\frac{1-\tilde{A}}{1-\tilde{A}e^{-\tau}}\right).$$

Here $R=rL$ is the shunt impedance of the structure. We may quantify the range of voltage variation achievable with the phase-knob, ϕ, by considering $\tilde{A} = +A$ and $\tilde{A} = -A$. After a bit of algebra one finds,

$$\frac{V_+}{RI_b} = 1-\left(\frac{1-e^{-\tau}}{\tau}\right)\left(\frac{1-A}{1-Ae^{-\tau}}\right),$$
$$\frac{V_-}{RI_b} = 1-\left(\frac{1-e^{-\tau}}{\tau}\right)\left(\frac{1+A}{1+Ae^{-\tau}}\right),$$

and the range of phase-knob adjustable voltage variation is

$$\frac{\Delta V}{RI_b} = \frac{V_+ - V_-}{RI_b} = \frac{A}{1-A^2e^{-2\tau}}\frac{2}{\tau}\left(1-e^{-\tau}\right)^2.$$

For purposes of practical, worst-case estimates, we may take the shunt impedance of an idealized W-Band cell (0.6MΩ) and derate this by a factor of 3, to obtain, for a 60-cell (6cm) structure R˜12MΩ, and *r*˜200MΩ/m. In terms of group velocity v_g and wall Q ,Q_w, the attenuation constant is

$$\alpha = \frac{\omega}{2Q_w v_g}.$$

For a group velocity $v_g=0.09c$, and a wall Q of Q_w˜2000, the attenuation constant is α˜5.3m-1, or τ=0.32. For I_b˜0.5A, RI_b˜6MV, and this is the tuning range ΔV for A=1. For 1dB of loss in the recirculation network, one has A˜0.89, and ΔV˜4.3MV (72%). For 3dB loss, A˜0.71 and ΔV˜2.7MV (45%). The peak gradient achievable is just rI_b˜100MV/m, corresponding to no attenuation, and perfect phasing. This corresponds to 4.7MW flowing to the structure output. For 1dB of loss, and perfect phasing, these figures are: 77MV/m and 2.8MW. For 3dB of loss: 56MV/m and 1.5MW. Without recirculation: 27MV/m and 0.3MW.

These scalings are summarized in a spreadsheet (see WWW), with an example of the output depicted below.

Scalings for a Tuned Structure and a VSWR=1 Ring w/Simple Loss				4/17/97	
Inputs					
betag	0.09	group velocity /c	pi	3.14159265	
lambda	0.0033	m, rf wavelength	clight	299790000	m/s
ncell	60	# of cells			
qwall	2000	wall Q of cell			
theta	120	transit angle in degrees			
ringatten	3	dB	**For 1 dB Attenuation**		
rshuntl	2.00E+08	Ohm/m, shunt impedance per unit length	Optimum Difference Voltage at 136 cells		
beamcurr	0.5	Amperes, beam current	Difference = 0.805 x Vmax = 12MV		
			-6.90	dB in structure	
Derived			**For 3 dB Attenuation**		
omega	5.708E+11	rad/sec	Optimum Difference Voltage at 178 cells		
alpha	5.28887652	m-1	Difference = 0.607 x Vmax = 12MV		
length	0.066	m, structure length	-9.58	dB in structure	
tau	0.34906585	attenuation parameter	**For 5 dB Attenuation**		
aparm	0.70794578	voltage reduction factor	Optimum Difference Voltage at 195 cells		
rshunt	1.32E+07	Ohm	Difference = 0.472 x Vmax = 10.1MV		
vmax	6.60E+06	Volts, max voltage, ideal case	-9.87	dB in structure	
vmax_actual	**3.35E+06**	V, at optimal phase			
vmin_actual	2.54E+05	V, at -180 deg			
vdiff	3.10E+06	V, voltage variation versus 180 deg phase knob			
gmin	4.17E+07	V/m at z=0,gradient (opt phase)			
gmax	5.89E+07	V/m at z=L, gradient (opt phase)			
gavg	5.08E+07	V/m, average (opt phase)			
powerin	8.21E+05	W, power at z=0			
powerout	**1.64E+06**	W, power at z=L			
ekilpatrick	2.38E+08	V/m, Kilpatrick			
ephenom	4.29E+08	V/m, Phenomenological, 0.1 microsec pulse			

Breakdown

Given that the pulse length for this experiment will be much longer than the natural fill-time for a W-Band travelling wave structure, it is good to revisit the phenomenology we have been adopting for breakdown. This is simply the empirical fit

$$E_{br} \approx E_K\left(1+\frac{4.5}{T_p(\mu s)^{1/4}}\right) \approx 1.8E_K,$$

with T_p the pulse length, and E_K the breakdown field according to Kilpatrick's criterion for a continuous wave (CW) pulse,

$$E_K \approx 25\tfrac{MV}{m}\sqrt{f(GHz)} \approx 240MV/m.$$

It should be recognized too that for power tubes, breakdown thresholds are known to be lower. According to this criterion, we might expect a hard limit in the range of 430MV/m. For a reasonable ratio of surface field to gradient, and for favorable ring attenuation, it would not be surprising to experience breakdown in our circuit, and to find ourselves pursuing a conditioning cycle for the ring. This suggests that instrumentation of the kind employed on the resonant ring at Test-Stand #4 should be considered (scintillator & PMT, RGA, gated CCD). Note that if one considers, as we have, running at 1A of beam current, it might be possible to reach a hard-limit in the conditioning cycle.

Additional Work

We are pursuing the following additional items along these lines:

(1) analysis of the amplification of the backward wave in the presence of multiple reflections in the recirculation arm.

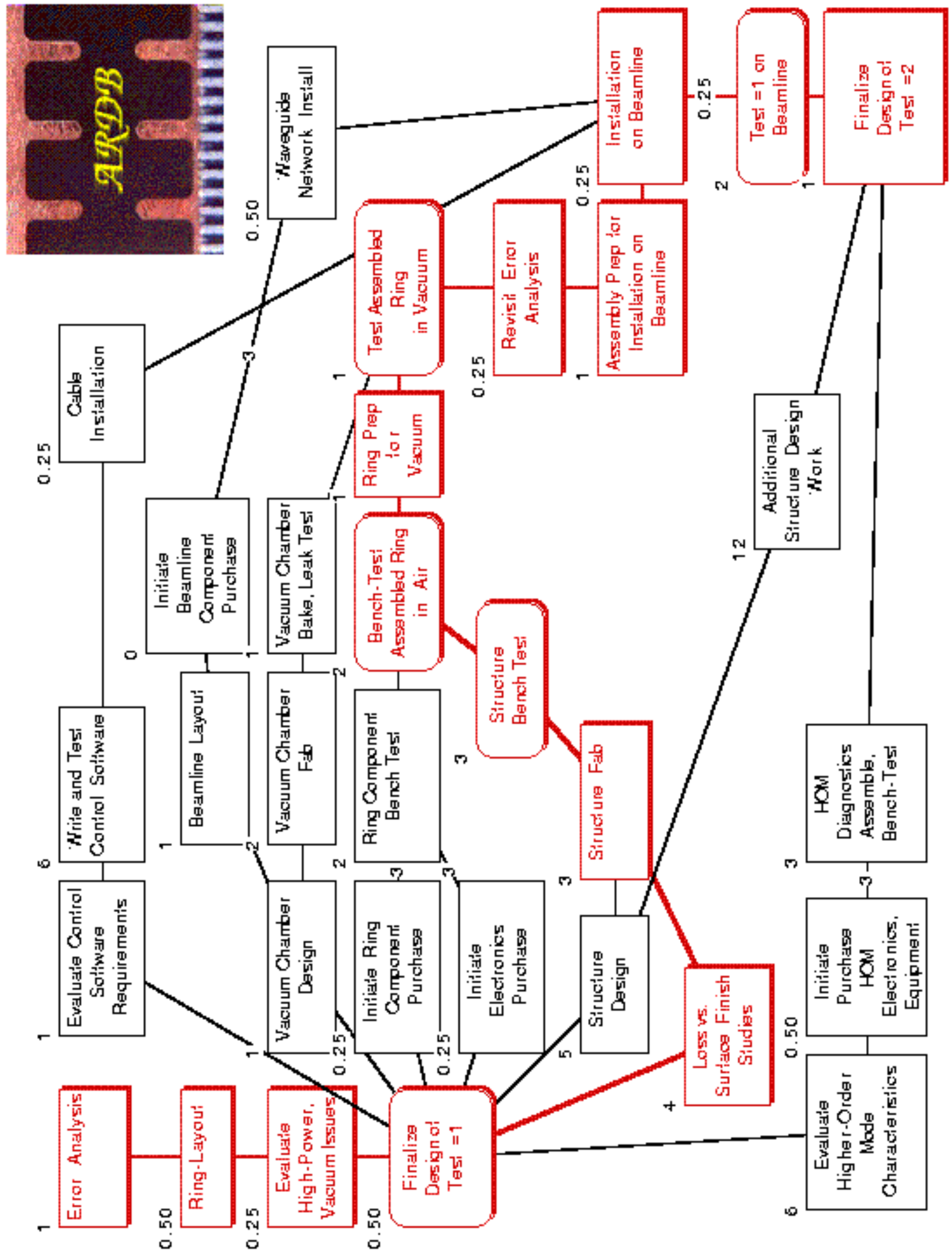
(2) effect of structure tuning errors

(3) effect of transverse gradients

(4) ring layout and error budget based on manufacturer spec for VSWR and loss, or ARDB-measured where available

(5) design of a phase-shifter --- this is being pursed by Mikhail Gershteyn and Michael Shapiro, Insight Product Co. These are the folks who do the design work for the MIT mode converters.

Timeline



ARDB
Error Analysis
Ring-Layout
Evaluate High-Power, Vacuum Issues
Finalize Design of Test =1
Evaluate Control Software Requirements
Write and Test Control Software
Cable Installation
Beamline Layout
Initiate Beamline Component Purchase
Waveguide Network Install
Vacuum Chamber Design
Vacuum Chamber Fab
Vacuum Chamber Bake, Leak Test
Initiate Ring Component Purchase
Ring Component Bench Test
Bench-Test Assembled Ring in Air
Ring Prep for Vacuum
Test Assembled Ring in Vacuum
Initiate Electronics Purchase
Structure Bench Test
Revisit Error Analysis
Structure Design
Structure Fab
Assembly Prep for Installation on Beamline
Installation on Beamline
Loss vs. Surface Finish Studies
Additional Structure Design Work
Test =1 on Beamline
Evaluate Higher-Order Mode Characteristics
Initiate Purchase HOM Electronics, Equipment
HOM Diagnostics Assemble, Bench-Test
Finalize Design of Test =2