A HIGH-POWER RADIOFREQUENCY FOCUSING CONTINUOUS WAVE ELECTRON LINAC

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Abstract

To simplify construction and reduce beam current losses, we introduce **R**adio **F**requency focusing in a high-power **C**ontinuous **W**ave **E**lectron **LIN**ear **AC**celerator by employing **R**ectangular **C**avity **B**iperiodical **S**tructures that have quadrupole-like focusing properties.

1 INTRODUCTION

The next generation compact high-power industrial electron accelerators will be high efficiency CWELs whose multi-megawatt average power beams will have energies up to 10 *MeV*. These CWEL accelerating structures must possess contradictory properties of high inter-cell coupling required for high beam and heat loading and also high shunt impedance. Strong RF focusing is also desirable since it would simplify the accelerator design and increase the accelerated current.

We use a horizontally focusing RCBS in our compact 70 *MeV* pulsed **R**ace-**T**rack **M**icrotron [1] to simplify the design. RCBSs have been realized with circular beam holes [2] as well as with rectangular beam slots [3]. By changing the aperture geometry, elongating it horizontally or vertically, and varying the cavity dimensions, we can change the focusing sign and strength from 0 to ~1,000/m^2.

It is known experimentally that increasing a biperiodic structure inter-cell coupling decreases its shunt impedance since the surface current distribution in both the coupling and accelerating cells are changed. Using extensive three-dimensional computer simulations coupling slot and cell geometries have been optimized to achieve large coupling with little decrease in the shunt impedance [4]. Our optimized RTM RCBS with no coupling slots [5] has a ~5% coupling which we achieved with only ~6% shunt impedance decrease. Here we present a RF focusing RCBS with optimized focusing, coupling, and shunt impedance for a high power CWEL.

2 RF FOCUSING OPTIMIZATION

In Fig. 1 we show the normalized horizontal (x) and vertical (y) focusing gradients, G$_x$ and G$_y$, respectively, and effective shunt impedance for a RCBS with rectangular beam slots but with no coupling slots.

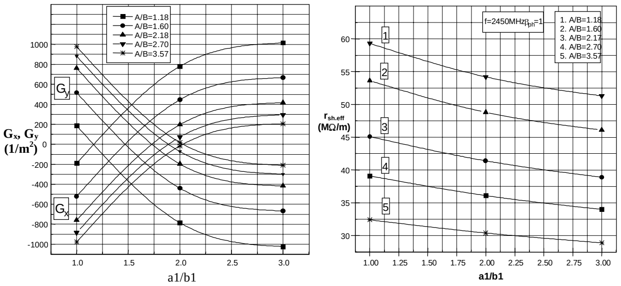

Fig. 1. Focusing gradient and shunt impedance with a$_1$/b$_1$.

The **E**lectro**D**ynamics **C**haracteristics depend on the ratios a$_1$/b$_1$ and A/B defined in Fig. 2. For a π/2 mode phase velocity equal to the speed of light (ß = 1) at 2,450 *MHz*, we obtained $-G_x$ and $+G_y$ up to ~1,000/*m*^{2} with a large A/B and a square or circular (a$_1$/b$_1$ = 1) beam hole by vertically elongating the structure. With a A/B ≈ 1 and large a$_1$/b$_1$ the focusing gradients were the same but with opposite sign.

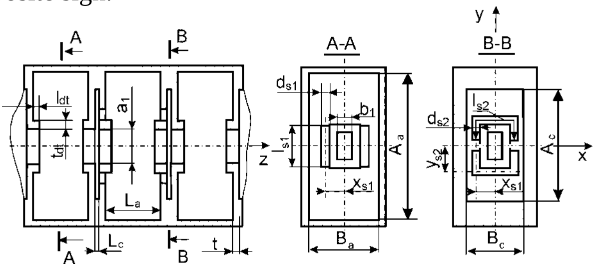

Fig. 2. RCBS with rectangular beam and coupling slots.

3 COUPLING AND SHUNT IMPEDANCE OPTIMIZATION

In biperiodic structures the coupling aperture dimensions and location modify differently accelerating and coupling cell eigenfrequencies [6]. Since the cell frequency detuning is inversely proportional to the cell volume and the accelerating cell is much larger than the coupling cell, a tuned structure with a high coupling requires a very small (A$_c$,B$_c$) coupling cell surface as seen in Fig. 2.

Fig. 3 shows the strong magnetic field in the coupling cells of the tuned structure that provides the inter-cell coupling. For small coupling cells and coupling slots close to axis, the surface current integral induced by this field in the coupling cells is small. Thus RF losses and shunt impedance change little from a structure without coupling slots**.**

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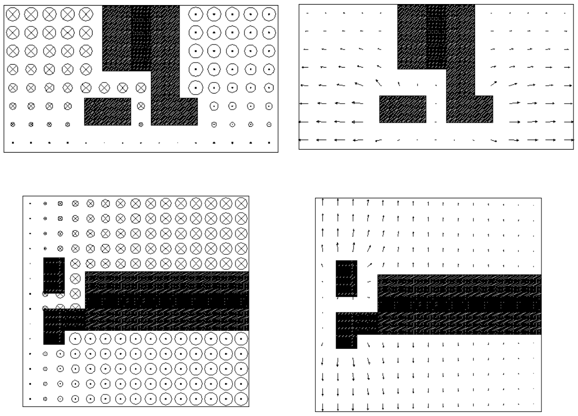
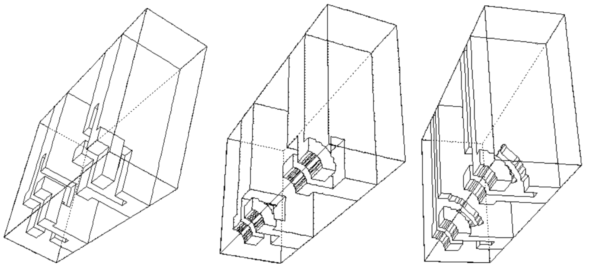


Fig. 3. Magnetic and electrical fields at xOz-yOz for a RCBS with beam holes and coupling slots.



(a) (b) (c)

Fig. 4. Three RCBS structures.

Table I. Structure dimensions in mm.

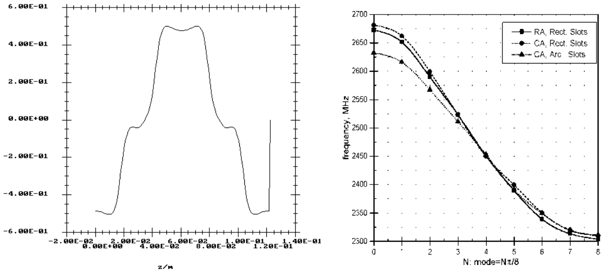
	(a)	(b)	(c)
A_a	130.00	130.00	130.00
A_c	68.00	36.00	130.00
B_a	63.84	65.40	64.96
B_c	44.00	36.00	50.70
$2r_1$	---	12.00	12.00
a_1	24.00	---	---
b_1	12.00	---	---
$D=\lambda_w/2$	61.20	61.20	61.20
L_a	44.00	44.00	44.00
L_c	4.60	4.60	4.60
T	6.30	6.30	6.30
l_{dt}	4.00	4.00	4.00
t_{dt}	6.00	6.00	6.00
x_{s1}	15.00	15.00	16.00
l_{s1}	36.00	35.00	32.00
d_{s1}	6.00	6.00	8.00
y_{s2}	21.00	15.00	16.00
l_{s2}	48.00	49.00	40.00
d_{s2}	6.00	6.00	8.00

We investigated three highly coupled RCBS variants. The first, which is appropriate for our RTM and is seen in Fig. 4(a), has rectangular beam and coupling slots. The second, seen in Fig 4(b), has circular beam holes and is coupled by rectangular slots. In the third, shown in Fig. 4(c), there are circular beam holes and the coupling is by circular holes. RCBSs with circular beam holes hold an advantage for CWELs because they have larger shunt impedance for the same focusing gradient as $a_1/b_1 = 1$ rectangular slotted structure. RCBS (b) has smaller coupling cells than (c) and has larger coupling with approximately the same EDC. Table I list the dimensions and Table II gives the EDC for these three structures.

Table II. Structure electrodynamics characteristics.

	(a)	(b)	(c)
k_c (%)	15.1	15.2	13.2
$r_{sh.eff}$ (MΩ/m)	40.4	48.9	48.8
G_x (m^{-2})	+275	−680	−650
G_y (m^{-2})	−275	+680	+650
Q	12,400	13,400	13,000

The axial longitudinal electrical field for structure (b) is seen in Fig. 5(a) and was obtained for a tuned structure consisting of two coupling cells, an accelerating cell, and two half accelerating cells and terminated with electric walls. Fig. 5(b) shows the structure dispersion.



(a) (b)

Fig. 5. (a) On-axsis E_z and (b) dispersion characteristics.

4 HIGH-POWER CWEL BEAM DYNAMICS

For pulsed electron LINACs beam focusing is most important after the injector, before the electrons become relativistic. However, focusing is critical in a high-power CWEL which in some respects is intermediate between a proton and a pulsed electron LINAC. Heat dissipation and efficiency limit the CWEL energy gain to only 1-4 *MeV/m*, so to achieve 10 *MeV*, several *MW* 'industrial strength' electron beams requires focusing to overwhelm the strong repulsive space charge forces. Thus, RCBSs that both accelerate and focus beams are desirable.

We explore these RCBS possibilities for a CWEL with a 2 *MeV/m* energy gain producing 10 *MeV*, several hundred *mA* beams. The initial relativistic 2 *MeV* beam is accelerated in a short $\beta_{ph}= 1$ section with a ~10° electron bunch prepared by a chopper, pre-buncher, and capture section. At 2 *MeV/m*, depending on the shunt impedance, between ~80 and 150 *kW/m* of RF power must be dissipated and 1 *MW/m* of RF power is required to accelerate a ~500 *mA* beam. For a several hundred kW CW S-band RF source, this accelerating structure will consist of short sections of several accelerating cells each whose number we vary to achieve the desired focusing.

The i^{th} accelerating cell focal length, f_i, is related to the normalized focusing gradients by

$$1/\,f_i = -\frac{\lambda^2 \sin\varphi_0}{8\pi p_i} G_{x,y}(0,0)_n E_{z1}(0,0), \qquad (1)$$

where λ is the RF wavelength, φ_0 is the accelerating phase, $E_{z1}(0,0)$ is the first harmonic amplitude, and p_i is the longitudinal momentum. Since the distance between accelerating cells is much less than the individual cell focal length, an N cell structure focal length is

$$\frac{1}{F_\Sigma} \approx \sum_{i=1}^{Ncell} \frac{1}{f_i} = \frac{p_1}{f_1} \sum_{i=1}^{Ncell} \frac{1}{p_i} = \frac{p_1 N_{cell}}{f_1\, \overline{p}}, \quad . \qquad (2)$$

$$\frac{1}{\overline{p}} = \frac{1}{N_{cell}} \sum_{i=1}^{Ncell} \frac{1}{p_i}$$

For horizontal/vertical cell dimensions, A/B, of ~2, a RCBS with circular beam holes, has a ~680/m^2 focusing gradient, a 2 *MeV/m* energy gain, a ~4 *MeV/m* first harmonic amplitude, and, from eqn.(1), a ~1.5 *m* single cell focal length at 2 *MeV*. From eqn.(2), a six cell section focal length is ~0.3 *m*.

In our RCBS zero phase particles get the maximum energy gain and, in contrast to our RTM, negative phases give stable longitudinal dynamics. For a ~–30° accelerating phase, the focal length for a 2 *MeV* beam is doubled to ~0.6 *m* and increases with beam momentum until at 10 *MeV* it is ~2.5 *m*. This focal length increase can be partially compensated for, if necessary, by shifting the accelerating field phase. On the other hand transverse space charge forces decrease as the square of the energy, so a focal length increase is not very important.

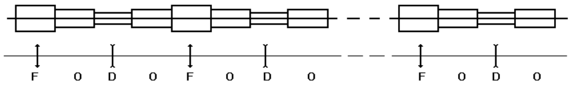


Fig. 6. High-power CWEL with RF focusing.

To focus the beam in both transverse planes, we rotate each RF quadrupole-like singlet section sequentially through 90° and separated them by axially symmetric accelerating structure drift spaces seen in Fig. 6.

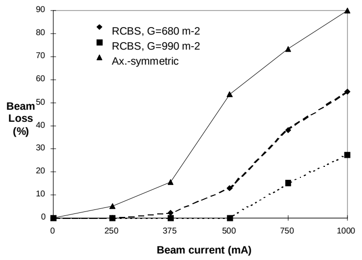


Fig. 7. CWEL beam loss with and without RF focusing.

Fig. 7 shows the beam current losses with the injected beam current calculated for an axially-symmetric LINAC and our RCBS LINAC with focusing gradients of 680 and 990/m^2 using A/B ~4. These calculations take into account space charge forces [7].

5 CONCLUSIONS

We have shown that a high focusing RCBS LINAC can accelerate a 500 *mA* beam from 2 to 10 *MeV* with no beam losses while a traditional axially symmetric LINAC begins to loose beam at ~100 *mA*. Although much remains to be done before achieving a final high power RF focusing CWEL design, we are encouraged.

6 ACKNOWLEDGEMENTS

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