A Traveling Wave Accelerator With HOM Outcouplers for FEL's

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Abstract

Electron beam brightness is a key issue in building efficient free electron lasers (FEL's), particularly for optical and shorter wavelengths. The application to FEL's of RF electron gun's [1] with laser driven photo-cathodes [2] has opened the door to developing efficient optical FEL's. The next task is to develop accelerator structures which can transport such beams with a minimum of beam degradation. A low cost approach to this is suggested in this paper: Four 1.26 meter constant gradient (CG) TW sections driven in parallel by a SLAC 5045 klystron. By using CG sections the higher order modes are incoherent due to the linearly decreasing group velocity along the structure. Together with incorporating higher order mode (HOM) outcouplers, this system is predicted to accelerate 1 nC per micropulse, 0.4 Amps per macropulse to 75 MeV from an injection energy of 5 MeV. Emittance growth is predicted to be 5 mm-mr. Rocketdyne is currently procuring these sections for testing.

[1] S. Benson, J. Schultz, B. Hooper, R. Crane, and J. Madey, Nucl. Inst. and Methods A272 (1988) 22
[2] M. Curtin, B. Bennett, R. Burke, A. Bhowmik, P. Metty, S. Benson, and J. Madey, "First Demonstration of a Free-Electron Laser Driven by Electrons from a Laser Irradiated Photocathode", #EX3.4, 11'th International Conference on Free Electron Lasers, Naples, Florida

Introduction

As a next step in obtaining high brightness, high energy electron beams for FEL's low emittance accelerator sections are being fabricated for Rocketdyne by Schonberg Radiation Corporation.

This paper is organized into four sections. Section 1 looks at several different structure variations and their impact on performance, measured chiefly by maximum charge per macropulse. Section 2 then analyzes energy spread and emittance growth in some structures without HOMO's. Section 3 discusses modeling to determine the effect of HOMO's on cavity modes and Q's, and on HOM Q's of the entire structure. Section 4 summarizes the results and concludes the paper with the choice of the four 1.26 meter structures.

Section 1

The most important design specification for the linac structure is that when driven by 50 to 60 MW from a SLAC 5045 S-band klystron it must increase the beam energy by 70 MeV including the effect of beam loading. These and other specifications are listed in Table I.

TABLE I

RF Gun Energy	5	MeV
RF Power to Gun	5	MW
Linac Output Energy	75	MeV
$\Delta E/E$	<1%	
RF Power to Linac	55	MW
Micropulse Charge	0.5 to 4 nC	
Micropulse Spacing	1.4 ns to 21 ns	
Beam Macropulse Length	>2.5 μs	
Normalized Emittance	>10 π mm-mr	
BBU Threshold Current	> 1 A	

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We will consider two configurations of either two full 3 meter SLAC sections, or four 1.26 meter portions thereof, driven in parallel by a single 5045 klystron which must also drive the RF gun. We begin by setting the values for the parameters which determine the energy gain and fundamental mode beam loading:

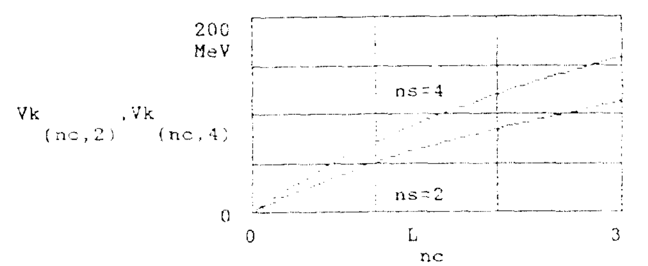
$ns := 1 .. 4$		Number of sections
$nc := 1 .. 86$		Number of cells per section
$L_{nc} := .035\ nc$	m	Length of each section
$P := 55$	MW	Power to linac sections
$r := 57$	MΩ/m	Shunt impedance

The attenuation for a section L(nc) long taken from the output end of the SLAC structure is:

$$\tau_{nc} := .5\ \ln\left[.711\ L_{nc} + 1\right] \qquad \text{Att./sect. in nepers}$$

The no load energy gain can now be calculated:

$$Vk_{nc,ns} := \sqrt{\left[1 - \exp\left[-2\ \tau_{nc}\right]\right] ns\ P\ L_{nc}\ r}$$



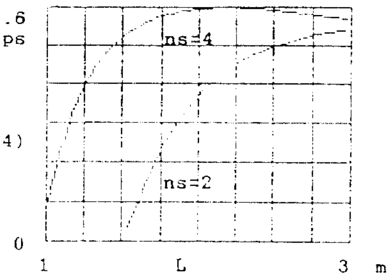
Energy gain in linac, 2&4 Sectons

The next function to calculate is the beam loading derivative to determine steady state energy dependance on beam current.

$$\delta Vb_{nc,ns} := \frac{ns}{2}\ r\ L_{nc}\left[1 - \frac{2\ \tau_{nc}\ \exp\left[-2\ \tau_{nc}\right]}{1 - \exp\left[-2\ \tau_{nc}\right]}\right]$$

The beam derivative for four short sections is 41 MeV/A, for two long sections it is 80 MeV/A. This means that the shorter sections are half as sensitive to micropulse charge fluctuations as the longer sections, possibly a critical difference in operating an FEL. The maximum current which can be run is given by:

$$Imax_{nc,ns} := \frac{Vk_{nc,ns} - 70}{\delta Vb_{nc,ns}}$$



Maximum Average Current @75 MeV for 2 and 4 sections.

A conservative estimate of the "Good beam" pulse length is the RF pulse length minus twice the structure filling time. The variation of fill time with structure length is:

$$T_f := .722\ \ln(.711\ L + 1)\ \mu$$

The maximum charge per macropulse, qmax, is the maximum current times the "good beam" pulse length;

$$q_{max} := I_{max}\ (T_{rf} - 2 \cdot T_f)\ \mu$$

The two configurations being considered transport almost identical charges, 1.1 μC each. However, Imax is lower for the four section case, and combined with the beam loading derivative this means that the four section case is much less sensitive to charge fluctuations. For example, 1% fluctuations of charge result in 0.58% energy fluctuations for the 3 m case, but only 0.22% energy fluctuations for the 1.26 m case. This is a considerable improvement for a beam with allowable rms energy spread of less than 1%.

Section 2

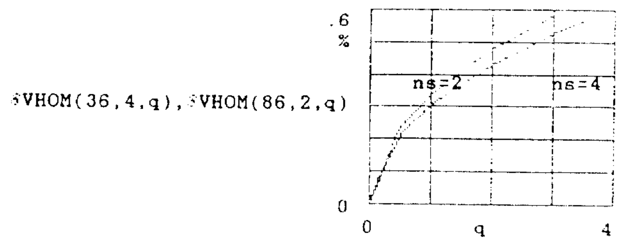
Next we must look at the energy spread and emittance growth caused by the higher order modes (HOM's). HOM frequencies are not rationally related to each other or the fundamental. Furthermore, the HOM fields decay to 1/e in a time $t = Q/\pi f$. Similarly, while the calculations by Yu and Wilson [3] assume a truly periodic structure, the actual structures are continuously tapered. For this reason it is appropriate to combine the effects of successive cells as if they were random.

First we will define and set the parameters of the problem:

$nc := 36 .. 86$		number of cells
$ns := 2 .. 4$		number of structures
$q := 0, 0.5 .. 4$	nC	charge per micropulse
$I_4 := .399$ $\quad I_2 := .544$		beam current
$Q := 15000$		Quality factor of HOM
$f := 4.3$	GHz	first HOM frequency
$Wl := 0.5 \cdot 10^{-3}$	MeV/nC/cell	Longitudinal wake potential

The percent energy spread due to the longitudinal wake is:

$$\sigma VHOM(nc,ns,q) := ns \cdot Wl \cdot \left[\sqrt{\frac{Q}{\pi f}\ nc}\ q\ I_{ns}\right] \cdot \left[\frac{100}{75}\right]$$



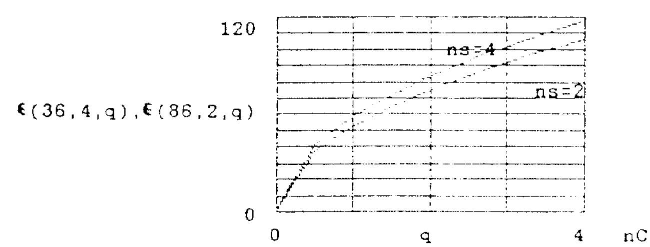
Percent Energy Spread vs. q for Two and Four Sections

The two 3 m sections marginally outperform the four 1.26 m sections; for 1 nC it is 0.34% for 1.26 m vs. 0.30% for 3 m. With regard to single bunch beam loading Bane [7] calculates the bunch wake function for a gaussian μpulse with $\sigma z = 1$ mm. The full energy spread is 3.2 V/pC/cell, which gives a total (4σ) single bunch energy spread of 2.5% for a 4 nC bunch. Running with bunches 6 degrees forward of the crest reduces the total energy spread in each bunch to 0.4% with rms of 0.2%. The next effect we must consider is emittance growth caused by long range dipole wakefields. The parameters involved are:

$r := 1$	mm	rms beam radius
$\sigma x := 1$	mm	rms beam centroid position
$Wd := 0.5$	MeV/nC	dipole wake potential/cell
$a := 10$	mm	accelerator disk hole radius
$\lambda := 75$	mm	first dipole mode wavelength
$f := 4.3$	GHz	first dipole frequency
$Q = 1.5 \cdot 10^{4}$		first dipole mode Q
$m0 := 0.511$	MeV	electron rest mass

The normalized emittance growth produced by the dipole wakefields is the product of the beam radius times the transverse momentum kick of the wakefields.

$$\epsilon(nc,ns,q) := r \cdot \left[\frac{Wd}{m0}\right] \cdot \frac{\sigma x}{a} \cdot \frac{\lambda}{2 \cdot \pi \cdot a} \cdot ns \cdot \sqrt{\left[\frac{Q}{\pi \cdot f}\right] \cdot q \cdot I_{ns} \cdot nc}$$



Normalized Emittance vs. Charge

Since these emittance contributions will dominate the emittance of the accelerator the structures have been designed to damp the higher order modes. It is possible to achieve a factor of 10 or more reduction in the HOM Q's. This results in at least a factor of 3 reduced emittance growth. By reducing beam centroid and rms radius by a factor of 3, emittance growth will be reduced to below 5 mm-mr.

Section 3

The higher order mode outcouplers (HOMO's) are expected to reduce emittance growth by at least a factor of 3. Analysis of this has not been completed. Existing 3-d codes do not have a fine enough mesh to model the tapered structure accurately.

J. W. Wang analyzed cavities with HOMO's to determine the effects of outcouplers on the Q's of the first several modes. URMEL and KN7C were the codes used. The results for selected Q's are:

MODE	Q	Q with HOMO
TM01	13,590	13,340
HEM11	15,344	8
TM011	12,500	600

The dominant HOM is the HEM11 mode, at the lowest frequency, 4.3 GHz, and highest undamped shunt impedance at 29.3 MΩ/m. The mode is very nearly a π mode, which is nearly a trapped mode in the structure. However, based on Brillouin diagrams for the HEM11 mode [9, fig. 7-29, p. 221] an initial calculation of the average group velocity through the 1.26 m structure gives an upper limit of ~1,500 for the Q confirming the order of magnitude reduction expected.

Section 4

After examining the above results, the accelerator system comprised of the four 1.26 m section was chosen to be built as a driver for the Rocketdyne FEL. Although higher in cost than just using the standard SLAC sections it was felt that the advantages to be gained were worth the cost differential. In particular, the reduced sensitivity to charge fluctuations in the energy spread, and reduced emittance growth due to the HOMO's will not only allow more efficient extraction at 1 μm but also allow for attempts at operation at even shorter wavelengths down the road. Confidence is high that the calculated performance will be realized as this system is based on an incremental improvement upon the well understood 3 m section and on ongoing research at SLAC on HOMO's.

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