A Linear Accelerator Bunch Length Monitor

A Thesis

Submitted to the College of Graduate Studies and Research

in Partial Fulfillment of the Requirements

for the Degree of Master of Science in Engineering Physics

in the

Department of Physics and

Engineering Physics

University of Saskatchewan

by

Darryl Sheldon Jessie

Saskatoon, Saskatchewan

CANADA

Fall, 1995

©1995 D. S. Jessie. All rights reserved.

+02000894918

In presenting this thesis in partial fulfilment of the requirements for a Postgraduate degree from the University of Saskatchewan, the author agrees that the Libraries of this University may make it freely available for inspection. The author further agrees that permission for copying of this thesis in any manner, in whole or in part, for scholarly purposes may be granted by the professor or professors who supervised the thesis work or, in their absence, by the Head of the Department or the Dean of the College in which the thesis work was done. It is understood that any copying or publication or use of this thesis or parts thereof for financial gain shall not be allowed without the author's written permission. It is also understood that due recognition shall be given to the author and to the University of Saskatchewan in any scholarly use which may be made of any material in the thesis.

Requests for permission to copy or make other use of material in this thesis in whole or part should be addressed to:

Head of the Department of Physics and Engineering Physics
University of Saskatchewan
Saskatoon, Saskatchewan S7N 0W0

Abstract

The Saskatchewan Accelerator Laboratory is a 300 MeV electron accelerator (Linac) and storage ring. Electrons are injected into the Linac in packets called bunches for acceleration by an electromagnetic field. The length of these bunches have a direct impact on the energy spread of the beam at the exit of the Linac. A large bunch length increases the background radiation in and around the Energy Compression System located at the end of the Linac and is an inefficient way of operating the accelerator.

Bunch length is dependent on the relative phase of the microwave power used by the Linac components. A monitor has been developed that will measure the bunch length early in injection so that the relative phase of the microwave power can be adjusted for optimal bunching.

The power available at two sufficiently separate harmonics in the frequency domain will give an indication of the bunch length in time. Simulations indicate the first and fourth harmonics fulfill this criteria.

The bunch length monitor consists of a circular disk of copper 1 cm in diameter located 3 mm from the inside surface of the beam pipe wall. It also includes a power splitter and two bandpass filters, one at the Linac RF frequency of 2.856 GHz and the other at the fourth harmonic, 11.424 GHz.

The bunch length monitor was tested in a number of trials. By varying the prebuncher phase, two minima in bunch length were observed; one minima due to the injector and the other to the first accelerating section. A reduction of 12 % in energy spread was observed and it is anticipated that with more thorough optimization, a reduction of up to 20 % could be realized.

Acknowledgements

I would like to thank my supervisor, Dr. Eric Norum, for his help and guidance in the research and preparation of this document. His uncanny insight and willingness to drop whatever he was doing to answer my most trivial questions is greatly appreciated. It is my hope that some of his superb engineering ability has been incorporated into this project.

The financial support that Dr. D. M. Skopik has made available is greatly appreciated. Many thanks to Dr. H. S. Caplan for kindling my interest in obtaining a graduate degree.

The knowledge and assistance of all the SAL staff, past and present, was very welcome. In particular Don Cruickshank's experience in microwave circuits and construction made difficult problems easy. I am also grateful to Dr. Jim Murphy who on short notice would find some beam time for something I just had to check out.

My fellow graduate students have made SAL a great place to make new friends. In particular, Don Tiller, Dave Hornidge and Keith Helgason have made some long winter months a lot of fun.

I appreciate the support my Father and Mother, Dallas and Dorothy, have given me over the years. Their enthusiasm and interest in my University career surpassed mine on many occasions.

Finally, I thank my wife, Julie, for her understanding and cheerfulness through some difficult times. You were always willing to help in whatever capacity you could, and it is to you that I dedicate my thesis.

Contents

1	Introduction	1
1.1	Saskatchewan Accelerator Laboratory	1
1.1.1	Accelerator Front End	3
1.1.2	The Transmitter	4
1.1.3	The Injector	4
1.2	Monitor Overview	7
1.3	Bunching Theory	9
2	Theory	16
2.1	Fourier Spectral Components	16
2.1.1	Fourier Analysis of a Gaussian Distribution	16
2.1.2	Fourier Analysis of a Differentiated Gaussian	19
2.2	Theoretical Output	20
2.2.1	Equivalent Circuit	20
2.2.2	Button Impedance	24
3	Filter Simulations	25
3.1	Transfer Function	25
3.2	Digital Simulation	29
3.3	Summary	35
4	The SAL Bunch Length Monitor	36
4.1	The Bench Test	36
4.1.1	Component Characterization	36
4.1.2	The Bench Measurements	41
4.2	Experimental Beam Trials	45

4.2.1	April Run	45
4.2.2	July Run	49
4.2.3	August Run	56
5	Summary and Conclusions	59
A	Filter Specifications	63
B	Computer Programs	64
C	Bench Test Results	79
D	April Results with Peak Power Meter	85
E	April Results with Crystal Detectors	91
	References	94

List of Tables

1.1	SAL Linac	6
3.1	Filter Specifications	25
3.2	Frequency Numbers	26
3.3	Component Values	28
3.4	Coefficients for Discrete Equation	31
3.5	Theoretical, Simulated and Experimental Values	33
3.6	Output Values for Differentiated Gaussian	35
4.1	Summary of Button Outputs	44
4.2	Summary of Button Output for April Test Run	47
4.3	Summary of Button Output from Crystal Detectors	49
4.4	Summary of Button Output for July Test Run	53
4.5	Energy Spread of Beam	54
4.6	Summary of Button Output for August Run, Section #1 Phase 69°	56
4.7	Summary of Button Output for August Run, Buncher Phase 75°	57
5.1	Energy Spread of Beam	60

List of Figures

1.1	SAL Layout	2
1.2	Injector Components	3
1.3	Pulse Relationships in Time: a) Gun Pulse Length, b) Bunch Period and Bunch Width, c) RF Pulse Width and Pulse Repetition Period .	6
1.4	Electron Variations before Buncher: a) DC Beam, b) End of Pre- buncher, c) End of Drift Space	10
1.5	Bunch Phasing	11
1.6	Theoretical Dependence of Bunch Width and Relative Phase Energy Spread	13
1.7	Comparison of Bunch Widths	14
1.8	Theoretical Dependence of Bunch Width on Prebuncher and Section #1 Phase	15
2.1	Gaussian Wavetrain	16
2.2	Fourier Harmonic Magnitudes	18
2.3	Fourier Harmonic Amplitudes for Differentiated Gaussian	20
2.4	Button Orientation	21
2.5	Circuit Model	21
2.6	Differentiated Gaussian Wavepackets	23
3.1	Desired Frequency Response	26
3.2	Low Pass Filter	27
3.3	Bandpass Filter	27
3.4	Bandpass Filter Response for First Harmonic	29
3.5	Bandpass Filter Response for Fourth Harmonic	29
3.6	First Harmonic Response	32
3.7	Fourth Harmonic Response	32

3.8	First Harmonic Filter Response for $\sigma = 8.0$ ps	34
3.9	Fourth Harmonic Filter Response for $\sigma = 8.0$ ps	34
4.1	Bunch Length Monitor with Test Fixtures	37
4.2	Theoretical and Experimental First Harmonic Response	38
4.3	Theoretical and Experimental Fourth Harmonic Response	38
4.4	Response of Detector for First Harmonic	40
4.5	Response of Detector for Fourth Harmonic	40
4.6	Test Setup	41
4.7	Switch Circuit	42
4.8	SRD Circuit	43
4.9	SRD Output	43
4.10	Experimental Test Setup	46
4.11	April Results:Experimental Dependence of Prebuncher Phase on Bunch Width	48
4.12	Output of Monitor after Noise Subtraction	49
4.13	April Result: First Harmonic Response with Prebuncher Phase 29° .	50
4.14	April Result: Fourth Harmonic Response with Prebuncher Phase 29°	50
4.15	July Result: First Harmonic Response with Prebuncher Phase 29° . .	51
4.16	July Result: Fourth Harmonic Response with Prebuncher Phase 29° .	51
4.17	Components Between Section #1 and Section #2	52
4.18	July Results: Experimental Dependence of Bunch Width on Pre- buncher Phase	55
4.19	July Results: Experimental Dependence of Beam Energy on Pre- buncher Phase	55
4.20	August Results:Experimental Dependence of Prebuncher Phase on Bunch Width for Section #1 Phase of 69°	58
4.21	August Results:Experimental Dependence of Prebuncher Phase on Bunch Width for Section #1 Phase of 75°	58

5.1	July Results: Experimental Dependence of Bunch Width on Prebuncher Phase	62
5.2	July Results: Experimental Dependence of Beam Energy on Prebuncher Phase	62
A.1	Response Curve for Various Filters	63
D.1	2856 MHz: Prebuncher Phase 29°	85
D.2	11424 MHz: Prebuncher Phase 29°	85
D.3	2856 MHz: Prebuncher Phase 19°	86
D.4	11424 MHz: Prebuncher Phase 19°	86
D.5	2856 MHz: Prebuncher Phase 10°	86
D.6	11424 MHz: Prebuncher Phase 10°	86
D.7	2856 MHz: Prebuncher Phase 29°	87
D.8	11424 MHz: Prebuncher Phase 29°	87
D.9	2856 MHz: Prebuncher Phase 39°	87
D.10	11424 MHz: Prebuncher Phase 39°	87
D.11	2856 MHz: Prebuncher Phase 49°	88
D.12	11424 MHz: Prebuncher Phase 49°	88
D.13	2856 MHz: Prebuncher Phase 59°	88
D.14	11424 MHz: Prebuncher Phase 59°	88
D.15	2856 MHz: Prebuncher Phase 69°	89
D.16	11424 MHz: Prebuncher Phase 69°	89
D.17	2856 MHz: Prebuncher Phase 79°	89
D.18	11424 MHz: Prebuncher Phase 79°	89
D.19	2856 MHz: Prebuncher Phase 29°	90
D.20	11424 MHz: Prebuncher Phase 29°	90
E.1	Raw 2856 MHz Signal	91
E.2	Raw 11424 MHz Signal	92

E.3	Output of Monitor after Noise Subtraction	92
E.4	Prebuncher Phase 9°	93
E.5	Prebuncher Phase 49°	93
E.6	Prebuncher Phase 69°	93

Chapter 1

Introduction

The bunch length monitor described in this thesis provides a means of determining the bunching efficiency with the accelerator in operation. An accelerated electron beam has an energy spread. The deviation from the monoenergetic ideal is caused by perturbations in beam acceleration, with the greatest effect due to the relative RF phasing of the injector components.

The injector is located at the front end of the linear accelerator (Linac) section of SAL. Immediately after the Linac is the Energy Compression System (ECS). If the injector component phasing is set to provide a broad energy spectrum, the energy defining slits located in the ECS will physically remove the energy deviant electrons from the beam and ultimately reduce the available electrons exiting the ECS. This has the undesirable effect of decreasing available current after the ECS while increasing the background radiation in the Linac vault. The optimal operating condition is to have the injector provide the smallest energy spectrum possible, causing a maximum in available current and a minimum in ECS radiation. This optimization can be done by limiting the bunch length of the electron packets early in the acceleration process, since this sets the ultimate limit on the narrowness of the energy spectrum [6].

1.1 Saskatchewan Accelerator Laboratory

The Saskatchewan Accelerator Laboratory is a 300 MeV electron accelerator and storage ring located on the University of Saskatchewan campus. Figure 1.1 illustrates the location of the bunch monitor with respect to other components.

Figure 1.1: SAL Layout

1.1.1 Accelerator Front End

The main elements of the Injector are illustrated in Figure 1.2. The different components are labelled and show relative orientation and structure. Oscilloscope displays are provided to give an intuitive idea of the pulse manipulation that occurs at each component. Brief descriptions of these elements will provide sufficient background for further discussion.

Figure 1.2: Injector Components

1.1.2 The Transmitter

The transmitter provides the electromagnetic energy for acceleration of the beam. As displayed in Figure 1.2, it consists of a microwave oscillator, modulator and klystron.

The main components of the klystron include the electron gun, two RF resonant cavities, and a collector. The microwave oscillator provides a frequency of 2856 MHz to the input cavity of the klystron. The cavity resonates at this frequency, and velocity modulates the DC beam supplied by the gun. The beam then travels through a drift space and into the output cavity, which couples the field of the bunched electron beam to waveguides for transport to the Linac beam line. The klystron beam is then dumped into the collector.

The klystron can supply brief pulses of about 20 MW of microwave power at a rate of up to 360 Hz. This rate is determined by the modulator trigger, which gates the klystron gun with pulses variable from 300 to 2200 ns. The main elements of the modulator are the Pulse Forming Network (PFN) and the hydrogen thyratron. The PFN slowly stores energy in capacitors, that discharge rapidly when the thyratron is fired. The transmitter thus provides a rectangular pulse of microwave power to the Linac beam line.

This microwave power is then split for use in the prebuncher (1kW), buncher (13 MW) and section seven (6+ MW) which is an accelerating section located just after the ECS. The power left over from the buncher is phase-shifted to provide power to Section #1 (≈ 9 MW).

1.1.3 The Injector

The injector consists of the gun, video deflector, prebuncher and buncher and are illustrated in Figure 1.2.

The electron gun supplies electrons by thermionic emission. The gun is of a triode configuration which includes a cathode, grid and anode. Its operation depends on the potential of the grid relative to the cathode. The cathode potential is at -220 kV

relative to the anode. When the grid potential is changed from -225 kV to -220 kV, a square pulse with rising and trailing edges of 200 ns and a width that can be set up to 5000 ns is provided for acceleration.

The video deflector is used to sharpen the gun pulse edges. The deflector consists of a parallel plate capacitor, magnets and collimator. First, the beam proceeds between metal plates, which have a potential between them. Magnets produce a magnetic field between the plates and perpendicular to the electric field. When a START is sent, the electric and magnetic fields produce forces on the beam that exactly cancel. The beam can then pass directly through the collimator. When a STOP is sent, the electric field is reduced in magnitude, and the beam is deflected into the face of the collimator.

The prebuncher is a 10.5 cm long resonant cavity that velocity modulates the beam much like the input cavity of the klystron. It does this by having the sinusoidal input from the transmitter superimposed upon the DC pulse of the gun. After the drift space between the prebuncher and buncher, the electrons are forced into packets of roughly 75° intervals of the RF phase [3, 6]. Approximately 65% of the incoming electrons are captured in these intervals [12] with the rest drifting toward the beam pipe wall at ground potential.

The buncher is 1.6 m in length and has these parts: an input coupler, a tapered structure that is connected directly to a constant phase velocity section, and an output coupler to provide power to the next accelerating section. The input coupler accepts power from the waveguide in a rectangular TE_{10} mode and transforms it to a circular TM_{01} mode for acceleration. The tapered section limits the phase velocity for one wavelength of the input RF to allow for greater capture efficiency from the prebuncher. After the tapered section, the beam has several MeV of kinetic energy. The constant velocity section adds more energy to the beam, which exits the buncher at approximately 13 MeV of energy and has a phase spread on the order of 20° . The output coupler then takes the TM_{01} mode and transforms it to the TE_{10} mode for waveguide transport to Section #1. For comparison, the relationships are sketched

in Figure 1.3 and are tabulated in Table 1.1.

Figure 1.3: Pulse Relationships in Time: a) Gun Pulse Length, b) Bunch Period and Bunch Width, c) RF Pulse Width and Pulse Repetition Period

Table 1.1: SAL Linac

Parameter	Symbol	Magnitude
Gun pulse length	L_g	5000 ns
Bunch period	T_b	350.14 ps
Bunch width	L_b	≈ 20 ps
RF pulse width	L_p	300 $\rightarrow$ 2200 ns
Pulse repetition period	T_r	2.78 $\rightarrow$ 500 ms

The beam is then accelerated through six sections and enters the ECS. The ECS provides a reduction in energy spread from 1% to 0.1% by the use of magnets, energy

defining slits and Section #7 [18]. The beam then enters the Electron Storage Ring of Saskatchewan (EROS) [8] for later experimental use.

1.2 Monitor Overview

The first step in the development of the SAL bunch monitor was to define the design requirements. It was found that five general specifications were needed to limit the information search for monitors that could be modified and used at SAL.

The most important specification was that the monitor should be non-intercepting. It is intended that monitoring occur during normal operation, which is an impossibility with an intercepting monitor. Fast and passive bunch measurement is also desirable; fast so that the bunch measurement can be done quickly and passive so that the beam is disturbed as little as possible. Mechanical simplicity is also a desirable trait, since a more complicated design is generally less reliable. Lastly, the least expensive monitor with the most accuracy is a fundamental objective.

A survey of previous monitor designs for bunch monitoring revealed some ingenious and effective methods. Below are some of the designs considered for the SAL bunch monitor.

One of the more accurate methods was that designed by J. C. Sheppard [26] for the Stanford Linear Collider Linac. The main components include a vacuum vessel containing a quartz radiator and window, a streak camera and analyzer electronics. The beam enters the vacuum vessel and strikes a quartz radiator. This produces Cerenkov light, which passes through a window to a streak camera. The analyzer electronics include an oscilloscope that provides bunch intensity as a function of time. Although a resolution of 2.4 ps for a bunch length of ≈ 10 ps is impressive, this method intercepts the beam and is also a complicated monitor.

A stripline monitor is a metallic plate close to the inside surface of the beam pipe wall. It has coaxial terminations through vacuum sealed upstream and downstream ports. Stripline monitors have been used for bunch monitoring at many facilities

[13]. These monitors are designed to detect two frequency harmonics of the revolving beam and take the ratio of their amplitudes. This type of monitor is simple and well understood but its capacitance is high, giving it lowpass characteristics. For our application, a bandwidth in the tens of gigahertz is required.

An absolute measurement of the bunch length can be done by using an RF sweeper. One plate is fed with RF from a klystron which also drives the injector. At the plate, the RF is changed in phase so that the beam is swept to allow passage through a slit. The beam is collected at the slit and a charge dependence per relative injector phase can be found [3, 6]. This method provides an accurate result, but cannot be used for our purposes since it intercepts the beam for a short time.

A resonant cavity method was also considered. This had been done at the Stanford Linear Accelerator in 1966 [3]. It involves the beam travelling through a specially designed pillbox cavity with a geometry that insures resonance at two harmonics of the beam frequency. The fields inside the cavity are then coupled out and their ratio taken to give relative bunching efficiency. Although this provides a non-destructive measurement of the beam, the cavity must have very accurate dimensions which are immune to expansion and contraction due to changes in temperature.

The most frequently used monitor is the electrostatic pickup monitor [14, 25]. A disc shape electrode “button” is center terminated to coaxial cables outside the pipe. The button is situated close to the inside surface of the beam pipe, and provides a signal by sensing the disturbance caused by the electromagnetic field of the beam. This monitor is mechanically simple, passive and inexpensive. It does not intercept the beam and provides a quick measurement of relative bunching efficiency. There is also abundant literature on its principles of operation. For these reasons, this design was selected for the SAL bunch length monitor.

1.3 Bunching Theory

To understand the bunching process, the prebuncher must be considered in more detail. As mentioned before, it is a pillbox cavity of 10.5 cm in length that operates in the TM_{010} mode. The RF drives the cavity via an N type coaxial loop. A phase shifter allows variation of the relative phase of the cavity with the buncher. An attenuator allows a range of power levels on either side of the 1kW nominal operating value.

The purpose of the prebuncher is to prepare the beam so that as many electrons as possible can be accelerated in the buncher [28]. This is done by concentrating the particles at a particular phase in the buncher which will remain synchronous with the wave through acceleration. This synchronous phase is denoted by ϕ_s .

As a continuous electron stream passes through the cavity, some electrons are accelerated and some decelerated. Since the electrons at this point are not relativistic, velocity modulation occurs and bunching is done mainly in the drift space between the prebuncher and buncher. The process follows the progression of Figure 1.4 where ΔE is the change in kinetic energy of the beam plotted as a function of the phase of the modulating field.

The electrons from the prebuncher are then captured by the buncher at a particular phase ϕ . Consider a single electron entering the buncher. Since the buncher operates in a TM_{01} mode, only the axial E_z field is of concern [12, 6, 17]. Figure 1.5 illustrates an axial electric field with the abscissa being the phase ϕ or z .

If the electron is located at ϕ_s , it will travel with the wave at a constant phase. A particle slightly ahead of ϕ_s will see a weaker electric field magnitude and therefore a smaller force, causing the electron to be driven back into ϕ_s . Conversely, if the particle is slightly behind ϕ_s it will have a stronger force directing it to the synchronous phase. For small and slow deviations in phase, an electron is trapped in a potential well and

Figure 1.4: Electron Variations before Buncher: a) DC Beam, b) End of Prebuncher, c) End of Drift Space

will undergo synchronous oscillations with frequency [17]:

$$\omega_\phi = \sqrt{\frac{\omega_o e E \sin \phi_s (1 - \beta_s^2)^{3/2}}{v m_0 \beta_s}} \quad (1.1)$$

where E is the electric field strength, e is the electron charge, β_s is the velocity of the synchronous particle normalized to the velocity of light c , and ω_o , m_0 are the frequency of the RF and rest mass of the electron, respectively. From Equation 1.1, as the velocity of the electron becomes large these oscillations almost cease to occur.

Figure 1.5: Bunch Phasing

The capture region of the buncher is defined as the limit in phase that an electron can deviate from ϕ_s and still be captured. If the electron is at a more negative phase than $-\phi_s$, this electron will drop even further back. This is the boundary on one side of the capture region. The boundary on the positive side has been shown by Kollath to be $\approx 2\phi_s$ [17] giving a capture region of $\approx 3\phi_s$. By inspection, a bunch with phase deviating far from the synchronous phase will have electrons drop out of the acceleration process.

The limit of phase deviation of the particles from ϕ_s due to the synchronous oscillations is given by [17]:

$$\Delta\phi = \frac{A}{\beta_s} \sqrt[4]{\frac{2\pi(1 - \beta_s^2)^{3/2}\beta_s}{m_0\lambda_0 e E \sin\phi_s}} \sin\omega_\phi t \quad (1.2)$$

where A is a constant. As the acceleration progresses, the electrons will have their os-

cillations damped and the total bunch width will shrink. This equation, like Equation 1.1, is only valid for small and slow variations in phase which Kollath approximates at energies below 0.5 MeV. This is sufficient, since this is where most of the bunching effect occurs.

Two cases of possible bunch injection will now be considered. If an electron bunch is injected into the buncher with the centroid of charge at ϕ_s , the oscillations will damp out, the bunch will shrink and the ideal case has occurred. However, if the packet is injected into the buncher with the centroid away from ϕ_s , many more particles will undergo oscillations. While the velocities increase and thus reduce the oscillations, the bunch will be smeared in phase about ϕ_s . This is how the phase and ultimately the energy spread of the beam is increased [6].

Brown *et al.* [5] have shown that the energy spread of a linear accelerator beam after injection into an accelerating section is dependent on two parameters; the phase deviation of the bunch from the peak electric field and on the bunch width. This is given by:

$$\delta V/V = 1 - \cos\left(\frac{\alpha}{2}\right)\left[1 + \left(\frac{\sin(\theta)}{\cos(\theta)}\right)^2\right]^{-\frac{1}{2}} + \sin\left(\frac{\alpha}{2}\right)\left[1 + \left(\frac{\cos(\theta)}{\sin(\theta)}\right)^2\right]^{-\frac{1}{2}} \quad (1.3)$$

where θ is the phase deviation from the maximum at the wave crest and α is the bunch width. By plotting Equation 1.3 for a bunch width of 30° , the illustration given in Figure 1.6 is obtained. A clear minimum occurs about the zero phase position.

As will be discussed in Chapter 2, the button monitor provides a differentiated Gaussian voltage signal in the frequency domain for each harmonic of the machine frequency. To provide a look at the effect of moving away from a small bunch width, the first harmonic signal is divided by the fourth harmonic signal as shown in Equation 1.4

$$\frac{V_1}{V_4} = 0.25e^{\frac{15\omega_0^2\sigma^2}{2}} \quad (1.4)$$

where V_1 is the voltage of the first harmonic signal and V_4 is the voltage at the

Figure 1.6: Theoretical Dependence of Bunch Width and Relative Phase Energy Spread

fourth. The variable ω_o is the Linac RF frequency and σ is the standard deviation of a Gaussian pulse.

For application to the injector only, the indication is that an exponential dependence is expected for the button output as the prebuncher phase is changed from ϕ_s . This dependence is assumed to be symmetrical for small deviations about the minimum bunch width and becomes approximately constant as the centroid of injected charge moves away from ϕ_s and approaches the peak of the sinusoidal field, as illustrated in Figure 1.7.

If the assumption is made that a change of one degree will vary the Gaussian σ by one picosecond, the superposition Figures 1.6 and 1.7 yields Figure 1.8. This curve is obtained by arbitrarily selecting the minimum for the injector at 50° and the minimum for Section #1 at 20° . It is clear that two minima would occur over the

Figure 1.7: Comparison of Bunch Widths

range of the prebuncher phase; one due to the injector and the other to Section #1 as demonstrated in Figure 1.8.

Bunch width is set at injection and remains constant throughout acceleration [3, 17], therefore microwave phasing at injection is important in limiting bunch length. This combined with the relative phasing of the bunches at entry to each section are major factors in limiting energy spread of the beam.

Figure 1.8: Theoretical Dependence of Bunch Width on Prebuncher and Section #1 Phase

Chapter 2

Theory

2.1 Fourier Spectral Components

The beam bunch monitor described in this thesis compares two components of the Fourier spectrum of the beam; the fundamental component which corresponds to the distances between bunches, and a higher harmonic which depends on the temporal shape of the beam [7]. The theoretical development leading to the magnitudes of these components will now be presented.

2.1.1 Fourier Analysis of a Gaussian Distribution

The derivation below has been done by Shafer [25]. The beam bunches are assumed to be Gaussian in current distribution as illustrated in Figure 2.1.

Figure 2.1: Gaussian Wavetrain

The charge packets can be described as travelling waves given by:

$$I_b(z, t) = \frac{Ne}{\sqrt{2\pi}\sigma} \exp\left(-\frac{(vt - z)^2}{2\sigma^2}\right) \quad (2.1)$$

where Ne is the total charge in each bunch, σ is the standard deviation of a Gaussian pulse and v is the velocity of the bunch. In the time domain this is written:

$$I_b(t) = \frac{Ne}{\sqrt{2\pi}\sigma} [\exp(\frac{-t^2}{2\sigma^2}) + \exp(\frac{-(t-T_b)^2}{2\sigma^2}) + \dots] \quad (2.2)$$

The period T_b was defined in Table 1.1 and t is the time that can vary from 0 to $+\infty$. The number of packets in the wavetrain is given by the ratio of RF pulse length and RF period, which is on the order of a few thousand. Therefore, the assumption is made that the wavetrain is continuous and periodic in the time domain. The Fourier series is then given by the Euler formula:

$$f(t) = \frac{a_0}{2} + \sum_{n=1}^{\infty} (a_n \cos \frac{2\pi n}{T} t + b_n \sin \frac{2\pi n}{T} t) \quad (2.3)$$

where T is the period of the periodic waveform. The coefficients are defined as

$$a_n = \frac{1}{T} \int_{-\frac{T}{2}}^{\frac{T}{2}} f(t) \cos(\frac{2\pi n}{T} t) dt \quad (2.4)$$

$$b_n = \frac{1}{T} \int_{-\frac{T}{2}}^{\frac{T}{2}} f(t) \sin(\frac{2\pi n}{T} t) dt \quad (2.5)$$

Since the Gaussian pulse is an even function, only the a_n survive. Therefore:

$$a_0 = \frac{Ne}{T}$$

$$a_n = \frac{Ne}{T\sqrt{2\pi}\sigma} \int_{-\frac{T}{2}}^{\frac{T}{2}} \exp \frac{-t^2}{2\sigma^2} \cos(\frac{2\pi n}{T} t) dt$$

where the term in parenthesis is equal to $n\omega_0 t$. Continuing

$$a_n = \frac{Ne\omega_0}{2\sigma\pi\sqrt{2\pi}} \text{Re} \int_{-\frac{T}{2}}^{\frac{T}{2}} \exp \frac{-t^2}{2\sigma^2} \exp i n \omega_0 t dt$$

$$= \frac{N e \omega_0}{\sigma \pi \sqrt{2\pi}} \exp\left(-\frac{n^2 \omega_0^2 \sigma^2}{2}\right) \operatorname{Re} \int_0^{\frac{T}{2}} \exp\left(-\frac{t}{\sqrt{2}\sigma} - \frac{i n \omega_0 \sigma}{\sqrt{2}}\right)^2 dt$$

If $\frac{T}{2} \gg \sigma$, the integral is nearly equal to $\sqrt{2\pi}\sigma$ [25] and we have

$$a_n = \frac{N e \omega_0}{\pi} \exp\left(-\frac{n^2 \omega_0^2 \sigma^2}{2}\right) \quad (2.6)$$

The coefficients have the amplitudes as illustrated in Figure 2.2. They are normalized to the $n = 0$ harmonic number of the $\sigma = 10$ ps pulse. The figure demonstrates two important phenomena. First, a Gaussian in the time domain is a Gaussian in the frequency domain. Secondly, as the pulse narrows in the time domain, the broader it becomes in the frequency domain.

Figure 2.2: Fourier Harmonic Magnitudes

The Fourier series of Equation 2.3 can be written in terms of the beam current I_b :

$$I_b(t) = \langle I_b \rangle + 2\langle I_b \rangle \sum_{n=1}^{\infty} A_n \cos(n\omega_0 t) \quad (2.7)$$

where $\langle I_b \rangle$ is the total charge divided by the bunching period and A_n is the exponential dependence of a_n .

2.1.2 Fourier Analysis of a Differentiated Gaussian

It will be shown that the button pickup used will differentiate the input signal. The Fourier components for a Gaussian pulse that has been differentiated will now be calculated.

A differentiated Gaussian pulse is given by:

$$\frac{d}{dt} \exp \frac{-t^2}{2\sigma^2} = \frac{-t}{\sigma^2} \exp \frac{-t^2}{2\sigma^2} \quad (2.8)$$

and by inspection can be seen that it is an odd function. This has the consequence that only the b_n survive from Fourier series of Equation 2.3. Then:

$$b_n = \frac{-Ne}{T\sqrt{2\pi}\sigma^3} \int_{-\frac{T}{2}}^{\frac{T}{2}} t \exp \frac{-t^2}{2\sigma^2} \sin\left(\frac{2\pi n}{T}t\right) dt \quad (2.9)$$

and:

$$\begin{aligned} b_n &= \frac{Ne}{2\pi\sigma^3\sqrt{2\pi}} \frac{d}{dn} \left[\int_{-\frac{T}{2}}^{\frac{T}{2}} \exp \frac{-t^2}{2\sigma^2} \cos\left(\frac{2\pi n}{T}t\right) dt \right] \\ &= \frac{Ne}{2\pi\sigma^3\sqrt{2\pi}} \frac{d}{dn} \left[\text{Re} \int_{-\frac{T}{2}}^{\frac{T}{2}} \exp \frac{-t^2}{2\sigma^2} \exp(in\omega_0 t) dt \right] \\ &= \frac{Ne}{\pi\sigma^3\sqrt{2\pi}} \frac{d}{dn} \left[\exp\left(-\frac{n^2\omega_0^2\sigma^2}{2}\right) \text{Re} \int_0^{\frac{T}{2}} \exp\left(-\frac{t}{\sqrt{2}\sigma} - \frac{in\omega_0\sigma}{\sqrt{2}}\right)^2 dt \right] \end{aligned}$$

again, if $\frac{T}{2} \gg \sigma$ the integral is nearly equal to $\sqrt{2\pi}\sigma$. Therefore, the magnitude is

$$b_n = \frac{Nen\omega_0^2}{\pi} \exp\left(-\frac{n^2\omega_0^2\sigma^2}{2}\right) \quad (2.10)$$

This result could also have been found by differentiating Equation 2.7 directly. These coefficients have the amplitudes as illustrated in the Figure 2.3 and are nor-

malized to the 6th harmonic of the $\sigma = 10\text{ps}$ curve. The ratio is seen to peak in the vicinity of the 5th harmonic but drops in magnitude for greater pulse widths.

Figure 2.3: Fourier Harmonic Amplitudes for Differentiated Gaussian

2.2 Theoretical Output

In the analysis of the physical parameters of the monitor assembly, it is desirable to obtain the equivalent circuit for the button and theoretical values of button impedance and capacitance. By utilizing the previous section, equations for expected button voltage for a given beam input will be shown.

2.2.1 Equivalent Circuit

A cut away view of the button position relative to the beam and pipe wall is sketched in Figure 2.4. The capacitance C is the natural capacitance formed by two conductors with a potential difference.

Figure 2.4: Button Orientation

The circuit model for the monitor is obtained by inspection of Figure 2.4 and is illustrated in Figure 2.5.

Figure 2.5: Circuit Model

The current source is the button, C is the capacitance from button to beam pipe wall and R is the termination resistance of the electrode. The output of the voltage pulse can be developed as follows [25].

The charge density in the beam pipe is given by

$$q_b(t) = \frac{I_b(t)}{\beta_b c}$$

where the variable β_b is the velocity of the electrons of the beam divided by the speed of light c .

The image charge on the inside surface of the pipe is opposite in polarity and equal in magnitude to the beam charge. The charge flowing in the button is:

$$Q_s(t) = -\frac{\phi l I_b(t)}{2\pi \beta_b c}$$

where ϕ equals the azimuthal width of detector and l is the length of the button in the z direction. If the button is circular, then ϕl is equal to the button area divided by the pipe radius. The current supplied by the probe is then

$$I_s(t) = \frac{\phi l}{2\pi \beta_b c} \frac{dI_b(t)}{dt} \quad (2.11)$$

As shown below, the capacitance is very small and almost all the current flows through the terminating resistance $I_s \simeq I_R$

$$V_{out}(t) = R I_R(t)$$

With a Gaussian beam current, the voltage out is:

$$V_{out} = -\left\{ \frac{Ne\phi l R}{(2\pi)^{\frac{3}{2}} \beta_b c} \right\} \frac{t}{\sigma^3} e^{-\frac{t^2}{2\sigma^2}} \quad (2.12)$$

which is a Gaussian doublet resembling Figure 2.6. The figure was obtained from Equation 2.12 with the variables in the curly brackets lumped together as a unitless constant equal to one and $\sigma = 8$ ps.

The peak output voltage will occur at approximately $t = \pm\sigma$ and from Equation 2.12 equals

Figure 2.6: Differentiated Gaussian Wavepackets

$$V_{peak} = \frac{Ne\phi l R}{(2\pi)^{\frac{3}{2}}\beta_b c} \frac{e^{-1/2}}{\sigma^2} \quad (2.13)$$

The rms voltage output for each harmonic of the input wave can be found by using Equations 2.7 and 2.11. This is found to be for a circular button:

$$V_{out}(\omega) = RI_s = \frac{RNer^2 n\omega_0}{\sqrt{2}T_b \rho \beta_b c} A_n \quad (2.14)$$

where r is the radius of the circular button and ρ is the radius of the beam pipe. Ne can be found by integrating the bunch current I_b over its width in time

$$\int I_b d\tau = Ne.$$

2.2.2 Button Impedance

To get an idea of the magnitude of actual impedance seen by the beam due to the button is, the actual impedance of the capacitor and resistor in parallel is

$$Z(\omega) = \frac{R}{1 + j\omega RC}$$

With the substitution of $Z(\omega)$ for R in the previous equations, and the voltage of Equation 2.14 is divided by the current from Equation 2.7, the impedance for a circular button is:

$$Z_b(\omega) = \frac{V_{out}(\omega)}{I_b(\omega)} = \frac{\omega r^2}{2\rho\beta_b c} \frac{R}{1 + j\omega RC} \quad (2.15)$$

The above result agrees with Goldberg [11]. The value of R is the characteristic impedance of the coaxial cable and C can be obtained from the equation for parallel plate capacitors. It is desirable for the capacitance to be very small, since this provides a time constant which is small compared to the charge collection time. This small time constant will provide good timing information since $RC \ll t_c$ [16].

Chapter 3

Filter Simulations

Simulations provide an important tool in the verification of developed theory. This chapter contains a digital simulation of the output of the monitor assembly. Filters are located at the button pickoff and are needed to select two sufficiently different frequency components of the beam; one at the first harmonic of the machine frequency and one at the fourth. For an input waveform, the filters need to be fast enough in the time domain to respond to short bunching and yet narrow enough in the frequency domain to limit the feedthrough of unwanted harmonics. For each filter, the transfer function is found and the results of a computer simulation are shown.

3.1 Transfer Function

The required bandpass (BP) filters were obtained from Rf Microwave Ltd. [20]. They are resonant cavity two pole filters with the specifications listed in Table 3.1.

Table 3.1: Filter Specifications

f_0 MHz	3 dB % f_0	3 dB MHz	20 dB % f_0	20 dB MHz
2856	0.5	14	1.5	43
11424	0.5	57	1.5	171

The tables used by Geis [10] define the width of the passband as the frequencies at which the maximum variation is equal to the passband variation. Since Chebychev filters are used, there is a ripple in the passband that will define the passband width. From the filter specifications, the 3 dB point occurs at 0.5 % of the center frequency. It is assumed that the passband width as defined by Geis is 0.35 % of the center frequency. A sketch of the desired frequency response is illustrated in Figure 3.1, and

Table 3.2 containing the resultant numbers.

Figure 3.1: Desired Frequency Response

Table 3.2: Frequency Numbers

symbol	frequency MHz	
f_0	2856	11424
f_1	2846	11384
f_2	2866	11464
f_3	2813	11253
f_4	2899	11595

With the numbers from Table 3.2 and the nomographs supplied by Geis [10], a filter of order two will have the desired response at both harmonics. This confirms the specifications from RF Microwave Ltd. [20].

The circuit for the lowpass (LP) prototype is illustrated in Figure 3.2, which is then transformed with the appropriate substitutions to the BP filter circuit of Figure 3.3.

Figure 3.2: Low Pass Filter

Figure 3.3: Bandpass Filter

To obtain the transfer function of the BP circuit, the voltage divider principle is applied in the Laplace domain

$$z_1 = (sL' + \frac{1}{sC'})$$

$$z_2 = (\frac{1}{sL} + sC + \frac{1}{R})^{-1}$$

$$\frac{V_{out}}{V_{in}} = \frac{z_2}{z_1 + z_2}$$

where L' and C' are the series inductance and capacitance respectively and L and C are the parallel inductance and capacitance respectively. After simplifying

$$\frac{V_{out}}{V_{in}} = \frac{LC'Rs^2}{L'C'LCRs^4 + L'C'Cs^3 + (CL + L'C' + C'L)Rs^2 + Ls + R} \quad (3.1)$$

The corresponding numbers for the ideal BP filter are illustrated in Table 3.3.

Table 3.3: Component Values

symbol	2856 MHz	11424 MHz
L	27.807 pH	6.9547 pH
C	111.587 pF	27.9078 pF
L'	373983.8 pH	93533.37 pH
C'	0.0082970 pF	0.0020751 pF
R	50 Ω	50 Ω

If the simulation is scaled so that the 1st harmonic period is 350 and the 4th harmonic is $\frac{350}{4}$, the scale has moved from picoseconds to seconds. The transfer function after frequency scaling is then for the 1st harmonic:

$$\frac{V_{out}}{V_{in}} = \frac{11.536s^2}{481406138s^4 + 86283s^3 + 310304s^2 + 27.81s + 50} \quad (3.2)$$

and for the 4th

$$\frac{V_{out}}{V_{in}} = \frac{0.72179s^2}{1883561s^4 + 1349.9s^3 + 19409.8s^2 + 6.9547s + 50} \quad (3.3)$$

Substituting $s = j\omega$ into Equation 3.2 and rewriting in phasor form, the Bode plot is obtained in Figure 3.4. This is also done for the fourth harmonic of Equation 3.3 and illustrated in Figure 3.5.

Figure 3.4: Bandpass Filter Response for First Harmonic

Figure 3.5: Bandpass Filter Response for Fourth Harmonic

3.2 Digital Simulation

To simulate the response of the monitor circuit and filters, a digital computer and time-sampling method was used. The time-sampling method involves obtaining the

Z-transform from the analogue transfer function of the filters, then transforming it to a difference equation from which the time response can be obtained for an arbitrary input using a computer program.

The Z-transforms for Equations 3.2 and 3.3 were obtained from a computer program called Octave. The Laplace transfer function is typed in, the sampling period is selected and the digital transfer function is the output. The sampling period is determined from the poles of the transfer function. For a quadratic denominator in an analog transfer function, the progression from the Laplace domain to the Z domain is

$$(s + a)^2 + b^2 \rightarrow z^2 - 2ze^{-aT}\cos bT + e^{-2aT} \rightarrow (z - z_1)(z - \bar{z}_1)$$

where $z_1 = e^{-aT}e^{jbT} = e^{-aT}\angle bT$. For the poles, the real component is a and the complex component is b .

In order for the sampling period to have an accurate effect [23], many samples should occur in the period of the time constant which is defined as $\frac{1}{a}$. Also, for a complex pole many samples per period of the sinusoid should be done or $bT < 1$.

The poles of Equations 3.2 and 3.3 are located at $-4.47\text{E-}5 \pm i1.8008\text{E-}2$ and $-4.47\text{E-}5 \pm i1.7882\text{E-}2$ for the 1st harmonic and $-1.80\text{E-}4 \pm i7.2032\text{E-}2$ and $-1.80\text{E-}4 \pm i7.1527\text{E-}2$ for the 4th harmonic.

Careful consideration must be given on the selection of the sampling period. If it is too small, the computer rounding errors will cause the program not to converge. If the period is too big, the output will lose accuracy. The various sampling periods used are displayed in Table 3.4 along with the corresponding coefficients.

For reference, Octave displays [9] polynomials in the format

$$Y(z) = \frac{a_3z^3 + a_2z^2 + a_1z^1 + a_0}{z^4 + b_3z^3 + b_2z^2 + b_1z^1 + b_0}X(z). \quad (3.4)$$

The difference equation that was used in the computer program was obtained from the Z domain transfer function Equation 3.4. After multiplying top and bottom by

Table 3.4: Coefficients for Discrete Equation

coefficient	2856 MHz		11424 MHz	
	($T = 0.5$ ps)	($T = 1.0$ ps)	($T = 0.1$ ps)	($T = 1.0$ ps)
a_3	2.995204529E-9	1.197997123E-8	1.916948822E-9	1.914908103E-7
a_2	-2.9952973435E-9	-1.198068932E-8	-1.916990122E-9	-1.915365697E-7
a_1	-2.9950188996E-9	-1.197853727E-8	-1.916865333E-9	-1.913992924E-7
a_0	2.995111825E-9	1.197925458E-8	1.916906966E-9	1.914450511E-7
b_3	-3.999749250	-3.999176260	-3.999825181	-3.988976491
b_2	5.999408910	5.998173464	5.999578677	5.977266560
b_1	-3.999570032	-3.998817884	-3.999681803	-3.987546835
b_0	0.9999103875	0.9998207831	0.9999283094	0.9992833251

z^{-4} the equation becomes:

$$Y(z) = \frac{a_3 z^{-1} + a_2 z^{-2} + a_1 z^{-3} + a_0 z^{-4}}{1 + b_3 z^{-1} + b_2 z^{-2} + b_1 z^{-3} + b_0 z^{-4}} X(z) \quad (3.5)$$

and knowing that:

$$X(z)z^{-n} \rightarrow x[(k - n)T]$$

where n becomes a delay in time, the discrete equation becomes

$$\begin{aligned} y(kT) = & a_3 x[(k - 1)T] + a_2 x[(k - 2)T] + a_1 x[(k - 3)T] + a_0 x[(k - 4)T] \\ & - b_3 y[(k - 1)T] - b_2 y[(k - 2)T] - b_1 y[(k - 3)T] - b_0 y[(k - 4)T] \end{aligned} \quad (3.6)$$

Since the system is causal, $y(-q)$ equals zero when q is any positive real number.

With a sinusoidal input of amplitude 1 and sampling periods of $T = 0.5$ ps for the 1st harmonic and $T = 0.1$ ps for the 4th, the simulations for the output of the filters are plotted in Figures 3.6 and 3.7.

Figure 3.6: First Harmonic Response

Figure 3.7: Fourth Harmonic Response

A closeup of the waveform of Figure 3.6 would illustrate a period of 350 ps and 87.5 ps for Figure 3.7. It is clearly visible that the filters reach steady state at 100 ns for the 2856 MHz case and 25 ns for the 11424 MHz case. This is within 5 time constants for each filter. A summary of values obtained from theory, bench test and digital simulations are illustrated in Table 3.5. The theory numbers are obtained from Figures 3.4 and 3.5. The bench test numbers were obtained by selecting an input to the filters of known magnitude and measuring the output as described in Chapter 4. The simulation numbers were obtained from Figures 3.6 and 3.7 at ≈ 100 ns.

Table 3.5: Theoretical, Simulated and Experimental Values

input frequency MHz	Attenuation dB		
	theory	simulation	experimental
2856	-0.00	-0.11	0.00
2840	-4.41	-4.33	-3.26
2830	-12.62	-12.53	-15.89
2815	-20.80	-20.89	-29.64
11424	0.12	-0.09	-0.09
11360	-4.45	-4.41	-2.95
11320	-12.64	-12.62	-15.60
11240	-22.86	-22.86	-28.29

The experimental numbers exhibit somewhat faster edges, but in general the three sets of numbers agree. For the simulations of a differentiated Gaussian input, Equation 2.12 with the braces normalized out and $\sigma = 8.0$ ps was used. The Figures 3.8 and 3.9 are the output.

Figure 3.8: First Harmonic Filter Response for $\sigma = 8.0$ ps

Figure 3.9: Fourth Harmonic Filter Response for $\sigma = 8.0$ ps

3.3 Summary

Table 3.6 contains the values of several simulation runs, with the maximum values of the output taken at approximately 100 ns, which is the steady-state output. The theoretical values were obtained from Equation 2.10 with the total current Ne normalized out.

The filter simulation amplitudes agree well with the expected values obtained from Equation 2.10. Given the pulse length of the SAL injector, the reponse time of 100 ns is fast enough for the filters to be used for the bunch length monitor.

Table 3.6: Output Values for Differentiated Gaussian

σ	2856 MHz		11424 MHz		$\frac{11424}{2856} \text{ sim}$	$\frac{11424}{2856} \text{ theo}$
	simulation	theory	simulation	theory		
	E-4 [1/ps ²]	E-4 [1/ps ²]	E-4 [1/ps ²]	E-4 [1/ps ²]		
8.0	1.0036	1.0153	3.4792	3.4792	3.4667	3.4267
10.0	0.9978	1.0094	3.1708	3.1708	3.1780	3.1413
12.0	0.9907	1.0023	2.8307	2.8307	2.8571	2.8242
14.0	0.9825	0.9939	2.4756	2.4756	2.5201	2.4924
16.0	0.9730	0.9844	2.1207	2.1208	2.1795	2.1545
18.0	0.9624	0.9736	1.7797	1.7797	1.8492	1.8284
20.0	0.9507	0.9618	1.4630	1.4630	1.5389	1.5224
22.0	0.9379	0.9489	1.1781	1.1782	1.2560	1.2426

Chapter 4

The SAL Bunch Length Monitor

The SAL bunch length monitor consists of a button port welded to a 35 cm length of beam pipe. The stainless steel beam pipe is 6 cm in diameter with vacuum seal flanges at each end. The button port is fashioned from a vacuum sealed type-N receptacle and located 8 cm from one end. The inner conductor of the receptacle protrudes into the interior of the pipe, and is flared to allow interchanging of button studs.

There were six buttons made for the bench tests, three circular and three square. The sizes selected were 0.5, 1.0 and 2.2 cm in diameter for the circular buttons and 0.5, 1.0 and 2.0 cm for the lengths of the square sides. All buttons were made of 2 mm copper with brass stubs inserted into the copper and then soldered. The total distance from the inside surface of the pipe to the inside surface of the button was 3 mm. Figure 4.1 illustrates the monitor as it appeared for the bench tests. The plates on the ends were used to mount type-N bulkhead receptacles with a thin wire stretched between them. The inside surface of the plates had a 0.15 mm layer of aluminum glued to them.

4.1 The Bench Test

The bench tests were necessary for two reasons. First, to establish that the buttons would provide a signal of significant power to be measurable. Secondly, that a relationship between button shape and output signal could be observed and with this information select the best button for the beam test.

4.1.1 Component Characterization

Some preliminary measurements needed to be completed before the actual tests could start. These included measuring the response curves for the filters and diode detectors

Figure 4.1: Bunch Length Monitor with Test Fixtures

and a measurement of the capacitance of the installed button.

Filter Measurements

The filters from RF Microwave were measured for their response over the bandwidth concerned. The test setup consisted of the HP 8672A signal generator with an output of 0 dbm set at the center frequency of the 2856 MHz filter. The filter was placed at the signal generator output and a HP 436A Power Meter was referenced to the filter output. The signal frequency was then adjusted at a few MHz per measurement and the output of the filter as measured by the power meter was recorded. This procedure was also done for the 11424 MHz filter. The results are illustrated in Figures 4.2 and 4.3, with the results of the theoretical response curves from Chapter 3 included.

Figure 4.2: Theoretical and Experimental First Harmonic Response

Figure 4.3: Theoretical and Experimental Fourth Harmonic Response

Detector Measurements

A similar procedure was used for the crystal detectors. The signal generator was set at the respective center frequency, either 2856 MHz or 11424 MHz, with the output power being varied in magnitude. The signal generator output is connected to the input of the crystal detector and the output of the detector is connected to an oscilloscope. A relationship between input power and output voltage can then be found as illustrated in Figures 4.4 and 4.5.

Capacitance Measurement

The capacitance measurement was done with a capacitance meter of 0.1 pF sensitivity. One microclip lead was placed on the outer conductor of the button port and the other microclip on the inside conductor. The combined capacitance of the button port and 1 cm diameter button was measured to be 6.2 pF. With the button removed it was measured to be 5.9 pF. Since the capacitances of the receptacle and button are in parallel, the button capacitance is 0.3 pF.

Figure 4.4: Response of Detector for First Harmonic

Figure 4.5: Response of Detector for Fourth Harmonic

4.1.2 The Bench Measurements

The test setup consisted of the components labeled in Figure 4.6, which include a signal generator (HP 8672A), switch circuit, amplifier (Minicircuits ZHL-42), circulator (Huggins HC-7240), Step Recovery Diode (SRD) circuit and Test Set Output (TSO). Each component will be discussed concerning the function it performs.

Figure 4.6: Test Setup

The synthesized signal generator provides a variable sinusoidal output from 1 to 18 GHz. The output power can be adjusted from -20 to +10 dbm.

Figure 4.7 is the block diagram of the switch which consists of a 555 timer, multivibrator, an ECL-TTL translator and M/A-COM SW-328 SPDT switch.

The discharge, threshold and trigger pins on the timer are biased to have an astable mode of operation [27]. The frequency was chosen to mimic a possible injector pulse of 360 Hz. The pulse width was 1.5 ms, with rising and falling edges of 200 ns. The timer is biased so that the pulse train has negative pulses from 0 to -5 V.

The multivibrator is set in monostable mode and uses the output of the timer as its trigger. The multivibrator utilizes a Schmitt trigger to provide insensitivity to variations in rising and falling edges from the timer [21]. The multivibrator operates

on ECL logic levels, therefore the 0 to -5 V logic levels of the timer are voltage divided to provide ECL logic levels of -0.8 V for a HI and -1.8 V for a LOW. External biasing sets the pulse width to $1\mu\text{s}$.

The next chip is the ECL-TTL translator. This is necessary since the GaAs switch is designed to work on voltage levels of 0 to -5 V [19]. The translator output is biased to provide these levels.

The SW-328 acts as a switch for the input RF. From the RF input when the switch is ON or closed, the RF is allowed passage through the chip at 1 db insertion loss to the TSO. When the switch is OFF, 30 db of isolation is obtained [19].

Figure 4.7: Switch Circuit

The amplifier increases the input power from ≈ 10 dbm to ≈ 30 dbm. The circulator was included to protect the switch and amplifier from reflected power.

Finally, the SRD M/A-COM 43004-91 was used to provide a strong fourth harmonic component to the TSO and is illustrated in Figure 4.8. When the input RF is driving the SRD into forward conduction, it is in its low impedance state and stores charge. When the SRD is in reverse conduction, the stored charge is removed, thereby committing the SRD to its high impedance state [1]. The output waveform is illustrated in Figure 4.9.

Figure 4.8: SRD Circuit

Figure 4.9: SRD Output

Output Power

The HP 8990A Peak Power Meter (PPM) was connected to the TSO of Figure 4.6. The raw peak output power from the TSO was 18 mW. By utilizing the filters, the output power for the first harmonic was 12 mW and for the fourth harmonic, $68\mu\text{W}$.

The next measurement involves the monitor with the 0.5 cm diameter button installed and a $50\ \Omega$ termination on the output of the button port connected. Stub tuners were connected at the input and output plates of the monitor pipe to provide a better impedance match to the test setup [24]. The 11424 MHz filter was connected to the pipe output and the tuners were optimized so that the fourth harmonic power reached a peak of $23\ \mu\text{W}$. The stub tuners were left in this state and the 2856 MHz filter was connected to the pipe output which had $300\ \mu\text{W}$ of power. The total power out was $850\ \mu\text{W}$.

Finally, with the PPM sensor and the $50\ \Omega$ termination from the button port exchanged, the total, first and fourth harmonic output power was obtained from each button. The values for each measurement are included in Table 4.1. Appendix C contains the scans of the pictures of the PPM display from which the values of Table 4.1 were obtained.

Table 4.1: Summary of Button Outputs

Dimensions	Area	Output Power (μW)		
Diameter (cm)	(cm^2)	Total	First Harmonic	Fourth Harmonic
0.5	0.196	17.0	3.50	2.37
1.0	0.785	34.0	14.5	1.50
2.2	3.80	57.0	28.5	0.509
Length (cm)				
0.5	0.250	24.0	4.50	3.65
1.0	1.00	40.0	15.7	2.25
2.0	4.00	30.0	19.2	0.702

It is clear from the data of Table 4.1 that the size (area) of the button is inversely proportional to the power coupled out at the fourth harmonic. This is an example of

how a larger RC time constant results in a loss of time information by smoothing out the input pulse.

4.2 Experimental Beam Trials

Three experimental trials were conducted on the button monitor when it was installed in the beam line. These occurred on April 10th, July 10th and August 10th 1995. Since each was unique, a brief description of procedures and the output data will be done separately.

For each test run, the 1 cm diameter button was used. It was found to have the best output power for both harmonics and did not have the sharp edges of the square button, which tend to accumulate charge [15]. After the button was installed, the monitor pipe was placed in the beam line and a 13.4 m length of Heliax cable was strung from the button port through an access hole in the Linac Vault to the Drive Room. From the Drive Room the cable continued to where a power divider was attached. The two signals are then fed into the two BP filters and then to the PPM. A NeXT workstation was used in the test area which had a GPIB cable connected from the PPM to the NeXT to allow for data transfer. Figure 4.10 illustrates the layout common for each run.

4.2.1 April Run

With Section #1 phase set at 74°, Section #2 transmitter off and the prebuncher phase at 29°, the measurement procedure began by saving this button output as displayed by the PPM. Then the prebuncher phase was changed, which directly affected the bunching, and the stored data were then subtract from each succeeding measurement. A definitive number for the output power for each of the three trials were obtained by averaging the last 300 ns of the output pulse at each prebuncher phase value.

In Table 4.2, it is the change in output power that is recorded, with the exception

Figure 4.10: Experimental Test Setup

of the first absolute measurement.

The Helix cable attenuated the first and fourth harmonics differently [2]. The cable attenuation was 1.94 db for the first harmonic and 4.25 db for the fourth harmonic. This factor is calculated into the Actual Output Power column in Table 4.2. The operator phase numbers should be multiplied by 1.72 to get the actual relative phase from succeeding measurements. The toroid current is measured at a toroid located just after the button monitor but before Section #2. It measures a voltage from the toroid which has been calibrated to provide the average current over the RF pulse width [4]. The plots that the data in Table 4.2 were derived from are included in Appendix D. Figure 4.11 is a graphical representation of the voltage ratio

in Table 4.2 versus prebuncher phase. For these data and subsequent data, error measurements are not included but are assumed to be constant for each data point for each test run.

Table 4.2: Summary of Button Output for April Test Run

Operator Phasing ($^{\circ}$)	Toroid Current (mA)	Raw Output Power (μ W)		Actual Output Power (μ W)		$\frac{V_1}{V_4}$
		First	Fourth	First	Fourth	
29	100	636	1850	995	4930	0.4490
19	95	-12.3	-1.05	-19.3	-2.80	0.4447
10	93	-37.2	-132	-58.2	-350	0.4520
29	100	-7.83	-45.0	-12.2	-120	0.4517
39	100	-5.29	-143	-8.28	-379	0.4653
49	95	-138	-279	-216	-742	0.4309
59	86	-293	-767	-458	-2040	0.4306
69	57	-452	-1380	-707	-3670	0.4773
79	33	-545	-1550	-852	-4130	0.4206
29	100	-6.72	-48.6	-10.5	-129	0.4526

Variation of Test Setup

The second phase of this run was a “proof of principle” of the ability of the monitor to make bunch measurements in a configuration close to its final form. The test assembly was changed to have the power splitter and filters connected directly to the button port with the crystal diode detectors connected to the filters. RG58 coaxial cables were laid on the same path as the Heliax through the Drive Room and on to the test area. A digital scope was used to observe the signals with GPIB interface to the NeXT. Scope displays were saved in encapsulated postscript.

To eliminate the transmitter noise, the ON and OFF triggers for the video deflector were made to coincide in time, allowing no beam to pass through the injector. In this way, the transmitter noise could be saved in the scope memory and subtracted from subsequent measurements.

Figure 4.11: April Results: Experimental Dependence of Prebuncher Phase on Bunch Width

Starting from the arbitrary 29° prebuncher phase and then varying it on either side, output obtained from the scope traces are illustrated in Appendix E and recorded in Table 4.3 by using the crystal detector calibration curves of Figures 4.4 and 4.5.

Although the magnitude of the ratios in Table 4.3 are in general somewhat larger than that for Table 4.2, the relative changes follow the same trend. This is confirmation that this setup configuration will provide the desired sensitivity. Figure 4.12 is an example of the output of the detectors at prebuncher phase of 29° and after subtracting the transmitter noise. The top trace is the first harmonic and the bottom is the fourth.

Table 4.3: Summary of Button Output from Crystal Detectors

Prebuncher Phasing (°)	Toroid	Output Voltage (mV)		$\sqrt{\frac{P_1}{P_4}}$
	Current (mA)	First Harmonic	Fourth Harmonic	
29	102	15	43	0.610
10	95	15	45	0.664
49	105	13	37	0.584
69	59	5	13	0.645

Figure 4.12: Output of Monitor after Noise Subtraction

It was decided that another run would be required to obtain more data and confirm the April results.

4.2.2 July Run

The experimental setup for this run was identical for that of the April 10th run except in one respect - the transmitters for Sections #2 - #6 were also running. This change would create havoc with the interpretation of the results since the noise from the button would be much greater.

Noise Discussion

With reference to Figures 4.13 and 4.14 two facts can be noted. First, that the magnitude of the power output is greater for Figure 4.14, and that it also has noise in the vicinity of the beam signal. These are plots from the April 10th run and correspond to the first row of data in Table 4.2.

The plots from the July 10th run are shown in Figures 4.15 and 4.16. It is clear that the output at the fourth harmonic is very much larger than that for the April run. To understand why, refer to Figure 4.17 which is a close-up of the structures between the two sections.

Figure 4.13: April Result: First Harmonic Response with Prebuncher Phase 29°

Figure 4.14: April Result: Fourth Harmonic Response with Prebuncher Phase 29°

Figure 4.15: July Result: First Harmonic Response with Prebuncher Phase 29°

Figure 4.16: July Result: Fourth Harmonic Response with Prebuncher Phase 29°

In the April run, microwave power was only available from Section #1. After it travels through Section #1, it proceeds into an output coupler and provides power for Section #7. Since all sections are essentially bandpass filters [22], the output of higher harmonics at the exit of Section #1 is very small. The stray fields of the first harmonic that continue past the output coupler are quickly attenuated by the 6 cm diameter beam pipe, which has a cutoff frequency of 3.83 GHz [24] and is essentially a highpass filter.

This situation is different for the input coupler of Section #2. The first harmonic power cannot travel back toward Section #1 because of the beam pipe, although the fourth harmonic can. With 20 MW of microwave power located only 170 cm from the monitor, it is easy to imagine a large amount of power being coupled to the button at the fourth harmonic.

Indeed, this is the case. In the August run, the transmitter for Section #2 was turned on and a large peak of noise similar to Figure 4.14 was observed. With this transmitter off, a clean and strong signal was obtained.

With this explanation in mind, the noise power was measured to be 32 mW on

Figure 4.17: Components Between Section #1 and Section #2

July 11th. The data recorded in Table 4.4 has the noise offset subtracted from the button output.

Table 4.4: Summary of Button Output for July Test Run

Operator Phase (°)	Toroid Current (mA)	Raw Output Power (μ W)		Actual Output Power (μ W)		$\frac{V_1}{V_4}$
		First	Fourth	First	Fourth	
23	32	95.2	10600	149	28200	0.07269
18	31	96.7	10100	151	26900	0.07492
13	31	97.6	9980	153	26600	0.07584
9	30	97.5	9440	152	25100	0.07782
23	32	95.4	8880	149	23600	0.07524
28	31	94.3	9660	147	25700	0.07563
33	31	92.7	10300	145	27400	0.07275
38	30	91.1	11100	142	29500	0.06938
43	30	88.5	11000	138	29300	0.06862
48	29	83.5	10100	131	26900	0.06978
53	27	73.0	7500	114	20000	0.07550
58	25	62.8	4850	98.2	12900	0.08725
63	15	45.2	2470	70.7	6570	0.1037
68	12	25.6	4660	40.0	12400	0.05680
73	11	21.9	5050	34.2	13400	0.05052
78	10	20.0	4800	31.3	12800	0.04945
23	32	96.2	9960	150	26500	0.07523

Energy Deviation

The July run was set up to prove that prebuncher phase is directly proportional to the energy spread. The procedure started with an arbitrary phase for the prebuncher and a magnet bent the electron path at the end of the Linac through a narrow slit and into a large iron block with an ammeter attached for current measurement.

The peak of the current pulse is displayed in the control room by varying the magnetic field of the magnet. Once this peak is found, the magnetic field is varied to reduce the current pulse to half its maximum on both sides of the peak. Another display relates the strength of the magnetic field to the electron energy. Table 4.5 contains the results of this procedure.

Figure 4.18 illustrates the first-to-fourth voltage ratio versus prebuncher phase of Table 4.4. Figure 4.19 is a plot of the energy difference versus prebuncher phase of Table 4.5. The two curves are plotted on the same prebuncher phase scale to illustrate that the minimum in voltage ratio or bunch width corresponds approximately to the narrowest energy spread.

Table 4.5: Energy Spread of Beam

Prebuncher Phase (°)	Peak Energy (MeV)	Half Current Energy (MeV)	Half Current Energy (MeV)	Difference (MeV)	% of Peak
11	264.705	262.895	266.780	3.89	1.47
30	265.000	262.699	266.519	3.85	1.45
53	264.116	266.151	267.806	3.69	1.39
70	269.083	266.684	270.753	4.07	1.51

Figure 4.18: July Results: Experimental Dependence of Bunch Width on Prebuncher Phase

Figure 4.19: July Results: Experimental Dependence of Beam Energy on Prebuncher Phase

4.2.3 August Run

The August run was identical to the April run, except that the PPM display was used to average the button pulse. As a result, the NeXT and GPIB interface was not required. With Section #2 transmitter off, the output was a very clean signal, much cleaner than found in the April run.

Two experiments were done, one with Section #1 phase at 69° and the other with Section #1 at 75°. The data is recorded in Tables 4.6 and 4.7 and plotted in Figures 4.20 and 4.21.

Figures 4.20 and 4.21 illustrate the effect of the prebuncher phase and Section #1 phase moving relative to one another. The bunch length minima from the Injector and Section #1 are clearly visible and appear to become more defined for greater Section #1 phase values.

Table 4.6: Summary of Button Output for August Run, Section #1 Phase 69°

Operator Phasing (°)	Toroid Current (mA)	Raw Output Power (μ W)		Actual Output Power (μ W)		$\frac{V_1}{V_4}$
		First	Fourth	First	Fourth	
29	96	578	4650	904	12400	0.2702
24	94	563	4500	880	11200	0.2711
19	82	542	4110	847	10900	0.2783
14	74	513	3570	802	9500	0.2906
10	70	504	3390	788	9020	0.2955
29	100	572	4600	894	12200	0.2703
34	101	538	4300	841	11400	0.2711
39	90	392	3000	613	7980	0.2771
44	79	312	2280	488	6070	0.2835
49	71	252	1750	394	4660	0.2908
54	65	217	1490	339	3960	0.2925
59	59	183	1220	286	3250	0.2969
64	53	152	927	238	2470	0.3104
69	46	121	625	189	1660	0.3373
74	41	92.0	386	144	1030	0.3742
79	37	66.3	160	104	426	0.4934
29	100	578	4640	904	12300	0.2705

Table 4.7: Summary of Button Output for August Run, Buncher Phase 75°

Operator Phasing ($^\circ$)	Toroid Current (mA)	Raw Output Power (μ W)		Actual Output Power (μ W)		$\frac{V_1}{V_4}$
		First	Fourth	First	Fourth	
29	104	564	5170	882	13800	0.2532
24	98	566	5080	885	13500	0.2559
19	87	546	4660	854	12400	0.2624
14	81	519	4070	811	10830	0.2737
10	81	510	3840	797	10220	0.2793
29	104	563	5150	880	13700	0.2534
34	101	520	4690	813	12500	0.2552
39	90	371	3160	580	8410	0.2626
44	81	302	2460	472	6550	0.2686
49	74	258	2060	403	5480	0.2713
54	69	222	1790	347	4760	0.2699
59	63	186	1540	291	4100	0.2664
64	56	153	1240	239	3300	0.2692
69	50	126	990	197	2630	0.2734
74	42	100	672	156	1790	0.2957
79	37	76.0	425	119	1130	0.3241
29	104	558	5100	873	13600	0.2535

Figure 4.20: August Results:Experimental Dependence of Prebuncher Phase on Bunch Width for Section #1 Phase of 69°

Figure 4.21: August Results:Experimental Dependence of Prebuncher Phase on Bunch Width for Section #1 Phase of 75°

Chapter 5

Summary and Conclusions

The principle of monitoring the bunch length at the front end of the Linac has been discussed. It has been shown that a narrow bunch width provides a minimum in energy spread, which was the motivation to develop the monitor. A literature search indicated that the best monitor for the application would be a button monitor mounted as close as possible to the injector. Its operation relies on the principle that in the time domain, a Gaussian beam pulse with standard deviation σ has in the frequency domain a Gaussian shape but with the standard deviation in the denominator of the argument. The effect is that a narrow pulse width in time is a broad pulse in frequency. By manipulating sufficiently wide harmonics, an indication of the bunch width in time can be obtained. The monitor exploits this characteristic by detecting power at the first and fourth harmonics of the machine frequency and divides them to provide a ratio related to bunch length.

Computer simulations on the feasibility of using this monitor at SAL were favourably demonstrated, and it was decided to construct the monitor and install it just after Section #1, as illustrated in Figure 1.2.

The bench tests revealed that a button of 1 cm diameter mounted 3 mm from the beam pipe wall would provide sufficient signal strength for signals to be brought upstairs. A power splitter and bandpass filters at 2856 MHz and 11424 MHz provided signals that are related to the first harmonic and the fourth.

After installation and three experimental runs, it has been proven that the monitor operates adequately. Clear minima can be seen in plots of voltage ratio versus prebuncher phase as shown in Figure 5.1. The two minima are due to the separate dependence of the injector and Section #1 on energy spread and it is clear that one of the minima is an absolute minimum.

As shown in Tables 4.5 and Table 5.1, by only changing the prebuncher phase, the percent energy spread of the beam can change from a value of 1.51 % to a value of 1.39 %. With more rigorous optimization, a value of 1.30 % or less could be realized.

Figure 5.2 illustrates the results from Table 5.1 in graphic form. It is plotted with the same horizontal scale to demonstrate the similarities in the curves. A clear minimum is observed about the 50° position and a maximum at $\approx 68^\circ$ in both Figures 5.1 and 5.2.

Table 5.1: Energy Spread of Beam

Prebuncher Phase (°)	Peak Energy (MeV)	Half Current Energy (MeV)	Half Current Energy (MeV)	Difference (MeV)	% of Peak
11	264.705	262.895	266.780	3.89	1.47
30	265.000	262.699	266.519	3.85	1.45
53	264.116	266.151	267.806	3.69	1.39
70	269.083	266.684	270.753	4.07	1.51

The monitor worked well with the raw signal transported upstairs where it was split and sent to filters and a Peak Power Meter. By substituting crystal detectors for the Peak Power Meter and connecting them along with the bandpass filters and power splitter directly to the button port, it was measured that sensitivity of the monitor with the crystal detectors was similar to that of the Peak Power Meter. In the future, this assembly would provide the front end electronics for the monitor. A dedicated microprocessor with analog-to-digital conversion capability and on-board RAM should be installed to handle the data acquisition.

In its final form, the operator will start the bunch length minimization procedure at an arbitrary prebuncher and Section #1 phase. It was intended that the monitor be used with the accelerator in operation and several suggestions on eliminating the transmitter noise from Section #2 have been discussed. The most likely method would be to separate the Section #2 transmitter pulse from the beam pulse in time so that the measurements can be done with a clean signal. This would cause less than a minute's delay in beam usage when the Section #2 transmitter pulse would

again accelerate electrons.

The data acquisition would use the trigger from the video deflector ON to provide timing. In order to allow transients in the beam pulse to decay and also to sample outside the filter time constants, a few hundred nanoseconds must elapse before the sampling begins. Several samples should be taken over the pulse, therefore a two port A/D of 50 MHz or greater is desired. The signals vary on the order of millivolts, so with no amplification the accuracy provided by a 12-bit A/D is adequate.

After the values of the two harmonics have noise subtracted from them they will be divided and the ratio is sent to an LED display in the control room. The operator can minimize the ratio by changing the prebuncher phase. The video deflector OFF ends the acquisition cycle for each pulse.

In this way, rapid and accurate bunching efficiency can be judged with minimal demand on beam time.

Figure 5.1: July Results: Experimental Dependence of Bunch Width on Prebuncher Phase

Figure 5.2: July Results: Experimental Dependence of Beam Energy on Prebuncher Phase

Appendix A

Filter Specifications

This is a scan of the data sheet faxed to SAL from RF Microwave Ltd. [?]

Figure A.1: Response Curve for Various Filters

Appendix B

Computer Programs

Filtersim1.c

```
/* This program has a sine wave for input to a 2.856 GHz BP filter and */
/* outputs the simulation data to a file. The output plot is Figure 3.6.*/
#include<stdio.h>
#include<math.h>
#define MAX 1000000
#define T 0.5
#define PI 3.141592653591
main ()
{
    FILE *outfile,*fopen();
    int limit,k;
    double y[MAX],a3,a2,a1,a0,b3,b2,b1,b0,w,q;
    outfile = fopen ("sin1.dat","w");
    /* w is just the center frequency of the filter in rad/s */
    w = 2*PI/350;
    /* the coefficents obtained from Octave for sampling period T = 0.5 ps */
    a3 = 2.99520452884394E-9;
    a2 = -2.99529734348880E-9;
    a1 = -2.99501889955422E-9;
    a0 = 2.99511182522139E-9;
    b3 = -3.999749249843368;
```

```

    b2 = 5.999408900937592;
    b1 = -3.999570032143500;
    b0 = 0.999910387540133;

/* this section fills the first four output values and writes to a file */
    y[1] = 0;
    y[2] = a3*sin(w*T);
    y[3] = -b3*y[2] + a3*sin(2*w*T) + a2*sin(w*T);
    y[4] = -b3*y[3] - b2*y[2] + a3*sin(3*w*T) + a2*sin(2*w*T)
+ a1*sin(w*T);
    fprintf(outfile,"%lf %20.18lf \n",1*T,y[1]);
        fprintf(outfile,"%lf %20.18lf \n",2*T,y[2]);
        fprintf(outfile,"%lf %20.18lf \n",3*T,y[3]);
        fprintf(outfile,"%lf %20.18lf \n",4*T,y[4]);

/* input from user is used to select the length of the simulation */
    printf("Enter the simulation length. i.e. 1000 is 500 psec \n");
    scanf("%d",&limit);

/* main program that fills the output array and sends to outfile */
    for (k=5; k < limit + 1; k++){
        y[k]= -b3*y[(k-1)] - b2*y[(k-2)] - b1*y[(k-3)] -
            b0*y[(k-4)] +
            a3*sin(w*T*(k-1)) +
            a2*sin(w*T*(k-2)) +
            a1*sin(w*T*(k-3)) +
            a0*sin(w*T*(k-4));
        if ( k % 50 == 0) /* this writes only every 50th point */
            fprintf(outfile,"%6.0lf %4.3lf \n",k*T,y[k]);
    }
    fclose(outfile);
}

```


Filtersim4.c

```
/* This program has a sine wave for input to a 11.424 GHz BP filter and */  
/* outputs the simulation data to a file. The output plot is Figure 3.7. */
```

```
#include<stdio.h>
```

```
#include<math.h>
```

```
#define MAX 1000000
```

```
#define T 0.1
```

```
#define PI 3.141592653591
```

```
main ()
```

```
{
```

```
FILE *outfile,*fopen();
```

```
int limit,k;
```

```
double y[MAX],a3,a2,a1,a0,b3,b2,b1,b0,w;
```

```
outfile = fopen ("sin4.dat","w");
```

```
/* w is just the center frequency of the filter in rad/s */
```

```
w = 2*PI*4/350;
```

```

/* the coefficients obtained from Octave for sampling period T = 0.1 ps */

a3 = 1.91694882190063E-9;
a2 = -1.91699012219715E-9;
a1 = -1.91686533312918E-9;
a0 = 1.91690696649260E-9;
b3 = -3.999825180552219;
b2 = 5.999578676849286;
b1 = -3.999681803027921;
b0 = 0.999928309389544;

/* this section fills the first four output values and writes to a file */

y[1] = 0;
y[2] = a3*sin(w*T);
y[3] = -b3*y[2] + a3*sin(2*w*T) + a2*sin(w*T);
y[4] = -b3*y[3] - b2*y[2] + a3*sin(3*w*T) + a2*sin(2*w*T)
+ a1*sin(w*T);

fprintf(outfile,"%lf %20.18lf \n",1*T,y[1]);
    fprintf(outfile,"%lf %20.18lf \n",2*T,y[2]);
    fprintf(outfile,"%lf %20.18lf \n",3*T,y[3]);
    fprintf(outfile,"%lf %20.18lf \n",4*T,y[4]);

/* input from user is used to select the length of the simulation */

printf("Enter the simulation length. i.e. 1000 is 100 psec \n");

```

```

scanf("%d",&limit);

/* loop that fills the output array and sends to outfile */

for (k=5; k < limit + 1; k++){

y[k]= -b3*y[(k-1)] - b2*y[(k-2)] - b1*y[(k-3)] -
      b0*y[(k-4)] +
      a3*sin(w*T*(k-1)) +
          a2*sin(w*T*(k-2)) +
      a1*sin(w*T*(k-3)) +
          a0*sin(w*T*(k-4));
if (k % 500 == 0) /* this writes only every 500th point */
    fprintf(outfile,"%7.0lf %4.3lf \n",k*T,y[k]);
}
fclose(outfile);
}

```

Filtersim1g.c

```
/* This program has a Gaussian wavetrain (Figure 2.5) for input of a      */
/* 2.856 GHz BP and outputs the simulated data to a file. The output      */
/* plot is Figure 3.8.                                                    */

#include<stdio.h>
#include<math.h>
#define MAX 1000000
#define T 1.0
#define PI 3.1415926535

main ()
{
    FILE *outfile,*fopen();
    int k,i,limit,count,start,period;
    double y[MAX],a3,a2,a1,a0,b3,b2,b1,b0,c,c3,m,s;
    outfile = fopen ("gaus1.dat","w");

    /* These are the initial conditions set by the user for the simulation. */
```

```

/* They include the length of simulation, the sigma of the Gaussian */
/* pulse, the period of the wavetrain and the position of the peak of */
/* the first doublet (mean). */

printf("Enter the value of k (1000 is 1000 psec).\n");
    scanf("%d",&limit);
    printf("Enter the value of sigma (8.0 is 8 psec).\n");
scanf("%lf",&s);
printf("Enter the value of period (350 is 350 psec).\n");
scanf("%d",&period);
printf("Enter the value of the mean (7.0 equals 7*sigma).\n");
scanf("%lf",&m);

/* initial conditions for 2.856 GHz */

start = 5;
    c = 2*s*s;
    c3 = s*s*s*pow(2*PI,0.5);
count = 0;
    k = 5;

/* the coefficients obtained from Octave for sampling period T = 1.0 ps */

    a3 = 1.19799712372526E-8;
    a2 = -1.19806893295049E-8;
    a1 = -1.19785372731940E-8;
    a0 = 1.19792545882902E-8;
    b3 = -3.999176259747399;

```

```

b2 = 5.998173464205498;
b1 = -3.998817883723882;
b0 = 0.999820783110653;

/* this section fills the first four output values and writes to a file */

y[1] = a3*(-((-m*s)/c3)*exp((-(-m*s)*(-m*s))/c));

y[2] = -b3*y[1] + a3*(-((T-m*s)/c3)*
exp((- (T-m*s)*(T-m*s))/c)) +
a2*(-((-m*s)/c3)*exp((-(-m*s)*(-m*s))/c));

y[3] = -b3*y[2] - b2*y[1] + a3*(-((2*T-m*s)/c3)*
exp((- (2*T-m*s)*(2*T-m*s))/c)) +
a2*(-((T-m*s)/c3)*exp((- (T-m*s)*
(T-m*s))/c)) +
a1*(-((-m*s)/c3)*exp((-(-m*s)*(-m*s))/c));

y[4] = -b3*y[3] - b2*y[2] - b1*y[1] + a3*(-((3*T-m*s)/c3)*
exp((- (3*T-m*s)*(3*T-m*s))/c)) +
a2*(-((2*T-m*s)/c3)*exp((- (2*T-m*s)*(2*T-m*s))/
c)) + a1*(-((T-m*s)/c3)*exp((- (T-m*s)*(T-m*s))/c)) +
a0*(-((-m*s)/c3)*exp((-(-m*s)*(-m*s))/c));

fprintf(outfile,"%lf %30.28lf \n",1*T,y[1]);
    fprintf(outfile,"%lf %20.18lf \n",2*T,y[2]);
    fprintf(outfile,"%lf %20.18lf \n",3*T,y[3]);
    fprintf(outfile,"%lf %20.18lf \n",4*T,y[4]);

```

```

/* The WHILE loop continues the FOR loop for the simulation length. The */
/* FOR loop continues the process of filling the output array for each */
/* successive wavetrain period. The k values represent the sampling points */
/* for the length of the simulation and i resets for each successive */
/* wavetrain period. */

```

```

while (k < limit ){

```

```

    for (i = start; i < period + 1; i++){

```

```

        y[k] = -b3*y[(k-1)] - b2*y[(k-2)] - b1*y[(k-3)] -

```

```

        b0*y[(k-4)] +

```

```

            a3*(-((T*(i-1)-m*s)/c3)*
            exp(-(T*(i-1)-m*s)*(T*(i-1)-m*s)/c)) +

```

```

            a2*(-((T*(i-2)-m*s)/c3)*
            exp(-(T*(i-2)-m*s)*(T*(i-2)-m*s)/c)) +

```

```

            a1*(-((T*(i-3)-m*s)/c3)*
            exp(-(T*(i-3)-m*s)*(T*(i-3)-m*s)/c)) +

```

```

            a0*(-((T*(i-4)-m*s)/c3)*
            exp(-(T*(i-4)-m*s)*(T*(i-4)-m*s)/c));

```

```

        if ( k % 50 == 0) /* only every 50th point is written */
            fprintf(outfile,"%6.0lf %8.7lf \n",k*T,y[k]);
        k++;
    }

    count++;
    k = count*period + 1;
    start = 1;
}

fclose(outfile);
}

```


Filtersim4g.c

```
/* This program has a differentiated Gaussian wavetrain (Figure 2.6) for */  
/* input of a 11.424 GHz BPF and outputs the simulated data to a file. The*/  
/* output plot is Figure 3.9. */
```

```
#include<stdio.h>
```

```
#include<math.h>
```

```
#define MAX 1000000
```

```
#define T 1.0
```

```
#define PI 3.1415926535
```

```
main ()
```

```
{
```

```
FILE *outfile,*fopen();
```

```
int k,i,limit,count,start,period;
```

```
double y[MAX],a3,a2,a1,a0,b3,b2,b1,b0,c,c3,m,s;
```

```
outfile = fopen ("gaus4.dat","w");
```

```
/* These are the initial conditions set by the user for the simulation. */
```

```
/* They include the length of simulation, the sigma of the Gaussian */
```

```

/* pulse, the period of the wavetrain and the position of the peak of      */
/* the first doublet (mean).                                                */

    printf("Enter the value of k (1000 is 1000 psec).\n");
    scanf("%d",&limit);
    printf("Enter the value of sigma (8.0 is 8 psec).\n");
scanf("%lf",&s);
printf("Enter the value of period (350 is 350 psec).\n");
scanf("%d",&period);
printf("Enter the value of the mean (7.0 equals 7*sigma).\n");
scanf("%lf",&m);

/* initial conditions for 11.424 GHz                                         */

start = 5;
    c = 2*s*s;
    c3 = s*s*s*pow(2*PI,0.5);
count = 0;
    k = 5;

/* the coefficients obtained from Octave for sampling period T = 1.0 ps */

    a3 = 1.9149081031955E-7;
    a2 = -1.91536569715822E-7;
    a1 = -1.91399292415184E-7;
    a0 = 1.91445051145323E-7;

```

```

b3 = -3.988976490760761;
b2 = 5.977266556236755;
b1 = -3.987546834871388;
b0 = 0.999283325130680;

/* this section fills the first four output values and writes to a file */

y[1] = a3*(-((-m*s)/c3)*exp((-(-m*s)*(-m*s))/c));

y[2] = -b3*y[1] + a3*(-((T-m*s)/c3)*
exp((- (T-m*s)*(T-m*s))/c)) +
a2*(-((-m*s)/c3)*exp((-(-m*s)*(-m*s))/c));

y[3] = -b3*y[2] - b2*y[1] + a3*(-((2*T-m*s)/c3)*
exp((- (2*T-m*s)*(2*T-m*s))/c)) +
a2*(-((T-m*s)/c3)*exp((- (T-m*s)*
(T-m*s))/c)) +
a1*(-((-m*s)/c3)*exp((-(-m*s)*(-m*s))/c));

y[4] = -b3*y[3] - b2*y[2] - b1*y[1] + a3*(-((3*T-m*s)/c3)*
exp((- (3*T-m*s)*(3*T-m*s))/c)) +
a2*(-((2*T-m*s)/c3)*exp((- (2*T-m*s)*(2*T-m*s))/
c)) + a1*(-((T-m*s)/c3)*exp((- (T-m*s)*(T-m*s))/c)) +
a0*(-((-m*s)/c3)*exp((-(-m*s)*(-m*s))/c));

fprintf(outfile,"%lf %30.28lf \n",1*T,y[1]);
      fprintf(outfile,"%lf %20.18lf \n",2*T,y[2]);

```

```

        fprintf(outfile,"%lf %20.18lf \n",3*T,y[3]);
        fprintf(outfile,"%lf %20.18lf \n",4*T,y[4]);

/* The WHILE loop continues the FOR loop for the simulation length. The */
/* FOR loop continues the process of filling the output array for each */
/* successive wavetrain period. The k values represent the sampling points */
/* for the length of the simulation and i resets for each successive */
/* wavetrain period. */

while (k < limit ){

    for (i = start; i < period + 1; i++){

y[k] = -b3*y[(k-1)] - b2*y[(k-2)] - b1*y[(k-3)] -

b0*y[(k-4)] +

        a3*(-((T*(i-1)-m*s)/c3)*
exp(-(T*(i-1)-m*s)*(T*(i-1)-m*s)/c)) +

        a2*(-((T*(i-2)-m*s)/c3)*
exp(-(T*(i-2)-m*s)*(T*(i-2)-m*s)/c)) +

        a1*(-((T*(i-3)-m*s)/c3)*
exp(-(T*(i-3)-m*s)*(T*(i-3)-m*s)/c)) +

        a0*(-((T*(i-4)-m*s)/c3)*

```

```

        exp(-(T*(i-4)-m*s)*(T*(i-4)-m*s)/c));

if ( k % 50 == 0) /* only every 50th point is written */
    fprintf(outfile,"%6.0lf %8.7lf \n",k*T,y[k]);
k++;
    }

count++;
k = count*period + 1;
start = 1;
}

fclose(outfile);
}

```

Appendix C

Bench Test Results

The results from the bench tests for various buttons are included below. All horizontal scales are 200ns/div. The vertical scales vary.

Figure C.1: V.S.=4mW/div; TSO Raw Output

Figure C.2: V.S.=200μW/div; Raw Beam Pipe Output

Figure C.3: V.S.=3mW/div; TSO Output at 2856 MHz

Figure C.4: V.S.=60μW/div; Beam Pipe Output at 2856 MHz

Figure C.5: V.S.= $30\mu\text{W}/\text{div}$; TSO Output at 11424 MHz

Figure C.6: V.S.= $7\mu\text{W}/\text{div}$; Beam Pipe Output at 11424 MHz

Figure C.7: V.S.= $5\mu\text{W}/\text{div}$; Raw Output for 0.5 cm Diameter Button

Figure C.8: V.S.= $8\mu\text{W}/\text{div}$; Raw Output for 1 cm Diameter Button

Figure C.9: V.S.=600 nW/div; 2856 MHz Output for 0.5 cm Diameter Button

Figure C.10: V.S.=2.5 μ W/div; 2856 MHz Output for 1 cm Diameter Button

Figure C.11: V.S.=500 nW/div; 11424 MHz Output for 0.5 cm Diameter Button

Figure C.12: V.S.=450nW/div; 11424 MHz Output for 1 cm Diameter Button

Figure C.13: V.S.= $12\mu\text{W}/\text{div}$; Raw Output for 2.2 cm Diameter Button

Figure C.14: V.S.= $6\mu\text{W}/\text{div}$; Raw Output for 2 cm Square Button

Figure C.15: V.S.= $6\mu\text{W}/\text{div}$; 2856 MHz Output for 2.2 cm Diameter Button

Figure C.16: V.S.= $6\mu\text{W}/\text{div}$; 2856 MHz Output for 2 cm Square Button

Figure C.17: Continuous Wave Output for 11424 MHz 2.2 cm Diameter Button

Figure C.18: Continuous Wave Output for 11424 MHz 2 cm Square Button

Figure C.19: V.S.= $8\mu\text{W}/\text{div}$; Raw Output for 1 cm Square Button

Figure C.20: V.S.= $6\mu\text{W}/\text{div}$; Raw Output for 0.5 cm Square Button

Figure C.1: V.S.= $2.5\mu\text{W}/\text{div}$; 2856 MHz Output for 1 cm Square Button

Figure C.2: V.S.= $800\text{nW}/\text{div}$; 2856 MHz Output for 0.5 cm Square Button

Figure C.3: V.S.= $450\text{nW}/\text{div}$; 11424 MHz Output for 1 cm Square Button

Figure C.4: V.S.= $800\text{nW}/\text{div}$; 11424 MHz Output for 0.5 cm Square Button

Appendix D

April Results with Peak Power Meter

The results of the April run are illustrated below. The output of the filters measured by the Peak Power Meter and were stored on the NeXT computer as digitized data points. The prebuncher phase was varied and the output was subtracted from the originally stored data points.

Figure D.1: 2856 MHz: Prebuncher Phase 29°

Figure D.2: 11424 MHz: Prebuncher Phase 29°

Figure D.3: 2856 MHz: Prebuncher Phase 19°

Figure D.4: 11424 MHz: Prebuncher Phase 19°

Figure D.5: 2856 MHz: Prebuncher Phase 10°

Figure D.6: 11424 MHz: Prebuncher Phase 10°

Figure D.7: 2856 MHz: Prebuncher Phase 29°

Figure D.8: 11424 MHz: Prebuncher Phase 29°

Figure D.9: 2856 MHz: Prebuncher Phase 39°

Figure D.10: 11424 MHz: Prebuncher Phase 39°

Figure D.11: 2856 MHz: Prebuncher Phase 49°

Figure D.12: 11424 MHz: Prebuncher Phase 49°

Figure D.13: 2856 MHz: Prebuncher Phase 59°

Figure D.14: 11424 MHz: Prebuncher Phase 59°

Figure D.15: 2856 MHz: Prebuncher Phase 69°

Figure D.16: 11424 MHz: Prebuncher Phase 69°

Figure D.17: 2856 MHz: Prebuncher Phase 79°

Figure D.18: 11424 MHz: Prebuncher Phase 79°

Figure D.19: 2856 MHz: Prebuncher Phase 29°

Figure D.20: 11424 MHz: Prebuncher Phase 29°

Appendix E

April Results with Crystal Detectors

The scope traces as saved by the NeXT computer are illustrated below. The raw output of the crystal detectors are given first in Figures D.1 and D.2. Then the noise is subtracted from the pulse and illustrated in Figures D.3 and D.4. The other Figures have the prebuncher phase varied and the output recorded.

Figure E.1: Raw 2856 MHz Signal

Figure E.2: Raw 11424 MHz Signal

Figure E.3: Output of Monitor after Noise Subtraction

Figure E.4: Prebuncher Phase 9°

Figure E.5: Prebuncher Phase 49°

Figure E.6: Prebuncher Phase 69°

References

- [1] Alpha Industries, *Microwave Semiconductors*, 1983.
- [2] Andrew Corporation, *Andrew Corporation Catalogue 33*, 1986.
- [3] J. Berk and R. F. Koontz, Injector, in *The 2 Mile Linear Accelerator*, edited by R. Neal, Benjamin, New York, 1968.
- [4] J. Borer and R. Jung, CERN Publications 84-15 , 438 (1984).
- [5] K. L. Brown and *et al.*, Proceedings of the 1961 International Conference on High Energy Accelerators, pp. 79–117, Brookhaven, 1961.
- [6] P. Brunet and X. Buffet, Electron Injectors, in *Linear Accelerators*, edited by P. M. Lapostolle, North-Holland Publishing Company, Amsterdam, 1st edition, 1970.
- [7] J. H. Cupérus, Nucl. Instrum. and Methods. **145**, 219 (1977).
- [8] L. O. Dallin, *High Duty Factor Monochromatic Extraction from EROS*, PhD thesis, University of Saskatchewan, 1990.
- [9] J. W. Eaton, *Octave Documentation Guide*, 1.0 edition, 1994.
- [10] L. J. Geis, *Transform Analysis and Filters*, Prentice-Hall, Inc., Englewood Cliffs, N.J., 1989.
- [11] D. A. Goldberg and G. R. Lambertson, AIP , 537 (1992).
- [12] Haimson Research Corporation, *13 MeV Injection Linear Accelerator Model HRC-735 Instruction and Maintenance Manual*, 1980.
- [13] T. Ieiri, A Bunch Length Monitor by Detecting Two Frequency Components of the Beam, in *Proceedings of the 7th Symposium on Accelerator Science and Technology*, Osaka, Japan, December 12-14 1989.
- [14] G. Jackson, private communication, 1994.
- [15] J. D. Jackson, *Classical Electrodynamics*, John Wiley & Sons, Inc., New York, 2nd. edition, 1975.
- [16] G. F. Knoll, *Radiation Detection and Measurement*, John Wiley & Sons, New York, 2nd. edition, 1989.
- [17] R. Kollath, *Particle Accelerators*, Sir Isaac Pitman and Sons Ltd., London, 1967.

- [18] R. E. Laxdal, Design of an Energy Compression System for the Saskatchewan Linear Accelerator, Master's thesis, University of Saskatchewan, 1980.
- [19] M/A-COM, *RF and Microwave Control Components*, 1993.
- [20] D. Mckay, private communication, 1994.
- [21] Motorola, *MECL Device Data*, 1987.
- [22] E. Persico, E. Ferrari, and S. E. Serge, *Principles of Particle Accelerators*, W. A. Benjamin, Inc., Amsterdam, 1968.
- [23] C. L. Phillips and J. H. T. Nagle, *Digital Control System Analysis and Design*, Prentice-Hall, Inc., Englewood Cliffs, N.J., 1984.
- [24] D. M. Pozar, *Microwave Engineering*, Addison-Wesley Publishing Company, Inc., New York, 1990.
- [25] R. E. Shafer, Beam Position Monitoring, in *AIP Conference Proceedings 212: Accelerator Instrumentation*, edited by E. R. Beadle and V. J. Castillo, New York, NY, 1990, American Institute of Physics.
- [26] J. C. Sheppard, J. E. Clendenin, M. B. James, R. H. Miller, and M. C. Ross, IEEE Transactions on Nuclear Science **NS-32**, 2006 (1985).
- [27] Texas Instruments, *Linear Circuits Data Book*, 1989.
- [28] H. Wiedemann, *Particle Accelerator Physics*, Springer-Verlag, Berlin, 1993.