DESIGN AND CALCULATION ERROR ANALYSIS OF A HIGH ORDER MODE CAVITY BUNCH LENGTH MONITOR*

Jiang Guo, Ze-ran Zhou, Qing Luo#, NSRL, University of Science and Technology of China, Hefei 230029, P. R. China

Abstract

A two-cavity bunch length monitor for linac of positron source is designed. Fifth harmonic cavity resonates at 14.28 GHz (fifth harmonic of the linac fundamental frequency 2.856 GHz) with mode TM_{020}, as this mode could provide larger cavity radius. Each cavity equipped with a filter to suppress unwanted signal. An improved bunch length calculation method was proposed. A simulation was conducted in CST Particle Studio for beam current from 100-300 mA, bunch length from 5-10 ps. Bunch length was calculated and compared by these two methods.

INTRODUCTION

With its simple prototyping and instrument operation, positron annihilation technique has become the most widely used microscopy technique [1]. Based on the past experience in slow positron beam, NSRL plans to build a fast positron beamline for deep tiny flaw detection. In this paper, a cavity bunch length monitor was designed for this positron source. And an improved bunch length calculation method was proposed.

The bunch length in the linac of positron source ranges from 5 to 10 ps. Autocorrelation method that detect CDR and CTR can measure bunch length noninvasively, but it's more effective for sub-picosecond bunches [2]. Wall current monitors that detect the image charge of the bunch are noninvasive but these devices are not fast enough, with minimum rise time 200 ps [3]. Cavity monitor techniques provide non-invasive beam signal with high signal-to-noise ratio and its measurement accuracy increases with the development of electronics.

A two-cavity bunch length monitor for linac of positron source was designed. Beamline of the positron source linac and position of the bunch length monitor are shown in Fig. 1. In this paper, the optimization for the process from the original cavity signal to the final bunch length calculation results is discussed. Two filters were designed to suppress unwanted signals and an improved bunch length calculation method was proposed to reduce error. Bunch length was calculated and compared by these two methods.

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# Corresponding author email: luoqing@ustc.edu.cn

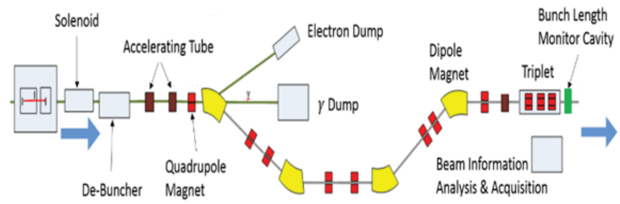

Figure 1: Beamline of the positron source linac and position of the bunch length monitor.

Table 1: Parameters of the Positron Source

Energy	E	10	MeV
Energy spread	σ_E	0.5%	
Horizontal Emittance	ε_x	6	mm rad
Bunch current	q	70	pC
Beam current	I	300	mA
RF frequency	f_0	2856	MHz
Bunch length	σ_τ	5~10	ps

THEORETICAL DERIVATION

A periodically bunched electron beam can be described as a Fourier series

$$I(t) = \frac{eN}{T} + \sum_{m=1}^{\infty} I_m \cos(m\omega_0 t) \quad (1)$$

The ω_0 is RF angular frequency, $\omega_0 = 2\pi f_0$. Each bunch includes N electrons, spaced by time interval T. The constant term $I_0 = \frac{eN}{T}$ represents a DC offset, successive terms represent contributions at integer multiples of ω_0, I_m is the amplitude of m-th harmonic current.

$$I_m = I_0 \exp\left(-\frac{m^2\omega_0^2\sigma_\tau^2}{2}\right) \quad (2)$$

Cavities, as a high impedance structure, would generate power P_m after the beam passage.

$$P_m = I_m^2 R_m = \left[I_0 \exp\left(-\frac{m^2\omega_0^2\sigma_\tau^2}{2}\right)\right]^2 R_m \quad (3)$$

For bunch length ranges from 5 to 10 ps, beam spectrum is shown in Fig. 2.

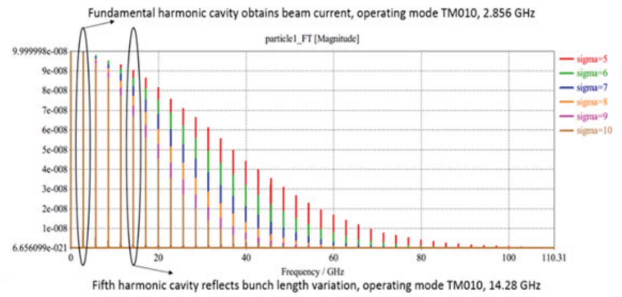

Figure 2: Beam spectrum for bunch length from 5 to 10 ps.

An amplitude ratio of two specified frequency components in the beam spectrum contains the information of bunch length. Therefore bunch length can be calculated by measuring output power of two cavities, usually a fundamental harmonic cavity（m=1）and a fifth harmonic cavity（m=5）. In the traditional bunch length calculation method, an approximate formula $P_1 \approx I_0^2 R_1$ is used and fundamental harmonic cavity works as a beam current monitor. I_0 is substituted to the expression of P_5 and bunch length can be calculated. But in the calculation, this approximation would bring systematic error about 1.2%.

$$\begin{cases} P_1 = \left[I_0 \exp(-\frac{\omega_0^2 \sigma_t^2}{2}) \right]^2 R_1 \\ P_5 = \left[I_0 \exp(-\frac{25\omega_0^2 \sigma_t^2}{2}) \right]^2 R_5 \end{cases} \tag{4}$$

In this paper, an improved bunch length calculation method was proposed. By establishing a set of simultaneous equations including power precise version of P_1 and P_5, beam current and bunch length can be calculated and error caused by approximation can be eliminated.

DESIGN OF CAVITY AND FILTER

Design of Two Cavities

Ordinary pill-box cavity was used while its radius was adjusted to exactly resonate at 2.856 GHz with operating mode TM_{010}. Coaxial antenna was penetrated to couple out the signals. The radius of the beam pipe is 5 mm, for pill-box cavity operating with TM_{010}, the cavity radius would be 6 mm, slightly larger than the beam pipe. So the fifth harmonic cavity resonates at 14.28 GHz with higher order eigen mode TM_{020}, the optimum radius is 19.32 mm. Coupling slot was used to couple out signals to waveguide.

Design of the Coaxial Line Filter

Preliminary simulation result shows that several high frequency components mixed in output signal. In order to optimize the output signal, each cavity was equipped with a filter to suppress these unwanted components [4].

A 5-th order low pass filter based on coaxial line was designed for the fundamental harmonic cavity. The inner conductor of coaxial line was made by different radius to formulate high Impedance section and low impedance section. The shift between these sections can provide adequate inductances and capacitances. Figure 3 shows the simulation model of coaxial line filter. The S21 of the filter is shown in Fig. 4. Cutoff frequency is 3 GHz considering 2.856 GHz as main frequency.

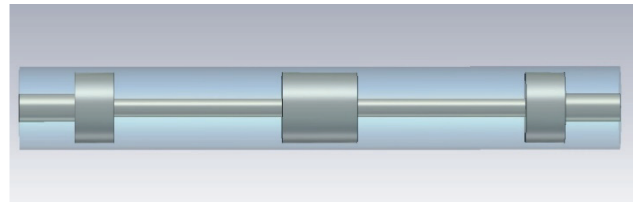

Figure 3: Simulation model for the coaxial line filter.

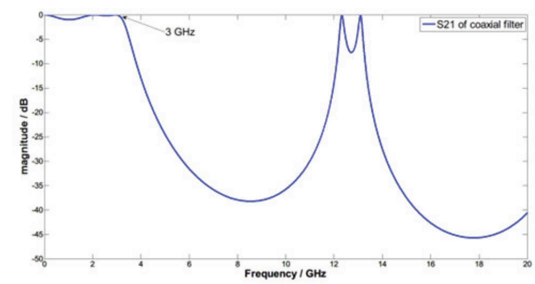

Figure 4: S21 of the coaxial line filter.

Design of the Waveguide Filter

A 4-th order waveguide iris bandpass filter was designed. Metal irises were loaded in the standard waveguide BJ-140. Simulation model of iris-loaded waveguide filter is shown in Fig. 5.

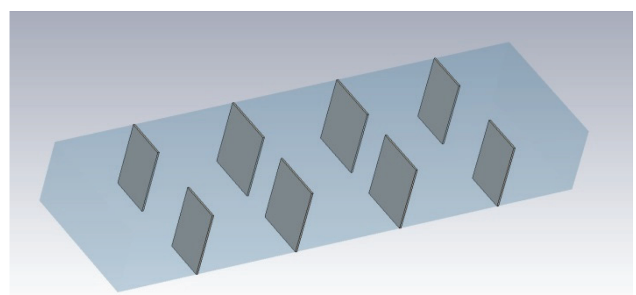

Figure 5: Simulation model for the waveguide filter.

The S21 of filter shows in Fig. 6. The size and spacing of irises were adjusted to meet the goal of bandpass filter: center frequency of passband 14.28 GHz.

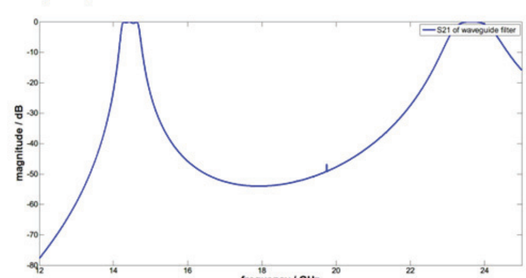

Figure 6: S21 of the waveguide filter.

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SIMULATION AND BUNCH LENGTH CALCULATION

The cavity bunch length monitor above was loaded with virtual beam to give a measurement simulation in CST. Typical parameters of virtual beam are given in table 1.

Change the bunch length from 5 to 10 ps while beam current is 300 mA. Output signals of the fundamental harmonic cavity and fifth harmonic cavity are shown in Fig. 7 and Fig. 8. Bunch length is calculated by traditional method and improved new method, shown in table 2. Theoretical bunch length and calculation results by two methods are shown in Fig. 9. Standard deviation are calculated to compare these two methods. Result shows that the standard deviation of improved method is smaller, which means that the calculation results of new method is closer to the theoretical bunch length.

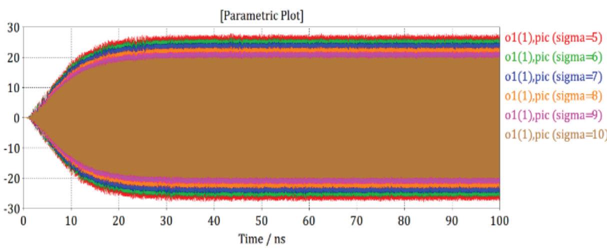

Figure 7: Output signals of fundamental harmonic cavity.

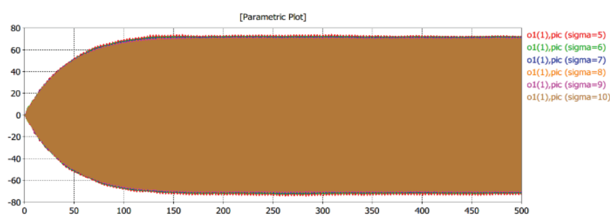

Figure 8: Output signals of fifth harmonic cavity.

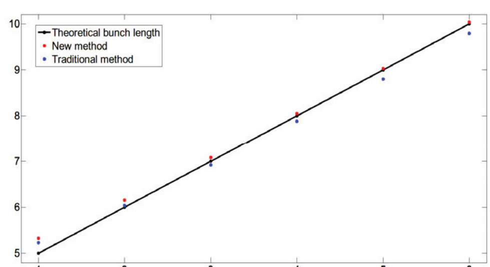

Figure 9: New method calculation results (red) compared with traditional method (blue).

Table 2: Bunch Length Calculation by Two Methods

Bunch length / ps	Traditional calculation / ps	Improved calculation / ps
10	9.80	10.03
9	8.81	9.03
8	7.88	8.05
7	6.92	7.08
6	6.04	6.16
5	5.23	5.33
Standard deviation	0.1609	0.1556

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