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A DESIGN STUDY OF INJECTOR SYSTEM FOR SYNCHROTRON LIGHT SOURCE

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Abstract

This work presents a design study of a 200 MeV electron linear accelerator consisting of an electron gun, bunchers, and accelerator structures. We aimed to design the linac with low emittance and low energy spread. A coasting beam from a thermionic electron gun is bunched using a series of buncher cavities: sub-harmonic buncher (SHB), a pre-buncher (PB), and a Buncher. The bunched beam is then accelerated up to 200 MeV with 4 cascaded accelerating structures. The SHB was designed with one-cell standing wave structure for improving the bunching efficiency. The two types of the 500 MHz SHB were considered: elliptical and coupled-cavity linac types. We also investigated constant-gradient and constant-impedance types of 3 GHz multi-cell traveling wave resonators for following buncher cavities and accelerating structures. Depending on the type, geometries of each traveling wave structure (TWS) cavity were determined, and then the electromagnetic fields were calculated. RF powers and phases of each cavity along this linac system were optimized using beam dynamics simulation. Furthermore, the beam distributions in the transverse direction are adjusted using solenoid magnets in the low-energy section as well as quad triplets in the high-energy section.

INTRODUCTION

We designed an electron linac as an injector to the storage ring based light source. Between linac and storage ring there will be a full energy booster ring. Therefore, our linac is required to accelerate the beam energy up to 200 MeV. There are two types of electron sources used in our linac system thermionic gun and RF photoinjector gun. In the linac systems such as NSLS II [1] and swiss light source (SLS) [2], the thermionic gun is used. The RF photoinjector gun is used in Advanced Photo Source (APS) and European X-ray Free Electron linac (EXFEL), etc [3, 4]. In this paper, the electron linac using a 90 keV thermionic gun was studied. The electron gun was modeled, the elective field was calculated, and the particle tracking simulation was done using CST's particle studio [5, 6]. In order to bunch a CW beam from the thermionic gun, buncher systems are needed. The buncher system is composed of SHB, PB, and Buncher. To accelerate the beam energy, four accelerating structures were used. The geometries of these RF structures were optimized and the eletric field were computed, using the Superfish code [7]. The layout of this eletron linac can be seen in Fig.1. Beam dynamics study explores the optimized parameters in the design of beam line for high quality beam delivery. In this paper, we present Parmela code [8] simulation results and beam dynamics study in the 200 MeV linac structure.

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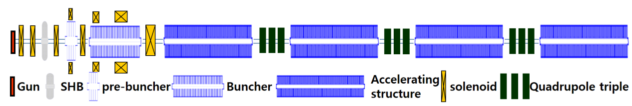

Figure 1: Electron linac layout.

DESIGN OF THE CAVITY

This injector linac has 4 types of cavities: SHB, PB, Buncher, Accelerating structures. The frequency of SHB is 500 MHz, while those of other cavities are 3 GHz. The main purpose of SHB is bunching of the continuous beam from the gun. In doing so, the standing wave structure(SWS) is chosen for SHB. Its design beta is 0.5 since the beam energy from the gun is 90 keV. Therefore, the cell length of SHB is $\beta\lambda/2 \approx 15$ cm. We considered two types of SHB shapes: Elliptical and CCL. The geometries of each type of SHB is described in Fig.2 [9]. Using the automatic design tool in Superfish, we modeled the geometries of the SHBs. These parameters are listed in Table 1. As a result of designing the cavity, the elliptical type has a larger Q value, while CCL has a larger transit time factor (TTF) and shunt impedance.

PB and Buncher are used for beam bunching and acceleration at the same time, while 4 accelerating structures are used only for beam acceleration. In these purposes, the TWS with a disc-loaded type is chosen for these cavities. In order to increase the bunching efficiency, the number of cells in PB and Buncher are 4 and 31, respectively. Also, the number of cells in 4 acceleraing structures is 94. The geometry of the TWS can be determined by cell length(d),

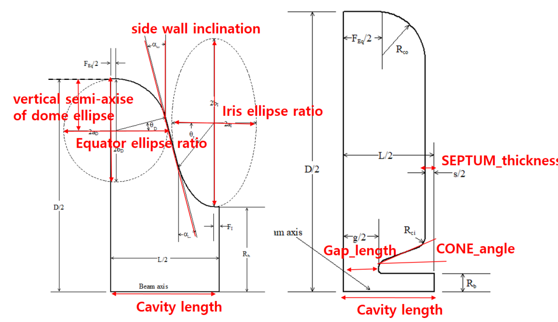

Figure 2: The sub-harmonic buncher geometry. (right: elliptical type , left: CCL type) [7].

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Table 1: The SHB Cavity Parameters

cavity parameters	Elliptical type	CCL type
frequency [MHz]	500.004	500.0007
Q-value	28,934.2	26,860.8
TTF	0.7619217	0.921409
shunt impedance [MΩ/m]	23.714	54.013
power loss [W]	5,444	3,122.066

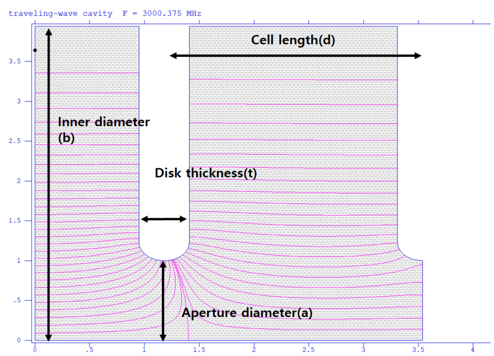


Figure 3: The traveling wave disk-load structure [7].

aperture diameter(a), inner diameter of the cell(b), and disk thickness(t), as described in Fig.3 [10]. Two cases of the TWS were considered:

- The constant impedance(const-Z) in which the electric gradient value decreases along the beam because its aperture diameters is constant.
- The constant gradient(const-E) which corrects electric gradient by changing aperture diameters of each cell.

All TWSs are operated with $2\pi/3$ mode and the cell length is $\beta\lambda/3$ [11]. In the const-Z type, the aperture diameter is kept constant, and determined by the electric filed gradient, as in Eq.(1).

$$\begin{aligned} E(z) &= E_0 e^{-\alpha z} - Ir(1 - e^{-\alpha z}) \\ E_0 &= \sqrt{2\alpha r P_{in}} \end{aligned} \quad (1)$$

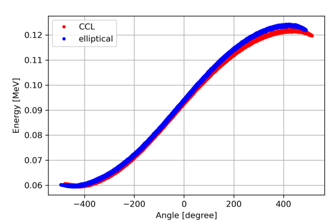
where P_{in} is input power, α is an attenuation factor, r is shunt impedance, I is beam current, and z is the distance along the beam axis. AS the aperture diameter increases, α decreases. The aperture diameter is determined by considering both values of E_0 and E(z). In the case of const-E, the gradient is calculated by the aperture diameter of the last cell. The aperture diameter of the last cell depends on the beam size. Buncher and Accelerating structures are modeled with both cosnt-Z and const-E types as with parameters listed Table 2. PB was designed only const-Z, because its length is short.

STUDY OF THE BEAM DYNAMICS

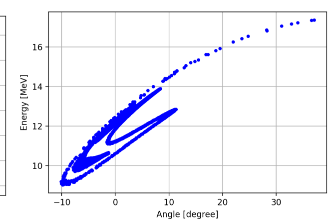
We performed beam dynamics simulations in the electron linac using Parmela code. The input beam distribution is calculated by twiss parameters from the thermionic gun. In each section of the linac, their positions and input phases are determined by considering beam states. Especially, we

Table 2: The Geometry of Travelling Wave Structure

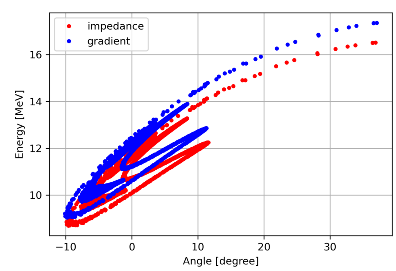
parameters	unit	PB	Buncher	Accelerating structure
constant impedance structure				
inner diameter	mm	39.4	39.6	39.1
aperture diameter	mm	8.4	12.42	10.5
the number of cell		4	31	94
constant gradient structure				
parameters	unit		Buncher	Accelerating structure
inner diameter	mm		39.6~39.35	39.1~38.4
aperture diameter	mm		12.42~11.5	10.5~5.6
the number of cell			31	94



(a) at the SHB exit



(b) at the PB exit



(c) at the Buncher exit

Figure 4: Longitudinal beam distributions at the exit of each buncher systems.

focused on the bunch length for the SHB, PB and Buncher and the beam energy for accelerating structures. Figure.4 shows the longitudinal beam distribution in the buncher system. The bunch length after passing through SHB was determined by SHB's EM field and drft distance between SHB and PB. For both types of SHBs, the bunch lengths are same as about 0.32 ns with similar gradient strengths of 0.285 MV/m(elliptical) and 0.23 MV/m(CCL). Therefore we chose the elliptical type, because of its simple shape. After PB, the bunch length is further shorter to 0.13 ns and the average energy is increased to 0.7 MeV. The drift length between PB and Bunhcer is kept short, since it affects the bunch length. At the Buncher, the range of the input phase was chosen to bunch and accelerate efficiently at the same time. The bunch length depends strongly on the input phase rather than the electric field strength. Therefore, the beam length after passing through the Buncher is equal to 0.037 ns for both const-Z and const-E types. Since the difference in the average beam energy is as small as 0.479 MeV, the const-Z type was selected due to its simple geometry for

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manufacturing. The input power of accelerating structures is determined to accelerate the beam energy up to 200 MeV. The input power of the const-Z type is 33 MW while that of the const-E is 20 MW. Since the gradient is constant

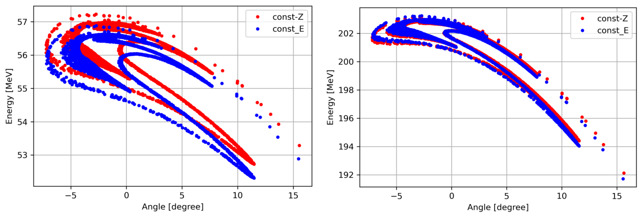

Figure 5: Longitudinal beam distributions at the exit of the accelerating system (first and fourth accelerating structures).

for const-E, the electron beam can be accelerated to higher energy using low power. Therefore, even if it is difficult to manufacture, const-E is more efficient than const-Z when considering the operation power. The bunch lengths of first and fourth accelerating structures are same. After the fourth accelerating structure, the average energy is 201 MeV and the standard deviation is 0.7%, as shwon in Fig.5. For beam matching in the transverse direction, solenoids were used in the low energy section and a quadrupole triplets were used in the high energy section. The position and intensity of the solenoids were determined so that beam loss can be minimized. When the beam energy is low, the beam loss occurs due to the space charge effect. Therefore solenoids are inserted outside the pre-buncher and buncher to mitigate these effects. quadrupole triplets were used to match twiss parameters between accelerating structures using TRACE3D code [12]. As shown in Fig.6, the beam envelope did not hit the cavity apertures. The beam loss was 4.5%, and most of them occurred in the buncher system.

CONCLUSION

This linac is designed to inject an electron beam with low emittance and low energy spread. The bunch length of 1ns from the thermionic electron gun was reduced to 18.5 ps through the electron linac. The phase standard deviation is 0.32%. The average energy was 201 MeV, which satisfies the target energy requirement. The energy standard deviation was 1.475 MeV, which is about 0.7%. The transverse RMS emittance is about 0.21 mm−mrad and the longitudinal RMS emittance is 3.13 deg−MeV. We are going to design an alternative linac with an RF photoinjector gun and then compare the beam dynamics simulation results for these two linacs, especially, operation powers, beam emittances, bunch lengths, etc.

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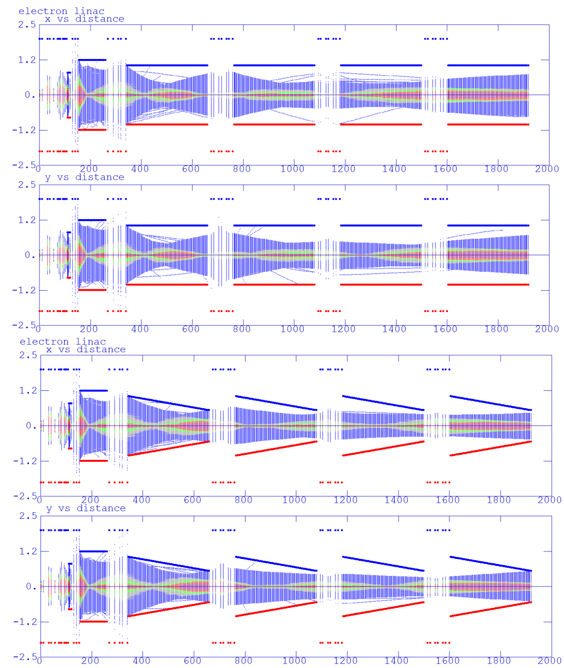

Figure 6: The beam envelopes in the electron linac (upper: const-Z, lower: const-E).

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