BEAM TRANSPORT SYSTEM OF THE PLS 2 GEV LINEAR ACCELERATOR

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Summary

The beam transport and focusing system of the PLS 2 GeV electron linac is described in this paper. This linac will serve as a full energy injector for the 2 GeV storage ring light source, currently being developed in Pohang, Korea. The system includes a 60 MeV injector which consists of an S-band prebuncher, buncher, and two accelerating columns powered by one klystron. The normalized transverse emittance is 0.015 πMeV/c cm rad. Along the linac, a total of 16 quadrupole triplets are employed to guide the accelerated beam throughout the linac. Three beam analyzing stations are allocated to monitor the beam properties. The transport system in this design has also the capability of delivering positrons, which is planned for the future upgrade program.

Introduction

The PLS 2 GeV linac is a 160-meter long, electron accelerator whose prime function is to inject a beam into the third-generation storage ring. This linac consists of a total of 44 accelerating sections powered by 12 klystrons. The klystron is a SLAC 5045 model and its peak power is rated as 65 MW. The operating power of the klystron will be around 50 MW. Out of 12 klystrons, 10 klystrons will employ Energy Doubler (ED) systems and these klystrons feed four accelerating sections. The remaining two klystrons feed two accelerating columns only; one klystron for the electron injector and the other klystron for the positron injector.

Injector System

The injector of the PLS 2 GeV linac consists of an electron gun, an S-band prebuncher, an S-band buncher, the first two accelerating sections and various associated auxiliary components. The electron gun is a triode type. The cathode-grid assembly is sealed by ceramic and connected to the gun body via a standard conflat flange. When the assembly is worn out, it can very conveniently be replaced by a new one. The cathode is made of barium and tungsten and can be exposed to the air several times. The pulser, used to drive the gun, with the avalanche transitors as the discharge element and the coaxial transmission line as the PFN, is placed in the vicinity of the cathode-grid assembly, and therefore maintenance is very easy. The pulse length from the electron gun is 2 ns. The anode voltage is 80 kV and the peak current is higher than 2 A. The repetition rate is 10 Hz (120 Hz maximum). The diameter of the cathode emitter region is 16 mm.

The 2-ns long output electron beam from the electron gun passes through the prebuncher and the buncher. The beam is then compressed in the form of several discrete bunches. Since the RF power for driving the prebuncher cavity has a frequency of 2856 MHz, the 2 ns beam pulse will form six micro bunches, which we call the linac bunch. The size of the linac bunch strongly affects the beam energy spread in the linac. In this design, the distance from the prebuncher to the buncher is 20 cm, a little shorter than that of SLAC's. This is to accommodate higher gun current. The input power for the prebuncher and the buncher is provided by klystron K1. Both the amplitude and the phase of the RF electric field of the bunchers are adjustable independently in order to optimize the bunching condition. The prebuncher is a re-entrant type, standing-wave cavity. The input power to this cavity is about 10 kW. To minimize the effects of temperature, mechanical distortions and electron beam loading on the cavity field, a low value of Q is desired. For this reason, stainless steel is selected for the material of the cavity. The cavity Q is 1000. The velocity modulation introduced by the prebuncher causes 62% of the electrons to be bunched within a 70° interval in the 20 cm drift space.

The buncher has a traveling-wave structure with only four cavities, including the input and output cavities. It is operated in the $2\pi/3$ mode with a phase velocity of 0.75c. Therefore, it has a length of one free-space wavelength (104.96 mm). A water-cooling tube is brazed to its outer surface and a focusing coil driven by an independent power supply will provide the necessary focusing field. The input RF power is about 1 MW and the peak field is about 3.5 MV/m. The desired electrons leave the buncher within a phase interval of 30° and with a velocity of 0.8 c. An electron beam dynamics study has been performed with the help of the computer program DYNAML1 [1]. This program simulates the longitudinal and transverse motion of particles from the electron gun to the end of the first accelerating section. Space charge effects are included in the calculation. The program solves the following equations numerically by using the Runge-Kutta method:

$$\frac{d\gamma_i}{d\xi} = A_{rf}(\phi_i, \xi) + A_{sc}(\phi_i, \phi_j) + A_{bl}(\phi_i, \phi_j)$$

$$\frac{d\phi_i}{d\xi} = 2\pi\ (\frac{1}{\beta_w(\xi)} - \frac{\gamma_i}{\sqrt{\gamma_i^2 - 1}})$$

$$\frac{dR_i}{d\xi} = R_i'$$

$$dR_i' = \frac{1}{\beta_i\gamma_i}\{-\frac{1}{\beta_i}\frac{d\gamma_i}{d\xi}\frac{dR_i}{d\xi} + \frac{\epsilon_0^2}{\beta_i\gamma_i R_i^3} + \frac{e\lambda}{m_0c^2} [\pi E_n(\xi)(\frac{1}{\beta_w\beta_i} - 1)\cos\phi_i + \frac{1}{2\beta_i}\frac{dE_n(\xi)}{d\xi}\sin\phi_i + \frac{IZ_0}{2\pi(\beta_i\gamma_i R_i)^2\lambda} - 4.397\times 10^2\frac{\lambda B_z^2}{\beta_i\gamma_i}]R_i\}$$

where $i = 1, 2\cdots$, $\xi = z/\lambda$ and

$$A_{rf} = -\sum_{n=-1}^{1}\frac{e\lambda E_n(\xi)}{m_0c^2}\sin(\phi_i + \frac{2n\phi\xi}{D})$$

$$A_{sc} = \frac{2e\lambda^2 IZ_0}{\pi m_0c^2R_0^2}\frac{1}{N}\sum_{j=1}^{N}G_i^j(\frac{R_0}{b}, Z')SIGN(\phi_i - \phi_j),$$

$$G_i^j(\frac{R_0}{b}, Z') = \sum_{n=1}^{\infty}[\frac{J_1(R_0\mu_{0n}/b)}{\mu_{0n}J_1(\mu_{0n})}]^2 e^{-(R_0\mu_{0n}Z'/b)},$$

$$Z' = |\frac{\beta_w(\xi)\lambda}{2\pi R_0}(\phi_i - \phi_j)\gamma_j|$$

$$A_{\xi i} = -\frac{e\lambda I r_l}{m_0 c^2 N}\sum_{j=1}^{N}\cos(\phi_i(\xi)-\phi_j(\xi))(1-e^{-\alpha\lambda f\beta_g t}),$$
$$when\ \ \xi > \beta_g f t,$$
$$A_{\xi i} = -\frac{e\lambda I r_l}{m_0 c^2 N}\sum_{j=1}^{N}\cos(\phi_i(\xi)-\phi_j(\xi))(1-e^{-\alpha\lambda\xi}),$$
$$when\ \ \xi \leq \beta_g f t,$$

In the above equations, R is the envelope of a beam/λ, ϵ_0 the initial emittance. I the beam current in amperes, B_z the magnetic field in gauss, D the length of period normalized to the wavelength of the RF wave, r_l the shunt impedance in Ω/m, α the attenuation parameter of the accelerating section in m^{-1}, t the pulse length of a beam in seconds, b the average bore radius of the accelerating section in m, μ_0 the root of the Bessel function, N the number of slices in one beam bunch for the computation, f the frequency of the RF system in Hz, β_w the phase velocity/c, β_g the group velocity /c, Z_0 the free space impedance which is 120 $\pi\Omega$, and finally E_n is the amplitude of the n^{th} space harmonic wave. In the calculation the beam bunch is conveniently divided into 22 slices, and space charge potentials for these bunches are calculated by using the formula listed above. The magnetic fields are calculated using the thick-layer formula [2]. The emittance from the gun was taken to be $rp_r = 2.3\pi \times 10^{-5}$ m m_0c.

The calculation indicates that when the gun current is as high as 2 A, 62% of the electrons are bunched within a phase interval of 7° at the end of the first accelerating section. Therefore, from

$$\frac{\Delta E}{E} = 1 - \cos(\frac{\Delta\phi}{2})$$

0.18% energy spectrum at the end of the 2 GeV linac would be expected if the other perturbations were negligible. The measured energy spread for the 1.1 GeV injector linac at BEPC [3] is 0.6% at FWHM. In Fig.1, we show the magnetic field and the calculated beam envelope along the injection section, from the gun to the end of the first accelerating section. The magnetic fields are trimmed in such a way that the beam forms a waist at the center of the prebuncher and the buncher, respectively.

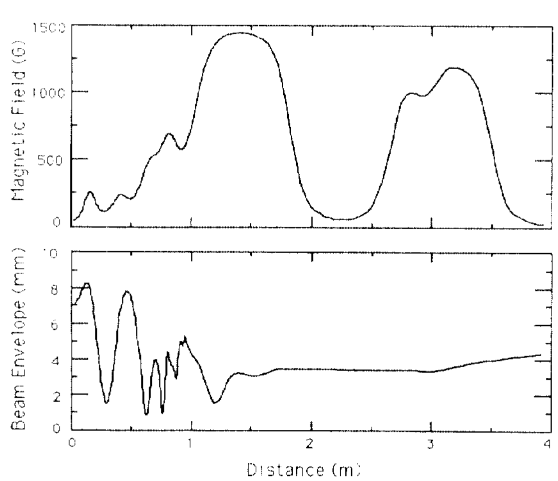

Fig.1 Magnetic field variation and beam envelope from the gun to the end of the first accelerating column

The 60 MeV injection section of the PLS linac will be purchased from the Institute of High Energy Physics (IHEP) in China. It is scheduled to be delivered by March, 1991. The klystron for this injector is 24 MW power (SLAC XK-5 model). Though this power is enough for the beam to reach the asymptotic phase at the first accelerating section, for the sake of operational safety, we plan to replace it by the 65 MW klystron immediately after delivery.

Electron Focusing System

With given initial conditions $(r_0, dr_0/dz)$, the motion of a relativistic electron beam through the constant-gradient accelerating section can be expressed in the following matrix form:

$$\begin{pmatrix} r \\ dr/dz \end{pmatrix} = \begin{pmatrix} 1 & L\log(1+\Delta)/\Delta \\ 0 & 1/(1+\Delta) \end{pmatrix}\begin{pmatrix} r_0 \\ dr_0/dz \end{pmatrix}$$

where $\Delta = \delta E/E_0$, E_0 is the initial energy and δE is the energy gain through a distance L. Therefore, for an electron linac the beam size grows logarithmically as the electron beam is transported through the linac. This follows from the fact that the space charge effect becomes negligible for a relativistic electron beam; space charge force is inversely proportional to the square of the relativistic γ. The logarithmic divergence of a beam necessitates the placement of quadrupoles along the transport line of a relatively long linac.

When considering the focusing system, alternating singlets provide a lower field gradient and thus tighter focusing than triplets and doublets. These singlets, however, require a wider bore size because they are wrapped around the accelerating columns. This is costly. In the PLS 160-m long linac, we consider the requirement for tight focusing need not be so stringent. In addition, triplets provide larger alignment tolerances and make it easier to obtain a symmetric beam size compared to alternating singlets and doublets. Therefore, a triplet focusing scheme was chosen for the PLS 2 GeV linac.

We have designed the beam transport system covered from 60 MeV to 2 GeV. This was carried out with the computer programs TRANSPORT and COMFORT. For the calculation, we assumed that the normalized emittance of the beam is 0.015 $\pi MeV/c\ cm$ after the first accelerating section. At this point (*i.e.* 60 MeV) the radius of the beam is assumed to be 5 mm. These values are the initial conditions needed to calculate the beam transport system of the linac. Fig.2 shows the schematic layout of the transport system for the PLS 2 GeV linac. Fig.3 shows the variation of the typical envelope of an electron beam along the 2 GeV linac.

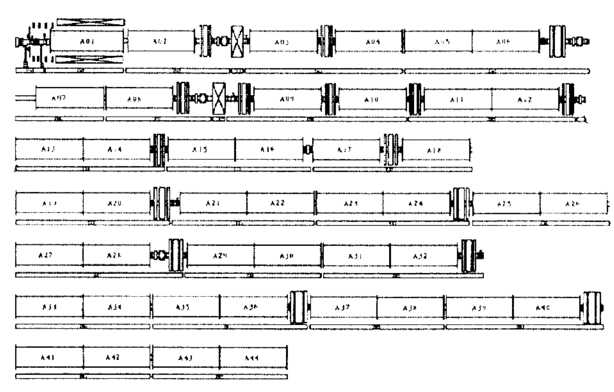

Fig.2 Schematic layout of the PLS 2 GeV linac

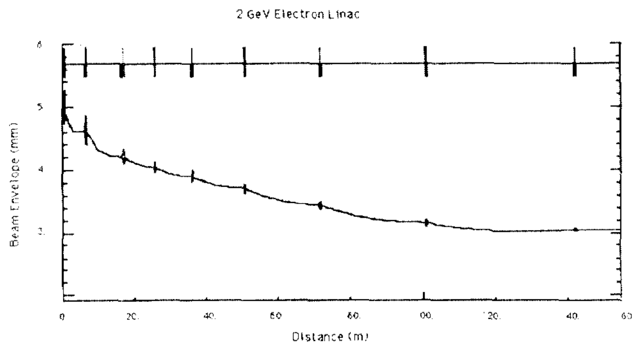

Fig.3 Typical beam envelope for 2 GeV electron

The designed system has a capability of accommodating an emittance up to a factor of three larger than the design value. A total of nine quadrupole triplets are used to keep the beam size within the accelerator aperture. The additional seven quadrupole triplets are reserved for the positron beam transport, which will be considered in the future when the storage ring demands positron injection. The remaining seven quadrupole triplets are not essential for the electron beam transport, but are considered helpful for a better performance. Therefore, a total of 16 quadrupole triplets will be incorporated in the 2 *GeV* linac.

Placement of the steering dipoles is necessary so as to correct the orbit distortion due to various perturbations in the linac. We employ in total 16 pairs of steering magnets, placed both horizontally and vertically. These magnets are placed in the vicinity of quadrupoles and attached to the accelerating section to save space. In order to prevent the weight of the steering magnet from damaging the accelerating section, a special support will be designed. The current and polarity of the power supply driving the steering magnet should be adjustable from the control room.

There are in total three bending magnets along the 2 *GeV* linac. These magnets will be used to analyze the accelerated electron (or positron) beam, and possibly to extract the beam for the basic physics research planned for the future. The basic parameters for the bending magnets are listed in Table I.

Table I

Parameters of bending magnets

	1	2	3
Distance from the gun (*m*)	9.5	35	165
Beam energy (*MeV*)	60	350	2000
Effective length (*m*)	0.5	0.42	1.12
Bending angle (*degrees*)	30	20	10
Magnetic field (*T*)	0.3	1.0	1.04

The first bending magnet, together with its associated beam analyzing station, is to be used for monitoring the beam from the 60 *MeV* injection system.

The main purpose of the second bending magnet is for future analysis of the positron beam when the upgrade to a positron acceleration system takes place.

The last bending magnet should be a precise analyzing magnet; it is a fanned magnet rather of a rectangular one. The profile monitor used to measure the final electron beam energy and energy spread of the linac will be located on the focusing plane.

Positron Focusing System

It is a well-known fact that in a storage ring the positron beam provides a longer lifetime than the electron beam. With electrons, the ions dissociated from the residual gas molecules become trapped around the path of the electrons, resulting in poor vacuum and beam quality.

The possibility of having the PLS linac inject either an electron or a positron beam into the storage ring is attractive. We will leave room for the positron converter upstream of the accelerating section No.7, where the electron beam energy will be 350 *MeV*. In the future, when the storage ring requires injecting of the positron beam, we will need only to mount the solenoids surrounding the accelerating section No.7 and No.8, and to locate the positron converter as well as a capture solenoid. A positron current of 8 *mA* could be achieved at the end of the linac without great difficulty.

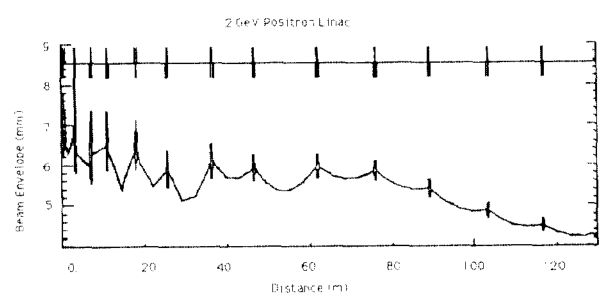

Fig.4 Typical beam envelope for 2 GeV positron

Due to the large emittance of the positron beam, we place 16 quadrupole triplets as described before. The normalized emittance of positrons after the accelerating section No. 8 was assumed to be 0.15π MeV/c cm, which is a factor of ten larger than that of the electron beam. The beam size at this point was also assumed to be 7 *mm*. Fig.4 shows the typical positron beam envelope along the linac.

References

[1] Y. Luo, Unpublished computer program
[2] M. Yoon, Argonne National Laboratory, LS-122 June 1988
[3] Y. Luo, Private Communications