

BEAM DYNAMICS IN 100 MEV S-BAND LINAC FOR CANDLE

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Abstract

The report presents the results of the beam dynamics study in 100 MeV S-band linear accelerator foreseen as an injector for the CANDLE light source. Pre-injector design includes the thermionic gun and the bunch formation systems. The gun is modulated by 500 MHz amplifier, which matched the beam pulse structure to the booster and storage ring RF buckets. The following bunching sections perform an additional sub-bunching of the beam to be accelerated in the 100 MeV S-Band linac. An impact of the excited transverse wake fields on the single bunch transverse emittance is given when the bunch is accelerated in 6 m long S-Band structure.

INTRODUCTION

As an injector for the CANDLE booster ring will be used a 100 MeV S-band linear accelerator based on the components already built for S-Band Linear Collider Test Facility at DESY [1,2]. The linac design and layout [3] will fulfill the following basic requirements

- Single and multi-bunch operation modes ;
- Nominal repetition rate 2 Hz;
- Energy spread in single pulse 0.5%;
- Pulse-to-pulse energy spread of 0.25%;
- Current injection rate at 100 MeV – 400 mA/min;
- Minimum beam losses.

The maximum duration of the single bunch at the electron gun exit is 1 ns with 1.6 nC charge ($\sim 10^{10}$ electrons, peak current 2.2 A), while the maximum duration of the bunch train for multi-bunch operation mode is 600 nsec with maximum total charge of 6 nC (10 mA pulse current). The 6 m long accelerating section of linac will operate with the gradient of 17 MV/m.

BUNCHING SECTION

The bunching section of the pre-injector consists of 500 MHz sub-harmonic pre-buncher (SPB) cavity, 1 GHz pre-buncher cavity (16 keV) and 3 GHz travelling wave structure. In order to perform an effective velocity modulation along the pulse, the SPB cavity voltage is optimised to 30 kV across the buncher gap.

The 6 dimensional phase space of the beam has been tracked along the bunching system. The initial beam shape is given by the elliptical distribution in three directions: longitudinal, horizontal and vertical. The longitudinal phase is expanded within the $-600 \div +600$ degree of 3 GHz structure that corresponds to particle longitudinal distribution of about 1.2 nsec. The SPB is located at the distance 43 cm and performs the bunching of the electron beam. This is accomplished by having a significant proper velocity modulation with the positive

energy-phase correlation of the particles that the head particles are slower and tail particles are faster. At the optimal bunching position, the energy-phase correlation still should have the positive slope therefore the optimal distance after the buncher has been found to be 29 cm.

After the 500 MHz SPB cavity, the compressed, 90 keV energy beam with more than 70% charge in one 3 GHz wavelength (10 cm) is entered to 1 GHz bunching cavity with the peak voltage of 16 kV.

The buncher cavity does not change the kinetic energy of the bunch that is still defined by the gun voltage of 90 kV which corresponds to velocity $\beta = v/c = 0.526$. As the direct acceleration of such a non-relativistic beam in $\beta = 1$ phase velocity main S-Band structure lead to large energy spread of about 5%, one 3 GHz traveling wave (TW) structure is used for pre-acceleration and bunching purpose before entering the beam into main linac structure. This is a $2\pi/3$ mode structure with a phase velocity of 0.6c and a length of 8 cm (4 cells). The input RF power is 3 MW and the gradient 4 MV/m. Figure 1 shows the beam longitudinal distribution at the entrance to 3 GHz TW structure.

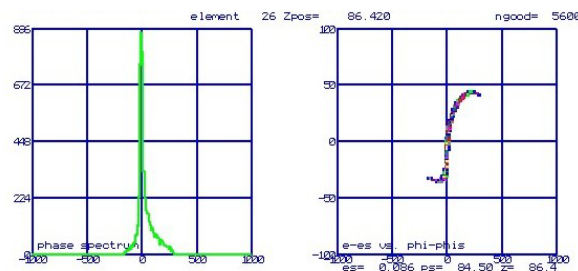


Fig. 1. Longitudinal distribution at the entrance to 3 GHz TW structure.

THE 100 MEV LINAC

The output current for 500 ns long electron pulse is given by the demand to fill the CANDLE storage ring within one minute to a mean current of 350 mA. Taking into account the booster synchrotron repetition rate of 2 Hz and revolution time 720 ns in storage ring of CANDLE one gets

$$I = \frac{350 \text{ mA} \cdot 720 \text{ nsec}}{60 \text{ sec} \cdot 2 \text{ sec}^{-1} \cdot 500 \text{ nsec}} = 4.2 \text{ mA} \quad (1)$$

Considering some losses in whole injection chain, a linac output current of 15 mA will be more than sufficient.

With one standard 6 m long accelerating section of SBLC type structure, the energy of 100 MeV is reached by beam loaded accelerating gradient of about 17 MV/m. The structure is the constant gradient type. The bunching system provides the capture of more than 90% particles by the main 3 GHz, 6m long linac section. The final

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stable longitudinal particle distribution in main linac accelerating section is shown in Figure 2, which contains more than 90% of particles in about 18° of 3 GHz structure. The bunch rms length σ_s is about 1.5mm.

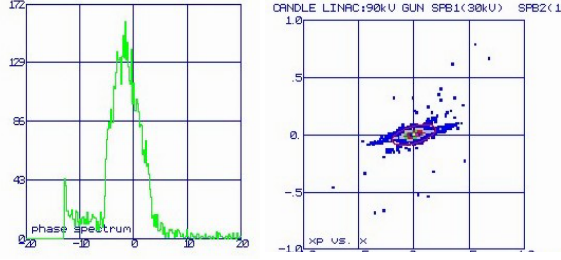


Fig.2. The longitudinal (left) and transverse (right) bunch distributions at the 100 MeV linac exit.

Figure 3 gives the number of transmitted particles along the bunching section and the main linac. From initial 5600 tracked particles, only 220 particles have been lost during the whole bunching and acceleration the beam to 100 MeV of energy.

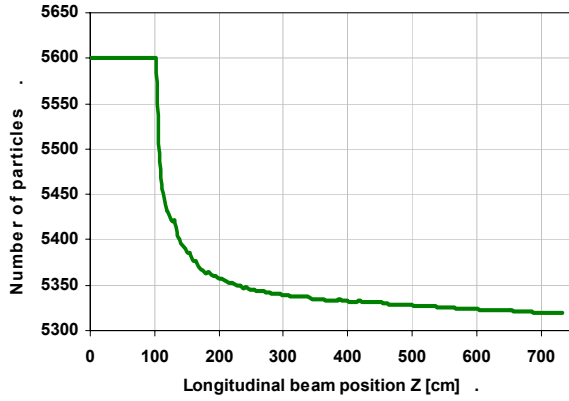


Fig. 3. Number of transmitted particles along the linac.

The evaluation of the normalized transverse emittances of the beam from the gun to linac exit is given in Fig.4. The predicted parameter list of the beam without the wakefield effects in the accelerating section is presented in Table 1.

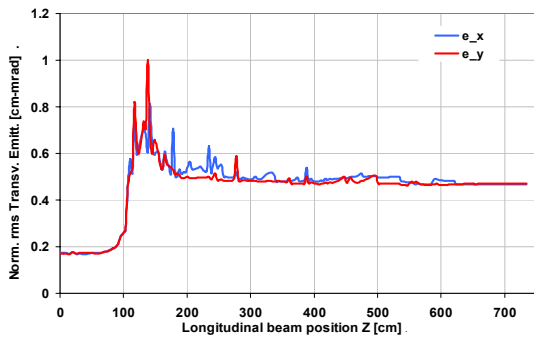


Fig. 4. The normalized transverse emittances of the beam during bunching and acceleration.

Table 1: Beam parameters in the linac

Injection energy E_0 (keV)	410
Max bunch charge Q (nC)	1.6
Bunch rms length σ_s (mm)	1.5
Norm. emittance ϵ (cm-mrad)	0.47
Final energy E (MeV)	100

EMITTANCE DILUTION

As off-axis electron bunch travels down to the main accelerating section, wake fields are excited which will act back on the bunch itself. While longitudinal wakefields modifies the energy spread along the bunch, the transverse wakefields tends to deflect the tail particle further away from the axis leading to emittance dilution [4]. The dipole transverse point wake potential for the S-band structure is obtained in Ref. [5] using a modal summation technique. The simple functional fits to these wakes is given by

$$w_{\perp}(s) = 4.1 \cdot [1 - (1 + 1.15s^{1/2}) \exp(-1.15s^{1/2})] \quad (2)$$

in $kV/pC/m^2$ units and distance s in mm . The transverse wake potential of the bunch is given by the convolution of the bunch longitudinal distribution $\rho(s)$ and the point wake potential as

$$W_{\perp}(s) = \int_{-\infty}^s \rho(s') w_{\perp}(s-s') ds' \quad (3)$$

Figure 5 shows the dipole transverse wake potential excited by 1.5mm rms length gaussian bunch in S-Band structure.

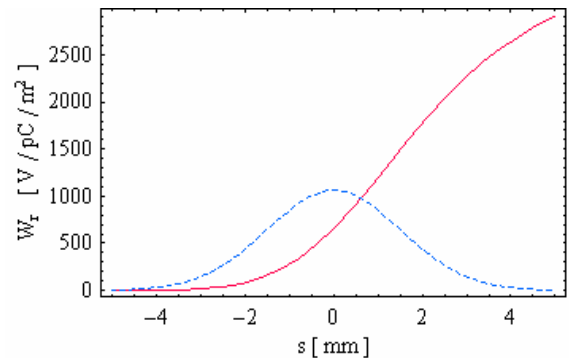


Fig. 5. Transverse wake potential for gaussian bunch ($\sigma_s = 1.5mm$).

The simplest model to evaluate the emittance growth due to transverse wakefield is a two particle model of the bunch [6]. Consider a Gaussian bunch, which is modelled by two macroparticles, each of charge $Q/2$ separated by a longitudinal distance $\Delta z = 2\sigma_s$, where σ_s is the rms bunch length. The head particle feels no transverse

wakefield while the tail particle obey the following equation of motion

$$x_2'' + Ax_2' = C_T \frac{E_0}{E} x_1 \quad (4)$$

where $C_T = eQw_\perp(2\sigma_s)/2E_0$, $A(z) = E'/E(z)$ is the adiabatic damping coefficient, $E_0, E(z)$ are the particle initial and actual particle energies in the linac and $E' = dE/dz$ is the energy gain per unit length, z is the bunch position along the linac. The solution of this inhomogeneous equation may be written in terms of the transport matrix $M(z_0, z)$ elements. For the relative displacement of the tail particle with respect to the head one $\Delta x = x_2 - x_1$ we get

$$\Delta x = C_T \int_0^z M_{12}(z', z) g(z') x_1(z') dz' \quad (5)$$

with $g(z) = E_0/E(z)$ and

$$M_{12}(z', z) = \frac{1}{A(z')} \ln \frac{E(z')}{E(z)} \quad (6)$$

Assuming that the bunch entering the accelerating section with offset x_0 parallel to z axis we get

$$\Delta x = C_T x_0 \frac{EE_0}{E'^2} (1 + g \ln g - g) \quad (7)$$

For squared relative particle displacement then we have

$$\frac{\langle \Delta x^2 \rangle}{\beta} = \frac{\langle x_0^2 \rangle}{\beta_0} C_T^2 A_0^{-4} \frac{\beta_0}{\beta} g^{-2} (1 + g \ln g - g)^2 \quad (8)$$

Assuming one standard initial offset of the beam ($\langle x_0^2 \rangle / \beta_0 = \varepsilon_0$, for the relative emittance growth along the linac we get

$$\frac{\Delta \varepsilon}{\varepsilon} = C_T^2 \frac{\beta_0}{\beta} \left(\frac{E}{E'} \right)^4 g (1 + g \ln g - g)^2 \quad (9)$$

where the actual beta value is given by the initial Twiss parameters $(\alpha_0, \beta_0, \gamma_0)$ and the accelerating section transport matrix as

$$\beta = g^{-1} \left[\beta_0 + 2 \frac{E_0}{E'} \alpha_0 \ln g + \left(\frac{E_0}{E'} \right)^2 \gamma_0 \ln^2 g \right] \quad (10)$$

For low injection energy E_0 and high accelerating rate ($E_0/E' \ll \beta$), the formula for emittance growth is simplifies to

$$\frac{\Delta \varepsilon}{\varepsilon} = C_T^2 \left(\frac{E}{E'} \right)^4 g^2 (1 + g \ln g - g)^2 \quad (11)$$

An electron bunch after the compression is entering to the main 6m long accelerating section with initial energy of $E_0 = 410 \text{ keV}$. Assuming the capturing of the accelerated bunch in 18 degree of 3 GHz structure, the average rms length of the bunch is approximately equal to $\sigma_s = 1.5 \text{ mm}$ thus the dipole wake potential seen by the trailing charge is $w_\perp(2\sigma_s) = 2.4 \text{ kV/pC/m}^2$. The maximum bunch charge of 10^{10} particles is $Q = 1.6 \text{ nC}$ and the energy gain per unit length is $E' = 17 \text{ MeV/m}$. Fig. 6 presents the single bunch emittance growth for the initial beta of $\beta_0 = 1 \text{ m}$ that corresponds to about 2.5mm of rms transverse size of the bunch at the entrance to accelerating section.

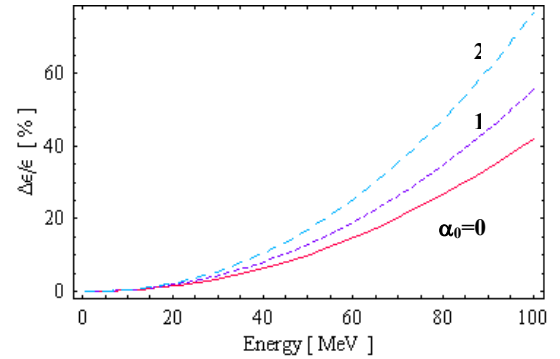


Fig. 6. Emittance growth along the linac.

The minimum emittance growth of about 40% is observed with the maximum bunch charge of 1.6 nC and $\alpha_0 = 0$. For the nominal multi-bunch operation mode, the single bunch charge is at the level of 1 nC and the emittance dilution in the linac is 16% with one sigma initial offset of the bunch at the linac entrance. This is the conservative approach as the bunch transverse position at the linac entrance will be controlled better than 0.5mm resulting on the wakefield emittance dilution at the level of 1%.

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