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RF emittance in a low energy electron linear accelerator

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A B S T R A C T

Transverse beam dynamics of an 8 MeV low current (10 mA) S-band traveling wave electron linear accelerator has been studied and optimized. The main issue is to limit the beam emittance, mainly induced by the transverse RF forces. The linac is being constructed at Institute for Research in Fundamental Science (IPM), Tehran Iran Labeled as Iran's First Linac, nearly all components of this accelerator are designed and constructed within the country. This paper discusses the RF coupler induced field asymmetry and the corresponding emittance at different focusing levels, introduces a detailed beam dynamics design of a solenoid focusing channel aiming to reduce the emittance growth and studies the solenoid misalignment tolerances. In addition it has been demonstrated that a prebuncher cavity with appropriate parameters can help improving the beam quality in the transverse plane.

1. Introduction

The IPM Electron Linac is an 8 MeV (upgradable to 11 MeV) S-band traveling wave electron linear accelerator under development at the Institute for Research in Fundamental Science (IPM), Tehran, Iran. As the first practice in design and construction of particle accelerators at IPM, the linac is mainly regarded as a research project providing hands-on experience in accelerator science and technology. In an effort to establish the domestic accelerator knowledge, it has been decided to build the accelerator based on the available technologies in Iran. Therefore, nearly all components of this accelerator are designed and constructed within the country including the RF power amplifier system (klystron and modulator), RF cavities, magnets, and beam diagnostics systems. The linac could serve as an X-ray source or play an injector role for a larger facility. The project is meeting its final stages and the linac commissioning is due in a few months.

The layout of the IPM Electron Linac is shown schematically in Fig. 1. A thermionic electron gun provides a beam with an energy and current up to 50 keV and 10 mA, respectively. The electrons are bunched through a traveling wave (TW) buncher and then accelerated in some constant impedance TW accelerating tubes. Beam dynamics and RF design of this buncher is described in [1,2] and the construction process in [3–6]. The buncher and the accelerating structures are connected together and fed with a 2 MW klystron at 2997.9 MHz frequency. The beam energy at the end of the 30 cm length buncher will be around 1.4 MeV. The accelerating structure is composed of two accelerating tubes of 60 cm length each. First and second tubes provide an energy gain of 3.2 MeV and 3.1 MeV, respectively. A third tube can be added if a higher energy is required. The buncher and the accelerating structures are embedded in a solenoidal magnetic field for the focusing. In this paper, this solenoidal field is referred as the main focusing channel. Two small solenoids between the gun and the main focusing channel serve as a matching cell. The matching cell ensures the appropriate beam parameters at the entrance of the main channel.

A characteristic feature of this linac is its low gradient long TW buncher. Such a structure offers a notable bunching performance. A detailed discussion on the bunching system and the corresponding longitudinal beam dynamics can be found in [7].

The initial beam parameters are obtained by CST simulation of the electron gun. The cathode with a diameter of 8 mm is warmed up to around 1100 °C. The beam parameters after the electron gun are listed in Table 1, for different gun voltages.

It can be shown that such a beam with a current at mA level is emittance dominated. In other words, the behavior of the beam envelope is determined by its emittance rather than the space charge forces [8]. Even more, the beam dynamics simulations show that the space charge effect can be neglected in this problem and one obtains rather the same results turning on or off the space charge forces.

In the transverse plane the main issue is to limit the emittance growth. The dominant emittance growth mechanism here is the one induced by the RF forces. Time dependent forces violating Liouville's theorem allow for the emittance growth. The transverse RF force in an axisymmetric TW structure in which the principle wave is dominant can

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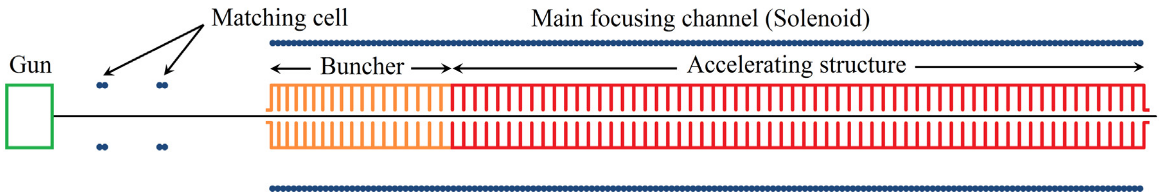

Fig. 1. Schematic layout of the IPM Linac.

Table 1
Beam parameters after the electron gun. The beam waist position is measured with respect to the cathode.

Gun voltage	Normalized rms emittance	Beam waist position	RMS Beam size at waist
10 kV	0.74 mm-mrad	17.4 cm	0.45 mm
30 kV	0.99 mm-mrad	16.4 cm	0.31 mm
50 kV	1.18 mm-mrad	17.2 cm	0.30 mm

be calculated as [9]

$$F_r = \frac{e\omega E_0}{c}\frac{\left(1-\beta\beta_{ph}\right)}{\beta_{ph}}\frac{I_1(\kappa r)}{\kappa}\sin\theta \tag{1}$$

with $\kappa = \frac{\omega}{\gamma_{ph}\beta_{ph}c}$. β_{ph} is the normalized phase velocity of the TW structure, θ the RF phase seen by each particle and E_0 the principle wave amplitude. Therefore, particles at different phases receive different focusing. The equation above can be rearranged in Eq. (2) approximating the Bessel function in the paraxial approximation ($\kappa r \ll 1$)

$$F_r = \frac{e\omega E_0}{2c}\frac{\left(1-\beta\beta_{ph}\right)}{\beta_{ph}} r\sin\theta. \tag{2}$$

According to the equation above, the RF defocusing and the resulting emittance growth vanishes as $\beta\beta_{ph}$ tends to 1 or for on crest acceleration ($\cos\theta = 1$). Particles are launched into the buncher at zero crossing ($\cos\theta = 0$) with $\beta \cong 0.4$. They afterwards are led gradually toward the crest by slowly increasing the phase velocity of the structure, resulting in the beam acceleration. Therefore, we expect a large rate for the emittance growth at the buncher entrance and nearly a constant emittance at the end of the buncher and through the accelerating structures.

In this paper, we first study the coupler induced asymmetry in the RF field and its effects on the beam quality. Next, a beam dynamics design of the solenoid focusing channel is presented. This channel is optimized with the goal of controlling the beam size and limiting the RF emittance with a solenoidal field of reasonable strength. Afterwards, we discuss how a prebuncher cavity helps improving the beam quality in the transverse plane. Finally, the effects of the solenoid misalignment on the transverse dynamics are investigated. The beam dynamics simulations presented in this paper have been carried out with the code ASTRA [10].

2. Field asymmetry near the couplers

In an ideal TW structure with azimuthal symmetry the transverse forces vanishes at the symmetry axis. This is not the case for a few cells near the couplers as shown in Fig. 2.

The asymmetry brought around by the coupler has two effects. First, these field components produce an additional time dependent force and hence an additional emittance in the vertical direction, usually known as coupler emittance. Without any focusing at the end of third cell, the emittance would reach 8.4 mm · mrad and 13.9 mm · mrad in the horizontal and in the vertical plane, respectively. Secondly, these dipole fields produce an RF kick in vertical direction. For a continuous beam with uniform distribution on phase we expect no kick on average as half of particles are kicked up and the other half down. As the bunching starts, particles accumulate around the synchronous particle receiving a net vertical kick. Fig. 3 shows the beam cross section at the end of third cell. The average vertical angle of particles, $\langle y'\rangle$, at the end of third cell is 4.6 mrad. In this simulation no solenoid focusing is applied in

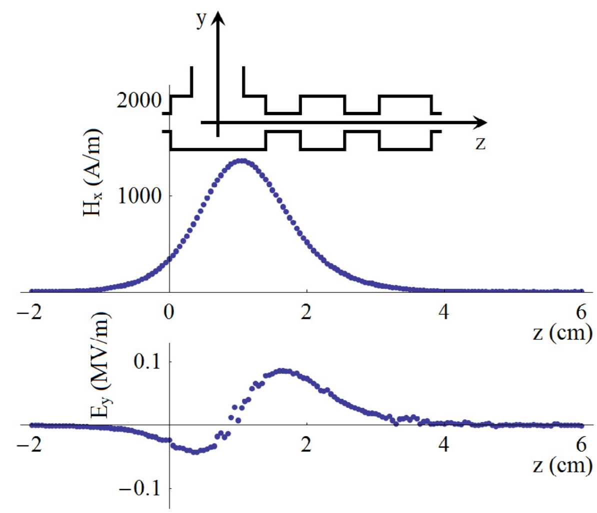

Fig. 2. Transverse field components on axis as function of longitudinal coordinate near the input coupler. The data are generated using HFSScode. The asymmetry extends up to third cell.

order to study the pure effect of the RF fields. With a solenoid focusing the beam offset resulting from the kick becomes smaller. In addition, the horizontal and vertical motions are no longer decoupled due to the interaction of the transverse particle velocity and the longitudinal magnetic field and we will have an additional emittance growth in both directions.

A similar effect is associated with the output coupler; however, with practically no emittance growth because the beam is bunched and all particles see rather the same transverse force.

Coupler asymmetry induces an emittance via two mechanisms: the RF kick itself and the resulting net kick. With a beam offset particles travel further off-axis (on average) experiencing a larger RF defocusing and hence a larger emittance growth. In the next section it has been shown that with a strong enough focusing the second mechanism can be effectively suppressed.

An interesting question is how much does the coupler asymmetry increase the beam emittance at different focusing levels? In order to answer this question a symmetric version of the RF field map is generated using the real asymmetric field data. For this purpose, we use $E_x(x,0,z)$ and $H_y(x,0,z)$ as polar coordinates E_r and H_φ because the coupler does not affect E_x and H_y coordinates in $x-z$ plane (see the reference coordinate in Fig. 2). Now, assuming an azimuthal symmetry the three dimensional field map is obtained using the following equations,

$$E_x = E_r\frac{x}{r}, \tag{3a}$$