BEAM DYNAMICS STUDIES OF A 30 MeV STANDING WAVE ELECTRON LINAC *

R. Dash#, HBNI, Mumbai 400094, India
J. Mondal, Archana Sharma, K.C. Mittal, BARC, Mumbai 400085, India

Abstract

For a high quality beam delivery to the users in application areas like material science and neutron spectroscopy, it is very important for the linac to keep the growth of transverse emittance and self field effects a minimum in order to limit the radioactivity and the cost of the linac itself and increase the transmission efficiency. This paper presents the results of electron beam tracking for a 30 MeV standing wave electron linac. This is a general purpose facility for neutron generation and will produce 10^{12}-10^{13} n/sec for measurement of neutron cross-section of (n, gamma), (n, xn) and (n, f) reactions. The effects of input beam size, divergence, field gradient and space charge effect on the beam quality have been studied with ASTRA beam dynamics code. This beam dynamics study explores the optimized beam parameters and beam quality for the linac operation.

INTRODUCTION

In this paper we have studied the beam dynamics of a 30 MeV, 6 kW bi-periodic coupled cavity standing wave electron linac under development at Electron Beam Centre (EBC) Kharghar, Navi Mumbai, India. In order to predict the quality of electron beam [1], [2], [3] the electron-tracking algorithm ASTRA [4] has been used. Although there are a few self-consistent space-charge codes that can be used to study the emittance evolution, we choose the ASTRA model in order to provide a fast parametric study.

The accelerating module (Fig. 1) contain a 85 keV thermionic electron gun, an injector section and two accelerating sections of 22 cell and 23 cell respectively operating in $\pi/2$ mode at a frequency of 2856 MHz. The injection section consists of three bunching cells and a power feed cell. The length of each accelerating cell is 52 mm, whereas the buncher cells are 45, 48 and 50 mm respectively. The bore radius is 5mm for all the buncher cells and accelerating cell. The effective shunt impedance for the buncher cells is ~ 80 MΩ/m, while for the accelerating cells, it is ~ 90 MΩ /m.

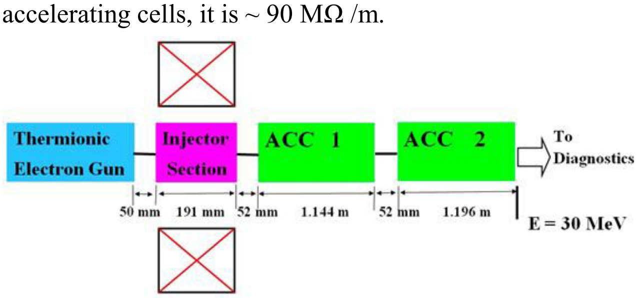

Figure 1: Schematic Layout of the 30 MeV Linac.

*Work supported by DAE, India
radhakanta.physics@gmail.com

MULTIPARTICLE SIMULATION WITH SPACE CHARGE

For the present work the longitudinal electric field components on the symmetry axis of the injector and accelerating sections have been computed using CST MWS [5]. The tracking code ASTRA does not need a geometrical description of the structures. For ASTRA code, the space-charge fields are calculated in the beam rest frame via Poisson's equation in free space and Lorentz's transformed back into the laboratory frame. ASTRA is based on Runge-Kutta integration of 4th order with fixed time step through the user defined external electric and magnetic fields, taking into account the space charge field of the particle cloud. A cylindrical grid, consisting of rings and slices, is set up over the bunch extension for the space charge calculations. The code automatically updates the mesh size as the simulation progresses. For all the simulations presented in the following, we have used 2.5 x 10^4 macro particles in uniform distribution. The initial energy of the particles injected in the guide is 85 keV. The particles are distributed quasi-randomly following the Hammersley sequence in such a way that statistical fluctuations are reduced and artificial correlations are avoided.

Effect of Space Charge on Beam Dynamics

Figure 2 gives the evolution of rms beam size for the nominal energy of 30 MeV. We have used a uniform distribution of particles having energy 85 ± 2 keV for the longitudinal direction with rms bunch length of 15.61 mm and bunch charge of 0.175 nC and Gaussian distribution in all transverse dimensions with rms beam sizes of 0.8 mm each. The results show that space charge gives rise to a transverse spread of the beam in the injection section and 1st cavity at low energies.

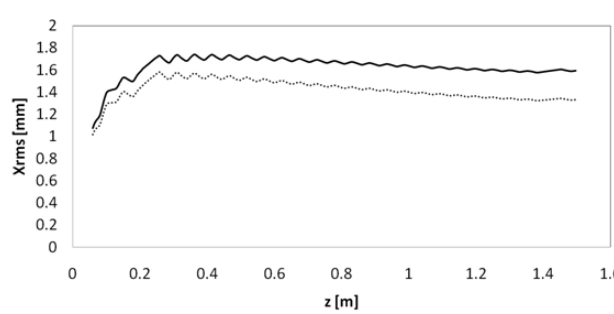

Figure 2: rms beam size without space charge (Dotted line) and with space charge (solid line).

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PARAMETRIC STUDY OF INPUT BEAM

Emittance of a beam is a suitable parameter to define the qualities of a beam in terms of size and divergence of the beam. Beam emittance is given approximately by the product of spot size and divergence, and is proportional to the volume of the bounding region that each bunch occupies in its region of six-dimensional phase space. The normalized RMS emittance is defined by [6]

$$\epsilon_{n,rms} = \beta\gamma\sqrt{\langle u^2\rangle\langle (u')^2\rangle - \langle uu'\rangle^2} \qquad (1)$$

All the simulations data presented in this section have been noted at z = 2.64 m, that is at the end of the linac.

Evolution of Emittance with Space Charge

The general increasing nature of transverse emittance in Fig. 3 shows what we would expect: the beam has more of a tendency to diverge due to higher magnitude of self fields and leads to overall transmission loss. This curve changes significantly as we vary other parameters such as initial spot size, field strengths, cavity phases, etc.

For example, if we decrease the input rms beam size from 0.8 mm to 0.1 mm, the space charge effects becomes quite prominent and leads to growth of curve at a faster rate as shown in Fig. 3.

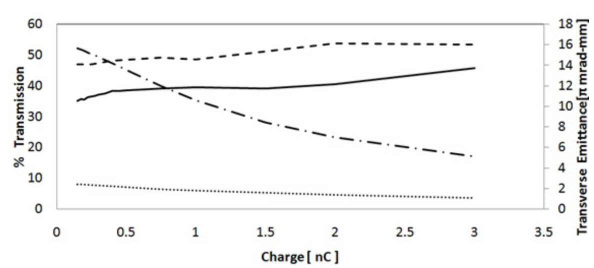

Figure 3: Effect of space charge on transverse emittance (solid line) and % transmission (Dash-dot-Dash) for rms beam size of 0.8mm .Transverse emittance (Dashed line) and % transmission (Dotted line) for rms beam size of 0.1 mm.

Evolution of Emittance with Beam Size

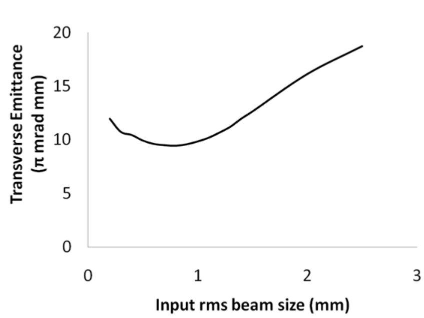

Figure 4: Evolution of transverse emittance with input beam size.

In rf cavities the radial component of the electric field grows quadratically with radius up to half of maximum radius of the rf cavity, whereas the longitudinal electric field increases linearly toward higher radii. As a result, the variation of the beam size (due to RF focussing) depends nonlinearly on the value of the beam size itself, therefore an increase of the emittance, proportional to the fourth power of the beam radius, is to be expected when a beam crosses a rf cavity .In order to numerically test this effect, we have tracked beams of charge 0.175 nC and of different transverse sizes through the rf cavity. Figure 4 describes the transverse emittance as a function of input rms beam size.

Evolution of Emittance with Divergence

In rf cavities the beam divergence strongly affects the beam behaviour. In order to study the emittance growth due to beam divergence we have taken an input beam of rms size 0.8 mm and varied the beam divergence as given in Table 1. We find that the transverse emittance shows a linear growth with increase in beam divergence, which leads to loss of electrons through the beam tube.

Table 1: Effect of Input Beam Divergence on Emittance

Input divergence	**Transverse Emittance**	**Percentage transmission**
2.1	7.71	55
6.2	8.53	54
9.4	9.67	53
12.5	10.65	52
15.6	11.48	50
18.7	12.52	47

Evolution of Emittance with Beam Aspect Ratio

We have studied the effect of the aspect ratio of the rms beam sizes in transverse direction and their effects on emittance growth. The summary of the results are given in Table 2. We observe that for any beam, the emittance growth in one transverse plane of the beam as compared to the other plane is within space-charge statistical error.

Table 2: Effect of Beam Aspect Ratio on Emittance

Beam Size x_{rms} (mm)	**Beam Size y_{rms} (mm)**	**Emittance, ϵ_x (π mrad-mm)**	**Emittance, ϵ_y (π mrad-mm)**
↑	1.5	11.25	12.67
0.82	2.0	9.24	17.83
↓	3.0	8.69	23.56
1.5	↑	13.65	10.33
2.0	0.82	18.18	8.91
3.0	↓	23.58	8.35

Thus we treat each plane irrespective of the other plane, i.e. the two transverse planes behave independently of each other.

Effect of Variation of Field Gradient

We have studied the evolution of the beam subject to variation in field gradient. The results are given in Table 3 and from this we can estimate the changes in the output due to errors in the field gradient. An error of ± 4% in the field gradient changes the output energy gain ≈ ± 4% and error in gradient of ± 8% changes the output energy gain ≈ ± 8%.

Table 3: Effect of Field Gradient on Output Beam

Field Gradient (MV/m)	Output Energy (MeV)	Energy Spread (keV)	Transverse Emittance (π mrad-mm)
22	27.5	1230	11.78
23	28.8	908	11.21
24	30.0	720	10.65
25	31.2	648	10.03
26	32.4	678	9.58

Effect of Solenoid Focusing on Beam Quality

We have studied the quality of beam subjected to solenoid focusing. An air core solenoid of length 15 cm and 15000 ampere-turns is applied over the injection section as shown in the Fig. 1.The solenoid field reduce the beam diameter from ~ 8 mm to ~ 4.5 mm and improve the overall transmission ≈ 9%. Figure 5 describes the computed beam envelope over the entire length of the linac without solenoid and with solenoid.

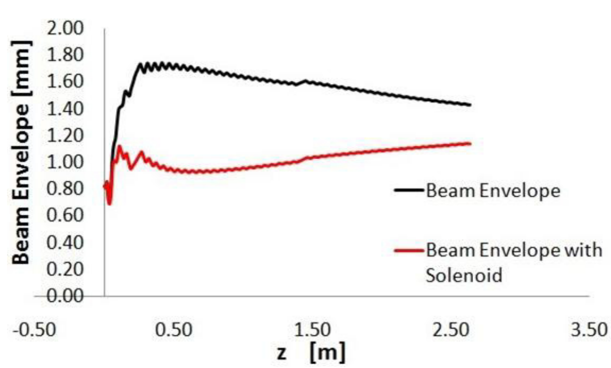

Figure 5: Computed beam envelope over the entire length of linac.

Transverse phase space of the electron beam at the end of the linac are shown in the Fig. 6 for without space charge effect and with space charge effect along with the focusing effect of the solenoid.

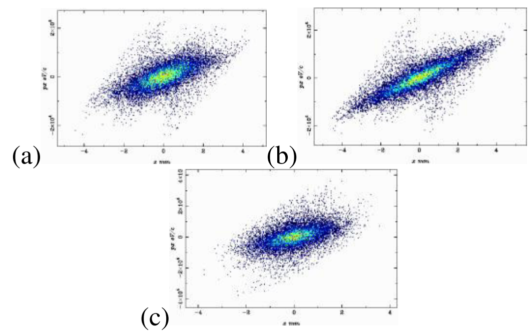

Figure 6: Transverse phase space of the electron beam at the end of the linac (a)without space charge, (b)with space charge, (c)with space charge and solenoid focusing.

CONCLUSION

We have investigated the effect of horizontal plane and vertical plane on beam dynamics and found that both the planes can be treated separately excluding space charge effect. A bunch charge of 0.175 nC is used to obtain a low emittance beam along the transverse and longitudinal direction with a reduced space charge effects. Also we have determined that a field gradient of 24 MV/m is to be maintained in order to have nominal energy gain of 30 MeV with minimum energy spread of 720 keV. We conclude from these beam dynamics studies that space charge effect plays a pivotal role in the injector section and 1st cavity of the 30 MeV linac. We have applied a solenoid of length 15 cm and 15000 ampere turns over the injector section to compensate the space charge effect. An energy spread of ~ 2.5% improves the quality of the output beam. With a beam size of ~ 4.5 mm in the bore of aperture diameter 10 mm, the beam loss on the cavity wall is minimized and the heavy irradiation of accelerator components is prevented.

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