ELECTRON LINEAR ACCELERATOR WITH THE VARIABLE ENERGY FROM 6 TO 11 MeV

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Abstract

A standing wave electron linear accelerator with a variable energy of 6-11 MeV was designed. Electron energy is controlled by the injected current. A buncher was designed to provide capture above 70 % for the all injected currents range. The influence of using a permanent radially magnetized toroidal magnet

INTRODUCTION

Dual energy electron linacs with an energy range up to 11 MeV found their wide range of applications in cargo inspection systems [1] [2] and industrial applications such as sterilization systems [3].

Usually, a conventional particle accelerator system works in S or C-band frequency ranges, because the installation sizes allow designing one meter – scale accelerators for 10 MeV energy. X – band is required when the space of the installation is limited and low energy is required [4]. S-band linacs simplify the manufacturing process of the complicated geometry accelerating structures, also RPE TORIY [5] already in dispose of an S-band 2856 MHz klystron with 4-6 MW variable output power, thus 2856 MHz has been chosen as an operating frequency. For the conventional purposes of the linac, the beam power must be as high as possible with a limited input power, so we designed an efficient buncher and accelerating section to obtain the accelerator efficiency, which defines as P_{beam}/P_{in}, higher than 60% in 6-11 MeV energy range. Also, we studied the decreasing of the beam radius when permanent toroidal magnets are used as a focusing system.

BEAM DYNAMICS

Accelerator was designed to fit the requirements below:

- RF power: 5.5 MW klystron with 4-6 MW variable power at 2856 MHz;
- Injection: 30 kV with 0.3-0.8 A variable current;
- Length: less than 1.4 m;
- Beam energy: 6-11 MeV;
- Efficiency >60%;
- Beam radius to the drift tube radius ratio < 0.5

Electron beam emittances at the electron gun exit were calculated for the 0.3-0.8 A injected currents range and then used as input parameters to simulate beam dynamics in 3-cells buncher. Buncher cells lengths and accelerating fields amplitudes were optimized to obtain the capture coefficient > 70 %.

Gun

Electrons are injected into the accelerating section from the 3-electrode gun (Fig. 1) with the fixed 30 kV anode potential and variable controlling electrode potential (9.4-12 kV) [6]. By varying the controlling potential value one can change the injected current (Fig. 3a). For the different currents beam Twiss parameters [7] (Fig. 2) also are different (Fig. 3b).

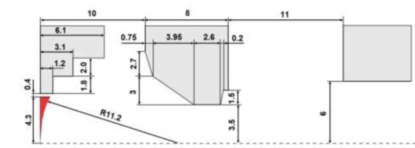

Figure 1: Electron trajectories in the gun at 0.5A current.

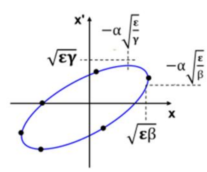

Figure 2: Twiss parameters to define a beam emittance.

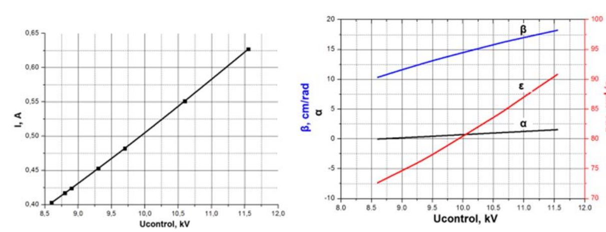

Figure 3: Electron current (a) and Twiss parameters (b) dependence in the gun from the control potential.

Buncher

Since the accelerator length is limited, standing wave is preferable because it allows getting higher energies than traveling wave structure on a shorter distance. We decided to use biperiodic structure (BPS) with inner coupling slots and nose cones [8] [9] because, even though the beam sees a π accelerating mode with a corresponding high shunt impedance (~80 MOhm/m), the RF structure itself operates at π/2 mode with a corresponding high coupling coefficient (~10%). Coupling coefficient basically describes the electric field distribution intolerance to the geometry change. Operating frequency is defined by the frequency of the klystron and is equal to 2856 MHz.

We optimized cells phase velocities and maximum electric field values on-axis (Table 1, Fig.4) both to obtain the capture >80% and energy spectrum less than 1 % after the 3rd cell with the 0.47 A injected current which corresponds

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to the estimated value to obtain 10 MeV on 1.4m with 5.5 MW input power. Beam parameters after the buncher are presented in Table 2 and in Fig.5.

Table 1: Buncher Cells Parameters

Cell #	**1**	**2**	**3**
β_{phase}	0.5	0.42	0.75
Length, cm	2.626	2.206	3.94
Ez_{max}, MV/m	0.9	4.5	16

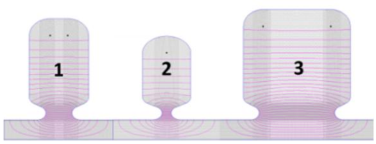

Figure 4: Electric field lines in the optimized buncher.

Table 2: Beam Parameters at the End of the Buncher

Beam power, MW	0.236
Average energy, MeV	0.59
Maximum energy, MeV	0.674
Current, A	0.388
Capture, %	83

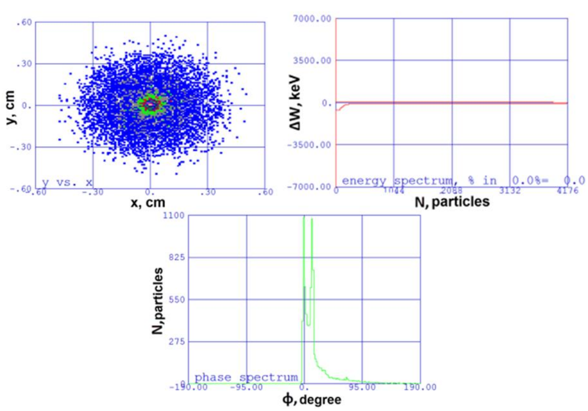

Figure 5: Beam profile (a), energy spectrum (b) and phase spectrum (c) after the buncher.

After the buncher optimization, the capture is 81% and an energy spectrum $\frac{dE}{E}$=2% . The beam radius after the buncher is equal to 0.3 cm with the 0.84 cm drift tube radius.

Accelerating Section

BPS structure allows accelerating electron beam to 10 MeV on the 1m length. It means 14 regular accelerating cells are used along with 3 bunching cells.

Table 3 and Fig.6 show the beam dynamics simulation results for the whole accelerator.

Table 3: Beam Parameters at the End of the Accelerator

Beam power, MW	3.705
Loss power , MW	1.745
Input power, MW	5.45
Average energy, MeV	10.09
Maximum energy, MeV	10.76
Current, A	0.365
Capture, %	78
Efficiency, %	68
Beam radius/ drift tube radius	0.36
Accelerator length, m	1

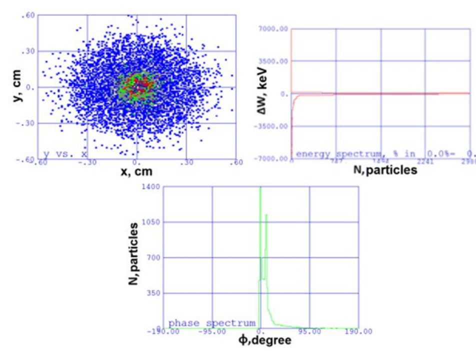

Figure 6: Beam profile (a), energy spectrum (b) and phase spectrum (c) after the buncher.

Thus we designed the 5.45 MW pulsed input power 10.1 MeV linac with further parameters:

1. Efficiency 68 % (with 78% capture);
2. Energy spectrum $\frac{dE}{E} = 2.5\%$;
3. The difference between average and maximum energy is < 0.7 MeV;

Energy Variation

Energy variation is performed by the most convenient way – by changing the input current in the 0.3-0.8 A range changing the controlling electrode potential. 10 MeV is achieved for the ~0.4 A current and 5.45 MW input power, so the overcoupling between the power coupler and accelerating section must be tuned to β=4.44 [10] to minimize the reflected power in the operating regime. Thus, one need to assume while varying the current that the overcoupling will be not optimal for currents other than 0.4 A i.e. additional reflected power must be assumed in the power balance.

Fig.7 shows the beam energy and capture and accelerator efficiency from the injected current.

Thus, by changing the injected current from 0.4 to 0.8 A and by switching the klystron power between 4.41 and 5.45 MW one can cover the 6.7-10.3 MeV energy range keeping the efficiency higher than 60 %.

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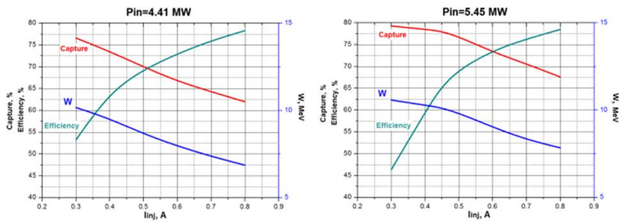

Figure 7: Average energy, efficiency and coupling coefficient dependences from the injected currents for the different power from the klystron: 4.41 MW (left) and 5.45 MW (right).

Additional Focusing

For the additional electron beam focusing one can use solenoids, but it requires an additional current source or the permanent toroidal magnets. We studied the possibility of the second option because a number of this magnet is already in TORIY disposal. Magnet geometry and it's on-axis magnetic field distribution are shown in Fig.8. The maximum B field on-axis value is 537 G.

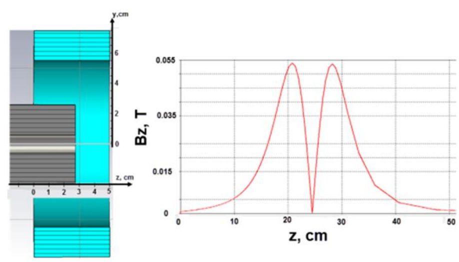

Figure 8: Magnet geometry (left) and on-axis magnetic field distribution (right).

We studied the dependence of the capture coefficient and rms beam radius from the magnet center longitudinal coordinate for the 10 MeV energy (Fig. 9a). Then, with the magnet placed at the optimum coordinate, we studied the same dependences from the second magnet center longitudinal coordinate (Fig. 9b). Simulations show that second magnet doesn't have any significant influence on the capture, i.e. having more than 1 magnet is not efficient.

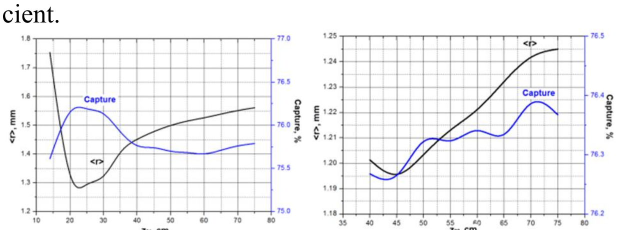

Figure 9: Capture coefficient and rms beam radius after the accelerating section dependence from the center coordinate of the first (left) and second (right, 1st magnet is in the optimum position) magnets.

When the magnet is placed at z_{01}=22 cm, rms beam radius at the end of the accelerator decreases by 20 % from 1.58 to 1.28 mm. capture coefficient is increased from 78% to 78.45 %. Fig. 10 shows the beam rms radius along the accelerator for 3 options: without magnets, with 1 magnet, and with 2 magnets. One can see once more, that the difference between options with 1 and 2 magnets is just ~4%, thus 2nd magnet is not required.

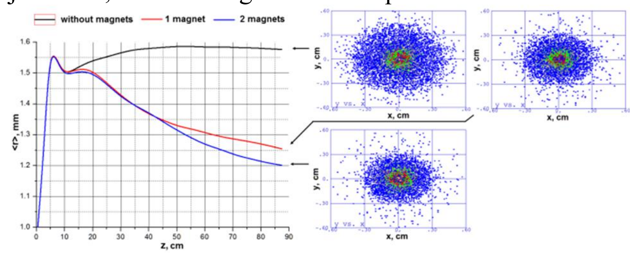

Figure 10: Beam rms radius along the accelerator without the additional focusing (black), with 1 magnet (red) and two magnets (blue).

CONCLUSION

Beam dynamics in the standing wave accelerator with 6.7-10.3 MeV variable energy was calculated. 3-cells buncher was designed to obtain the accelerator efficiency higher than 60% in the all energy range and the beam radius to the drift tube radius ratio <0.25 at the end of the accelerator. Also, the optimal longitudinal position for the permanent toroidal magnet was found to reduce the beam radius at the end of the accelerator by 20%.

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