ELECTRON BEAM DYNAMICS CALCULATION AND ACCELERATING STRUCTURE GEOMETRY DESIGN IN 10 MeV HYBRID ELECTRON LINAC

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Abstract

Electron linear accelerators with an energy of 10 MeV are widely used for industrial purposes. This article presents the electron dynamics calculations and the design of linac with a standing wave (SW) buncher based on the biperiodic accelerating structure and a constant impedance backward traveling wave (BTW) after it. In such accelerator, all unused RF power coming out from BTW section is used in SW section to improve the linac efficiency. Thus, no RF load is needed. Also, a beam is experiencing an RF focusing in the SW buncher. Solenoid focusing field influence on the beam dynamics in the TW section was studied.

INTRODUCTION

Electron linear accelerators to the fixed 10 MeV energy are in demand for the industrial purposes. For example, for the sterilization of medical supplies, food, cosmetics etc. [1]. One of the first choices the developer is faced – it is the choice between SW or TW operating regimes. Both options have their own advantages, disadvantages, and special issues. TW is suitable for the acceleration of high electron currents. In the meantime, SW buncher is much shorter than TW buncher and doesn't require additional focusing fields [2]. The way to combine advantages of both SW and TW structures is a hybrid linac [3], where the beam is bunching in the biperiodic accelerating SW structure (BPS) [4] and continuing to accelerate in TW structure based on the reliable diaphragm loaded structure technology.

ACCELERATOR SCHEME

We propose the hybrid structure (Fig.1), where the unused for the acceleration in BTW RF power goes not to the load but, via the rectangular waveguide, to the BPS buncher (Fig.2).

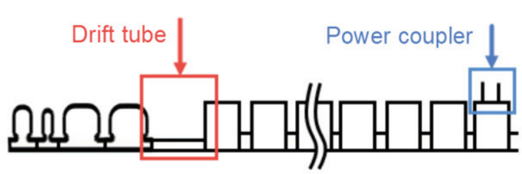

Figure 1: Hybrid linac scheme. Before the drift tube – BPS, after – BTW.

In the operating regime, power reflection from BPS, tuned to the optimal overcoupling [5], is equal to zero, thus accelerating section is operating in the TW regime. Accelerator operates at 2856 MHz frequency.

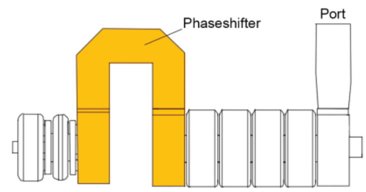

Figure 2: BTW and BPS connection.

ACCELERATOR GEOMETRY

Accelerating Section

Accelerating section for the relativistic particles is made from the disk-loaded waveguide (DLW) with an additional magnetic coupling. Magnetic coupling is designed to be higher than electric coupling, because for using BAS as a load, power flow in accelerating section should be in opposite direction to the beam propagation, i.e. negative group velocity. We studied dependencies of the main electrodynamics characteristics of BTW, such as shunt impedance r_{sh}, group velocity β_{gr}, Q-factor, attenuation coefficient α and normalized accelerating gradient $E\lambda/P^{1/2}$ as a function of phase shift per cell and normalized to the wavelength aperture radius a/λ. Shunt impedance is the highest at $2\pi/3$ mode and the optimum relative group velocity is ~1%. Table 1. shows, that shunt impedance rises with smaller aperture radius. We decided to choose $a/\lambda=0.08$ to both achieve high shunt impedance and avoid beam losses in accelerator walls.

Table 1: BTW electrodynamics parameters dependence from the normalized aperture radius at $2\pi/3$ mode, constant group velocity and 2856 MHz operating frequency.

a/λ	**0.06**	**0.08**	**0.1**
r_{sh}, MOhm/m	82.9	71.2	62.1
β_{gr}, %	1.3	1.2	1.2
Q	12500	12200	12000
α, m^{-1}	0.18	0.19	0.2
$E\lambda/P^{1/2}$	578	547	531

Phase Control Between Sections

Buncher and accelerating section are connected to each other by a rectangular waveguide with a fixed length and are separated by a drift tube. To ensure, that the accelerating mode phase difference between the last buncher cell and the first accelerating cell is suitable for the acceleration in resonance, i.e. $\Delta\varphi=180+/-2\pi$, we designed a waveguide phase shifter which allows tuning this phase difference in the whole 2π range (Fig.3). It consists of the

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3dB waveguide bridge and 2 shorting plungers. While moving these plungers one changes the phase of the wave propagating through other two ports.

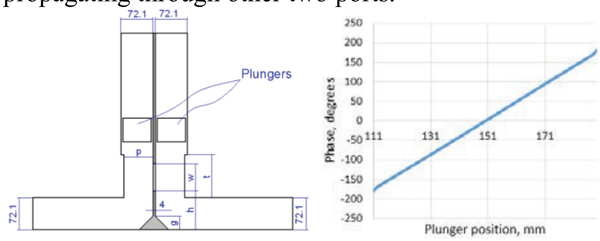

Figure 3: Waveguide phase shifter geometry (left) and transmitted wave phase dependence from the plungers position (right).

BEAM DYNAMICS

Beam Dynamics in the Accelerator

Injected beam parameters are set up by the existing gun [6] geometry. We chose the buncher cells parameters (Fig. 4) to achieve the highest capture after it which characterizes the buncher performance. Accelerator length and injected current are chosen in order to achieve 10 MeV at the end of linac and to achieve the output power from BTW equal to the required power to feed the buncher. This is an iterative process and we calculated 1.4 m length and 0.43 A injected current. Beam parameters are shown in Table 2 and Fig. 5.

Figure 4: Electric field lines in the optimized buncher.

Table 2: Beam Parameters at the End of the Accelerator

Beam power, MW	2.93
Loss power , MW	2.27
Input power, MW	5.5
Average energy, MeV	10.13
Maximum energy, MeV	11.8
Current, A	0.274
Capture, %	63.7
Efficiency, %	53.3
Beam radius/ drift tube radius	0.5
TW section length, m	1.4

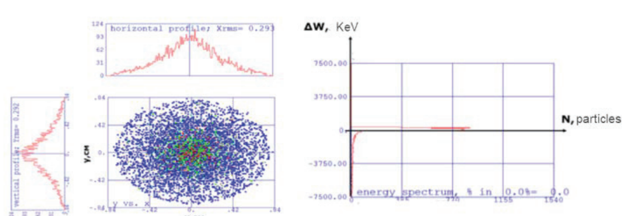

Figure 5: Beam profile (left) and it's energy spectrum (right) at the end of the linac.

Magnetic Focusing

The simulation shows that the major beam losses are in the TW section, so we can introduce the additional focusing solenoids to increase the efficiency of the LINAC. We were varying the number of magnets, its positions and magnetic field amplitude and decided that the optimum option is to use 2 magnets with 650 G maximum on-axis magnetic field (Fig.6).

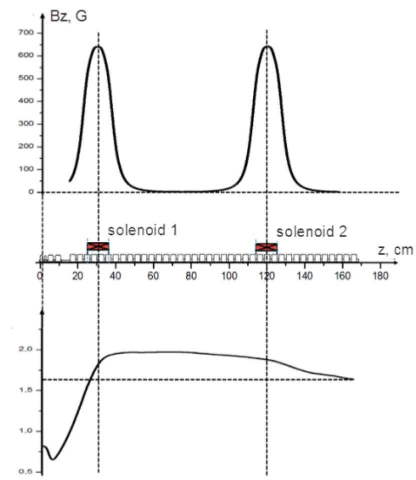

Figure 6: Focusing magnetic field length (top) and beam RMS radius (bottom) along the accelerator. Optimal solenoids centers coordinates are z_1=25 cm and z_2=120 cm.

While comparing beam parameters at the end of a linac with and without the focusing magnetic field one can see a 14% efficiency improvement with a magnetic field (Table 3).

Table 3: Beam parameters at the end of the accelerator with and without an additional focusing field

	No solenoids	2 solenoids
Beam power, MW	2.93	3.7
Current, A	0.274	0.35
Capture, %	63.7	80.8
Efficiency, %	53.3	67

EQUIVALENT CIRCUIT METHOD

To simulate the RF field distribution in the designed accelerating structure we used the software based on the equivalent circuit. A circuit shown in the Fig. 7 was used as an equivalent circuit for SW and TW cells. Its appropriateness was proven in papers [7].

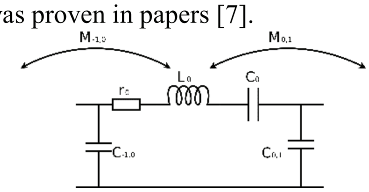

Figure 7: Equivalent circuit used to describe accelerator cells.

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Buncher cells parameters were tuned according to the optimal accelerating field amplitudes in cells, obtained during the beam dynamics optimization. Tuning was done by varying electric and magnetic coupling coefficients of the buncher cells. In Fig. 8 electric field amplitude distribution in buncher (where odd cells are coupling cells and even cells are accelerating) along with the S_{11} distribution in the frequency range without the beam loading, so we can see overcoupling at the operating frequency.

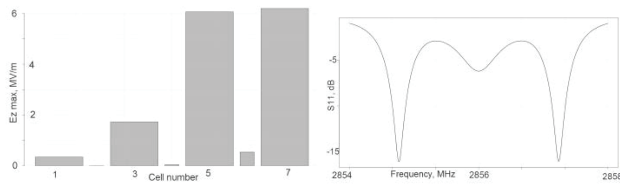

Figure 8: Distribution of the electric field (left) and S_{11} in the frequency range for the buncher (right).

When the beam loading is on, there is no reflection from the buncher, so we optimized an input coupler to minimize reflection using analytical expressions.

Results of the hybrid linac with the beam loading i.e. no reflection from buncher and TW regime in the accelerating section are shown in Fig.9. One can see that field amplitude in TW section decays according to the attenuation coefficient and phase shift per cell is $2\pi/3$.

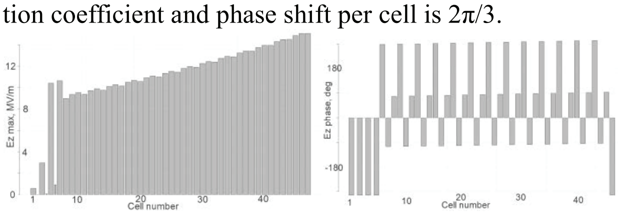

Figure 9: Electric field amplitude (left) phase (right) distribution in the hybrid linac in the operating regime.

The input impedance was calculated for two cases of the operation: with and without beam loading. Input reflection characteristic of the structure for these modes of operation is shown in Fig. 10.

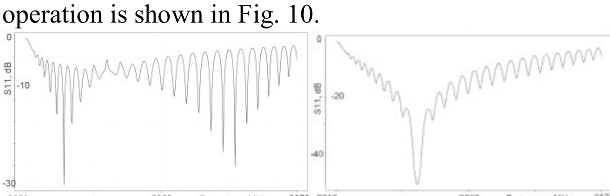

Figure 10: S_{11} in the frequency range for the hybrid linac with beam off (left) and on (right).

Fig.10 shows that without a beam power coupler sees a significant reflection because of the buncher overcoupling. When the beam and high power are on, buncher is matched with the TW section and power coupler sees no reflection.

CONCLUSION

We showed the possibility of using a hybrid electron linear accelerator as a source of 10 MeV electrons. Buncher cells are optimized to obtain the highest efficiency without an external focusing magnetic field and the connection between SW buncher and TW accelerator is optimized to use buncher as a load for the unused output power from TW section.

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