# BEAM LOADING EFFECT OF HIGH CURRENT TRAWLING WAVE ACCELERATOR DYNAMIC STUDY

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*Abstract*

The beam loading effect is one of main problems limiting the beam current. Traditionally this effect takes to account only in high energy electron linacs. Nowadays the beam current in low energy electron and, especially, ion linacs will increase. The beam loading effect should be considered here. In the paper the methods of self consistent beam dynamics study are discussed taken into account both Coulomb field and beam loading. The new code BEAMDULAC-BL will describe. The examples of the test simulations will carry out. The results of simulation are compared with experiment which was done on NRNU MEPhI electron linac.

## INTRODUCTION

Charged particles accelerators research and development are the important area of a science and techniques for a long time. The wide application was received both linear and cyclic accelerators. Interesting prospects open the high intensity beam linacs usage in new materials technology, power engineering (including thermonuclear), micro- and nanoelectronics, medicine, nondestructive control.

The important part of accelerators design is the charged particles beams dynamic investigation in various systems, such as transport, formation and acceleration systems. High intensity accelerators or accelerators with precision beams development require the charge particles self fields (static and RF) to be taken into account. In this connection, since seventieth years, there were works where the main effects (beam loading and Coulomb repulsion) were considered in a set motion approach.

Serious problem in high current RF accelerator was appeared to calculate beam output characteristics with account of current pulse shape and size (beam loading effect). This effect deal with RF field induced by particles in resonant accelerating system increased due to beam current grows. In high current accelerators it is necessary to calculate charged particles beam dynamics in the self-consistent electromagnetic field. This approach is the rather difficult mathematical problem which correct decision can be received in most cases only by computer simulation.

At low beam energies only Coulomb field repulsion is considering in calculation, and RF self field is neglected. At high energies and well bunched beam RF self field is considering only. The both parts of self field calculation are not carried out usually, though its necessity for high beam currents is obvious. That is why three-dimensional self-consistent computer simulation of high current beam bunching with transverse and longitudinal motion coupling is very actually.

The mathematical model for this calculation has been created in MEPhI; results are described in [1-2]. In 1978 on the basis of the received results the computer code has been computed, allowing to calculate the two dimensional dynamics for axial-symmetry systems with account of beam loading effect. The obtained results were highly restricted by that day computers. Besides, for accelerators of the end 70th - the beginnings of 80th years the problem of the beam current loading was not so actually. Now beam intensity in linacs has considerably increased so the account of beam loading became necessary. It has led to necessity of creation of the code for modern computers. The new mathematical model for three-dimensional computer simulation for the Cartesian coordinates system has been developed. It allows not only electron but and also proton and ion beam dynamics simulate.

The purpose of the present work is self-consistent high current relativistic beam dynamics investigation in uniform and non-uniform traveling wave accelerating structures by means of three-dimensional program BEAMDULAC-BL. The code BEAMDULAC is developed in MEPhI since 1999 [3] for high current beam dynamics simulation in linear accelerators and transport channels.

Usually a longitudinal movement of charge particles is considered only for high current beam dynamics calculation in linacs including self-consistent fields. Thus it is assumed, that the beam is in strong enough focusing field and transverse motion can be neglected. In traditional linear resonant accelerators where longitudinal components of current density $j_z >> j_\perp$, such approach is quite reasonable as the integral of current density and field interaction is defined by amplitude and a phase of a field $E_z$ and the system of the equations of longitudinal dynamics and field excitation will be self-contained. In this approach transverse motion is completely defined by the longitudinal.

For a long current pulse duration $\tau_u \geq T_f$, considering periodicity on time $T_f$, it is enough to divide at «large particles» only one bunch. For reduced longitudinal field amplitude on an axis $A_z = e\cdot\lambda\cdot E_{z1}/m\cdot c^2$. Here $e$ – the electron charge; $A_z$ – the field amplitude; $\lambda$ – the wave-length; $E_z$ – longitudinal component of electric field; $m$ – the mass of electron; $c$ - speed of the light.

All received results have been extended easily to an axially asymmetrical case if to calculate $E_x$ and $E_y$ field components.

## ELECTRON AND PROTON BEAM DYNAMICS SIMULATION

The results of beam dynamics simulation were compared with the measurement data obtained on the traveling wave electron linac U-28 of Radiation-accelerating centre in National research nuclear university "MEPhI". The main U-28 characteristics are given at Table 1. Three-dimensional code BEAMDULAC-BL has been used for beam dynamics simulation in U-28.

Table 1: Parameters of U-28 linac

| Parameterer | Value |
|---|---|
| Average output energy, MeV | 10 |
| Range output energy, MeV | 2 - 12 |
| Max pulse beam current, mA | 440 |
| Max average beam current, μA | 170 |
| Normalized energy spectrum $(\Delta W/W)_{min}$, % | 3 |
| Pulse duration, μs | 0,5 – 2,5 |
| Pulse repetition, 1/s | 400 |

The results of simulation are presented in the Table 2 and in Fig. 1. It is shown, that beam loading effect is too small for beam current $I\leq 0.2$A. Results of numerical simulation are in a good agreement with experimental one.

Table 2: Results of the electron beam dynamic simulation

| Parameter | Injection | Output |
|---|---|---|
| Velocity, β | 0,5681 | 0,999 |
| Average energy, MeV | 0,6219 | 9,525 |
| Beam current, mA | 200 | 103 |
| Current transmission, % | 51,7 | |
| Phase losses, % | 45,4 | |
| Transverse losses, % | 3,0 | |

The computer simulation in a wide range input beam current has been carried out to study the beam loading effect on beam output energy (Fig. 2). Initial current variation leads to the beam capture and current transmission factors vary. In particular, at the high initial currents more than half injected particles were lost, that leads to beam loading effect attenuation and deep beam energy adjustment impossibility.

The especial version of computer code has also been developed to study the beam loading effect in proton linacs Due to not relativistic particles velocities beam static self field become very essential. Computer simulation results are presented in Table 3. It was shown that the Coulomb field has the main influence to particle dynamics. For low injection current ($I$<0.24 A at our example) beam loading effect has weak influence to the proton beam bunching. It can be explained by low output beam energy comparatively to input RF power and small value of the parameter $E\cdot\lambda/\sqrt{P}$ defining beam and structure coupling. It is interesting to consider the possibility of average output protons energy adjustment for high beam currents. It's would be possible to change output beam energy by injection beam current changing. Computer simulation results for proton linac with different input beam currents are shown in Fig.3. It is not obviously possible to change average proton linacs output energy by input current varying because of low system efficiency.

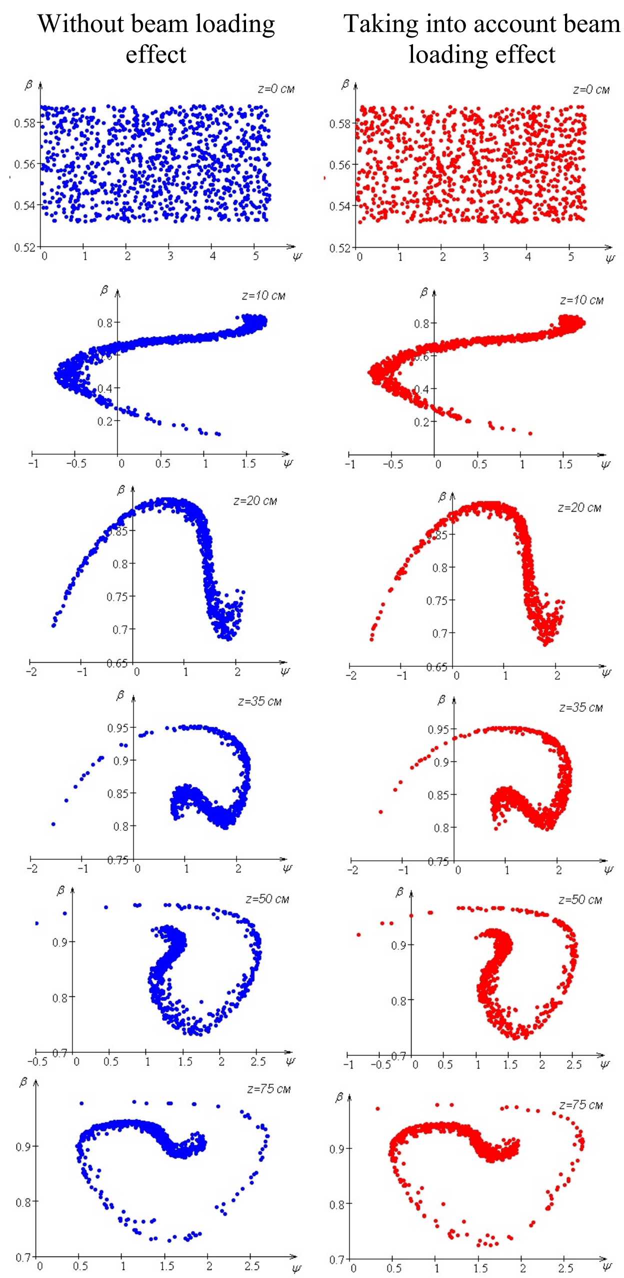


Figure 1: Electron beam bunching

Table 3: Results of the proton beam dynamics simulation

| Parameter | Injection | Output |
|---|---|---|
| Velocity, β | 0,015 | 0,057 |
| Average energy, MeV | 0,1055 | 1,553 |
| Beam current, mA | 200 | 154 |
| Current transmission, % | 77 | |
| Phase losses, % | 23 | |

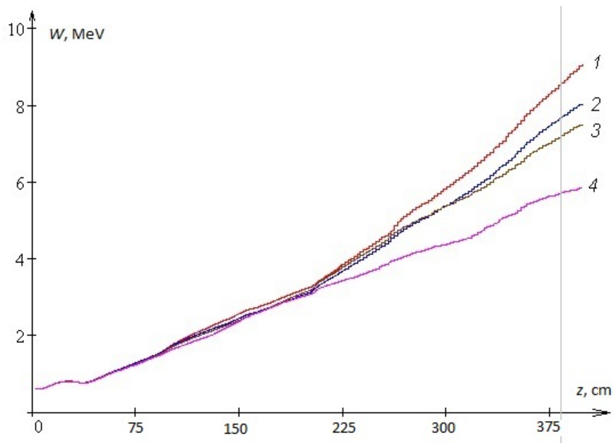


Figure 2: Electron beam energy dependence on accelerator length for different beams current: 1-$I$=0.2A; 2-$I$=1A; 3-$I$=2A; 4-$I$=5A.

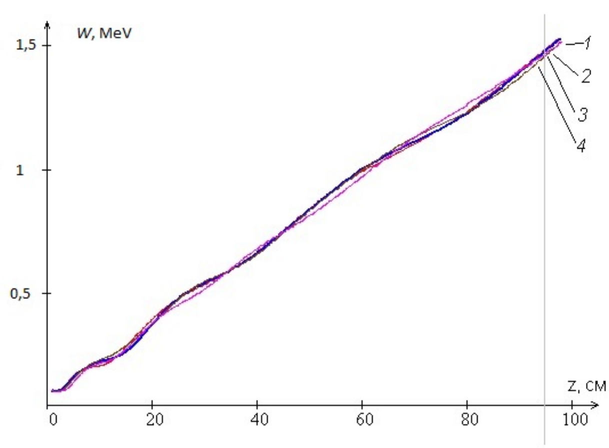


Figure 3: Proton beam energy dependence on accelerator length for different beams current: 1-$I$=0.2A; 2-$I$=1A; 3-$I$=2A; 4-$I$=5A.

The beam dynamics was simulated also in structure with the high rate of energy gain for photo gun [4]. The beam loading has been considered. The simulation was done with the accelerator parameters: injection pulse beam current $I$=5 A, injection and output beam energy 1,985 and 4.0 MeV, π/2 RF field mode, structure length $L$=94 mm (4 cells) and $L$=188 mm (8 cells). The results of this simulation are shown in Table 4. Evaluation of the accelerating field based on a formula $E{\cdot}\lambda/\sqrt{P}=A/(a/\lambda)^2$ for the ratio of $a/\lambda$=0,12. Here $E$ - amplitude of the accelerating RF field; $P$ – pulse RF power; $A$=5,56 for the ratio of $a/\lambda$=0,12 and RF field mode π/2; $a$ – aperture of channel. It was shown that the output beam energy 4 MeV can be reached with RF power equal to 35 MW in 4 cells structure and 10 MW in 8 cells accelerator. The structure length is not so large and using of 8 cell system is more preferable.

Table 4: Results of an electron beam dynamics simulation in photo gun

| ***P*, MW** | ***E*, kV/cm** | **$W_{max}$, MeV** | |
|---|---|---|---|
| | | ***L*=94mm** | ***L*=188mm** |
| 80 | 350 | 5.092 | 8.103 |
| 60 | 300 | 4.650 | 7.220 |
| 40 | 240 | 4.116 | 6.195 |
| 35 | 220 | **3.936** | 5.843 |
| 30 | 210 | 3.851 | 5.660 |
| 20 | 170 | 3.516 | 4.955 |
| 10 | 120 | 3.065 | **4.063** |
| 5 | 90 | 2.800 | 3.531 |
| 1 | 40 | 2.346 | 2.578 |

The simulation was carried out for zero-current beam also. The output energy will equal to 3.931 and 4.121 MeV for 4- and 8-cell accelerator respectively. Thus the beam loading has not very large influence to beam dynamics with this current.

## CONCLUSIONS

The high current electron beam dynamics study in the linear accelerator is carried out for stationary beam loading. The mathematical model of self-consistent three-dimensional high current relativistic beams simulation in linacs has been described. Using this model the algorithm and computer code was done. The analysis of an electron beams dynamic in the traveling wave linacs let us make the conclusion, that even for low beam current (less than $I$<1 A) beam loading effect should be taken into account. Computer simulation of beam loading effect at real high current electron and proton beam linacs is done. The developed methods can be used to solve the wide range of accelerator and RF electronics problems.

## REFERENCES

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