

Electron Bunch Space Charge Influence upon  
Its Energy Spread and Sizes under the Motion  
in Free Space.

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Summary

The influence of Coulomb repulsion in electron bunch upon its energy spread and sizes under the motion in free space after leaving the linac is considered. Space charge field calculations based upon the model of charged ellipsoid, were carried out in the range of electron energies from 1.0 to 10.0 MeV and beam pulse currents from 0.2 to 10 mA. The bunch travelling path being 2.5 m longitudinal Coulomb repulsion results in relative energy spread of a bunch from  $10^{-4}$  to  $2 \cdot 10^{-2}$ . The effect examined should be taken into account when electron linac with high energy resolution is designed.

Introduction

Some possible applications of electron linacs put forward strict requirements for monochromatism and precise transverse size. For example, electron microscopy demands beams with relative energy spread, less than  $10^{-3}$  at energies of 1 - 10 MeV<sup>1</sup>. Conventionally accelerated electrons are introduced into some magnetic forming system which for the linacs with precise parameters elaborated now is of 1 - 2m length. In case of strict requirements to beam parameters it is necessary to study space charge influence upon energy spread and bunch sizes during this motion after acceleration.

Beam Dynamics Calculation

This paper deals with Coulomb repulsion influence in electron bunch

when it moves in field - free space. For space charge field calculation we used uniform charged ellipsoid model, which was applied earlier for beam dynamics investigations in linacs<sup>2,3,4</sup>. This model is sufficiently applicable for this case. because we deal with already formed bunches both in longitudinal and transverse directions. Using definitions, introduced in the paper<sup>3</sup> components of ellipsoid Coulomb fields can be written:  $E_z = \frac{0.09}{m_0 c^2} \cdot \frac{1-2\beta_c}{R_m \cdot Z_m} \cdot I \cdot (z-z_c)$  (1)

$$E_r = \frac{0.09}{m_0 c^2} \cdot \frac{M_r(1-\beta_c)}{R_m \cdot Z_m} \cdot I \cdot r \quad (2)$$

$M_r = f(Z_m/R_m, \beta_c)$  form factor of ellipsoid,  $z$  - coordinate along the linac axis, normalized by the generator wavelength  $\lambda$ ,  $r$  - normalized distance from the accelerator axis in radial direction;  $I$  - pulse beam current, A;  $Z_m, R_m$  - longitudinal and transverse semiaxes of ellipsoid accordingly  $Z_c$  - bunch center longitudinal coordinate;  $\beta_c$  - relative bunch center velocity;

The components  $E_z$  and  $E_r$  are reduced to normalized form in the following manner:  $E_z = e E_z \lambda / m_0 c^2$ ;

$E_r = e E_r \lambda / m_0 c^2$ ; where  $e, m_0$  - charge and rest mass of electron,  $c$  - velocity of light.

Calculations were made by means of radial-phase beam dynamics simulation code, available from<sup>5</sup>. Every particle is described by four variables: relative energy  $\gamma$ , phase in accelerating

field  $\Phi$ , radius  $r$  and divergence  $r'$ . Investigation was made in an energy range of 1 - 10 MeV. Bunch phase length  $\Delta\Phi$  is selected from required energy spread  $\Delta W/W$  by means of relation<sup>6</sup>

$$\Delta W/W = 1/8 (\Delta\Phi)^2 \quad (3)$$

To obtain energy spread  $10^{-3}$ ,  $10^{-4}$  and  $10^{-5}$  phase length should be equals to  $5^\circ$ ,  $1,5^\circ$  and  $0.5$  accordingly. Relative radius of the beam was supposed to be equal to 0.01 that for frequency range of 3000 MHz corresponded to 1mm. Beam current value was determined from selected bunch sizes and electron density in a bunch at the linac output. Analysis of linacs in operation<sup>7</sup> shows that electron density of accelerated beams lies in a range of  $5 \cdot 10^8$  -  $3 \cdot 10^{10} \text{ cm}^{-3}$ . In our calculations it is equal to  $10^9$  and  $5 \cdot 10^9 \text{ cm}^{-3}$ . At the described parameters pulse beam current varied in limits of 0.2 - 10mA. At the beginning of drift space, under consideration length of which equals 2.5m beam is supposed monokinetic.

### Results

The figure and the table contain the results obtained, where energy spread, phase length, radius and divergence of bunch at the end of the drift space are presented.

These data show that energy spread due to Coulomb repulsion in electron bunch is considerable for high energy resolution linac. It varies from few per cent at small energies to  $10^{-4}$  for 10MeV.

Importance of accelerated particle radial characteristics appears from strict requirements to electron beam brightness, which must be as high as  $10^7$  -  $10^8 \text{ Acm}^{-2} \text{ ster}^{-1}$  1,9. At low beam energies space charge results in considerable deterioration of

beam quality (bunch radius increase in several times, appearance of additional divergence, greater than  $10^{-3} \text{ rad.}$ ) For the energies greater than 5MeV its influence is much weaker. For instance, transverse divergence doesn't exceed  $2 \cdot 10^{-4} \text{ rad.}$  To take into account the influence of non-zero energy spread at the end of accelerator the calculation was carried out for the initial value of relative energy spread equals  $10^{-3}$  Energy distribution along the bunch length was determined by its position with respect to accelerating wave.

Calculations show that energy spread decrease in afteracceleration motion takes place provided the bunch was accelerated behind the wave crest while acceleration in a pre-crest phase results in its increase. Compensation of initial spread in this case gives the best results at energies of 3 - 5MeV. At lower initial values of energy spread, the best compensation occurs at higher energies.

For instance calculation was made for the beam parameters of electron linac with high energy resolution<sup>8</sup>: beam current - 3mA, radius - 0.5mm, bunch phase length - less than  $5^\circ$ , electron energy - 5MeV. The results gave energy spread of  $4 \cdot 10^{-4}$  per 1m length as compared to  $5 \cdot 10^{-5}$  obtained in<sup>8</sup> at the active monochromatization system output. In the other project of a 5MeV electron microscope<sup>9</sup> they expect to obtain output beam with divergence  $5 \cdot 10^{-5} \text{ rad}$  having virtual source with radius 0.4mm with brightness not less than  $2.5 \cdot 10^8 \text{ Acm}^{-2} \text{ ster}^{-1}$  and energy spread equals  $2 \cdot 10^{-5}$ . At these parameters electron density value is near  $10^9 \text{ cm}^{-3}$ . At drift space length of 1m space charge will result

in energy spectre expansion to  $2.7 \times 10^{-4}$  and additional radial divergence  $3 \times 10^{-5}$  rad.

Results obtained show that for electron linac with high precision beam parameters space charge forces effecting the motion of bunch after acceleration should be taken into account. If their influence is noticeable correction of beam parameters or electron density decrease in accelerated bunches. should be provided.

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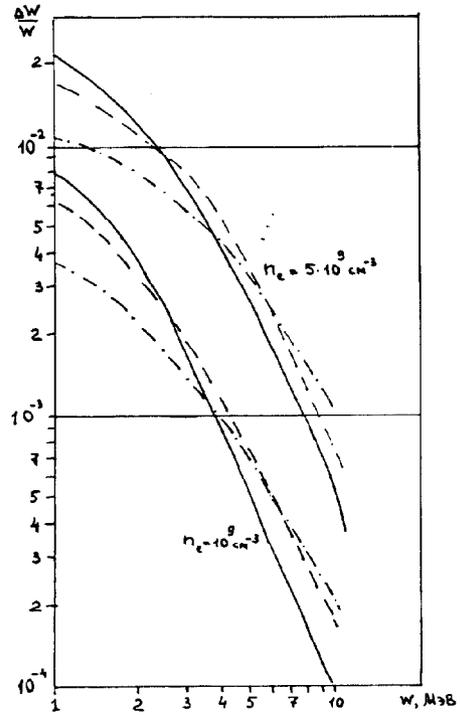


Figure. Energy spread dependence upon electron energy and bunch phase length:

—  $\Delta\phi = 5^\circ$   
 - - -  $\Delta\phi = 1.5^\circ$   
 - · - ·  $\Delta\phi = 0.5^\circ$

Table

| Initial values: $\Delta\phi = 0.08727 (5^\circ)$ , $r = 0.01$ , $\Delta W/W = 0.$ , $r' = 0.$ |       |      |      |       |        |       |       |      |      |       |
|---|-------|------|------|-------|--------|-------|-------|------|------|-------|
| $I, \text{ mA}$   | 2.0   |      |      |       |        | 10.0  |       |      |      |       |
| $W, \text{ MeV}$  | 1.0   | 2.0  | 3.0  | 5.0   | 10.0   | 1.0   | 2.0   | 3.0  | 5.0  | 10.0  |
| $\Delta\phi_{out} \times 10^{-2}$ radian  | 15.80 | 9.67 | 8.95 | 8.76  | 8.73   | 31.40 | 12.70 | 9.79 | 8.88 | 8.73  |
| $\tau_{out} \times 10^{-2}$   | 2.90  | 1.54 | 1.21 | 1.06  | 1.01   | 6.91  | 3.12  | 1.94 | 1.28 | 1.04  |
| $\frac{\Delta W}{W}_{out} \times 10^{-3}$   | 7.9   | 3.52 | 1.53 | 0.476 | 0.099  | 21.3  | 11.9  | 6.76 | 2.49 | 0.496 |
| $\tau'_{out} \times 10^{-4}$  | 11.7  | 3.93 | 1.64 | 0.456 | 0.0454 | 30.7  | 13.2  | 6.61 | 2.12 | 0.332 |