NONLINEAR ELECTRON BEAM DYNAMICS WITH LARGE ENERGY SPREAD IN THE MAGNETIC MIRROR

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Abstract

One of the features of new injection system for Kurchatov source of synchrotron radiation is an energy doubling of electron beam in forinjector – linear accelerator. The magnetic mirror provides 180° turn of electron beam into acceleration structure of linac for twice beam energy increase [1]. This paper describes linear and nonlinear electron beam dynamics with energy 80 MeV and large energy spread in the magnetic mirror. The theoretical first order optical functions of the magnetic mirror and the results of computer simulation of electron beam trajectories taking into account large energy spread and curvature of trajectories are presented. The structure of the magnetic mirror providing the achromatic and isochronous 180° turn of electron beam with 7% energy spread is suggested. Mutual influence of "the head" and "the tail" of electron beam when colliding in a straight section spaced in between linac output and magnetic mirror on particle losses and on the longitudinal and transversal parameters are considered.

MAGNETIC MIRROR

The magnetic mirror is a main element of new upgraded forinjector (see Fig. 1). The magnetic mirror has to provide simultaneously the following: a) achromatic and isochronous bend, b) the saving spatial and angular beam size, c) the correction of beam position and angle. In addition, the design of magnetic mirror has to provide correction of electrons enters phase into linac after U-turn.

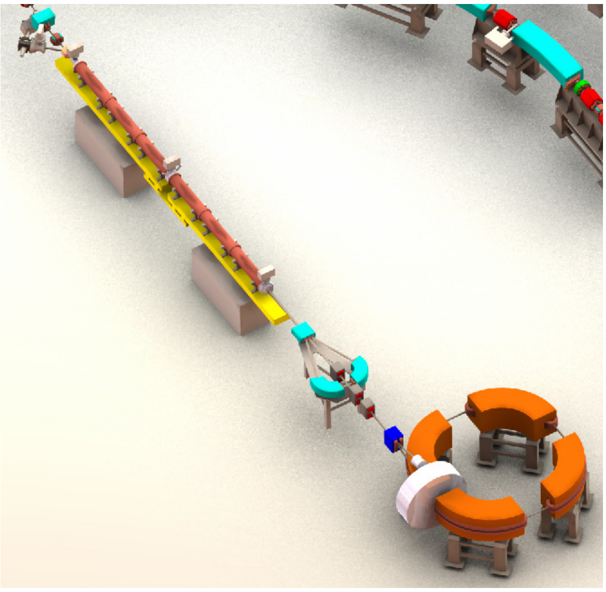

Figure 1: Upgraded forinjector.

The magnetic mirror consists from one 20° turn bending magnet and two complex mirror-symmetrical bending magnets with combined functions. This complex magnet has three components of the magnetic field (dipole, quadrupole and sextupole components) providing simultaneously 110° turn and beam focusing. Structurally the magnet consist from 3 part (see Fig. 2). The first part of magnet has all three components of magnetic fields. The central and the third parts have dipole and quadrupole components of magnetic fields. Dipole component of magnetic field in all three magnet parts is the same and quadrupole component is also the same, but has alternating values. The length of all three parts of the magnet is different.

The most important focusing property of complex bending magnet is the achievement of its length change in the sign of the dispersion function, which allowed to create on the basis of this magnet compact isochronous U-turn (see Fig. 3).

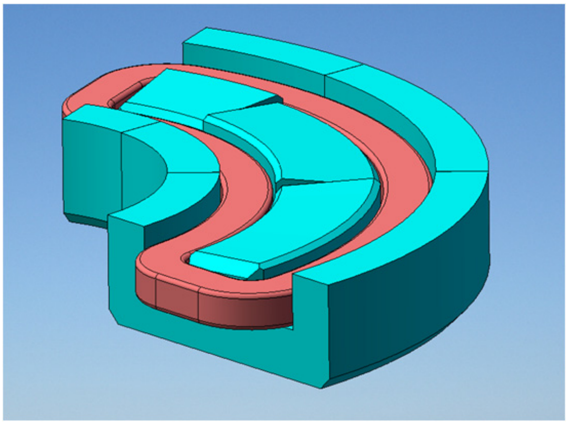

Figure 2. Bending magnet design.

The control of beam will be provided with help collimators, luminophor probes and correctors of trajectory.

LINEAR BEAM DYNAMICS

For magnetic mirror we choose mirror-symmetrical magnetic structure. This structure provides the coincidence of the initial and final values of the optical functions and their derivatives. In addition, in this structure the dispersion function and its derivative is zero and momentum compaction factor is almost zero. This provide achromatic and isochronous bend. The linear optical functions are shown in Fig. 3.

Made early calculations are not quite right for large energy spread (7%) of electrons, because they performed when electrons beam has small energy spread ($\Delta p/p \ll 1$) [1]. To improve our calculations, we take into account large energy spread into linear equations of motion. But we will be use the following standard approximation:

- No space charge.
- No interaction between electrons.
- No synchrotron radiation losses.
- Magnet elements have piecewise-constant fields distribution.
- Longitudinal magnetic field component is zero.

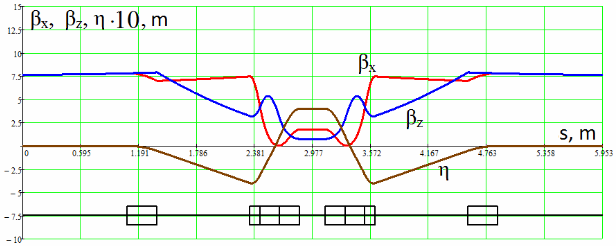

Figure 3. Linear optical functions.

For calculate linear beam dynamics into magnetic mirror we use the following linear equation of motion:

$$X'' + ((2\frac{p_0}{p} - 1)h^2 + \frac{p_0}{p}k)X = h\frac{\Delta p}{p_0}\frac{p_0}{p} \tag{1}$$

where $p = p_0 + \Delta p$ - electron momentum, p_0 - momentum of reference electron, $h = B_z/B\rho$ - curvature, $k = G/B\rho$ - focusing coefficient.

Here we present electron beam dynamics only into median horizontal plane, because the motion in this plane is the determining and defining the magnetic mirror structure [1].

The initial data for tracking are the horizontal deviation of electron from reference orbit and its derivative and momentum deviation from reference momentum. This data were obtained by calculation electron beam dynamics into linear accelerator [2]. The beam in horizontal phase space at the beginning of the magnetic mirror is presented at Figure 4.

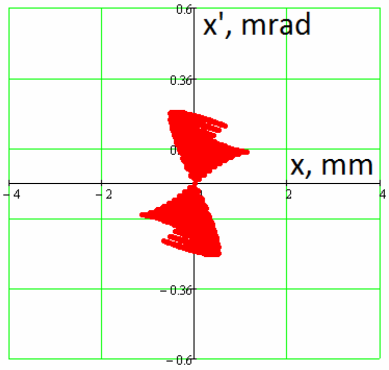

Figure 4. The beam in horizontal phase space at the beginning of the magnetic mirror.

The final data are electron trajectory into magnetic mirror (horizontal deviation of electron from reference orbit and its derivative at any point in the magnetic mirror) and trajectory length into magnetic mirror.

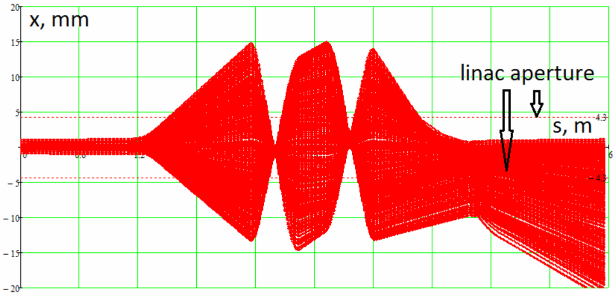

Figure 5. Electron beam trajectories.

Electron beam trajectories without corrections is presented at Figure 5. As seen, electron beam at the end of magnetic mirror have very large size and a large part of the beam will be lost.

The relative deviation of electron trajectory depending on the momentum deviation is shown on Figure 6. We can see, that both achromatic and isochronous bend are absent.

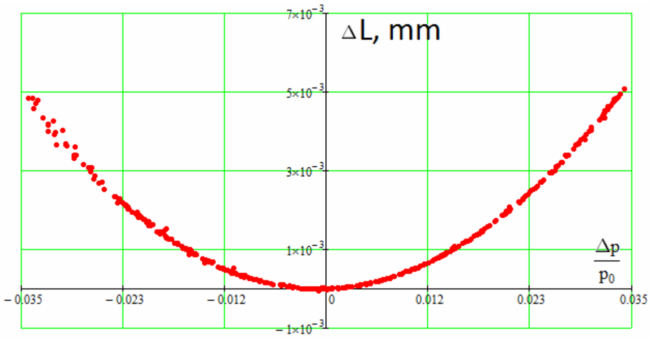

Figure 6. Relative deviation of electron trajectory depending on the momentum deviation.

For linear case we will not perform the correction of electron beam trajectories, because without the use of sextupole fields we can't good electron beam at the end of magnetic mirror.

NONLINEAR BEAM DYNAMICS

As an the linear case, we will consider the motion of electrons only into median horizontal plane. For calculate nonlinear beam dynamics into magnetic mirror we use the following equations of motion:

$$\begin{gathered} X'' - h(1 + h\cdot X) + \frac{\ddot{s}}{\dot{s}^2}X' = -\frac{e}{p}\frac{v}{\dot{s}}(1 + h\cdot X)B_z \\ \frac{v}{\dot{s}} = \frac{dL}{ds} = \sqrt{X'^2 + (1 + h\cdot X)^2} \\ \frac{\ddot{s}}{\dot{s}^2} = -\frac{2h\cdot X'}{1+h\cdot X} + \frac{1}{1+h\cdot X}X'B_z \end{gathered} \tag{2}$$

where $e = 1.6\cdot 10^{-19}C$ - electron charge, L - the length of trajectory.

Solving the equations of motion (2) and assuming what there are only dipole and quadrupole components of magnetic field and no corrections, we get the trajectories presented at Figure 7. The magnetic fields in this case and in the case when we solving equation (1) are identical, but electron trajectories are slightly different. We are seen an increase in betatron oscillations amplitude and the beam now has a greater asymmetry. Similarly the beam losses and beam divergence will be more essential, that in linear case.

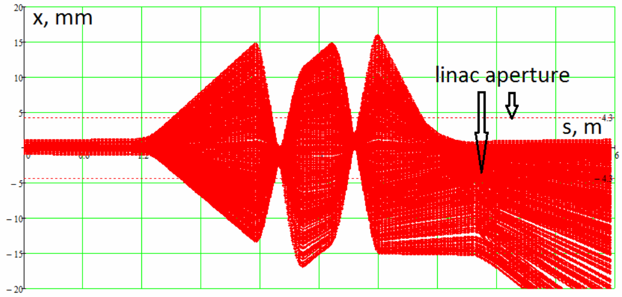

Figure 7. Electron beam trajectories.

To achieve the required parameters of magnetic mirror, we must perform correction of electron beam. We will use sextupole magnetic field component in one part of complex magnets (the part closest to separator magnet) and one quadrupole correctors in each straight sections between complex and separator magnets. Such placing sextupoles allow them to make the weaker, because phase shift is 2π. Furthermore, we shift energy deviation of electrons at the beginning of magnetic mirror from ±3.5% to -3% ÷ +4%. This allow to make the beam at the end of magnetic mirror more symmetrical.

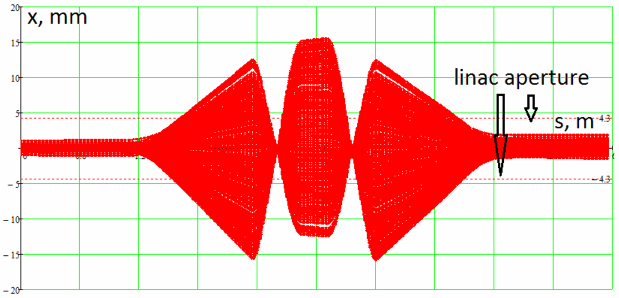

Figure 8. Electron beam trajectories.

At Figure 8 we presented the final electron beam trajectories into magnetic mirror with corrections. The beam in horizontal phase space at the end of the magnetic mirror is presented at Figure 9. Electron beam at the end of magnetic mirror after corrections will be inside the linac aperture and resulting beam divergence provides further passing of the electron beam through the linac acceleration structure.

At Figure 10 we presented relative deviation of electron trajectory depending on the momentum deviation. As in the linear case (see Fig. 6), for large momentum deviation the dominant term in the expansion of momentum compaction factor into the Taylor's series is quadratic term. Thus vanish linear term of momentum compaction factor doesn't make sense.

The maximum change in the longitudinal bunch length is about 2 mm, which is significantly less than the bunch length. The electrons with higher energy have a longer trajectory length and, hence, more magnetic mirror passage time, than the electrons with lower energy. So we will have decrease in electron microbunch length, because electrons with high energy are located into "the head" of microbanch and electrons with low energy - into "the tail" of microbunch [1].

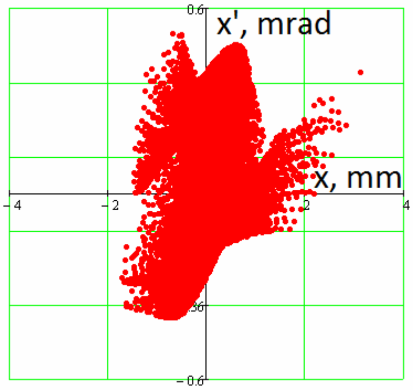

Figure 9. The beam in horizontal phase space at the end of the magnetic mirror.

In straight section spaced in between linac output and magnetic mirror "the head" and "the tail" of electron beam will be influence each other when colliding. This mutual influence in our case will be negligible, because the angles obtained by the interaction will be much smaller when available range of angles in electron beam. Note that the interface will be only 1/6 of "the head" and 1/6 of "the tail" of the beam.

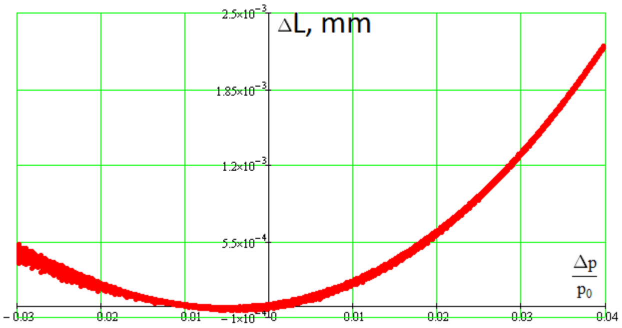

Figure 10. Relative deviation of electron trajectory depending on the momentum deviation.

Although the claim to the magnetic mirror is not satisfied, at the end of magnetic mirror we have received satisfactory to further accelerate beam without losses.

REFERENCES

[1] A. Anoshin and all, “Electron Beam Dynamics in Linac of Kurchatov Source of Synchrotron Radiation with Energy Doubling”, RuPAC’08.

[2] Ya. Fomin, V. Korchuganov, “Electron Beam Dynamics with Space Charge in Linear Accelerator”, RuPAC’10.