PRECISION BEAM FORMATION IN 2 GeV LINEAR ACCELERATOR OF ELECTRONS

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Summary

Data is presented pertaining to the phase volume increase at the linac and beam transport system exits. Also, a comparison is drawn between two achromatic beam transport systems, showing that the quinti-lense system has certain clear-cut advantages over the tri-lens one.

Introduction

Improving the parameters of charged particle beams while increasing their energy and intensity, is a characteristic goal of accelerator equipment development.

The precision of a physical experiment (and in some cases the feasibility of carrying it out) relies fundamentally on the beam emittance and energy spread. The attainment of the necessary parameters for precision beam formation (energy spread of about 0.01%, and beam emittance less than 0.01 mm-mrad) is a very complicated problem which so far has not been satisfactorily solved for electron linacs.

This paper puts under consideration some precision beam formation methods which are being currently used in Kharkov's 2 GeV electron accelerator.

The Energy Spread

In a multisection linac there exists a coupling between transverse and longitudinal motions. Transverse rf fields[1] are primarily responsible for the observed coupling. The trajectories of particles, whose initial parameters differ only in their longitudinal motion (or phase), can be seen to undergo deviations from the system axis under the influence of transverse fields. The existence of this coupling can be used to create a so-called "Narrow Phase Channel" (NPC) as well as form an energy-spread electron beam. The Kharkov accelerator-developed NPC[2] contains a number of remote-controlled collimators and quadrupole doublets. A 20-MeV acceleration section is used as an injector, where electrons are bunched along the start-up stretch, with the wave phase velocity varying in step-up stages from 0.7 to 1.0 C.

When this method of formation was employed, the energy spectrum proved to be wider than was calculated; its semi-height width being 0.13% against the theoretically expected 0.05%. The initial energy-spectrum width was 1%. The difference between the spectral experimental and theoretical widths is conceivably the result of amplitude-phase fluctuations.

Two main problems whose handling is indispensable in forming the monochromatic electron beam will be discussed. These problems are: (a) bunch formation of insignificant longitudinal dimensions, and, (b) quenching various fluctuations down to the needed level.

All the fluctuations can be roughly divided into two categories: slow ones, that go from impulse-to-impulse, and, fast fluctuations, which occur during the impulse. The very existence of the amplitude-phase fluctuation, stochastic-stabilization mechanism of the acceleration-imparting field in multisection linacs, enables us to fulfill the task of quenching the fast fluctuations.[3]

Beam Emittance

The effective beam emittance (its multipulse integrated mean-profile value) immediately prior to the exit from the linac, is substantially different from the "superinstant" one, which is measured during an infinitesimal fraction of the bunch duration. The beam transverse phase space volume increase occurs largely due to the following phenomena:

- Phased transverse particle separation;
- Fast amplitude-phase fluctuations during the acceleration impulse;
- Slow fluctuations in the connection, focusing and control systems.

Emittance stratification of numerous phases across the phase-profile, takes place in the acceleration process, thus giving rise to the beam effective emittance increase prior to the exit from the linac. This can be expressed as:

$$S = K\, E_o/E\, S_o$$

where S_o, S are entry and exit emittance values, K is the increase coefficient arising from phased particle separation, and E_o, E are the beam energy at the injector and linac exits, respectively. To suppress the effect, a supplementary beam focusing system is used which includes quadrupole doublets to zero-in the "superinstant" linac exit beam emittance on the same phase-profile center. The increase coefficient is observed to be K = 1.2, for longitudinal bunch measurement of t = 8°.

The experimental studies have demonstrated the beam emittance at the impulse median position to be less than at its extreme positions, for which K = 2.3. Clearly shown here is the role of fast amplitude-phase fluctuations.

The effective pulse train emittance exceeds a single-impulse emittance, with K = 2.1 for n = 10 (where n is the impulse number).

The ways of quenching these effects are obvious, namely: stabilizing klystron high voltage impulse peaks as well as stabilizing the power supplies of the beam focusing and control systems. Figure 1 shows the progress to date in low emittance beam formation for the 2 GeV linac.

Beam Transport System Influence on the Emittance

Up to 1976, the electron beam parallel transfer from the 2-GeV linac to the magnetic spectrometers was accomplished by employing the beam transport system (BTS) which consisted of two bending magnets ($\theta = 45^{o}$), three quadrupole lenses between the magnets, and a quadrupole triplet at the exit of the second magnet. This system's design and its peculiar features, are given in minute detail coverage in Ref. 4. This system is good for forming an image of several mm with 1-mrad semi-divergence, that is well suited to electron beam spectrometric experiments.

However, in the case of the experiments with polarized gamma quanta generated on the goniometric device diamond monocrystal, it was necessary to reduce both the electron beam emittance and its divergence.

Figure 2 gives the schematic layout of the BTS. The system was rebuilt to include two additional quadrupole lenses: L_1 and L_5. The previously employed system was achromatic (Panofsky inversion system); however, the beam envelope reached several cm in the long drift spaces between the magnets. This in turn, led to the effective on-target beam emittance increase because of quadratic aberrations. While in the present case chromatic aberrations have the predominant influence.

Several attempts were made to decrease the effective beam emittance by determining the optimal angle cut for bending magnets in the traditional Panofsky scheme. As a result, the envelope curve maximum horizontal excursions were cut in two, while the effective emittance at the system's outlet in that same plane decreased three times. Still, as expected, the BTS under those conditions gets extremely sensitive to the vertical beam emittance. The change in beam divergence by 0.03 mrad from the precalculated data, results in doubling the beam size at the second bending magnet's exit, with the beam getting partially scraped on the chamber walls. Those conditions, therefore, cannot be operational for a prolonged experiment.

The next step was an attempt at reducing the chromatic aberrations by introducing non-linearity field quadratic into the central lens. The field non-linearity was accomplished by changing the magnetic potentials of two poles by way of a manganin shunt. The quadratic non-linearity of approximately 1%, resulted in decreasing the effective emittance on the horizontal plane by half. Nonetheless, the trial run of this system displayed the same difficiencies as with the original design, i.e., superhigh sensitivity both to the emittance shape and current fluctuations in magnetic elements. Finally, it was only in the quinti-lensed BTS that any further emittance reduction could be achieved. According to calculations, the BTS-5 has certain advantages over the BTS-3, namely:

(a) particle trajectories on both planes agree irrespective of the entry beam parameters;
(b) Chromatic aberration contributions to the effective emittance increase is insignificant (one-eighth that of the BTS-3).

The absolute requirements for the BTS-5, though, put restrictions on the bending magnets' input power stability and the L_3 adjustment. To this end, there has been developed a system for the bending magnet current supply from a single generator whose permissible fluctuation level, though, should not exceed 0.05%. The difference of the magnetic parameters (less than 1%) was eliminated by exciting the second magnet's auxiliary winding from a high stability source. This mode of operation for the magnet ensured the equivalent stabilization to be less than 0.001% and helped reduce the beam on-target fluctuations to $\Delta = 1.2$. This accomplished, it was possible to determine each magnetic element's contribution to the beam on-target fluctuations. With this in mind, the derivatives of beam on-target current induced deviations in each magnetic element were measured and the correlation analysis carried out. The results were used to ascertain each element's contribution to the beam median position fluctuations. The adjusting was done by a combined method. First, the derivatives of beam on-target deviations were employed to determine the quadrupole deviations from the optical axis. Then the adjusting proper was carried out, involving the use of a "local system" of calculations and some geodetic surveying technique. The lowest possible reading of beam on-target deviation derivatives served as the criterion. The lenses adjusted, the mean quadratic value of on-target charge center fluctuations equaled $\Delta = 0.72$ mm. The top contributions to this parameter were made by the current fluctuations in the lens L_3. Its power stabilization improvement to 0.05% decreased the on-target charge center fluctuations down to 0.2 mm, which met the requirements of the experiment. The experimental research conducted over a wide energy range, as well as the BTS-5's two-year operation service, both prove its superiority to the BTS-3.

References

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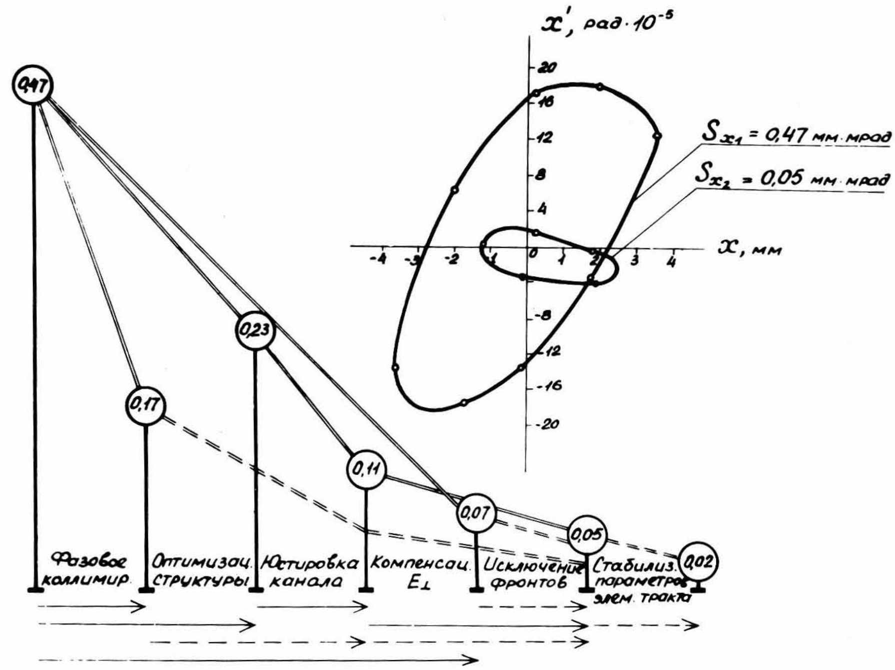

Fig. 1 2-GeV linac beam emittance decrease (the completion of the experiment in question is schematically staged from left to right in the following order):
- NPC
- Focusing system structural optimization
- Channel adjustment
- Compensation E_1
- Impulse rise time elimination
- Stabilization of power supply system

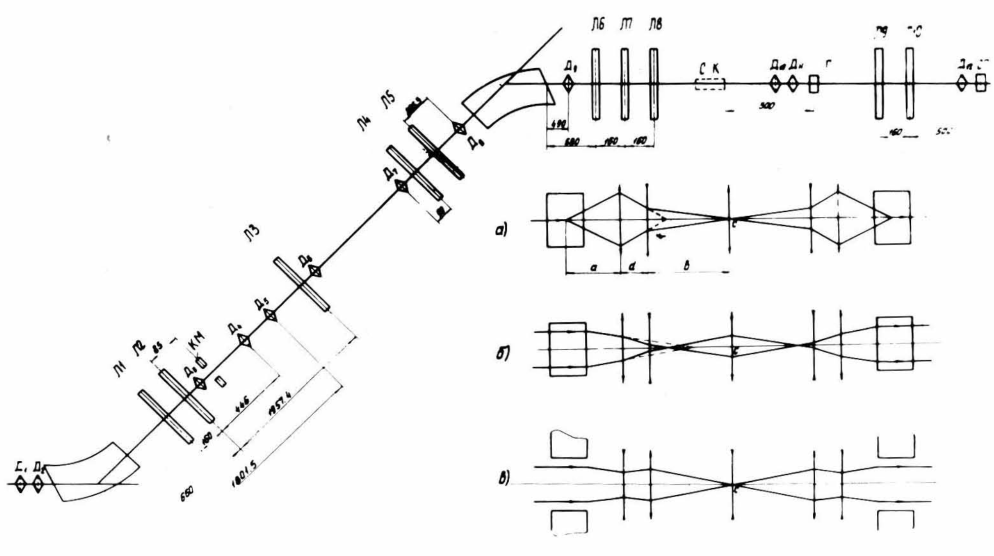

Fig. 2 2-GeV linac BTS layout

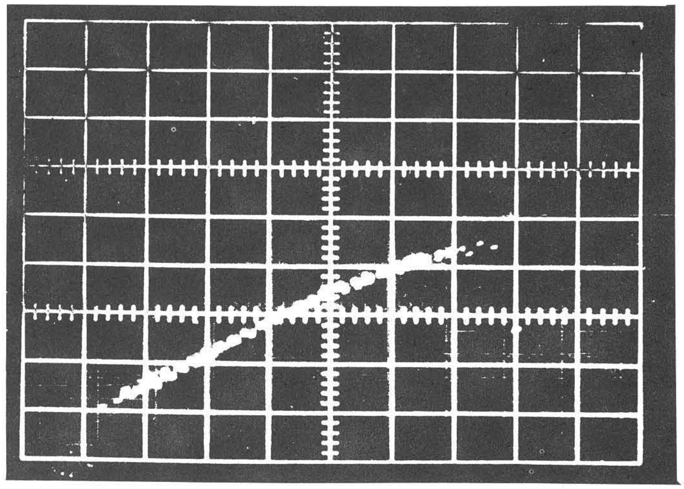

Fig. 3 A comparison of the BTS-3 and BTS-5 exit beam emittance on the horizontal plane (see BTS-3 above: horizontally - 1mm/div; vertically - 1 mrad/div; BTS-5 below: horizontally - 1mm/div; vertically - 0.08 mrad/div)