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STUDY OF BEAM INJECTION INTO A MULTIFUNCTIONAL ACCELERATOR COMPLEX

P.I. Gladkikh, I.S. Guk
National Science Center "Kharkiv Institute of Physics and Technology", Kharkiv, Ukraine
E-mail: guk@kipt.kharkov.ua

By modeling the beam motion in the recirculator of the MAC multifunctional accelerator complex, the machine's acceptance criteria were evaluated, and an analysis of the permissible alignment errors of the structural elements was conducted. The possibility of correcting the influence of nonlinear magnetic field effects on the structural elements of the recirculator was demonstrated.

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INTRODUCTION

The main trend in the design and construction of modern electron accelerators with energies up to 1 GeV is the use of niobium accelerating structures operating at liquid helium temperatures [1]. As a result, this makes it possible to obtain quasi-continuous electron beams that meet the modern requirements of research in high-energy physics, nuclear physics, neutron physics, and free-electron laser physics, as well as their use for the implementation of radiation technologies in industry, energy, medicine, biology, and other fields of science and technology [2–27].

The key to obtaining an electron beam with the parameters required to perform the specified tasks is the correct choice of injection system. For example, accelerator guns designed to produce medical isotopes [2–6] use both thermionic [2, 3, 5] and photocathodes. The electron guns of these accelerators allow for the injection of beams with energies of 100…350 keV and currents up to 40 mA. Depending on the task, these beams are first modulated and directed into the accelerating structures, where they gain an energy increase of 9 to 75 MeV using one to six accelerating modules.

Figs. 1 and 2 show general views of two accelerators designed primarily to produce the diagnostic medical isotope ^{99}Mo without the use of highly enriched uranium.

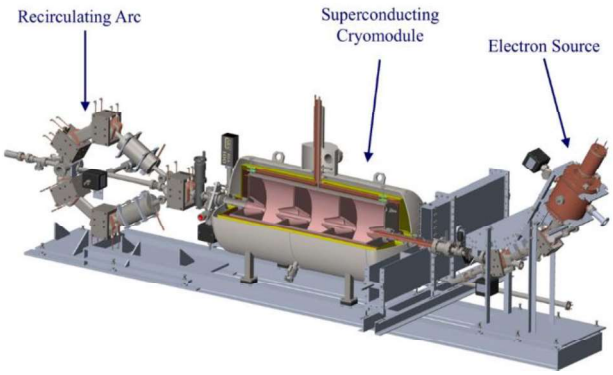


Fig. 1. Superconducting linac for commercial applications [2] with energies up to 10 MeV

An essential component of the injection assembly in the injectors of these accelerators is the beam shaping and transport system, as well as the beam parameter monitoring system. The length of the beam transport channels must be sufficient to accommodate these systems.



Fig. 2. The LIGHTHOUSE superconducting accelerator with an energy of 75 MeV, currently under development in Belgium [4]

The CBETA facility has been built and commissioned at Cornell [11, 12, 22, 25]; it serves as a prototype for the world's first energy-recovery linear accelerator (ERL). The goal of this project was to test new technologies that could be used for the future Electron-Ion Collider (EIC) [11]. ERL technology will be used in the collider project to cool proton and heavy-ion beams. Fig. 3 shows the injection system into the facility [11].

The DC gun, developed at Cornell, currently operates at a current of 75 mA. The beam energy after the injector cryomodule is 6 MeV. The maximum beam energy after the fourth pass through the accelerating cryomodule can reach 150 MeV.

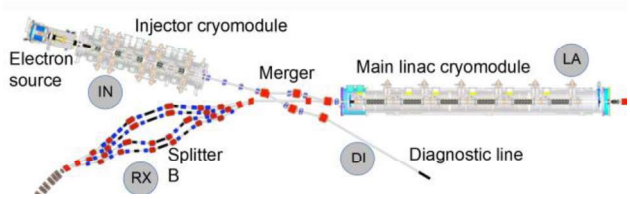


Fig. 3. Injection into the CBETA facility [11]

The accelerator complex in Rosendorf [14] was built as a Center for Ionizing Radiation Sources based on a superconducting linear accelerator, which generates various types of secondary radiation for a range of research purposes: from materials science to medicine (Fig. 4). One of the center's main objectives was to study the behavior of superconducting accelerating structures over time and to expand the scope of research by creating superconducting RF injectors. This necessitated the creation of two injection channels with different characteristics.

The channel based on a thermionic gun provides injection of a pulsed electron beam with an energy of 235 keV, a charge in the bunche of up to 100 pC, and an average beam current of up to 1.6 mA.

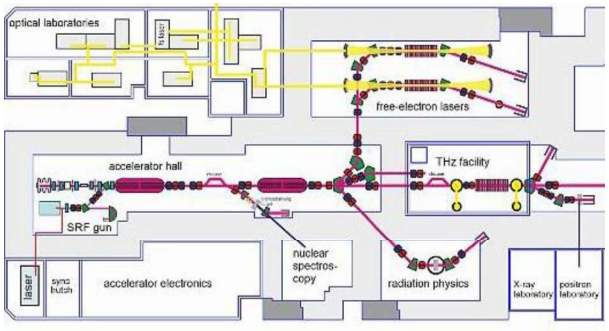


Fig. 4. The ELBE accelerator complex [25]

The objectives of the superconducting microwave gun project were to create a new electron source with an average current of 1 mA in continuous operation, as well as to demonstrate its potential for future applications in FEL light sources for energy-recovery linear accelerators.

Since 2015, the gun has been capable of delivering an electron beam with an energy of 4 MeV and a charge in the bunche of up to 300 pC to the accelerator via a special channel.

The schematic of the beam injection channel from the superconducting microwave gun, together with the beam diagnostics system, is shown in Fig. 5.

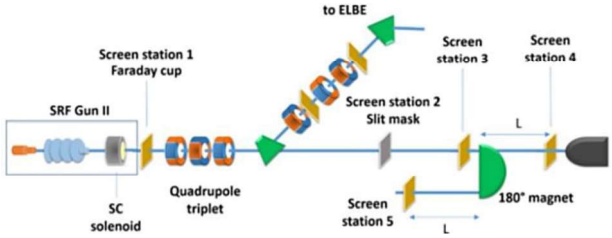


Fig. 5. Beam injection channel from the microwave gun into the accelerator [14]

The accelerator launched at the Turkish Accelerator and Radiation Laboratory (TARLA) [13] – which was developed using technology from the ELBE complex – will be used to study free-electron lasers (FELs) and the application of bremsstrahlung. Due to a significant reduction in the scope of the tasks, it has only one injector, which is a replica of the first ELBE injector. The characteristics of this injector fully meet the requirements of the planned physics experiments.

The task of selecting an injection system is significantly more complex in facilities designed to conduct research in several unrelated areas of physics. Examples include the PERLE project [10, 20, 26] and the MESA project [19, 27].

PERLE is designed as a facility to demonstrate the basic principles of ERL and as a means for high-precision experiments on the elastic scattering of electrons and protons, as well as photonic nuclear experiments.

ERL technology allows for energy savings, which is already an important requirement for all future accelerator projects.

The injector must ensure the facility operates at a current of 20 mA with an injector beam energy of 7 MeV. A general view of the gun and the acceleration module is shown in Fig. 6 [26].

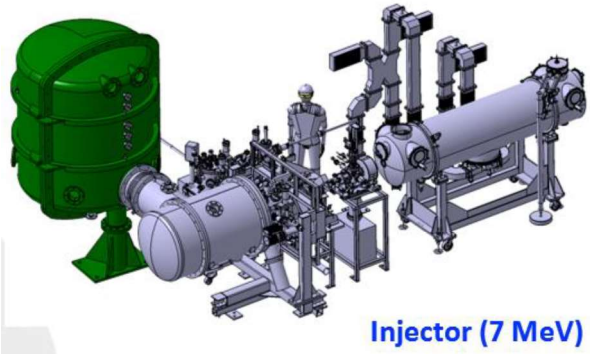


Fig. 6. PERLE injector

The general view of the MESA installation is shown in Fig. 7 [27].

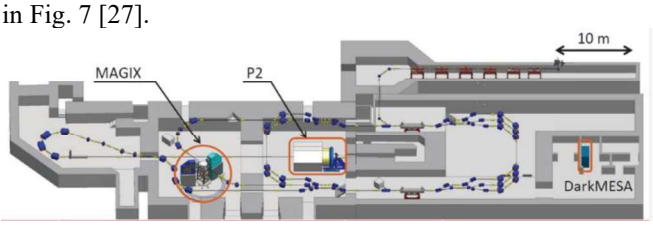


Fig. 7. The MESA system

Since the MESA scientific program is aimed not only at studying beam dynamics in a magnetic system but also includes a broad program of nuclear physics research, the facility's injector (Fig. 8) must be capable of operating with both unpolarized and polarized electron beams.

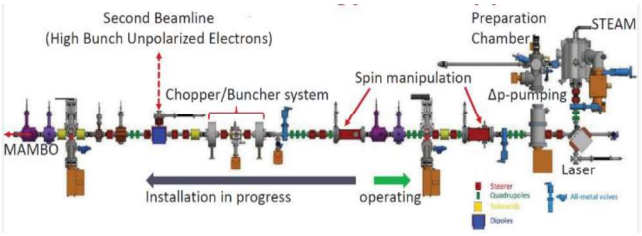


Fig. 8. Transport channel for beams of polarized and unpolarized electrons in the MESA system [27]

The primary objective of developing the conceptual design and, subsequently, constructing the Multifunctional Accelerator Complex (MAC) at the National Science Center "Kharkiv Institute of Physics and Technology" (NSC KIPT) is to establish the material and technical infrastructure necessary for the revival of nuclear physics research and to lay the groundwork for training specialists in this field in Ukraine [1]. When selecting the main parameters of the complex, the fundamentals of the concept outlined in [28] for a state-targeted program to develop the NSC KIPT's experimental base for fundamental and applied research in nuclear physics, high-energy physics, and the interaction of radiation with matter were taken into account. The main trends in the creation of such facilities in Europe and worldwide were also taken into account [1, 29, 30].

The desire to create conditions within a single complex for conducting the widest possible range of research poses additional challenges when selecting the electron injection and acceleration system for such a facility. Let us consider the requirements that must be met to correctly select the parameters of the injector, which must ensure the efficient operation of the acceleration complex.

1. REQUIREMENTS FOR THE RECIRCULATOR INJECTION CHANNEL

The primary purpose of the injection channel is to transport the electron beam from the electron source to the entrance of the recirculator rings and to ensure the necessary phase matching. From a beam optics perspective, it is necessary to match the Twiss parameters at the electron source output with the Twiss parameters at the beam injection point into the recirculator ring, whose values are [1, 30]:

• amplitude functions in the horizontal and vertical planes $\beta_x = \beta_y$ = 29.337 m;

• slopes of phase ellipses $\alpha_x = \alpha_y = -0.683$.

As can be seen from the available data on the electron injectors of these systems [2–27], their main parameters fall within the range of:

• beam energy E_0 = 4…9 MeV;

• geometric emittance $\varepsilon_{x,y}$ = 1…15 mm·mrad;

• energy spread δ = 5…15 keV;

• injector outlet beam diameter = 4…5 mm.

To model the injection and evaluate the acceptor of the recirculator [1, 30], a beam with the following parameters was selected:

• maximum beam dimensions $\sigma_{x,y}$ = 2.5 mm;

• the beam is a cross-section, and its maximum divergence is determined by the emittance and the dimensions listed above;

• the duration of the bunch is ± 3 mm (2 ps);

• pulse spread $\Delta p/p_0$ = ± 0.5%;

• all 100% of the particles are placed inside the phase ellipses with the above dimensions.

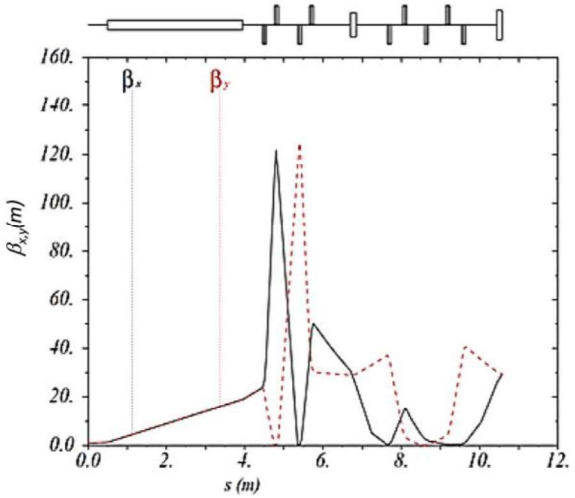


Fig. 9. Matching the injector and recirculator TWIS parameters

An example of matching the Twiss parameters of the injector and recirculator is shown in Fig. 9. The matching is carried out by two quadrupole doublets after the accelerating module with an energy set of Δ*E* = 25 MeV and five-lens parallel beam transfer. Such a structure allows matching the phase volumes in all ranges of changes in the injection beam parameters. The general view of the selected injection structure is presented in Fig. 10.

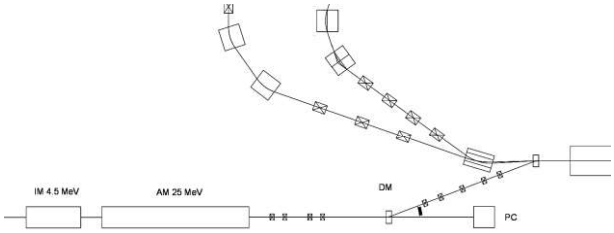


Fig. 10. Injection part of the complex

2. RECIRCULATOR ACCEPTANCE

Due to errors in the alignment of the elements of the recirculator structure, the beam trajectory deviates from the equilibrium one. Technically possible alignment accuracies are about 100 μm in the transverse plane, 0.5 mm in the longitudinal plane and about 1 mrad in the angles of rotation of the element relative to the axes of the coordinate system. Unfortunately, calculations show that with such tolerances, the deviations of the beam orbit from the ideal significantly exceed the aperture of the recirculator vacuum chamber. Under such conditions, it is necessary to develop an algorithm for guiding the beam from the injector to the output points, which will be one of the tasks of further designing the recirculator focusing structure. The result of developing an algorithm for guiding the beam along the structure will be the selection of the optimal placement of correctors and position monitors and computational correction procedures. Such procedures in practice allow to correct the mean square deviations of the equilibrium orbit within about 1 mm.

The dipole magnets intended for use in the structure have a fairly significant sextupole field component.

$$K_2 = \left(1 / B_0 \rho \right) \partial^2 B_y / \partial x^2 = -15 \text{ T/m}^2.$$

The deviation of the beam center of gravity from the ideal orbit leads to a significant influence of the nonlinear components of the magnetic field. Fig. 11 shows one of the possible variants of the beam orbit with root-mean-square deviations of the orbit of approximately 1.3 mm in both transverse planes, and Fig. 12 shows the results of modeling the beam motion under these conditions for three values of the transverse emittance. The figure shows that due to the field nonlinearities, the large emittance degrades significantly, and the beam begins to die at the physical apertures. Dynamics modeling shows that at an emittance of 6 mm·mrad, 25 particles out of 2500 are lost at the recirculator inlet, and at an emittance of 7 mm·mrad, the beam losses are already approximately 300 particles. With some margin, the acceptance of the designed focusing structure is 5 mm·mrad in both transverse planes.

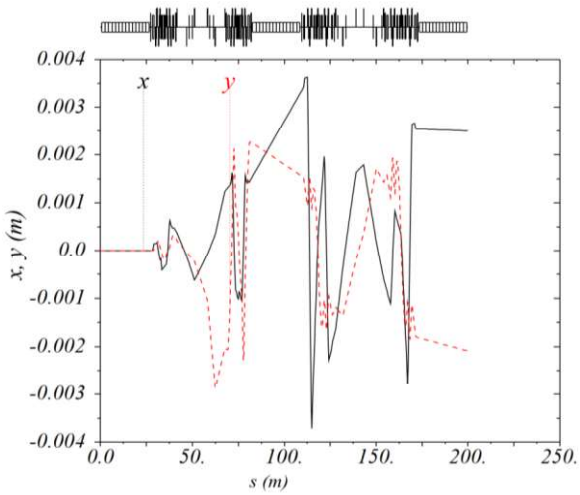


Fig. 11. Beam orbit in both recirculator rings

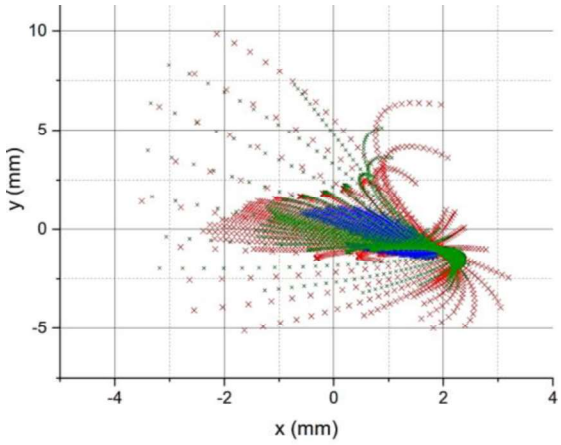


Fig. 12. Cross-section of the beam after the third pass through the accelerator. The beam emittance is 1 μm (blue symbols), 6 μm (green symbols) and 7 μm (red symbols)

To correct the influence of the field nonlinearities of the magnetic elements, appropriately placed sextupole lenses were introduced into the focusing structure. Figs. 13 and 14 show an example of such correction. The phase portraits of the beam are shown at the accelerator exit after its third pass.

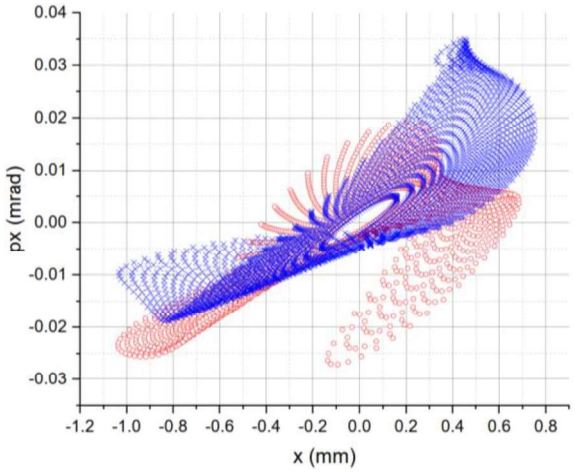


Fig. 13. Correction of the influence of nonlinearities in the radial plane. Uncorrected motion (red symbols), phase plane after correction (blue)

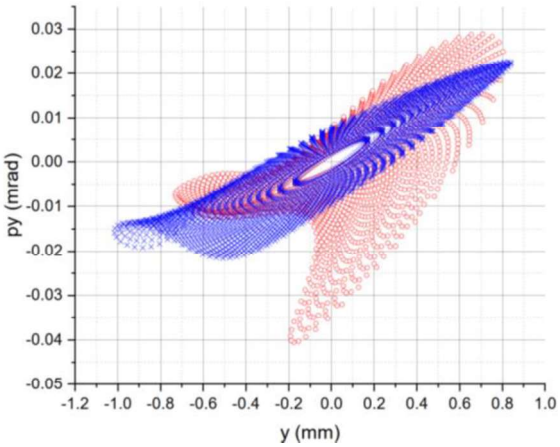


Fig. 14. Uncorrected and corrected beam motion in the vertical plane

RESULTS

The paper considers one of the possible variants of the beam injection system into the recirculator, which are determined by the list of physical tasks set. The analysis of permissible errors in the alignment of structural elements is carried out, the acceptance of the machine is estimated, and the possibility of correcting the influence of nonlinear effects of the magnetic field of the recirculator structural elements is shown.

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ДОСЛІДЖЕННЯ ІНЖЕКЦІЇ ПУЧКА В БАГАТОФУНКЦІОНАЛЬНИЙ ПРИСКОРЮВАЛЬНИЙ КОМПЛЕКС

П.І. Гладких, І.С. Гук

За допомогою моделювання руху пучка в рециркуляторі багатофункціонального прискорювального комплексу МАС оцінений аксептанс машини, проведено аналіз допустимих помилок юстування елементів структури. Показана можливість корегування впливу нелінійних ефектів магнітного поля елементів структури рециркулятора.