SOLENOID ALIGNMENT FOR THE SRF PHOTOINJECTOR OF bERLinPro AT HZB

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Abstract

The Berlin Energy Recovery Linac Prototype (bERLinPro) at Helmholtz Zentrum Berlin (HZB) aims to deliver a continuous-wave (CW) electron beam of high average current (100 mA) and brilliance (normalized emittance below 1 mm mrad). The achievement of these demanding goals depends significantly on the performance of the electron source, a superconducting RF (SRF) photoinjector. A critical component for the quality of the generated beam is the superconducting solenoid magnet. In order to optimize its operation and minimize parasitic contributions, special attention has been given to the precise alignment of this element using a hexapod mover.

Due to the strict limitations inside a cryostat, a complex coupling between the solenoid in vacuum and the hexapod in air has been realized, requiring sophisticated software and hardware mechanisms to prevent collisions. Along with this setup, the developed beam-based alignment procedure and its performance are demonstrated in this article.

INTRODUCTION

A new Energy Recovery Linac (ERL) is being constructed at Helmholtz Zentrum Berlin (HZB) under the name Berlin Energy Recovery Linac Prototype (bERLinPro). The goal of this project is to develop the ERL operation principle towards user-oriented applications. The design of bERLinPro is that of a single-pass electron ERL which utilizes superconducting radiofrequency (SRF) technology to deliver a continuous-wave (CW) operation of high average current (100 mA) and brilliance (normalized emittance below 1 mm mrad) [1]. These beam parameters should already be demonstrated at the electron source, an SRF photoinjector, which influences greatly the overall beam quality. Therefore, a dedicated test-stand is established at HZB for the commissioning, characterization and optimization of the bERLinPro photoinjector, the GunLab facility [2].

As in any photoinjector, the solenoid magnet is a crucial component responsible for the emittance compensation before the next acceleration stage [3]. An accurate alignment of its magnetic axis with respect to the beam trajectory is necessary in order to avoid considerable deterioration of the beam emittance [4]. The issue of solenoid positioning becomes especially important for superconducting systems, due to the thermal expansion and mounting restrictions inside a cryovessel.

This paper describes the implementation of a precise positioning solution for the superconducting solenoid of bERLinPro using a hexapod mover, together with the employed software and hardware collision-prevention mechanisms. Finally, the beam-based alignment method which is developed for the experiment is demonstrated.

HEXAPOD MOVER FOR A SUPERCONDUCTING SOLENOID

The superconducting solenoid of bERLinPro is composed of a NbTi coil with a 4.5:1 ratio of Cu, a low-carbon steel yoke for field enhancement and a magnetic shield for the protection of the SRF cavity from the residual field. Designed for a nominal peak magnetic field of 600 mT at a current of 7 A, it will be able to provide sufficient focusing for a beam energy of up to 5 MeV.

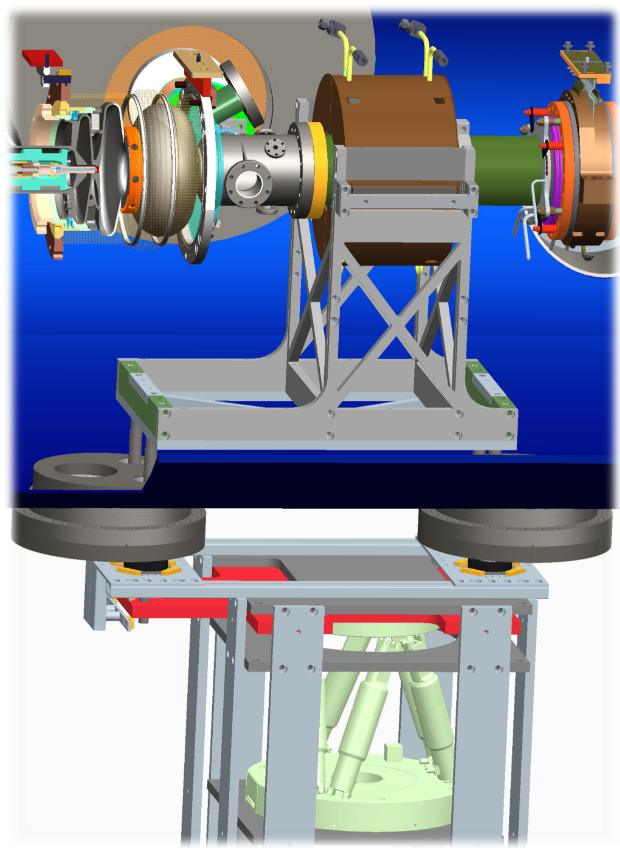

Figure 1: Inside the cryostat (blue) and next to the accelerating cavity (upper left corner, silver), the solenoid (brown) is mounted on a holding frame (grey), which is fixed to a plate (red) on top of the hexapod (bottom, light green). Protective end-switches (orange) are positioned around the four air-to-vacuum connector flanges (black), as well as above and below the hexapod plate.

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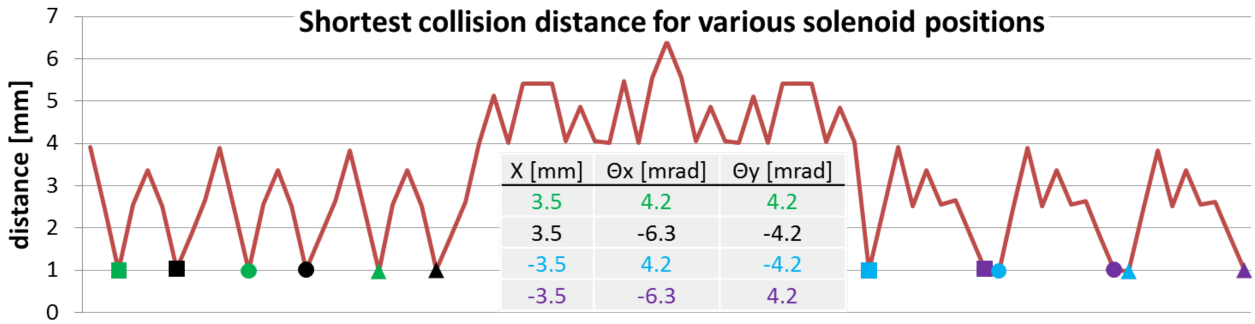

Figure 2: Shortest collision distance within the defined workspace configuration of the solenoid. The solenoid position at the local minima, where the end-switches are activated, is indicated with markers coloured according to the legend for a vertical (Y) coordinate of -4.5 mm (square), 0 mm (circle) and 4.5 mm (triangle).

For the alignment of the solenoid, a hexapod mover[1] has been chosen in order to get a full 6-D motion capability with a micrometer and microrad precision and repeatability. The hexapod is positioned outside the cryomodule and is connected with the solenoid through a supporting structure which enables the coupling between air and vacuum (Fig. 1). With its travelling range being nominally up to tens of millimetres and tenths of rad for single-axis motions, it is drastically reduced by the environmental restrictions for coupled-axis motions. Therefore, significant effort has been invested into defining the available space limitations and prevent collisions with neighbouring components.

SOFTWARE AND HARDWARE COLLISION PROTECTION

For the definition of the available workspace, the PIVeriMove software, provided by the hexapod manufacturer (Physik Instrumente, PI), was utilized. This tool is able to simulate the movement in each direction of a reference point (solenoid center in this case) with respect to the hexapod center and calculate the shortest collision distance between environmental objects, which are described in a 3-D format. The result of such a simulation for the bERLinPro setup can be seen in Fig. 2, which shows that an 1 mm safety distance can be achieved for a horizontal and vertical solenoid movement of ∼±4 mm and a respective rotation of ∼±5 mrad, with zero longitudinal movement and rotation. The same safety distance can also be achieved with other movement-to-rotation ratios between the different axes, but this compromise was estimated to be reasonable for the expected misplacements due to mounting errors and temperature contraction according to past experience. The selected boundaries can be programmed as soft-limits for each axis and the whole 3-D configuration model can be uploaded to the hexapod controller so that movements towards occupied areas are prohibited. The shortest collision distance is observed between the connector flanges and the cryostat ports as well as between the solenoid and the beampipe.

Besides the software-based protection, end-switches are employed as an additional hardware protection of the areas susceptible to collisions. When a switch is activated, the hexapod first receives a stop command and then its power is cut. These switches are placed around each vacuum-to-air connector flange for the horizontal movement and above and below the hexapod plate for the vertical movement. Their exact position is directed by the simulation described in the previous paragraph: the movement corresponding to each local minimum of Fig. 2 is reached and the end-switch towards the direction of the nearest collision point is fixed adjacently to the corresponding component (flange or plate), with the help of a mounting plate (Fig. 3).

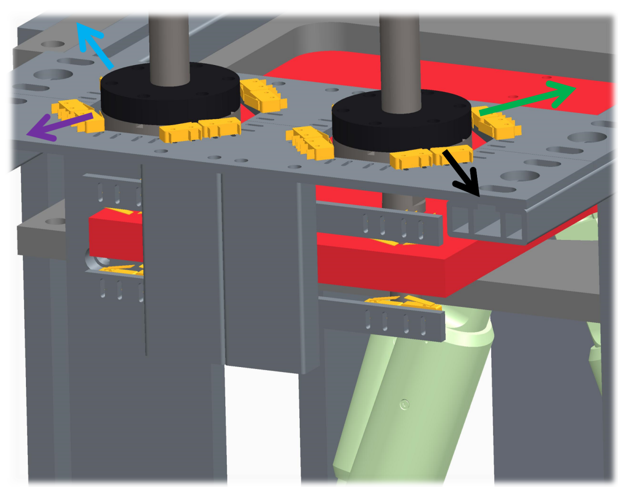

Figure 3: Zoomed view of the end-switches (orange) on their mounting plates (grey). The switches for the horizontal plane are located around the vacuum-to-air connector flanges (black), while for the vertical plane above and below the hexapod plate (red). The arrows point to the direction of the nearest collision point for a solenoid movement with the respective colour code as in Fig. 2.

[1] movable platform controlled by six legs of adjustable length

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BEAM-BASED ALIGNMENT METHOD

Once the moving mechanism is installed and secured, the next step is the proper positioning of the solenoid, i.e. the alignment of its magnetic axis with respect to the particle trajectory. Due to the thermal expansion of the cryogenic components and the frequently changing properties of the laser and electron beams in a photoinjector, the safest method to achieve that is through a direct observation of the generated electrons and their reaction to the imposed field, the so-called beam-based alignment (BBA).

A widely used BBA technique relies on the measurement and the subsequent minimization of the deviation of the beam centroid while scanning the solenoid field strength [5]. While a properly aligned solenoid has no impact on the beam position, potential misalignments result in unwanted kicks. The effect of these kicks on the beam centroid at a certain location downstream can be calculated by the beam envelope equation and Busch's theorem [6]. Since the design of the bERLinPro photoinjector is such that the solenoid field is not interfering with the fields of the accelerating cavity, the calculation of the beam dynamics is fairly simple and can be solved analytically, especially regarding the beam centroid, which is independent of space charge and the shape of the particle distribution. Therefore, no specialized tracking software is required and the result can be derived in milliseconds using a straightforward computer script.

After the measurement of the beam position during a scan of the solenoid field, the developed script can be used iteratively to estimate the misalignment: various combinations of 4-D (horizontal and vertical) solenoid misplacements are simulated and the difference from the measured data is evaluated by the least square method. In order to achieve a quick convergence, the Particle Swarm Optimization (PSO) technique was applied as a fast evolutionary algorithm suitable for measured data [7]. The performance of the developed BBA tool is demonstrated in Fig. 4, where the misalignment from a simulated solenoid scan using the well-established tracking code ASTRA [8] was able to be calculated with an accuracy of tens of micrometers within seconds.

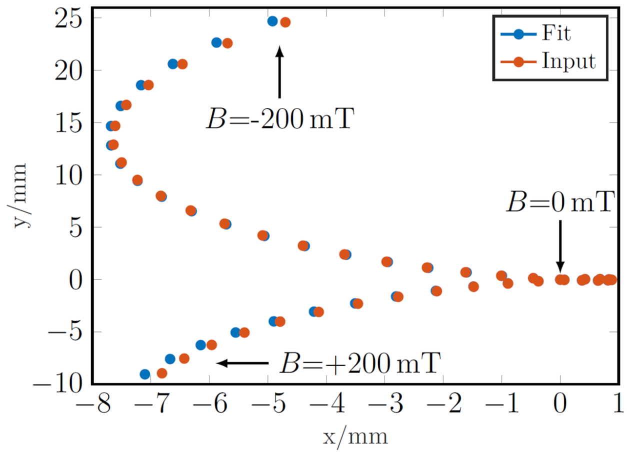

Figure 4: Beam centroid positions during a solenoid scan as generated by ASTRA for a misalignment of Δx=-2 mm, Δy=1 mm, Θx=3 mrad, Θy=5 mrad (red) and the corresponding fitting result from the optimization (blue), which yields less than 3% error in each direction. The beam energy is 3 MeV, the drift length 1.3 m and the scanning range [-200, 200] mT.

CONCLUSION

A novel solution was implemented at HZB for the solenoid alignment of the SRF photoinjector of bERLinPro using a hexapod mover. The toll of high flexibility, precision and repeatability offered by this system is the complicated collision prevention between the involved components, both inside and outside the cryomodule. This issue was addressed with a multi-layer protection scheme based on software and hardware mechanisms. In addition, a fast beam-based alignment tool, which utilizes a particle swarm optimization algorithm, has been prepared and is expected to be applied to measured data within 2017.

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