OPTICS DEVELOPMENT AND TRAJECTORY TUNING OF bERLinPro AT LOW ENERGIES*

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Abstract

The Berlin Energy Recovery Linac project has taken shape during the past year. The magnets have been set up in the newly constructed subterraneous hall; first electrons are expected in the SRF-gun test laboratory in June 2017. Starting in February 2018 the complete gun module will be transferred to the accelerator hall for the commissioning of bERLinPro. For the first months, operation is planned without further accelerating structures (booster and linac), due to delays in their fabrication. Several modes of operation are applicable at this early stage [1]. The available hardware is displayed and the adapted optics at 2.7 MeV and at 6.5 MeV (including the booster) are presented. The trajectory distortions under the influence of the earth magnetic field are studied. The concept for trajectory correction is outlined.

INTRODUCTION

bERLinPro is an energy recovery linac project, with the goal to explore the challenges and limits of ERL technology with respect to its potential as a 4th generation synchrotron light source. The new building is finished and early this year the magnet system has been installed in the subterraneous hall. The vacuum system for the low energy part, Fig. 2, will be delivered end of 2017 and first electrons in bERLinPro are expected during autumn of 2018. Meanwhile, the 1.3 GHz superconducting RF gun is being taken into operation in 'GunLab', a separate infrastructure for SRF gun testing and development. Preparations for commissioning of bERLinPro are well under way [2]. This paper deals with the preparation of the optics for the different scenarios of the stage wise setup of the machine. Starting without the booster accelerator and without the 50 MeV linac module, the initial energy will be limited to 2.7 MeV. The current will be in the few mA range. Only the diagnostic line will be used, mainly to confirm the results achieved in GunLab after the transfer of the gun module to the bERLinPro hall. At this low energy, the earth magnetic field (EMF) plays a major role in the beam transfer. After the installation of the booster (early 2019), the energy will reach 6.5 MeV and the beam can be transported through the merger and the linac replacement line to the high power beam dump (Banana). The second gun module (2019) will be equipped with high power couplers optimized to reach 100 mA. Despite the delay in the development of the linac due to the other HZB-project [3], many of the project goals, such as the low emittance <1 π mm mrad normalized, high current up to 100 mA, low losses to keep radiation safety efforts on a reasonable level or ion trapping issues, can be studies with the reduced set up.

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EARTH MAGNETIC FIELD

After the setup of the geodetic net, the 'blueline', i.e. the future path of the electrons has been marked on the floor of the accelerator hall. A 3D hall probe (limited to 1 Gs) has been used to measure the EMF along the design trajectory, prior to the setup of the machine. Figure 1 shows the EMF along the diagnostic line (top) and along the Banana (bottom). The results show a relatively constant horizontal field, B_x ~0.25 Gs and a strongly varying vertical field, B_y, the data being limited by the hall probe to +/- 1 Gs. The variations are contributed to the iron incorporated in the concrete of the building. The measured fields have been approximated by a step function (top, straight lines) to be used in tracking calculations. The measurements have been repeated at fewer points along the Banana after the installation of the girders and the lower half of the magnets, before the integration of the vacuum chamber (bottom straight lines). Strong local deviations (at 8 m, 20 m, 26 m) are probably due to residual fields in the magnets and to magnetization of the iron girders. The resulting trajectories show slightly lower deflections, due to the alternating signs.

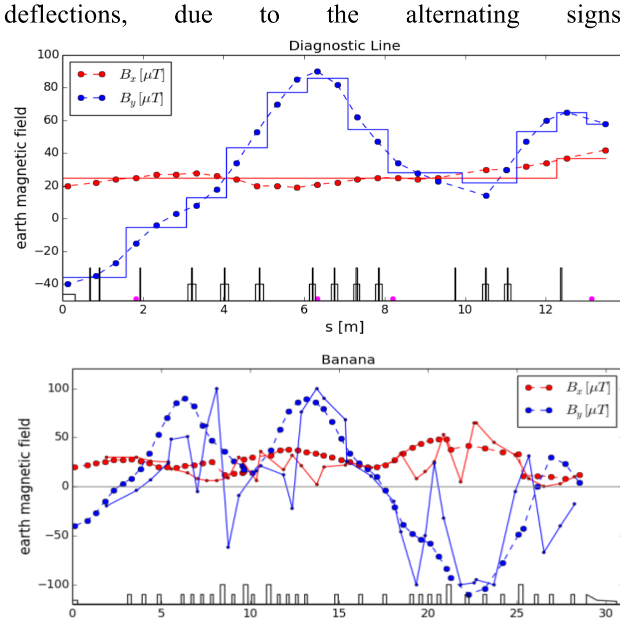

Figure 1: Earth magnetic field (B_x: red dots, B_y: blue dots) measured along the future electron path. Top: Diagnostic line with approximating step functions; Bottom: Banana with control measurement after magnet installation.

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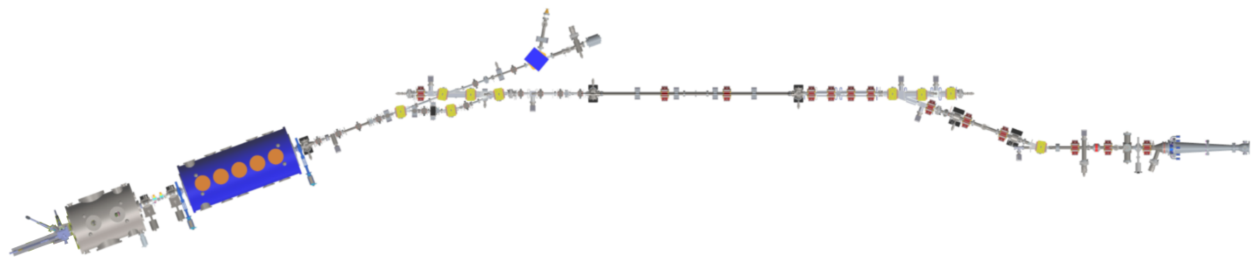

Figure 2: The layout of the low energy part of bERLinPro: the diagnostic line in straight continuation of the gun with the spectrometer arm, and the so called 'Banana' with quadrupoles replacing the linac module and the high power beam dump.

Magnetic Shielding of Modules

The bERLinPro SRF modules are constructed without a global magnetic shield. Local magnetic shielding is provided around each cavity and the solenoid magnet in the gun module. Simulations of the penetration of a constant outer magnetic field onto the beam axis for the booster module are shown in Fig. 3. The maximal amplitude of the field between local shields is only 70 %. The field on axis can be approximated by a step profile, with a reduction of the field amplitude of 50 % between local shields and 70 % at the beginning and the end of the module, compared to the outer field. Similar results are assumed for the gun module.

The vertical component of the EMF varies between 0 and 80 μT over the length of the booster module. The remaining field amplitudes at the trajectory of up to 40 μT will deflect the 2.7 MeV beam to mm offsets in the cavities with resulting beam property deterioration. Therefore, cold correctors inside the booster are mandatory; it has been decided to implement three cold correctors, as indicated by arrows.

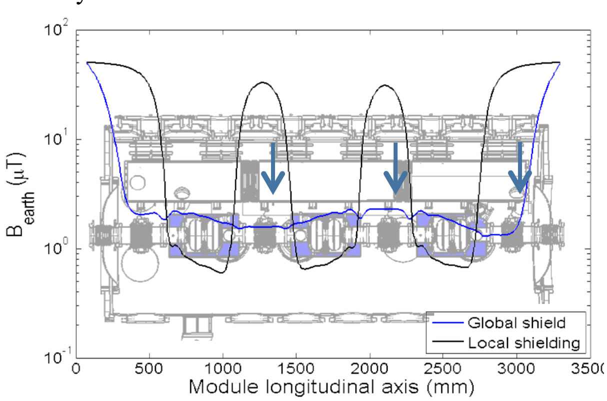

Figure 3: Simulations of the penetration of a 50 μT outer field onto the axis of the booster module with global (blue) and local (black) magnetic shielding. The arrows indicate the corrector positions.

DIAGNOSTIC LINE

The diagnostic line provides space for diagnostic devices, like a transverse deflecting cavity and a spectrometer dipole in straight continuation of the gun module. Its purpose is to study the bunch properties provided by the gun. The beam energy for the design gun field of 30 MV/m will be ~2.7 MeV for currents up to 4 mA, limited by the 50MHz laser and 77pC per bunch. During the absence of the booster, three quadrupoles (taken from the recirculator) will be installed. The settings of the gun and solenoid are unchanged compared to the reference optic, to study the design performance of the gun. The resulting beam sizes along the diagnostic line, as well as the quadrupoles, the correctors and the BPMs are displayed in Fig. 4. At these low energies, the emittance varies strongly between 0.65-0.9 π mm mrad horizontally and 0.5 and 1.1 π mm mrad vertically for the design bunch charge of 77 pC. The project goal of showing emittance from a SRF gun below 1π mm mrad is in sight. The bunch length increases from 1.8 mm to 3.3 mm rms due to the lack of acceleration.

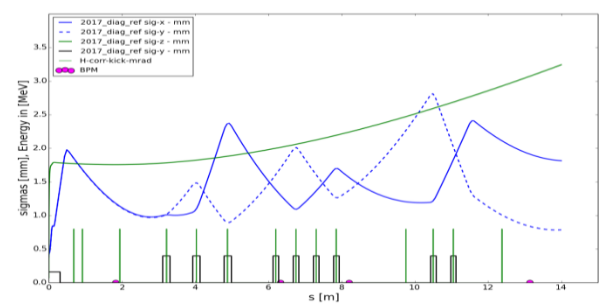

Figure 4: Beam size (x-blue; y-dashed, z-green) at 2.7 MeV and 77 pC; quadrupoles (black), correctors (green) and BPMs (magenta) in the Diagnostic line.

BANANA

The installation of the SRF booster is planned late 2018. The module hosts three 2-cell cavities. The dogleg merger leads the beam onto the linac straight, where the SRF linac module is replaced by three (recirculator) quadrupoles. The optics up to the linac is identical to the final bERLinPro optics, in order to verify the design goals, Fig. 5. The chicane behind the linac leads the beam to the 650 kW beam dump. The booster allows for energies up 6.7 MeV. The expected emittance in front of the linac is ~0.7 (horizontally) and 0.6 π mm mrad (vertically) for full bunch charge. The bunch length is 1.4 mm rms after compression in the merger.

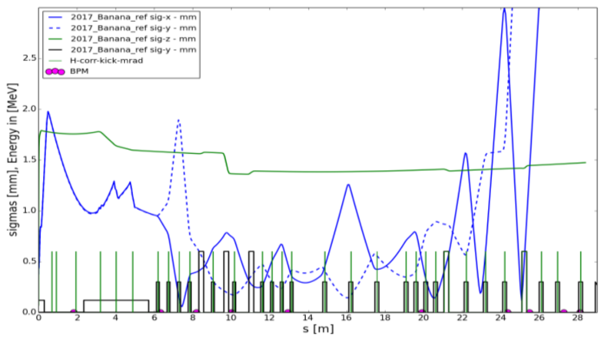

Figure 5: Beam size (x-blue; y-dashed, z-green) at 6.7 MeV and 77 pC; magnets (black), correctors (green) and BPMs (magenta) in the Banana; beyond 24 m the beam is widened for the dump.

TRAJECTORY CORRECTION

The concept for trajectory correction of bERLinPro has been presented in [4]. Sensitivity matrices of the correctors will be measured and the SVD (singular value decomposition) method is used to determine the trajectory correction. In those studies the EMF has been neglected.

OPAL3D (official release in 2017) [5] has now been used to calculate the trajectories, including the effect of the measured EMF. OPAL3D allows for arranging fields arbitrarily in 3D space. The stepwise approximated EMF has been implemented as extended dipole fields, overlaying the magnetic structures.

It turns out, that the beam excursions due to the errors considered in [4] of ~4 mm in the Banana, are small compared to those due to the EMF, where the beam offsets exceed the vacuum aperture already ~7 m behind the cathode, without correction in both cases.

In transfer lines, only the information of downstream BPMs can be used to optimize the corrector strength, so the decreasing number of BPMs towards the end might lead to larger excursions of the beam towards the end of the beam line, up to 7 mm in the diagnostic line, Fig. 6. Also the lack of BPMs in the booster and linac replacements sections lead to large offsets. To correct those deflections, virtual BPMs are located at strategic locations (often the places of maximal excursions), and the correction is repeated with the additional information. The success of this method depends on the accuracy of the predictions by the model, i.e. on accuracy of the fit of the model sensitivity matrix to the measured one. Fig. 6 shows the improvement of the trajectories after adding two virtual BPMs to the diagnostic line in the horizontal plane (magenta triangles), and one vertically. In the Banana, up to three virtual BPMs are needed in each plane, to keep the trajectory below 2 mm offsets. Two of them are located in the linac section of 5m length. After installation of the linac, the defections of the beam will be reduced by a factor of ~8 due to the acceleration, and the foreseen hardware will be sufficient. During commissioning, the beam will initially be threaded manually to the dump. BPM signals will be available at currents of a few μA, with accuracies depending on the bunch pattern of

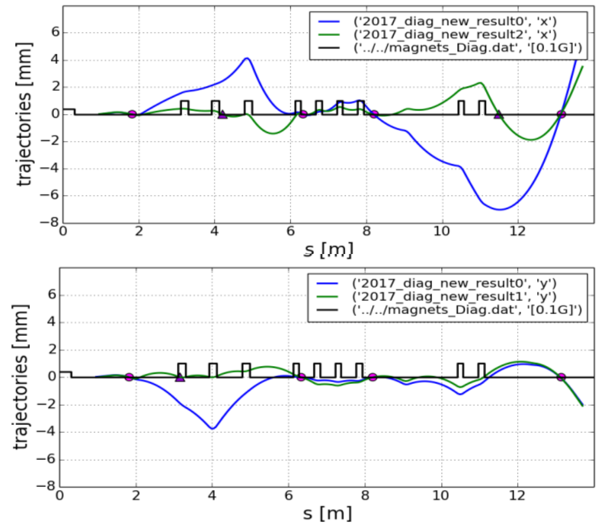

Figure 6: Diagnostic line, green, top: horizontal plane; bottom: vertical plane, correction with 2 and 1 virtual BPMs, respectively (triangles). Blue: regular correction.

<0.25 mm. The measured sensitivity matrices will be used to fit the model optics and the assumed EMF to reproduce the impact of the correctors.

CONCLUSION

bERLinPro will go into operation at very low energies, until the booster module, and later the linac, can be installed. Optics have been developed for the diagnostic line, as well as for the Banana, that allow to demonstrate some of the design goals. The trajectories will be strongly influenced by the earth magnetic field. The method of introducing virtual BPMs can be used to keep the trajectory excursions limited to below 2 mm. Good knowledge of the actual EMF will be important for the fitting of the theoretical to the measured sensitivity matrix. The measurements of the EMF will be repeated, when the machine is completely set up. To which extend one can distinguish between the effect of the EMF and the actual optics is subject to experiments.

ACKNOWLEDGEMENT

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