ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-THPOPT045

OPAL SIMULATIONS OF THE MESA INJECTION SYSTEM

S. Friederich[1]*, C.P. Stoll[1], K. Aulenbacher[1,2,3],
[1]Institut für Kernphysik, Johannes Gutenberg-Universität Mainz, Germany
[2]Helmholtz Institut Mainz, Germany
[3]GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt, Germany

Abstract

The MESA injection system will produce the spin-polarized electron beam for the upcoming accelerator MESA in Germany. The photoemission electron source (STEAM) will deliver 150 µA of spin-polarized electrons from GaAs-based photocathodes for the P2 experiment. Afterwards the low-energy beam transportation system (MELBA) can rotate the spin using two Wien filters and a solenoid for polarization measurements and to compensate for the spin precession in MESA. A chopper and buncher system prepares the phase space for the first acceleration in the normal-conducting pre-booster MAMBO. First OPAL simulation results of MELBA were presented at IPAC'21. Meanwhile these simulations have been extended by a 270-degree-bending alpha magnet as well as the electrostatic and magnetostatic fieldmaps of the Wien filters. Furthermore the fieldmaps of the 4 modules of the pre-accelerator MAMBO have been implemented. Hence, the complete MESA injection system could be simulated in OPAL and the results will be shown.

INTRODUCTION

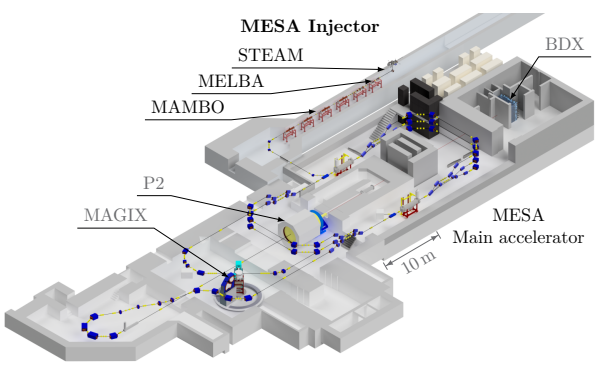

Figure 1: Scheme of MESA with its three experiments: P2, MAGIX and Beam dump experiment (BDX).

Figure 1 shows a scheme of the Mainz Energy-recovering Superconducting Accelerator (MESA) [1]. Operating at $f = 1.3$ GHz it will provide 150 µA of longitudinally spin-polarized electrons for the long-run parity violation experiment P2 at an energy of 155 MeV. The main tasks of the MESA injector are to emit the spin-polarized electrons, align the spin direction and prepare the phase space for the main accelerator.

* sifriede@uni-mainz.de

THE MESA INJECTOR

The MESA injector consists of three parts: The Small Thermalized Electron Source At Mainz (STEAM) [2], the MESA Low-energy Beam Apparatus (MELBA) [3] and the Milliampere Booster (MAMBO) [4].

The DC photoemission source STEAM operates at 100 kV and emits longitudinally spin-polarized electrons from GaAs-based photocathodes illuminated by infrared laser light into MELBA. An alpha magnet bends the vertically emitted beam by 270° into the horizontal accelerator plane where the beam passes MELBA's spin rotation system.

The electron spin experiences a total precession of 638° when passing through the three recirculations of MESA until it hits the P2 target [5]. A Wien filter is used to compensate for the precession by rotating the spin clock-wise by 82°. The electron spin can be flipped by changing the helicity of the laser, yet an additional solenoid in the spin system allows to flip the spin independently and, hence, offers further instrumentation serving the control of systematic errors. But this method also requires a second Wien filter to rotate the spin before entering the solenoid by 90°. As the solenoid has to be operated at about 15 mT ($\int B_z dz = 1.75$ mT m) that leads to a strong focus. Therefore, in this operation mode it is challenging to keep up the beam quality and the spin solenoid is turned off in the presented simulations. Yet, to investigate their influence, both Wien filters are fully excited.

Further downstream the beam enters the chopper system, which consists of two deflecting cavities, two solenoids and a movable collimator. The first chopper cavity deflects the beam circularly over the collimator and the solenoids focus it back onto the reference orbit where the second cavity cancels out the superimposed transverse momenta. Hence, this system chops the electron bunch head and tail that may not fit into the phase space acceptance of the main accelerator. Further down the MELBA beam line, the buncher cavities focus the beam longitudinally into the first section of MAMBO. All of its four modules accelerate the electrons up to 5 MeV. In-between all these main devices, quadrupole singlets, doublets or triplets as well as double solenoids, i. e., split solenoids with identical field amplitudes $|B_\parallel|$ yet alternating orientation in order to avoid further spin precession, guide the beam through the MESA injector.

The following simulations promoted the design process of the injector. The aim was to see if the beam can travel 9 m through the different devices and small apertures of MELBA, see Fig. 2, without a significant amount of beam loss. That would lead to gas desorption, to vacuum pressure degradation and, hence, to a reduced photocathode lifetime.

ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-THPOPT045

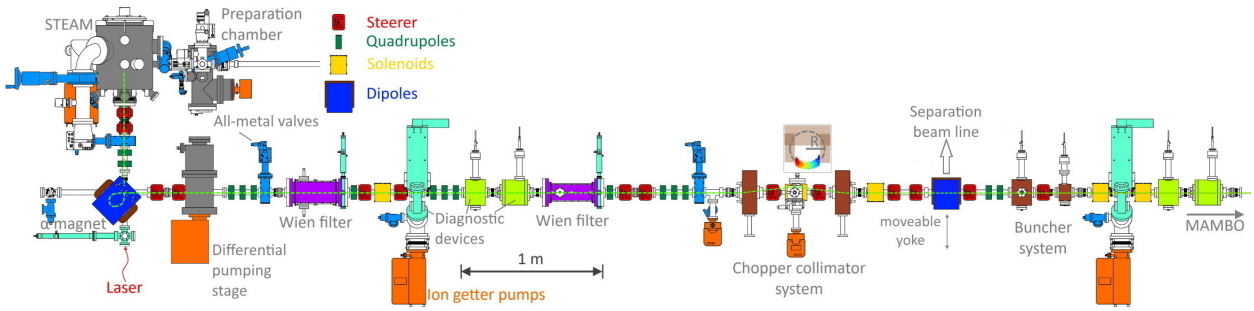

Figure 2: Side view of the latest MELBA design. Since the last proceeding [6], more diagnostic devices to measure the helicity-correlated asymmetries [7] have been added to the beam line and the vacuum concept has been finished. The design was optimized, so that the total length only slightly increased by 0.4 m.

OPAL SIMULATIONS

Expansion of Preceding MELBA Simulations

Based on the preceding STEAM and MELBA simulations [6], the complete MESA injector has now been simulated with the Object Oriented Parallel Accelerator Library [8] (OPAL).

The initial particle distribution emitted from STEAM and the 3D fieldmaps of the alpha magnet, the MELBA and MAMBO double solenoids as well as the chopper, buncher and MAMBO cavities have been simulated with Computer Simulation Technology (CST)[9] and imported into OPAL. For the MELBA quadrupoles the internal fieldmaps of OPAL configured by the thickness and aperture of about 40 mm were used. The electro- and magnetostatic fieldmaps of the Wien filters were calculated with TOSCA and CPO-3d [10] and have now been fully implemented in the OPAL simulations including fringe fields.

MESA Injector Simulation Results

Figure 3 shows the course of the RMS beam sizes, the transverse normalized RMS emittances as well as the total energy and energy spread along the position of the reference particle in the beam line s. Additionally, a side view of the MESA injector CAD model illustrates the passed elements. Some values at important positions are also listed in Table 1.

A total bunch charge of 0.2 pC distributed on 10^5 particles is injected at 0.3 m, i. e., the exit of STEAM, in $-y$-direction. The 33 mT B_x field of the alpha magnet bends the beam by 270° into the horizontal accelerator plane. From here on x represents the horizontal, y the vertical and s the longitudinal direction. The bending of the alpha magnet causes a shift of the center of mass by $\Delta\mu_y = +0.5$ mm and increases the divergence in y-direction. If necessary, the shift can be compensated for by steering magnets in the real injector, whereas a quadrupole doublet in the vertical source beam line can be used to adjust for the preceding divergence. However, in the presented simulation the vertical quadrupole doublet ($s = 0.5$ m) is not yet excited.

After 2 m the first quadrupole triplet leads the beam towards the spin rotation system. In order to investigate their influence the Wien filters are fully excited. Their equilibrium field values $E_x = 1.1\,\mathrm{MV\,m^{-1}}$ and $B_y = 6.7$ mT leave the reference particle unaffected but due to a finite bunch size the beam is focused inside the Wien filter in x-direction down to 80 µm. This is because of the change in the potential energy of electrons with deviations in direction towards the electrodes which results in a focusing force due to the deviation of velocity from that of the reference particle. The bunch is unaffected in the y-direction, hence, a single quadrupole placed behind the Wien filter compensates for the beam divergences. As mentioned earlier the spin solenoid was not excited in the presented simulation but will be investigated further in future simulations. After the singlet another quadrupole triplet guides the beam to the second Wien filter which is rotated by 90° with respect to the first one around the beam axis, hence, the bunch is now focused in y-direction.

The third quadrupole triplet focuses the beam into the chopper system. As the initial RMS bunch length of 8 mm is short enough no particles are lost at the collimator. Hence, in the real injector no increase in vacuum pressure and no back streaming particles would be expected here. A double solenoid positioned closely to the chopper system guides the beam to the next quadrupole doublet over a distance, where the beam can be extracted towards a polarimeter. The design of this so-called *separation beam line* is discussed in [11].

Finally the buncher system focuses the beam longitudinally down to $\sigma_s = 0.3$ mm within a drift space of about 1.5 m into MAMBO ($s = 9.6$ m). The injection phase was set to −11° with respect to the maximum of the sine.

As the electrons are not yet relativistic the first MAMBO module is a graded-β structure. Six large solenoids with $B_{\parallel,\max} = 5$ mT are imposed on the first module and each drift space between the modules contains a double solenoid with $B_{\parallel,\max} = 17.5$ mT. This setup also allows to transport high bunch charges [4]. All MAMBO modules accelerate the electrons up to 5 MeV within the next 11 m with an energy spread of 3 keV.

Discussion

The simulation results look promising concerning the loss-free transportation of 0.2 pC through the 21 m of MESA injector beam line. This bunch charge corresponds to almost two times the 115 fC bunch charge required for the P2 ex-

ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-THPOPT045

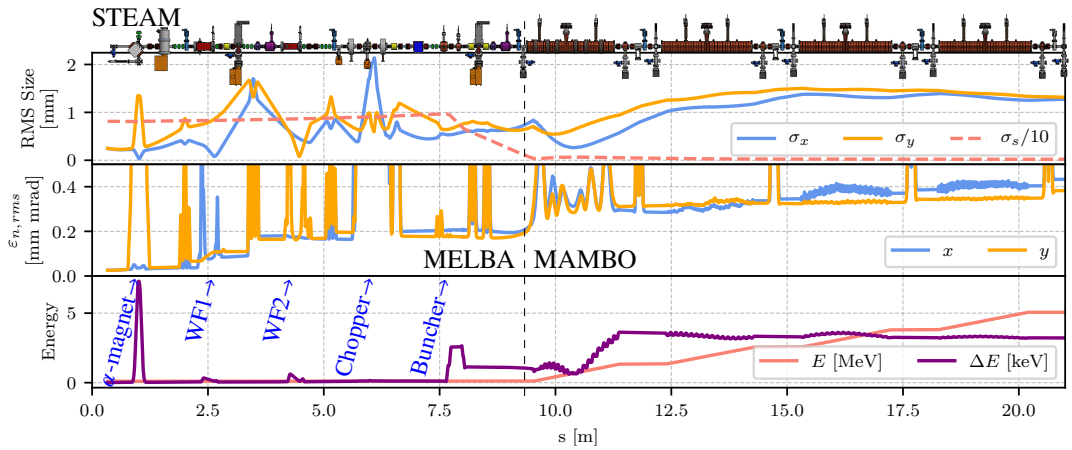

Figure 3: OPAL simulation results and an illustration of the MESA injector: RMS beam sizes ($\sigma_x, \sigma_y, \sigma_s$), transverse normalized RMS emittances ($\varepsilon_{\mathrm{n,rms},x}, \varepsilon_{\mathrm{n,rms},y}$) as well as energy E and energy spread ΔE.

Table 1: Simulation Results at Some Important Positions

Location	s m	σ_x mm	σ_y mm	σ_s mm | ° | ps	$\varepsilon_{x,\mathrm{n,rms}}$ mm mrad	$\varepsilon_{y,\mathrm{n,rms}}$ mm mrad	Energy MeV	ΔE_{rms} keV
Initial	0.3	0.2	0.2	8.1 | 23.1 | 50.0	0.03	0.03	0.1	0
MELBA exit	9.4	0.8	0.7	0.8 | 2.3 | 4.9	0.22	0.20	0.1	1
Injector exit	20.4	1.3	1.3	0.2 | 0.3 | 0.6	0.40	0.35	5.1	3

periment. The position of the magnets can be fixed now as they allow to keep the RMS beam sizes sufficiently small in order to pass through small apertures.

While the requirements for a small energy spread for the MESA experiments are met, the transverse emittances can still be optimized. The simulation has multiple parameters, i. a., 12 quadrupole and 15 solenoid field settings as well as 11 cavity phases and amplitudes, that can be utilized for an optimization. Furthermore the fieldmaps of steering magnets have been prepared but not yet implemented. They can be utilized to compensate for the shift in the center of mass and, hence, redirecting it to the reference orbit which could also increase the beam quality. Yet the fringe fields of the steering magnets could as well deteriorate it in the same manner or even worse.

The presented simulations results serve as an important reference point in the injector design and they can easily be extended from this point on. For example a preliminary study on misalignments where single components are shifted in horizontal direction while all other parameters are kept constant has revealed that an positioning of $\Delta x \leq 1$ mm of the third quadrupole triplet and the first Wien filter is crucial in order to prevent immense beam losses.

SUMMARY

The 3D fieldmaps for the alpha magnet and Wien filters have been successfully implemented in the previous OPAL simulations. Hence, the challenging 270°-bending and parts of the spin-rotating system have been simulated aiding the design process of MELBA. The simulation with a fully excited spin solenoid is yet to be investigated. Additionally, by adding the fieldmaps of the MAMBO modules the simulation of a 0.2 pC bunch through the MESA injector lead to already promising results. Some of the simulation properties, e. g., magnetic field strengths of the solenoids or phase offsets of the cavities, can still be improved and further elements, e. g., steering magnets, may be implemented in order to increase the already satisfying beam quality further.

OUTLOOK

The design process of the MESA injector has been completed and it's build-up has already started. The first 100 keV beam is expected within the next year. MELBA's diagnostic devices will then provide the opportunity to compare the simulation results with experimental data.

Ongoing investigations for the separation beam line in MELBA and the emission of high bunch charges for the internal target experiment MAGIX can be extended based on these simulations. A next step is to process the injector particle distribution as input for simulations that will deal with the design of the MESA injection arc connection the injector and the main accelerator. This region will include a chicane, deflecting devices, bending magnets as well as a polarimeter and a 5 MeV beam dump.

ACKNOWLEDGMENT

The author would like to thank his colleagues P. Heil, R. Heine, C. Matejcek and V. Tioukine for providing the different CST models and the Wien filter fieldmaps. This work is supported by the DFG excellence initiative PRISMA+.

ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-THPOPT045

REFERENCES

[1] F. Hug, K. Aulenbacher, R. G. Heine, B. Ledroit, and D. Simon, "MESA - an ERL Project for Particle Physics Experiments," in *Proc. 28th Linear Accelerator Conf. (LINAC'16)*, East Lansing, MI, USA, 2016, pp. 313–315. doi:10.18429/JACoW-LINAC2016-MOP106012

[2] S. Friederich and K. Aulenbacher, "Test electron source for increased brightness emission by near band gap photoemission," in *Proc. IPAC'15*, Richmond, VA, USA, May 2015, pp. 1512–1514. doi:10.18429/JACoW-IPAC2015-TUPWA044

[3] C. Matejcek, K. Aulenbacher, and S. Friederich, "Low-energy beam transport system for MESA," *Journal of Physics: Conference Series*, vol. 1350, p. 012 027, 2019. doi:10.1088/1742-6596/1350/1/012027

[4] R. Heine, "Preaccelerator concepts for an energy-recovering superconducting accelerator," *Physical Review Accelerators and Beams*, vol. 24, no. 1, 2021. doi:10.1103/physrevaccelbeams.24.011602

[5] C. Matejcek, "Strahldynamik der Niederenergie-Strahlführung von MESA unter Berücksichtigung von Raumladung und Multipol-Beiträgen höherer Ordnung," de, Ph.D. dissertation, 2021. doi:10.25358/OPENSCIENCE-5654

[6] S. Friederich, K. Aulenbacher, and C. Matejcek, "Status of the Polarized Source and Beam Preparation System at MESA," in *Proc. IPAC'21*, Campinas, Brazil, May 2021, pp. 2736–2739. doi:10.18429/JACoW-IPAC2021-WEPAB063

[7] R. Kempf, J. Diefenbach, F. Fichtner, and K. Aulenbacher, "Beam parameter stabilization for the P2 experiment at MESA," *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 982, p. 164 554, 2020. doi:10.1016/j.nima.2020.164554

[8] A. Adelmann *et al.*, "OPAL a Versatile Tool for Charged Particle Accelerator Simulations," *arXiv e-prints*, paper arXiv:1905.06654, 2019.

[9] Computer Simulation Technology, *CST Studio Suite*, http: //www.cst.com/

[10] V. Tioukine and K. Aulenbacher, "Operation of the MAMI accelerator with a wien filter based spin rotation system," *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 568, no. 2, pp. 537–542, 2006, doi:10.1016/j.nima.2006.08.022

[11] A. A. Kalamaiko, K. Aulenbacher, M. A. Dehn, S. Friederich, and C. P. Stoll, "High Bunch Charges in the Second Injection Beamline of MESA," presented at IPAC'22, Bangkok, Thailand, Jun. 2022, paper THPOPT007, this conference.