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BEAM DYNAMICS LAYOUT OF THE MESA ERL*

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Abstract

The MESA project is currently under construction at Johannes Gutenberg-Universität Mainz. It will be used for high precision particle physics experiments in two different operation modes: external beam (EB) mode (0.15 mA; 155 MeV) and energy recovery (ERL) mode (1 mA; 105 MeV). The recirculating main linac follows the concept of a double sided accelerator design with vertical stacking of return arcs. Up to three recirculations are possible. Acceleration is done by four TESLA/XFEL 9-cell SRF cavities located in two modified ELBE cryomodules. Within this contribution the recirculation optics for MESA will be presented. Main goals are achieving best energy spread at the experimental setups in recirculating ERL and non-ERL operation and providing small beta-functions within the cryomodules for minimizing HOM excitation at high beam currents.

INTRODUCTION

The Mainz Energy-recovering Superconducting Accelerator (MESA) is a low energy continuous wave (cw) recirculating electron linac for particle and nuclear physics experiments under construction at Johannes Gutenberg-Universität Mainz [1-3]. The first phase of operation foresees to serve mainly three experiments, two of them running in external beam mode (EB) and one in energy recovering mode (ERL). MESA construction was funded in 2012. The facility and its experiments [4-6] have undergone several design changes since then. The latest change of layout has been applied in spring 2019 and was presented already in [7]. Therefore, start to end tracking simulations for the complete machine [8] are still based on an older layout version and need to be repeated for the new one. Nevertheless, the main design of MESA has been kept up throughout the changes of accelerator layout. MESA will be constructed in a double sided accelerator layout with two superconducting linacs and vertically stacked return arcs. In EB mode, up to three linac passes are possible and maximum beam energy and current yield 155 MeV and 150 µA respectively. In ERL operation only two passes can be used for acceleration and after experimental use of the beam for deceleration again. The maximum beam energy reduces to 105 MeV but the maximum beam current is not limited by installed rf power anymore and can go up to 1 mA. In a later stage of MESA operation, the beam current shall be increased to the maximum available current from the injector linac (10 mA) [9].

All MESA experiments rely on excellent beam quality in order to perform precision experiments on nuclear and particle physics searching for dark particles and beyond standard model physics. Therefore, a relative energy spread of the beam of approx. 10^{-4} (RMS) or better is required for not being the main source of error in electron scattering experiments. In addition, beam quality needs to be kept stable for long time measurement runs. In particular, in ERL mode reaching these conditions can be quite challenging, as high beam intensities can deteriorate the bunches and decrease beam quality. Furthermore, instabilities due to high beam current like beam break-up (BBU) have to be considered when designing the MESA optics. In the following sections we will present the MESA optics layout and will discuss the possibility to achieve best energy spread by application of certain non-isochronous longitudinal working points.

MESA LAYOUT

General Layout

The MESA beam is produced at a polarized dc photogun on an extraction voltage of 100 kV [10]. The gun injects the beam into the low energy beam transport system (MELBA) [11]. Here, spin manipulation can be applied and a chopper-buncher section is used for longitudinal matching into the normal-conducting booster linac MAMBO. In the booster linac the electrons are further accelerated by four normalconducting injector cavities up to 5 MeV beam energy up to10 mA cw beam current [12,13]. The simulated transverse and longitudinal phase space from MAMBO has been used in simulations presented within this contribution [14]. The 5 MeV beam is transferred into the main linac through a 180° arc afterwards, which can also be used as bunch compressor in order to reach shortest possible bunches at the position of the first SRF cavity of the main linac [14,15]. The recirculating main linac is using a double sided accelerator design with two superconducting linac modules [16], each on either side, containing in total four SRF cavities and providing an energy gain of 25 MeV per turn. Recirculation arcs are stacked vertically. Figure 1 illustrates the MESA layout.

Vertical Spreaders and Combiners

The vertical spreader and combiner sections need to separate the beams of different energies to their return arcs. In addition, vertical dispersion needs to be cancelled out at the end of each spreading or combining section. Longitudinal dispersion, also known as momentum compaction, adding

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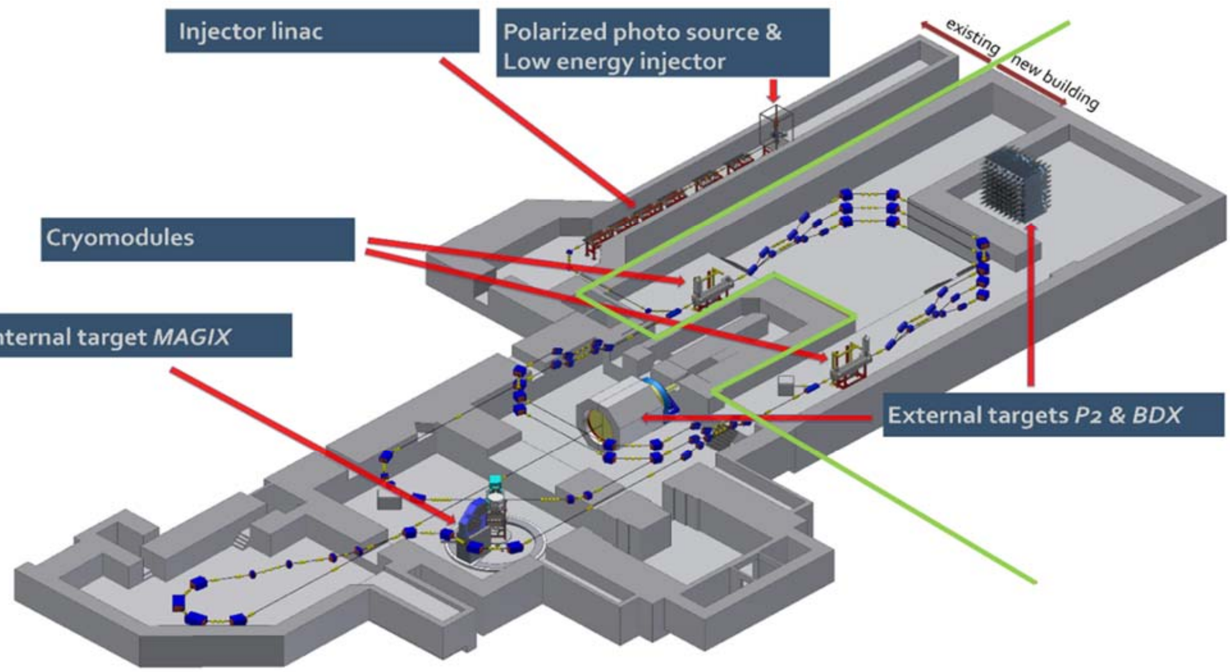

Figure 1: Layout of the facility [7]. The accelerator will be located in existing and newly constructed underground halls. The boundary between the old and new parts of the building is marked by a green line. The layout comprises of two main linac cryomodules and vertically stacked return arcs. The internal experiment MAGIX can be run in multi-turn ERL mode (courtesy of drawing: D. Simon).

up inside the spreader sections can be corrected and adapted in the subsequent horizontal return arc. The spreader design uses a symmetric sequence of dipole magnets with parallel yokes cancelling out any transverse dispersion at the end of the section (see Fig. 2). Furthermore, the two highest energy beams can receive an extra kick from additional dipole magnets. This setup can be used for running MESA on different beam energies than the designed maximum energy. This flexibility in maximum energy is required by the experiments in order to perform electron scattering on variable momentum transfer. The additionally added dipoles enable fine tuning of the allowed energy ratios between injector linac and main linac. In ERL mode the only top two beamlines are used. This setting allows to focus the beam to very low transverse beta functions inside the cryomodules and is beneficial for mitigating BBU. Actually, simulated BBU threshold currents using the MESA optics lay above 10 mA [17,18].

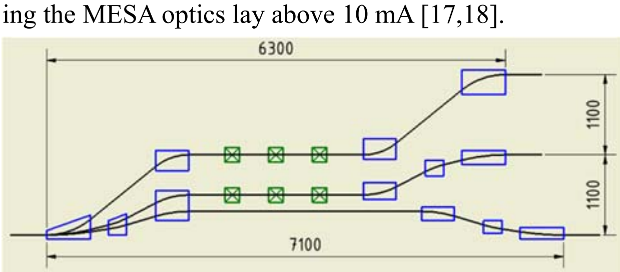

Figure 2: Layout and size of the MESA spreader sections. The beam with lowest energy will be transported to the top beamline and the one with highest energy on the bottom. The design follows a double dogleg for the lowest two energies and a chicane for the highest energy (courtesy of drawing: D. Simon).

Return Arcs

Return arcs for MESA consist of two double bends with a long straight section in between. Within each double bend three quadrupole magnets are located, which can be used to manipulate dispersion functions and transverse focusing. Along the long straight line, the transverse dispersion is still present but angular dispersion is set to zero. The optics of a complete arc is symmetric with respect to the middle of the long straight line having $\alpha = 0$ in the middle. The return arcs are highly flexible in providing variable amounts of momentum compaction, which is beneficial for running the accelerator on different longitudinal working points in the future. This topic will be further discussed in the next section. By adjusting the quadrupole settings, the longitudinal dispersion R_{56} can be varied by approx. 1 m without imposing any transverse dispersion. The complete arc including spreader and combiner sections is set to zero horizontal and vertical dispersion to have each beam free of transverse dispersion on each linac section. At present, no sextupole magnets are considered yet within the return arcs but may be in the future for longitudinal phase space linearization. As MESA will be run on different beam energies, a path length manipulation system for each return arc will be necessary. At least 40 deg of RF phase will be needed meaning a minimum path length adjustability of 2.6 cm. Such a system can be either realized by integrating chicanes into the long straight section of the return arcs or by using movable magnets. Figure 3 illustrates the optics for one complete MESA arc.

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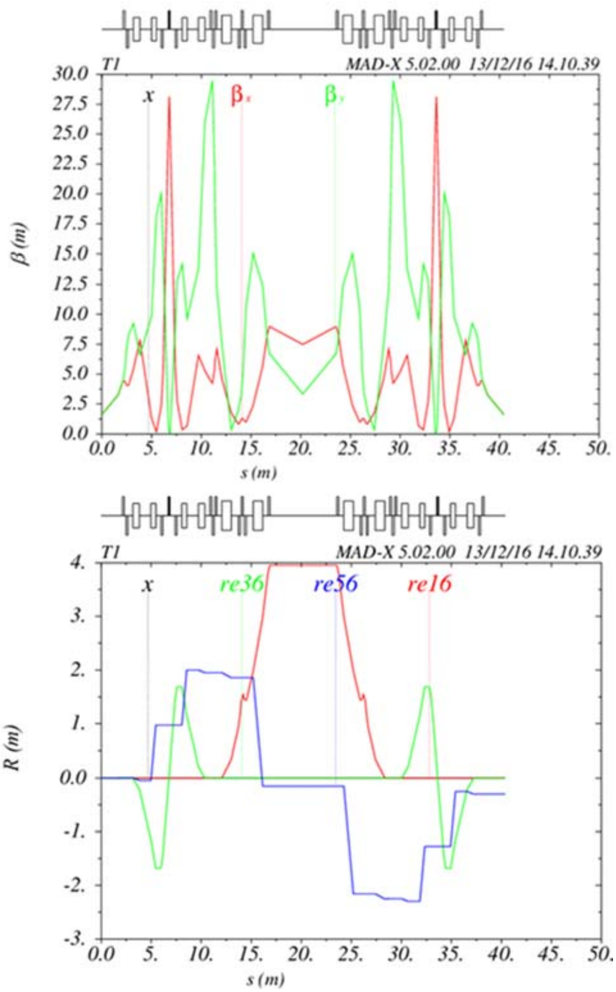

Figure 3: MESA arc optics. On top: Horizontal and vertical β-functions. The symmetry of the arcs can be seen. At the beginning and the end the beam coming from or travelling to the cryomodules is round and convergent having its focus in the middle of the modules. On bottom: Dispersion functions along the arc. Vertical and horizontal dispersion vanish at the end. Longitudinal dispersion is set to the design value for external beam mode (simulations by D. Simon).

LONGITUDINAL BEAM DYNAMICS

Non-Isochronous Multi-Turn Operation

Short recirculating electron linacs and in particular energy recovering linacs (ERLs) are commonly operated with on crest acceleration when aiming for smallest energy spread. In few-turn recirculators, this requires to keep the bunch length constantly small ($< \pm 1°$) using achromatic and isochronous recirculation arcs. Isochronicity is a property of beam optics meaning all electrons of different energies have the same time of flight through the optics ($dt/dE = 0$). It is also known as the momentum compaction factor of the recirculating lattice. In the special case of ultra-relativistic electrons ($v \approx c$) isochronicity is achieved when the path length of all electrons is equally long represented by having a longitudinal dispersion matrix element of $R_{56} = 0$. The resulting energy spread is mainly determined by the short bunch length for an electron linac operated on crest, if the amplitude and phase jitters of the accelerating cavities are uncorrelated. In superconducting few-turn linacs, like most smaller ERLs, these jitters can add up coherently throughout the small number of linac passages due to the large time constant of field changes compared to the short travelling time of the electrons through the complete machine. This can be overcome by changing the longitudinal working point to a non-isochronous one like first described in [19,20]. On a non-isochronous longitudinal working point off crest acceleration and finite longitudinal dispersion of return arcs are combined. Now the electrons perform synchrotron oscillations in longitudinal phase space, which additionally increases operational stability if the oscillations are bound. In contrary to synchrotrons, small integer multiples of synchrotron oscillations are desired [20]. In fact, half or full integer numbers of synchrotron oscillations lead to the best energy resolution of the extracted beam as resulting energy spread at extraction is only determined by the energy spread at injection and all errors caused by RF jitters of the main linac cavities are cancelled out completely [19,20]. In addition, the linac is much less sensitive for external errors like e.g. path length errors. For few turns this concept has been tested already successfully by tuning the three pass superconducting linac S-DALINAC [21] on a non-isochronous working point with a half rotation in longitudinal phase space reducing its energy spread and enhancing its stability significantly [22,23]. This experiment and the simulation methods are described in more detail in [22-24]. The resulting energy spread improvement can be seen in Fig. 4. For the EB mode of MESA an optimized working point has been calculated as well, again running on a half rotation in longitudinal phase space along the three turns recirculating acceleration process. By setting the return arcs to R_{56} = -0.26 m and choosing an acceleration phase off crest by $\phi_S = -5.8°$, a relative energy spread at the experiment of $\Delta E_{rms}/E = 5.5 \cdot 10^{-5}$ can be expected [25].

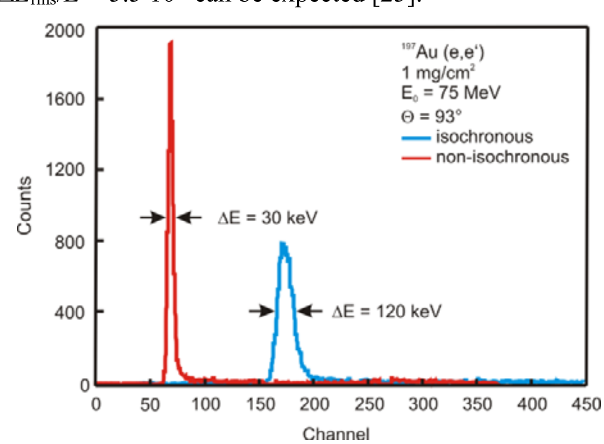

Figure 4: Energy spread of an electron beam from a three pass linac measured by elastic scattering on a thin gold target [22]. Blue: isochronous; Red: non-isochronous longi-

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tudinal working point. For better visibility the blue spectrum has been shifted in horizontal direction. The energy spread could be reduced significantly.

Non-Isochronous Beam Dynamics in ERLS

In ERLs not only the acceleration process but also the deceleration process needs to be considered while operating on non-isochronous working points. If the beam quality is reduced too much within the deceleration process, beam loss can occur making an ERL operation impossible. Nevertheless, off crest acceleration and deceleration is rather common in single turn ERLs but mostly for inducing an energy chirp to the beam allowing bunch compression afterwards and therefore the production of short pulses, which is of greatest interest in radiation experiments like FELs [26]. The decelerating phase though has to be chosen at a phase shift close to 180°, in order to reach optimum ERL efficiency. When applying such a 180° phase shift to a non-isochronous multi-turn lattice like presented in the section before, the slope of the RF curvature is changing its sign from acceleration to deceleration while the longitudinal dispersion of the arcs stays constant as the same beamline is passed by the beam again in the deceleration process. This results in an unbound longitudinal motion and therefore in an increasing energy spread throughout the complete deceleration process. The beam would be lost finally before reaching the beam dump [27]. A phase shift of $\delta\phi$ = 180° -2·ϕ_S could mitigate the problem of increasing energy spread in deceleration but efficiency of energy recovery would decrease drastically (see Fig. 5). On the other hand, one could discuss implementing individual return arcs for accelerating and decelerating particles, which would allow to manipulate each turn independently but also would result in doubling the reqired amount of arc magnets [26].

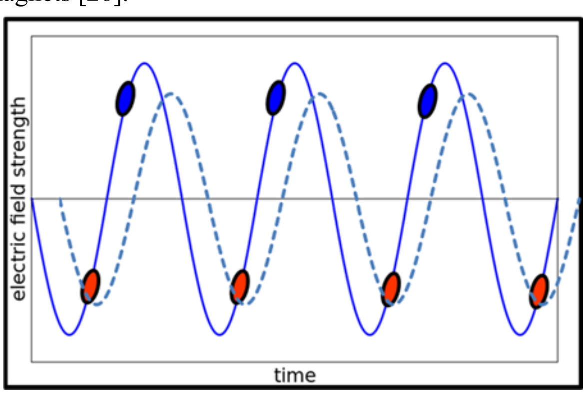

Figure 5: Bunches in non-isochronous ERL operation mode set on a different phase shift than 180° between acceleration and deceleration [25]. The accelerated bunches are plotted in blue, the decelerating bunches in red. Injecting the decelerating bunches on the optimum position regarding energy spread, the ERL efficiency reduces (illustrated by the dashed line for the excited RF wave by the decelerated particles, which is completely different in phase and amplitude to the desired RF wave).

Nevertheless, the double sided layout of the MESA accelerator with two acceleration linacs on each side followed by a return arc allows considering a different non-isochronous operation mode for ERLs. At MESA, the total number of linac passes and recirculation arcs each add up to a number of four. So the phase space can be rotated half way throughout the first two linac passes already having an optimum energy spread. Afterwards, the beam is transferred to the next linac section by an isochronous arc and the second two linac passes can be used to rotate the phase space back to its initial orientation by accelerating on the other crest of the acceleration field, now requiring a different sign of longitudinal dispersion as well. This acceleration scheme combines two benefits: it allows to apply the stabilization methods mentioned above [19-24] but now distributes two bunches on either crest of the RFwave in acceleration as well as in deceleration, not implying a deterioration of RF phase anymore (see Fig. 6). The decelerated bunches start on a phase of $\delta\phi$ = 180° -2·ϕ_S and profit from a bound oscillation passing the high energy arcs at the right slope of R_{56} first. Afterwards the sign of both, RF slope and R_{56} changes again and the bound oscillation continues. This results in having best energy spread at the experimental setup as well as on the way to the beam dump. The additional RF power needed for such an ERL operation only compensates the increased dynamic losses of the RF cavities due to the required field overshoot. It should be mentioned, that some margin in cryogenic power is needed to run the accelerator this way, indeed. First results of tracking simulations for MESA non-isochronous ERL operation show an improved energy spread of $\Delta E_{rms}/E$ = 8.9·10^{-5} [24]. The simulated optics parameters for the best setting now have different signs due to the changing rotation direction in longitudinal phase space: R_{56}(1st) = +0.155 m; R_{56}(2nd) = 0, R_{56}(3rd) = -0.645 m and ϕ_S = -5.8° [25].

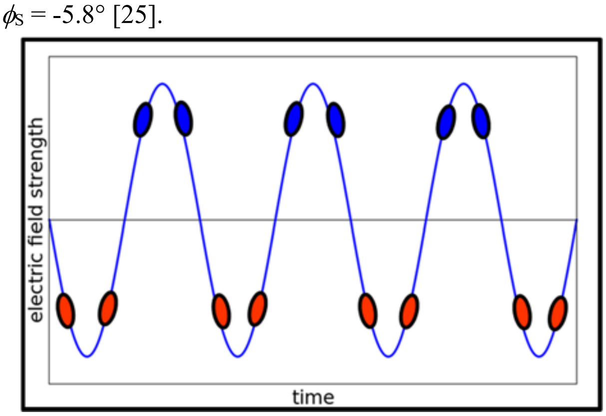

Figure 6: Non-isochronous ERL operation mode with acceleration and deceleration on either side of the accelerating/decelerating field [25]. Here the excited wave is in phase with the required one.

SUMMARY AND OUTLOOK

Within this contribution the current MESA layout and beam optics have been presented with emphasis on the dispersive spreaders and return arcs. Both need to provide great flexibility for matching the requirements of different

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MESA operation modes. As the design of MESA changed very recently [7], all optics need to be re-evaluated. This work is in process. Nevertheless, the general layout of the recirculator has been kept throughout the latest design change. Therefore, only minor corrections will be necessary. New start-to-end tracking simulations will follow soon.

A non-isochronous longitudinal working point with half-integer phase advance can reduce the energy spread of the electron beam in few-turn recirculators significantly. For MESA, such an operation will be applied in external beam operation and is under further investigation for ERL operation as well. Here the acceleration on both crests of the RF wave show promising results. Beam experiments on flexible multi-turn ERL setups, like S-DALINAC, in the future would be beneficial to study the behavior of the RF system at such a bunch distribution scheme. The non-isochronous ERL operation will be investigated more precisely in the future. The presented longitudinal dynamics indeed shows some similarity with longitudinal manipulation for providing short bunches like presented during this conference, so called chirp flipping [26,28]. A collaborative approach in investigating such optics has been started already.

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