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Injector linac stability requirements for high precision experiments at MESA

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Abstract. MESA is a recirculating superconducting accelerator 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 and energy recovery (ERL) mode. The operating beam current and energy in EB mode is 0.15 mA with polarized electrons at 155 MeV. In ERL mode an unpolarized beam of 1 mA at 105 MeV will be available. In a later construction stage of MESA the beam current in ERL-mode shall be upgraded to 10 mA. In order to achieve high beam stability and low energy spread in recirculating operation for external beam the acceleration in the main linac sections will be done on a certain phase with respect to the maximum of the accelerating field (off crest) while the return arcs provide longitudinal dispersion. On specific longitudinal working points this can result in a setting where any RF phase or magnitude jitters from main linac do not contribute to the resulting energy spread of the final beam at all. Then the resulting energy spread of the beam at the experiment is mostly determined by the beam properties provided by the injector linac. On the other hand the acceleration in ERL operation mode most likely needs to be done on crest of the accelerating field aiming for the highest efficiency in the energy recovering process albeit we are currently investigating different recirculation schemes for the ERL mode as well. Using on crest acceleration the achievable energy spread is determined by the longitudinal phase space properties behind the injector linac again but mostly by the bunch length of the beam injected to the main linac. Within this contribution we will investigate the requirements on the stability of the MESA injector linac MAMBO for achieving the experimental goals under both operating conditions.

1. Introduction

The design work on the MESA accelerator has undergone several changes since the accelerator has been proposed the first time in approx. 2009 [1] Since that time the layout of accelerator as well as requirements of the experiments have been refined continuously [2,3]. The latest layout, which is now defined as the final one, is given in figure 1. MESA will run in two completely different operation modes, an external beam mode and a multi-turn ERL mode, which implies different beam dynamics for running these operation modes.

Using the external beam mode the polarized electrons can be accelerated to a maximum energy of 155 MeV and to a maximum beam current of 150 µA. The P2 experiment served in external mode aims on a precise determination of the electroweak mixing angle (Weinberg angle), using the method of a parity violation asymmetry measurement [4,5]. To do so the polarization of the beam is flipped

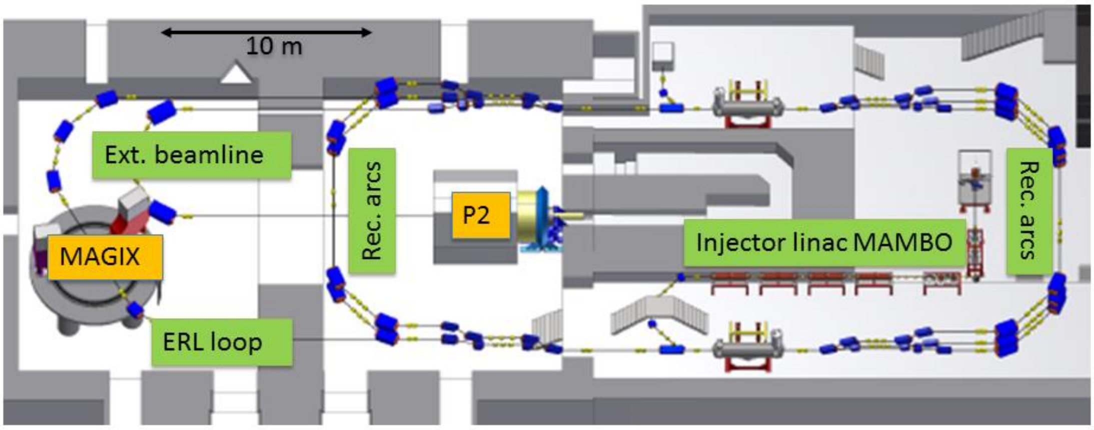

Figure 1. Layout of the MESA accelerator and planned main experiments MAGIX and P2.

with a frequency of 1 kHz using a pockels cell [6]. In order to achieve the precision needed for that experiment highest beam quality in energy spread, beam current and beam position is crucial. Concerning the latest an active stabilization of beam position is being developed [7]. In particular the errors correlated to polarization flips need to be suppressed strongly. Otherwise the experiment will measure false asymmetries and overestimate the parity violation effect. In this contribution we are focussing on the error contributions at the experiment resulting from the injector linac MAMBO.

In ERL mode maximum beam energy of 105 MeV and maximum beam current of 1 mA are planned, while in a later construction stage of MESA this beam current shall be increased to a maximum of 10 mA. For such high beam currents no polarization of the beam is planned so far due to very short lifetimes of polarized photocathodes at such high currents. The experimental setup running with ERL beam is the high resolution spectrometer facility named MAGIX [8]. Experimental goals of MAGIX amongst others are searching for dark photons and measurements of the proton radius. In electron scattering experiments the achievable resolution is determined by the statistical errors resulting from the beam energy spread and the resolution of the spectrometer itself. At MAGIX a relative energy spread of the beam of approx. 10^{-4} (RMS) is needed for not being the main source of error. Again we will focus on the contribution resulting from injector beam properties.

2. MESA injector chain

The electrons for the MESA accelerator will be extracted from a polarized inverted DC photo gun [9]. The gun section is followed by a low energy beam transport containing the required spin manipulation for P2 as well as a chopper-buncher section for longitudinal matching into the accelerating structures of the injector. The normal conducting injector linac MAMBO consists of four accelerating modules. The first one is a graded-β cavity followed by three fixed-β cavities (one for $\beta = 0.977$ and two for $\beta = 1$). It is capable for beam currents of up to 10 mA [10,11]. MESA will be operated in a continuous wave mode with each longitudinal bucket filled by a bunch (duty cycle 100%). The spacing of two bunches equals one RF wavelength or 796 ps. After leaving the injector the beam is transferred into the main linac following a 180° arc. This arc can be used for further bunch compression when needed.

2.1. Longitudinal phase space of the injector beam

The longitudinal phase space provided by the MAMBO injector strongly depends on the beam current and on the chosen accelerating phases of the four linac sections. When operating in EB mode with 150 μA beam current (corresponding bunch charge 0.12 pC) the injector will be tuned for minimum energy spread of the extracted beam. The beam is then transferred to the main accelerator and accelerated to final energy using a non-isochronous recirculation scheme like presented in [12-14]. In such a setting the energy spread of the injected beam determines the final energy spread and therefore

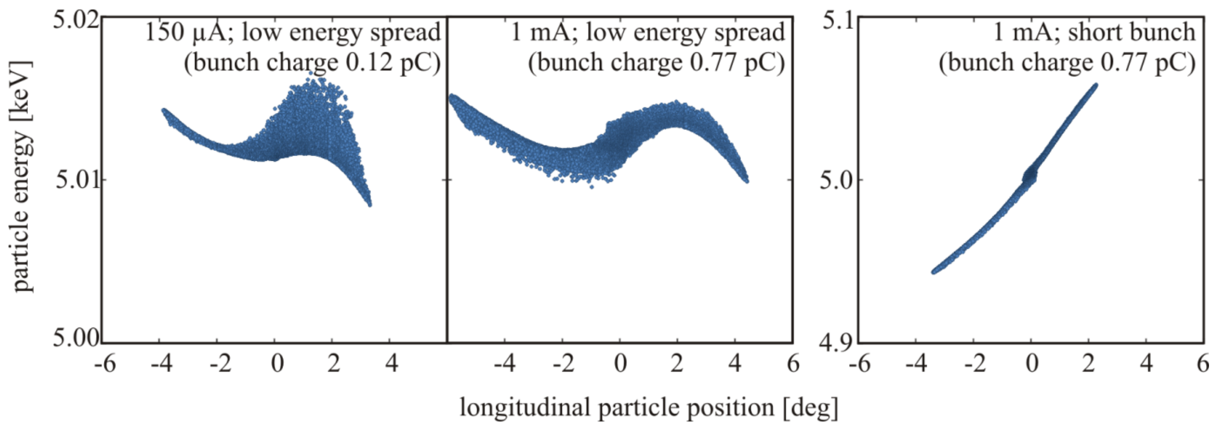

Figure 2. Simulated longitudinal particle distributions at the end of the MAMBO injector for different beam currents and optimized for different operating conditions. The RMS bunch length and energy spread is listed in table 1.

needs to be minimized. The longitudinal phase space of the 150 µA beam is plotted in figure 2. The corresponding longitudinal beam properties are given in table 1.

Table 1. Longitudinal Properties of the MAMBO Beam.

Beam current (bunch charge)	σE [keV]	$\sigma\phi$ [deg]	ε_{rms} (deg·keV)
150 µA (0.12 pC)	0.72	1.36	0.978
1 mA (0.77 pC)	0.87	1.91	1.59
1 mA, short bunch	20.4	0.95	2.76

When operating in ERL mode bunches should be optimized for short length rather than for best energy spread as motivated in the following section. In figure 2 the 1 mA beam (bunch charge 0.77 pC) is plotted once optimized for best energy spread and once for shortest bunch-length. The increasing non-linear space charge forces are deforming the particle distribution in phase space. This results in an increase of the RMS emittance of the beam which appears in an increase of RMS bunch length and RMS energy spread. Nevertheless the beam optimized for short bunches is capable to be further compressed within the 180° injection arc.

2.2. Injector stability
The operational stability of the injector affects the beam properties of the electrons provided to the main accelerator as well. Phase or magnitude jitters in the first section affect bunch-length and time of flight through the injector mostly whereas errors in the sections 2-4 have larger impact on the mean energy of the MAMBO beam.

3. Beam properties at experiments
The simulated bunches from the injector have been taken as input for beam dynamics simulations of the recirculating main linac. The simulation method is discussed in more detail in [15]. Here we need to distinguish again between EB and ERL operation modes.

3.1. Investigations on external beam stability
In EB mode non-isochronous recirculation with acceleration on edge of the accelerating field is used. In this operation mode the energy spread is reduced significantly if the longitudinal phase advance over the complete acceleration process reaches a half- or full-integer number of synchrotron

oscillations in phase space. The optimized working point for EB mode yields to a relative energy spread of $\Delta E_{rms}/E = 5.5 \cdot 10^{-5}$ (isochronous: $\Delta E_{rms}/E = 3.4 \cdot 10^{-4}$) [16]. The achieved energy spread fulfils the experimental requirements. In subsequent calculations we investigated the stability of the optimized longitudinal working point against variations of the injected beam in mean phase and energy. The results are plotted in figure 3. As it can be seen the mean energy of the beam at the experimental setup varies with respect to the fluctuations in the injected beam. These results are of importance for the P2 experiment. E.g. if the helicity flip of the spin-polarization causes a time of flight difference of the particles before entering the injector this can be seen as a phase offset of the first accelerating MAMBO cavity. As a consequence the energy error at the experimental setup would be helicity correlated and can cause false asymmetries.

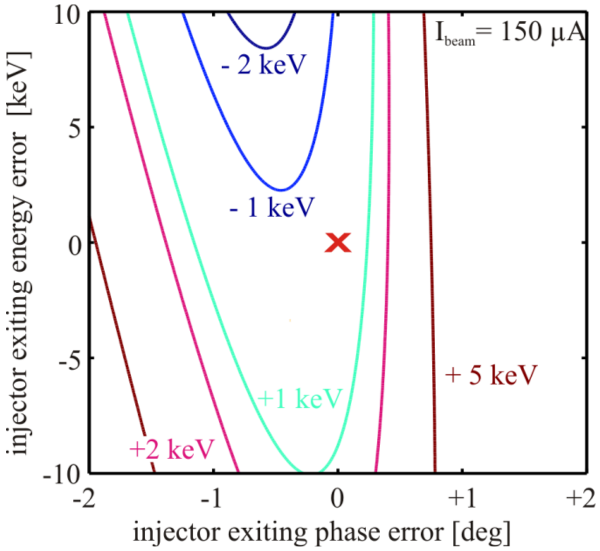

Figure 3. Simulated deviation of mean energy (contours of same levels) to design energy at the P2 experiment under variation of injected mean energy and mean phase. X marks the design energy (0 keV deviation).

3.2. Investigations on ERL beam stability

In ERL mode the acceleration of the beam most likely needs be done on crest of the accelerating field. Therefore the injector beam affects the final energy spread mostly by bunch length as simulations given in figure 4 show. On the contrary in ERL mode the energy spread of the MAMBO beam will not be crucial for resulting beam quality. Relaxing the demands on energy spread allows for much shorter bunch lengths and for an improvement in energy spread. Doing so the energy spread can be reduced from $\Delta E_{rms}/E = 7.2 \cdot 10^{-4}$ to $\Delta E_{rms}/E = 1.99 \cdot 10^{-4}$ using the short bunch setting.

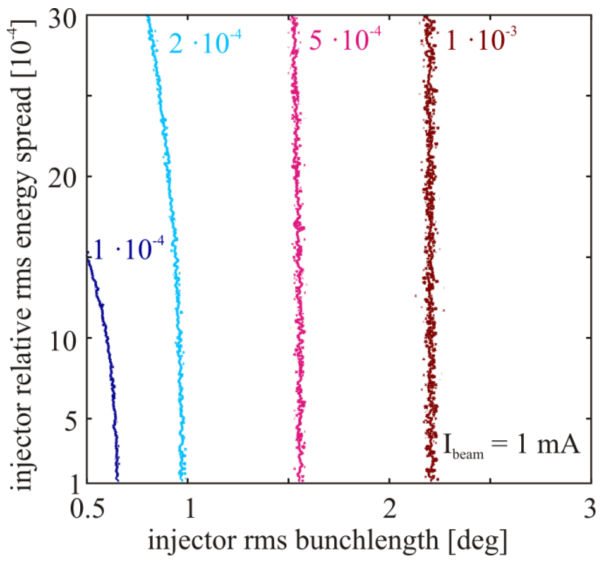

Figure 4. Hill plot of simulated energy spread at the position of the MAGIX experiment in dependency of injected energy spread and bunch length.

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4. Summary and outlook

The MESA accelerator can operate either as ERL or recirculating linac with external beam and will serve two different experiments with high demands on beam quality. Within this work we presented the influence of injector beam properties on the resulting beam stability and quality at the experimental setups. In order to achieve best experimental conditions the injector needs to be well understood and the requirements on RF-control of the injector need to be chosen according to the required beam stability. Work on this topic is going on. Furthermore, investigations on the benefit of an additional feedback system to stabilize the time of arrival of bunches at the main linac are planned in the future.

Acknowledgments

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