BEAM BREAKUP SIMULATIONS FOR THE MESA ACCELERATOR

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Abstract

MESA is a recirculating superconducting accelerator under construction at Johannes Gutenberg-Universität Mainz. It will be operated in two different modes: the first is the external beam (EB) mode, where the beam is dumped after being used at the experiment. The required beam current in EB mode is 150 µA with polarized electrons at 155 MeV.

In the second operation mode MESA will be run as an energy recovery linac (ERL) with an unpolarized beam of 1 mA at 105 MeV. In a later construction stage of MESA the achievable beam current in ERL-mode shall be upgraded to 10 mA. To understand the behaviour of the superconducting cavities under recirculating operation with high beam currents simulations of beam breakup have to be performed. Current results for transverse beam break up calculations and simulations with Beam Instability (bi) [1] code are presented.

INTRODUCTION

The Mainz Energy-recovering Superconducting Accelerator (MESA) is currently being built at Johannes Gutenberg-Universität Mainz. The accelerator will be constructed in a double sided layout with two linacs and vertically stacked recirculation arcs. It will be operated in either an external beam mode (EB) with three recirculations or in an ERL mode with up to two recirculations.

Within this contribution we focus on the ERL operation mode which is planned to provide electron beams of 1 mA and later 10 mA at a beam energy of 105 MeV. With an injection energy of 5 MeV up to 100 MeV of beam energy can be recovered from the beam in ERL mode.

Further information on the MESA facility can be found in [2] and in [3]. A sketch of the lattice configuration can be seen in Fig. 1. As there are no SRF multiturn ERLs existing so far, investigations on beam stability in such an operation mode are accessible by simulations or theory only. A thorough understanding of beam stability is necessary for optimizing the layout of the accelerator before construction.

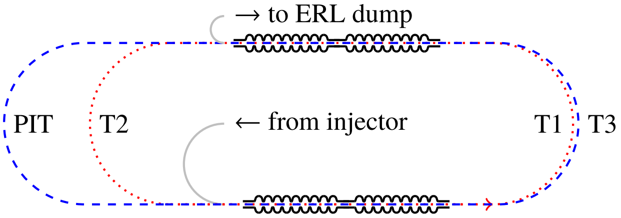

Figure 1: Lattice configuration for the ERL-mode of MESA. T1 to T3 are the return arcs for the different energies while the Pseudo Internal Target (PIT) arc contains the experiment and the 180° phase shift for the energy recovery mode.

SRF Cavities and Cryomodules

For MESA main accelerators two modified ELBE-type cryomodules were chosen [4], which each consist of two 9-cell superconducting radio frequency (SRF) cavities of the TESLA/XFEL-type. The modifications aim on the improved cw-operation of the cryomodules and include the integration of fast piezo tuners as well as an improved cooling of the HOM-coupler antennas [4].

The accelerating cavities will provide a gradient of 12.5 MeV at $Q_0 = 1.25 \times 10^{10}$ while being operated at 1.8 K and 1.3 GHz. A CAD model of the full cavity string is provided in Fig. 2. Besides the wanted accelerating π-mode, also unwanted HOMs with high quality factors can exist in the cavity. For the first calculations presented here the transverse BBU induced by dipole HOMs was investigated as quadrupole and higher order HOMs have weaker influence on the beam unless they are very strong with respect to the dipole HOMs.

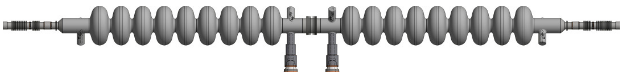

Figure 2: CAD Model of the MESA cavity string. In the bottom center the two HF power couplers can be seen, the four other visible ports (bottom left and right, top center) are the HOM couplers.

TRANSVERSE BBU

Electron bunches that enter a SRF cavity with a small deviation from the reference orbit excite dipole HOMs in said cavity. Due to their naturally high Q_L, these modes can persist until the next bunch arrives at the cavity. The magnetic field of an excited mode deflects the following bunches that do not travel on the reference orbit. The deflection angle produced by the mode translates into a transverse displacement at the cavity after recirculation. The recirculated beam induces a HOM voltage, depending on the magnitude and direction of the beam displacement.

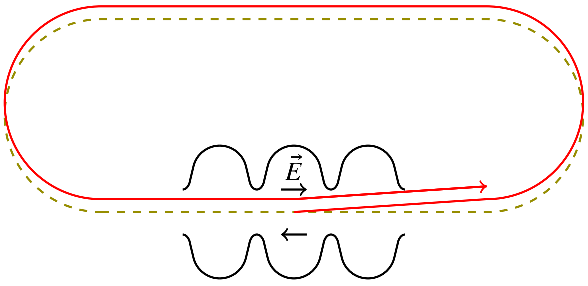

Figure 3: Orbit deviation (red) from the reference orbit (green) induced by dipole HOMs.

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This can lead to a periodic unstable growth of the HOM voltage, which finally results in loss of the beam, see Fig. 3, and depends strongly on the bunch charge and thereby the average beam current [5]. Since the beam rigidity is proportional to beam energy, the first cavity behind the injection and the last cavity before the beam dump are of particular concern. This conclusion has been found as well for recirculating accelerators without energy recovery where transverse BBU has been investigated in the past for mictrotrons or normalconducting and superconducting few-turn linacs [6]. As a rule of thumb the onset current for BBU scales linear with the injection energy into the first cavity of the multi-pass linac when keeping the other parameters like recirculation optics or HOM frequencies and quality factors fixed [6].

THRESHOLD CURRENT IN ERLS

An important concept for the description of BBU behaviour is the so-called threshold current, which is the maximum beam current that can be safely transported through the lattice without the risk of beam loss. See Fig. 4 for a visualisation of this behaviour as produced with simulation data of bi.

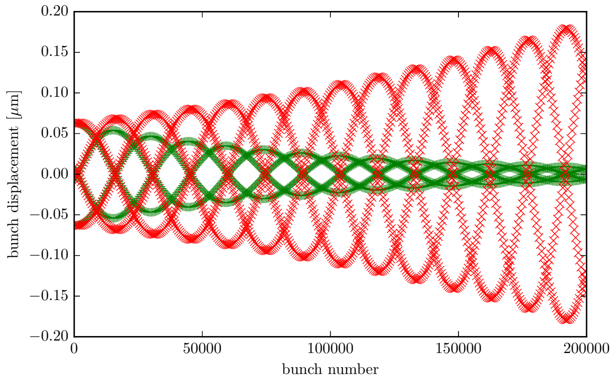

Figure 4: Bunch displacement as a result of subsequent bunches entering the cavity with a transverse offset. The points in green show the typical behaviour below the threshold current, in red an unstable beam current above the threshold. The data was obtained via bi simulation with an early iteration of the MESA lattice.

For multiturn ERLs, the threshold current for a single HOM was described by Hoffstätter et. al. in [7]:

$$I_{\mathrm{th}} = -\frac{2c^2}{e\left(\frac{R}{Q}\right)_\lambda Q_\lambda \omega_\lambda} \frac{1}{\sum_J^{N_p} \sum_I^{N_p} \frac{1}{p_I} \sin(\omega_\lambda [t^I - t^J]) T^{IJ}},$$

where I_{th} is the threshold current, $(R/Q)_\lambda$ and Q_λ the shunt impedance and quality factor of the HOM, ω_λ the frequency of the HOM, p the particle momentum and:

$$T^{IJ} = T_{12}^{IJ} \cos^2(\theta) + \frac{1}{2}(T_{14}^{IJ} + T_{23}^{IJ}) \sin(2\theta) + T_{34}^{IJ} \sin^2(\theta),$$

the transport line parameter from the end of one cavity to the end of the next. Assuming worst case for the recirculating path length $\sin(\omega_\lambda[t^I - t^J]) = -1$ and with an approximation of the lattice matrix elements for a polarisation angle $\theta = 0$ via:

$$T^{IJ} = T_{12}^{IJ} = T_{12} = \sqrt{\frac{\gamma_i \cdot \beta_i \cdot \beta_f}{\gamma_f}},$$

some general information about the strength of certain HOMs and their importance can be obtained. As there are multiple HOMs existing in each cavity the threshold current obtained by using the formula described in [7] needs to be calculated multiple times for the complete HOM spectrum of the accelerating cavities. Doing so the most dangerous HOMs for a given recirculation optic setting can be found.

Wanzenberger et al. presented simulations of the TESLA/XFEL type cavity HOM spectrum in [8]. Those HOM parameters and the knowledge about the twiss β and Lorentz γ at the end of the first cavity and the start of the second were used to identify the most dangerous HOMs with respect to BBU for the MESA ERL. The obtained parameters are presented in table 1 for the two strongest HOMs, with approximated values for $\mathrm{Q}_{\mathrm{ext}}$.

Table 1: HOM parameters as stated in [8]

f [GHz]	R/Q [Ω]	$\mathrm{Q}_{\mathrm{ext}}$	θ
1.7391	58.604	$2 \cdot 10^4$	127.2°
2.5785	45.064	$5 \cdot 10^4$	11.6°

In table 2 the results for the corresponding threshold currents of the two most dangerous HOMs are presented using the calculation from [7] at twiss $\beta_{i,f} = 10\,\mathrm{m}$. In addition the simulated threshold values using the bi-code are given in table 2.

Table 2: Calculated and simulated threshold currents

f [GHz]	$\mathrm{I}_{\mathrm{theo}}$ [mA]	$\mathrm{I}_{\mathrm{simu}}$ [mA]
1.7391	6.11	14.43 ± 0.01
2.5785	2.14	75.35 ± 0.06

The threshold current values presented here should be treated with care. Firstly, the numerical calculation is a big simplification of the process and a worst case approximation. Secondly, the simulations are currently performed with an old iteration of the MESA lattice which is without injection and starts at 30 MeV. Scaling down the injection energy to 5 MeV the threshold current is exspected to be reduced by a factor of 6, which even in the worst case presented in table 2 still would be sufficient for achieving the 1 mA design current of MESA stage 1. For MESA stage 2 running at a design current of 10 mA further optimizations would be necessary.

At the moment, the HOM parameters for MESA are updated. As MESA uses TESLA/XFEL cavities the HOMs are expected to be very similar to those presented in [8]. Nevertheless these values need to be simulated again for the full

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MESA cavity string also taking beamline elements, power couplers and HOM-couplers into consideration. Currently the new HOM simulations for the MESA cold string are being performed at TU Rostock. So far the values given in table 1 were used to further develop and test the bi framework for the twice recirculating double-sided MESA design.

Simulations with bi

The code bi uses beam tracking of point-like bunches through a 6×6 transfer matrix representation of the lattice. It calculates the beam position as a function of time and determines the threshold current by variation of the beam current.

A framework for bi was built in python, which handles an arbitrary number of HOMs and scans for the strongest, or performs frequency spread analysis of the HOMs. In reality, each cavity is produced with certain manufacturing tolerances. Since the frequencies of HOMs in a cavity strongly depend on the geometry of the cavity, every cavity can have slightly different HOM frequencies. Consequently the transverse phase advances throughout the recirculations vary slightly, which can increase the threshold current.

For this study, a sample of 4000 frequencies was used, where the frequencies were drawn from a uniform distribution with 1 MHz spread around 1739.1 MHz. Each frequency was assigned to one of the four cavities of MESA, and 1000 sample runs of bi were performed. The $R/Q = 58.604\,\Omega$ and $Q_0 = 20\,000$ were kept constant throughout the runs. The result of the simulation can be seen in Fig. 5. The threshold current without frequency spread was 14.43 mA, with frequency spread included the minimal threshold current was 21.49 mA. As expected an increased threshold current can be observed using more realistic cavity parameters in the simulations.

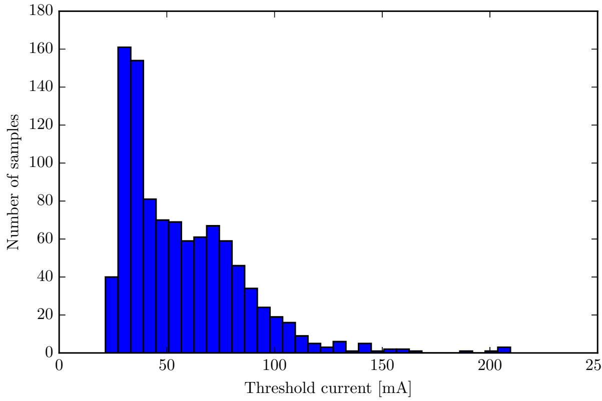

Figure 5: Threshold currents for 1000 runs with frequency spread of 1 MHz.

In all calculations and simulations performed so far the dampening effect of the HOM couplers was not considered, since it has not been measured or simulated for the MESA cryomodules yet.

CONCLUSION

The bi code for simulations of Beam Break Up for MESA was prepared. For future calculations the MESA lattice will be updated and the simulation will start at the injection energy of 5 MeV. As soon as new information on cavity parameters or lattice improvements are available, more realistic threshold currents for MESA can be obtained. Additional simulations with BMAD [9] are currently prepared and should be available soon to further prove the bi numbers. Furthermore with BMAD feedback and optimisation for finding the optimum lattice for maximum current will be possible. Currently, the critical point is the cavity right after injection and right before ejection since the lowest energy beam has the least rigidity. An optimisation of the injection optics will be performed.

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