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BEAM BREAKUP SIMULATIONS FOR THE MAINZ ENERGY RECOVERING SUPERCONDUCTING ACCELERATOR MESA*

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Abstract

MESA is a two pass energy recovery linac (ERL) currently under construction at the Johannes Gutenberg-University in Mainz. MESA uses four 1.3 GHz TESLA type cavities with 12.5 MV m^{-1} of accelerating gradient in two modified ELBE type cryomodule with improved thermal connection of the HOM antennas and cw operation. In the first stage of MESA operation 1 mA of beam current is foreseen, which will later be upgraded to 10 mA. One potential limit to maximum beam current in ERLs is the transverse beam breakup (BBU) instability induced by dipole Higher Order Modes (HOMs). These modes can be excited by bunches passing through the cavities off axis. Following bunches are then deflected by the HOMs, which results in even larger offsets for recirculated bunches. This feedback can even lead to beam loss. Simulation results for HOM spectra of a single TESLA cavity are available for example in [1]. It was possible to measure the HOM spectra in the cold, not tuned cavities at DESY and in the cold string tuned to the 1.3 GHz fundamental mode at Mainz. Results for the maximum beam current for MESA, limited by BBU, for the various HOM spectra are presented.

MESA

The Mainz Energy-recovering Superconducting Accelerator (MESA) is a small-scale, multi-turn, double-sided recirculating linac with vertical stacking of the return arcs currently being built at the Johannes Gutenberg Universität Mainz [2]. The operation modes planned are a thrice recirculating external beam mode (EB) with 150 µA current and 155 MeV particle energy for precision measurements of the weak mixing angle at the P2 Experiment or a twice recirculating energy recovering mode (ER) with 1 mA and later 10 mA current at a beam energy of 105 MeV where 100 MeV of beam energy can be recovered from the beam and fed back into the cavities. A windowless gas target as part of the MAGIX experiment will enable electron scattering experiments with different atoms. An overview of the MESA facilities is given in Fig. 1. The electron source (STEAM) provides up to 1 mA of polarized beam at 100 keV. It is followed by a spin manipulation system containing two Wien filters. A chopper system with a collimator and two buncher cavities prepares the longitudinal phase space of the bunches for the normal conducting milliampere booster (MAMBO), which accelerates them to 5 MeV. A 180° injection arc delivers the beam to the first cryomodule. Depending on the operation mode the beam is either twice or thrice recirculated. This paper focusses on the high current twice recirculating ERL operation, where the beam passes each cavity 4 times and is then dumped at 5 MeV in the ERL beam dump.

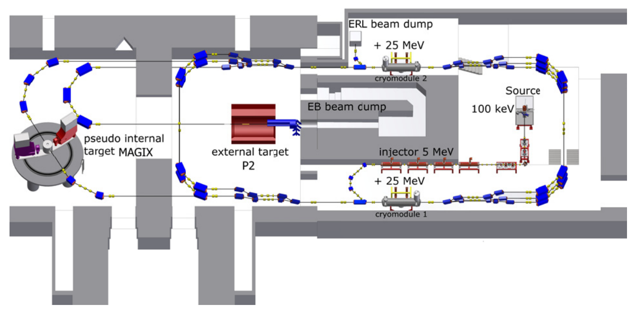

Figure 1: Overview of the MESA facilities.

SRF CAVITIES AND CRYOMODULES

For the MESA main accelerator two ELBE-type cryomodules were chosen [3] and modified for ERL operation [4]. Each module contains two 9-cell superconducting radio frequency (SRF) cavities of the TESLA-type. These 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 exist in the cavity. As the TESLA-type cavities are elliptical cavities, dipole modes naturally occur in pairs of two with polarisations separated by approximately 90° and very small differences in frequency. For a simulation of the threshold current at least two HOMs have to be present in one cavity.

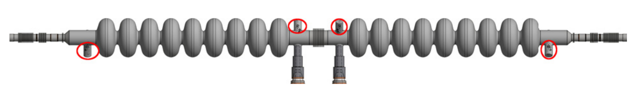

Figure 2: CAD Model of the MESA cavity string. In the bottom center the two HF power couplers can be seen, the four other ports (red circles) are the HOM couplers.

As can be seen in Fig. 2 two HOM ports, which allow for the measurement of HOMs for each cavity, are present. As part of the quality control and site acceptance tests the HOM spectra were measured first in the vertical cold test, not yet tuned to the fundamental mode, and a second time for each cavity in the fully assembled string in the cold cryomodule tuned to the 1.3 GHz fundamental mode.

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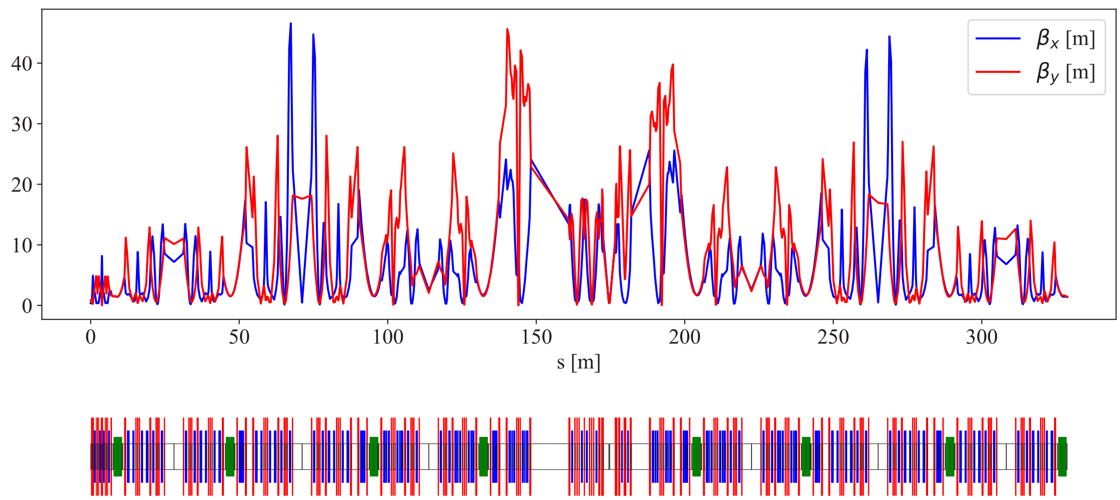

Figure 3: Horizontal and vertical beta functions along the beamline for a start to end ERL configuration of MESA simulated in ELEGANT [5]. The layout below the graph depicts the optical elements. Dipole magnets are blue, quadrupole magnets are red and accelerating/decelerating cavities are green.

LATTICE SIMULATIONS FOR ERL MODE

Optimisation of the MESA lattice for ERL operation is still ongoing as was last presented in [6]. In Fig. 3 the horizontal and vertical beta functions along the beamline are shown. A symmetrical adjustment of the beam optics around the mirror plane of the main linac cryomodules shows very promising results for the ER mode. Horizontal and vertical envelopes stay below 2 mm and 1.2 mm respectively. The lattice has been optimised for both symmetry around cryomodules and minimum beta functions, as beam size at the position of the cavities is relevant to HOM excitation. In addition, horizontal and vertical beta functions are set to the same value along the cryomodules, producing round beams and minimizing quadrupole and higher order mode excitation.

TRANSVERSE BBU

Electron bunches that enter a SRF cavity with a small deviation from the reference orbit excite dipole (quadrupole, sextupole, etc.) HOMs in above-mentioned cavity. Due to their potentially high Q_0, 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 kick induced by the dipole HOM 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. This can lead to a periodic unstable growth of the HOM voltage, which finally results in loss of the beam and depends strongly on the bunch charge and thereby the average beam current [7]. The maximum current that can be recirculated before BBU occurs is called threshold current. For multiturn ERLs with a number of passes N_p, this was described by Hoffstaetter et. al. in [8]:

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

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:

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

is the transport line parameter from the end of one cavity to the end of the next, where θ is the polarisation of the HOM. In general, it is expected to find the threshold current limited by a single HOM, if the frequency deviation between neighbouring modes is in the order of ≈ 1 MHz. In the presence of multiple polarized HOMs, as it is the case in elliptical cavities, this assumption does no longer hold [9]. Consequently, in the simulation of the threshold currents at least 2 HOMs were analysed in each cavity. In reality, each cavity is produced with certain manufacturing tolerances and tuned to the fundamental mode. Since the frequencies of HOMs in a cavity depend on the geometry of the cavity, every cavity can have slightly different HOM frequencies. This can significantly increase the achievable threshold currents since there is less crosstalk between cavity HOMs as was investigated for example for the Cornell-Brookhaven 4-Pass ERL [10] or for MESA in [11].

SIMULATIONS WITH BI

The code bi [12] uses tracking of point-like bunches through a 6×6 transfer matrix representation of the lattice. It

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calculates the beam position as a function of time and determines the threshold current by variation of the beam current. The transfer matrices were taken from a simulation of the MESA ERL-lattice with ELEGANT starting right behind the 5 MeV injection arc. For simulations of the achievable threshold current for MESA, measured Q-values and frequencies of the 4 cavities cold tests at DESY Hamburg [13] as well as measured data from horizontal tests obtained at the Helmholtz Institut Mainz (HIM) were combined with polarisation and R/Q data from simulation [1]. In total, the Q values and frequencies (first two passbands) of up to 36 dipole HOMs were measured for each cavity. In Fig. 4 a comparison of the measured and simulated Q values is shown. A difference between the measurement at DESY and HIM was expected, since the assembly of the cryomodule with 2 cavities and the tuning to the fundamental mode changes the geometry of the cavity and thus its HOM frequencies and bandwidths which impacts the Q values. Overall both measurements and the simulation are in good agreement.

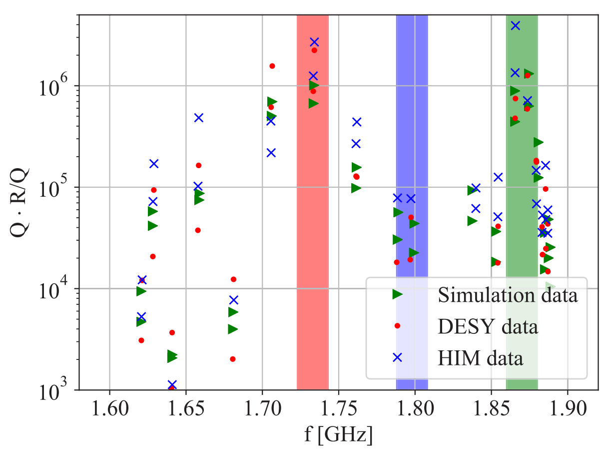

Figure 4: Comparison of measured and simulated Q · R/Q values shown for cavity 7. The cavities are numbered from 7 to 10 with cavity 7 and 8 in one module and 9 and 10 in the other one.

Figure 5 shows the absolute frequency deviation between the 4 cavities. It varies between 0 and 1.955 MHz with an average of 0.59 MHz. Three regions of interest can be noticed here, one around 1.73 GHz, the second around 1.78 GHz and the last one around and above 1.87 GHz. In all three of these areas, frequency spread is considerably smaller then anywhere else. Considering the same areas in Fig. 4 and Fig. 6 a pattern is visible. Relatively high Q values and low frequency spread coincide with low threshold currents as was also expected from theory. In the second area this is negated by the smaller Q values and above 1.87 GHz by very small shunt impedances R/Q of the modes. In Fig. 6 the threshold current for the first two passbands of HOMs is shown. For the measured HOMs in the dressed and tuned MESA cryomodules a threshold current of 19.8 mA in region 1 (red) is expected and a threshold current of 13.4 mA

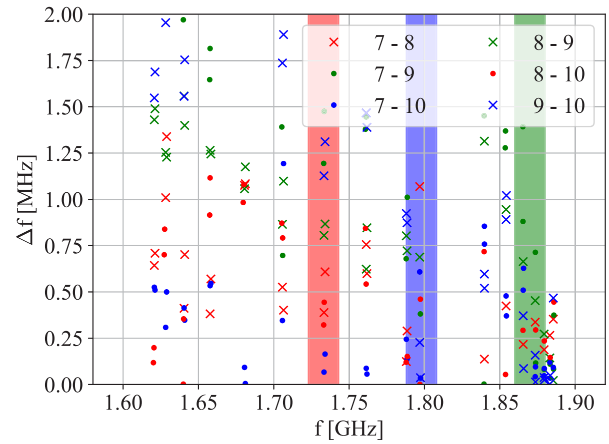

Figure 5: Comparison of absolute frequency deviation between cavity HOMs as measured at HIM.

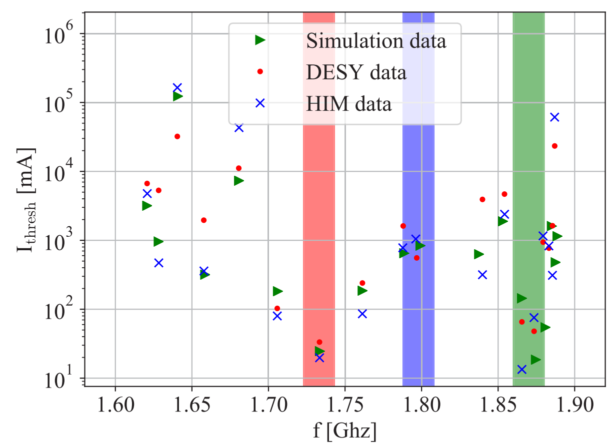

Figure 6: Simulation of threshold current values for different data sets. Red: All values from simulated data, blue: Q and f values from vertical cold test measurements at DESY and green: Q and f values measured in the cryomodule tuned to 1.3 GHz.

in region 2 (green). Both values exceed the 10 mA design current for MESA stage 2.

CONCLUSION AND OUTLOOK

Transverse BBU will not limit the MESA stage 1 operation with 1 mA. For stage 2 a perfectly aligned machine with no steering errors could achieve 10 mA in a 4-pass ERL configuration. Investigation of alignment errors of the magnets and their impact on the beam parameters and BBU limits will further be conducted. Future studies need to investigate the heating of the HOM antennas with respect to beam current as HOM antenna quenching could be another limiting factor. Afterwards ultimate beam current limits for MESA using the presented cryomodule can be derived.

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REFERENCES

[1] W. Ackermann, H. D. Gersem, C. Liu, and T. Weiland, "Eigenmode calculations for the tesla cavity considering wave-propagation losses through fundamental and higher-order mode couplers,"

[2] F. Hug, K. Aulenbacher, R. Heine, B. Ledroit, and D. Simon, "MESA - an ERL Project for Particle Physics Experiments," in *Proc. LINAC'16*, (East Lansing, MI, USA), May 2017, pp. 313–315. DOI: 10.18429/JACoW-LINAC2016-MOP106012.

[3] F. Schlander, A. Arnold, K. Aulenbacher, R. Heine, and D. Simon, "Investigation of Cryomodules for the Mainz Energy-recovering Superconducting Accelerator MESA," in *Proc. IPAC'14*, (Dresden, Germany), Jul. 2014, pp. 2505–2507. DOI: 10.18429/JACoW-IPAC2014-WEPRI013.

[4] T. Stengler *et al.*, "Status of the Superconducting Cryomodules and Cryogenic System for the Mainz Energy-recovering Superconducting Accelerator MESA," in *Proc. IPAC'16*, (Busan, Korea), Jun. 2016, pp. 2134–2137. DOI: 10.18429/JACoW-IPAC2016-WEPMB009.

[5] M. Borland, "Elegant: A flexible sdds-compliant code for accelerator simulation," *Advanced Photon Source LS-287*, September, 2000.

[6] D. Simon, K. Aulenbacher, R. Heine, and F. Schlander, "Lattice and Beam Dynamics of the Energy Recovery Mode of the Mainz Energy-recovering Superconducting Accelerator MESA," in *Proc. IPAC'15*, (Richmond, VA, USA), Jun. 2015, pp. 220–222. DOI: 10.18429/JACoW-IPAC2015-MOPWA046.

[7] E. Pozdeyev, C. Tennant, J. J. Bisognano, M. Sawamura, R. Hajima, and T. I. Smith, "Multipass beam breakup in energy recovery linacs," 2005.

[8] G. H. Hoffstätter and I. V. Bazarov, "Beam-breakup instability theory for energy recovery linacs," *Physical Review Special Topics - Accelerator and Beams*, vol. 7, no. 054401, p. 13, May 2004.

[9] G. H. Hoffstaetter, I. V. Bazarov, and C. Song, "Recirculating beam-breakup thresholds for polarized higher-order modes with optical coupling," *Physical review special topics - Accelerators and Beams*, 2007. DOI: 10.1103/PhysRevSTAB.10.044401.

[10] W. Lou and G. Hoffstaetter, "Beam-breakup studies for the 4-pass cornell-brookhaven energy-recovery test accelerator," *Journal of Physics: Conf. Series 1067(2018) 062014*, 2018. DOI: 10.1088/1742-6596/1067/6/062014.

[11] C. Stoll, F. Hug, and D. Simon, "Beam Break Up Simulations for the MESA Accelerator," in *Proc. ERL'17*, (Geneva, Switzerland), May 2018, pp. 26–28. DOI: 10.18429/JACoW-ERL2017-MOPSPP009.

[12] I. V. Bazarov, *Bi - beam instability bbu code*, http://www.lepp.cornell.edu/ ib38/bbucode/src.

[13] T. Stengler, K. Aulenbacher, F. Hug, T. Kürzeder, and D. Simon, "Cryomodule Fabrication and Modification for High Current Operation at the Mainz Energy Recovering Superconducting Accelerator MESA," in *Proc. SRF'17*, (Lanzhou, China), Jan. 2018, pp. 297–300. DOI: 10.18429/JACoW-SRF2017-MOPB101.