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.

1. 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.
2. 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 $\pi$-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.

3. 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
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.

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.

4. 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]:

$$I_{th} = -\frac{2e^2}{e\left(R/Q\right)_\lambda Q_\lambda \omega_\lambda \sum_{j}^N_p \sum_{l}^N_p \frac{1}{p_j} \sin(\omega_\lambda [t^I - t^J]) T^{IJ}},$$

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

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

is the transport line parameter from the end of one cavity to the end of the next, where $\theta$ 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 \( \approx 1 \text{ MHz} \). In the presence of multiple polarized HOMs, as it is the case in elliptical cavities, this assumption does no longer hold \cite{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 \cite{10} or for MESA in \cite{11}.

5. Simulations with bi

The code bi \cite{12} uses tracking of point-like bunches through a \( 6 \times 6 \) 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. 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 \cite{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 \cite{1}. In total, the Q values and frequencies (first two passbands) of up to 36 dipole HOMs were measured for each cavity.

![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.](image)

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 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.

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

6. 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] Ackermann W, De Gersem H, Liu C and Weiland T  Eigenmode calculations for the tesla cavity considering wave-propagation losses through fundamental and higher-order mode couplers
[2] Hug F, Aulenbacher K, Heine R, Ledroit B and Simon D 2017 MESA - an ERL Project for Particle Physics Experiments Proc. of Linear Accelerator Conference (LINAC'16), East Lansing, MI, USA, 25-30 September 2016 (Linear Accelerator Conference no 28) (JACoW) pp 313–5
[3] Schlander F, Arnold A, Aulenbacher K, Heine R and Simon D 2014 Investigation of Cryomodules for the Mainz Energy-recovering Superconducting Accelerator MESA Proc. IPAC’14 International Particle Accelerator Conference (JACoW) pp 2505–7
[4] Stengler T et al. 2016 Status of the Superconducting Cryomodules and Cryogenic System for the Mainz Energy-recovering Superconducting Accelerator MESA Proc. IPAC’16 International Particle Accelerator Conference (JACoW) pp 2134–7
[5] Borland M September, 2000 Advanced Photon Source LS-287
[6] Simon D, Aulenbacher K, Heine R and Schlander F 2015 Lattice and Beam Dynamics of the Energy Recovery Mode of the Mainz Energy-recovering Superconducting Accelerator MESA Proc. IPAC’15 International Particle Accelerator Conference (JACoW) pp 220–2
[7] Pozdeyev E, Tennant C, Bisognano J J, Sawamura M, Hajima R and Smith T I 2006 Nuclear Instruments and Methods in Physics Research A 557, 1 176–88
[8] Hofstätter G H and Bazarov I V 2004 Physical Review Special Topics - Accelerator and Beams 7 054401
[9] Hofstätter G H, Bazarov I V and Song C 2007 Physical review special topics - Accelerators and Beams 10 044401
[10] Lou W and Hofstätter G 2018 Journal of Physics: Conf. Series 1067 062014
[11] Stoll C, Hug F and Simon D 2018 Beam Break Up Simulations for the MESA Accelerator Proc. ERL’17 ICFA Advanced Beam Dynamics Workshop (JACoW) pp 26–8
[12] Bazarov I V bi - beam instability bbu code http://www.lepp.cornell.edu/~ib38/bbucode/src
[13] Stengler T, Aulenbacher K, Hug F, Kürrzeder T and Simon D 2018 Cryomodule Fabrication and Modification for High Current Operation at the Mainz Energy Recovering Superconducting Accelerator MESA Proc. SRF’17 International Conference on RF Superconductivity (JACoW) pp 297–300