BEAM BREAKUP LIMIT ESTIMATIONS AND HIGHER ORDER MODE CHARACTERISATION FOR 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 two 1.3 GHz TESLA type cavities with 12.5 MV/m of accelerating gradient in a modified ELBE type cryomodule in c.w. operation. One potential limit to maximum beam current in ERLs is the transverse beam breakup (BBU) instability induced by dipole 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. To measure the quality factors and frequencies for the dressed as well as undressed cavities improves the validity of any current limit estimation done.

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 [1]. 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.

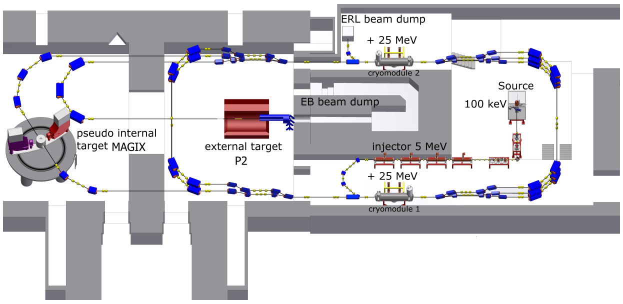

Figure 1: Overview of the MESA layout as used in this work.

SRF CAVITIES AND CRYOMODULES

For the MESA main accelerator two ELBE-type cryomodules were chosen [2] and modified for ERL operation [3]. 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.

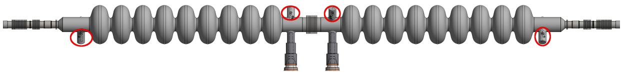

Figure 2: CAD Model of the MESA cavity string. In the bottom center the two HF power couplers can be seen, the four other ports (red circles) are the HOM couplers.

As can be seen in fig. 2 two HOM ports, which allow for the measurement of HOMs for each cavity, are present.

DIPOLE HIGHER ORDER MODES

In [4] a dedicated study of HOMs in TESLA type cavities including the effects of fundamental power couplers and higher order mode couplers was presented. A total of 86 dipole HOMs is presented. Each dipole HOM has a polarisation, a quality factor Q and a shunt impedance R/Q. In fig. 3 an example of the field distribution in a dipole HOM can be seen. 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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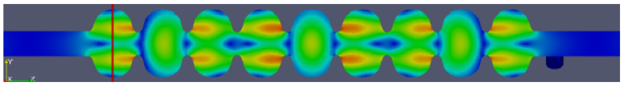
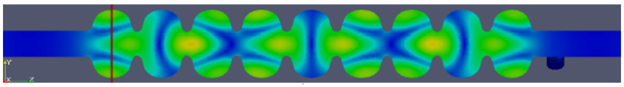
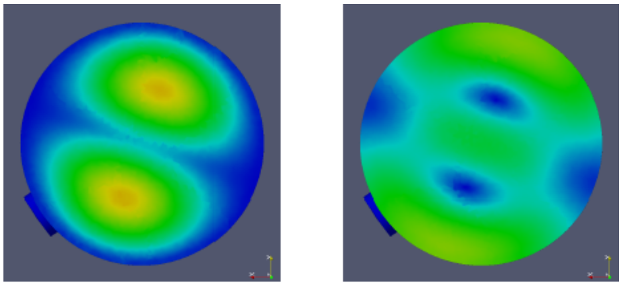


(a) Electric field of a dipole HOM in a TESLA cavity.



(b) Magnetic field of a dipole HOM in a TESLA cavity.



(c) Cut view of electric field (left) and magnetic field (right) at the red line indicated in fig. 3a and 3b

Figure 3: Example of a dipole HOM in a TESLA cavity taken from [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.

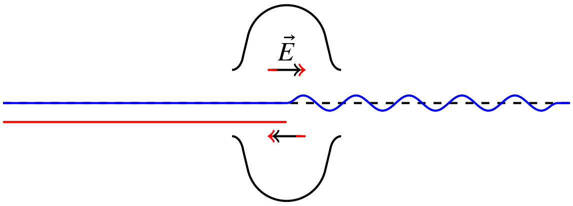


Figure 4: Simplified picture of the transverse BBU instability. A bunch (blue) gets deflected by the magnetic field of the dipole HOM and a bunch travelling off axis (red) can exchange energy with the elctric field of the HOM further powering the instability.

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 [5]. 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 [6]:

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

where $I_{\rm th}$ 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 [7]. Consequently, in the simulation of the threshold currents at least 2 HOMs were analysed in each cavity.

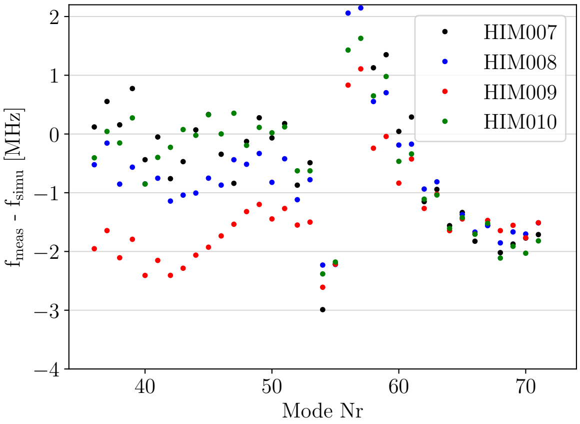


Figure 5: Deviation of the measured HOM frequency from the simulated frequencies for the first two passbands of dipole HOMs as measured at Helmholtz Institute Mainz.

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, as can be observed in the comparison of the results measured at Helmholtz Institute Mainz (HIM) shown in fig. 5. 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 [8] or for MESA in [9].

SIMULATIONS WITH BI

The code bi [10] uses 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.

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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 [11] 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 [4]. In total, the Q values and frequencies (first two passbands) of up to 36 dipole HOMs were measured for each cavity. In fig. 6 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. The larger Q spread for the two different polarisations in each cavity can be explained by a deviation from the elliptical shape as compared to the simulated geometry. The overall higher Q factor results from a deviation of the HOM coupler gap width as compared to the simulated geometry [12].

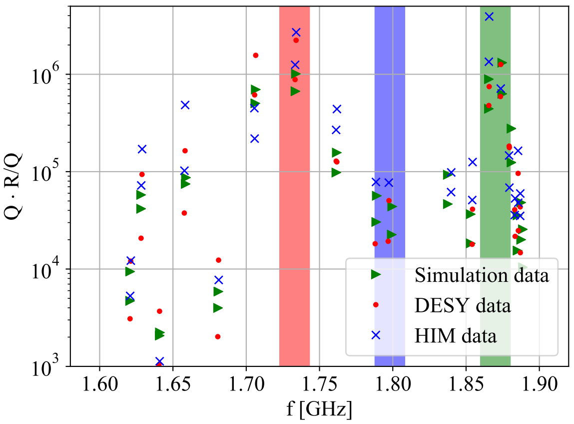

Figure 6: Comparison of measured and simulated $Q \cdot R/Q$ values shown for cavity 7. The cavities are numbered from 7 to 10 with cavity 7 and 8 in one module and 9 and 10 in the other one.

Figure 7 shows the absolute frequency deviation between the 4 cavities as presented in [13]. 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. 6 and fig. 8 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. 8 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.

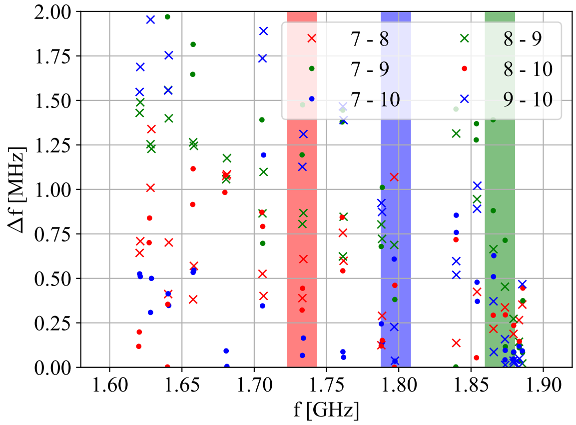

Figure 7: Comparison of absolute frequency deviation between cavity HOMs as measured at HIM.

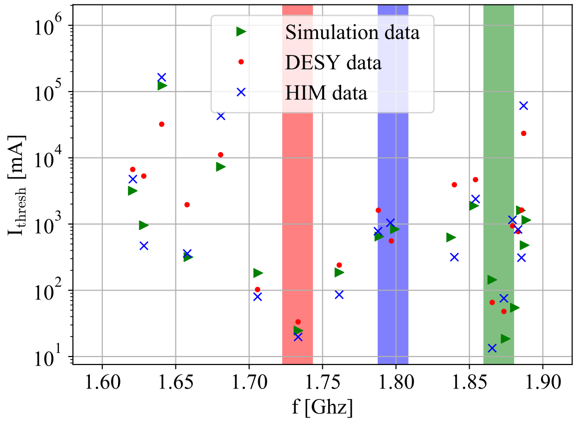

Figure 8: Simulation of threshold current values for different data sets. Red: All values from simulated data, blue: Q and f values from vertical cold test measurements at DESY and green: Q and f values measured in the cryomodule tuned to 1.3 GHz.

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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