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BEAM DYNAMICS SIMULATIONS FOR THE SUPERCONDUCTING HELIAC CW LINAC AT GSI*

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Abstract

The superconducting (SC) continuous wave (CW) heavy ion linac HELIAC (HElmholtz LInear ACcelerator) is a common project of GSI and HIM under key support of IAP Frankfurt. It is intended for future experiments with heavy ions near the Coulomb barrier within super-heavy element (SHE) research and aims at developing a linac with multiple CH cavities as key components downstream the High Charge State Injector (HLI) at GSI. The design is challenging due to the requirement of intense beams in CW mode up to a mass-to-charge ratio of 6, while covering a broad output energy range from 3.5 to 7.3 MeV/u with minimum energy spread. In 2017 the first superconducting cavity of the linac has been successfully commissioned and extensively tested with beam at GSI. In the light of experience gained in this research so far, the beam dynamics layout for the entire linac has been updated and optimized in the meantime. This contribution will provide a brief overview of the recent progress on the project, as well as a potential modification to the linac layout.

BEAM DYNAMICS CONCEPT

A preliminary beam dynamics design - based on the EQUUS (Equidistant Multigap Structure) concept - has been published in 2009 [1]. Meanwhile many experiences have been gained at GSI/HIM [2–7] and IAP [8–16] in design, fabrication and operation of superconducting CH (Crossbar *H*-mode) cavities (Fig. 1) and the associated components. In this context, a revision of the beam dynamics concept was strongly recommended and has been published in 2020 [17]. The EQUUS beam dynamics concept differs from the widely used constant phase approach in a way that the gap center distances in a cavity are equidistant. As the velocity of a bunch increases inside a cavity, EQUUS leads to a varying synchronous phase of the bunch for each gap.

RECENT PROGRESS

In the current advanced demonstration stage, an extended beam test with a first fully equipped series cryomodule is planned to take place shortly at GSI. In recent years, the corresponding infrastructure at GSI has been built and expanded. Among other things, this includes a radiation-shielding area with a connection to the existing 4 K helium liquefier. In addition, the commissioning of an ISO-class 4 clean room at the Helmholtz Institute Mainz (HIM) providing the high-purity environment required for the adequate assembly of superconducting RF structures took place.

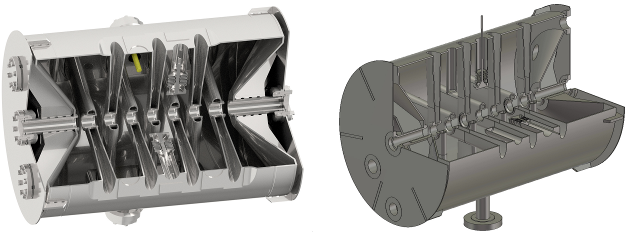

Figure 1: Two of the twelve CH cavity models used to obtain realistic assumptions of gap and drift lengths, as well as gap voltage distributions. Autodesk Inventor rendering of CH1 *(left)* and CST model of CH4 *(right)* [12].

Furthermore, activities on the normal-conducting HLI-injector are underway: This includes R&D for the existing and for a new HLI-RFQ [18] as well as the started tendering for two IH structures for acceleration from 300 keV/u to 1.4 MeV/u by means of an APF beam dynamics concept [19]. Finally, there are considerations regarding an upgrade of the ECR ion source from 14 GHz to 18 GHz to fulfill demands for higher charge states.

Table 1: Basic HELIAC Design Parameters [1]

Parameter	**Value**
W_{in}	1.4 MeV/u
W_{out}	3.5–7.3 MeV/u
ΔW_{out}	±3 keV/u
I	$\leq$ 1 mA
A/z	$\leq$ 6

The main requirements and boundary conditions for the linac design are summarized in Table 1. With a relatively low beam current, CW-operation and limited longitudinal space, this linac is predestined to be operated in the superconducting mode. Further thoughts on the choice of technology with regard to superconducting or room-temperature operation can be found in [20].

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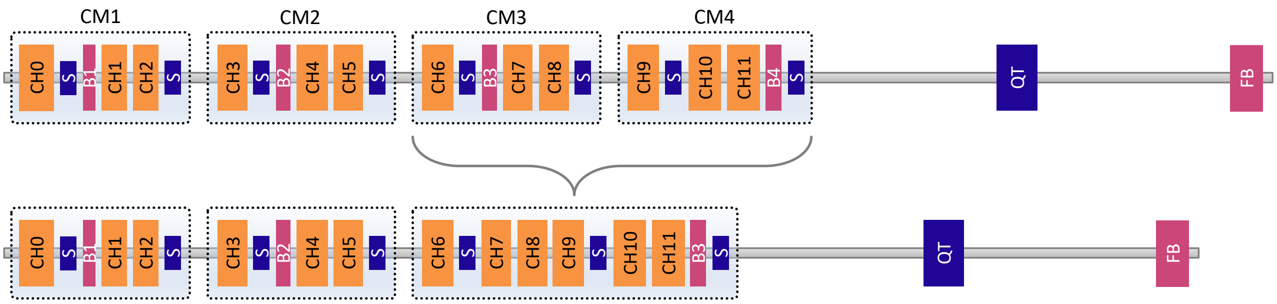

Figure 2: Current about 30 m-long HELIAC layout *(top)* and investigated variant in which CM3 and CM4 were combined into one cryomodule *(bottom)*. With the new approach, a buncher cavity, as well as a solenoid magnet, could be omitted.

RECENT BEAM DYNAMICS STUDIES

The 2020 HELIAC reference layout is simulated with LORASR [21] and based on twelve multicell CH-type DTL-cavities operating at 216.816 MHz (doubling the HLI operating frequency). They are grouped in four cryomodules (CM1 to CM4). Each cryomodule comprises three CH cavities, one spoke-type buncher and two superconducting solenoids. This superconducting part is followed by a room temperature transport section with a final buncher cavity (FB) at the end (Fig. 2). To optimize the beam dynamics design in terms of acceleration efficiency, $E_a = 7.1$ MV/m has been chosen as maximum design gradient for the CH cavities in case of mass-to-charge ratio $A/z = 6$ (see Table 1).

Due to the well-advanced design phase of the first standard cryomodule ("Advanced Demonstrator", CM1), all positions and lengths of the HELIAC beam line elements including the beam diagnostics were updated at last.

Benchmark with TraceWin

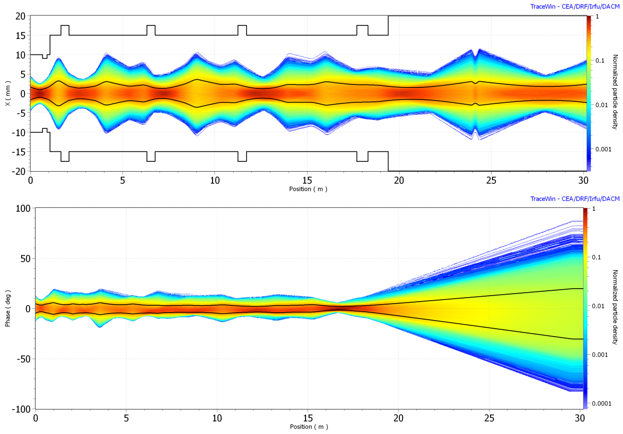

Figure 3: TraceWin-simulated transverse $x(z)$ *(top)* and phase *(bottom)* beam density along the entire HELIAC. The black curves show the rms-width.

For future start-to-end beam dynamics simulations, TraceWin is a suitable and widely used code. When the RF designs of all HELIAC cavities are finalized, the use of 3D field maps for precise simulation of the electric field distribution within the cavities is recommended for a high simulation accuracy. In a first step, it has been investigated for the 2020 HELIAC design to what extent a *thin gap* approximation already provides sufficiently accurate results (Fig. 3), i. e. comparable with LORASR, despite the strong simplification of the gap geometry. When comparing the beam envelopes simulated with TraceWin with those simulated with LORASR, a very good agreement was found. The same holds true for the phase space density plots at the HELIAC exit and thus also the growth in emittance. Deviations between the two codes are within the expected range, especially caused by the *thin gap* approximation. Further details can be found in [22] as well as details of a comparable study in [23].

Merging CM3 and CM4

Recent findings have indicated that longer cryomodules than previously envisioned could possibly be used. This approach with cryomodule lengths > 5 m was initially rejected for handling reasons, among others. However, if it turns out that the use of longer cryomodules is indeed possible, cryomodules 3 and 4 could be merged and combined into one cryomodule. At the same time, the significantly reduced drift distances could also save a solenoid magnet and a buncher cavity. While the removal of these elements could result in a slight degradation of beam quality, it would also result in noticeable cost savings as well as valuable shortening of the overall length of the linac by 2.49 m. A first beam dynamics approach for this case is shown in Figs. 2, 4, 5 and 6.

CONCLUSION

As the GSI UNILAC is being upgraded for FAIR with short pulse operation and high intensity [24–27], the HELIAC is favorable to meet the user's requirements for SHE research [28]. A promising beam dynamics layout was developed, showing a possible design approach for the upcoming HELIAC which essentially meets the required beam parameters [29, 30]. Taking the already achieved encouraging experimental data, as well as the presented results of beam dynamics simulations into account, the SC CW linac HELIAC is of high interest for the accelerator community. The upcoming extended beam test with a first fully equipped cryomodule is scheduled to take place soon at GSI and will mark the next milestone on the way to the entire HELIAC.

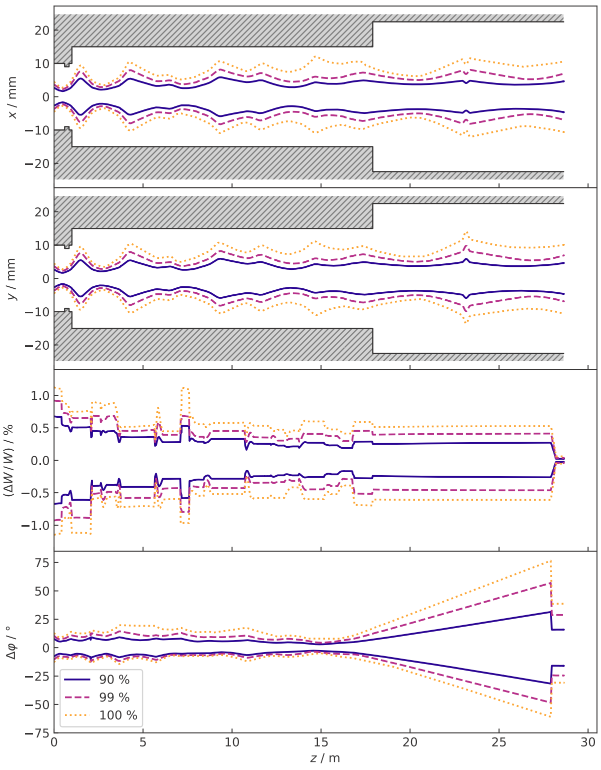

Figure 4: Simulated particle envelopes along the entire HELIAC; the phase jump at the end of the beam line corresponds to the halved RF frequency for the final buncher (FB).

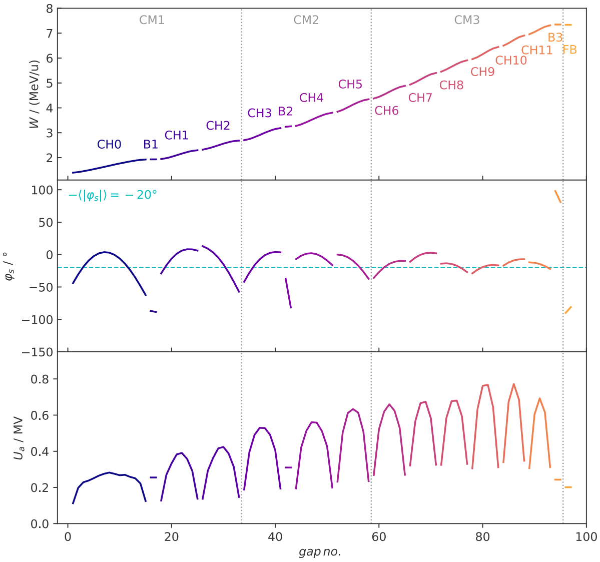

Figure 5: Evolution of the mean bunch energy W, the synchronous phase φ_s and the effective voltage per gap U_a.

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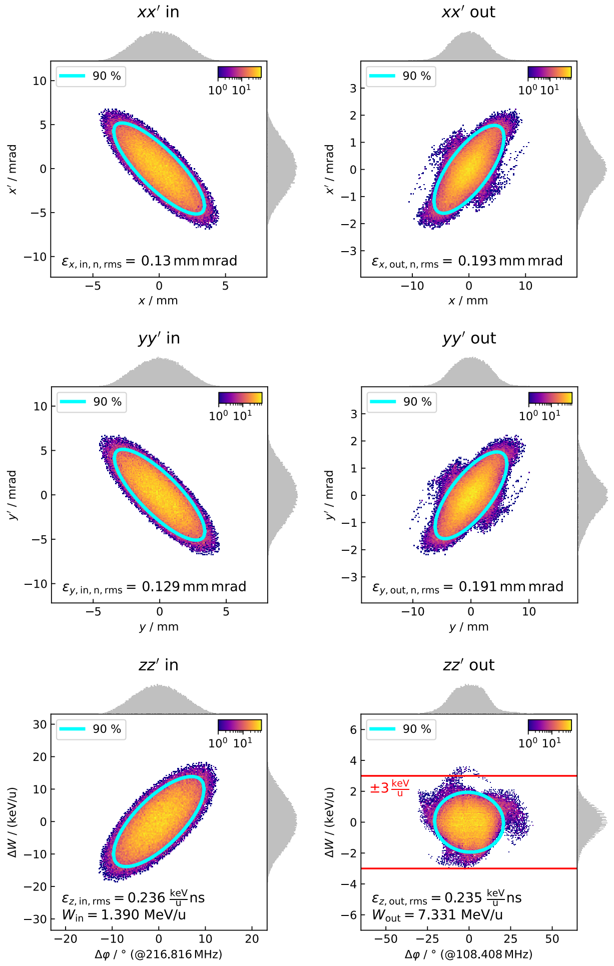

Figure 6: Simulated transverse and longitudinal phase space portraits downstream the HELIAC. The particle density is logarithmically color-coded.

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