ISBN: 978-3-95450-240-0 ISSN: 2673-5547 doi:10.18429/JACoW-HIAT2022-TH3C2



# ALTERNATING PHASE FOCUSING BASED IH DTL FOR HEAVY ION APPLICATION

S. Lauber*, [1,2,3], M. Basten[1,2], S. Yaramyshev[1,2], K. Aulenbacher[1,2,3], W. Barth[1,2,3], C. Burandt[1,2], M. Droba [4], F. Dziuba[1,2,3], P. Forck[1], V. Gettmann[1,2], T. Kürzeder[1,2], J. List[1,2,3], M. Miski-Oglu[1,2], H. Podlech[4,5], A. Rubin[1], M. Schwarz[4]
[1]GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt, Germany
[2] Helmholtz Institute Mainz, Mainz, Germany
[3]Johannes Gutenberg-University, Mainz, Germany
[4]Institut für Angewandte Physik, Frankfurt, Germany
[5]Helmholtz Research Academy Hesse for FAIR, Frankfurt, Germany

*Abstract*

The continuous wave (CW) operated HElmholtz LInear ACcelerator (HELIAC) is going to reach the next milestone with the commissioning of the superconducting (SC) Advanced Demonstrator cryomodule, comprising four SC Crossbar H-mode (CH) cavities and SC steerer magnets. In parallel with the commissioning of the SC main accelerator, the normal conducting injector consisting of an ECR ion source, a RFQ and two Interdigital H-mode (IH) cavities will be built based on an Alternating Phase Focusing (APF) beam dynamics scheme. Both IH cavities will provide a beam energy gain from 300 keV/u to 1400 keV/u with a maximum mass to charge ratio of 6, requiring only one external quadrupole triplet and beam steerer elements between them. The APF concept allows stable and effective beam transport with transverse and longitudinal focusing, enabling an efficient and compact design. Due to the stringent requirements of the APF concept on the voltage distribution and the CW operation, optimization of each cavity in terms of RF, mechanical and thermal properties is crucial for successful operation of the HELIAC injector. The current layout of the APF based and CW operated injector will be presented.

## INTRODUCTION

At GSI Helmholtzzentrum für Schwerionenforschung (GSI, Germany), the UNIversal Linear ACcelerator (UNILAC) [1–3] is being upgraded to deliver high intensity, low repetition rate beam to the main synchrotron SIS100 [4] of the Facility for Antiproton and Ion Research (FAIR), which is currently under construction. The new scope of operation of UNILAC will have an impact on beam supply for the GSI material and superheavy element research program, which requires ideally a low peak current, continuous wave beam. To allow for further discoveries of new superheavy elements [5], a dedicated linear accelerator is under construction, namely the HElmholtz LInear ACcelerator (HELIAC, see Fig. 1). The operational parameters of the new machine are listed in Table 1; the machine has been specially designed to allow for a variable output beam energy [6, 7].

Whilst the variable output energy is attained by employing the EQUidistant mUltigap Structure (EQUUS [8]) beam dynamics concept in the superconducting accelerator [9, 10], the normal conducting injector has to deliver a fixed output energy and high beam quality. Thus, the normal conducting cavities in the warm injector are designed using a different beam dynamics approach, namely Alternating Phase Focusing (APF [11–15]).

Table 1: General Characteristics of the HELIAC Accelerator

| Property | Value |
|---|---|
| Frequency | 108.408 MHz (216.816 MHz[1]) |
| Mass-to-charge ratio | ≤ 6 |
| Repetition rate | Continuous wave |
| Beam current $I$ | ≤ 1 mA |
| Output energy | 3.5 MeV/u to 7.3 MeV/u |
| Injector output energy | 1.4 MeV/u |
| Normal conducting cavities | 3 |
| Superconducting cavities | 12 |

[1] The SC CH cavities operate on the second harmonic.

This beam dynamics approach is very attractive, as it allows removing (costly) internal magnetic quadrupole multiplets from the cavities, and thus offers for a high beam quality, compact, and modular layout of the injector, supporting stable long-term operation of the machine. In order to omit internal magnetic lenses in the cavities, the beam is focused also transversally using the electric fields in between the drift tubes. Commonly, negative synchronous phases (i.e., the RF phase when the accelerated particle beam passes the RF gap) are employed to provide for longitudinal focusing (and transverse defocusing). Positive synchronous phases have the opposite effect on beam focusing, so that the beam is transversely focused and longitudinally defocused.

In order to alter the synchronous phases (and thus the focusing properties) in between individual gaps, the lengths of the neighboring tubes are adjusted

$$L_{\text{cell}} = \frac{\beta\lambda}{2} + \beta\lambda\frac{\Delta\phi}{360^\circ} \quad , \tag{1}$$

with the relative velocity $\beta = v/c_0$, RF wavelength $\lambda$, and change of synchronous phase in between two neighboring gaps $\Delta\phi = \phi_{i+1} - \phi_i$.

* s.lauber@gsi.de

ISBN: 978-3-95450-240-0 ISSN: 2673-5547 doi:10.18429/JACoW-HIAT2022-TH3C2

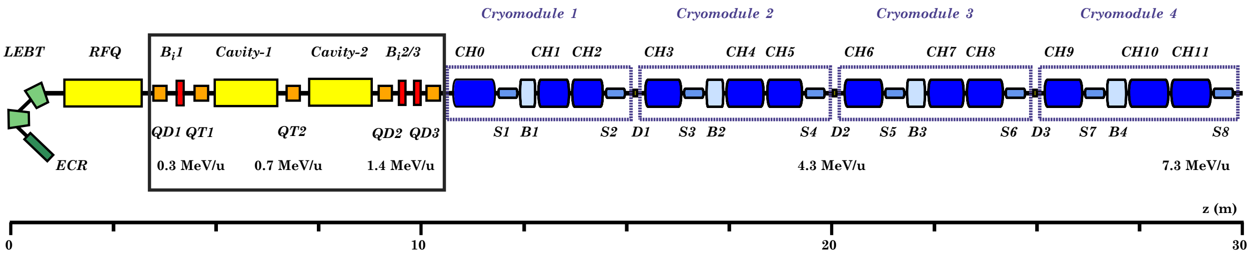


Figure 1: Layout of the HELIAC comprising four cryomodules and its dedicated injector; this publication focuses on the injector DTL with its relevant components: Quadrupole Doublets (QD), Bunchers (B), Quadrupole Triplets (QT), Interdigital H-Mode Cavities (IH), Crossbar H-Mode Cavities (CH), Solenoids (S)

The coupling of beam dynamics design on the cavity geometry imposes a circular dependency: The selection of synchronous phases impacts the geometry. The geometry alters the voltage in each gap. Ultimately, the altered gap voltage affects the beam dynamics, and a new optimum set of synchronous phases has to be found. The optimum solution is thus obtained iteratively.

## METHODS

The APF cavities were designed in parallel from an RF and beam dynamics point of view. Two full length papers were submitted to peer-reviewed journals [14, 16] describing both views in detail. The RF design team had to take continuous wave operation into account, and design the cavities accordingly to reduce the thermal load in each cavity as much as possible. The tube and gap lengths are adjusted during the design of the beam dynamics with the aid of a Monte Carlo simulation, whereby the maximum temperature as well as the electrical peak fields at the drift tubes must be taken into account. Therefore, the tube-lengths in Cavity-1 were bound to range from 16 mm to 60 mm and in Cavity-2 from 20 mm to 80 mm. On one hand, this prevents too short tubes, which have a high power density and thus a high maximum surface temperature. On the other hand, the tip of too long tubes would be cooled ineffectively due to its distant position from the stem, which is mounted on the water-cooled girder.

The cavity is made from copper plated forged mild steel and the stems, tubes, and tuners are made from massive copper. The highest heat load (about 400 K) appears in the drift tubes for our design, as they are located relatively far from the embedded water cooling system in the Interdigital H-Mode (IH) cavity's girder.

Furthermore, the cavity is equipped with three capacitive frequency tuners to allow standard operation. The tuners were specially investigated to minimize their impact on the voltage in each individual gap (below 2 % deviation from the design voltage distribution), allowing high beam quality even with mechanical expansion due to the temperature distribution.

As mentioned above, a Monte Carlo simulation (employing the beam dynamics solver Dynamion [17]) has been developed to find the optimum set of synchronous phases $\vec{\phi}$ along a cavity. The optimum has been defined by means of an objective function $f(\vec{\phi})$, targeting high beam quality (i.e., low emittance growth $\hat{\epsilon}$) and efficient energy gain ($E_{\text{target}} - E_{\text{out}}$) [14]:

$$f(\vec{\phi}) = \left(\frac{\hat{\epsilon}_{x,y} - 1}{t_{x,y}}\right)^2 + \left(\frac{\hat{\epsilon}_z - 1}{t_z}\right)^2 + \frac{E_{\text{target}} - E_{\text{out}}}{t_{\text{E}}} \tag{2}$$

A low longitudinal emittance growth is preferred. The longitudinal tolerance was set to $t_z = 0.5\,\%$ and the transverse tolerance to $t_{x,y} = 1\,\%$. A deviation from the design energy is tolerated with $t_{\text{E}}$ =50 keV.

## RESULTS

The two cavities have been designed by means of Monte Carlo optimization using Eq. (2). An intermediate energy of 700 keV/u has been adopted to separate Cavity-1 and 2, allowing Cavity-1 to be designed for high beam quality transport and Cavity-2 to be stronger oriented towards acceleration of the ion bunches. The cavities are separated by an external quadrupole triplet, offering for additional transverse focusing, which improves the beam quality of our design and also offers the required adaptability of the machine for operation with very different ion species from Protons to Uranium (A/Z ≤ 6).

The final layouts of the two cavities are depicted in Figs. 2 and 3. An average field gradient of 3 MV/m in Cavity-1 and 3.1 MV/m in Cavity-2 has been adopted, yielding a Kilpatrick value of 2.5 for both cavities (see Table 2).

The obtained set of synchronous phases of Cavity-1 (see Figure 2) is semi-sinusoidal, as present also for other APF linacs [18, 19]. The synchronous phase pattern in Cavity-2 is adapted to refocus the beam longitudinally, because it was defocused along the preceding intertank section. The effective refocusing to a 10° beam length allows embedded synchronous phases of about 0° for efficient acceleration with minor impact to the beam quality. The occurrence of negative phases below −90° is out of scope for this paper and discussed in [14].

The (average and maximum) envelopes within the cavity oscillate transversely and longitudinally in opposite direction of each other. In conventional (constant synchronous phase) linacs an oscillation of the beam length would indicate a mismatched beam. But for APF linacs this behavior is intended to allow for different focusing strength in longitudinal and transverse direction.

ISBN: 978-3-95450-240-0 ISSN: 2673-5547 doi:10.18429/JACoW-HIAT2022-TH3C2



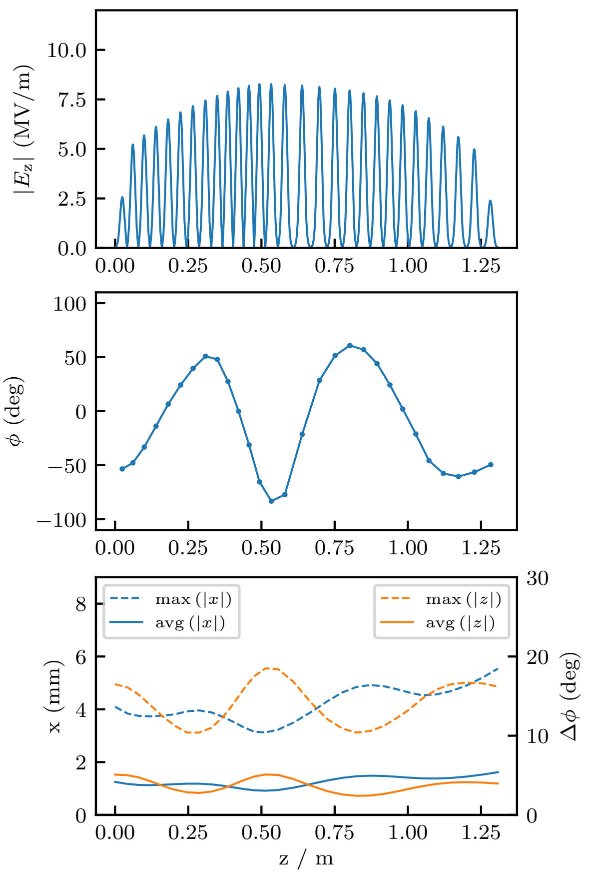


Figure 2: Gap voltages (*top*), synchronous phases (*center*) and resulting longitudinal and transverse beam envelopes (*bottom*) along Cavity-1.

Table 2: Final RF Parameters [16]

| **Property** | **Cavity-1** | **Cavity-2** |
|---|---|---|
| Design frequency | 108.408 MHz | 108.408 MHz |
| Number of gaps | 29 | 27 |
| Effective length $L_{\text{eff}}$ | 1.31 m | 1.75 m |
| Length (outer cavity) | 1.5 m | 2.0 m |
| Electric peak field | 2.47 Kilpatrick | 2.52 Kilpatrick |
| RF-Power (CW) | 20 kW | 48 kW |
| Quality factor $Q_0$ | 19000 | 22000 |
| Shunt impedance $Z_0$ | 690 MΩ/m | 425 MΩ/m |
| Max. temperature | ≈ 413 K | ≈ 441 K |
| Accelerating gradient | 3.0 MV/m | 3.1 MV/m |
| Effective accelerating gradient | 2.61 MV/m | 2.81 MV/m |
| Drift tube aperture radius | 9 mm | 9 mm |
| Drift tube outer radius | 14 mm | 17 mm |

Finally, the beam is accelerated with full transmission from 300 keV/u to 1400 keV/u within 4.5 m (1.3 m Cavity-1 + 1.5 m intertank + 1.7 m Cavity-2) with low effective emittance growth of ≤5 % (accounting for 90 % of all particles, see Table 3).

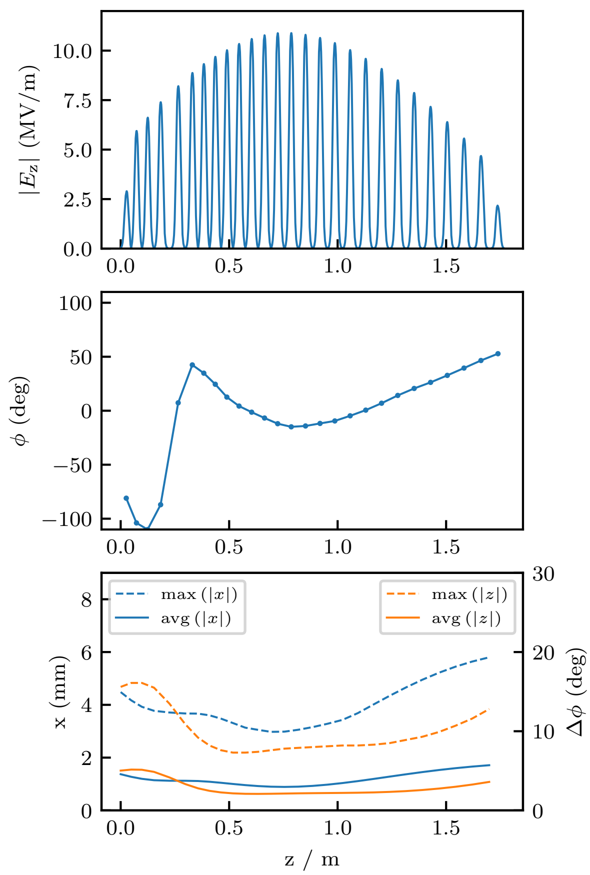


Figure 3: Gap voltages (*top*), synchronous phases (*center*) and resulting longitudinal and transverse beam envelopes (*bottom*) along Cavity-2.

Table 3: IH-DTL — Final Design Parameters and Beam Dynamics Results [14]

| **Property** | **Value** |
|---|---|
| Beam transmission | 100 % |
| Input beam energy | 300.0 keV/u |
| Output beam energy | 1400.0 keV/u |
| Mean beam spot radius | 4 mm |
| Max beam spot radius | 7 mm |
| Emittance Growth $\hat{\epsilon}_{90\%}$ | |
| x | 5.0 % |
| y | 5.0 % |
| z | 3.0 % |
| Emittance Growth $\hat{\epsilon}_{100\%}$ | |
| x | 23.0 % |
| y | 23.0 % |
| z | 17.0 % |

## CONCLUSION

A normal conduction continuous wave heavy ion Alternating Phase Focusing drift tube linac has been designed to serve as injector for the HElmholtz LInear ACcelertor. The designed DTL provides for full transmission and low

ISBN: 978-3-95450-240-0 ISSN: 2673-5547 doi:10.18429/JACoW-HIAT2022-TH3C2

emittance growth below 5 %. The associated RF layout of the cavity aims to limit heating of the cavities to 440 K and is designed so that the acceleration voltages are below a relative change of 2 %.

## REFERENCES


[1] W. Barth, R. Hollinger, A. Adonin, M. Miski-Oglu, U. Scheeler, *et al.*, "LINAC developments for heavy ion operation at GSI and FAIR," *Journal of Instrumentation*, vol. 15, no. 12, p. T12012, 2020, doi:10.1088/1748-0221/15/12/t12012

[2] W. Barth, W. Bayer, L. Dahl, L. Groening, S. Richter, *et al.*, "Upgrade program of the high current heavy ion UNILAC as an injector for FAIR," *Nucl. Instrum. Methods Phys. Res. A*, vol. 577, no. 1, pp. 211–214, 2007, doi:10.1016/j.nima.2007.02.054

[3] W. Barth, G. C. L. Dahl, P. Gerhard, L. Groening, B. Lommel, *et al.*, "High current $U^{40+}$-operation in the GSI-UNILAC," 2022.

[4] P. Spiller, R. Balss, P. Bartolome, J. Blaurock, U. Blell, *et al.*, "The FAIR heavy ion synchrotron SIS100," *Journal of Instrumentation*, vol. 15, no. 12, p. T12013, 2020, doi:10.1088/1748-0221/15/12/t12013

[5] J. Khuyagbaatar, A. Yakushev, C. E. Düllmann, D. Ackermann, L. L. Andersson, *et al.*, "Search for elements 119 and 120," *Phys. Rev. C*, vol. 102, no. 6, p. 064 602, 2020, doi:10.1103/PhysRevC.102.064602

[6] W. Barth, K. Aulenbacher, M. Basten, F. Dziuba, V. Gettmann, *et al.*, "A superconducting CW-linac for heavy ion acceleration at GSIX," *EPJ Web Conf.*, vol. 138, p. 01 026, 2017, doi:10.1051/epjconf/201713801026

[7] M. Schwarz, S. Yaramyshev, K. Aulenbacher, W. Barth, M. Basten, *et al.*, "Reference beam dynamics layout for the SC CW heavy ion HELIAC at GSI," *Nucl. Instrum. Methods Phys. Res. A*, p. 163 044, 2019, doi:10.1016/j.nima.2019.163044

[8] S. Minaev, U. Ratzinger, H. Podlech, M. Busch, and W. Barth, "Superconducting, energy variable heavy ion linac with constant $\beta$, multicell cavities of CH-type," *Phys. Rev. ST Accel. Beams*, vol. 12, p. 120 101, 2009, doi:10.1103/PhysRevSTAB.12.120101

[9] W. Barth, K. Aulenbacher, M. Basten, M. Busch, F. Dziuba, *et al.*, "First heavy ion beam tests with a superconducting multigap CH cavity," *Phys. Rev. Accel. Beams*, vol. 21, p. 020 102, 2018, doi:10.1103/PhysRevAccelBeams.21.020102

[10] W. Barth, K. Aulenbacher, M. Basten, M. Busch, F. Dziuba, *et al.*, "Superconducting CH-cavity heavy ion beam testing at GSI," *J. Phys. Conf. Ser.*, vol. 1067, p. 052 007, 2018, doi:10.1088/1742-6596/1067/5/052007

[11] J. H. Adlam, "A method of simultaneously focusing and accelerating a beam of Protons," *AERE GP/M*, no. 146, 1953.

[12] M. L. Good, "Phase-reversal focusing in linear accelerators," *Phys. Rev.*, vol. 92, p. 538, 1953, Berkeley Radiation Laboratory report.

[13] I. B. Fainberg, "Alternating phase focusing," in *Proc. Conf. on High Energy Accelerators*, 1956, doi:10.5170/CERN-1956-025.91

[14] S. Lauber *et al.*, "An alternating phase focusing injector for heavy ion acceleration," (submitted to NIMA).

[15] S. Lauber, M. Basten, S. Yaramyshev, K. Aulenbacher, W. Barth, *et al.*, "Alternating phase focusing beam dynamics for drift tube linacs," in *Proc. International Conference on Accelerators for Research and Sustainable Development: From Good Practices Towards Socioeconomic Impact*, 2022 (to be published).

[16] M. Basten *et al.*, "Continuous wave interdigital H-mode cavities for alternating phase focusing heavy ion acceleration," (submitted to RSI).

[17] S. Yaramyshev, W. Barth, L. Groening, A. Kolomiets, and T. Tretyakova, "Development of the versatile multi-particle code DYNAMION," *Nucl. Instrum. Methods Phys. Res. A*, vol. 558, no. 1, pp. 90–94, 2006, doi:10.1016/j.nima.2005.11.018

[18] M. Otani, T. Mibe, M. Yoshida, K. Hasegawa, Y. Kondo, *et al.*, "Interdigital H-mode drift-tube linac design with alternative phase focusing for Muon linac," *Phys. Rev. Accel. Beams*, vol. 19, no. 4, p. 040 101, 2016, doi:10.1103/PhysRevAccelBeams.19.040101

[19] Y. Iwata, S. Yamada, T. Murakami, T. Fujimoto, T. Fujisawa, *et al.*, "Alternating-phase-focused IH-DTL for an injector of heavy-ion medical accelerators," *Nucl. Instrum. Methods Phys. Res. A*, vol. 569, no. 3, pp. 685–696, 2006, doi:10.1016/j.nima.2006.09.057