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FIRST ACCELERATION OF HEAVY ION BEAMS WITH A SUPERCONDUCTING CONTINOUS WAVE HIM/GSI CW-LINAC

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Abstract

First acceleration of heavy ion beams with a superconducting continuous wave HIM/GSI cw-Linac. After successful RF-testing of a new superconducting Linac RF-cavity at GSI Helmholtzzentrum für Schwerionenforschung and a short commissioning and ramp up time of some days, this 15-gaps Crossbar H-cavity accelerated first time heavy ion beams with full transmission up to the design beam energy. The design acceleration gain of 3.5 MV inside a length of less than 70 cm has been verified with heavy ion beam of up to 1.5 pμA. The measured beam parameters show a nice beam quality. The machine commissioning with beam is a milestone of the R&D work of Helmholtz Institute Mainz (HIM) and GSI in collaboration with IAP Goethe-University Frankfurt in development of the superconducting heavy ion continuous wave linear accelerator cw-Linac.

INTRODUCTION

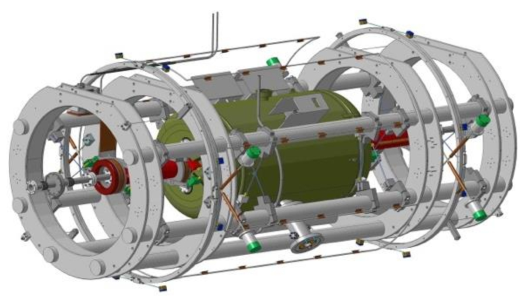

Figure 1: Demonstrator CH-cavity (CH0) with two sc-solenoids inside the support frame.

The design and construction of cw high intensity Linacs is a crucial goal of worldwide accelerator technology development [1]. Above all, compactness of a particle accelerator is a beneficial demand for the development of high intensity cw proton and ion Linacs [2]. In the low- and medium-energy range cw-Linacs can be used for several applications, as boron-neutron capture therapy, high productivity isotope generation and material science. A high-energy Linac is an integrated and essential part of several large scale research facilities, as spallation neutron sources or accelerator driven systems. Thus the study and investigation of the design, operation and optimization of a cw-Linac, as well as progress in elaboration of the superconducting technology [3] is of high relevance.

For the HIM/GSI cw-Linac HELIAC (HElmholtz LInear ACcelerator) several superconducting CH cavities operated at 217 MHz should provide for ion acceleration to beam energies between 3.5 MeV/u and 7.3 MeV/u, while the energy spread should be kept smaller than ±3 keV/u. The cw-Linac allows the acceleration of highly charged ions with a mass to charge ratio of up to 6. For proper beam focusing superconducting solenoids have to be mounted between the CH cavities. The general parameters are listed in Table 1 [4]. R&D and prototyping (demonstrator project) [5] in preparation of the proposed HELIAC is assigned to a collaboration of GSI, HIM and GUF. The demonstrator setup is located in straightforward direction of the GSI–High Charge State Injector (HLI).

Table 1: Design Parameters of the cw-Linac

Mass/charge		6
Frequency	MHz	216.816
Max. beam current	mA	1
Injection energy	MeV/u	1.4
Output energy	MeV/u	3.5 – 7.3
Output energy spread	keV/u	±3
Length of acceleration	m	12.7
Sc CH-cavities	#	9
Sc solenoids	#	7

The demonstrator comprises a 15 gap sc CH-cavity (CH0) embedded by two superconducting solenoids; all three components are mounted on a common support frame (see Fig. 1) [6]. The beam focusing solenoids provide maximum fields of 9.3 T, the free beam aperture is 30 mm. A configuration of one main Nb_3Sn-coil and two compensation coils made from NbTi shields the maximum magnetic field of 9.3 T within a longitudinal distance of 10 cm down to 30 mT. The solenoids are connected to LHe ports inside the cryostat by copper tapes allowing dry cooling. The sc CH structure CH0 is the key component and offers a variety of research and development [7].

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PREPARATION OF RF-CAVITY AND SUPPLY SYSTEM

The sc 15 gap CH-cavity is directly cooled with liquid helium, supported by a helium jacket made by titanium. The vendor Research Instruments GmbH (RI) provided for sufficient cavity preparation. After high pressure rinsing (HPR) a performance test in a vertical cryostat at low RF power was performed at IAP, reaching gradients up to 7 MV/m. After the final assembly of the helium vessel and further HPR preparation at RI, the cavity was tested again, but in a horizontal cryostat. As shown in Fig. 2, the cavity showed improved performance due to an additional HPR treatment, the initial design quality factor Q_0 has been exceeded by a factor of four, a maximum accelerating gradient of E_{acc} = 9.6 MV/m at $Q_0 = 8.14\times10^8$ has been achieved [8-10]. Prior beam commissioning of the cavity, the RF power couplers [11-12] were tested and conditioned with a dedicated test resonator [13].

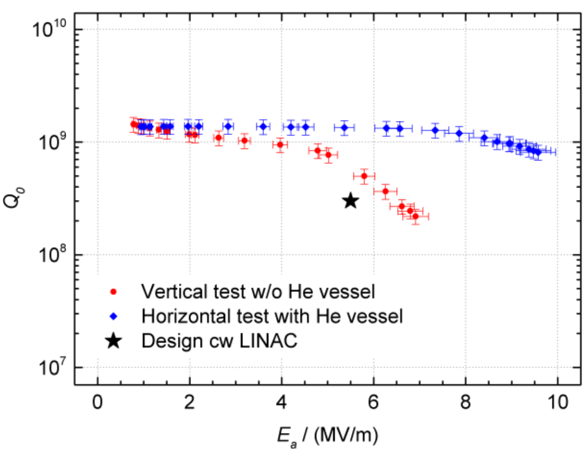

Figure 2: RF-testing of CH-demonstrator cavity - improved performance (add. HPR), low field emission rate, high field gradient, therm. quenching beyond 9.6 MV/m.

The couplers are equipped with sensors to control the temperature of the ceramic windows and Langmuir probes to detect the multipacting current. A first conditioning [14] has been performed with pulsed RF (up to 5 kW) and finally in cw-mode (up to 2 kW). Further increase of the forward cw-RF power leads to a temperatures rise of more than 80°C at the ceramic window, potentially sufficient to damage the coupler. During the operation, the "cold" coupler window has been anchored to the liquid nitrogen supply tube by copper ribbons. In a clean room of class ISO4 the power couplers were integrated in the RF-cavity, as well as three frequency tuners, developed at IAP [15] and manufactured at GSI for the control of resonance frequency. Furthermore, the CH-cavity and both solenoids were assembled on a string. After leak testing of the accelerating string the complete cold mass was integrated [16] into the cryostat outside of the clean room.

DEMONSTRATOR-BEAM DYNAMICS

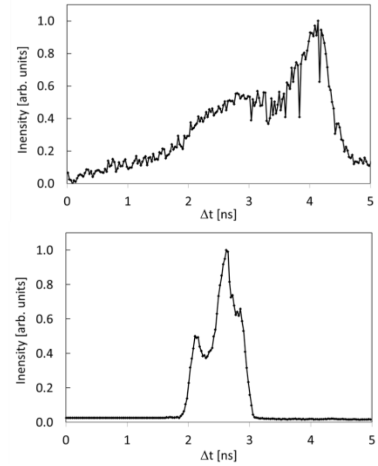

Figure 3: Bunch shape measurement for HLI beam at 1.366 MeV/u (top) and at same energy for matched case with rebuncher R1 and R2 (down).

The beam dynamics layout behind the HLI at 1.4 MeV/u has been simulated in advance. In a preparing beam test run, it could be confirmed, that the room temperature focusing quadrupoles (triplet and two duplets) and two rebuncher cavities are sufficient to provide for full 6D-matching to the demonstrator [17]. At the same time, the input beam is axially symmetric for further solenoid focusing due to especially chosen gradients, while bunch length (see Fig. 3) and momentum spread are matched as well.

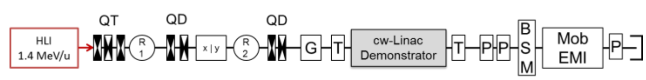

Figure 4: Layout of matching line to the Demonstrator and beam diagnostics test bench; QT/QD = quadrupole triplet/duplet, R = rebuncher, X/Y = beam steerer, G = SEM-grid, T = current transformer, P = phase probe, BSM = bunch shape monitor, EMI = emittance meter.

The transport line (see Fig. 4) provides also for beam instrumentation. Moreover, beam transformers, Faraday cups, SEM-profile grids, a dedicated emittance meter, a bunch structure monitor and phase probe pickups (beam energy measurements applying time of flight) provide for proper beam characterization behind the demonstrator.

The beam dynamics layout of the sc cw-Linac is based on the EQUUS (EQUidistant mUltigap Structure) concept, as proposed in [18]. It features high acceleration efficiency with longitudinal and transversal stability, as well as a straightforward energy variation. Energy variation can easily be achieved by varying the applied RF-voltage or the RF-phase of the amplifier. Highly charged ions with a mass-to-charge ratio of maximum 6 will be accelerated from 1.4 MeV/u up to 3.5 - 7.3 MeV/u. Energy variation while maintaining a high beam quality is the core issue with respect to beam dynamics, simulated using advanced software [19-20] and previously developed algorithms [21-24]. The cell length inside an EQUUS designed cavity is

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kept constant and is fixed with a higher (geometrical) β compared to the injection beam energy (constant-β structure). As a consequence the constant-β structure leads to a sliding movement in longitudinal phase space. Trajectory and energy gain depend strongly on the initial phase at the first gap centre and the difference between particle energy and design energy. The corresponding transversal emittance evolution has been measured in a broad range with small emittance growth.

Beam dynamics behind the HLI has been carried out with the LORASR code (see Fig. 5) [25]. The quadrupole triplet and duplets provide for an axially symmetric input beam for further solenoid focusing. The beam is matched to the demonstrator in the 6d phase space.

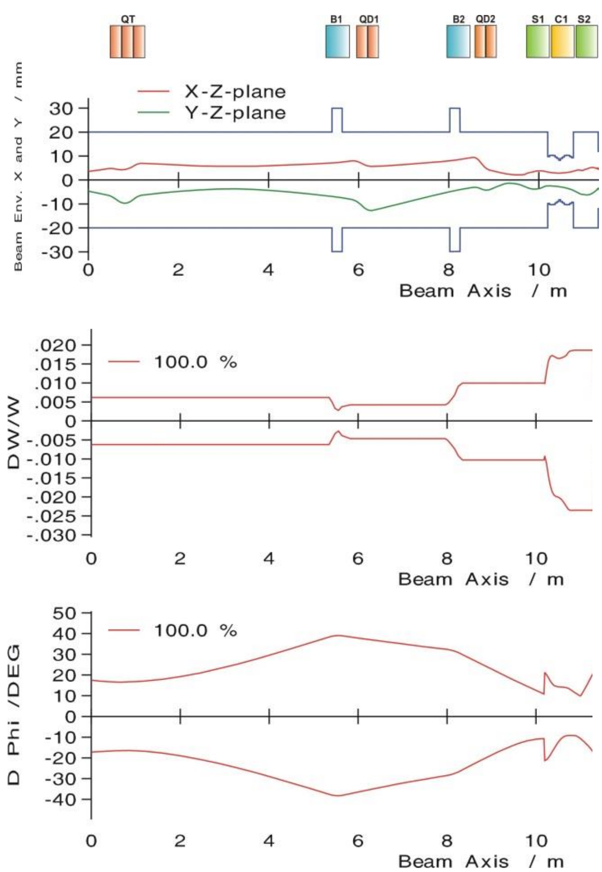

Figure 5: Beam envelopes (matching the demonstrator).

FIRST BEAM ACCELERATION

At June 2017, after successful RF-testing of the sc RF-cavity in 2016, set up of the matching line to the demonstrator and a short commissioning and ramp up time of some days, the CH0-cavity first time accelerated heavy ion beams (Ar^{11+}) with full transmission up to the design beam energy of 1.866 MeV/u (ΔW_{kin} = 0.5 MeV/u) [26], as shown in Fig. 6. For the first beam test the sc cavity was powered with 10 Watt of net RF power, providing an accelerating voltage of more than 1.6 MV inside a length of 69 cm. Further on the design acceleration gain of 3.5 MV has been verified and even exceeded by acceleration of beam with high rigidity (A/q = 6.7). As summarized in Table 2, argon and helium ion beams with different charge state from an ECR ion source ($^{4}He^{2+}$, $^{40}Ar^{11+}$, $^{40}Ar^{9+}$, $^{40}Ar^{6+}$) were accelerated at HLI with the demonstrator. For longitudinal beam matching the rebuncher settings were adapted according to the mass of charge ratio A/q, as well as the acceleration voltage.

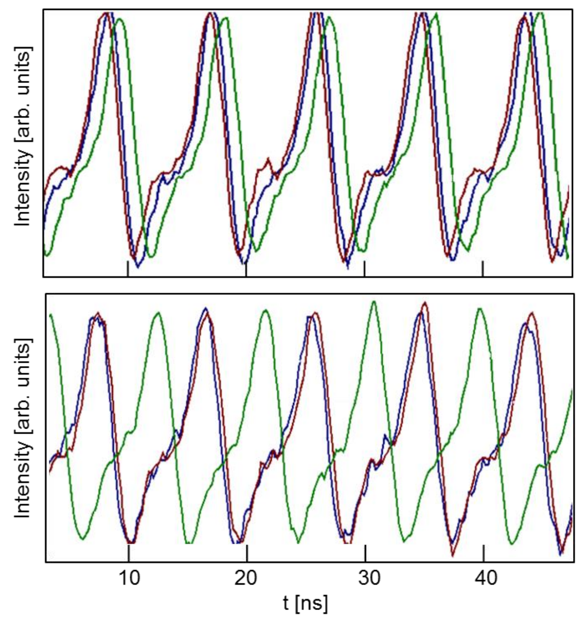

Figure 6: First RF-acceleration with the 216.816 MHz-CH-cavity; measured Ar^{11+}-phase probe signals from HLI beam at 1.366 MeV/u (top), HLI-RF-frequency is 108.408 MHz (T = 9.224 ns). By acceleration up to the nominal beam energy (down), the coarse time of flight between blue and red signal is slightly reduced. The time of flight for the fine measurement between red and green signal is significantly shifted, according to the beam energy of 1.866 MeV/u.

Table 2: RF- Parameters for Matched Case

A/q	**He^{2+}** *2.0*	**Ar^{11+}** *3.6*	**Ar^{9+}** *4.4*	**Ar^{6+}** *6.7*
$U_{Reb1,eff.}$ [kV]	8.3	15.0	18.3	27.9
$U_{Reb2,eff.}$ [kV]	22.7	40.8	49.9	75.9
$E_{acc,CH}^{*}$[MV/m]	1.8	3.2	3.9	5.9
U_0 [MV]	1.2	2.2	2.7	4.0

* E_{acc} = *transit time factor × total accelerating voltage/(n×0.5×βλ)*

A maximum average beam intensity of 1.5 pμA has been achieved, limited only by the beam intensity of the ion source and maximum duty factor (25%) of the HLI, while the CH-cavity was operated in cw-mode. All presented measurements were accomplished with high duty factor beam and maximum beam intensity from the HLI.

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SYSTEMATIC BEAM INVESTIGATIONS

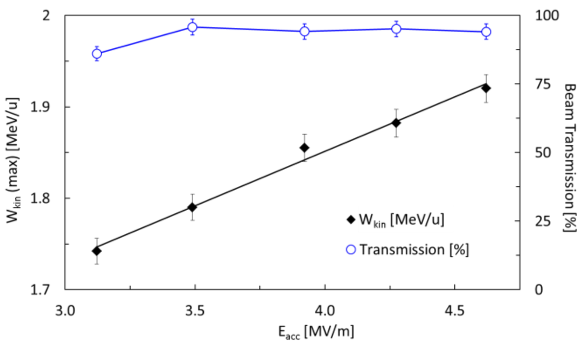

Figure 7: Acceleration of an Ar^{9+}-beam; maximum achieved beam energy and transmission as function of the (eff.) accelerating gradient [26].

A full measured 2D-scan of beam energy and beam transmission for a wide area of different accelerating fields and RF-phases has been performed. The linear increase of beam energy with ramped accelerating gradient (as shown in Fig. 7) could be observed for different RF-phase settings, while the beam transmission is kept above 90 %. In general these measurements confirm impressively the EQUUS beam dynamics, featuring effectively beam acceleration up to different beam energies without particle loss and significant beam quality degradation. As measured with helium beam, for lighter ions a maximum beam energy of up to 2.2 MeV/u could be reached with the demonstrator cavity, but with reduced beam quality.

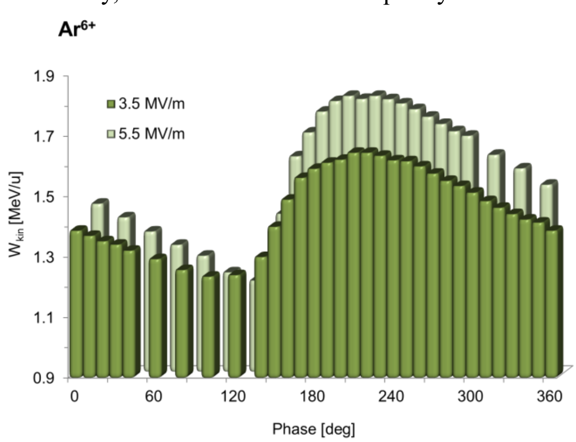

Figure 8: Phase-scan of Ar^{6+}-beam energy for 3.5 MV/m and 5.5 MV/m [26].

With Ar^{6+}-beam ($A/q = 6.7$), an energy gain above 0.5 MeV/u could be reached with an accelerating gradient of 6 MV/m. As an example, Fig. 8 shows a fully measured 360° phase scan for two different accelerating gradients (3.5 MV/m and 5.5 MV/m). All individual data as well as the characteristic shapes of the phase scans are in good agreement according to the accelerating gradient. For an increased gradient the maximum beam energy at an RF-phase of 210° boosts as well, while the minimum beam energy at 130° could be decreased down to 1.2 MeV/u. The bunch length detected with a bunch shape monitor (BSM) [27-28] was measured as very sensitive to RF-phase changes. A change of RF-phase by 30° only, leads to a significant change of bunch length (by more than a factor of 4), while the beam transmission is not affected. For further matching to another CH-cavity, the adjustment of the beam energy setting by changing the RF-amplitude is more favourable - compared to changing the RF-phase - as no significant bunch shape change could be observed.

PHASE SPACE MEASUREMENTS

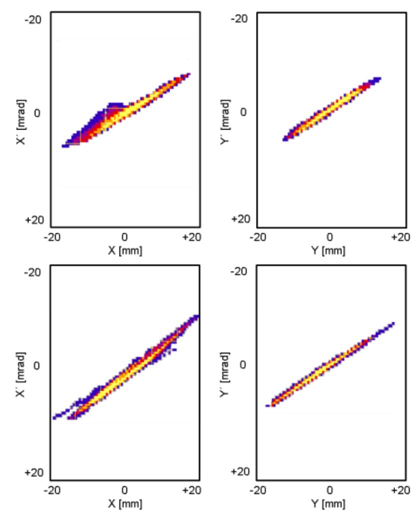

Figure 9: Ar^{9+}-beam emittance at 1.366 MeV/u (top) and at 1.85 MeV/u (down); normalized (horizontal) emittance growth is measured for 15% [26].

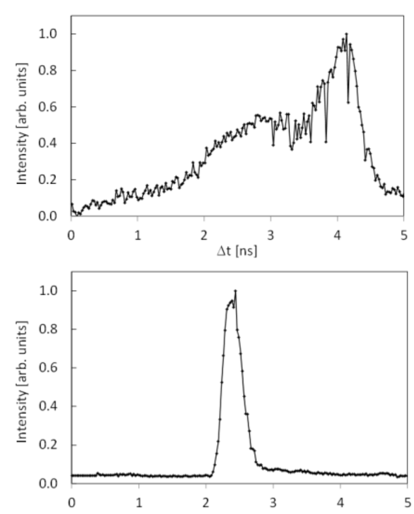

Figure 10: Bunch shape of Ar^{9+}-beam at 1.366 MeVu (top) and fully matched after acceleration to 1.85 MeV/u (down) [26].

The beam quality has been characterized by measuring the phase space distribution, as shown in Fig. 9. The measured emittance of the argon beam, delivered by the ECR and HLI, shows an adequate beam quality: the total 90% horizontal beam emittance is measured for 0.74 µm, while

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in the vertical plane the total 90% emittance is 0.47 µm only. All measurements have been performed without solenoidal field, therewith any additional emittance degradation effects by different beam focusing could be avoided. The measured (normalized) beam emittance growth at full beam transmission is sufficiently low: 15 % (horizontal plane) and 10% (vertical plane). Selective measurements at other RF-amplitudes and -phases, as well as for other beam rigidities confirmed the high (transversal) beam performance in a wide range of different parameters. Besides beam energy measurements the bunch shape was measured after successful matching (see Fig. 10) with the Feschenko monitor [28]. As shown, an impressive small minimum bunch length of about 300 ps (FWHM) and 500 ps (base width) could be detected, sufficient for further matching to and acceleration in future RF-cavities

ADVANCED R&D

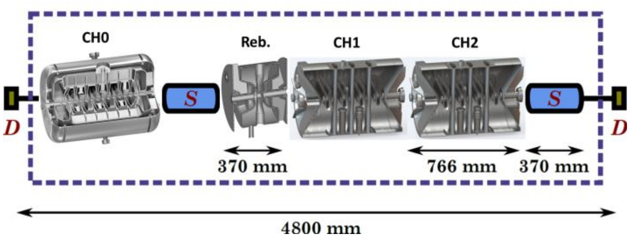

Figure 11: Advanced cryo module layout containing demonstrator CH0 cavity, two short CH cavities, a rebuncher and two solenoids.

Up to now, the reference design for the cw-Linac dates back to [4]. Meanwhile many experiences have been gained in design, fabrication and operation of sc CH-cavities and the associated components. In this context, a revision of the Linac layout was recommended. Optimized cavity layouts [29] resulted in modified voltage distributions. Furthermore, the layout - now with three CH-cavities and a rebuncher (see Fig. 11) [30] per cryo module - has been specified with more details. It features high acceleration efficiency with longitudinal and transversal stability, as well as a straightforward energy variation. Energy variation can easily be achieved by varying the applied RF-voltage or the RF-phase of the amplifier. Highly charged ions with a mass-to-charge ratio of maximum 6 will be accelerated from 1.4 MeV/u up to 3.5- 7.3 MeV/u. Energy variation while maintaining a high beam quality is the core issue with respect to beam dynamics, simulated using advanced software [19-20] and previously developed algorithms [21, 24, 31-33].

Promising power and beam tests with the 15-gap CH0 showed successfully, that higher accelerating gradients can be achieved, thus leading to a more efficient design with four cryo modules (CM1-CM4). Consequently an advanced beam dynamics layout [34] is carried out with respect to the ambitious beam-, RF- and mechanical requirements. Fig.12 shows phase space portraits based on the recent advanced layout applying a max. accelerating gradient of 7.1 MeV/u. Applying the advanced beam dynamics layout for lower mass to charge ratios, significant higher beam energies could be achieved (e.g. up to 14.6 MeV for a p^+-beam).

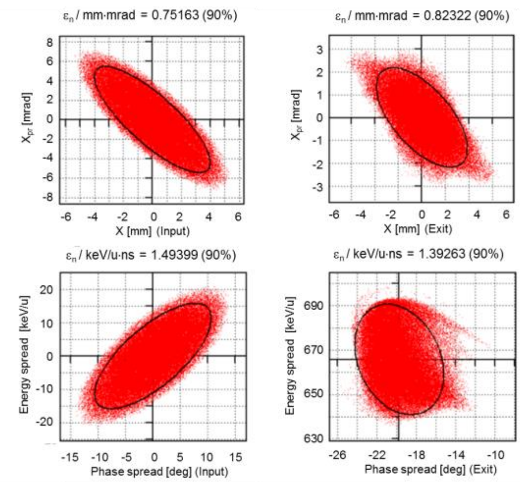

Figure 12: Phase space portraits applying an advanced Linac layout; top: x - x', bottom: $\Delta\varphi$ - ΔW, left: CM1-Input (emittance size as at HLI), right: Output of CM4 [35].

SUMMARY

An advanced cw-Linac approach, based on a standard cryomodule equipped with three CH-cavities and a sc-rebuncher, demonstrates the high capabilities due to energy variation preserving the beam quality, as shown in the first beam test. The design acceleration gain of the first sc CH-cavity was achieved with heavy ion beams even above the design mass to charge ratio at full transmission and maximum available beam intensity [35]. The beam quality was measured as excellent in a wide range of different beam energies, This new design could provide beam acceleration for a wide range of different ions (protons to uranium) above the design beam energy, featuring the ambitious GSI-user program [36], while the GSI-UNILAC is upgraded for short pulse high current FAIR-operation. [37]. The achieved demonstrator beam commissioning confirms the capabilities of the applied EQUUS beam dynamics design and is a major milestone paving the way to the cw-Linac HELIAC.

ACKNOWLEDGEMENTS

Successful beam testing could not be accomplished without strong support of highly committed people from different GSI-departments. The beam test is a milestone of the R&D work of HIM and GSI in collaboration with GUF in preparation of a superconducting heavy ion continuous wave linear accelerator.

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