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SUPERCONDUCTING CH-CAVITY HEAVY ION BEAM TESTING AT GSI

W. Barth[1,2], K. Aulenbacher[1,3], M. Basten[4], M. Busch[4], F. Dziuba[1], V. Gettmann[1], M. Heilmann[2], T. Kürzeder[1], M. Miski-Oglu[1], H. Podlech[4], A. Rubin[2], A. Schnase[2], M. Schwarz[4], S. Yaramyshev[2]
[1] Helmholtz Institute Mainz, Germany
[2] GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt, Germany
[3] Johannes Gutenberg-Universität Mainz, Mainz, Germany
[4] IAP Goethe-Universität Frankfurt, Frankfurt, Germany

Abstract

Recently the first section of a standalone superconducting (sc) continuous wave (cw) heavy ion Linac as a demonstration of the capability of 217 MHz multi gap Crossbar H-mode structures (CH) has been commissioned and extensively tested with beam from the GSI High Charge State Injector (HLI). The demonstrator set up reached acceleration of heavy ions up to the design beam energy and beyond. The required acceleration gain of 0.5 MeV/u was achieved with heavy ion beams even above the design mass to charge ratio at maximum available beam intensity and full beam transmission. This contribution presents systematic beam measurements with varying RF-amplitudes and -phases of the CH-cavity, as well as versatile phase space measurements for heavy ion beams with different mass to charge ratio. The worldwide first and successful beam test with a superconducting multi gap CH-cavity is a milestone of the R&D work of Helmholtz Institute Mainz (HIM) and GSI in collaboration with Goethe University Frankfurt (GUF) in preparation of the sc cw heavy ion Linac project and other cw-ion beam applications.

INTRODUCTION

R&D and prototyping (demonstrator project) [1,2] in preparation of the proposed HElmholtz LInear ACcelerator (HELIAC) is assigned to a collaboration of GSI, HIM and GUF. The demonstrator setup, embedded in a new radiation protection cave, is located in straightforward direction of the HLI (Fig. 1).

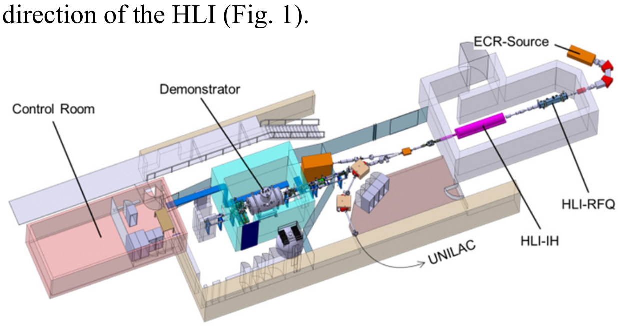

Figure 1: CH-cavity test environment at GSI.

The liquid helium (LHe) supply is covered by a 3000 l tank, while the consumed helium gas is collected in a 25 m^3 recovery balloon and bottled by a compressor. The demonstrator [3] comprises a 15 gap sc CH-cavity (CH0) embedded by two superconducting solenoids; all three components are mounted on a common support frame [4-6]. The support frame, as well as the accelerator components, are suspended each by eight tie rods in a cross-like configuration balancing the mechanical stress during the cool down and warm up. 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 (Fig. 2) is the key component and offers a variety of research and development. [7]

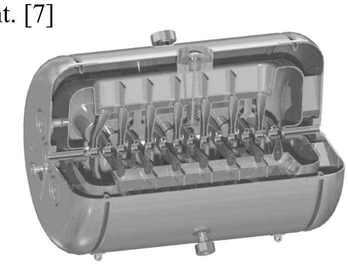

Figure 2: Sectional drawing of the 15-gap demonstrator CH-cavity (CH0).

EQUUS BEAM DYNAMICS AND ADVANCED LINAC LAYOUT

The beam dynamics layout of the entire sc cw-Linac (see Fig. 3) is based on the EQUidistant mUltigap Structure (EQUUS) concept, as proposed in [8]. 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.

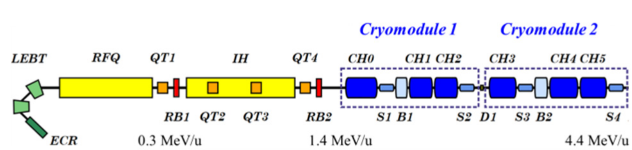

Figure 3: Advanced layout with three sc CH-cavities per cryomodule (two of four cryomodules are shown). Captions: QT = Quadrupole Triplet, RB = Rebuncher, S = Solenoid, B = 2-Gap-Buncher, D = Diagnostics.

Energy variation while maintaining a high beam quality is the core issue with respect to beam dynamics, simulat-

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ed using advanced software [9,10] and previously developed algorithms [11-16]. The cell length inside an EQUUS designed cavity is 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.

Table 1: CW-Linac Beam Energies

Cryo Module	**Cavity**	**Output energy [MeV/u]**		
		A/q=6	***A/q=3***	***A/q=1***
	HLI	*1.4*	*1.4*	*1.4*
CM1	CH0	2.1	2.2	3.0
	CH1	2.6	3.0	4.2
	CH2	2.9	3.6	4.6
CM2	CH3	3.4	4.3	5.7
	CH4	3.8	4.8	6.3
	CH5	4.2	5.5	7.7
CM3	CH6	4.7	6.2	8.6
	CH7	5.2	7.0	9.9
	CH8	5.8	7.8	10.9
CM4	CH9	6.4	8.7	12.3
	CH10	7.0	9.5	13.2
	CH11	7.6	10.5	14.6

Up to now, the reference design for the cw-Linac dates back to [17]. 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 (Fig. 3 and Fig. 4). Optimized cavity layouts [18] resulted in modified voltage distributions. Furthermore, the layout - now with three CH-cavities and a rebuncher [19] per cryo module - has been specified with more details.

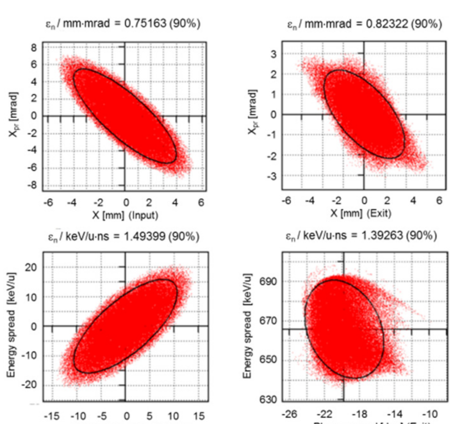

Figure 4: Phase space portraits applying an advanced Linac layout; top: x - x', bottom: $\Delta\varphi$ - ΔW, left: CM1-Input (emittance size as at HLI), right: Output of CM4 [20].

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 [20] is carried out with respect to the ambitious beam-, RF- and mechanical requirements. Fig. 4 shows phase space portraits based on the recent advanced layout applying a max. accelerating gradient of 7.1 MeV/u. In Table 1 the achievable beam energies for the cw-linac applying the advanced beam dynamics layout is shown for different mass to charge ratios; e.g. a proton beam could be accelerated up to 14.6 MeV.

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) [21]. 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 ECR ion source ($^{4}He^{2+}$, $^{40}Ar^{11+}$, $^{40}Ar^{9+}$, $^{40}Ar^{6+}$) were accelerated at HLI for further beam tests 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 U.

Table 2: RF- Parameters for Matched Case

	He^{2+}	**Ar^{11+}**	**Ar^{9+}**	**Ar^{6+}**
A/q	*2.0*	*3.6*	*4.4*	*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.

SCANS OF AMPLITUDE, PHASE AND BUNCH STRUCTURE

In Fig. 5 and 6 a full measured 2D-scan of beam energy and beam transmission for a wide area of different accelerating fields and RF-phases is depicted. The linear increase of beam energy with ramped accelerating gradient

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could be observed for different RF-phase settings, while the beam transmission is kept above 90 %. To aim for the maximum beam energy at a given accelerating gradient the RF-phase has to be adapted slightly. 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.

The bunch length detected with a bunch shape monitor (BSM) [22,23] 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 effected. 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.

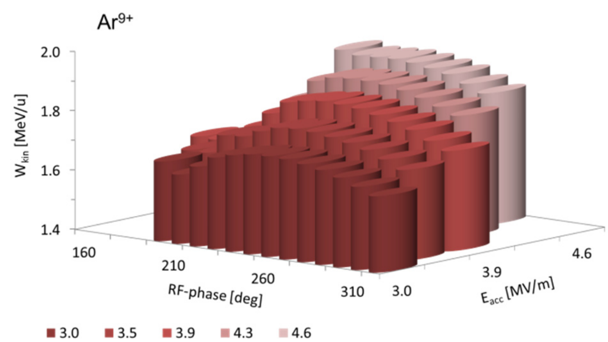

Figure 5: 2D-scan of Ar^{9+}-beam energy versus accelerating gradient and RF-phase [21].

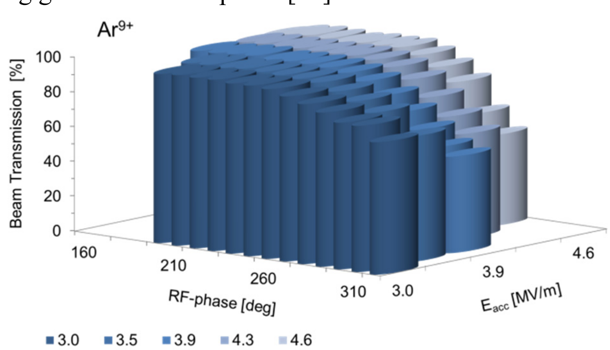

Figure 6: 2D-scan of Ar^{9+}-beam transmission versus accelerating gradient and RF-phase [21].

PHASE SPACE MEASUREMENTS

The beam quality has been characterized by measuring the phase space distribution. 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 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. 7) with the Feschenko monitor [23]. 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.

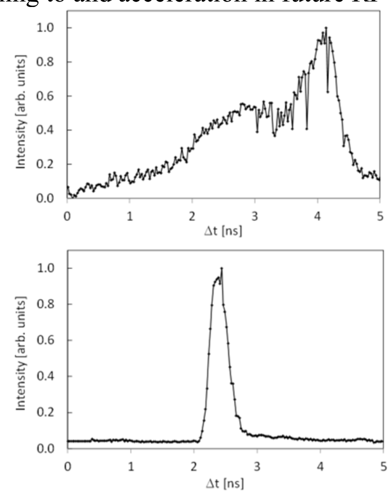

Figure 7: Bunch shape of Ar^{9+}-beam at 1.366 MeVu (top) and fully matched at 1.85 MeV/u (down) [21].

SUMMARY

The achieved demonstrator beam commissioning is a major milestone paving the way to the cw-Linac HELIAC. The design acceleration gain was achieved with heavy ion beams even above the design mass to charge ratio at full transmission and maximum available beam intensity from the HLI. The beam quality was measured as excellent in a wide range of different beam energies, confirming the capabilities of the applied EQUUS beam dynamics design. An advanced cw-Linac layout based on four cryomodules, each equipped with three CH-cavities and a sc-rebuncher [24,25], demonstrates the high capabilities due to energy variation preserving the beam quality, as shown in the first beam test. 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 [26], while the GSI-UNILAC is upgraded for short pulse high current FAIR-operation. [27-32]

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