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FURTHER LAYOUT INVESTIGATIONS FOR A SUPERCONDUCTING CW-LINAC FOR HEAVY IONS AT GSI

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Abstract

Very compact accelerating-focusing structures, as well as short focusing periods, high accelerating gradients and very short drift spaces are strongly required for superconducting (sc) accelerator sections operating at low and medium beam energies. To keep the GSI-Super Heavy Element program competitive on a high level and even beyond, a standalone sc continuous wave Linac in combination with the GSI High Charge State injector (HLI), upgraded for CW-operation, is envisaged. The first Linac section (financed by HIM and GSI) as a demonstration of the capability of 217 MHz multi gap Crossbar H-structures (CH) is still in the beam commissioning phase, while an accelerating gradient of 9.6 MV/m (4 K) at a sufficient quality factor has been already reached. Recently the overall Linac design, based on a standard cryomodule, comprising three CH cavities, a rebuncher section and two 9.3 T-solenoidal lenses, has to be fixed. This paper presents the status of the Linac layout studies as well as the integration in the GSI accelerator facility.

INTRODUCTION

An UNILAC upgrade program is ongoing, designated to prepare for high intensity high current synchrotron injector operation for Facility of Antiproton and Ion Research (FAIR) [1-3]. As a result high duty factor beam time availability for SHE-research at GSI UNILAC will be strongly diminished due to the duty factor limitation for FAIR injector operation. Besides, an upgrade program of the HLI was already initialized comprising a new 18 GHz Electron Cyclotron Resonance in source (ECR), a CW capable RFQ and an IH-DTL [4], keeping the SHE program at GSI competitive [5]. An additional standalone sc CW-Linac [6] is assumed to meet the demands of the experimental program at its best. With significantly higher beam intensity the SHE production rate will be increased as well.

The design and construction of CW high intensity Linacs is a crucial goal of worldwide accelerator technology development [7-10]. Above all, compactness of a particle accelerator is a beneficial demand for the development of high intensity CW proton and ion Linacs [11-13]. 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 (Fig. 1), is of high relevance.

Figure 1: CW-Linac demonstrator cavity@new clean room.

CW-LINAC LAYOUT AND R&D

Nine superconducting CH cavities operated at 217 MHz 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. A conceptual layout [6] of this sc CW-Linac was worked out eight years ago. It 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 CH cavities. The general parameters are listed in Table 1.

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

R&D and prototyping (demonstrator project) [14, 15] in preparation of the proposed CW-Linac is assigned to a collaboration of GSI, HIM and IAP. The demonstrator

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setup, embedded in a new radiation protection cave, is located in straightforward direction of the HLI (Fig. 2).

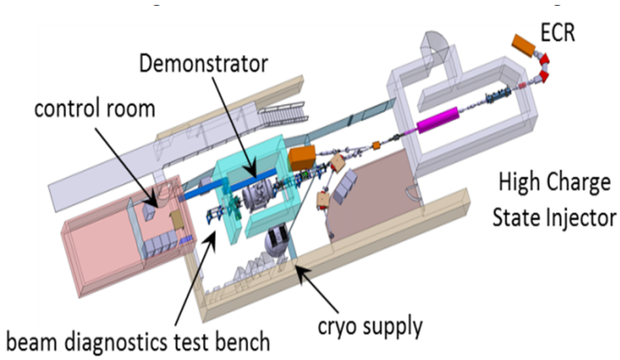

Figure 2: CH-multi cavity test environment@GSI.

The liquid helium (LHe) supply is covered by a 3000 l tank, while the consumed helium is collected in a 25 m^3 recovery balloon and bottled by a compressor. For 6D-beam matching two rebuncher cavities and an additional quadrupole doublet are in use. 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) provides for proper beam characterization in front and behind of the demonstrator.

The demonstrator [16] comprises the superconducting CH cavity (Fig. 3) embedded by two superconducting solenoids; all three components are mounted on a common support frame (Fig. 4) [17, 18]. 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 cooldown and warm up (Fig. 4). The beam focusing solenoids provide maximum fields of 9.3 T, the free beam aperture is 30 mm. A configuration of one main coil out of NbSn 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 [14]. The solenoids are connected to LHe ports inside the cryostat by copper tapes allowing dry cooling.

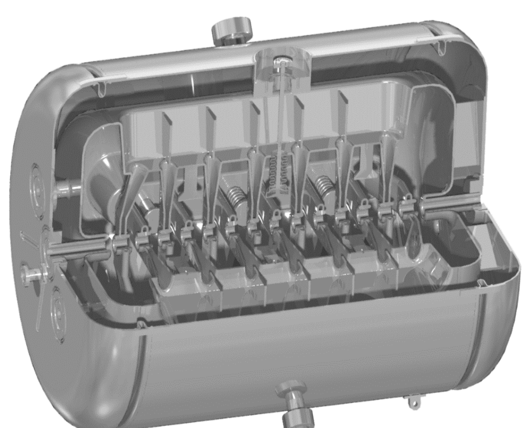

Figure 3: Sectional drawing of the 15-gap demonstrator CH-cavity [19].

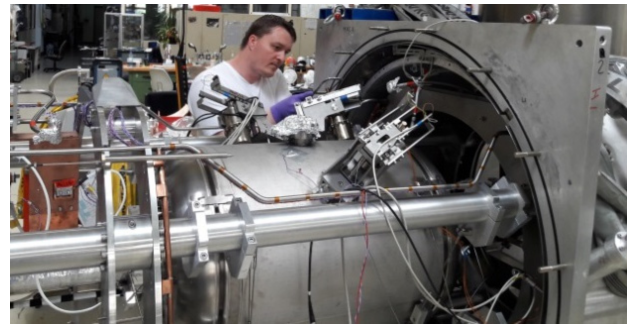

Figure 4: Installation of demonstrator cryo module comprising CH cavity embedded by two sc solenoids on a support frame.

The sc CH structure (Fig. 3) is the key component and offers a variety of research and development. The cavity is directly cooled with LHe supported by a helium jacket out of titanium. The vendor RI (Research Instruments GmbH, Germany) provided for sufficient cavity preparation. After high pressure rinsing (HPR) a performance test at low temperature (4.2 K) and with low RF power was performed at IAP [19]. Three piezo frequency tuners are manufactured at GSI, tuning the resonance frequency, while RF-operation. Therefore, a tuner dummy was already tested at IAP [20]. After the final assembly of the helium vessel and further HPR preparation at RI, the cavity was tested again in a horizontal cryo module. At a low field level a maximum Q-value (Q_0) of $1.37 \cdot 10^9$ has been achieved, 4.9 % lower in comparison to the first (vertical) test - caused by worse magnetic shielding leading to a less residual surface resistance. Nevertheless, the cavity showed improved performance due to the advanced HPR treatment: The initial design quality factor has been exceeded by a factor of 4; finally a maximum accelerating gradient of $E_a = 9.6$ MV/m at $Q_0 = 8.14 \cdot 10^8$ have been achieved [21].

FIRST BEAM TEST

After successful RF-testing of the superconducting RF-cavity in 2016 and a short commissioning and ramp up time of some days, recently (June 28, 2017) the CH-cavity accelerated first time heavy ion beams with full transmission up to the design beam energy of 1.85 MeV/u ($\Delta W_{kin} = 0.5$ MeV/u). For the first beam test the superconducting 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. Meanwhile the design acceleration gain of 3.5 MV has been verified with heavy ion beam (A/q = 6.7). A maximum average beam intensity of 1.5 pμA has been achieved, limited only by the pulse intensity of the injector and its maximum duty factor (25%), while the CH cavity was operated in CW-mode. The measured parameter of the heavy ion beam, delivered by ECR and HLI, show a nice beam quality: Transversal beam emittance as well as measured bunch structure for the accelerated beam is depicted in Fig. 5. The transversal beam emittance growth (90%, total) is less than 15%; a minimum bunch length of about 300 ps

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(FHWM) could be detected. Further and more detailed tests and careful evaluation of data are envisaged.

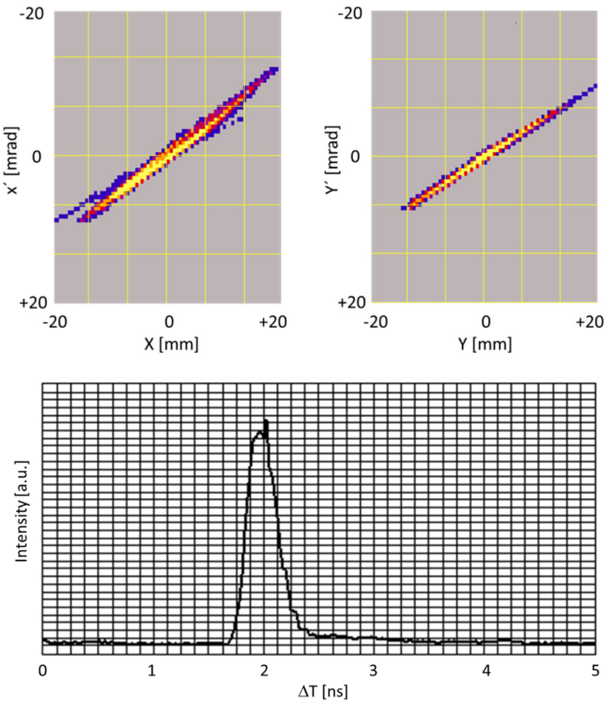

Figure 5: Measured horizontal (top left) and vertical (top right) beam emittance and bunch structure (bottom) for accelerated heavy ion beam behind demonstrator set up.

ADVANCED DEMONSTRATOR

The successor of the demonstrator R&D is the Advanced Demonstrator (AD) project. It is planned to build the first quarter of the entire CW Linac. Based on beam dynamics calculations [22, 23], a standard CW-Linac cryo module, comprising three CH cavities, a rebuncher cavity and two solenoids, was newly defined. While the demonstrator cavity will serve as the first accelerating cavity for the AD, two short CH-cavities (see Table 2) are under construction at RI, complementing the first cryomodule (CM1) [24]. Besides CM1, the revised design of the sc CW-Linac comprises three additional cryo modules (CM2-CM4) each equipped with three short CH-cavities [25, 26]. The short cavity (Fig. 6) has a design gradient of 5 MV/m as well.

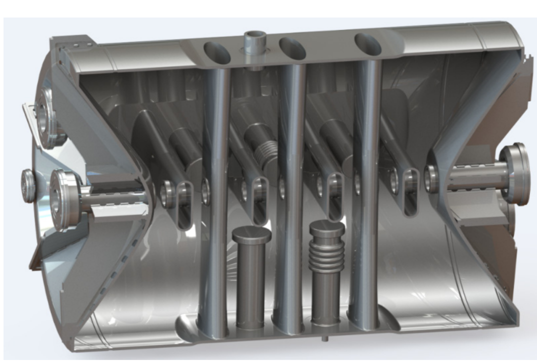

Figure 6: Sectional drawing of the short cavities for CM1 [26].

The cavity design is based on 8 equidistant gaps, equipped with two dynamic tuners and stiffening brackets at front and end cap to reduce pressure sensitivity. The design is without girders to preserve cylindrical symmetry and to avoid high fabrication costs and extended fabrication duration. First intermediate measurements on the first short CH-cavity have been already performed [27].

Table 2: Design Parameters of ShortCH-Cavities for CM1

β		0.069
Frequency	MHz	216.816
Cell number	#	8
Length (βλ-definition)	mm	381.6
Cavity diameter (outer)	mm	400
Cell length	mm	47.7
Aperture diameter	mm	30
Static tuner	#	3
Dynamic bellow tuner	#	2
Wall thickness	mm	3-4
Accelerating gradient	MV/m	5
E_p/E_a		5.2
B_p/E_a	mT/(MV/m)	<10
G	Ω	50
R_a/Q_0		1070

The usage of short CH-cavities should allow for more flexibility in tuning the entire CW-Linac, maintaining the necessity of variable output energy and almost minimizing emittance growth during the acceleration process.

CONCLUSION AND OUTLOOK

Generally, the proposed Linac should facilitate variable output energy from 3.5 to 7.3 MeV/u. The achieved beam commissioning of the demonstrator is a major milestone paving the way to the entire CW-Linac. The demonstrator set up, as the first section of a CW-Linac almost reached acceleration of heavy ions up to the design beam energy [28-30]. The design acceleration gain was achieved with heavy ion beams even above the design mass to charge ratio at high beam intensity (1.5 pμA). At full beam transmission the beam quality was measured as excellent.

Recently the possibility for acceleration of protons, as well as Uranium ion beams is under investigation [31]. The experimentally reached higher acceleration gradient for the first CH-cavity has to be taken into account for further studies. Therefore the original Linac layout has to be revised by decreasing the number of gaps per cavity, preserving the total cavity voltage and high accelerating gradient. The maximum beam energy, which could be potentially reached by an advanced Linac layout, has been estimated for ions with different mass to charge ratio (1≤A/Z≤6). Moreover the effective acceleration of Uranium ion beams (A/Z=8.5) is potentially achievable.

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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 IAP in preparation of a superconducting heavy ion continuous wave linear accelerator.

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