

FURTHER INVESTIGATIONS FOR A SUPERCONDUCTING CW-LINAC AT GSI

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Abstract

For superconducting (sc) accelerator sections operating at low and medium beam energies very compact accelerating-focusing structures are strongly required, as well as short focusing periods, high accelerating gradients and very short drift spaces. The Facility for Antiproton and Ion Research (FAIR) is going to use heavy ion beams with extremely high peak current from UNiversal Linear ACcelerator (UNILAC) and the synchrotron SIS18 as an injector for the SIS100. 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 upgraded GSI High Charge State injector is envisaged. In preparation for this, testing of 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 ongoing, while an accelerating gradient of 9.6 MV/m (4 K) at a sufficient quality factor has been already reached in a horizontal cryostat. As a final R&D step towards an entire linac one advanced cryo module, comprising three CH cavities and one rebuncher cavity, should be built until 2019, serving for first user experiments at the coulomb barrier.

INTRODUCTION

Providing heavy ion beams for the ambitious experiment program at GSI, the UNILAC combined with the High Charge State Injector (HLI) served at last as a powerful high duty factor (25%) accelerator. An UNILAC upgrade program is ongoing, designated to prepare for high intensity high current synchrotron injector operation for FAIR [1-3]. As a result beam time availability for SHE-research will be strongly diminished due to the duty factor limitation for the UNILAC FAIR injector operation. An upgrade program of the HLI was already initialized comprising a new 18 GHz ECR source, a cw capable RFQ and an IH-DTL [4], keeping the SHE program at GSI competitive [5]. A standalone sc cw-linac [6] in combination with the upgraded HLI 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. In general, 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. The 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, is of high relevance for the accelerator community.

GENERAL CW-LINAC LAYOUT

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 at a beam energy of 1.4 MeV/u from the upgraded HLI. For proper beam focusing superconducting solenoids have to be mounted between the 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

CW-LINAC R&D

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

setup, embedded in a new radiation protection cave, is located in straightforward direction of the HLI (Fig. 1).

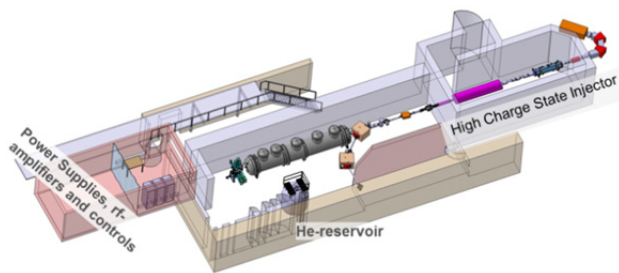


Figure 1: CH-multi cavity test environment@GSI.

The liquid helium (LHe) supply is covered by a 3000 l tank, while the consumed helium is collected in a 25 m³ recovery balloon and bottled by a compressor. For 6D-beam matching an existing rebuncher in combination with another new rebuncher cavity and an additional quadrupole doublet will be used. Moreover, beam transformers, Faraday cups, SEM-profile grids, a dedicated emittance meter and phase probe pickups (beam energy measurements applying time of flight) provides for proper beam characterization in front and behind of the demonstrator.

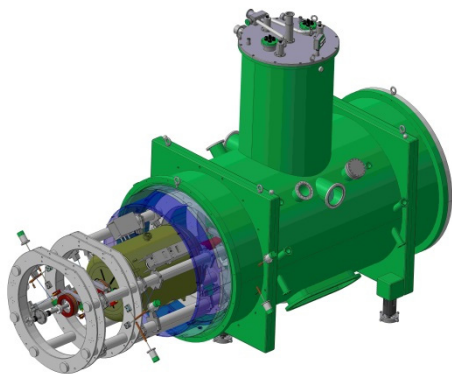


Figure 2: Cryostat with CH-cavity, high field solenoids, cold warm transitions and support system (Cryogenic Limited).

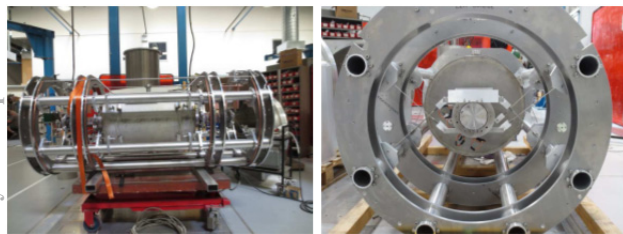


Figure 3: Demonstrator comprising CH cavity embedded by two sc solenoids on a support frame (left); detailed view of tie rods in a cross-like configuration (right).

The demonstrator (Fig. 2) [16] comprises a superconducting CH cavity embedded by two superconducting solenoids; all three components are mounted on a common support frame (Fig. 3) [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. 3). As a consequence the suspended components may always stay within the tolerance limits related to the beam axis. 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 [16], acceptable at the position of the neighbored cavity (first RF-gap). The solenoids are connected to LHe ports inside the cryostat by copper tapes allowing dry cooling.

The sc CH structure 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 Goethe University Frankfurt [20]. After the final assembly of the helium vessel and further HPR preparation at RI, the cavity was delivered to GSI and prepared for a second RF test in a horizontal cryo module. The maximum Q-value (Q_0) at a low field level was measured for $1.37 \cdot 10^9$ which is 4.9 % lower in comparison to the first (vertical) test. This minor discrepancy is caused by worse magnetic shielding leading to a less residual surface resistance. Nevertheless, recently the cavity showed an improved performance due to the advanced HPR treatment. The initial design quality factor at 5.5 MV/m has been exceeded by a factor of 4. Furthermore a maximum accelerating gradient of $E_a = 9.6$ MV/m at $Q_0 = 8.14 \cdot 10^8$ was reached [21]. The maximum gradient is limited by cavity quenches presumably caused by a thermal defect since the degeneration of the Q-value is still quite low. Beam commissioning of the whole demonstrator is planned for summer 2017.

ADVANCED DEMONSTRATOR

The successor of the demonstrator R&D is already the “Advanced Demonstrator” (AD) project. It is planned to build the first quarter of the future entire cw linac. Based on calculations of the beam dynamics [22, 23], a standard cw-linac cryomodule, comprising three CH cavities, a rebuncher cavity and two superconducting solenoids, was newly defined. While the demonstrator cavity will serve as the first accelerating cavity for the AD, presently two short CH-cavities are under construction at RI, complementing the first cryomodule (CM1). Besides CM1, the revised design of the sc cw-linac comprises three additional cryomodules (CM2-CM4) each equipped with three short CH-cavities [24, 25]. The short cavity

(Fig. 4) has been designed for high power applications at a design gradient of 5 MV/m as well [26].

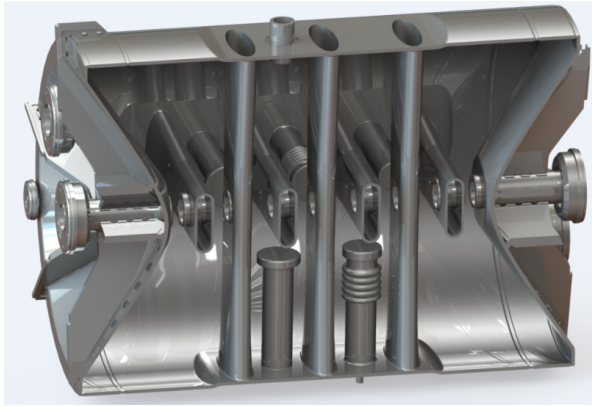


Figure 4: Sectional drawing of the newly designed short cavities for CM1 [26].

It is based on 8 equidistant gaps, equipped with two dynamic tuners and stiffening brackets at the front and end cap to reduce pressure sensitivity. The cavity design is without girders to preserve cylindrical symmetry and avoid high fabrication costs and extended fabrication duration. First intermediate measurements on the first short CH-cavity have been performed in April 2017 [27]

Table 2: Design Parameters of the Two Short CH-Cavities for CM1

β		0.069
Frequency	MHz	216.816
Cell number	#	8
Length ($\beta\lambda$ -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 allows more flexibility in tuning the entire cw-linac, maintaining the necessity of variable output energy and almost neglectable emittance growth during the acceleration process. The accelerating design gradient of $E_a = 5.5$ MV/m provides an effective accelerating voltage of 1.8 MV per (short) cavity.

CONCLUSION AND OUTLOOK

Generally, the proposed linac should facilitate variable output energy from 3.5 to 7.3 MeV/u. The planned beam commissioning of the demonstrator is a major milestone paving the way to the entire cw-linac. Recently the acceleration of ions with mass to charge ratio between 3 and 6 for even higher energies is under consideration.

Additionally the possibility for acceleration of protons, as well as Uranium ion beams is under investigation. 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 ($1 \leq A/Z \leq 6$). Moreover the effective acceleration of Uranium ion beams ($A/Z=8.5$) is potentially achievable.

Recent investigation efforts, to be confirmed by further beam dynamics simulations on the base of the future individual layout of each RF-cavity, demonstrates the high potential of the cw-linac for operation with a wide spectra of ions with different mass to charge ratio [28].

REFERENCES

- [1] W. Barth *et al.*, Phys. Rev. ST Accel. Beams **18(4)**, 040101 (2015).
- [2] W. Barth *et al.*, “High Current Uranium Beam Measurements at GSI-UNILAC for FAIR”, in *Proc. HB’16*, Malmö, Sweden, (2016).
- [3] W. Barth *et al.*, Phys. Rev. ST Accel. Beams **18(5)**, 050102 (2015).
- [4] W. Barth *et al.*, “UNILAC-upgrade programme for the heavy element research at GSI-SHIP”, in *Proc. EPAC’06*, Edinburgh, Scotland (2006).
- [5] S. Hofmann *et al.*, “Heavy Element Research at GSI-SHIP”, in Proceedings of EXON’04, Peterhof, Russia (2004).
- [6] S. Minaev *et al.*, Phys. Rev. ST Accel. Beams **12**, 120101 (2009).
- [7] C. Prior, “Overview of High Intensity Accelerator Projects”, in *Proc. HB’10*, Morschach, Switzerland (2010).
- [8] T.V. Kulevoy *et al.*, Atomic Energy, Vol. **117**, No. 5, 117:347 (2015).
- [9] P. N. Ostroumov, “Advances in CW Ion Linacs”, in *Proc. IPAC’15*, Richmond, VA, USA (2015).
- [10] N. Solyak *et al.*, “The Concept Design of the CW Linac of the Project X”, in *Proc. IPAC’10*, Kyoto, Japan (2010).
- [11] S. M. Polozov *et al.*, “Beam Dynamics Simulations and Code Comparison for a New CW RFQ Design”, in *Proc. HB’16*, Malmö, Sweden (2016).
- [12] L. Weissman, D. Berkovits *et al.*, Journal of Instrumentation, **10**, T1004 (2015).
- [13] G. V. Trubnikov *et al.*, Physics of Particles and Nuclei Letters, 2016, Vol. **13**, No. 7, p. 915–918 (2016).
- [14] S. Mickat *et al.*, “The sc cw-linac Demonstrator – SRF technology finds the way to GSI”, in *Proc. SRF’11*, Chicago, USA (2011).
- [15] V. Gettmann *et al.*, “The sc cw-linac Demonstrator – an R&D project for SRF technology”, in *Proc. SRF’11*, Chicago, USA (2011).

- [16]. S. Mickat *et al.*, “Status of the superconducting cw linac at GSI”, DOI: 10.1142/9789814508865_0044, Vladivostok, Russia, (2013).
- [17] V. Gettmann *et al.*, “The sc cw -linac Demonstrator - First section of a sc cw -linac”, in *Proc. SRF'11*, Chicago, Illinois, USA (2011).
- [18] V. Gettmann *et al.*, “Recent status new superconducting cw heavy ion linac@GSI”, in *Proc. SRF'15*, Whistler, Canada (2015).
- [19] F. Dziuba *et al.*, “First Performance Test on the Superconducting 217 MHz CH Cavity at 4.2 K”, presented at LINAC'16, East Lansing, MI, U.S.A. (2016), unpublished.
- [20] M. Amberg *et al.*, “The fast Piezo-based frequency tuner for sc CH-cavities”, in *Proc. LINAC'14*, Geneva, Switzerland (2014).
- [21] F. Dziuba *et al.*, “First Cold Tests of the Superconducting cw Demonstrator at GSI”, in *Proc. RUPAC'16*, St. Petersburg, Russia, p. 83-85 (2016).
- [22] M. Schwarz *et al.*, “Beam Dynamics for the sc cw heavy ion linac at GSI”, in *Proc. IPAC'15*, Richmond, U.S.A. (2015).
- [23] S. Yaramyshev *et al.*, “An Advanced Procedure for Longitudinal Beam Matching for SC CW Heavy Ion linac With Variable Output Energy”, in *Proc. HB'16*, Malmö, Sweden (2016).
- [24] W. Barth *et al.*, “Further R&D for a New Superconducting cw Heavy Ion Linac@GSI”, in *Proc. IPAC'14*, Dresden, Germany, p. 3211-3213 (2014).
- [25] H. Podlech, “Proposal for a Superconducting 217 MHz CH-Cavity”, institute report: IAP-ACCC-01122013 (2013).
- [26] M. Basten *et al.*, “R&D Status of the new superconducting CW Heavy Ion linac@GSI”, GSI annual report 2016, to be published, (2017).
- [27] M. Basten *et al.*, “First measurements of the next sc CH-cavities for the new superconducting CW heavy ion LINAC@GSI”, will be presented at *SRF'17*, Lanzhou, China, 2017, unpublished.
- [28] S. Yaramyshev *et al.*, “Beam dynamics study for the HIM/GSI heavy ion sc cw linac”, presented at IPAC'17, Copenhagen, Denmark, May 2017, this conference.