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BEAM DYNAMICS SIMULATIONS FOR THE NEW SUPERCONDUCTING CW HEAVY ION LINAC AT GSI*

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Abstract

For future experiments with heavy ions near the coulomb barrier within the super-heavy element (SHE) research project a multi-stage R&D program of GSI/HIM and IAP is currently in progress. It aims at developing a superconducting (sc) continuous wave (CW) LINAC with multiple CH cavities as key components downstream the High Charge State Injector (HLI) at GSI. The LINAC design is challenging due to the requirement of intense beams in CW mode up to a mass-to-charge ratio of 6, while covering a broad output energy range from 3.5 to 7.3 MeV/u with the same minimum energy spread. Testing of the first CH-cavity in 2016 demonstrated a promising maximum accelerating gradient of E_a = 9.6 MV/m; the worldwide first beam test with a sc multi-gap CH-cavity in 2017 was a milestone in the R&D work of GSI/HIM and IAP. In the light of experience gained in this research so far, the beam dynamics layout for the entire LINAC has recently been updated and optimized.

INTRODUCTION

In the last decades the periodic table was essentially extended up to the nuclei with proton number $Z = 118$ and neutron number $N = 177$. It turned out, that the most successful methods for the laboratory synthesis of heavy elements are fusion-evaporation reactions using heavy-element targets, recoil-separation techniques and the identification of the nuclei by known daughter decays [1]. For the production of SHE, hot fusion reactions with ^{48}Ca projectiles and targets made of actinide elements ranging from ^{231}Pa to ^{254}Es are considered promising.

To sum it up, all of the experiments have the common challenge of very low cross sections and therefore require the separation of very rare events within weeks of beamtime from intense backgrounds [2]. Fortunately, the yield of SHE and therefore the number of events per unit time depends not only on the cross section but also on the projectile beam intensity, overall beam quality and target thickness. Thus, progress in SHE research is highly driven by technical developments in this fields [3]. Furthermore, the scientific fields of nuclear chemistry and spectroscopy as well as materials research and biology could benefit from these developments.

At GSI a comprehensive upgrade programme is performed. In this context, the UNILAC (Universal Linear Accelerator) is upgraded to the requirements of FAIR (Facility for Antiproton and Ion Research) and will be used as injector [4–9]. The duty factor will be relatively low (below 1 %). Conversely, for SHE experiments a high duty factor is required, which is why the presently available duty cycle of 25 % (5 ms pulse length @50 Hz) will be upgraded to CW-mode [10, 11]. Consequently a superconducting CW-LINAC was proposed [12] and is further investigated and developed [13–18].

BEAM DYNAMICS CONCEPT

Up to now, the reference design for the CW LINAC dates back to the publication of Minaev et al. in 2009 [12]. Meanwhile many experiences have been gained in design, fabrication and operation of superconducting CH-cavities and the associated components. In this context, a revision of the beam dynamics layout was recommended. Optimized cavity layouts resulted in modified voltage distributions. Furthermore, the cryomodule layout and intertank sections were specified in more details. Promising RF- and beam testing with the 15-gap CH0 showed, that higher accelerating gradients can be achieved [19], thus leading to a more efficient design approach. Consequently, extensive beam dynamics studies are carried out to fix the best layout with respect to the beam and all other RF and mechanical requirements. The beam dynamics concept for the CW-LINAC is based on multicell CH-type DTL-cavities operating at 216.816 MHz (f_{HLI} = 108.408 MHz) and focusing by superconducting solenoids. The main requirements and boundary conditions for the LINAC design are summarized in Table 1:

Table 1: Basic CW-LINAC Design Parameters

Parameter	Value
W_{in}	1.4 MeV/u
W_{out}	3.5–7.3 MeV/u
ΔW_{out}	±3 keV/u
I	≤ 1 mA
A/q	≤ 6

With a relatively low beam current, CW-operation and limited longitudinal space, this LINAC is predestined to be operated in the superconducting mode. Further thoughts on

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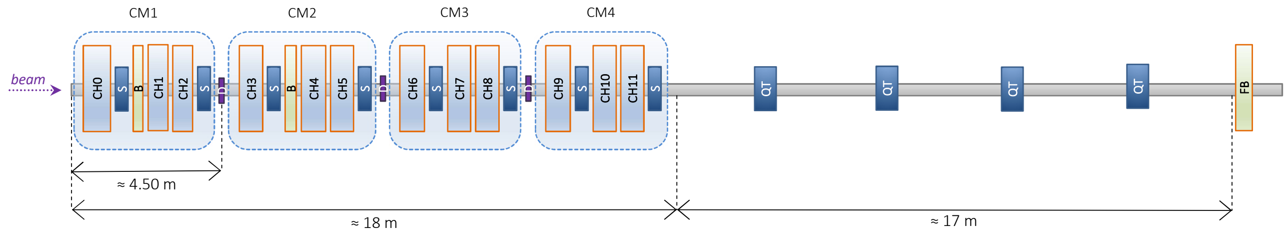

Figure 1: Study for a CW-LINAC layout design with twelve superconducting CH-cavities in four cryomodules. The length of the transport section (here 17 m) has not yet been determined finally and is likely to be shorter. Captions: CM = Cryomodule, S = Solenoid, D = Diagnostics, B = 2-Gap-Buncher, FB = Final 1-Gap-Buncher, QT = Quadrupole magnet triplet.

the choice of technology with regard to superconducting or room-temperature operation can be found at [20].

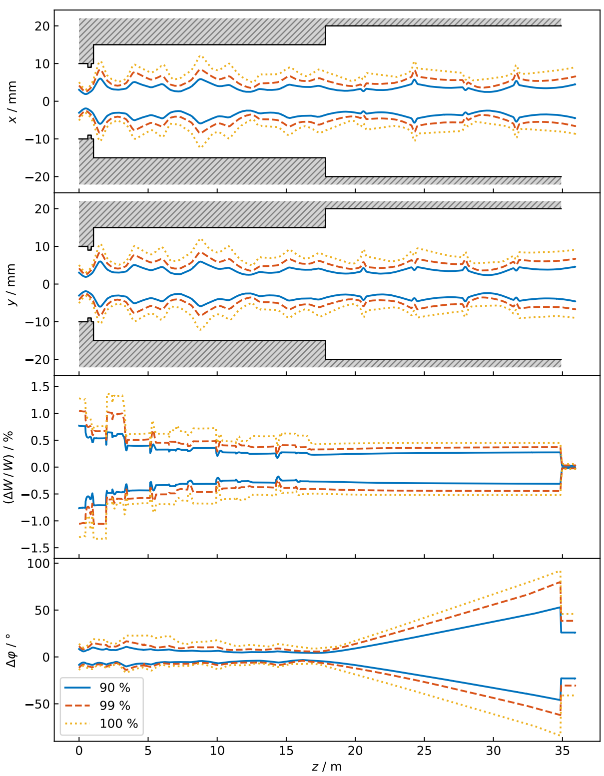

Figure 2: Beam envelopes. From top to bottom: Horizontal *(x)* and vertical *(y)* plane, energy spread in relation to mean energy and longitudinal (phase) envelopes for the studied layout as shown in Fig. 1. Since the final buncher at about $z = 35$ m is operated at 108.408 MHz in this design study, a phase jump is visible.

Recent Beam Dynamics Studies

To optimize the beam dynamics design in terms of acceleration efficiency and therefore relating to total LINAC length, $E_a = 7.1$ MV/m was chosen as design gradient for the upcoming CH-cavities in the nominal case of $A/q = 6$ (see Table 2). This allows to keep the LINAC length comparably short. A revised cryomodule (CM) layout was studied and simulated with LORASR [21] (100,001 particles,

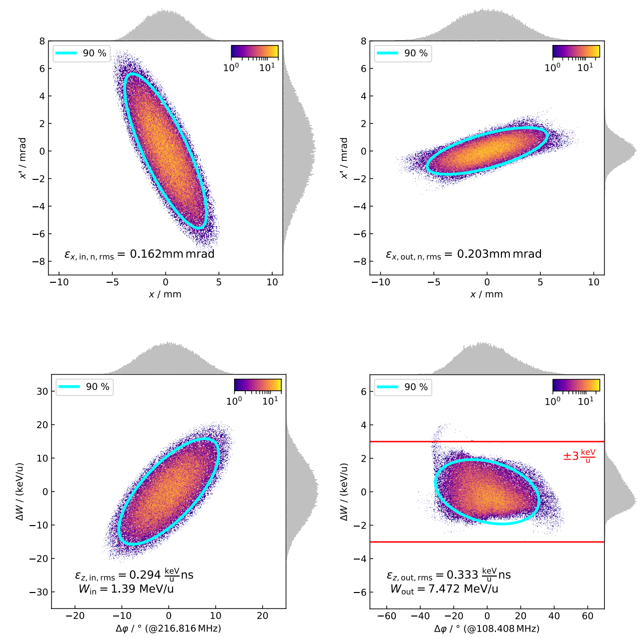

Figure 3: Phase space distributions for the recent beam dynamics layout simulated with LORASR: $x - x'$ *(top)*, $\Delta\varphi - \Delta W$ *(bottom)*, input for first cryomodule *(left)*, output behind the final buncher *(right)*. The particle density is logarithmically color-coded.

$I = 1$ mA, $A/q = 6$). It comprises three CH-DTL cavities and two solenoids per module. Additionally 2-gap Buncher-cavities are foreseen at least in CM1 and CM2 - depending on the outcome of the ongoing simulations for energy variation. This new approach partly reduces the overall drift lengths compared to former considerations and is recently studied in detail. This approach was periodically extended to four cryomodules (see Fig. 1). The beam envelopes for $W_{\mathrm{out}} = 7.3$ MeV/u are shown in Fig. 2. The final rms-emittance growth is 13 % for the longitudinal and 26 % for the transverse planes. In this design study, the solenoids provide a magnetic field of up to 7 T for beam focusing. While final transverse matching is not completely optimized and the length of the beam transport line towards the experimental area is not fixed yet, emittance growth and a slight deformation of the beam in transverse phase space is inevitable, mainly due to RF-defocusing in the high ac-

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celerating gradient cavity fields. The longitudinal phase space distribution stays largely compact through the whole LINAC design, overcoming the challenge of many drifts due to the boundary conditions of a superconducting design. On its way to the experimental area (here roughly initially assumed with 17 m), the bunch length grows to about 175° (@216.816 MHz). The bunch can be easily rotated in phase space by a Rebuncher (here operated @108.408 MHz), resulting in the required energy spread of $\Delta W_{\mathrm{out}} = \pm 3\,\mathrm{keV/u}$ (see Fig. 3).

Table 2: Cavity Specifications Overview

	Gaps	$(\beta\lambda/2)$/mm	E_{a}/(MV/m)
CH0	15	40.8	5.75
B1	2	44.1	5.73
CH1	8	47.7	6.00
CH2	8	47.7	6.50
CH3	8	56.7	7.10
B2	2	57.3	5.50
CH4	8	59.6	7.10
CH5	7	62.4	7.10
CH6	7	70.3	7.10
CH7	6	73.6	7.10
CH8	6	73.9	7.10
CH9	6	80.4	7.10
CH10	6	83.6	7.10
CH11	6	83.9	7.10
FB	1	86.05 / 172.1	TBD

Outlook

A promising new beam dynamics layout was developed, showing a possible design approach for the upcoming CW-LINAC which essentially meets the beam parameter requirements. Beside the presented simulations, extensive beam dynamics studies are ongoing, to finally optimize the current CW-LINAC design. Further simulations for the acceleration of a wide range of different ions (protons to uranium) along the required energy range are in progress. Since maintaining a good beam quality for $3.5\,\mathrm{MeV/u} < W_{\mathrm{out}} < 7.3\,\mathrm{MeV/u}$ is essential, special attention is paid to this and further results will be published soon. In-depth benchmarking the layout with respect to comprehensive error studies for cavity voltage and phase as well as magnet placement and gradient deviations are envisaged as well.

REFERENCES

[1] S. Hofmann, "Super-heavy nuclei", *J. Phys. G: Nucl. Part. Phys.*, vol. 42, no. 11, p. 114001, 2015.

[2] M. Block *et al.*, "Direct mass measurements above uranium bridge the gap to the island of stability", *Nature*, vol. 463, pp. 785–788, Feb. 2010.

[3] G. Münzenberg, "From bohrium to copernicium and beyond SHE research at SHIP", *Nucl. Phys. A*, vol. 944, pp. 5–29, Dec. 2015.

[4] W. Barth *et al.*, "Upgrade program of the high current heavy ion UNILAC as injector for FAIR", *Nucl. Instr. Meth. Phys. Res. Sect. A*, vol. 577, pp. 211–214, 2007.

[5] W. Barth *et al.*, "U^{28+}-intensity record applying a H2-gas stripper cell", *Phys. Rev. ST Accel. Beams*, vol. 18, p. 040101, Apr. 2015.

[6] W. Barth *et al.*, "Heavy ion linac as a high current proton beam injector", *Phys. Rev. ST Accel. Beams*, vol. 18, p. 050102, May 2015.

[7] W. Barth *et al.*, "High brilliance uranium beams for the GSI FAIR", *Phys. Rev. Accel. Beams*, vol. 20, p. 050101, May 2017.

[8] A. Adonin and R. Hollinger, "Beam brilliance investigation of high current ion beams at GSI heavy ion accelerator facility", *Rev. Sci. Instrum.*, vol. 85, p. 02A727, 2014.

[9] L. Groening *et al.*, "Upgrade of the Universal Linear Accelerator UNILAC for FAIR", in *Proc. IPAC'16*, Busan, Korea, May 2016, paper MOPOY017, pp. 880–882.

[10] P. Gerhard *et al.*, "Status and Perspectives of the CW Upgrade of the UNILAC HLI at GSI", in *Proc. HIAT2015*, Yokohama, Japan, Sep. 2015, paper WEA1C03, pp. 1–3.

[11] D. Koser *et al.*, "Prototype Design of a Newly Revised CW RFQ for the High Charge State Injector at GSI", in *Proc. IPAC'17*, Copenhagen, Denmark, May 2017, paper THPIK021, pp. 4142–4144.

[12] S. Minaev *et al.*, "Superconducting, energy variable heavy ion linac with constant beta, multicell cavities of CH-type", *Phys. Rev. ST Accel. Beams*, vol. 12, p. 120101, 2009.

[13] W. Barth *et al.*, "A superconducting CW-LINAC for heavy ion acceleration at GSI", *EPJ Web Conf.*, vol. 138, p. 01026, Mar. 2017.

[14] W. Barth *et al.*, "First heavy ion beam tests with a superconducting multigap CH cavity", *Phys. Rev. Accel. Beams*, vol. 21, p. 020102, 2018.

[15] W. Barth *et al.*, "Superconducting CH-Cavity Heavy Ion Beam Testing at GSI", in *Proc. IPAC'18*, Vancouver, BC, Canada, May 2018, paper TUPAK004, pp. 962–965.

[16] M. Basten *et al.*, "Final factory-side Measurements of the Next SC CH-Cavities for the HELIAC-Project", in *Proc. IPAC'18*, Vancouver, BC, Canada, May 2018, paper TUPAF088, pp. 943–945.

[17] T. Kuerzeder *et al.*, "Infrastructure for Superconducting CH-Cavity Preparation at HIM", in *Proc. IPAC'18*, Vancouver, BC, Canada, May 2018, paper WEPML045, pp. 2796–2799.

[18] S. Yaramyshev *et al.*, "Advanced Approach for Beam Matching along the Multi-Cavity SC CW Linac at GSI", in *Proc. IPAC'18*, Vancouver, BC, Canada, May 2018, paper TUPAK002, pp. 955–958.

[19] F. Dziuba *et al.*, "First Cold Tests of the Superconducting cw Demonstrator at GSI", in *Proc. RuPAC'16*, St. Petersburg, Russia, Nov. 2016, paper WECBMH01.

[20] H. Podlech, "Superconducting versus normal conducting cavities", CERN Yellow Report CERN-2013-001, Mar. 2013.

[21] R. Tiede *et al.*, "LORASR Code Development", in *Proc. EPAC'06*, Edinburgh, Scotland, 2006, paper WEPCH118, pp. 2194–2196.