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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 upgraded High Charge 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 minimum energy spread. After successful tests with the first CH cavity in 2016 demonstrated a promising maximum accelerating gradient of $E_a = 9.6$ MV/m, recently first beam tests have been started as next milestone at GSI, confirming its flawless functionality [1].

INTRODUCTION

In the last decades the periodic system was essentially extended up to the nuclei with proton number $Z = 118$ and neutron number $N = 177$. Compared to the heaviest known stable nuclei, $^{208}_{82}$Pb and $^{209}_{83}$Bi, the mass of the overall heaviest nuclei was continuously increased. Most recently by more than 40 % with the discovery of $^{294}_{118}$Og [2]. 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 [3]. As an example 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 very 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. Fortunately, the yield of SHE respectively the number of events per time unit 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 [4].

At GSI a comprehensive upgrade programme is performed. In this context, the UNILAC (Universal Linear Accelerator) is upgraded to the requirements of FAIR and will be used as injector [5]. 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 (duty cycle = 100 %) [6, 7]. Consequently the superconducting CW-LINAC was proposed [8] and is further investigated [9–11].

BEAM DYNAMICS

The beam dynamics concept for the CW-LINAC is based on multicell CH-DTL cavities, operating at 216.816 MHz ($f_{HLI} = 108.408$ MHz). The main requirements and boundary conditions for the LINAC design are as follows:

- ⊕ $W_{in} = 1.4$ MeV/u (at the HLI exit)
- ⊕ $W_{out} = 3.5–7.3$ MeV/u
- ⊕ $\Delta W_{out} = \pm 0.003$ MeV/u
- ⊕ $I \leq 1$ mA
- ⊕ $A/q \leq 6$

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 the choice of technology with regard to superconducting or room-temperature operation can be found at [12].

A revised cryomodule (CM) layout is currently being studied. It comprises three CH-DTL cavities, two solenoids and a short buncher DTL-cavity (see Fig. 1). This approach partly reduces the overall drift lengths compared to the former consideration of CMs equipped with 2 CH-cavities.

Enabling First Experiments with 1 CM

By increasing the accelerating gradient and the RF-phase of the buncher (to use it for acceleration), LORASR simulations (100,001 particles, $I = 1$ mA, $A/q = 3$) show that the minimum output energy of the full CW-LINAC could already be reached in this early intermediate expansion stage. Instead of halving the accelerating gradient due to the halved mass-to-charge ratio, increasing E_a for CH1 and CH2 up to

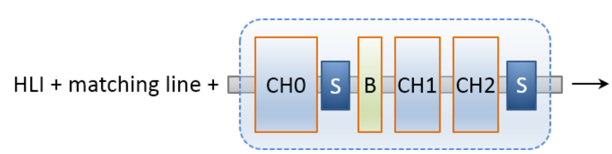

Figure 1: Proposed Layout for the first cryomodule of the CW-LINAC with 3 CH-DTLs, 2 solenoids and 1 buncher cavity. The flange-to-flange length is nearly 4.5 m.

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Table 1: Cavity Specifications for the Medium-Gradient Approach

	Gaps	Length/mm	$(\beta\lambda/2)$/mm	$\beta_{geom.}$	$W_{kin,geom.}$/(MeV/u)	E_a/(MV/m)	U_a/MV
CH0	15	811.5	40.8	0.059	1.628	5.5	3.37
Buncher	4	≈ 359	44.1	0.064	1.900	2.8	0.5
CH1/2	8	593	47.7	0.069	2.233	5.0	1.91
CH3/4	7	≈ 616	53.6	0.076	2.817	5.0	1.88
CH5/6	6	≈ 595	59.9	0.085	3.417	5.0	1.77
CH7/8	6	≈ 625	63.7	0.092	3.983	5.0	1.92
CH9/10	6	≈ 652	68.2	0.099	4.567	5.0	2.04
CH11	6	≈ 681	72.9	0.105	5.217	5.0	2.19

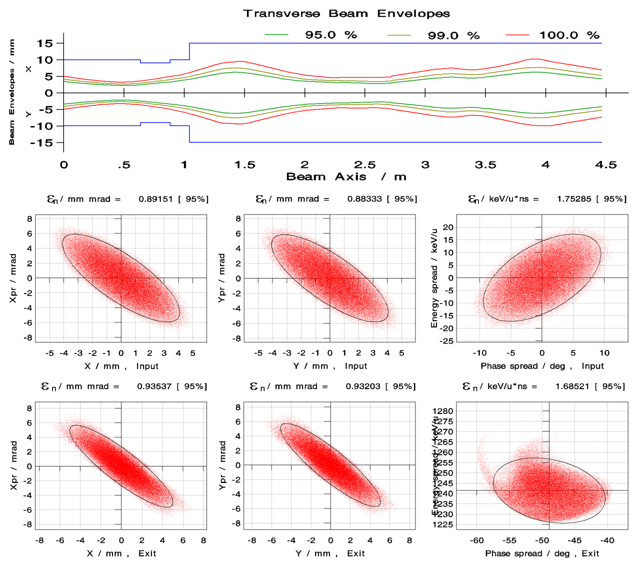

Figure 2: Transverse envelopes and phase space distributions of a LORASR simulation with a maximum-acceleration setting up to W_{out} = 3.5 MeV/u within the first cryomodule.

7.1 MV/m and for the buncher from 2.8 to 4.5 MV/m accelerates the beam to an energy more than 50 % above their design energy. Nevertheless, the beam quality even in this first iteration of this exceptional user scenario is still sufficient with rms-emittance growths between 15 and 25 %, allowing first experiments at 3.5 MeV/u (see Fig. 2).

Beam Dynamics Layout

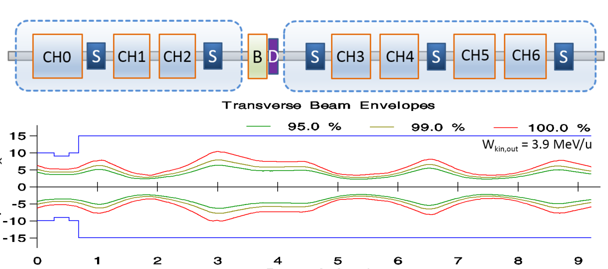

Figure 3: Design study with 4 CH cavities inside the second CM and a buncher cavity at room temperature. 100,001 particles with I = 1 mA and A/q = 6. Low transversal and longitudinal rms-emittance growth of 5 and 12 %.

The design accelerating gradients of the upcoming CH cavities will be at least $E_a \geq 5$ MV/m since the cold tests with CH0 in 2016 exceeded the design value and reached a maximum accelerating gradient of E_a = 9.6 MV/m [13]. Even in case that not all subsequent CH cavities reach this value, mainly two contrary possibilities for a revised CW-LINAC design arise from this successful measurements:

Medium-Gradient Approach While retaining a considered to be smooth and reliable accelerating gradient of E_a = 5 MV/m for A/q = 6, the overall LINAC length has to be longer to reach the maximum output energy of W_{out} = 7.3 MeV/u. In contrast, this allows easy upscaling in operation to E_a = 7.1 MV/m for A/q = 8.5, thus being able to accelerate heavy ions like $^{238}U^{28+}$ also, while maintaining the beam quality. This approach features good acceleration efficiency whilst staying on the safe side by not exhausting the maximum possible gradient. Simulation results for the cavity parameters in Table 1 are shown in Fig. 4.

High-Gradient Approach To optimize the Beam Dynamics design in terms of acceleration efficiency and therefore relating to total LINAC length, E_a = 7.1 MV/m could already be used as design gradient for the nominal case of A/q = 6. This could reduce the LINAC length significantly or even increase the final output energy. At the same time, however, it is essentially complicating the use of A/q = 8.5.

Outlook

Beside the presented studies, more beam dynamics investigations are ongoing, which focus on the evaluation of the best choice of CH-DTL geometrical beta, where unique cavities instead of identical pairs could be advantageous. Furthermore, additional buncher cavities, also for possible acceleration in special user scenarios, as well as a cryomodule layout comprising 4 instead of 3 CH cavities, are under examination. The latter one could be preferable from a beam dynamics viewpoint. Drift lengths would decrease once again and periodicity is improved (see Fig. 3). On the downside, however, the mountability, maintenance and overall handling of the cryomodule would be more complex so that this approach is currently not resolutely pursued.

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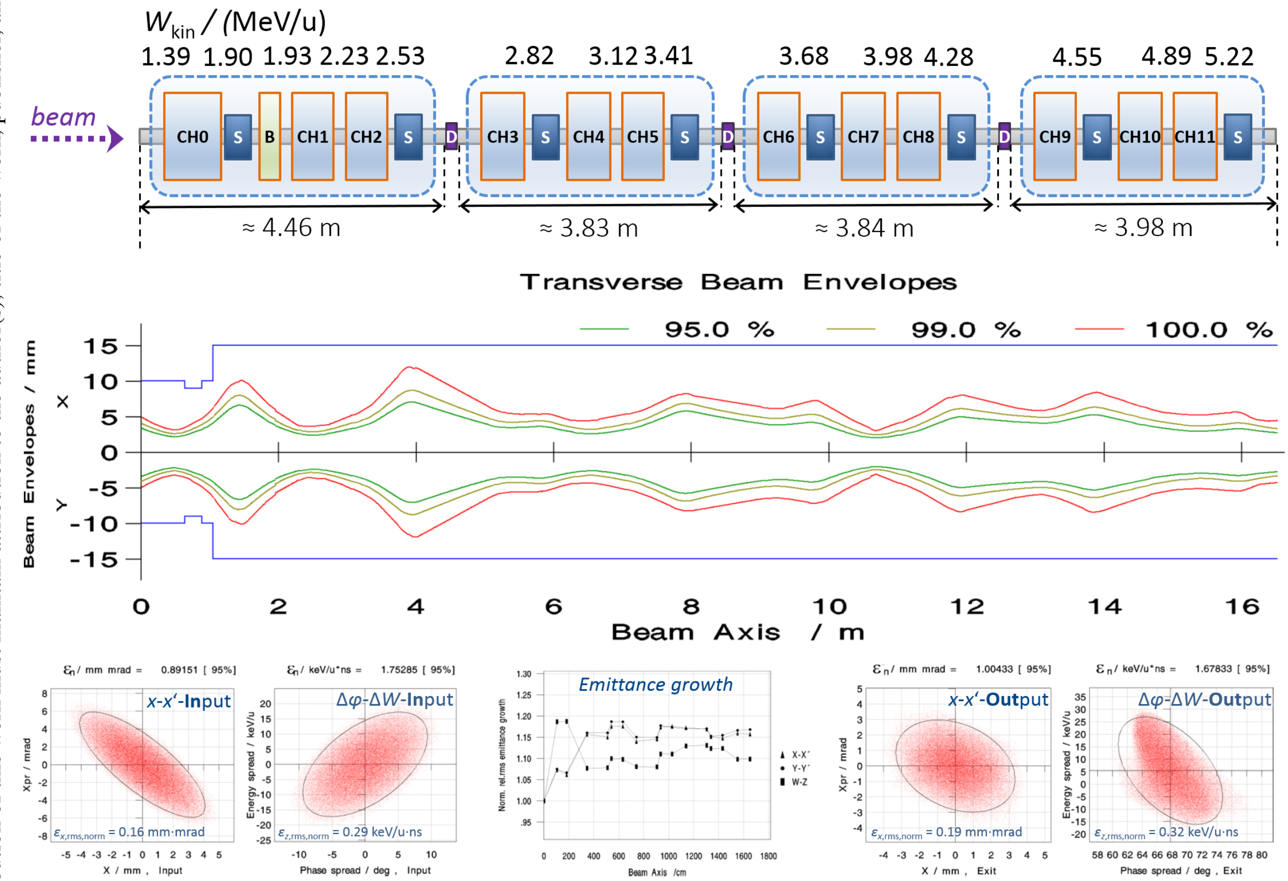

Figure 4: Schematic layout of a medium-gradient approach design study up to CM4 *(top)*. Transverse envelopes show 100 % transmission *(center)* while the input beam matching could be further improved. Phase space distributions show low deformation with moderate rms-emittance growth *(bottom)*. 100,001 particles with $I = 1$ mA and $A/q = 6$.

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