FURTHER STEPS TOWARDS THE SUPERCONDUCTING CW-LINAC FOR HEAVY IONS 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 [1]. It aims at developing a superconducting (sc) continuous wave (cw) LINAC with multiple CH cavities as key components downstream the upgraded High Charge State Injector (HLI) at GSI (Fig. 1). 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. The next milestone will be a full performance beam test of the first expansion stage at GSI, the Demonstrator, comprising two solenoids and a 15-gap CH cavity inside a cryostat.

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, ${}^{208}_{82}\mathrm{Pb}$ and ${}^{209}_{83}\mathrm{Bi}$, the mass of the overall heaviest nuclei was continuosly increased. Most recently by more than 40 % with the discovery of ${}^{294}_{118}\mathrm{Uuo}$ [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]. For the production of SHE, hot fusion reactions with ${}^{48}\mathrm{Ca}$ projectiles and targets made of actinide elements ranging from ${}^{231}\mathrm{Pa}$ to ${}^{254}\mathrm{Es}$ were considered the most promising.

However, despite all advantages hot fusion with actinide targets gives, the production cross sections of SHE will be in the range of picobarns at best (Fig. 2). Decay properties of nuclei made of this reactions revealed a significant increase in their stability with increasing neutron number. Unfortunately, isotopes with more excess neutrons can be reached only by using complete-fusion reactions with projectiles heavier than ${}^{48}\mathrm{Ca}$, whose cross sections were predicted to be much lower [4].

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 [6].

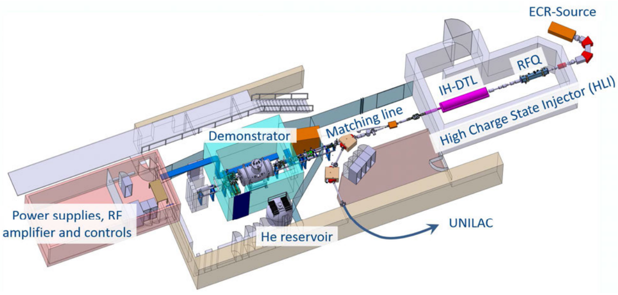

Figure 1: CH cavity test environment for a full performance test of the sc cw-LINAC Demonstrator at GSI.

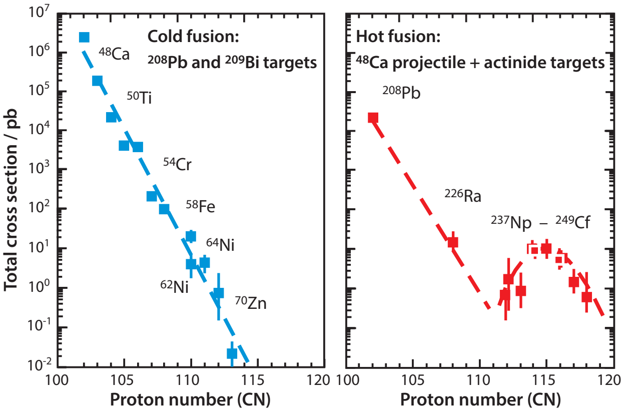

Figure 2: Measured cross sections for cold and hot fusion reactions depending on the proton number of the compound nucleus (CN). The plotted total cross section is the maximum value of the sum of neutron evaporation channels measured as a function of the beam energy. Data taken from [5]. The curves are drawn to guide the eye.

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 [7]. 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

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* Work supported by BMBF contr. No. 05P15RFRBA
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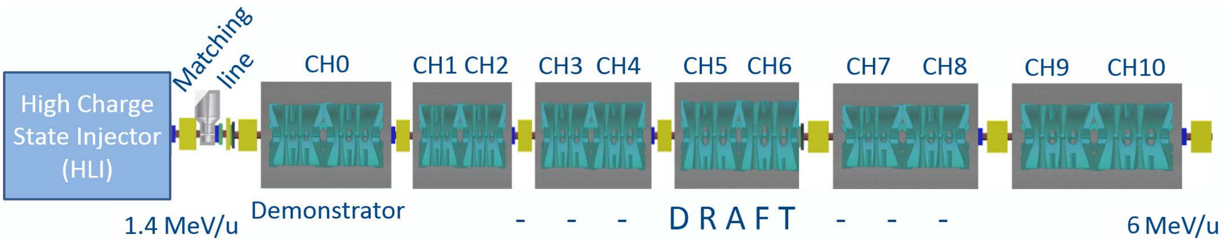

Figure 3: Schematic layout of the proposed Optimized Advanced Demonstrator, as an intermediate step towards the complete cw-LINAC. Distances not to scale. Corresponding beam dynamics simulations are in process. Details concerning CH1 and CH2 can be found in [8].

upgraded to cw-mode (duty cycle = 100 %) [9, 10]. Consequently the superconducting cw-LINAC was proposed [11].

BEAM DYNAMICS

The beam dynamics concept for the sc cw-LINAC is based on multicell CH-DTL cavities (Fig. 3, [12]), operating at 216.816 MHz ($f_{\text{HLI}} = 108.408$ MHz). The requirements and boundary conditions for the LINAC design are as follows:

⊕ $W_{\text{in}} = 1.4$ MeV/u (at the HLI exit)
⊕ $W_{\text{out}} = 3.5$–7.3 MeV/u
⊕ $\Delta W_{\text{out}} = \pm 0.003$ 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 respect to superconducting or roomtemperature operation can be found at [13]. The accelerating gradients of the CH cavities will be in the range of up to about $E_{\text{a}} = 5$–6 MV/m depending on the desired output energy. This allows a high acceleration efficiency while staying on the safe side by not exhausting the maximum possible gradient. Energy variation whilst maintaining a high beam quality is important for an ideal fusion reaction to prevent a nuclear fission. Furthermore, it is the core issue with respect to beam dynamics. It can be achieved by varying the applied rf voltage (even down to “switched off“ and detuned cavities) or the rf phase of the cavities (Fig. 4).

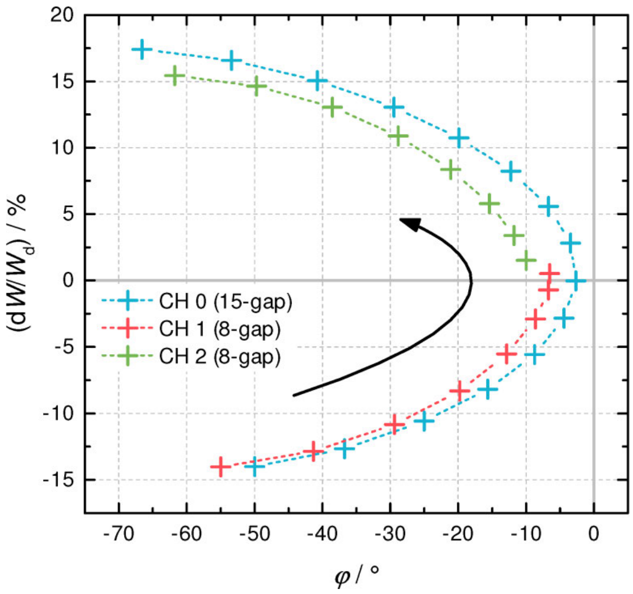

Figure 4: Exemplary movement of the bunch-center particle in longitudinal phase space for the first three CH cavities as a function of the initial (synchronous) phase at the first gap center. Additionally, the sliding movement in phase space or rather the energy gain depend on the difference between particle energy W and the cavitys design energy W_{d}.

LORASR OPTIMIZATION

A MATLAB-Code is currently under development for efficient use of the LORASR [14] batch-version. It allows an automatic variation of parameter like cavity phase and voltage as well as magnet gradients in the LORASR input-file within an entered range of values. Afterwards, simulations are started automatically and distributed to all CPU-threads to benefit from multicore-processors. Analysis of the simulation results can then easily be performed with own plotroutines and a detailed numerical result file.
Desirable features such as distributed computing to spread simulation jobs over several computers and a Nelder-Mead (downhill simplex) based optimization algorithm for a significant reduction of the total number of simulations and hence simulation time are currently being worked on.

DEMONSTRATOR CAVITY STATUS

The 15-gap CH cavity for the Demonstrator (Fig. 6) has been delivered to IAP in autumn 2015 for a first performance test @4 K without beam operation (Fig. 5). An effective gradient of $E_{\text{a}} = 7$ MV/m was already achieved within this first test and without having carried out the final surface preparation. In spring 2016 the cavity was sent back to the manufacturer to attach the helium shell. Further information and detailed results of the measurements will be published soon by F. Dziuba et al. [15, 16].

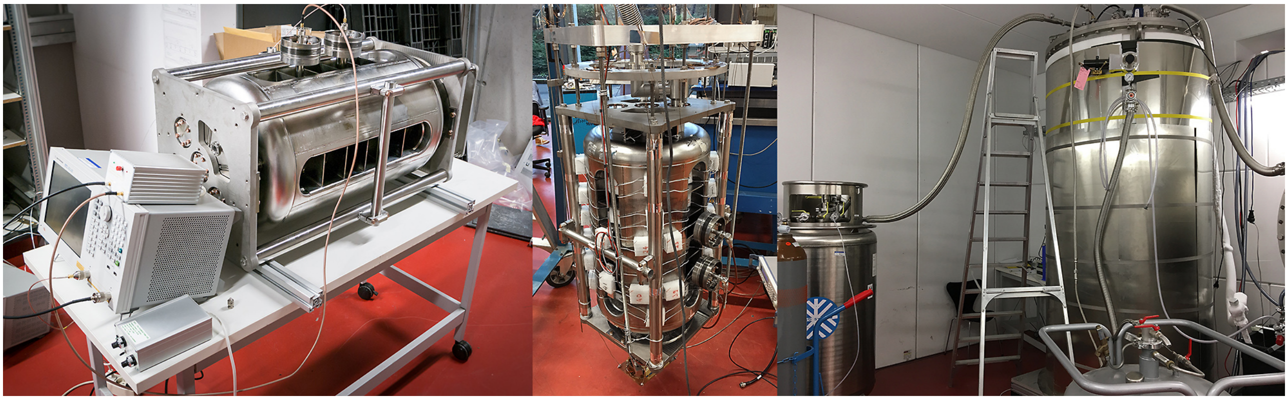

Figure 5: Frequency measurement on the 15-gap CH cavity *(left)*. Thermoluminescent dosimeters (TLDs) were mounted around the cavity for field emission measurements *(center)*. Conditioning and power tests were performed at IAP with a vertical cryostat *(right)*.

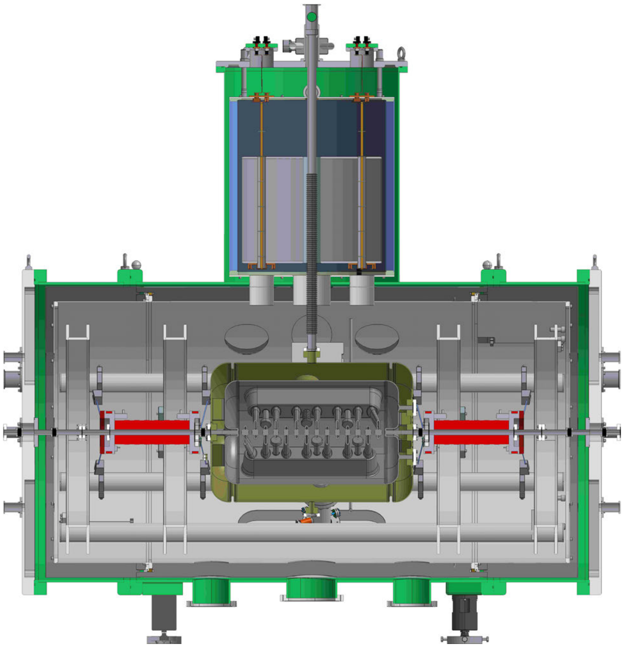

Figure 6: Sectional View of the Demonstrator cryostat containing two solenoids *red* and the 15-gap CH cavity.

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