BEAM DYNAMICS STUDY FOR THE HIM&GSI HEAVY ION SC CW-LINAC

Stepan Yaramyshev [1,5], Kurt Aulenbacher [2,4], Winfried Barth [1,2,5], Markus Basten [3], Marco Busch [3], Florian Dziuba [2], Viktor Gettmann [2], Manuel Heilmann [1], Maksym Miski-Oglu [2], Holger Podlech [3], Malte Schwarz [3]
[1]GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt, Germany
[2]HIM, Helmholtz Institute Mainz, Germany
[3]IAP, Goethe-University Frankfurt am Main, Germany
[4]IKP, Johannes Gutenberg-University Mainz, Germany
[5]National Research Nuclear University - Moscow Engineering Physics Institute, Russia

Abstract

A sc CW-Linac with variable output energy from 3.5 to 7.3 MeV/u for ions with mass to charge ratio of A/Z<6 is recently under development at HIM and GSI. Following the results of the latest RF-tests with the newly constructed sc CH-DTL cavity, even heavier ions (up to Uranium 28+) could be potentially accelerated with the already reached higher RF-voltage. Also the possibility for an up to 10 MeV/u increased output energy, using the same 13 independent cavities, is under consideration. All these options require an advanced beam dynamics layout, as well as a versatile procedure for transverse and longitudinal beam matching along the entire linac. The proposed algorithms are discussed and the obtained simulation results are presented.

INTRODUCTION

Operation of the new GSI Facility for Antiproton and Ion Research at Darmstadt (FAIR) foresees the UNILAC as a heavy ion high intensity injector for the synchrotron SIS18. Therefore beam time availability for Super-Heavy Elements research (SHE) is decreased [1,2]. To keep the SHE program at GSI on a high competitive level, a multi-stage program for the development of a heavy ion superconducting (sc) continuous wave (cw) linac is in progress at HIM, GSI and IAP. Such a machine will provide for significantly higher beam intensities and an increased rate of SHE production [3].

In accordance with the recent linac layout, the beam with the design mass to charge ratio of A/Z=6 will be accelerated by up to thirteen multi-gap CH cavities [4]. The CW-Linac should provide the beam for physics experiments, smoothly varying the output particle energy from 3.5 to 7.3 MeV/u, simultaneously preserving high beam quality.

Besides this, a potential implementation of the CW-Linac for acceleration of a wide spectra of ions, from protons up to uranium, is recently under consideration. An acceleration gradient, twofold compared to the initial design, has been experimentally reached in 2016 [5]. Therefore a higher output beam energy is potentially achievable, especially for medium ions with a low mass to charge ratio (A/Z=3).

Due to the wide range of available rf-voltage and rf-phase settings for each CH-cavity, a variable beam energy could be provided by each cavity separately. Therefore an advanced beam dynamics layout and a proper longitudinal beam matching are the key tasks. A dedicated algorithm for a longitudinal beam matching, providing for the optimum machine settings (voltage and RF phase for each cavity), has been developed [6].

SC CW DEMONSTRATOR

A multi-cavity advanced SC Demonstrator is recently under construction at GSI [7-10]. The existing High Charge State Injector (HLI) provides heavy ion beams with an energy of 1.4 MeV/u, delivered with a dedicated beam transport line to the demonstrator cave (Fig. 1).

Besides the room temperature focusing magnetic quadrupoles (triplet and two doublets), the setup comprises two rebuncher cavities, beam diagnostics and cold-warm junction of the cryostat. Adequately chosen gradients of

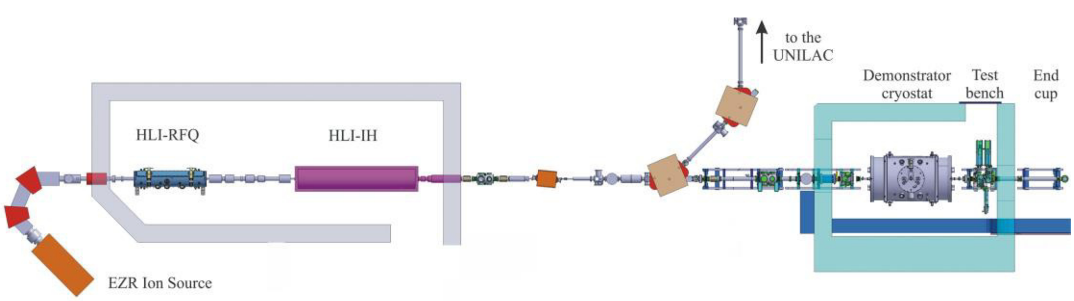

Figure 1: Recent schematic layout of the HLI injector and sc cw Demonstrator at GSI

* S.Yaramyshev@gsi.de

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the quadrupole lenses make the input beam at the Demonstrator entrance axially symmetric in 4D transverse phase plane for easier further focusing by the solenoids. The rebuncher cavities, operated at 108 MHz, provide for the required longitudinal matching. Therefore the 6D beam matching to the demonstrator is accomplished [11].

The commissioning of the CW-Demonstrator, consisting of two superconducting solenoids and the superconducting 15-gap CH-cavity (CH0), has already started in 2016, the first test with beam is planned for summer 2017 [12]. Two identical shorter 8-gap cavities CH1 and CH2 are already ordered; delivery to GSI is expected in 2017. After successful testing of the first cryostat, the construction of an extended cryomodule is under consideration.

BEAM DYNAMICS SIMULATIONS

As an input for the beam dynamics simulations for the transport line from HLI to the Demonstrator the previously performed simulations for the whole HLI injector have been used. Due to the beam current below 1 mA and a relatively high particle energy (above 1.4 MeV/u), the space charge effects could be neglected. Therefore, as a first approach, the longitudinal beam dynamics can be treated separately from the transverse one.

The capability of the two-buncher system for longitudinal beam matching has been proved and confirmed for a wide range of longitudinal Twiss-parameters at the entrance of the Demonstrator cavity. Beam dynamics simulations for the transport line have been carried out with the envelope code TRACE-3D [13] and the multiparticle code DYNAMION [14].

The 15-gap CH cavity [7], as well as the shorter 8-gap CH cavities [10] are designed on the base of KONUS/EQUUS beam dynamics scheme; as a consequence particle motion in each such accelerating cavity is very sensitive to the initial rf phase and the cavity voltage. Higher acceleration gradient and/or different mass to charge ratio A/Z, potentially enabling for a higher beam energy, make beam dynamics layout of the entire linac even more complicate.

The beam dynamics simulations for the cavities has been performed by means of the DYNAMION code, which calculates the shape of an external electrical field in a DTL linac on the base of the real topology of tubes and gaps. A distribution of voltage at each gap along a cavity has been defined by the CST simulations [15], taking into account details of the cavity design and position of the plungers (Fig. 2).

VARIABLE BEAM ENERGY

Generally the proposed linac should facilitate variable output energy from 3.5 to 7.3 MeV/u. Also acceleration of ions with a mass to charge ratio of 3<A/Z<6 even for higher energies is planned. Additionally a potential possibility for an acceleration of protons, as well as uranium ions is recently under investigation. The experimentally reached higher acceleration gradient has been taken into account for such a study.

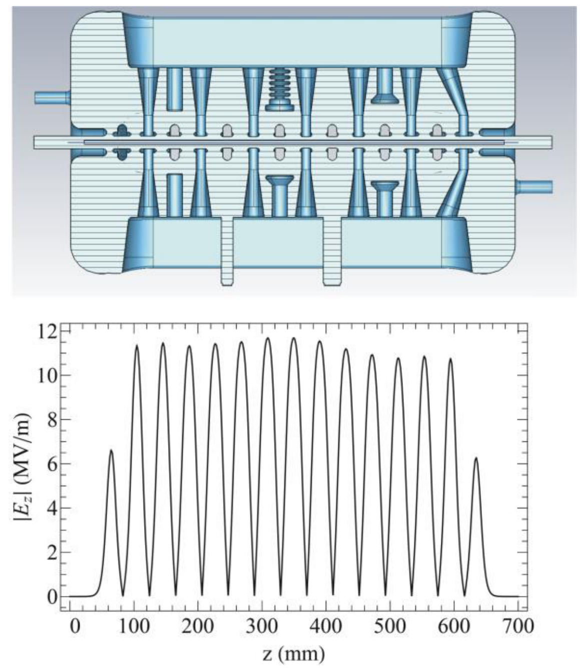

Figure 2: CST model for the 15-gap CH cavity (top) and the calculated accelerating electrical field along the cavity (bottom).

Therefore the original linac layout could be revised: the number of gaps per cavity has been decreased, preserving the total cavity voltage and high accelerating gradient.

The recently presented simulations have been accomplished calculating only the accelerating cavities, while the future real layout of the CW-Linac is not taken into account. Also a transverse evolution of the beam has been neglected by use of a pencil beam (X=X'=Y=Y'=0).

In longitudinal phase space the monoenergetic particles are distributed uniformly from -180° to +180°, what imitate the whole range of the cavity rf phase to calculate the beam energy, which potentially could be reached with the given conditions, namely input particle energy and cavity voltage. Therefore the results of investigation represent an estimated upper limit of an energy gain for the entire CW-Linac.

An example of the output beam phase portrait (on the plane energy-phase) illustrates an evolution of the longitudinal beam emittance and indicates the areas with its relatively low non-linear deformation (Fig. 3). This data has been used to define the working point of the cavity.

An increased acceleration gradient of 7.1 MV/m has been applied. Compare to the design value of 5 MV/m, it leads to a factor of 1.42 higher cavity voltage.

A preliminary geometrical layout for the cavities CH3-CH13, based on the already designed 8-gap cavities CH1 and CH2, has been scaled proportionally to the increased particle velocity.

The internal topology of the multi-gap cavities has been designed for a smooth glide of the synchronous phase along the channel to provide for a longitudinal focusing of the beam.

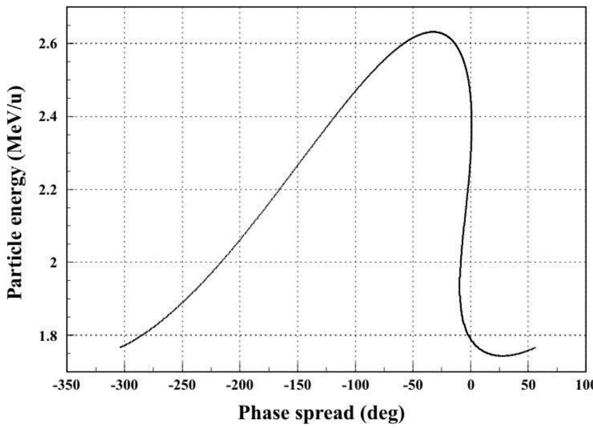

Figure 3: Longitudinal beam phase portrait, indicating the potential working point with a high output energy and a low non-linear deformation of the beam emittance.

As a consequence, a conversion of rf power to acceleration of the ions might be not optimal, especially with an increased voltage and particle velocity along a multi-gap cavity. Thus, for these preliminary simulations, the number of gaps per cavity has been reduced from 8 to 7 (CH3-CH4) and to 6 (CH5-CH12), preserving the total cavity voltage. Such a layout of the cavities provides simultaneously for high efficiency and flexibility of the CW-Linac.

The simulations have been performed iteratively: the results of the beam dynamics in the cavities CH0, CH1 and CH2 define an area where the output beam energy is high, but a non-linear deformation (effective growth) of the longitudinal beam emittance is still acceptable. The reached beam energy, in combination with an estimated energy gain in the following cavity, provides for a scaling coefficient for the layout of the following DTL structure. Three gradations of the cavity voltage have been implemented: 1.0, 1.21 and 1.42 of the nominal acceleration gradient. The rf phase of the cavity CH_i was varied from -180° to +180°.

The results of the beam dynamics simulations through the cavity CH_i were used to define its potential working point and the output beam energy. Then the same procedure has been performed for the following cavity CH_{i+1}. The resulted beam energy behind each cavity is presented in Table 1.

As a next step, an acceleration of the ions with mass to charge ratio A/Z=3, as well as for protons has been calculated applying the fixed layout of the CH cavities.

LONGITUDINAL BEAM MATCHING

The layout of the CW-Linac requires proper settings (voltage and phase) for each of the 13 independently operated cavities, providing for sufficient acceleration, as well as for low emittance growth. Thus the longitudinal beam matching to each cavity is of highest importance. In general it is hampered by strong dependence of particle motion on beam dynamics in all previous cavities. The dedicated method for the beam matching [6], based on the previous investigation and analysis of advanced beam dynamics simulation results [16,17], has been developed to cover numerous scenarios for linac operation.

A flexible constructed mismatch parameter allows for machine optimization for a wide range of the ions with different mass to charge ratio, as well as for the required output beam energy and even beyond.

Table 1: Beam Energy Behind Each Cavity

Cryo Module	Cavity	Output energy (MeV/u)		
		A/Z=6	***A/Z=3***	***A/Z=1***
	HLI	*1.4*	*1.4*	*1.4*
CM1	CH0	2.1	2.2	3.0
	CH1	2.6	3.0	4.2
	CH2	2.9	3.6	4.6
CM2	CH3	3.4	4.3	5.7
	CH4	3.8	4.8	6.3
	CH5	4.2	5.5	7.7
CM3	CH6	4.7	6.2	8.6
	CH7	5.2	7.0	9.9
	CH8	5.8	7.8	10.9
CM4	CH9	6.4	8.7	12.3
	CH10	7.0	9.5	13.2
	CH11	7.6	10.5	14.6
	CH12	8.0	11.4	15.6

CONCLUSION

The high intensity heavy ion SC CW linac project, conducted by GSI and HIM, is fully in line with other modern type and high efficient CW linac projects, mainly for proton and light ion acceleration, which are under development at different leading accelerator centers worldwide [18-26].

On the base of the recent experimentally obtained results, an increased acceleration gradient of 7.1 MV/m is considered.

An estimated upper limit for the beam energies, potentially reachable in a revised linac layout, has been calculated for ions with different mass to charge ratio (1<A/Z<6). An effective acceleration of U28+ ions (A/Z=8.5) is also expected.

A dedicated algorithm for the longitudinal beam matching with a DTL cavity has been developed to be implemented for the CW-Linac, comprised by 13 independently powered multi-gap cavities.

The presented study demonstrates potentially high operation capabilities of HIM&GSI CW-Linac for acceleration of a wide spectra of ions with different mass to charge ratio (from protons up to uranium), using optimized linac settings.

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