AN ADVANCED PROCEDURE FOR LONGITUDINAL BEAM MATCHING FOR SC CW HEAVY ION LINAC WITH VARIABLE OUTPUT ENERGY

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Abstract

A multi-stage program for the development of a heavy ion superconducting (SC) continuous wave (CW) linac is in progress at HIM (Mainz, Germany), GSI (Darmstadt, Germany) and IAP (Frankfurt, Germany). The main beam acceleration is provided by up to nine multi-gap CH cavities. Due to variable beam energy, which could be provided by each cavity separate, a longitudinal beam matching to each cavity is extremely important. The linac should provide the beam for physics experiments, smoothly varying the output particle energy from 3.5 to 7.3 MeV/u, simultaneously keeping high beam quality. A dedicated algorithm for such a complicate matching, providing for the optimum machine settings (voltage and RF phase for each cavity), has been developed. The description of method and the obtained results are discussed in this paper.

INTRODUCTION

The High Charge State Injector (HLI) in combination with the Universal Linear Accelerator (UNILAC) serves as a powerful high duty factor (up to 25%) accelerator, providing heavy ion beams for the experiment program at GSI [1,2]. 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 [3]. To keep the SHE program at GSI on a high competitive level, the development of a heavy ion superconducting (SC) continuous wave (CW) linac is in progress (Fig. 1). Such a machine will provide for significantly higher beam intensities and an increased rate of SHE production [4].

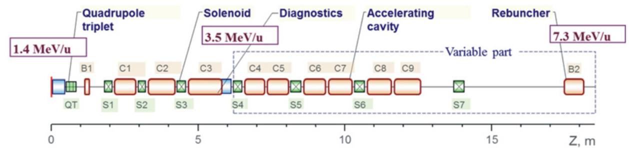

Figure 1: The conceptual layout for SC part of the CW linac at GSI.

SC CW DEMONSTRATOR

The multi-cavity advanced SC Demonstrator is recently under construction at GSI [5-7]. The existing HLI serves as injector and provides heavy ion beams with an energy of 1.4 MeV/u, delivered with a dedicated transport line to the demonstrator cave (Fig. 2).

Besides the room temperature focusing magnetic quadrupoles (triplet and 2 doublets), the setup comprises two rebuncher cavities, beam diagnostics and cold-warm junction of the cryostat. Adequately chosen gradients of 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 beam 6D matching to the demonstrator is accomplished [8].

The commissioning of the CW-Demonstrator, consisting of two superconducting solenoids and the superconducting CH-cavity, has already started in 2016 [9].

After successful testing of the first cryostat, the construction of an extended cryomodule, which is foreseen to comprise two shorter CH cavities is planned to be tested until end of 2017. Two identical short CH cavities are already ordered; delivery to GSI is expected until summer 2017. The schematic layout of the machine is shown on Fig. 3.

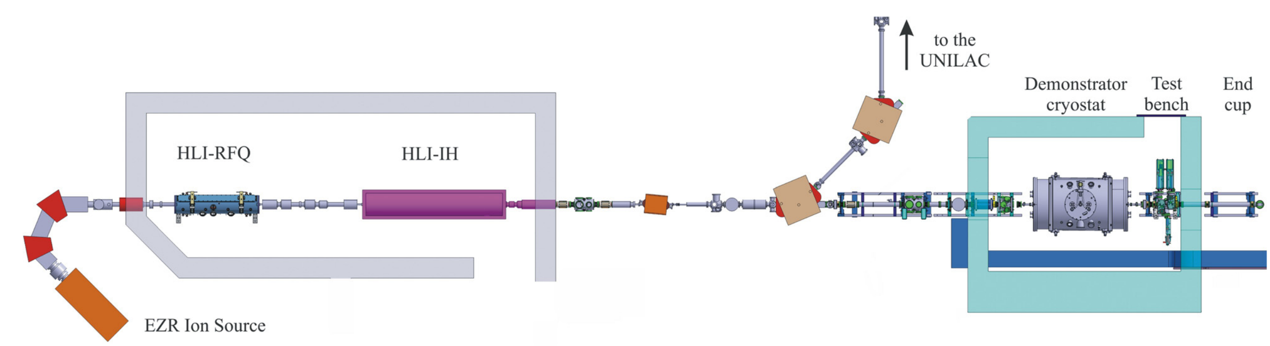

Figure 2: Recent schematic layout of the SC Demonstrator at GSI.

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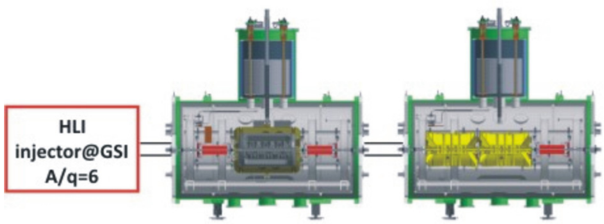

Figure 3. The schematic layout of the linac (expected to be constructed until the end 2017).

LONGITUDINAL BEAM DYNAMICS

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 a low beam current (below 1 mA) and 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 separated 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 have been carried out by means of the codes TRACE-3D [10] and the DYNAMION [11].

The 15-gap CH cavity, as well as the shorter 8-gap CH cavities [12] are designed on the base of KONUS/EQUUS beam dynamics scheme as not fully resonance accelerators. This design feature allows for the desired high accelerating gradient. Although some of the gaps are designed to perform a longitudinal beam focusing at the expense of acceleration. Therefore particle motion in each such accelerating cavity is extremely sensitive to the initial RF phase and the cavity voltage.

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 [13], taking into account details of the cavity design and position of the plungers (Fig. 4-5).

Generally the proposed linac should facilitate a variable output energy from 3.5 to 7.3 MeV/u. Also acceleration of ions with mass to charge ratio from 3 to 6 even for higher energies is planned. Therefore the original linac layout has been revised: the number of gaps per cavity has been decreased and number of cavities has been extended from 9 to 13. This layout requires proper settings (voltage and phase) for each of the 13 independently operated cavities, which provide for a required acceleration but sufficiently low emittance growth. Thus the longitudinal beam matching to each cavity is of high importance, hampered by strong dependence of particle motion inside a cavity from beam dynamics in all previous cavities. Therefore a dedicated method for optimization of the matching should be developed, especially due to the numerous scenarios for linac operation.

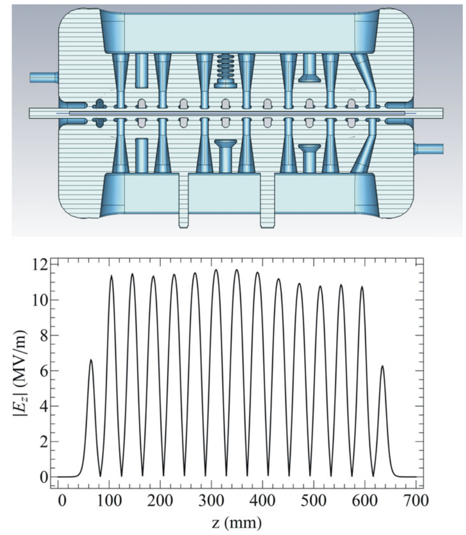

Figure 4. CST model for the 15-gap CH cavity (top) and accelerating electrical field along the cavity (bottom).

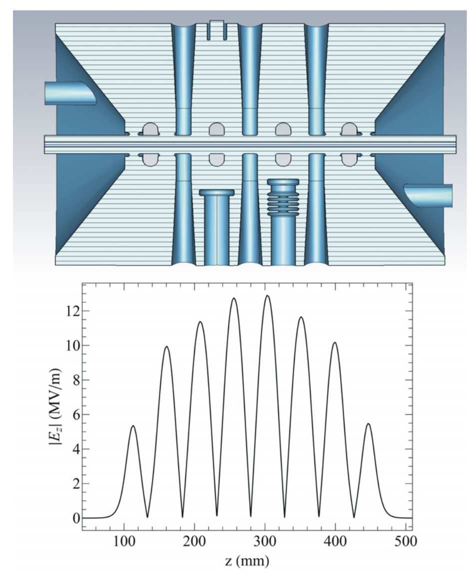

Figure 5. CST model for the 8-gap short CH cavity (top) and accelerating electrical field along the cavity (bottom).

LONGITUDINAL BEAM MATCHING

As particle acceleration in the presented CH cavities is not fully resonance, the input beam parameters, as well as RF phase and voltage of cavity, should be determined to provide for sufficient acceleration and low emittance growth. For instance a strong deformation of an elliptical emittance shape should be limited or even avoided, while such deformation is a typical effect for the KONUS beam dynamics and similar accelerating schemes. Obviously such a deformed beam emittance becomes problematic for further acceleration by subsequent cavities. Also a transverse focusing (by solenoids or magnetic quadrupoles) depends on particle velocity, therefore such longitudinal beam shape potentially drives to a degradation of the transverse beam quality and particle losses.

Thus the matched longitudinal Twiss-parameters, as well as an optimum RF phase of the cavity, should be

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determined for the given (or also optimized) cavity voltage and known longitudinal beam emittance. Fast envelopes codes as TRACE-3D are not applicable for this study due to a strong non-elliptical deformation of the longitudinal beam emittance. Obviously, a direct enumeration of all possible input parameters with full beam dynamics simulations by means of multiparticle codes (10^4-10^6 particles for each run) is extremely time consuming. Therefore the method, already proposed and implemented for a transverse beam matching [14], has been extended for the longitudinal optimization of beam dynamics.

Thus a longitudinal beam phase portrait is represented by only 100 macroparticles, forming an ellipse in the longitudinal phase plane. The ellipse area, divided by π, represents the beam emittance. Transversally all macroparticles could be set on axis due to negligibly low space charge effects and a minor influence of transverse focusing on longitudinal particle motion.

Main parameters of the ellipse could be set randomly:

- Twiss parameters **α** and **β**;
- energy of center;
- coordinate of center.

The last parameter substitutes a variation of the RF phase of the cavity. Therefore a big number of such macroparticle ensembles could be simulated in one run.

Generally an analysis of the output particle distribution could be performed due to dedicated DYNAMION feature of an unique ID number of each macroparticle. The same method could be also implemented to beam dynamics simulations by means of CST Particle Studio.

An example of a typical evolution of the particle ensemble inside the 15-gap demonstrator cavity is shown in Fig. 6. The particles are accelerated to a reasonable energy, while the output distribution is far from elliptical shape.

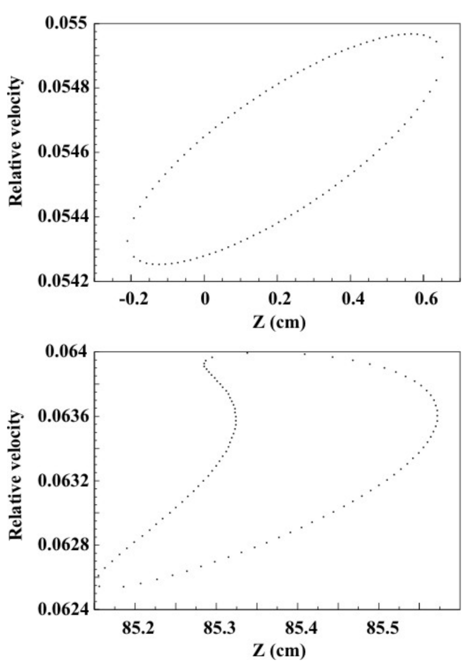

Figure 6. An example of a typical input (top) and output (bottom) 100-particle ensemble.

A series of points (***Z***, ***Z'***) could be approximated by an ellipse, assuming the standard equation:

$$cZ^2 + 2aZZ' + bZ'^2 = 1 .$$

The Twiss-parameters ***α***, ***β***, ***γ*** of such an ellipse could be obtained by means of least squares method:

$$\alpha = a\sqrt{bc - a^2} , \ \beta = b\sqrt{bc - a^2} , \ \gamma = c\sqrt{bc - a^2} .$$

Then the parameter ε_i is enumerated for each particle of the output 100-particle ensemble:

$$\varepsilon_i = \gamma Z^2 + 2\alpha ZZ' + \beta Z'^2 .$$

Three factors are calculated for each output 100-particle ensemble: emittance growth (F_1), deformation of elliptical shape (F_2) and energy gain (F_3):

$$F_1 = \frac{\varepsilon_{\max}}{\varepsilon_{input}} ,$$

$$F_2 = \frac{\varepsilon_{\max} - \varepsilon_{\min}}{\varepsilon_{input}} ,$$

$$F_3 = \frac{\beta_{out} - \beta_{in}}{\beta_{in}} ,$$

where ε_{max} and ε_{min} are the maximum and minimum values of the series ε_i ; ε_{input} is total unnormalized longitudinal beam emittance; β_{in} and β_{out} are the input and output relative velocities, averaged on the 100-particle ensemble.

Without acceleration an elliptical shape of the longitudinal beam emittance is well preserved. But for the maximum acceleration a dramatic deformation of the beam emittance occurs. Generally a combination of factors

$$F_1^{\,p} F_2^{\,q} F_3^{-s}$$

with the weight coefficients ***p***, ***q***, ***s*** could be constructed and used as mismatch parameter in dependence of the required goal in between of two limits: the highest acceleration or the best beam quality.

The above described algorithm has been implemented by means of the DYNAMION code, adjusted for numerous simulation in a batch mode and using a Monte-Carlo method with random generation of input beam parameters. The dedicated software has been written to analyze the obtained millions of ensembles and to select some hundreds of the best combinations. Fig. 7 shows the lowest mismatch factors F_2 and the corresponding Twiss-parameters. The dashed lines illustrate a clear coincidence of the method.

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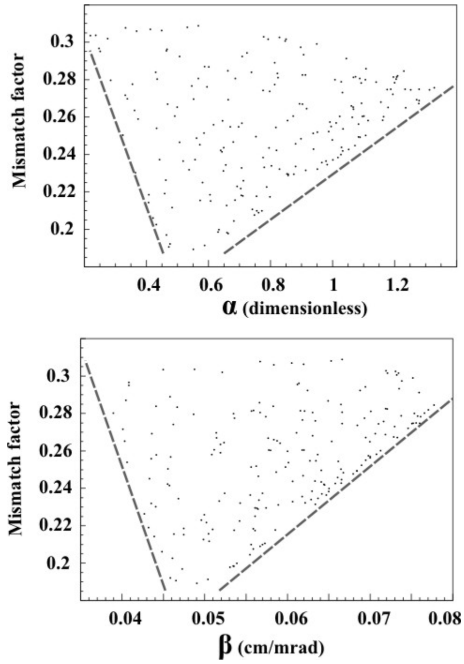

Figure 7. The lowest mismatch factors F_2 and the corresponding Twiss-parameters $\boldsymbol{\alpha}$ (top) and $\boldsymbol{\beta}$ (bottom).

An example of a well matched input 100-particle distribution is shown on Fig. 8. The particles are accelerated to a reasonable energy and the output distribution is close to an elliptical shape. Therefore the matched input beam characteristics as Twiss-parameters, energy and coordinate (cavity RF phase) are determined.

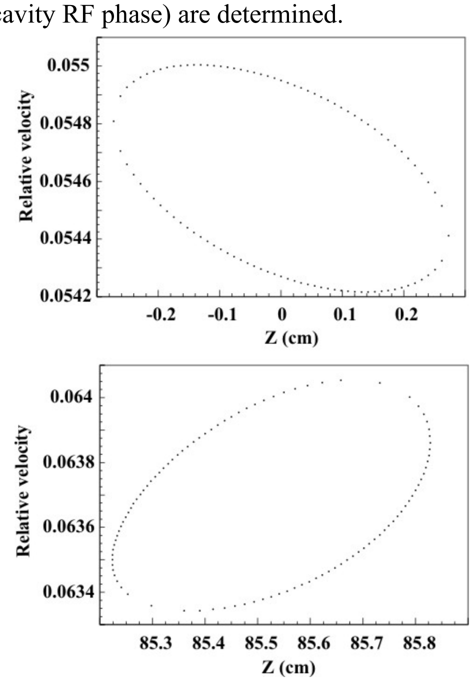

Figure 8. A typical example of the matched input 100-particle ensemble (top) and the corresponding output (bottom).

CONCLUSION

The new heavy ion SC CW linac project, conducted by HIM and GSI, 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 [15-20].

A dedicated algorithm for the longitudinal beam matching with a DTL cavity is developed. The method is foreseen to be implemented for the new GSI heavy ion SC CW linac, comprised by 13 independently powered multigap cavities, developed at IAP. 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 from 3.5 to 7.3 MeV/u and higher (for medium ions).

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