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Advanced Approach for Beam Matching along the Multi-Cavity SC CW Linac at GSI

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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) and GSI (Darmstadt, Germany) under support of IAP (Frankfurt, Germany). In 2017 the first section of the CW-Linac has been successfully commissioned at GSI. Beam acceleration at the CW-Linac is foreseen to be performed by twelve multi-gap Crossbar H-type (CH) cavities. 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. Due to a wide variation of the input and output beam energy for each cavity, a longitudinal beam matching to every cavity is of high importance. An advanced algorithm for an optimization of matched beam parameters under variable rf-voltage and rf-phase of each cavity has been developed. The description of the method and the obtained results are presented.

1. Introduction

The design, construction and operation of continuous wave (cw) proton and ion linacs is a crucial goal of worldwide accelerator technology development.

Also a high energy cw linac is an essential part of a large scale research facility, as an accelerator driven system or a spallation neutron source [1-3].

A cw linac in the medium energy range could be used for several applications, as high productivity isotope generation, material science and boron-neutron capture therapy. The compactness of such cw facilities, accomplished by the use of superconducting (sc) elements, is a modern trend for the development of high intensity ion linacs [4-8]. Therefore the elaboration and optimization of a cw linac, as well as progress in elaboration of the superconducting technology, is of high relevance.

2. SC CW-Linac at GSI

Recently operated at GSI the High Charge State Injector (HLI), followed by the UNIversal Linear ACcelerator (UNILAC), serves as a high duty factor (up to 25%) heavy ion accelerator for the Super-Heavy Elements (SHE) program at GSI [9-11]. Future operation of the new GSI Facility for Antiproton and Ion Research at Darmstadt (FAIR) foresees an upgrade of the UNILAC [12-18] as high intensity low duty factor injector for the synchrotron SIS18. Therefore beam availability for SHE production is strongly decreased.

To keep the user program at GSI, the development of a heavy ion sc cw HELIAC (HElmholtz LInear ACcelerator) (Figure 1) is still in progress [19, 20]. The proposed linac comprises twelve multi-gap Crossbar H-type (CH) cavities and should facilitate a variable output energy of ions with mass to charge ratio *A/Z*≤6 from 3.5 to 7.3 MeV/u. The potential acceleration of heavy ions (*A/Z* up to 8.5) or light ions even for higher energies has been already confirmed by the dedicated simulations.

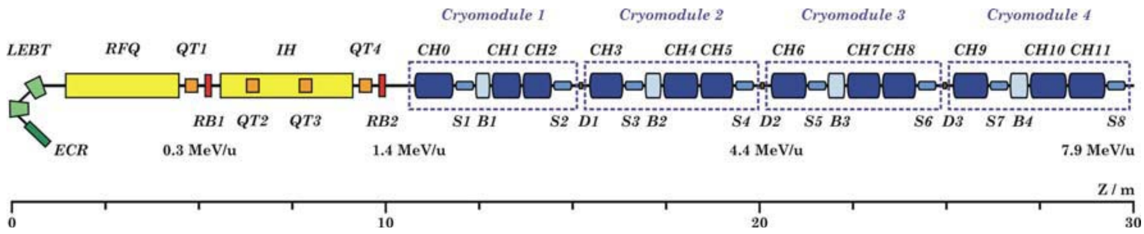

Figure 1. Conceptual layout of heavy ion superconducting CW-Linac with warm injector.

2.1. SC CW Demonstrator

The existing injector HLI provides heavy ion beams with an energy of 1.4 MeV/u, delivered with a dedicated transport line to the demonstrator cave (Figure 2). In July 2017 the sc cw Demonstrator, consisting of the superconducting 15-gap CH-cavity and two superconducting solenoids, has been successfully commissioned with heavy ion beam at GSI. The required acceleration gain has been achieved with heavy ion beams even above the design mass to charge ratio at high beam intensity and full beam transmission [5].

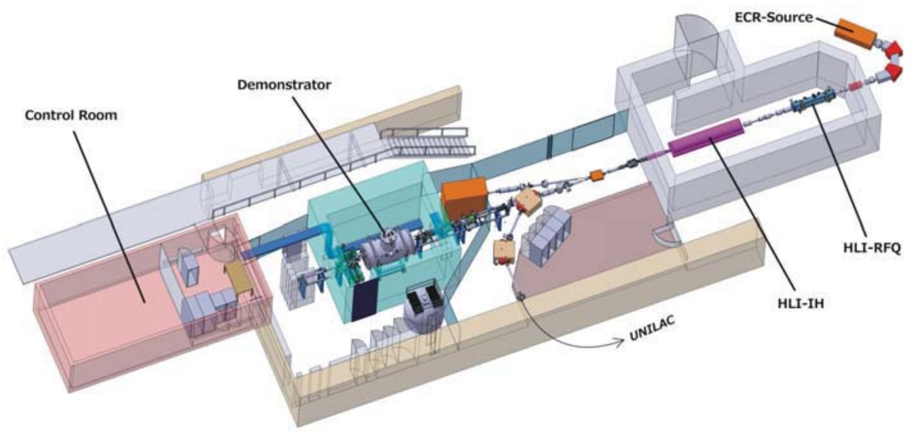

Figure 2. Demonstrator enviroment at GSI.

3. Longitudinal beam dynamics

Two buncher cavities, operated at 108 MHz, perform longitudinal matching of the beam from HLI to sc linac. The capability of such two-buncher system to provide for a wide range of longitudinal Twiss-parameters at the entrance of the first CH cavity has been demonstrated numerically [21] and experimentally [5].

Due to a low beam current (below 1 mA) and relatively high particle energy (above 1.4 MeV/u), space charge effects could be neglected at this stage of beam dynamics simulations. Hence the longitudinal particle motion can be calculated independently from the transverse one.

The commissioned 15-gap CH cavity, as well as the already fabricated shorter 8-gap CH cavities are designed on the base of EQUUS (EQUidistant mUltigap Structure) beam dynamics scheme [4]. This design feature allows for the desired high accelerating gradient using synchronous phase close to

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0° in the central gaps. Although some of the gaps with synchronous phase from -70° to -40° are designed to perform a longitudinal beam focusing at the expense of acceleration. Therefore particle motion in such accelerating channel is extremely sensitive to the rf-phase and the cavity voltage, as well as to input longitudinal Twiss-parameters.

The presented beam dynamics simulations have been performed by means of the DYNAMION code [22], which calculates the shape of an external electrical field in a Drift Tube Linac on the base of the real geometry of tubes and gaps.

4. Longitudinal beam matching

The CW-Linac layout requires for proper settings of rf-voltage and rf-phase for each of the twelve multi-gap cavities, as well as for each of the four bunchers, recently added on the base of dedicated studies [23]. Moreover the required acceleration has to provide for sufficiently low growth of the longitudinal emittance. Thus the longitudinal beam matching to each cavity is of high importance, hampered by strong dependence of particle motion inside a cavity on beam dynamics in all previous sections. Therefore a dedicated method for longitudinal beam matching [24] is envisaged, in particular due to the recently extended set of non-scaled scenarios for the linac operation with ions from protons to uranium (A/Z =8.5).

Acceleration in the developed CH cavities is mainly accomplished at a synchronous phase of about 0°, so as a consequence the longitudinal particle motion is remarkably non-linear. This unavoidably leads to longitudinal emittance growth and/or deformation. Therefore the matched Twiss-parameters, as well as rf-phase and rf-voltage of the cavities, should be optimized to provide for a sufficient energy gain and simultaneously for the high beam quality. For instance, an irreversible deformation of an elliptical shape of the longitudinal emittance, typical for the EQUUS beam dynamics and similar accelerating schemes, should be preferably reduced.

Fast matrix/envelope codes are not applicable for this study because of a non-linear particle motion, leading to a deformation of the longitudinal beam emittance. A reliable non-linear evolution of the particle ensemble could be modeled only under detailed description of the electrical field. Obviously, a direct enumeration of beam dynamics by means of multiparticle codes (10^4-10^6 particles for each run) considering all possible input beam- and cavities -parameters is extremely time consuming.

4.1. Description of the Method

A longitudinal beam phase portrait could be represented by only 100 macroparticles, forming an ellipse on 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 the transverse particle motion on the longitudinal one (paraxial approximation) at the considered beam energy range above 1.4 MeV/u.

The main characteristics of such an ellipse, i.e. Twiss-parameters α and β, central energy and central coordinate could be set randomly. The last parameter virtually substitutes a variation of the rf-phase of the cavity. Therefore a large number of such 100-particle ensembles could be assembled as one input particle distribution for simulation in one run of the computer code. Finally different output ensembles could be analyzed separately, using dedicated DYNAMION feature of an unique ID number, assigned to each macroparticle [25].

An example of the typical evolution of the 100-particle ensemble inside the 15-gap CH cavity is shown in Figure 3. The particles are accelerated to the design energy, while the output distribution is far from elliptical shape.

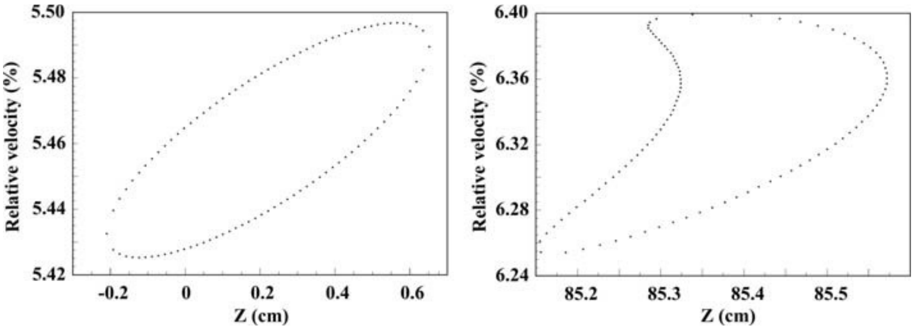

Figure 3. Example of typical 100-particle ensemble at the entrance (left) and at the exit (right) of the cavity.

4.2. Analysis of Simulation Results

A series of points (*Z, Z′*), representing 100-particle ensemble on the longitudinal phase plane, could be approximated by an ellipse, assuming the standard equation. The Twiss-parameters α, β, γ of such an ellipse could be obtained by means of the least squares method; then the parameter ε_i is enumerated for each particle:

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

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

$$F_1 = \frac{\varepsilon_{\max}}{\varepsilon_{input}},\ F_2 = \frac{\varepsilon_{\max} - \varepsilon_{\min}}{\varepsilon_{input}} \text{ and } F_3 = \frac{\beta_{out} - \beta_{in}}{\beta_{in}},$$

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

Without acceleration an elliptical shape of the longitudinal beam emittance is obviously preserved, while maximum acceleration leads to a dramatic deformation of the beam emittance. A combination of factors

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

indicates the quality of matching, while the weight coefficients *p*, *q*, *s* should be defined in dependence of the required goal in between of two limits: the highest acceleration or the best beam quality.

The described algorithm has been realized by means of the DYNAMION code, adjusted for numerous simulations in a batch mode and using a Monte-Carlo method for random generation of input beam parameters. The dedicated software has been written to analyze and to select some hundreds of the best combination from the simulated millions of ensembles.

An example of a well matched 100-particle distribution is shown on Figure 4. The particles are accelerated to the design energy and the output distribution almost keeps an elliptical shape. So the matched input beam characteristics as Twiss-parameters, energy and central coordinate (cavity rf-phase) are determined.

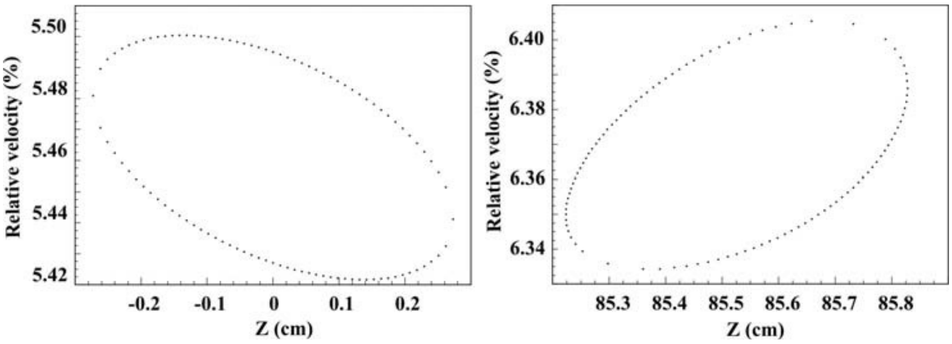

Figure 4. Example of matched 100-particle ensemble at the entrance (left) and at the exit (right) of the cavity.

4.3. Proof of the Method

The standard multiparticle beam dynamics simulations have been performed with beam and cavity parameters, corresponding to the matched (Figure 4) and mismatched (Figure 3) cases. The results have been analyzed in a standard way, calculating RMS and total longitudinal beam emittances for a different percentage of particles inside a given emittance (Figure 5).

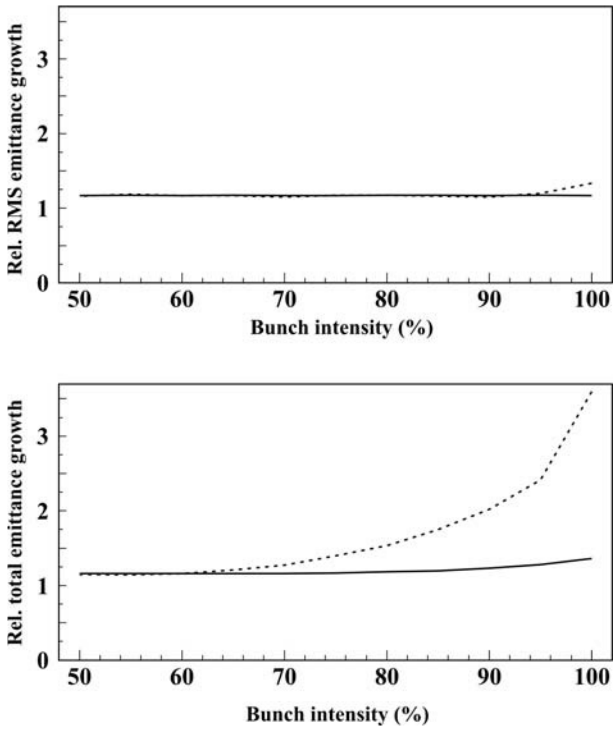

Figure 5. RMS (top) and total (bottom) emittance growth for a different percentage of particles for matched (solid line) and mismatched (dashed line) cases.

The graph for the mismatched case clearly indicates a dramatical growth of the total beam emittance (compare to the matched one), while an rms emittance demonstrates some small increase only. Therefore the proposed method, applying matching of a 100-particle elliptical ensemble, provides for a reliable indication of the optimized input beam parameters and machine setting. The required beam dynamics simulations could be performed about two orders of magnitude faster than usual ones, enabling for a multi-run optimization study.

5. Conclusion

The new heavy ion sc CW-Linac, conducted by HIM and GSI in collaboration with IAP [26, 27], is fully in line with modern high efficiency cw linac projects, which are under development at different leading accelerator centers worldwide [28-32].

In July 2017 the first superconducting 15-gap CH cavity, designed on the base of EQUUS beam dynamics, has been successfully commissioned at GSI with heavy ion beams.

Fast and reliable algorithm has been developed for the longitudinal beam matching and for the smart (non-scaled) machine optimization for different heavy ions, as well as for smoothly variable from 3.5 to 7.3 MeV/u beam energy. The proposed method is foreseen to be implemented for the entire CW-Linac, comprising twelve independently powered multi-gap CH cavities and four bunchers.

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