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BEAM DYNAMIC SIMULATIONS FOR THE DTL SECTION OF THE HIGH BRILLIANCE NEUTRON SOURCE

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Abstract

As various experimental reactors in Europe are already or will be decommissioned over the next years, new neutron sources will be necessary to meet the demand for neutrons in research and development. The High Brilliance Neutron Source is an accelerator driven neutron source planned at the Forschungszentrum Jülich . The accelerator will accelerate a proton beam of 100 mA up to an end energy of 70 MeV, using normal conducting CH-type cavities. Due to the high beam current, the beam dynamics concept requires special care. In this paper, the current status of the beam dynamics for the drift tube linac is presented.

OVERVIEW HBS, REQUIREMENTS AND BOUNDARY CONDITIONS

The HBS drift tube linac [1] will accelerate the 100 mA proton beam coming out of the MEBT2 section with an energy of 2.5 MeV up to an end energy of 70 MeV using CH-type normal conducting cavities [2]. The top level requirements and most important parameters of the HBS linac can be found in Table 1.

Table 1: General Parameters and Top Level Requirements for the HBS Linac

Design Parameters	Value
Input energy	2.5 MeV
End energy	70 MeV
Beam current	100 mA
Particles	Protons
Resonance frequency	176.1 MHz
Number of cavities	45
Peak beam power	7 MW
Average beam power	336 kW
Duty cycle (beam/RF)	4.8 / 10 %
Beam pulse length	167/667 µs

The beam dynamics concept is carefully chosen to keep the emittance growth along the beam line as low as possible, which is the most challenging aspect concerning the beam dynamics calculations, due to the high beam current and the resulting space charge forces involved. Furthermore the linac is designed to accelerate the beam as efficient as possible, minimizing the number of cavities, required equipment and infrastructure.

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Three rebunching cavities will provide longitudinal focussing, while the transversal focussing lattice consists of quadrupole triplets installed between the cavities.
It can be observed that at low energies, the longitudinal phase spread of the beam will increase in the drift after an accelerating cavity to an extend so that the longitudinal acceptance of the next cavity would have to be much to high for efficient acceleration. Therefore, the three rebunchers are necessary to guarantee efficiency and stability. Another conclusion from this observation is that the distance between cavities should be kept as short as possible. Therefore, the lengths and transversal geometry of the quadrupole triplets are chosen to be identical and as short as technically feasible.
However, there are further boundary conditions concerning the feasibility of the parts. The length of the cavities should not exceed 1.5 m and the maximum magnetic field strength of the quadrupole lenses should be 1.2 T. All beam dynamics calculations have been performed with LORASR [3], a beam dynamics code developed at the IAP, Frankfurt, Germany.

AUTOMATION OF CALCULATION USING PARTICLE SWARM OPTIMIZATION

The high number of cavities naturally leads to a high number of free parameters for the beam dynamics concept. Therefore the beam dynamics calculations for the HBS DTL section have been largely automated using python programmes. For optimization of the beam dynamics layout, particle swarm optimization (PSO) has been chosen. This optimization algorithm has several advantages: It does not use gradients. This is necessary when optimizing beam dynamics, because one can not assume that a chosen cost function is differentiable. Furthermore, it is possible to parallelize the calculation of the candidate solutions in one iteration, which saves an considerable amount of time.
A particle swarm optimization algorithm which supports multithreading has been coded in python. The parameters to be optimized are the cavity phases and the magnetic field strengths of the lenses. The candidate solutions are fed to several instances of LORASR run in batch mode and calculated on different cores of the processor at the same time. The results are read out and the cost function is calculated. The python code runs over a fixed number of cavities at once, after which it moves automatically on to the next cavities. This way, creating the beam dynamics concept for the HBS

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linac as been automated to a high degree with already satisfying results.

One of the main aspects of optimization is the choice of the cost function. Several possibilities have been tested, of which the following, simple function proved to provide the best results:

$$f_{cost} = w_x + w_y + w_E + (L+10)^3 + |f - 60\%| \cdot c_1, \quad (1)$$

with the percentage growth of the emittance w, the occurring losses L, the maximum filling factor of the cavities f and a constant c_1, which is set to 0 when the maximum filling factor is below 60 %, thus avoiding solutions with very large beam diameters. The number of cavities optimized at once is set to three for the following results.

The above function has the advantage of leading straight to a solution with very good beam quality. However, it might provide a solution that hardly or not at all can be injected into the next cavity, e.g. a defocussed beam coming out of the last of the three cavities. To avoid this behaviour of the algorithm, three cavities are optimized at once, but only the results for the first two cavities are being used. After those two optimized cavities, the beam will naturally be matched to be injected into a following cavity.

For the next iteration along the beamline, the third cavity becomes the first one of the three cavities to be optimized. With this method, a more complex and therefore more sensitive cost function can be avoided.

The performance of the PSO has been tested. An optimization of the first three cavities has been tested (using the parameter range explained in the next chapter) using different numbers of swarm sizes. For each swarm size, three different optimization runs have been performed, with different numbers of iterations. The results are shown in Fig. 1. It can be observed that the lowest found minimum of the cost

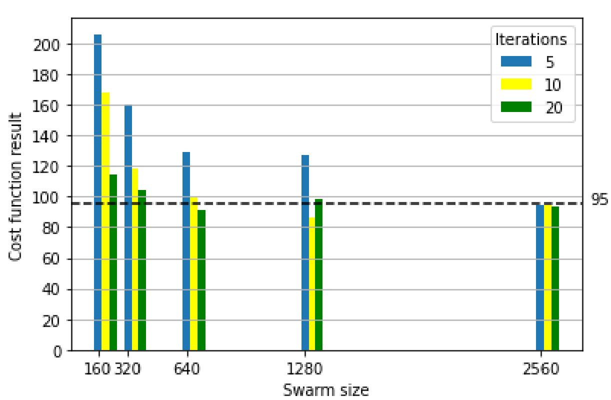

Figure 1: Performance test of the PSO.

function is about 95, varying only a few percent. A solution of this magnitude is definitely found with a swarm size over 640 and 10 iterations or more. Therefore, those values are chosen for the current optimization approach to get a good, yet time saving result.

BEAM DYNAMICS CONCEPT

The beam dynamics have been calculated using the PSO, with a swarm size of 640 and 10 iterations. The voltages of the cavities have been chosen moderately for the first cavities and then set up to maximum possible voltage for the later ones. The number of gaps is determined by the transversal focussing at low energies and the maximum length of 1.5 m at higher energies. The phases are optimized in an range between −20 ° and −40 ° for accelerating and −80 ° and −95 ° for bunching cavities. The gradients of the quadrupoles are optimized in a range varying with the beam energy. The generation of a beam dynamics concept up to 70 MeV beam energy takes about four days of calculation for the optimization code.

A 4D-Waterbag distribution created by LORASR serves as input distribution. The resulting beam design consists of 45 cavities, of which three are rebunching cavities. The linac is 67 m long, from beginning of the first to the end of the last cavity. Table 2 lists the resulting rms emittances.

Table 2: Input and output values for the current beam dynamics design of the HBS linac

Value	Input	Output
Energy /MeV	2.5	70.0
$\epsilon_{rms,x}$ /mm mrad	1.67	2.28 (+36.53 %)
$\epsilon_{rms,y}$ /mm mrad	1.82	2.47 (+35.7 %)
$\epsilon_{rms,E}$ /keV ns	18.64	23.7 (+27.25 %)

The corresponding emittance ellipses can be found in Fig 2. Here, a beginning filamentation in longitudinal space and a few halo particles can be observed.

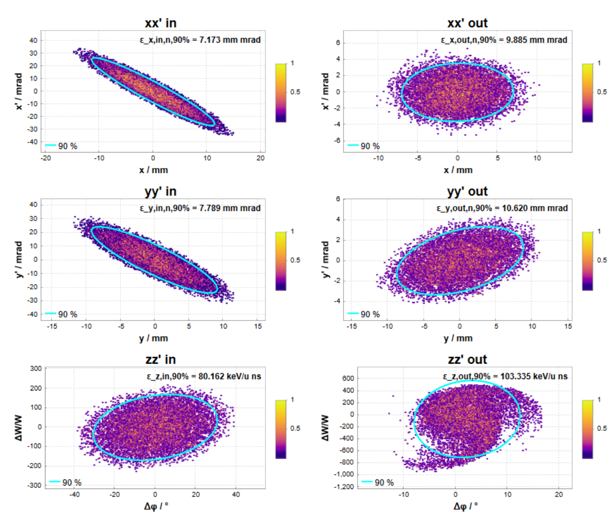

Figure 2: Longitudinal and transversal beam input and output emittances.

The transversal and longitudinal beam envelopes can be found in Fig. 3. The energy gain, synchronous phases and effective voltages of the cavities for the current design are shown in Fig. 4. Here, the moderately chosen voltages for

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the first cavities, especially for the rebunchers can be seen.

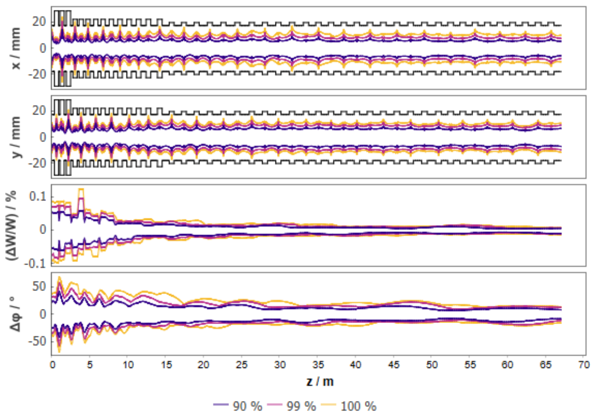

Figure 3: Longitudinal and transversal beam envelopes.

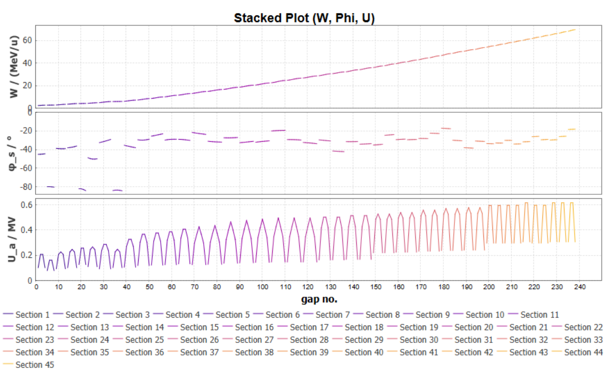

Figure 4: Beam energy, phases and voltages.

ALTERNATIVE EQUUS DESIGN

EQUUS cavities, which use a constant beta acceleration profile, are easier to construct and therefore more cost efficient. An alternative design for the higher energy part of the HBS accelerator is currently in preparation. It will consist of duplets, meaning each two cavities are geometrically identical. This reduces the production costs even further.

SUMMARY AND OUTLOOK

An optimization algorithm for the automation of the beam dynamics calculations for the HBS drift tube linac has been coded. A design approach up to 70 MeV end energy consisting of 45 cavities has been presented, with optimized phases and focussing strengths only leading to moderate emittance growth for a beam current of 100 mA.

For further optimization of the concept the next step will be to add the voltages of the cavities to the parameters to be optimized. More parameters will extend the time needed for the optimization, but will hopefully also result in a even more efficient and reliable design, providing even better beam quality.

In parallel to this, an EQUUS design approach for cavities with higher input energy will be tested and both approaches will be compared regarding beam quality and efficiency.

Because of the sensitivity of the beam dynamics to variation of the density of the input distribution originating in the high space charge forces, reliability studies are planned for various distribution densities. Additionally, studies are planned to test the adaptiveness of the design with already fixed geometrical properties to above mention variation of the input distribution, as well as other possible occurrences, such as cavity failure.

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