IMPROVED BEAM DYNAMICS AND CAVITY RF DESIGN FOR THE FAIR PROTON INJECTOR*

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Abstract

The FAIR facility at GSI requires a dedicated 70 MeV, 70 mA proton injector for the research program with intense antiproton beams. The main accelerator part consists of six 'Crossbar H-type' (CH) cavities operated at 325 MHz. Recently the beam dynamics has been revised with the goal of fixing all parameters and thus starting the construction of the main linac components. The MEBT behind the RFQ was slightly extended, the gap numbers per CH cavity and the voltage distributions were optimized and the intermediate diagnostics section including a rebuncher cavity at 33 MeV was redesigned. Finally, detailed machine error studies were performed for checking the error sensitivity of the new design and the steering concept. The final parameters obtained from the beam dynamics update are now used for finalizing the CH-DTL cavity design by CST-MWS calculations.

REVISED FAIR PROTON LINAC DTL BEAM DYNAMICS DESIGN

Our group at IAP/Frankfurt University is designing and developing the FAIR Proton Linac in close collaboration with the GSI/FAIR staff, both as a whole [1] [2] [3] and in its main components, like for example the recently power tested coupled CH-DTL prototype cavity [4] [5]. However, when starting the rf design for all six CH cavities, some weak points in the beam dynamics and overall linac layout valid at that time were detected, which lead to the revised beam dynamics design as presented in this paper. The main changes were as follows:

The MEBT section behind the RFQ was slightly extended in length and quadrupole number, including the necessary elements for steering, diagnostics and vacuum. Two identical quadrupole triplet lenses now allow a flexible beam matching into the CH-linac.

The rather long diagnostics and beam cleaning section at 35 MeV has been reduced in length from 3.0 to 1.8 meter, still containing the necessary beam diagnostic, steering and vacuum handling components, as well as a 4 gap, 1.6 MV rebuncher cavity. This section is now positioned at a beam energy of 33 MeV (see next paragraph).

The gap voltage distribution along the whole linac has been moderately changed: The total number of gaps per cavity and the voltage distribution inside each cavity have been optimised with the aim to get more homogeneous on axis gap field distributions and particularly to reduce the maximum field values in the first coupled CH-DTL for safety reasons (from 16.6 to 14.7 MV/m, see Table 1). Moreover, the matching of power requirements of each cavity for using identical amplifiers was improved.

Table 1: Main Parameters of the FAIR Proton Linac DTL

CH-DTL		
f [MHz]	325.224	
energy range [MeV]	3 - 70	
main components	3 coupled CH (CCH), 3 single CH-DTL (CH)	
number of gaps	21 – 30 (CCH); 20 (CH)	
tube inner diam. [mm]	20 - 23	
eff. gap volt. [kV]	270 (CCH1) to 670 (CH)	
max. on axis field [MV/m]	14.7 (CCH1) down to 5.5 (CH6)	
cavity effective length [m]	1.4 to 3.6 (CCH); 2.5 to 3.2 (CH)	
Magnetic quadrupole triplets		
effective length [mm]	375	
eff. gradients [T/m]	45 - 62	
aperture diam. [mm]	30	
Beam parameter		
design current [mA]	75	
	input	output
$\varepsilon_{n,95\%\ transv.}$ [mm·mrad]	1.35	2.6
$\varepsilon_{rms\ transv.}$ [mm·mrad]	0.266	0.455
$\varepsilon_{n,95\%\ long.}$ [keV·ns]	12.0	15.6
$\varepsilon_{rms\ long.}$ [keV·ns]	2.4	2.9

The above-mentioned measures lead to the final linac parameters as shown in Table 1 and to the beam dynamics results illustrated by Figure 1 and expressed by the emittance numbers shown in Table 1. All simulations were done with the in-house developed code LORASR [6], which is well accepted within the Linac community and has been often benchmarked with other codes.

Figure 1, upper plot shows a transversally well matched beam with small envelope oscillations, except for the typical quadrupole triplet channel pattern. There is also enough safety margin between beam and aperture (in blue), which could be confirmed by error study results (see next chapter). The triplet lenses are either integrated into the CH-cavities (CCH1 to CCH3) or placed externally.

For the particle motion in the longitudinal space the 'combined zero degree' concept was applied [7] [8]. The longitudinal beam envelopes (Figure 2, lower plots) also show stable behaviour with small oscillations particularly at higher energies and small output energy and phase spreads. The emittance growth (see Table 1) is well below or comparable to what was achieved by previous designs.

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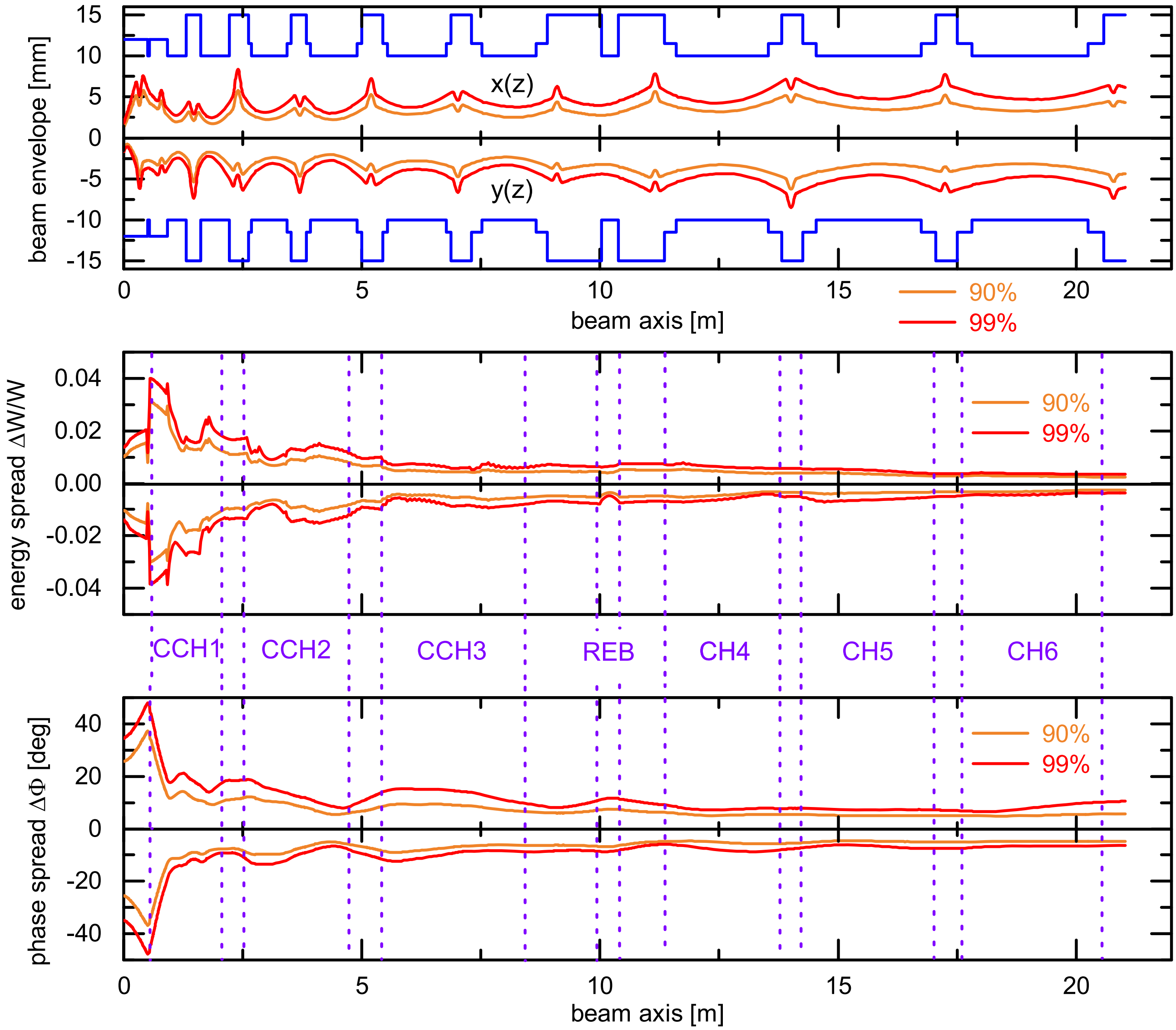

Figure 1: Beam envelopes of the revised FAIR Proton Linac design at 75 mA beam current.

MACHINE ERROR STUDIES

Investigations of the beam dynamics response to machine errors are nowadays mandatory in the planning stage of linacs. In our case these simulations were also done by the LORASR code, which is equipped with several error setting and analysis tools [9].

The type and maximum range of machine error settings are listed in Table 2. The values are derived from manufacturing and machine operation experience gained so far. Several sets of settings were tested, but in this paper only two cases are shown, whereby only the parameter 'transverse lens displacement' has been varied between 0.1 and 0.2 mm. The experience from several previous studies within this [10] and other projects shows that the lens displacement error is the most sensitive parameter for quadrupole triplet channels in combination with multigap cavities, having the highest contribution to particle losses.

This could be confirmed by the present study, as illustrated by Figure 2: In the upper plot the beam envelope of the nominal run (in green) is shown together with the overlap of all envelopes (in red) from all runs (sets of 500 runs were performed for each setting).

Table 2: Machine Error Settings

Lens		
	setting 1	setting 2
transv. displacement [mm]	0.1	**0.2**
rotation [mrad]	2.0	
Source		
transv. displacement [mm]	0.1	
rotation [mrad]	2.0	
beam energy offset [%]	0.2	
beam phase offset [deg]	1.0	
Cavity		
voltage ampl. offset [%]	0.2	
phase offset [deg]	0.5	

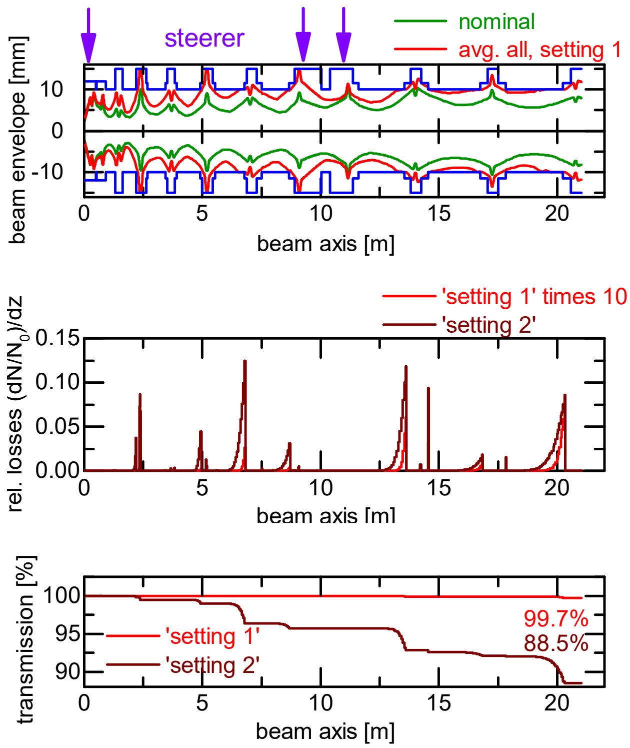

Figure 2: Averaged loss profiles and transmission rates.

This representation gives an impression of the critical points along the beam line. The quantity of losses and their local distribution are shown in the lower plots of Figure 2 (loss profile and transmission rate). According to this study, for the present FAIR Proton Linac design with 3 foreseen xy steerers placed as shown in Figure 2, losses are mainly expected in the centre and towards the end of longer sections containing no steering elements, particularly towards the end of the drift tube sections and at the entrance of quadrupole triplets. The loss rates are strongly depending on the maximum lens displacement value: Below 0.1 mm the transmission is above 99.7%.

Thus the main outcome of the present study is to ask for manufacturing and alignment tolerances of the quadrupole lenses below 0.1 mm. This value is meanwhile accepted as a standard by many manufacturers. As for the alignment of 'bulky' triplet lenses, reliable concepts were developed over the years. Increasing the number of steerer seems not to be necessary, as the situation might be improved in real machine operation by applying more sophisticated steering correction strategies than could be provided by the elementary routine implemented for the present error studies.

CAVITY RF DESIGN

The main scope of the updated FAIR Proton Linac design was to fix all relevant parameters and be able to start the cavity rf design, construction and tuning. This challenging task is well advanced and close to finalization. As an example, the final layout (CST MWS model) of the first coupled CH-DTL (CCH1) is shown in Figure 3, together with the simulated on axis field distribution.

The final numerical results from all cavities will be of course used for a conclusive beam dynamics cross check.

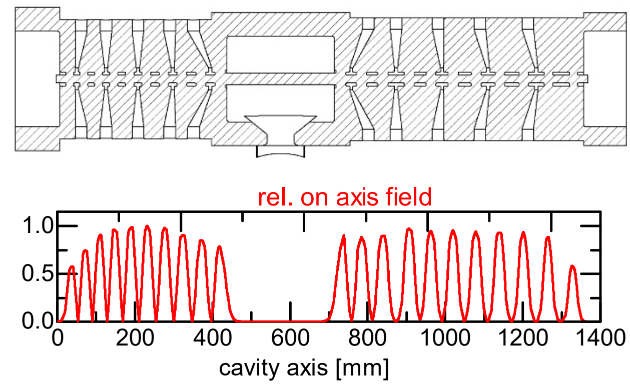

Figure 3: CST-MWS model and on axis field distribution for the first coupled CH-DTL (CCH1).

CONCLUSION

The beam dynamics design of the FAIR Proton Linac is completed. Machine error studies were performed for detecting weak points and defining tolerances. The fixing of basic cavity parameters (number of gaps, voltage distribution) was an important step for starting the cavity rf design and mechanical construction, which is almost completed for all FAIR Proton Linac cavities.

Valuable experience could be achieved from the design, manufacturing, tuning and successful power testing of a prototype cavity [3] [4] [5] which corresponds to the CCH2 cavity of the FAIR Proton injector. This prototype is the first accelerator cavity of the Coupled CH type ever built.

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