BEAM DYNAMICS LAYOUT AND LOSS STUDIES FOR THE FAIR P-INJECTOR*

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Abstract

The development of coupled CH-DTL cavities represents a major achievement in the development of the 325 MHz, 70 MeV FAIR Proton Injector. This coupled-cavity solution has important consequencies on the beam dynamics design which has to be adapted to this new kind of resonator. In combination with the KONUS beam dynamics, this solution allows to achieve all the requirements of the FAIR project in terms of beam intensity and quality, with a reduced number of focusing elements when compared to traditional DTL's. A layout based on six CH coupled modules [1] is presented and compared with a solution composed of three coupled modules up to 35 MeV followed by three long single resonators up to the energy of 70 MeV. A redesigned 35 MeV intertank section became necessary to avoid beam losses and emittance growth. Finally, the effect of random mistakes such as quadrupole misalignments and rotation, phase as well as voltage setting errors have been investigated to determine the tolerances for mechanical construction and rf controls during operation.

PROTON INJECTOR LAYOUT

The FAIR proton injector will be used as a dedicated injector for the SIS18 providing a 35 mA beam at the final energy of 70 MeV with a 0.02% duty cycle. The proton injector starts with an ECR source generating a proton beam at 95 keV followed by a Radio-Frequency Quadrupole which accelerates the beam to 3 MeV. The beam is then boosted by three coupled CH resonators to 35 MeV where a dedicated section for diagnostics is planned. Other three coupled resonators perform the final acceleration to 70 MeV where the beam enters the transfer channel towards the SIS 18. Both RFQ and CH cavities are operated at the resonance frequency of 325.2 Mhz, nine times the basic resonance frequency of the UNILAC complex.

The main beam properties, simulated with a peak current of 45 mA are summerized in Tab.1. In order to get the most realistic results it was decided to use a realistic RFQ output distribution and to avoid any other artificial one such as gaussian or KV.

The input and output distribution are shown in Fig.1.

Table 1: The main beam parameters of the Proton Injector

Beam Parameter	Input	Output
$95\%\epsilon_{norm}$ X-X' [μm]	1.32	2.27
RMS ϵ X-X'	0.26	0.40
$95\%\epsilon_{norm}$ Y-Y' [μm]	1.31	2.65
RMS ϵ Y-Y'	0.26	0.44
ϵ $\Delta\Phi\Delta$W [keV ns]	8.99	13.90
RMS ϵ $\Delta\Phi\Delta$W	1.28	2.09

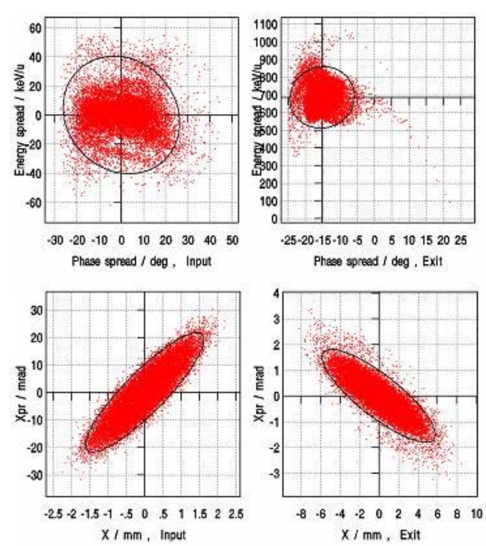

Figure 1: The input and output distribution for the proton injector. The ellipses contain 95% of the beam.

ERROR STUDIES

The error study is performed on the main linac, i.e. after the end plate of the RFQ. The goal of this investigation is to fix the mechanical tolerances and to evaluate the robustness of the linac design with respect to fabrication errors, quadrupole rotation or translation, or random variation of operational parameters such as voltage levels or phase oscillations from the amplifiers. In a first step, the sensitivity with respect to each single source of error is investigate to set the tolerances for each parameter. Afterwards all error sources within the given tolerances are added up to evaluate the potential loss profile and the emittance degradation along the linac. Simulations are performed with the LORASR code which was updated to evaluate that specific topic: the implemented errors analysis includes

- Quadrupole translations in the transverse plane;
- Quadrupole rotations in the 3D space;
- Single gap errors;
- Klystron voltages and phase oscillations;

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Quadrupole translations are applied separately to each lens while rotations are applied to the entire triplets used in the KONUS beam dynamics. The errors, including amplitude and phase are generated randomly with a Gaussian distribution cut at 2 σ. In order to determine the probability to have some losses at a specific position along the linac 1000 runs were performed for each single error with a 100000 particle distribution per run.

Single Error Analysis

The first analysis was dedicated to fix acceptable upper bound tolerances for each type of error along the CH-DTL. Previous analysis [2] showed that the beam losses are mainly due to quadrupole misalignments of the transversal plane. As an example, figure 2 displays the relative emittance variation with respect to the nominal case, if a random transverse translation of the quadrupoles is applied within $\pm$ 0.1 mm; figure 3 shows the transmission rate average over 1000 runs.

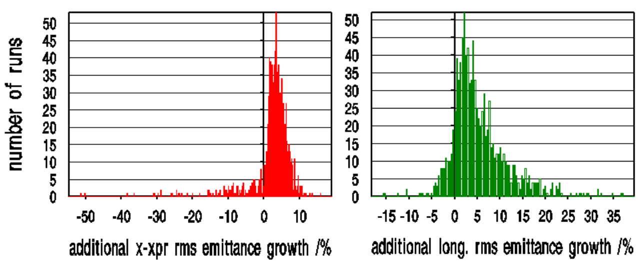

Figure 2: The relative emittance variation with respect to the nominal case in case of quadrupole misalignements.

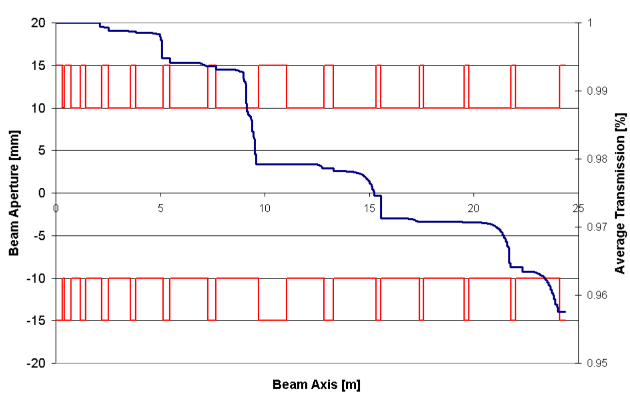

Figure 3: The transmission rate averaged over 1000 runs in case of quadrupole misalignments within $\pm$ 1 mm.

Due to the quadrupoles misalignment the emittance variation with respect to the nominal case shows a typical Poissonian distribution. The transverse beam emittance variation remains within $\pm$ 5% for 70% of the runs in the transversal planes while 82% of the runs show an emittance variation within $\pm$10% in the longitudinal plane.

The average transmission rate is around 96 % and the main probable losses are concentrated along the sixth accelerator section. Further losses are mainly due to the cumulated steering effects and can be corrected during real operation by use of X-Y steerers placed in the 35 MeV transport line. Typical parameters used for the published case are shown below and are in agreement with loss errors performed on other machines [4].

- Transverse displacements: $\delta x, \delta y = \pm$ 0.1 mm;
- Pitching and yawing angles : $\phi_x, \phi_y =$ 0.1 mrad;
- Rolling angle : $\phi_z = \pm$ 0.5 mrad
- Sinle Gap field: $\Delta E_{gap}/E_{gap} = \pm$ 1%;
- Klystron field $\Delta V_{klys}/V_{klys} = \pm$ 1%;
- Klystron phase $\Phi_{klys} = \pm 1°$;

A further set of runs will investigate the possibility to increase those upper limits. Tab.2 summarizes the results of single errors. Also in this analysis the critical parameter appears to be the quadrupole transverse alignment while all the other parameters induces only a modest emittance growth with very few losses. The rms degradation due to voltage oscillation can be improved in real operation by switching lightly the working point towards higher voltage as routinely done with existing H-mode cavities.

Table 2: Summary of Single error analysis showing the relative emittance variation with respct to the nominal case

Error and Amplitude	$\lvert\Delta\epsilon_x/\epsilon_x\rvert$ Probability	$\lvert\Delta\epsilon_y/\epsilon_y\rvert$ Probability	$\lvert\Delta\epsilon_z/\epsilon_z\rvert$ Probability
$\delta x, \delta y$ $\pm$0.1 mm	$<$ 5% 69.3 $<$ 10% 94.2	$<$ 5% 93.2 $<$ 10% 99.2	$<$ 5% 60.5 $<$ 10% 82.4
ϕ_x, ϕ_y $\pm$0.1 mrad	$<$ 5% 100	$<$ 5% 100	$<$ 5% 100
ϕ_z $\pm$0.5 mrad	$<$ 5% 100	$<$ 5% 100	$<$ 5% 100
$\Delta V_{klys}/V_{klys}$ $\pm$1%	$<$ 5% 80.3 $<$ 10% 96.9	$<$ 5% 82.3 $<$ 10% 97.8	$<$ 5% 80.6 $<$ 10% 60.5
$\Delta\Phi_{klys}\pm1°$% $\pm$1°%	$<$ 5% 100	$<$ 5% 97.4 $<$ 10% 100	$<$ 5% 67.1 $<$ 10% 87.6

Proton Injector Loss Studies

In a last case all possible sources of errors were added up together within the tolerances got from single error analysis. Figure 4 and 5 show the relative emittance growth and the average transmission rate: comparing those plots with Fig. 2 and 3 it is straight forward to conclude that only quadrupole translation represents the major risk in terms of beam losses and emittance degradation.

ALTERNATIVE DESIGN

One of the main advantages of the KONUS beam dynamics [3] is the reduced number of quadrupole elements required for the transvers focus of the beam. The reduced

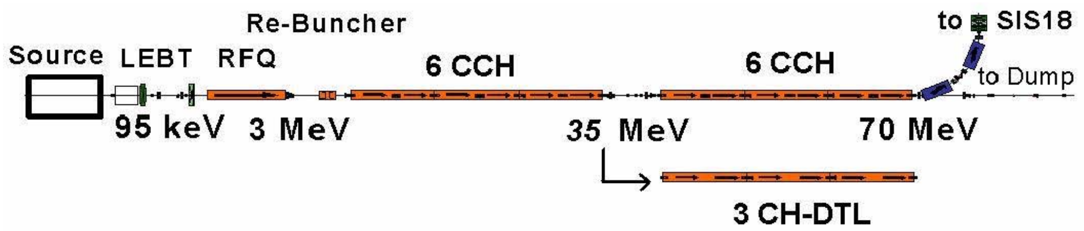

Figure 6: A comparision between the proposed options for the FAIR proton injector.

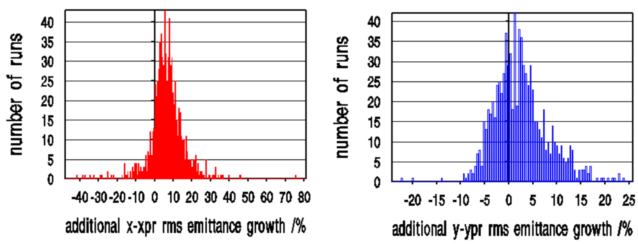

Figure 4: The relative emittance variation in the transversal planes when all errors are applied.

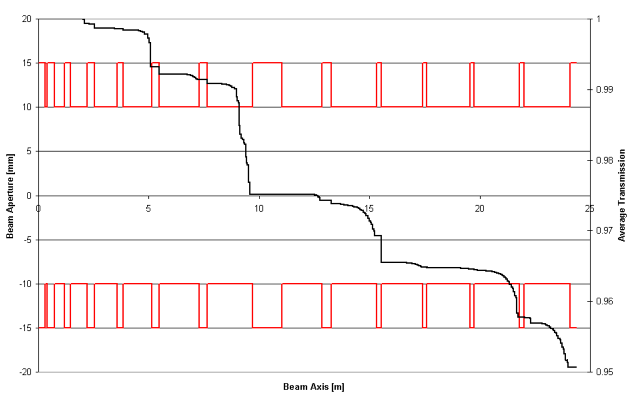

Figure 5: The transmission rate averaged over 1000 runs with all sources of mistakes mixed together.

RF defocusing effect allows to build relative long acceleration sections free of quadrupole lenses. Observing how the quadrupole misalignments represent the highest potential for beam losses, it was decided to investigate a second design for the FAIR proton injector where, after the diagnostics section, only three standard CH cavities would replace the three coupled resonators of the original design. This solution presents other advantages since the reduction of the focusing elements corresponds to a mechanical simplification reducing the overall costs of the machine.

CONCLUSION

A statistical errors analysis was performed in order to fix the mechanical and operational tolerances. The results indicate that only quadrupole transversal misalignments play a major role in terms of beam losses and emittance growth

Table 3: The output beam parameters of the Proton Injector with the new scheme based on the coupled CH-DTL and three standard resonators

Beam Parameter	**Output**
$95\%\epsilon_{norm}$ X-X' [μm]	2.35
RMS ϵ X-X'	0.41
$95\%\epsilon_{norm}$ Y-Y' [μm]	2.42
RMS ϵ Y-Y'	0.42
ϵ $\Delta\Phi\Delta$W [keV ns]	13.90
RMS ϵ $\Delta\Phi\Delta$W	2.00

along the machine.

In order to simplify the mechanical design and to reduce the overall costs of the machine a new scheme based on three coupled CH cavities followed by three standard resonators is under investigation: the reduced number of focusing elements could reduce the possibility of beam losses due to quadrupole misalignments. A dedicated loss study with is under performance to evaluate the loss profile along the linac with this new scheme.

ACKNOWLEDGEMENTS

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