

THE FAIR PROTON LINAC: THE FIRST LINAC BASED ON A ROOM TEMPERATURE CH-DTL

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Abstract

The antiproton program at FAIR requires a dedicated proton linac to be used as injector for the SIS 100 synchrotron. This 325 MHz linac will accelerate up to 70 mA proton beam to the injection energy of 70 MeV. This linac will be the first machine based on CH-DTL's, the novel cavity developed at the Frankfurt University. This new cavity is characterized by slim drift tubes without internal focusing elements which allow the construction of very compact cavities resulting in higher shunt impedance when compared to conventional RF structures. The proton linac is based on 3 coupled CH-cavities followed by three standard CH's for a total length of around 22 meters. A complete description of the beam dynamics together with the general status of the project is presented and discussed.

INTRODUCTION

The FAIR Project [1] (Facility for Antiprotons and Ions Research) requires a massive upgrade of the existing GSI accelerator facilities in terms of beam intensities and quality.

In particular a considerable increase of ion beam intensities up to a factor of 5 at the end of the UNILAC is required from the heavy ion physics program while a new proton injector [2] will start the accelerator chain for the production of cooled antiprotons.

The final goal is to provide primary proton fluxes of $2 \cdot 10^{16}$ protons/h by the accelerator chain shown in Fig. 1. Taking into account the pbar production and cooling rate this primary beam will lead to a secondary beam of $7 \cdot 10^{10}$ cooled antiprotons/h.

The dedicated proton linac will deliver a proton beam of 70 MeV which will be then injected into the SIS 18. At this energy in fact the saturation of *p-bar* production [2] is reached. The injection into the synchrotron is planned by a multiturn injection scheme. The horizontal acceptance of the SIS 18 will be filled by a 35 mA within a normalized brilliance of $16.5 \text{ mA}/\mu\text{m}$, while a momentum spread of less than 1 ‰ is required. The maximum repetition rate is fixed at 4 Hz.

Concerning the RF frequency, a multiple of the basic resonance frequency of the UNILAC HSI (36.136 MHz) has been considered as the best option. The value of 325.224 MHz meets this criterion and allows the use of the 3 MW klystrons developed for the JPARC facility at 324 MHz. The adaption to the small difference in frequency has been straightforward.

The general parameters of the proton linac are listed in Table 1.

Table 1: The Main Parameters of the FAIR Proton Linac

Source	H ⁺ , 95 keV, max. 100 mA
LEBT	95 keV, 100 mA, $\epsilon_{\text{norm.}}=1.8 \mu\text{m}$
RFQ	3 MeV, 90 mA, $\epsilon_{\text{norm.}}=2 \mu\text{m}$
DTL	3 CCH+ 3 CH-DTL, 70 MeV
Frequency [MHz]	325.224
Current [mA]	70 (design), ≥ 35 (operation)
Emittance (μm)	≤ 2.8
Mom. Spread [%]	≤ 1
RF Pulse [μs]	70
Max Beam Pulse [μs]	36
Repetition Rate [Hz]	4
Duty Factor [%]	0.1
Total Length [m]	~ 30

LINAC GENERAL DESIGN

The general layout of the proton injector is presented in Fig.2: an ECR ion source developed at CEA, Saclay, will provide a proton beam extracted at 95 kV. The first stage of acceleration to 3 MeV is provided by a four-rod RFQ [3] investigated at the University of Frankfurt. After a compact matching section which includes a quadrupole triplet, an RF buncher, a doublet and the required diagnostics, the beam enters the first section of the main linac. Three coupled cavities [4] provide the acceleration to the intermediate energy of 37 MeV where a 1.6 meter long dedicated diagnostic section is foreseen.

This section will include the main diagnostic devices such as an emittance scanner, phase probes, current transformers and transverse scrapers to get rid of particles with larger emittances with respect to the beam

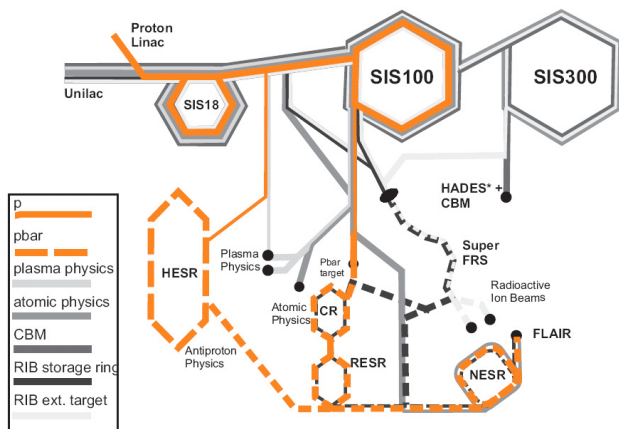


Figure1: The schematic view of FAIR showing in the detail the accelerator chain for the production of antiprotons.

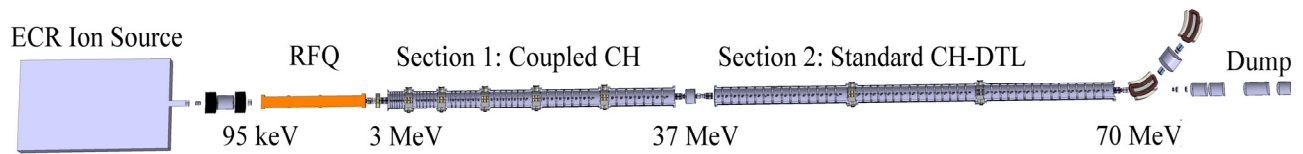


Figure2: The proposed layout for the FAIR Proton injector.

core. From 37 MeV onwards the defocusing effects of space charge and RF are less of concern and, by use of the KONUS beam dynamics, long lens free sections can be built with slightly different beam aperture at the cavity ends.

Three of those long standard CH cavities perform the last stage of acceleration up to 70 MeV. This choice results in a reduction of the number of triplets while the mechanical and RF design becomes simpler resulting in an effective cost saving. RF simulations showed that energy gains of 10 MeV along 10 to 21 gaps could be achieved within a maximum power demand of 950 kW per individual CH cavity. Table 2 summarizes the main parameters of the 9 drift tube sections which form the proton injector.

Table 2: RF Parameters of the CH Xavities

Cavity	Eff. Voltage [MV]	Energy [MeV]	Gap
1a	3.65	3 – 6.6	10
1b	5.78	6.6 - 11.6	12
2a	6.23	11.6 – 17.4	13
2b	7.26	17.4 – 24.1	14
3a	6.86	24.1 – 30.5	15
3b	7.71	30.5 – 37.6	17
4	10.92	37.6 – 48.1	20
5	11.44	48.1 - 59.3	21
6	11.44	59.3 – 70	22

BEAM DYNAMICS LAYOUT

Beam dynamics simulations through the main linac have been performed with the LORASR code [5] starting with different RFQ output distributions and with different output currents. The ECR ion source can in fact deliver a maximum current of 100 mA and the RFQ tracking performed with TOUTATIS [6] and PARMTEQ [7] has shown a transmission higher than 97 % within a current range from 45 to 100 mA by use of a waterbag input distribution. The lattice of the CH sections was designed assuming an RFQ output current ranging from 45 to 70 mA [8, 9] and the final results fulfilled the FAIR requirements for the injection into the SIS 18.

Recently, a realistic 100 mA LEBT output distribution was calculated at CEA and tracked at GSI with the DYNAMION code through the RFQ. From the resulting RFQ output distribution, a sample including particles with a phase spread less than 40 degree and corresponding to 78 mA was selected and then used as an input distribution for the CH-DTL section. Table III presents the main beam emittances at the RFQ exit and at the final energy of 70 MeV.

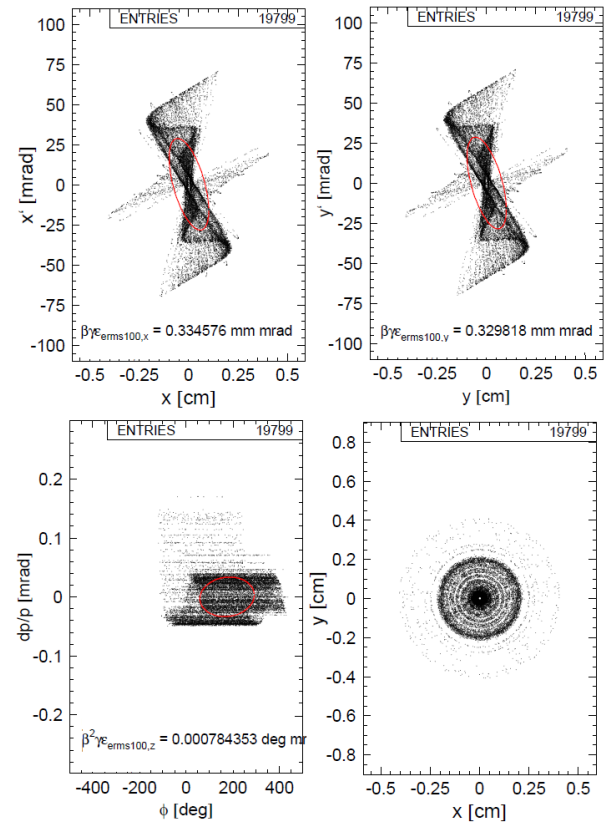


Figure 3: Calculated particles distribution at the entrance of the RFQ.

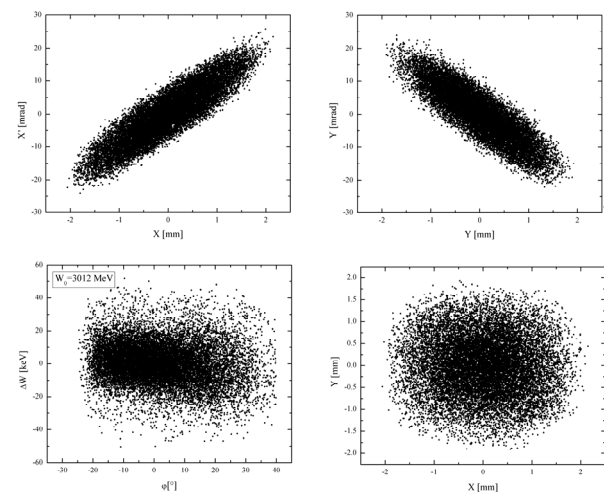


Figure 4: The particles distribution at the RFQ exit.

Table 3: The RMS normalized emittance at the RFQ exit and at the end of the proton linac

Energy	3 MeV	70 MeV
RMS ϵ norm X-X' mm mrad	0.23	0.46
RMS ϵ norm Y-Y' mm mrad	0.21	0.46
RMS ϵ norm $\Delta\Phi$ - ΔW keV/ ns	1.41	2.65

The beam envelopes for the RFQ output current of 78 mA are shown in Fig. 5, from which one can see that a safety margin is available against beam loss along the whole structure. The factor two in currents with respect the required 35 mA at the injection offer not only a reasonable safety margin against beam losses but could also be used to introduce flexibility concerning the injection scheme, as a higher current would imply a shorter beam pulse. Brilliance analysis shows that the best window for the injection into the synchrotron occurs between 50 and 60 mA. This is shown in Fig. 6 where the dependence of the beam current within the corresponding emittance is compared with the FAIR brilliance requirements.

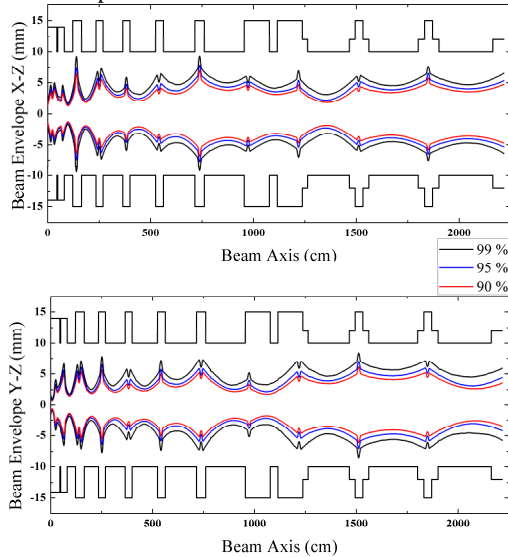


Figure 5: Beam envelopes on the transverse planes.

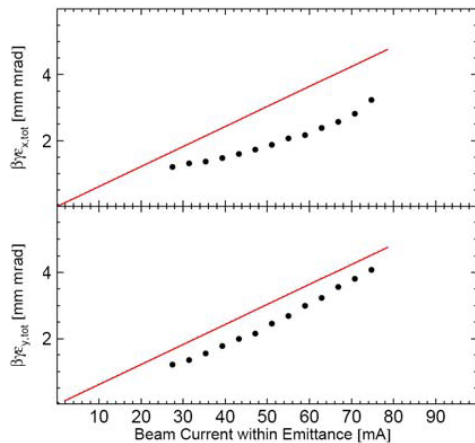


Figure 6: Evaluation of the beam emittance as function of the correspondent current at the energy of 70 MeV. The red line represents the FAIR requirements.

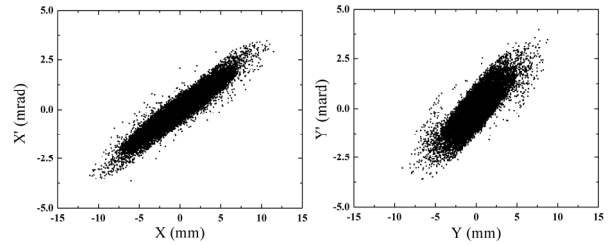


Figure 7: The output transversal emittances at the exit of the proton linac

ERROR STUDIES

The main parameters which could influence the correct operation of the machine are, in terms of tolerances, the quadrupole errors in the transverse positioning together with the quadrupole rotation errors in 3D space. On the other hand, voltage and phase oscillations could result from instabilities from the power supplies, while single gap voltage could slightly differ from design values.

All those effects could lead to beam dynamics results significantly different from the design settings. In order to investigate the robustness of the FAIR proton injector against those errors, several simulations have been performed.

In LORASR quadrupole translations are applied separately to each singlet while rotations are applied to the entire triplets.

The errors, including amplitude and phase are generated randomly with a Gaussian distribution cut at 2σ . Previous investigations [8] have shown that only quadrupole translations represent a major risk in terms of beam losses and emittance degradation while the single tolerances, in accordance with other projects like CERN LINAC 4 [10] are fixed at:

- Transverse displacements: $\Delta x, \Delta y = \pm 0.1$ mm;
- Pitching, yawing and rolling angle: $\Delta\Phi_{x,y,z} = 0.5^\circ$;
- Single Gap Voltage: $V_{\text{gap}}/V_{\text{design}} = \pm 5\%$;
- Klystron Voltage: $V_{\text{klys}}/V_{\text{design}} = \pm 1\%$;
- Klystron phase: $\Phi_{\text{klys}}/\Phi_{\text{design}} = \pm 1^\circ$.

3000 runs were performed with a 20000 particles RFQ-output distribution to evaluate the effect of all errors when applied at the same time. No steering correction was included as this feature is still under implementation for LORASR.

Figure 8 shows the relative rms growth with respect to the nominal case while Fig. 9 describes the statistical analysis of the single run transmissions. The analysis of the relative rms growth shows that the beam quality remains acceptable in the transversal plane while, considering the longitudinal plane most of the runs are even within $\pm 5\%$ deviation from the nominal case.

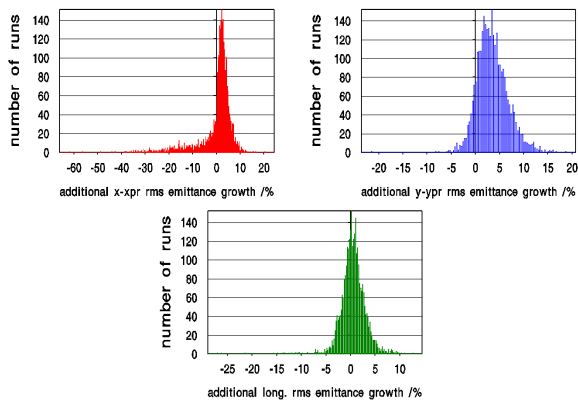


Figure 8: The relative RMS emittance growth resulting from the error analysis.

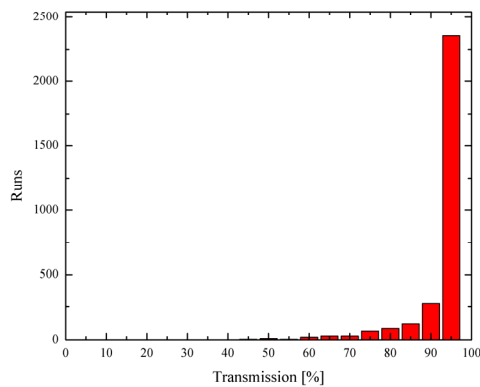


Figure 9: The statistical analysis of the transmission when errors are applied.

Finally, even if no steering correction is applied more than 75% of the runs show a transmission higher than 95%. As a next step particle numbers out of the RFQ will be increased to cross check all the specifications with respect to mechanical tolerances and sensitivity during operation.

CAVITY DESIGN

In order to prove the validity of the coupled scheme for the CH cavities, a scaled model of the second coupled cavity of the FAIR proton injector, has been built and tested at Frankfurt University. The main goal was to experimentally verify all the RF properties and to define the best tuning strategy concerning the coupling.

The coupling between the acceleration sections and the coupling cell is accomplished by RF-fields around the coupling drift tube as well as by the gap capacity. The corresponding drift tube inside the coupling cell is charged oppositely at the ends in the mode of operation. This means, that it acts like an Alvarez type drift tube.

The coupling factor is around 0.3%. This means, the spacing between the 0-mode and the $\pi/2$ -mode is about 1.3MHz [11]. Possibilities for an increased mode

separation are actually investigated at the RF model. Concepts for fine tuning of the voltage distribution already during cavity fabrication with static tuners are studied. The results seem very promising.

In 2010 the construction of the full scale prototype has started. In a first stage the cavity will be tested with dummy stems (made from aluminium) which will allow precise frequency and field tuning. Copper plating and low level RF tuning are foreseen within summer 2011. A full power test will be performed at the new GSI test stand for the end of the same year.

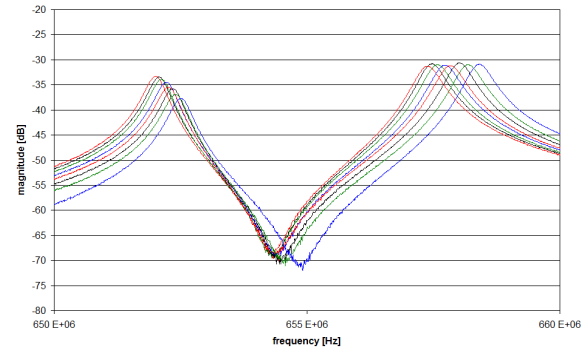


Figure 10: Frequency shift due to the movable tuner inserted in the coupling cell.

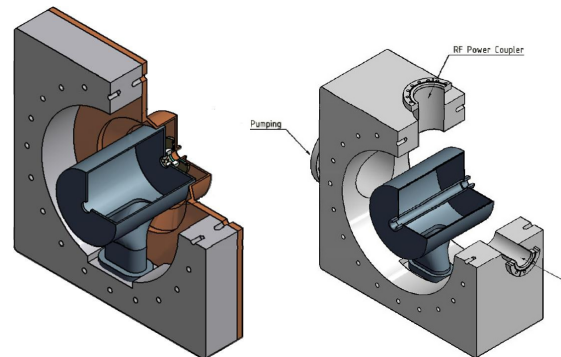


Figure 11: On the right side the design of the end cell showing the last half drift tube housing the focusing elements. On the right side the coupling cell with the internal triplet.

CONCLUSIONS AND FURTHER MILESTONES

The GSI Proton injector will be the first linac based on a room temperature CH-DTL with a KONUS beam dynamics lattice. The layout has been designed assuming an input current up to 70 mA and later assuming up to 80 mA at the RFQ exit. Loss studies showed that the design is robust against machining tolerances and random operational errors. At present, IAP is producing the technical drawings of the second resonator of the proton injector after the RF coupling scheme was developed successfully by simulations and by measurements on the scaled model. The construction of this cavity will finish in summer 2011 and a high power test will follow at the GSI test bench.

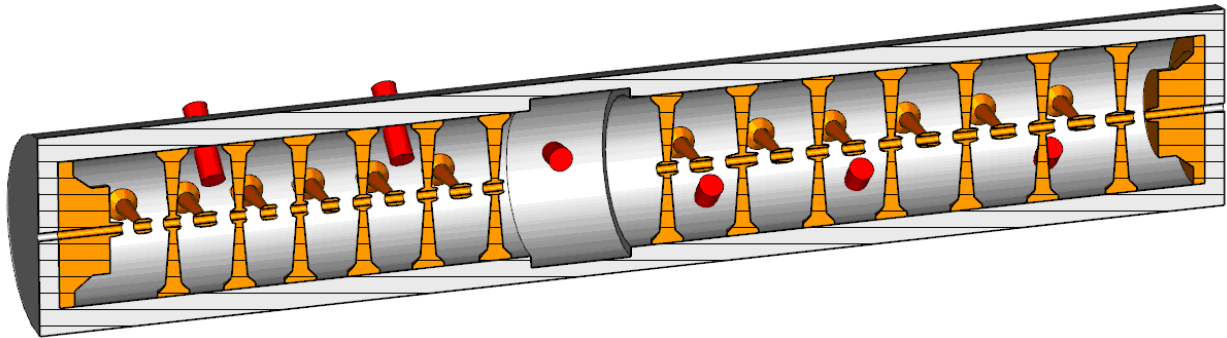


Figure 12: Scaled model of the second coupled resonator of the proton injector showing the position of the tuners. The central drift tube housing the focusing triplet has been removed from the drawing.

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