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BEAM DYNAMICS FOR THE FAIR PROTON-LINAC RFQ

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Abstract

The FAIR (Facility for Antiproton and Ion Research) Proton-Linac (P-LINAC) will be started with a 325.224 MHz, 3 MeV Radio-Frequency Quadrupole (RFQ) accelerator. To ensure that a ≥35 mA beam can be injected into the downstream synchrotrons, the design beam intensity of this Proton-RFQ (P-RFQ) has been chosen as 70 mA. Based on the so-called NFSP (New Four-Section Procedure) method, two new beam dynamics designs with varying and constant transverse focusing strength, respectively, have been worked out to meet the latest design requirements using a compact structure. This paper presents the main design concepts and simulation results.

INTRODUCTION

In the near future, a new international accelerator-based science center, FAIR, will be built at GSI, Germany [1]. To enable various unique physics experiments, the FAIR facility is aiming to provide antiproton and ion beams with unprecedented intensity and quality.

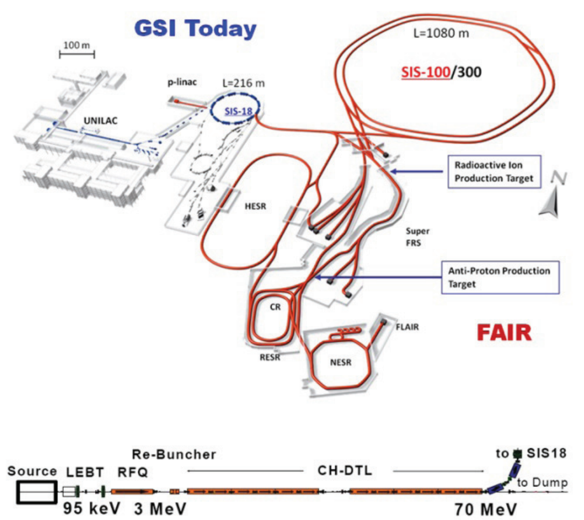

Figure 1: Overview of the FAIR Facility & the P-LINAC.

As shown in Fig. 1, the planned P-LINAC which is in parallel to the existing UNILAC will mainly consist of an RFQ accelerator and several Drift-Tube Linac (DTL) cavities working at 325.224 MHz. It is required to provide a ≥35 mA, 70 MeV proton beam for the downstream synchrotrons at a duty cycle (dc) of 0.0144%.

The old reference design published in 2009 [2] was optimized for 45 mA and can provide good beam performance e.g. ≥95% transmission efficiency for up to 100 mA input beams. This 3.2 m long RFQ is very compact when considering the relatively high input energy W_{in} of 95 keV (compared with the W_{in} values adopted by CERN LINAC4 RFQ [3], J-PARC RFQ-III [4], and SNS-RFQ [5], see Table 1), as the length of the adiabatic bunching section is proportional to β^3 [6].

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Table 1: Design Requirements for the P-RFQ in Comparison with the Design Parameters of Some RFQs

	FAIR P-RFQ	**CERN** LINAC4	**J-PARC** RFQ-III	**SNS**
Ion	H^+	H^-	H^-	H^-
f [MHz]	325.224	352.2	324	402.5
W_{in} [keV]	95	45	50	65
W_{out} [MeV]	3.0	3.0	3.0	2.5
I_{in} [mA]	70	70	60	60
$E_{s,\,max}$ [MV/m]	≤33	34	31	36
KF	≤1.87	1.84	1.72	1.85
L [m]	≤3.5	3.0	3.6	3.7
dc [%]	0.0144	0.08-5	0.08	6.2

Listed in Table 1, the recently updated design requirements for the P-RFQ have two main changes:

- As usually more particle losses will happen in reality than in simulation, the design beam intensity I_{in} has been fixed as 70 mA for safety.
- The allowed maximum surface electric field $E_{s,\,max}$ is lowered to 33 MV/m, corresponding to a Kilpatrick Factor (KF) of 1.87 (formerly KF≤2.0). The practice shows [6]: 1) The typical KF-range for RFQs is 1.5 – 2.0. 2) The reference KF-value for reliable CW operation is 1.8 (given by the LEDA-RFQ [7] experiments). 3) For low dc especially pulse length τ≤1 ms, KF>2.0 can be also used. For the P-RFQ (dc=0.0144%, τ=200 μs), therefore, the new limitation is relatively conservative.

The design study for the P-RFQ is now becoming more challenging, because the focusing field strength must be lower and the design intensity is higher, but meanwhile the difficulties from the high input energy are remained.

DESIGN CONCEPTS & METHODS

The RF-structure type of the P-RFQ has not yet been finally decided. In principle, the beam dynamics design

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which determines only the shape of the electrode tip is independent to the choice of the RF structure. But here some concerns about how to build and tune the RFQ are partly integrated into the following design concepts:

- Simply same as the old design, the input emittance ε_{in} and the inter-vane voltage U are 0.3 π mm mrad and 80 kV, respectively.
- The RFQ length should be kept at ~3 m, because this length is comfortable for the 4-rod structure to use only 1 tank and for the 4-vane structure to be divided into only 3 segments (typically 1 m per segment) without increasing construction time and costs.
- Concerning the mid-cell aperture r_0 along a 4-vane RFQ, the conventional way which was developed at the beginning of 1980s always keeps it constant for easy tuning. However, it is not reasonable especially at high beam intensities [8, 9] and also not necessary any more with the help from modern machining and tuning technologies e.g. the two famous 4-vane RFQs, LEDA and IFMIF [10], have non-constant r_0. Anyway, two new designs with varying and constant r_0, respectively, will be made for the P-RFQ.
- An important goal of the new design study is to minimize the output longitudinal emittance for making the matching to the downstream DTL easier and avoiding beam losses in the high-energy range.

Due to the success with the old design, the NFSP method is still adopted for both new designs. Different than the traditional LANL Four-Section Procedure [11], the NFSP method is characterized by a soft and symmetric pre-bunching, a fast main bunching, and then a fine bunching with a mixture of bunching and acceleration in the longitudinal plane as well as a varying focusing strength in the transverse plane which is adapted to the changing space-charge situation along the bunching process [8, 9]. Therefore, the NFSP method is an efficient way to achieve a compact RFQ with good beam performance simultaneously even at very high beam intensities e.g. 200 mA [9]. A difference between the two new P-RFQ designs is that the constant-r_0 version uses a so-called modified NFSP (mNFSP) method [12]: it has a NFSP-style longitudinal bunching but with a constant transverse focusing strength throughout the main RFQ.

DESIGN & SIMULATION RESULTS

The detailed results of the two new designs, CZ2014a and CZ2014b, as well as the old reference design, CZ2009, are compared in Table 2. All simulations have been performed using 10^5 input macro-particles, and all transported particles are included i.e. no particles are removed from the simulation in the longitudinal plane.

The RFQ is now even 10 cm shorter. As a result of the lowered $E_{s,\,max}$, the beam transmission efficiencies T of the new designs are lower than the old design. But in both cases, the difference in T for transported and accelerated particles is only 0.1%, which means most particles are well bunched and accelerated. This can be also seen in Fig. 2, where the green ellipses include 99% of the beam and the red curves indicate the separatrix.

Table 2: Comparison of the Three P-RFQ Designs

	CZ2014a NFSP r_0≠Const.	**CZ2014b** mNFSP r_0=Const.	**CZ2009** 70mA matched
U [kV]	80	80	80
$E_{s,\,max}$ [MV/m]	33	33	36
KF	1.87	1.87	2.0
m_{max}	2.3	2.4	2.1
a_{min} [cm]	0.19	0.19	0.22
r_0 ($r_{0,\,avg.}$) [cm]	0.34	0.34	0.35
$\varepsilon_{in,\,trans.,\,n.,\,rms}$ [π mm mrad]	0.30	0.30	0.30
$\varepsilon_{out,x,\,n.,\,rms}$ [π mm mrad]	0.31 (all) 0.30 (acc.)	0.32 (all) 0.31 (acc.)	0.39 (all) 0.30 (acc.)
$\varepsilon_{out,\,y,\,n.,\,rms}$ [π mm mrad]	0.31 (all) 0.30 (acc.)	0.32 (all) 0.31 (acc.)	0.42 (all) 0.30 (acc.)
$\varepsilon_{out,\,z,\,rms}$ [keV-deg]	556 (all) 125 (acc.)	826 (all) 123 (acc.)	6079 (all) 153 (acc.)
L [m]	3.1	3.1	3.2
T [%]	96.5 (all) 96.4 (acc.)	89.8 (all) 89.7 (acc.)	99.4 (all) 97.2 (acc.)

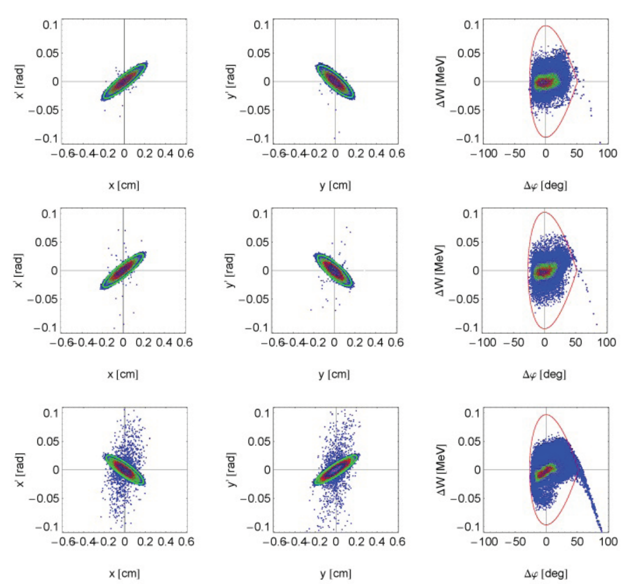

Figure 2: Output Phase Spaces (top: CZ2014a; middle: CZ2014b; bottom: CZ2009).

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Generally speaking, the two new designs are similar – this can be further seen in Fig. 3 – except in the CZ2014b design which keeps the transverse focusing strength constant, T is 6.7% lower. It is because that the increasing space-charge effects during the bunching could not be balanced and caused a blow-up in transverse beam size.

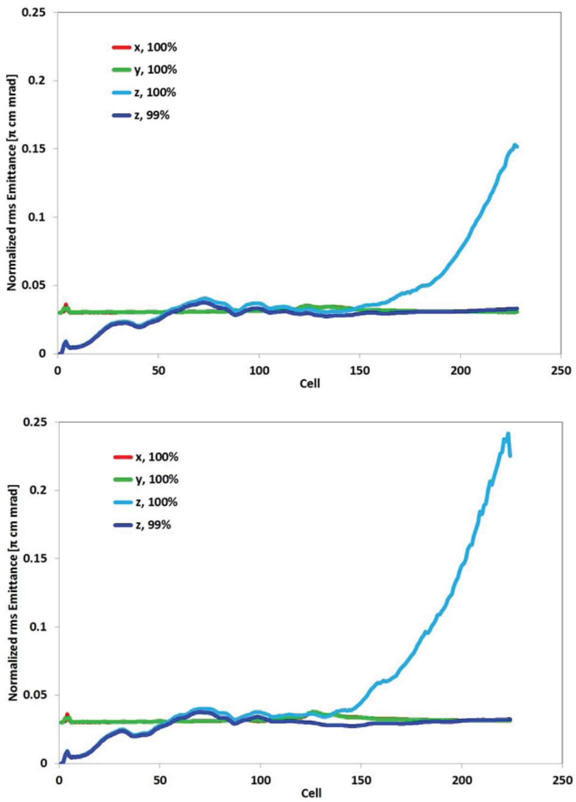

Figure 3: Emittance Evolutions along the RFQ (top: CZ2014a; bottom: CZ2014b).

Table 3: Design CZ2014a (acc.) vs. Other RFQ Designs

	FAIR P-RFQ	CERN LINAC4	J-PARC RFQ-III	SNS
U [kV]	80	78	81	83
m_{max}	2.3	2.4	2.1	N/A
a_{min} [cm]	0.19	0.18	0.22	N/A
r_0 ($r_{0,\,avg.}$) [cm]	0.34	0.33	0.35	0.35
$\varepsilon_{in,\,trans.,\,n.,\,rms}$ [π mm mrad]	0.30	0.25	0.20	0.20
$\varepsilon_{out,x,\,n.,\,rms}$ [π mm mrad]	0.30	0.25	0.21	0.21
$\varepsilon_{out,\,y,\,n.,\,rms}$ [π mm mrad]	0.30	0.25	0.21	0.21
$\varepsilon_{out,\,z,\,rms}$ [keV-deg]	125	130	110	103
L [m]	3.1	3.0	3.6	3.7
T [%]	96.4	95	98.5	>90

In Table 3, a further comparison was made between the CZ2014a with the simulation results for accelerated particles and the designs of the other RFQs mentioned in Table 1. It is shown that most parameters, e.g. U and r0, and performance, e.g. Δε and T, of this P-RFQ are very close to those of the other three RFQs, except L. The P-RFQ is about 0.5 m shorter than the J-PARC RFQ-III and the SNS RFQ and has a similar length to the LINAC4-RFQ. However, it should be mentioned that the P-RFQ has much higher input energy than the others, especially Win, P-RFQ > 2Win, LINAC4-RFQ. Therefore, it can be concluded that the P-RFQ is most compact among these machines.

CONCLUSION

Having fulfilled the up-to-date design requirements of the FAIR Proton-Linac RFQ, two new beam dynamics designs have been developed using the efficient NFSP method. Though the allowed maximum surface electric field is lower and the design intensity is higher than those in the old reference design, the RFQ provides better beam quality and is even more compact. As trade-offs, the transmission efficiencies of the new designs have some decreases, but still acceptable. If the KF-limit which is relatively conservative for this very-low-duty-cycle RFQ could be properly relaxed, the beam transmission will be certainly increased.

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