

BEAM DYNAMICS DESIGN, SIMULATION AND BENCHMARKING FOR THE C-ADS INJECTOR-II RFQ

Chuan Zhang[#], GSI Helmholtz Center for Heavy Ion Research, Planckstr. 1, Darmstadt, Germany
 Chen Xiao, Institute for Applied Physics, Goethe-University, Frankfurt a. M., Germany

Abstract

The planned Chinese Accelerator Driven System (C-ADS) will use two 10 MeV, up to 10 mA, and CW (Continuous Wave) proton linacs in parallel as injectors. Two versions of the injectors with different resonant frequencies as well as different cavity configurations are under development. This paper will focus on the beam dynamics design, simulation and benchmarking performed for the 162.5 MHz, 2.1 MeV Injector-II RFQ (Radio-Frequency Quadrupole).

INTRODUCTION

It's beyond question that an ADS-use driver linac has to reach extremely high reliability in CW operation. For such a linac, the front end i.e. the RFQ accelerator which has the strongest space-charge effects, the smallest distance between electrodes, and the most complicated water-cooling problems could be a bottle-neck. Therefore, a good RFQ beam dynamics design is a first step towards a successful ADS facility.

The design requirements for the C-ADS Injector-II [1] RFQ are listed in Table 1. The design beam intensity is 15 mA for safety margins, and it is also demanded that the design should still keep good performance up to 20mA. The output energy is chosen as 2.1 MeV for two reasons: 1) to keep the RFQ length shorter than 4.5m; 2) to keep the energies of lost particles lower than 2.16 MeV, the threshold energy of the ⁶⁵Cu(p, n)⁶⁵Zn reaction.

Table 1: Design Requirements

Parameters	Injector-II RFQ
Particle species	H ⁺
f [MHz]	162.5
W_{in} / W_{out} [MeV]	0.035 / 2.1
Duty factor [%]	100
I_{peak} [mA]	15 (up to 20)
$\epsilon_{in}^{trans.,n,rms}$ [π mm mrad]	0.30
$\Delta\epsilon^{trans.}$ [%]	≤ 10
$\epsilon_{out}^{longi.,n,rms}$ [keV ns]	≤ 1.0
T [%]	95
Twiss α [%]	≤ 1.5

[#]c.zhang@gsi.de (old address: zhang@iap.uni-frankfurt.de)

In Table 1, two special design goals can be highlighted:

- Only very small output longitudinal emittance, ≤ 1.0 keV ns, is allowed. As the superconducting part will be started directly behind the RFQ, transported but not-well-accelerated particles should be carefully avoided.
- For easier matching at the entrance and exit of the RFQ, the Twiss α parameters of the input and output distributions are limited to be ≤ 1.5 .

DESIGN AND SIMULATION STUDIES

The C-ADS Injector-II RFQ has been designed mainly using the New Four-Section Procedure (NFSP) [2] which can be characterized by special 3-stage bunching (soft and symmetric prebunching + efficient main bunching + fine final bunching) and adaptive transverse focusing. As the cavity and system developer of the Injector-II RFQ, LBNL used the 4-vane RFQ as the resonator structure and preferred to have a constant transverse focusing strength B like the conventional way for easier tuning.

Figure 1 shows the main parameters of the beam dynamics design generated using a modified NFSP method ($B = \text{constant}$), where a is the minimum electrode aperture, m the electrode modulation, V the inter-vane voltage, W_s the synchronous energy and ϕ_s the synchronous phase.

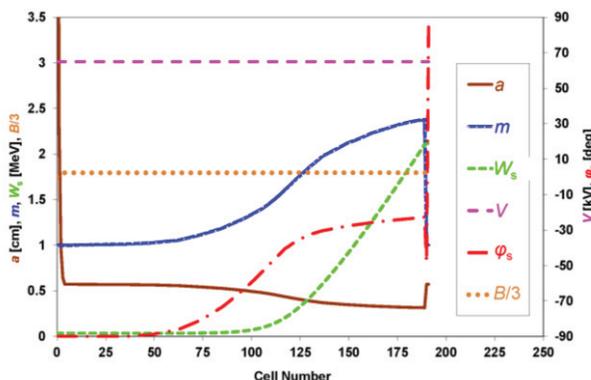


Figure 1: Evolution of main design parameters.

With a 4D-Waterbag input distribution, the beam transport simulation along the RFQ was performed using the PARMTEQM code [3]. In Fig. 2, one can see that the transverse beam envelopes have blowups around Cell 100. Such a blowup is a natural result of the application of a constant B . But it is still acceptable in this case, because: 1) though it will cause $\leq 0.5\%$ beam losses, no activation danger exists at such low energies; 2) the transverse size of the main beam is almost constant along the RFQ, so the beam quality remains good.

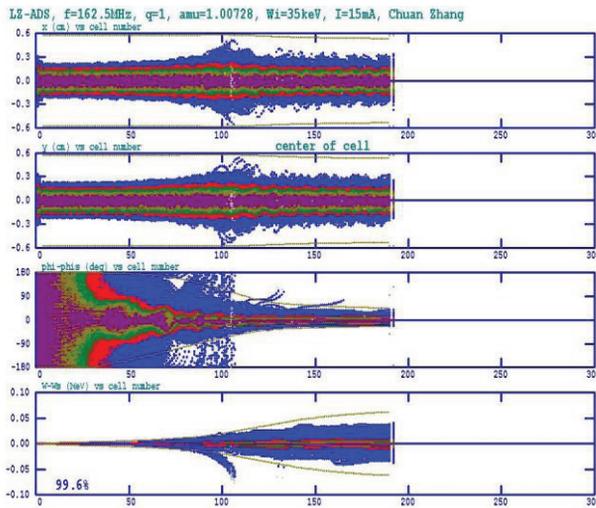


Figure 2: Beam dynamics simulation using PARMTEQM.

To obtain the desired Twiss α parameters at the RFQ exit, two transition cells are introduced there: 1) the first one makes a smooth transition from $m > 1$ to $m = 1$ and ends the electrode tips with quadrupole symmetry; 2) the second one keeps $m = 1$ and changes the orientations of the transverse emittance ellipses.

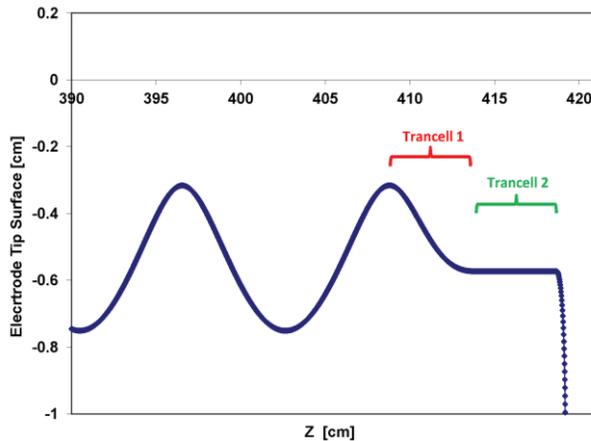


Figure 3: Exit transition cells.

Table 2: Simulation Results

Parameters	Injector-II RFQ
V [kV]	65
$E_{s,max} / E_k$	1.2
$\epsilon_{in}^{trans.,n,rms}$ [π mm mrad]	0.30
$\epsilon_{out}^{trans.,n,rms}$ [π mm mrad]	0.31
$\epsilon_{out}^{longi.,rms}$ [keV ns]	0.92
Twiss $\alpha_{in,max} /$ Twiss $\alpha_{out,max}$	1.21 / 0.36
T [%]	99.6 (99.1@20mA)
L [m]	4.21

Table 2 summarizes the detailed simulation results, where the Kilpatrick factor is only 1.2, very reliable for CW operation.

BENCHMARKING ACTIVITIES

PARMTEQM is the first RFQ simulation code and is still being used widely by the community. Most built RFQs in the world were based on the simulation results by this code. Recently, several new codes, e.g. TRACK [4], TOUTATIS [5], and LIDOS [6], are developed and are aiming to simulate the RFQ beam dynamics more accurately. In the TRACK simulation, the RFQ fields can be described by numerical 3D maps or by 8-term potential expansion of the cells.

For the C-ADS Injector-II RFQ, TRACK is chosen for benchmarking with the design code PARMTEQM. The geometric parameters and 8-term potential expansion of all cells are imported into the TRACK input file from the PARMTEQM output file. The beam transmission efficiency given by TRACK is 98.9%, slightly lower than the PARMTEQM value 99.6%.

Figure 4 gives the maximum transverse beam sizes along the RFQ for both TRACK and PARMTEQM simulations. It can be seen that these envelopes are actually quite similar.

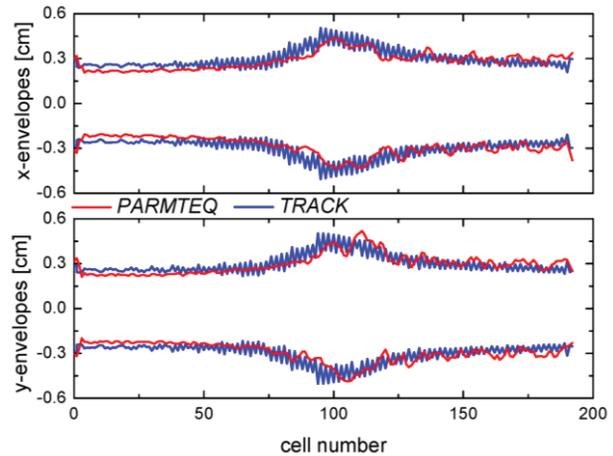


Figure 4: Transverse beam envelopes.

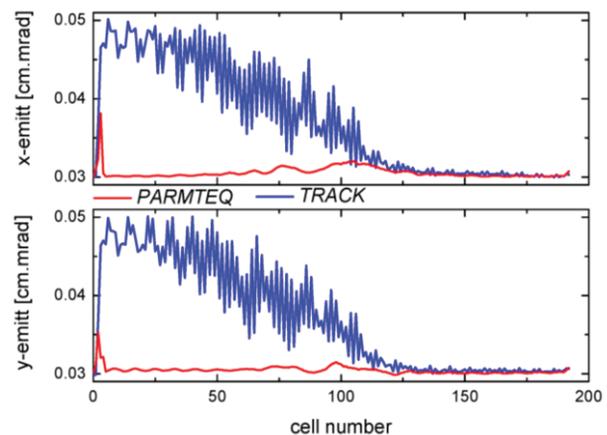


Figure 5: Transverse normalized rms emittances.

In Fig. 5, the normalized rms emittances in the transverse planes are compared. Obviously, the TRACK and PARMTEQM results are very different before Cell 100 – in the TRACK code, the transverse emittances increase rapidly at the beginning of the RFQ and gradually decrease when the injected DC beam becomes bunched – but almost identical after Cell 125. One possible explanation is: when a beam is injected into the RFQ, there is a transition from a phase with time-independent features to a phase with proper variations as a function of time, and TRACK does the emittance calculation in a different way. This problem needs to be further studied and understood.

Then the longitudinal emittance curves are plotted in Fig. 6. Generally speaking, the results agree with each other very well except an obvious difference around Cell 100. Very likely, in the PARMTEQM simulation, the above-mentioned beam blowup causes a few bad particles in the longitudinal plane and accordingly a sudden emittance growth there, but after these particles are lost, the emittance comes to normal again.

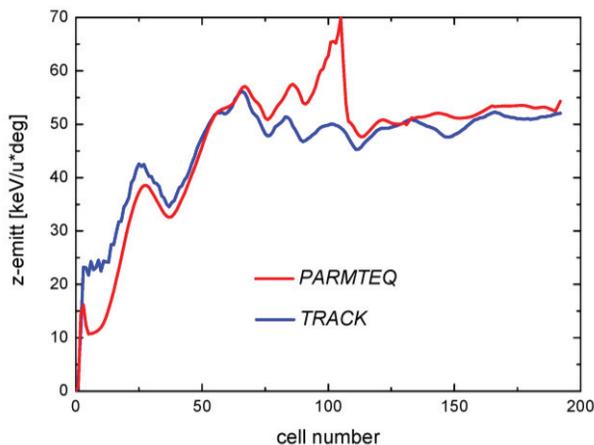


Figure 6: Longitudinal rms emittances.

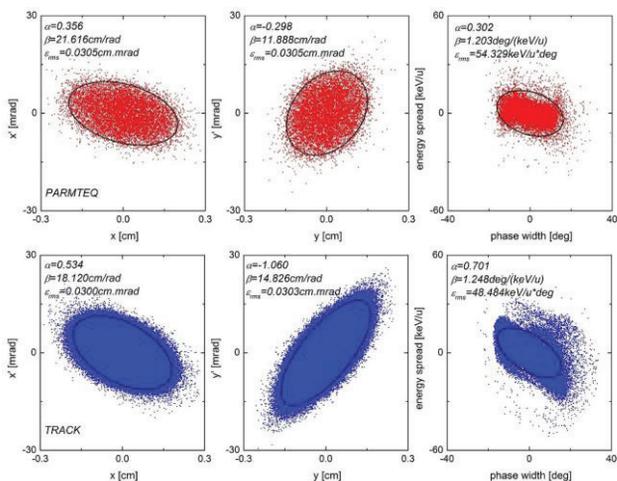


Figure 7: Output particle distributions (top: PARMTEQM; bottom: TRACK).

For the output particle distributions shown in Fig. 7, most Twiss β parameters and emittance values are

comparable, but differences in distribution shape and orientation can be observed. These differences might come from different treatments of the exit transition cells by the two codes. More careful studies with respect to this topic will be needed.

CONCLUSIONS

By taking advantage of the modified New Four-Section Procedure, a 4.21m long RFQ was design for the C-ADS Injector-II, with all design requirements satisfied. Based on this beam dynamics design, the cavity and system designs have been done by LBNL. Now the RFQ is under construction.

Recently, benchmarking activities between the TRACK code and PARMTEQM code have been performed on this RFQ. The results are still very preliminary. Further work for more detailed comparisons in calculation methods, simulation settings, and results will be carried out in the near future.

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