NUMERICAL SIMULATION OF PROJECT-X/PXIE RFQ*

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Abstract

Project-X is a proposed superconducting linac-based high intensity proton source at Fermilab[1]. The machine first stages operate in CW mode from 2.1 to 3 GeV. A high bandwidth chopper is used to produce the required bunch patterns. A 162.5 MHz CW RFQ accelerates the beam from 30 keV to 2.1 MeV. A concern with CW operation is that losses either within the RFQ or in the downstream modules should be well-understood and remain very low to ensure safe and/or reliable operation. In this contribution, we use the code TOUTATIS to perform RFQ simulations.

INTRODUCTION

Project-X is a multi-institutional collaboration. The latter includes LBNL, which in view of its considerable experience, has been assuming the responsibility of designing and delivering the RFQ. The latter is now ready for fabrication; delivery at Fermilab is expected sometime next year. The LBNL design work has been performed using an in-house version of Los Alamos suite of RFQ codes, which includes PARMTEQM. The code is by now well-established and has been used to design numerous successfully operated devices.

The LBNL group has performed extensive numerical studies of its design. In particular, detailed studies of the impact of imperfections on the performance of their RFQ have been reported at a recent Project-X collaboration meeting [3]. In this contribution, we present a first attempt at a similar type of analysis, using TOUTATIS, an alternative RFQ simulation code licensed from CEA/Saclay. This code possesses certain features that are attractive. Among them is the fact that field computations are performed directly from a geometric description of the vanes and are not based on a series expansion. The space charge solver employs a 3D multigrid algorithm and is self-consistent. Integration is performed using time, rather than longitudinal position as an independent variable. Finally, there is, no artificial limitation on the number of particles that can be tracked.

RFQ DESIGN

A set of relevant parameters for the LBNL designed PXIE [2] RFQ is presented in Table 1. It is a conventional device in that it includes the usual radial matcher, gentle buncher and acceleration sections. The downstream termination is of the Crandall type, i.e. it involves one cell where the modulation transitions from $m > 1$ to $m = 1$ followed by another where $m = 1$ whose length is adjusted to control exit beam parameters and to prevent phase dependent exit kicks. The design provides an output beam which is geometrically round with minimal angular divergence. Sections are clearly distinguishable on Figure 1, which shows the vane profile in the horizontal plane. Overall transverse and longitudinal rms beam envelopes are shown in Fig. 2.

Parameter	Value
Vane Length	4.44 m
Energy	30 keV - 2.1 MeV
Input Emittances	0.12,0.12, 0.0 mm-mrad
Output Emittances	0.15 (x),0.15(y), 0.21(z) mm-mrad

Table 1: Some relevant parameters for the Project-X RFQ.

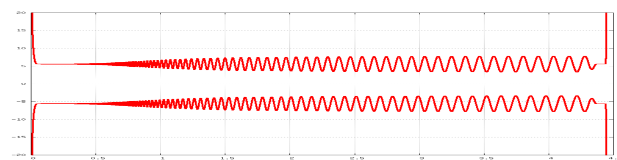

Figure 1: Vane profile in the horizontal plane.

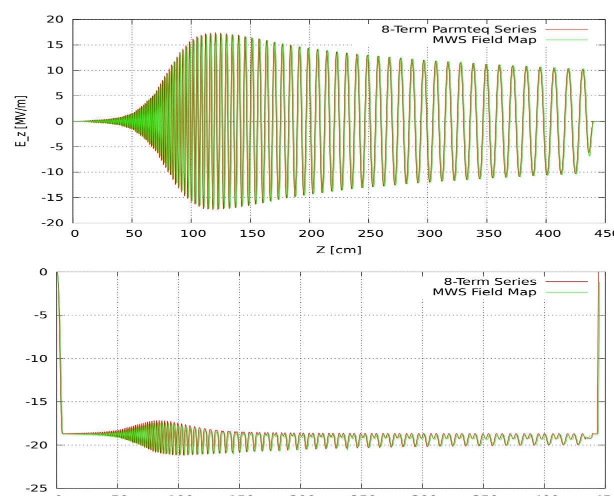

Figure 2: Field profile in the PXIE RFQ.

CODES

The Los Alamos code PARMTEQ is a tracking code where the RFQ field is modelled in the electrostatic approximation between the vanes. The field is obtained from an an 8-term axial expansion solution of Laplace's equation. PARMTEQ does not compute the series coefficients; the latter are interpolated from a parametrized table of pre-computed coefficients extracted from a full so-

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lution of Laplace equation for cells with different modulation/period ratios. These computations were performed separately with a code based on an integral equation formulation of Laplace's equation. A question that often arises is how accurate is the field obtained from the series compared with the exact solution. Fig. 2 compare the fields obtained from a numerical solution with CSR Microwave Studio to the field obtained from a series using the coefficients used by PARMTEQ. As can be seen, the agreement near the axis is excellent. That said, the accuracy of the series tends to degrade when the radial position approaches the edge of the vanes aperture. Another issue is the the space charge model in PARMTEQ, assumes a beam with azimuthally symmetric geometry while the actual beam is clearly not because of alternating gradient focusing.

The output beam phase space predicted by PARMTEQ was compared to the predictions of two other codes that provide a full-3d space charge model: TRACK (from ANL) and TOUTATIS (from CEA/Saclay). Overall, all three codes agree very well. While the predicted output rms beam parameters are identical, small differences can nevertheless be observed in the "halo" region. As an example, Fig. 3 compares the longitudinal phase space predicted by PARMTEQ and TOUTATIS.

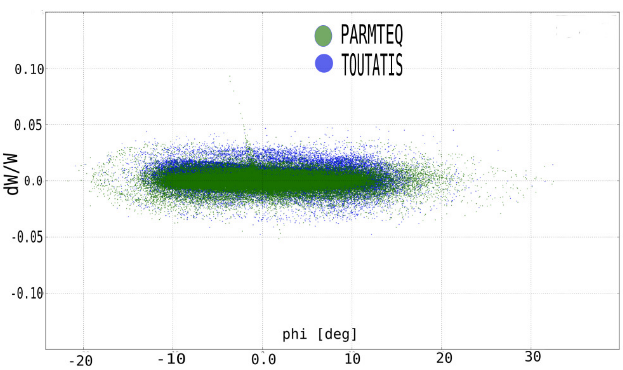

Figure 3: Longitudinal phase space at the rfq output. 100k particles, identical inputs.

LINAC ACCEPTANCE

An important technical challenge for Project-X is to keep losses well below 1 W/m in the CW superconducting linac downstream of the RFQ. A main source of concern is longitudinal phase space, specifically the characteristic "low energy tail" of the beam emerging from the RFQ. While particles populating this tail are transmitted through the RFQ, their phases gradually slip with respect to the synchronous phase because of slightly lower energies,. Eventually synchronism is lost, energy drops significantly below synchronous energy and the halo particles are deflected transversely out of the useful aperture by magnetic Unfortunately, the process of converting a longitudinal "tail" into a transverse one occurs over many betatron periods and collimation cannot be performed inside a cryomodule. In general, rf capture efficiency in an RFQ is not total because the longitudinal vane modulation must be established over a finite length; in other words, the process is not be perfectly adiabatic. Acceptances for the Project-X MEBT and Linac have been estimated by tracking particles initially covering a large area of phase space and determining those which survive. Note that this estimate ignores space charge effects, and is therefore likely to be a modest overestimation. Fig. 4 shows longitudinal acceptance plots for the combined MEBT and linac, about 5π mm-rad. The limiting longitudinal acceptance is the linac. The corresponding transverse acceptance boundaries are not shown, but have a more regular shape. The predicted transverse acceptance is on the order 5π mm-mrad for the MEBT-linac combo. This transverse acceptance is limited by the MEBT, which includes transverse collimation intended to sweep out particles in the "far tail" of the energy distribution; the transverse acceptance of the linac is about twice as large.

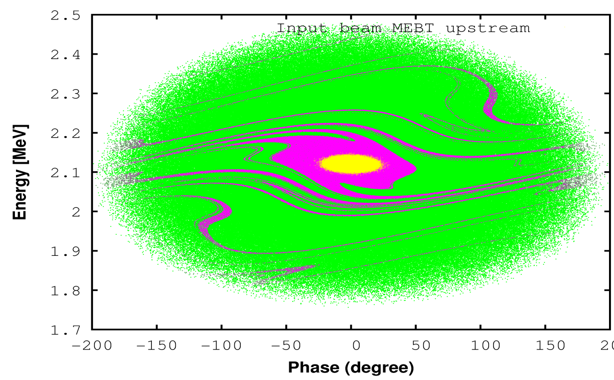

Figure 4: Longitudinal phase space acceptance for the combined MEBT and Linac. The acceptance is the cyan area. The yellow area is a 3σ beam.

IMPERFECTIONS

A real RFQ obviously deviates from the design ideal. Many types of "errors" can be studied. Among relevant ones are voltage profile errors, which may also themselves be a side-effect of mechanical imperfections. Within the vanes region, the RFQ fields are quasi-TEM. The effective longitudinal vane voltage distribution is analogous to that in a transmission line and is determined by the geometry along the device and at both extremities. Tuners are provided correct the voltage profile. The adjustment is however, static. Various effects, in particular thermal effects, or mechanical resonances can still induce dynamic deviations. Fig. 5 shows predicted losses as a function of the voltage on the vanes. The nominal inter-vane voltage is uniform (60 kV). Three curves are presented. The curve labelled RFQ is the fraction lost within the RFQ. The second curve, labelled "MEBT" is the fraction which is more than 0.2 MeV away from the nominal energy and outside a $25\epsilon_t$ transverse acceptance. Those particles are most likely collimated in the MEBT. The third curve, labelled "LINAC" is a fraction outside of $25\epsilon_\ell$ acceptance is likely to be lost in the downstream linac. Fig. 6 illustrates the impact on transmission of a non-uniform voltage profile. The error voltage ramps linearly and goes through 0 half-way into the RFQ. A 1% ramp means that the voltage varies from -0.5% to +0.5%. All computations were performed with TOUTATIS. These results confirm that the design is relatively insensitive to voltage perturbations, comfortably so within a few %.

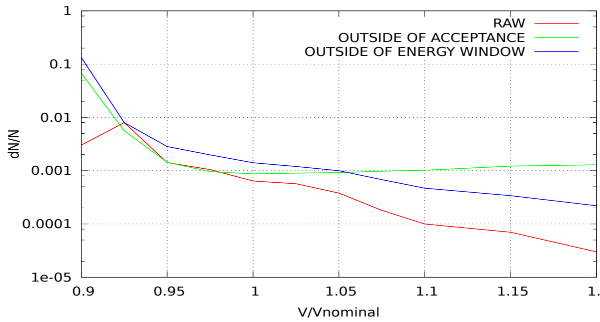

Figure 5: Estimated loss fractions vs relative voltage.

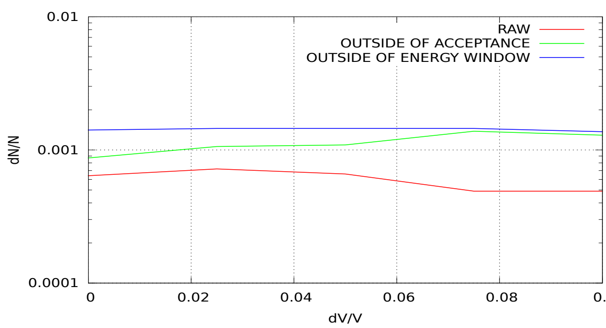

Figure 6: Estimated loss fractions vs linear voltage ramp.

MISMATCH AND INJECTION ERROR

Because the radial matcher section has a finite length, transverse focusing is also not established in a perfectly adiabatic manner. As a consequence, there exists an optimal set of beam parameters, – the matched parameters –, which minimize envelope oscillations within the RFQ. These parameters are close to, but do not correspond exactly to the periodic α, β for the first cell downstream of the radial matcher for the synchronous particle. This is mostly because for each particle, transverse focusing depends on the rf phase upon arriving at the cell. While the LEBT provides some adjustment for matching, vacuum fluctuations and corresponding neutralisation effects are difficult to control and can induce mismatch and injection errors at the RFQ input. Fig. 7 illustrates the impact of a 50% horizontal transverse mismatch on the emittances. Not surprisingly, both transverse emittances are over 20% higher than nominal; the longitudinal one is minimally increased. Fig. 8 illustrates the impact of a vertical injection error of 2 mm and 2mrad. 8.5 % of the beam is lost within the RFQ. In this case, the output transverse emittances are double of nominal while the longitudinal is only 20% higher.

CONCLUSION

The Project-X/PXIE RFQ will be one among few RFQs operating in CW mode. By cross-checking with available

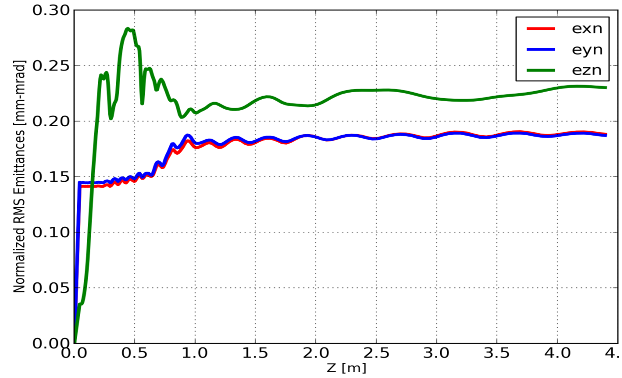

Figure 7: Emittances with a 50 % hor. input mismatch. Losses are not affected.

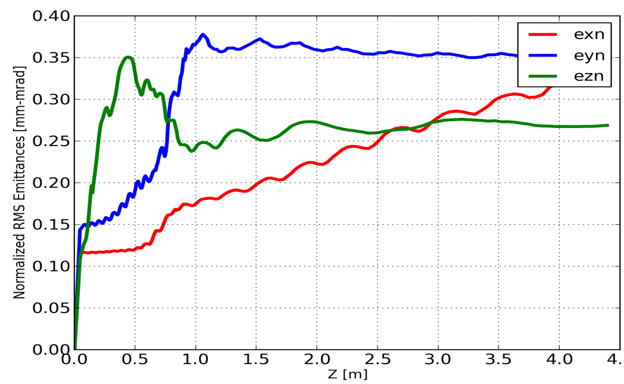

Figure 8: Emittances with 2 mm, 2 mrad vert. input error.

codes and models involving different physics details, our objective is to be well-prepared to better understand and analyse the device performance once it is put in operation. This exercise has allowed us to confirm LBNL results to the effect that that the design is relatively robust with respect to various type of errors. We intend to continue and analyse other types of imperfections; planned future work also includes tracking with a PIC code and a full electromagnetic model based on as-build geometry. Early efforts in that direction have already been described[4].

ACKNOWLEDGEMENTS

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