PIC SIMULATIONS IN LOW ENERGY PART OF PIP-II PROTON LINAC.*

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Abstract

The front end of Proton Improvement Plan at Fermilab (PIP-II) linac is composed of a 30 keV ion source, low energy beam transport line (LEBT), 2.1 MeV radio frequency quadrupole (RFQ), and medium energy beam transport line (MEBT). This configuration is currently being assembled at Fermilab to support a complete systems test. The front end represents the primary technical risk with PIP-II, and so this step will validate the concept and demonstrate that the hardware can meet the specified requirements. SC accelerating cavities right after MEBT require high quality and well defined beam after RFQ to avoid excessive particle losses. In this paper we will present recent progress of beam dynamic study in the low energy part of the linac and describe the simulation technique with the use CST Studio Suite and TRACK

INTRODUCTION

The Proton Improvement Plan-II [1] is structured to deliver, in a cost effective manner, more than 1 MW of beam power while creating a flexible platform for longer-term development of the Fermilab complex to multi-MW capabilities in support of a broader research program, as future resources become available. The central element of PIP-II is a new 800 MeV superconducting linac with continuous wave (CW) capable cavities and cryomodules, injecting into the existing Booster.

One of the novel features of the new linac is acceleration of H^- beam by low energy SC cavities right after room temperature 2.1 MeV CW RFQ. Complications during high-current beam acceleration can be due to beam loss of the RFQ longitudinal tails in SC linac and halo generation by beam space charge.

In this paper a recent beam dynamic study in support of the low energy section experiment [2] is presented with the focus on the technical details of the simulations. The beam dynamic simulations were performed with the use of CST Particle Studio and TRACK simulation code [3], and the comparison of the results is reported.

INPUT BEAM GENERATION

CST PS and TRACK don't have elaborated particle source models, but both allow importing beams prepared externally. The input beam for the LEBT was generated basing on the measurements of the beam from the ion source IS [4]. The input beams for RFQ were based on the design parameters [5] with variances within tolerances.

Transverse particle distribution of the initial DC beam from IS was assumed to be Gaussian and properly centred in the transverse plane. To prepare the input particle file the Mathematica procedures were used to generate random binormal particle distribution in transverse plane basing on the initial beam RMS parameters σ, σ` and covariance coefficient $\rho=\sqrt{1-(\varepsilon_{rms}/\sigma\sigma`)^2}$.

For the CST Tracking solver (CST TRK) a binormal particle distribution is generated in a single transverse plane at given longitudinal coordinate, since the code generates DC beam automatically. The particle distributions for X and Y coordinates are generated independently.

For TRACK a DC beam must occupy the longitudinal distance that is equivalent to 180° phase interval of the RFQ operating frequency. Therefore a beam for TRACK consists of a number of "slices" distributed over 180° with chosen step. A binormal random particle distribution is generated independently for each time step and each coordinate.

<u>Measured beam parameters:</u>
Current 5 mA
Energy 30 keV
$\alpha_{x,y}$ = - 4.48
$\beta_{x,y}$ = 1.51 mm/mrad
ε_{rms} =12 π·mm·mrad
2σ = 8.5 mm
2σ` = 25.8 mrad

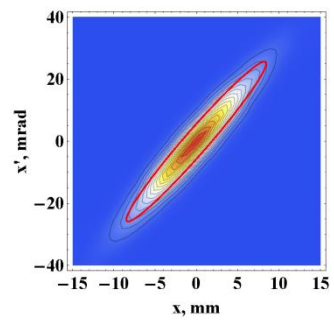

Figure 1: The measured beam parameters from ion source and the density plot of the corresponding generated Gaussian beam.

In the CST Particle-in-Cell (CST PIC) solver the beam structure is similar to the TRACK one, but without boundary conditions that imitate an infinite DC. So, a bunch should be long enough (4-5 RF periods) to consider its central part as a DC beam. The beam slices in the CST PIC solver can be distributed in space or in time.

Typical number of the macroparticles was 10K for CST TRK and ≈100K for TRACK. The phase portrait of the generated input beam for the LEBT is shown in Fig.1.

CST PARTICLE STUDIO VS TRACK

A number of preliminary variants of beam optics in the LEBT (see Fig.2) were considered to estimate emittance growth and possibility of good beam matching to RFQ. Another goal of the simulations was a comparison of TRACK and CST Particle Studio.

The LEBT layout currently has three focusing solenoids. In the present simulations the same 3D magnetic field maps have been imported from CST Magnetostatic Studio model into the TRACK and the CST TRK models.

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The TRACK code and the CST TRK solver have different approach to beam simulation, and that makes a comparison of the simulation results neccessary in terms of mutual verification.

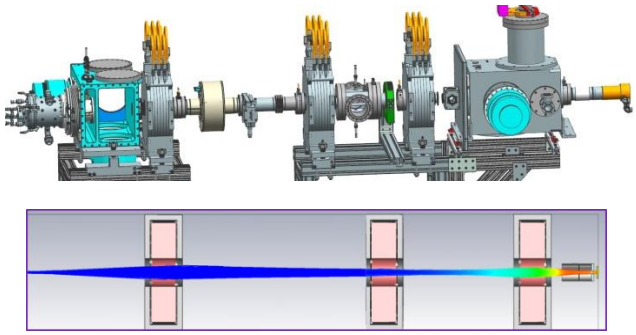

Figure 2: One of the possible LEBT configurations [6] and one of the possible beam profiles (CST TRK).

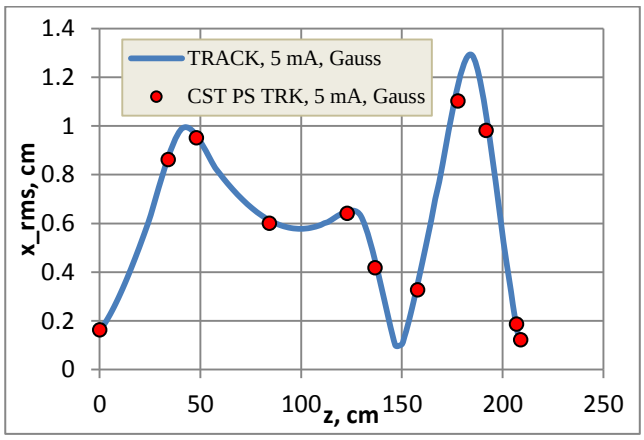

Figure 3:The RMS beam envelopes in the LEBT simulated by TRACK and CST TRK.

An excellent agreement has been achieved after the 3D magnetic field maps have been imported into TRACK, and after its analytical water bag beam model has been replaced by binormal beam distribution used in CST TRK. The rms beam envelopes simulated by the codes are shown in Fig.3. The density distributions of the output beams in transverse phase plane shown in Fig.4 are also in a good agreement. The similarity of the beam phase portraits is especially important since the beam models in the codes are different in principle.

There is a small difference in the rms emittance growth - up to 5 %. The most probable reason for that is the mentioned difference between beam models in the codes. In TRACK a lengthy beam bunch may have some longitudinal variations. These variations being projected on the single plane may generate the discrepancy. The total emittance growth along the LEBT exceeded 100% in some particular scenarios of the beam optics.

TRACK is much faster than the CST TRK, and it is many times faster than the CST PIC. That makes TRACK more effective tool when it comes to beam matching and beam line layout optimization.

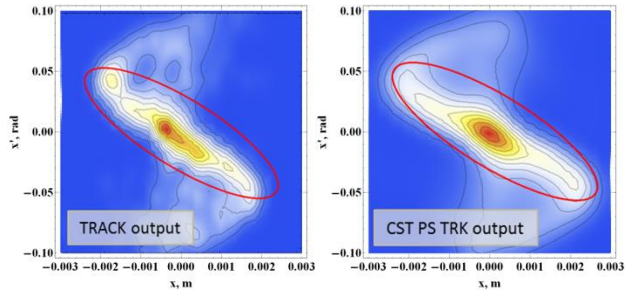

Figure 4: The density plots of the particle distributions in transverse phase plane at the RFQ entrance. The phase ellipse of $4\varepsilon_{rms}$ matched to the RFQ is shown in red.

TOLERANCES FOR RFQ INPUT BEAM

It is very unlikely that it would be possible in practice to achieve a perfect beam matching between the RFQ and the LEBT. To evaluate an impact of imperfect input beam matching on the quality of output beam from the RFQ, the beam dynamic simulations in the RFQ with variable input beam parameters were conducted.

For this study the RF fields were exported from complete CST model of the RFQ. The RFQ model compare to its predecessor [7] received PISLs and tuners. Also the model has been "re-tuned" to flatten the field distribution.

The simulations were performed for two transverse emittances: ε_{rms_norm} = 0.11 π mm mrad (nominal value) and ε_{rms_norm} = 0.23 π mm mrad (maximum value obtained in the simulations of the LEBT). For each emittance two particle distributions were considered: uniform ("waterbag") and Gaussian. The input Twiss parameters α and β were swept assuming axial symmetry of the input beam in the intervals, where particle losses inside the RFQ did not exceed 10%.

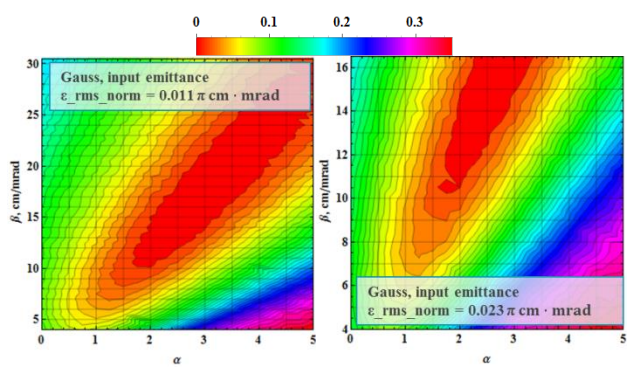

Figure 5: The contour plots of the output transverse emittance $4\varepsilon_{rms_norm}$, cm·mrad, as a function of input Twiss parameters.

During the input beam Twiss parameters sweep, it was found that only losses inside the RFQ and the output transverse emittance have clearly expressed optimums. Since the losses show larger tolerances, the output transverse emittance was chosen as a criterion of output beam quality.

The contour plots in Fig.5 show the results of the Twiss parameters sweep for Gaussian beam (for uniform beam the results are very close). It turned out that the tolerances for the input Twiss parameters are rather relaxed: for the pretty large central contour area emittance growth in the RFQ does not exceed 20% and the losses do not exceed 2%, which is acceptable by the design requirements. Input β has an additional limitation that comes from the input aperture in the RFQ end-wall.

BEAM MATCHING

The standard beam matching at the RFQ entrance means an adjustment of the LEBT layout and focusing field levels to get required values for the Twiss parameters of output beam. Let α_{opt}, β_{opt} and γ_{opt} be required Twiss parameters at the LEBT output, while α, β and γ are current values for the given focusing fields set. Then the objective function, minimum of which corresponds to perfect matching, is [8]

$$\mathrm{Min} = \sqrt{R/2 + \sqrt{R^2 - 4}} - 1, \text{ where } R = \beta\gamma_{opt} + \gamma\beta_{opt} - 2\alpha\alpha_{opt}.$$

Optimization was performed by Nelder-Mead algorithm realized in Mathematica, while the Twiss parameters for the objective function were calculated by TRACK, which served as an external procedure for Mathematica.

The beam matching using Twiss parameters is effective and fast, but this way of matching is not adequate in case of strong non-linear forces. Generally a beam in phase space does not form a perfect ellipsoidal shape - it's distorted and has a halo and the tails. TRACK generates rms Twiss parameters taking into account all particles, including tails. As a result a perfect matching of the rms Twiss parameters does not guarantee maximal number of particles inside RFQ's acceptance. There is one more nuance – the result is the magnetic field levels, which provide matching in the model, but not necessarily in the real LEBT due to the unavoidable differences between the two.

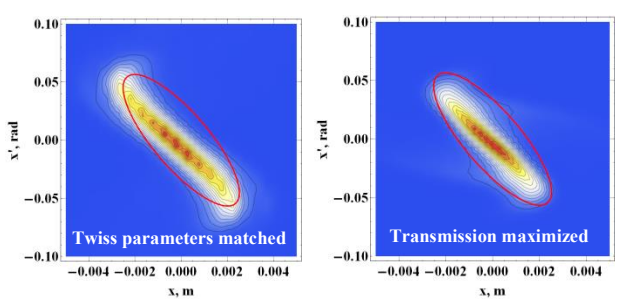

Figure 6: The phase space density plots of the matched input beams. The RFQ acceptance is in red.

An alternative objective function, which is simply a number of particles inside required phase space area, was successfully used. But the optimization with this objective function found to be very slow. Finally, optimization was performed in two stages: first, fast matching of the rms Twiss parameters to get closer to the optimum, then time consuming maximization of the particles captured in the required ellipse at the RFQ entrance (Fig.6). Actually a kind of this approach is already used in practice as the maximization of the RFQ transmission.

UNSTABILIZED RFQ

Due to budget constraints, we may not be able to procure a cooling system for the RFQ commissioning that can adequately maintain the 162.5 MHz resonant frequency during operation. A proposal was made to allow the RF system to track the resonant frequency of the RFQ as it drifts and allow the bunched beam frequency to drift with it.

The simulations proved that we can start commissioning the RFQ without comprehensive frequency stabilization system. We can allow frequency deviation as big as ± 1 MHz still having an output beam of quality acceptable for commissioning. Further acceleration is questionable though.

The beam losses inside the RFQ are negligible, if the input beam has the nominal emittance and is properly matched at 162.5 MHz. There is no need to re-match the input beam during frequency drift.

CONCLUSION

The simulation results performed with TRACK code, CST TRK and PIC solvers are in a very good agreement.

The tolerances for the RFQ input beam parameters were defined and found rather relaxed.

The RFQ transmission maximization is a good practical approach, while rms Twiss parameters matching is convinient as an initial step for LEBT commissioning.

The RFQ commissioning can be started without comprehensive frequency stabilization system.

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REFERENCES

[1] Proton Improvement Plan website, http://www-ad.fnal.gov/proton/PIP/PIP_index.html
[2] S. Holmes, "Project X Front End R&D Program – PXIE", Project X Document 966-v3, January 2012.
[3] The beam dynamics code TRACK: http://www.phy.anl.gov/atlas/TRACK.
[4] Q.Ji, "Project X H- Ion Source Acceptance Test and Future Plan", Project X Document 890-v1, May 2011
[5]. J. Staples and Q. Ji, "LEBT and RFQ", Project X Document 846-v1, April 2011.
[6] Rich Andrews et al, "Status of Mechanical Design of LEBT", Project X Document 1279-v1, April 2014.
[7] G.Romanov, "Beam Dynamics Simulations In Project X RFQ With CST Studio Suite", MOPPC082, IPAC12, New Orleans, USA, 2012.
[8] K.R.Crandall and D.P.Rusthoi, "TRACE 3D Documentation", LA-UR-97-886, LANL, Los Alamos, May 1997.