ESS END-TO-END SIMULATIONS: A COMPARISON BETWEEN IMPACT AND MADX

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Abstract

The European Spallation Source will be a 5 MW superconducting proton linac for the production of spallation neutrons. It is composed of an ion source, a radio frequency quadrupole, a drift tube linac and a superconducting linac as well as the low, medium and high, energy beam transport sections. At present these components of the linac are in the design phase: the optimization of the accelerator parameters requires an intensive campaign of simulations to test the model of the machine under possible operational conditions. In this paper the results of simulations performed with the IMPACT and MADX-PTC codes are presented and a comparison is made between them and independent simulations using TraceWin. The dynamics of the beam envelope and single and multi-particle tracking are reported.

INTRODUCTION

The European Spallation Source is a project, currently in the design phase, for the production of high brightness neutron beams through the spallation process. A comprehensive description of the project is presented in the Conceptual Design Report (CDR) [1]. For the purpose of this paper, only the superconducting proton linac part is considered, and studies are focused on the beam dynamics from the end of the Radio Frequency Quadrupole (RFQ) to the spallation target station (Fig. 1).

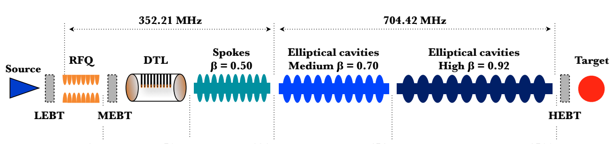

Figure 1: ESS proton linac scheme.

The design parameters of the accelerator, reported in the CDR, are summarized in Tab. 1. The choice of the optical functions (α and β) at the beginning of the machine is aimed at creating a periodic beam in the FODO cells of the superconducting part of the accelerator. Those parameters are generated numerically via the code TraceWin [2] for the configuration at 50 mA and summarized in Tab. 2. The zero current (no Space Charge) layout shares the same initial conditions but with a re-matched lattice.

TraceWin is also adopted as the main reference code in the ESS study because it was largely used during the design of the accelerator and the setting of the parameters as reported in [3].

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Table 1: Beam Parameters

Parameter	Value
Kinetic Energy after the RFQ	3 MeV
Beam Peak Current	50 mA
Particles per bunch	8.8×10^8
Duty Cycle	4%
Freq. before the Medium β sect.	352.21 MHz
Freq. after the Medium β sect.	704.42 MHz
Horizontal Normalized Emit.	0.22×10^{-6} m rad
Vertical Normalized Emit.	0.22×10^{-6} m rad
Longitudinal Normalized Emit.	0.29×10^{-6} m rad
Optimal β in Spokes	0.50
Geometrical β in Medium β sect.	0.70
Geometrical β in High β sect.	0.92

Table 2: Initial Conditions for the Optical Functions

Parameter	Value	
Horizontal α	0.535	
Horizontal β	0.163	m rad
Vertical α	-1.323	
Vertical β	0.358	m rad
Longitudinal α	-0.437	
Longitudinal β	1.203	m rad

MADX-PTC

MADX is a widely used code for the design and study of accelerator rings as well as beam lines [4]. It has been complemented with the PTC library [5] to overcome some of its limitations, allowing calculations of six dimensional beam dynamics parameters and beam acceleration [6, 7].

In beam dynamics simulations for hadron linacs, the method of modelling RF cavities can have a large impact on the predicted beam behaviour, probably more so than in simulations of rings. It is therefore important to use as realistic a model as possible and integrate the motion based on numerical values of the electromagnetic fields. Even when such information is not available and one cell of a cavity is modelled simply as "drift-kick-drift", it is common to include details such as the displacement of the electric center with respect to the physical center of the cell as well as effects from the transit time factor and its derivatives on the transverse and longitudinal behaviour of the beam [2, 8, 9]. Although the MADX and PTC codes already include the RF cavity as an accelerator element, they do not include such detailed effects. Hence, when producing a lattice for MADX and PTC based on that from the TraceWin, a finite length RF cavity in TraceWin is converted to a thin RF cavity and a thin 4×4 matrix, providing transverse kicks with drifts on each side, as described in [8, 9]. An issue

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for MADX and PTC in modelling an RF cavity like this is that thin-lens matrices cannot be used for PTC, which can therefore be used only to calculate the acceleration. Another issue is the space charge in the beam. Efforts have been made to introduce space charge into the MADX-PTC framework [10] but it has not been implemented yet in the standard version. It is important for ESS and similar studies that a detailed modelling of a finite length RF cavity with space charge effects is developed for MADX-PTC in the near future.

IMPACT

Comparative modelling has been carried out using the IMPACT code developed at LBNL in the early 90's [11]. Written in Fortran90, the code uses a split-operator method based on a symplectic treatment of Hamilton's equations of motion, and has options of both first and third-order (Lorentz) integrators. The main difference between IMPACT and the TraceWin-MADX-PTC combination is that it uses field maps for the RF cavity fields, thus providing a more realistic form of tracking than the instantaneous kick-in-gap method. Space charge is calculated using fast Fourier transform methods and a variety of boundary conditions are available. The code has also been adapted to run on multi-processors, though in the work reported here a single desktop PC has been adequate. Over the years IMPACT has been regularly subjected to extensive benchmarking (for example, during the EU HIPPI study [12]). It was also used to model the J-PARC and SNS linacs; as a result, the authors feel confident that it represents a suitable tool to model ESS and to check the results of the TraceWin-based studies.

There are several challenges in carrying out a reliable comparison between IMPACT and TraceWin[1]. Not least is the transformation between the different lattice formats and input distributions. IMPACT, for example, does not use Twiss parameters, and a clear understanding of the connection between the different types of coordinate system is necessary. Several additional Fortran modules and Perl scripts were written to allow design changes to be quickly and efficiently assimilated. Close attention was paid to developing realistic field maps for the DTL, Spoke and medium and high-beta sections of the linac. Also, because IMPACT uses absolute phases settings while TraceWin relies on relative phases, a new code was written, based on iterative phase scanning, to complete the final transition between the input datasets, ensuring consistency between the codes particularly in terms of energies gained by the synchronous particle at each RF section of the linac.

RESULTS

Fig. 2 compares the kinetic energy of the beam at each location of the linac calculated from the three codes. The codes are in very good agreement, as indeed should be the case because of the similarity in the calculations and the way the input datasets were set up.

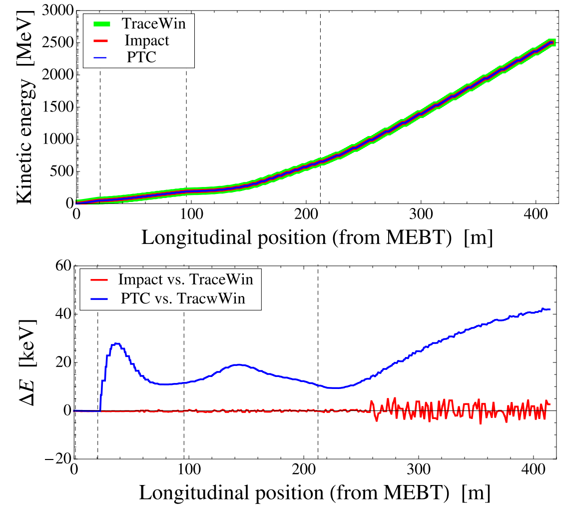

Figure 2: Comparison of kinetic energies calculated by the TraceWin, IMPACT, and MADX-PTC. Dotted lines represent transitions between two sections.

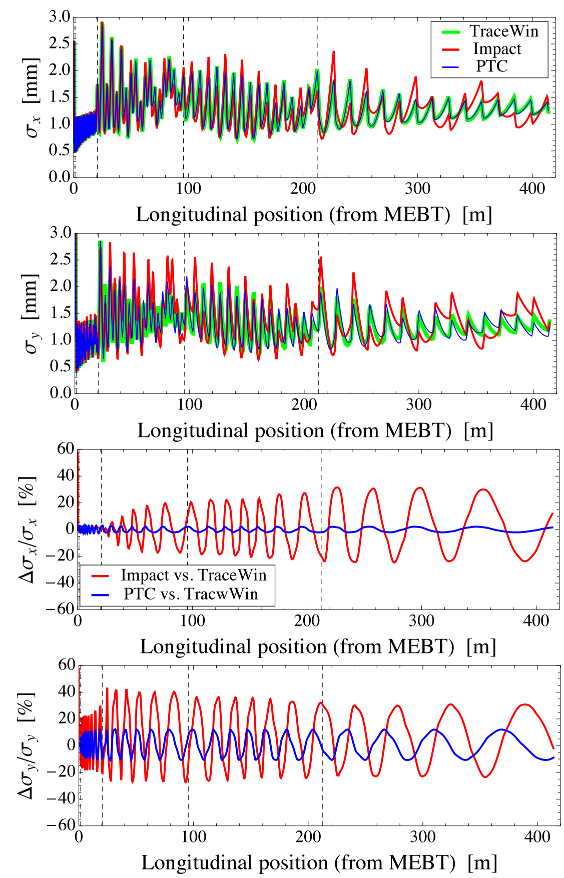

Figure 3: Comparison of RMS beam size calculated by the TraceWin, IMPACT, and MADX-PTC for the zero current. Dotted lines represents transitions between two sections.

Fig. 3 compares the transverse beam RMS size calculated from the three codes for the case of zero current. The third and fourth plots show the relative differences of

[1]The authors are grateful to J. Qiang (LBNL) for his help in overcoming teething problems at the outset of the study.

beam RMS sizes calculated from IMPACT and MADX-PTC with respect to those from TraceWin. In TraceWin and MADX-PTC, each cell of a cavity is treated as "drift-kick-drift" but the kicks of the two codes are identical only to first order. This difference in the modeling generates the difference in the RMS sizes at the beginning of the DTL. The amplitudes of $\Delta\sigma_x/\sigma_x$ and $\Delta\sigma_y/\sigma_y$ remain the same in the spokes, medium-β and high-β sections, which suggests the difference between TraceWin and MADX-PTC is only in the beginning of the DTL and may not be significant.

On the other hand, despite the care taken to ensure parity between the initial set-ups, some discrepancies are evident in the predictions from TraceWin and IMPACT, largely due to the different orders of tracking and the use of field maps in IMPACT but not in TraceWin. In order to trace these effects, IMPACT tracking was carried out using a straightforward 6D-Waterbag model distribution, rather than the highly non-linear dataset generated by modeling the RFQ. 100,000 particles were used and space charge was turned off. Close analysis of the transverse focusing reveals small differences at each RF cavity. TraceWin shows sudden changes in RF beam size from the drift-kick-drift technique which approximates well with IMPACT's field map integrator on a local scale but slight differences in beam divergence then grow progressively down the linac until the disagreement is quite marked. The explicit effects of third as compared with first order tracking have yet to be explored but non-linear effects including space-charge are likely to add to these differences and a proper study of phenomena such as halo formation and growth is now a priority.

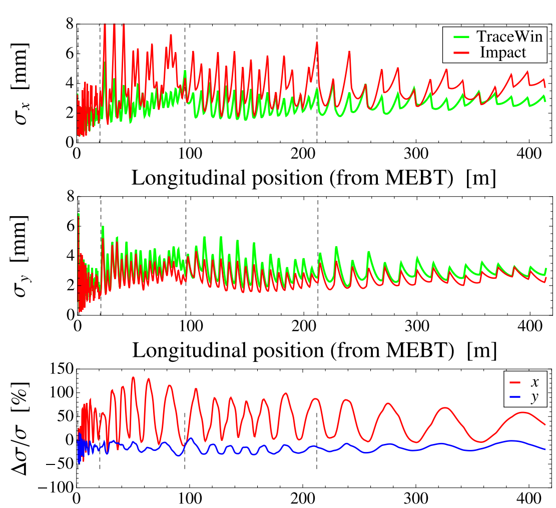

Figure 4: RMS beam envelope from IMPACT simulation with full space-charge.

A further comparison can be made with Fig. 4, which shows results from an IMPACT simulation using a 6D-Waterbag and full space-charge (50 mA). The non-uniformity of the oscillations, differences between the horizontal and vertical planes and general non-linear growth are evident, suggesting that much needs to be done to optimize the system, not only for basic beam dynamics but also for non-linear effects.

CONCLUSIONS

This preliminary study shows that the three codes under consideration are in good agreement for the dynamics of the core of the beam in a linear regime. Nevertheless a detailed campaign of simulations has to be performed in order to understand the non-linear behaviour of the accelerator in conditions that are both ideal and realistic (including field errors, jitter, etc.). MADX-PTC requires a more accurate RF model as well as a suitable space-charge routine, while the IMPACT can be pushed forward and used to optimize the focusing/accelerating structures with RF field maps.

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