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Published in:
LINAC14: Proceedings of the 27th International Linear Accelerator Conference

2014

Citation for published version (APA):
Tanke, E., de Prisco, R., Eshraqi, M., Ponton, A., Sargsyan, E., & Miyamoto, R. (2014). Benchmark of beam dynamics code DYNAC using the ESS proton linac. In *LINAC14: Proceedings of the 27th International Linear Accelerator Conference* (pp. 945-947). JACoW Publishing.

Total number of authors:
6

BENCHMARK OF BEAM DYNAMICS CODE DYNAC USING THE ESS PROTON LINAC

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Abstract

The beam dynamics code DYNAC was benchmarked using the European Spallation Source (ESS) Proton Linac. The code contains three space charge routines, including a 3D version. For beam dynamics, it contains a numerical method, capable of simulating a multi-charge state ion beam in accelerating elements (i.e. cavities) as well as an analytical method, capable of modelling protons, single charge state heavy ions and non-relativistic electrons. The benchmark includes comparisons of both methods with the beam dynamics models in use at ESS. As the analytical method used in DYNAC is fast, it is a prime candidate for use as an online beam simulation tool.

INTRODUCTION

The high current (62.5 mA) beam of protons is accelerated up to 2.0 GeV in a sequence of normal conducting and superconducting accelerating structures in the ESS linac. The accelerated protons are to be used for the bombardment of neutron rich nuclei in the target to produce a high flux of pulsed spallation neutrons. The 5 MW proton linac delivers beams to the target in long pulses of 2.86 ms with a repetition rate of 14 Hz, corresponding to a duty cycle of 4 %. Such beam powers are unprecedented and extensive simulations are needed to make sure that the loss levels are well controlled (<1W/m) and do not prevent hand-on maintenance of the accelerator components.

It is important that beam dynamics simulations for such a linac be tested with independent codes to eliminate unknown bugs in the codes, though each code has undergone careful debugging.

THE ESS LINAC

The ESS linac [1] is composed of a normal conducting front-end, consisting of an ion source, Low Energy Beam Transport (LEBT), Radio Frequency Quadrupole (RFQ), Medium Energy Beam Transport (MEBT) and Drift Tube Linac (DTL). The front-end is followed by a Super Conducting Linac (SCL). Each section, starting from the RFQ, is briefly described below.

RFQ

The 4.55 m long ESS RFQ is a four-vane structure, which bunches and accelerates the beam from 0.075 to 3.62 MeV. The transverse radius of curvature of the vane tips is constant along the RFQ length. The inter-vane voltage varies from 80 to 120 kV along the RFQ length.

MEBT

The MEBT consists of eleven quadrupoles and three bunching cavities to keep the beam focused and matched to the following DTL. To achieve a proper matching, the MEBT also includes diagnostics devices to characterize the beam positions and profiles in all three planes.

DTL

The DTL accelerates the beam from 3.62 to 89.68 MeV in 5 tanks. Permanent Magnet Quadrupoles (PMQs) perform the transverse focusing in a FODO lattice. The “empty” drift tubes are equipped with steerers and beam diagnostics.

SCL

The SCL consists of cryomodules arranged in three sections: the spoke section, the medium and the high beta elliptical sections. Quadrupole pairs that are placed before each cryomodule provide the transverse focusing along the SCL. Thirteen pairs of double spoke cavities with an optimal beta of 0.5 are housed in 13 cryomodules. Nine cryomodules house the medium beta 6-cell elliptical cavities with a geometric beta of 0.67, arranged in groups of four cavities. The high beta section, providing more than 70% of the total energy gain contains 84 five-cell elliptical cavities with a geometric beta of 0.86, also arranged in groups of four.

SIMULATION CODES

DYNAC

The original version of DYNAC [2] was developed by CERN, in collaboration with CEA Saclay. In that version a set of accurate quasi-Liouvillian beam dynamics equations was introduced for accelerating elements, applicable to protons, heavy ions and non-relativistic electrons.

Since then, a numerical method has been added capable of simulating both single and multi-charge state ion beams in accelerating elements. Other additions are an RFQ model and more recently the description of the Radial Matching Section has been improved. Sextupoles, quadrupole-sextupoles, and electrostatic devices as well as the capability of second order calculations for a multi-charge state beam have been added.

DYNAC contains three space charge routines, including a 2D (modified SCHEFF) and a 3D (HERSC) version. The modified SCHEFF routine can perform space charge calculations for a multi-charge state beam with separated bunches.

TraceWin

The TraceWin code [3] is developed and maintained by CEA, Saclay, France. It has the capabilities of envelope (matrix) and multi-particle tracking of protons and heavy-ions.

The usual linac elements are analytically modelled in the code, however, one can also use the field maps (static, and dynamic) for all electromagnetic field configurations. TraceWin contains four space charge routines, including 2D and 3D.

Benchmarking

The benchmarking was performed using a beam of ~50k macro particles. This beam was generated at the input of the RFQ at 4xsigma and transported through it. The output beam is used for all the simulations, except RFQ comparisons.

In the numerical method for accelerating elements in DYNAC, the number of arches in the field is automatically calculated. Bode's method is then used, whereby for this benchmark the number of integration intervals were set to 8 per arch.

The 3D space charge routine is used for all the simulations in TraceWin, with both 25 space charge calculations and beam dynamics steps per βλ, unless otherwise mentioned. The mesh is a cube of 10^3.

SIMULATION RESULTS

Initially benchmarking was done at zero beam current to verify the lattice descriptions are identical. Then each section has been simulated using the beam at its input from TraceWin at full current.

RFQ

For the benchmark with the RFQ, DYNAC results were compared to those obtained with TOUTATIS [3]. The transmission was higher with TOUTATIS than with DYNAC (approximately 98% vs. 93.5% respectively for a higher current of 70 mA). A difference was found in the TOUTATIS description of the input fringe field and RMS region of the RFQ compared to the one in DYNAC. Adding the capability in DYNAC for this region of deriving the fields directly from the electrode shape (as opposed to using the usual coefficients) is now being considered.

MEBT

For the 0 mA case, the largest emittance difference is in the longitudinal plane (0.16%). For the optics functions the largest difference is in the horizontal plane with 1.5% difference in the β functions.

For the 62.5 mA case, the Twiss parameters of the output distributions in the horizontal plane show a difference of 3.7% and 2.6% in emittance and β function respectively and lower values in the vertical plane. In the longitudinal plane the largest difference was in the α function (-0.28 for TraceWin and -0.20 for DYNAC). Fig. 1 shows RMS envelopes for all three planes and their differences between two codes. The agreement at the end is good with the vertical and longitudinal planes showing up to 3% and 5% differences for each at some locations.

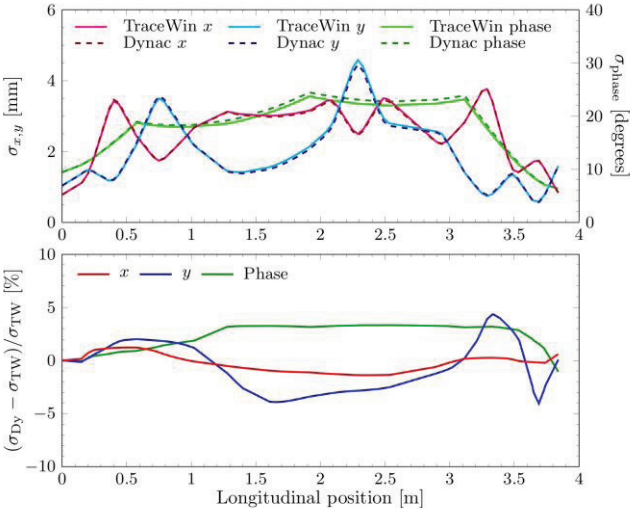

Figure 1: Envelopes and their difference in x, y, and phase in the ESS MEBT at the full current.

DTL

For this case, the CAVSC model was applied in DYNAC, which makes use of the usual transit time factors and their derivatives as well as the 3D space charge model. TraceWin uses zero length gap elements with E_0TL as voltage and derivatives of T. Good agreement is found between the two codes (see table 1).

Table 1: Beam Parameters for the DTL Case

DTL output	α	β (mm/mrad) or (deg/keV)	ε_{rms} (mm.mrad) or (keV.deg)
DYNAC xx'	-3.35	7.54	1.18
TRACEWIN xx'	-3.43	7.77	1.17
DYNAC yy'	1.12	4.46	1.20
TRACEWIN yy'	1.14	4.49	1.20
DYNAC w-ϕ	-0.21	0.033	629.6
TRACEWIN w-ϕ	-0.20	0.033	601.5

SCL

The cavities in both codes are modelled using one-dimensional field maps on the beam axis. The longitudinal and radial fields in the cavities are calculated analytically in each code. It was found that the accuracy of the calculations in TraceWin is improved when the number of calculations is equivalent to the number of steps in the field map file (1000 calculations per βλ). As an example, by changing the number of steps from 25 to 1000 per βλ, the energy gain in the spoke linac changed by more than one per cent.

Table 2: Beam Parameters for the End-to-End Case at the Linac Output

	DYNAC (numerical method)			DYNAC (analytical method)			DYNAC (analytical method, 1k part.)			TraceWin (25 steps per βλ)		
	xx'	yy'	w-ϕ	xx'	yy'	w-ϕ	xx'	yy'	w-ϕ	xx'	yy'	w-ϕ
α	-1.03	0.12	-0.12	-1.09	0.11	-0.10	-1.05	0.22	-0.24	-1.81	0.32	-0.15
β	35.29	26.54	0.0014	36.55	27.19	0.0016	37.68	25.80	0.0015	60.8	44.22	0.0022
ε_{rms}	1.36	1.33	1345	1.26	1.27	1358	1.15	1.26	1323	1.27	1.28	1270

For the 62.5 mA case the 3D space charge routine of DYNAC is used for the comparison with TraceWin. The differences between the two codes are more pronounced at the full beam current, with <9% for the emittances and <14% for the β functions (see Fig. 2).

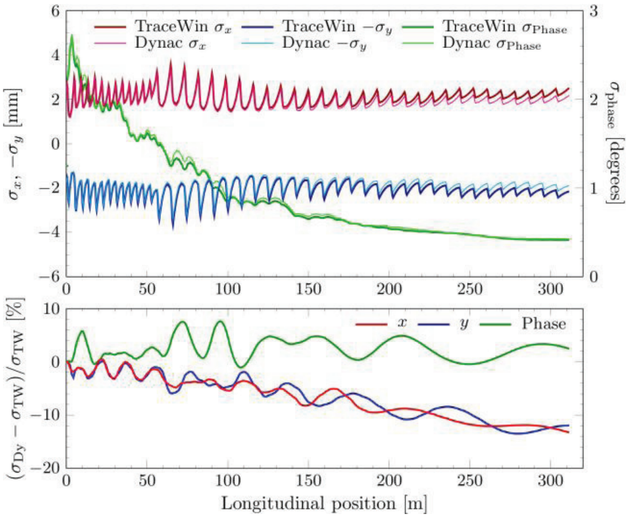

Figure 2: Envelopes and their difference in x, y, and phase in the ESS SCL at the full current.

End-to-End

To check the matching and cumulative effects an "End-to-End" simulation through the MEBT, DTL and SCL was performed with both codes with 50k particles. The results are shown in Table 2 and Fig. 3. In DYNAC, the 2D space charge method was used all along the linac, which partially explains the differences observed: there is a limitation in the 2D space charge model when the bunch does not have rotational symmetry. Better agreement with TraceWin can be achieved by selecting the 3D space charge routine in DYNAC. In addition, the differences observed are affected by the number of steps chosen in TraceWin.

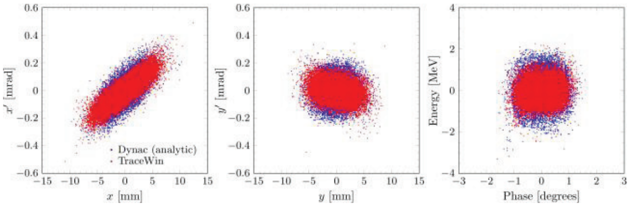

Figure 3: End-to-End output distributions for TraceWin (red) and DYNAC (analytical, blue).

CPU TIME

The CPU times for the End-to-End simulations were compared on a MAC with an Intel Core i7 and a 1600MHz DDR. For DYNAC the CPU time was about 350 s for the numerical method (more than a factor 2 faster than TraceWin) and about 54 s for the analytical method. Reducing the number of particles to 1000, 2.5 s was achieved with DYNAC.

CONCLUSION

A set of simulations with two codes, TraceWin and DYNAC, was performed. Initially this was done with zero current to check the validity of the lattice conversion. Then the simulations were done at the full current, section by section and finally as an end-to-end simulation. The differences, when observed, are within acceptable limits and much lower than the measurement errors we expect.

The CPU times obtained with DYNAC makes this code a good candidate for online modelling.

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ISBN 978-3-95450-142-7