# THE ESS LINAC SIMULATOR: A FIRST BENCHMARK WITH TRACEWIN

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*Abstract*

The ESS Linac Simulator, ELS, will be the core of the online model used in the normal operations of the ESS linac. ESS Linac Simulator will operate through the eXtensible Accelerator Language, XAL, in order to provide an effective interface capable to simulate and predict the beam dynamics of the accelerator. The ELS is capable of simulating the dynamics of the beam envelope in both transverse and longitudinal planes in real time. In order to validate the effectiveness of the physics implemented, the ELS calculations are here benchmarked with TraceWin: the simulation code used for the design of the accelerator.

## INTRODUCTION

In this work the ESS Linac Simulator is compared to the TraceWin code in order to benchmark it. ELS will be part of the ESS control system and it will be used also as a support tool for the design of the accelerator, so the physics implemented in ELS requires a detailed validation. The benchmarking presented here is based on two different cases: the first case analyses the section of ESS containing only the Spoke resonators, while the second case is the study of the full ESS superconducting linac.

The initial conditions used for both cases are collected in the Table 1.

The simulations were performed with and without the space charge respectively with a current of $62.5$ mA and $0$ mA; this choice is used to emphasise the difference between the linear and non-linear dynamics.

## THE ESS LINAC SIMULATOR

The ESS Linac Simulator (ELS) is a code under development that will be included in the OpenXAL project. ELS will be used as the online model for the ESS operations. This implies that the code must be fast and reliable at the same time. A version of ELS for offline multi-particle tracking will also be developed as a tool for the physicist to simulate more sophisticated phenomena.

The elements currently implemented in ELS are the drifts, the bending magnets, the quadrupoles, the high order multipoles up to the dodecapole, the RF cavities and the space charge. The first three elements are described as the usual $6 \times 6$ matrices (pp. 73-75 of [1]); for the bending magnets the edge focusing is also included. The higher order multipoles are evaluated as the multipolar expansion of the magnetic field and the components are:

Sextupole: $x^2 - y^2, 2xy$
Octupole: $x^3 - 3xy^2, 3x^2y - y^3$

Table 1: Beam Parameters

| Parameter | Value |
|---|---|
| Initial Kinetic Energy | 77.63 MeV |
| Beam Peak Current | 62.5 mA |
| Particles per bunch | $1.1 \times 10^9$ |
| Duty Cycle | 4% |
| Freq. before the Medium $\beta$ sect. | 352.21 MHz |
| Freq. after the Medium $\beta$ sect. | 704.42 MHz |
| Horizontal Normalized Emit. | $0.25 \times 10^{-6}$ m rad |
| Vertical Normalized Emit. | $0.25 \times 10^{-6}$ m rad |
| Longitudinal Normalized Emit. | $0.33 \times 10^{-6}$ m rad |
| Optimal $\beta$ in Spokes | 0.50 |
| Geometrical $\beta$ in Medium $\beta$ sect. | 0.65 |
| Geometrical $\beta$ in High $\beta$ sect. | 0.86 |

Decapole: $x^4 - 6x^2y^2 + y^4, 4x^3y - 4xy^3$
Dodecapole: $x^5 - 10x^3y^2 + 5xy^4, 5x^4y - 10x^2y^3 + y^5$

The space charge force is evaluated for a 3D Gaussian beam: for each step the dynamics the three $\sigma$ of the beam are evaluated according to the size of the $\beta$ function and the emittance. The kick of the space charge is computed and applied as a non-linear force. The description of the space charge force is in [2].

The RF cavity is modelled as a sequence composed by a drift followed by a thin accelerating gap and another drift. The matrix of the accelerating gap is obtained using the equation of motion (7.38) and (7.39) p. 209 of [3] normalising the determinant to the ratio of the energy before and after the cavity: $|\mathrm{Gap}| = \frac{(\beta\gamma)_{\mathrm{after}}}{(\beta\gamma)_{\mathrm{before}}}$.

## A SINGLE ACCELERATING STRUCTURE

The first sequence considered for the benchmarking is the one of the Spoke resonators. This section is composed by 30 accelerating structures for a total length of 61 m. The beam accelerates from 77.6 MeV up to 222.6 MeV. The RF frequency is fixed at 352.21 MHz.

### *Without Space Charge*

The two codes, ELS and TraceWin, are compared in the $I = 0$ mA case and the envelope of the beam in the 3 planes is shown in Fig. 1.

There is a perfect agreement between the two simulators: this is due to the implementation of the linear elements that is probably identical in the two codes, generating the same output starting from the same initial conditions.

### *With Space Charge*

When the current is set up at its nominal value of 62.5 mA the space charge shows its effect on the particles and the resulting envelopes are in Fig. 2.

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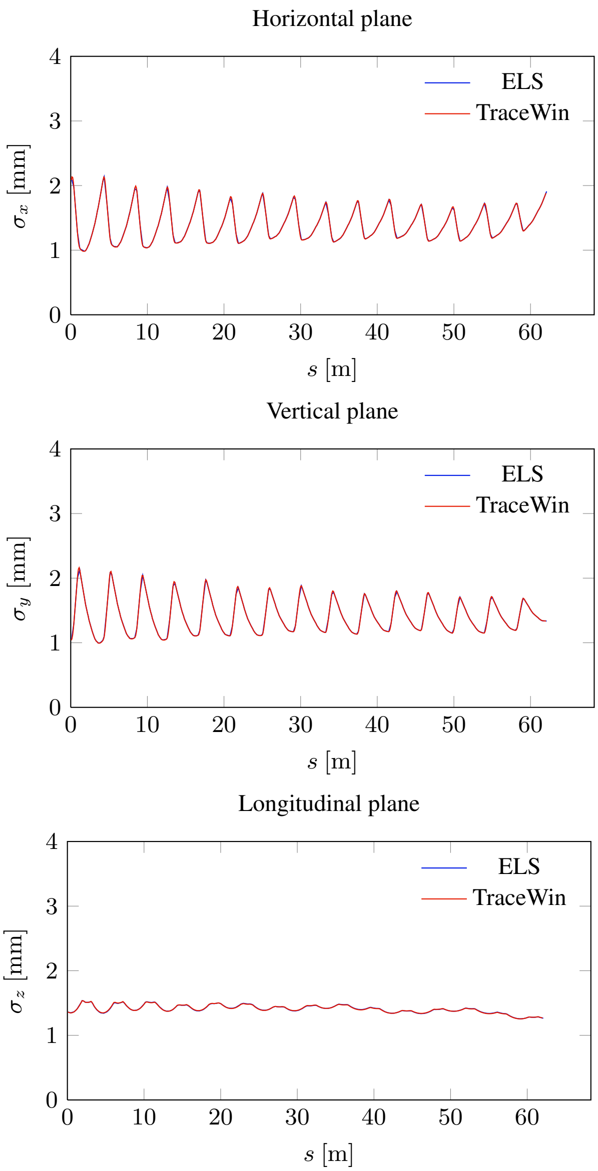


Figure 1: Simulation of the ESS Spoke section with ELS and TraceWin without the space charge ($I = 0$ mA).

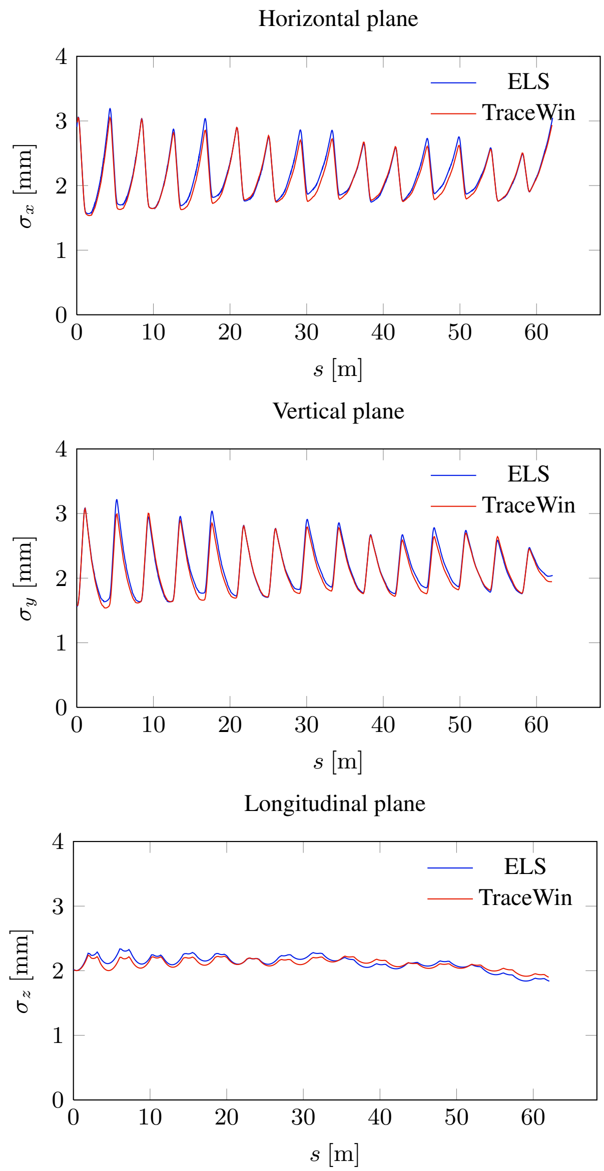


Figure 2: Simulation of the ESS Spoke section with ELS and TraceWin with the space charge ($I = 62.5$ mA).

In this comparison it is possible to appreciate a small difference between the two codes: the larger discrepancy, located on the longitudinal plane, is 5% while the average difference in the three planes is below 2%.

The difference between the two simulators is probably produced by the different models used for the space charge: TraceWin assumes an uniform distribution of the particles in a 3D ellipsoid while ELS uses a 3D Gaussian distribution.

## ESS SUPERCONDUCTING LINAC

The good agreement obtained in the Spoke section shows that the two codes are implementing the same physics (with some differences in the space charge model). A full simulation of the superconducting linac is then possible: the accelerator is here composed by 150 accelerating structures (30 from the Spoke section and 120 from the elliptical cavities). The total length is 310 m and the energy goes from 77.6 up to 2000 MeV. The dynamic is complicated by the RF frequency jump between the Spokes and the elliptical cavities: it doubles from 352.21 to 704.42 MHz.

### *Without Space Charge*

The ESS superconducting linac simulated without the space charge is shown in Fig. 3.

As for the previous case, the Spoke section, the two codes are in perfect agreement.

### *With Space Charge*

With the space charge it is possible to see a difference between ELS and TraceWin especially on the longitudinal dynamics. The results are summarised in the Fig. 4. The difference due to the space charge creates a mismatch of


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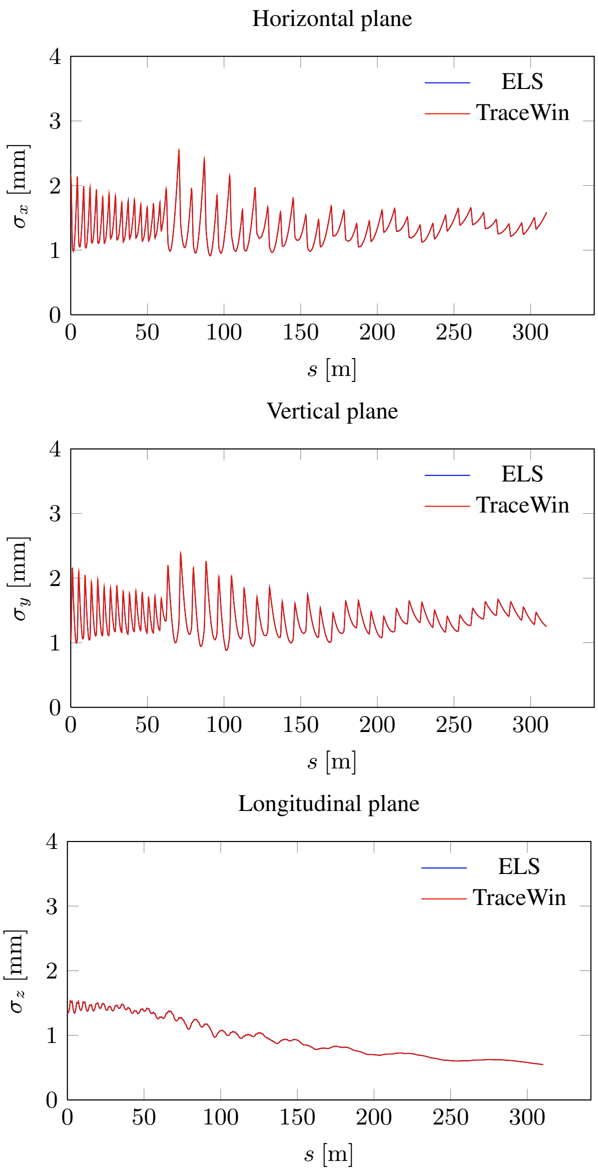


Figure 3: Simulation of the ESS Superconducting linac with ELS and TraceWin, without the space charge ($I$ = 0 mA).

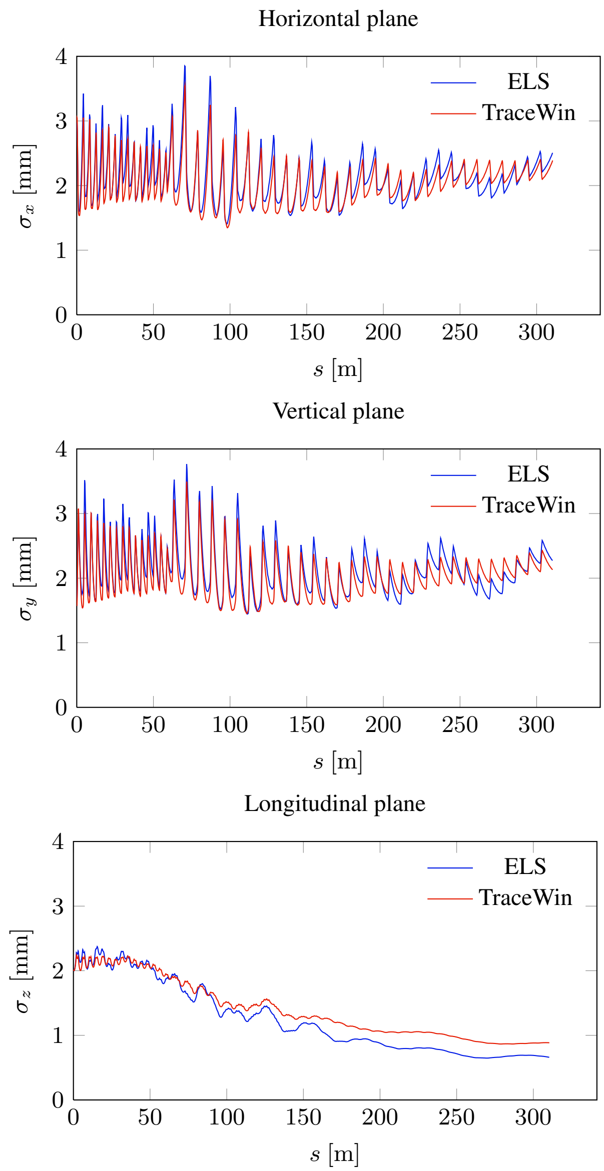


Figure 4: Simulation of the ESS Superconducting linac with ELS and TraceWin, with the space charge ($I$ = 62.5 mA).

the beam that propagates with a beating that is clearly visible in both horizontal and vertical plane. Such mismatch is amplified in the longitudinal plane by the frequency jump between the low and high $\beta$ sections, producing a difference of 20% in the worst case and 11% in average.

## CONCLUSION

The ESS Linac Simulator shows results in good agreement with TraceWin. The differences due to the space charge can be mitigated rematching the initial conditions of the beam in ELS: for the purpose of this paper the initial conditions of the beam were matched with TraceWin and used unchanged in ELS. This generate a beam that is well adapted for an elliptical space charge force but not for the Gaussian force.

The space charge model can be improved with a Particle-In-Cell code detaching the model from the Gaussian distribution.

The RF cavities can be simulated with a model based on the field maps as proposed in [2] that takes into account the strong non-linear behaviour of the ESS cavities.

## REFERENCES

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