BENCHMARKING OF SIMULATION CODES TRACK AND ASTRA FOR THE FNAL HIGH-INTENSITY PROTON SOURCE *

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Abstract

The FNAL High-Intensity Proton Source is an 8-GeV superconducting H^- linac conceived with the primary mission of increasing the intensity of the Main Injector for the Fermilab neutrino program. The main tool used for the design of the accelerator is the beam dynamics code TRACK developed by Argonne National Laboratory to fulfill the requirements of proton and heavy-ion linacs. ASTRA, developed by DESY (Hamburg, Germany) and mainly used for the design of electron photo-injectors, also offers the possibility to simulate acceleration of hydrogen ions. This paper presents benchmarking of TRACK and ASTRA.

INTRODUCTION

Major components of the 8-GeV H^- linac are an ion source, an RFQ (exit energy ~2.5 MeV), 18 room-temperature spoke resonators (~10 Mev) , 51 superconducting (SC) single-spoke resonators (~210 MeV), 42 SC triple-spoke resonators (~420 MeV), 56 squeezed ILC type cavities (~1.2 GeV) and 287 ILC-type cavities (~8 GeV). The remarkable feature of this accelerator is the small number of klystrons (11 in the baseline design) used to power the independently phased SC resonators. The operating frequency is 325 MHz up to 420 MeV and 1300 MHz beyond for a total length of ~678 meters. A detailed description of the current lattice is presented in [1].

CODES DESCRIPTIONS

The general equation of motions for a particle in an electromagnetic field are :

$$\frac{d\vec{r}}{dt} = \frac{\vec{p}}{m_0\gamma} \quad ; \quad \frac{d\vec{p}}{dt} = q(\vec{E} + \frac{\vec{p}}{m_0\gamma} \times \vec{B}) \qquad (1)$$

with $\vec{r}$ the particle coordinate, $\vec{p}$ the mechanical momentum, $\gamma = \sqrt{1-\beta^2}$, $\beta = v/c$, v and c particle and light speed, q and m_0 charge and rest mass of accelerated particle and $\vec{E}$ and $\vec{B}$ the electric and magnetic fields. Both codes TRACK [2] and ASTRA [3] perform the integration of Equations 1 by the Runge-Kutta method of forth order with a variable time step for TRACK and fixed time step for ASTRA. The fields $\vec{E}$ and $\vec{B}$ include external contribution from accelerating and focussing fields and internal from the beam space charge forces .

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Space Charge Fields

For the simulations presented in this paper, the space-charge forces were computed using the 3D space charge calculation available in TRACK and ASTRA. For both codes, the space-charge fields are calculated in the beam rest frame via Poisson's equation :

$$\nabla^2\phi(r,\theta,z) = -\frac{\rho(r,\theta,z)}{\epsilon_0} \qquad (2)$$

with ϕ the electrostatic potential, ρ the charge density, ϵ_0 the dielectric constant and Lorentz's transformed back into the laboratory frame. A 3D cartesian grid is used for both codes with the calculation of the electrostatic potential at each grid points. On the boundaries, TRACK considers ideal parallel conducting walls transversely and free-space longitudinally while ASTRA solves the Poisson's equation in free-space.

Figure 1 shows the excellent agreement between analytical longitudinal space charge field of a three-dimensional uniform ellipsoid filled with 500k particles of unit charge (with semi-axis length of 1 cm transversely and 2 cm longitudinally) and the simulation codes TRACK and ASTRA. Reference [4] shows that at the conditions of negligible image charge effects and properly setting up of the 3D space charge routine, both codes give similar space charge fields for similar input distribution.

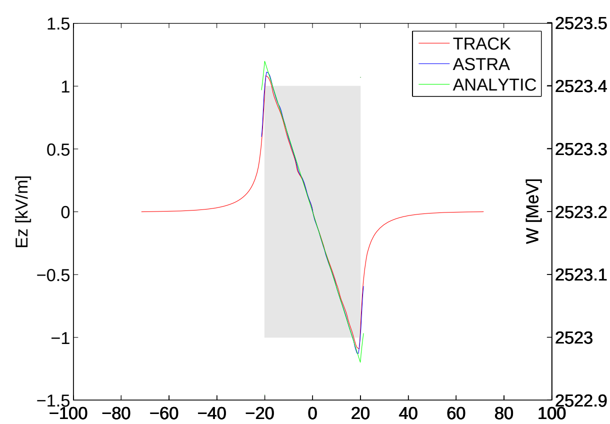

Figure 1: Longitudinal electric field of an uniform ellipsoidal bunch from TRACK, ASTRA and analytical method. The gray box represents the longitudinal phase space (right axis).

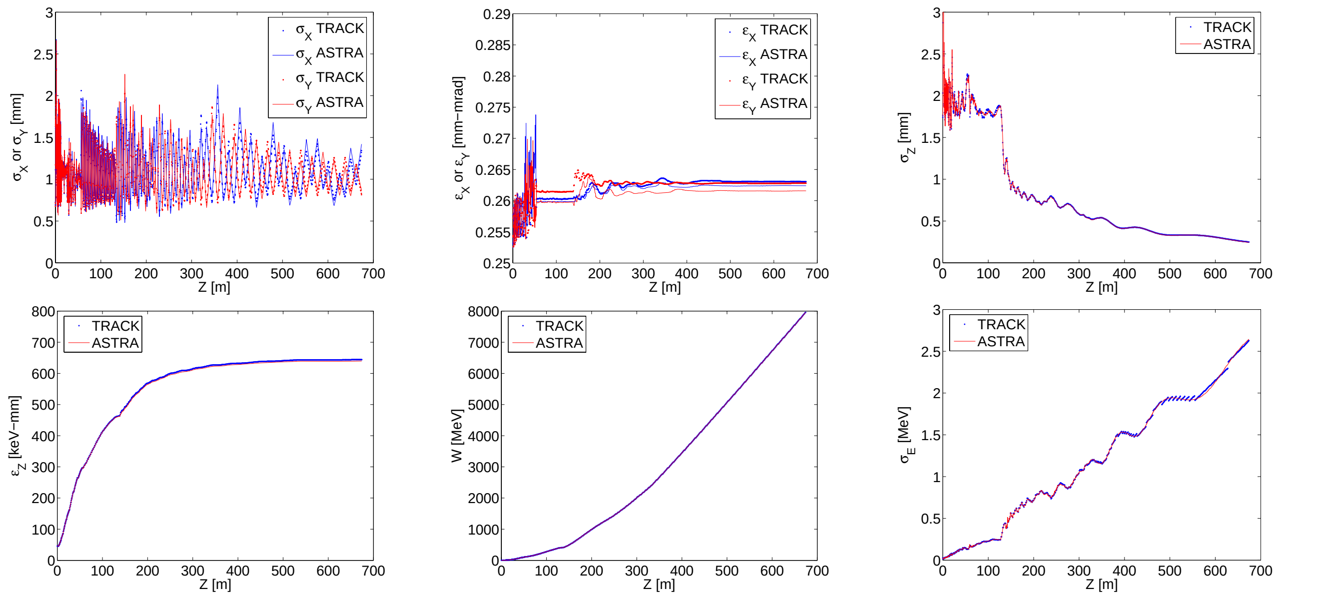

Figure 2: TRACK and ASTRA simulations of the High-Intensity Proton Source for Zero Current, from the RFQ exit to the last accelerating cavity. From top left to bottom right : transverse RMS size, transverse RMS normalized emittance, RMS bunch length, longitudinal RMS normalized emittance, kinetic energy and RMS energy spread.

CODES COMPARISONS

Benchmarking of TRACK and ASTRA is presented in this paper from the exit of the RFQ to the end of the accelerating section (total lentgh of ∼674.1 m) and for two beam currents : zero current and 43.25 mA. An identical initial particle distribution (provided by P. Ostroumov, ANL) of 10k and 200k particles for respectively the zero current and the 43.25 mA cases were supplied for both codes. Table 1 shows the beam parameters issued from each initial distribution.

Table 1: Initial beam parameters (at $z = 0$ m, RFQ exit).

Beam parameters	Zero Current	43.25 mA
RMS size σ_X	0.71 mm	0.74 mm
RMS size σ_Y	0.69 mm	0.72 mm
Norm. RMS emittance ϵ_X	0.25 mm-mrad	0.25 mm-mrad
Norm. RMS emittance ϵ_Y	0.26 mm-mrad	0.25 mm-mrad
RMS bunch length σ_Z	1.75 mm	1.85 mm
Norm. RMS emittance ϵ_Z	45.9 kev-mm	25.6 kev-mm
Kinetic Energy W	2.51 MeV	2.52 MeV
RMS energy spread σ_E	28.6 keV	17.8 keV

Zero Current

The zero current case enables code benchmarking without space charge. Both codes were provided identical 3D electric map fields for each one of the 454 cavities. TRACK used 3D magnetic map fields for each one of the 55 solenoids while only the magnetic field on axis for these solenoids was provided to ASTRA. In fact, the current version of ASTRA does not support 3D magnetic field maps. Figure 2 shows TRACK and ASTRA simulations of the FNAL High-Intensity Proton Source for a zero current lattice. Table 2 reports the beam parameters at the end of the simulations.

Table 2: Final TRACK and ASTRA outputs for zero current.

Beam parameters	TRACK	ASTRA
RMS size σ_X	1.34 mm	1.39 mm
RMS size σ_Y	0.82 mm	0.86 mm
Norm. RMS emit. ϵ_X	0.263 mm-mrad	0.259 mm-mrad
Norm. RMS emit. ϵ_Y	0.263 mm-mrad	0.260 mm-mrad
RMS bunch length σ_Z	0.248 mm	0.248 mm
Norm. RMS emit. ϵ_Z	644 kev-mm	642 kev-mm
Kinetic Energy W	7957 MeV	7955 MeV
RMS energy spread σ_E	2626 keV	2633 keV

The transverse emittance reported in Figure 2 and Table 2 appears slightly (∼2%) lower in ASTRA than in TRACK and the transverse spot size is few percent different between the codes. Longitudinally, the agreement between the codes is excellent. In fact, for a zero current case the transverse and longitudinal beam dynamics are decoupled and the transverse disagreement between the codes is most likely due to a difference between the ASTRA decomposition of the solenoid magnetic fields and the TRACK 3D map fields.

43.25 mA

The 43.25 mA case represents the necessary RFQ output peak current to provide $1.56{\cdot}10^{14}$ protons per cycle to the

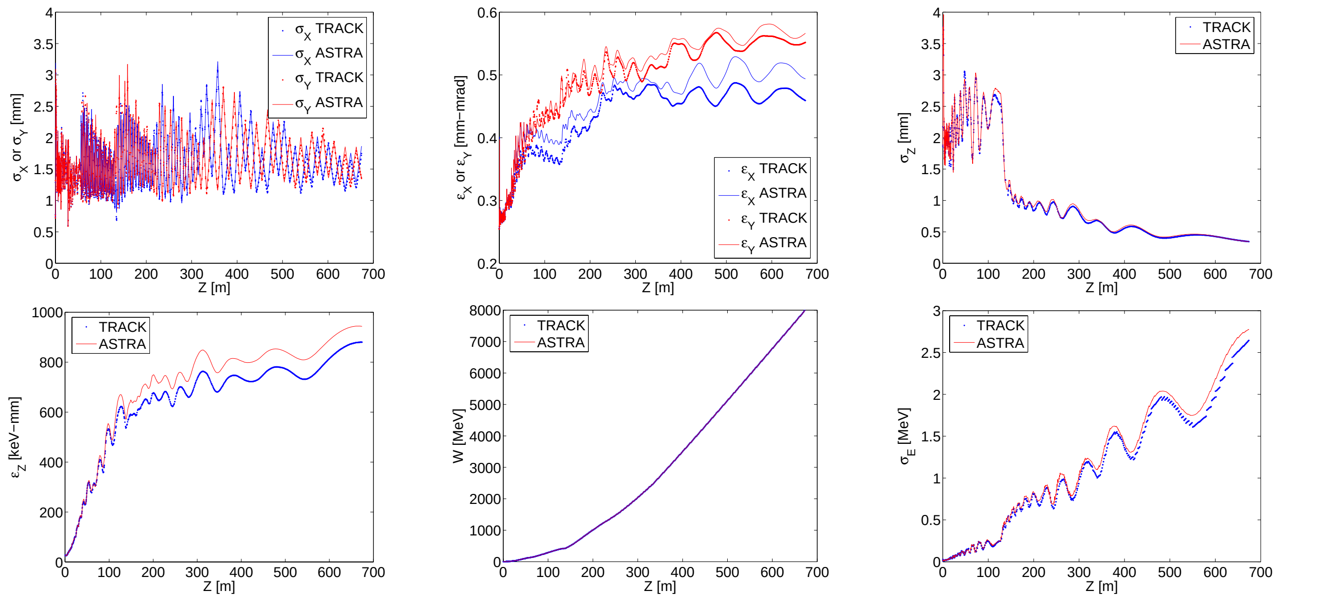

Figure 3: TRACK and ASTRA simulations of the High-Intensity Proton Source with 43.25 mA peak current, from the RFQ exit to the last accelerating cavity. From top left to bottom right : transverse RMS size, transverse RMS normalized emittance, RMS bunch length, longitudinal RMS normalized emittance, kinetic energy and RMS energy spread.

FNAL Main Injector, corresponding to 2 MW beam average power at 8 GeV for a repetition rate of 10 Hz. Figure 3 presents TRACK and ASTRA simulations for 43.25 mA, from the RFQ exit to the last accelerating cavity and Table 3 outputs at the end of the simulations. For space charge calculations, a grid of 64×64×64 was implemented into ASTRA and an adjustable grid of 65×65×129 for the first two cavities, 65×65×65 in the SC single-spoke resonator section and 129×129×65 beyond into TRACK. Figure 3 and Table 3 report that the transverse beam dynamics agrees within 10% between both codes and, as previously mentioned, solenoid magnetic fields might explain this disagreement. In contrast to the zero current case, some disagreement (∼10%) concerning longitudinal beam dynamics occurs at 43.25 mA, starting mainly from the exit of the Triple-Spoke Resonators (∼137 m) where the frequency jumps from 325 MHz to 1300 MHz and the bunch length shrinks by a factor ∼2. The longitudinal disagreement is more pronounced for the energy spread and longitudinal emittance than the bunch length. More simulations [5] are necessary to understand this disagreement.

CONCLUSIONS

Beam dynamics simulations of the FNAL High-Intensity Proton Source using TRACK and ASTRA have been presented in this paper, for zero current (space charge off) and 43.25 mA (using 3D space calculations). The simulations were performed on a length of ∼674.1 m, from the exit of the RFQ (∼2.5 MeV) to the last ILC-type accelerating cavity (∼8 GeV). A good agreement (within 10%) was found between both codes.

Table 3: Final TRACK and ASTRA outputs for 43.25 mA.

Beam parameters	**TRACK**	**ASTRA**
RMS size σ_X	1.75 mm	1.86 mm
RMS size σ_Y	1.35 mm	1.34 mm
Norm. RMS emit. ϵ_X	0.46 mm-mrad	0.49 mm-mrad
Norm. RMS emit. ϵ_Y	0.55 mm-mrad	0.57 mm-mrad
RMS bunch length σ_Z	0.34 mm	0.34 mm
Norm. RMS emit. ϵ_Z	880 kev-mm	943 kev-mm
Kinetic Energy W	8014 MeV	8010 MeV
RMS energy spread σ_E	2644 keV	2773 keV

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