Start-to-end simulation of TAC SASE FEL facility

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Abstract. We study start-to-end simulation of the proposed Turkish Accelerator Center (TAC) Self Amplified Spontaneous Emission (SASE) Free Electron Laser (FEL) Facility. Astra Code is used to simulate the electron gun, including space charge effects and Elegant Code is used to track particle distribution from the accelerator modules through the entrance of the undulator including weak fields but not including space charge effects. Undulator optimization is performed using Genesis 1.3. In this study, tentative electron beam and laser parameters of the SASE FEL Facility are given.

1. Introduction
The goal of the Turkish Self Amplified Spontaneous Emission Free Electron Laser (TAC SASE-FEL) Project is to provide a source of bright, coherent, and tunable free electron laser light that enables diverse range of application areas from science to industry. The project aims to cover VUV to soft X-Ray region with an electron beam energy 1 GeV. Throughout the paper, start-to-end simulation studies of the project is explained in a detailed way. From the electron gun until the end of the undulator, three main programs Astra [1], Elegant [2], and Genesis 1.3 [3] are used, where in between, two interface programs and converters (astra2elegant and elegant2genesis) take care of the outputs from previous program and prepare it for the next one respectively. SDDS (Self Describing Data Set) [4] and IDL (Interactive Data Language) [5] are used in order to display the graphical outputs of the simulations.

2. Beam Dynamics and Start-To-End Simulations
For the start-to-end simulation of the Proposed Facility, 1 GeV electron beam energy with photocathode RF gun and superconducting linac is considered. TAC SASE-FEL Facility layout is displayed in Figure 1.

Figure 1. Proposed SASE-FEL Facility Layout
Beam parameters for the proposed SASE-FEL Facility are shown in Table 1. Astra is used to simulate the beam dynamics from the cathode up to the end of the first linac module. In the SASE-FEL system, accelerating RF field with 1.3 GHz gun is considered for modelling. Some important Astra features are given below:

- Astra is nominally cylindrically symmetric code,
- Astra tracks the particles by taking into account space charge, thus charge in time, current behaves like the Gaussian shape statistically,
- Astra does not consider weak-field effects.

**Table 1. Proposed Beam Parameters for SASE FEL Facility.**

| Parameter             | Unit  | Value |
|-----------------------|-------|-------|
| Electron beam energy  | GeV   | 1     |
| Bunch charge          | nC    | 1     |
| Normalized emittance  | πmm.mrad | < 2  |
| Transverse emittances | Nm    | 3.2   |
| FWHM bunch length     | μm    | 150   |
| Peak current          | kA    | 2     |
| Energy spread         | -     | < 0.02|
| Macropulse Repetition Rate | Hz  | 10    |

By using Astra - Ps Viewer [6] interface codes, particles are simulated after being released from the gun. Bunch current is shown in Figure 2 for 2 nC charge and 100000 particles.

**Figure 2.** Longitudinal current profile along the bunch
Behaviour of the bunch current is Gaussian shape as expected starting from the cathode. An initial bunch was produced with both the gun and linac operating on-crest with gun’s solenoid peak field of 0.226 T. Figure 3 shows the evolution of rms parameters throughout the beamline. Beam emittance, beam size, bunch length, energy spread, particle velocity etc versus the longitudinal beam position are displayed. In the first plot, horizontal and vertical emittances are shown along the z-axis. Beam starts to emit after cathode warm up. In the second graph, a constant emittance is not achieved because of the high solenoid field. There is one solenoid in the RF gun around 0.1 m, but emittance seems diverging around 0.4 m. In order to prevent the divergence, one can reduce solenoid magnetic field.

![Figure 3. Astra results - evolution of rms beam parameters along the beamline.](image)
3. Linac Beam Dynamics Simulations and Laser Optimizations
SASE-FEL start-to-end simulations are performed using Elegant and Genesis 1.3 for linear accelerations and undulator sections respectively.

3.1. Particle Tracking with Elegant
Once the Astra output is obtained, the bunch is converted and fed into Elegant for tracking through the linac and the bunch compressors. Elegant uses six dimensional phase space. These are transverse coordinates, slopes, total-equivalent distance travelled, fractional momentum deviation. Elegant code includes RF magnet, wakefield effects, all strength parameters, power supplies, electrical connectors, accelerators, quadrupoles, dipoles and drift properties. In Elegant simulation, graphical outputs are obtained using SDDS interface. Figure 4 can be obtained directly from Elegant by using SDDS. This figure shows the twiss parameters to explain beam ellipses (horizontal and vertical beta functions) without matching.

![Figure 4. Beta function along the beamline](image)

Between two lattice locations, transfer matrix for twiss parameters is given by beta, alpha, and gamma. Red shows $\beta_y$ while black shows $\beta_x$. To get the size of the particle bunch, we determine the beta function. One can get transverse beam size by using the $\sigma = \sqrt{\text{emittance}} \times \beta / \gamma$. Although superconducting type of accelerator is foreseen for the proposed facility simulations, both superconducting and normal conducting type of accelerator parameter sets are given in the following table because normal conducting accelerator case is yet not out of consideration.

| Parameter                | Tesla Structure | S Band Linac |
|--------------------------|-----------------|--------------|
| Frequency (GHz)          | 1.3             | 3            |
| Gradient (MV/m)          | 30              | 30           |
| Input Power (MW)         | 10              | 35           |
| Pulse Length (\(\mu\)s) | \(~ 10\)        | \(~ 10\)     |
| Number of Structure      | 35              | 12           |
| Linac Length (m)         | \(~ 100\)       | 45           |
3.2. Undulator and Laser Optimization

Hybrid with Iron [7] is chosen as undulator material because it produces the magnetic field that enables coverage from VUV to soft X-Ray. Undulator gap is very important for lasing; smaller gap, lower current or smaller volume of magnetic material is needed to reach a given magnetic field. In vacuum undulator studies and for seeding HHG, HGHG possibilities are still understudy. One and three dimensional gain length, saturation power and beam power are both analytically calculated and simulated using Genesis 1.3 Code. Genesis can be used for steady-state and time dependent FEL simulations. Lattice, electron beam, radiation field steps are needed to figure out propagation of the beam. The external magnetic field input file has four sections: as ID, Strength, length, and offset to the previous element. Radiation power, ponderomotive phase, radiation growth rate, energy, growth of bunching, radiaton size, vertical and horizontal sigma are obtained by using IDL (see Figures 5 and 6).

Proposed SASE-FEL Facility laser parameters are shown in the Table 3.

| Laser Parameters                      |       |
|---------------------------------------|-------|
| Wavelength Range (nm)                 | 3 – 60|
| Maximum Peak Power (GW)               | 1.3   |
| Peak Brilliance (photons/s/mrad²/mm²/0.1%bw) | ~10²⁹ |
| Peak Energy (µJ)                      | 130   |

**Figure 5.** End of the undulator, laser properties (power, growth, energy, and bunching) as a result of Genesis 1.3.
The growth rate tends to decrease after 20 m, this can be explained by the electron motion and with its period length. In Genesis 1.3, we consider 1 GeV electron beam energy with Rayleigh range $1.2916 \times 10^2$ m and current peak of $2 \times 10^3$ A with a slice of 8192. As a result of Genesis 1.3 Code, we have obtained saturation power as $1.3977 \times 10^9$ W with a Saturation length 21.48 m.

![Figure 6](image)

**Figure 6.** Laser properties (photon beam size and sigma) as a result of Genesis 1.3.

As a result, simulation studies for the Proposed SASE-FEL Facility continue. In the future, seeding properties and some other new features that can give shorter wavelengths to cover soft x-ray region will be included.

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