

MODELING AND OPTIMIZATION OF THE APS PHOTO-INJECTOR USING OPAL FOR HIGH EFFICIENCY FEL EXPERIMENTS*

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Abstract

The Linac Extension Area (LEA) is a new beamline planned as an extension of Argonne's APS linac. An S-band 1.6-cell copper photo-cathode (PC) RF gun has been installed and commissioned at the APS linac front end. The PC gun will provide a beam to the LEA for accelerator technology development and beam physics experiments, in interleaving with a thermionic RF gun which provides a beam for APS storage ring operations. Recently an experiment was proposed to demonstrate the TESSA high-efficiency concept at LEA. In support of this experiment, we have begun simulating the photo-injector using the code OPAL (Object-oriented Particle Accelerator Library). In this paper, we first benchmark OPAL simulations with the established APS photo-injector optimization using ASTRA and ELEGANT. Key beam parameters required for a successful high-efficiency TESSA demonstration are discussed.

OVERVIEW

The Advanced Photon Source (APS) linac provides electrons at up to 500 MeV for operation of the APS storage ring. The end of the APS linac beamline has been extended to create a new beamline called the Linac Extension Area (LEA) that will be fed by an alternate photo-injector operating in-between top-up cycles for the synchrotron. The LEA beamline will serve as an area for performing a variety of experiments requiring flexible, high-brightness electron beams.

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The Tapering Enhanced Stimulated Superradiant Amplification (TESSA) concept [1] is a novel FEL scheme that allows for extremely high extraction efficiencies (as much as 50%). Design of an undulator to test the TESSA concept at 266 nm is underway, with plans to perform a proof-of-principle experiment at the LEA beamline.

We will discuss simulation studies of the photo-injector and APS linac to ensure that sufficient beam quality can be achieved to meet requirements for TESSA. We first show comparisons between the code ASTRA, previously used for the injector modeling, and OPAL, which is now being used. We then look at the electron beam requirements for TESSA and some of the challenges to meeting these requirements.

LEA and the APS Linac

The APS linac, shown in Fig. 1, serves as the start of the accelerator chain feeding the APS light source. When operating in this capacity a thermionic rf gun (RG2) is used, electron bunches are accelerated to 450 MeV in the linac and fed into the booster. During normal top-up operation the linac is only used for twenty seconds every two minutes. During the downtime on this interval the linac will be used to feed electron bunches from the photocathode gun (PCG) to the Linac Extension Area (LEA). The timing structure for LEA/APS operation is shown in Fig. 2.

Beam from the PCG will reach the L2 linac at 40 MeV where it will then be using the same lattice as beam from thermionic guns. Previous efforts at APS have optimized lattice settings that can accommodate the disparate properties of both PCG and RG2 beams [2]. From L2 the beam is

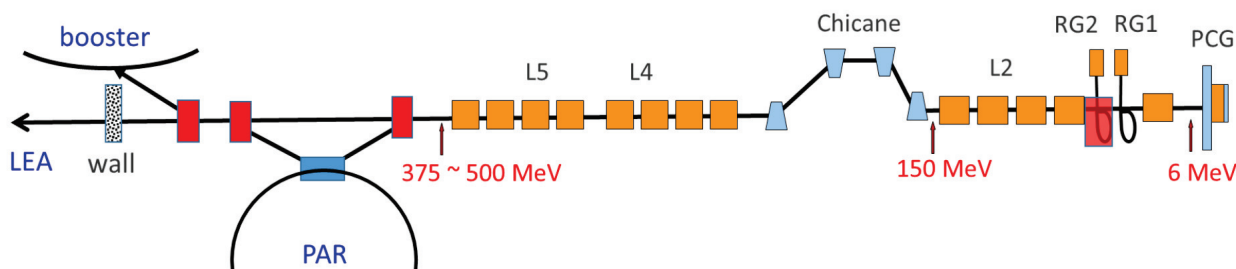


Figure 1: Schematic of the APS beamline showing the thermionic rf guns (RG1 and RG2), photocathode gun (PCG), accelerating sections (L2, L4 and L5), and Linac Extension Area (LEA) at the end of the beamline.

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accelerated up to 150 MeV before reaching the compression chicane and followed by the L4 and L5 linacs sections which can provide a final energy of 375 MeV to 500 MeV. Beam from the PCG will bypass the PAR and Booster and enter the LEA beamline section at the end of the linac. There will be a several meter space for experimental device setup upstream of a dipole spectrometer and beam dump. Expected parameters for the electron beam at LEA are shown in Table 1.

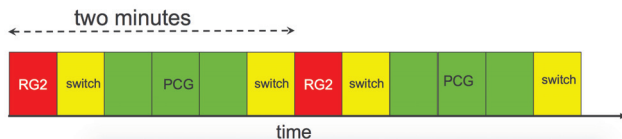


Figure 2: Timing structure for photocathode gun (PCG) and thermionic gun (RG) interleaving operation.

Table 1: Beam Parameters of the LEA Beamline

Property	Value
Energy	< 500 MeV
Energy Spread	250 keV to 500 keV
Bunch Charge	50 pC to 500 pC
Emittance (Normalized)	0.5 μm to 1.5 μm
Bunch Length	100 fs to 1000 fs

MODELING THE PHOTO-INJECTOR

The photocathode injector is an S-band, LCLS-type gun [3], capable of a peak field of 120 MV/m. It is powered by Nd:glass laser which provides pulses with an rms length of 2 ps to 4 ps. Nominal beam energy out of the injector is ~ 5 MeV, immediately following the injector is an accelerating section that brings the beam up to ~ 40 MeV. In this initial portion of the beamline, where space charge effects are particularly important simulations have previously been performed in ASTRA [4]. In the following section we discuss implementation of the injector in OPAL and show compare to the previous ASTRA model.

OPAL

The Object-Oriented Parallel Accelerator Library (OPAL) is a framework for modeling charged particle optics in particle accelerators [5]. Though OPAL comes in several flavors, we use version 1.4.0 of OPAL-T in all work shown here. OPAL-T is time based tracking code that includes a fully 3D particle-in-cell implementation of space charge, with an integrated Green's function Poisson solve. Space charge is calculated in the electrostatic approximation in a comoving frame with the bunch.

Many common accelerator elements are included in the code and beamlines may be constructed using a MAD-like syntax. Electrostatic, magnetostatic, and electrodynamic

fields may be specified in several 1D or 2D formats. Especially important for the work shown here, OPAL-T includes a 1D coherent synchrotron radiation model, based on Saldin *et al.* [6]. While this model is only valid in the ultra-relativistic approximation this should not pose an issue for modeling the APS linac, as the chicane is at a beam energy greater than 100 MeV. Wakefunctions may be imported in SDDS format for calculation of short-range, transverse and longitudinal wakefields.

Benchmarking OPAL-T with ASTRA

Our initial work required conversion of the prior ASTRA model of the injector and L1 accelerating section over to OPAL-T. The benchmark shown here begins at the photo-injector and run to the entrance of L2 in Fig. 1. To provide an equivalent comparison an externally defined 1000-macroparticle bunch was used in both simulation versions. The space charge solve in OPAL-T was carried out on a $32 \times 32 \times 32$ grid with open boundaries in all dimensions.

The beam energy gain through the injector and L1 accelerating section are shown in Fig. 3. It should be noted a $\sim 20\%$ adjustment of the L1 phase specified in ASTRA was required to bring the two results in agreement. This adjustment also corrected previously observed differences in curvature in the longitudinal phase space. The normalized transverse emittances and rms sizes along the accelerator are shown in Fig. 4. Because ASTRA provides emittance calculated with the canonical momentum while OPAL-T does not by default there is large discrepancy between the two in the injector solenoid field. Finally, Fig. 5 compares the bunch length and rms energy spread.

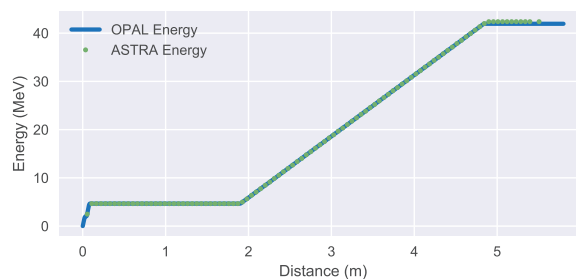


Figure 3: Average bunch energy along the beamline from OPAL and ASTRA.

Overall, extremely good agreement between the two codes is seen in all parameters. This provides confidence in the transition from ASTRA to OPAL-T moving forward with start-to-end studies. As part of this effort work is currently underway to extend the OPAL-T model past the end of the bunch compression chicane. This will allow modeling that fully captures any lingering space charge effects. Because the linac does not include any correction for longitudinal curvature, compression will likely yield a non-uniform current with a large spike at the head. This will exacerbate CSR [7] and together with longitudinal space charge effects may produce energy fragmentation [8].

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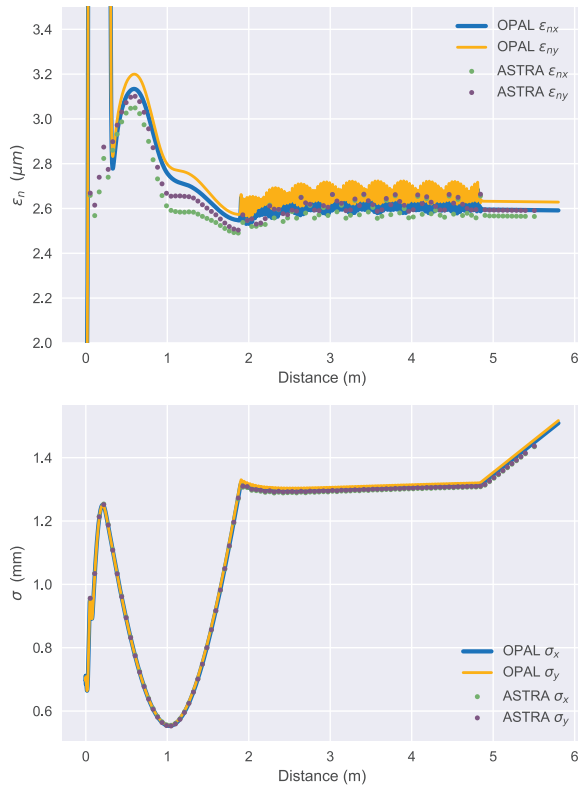


Figure 4: Top: The normalized transverse emittance along the beamline from OPAL and ASTRA. Bottom: The rms spot size of the bunch.

ELECTRON-BEAM REQUIREMENTS FOR TESSA

The nominal electron beam parameters from the LEA photo-injector should be able to easily achieve requirements, shown in Table 2, necessary for the 266-nm TESSA experiment. Even with degradation from effects such as CSR the transverse emittance at the undulator should remain below the 2- μm requirement.

Table 2: Beam-Quality Requirements at the Undulator Entrance for the TESSA Experiment at LEA

Property	Value
Energy	300 MeV
Energy Spread	0.02 % to 0.1 %
Peak Current	1 kA
Emittance (Normalized)	2 μm
spot size (rms)	30 μm to 40 μm
$\beta_{x,y}$	0.54 m to 1 m

The biggest foreseeable challenge is meeting the required peak current with a sufficient fraction of the bunch and min-

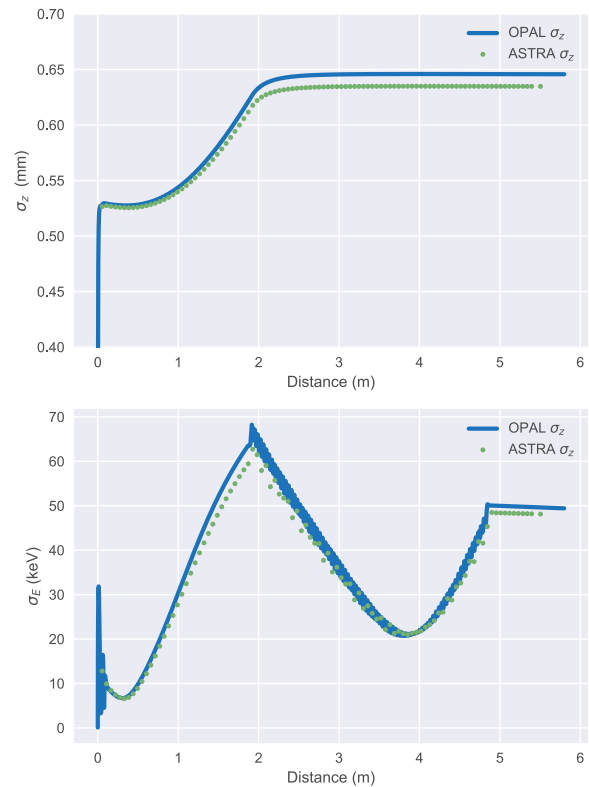


Figure 5: Top: The rms bunch length along the beamline from OPAL and ASTRA. Bottom: The rms energy spread of the bunch.

imal adverse effects to the energy distribution of the bunch. Because the APS linac does not have a linearizer, nonlinear effects – T_{655} from the rf and T_{566} in the chicane – will create a curved longitudinal phase space distribution with a large spike in the current, as exhibited in Fig. 6. This will result in larger uncorrelated energy spread at the high-current portion of the bunch. Furthermore, collective effects from this short, high-current region may spoil the energy distribution and interfere with the prebunching required for TESSA. Modeling of the linac in OPAL-T past the end of the compressor is underway in order to better understand what may be done to mitigate these problems.

CONCLUSION

Planning is underway to use the new LEA beamline area at the APS linac to test the high efficiency FEL concept TESSA. In preparation for this experiment start-to-end modeling of the linac and LEA beamline is underway. As part of this effort modeling of the linac photo-injector is being performed with the code OPAL. Comparisons of OPAL to previous simulations in ASTRA have shown excellent agreement. Work is now being carried out to further extend the OPAL beamline model and optimize the accelerator optics to negate possible adverse effects resulting from bunch compression.

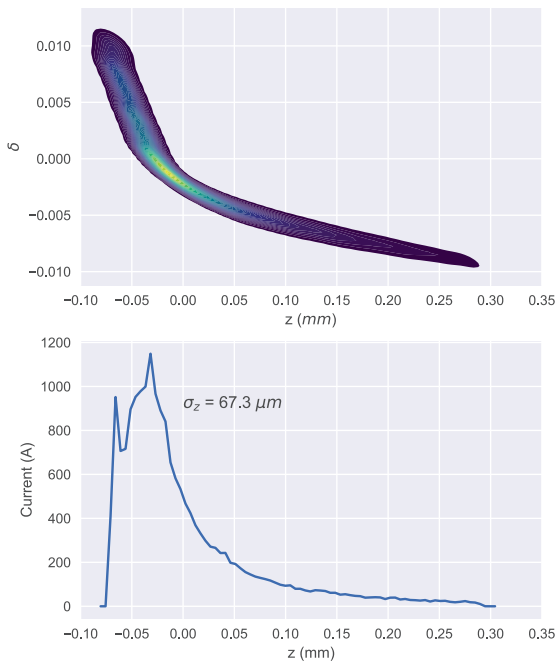


Figure 6: Top: The simulation of the longitudinal phase space of a bunch at the LEA beamline. Bottom: The current distribution of the same bunch.

ACKNOWLEDGMENT

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