PHOTO-INJECTOR OPTIMIZATION AND VALIDATION STUDY WITH THE OPAL BEAM SIMULATION CODE

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Abstract

A 42 keV x-ray free electron laser (XFEL) is a plausible technology alternative for the Matter Radiation Interactions in Extremes (MaRIE) experimental project, a concept developed by Los Alamos National Laboratory. An early preconceptual design for such an XFEL calls for 100 pC electron bunches with very low emittance and energy spread. High fidelity simulations that capture all beamline physics will be required to ensure a successful design. We expect to use the beam simulation code OPAL as one of the tools in this process. In this study, we validate OPAL as a photo-injector design tool by comparing its performance with published PITZ experimental data and simulations.

INTRODUCTION

The design of a 42 keV XFEL is driven by the requirement that there is good overlap between the electron beam and x-ray phase spaces. The Los Alamos National Laboratory XFEL preliminary concept for the MaRIE project has a 12 GeV electron linac producing 42 keV photons from the wiggler. The phase-space overlap requirement limits the normalized transverse emittance of the electron beam at the wiggler entrance to $\epsilon_n \leq \beta\gamma\lambda_x/4\pi$, where β and γ are the electron beam's relativistic factors, and λ_x is the x-ray wavelength. The normalized transverse emittance goal for the MaRIE XFEL concept is 0.20 μm at the wiggler entrance. Such a small transverse emittance leaves little space for emittance growth throughout the linac, and places stringent demands on the transverse emittance from the photo-injector. The MaRIE concept goal transverse emittance from the photo-injector is less than 0.1 μm for a 100 pC electron bunch. Ensuring a successful photo-injector design concept requires high-fidelity simulations. We have selected the OPAL beam dynamics code [1] for our simulations, due to its fully 3D space charge algorithm, and our ability to incorporate necessary physics into the OPAL code through our local OPAL code developers.

In this proceedings, we present our results validating the OPAL code from published results of optimization of the PITZ (Photo Injector Test facility at DESY, Zeuthen site) photo-injector [2].

PITZ PHOTO-INJECTOR

The PITZ photo-injector is designed to minimize the transverse emittance for a 1 nC bunch. Simulations with the ASTRA [3] code have predicted a minimum projected transverse emittance of 0.607 μm for this bunch charge. This photo-injector configuration was experimentally demonstrated to have a minimum transverse emittance of 0.696±0.020 μm in 2011. For 100 pC, the bunch charge anticipated for a MaRIE XFEL, PITZ demonstrated 0.212±0.006 μm, with ASTRA predicting a projected transverse emittance of 0.173 μm [2]. Given that PITZ is designed to meet the European XFEL requirement of 0.9 μm for a 1 nC bunch in the injector, the PITZ design represents a promising starting point for a photo-injector design to meet the MaRIE XFEL concept requirement of 0.1 μm for a 100 pC bunch charge. As such, simulations of the PITZ photo-injector were selected for the photo-injector optimization study to validate the performance of the OPAL code.

SIMULATIONS AND OPTIMIZATION APPROACH

The OPAL simulations we performed were based on previous, publicly available ASTRA simulations of the PITZ photo-injector and Poisson/Superfish input files for the PITZ photo-injector and PITZ solenoid taken from the 37th ICFA Advanced Beam Dynamics Workshop on Future Light Sources PITZ benchmark problem [4]. It should be noted that these simulations are not exactly equivalent to those used in Ref. [2], to which we compare our results. Thus, it is natural to expect that these results will not be exactly the same as the numbers we compare to in Ref. [2], however the results should be similar.

The PITZ photo-injector consists of a 1.6 cell L-band normal conducting RF cavity, with a Cesium Telluride cathode. The combination of a large, main solenoid, and a bucking solenoid provide the magnetic field for emittance compensation, and prevent magnetic field at the cathode. A cut disk structure booster cavity, specially designed for PITZ, is located with its first iris at 3.24 m from the cathode. A beam monitor is located at 5.74 m from the cathode, and it is at this location that emittance measurements have been taken to determine the minimum transverse projected emittance [2]. Similarly, our simulations specifically aimed to minimize the emittance at this location.

Starting with the ASTRA simulation input, the goal was to optimize the settings of a PITZ-like photo-injector for injector bunch charges of 0.02, 0.1, 0.25, 1 and 2 nC. Simple linear optimization of parameters was used, as basic tools were available to perform such a scan. More advanced optimization methods, such as automated Pareto Front optimization, are desirable and likely more efficient in terms of person-hours. Different charge runs were performed by different authors, to obtain the best optimization for each

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case possible in the time available with the given tools. Our simulations results are discussed in the following section.

RESULTS

The simulation parameters for the best optimization obtained for each bunch charge are given in Table 1. The peak electric field of the booster cavities was simply held fixed to the values given by PITZ [2]. Fig. 1 shows that further small decreases in the projected transverse emittance can be made by decreasing the booster peak fields, but these come at the expense of significantly decreasing the beam energy. To simplify comparison with the PITZ results, the booster peak field was held fixed. We varied the solenoid peak field, B_z^{max}, the laser rms spot size, σ_{xy}, and the 1.6 cell gun cavity and booster phases, Φ_{PI} and Φ_{boost} respectively, measured relative to the phases of maximum kinetic energy gain. Parameters for the best emittance cases are given in Table 1.

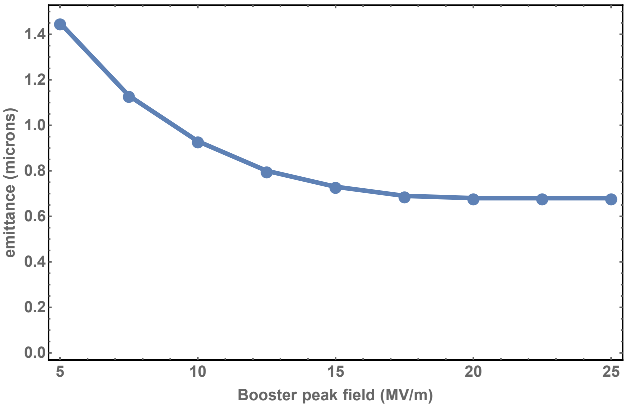

Figure 1: Projected transverse emittance at $z = 5.74$ m as a function of peak booster field, $E_{z,boost}^{max}$. The value used in the PITZ simulations [2], 19.76 MV/m, was used in our 1 nC simulations and held fixed.

Figures 2 through 4 show the change in emittance at the location $z = 5.74$ m with variation of simulation parameters. Fig. 2 shows the emittance growth with variation in the peak solenoid field, B_z^{max}, for the different bunch charges studied, and Fig. 3 shows this change with variation in the laser spot size, σ_{xy}. Fig. 3 shows that the emittance minimum found for the 100 pC case is a local minimum, and that further improvement for the minimum emittance may be obtained by locating the true minimum in the simulation. This is one of the difficulties in performing a simple linear optimization and is discussed further below. Figure 4 shows the emittance growth with variation of the gun and booster cavity RF phases, Φ_{PI} and Φ_{boost} respectively, for the 1 nC case.

DISCUSSION

Our simulation results compare well with the ASTRA results published by PITZ [2]. Comparison of the plots published in Ref. [2] indicate the same overall behavior in emittance growth at $z = 5.74$ m. Furthermore, our obtained minimum projected transverse emittance values at $z = 5.74$ m vary from the published ASTRA simulation results by -1.6, 1.2, 18.3, 11.9, and 13.5 percent for the 0.02, 0.1, 0.25, 1.0, and 2.0 nC cases, respectively, where the negative result indicates we obtained a smaller minimum emittance value.

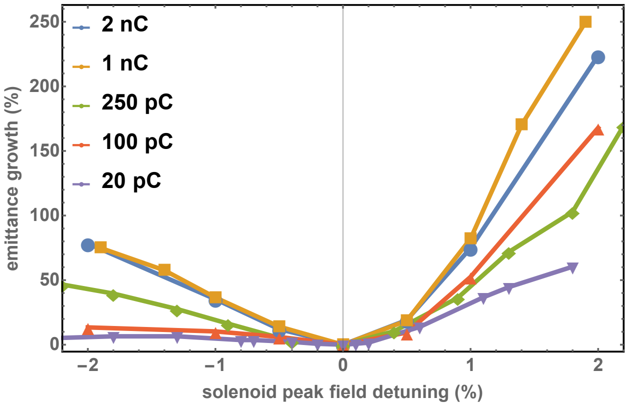

Figure 2: Emittance growth at $z = 5.74$ m with variation of the peak solenoid field, B_z^{max}.

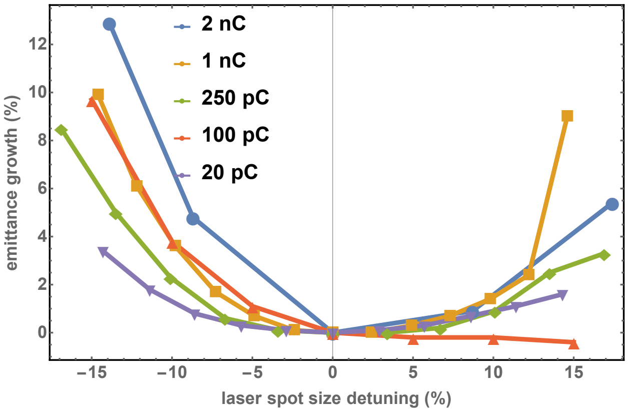

Figure 3: Emittance growth at $z = 5.74$ m with variation of the laser spot size, σ_{xy}.

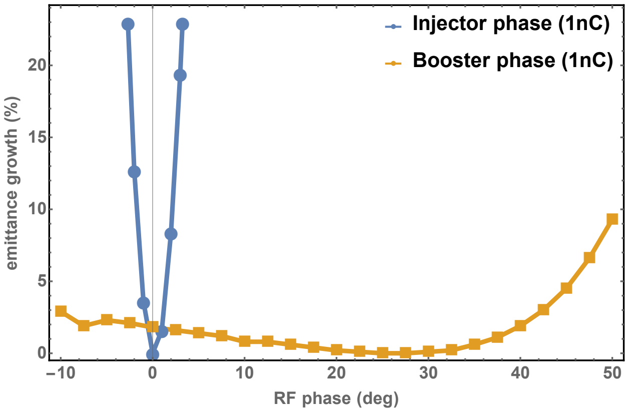

Figure 4: Emittance growth at $z = 5.74$ m with variation of the gun and booster RF phases for the 1 nC case. Phases are with respect to those of maximum kinetic energy gain of the beam.

Table 1: Table of simulation optimization parameters. The photo-injector and booster phases are relative to the phase of maximum kinetic energy gain. The first four parameters were varied in optimization. The last two entries are the maximum beam kinetic energy and projected transverse emittance given by our simulations. σ_{xy} is defined in the same way as Ref. [2], $\sigma_{xy} = \sqrt{\sigma_x \sigma_y} = \sigma_x = \sigma_y$.

		Bunch Charge (nC)				
Parameter	**Unit**	0.02	0.1	0.25	1.0	2.0
Solenoid peak field, B_z^{max}	mT	227.0	227.4	227.8	229.0	229.0
Laser rms spot size, σ_{xy}	mm	0.035	0.102	0.230	0.410	0.575
Photo-injector phase, Φ_{PI}	deg	3.8	2.6	0.0	0.0	-2.8
Booster phase, Φ_{boost}	deg	-2.5	-8.0	10.0	27.5	9.5
Peak booster field, $E_{z,boost}^{max}$	MV/m	20.0	20.0	20.0	19.76	20.0
Energy	MeV	23.9	23.6	23.4	21.7	23.6
Transverse emittance,$\epsilon_x(z = 5.74$ m)	μm	0.060	0.175	0.310	0.679	1.298

The PITZ photo-injector is designed to give the minimum transverse emittance at the monitor at $z = 5.74$ m. One difficulty in optimizing this arrangement for other charge configurations is that there are two local transverse emittance minima after the gun. The entrance to the booster cavity is located at the maximum between the two minima for the 1 nC optimized case. This will not be true for the other charge configurations, and the start of the optimization may be far from the parameters that lead to the smallest transverse emittance at $z = 5.74$ m. The existence of two local minima when using a linear optimization technique mean that either of the local minima may initially be found. It may only become evident that this is not the true minimum when a wider parameter variation is taken, such as the case shown in Fig. 3 for the 100 pC bunch charge.

In Ref. [2], the 0.25, 1 and 2 nC cases showed very similar emittance growth with peak solenoid field in the ASTRA results. Our results, shown in Fig. 2 resulted in greater emittance growth for the 1 nC case when compared to the 2 nC case, and for both of these compared to 0.25 nC, suggesting that further improvements in minimum emittance is possible in at least some cases. The simulations we performed were optimized as best possible given the linear optimization approach and time available.

While the PITZ injector is optimized for the 1 nC case, the 100 pC minimum emittance case is of particular interest as a possible starting point for a MaRIE project photo-injector. As previously mentioned, PITZ demonstrated a projected transverse emittance of 0.212±0.006 μm, with ASTRA predicting 0.173 μm [2] for the 100 pC case. Our simulations gave a transverse emittance in agreement with the ASTRA result, with further room for improvement. Furthermore, a photo-injector specifically optimized for 100 pC is expected to obtain a significantly lower minimum emittance value, suggesting a PITZ-style photo-injector is a good starting design point, if a 42 keV XFEL is chosen for use in the MaRIE project.

CONCLUSION

We have used the OPAL beam dynamics code to optimize a PITZ-style photo-injector, and compared our results with those of Ref. [2], which used the ASTRA code. Our results show good agreement with those of Ref. [2], with the minimum projected transverse emittance obtained varying in the 0.02, 0.1, 0.25, 1.0, and 2.0 nC bunch charge cases by -1.6, 1.2, 18.3, 11.9, and 13.5 percent respectively. We thus conclude that OPAL is an appropriate choice of tool to use for high-fidelity photo-injector simulations.

Furthermore, the predicted 0.175 μm emittance for the 100 pC case demonstrates that a PITZ-style L-band photo-injector makes a useful starting point for a MaRIE XFEL concept photo-injector. When specifically optimized for 100 pC bunch charge, instead of 1 nC, it shows promise for reaching the 0.1 μm projected transverse emittance needed for the XFEL concept photo-injector.

REFERENCES

[1] A. Adelmann *et al.*, “The OPAL (Object Oriented Parallel Accelerator Library) Framework", Technical Report PSI-PR-08-02, Paul Scherrer Institut, Switzerland, 2008-2014.

[2] M. Krasilnikov *et al.*, “Experimentally minimized beam emittance from an *L*-band photoinjector", Phys. Rev. ST Accel. Beams, vol. 15, p. 100701, 2012.

[3] K. Floetmann, ASTRA, `http://www.desy.de/~mpyflo/`.

[4] 37th ICFA Advanced Beam Dynamics Workshop on Future Light Sources (FLS 2006), `http://adweb.desy.de/mpy/FLS2006/proceedings/HTML/SESSION.HTM`.