BEAM DYNAMICS CONSIDERATIONS FOR APEX A HIGH REPETITION RATE PHOTOINJECTOR*

Christos F. Papadopoulos†, Daniele Filippetto, Fernando Sannibale, Russell Wells
LBNL, 1 Cyclotron Road, Berkeley, CA 94720, USA

Abstract

The Advanced Photoinjector Experiment is a photoinjector project at Lawrence Berkeley National Lab, designed to test the performance of a high repetition rate (1 MHz) VHF normal conducting electron gun. The requirements of high beam brightness, as well as significant compression at low energy determine the base setup for the injector transport line. The beam dynamics considerations for a high repetition rate injector are discussed and the potential to use multiple bunch charges that require different tunings of the base setup is explored.

INTRODUCTION

Motivated by the user demand for 4th generation light sources that require high beam quality, a program for the development of a high repetition rate photoinjector is undertaken at the Lawrence Berkeley National Lab. The goals of the Advanced Photoinjector Experiment (APEX) include the demonstration of a high brightness, high repetition rate VHF Gun [1], as well as beam manipulation and transport at low energies, where nonlinear space charge may spoil the initial beam quality.

The current status of the project is reported in [1], and the main focus of this paper is to report on the beam dynamics considerations that have informed the mechanical and electrical design. In addition to this, phase space properties of the beam relevant to FEL physics will be discussed.

APEX SETUP

The conceptual schematic of APEX beamline, currently in the design stage, is shown in Fig. 1 and is simplified in order to exemplify the components important for beam dynamics. The electron beam originates at the cathode of the VHF electron gun, which is illuminated by a high rep. rate laser, causing electrons to be extracted at the required rep. rate. After the gun, two solenoids and one single-cell, Cornell-type cavity [2] are placed, as close to the gun as mechanically possible. After this, three 7-cell normal conducting accelerating cavities are placed, the design of which are based on an ANL design [3].

The knobs described in Fig. 1 are the ones varied during the optimization procedure described in the next section, along with the 3 positions of the accelerating cavities. These last knobs will of course be fixed once the decision for the final design point is made, while the rest of the knobs will be still allowed to change. Allowing the phases and gradients of the 4 1.3 GHz cavities to change poses an engineering requirement, namely the full and independent control of those quantities. The initial size and length of the electron bunch can be controlled through the laser pulse with appropriate laser-shaping schemes.

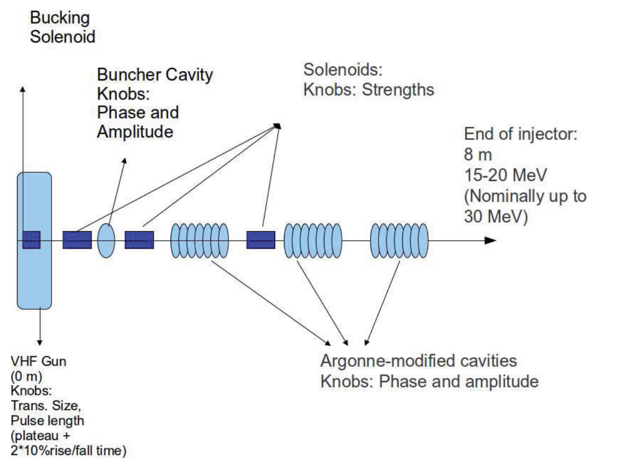

Figure 1: Schematic of APEX, with the available optimizer knobs.

The accelerating field at the cathode is of the order of 20 MV/m, and the resulting beam energy at the exit of the gun is in the range 730-750 keV. These numbers are determined by the geometry of the cavity and the power and stability provided by the power supply, and do not lend themselves to much optimization, since higher values for both are always desirable.

For the purposes of the initial design, a Cs_2Te photocathode [4] is assumed, which gives an initial, normalized rms transverse emittance $\epsilon_{nx} = 1 \times \sigma_x$ mm-mrad, where σ_x is the initial transverse rms size of the beam. Other photocathodes may also be used, and a load-lock system is in place to accommodate such changes.

The field of the bucking coil placed behind the cathode is appropriately scaled with the field of the first solenoid after the gun, in order to have zero net magnetic field at the cathode. That is, the beam has no initial correlations due to a magnetic field, although the ability to induce them is kept.

* This work was supported by the Director of the Office of Science of the US Department of Energy under Contract no. DEAC02-05CH11231
† cpapadopoulos@lbl.gov

ISBN 978-3-95450-117-5

BEAM DYNAMICS OPTIMIZATION

As seen in Fig. 1, a number of independently controlled knobs exist that can influence the dynamics of the beam. The first ones are the initial size and length of the electron bunch at the cathode. Downstream, the solenoids after the gun are used for the transverse confinement of the beam and the emittance compensation process [5] that keep the total, projected transverse emittance of the beam low.

The independently varying gradients and phases of the 4 RF cavities after the gun play a vital role in the longitudinal compression of the beam, since a combination of ballistic [6] and velocity [7] bunching is used. That is, the single cell cavity is set at zero-crossing with respect to the electron bunch, initiating the ballistic bunching procedure, while the rest of the cavities are dephased from the maximum accelerating phase, as required for velocity bunching, but are not set to 0. This means that the final beam energy changes from solution to solution, and is below the nominal value of 30 MeV

The three position knobs play an important role in both these low energy bunching processes, since a drift space is required for the tail to catch up to the head.

The choice of 300 pC for the design point of the injector is based on the demands on the electron beam at the FEL undulators [8], and in particular, the emittance and the peak current. Part of the experimental program of APEX will be to study other charge values, as discussed in the following sections.

The numerical code used to simulate the beam dynamics is Astra, which is widely used and thoroughly benchmarked for the energy and charge ranges discussed here [9].

For the optimization of the beam properties, a multiobjective genetic algorithm is used, as described in [10], [11]. The choice of the objective functions is based on the well known influence of nonlinear space charge forces as a major driver of emittance growth. Hence, in order to have a pair of objectives to be minimized, that also have a manifest trade-off, we choose the normalized transverse rms emittance and the bunch length, which for reasonably well controlled beams scales inversely with the current, and hence with space charge force.

In the case of multiobjective optimization schemes such as NSGA2, the one used here, the final result is not a single solution, but a set of solutions that are optimal in a Pareto sense [11]. That is, the resulting solutions lie on a 1 dimensional curve in 2 dimensional objective space (emittance-bunch length), and decreasing one property further will lead to an increase in the other property.

The final decision on a working point is not based solely on the values of the emittance and the bunch length, but also on factors that are not a priori obvious. Indeed, the shape of the current profile and the longitudinal phase space are also important, especially with regards to the longitudinal tails that are a result of nonlinear space charge forces. The slice emittance across the bunch is an important quantity in multiple mode FELs, and hence has to be controlled as well, and also informs the decision process.

Following this procedure, we pick one point design for the APEX beam, and the final beam properties of this solution are shown in Fig. 2.

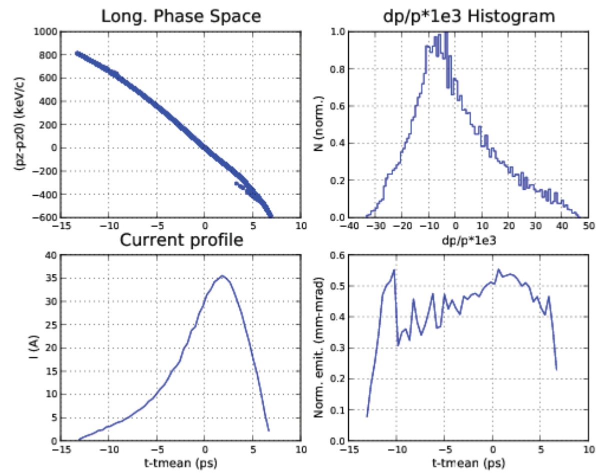

Figure 2: Longitudinal phase space and projections for the point design solution, 300 pC at 17.15 MeV

The beam parameters for the solution shown in Fig. 2 are given in Table 1, again at the exit of the APEX injector.

Table 1: Beam Parameters at the Injector Exit

Beam Parameter	Value
Bunch Charge (pC)	300
Bunch length (mm)	1.15
100% norm. x emit. (mm-mrad)	0.51
Peak current (A)	35
Final energy (MeV)	17.15

Transition to Higher Energy

From a beam dynamics point of view, the injector is the part of the machine where low energy dynamics are important. In our case, the relevant dynamics are dominated by the transverse space charge forces, which drive the emittance growth and scale as $F_{sc} \sim I/\gamma^3$ (I is the beam current and γ the usual relativistic factor). On the other hand, both ballistic and velocity bunching take advantage of the energy dependence of velocity at low energies, which scales as $\delta\beta = \delta\gamma/\gamma^3$ for higher energies.

That is, the importance of both processes falls rapidly with increasing energy. In the case of emittance, this phenomenon is sometimes called “freezing-in” of the space charge forces, while in the case of bunching, other means of compression, such as magnetic chicanes, have to be used.

The exact point where this happens is somewhat arbitrary and obviously depends on a number of factors, but,

ISBN 978-3-95450-117-5

as seen in Fig. 3, the bunch length does not change significantly towards the end of the injector, especially after the last accelerating section boosts the energy to more than 17 MeV. On the other hand, the oscillations in the emittance

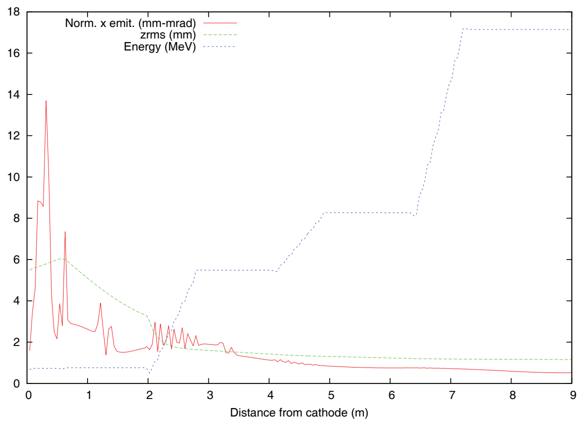

Figure 3: Evolution of the energy, rms bunch length and rms emittance across the APEX injector.

that are associated with the compensation process are not fully damped, and hence this process is not fully converged, but very close to being so. Indeed, simulations of a similar setup [12] show that for similar parameters, energies up to 70 MeV may be required for the emittance to be fully frozen-in. This does not imply a worsening of the beam quality, but merely reflects the fact that at these energies the electron beam has only partially "stiffened".

Higher Order Correlations

One feature of the beam that can play a significant role are correlations in the $z - p_z$ phase space of order higher than 2. The reason for this is that the linear correlations can be physically removed by dephasing the downstream linac sections, and most current linac FEL drivers [13] include a 3rd harmonic linearizing section before the bunch compressors in order to remove 2nd order correlations. Hence, after removing these first two orders, the correlations left will be in principle transported downstream, and may affect the beam dynamics in the linac and the FEL undulators.

Although the higher order terms are obviously not stochastic, and hence can in principle be removed, no practical method addressing this issue has been proposed yet.

In Fig. 4, we show the longitudinal phase space plot of Fig. 2, with the numerical value of the second order polynomial fit $p_z(z) = c_0 + c_1 z + c_2 z^2$ subtracted from the momentum of every particle. We see thus that although the linear and quadratic correlations are dominant (on the order of 1.4 MeV peak-to-peak), the remainder is still significant, resulting in an 80 keV P-P modulation across the beam, much larger than the truly random spread represented by the thickness of the beam, which is on the order of 10 keV P-P at this stage.

This correlation may become important if the beam is compressed downstream, as is the case for FEL amplifier

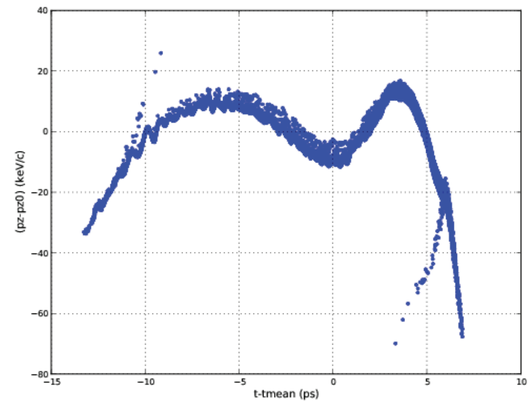

Figure 4: Phase space projection of the beam in the $z - p_z$ plane, with the linear and quadratic correlation removed.

drivers that require high peak current. Then, the final energy (or momentum) spread, according to Liouville's theorem for longitudinal emittance, will be 8 times higher than the value it would have in the absence of the higher order correlations. This may of course significantly affect the the FEL performance, if not addressed properly [12]. As mentioned before, the APEX photoinjector is designed to study this kind of effect, and will include the time dependent longitudinal diagnostics that can measure this type of correlation.

MULTIPLE BUNCH CHARGES

Once the optimization of the injector is completed for the design point of 300 pC, the mechanical schematics are set, since moving such components is not practical during operations.

As discussed before, in addition to the bunch charge of 300 pC, the APEX project plans to explore a range of charges, from few 10s of pC to 1 nC. These are interesting for FEL physics, since lower charges tend to give better efficiency, while higher charges correlate with higher peak power and longer pulses. Indeed, the decision of which bunch charge to use will have to be informed by the initial beam quality of said bunches.

In order to address the question of whether the mechanical design can accommodate the study of different bunch charges, a genetic optimizer is used as before. In this case though, the positions of all the elements are kept constant, but the other knobs are allowed to change. The goal of this exercise is to see whether the expected range of values for the emittance and bunch length can be reached, without modifying the mechanical setup.

The results of the optimization runs for different charges are shown in Fig. 5, for the range of 10 pC-1 nC. As expected, lower charge bunches demonstrate lower emittance as well as lower bunch length. On the other hand, the highest charge case of 1 nC is clustered around the emittance

ISBN 978-3-95450-117-5

value of 1 mm-mrad, which is the highest value allowable by the optimizer.

Since the design already allocates space for transverse and longitudinal diagnostics [1], it is suitable for experimental studies of the beam dynamics of different charges.

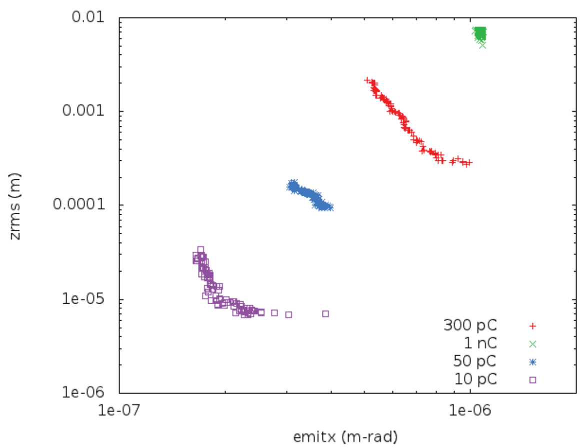

Figure 5: Pareto fronts for different bunch charges. Note the log. scale.

CONCLUSIONS

In this paper we report on the beam dynamics status for the APEX project. In particular, we see that the mechanical and electrical design of the injector allow for the full exploration of the parameter space relevant for the optimization process.

We also show that the current design of the injector can accommodate bunch charges in the 10pC-1nC range, and is ideal for the study of low-energy phenomena in the transport of high quality electron beams, such as emittance compensation, ballistic and velocity bunching, as well as space charge induced high-order correlations in longitudinal phase space.

REFERENCES

[1] F. Sannibale et al., THPB14, Proc. of FEL'11, Shanghai, China.

[2] V. Veshcherevich, S. Belomestnykh, Buncher cavity for ERL, TPAB008, Proc. of PAC 2003, Portland, USA.

[3] J.G. Power et al., Upgrade of the drive linac for the AWA facility dielectric two-beam accelerator, THPD016, Proc. of IPAC 2010, Kyoto, Japan.

[4] V. Miltchev et al., Measurements of thermal emittance for cesium telluride photocathodes at PITZ, THPP042, Proc. of FEL 2005, Palo Alto, USA.

[5] B.E. Carlsten, Space Charge Induced Emittance Compensation In High brightness photoinjectors, Part. Accel. 49 (1995) pp.27-65

[6] J.W. Lewellen IV, S.V. Milton, Preliminary calculations of ballistic bunch compression with thermionic cathode rf guns, Proc. SPIE - Int. Soc. Opt. Eng (Coherent Electron Beam X-Ray Sources: Techniques and Applications), Vol. 3154

[7] L. Serafini, M. Ferrario, Velocity bunching in photoinjectors AIP Conf. Proc. 581 (2001), p. 87

[8] J. Corlett et al., TUPB26, Proc. of FEL'11, Shanghai, China.

[9] K. Flottmann, ASTRA: A space charge tracking algorithm, user's manual available at `http://www.desy.de/~mpyflo/Astra_dokumentation`

[10] I.V. Bazarov and Charles K. Sinclair. Multivariate optimization of a high brightness dc gun photoinjector. PRSTAB, `8(3):034202+`, Mar 2005.

[11] K. Deb, Multi-objective optimization using evolutionary algorithms. Wiley, 2001.

[12] C.F. Papadopoulos et al, TUPB12, Proc. of FEL'11, Shanghai, China.

[13] P. Emma et al., Nature Photonics 4, 641 - 647 (2010)

ISBN 978-3-95450-117-5