VERIFICATION OF THE AWA PHOTONJECTOR BEAM PARAMETERS REQUIRED FOR A TRANSVERSE-TO-LONGITUDINAL EMITTANCE EXCHANGE EXPERIMENT

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Abstract

A transverse-to-longitudinal emittance exchange experiment is in preparation at the Argonne Wakefield Accelerator (AWA). The experiment aims at exchanging a low \((\varepsilon_z < 5 \mu m)\) longitudinal emittance with a large \((\varepsilon_x > 15 \mu m)\) transverse horizontal emittance for a bunch charge of \(-100 \text{ pC}.\) Achieving such initial emittance partitioning, though demonstrated via numerical simulations, is a challenging task and needs to be experimentally verified. In this paper, we report preliminary emittance measurements of the beam in the transverse and longitudinal planes performed at \(-12 \text{ MeV}.\) The measurements are compared with numerical simulations.

INTRODUCTION

Plans are underway at the Argonne Wakefield Accelerator (AWA) [1] to perform a proof-of-principle experiment at demonstrating the exchange of a large transverse emittance with a lower longitudinal one. The transverse-to-longitudinal emittance exchange concept could have application in FELs where the reduction of the transverse emittance at its implementation could eventually eliminate the need for an electron damping ring. The linear collider where its implementation could eventually replace the transverse emittance with a lower longitudinal one. The emittance exchange experiment discussed in the Paper requires a different mode of operation where the longitudinal emittance is made smaller than the transverse one by a factor \(-3.\)

NUMERICAL MODELING

We relied on extensive beam dynamics modeling to seek an operating mode of the AWA capable of achieving an emittance partition with \(-\varepsilon_x/\varepsilon_z > 3.\) The program AstrA [3] along with a multi-objective genetic optimization algorithm [2] were used to find possible operational settings. In these simulations the photocathode drive laser was taken to be transversely uniform with a Gaussian temporal distribution. The variable parameters used for the optimization were the laser pulse duration \(\sigma_t,\) its transverse beam size on the photocathode \(\sigma_x,\) the rf gun phase and peak E-field, the peak B-field associated to the three solenoids surrounding the rf gun, and the booster phase and peak E-field. The optimization was constrained to achieve and emittance ratio \(-\varepsilon_x/\varepsilon_z > 3\) with \(-\varepsilon_x < 20 \mu m\) and the longitudinal phase space correlation was required to match a value close to \(-d\delta/dz|_{z=0} \approx 8 \text{ m}^{-1}\) to minimize emittance dilution in the exchanger beamline [7].

Astra simulations indicates, for a laser pulse length of \(-\sigma_t \approx 0.56 \text{ ps},\) that the achievable emittance partition is \((-\varepsilon_x/\varepsilon_z) = (15.9, 3.75) \mu m;\) see Fig. 2. For the series of measurement reported below the laser pulse length was \(-1.85 \text{ ps}\). The corresponding parameters are gathered in Table 1 where all the settings but \(-\sigma_t\) result from the aforementioned optimization and the emittances correspond to...
Figure 1: Layout of the emittance exchange proof-of-principle experiment at the AWA. The green and red rectangles respectively correspond to dipoles and quadrupoles magnets. The labels L1, L2, L3 indicates the locations of the three solenoids around the gun. The locations of planned transverse and longitudinal emittance diagnostics are also shown.

the experimentally achieved value of $\sigma_t \simeq 1.9$ ps.

**MEASUREMENTS**

The purpose of the series of experiments reported below was to confirm the parameters simulated with ASTRA for a laser pulse duration $\sigma_t = 1.9$ ps. The required laser spot size of 4 mm (rms) is significantly larger than the nominal one and we presently observe significant intensity non-uniformities across the area of the uv laser. These non-uniformities have significant impact on the transverse and longitudinal emittance produced by the rf gun.

The parameters resulting from the numerical optimization of the beamline were used as initial settings for the AWA beamline and were then slightly altered to match experiment with simulations. In particular the simulated beam energy and evolution of the transverse envelop shown in Fig. 2 were experimentally reproduced.

![Figure 2](image)

**Table 1:** Optimized settings and beam parameters at $z = 2.79$ m using ASTRA and corresponding experimental values. The value of $\sigma_t$ was the one experimentally achieved.

<table>
<thead>
<tr>
<th>Symbol (unit)</th>
<th>ASTRA</th>
<th>Experiment</th>
</tr>
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<tbody>
<tr>
<td>$Q$ (pC)</td>
<td>100</td>
<td>100 ± 10</td>
</tr>
<tr>
<td>laser $\sigma_t$ (ps)</td>
<td>1.95</td>
<td>1.85 ± 0.2</td>
</tr>
<tr>
<td>rms laser size (mm)</td>
<td>4.0</td>
<td>4.0</td>
</tr>
<tr>
<td>gun field (MV/m)</td>
<td>43.92</td>
<td>47 ± 2</td>
</tr>
<tr>
<td>gun phase (deg.)</td>
<td>65</td>
<td>60 ± 5</td>
</tr>
<tr>
<td>booster field (MV/m)</td>
<td>15.75</td>
<td>15.5 ± 1</td>
</tr>
<tr>
<td>booster phase (deg.)</td>
<td>50.35</td>
<td>52 ± 4</td>
</tr>
<tr>
<td>L1 peak B-field (T)</td>
<td>0.062</td>
<td>0.0618 ± 0.0031</td>
</tr>
<tr>
<td>L2 peak B-field (T)</td>
<td>-0.062</td>
<td>-0.0626 ± 0.003</td>
</tr>
<tr>
<td>L3 peak B-field (T)</td>
<td>-0.228</td>
<td>-0.228 ± 0.0014</td>
</tr>
<tr>
<td>$\varepsilon_x$ ($\mu$m)</td>
<td>19.5</td>
<td>18.5 ± 2</td>
</tr>
<tr>
<td>$\varepsilon_y$ ($\mu$m)</td>
<td>19.5</td>
<td>21.2 ± 2</td>
</tr>
<tr>
<td>$\varepsilon_z$ ($\mu$m)</td>
<td>7.40</td>
<td>-</td>
</tr>
</tbody>
</table>

The transverse emittance was measured using a standard quadrupole scan technique [5]. Simulations of the method with IMPACT-T [4] support the use of a fitting algorithm that does not include linear space charge force to infer the emittance values. The squared beam size dependence on the quadrupole magnetic strength $k$ is parametrized by a second-order polynomial $\sigma^2 = Ak^2 + Bk + C$ and the emittance is estimated as $\varepsilon = \frac{|4AC - B^2|^{1/2}}{2D^2}$. Fig. 3 shows the measured squared beam size as a function of $k$ along with the corresponding quadratic fit. The inferred emittance values are in good agreement with the one predicted by ASTRA; see Table 1.

The longitudinal emittance is measured by scanning the booster phase and measuring the resulting energy spread. A fitting technique similar to the one used in the quadrupole scan method provides the longitudinal emittance; see e.g. Ref [8]. Because of the low energies (few MeV) reached during the phase scan, the longitudinal transport matrix [in
Figure 3: Squared horizontal (left) and vertical (right) beam sizes versus quadrupole magnetic strength. The data (blue circles) and corresponding quadratic fit (green lines) are shown. Emittance values inferred from the quadratic fit are \( \varepsilon_x = 18.5 \pm 2 \, \mu \text{m} \) and \( \varepsilon_y = 16.2 \pm 2 \, \mu \text{m} \).

\((z, \delta)\) phase space] of the booster was modeled as a series of thin-lens cavity matrix interleaved by drift spaces of length \( L \) with longitudinal dispersion \( R_{56} = -L/\gamma^2(z) \) where \( \gamma(z) \), the Lorentz factor, varies as the beam propagates through the booster. We verified the thereby devised semi-analytical model for the transfer matrix is in agreement with the one numerically evaluated from particle tracking simulations; see Fig. 4.

The energy spread is measured downstream of a vertically-bending spectrometer, located \( \approx 2 \, \text{m} \) downstream of the booster, where the vertical dispersion is \( |\eta_y| \approx 18 \, \text{cm} \). An horizontal slit located upstream of the dipole, is imaged onto the YAG screen to improve the energy spread measurement resolution. Fig. 5 shows the evolution of beam’s mean and rms momentum as a function of the booster phase. The data are consistent with numerical simulations with \( \sim 8 \, \mu \text{m} \) longitudinal emittance.

**FUTURE PLANS & SUMMARY**

Although the transverse emittances measured are in good agreement with the predicted one, the longitudinal emittance measurement needs to be refined. We have tested a maximum-entropy-based tomography algorithm [9] using simulated data (see Fig. 6) and plan on using this algorithm to measure the longitudinal emittance.

On the experimental side several improvements are needed. In particular the photocathode laser transverse uniformity requires further work and the observed significant phase jitter need to be addressed. Nevertheless the preliminary measurements presented in this Paper indicate that AWA can operate with an emittance partition providing a transverse emittance more than twice the longitudinal emittance.

**REFERENCES**