APPLICATION OF PYAPAS IN PWFA BEAM COMMISSIONING

Y. Zhao, X. Lu, H. Ji, N. Li, C. Shen, C. Meng, Y. Wang, Z. Ming, H. Xu
Accelerator Physics Group, Accelerator Center, IHEP, CAS, China

Abstract

The Plasma Acceleration is an important development direction for future accelerators for its high acceleration gradient. The PWFA experimental platform in IHEP consists of two beamlines. Beamline 1 (BL1) transports the electron-positron beams from the BEPCII linear accelerator, with a beam energy of about 2 GeV. At present, BL1 has achieved the penetration of electrons and positrons, as well as the parameter measurement of electron beams. Beamline 2 (BL2) is a new linear accelerator featuring an energy of 150 MeV and a bunch charge exceeding 5 nC. The hardware installation of BL2 is drawing to a close, and the beam commissioning will start very soon. Together, these two beamlines support a range of plasma acceleration experiments, including positron acceleration, electron-cascade acceleration, high transformer-ratio electron acceleration, and external-injection electron acceleration. Pyapas, an independently developed High-Level Application (HLA) by the Institute of High Energy Physics (IHEP), has been successfully applied on beam commissioning of High-Energy Photon Sources(HEPS). We have achieved the successful porting and application of Pyapas in the beam commissioning of the PWFA linear accelerators.

INTRODUCTION

Plasma wakefield acceleration (PWA) achieves gradients up to 100 GV/m, two orders of magnitude higher than conventional RF accelerators [1], enabling compact high-energy accelerators. IHEP has constructed a dual-beamline PWFA platform: BL1 transports 2 GeV electron/positron beams from BEPCII for positron and cascade acceleration studies. The critical challenge is matching the three-dimensional beam sizes produced by conventional radio-frequency (RF) accelerators to the plasma accelerating structures. With innovative design concept, the beam from BEPCII achieves a tenfold compression of the three-dimensional beam sizes. BL2 is a newly constructed 150 MeV, > 5 nC linac and a peak current above 10 kA. The layout of BL1 and BL2 is shown in Fig. 2.

Efficient commissioning and precise diagnostics are essential for PWFA. PYAPAS a pure Python-based Accelerator Physics Application Set [2], features modular design, physical-quantity-based control, and dual-layer physical modeling. It has been sucessfully used in the commissioning of HEPS LINAC [4], Booster [5] and Storage Ring.

PORTING AND EXTENSION OF PYAPAS

PYAPAS is selected as the commissioning tools of PWFA. To meet the requirements of PWFA beam commissioning, a series of Pyapas-based applications have been developed and ported, including the PWFA controller for machine control with physical values, model manager for optics parameters saving and restoring, online simulator to displays physical parameters in real time and facilitate beam commissioning, beam-based alignment (BBA), emittance measurement, energy and energy spread measurement, response matrix measurement and orbit correction, and so on. These applications provide a unified software environment for daily beam tuning and diagnostic measurements. Some program interfaces are shown in Fig. 1.

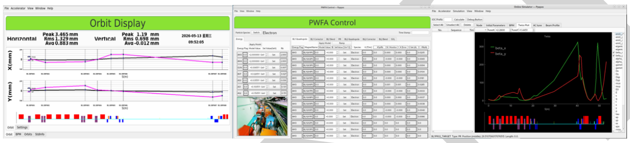

Figure 1: Some applications of Pyapas for PWFA.

Due to the unique characteristics of the PWFA beamlines, especially the ultra-wide energy range of AM4 (0.05-25 GeV) and the requirement for flexible emittance measurement with solenoid scanning method, further functional extensions are implemented in Pyapas.

Emittance Measurement via Solenoid Scanning

The emittance and Twiss parameters are critical indicators of beam quality and key parameters for plasma wakefield acceleration. The quadrupole-scanning algorithm in Pyapas has been implemented and used in HEPS. Now, it was extended to measure with solenoids. The solenoid transfer matrix including coupling effect was implemented first, and a solenoid-scanning option was added to the GUI (Fig. 3). Based on the beam envelope theory, the squared beam size measured at profile monitors has a linear relation with Twiss parameters and emittance. For the case of measure with scanning solenoid method it is expressed in matrix form as Eq. (1):

where σ_{xi}^2, σ_{yi}^2 are squared horizontal/vertical beam sizes at the i-th monitor, $m_{ij,k}$ denotes the (i, j) element of transfer matrix at the k-th solenoid setting, $\beta_{x,y}$, $\alpha_{x,y}$, $\gamma_{x,y}$ are Twiss parameters, and $\varepsilon_{x,y}$ are horizontal/vertical emittances.

We tested the code with virtual accelerator based on BL2 lattice. The beam spot sizes under different solenoid settings are shown in Fig.3. The results yielded horizontal/vertical emittances of 0.17 µm and 0.24 µm, which means the fitting error is < 4%, as shown in Table 1 and Fig. 3(Lower).

Energy and Energy Spread Measurement Using 2D Interpolation

There are several bending magnets and PR targets used for energy and energy spread measurement, such as AM4 and PR03 in BL1, BL2BC02 and BL2PR02, BL2BC04 and

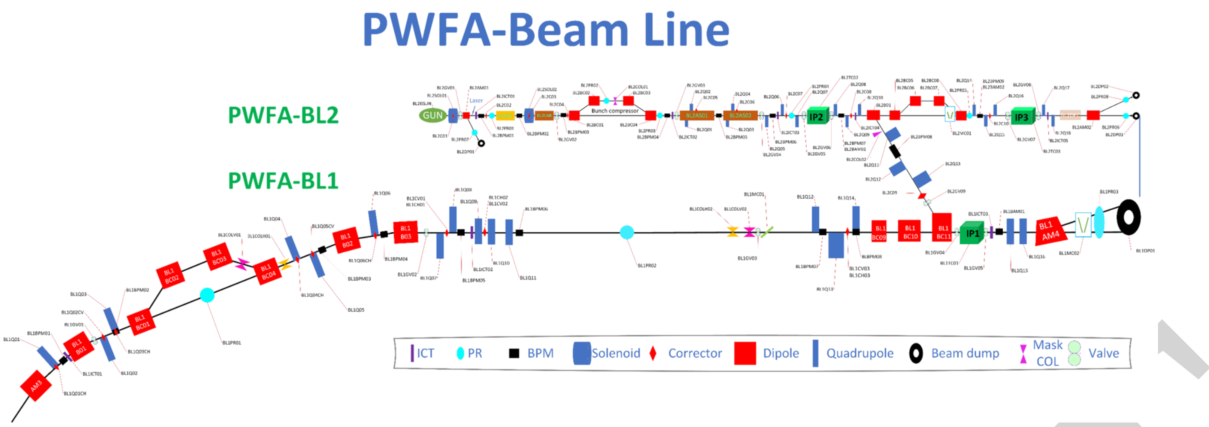

Figure 2: The lattice layout of PWFA.

$$
\underbrace{\begin{pmatrix} \sigma_{x1}^2 \\ \sigma_{x2}^2 \\ \vdots \\ \sigma_{xn}^2 \\ \sigma_{y1}^2 \\ \sigma_{y2}^2 \\ \vdots \\ \sigma_{yn}^2 \end{pmatrix}}_{2n\times 1} = \underbrace{\begin{pmatrix} m_{11,1}^2 & -2m_{11,1}m_{12,1} & m_{12,1}^2 & m_{13,1}^2 & -2m_{13,1}m_{14,1} & m_{14,1}^2 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ m_{11,n}^2 & -2m_{11,n}m_{12,n} & m_{12,n}^2 & m_{13,n}^2 & -2m_{13,n}m_{14,n} & m_{14,n}^2 \\ m_{31,1}^2 & -2m_{31,1}m_{32,1} & m_{32,1}^2 & m_{33,1}^2 & -2m_{33,1}m_{34,1} & m_{34,1}^2 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ m_{31,n}^2 & -2m_{31,n}m_{32,n} & m_{32,n}^2 & m_{33,n}^2 & -2m_{33,n}m_{34,n} & m_{34,n}^2 \end{pmatrix}}_{2n\times 6} \cdot \underbrace{\begin{pmatrix} \beta_x\varepsilon_x \\ \alpha_x\varepsilon_x \\ \gamma_x\varepsilon_x \\ \beta_y\varepsilon_y \\ \alpha_y\varepsilon_y \\ \gamma_y\varepsilon_y \end{pmatrix}}_{6\times 1} \tag{1}
$$

Figure 3: Emittance measurement GUI with solenoid-scanning option (Up), and the corresponding result based on virtual accelerator (Down).

BL2PR03, and so on. The most complicated situation is AM4 and PR3, since the so large energy spans 0.05-25 GeV. It well beyond the bending capacity of AM4. The target assembly of PR03 has an overall width of approximately 320mm, consisting of YAG and OTR targets, each constructed by four segmented target plates. Since particles with different energies follow distinct trajectories inside the

Table 1: Measured Emittance and Twiss Parameters

α_x	β_x (m)	ε_x (μm)	α_y	β_y (m)	ε_y (μm)
−8.241	18.938	0.171	−6.008	15.652	0.236
±0.013	±0.030	±0.0002	±0.009	±0.024	±0.0002

AM4 magnet, they experience different incident angles, exit angles, and effective lengths. The At 230 A, $E > 7$ GeV beams bypass the magnet pole, as shown in Fig. 4. Conventional ideal-trajectory methods fail to deal with this situation.

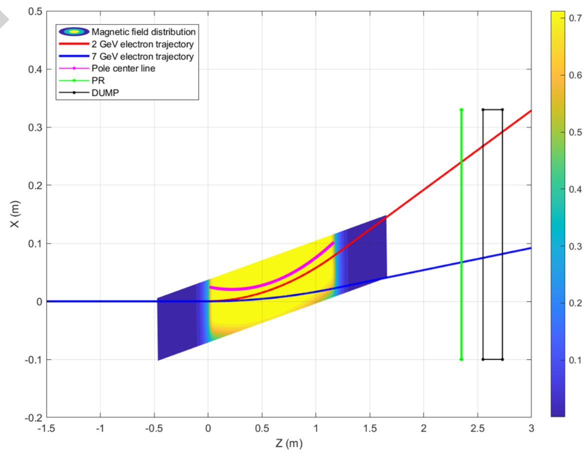

Figure 4: Magnetic field distribution and trajectories for 2 GeV and 7 GeV beams in AM4.

So we Pre-track trajectories for $0.05 \leq E \leq 25$ GeV at various AM4 currents and implemented the data to the online GUI code. Then, the 2D interpolation is used to yields beam energy and energy spread. The GUI interface is shown in Fig. 5. In this figure, the loaded pre-track data is shown in the Upper one. different color means different AM4 energy(or bending angle). The asterisk denotes the beam energy obtained via interpolation from the AM4 energy and the beam position on the PR target. The lower one is shows the beam spot on the BL1PR03 target.

SUMMARY

The PYAPAS code is an accelerator simulation and online beam commissioning program independently developed by the Institute of High Energy Physics (IHEP) based on the HEPS project. We have successfully ported PYAPAS to the PWFA project, and the online beam commissioning has been successfully realized. In addition, further extensions have been implemented at the application development level. The method of emittance measurement via solenoid scanning has been established. Meanwhile, by adopting the 2D interpolation of energy and position, the measurement of energy and energy spread over an extremely wide energy range has been achieved.

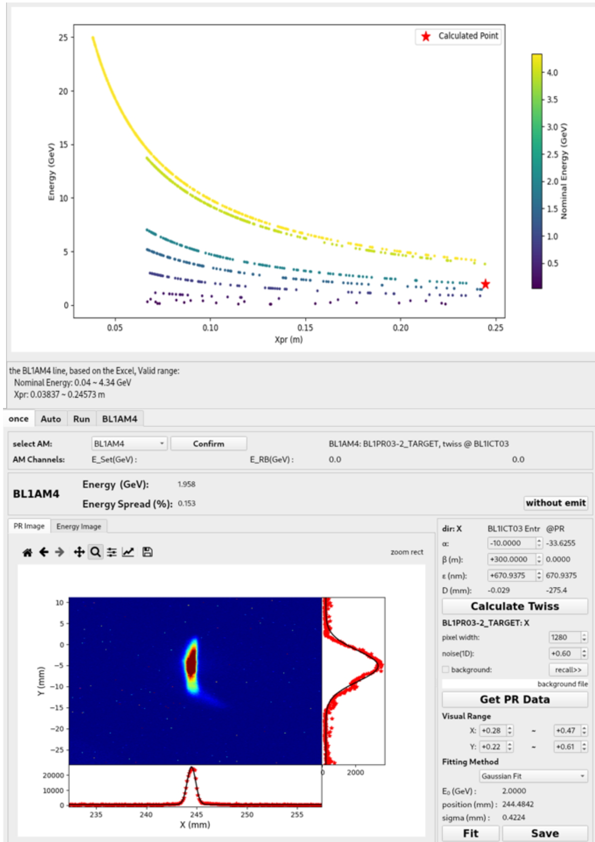

Figure 5: The interface of Energy and Energy Spread measure application.

REFERENCES

[1] P. Chen, J. M. Dawson, R. W. Huff, and T. Katsouleas, "Acceleration of electrons by the interaction of a bunched electron beam with a plasma," *Phys. Rev. Lett.*, vol. 54, pp. 693–696, 1985. doi:10.1103/PhysRevLett.54.693

[2] Xiaohan Lu, et al, "A new modular framework for high-level application development at HEPS", *J. Synchrotron Radiat.*, 31: 385-393, 2024. doi:10.1107/S160057752301086X

[3] X. Shi *et al.*, "Three-dimensional beam size compression for external injection of plasma wakefield acceleration," *Radiat. Detect. Technol. Methods*, vol. 10, pp. 169–179, 2026, doi:10.1007/s41605-025-00584-y

[4] Y.-L. Zhao, *et al.*, "The high level applications for the HEPS Linac", *J. Instrum.*, vol. 18, p. P06014, Jun. 2023, doi:10.1088/1748-0221/18/06/P06014

[5] Y. Peng, *et al.*, "Development of high-level applications for High Energy Photon Source booster", *J. Instrum.*, vol. 19, p. P08013, Aug. 2024, doi:10.1088/1748-0221/19/08/P08013