Measuring particle beam emittance for FACET-II

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Plasma Wakefield Acceleration (PWFA) is a novel acceleration method which can be used to accelerate charged particles to high energies over orders of magnitude less distance than traditional acceleration methods. This paper details a user interface for data analysis on beam emittance - a parameter pertaining to phase coherence or "quality" of the beam. Emittance is an important parameter for making electron/positron beams useful in applications such as free-electron lasers or synchrotron x-ray sources.

I. BACKGROUND

The emittance of a particle beam is an important quantity in accelerator physics, especially in the context of Plasma Wakefield Acceleration experiments. Emittance plays a critical role in determining the performance and efficiency of particle accelerators. In PWFA, maintaining low emittance values at the entry and exit of the plasma chamber is crucial for achieving high-energy gain acceleration. Emittance affects beam quality, beam transport, and the final energy spread of the accelerated particles.

One of the key developments required in order to demonstrate PWFA as a viable acceleration technology is emittance preservation - meaning that the emittance at the end of the plasma chamber is the same as at its entrance, a feat that has not been yet achieved for any significant energy gain in PWFA.

Emittance is a parameter related to the 6 dimensional phase space of a particle beam that describes the correlations between position and momentum distributions. Emittance defines properties of the beam such as the smallest achievable spot size.

There a various means of measuring emittance. This tool utilizes dipole spectrometers to get single shot, energy-dependant measurements. The measurement principle of dipole spectrometers is based on the fact that charged particles experience a magnetic field, causing them to deflect proportionally to their momentum. Higher-energy particles are less affected by the magnetic field and experience smaller deflections, while lower-energy particles undergo larger deflections. This results in a spread of particle positions on a detector screen, as illustrated in Figure 1.

The horizontal size of the beam at a given energy is directly related to the emittance, as well as several other parameters relating to their position within the beam transport. By analyzing the beam's profile as a function of energy, accelerator physicists can extract valuable information about emittance. The horizontal and vertical profiles of the beam provide insights into the beam's size in both position and momentum space.

Measuring emittance accurately is essential for optimizing the performance of accelerators. A low emittance beam is desirable because it leads to better beam quality, narrower energy spreads, and more efficient acceleration. Conversely, high emittance beams can result in increased beam losses, larger energy spreads, and reduced overall efficiency.

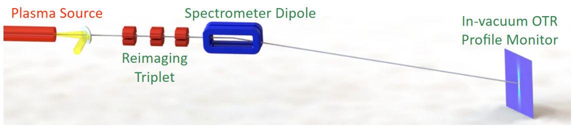

FIG. 1. Higher energies are more "rigid" meaning they are bent less by the dipole while lower energies are bent more - this gives a profile the transverse size of the beam as a function of the beam energy.

In the context of the Facility for Advanced Accelerator Experimental Tests (FACET-II), which focuses on PWFA research and development, accurate emittance measurements are crucial for understanding and optimizing the accelerator's performance. This is particularly important given the challenges associated with maintaining low emittance in high-energy gain acceleration scenarios.

To facilitate emittance analysis and streamline the process of extracting relevant data, a MATLAB App Designer GUI has been developed. This GUI serves as a user-friendly tool for accelerator physicists at FACET-II, allowing them to efficiently determine emittance values and associated data for various experimental datasets. The GUI is designed to provide quick access to images generated by dipole spectrometers, which reveal information about the energy spread and beam width correlations within recorded spectra.

The development of this GUI represents a significant advancement in the capabilities of the FACET-II team, enabling them to make informed decisions about beam quality and emittance control in their PWFA experiments. With this tool at their disposal, researchers can more effectively fine-tune their accelerator setups and achieve improved results in their quest for high-energy particle acceleration.

II. APP DESIGN

The emittance analysis app which is stored as F2_Emit is designed to be an aid for the scientists to easily and quickly analyze beam profile data from the dipole spectrometers. By loading the experiment and data set ID, the GUI searches the NAS to find the available cameras for the selected data set. Once the camera and image number have been selected, other various parameters auto-populate by drawing from the DAQ

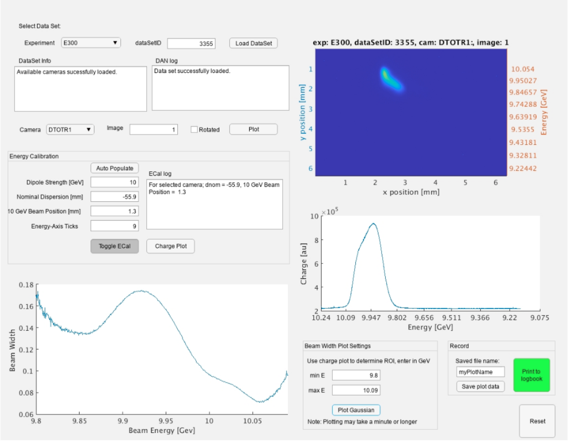
Select Data Set:
Experiment: E300
dataSetID: 3355
DataSet Info: Available cameras sucessfully loaded.
DAN log: Data set successfully loaded.
Camera: DTOTR1
Image: 1
☐ Rotated
Dipole Strength [GeV]: 10
Nominal Dispersion [mm]: -55.9
10 GeV Beam Position [mm]: 1.3
Energy-Axis Ticks: 9
ECal log: For selected camera; dnom = -55.9, 10 GeV Beam Position = 1.3
Use charge plot to determine ROI, enter in GeV
min E: 9.8
max E: 10.09
Note: Plotting may take a minute or longer
Saved file name: myPlotName

FIG. 2. The emittance analysis app with a loaded sample data set.

metadata as well as pre-loaded camera information of the selected image including: pixel to position conversion in mm, proper pixel calibration for previously selected regions of interest already present in dataset, and image orientation such that the energy spread axis is always along the y-axis of the plot (which can be overridden in case of changes to camera orientation). Metadata concerning the conversion of the vertical position of data on the dipole spectrometer from mm to GeV is also pre-loaded. Such information includes: dipole strength (loaded upon pressing the "Auto Populate" button, will update if specified for a given dataset, otherwise automatically set to 10 GeV), nominal dispersion from the top of the spectrometer screen to the infinite energy axis, and the position of the beam at 10 GeV. In the case that any pre-loaded value is for some reason incorrect or does not match user expectations they can be manually updated by the user.

F2_Emit is able to provide three plots pertaining to the spectrometer data, the first of which being the actual profile monitor of the beam energy spread. This allows the user to see the densities of energies present within the particle bunch with reference to their transverse position. Next is the charge plot which makes a vertical projection of the beam profile into an easily legible graph that can be expressed in either energy or position versus charge. This plot allows the user to better identify what energies are represented in beam and in what densities. This is especially useful in determining the specific ROI for the last plot; the beam energy versus beam width. This plot takes a gaussian fit of the intensity profile along each energy "slice" of the beam profile then compiles a plot of each energy value versus the width of the gaussian for the respective energy "slice." This provides correlated vectors for beam width as a function of energy which can be used in the equation specified in the "remaining steps" to output a specific value for emittance. However, this plot also stands alone as a valuable insight into the phase coherence of the particle bunch.

III. WORK FLOW AND ACCESSIBILITY

For best functionality of the app, the following steps should be taken in order to analyze spectrometer data: Select experiment, enter specific dataset ID and press "Load DataSet" button, select camera from the preloaded options, enter image for analysis and press "Plot" button, press the "Charge Plot" button, select the "Auto-Populate" button and make sure all calibration values are correct, specify desired number of energy tick marks, note that for cameras with larger ROIs such as LFOV, less tick marks are required than for cameras with smaller ROIs such as DTOTR Press "Toggle ECal" button - note that this button is a toggle and can be reversed to return to position values - if for some reason energy values are incorrectly spaced, try toggling and un-toggling ECal. Next, use energy calibrated charge plot to enter minimum and maximum energies to apply to beam width plot, note that energy decreases from left to right, min E and max E should still be entered accordingly. Note that the gaussian plot is especially sensitive to noise as it takes a series of gaussians - as such it is important to choose the energy ROI carefully to ensure the plot does not get overwhelmed by useless and noise. The number of tick marks on energy axis can be increased to ensure precise choice of ROI. Finally, press the "Plot Gaussian" button.

The app can be found in the path:
fphysics/USER/git_work/matlabTNG/F2_Emit.

IV. REMAINING STEPS

There are some features that still require work such that F2_Emit can function completely. Most importantly is to Use outputted values for beam energy vs. beam width (which have already been stored as correlated vectors) to calculate transport matrix elements and plug into equation 1 to output an actual value for emittance.

$$(\sigma_X(E))^2 = \frac{\varepsilon_n}{\gamma_b(E)}[M_{11}(E)^2\beta_0 - 2M_{11}(E)M_{12}(E)\alpha_0 + M_{12}(E)^2\frac{1+\alpha_0^2}{\beta_0}] \tag{1}$$

α_0 and β_0 are twiss parameters, γ_b is the Lorentz factor, σ_x is the horizontal beam width, ε_n is the emittance, and M are the transport matrix elements.

V. CONCLUSION

This paper has detailed the development of a user interface, F2_Emit, designed to streamline the analysis of beam emittance data within the context of Plasma Wakefield Acceleration (PWFA). Emittance, a critical parameter governing the phase coherence and quality of particle beams, plays a pivotal role in PWFA experiments, impacting beam transport, beam quality, and final energy spreads. The user interface facilitates the extraction of pertinent data from dipole spectrometers, enabling researchers to assess beam quality and emittance characteristics efficiently.

By empowering accelerator physicists with a user-friendly tool for emittance analysis, F2_Emit enhances the capabilities of PWFA research, enabling researchers to fine-tune accelerator setups, optimize beam quality, and achieve precise beam control. This development represents a significant advancement in the field, ultimately contributing to the realization of PWFA's potential for high-energy particle acceleration. As PWFA continues to evolve, tools like F2_Emit will remain essential for advancing our understanding and harnessing the full potential of this groundbreaking acceleration method.

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