SYSTEMATIC OPTICS STUDIES FOR THE COMMISSIONING OF THE AWAKE ELECTRON BEAMLINE

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Abstract

The commissioning of the AWAKE electron beam line was successfully completed in 2018. Despite a modest length of about 15 m, this low-energy line is quite complex and several iterations were needed before finding satisfactory agreement between the model and the measurements. The work allowed to precisely predict the size and positioning of the electron beam at the merging point with the protons inside the plasma cell, where no direct measurement is possible. All the key aspects and corrections which had to be included in the model, precautions and systematic checks to apply for the correct setup of the line are presented. The sensitivity of the ~18 MeV electron beam to various perturbations, like different initial optics parameters and beam conditions, energy jitters and drifts, earth's magnetic field etc., is described.

INTRODUCTION

The self-modulation of a 400 GeV high intensity ($3{\cdot}10^{11}$) proton bunch in a plasma was observed for the first time in 2016 by the AWAKE experiment at CERN [1]. The creation of wake-fields inside the plasma could then be probed by injecting a ~18 MeV witness electron beam which was accelerated up to 2 GeV [2] at the exit of the 10 m long plasma cell.

The electron beam is produced by an RF gun [3] and is transported towards the plasma cell through a 15 m transfer line [4]. The line consists of a first triplet which is mainly used for emittance and optics measurements. A vertical dogleg and a horizontal achromat are used to merge the electron beam with the protons. They consist of two pairs of dipoles which bend the beam first vertically by ±18° and then horizontally by 2×32°. A final focusing system, composed by a triplet of quadrupoles, allows to tailor the transverse beam size to the experiment requirements. Finally, a system of correctors is used to steer the electron beam and inject it either on-axis or with an offset and an angle with respect to the proton beam.

DESIGN PARAMETERS AND EXPERIMENT REQUIREMENTS

The original beam and optics parameter specifications, which were used for the design of the electron beam line, are shown in Table 1. The beginning of the line corresponds to the entrance of the first quadrupole of the initial triplet.

Table 1: Beam and Twiss ($\beta_{x,y}, \alpha_{x,y}$) parameter specifications which were used for the design of the AWAKE electron beam line

Parameter	**Value**
Momentum [MeV/c]	10-20
Momentum spread $\Delta p/p$ [%]	0.5
Electrons per bunch [10^9]	1.2
Initial $\beta_{xi,yi}$ [m]	5
Initial $\alpha_{xi,yi}$ [rad]	0
R.M.S. normlalised emittance ε_n [mm mrad]	2
$\sigma_{xf,yf}$ at focal point [mm]	0.25

The transverse beam size is defined as:

$$\sigma_{xf,yf} = \sqrt{\beta_{xf,yf}\varepsilon_{x,y} + (D_{xf,yf}\Delta p/p)^2} \qquad (1)$$

where $\varepsilon_{x,y}$ is the geometric emittance (e.g. the ratio between ε_n and the relativistic factor $\beta\gamma$) and $D_{xf,yf}$ the dispersion at the focal point. The experiment requires to be able to know the position of the focal point and the spot size with the best possible accuracy. These parameters can only be predicted from the model since no direct measurement is possible inside the plasma cell. At the best, a ±15% accuracy within ±10 cm can be expected.

ACCEPTANCE STUDIES

The nominal longitudinal position of the focal point is at a 10 mm diameter iris which determines the start of the plasma cell. The possibility of varying the longitudinal position of the focal point while keeping the transverse spot size variation ≤20% and the beam transmission through the iris ≥95% is requested by the experiment. Moreover the option of injecting the electrons with a vertical offset and an angle with respect to the plasma channel axis has to be granted since, according to simulations, this allows to optimise the wakefield capture efficiency [5]. In case the design parameters in Table 1 can be achieved, all conditions are fulfilled focusing the beam up to 0.8 m inside the plasma cell. By relaxing the requirements on the spot-size to twice the nominal value, the focal point can be moved 3.9 m downstream of the iris when injecting with up to a 3 mm vertical offset (Fig.1). Any deviation from the design beam parameters, which causes an increase in the beam dimensions (larger ε_n and/or $\Delta p/p$), determines a reduced flexibility. Also the local earth magnetic field (42 μT and 22 μT in the horizontal and vertical plane respectively) has a non-negligible effect on the low energy electrons and has to be taken into account [6]. The

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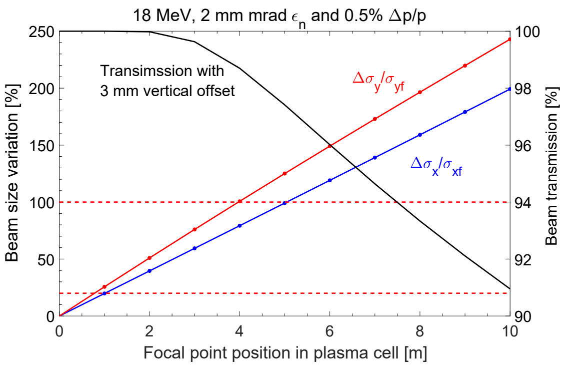

Figure 1: Horizontal and vertical beam size variations with respect to the nominal 250 μm when moving the focal point from the iris up to the end of the plasma cell (left axis). Also the beam transmission when applying a vertical offset of 3 mm is shown (right axis).

last two orbit correctors at the end of the line can be used to compensate for that with kicks of the order of a few mrad. This allows to maximise the transmission and properly steer the beam to perform either on-axis or of off-axis injection.

Momentum Acceptance

The strong quadrupole and bending magnets in the AWAKE electron beam line make it particularly sensitive to chromatic aberrations and energy errors (Fig 2). A knowledge of the central momentum at the 0.1% level (~20 keV) allows to control the optics and predict the transverse beam size at the focal point with the required precision.

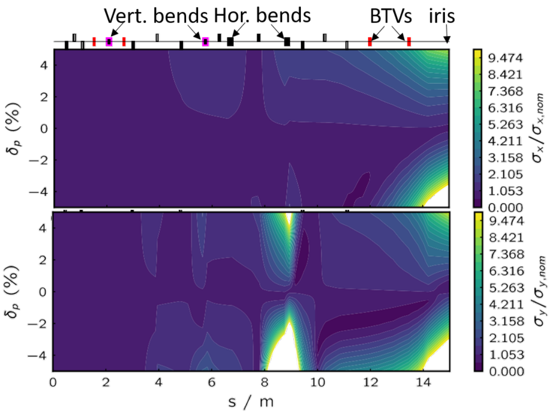

Figure 2: Horizontal (top) and vertical (bottom) beam size variations along the electron beam line due to momentum errors (δ_p). The largest variations are observed at the last horizontal dipole, at the beam profile monitors (BTVs) and the iris at the end of the line.

A python script was deployed which allows measuring the momentum of the beam and matching the line accordingly. In particular, the script changes the strength of all the magnets in the line as to normalise it to different momenta. This is equivalent to varying the energy of the beam while keeping the optics unchanged. The position of the beam at two Beam Position Monitors (BPMs), which are installed in the vertical dog-leg at a relative betatronic phase advance of ~180°, is recorded for the different momenta. When the optics is matched to the beam momentum ($\delta_p = 0$), the following relation between the vertical beam positions ($y_{1,2}$) and the β-functions ($\beta_{y1,y2}$) at the two BPMs can be written:

$$\frac{y_1}{\sqrt{\beta_{y1}}} = \frac{y_2}{\sqrt{\beta_{y2}}}. \tag{2}$$

The beam energy can be calculated by plotting these values as a function of the equivalent momenta and identifying the crossing point between the two curves (Fig. 3). The theoretical β-functions, as calculated by MADX, are used. The initial conditions have to be systematically measured and the optics adapted accordingly in order to keep the momentum error within specifications. The condition $\delta_p \leq 0.1\%$ is fulfilled for up to 40% difference between real and theoretical local β_y. Also energy drifts and jitters affect the optics and have to be carefully kept under control to ensure the reproducibility of the line.

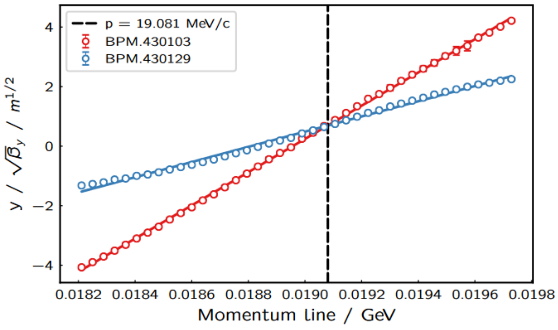

Figure 3: Measured vertical position, normalised with respect to the theoretical β-functions, at the two BPMs in the vertical dogleg as a function of the equivalent beam momenta.

OPTICS MEASUREMENTS

Optics measurements were repeated several times and the theoretical model iteratively adapted based on the different findings until an adequate agreement was found.

Kick Response

A kick-response was performed to check the optics along the full line. This method consists in producing beam oscillations with different amplitude and phase by applying single kicks at all the correctors, both in the horizontal and vertical plane. The comparison between the measured beam position at the different monitors with respect to the theoretical oscillation amplitude allows to assess the consistency of the optics model. An initial large discrepancy, in particular in the vertical plane, was mitigated by including in the model the fringe fields components of the main dipoles (Fig. 4).

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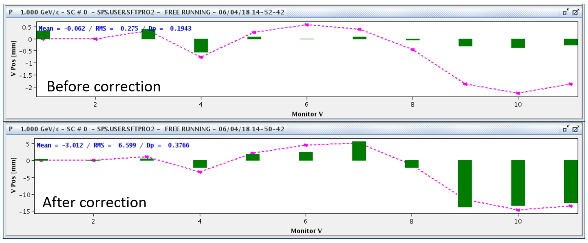

Figure 4: Example of a kick response result before (top) and after (bottom) including the dipole fringe field components in the optics model. The green bars represent the beam position as recorded at the BPMs installed along the line, while the purple line defines the theoretical expected amplitude.

Initial Optics Conditions

The RF gun source can produce different currents (100, 200 and 600 pC) and an accurate setup is needed to optimise the beam quality for each of them (i.e. minimise emittance and momentum spread while maximising the beam stability). Depending on the settings, the optics parameters at the exit of the source can vary and should be systematically measured. The beam-size-free optics determination [7] method is used to measure the Twiss parameters at the beginning of the electron beam line. This method is particularly convenient since it prescinds from the absolute measurement of the beam size and is therefore not affected by systematic errors of the beam-size monitors (BTV). The first two quadrupoles of the initial triplet and a BTV, all installed in a dispersion-free region, are used to perform the scan. The method consists in finding the quadrupole strengths corresponding to the minimum beam size at the monitor. These strengths are then used in a system of two equations, which are derived from the transfer matrix for the propagation of the Twiss parmeters in the lattice, and which represent a curve and a line in the $\alpha - \beta$ plane. The initial optics conditions are given by the solution of the system of equation, i.e. by the crossing between the line and the curve (Fig. 5). The measurements are performed in the horizontal and vertical plane separately and, in order to maximise the accuracy, no thin-optics approximation is applied to derive the equations. For the measurement shown in Fig. 5, an agreement within 10% with the model was found when simulating the scan with MADX. This method is quite sensitive to the quality of the scan and the precision in determining the strengths of the quadrupoles which minimise the beam size. At some occasions, several consecutive scans were repeated in order to obtain satisfactory results.

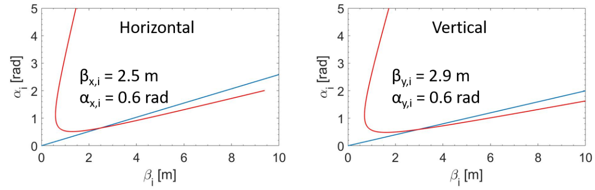

Figure 5: Results of one optics measurement performed using the beam-size-free determination method. The initial Twiss parameters are defined by the crossing of the red curve and the blue line.

Focal Point Scan

Even after matching the line to the measured momentum and adapting the optics according to the measured initial conditions, a discrepancy was found between the theoretical and the real focal point position. In particular, the final triplet strength had to be systematically increased by ~2%, with respect to the values predicted by the model, in order to actually focus the beam at three different BTVs installed in front of the plasma cell. After several investigations, a 1.7% difference between the measured and theoretical quadrupole gradient was discovered. By applying this last correction to the model, the problem of the focal point shift disappeared and a satisfactory agreement was found between predicted and measured beam size. This was evaluated both using the BTVs and, at the iris, by performing aperture scans and recording the losses to reconstruct the beam profile [8].

Dispersion Measurements

The good agreement with the final model is also confirmed by the dispersion measurements as shown in Fig. 6.

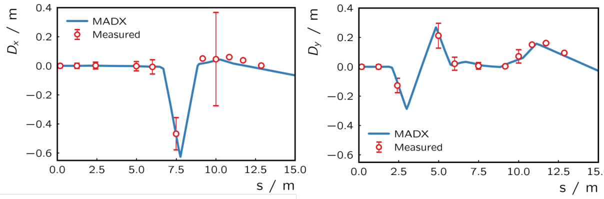

Figure 6: Comparison between measured (red dots) and theoretical (blue line) dispersion along the AWAKE electron beam line after correcting the quadrupole gradient.

The momentum matching data can be used to evaluate the dispersion along the line, once the beam energy is defined. The contribution of the orbit correctors has to be included in the model to fully reproduce the measurements.

CONCLUSION

The commissioning of the AWAKE electron beam line was particularly challenging and took several months. The experiment requires a lot of flexibility while keeping the control of the beam size and the positioning at the injection point. Due to the lack of diagnostics inside the plasma cell, an accurate knowledge of the optics model is required for precise predictions which are then used to reconstruct the physics of the wake-field capture process. The commissioning period allowed to tune and refine the model to be compatible with the experiment needs. A detailed procedure for the correct setup of the line is explained. Moreover, the key parameters, which have to be systematically measured and checked to ensure the consistency between reality and the model, are defined.

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