OPTICS TUNING KNOBS FOR FACET*

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Abstract

FACET is a new facility under construction at the SLAC National Accelerator Laboratory. The FACET beam line is designed to provide 23 GeV tightly focused and compressed electron and positron bunches for beam driven plasma wakefield acceleration research and other experiments. Achieving optimal beam parameters for various experimental conditions requires the optics capability for tuning in a sufficiently wide range. This will be achieved by using optics tuning systems (knobs). Design of such systems for FACET is discussed.

INTRODUCTION

FACET is a new experimental facility under construction at the SLAC National Accelerator Laboratory [1]. It will serve as a replacement for the Final Focus Test Beam [2] which had been dismantled in order to allow the construction of the LCLS [3]. The FACET beam line will be installed in the Sector-20 of the SLAC linac, just upstream of the LCLS. It is designed to deliver tightly focused and compressed electron and positron bunches with up to 23 GeV energy and 3.2 nC bunch charge for beam driven plasma wakefield acceleration research and other experiments. The FACET optics functions from the beginning of Sector-20 to IP are shown in Fig. 1 [4]. The Sector-20 contains a bunch compression chicane, a Final Focus (FF), and $\approx$ 25 m of experimental section with a dump. This line will allow to transport either e^- or e^+ bunches. In the future, a second chicane can be added in this section for simultaneous delivery of e^- and e^+ bunches which can be used as drive and witness bunches in the plasma wakefield acceleration experiment.

Compensation of machine optical errors and achieving optimal beam parameters for various experiments requires the optics capability for tuning in a sufficient range. It is typically achieved by implementing optics tuning systems (see for example [5]). Several such systems designed for FACET are discussed below.

TUNING SYSTEMS

A tuning system uses adjustment of magnet strengths to vary an optics parameter in a specified range. Ideally, it should not affect the other optics parameters and be orthogonal to other systems. For minimal perturbations, it should be as local as possible and use magnets at optimal positions. In some cases the residual effects may not be canceled due to, for example, limited number of available magnets. In this case, one must verify that the perturbations are acceptable. For machine implementation, the tuning systems are often approximated in the form of linear knobs where magnet strengths are changed linearly with the target parameter. Such linear approximation would also result in residual effects which will determine the knob range where such effects are acceptable. Below we describe tuning systems for various FACET optics parameters.

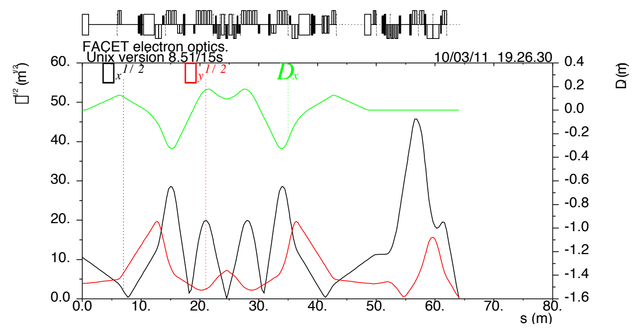

Figure 1: Optics from the beginning of Sector-20 to IP.

IP Beta Functions

The nominal values at the FACET IP are $\beta_x^* = 1.5$ cm, $\beta_y^* = 15$ cm. The ratio of 10 is used to obtain a round beam spot for the linac normalized emittances of $\gamma\epsilon_x = 50$ μm-rad, $\gamma\epsilon_y = 5$ μm-rad. The β^* tuning system uses four out of five Final Focus (FF) quadrupoles. This is sufficient to adjust β_x^* and β_y^* while keeping $\alpha_x^* = \alpha_y^* = 0$. And because the dispersion is canceled in the FF, these quadrupoles do not generate dispersion. For a small change of quadrupole strength ΔKL variation of β^* is:

$$\Delta\beta_{x,y}^* \approx \mp \Delta KL \beta_{x,y}^* \beta_{x,y}^q \sin 2\Delta\mu_{x,y}, \tag{1}$$

where β^q is at the quadrupole location and $\Delta\mu$ is phase advance from the quadrupole to IP.

Various FACET experiments will require different values of β^* in a relatively a large range. As an example, the quadrupole K-values were calculated for the range of β^*/β_0^* from 0.5 to 16 using MAD [6], as shown in Fig. 2, where the beta ratio of 10 was maintained at each point. Similar calculation can be done for separate adjustment of β_x^* and β_y^*. Due to the large range, the strengths in Fig. 2 cannot fit well to a linear knob. In this case, one can split the range in short steps and create a linear knob for each step.

IP Waist Position

Adjustment of longitudinal position of IP waist will allow flexibility for mechanical layout of various experimen-

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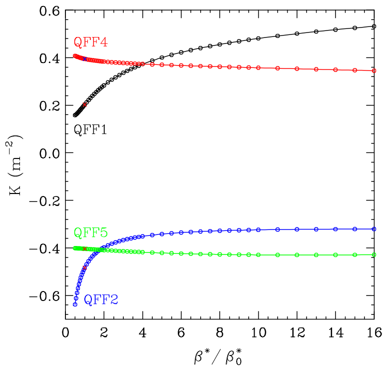

Figure 2: FF quadrupole K-values for tuning β^*.

tal hardware. A smaller variation will be used to compensate possible machine errors. For a small change of quadrupole strength ΔKL, the waist shift is:

$$\Delta s^*_{x,y} \approx \pm \Delta KL\, \beta^*_{x,y} \beta^q_{x,y} \cos 2\Delta\mu_{x,y}. \qquad (2)$$

As for the β^* tuning, the same four FF quadrupoles can be used to vary the IP waist position in a large range as shown in Fig. 3, where β^* is kept constant. Even larger shifts are possible (3-4 m), but with somewhat larger β^* value in order to avoid too high β functions in the FF quads.

Another system was constructed using chicane quadrupoles located upstream of the FF. This may be useful in the future FACET upgrade when the second chicane is added for simultaneous e^- and e^+ transport. In this case the FF quads are shared by the two bunches, so they will affect the waist for both e^- and e^+. Therefore, for separate adjustment of the e^- or e^+ waist one can use quadrupoles in the corresponding chicane. Due to the non-zero chicane dispersion, these quadrupoles will also generate IP dispersion. This effect has to be canceled or minimized to acceptable level in the knob design. An example of a linear β^*_x waist shift knob using four chicane quadrupoles is shown in Fig. 4, where the dash lines represent the linear knob fit for the matched K-values (solid). This knob provides a small tuning range suitable for corrections of machine errors. The four quadrupoles, however, are not sufficient for exact optics match. This results in residual $\Delta\beta^*/\beta^*$ of up to 10% and IP dispersion of up to 0.2 mm. These distortions would cause up to a few percent change of IP beam size which seem to be

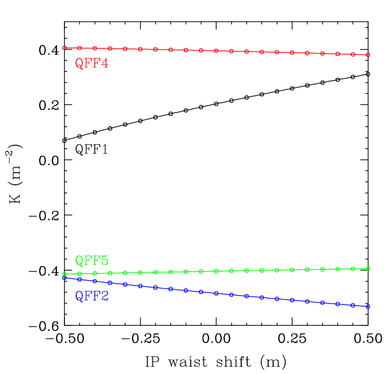

Figure 3: FF quad K-values for tuning IP waist position.

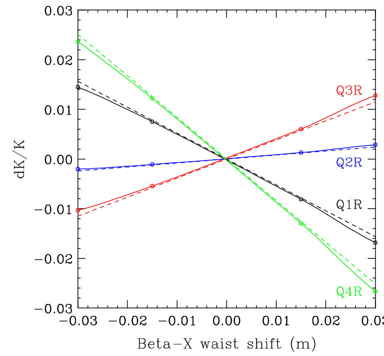

Figure 4: Chicane quadrupole $\Delta K/K$ values for tuning β^*_x waist position. Dash - linear knob, solid - MAD match.

acceptable. Moreover, they can be iteratively reduced by other knobs.

IP Dispersion

The nominal IP dispersion is canceled by the design. However, its adjustment can allow deliberate correlation between horizontal and longitudinal motion on the beam through the correlated energy spread in the bunch for studying instabilities such as electron hose in the plasma wakefield experiment. In order to create the IP dispersion $\Delta\eta^*$, one or more of tuning quadrupoles must be in the dispersive region because the effect is proportional to dispersion η^q at quadrupole location:

$$\Delta\eta^*_x \approx -\Delta KL\, \eta^q_x \sqrt{\beta^*_x \beta^q_x} \sin \Delta\mu_x. \qquad (3)$$

An example of a linear dispersion knob using 5 chicane quadrupoles and 3 FF quadrupoles is shown in Fig. 5. The provided dispersion range is ± 2 mm which seems adequate. This knob leaves small residual perturbations of $\Delta\beta^*/\beta^*$ up to 10% and dispersion slope up to 50 μrad at the IP which are acceptable.

Variation of R_{56}

Bunch compression is achieved through optimization of the linac RF accelerating phase and R_{56} values in the bending sections. The Sector-20 chicane provides $R_{56} = 4$ mm for the final stage of compression. Ability to vary the R_{56}

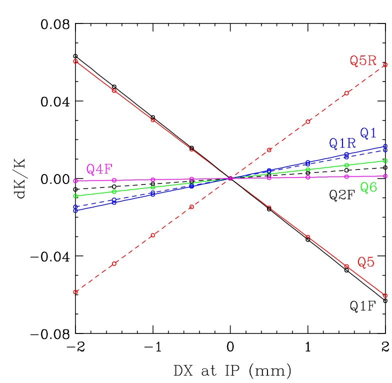

Figure 5: Quad $\Delta K/K$ values for tuning IP dispersion.

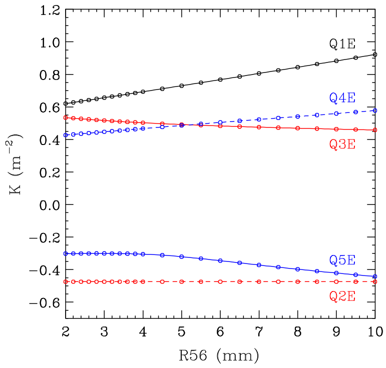

Figure 6: Quadrupole K values for variation of R_{56}.

will add flexibility for the bunch compression as well as for two bunch production using the notch collimator for plasma wakefield experiment. Variation of R_{56} requires adjustment of dispersion at dipoles in the chicane which can be achieved by adjustment of the chicane quadrupole strengths. Fig. 6 shows matched quadrupole strengths for the range of R_{56} from 2 to 10 mm which is adequate for most applications. The strength variation is rather linear for the ranges above and below the nominal R_{56}, hence two linear knobs may be constructed for these ranges.

Plasma Density Variation

In the plasma wakefield acceleration experiment the bunches will travel through plasma installed after the IP. The effect of plasma is an extremely strong focusing on the beam. In linear approximation, it is similar to quadrupole focusing, but equal in both transverse planes. The corresponding K-value is $K = 3.9337 \cdot 10^4 (\frac{n}{10^{17}})(\frac{23}{E})$, where $n[cm^{-3}]$ is plasma density and $E[GeV]$ is beam energy. For a typical density range from 10^{16} to $3 \cdot 10^{17} cm^{-3}$ this K-value is 4 orders higher than in the FF quadrupoles which results in the "matched" plasma β function $\beta_m = 1/\sqrt{K}$ as low as 3 mm. It is desirable to attain a constant beam size through the plasma, therefore one must try to match the IP β functions to the plasma β_m value to avoid β beating. Since the plasma density will vary for different experimental conditions, the β match should be tunable.

The plasma was modeled in MAD using a sequence of matrix elements producing equal X and Y focusing and $K\Delta L \sim n(s)$ according to density profile in Fig. 7. For a good approximation the drift length ΔL between matrix elements must be small: $(\Delta L)^2 \ll 1/K$. For a given density n_0 at plasma center, the match can be achieved by variation of β^* value and IP waist position relative to plasma. However, due to equal X and Y plasma focusing, an exact match from IP to plasma separated by a drift is only possible when $\beta^*_x = \beta^*_y$. For FACET condition with $\beta^*_y = 10\beta^*_x$ one can either match in one plane leaving the other plane unmatched or minimize β beating in both planes as shown in Fig. 8. The latter option seems more appropriate for the plasma wakefield experiment. The corresponding variations of β^*_x (with $\beta^*_y = 10\beta^*_x$) and distance from IP to the beginning of plasma constant density section are shown in

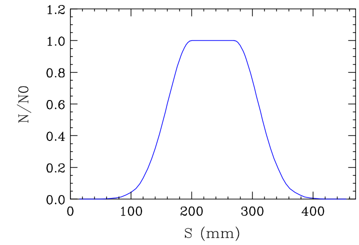

Figure 7: Normalized plasma density profile where tails are modeled as $\frac{n}{n_0} = e^{-\frac{(s-s_0)^2}{2\sigma_s^2}}$ with $\sigma_s = 39.71$ mm.

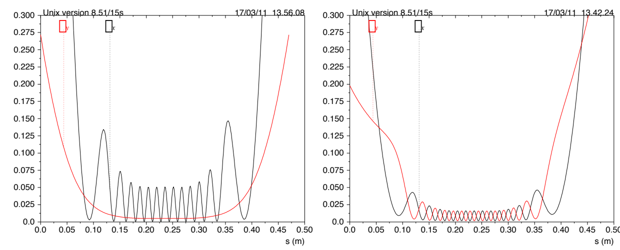

Figure 8: Examples of match in one plane (left), and minimal β beating in both planes (right) for $n_0 = 10^{17} cm^{-3}$.

Fig. 9. These variations can be produced by the β^* and IP waist tuning systems described earlier.

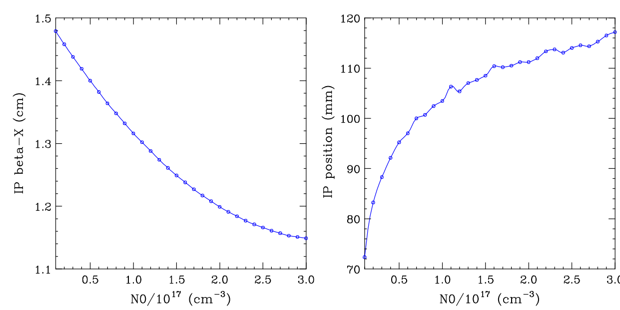

Figure 9: β^*_x ($\beta^*_y = 10\beta^*_x$) and distance from IP to the beginning of plasma constant density section versus n_0.

SUMMARY

Several optical tuning systems have been designed for FACET to vary the IP β functions and dispersion, the IP waist position, the R_{56}, and plasma density in the desired range. Linear knobs for machine operation can be constructed based on these systems.

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