DESIGN OF A NEW BEAMLINE FOR THE ORGAD HYBRID RF-GUN AT ARIEL UNIVERSITY

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Abstract

The ORGAD Hybrid RF-gun was commissioned in Ariel University. The main beamline of the hybrid S-band (2856 MHz) photo injector is currently driving a 150 kW, short pulse THz-FEL. In order to use the RF gun for other applications, a new and independent beam line is required. A secondary beamline is only feasible with the design of a dispersive beam-line dogleg section. High quality beam is crucial for the designated applications such as Ultra-fast Electron Diffraction (UED). The design is based on transfer matrices analytical model followed by simulations. Full 3D GPT (General Particle Tracer) simulations were done on this secondary beamline in which we manipulate and compress the beam to maintain beam emittance and pulse duration. An optimization procedure of the design using realistic field-maps and fringe fields of the quadrupoles was performed to reconstruct the electron beam quality parameters after passing through the dispersive dogleg section. The optimization results demonstrate improved beam quality are presented.

INTRODUCTION

The main beamline of the hybrid S-band (2856 MHz) photo injector [1] ORGAD accelerator is currently used to drive a 150 kW, short-pulse THz-FEL. Using a 90 cm Undulator the THz-FEL is emitting super-radiantly (radiation emitted coherently from all the electrons within the pulse [2]) at 1–3 THz. In order for the electrons to emit coherently in the super-radiant regime, the emitting electron bunch must be shorter than the wavelength of the emitted radiation, in this case less than 100 µm.

A new and independent beam line is required for additional e-beam emission based experiments such as MeV-UED, Compton scattering, noise suppression and enhancement schemes, sub-radiant emission, etc. This secondary beamline is feasible with the design of a dogleg section [3]. A dogleg is constructed of two dipole sections, with higher-order magnetic electron-optics such as quads and sextupoles, added to prevent dispersion. The construction of a dogleg requires a full 3D start-to-end simulations of the entire RF GUN and beamlines. In this work, simulations were carried out using the General Particle Tracer code (GPT), and optimization procedure [4] was performed on these simulations using realistic field-maps. Figure 1 shows the two beamlines and the beam-optics elements. The major challenge in the design was maintaining beam parameters at optimal values for the additional e-beam emission based experiments.

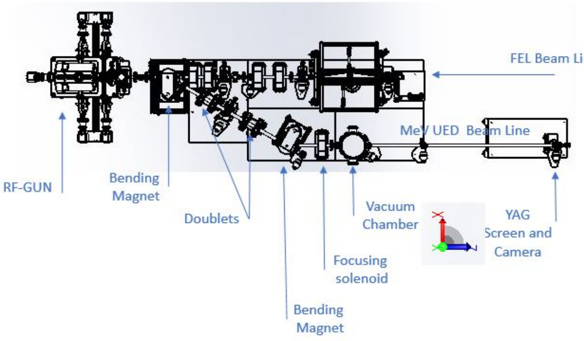

Figure 1: Ariel University's Hybrid Gun. The top beamline is the superradiant THz FEL. The lower beamline is designed for different experiments such as MeV-UED.

DESIGN

The hybrid gun was designed to produce an extremely short pulse in order to emit THz super-radiantly. For this reason, the traveling-wave section of the gun is used to apply a negative chirp on the beam. This is achieved by setting a phase difference of $-\frac{\pi}{2}$ between the standing wave and the traveling-wave sections. However, if required, this phase difference can be varied, resulting with a higher beam energy, or a positive chirp. A dogleg section is designed as a bunch compressor and a positive chirp at the entrance is essential. The planned oblique section of the dogleg design is symmetric around its center and consists of two doublets (focusing and defocusing quadrupoles), with the defocusing quadrupoles facing the center of the section. Sextupole magnets are located on the top of, or next to, the focusing quadrupoles to decrease second order longitudinal dispersion (Fig. 2).

This symmetric configuration of the dogleg electron-optics suggests a preferred beam transport design in which the longitudinal waist is located at the center of the section. Thus, the beam arrives to the center with a positive chirp and emerges with a negative chirp. We begin with an analytical model based on transfer matrices [3] before starting the numerical simulation and optimization procedure. We calculate the transport matrix of the entire dogleg system as the product of the thin lens first order (see Eq. (1)) and second order matrices of the electron optical elements [3].

We find out the value of the longitudinal dispersion parameter at the center of the dogleg, for our given electron optics configuration using the analytical expression (Eq. (2)) to be $R_{56} = -0.0297$ m. The second order matrices were solved analytically using a MATLAB script. The second order dispersion element T_{566} obtained is -0.63 m with no

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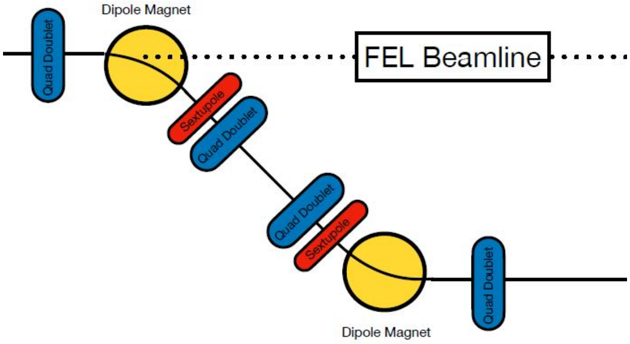

Figure 2: Schematics of the dogleg section with its electron-beam optical elements. Dipole magnets in Yellow, Quadrupoles doublets in Blue and Sextupoles in Red.

Sextupoles.

$$\begin{bmatrix} x(t) \\ x'(t) \\ y(t) \\ y'(t) \\ l(t) \\ \delta(t) \end{bmatrix} = \begin{bmatrix} R_{11} & R_{12} & 0 & 0 & 0 & \eta_x \\ R_{21} & R_{22} & 0 & 0 & 0 & \eta'_x \\ 0 & 0 & R_{33} & R_{34} & 0 & 0 \\ 0 & 0 & R_{43} & R_{44} & 0 & 0 \\ R_{51} & R_{52} & 0 & 0 & 1 & \eta_z \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x_0 \\ x'_0 \\ y_0 \\ y'_0 \\ l_0 \\ \delta_0 \end{bmatrix} \quad (1)$$

$$R_{56} = \eta_z = \frac{L}{\beta^2\gamma^2} - \alpha\rho + \frac{\alpha\rho}{\gamma^2} + \rho\sin(\alpha) \quad \text{(center of dogleg)} \quad (2)$$

SIMULATIONS

Full 3D simulations of the hybrid RF-gun and its parallel beamline including full space-charge effects were performed using GPT. The simulations start from the cathode, with randomized normal distribution of particles, using a charge of -30 pC. As mentioned previously the dogleg section is designed as a bunch compressor with a positive chirp at the entrance. The chirp at the end of the dogleg will become negative and a drift section downstream the dogleg will allow us to obtain a waist at a location of our choice Fig. 3. We set the ”sweet-spot” of this simulation to be 5 m downstream from the cathode, at the designated vacuum chamber. A significant beam-quality degradation was expected downstream the dogleg and the purpose of this process was to minimize the degradation and obtain optimal parameters for the secondary parallel beam-line.

The simulation goal is optimal emittance and bunch length parameters at this ”sweet-spot” location. This procedure was continuously compared to the analytical calculations. The transverse emittance analytical expression includes several first order (R_{16},R_{26}) and second order (T_{166}, T_{266}) dispersion elements. The first order dispersion elements are minimized using the quadrupoles doublets, while the second order dispersion elements values, T_{566}, are both minimized by the sextupoles. Both the first and second longitudinal dispersion corrections minimize the transverse emittance value.

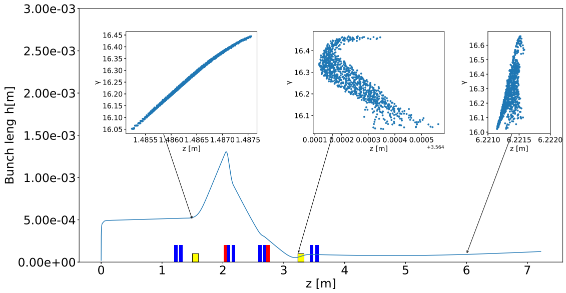

Figure 3: Electron bunch length along the beam trajectory. Longitudinal phase-space at locations before during and downstream the dogleg are presented in frames.

OPTIMIZATION PROCEDURE

We suggested an optimization procedure on the design of the beam-line with the dogleg, aimed to reconstruct the electron beam quality parameters after passing through the dispersive section. The optimization process was performed on a large number of variables as was possible. Typical field maps for quadrupoles in simulation software were based on ideal field maps and included non-fringe field components. The Quadrupoles were modeled using a realistic 3D field map imported from CST. In the first optimization process we iterated through four different parameters:

- L1- The doublet location. The distance from the dogleg dipoles (center of dipole) to the doublet centers.
- L2- The gap in the doublets (between the centers of the focusing and defocusing quadrupoles).
- gf- The focusing quadrupole magnetic field gradient.
- gd- The defocusing quadrupole magnetic field gradient.

The optimization process consisted of iterating through all parameters, exploiting the fact that the dogleg section between the two bends is symmetric, which enables variation of both doublets parameters simultaneously. To find the optimal locations and field strengths of the quadrupoles we define a figure of merit: $A = \epsilon_x \cdot \sigma_z$ for which we search for a minimal value as a function of the desired parameters, Fig. 4.

In the other optimization step, we added two sextupoles on top of the quadrupoles (or positioned next to the doublets). Sextupole field gradients optimization was performed on the ideal GPT sextupole model. Our code scanned the first sextupole field gradient parameter, while the second sextupole field gradient parameter polarity was inverted. Sextupole field values were derived in a similar method such as in the quads optimization, by plotting a contour map for the parameter A. For a charge of -30 pC and beam energy of 7.8 MeV the optimization procedures resulted in recompression of the electron beam to a length of σ_z= 37 µm and an emittance of ϵ_x= 1.48 µm. These results show minor degradation of beam normalized emittance and pulse duration.

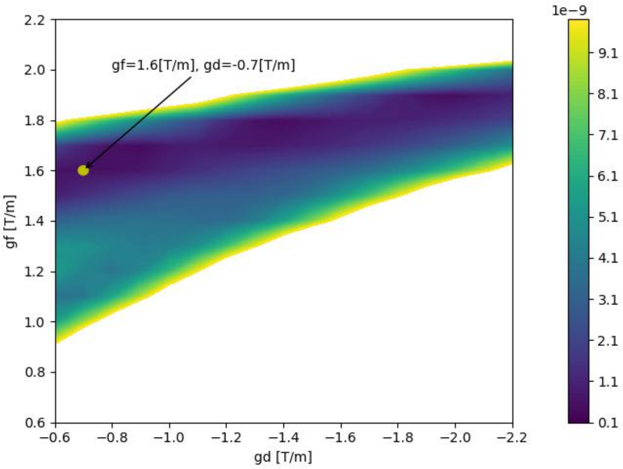

Figure 4: Contour map of beam parameter A. Y axis is beam optics focusing quad gradient and x axis is the defocusing quad gradient strength. Using the selected value (using the minimal value of the parameter A) marked in a yellow dot, we obtain the required magnetic field gradients of the quad doublets.

CONCLUSIONS

We performed an analytical design and full 3D simulations of a dogleg section for a secondary parallel beam-line driven by a hybrid RF photo-injector. Optimization procedure presented here, based on realistic consideration of simulated and measured field maps of quadruples, enables recuperation of beam parameters after a dispersive dog-leg. The optimized recuperated beam parameters attainable for the ORGAD RF-Linac are suitable for operation in high quality beam demanding applications as UED.

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