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PHYSICS DESIGN OF ELECTRON FLASH RADIATION THERAPY BEAMLINE AT PITZ

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Abstract

The Photo Injector Test facility at DESY in Zeuthen (PITZ) is preparing an R&D platform for electron FLASH radiotherapy, very high energy electron (VHEE) radiotherapy and radiation biology based on its unique beam parameters: ps scale bunches with up to 5 nC bunch charge at MHz bunch repetition rate in bunch trains of up to 1 ms in length repeating at 10 Hz. This platform is called FLASHlab@PITZ. The PITZ beam is routinely accelerated to 22 MeV, with a possible upgrade to 250 MeV for VHEE radiotherapy in the future. The 22 MeV beam will be used for dosimetry experiments and studying biological effects in thin samples in the next years. A new beamline to extract and match the beam to the experimental station is under physics design. The main features include: an achromatic dogleg to extract the beam from the PITZ beamline; a sweeper to scan the beam across the sample within 1 ms for tumor painting studies. In this paper, the beam dynamics with bunch charges from 10 pC to 5 nC in and the preparation of the new beamline will be presented.

INTRODUCTION

The FLASH radiation therapy (FLASH-RT) has drawn worldwide attention in recent years for its reduced damage to healthy issues [1, 2]. FLASH-RT usually uses an ultra-high peak dose rate (>40 Gy/s), that is two orders of magnitude higher than that in conventional radiotherapy and thus needs much shorter treatment time. While the underlying biological mechanisms are still not fully understood, a broad parameter space study will help to define the optimal working window for FLASH-RT. Therefore, the Photo Injector Test facility at DESY in Zeuthen (PITZ) has proposed an R&D platform for electron FLASH-RT as well as very high energy electron (VHEE) radiotherapy and radiation biology. This platform, called FLASHlab@PITZ, will take advantage of the unique beam parameters at PITZ. The PITZ accelerator runs in the RF burst mode, with an RF pulse length up to 1 ms and a repetition rate at 1-10 Hz. The electron bunches in the RF pulse repeat at a frequency of 1 MHz, making a bunch train of 1000 at maximum. Meantime, the bunch charge can be tuned from sub-pC to 5 nC. The 22 MeV beam will be used for dosimetry experiments and studying biological effects in thin samples in the next years [3]. The very flexible electron beam parameters and widely tunable dose distributions and rates are summarized in Table 1. In this paper, we report the beam dynamics studies performed at a few typical bunch charges up to 5 nC.

Table 1: Parameter Space Summary for FLASHlab@PITZ

Parameters	**Low dose case**	**High dose case**
Energy	22 MeV	22 MeV
Charge	0.1 pC	5 nC
Single bunch	single	bunch train
or train	bunch	1 ms × 1 MHz
RF pulse rep. rate	1 Hz	10 Hz
Dose per bunch	0.0002 Gy	10 Gy
Peak dose rate within train	-	1×10^7 Gy/s
Avg. dose rate	0.0002 Gy/s	1×10^5 Gy/s

* Assuming e-beam in water with 1 cm^3 irradiation volume.

DESIGN OF FLASH-RT BEAMLINE

The PITZ photoinjector consists of an L-band RF gun with a CsTe semiconductor photocathode, a cut-disk-structure (CDS) booster accelerator and various transport and diag-nostic devices, e.g., momentum spectrometers, phase space scanner, steerer and quadrupole magnets. The gun runs at a gradient ≤ 60 MV/m, providing a maximum beam energy of 6.2 MeV. After acceleration in the booster, the beam energy can reach as high as 22 MeV. Then the beam will travel a long way before being sent to a downstream undulator in the tunnel annex (~25 m downstream the photocathode) for the generation of THz radiations, as shown in Fig. 1.

The new FLASH-RT beamline will be installed in the tunnel annex, in parallel with the THz free electron laser (FEL). The electron beam will be translated by ~22 m with a dogleg, which consists of two dipole magnets which deflect the beam in opposite directions with bending angles of 60 degrees and two pairs of quadrupole magnets. To remove dispersive effects at the dogleg exit, the strengths of quadrupoles in the dogleg should be properly chosen. This can be done with transfer matrix method, as implemented in the software Elegant [4]. By making it achromatic (i.e., $\eta_x = 0$, $\eta_x' = 0$), the beam quality degradation due to energy dispersion is minimized, which is especially critical at high

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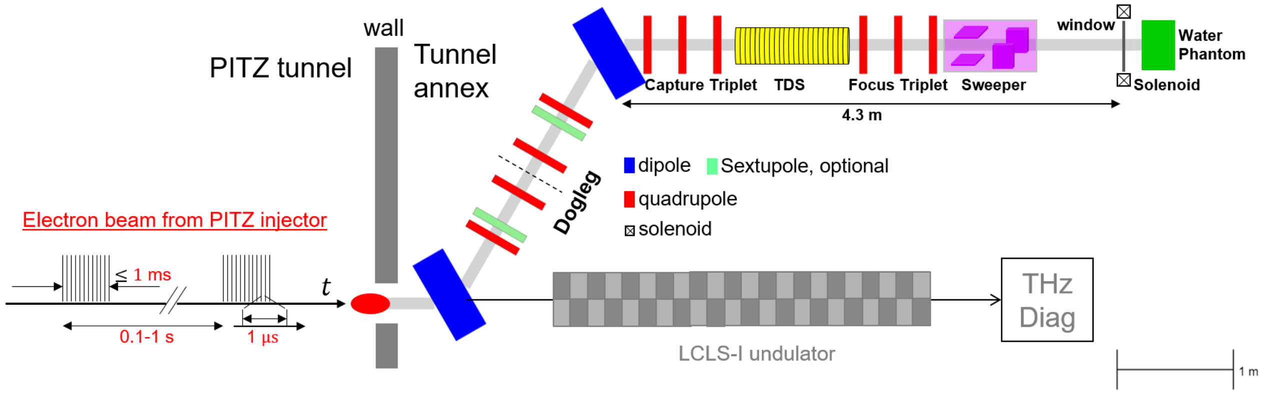

Figure 1: The layout of the FLASH radiation therapy beamline at PITZ.

charges. The transfer matrix of the achromatic dogleg has a nonzero R56 (0.11 m here), which allows to manipulate the bunch length by tuning the longitudinal phase space with the booster accelerator phase. A pair of sextupole magnets are being considered to minimize higher order effects. The dispersion functions along the dogleg are shown in Fig. 2. The dispersion was removed by the pair of quadupoles next to the dipoles while the other pair focus the beam in the non-deflection plane.

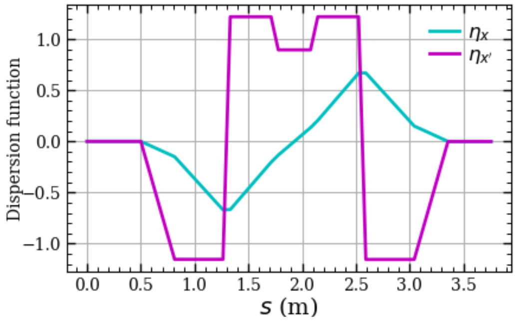

Figure 2: The dispersion functions along the dogleg.

Following the dogleg is a quadrupole triplet that captures the electron beam from it. The quadrupoles can also be used to focus the beam in the measurement of longitudinal bunch profiles by the transverse deflection system (TDS), which prefers a small beam size in the streaking plane for better resolution and also a tight beam in the other plane for higher signal-to-noise ratio. Together with the second quadrupole triplet, it will enable a widely controllable beam size at the exit window: from sub-mm to cm RMS.

In the case of a small focused beam, the electric sweeper can be used to kick the bunch train transversely to cover the sample within less than 1 ms for tumor painting studies. Besides, a short pulsed solenoid installed around the window is under consideration for focusing the kicked electron beams again to the sample, in order to produce a Bragg-peak like dose distribution in the samples [5, 6].

START-TO-END SIMULATION

To ensure the exploration of the full parameter space provided by the PITZ photoinjector, start-to-end simulations have been carried out at four different bunch charges: 10 pC, 100 pC, 1 nC and 5 nC. Below 10 pC, the space charge effects are negligible, therefore simulation results at 10 pC also work for lower charges.

Optimization of Photoinjector

In the simulations, the initial beam distributions were generated according to the photocathode laser at PITZ. The Gaussian laser has a FWHM of 7-8 ps and an adjustable RMS size (typically ~ 1 mm). A so-called beam shaping aperture (BSA) can cut out an approximately uniform transverse distribution when the BSA diameter is small, that works for charges below 1 nC. At 5 nC, a Gaussian truncated distribution is assumed instead, due to the large BSA size necessary for emission. The BSA diameter was optimized at each charge together with the main solenoid current, in order to reduce the beam emittance right after the booster (5.28 m downstream the photocathode). The simulations were done by the particle tracking software Astra [7]. The optimized beams were then matched to the dogleg (25.3 m downstream the photocathode) with the Ocelot code [8], as discussed below. After that, the booster phase was tuned to minimize the energy spread at the dogleg. This step was not done earlier because the space charge effects would change the energy spread during the transport from the booster exit to the dogleg.

In Fig. 3, it shows on the left the beam emittance as a function of the main solenoid current at various BSA diameters and on the right the RMS and correlated energy spread at the dogleg as a function of the booster phase, for the bunch charge of 1 nC. The correlated enegy spread, defined as $\sigma_E^{\text{corr}} = \langle E_k z \rangle / \sigma_z$, measures the correlation between the energy and longitudinal position of the electron bunch. It will be studied in the future for tuning the bunch length by the dogleg. At other charges, similar results have been observed as well.

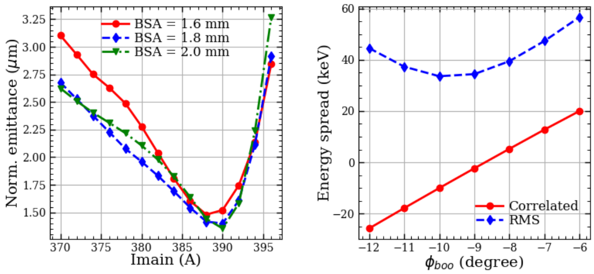

Figure 3: Normalized beam emittance vs solenoid current vs the BSA diameter (left) and correlated and RMS energy spreads vs booster accelerator phase with respect to the maximum mean momentum gain phase (right).

Matching of the Beam into the Dogleg

For the beam transport in the dogleg, a symmetric beam envelop with respect to the midplane of the dogleg (dashed line in Fig. 1) was considered, that means $\alpha_x = \alpha_y = 0$ at the midplane. By scanning the beta functions at the midplane, various beam distributions could be found at the dogleg entrance by back tracking. Under this condition the beam is always converging in the deflection plane at the dogleg entrance. Since the last matching quadrupole upstream the dogleg is far, a small alpha function is favored in the deflection plane to avoid a too big beam size near the last matching quadrupole. At 5 nC, the smallest alpha function found from beta function scan still resulted in a too big beam there due to strong space charge effects, the alpha function was reduced further, making a slightly asymmetric beam envelop in the dogleg, as shown in Fig. 4. The matching process has been simulated at each bunch charge, using a similar strategy described in [9].

In Fig. 4, it shows the beam transport from photocathode ($s = 0$ m) to the exit window ($s = 33$ m) for the four cases, where a symmetric beam envelop can be found in the dogleg (starting from ~ 25 m) for three low charge cases. For all, the RMS beam size near the last matching quadrupole fits well with a 35 mm diameter beam pipe.

Focusing of the Beam at the Exit Window

There are a few application scenarios for the FLASH-RT study at PITZ. For example, the sample could be irradiated by one high charge beam in tens of picoseconds, or irradiated by many strongly focused low charge beams scanned across the sample within 1 ms. The latter could mean better uniformity. In Fig. 4, the beam has been strongly focused for all cases, the resulting beam size ranging from 0.02 mm RMS at 10 pC to 0.5 mm RMS at 5 nC. To demonstrate the adjustable beam size, the 1 nC case has been studied in details. In Fig. 5, it compares the strongly focused beam (left) with an intentionally enlarged beam (right, by a factor of 10) at the position of the exit window. Although the focused beam has a square-like shape due to strong focusing and space charge effects, it is worth noting that the scattering effects in the exit window will dominate the following beam transport, which makes the transverse profiles into a Gaussian distribution after drifting for a few cm in the air [10].

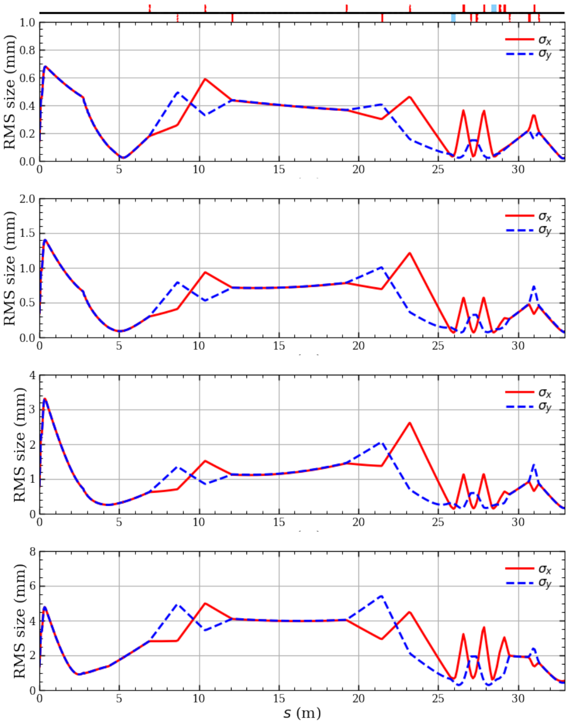

Figure 4: Start-to-end simulations on the beam transport at 10 pC, 100 pC, 1 nC and 5 nC from top to bottom.

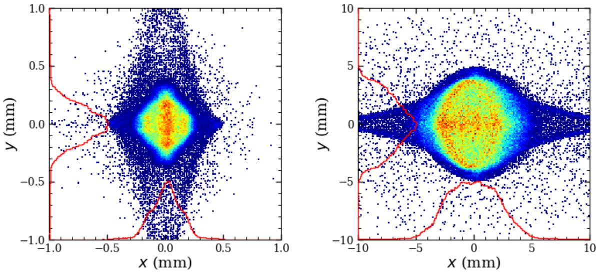

Figure 5: Transverse distributions with the electron beam strongly focused (left) and enlarged by purpose (right).

CONCLUSION

An R&D platform for exploring the wide parameter space at PITZ for studying the FLASH radiation therapy is currently under design. By adding a parallel beamline to the THz FEL in the tunnel annex, the new beamline has been studied by start-to-end simulations and its capability of delivering widely adjustable beam profiles at various bunch charges has been demonstrated. The bunch length manipulation in the dogleg will be studied next and device acquisition will be started in the meantime.

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