FINDING OPERATION CONDITIONS FOR ULTRA-HIGH DOSE-RATE ELECTRON BEAM DELIVERY AT FLUTE

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Abstract

The linac-based test facility FLUTE (Ferninfrarot Linac- und Test-Experiment) at the Karlsruhe Institute of Technology (KIT) was designed to operate over a broad range of beam parameters and to generate ultra-short electron bunches. This versatility enables studies beyond accelerator physics, including applications in medical research. In particular, FLUTE can be used to explore operation modes suitable for investigating the effects of ultra-high dose-rate radiotherapy (FLASH RT) compared to conventional radiotherapy. Achieving the required dose rates for both modalities involved adjusting key beam parameters such as charge, repetition rate, and transverse size. This contribution discusses the strategies used to reach these conditions, the encountered technical challenges, and the results of initial tests on the achievable dose-rate ranges.

INTRODUCTION

With the increase in attention for the FLASH effect caused by ultra-high dose rates (UHDR) in radiotherapy (RT) over the last years, research into the underlying mechanisms and physical requirements has become increasingly important [1]. While it is mostly agreed upon, that the FLASH effect occurs for dose rates above 40 Gy/s, there are other parameters such as pulse length and repetition rate, which affect the average dose rate and the instantaneous dose rate, that depend strongly on the used source of radiation [2].

While clinical linacs operate commonly with pulse duration in the order of microseconds, research accelerators can reach pulse durations in the order of picoseconds. The linac-based test facility FLUTE at KIT is designed to provide electron bunches with bunch lengths down to a few femtoseconds via bunch compression in a magnetic chicane. For experiments towards the FLASH effect, bunch lengths in the order of 1 ps are used. Typical operational parameters are given in Table 1.

Table 1: Operation Parameters for UHDR Experiments

Beam energy	10-30 MeV
Repetition rate	10-50 Hz
Bunch charge	100-350 pC
Bunch length	≈1 ps
Transverse spot size (rms)	≈2-5 mm

For the irradiation experiments, an experimental station was constructed at the end of FLUTE, where the electron beam can be used directly in air before it is absorbed by the beam dump [3]. The exit window from the vacuum section is a 20 µm thick Havar foil.

OPERATION PARAMETERS

The FLASH effect is expected to occur at average dose rates above 40 Gy/s. While clinical linacs provide transverse field sizes of a few centimeters squared, typically up to 20x20 cm, research linacs are typically optimized for small transverse beam sizes in the order of or smaller than 1 mm. To achieve a more homogeneous irradiation of samples, we used the available quadrupoles at FLUTE to widen the transverse beam size at the in-air setup. Transverse beam sizes (1σ rms) up to 5 mm were achieved, while maintaining a mostly symmetric round shape and keeping the measured dose rate above 40 Gy/s at a bunch charge of 300 pC. When going to bigger transverse sizes, the outer parts of the beam start to be scraped off by the vacuum exit window. Therefore, beam sizes between 2 and 5 mm (rms) were typically used.

To allow operation with higher bunch charges in the order of 300 pC, the power density of the UV photo-injector laser pulse on the cathode has to be reduced to avoid damage. This is achieved by defocusing the UV pulses and stretching them in time. The beam optics, e.g., solenoid strength, RF phase in linac, quadrupoles and correctors, was adjusted to ensure that the whole charge per bunch reaches the in-air section at the end of FLUTE. A beam energy of 30 MeV was chosen, as it offers a good compromise of providing enough acceleration in the linac to avoid a strong emittance growth due to space charge also after the linac. At the same time, 30 MeV is still feasibly low to avoid a long penetration depth and therefore the need for some additional build up material in front of the samples. Energies as low as 10 MeV have been demonstrated at FLUTE, although it should be noted that a slightly smaller percentage of the charge could be transported through the machine.

When comparing the beam energy with parameters at more typical clinical linacs, it has to be considered that due to the significantly smaller field size, the percentage depth dose curve is different. For wide field sizes, in the order of several centimeters, the scattering of electrons in the material mainly reduces the density at the edges, while in the middle the number of scattered electrons leaving the volume is balanced by an equal number of electrons scattering into that volume (lateral scatter equilibrium (LSE)) [4]. For smaller field sizes in the millimeter range, scattering reduces the electron density also in the middle and causes a significant widening of the field size, which then changes how the deposited energy is distributed along the penetration depth.

An additional knob to adjust the average dose rate is the repetition rate of the bunches. As FLUTE operates with one

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bunch per laser and RF pulse and not with bunch trains, the number of deposited electrons and, therefore, the dose for a given time scales linearly with the repetition rate. The repetition rate at FLUTE can be tuned from 1 to 50 Hz. To be able to maintain operation at 50 Hz with at least 30 MeV, a previously cracked RF window in the RF wave guide leading to the traveling wave acceleration structure had to be replaced in summer of 2025. For more details see [5].

DOSIMETRY

For live readout of the dose and dose rate, an Advanced Markus Chamber (AMC) [6] as well as a flashDiamond (FD) [7] detector from PTW Freiburg GmbH (Freiburg, Germany) were used. In addition, radiochromic films were irradiated and afterwards analyzed by scanning the resulting discoloration.

Due to a comparably small transverse size and Gaussian charge distribution of the electron beam, the sensitive volume of the detectors might have been irradiated in-homogeneously. The sensitive volume of the AMC is 20 mm^3 with 2.5 mm radius and 1 mm depth, and that of the FD is only 0.00113 mm^3 with 0.6 mm radius and 1 µm depth. Assuming a transverse bunch size of $\sigma_{\mathrm{x,y}} = 2.5$ mm or, alternatively, of $\sigma_{\mathrm{x,y}} = 5$ mm leads to a drop in charge at the edge of the AMC to about 61 %, respectively 88 %, of the charge at the peak. For the FD, degradation over the detector transverse extension is only about 3 % down to 97 % (respectively 1 % down to 99 %) of the charge at the peak.

It has been reported in the past, that the linearity of dosimetry detectors can decrease with the ultra-high dose rates for FLASH RT. To make this effect visible for our setup, we measured the average dose rate as a function of bunch charge as shown in Fig. 1. The AMC stayed rather linear up to approximately 100 pC. Above this level, it shows a slowly increasing deviation from the linear behavior, presumably caused by reduced charge collection efficiency due to the occurrence of ion recombination with increasing charge per bunch [8]. The flashDiamond detector (FD), shows the same linear dependence up to about 100 pC and then quickly saturates to a near constant value. This is suspected to be caused by the full saturation of the crystal defects in the detector material. In our case it occurred at about 0.4 Gy per pulse. While this is lower by a factor of 20 than the value given by the manufacturer, the <1 ps pulse length in our case is a factor of $4 \cdot 10^6$ lower than the reference value given by the manufacturer. Two pulse repetition rates, 50 and 10 Hz, as well as two possible orientations of the detector[1] have been tested and resulted in the same saturation level for the dose per pulse. For a bigger distance of the detector to the vacuum exit window, the point of saturation is shifted to a slightly higher bunch charge of about 200 pC, where the same saturation level for the dose per pulse is reached. This is caused by the divergence in the electron beam, leading to a bigger spot size at the more distant point of measurement and therefore to a lower charge density impacting on the detector volume. Due to the full saturation of the flashDiamond detector, it is not possible to derive a calibration function to compensate for this effect. For the AMC on the other hand, we can try to correct the measured dose rate assuming a linear dependency of the dose rate from the bunch charge by extrapolation. This assumption leads to the orange, dashed line in the left subplot of Fig. 2.

The deviation from a linear charge dependency originates mainly from the saturation of the detectors, as described above, but it is in addition affected by the beam dynamics of the electron beam. With increasing bunch charge the influence of the space charge effect increases the emittance of the beam. For a fixed beta-function, this results in a slightly larger transverse bunch size for higher bunch charges. To attempt considering this influence on the dose rate to bunch charge dependence, the transverse bunch sizes were measured as a function of the bunch charge (see Fig. 2 right subplot). In both dimensions, the change with bunch charge seems rather linear within the charge range measured. This allows the extraction of a linear fit for the relative change of the bunch size with charge. For these measurements, a YAG screen was placed in the in-air section and recorded with a high-resolution camera, while the bunch charge was changed stepwise. From the changes in bunch size, a change in the average charge density seen by the detector can be calculated by integrating the two dimensional Gaussian charge distribution up to the radius of the sensitive detector area. For an ideal constant bunch size, the average charge density rises linearly with bunch charge while for a charge dependent bunch size the rise is slower than this linear behavior. The ratio between the change for a constant bunch size and for the realistic case of increasing bunch size is used to correct the extrapolated detector response for no detector saturation. The result is the dotted green, line in Fig. 2 (left subplot) which represents the expected dose rate values for the assumption of no detector saturation but with an increasing bunch size with bunch charge. This calculation was done for the example of a bunch size in the order of 5 mm (rms).

This correction procedure is useful to calculate the actual dose rate based on the measured values despite the saturation and use the AMC as online diagnostic when setting up the machine. For accurate reference measurement during irradiation experiments radiochromic films are used. After post-processing, they provide the absolute deposited dose, including the spatial distribution (see Fig. 3).

FEW-BUNCH IRRADIATION

To mimic typical irradiation treatments during radiotherapy distributed into multiple fractions, a total dose of 1.8 to 2 Gy needs to be delivered per sample. For cell survival studies the dose ranges up to ~8 Gy. For an average dose rate of 40 Gy/s this requires an irradiation duration of 0.05 s to 0.2 s. As FLUTE operates with high dose per bunch, this corresponds to an irradiation with only a few electron

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[1] The vertical orientation refers to the detector sitting perpendicular to the beam axis. In the horizontal orientation the detector lies in the direction of the beam.

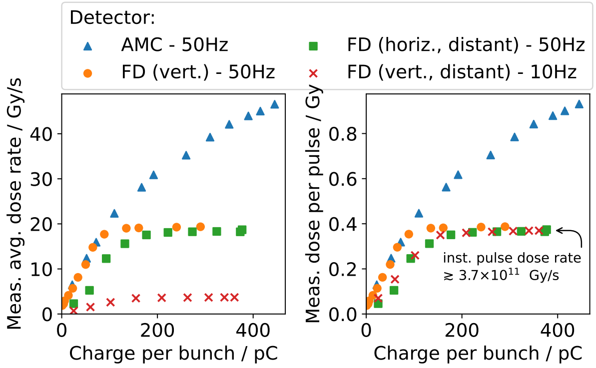

Figure 1: Measured average dose rate as a function of bunch charge (left) and calculated from this, the dose per bunch as a function of bunch charge (right).

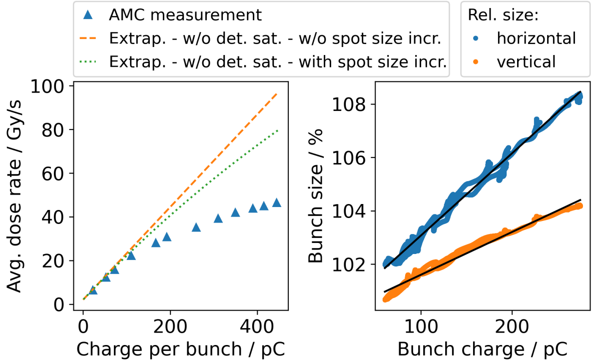

Figure 2: Influence of increasing bunch size. Left: Extrapolation of dose rate as a function of bunch charge assuming no detector saturation, without and with considering the effect of the increasing bunch size. Right: The relative change in measured transverse bunch size is plotted as a function of the bunch charge with a linear fit shown in black.

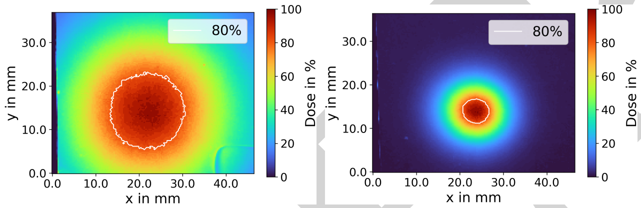

Figure 3: Radiochromic film dosimeters. Analyzed scan of the films showing the transverse distribution of the absolute dose detected for two different transverse bunch sizes (left: $\sigma \approx 5$ mm, right: $\sigma \approx 2$ mm).

bunches. While it is simple to switch on and off the laser generating the electron bunches at the photo-cathode of the electron gun, we have seen in measurements, that the dark current, generated with RF power on but no laser pulse on the cathode, contributes a small but non-negligible effect to the measured dose. The dose rate from the dark current alone was measured to be in the order of 0.2 Gy/s. With the time it takes to move the samples with a motorized stage into the beam path and until the actual irradiation occurs, this could accumulate to a relevant contribution. To minimize this effect of the dark current outside of the intended irradiation duration, a more complex procedure is used, besides switching the gun laser on and off. Via the EPICS control system, a script steps through the predefined list of 1. switching off the LLRF forward power (stopping the emission of dark current), 2. opening valve, 3. switching laser pulse picker on, 4. waiting for user defined irradiation time, 5. switching laser pulse picker off, 6. switching LLRF forward power off, 7. closing valve and lastly 8. switching LLRF forward power back on, so that the klystron and gun temperature stay in equilibrium while waiting for the next irradiation. This completely removes the irradiation with dark current during the positioning of the samples. The achieved accuracy is ±1 bunch. For example requesting 2 bunches (0.04 s) results in a delivery of 2 or 3 bunches.

CONVENTIONAL DOSE RATE

To be able to conduct comparative studies between FLASH RT and conventional RT, it is necessary to provide low dose rates around 0.05 Gy/s. As mentioned above, the typical dark current at FLUTE already results in a dose rate of 0.2 Gy/s. To reduce this further, the chicane after the linac is used as an energy filter. Additionally, a scraper, positioned in the middle of the chicane in the dispersive section between the second and the third dipole, is inserted partially to reduce the charge even more. This results in the desired dose rate of 0.05 Gy/s using only dark current.

To be able to switch between the ultra-high dose rate and the conventional dose rate settings, a save-and-restore module available in the control system is used. This allows automatic switching between the two operation settings, which makes the consecutive irradiation of multiple samples with different doses and dose rates fast and convenient.

SUMMARY AND OUTLOOK

Within the operation parameters of FLUTE, it is possible to provide conditions suitable for research towards FLASH radiotherapy with electron beams. We demonstrated average dose rates above 40 Gy/s with instantaneous dose rates well above 10^{11} Gy/s. For sample irradiation, the electron beam can be switched on and off for a user-defined number of bunches with single-bunch accuracy, enabling precise control of the delivered dose while minimizing additional dose contributions from dark current outside the intended irradiation time. The rapid switch to a conventional dose rate of 0.05 Gy/s has been demonstrated and allows comparative studies of FLASH RT with conventional RT. Electron beam energies from 10 MeV up to 30 MeV have been tested with this operation condition. For future tests, if of interest, FLUTE is designed to provide energies up to 85 MeV.

The ultra-high dose rate operation conditions have already been used for first experiments towards the irradiation of biological samples [3] as well as for first tests towards novel concepts of non-destructive in-air electron beam diagnostics [9].

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