

# ULTRA-HIGH DOSE-RATE IRRADIATION EXPERIMENTS AT FLUTE

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## Abstract

The linac-based test facility FLUTE at the Karlsruhe Institute of Technology (KIT) can be operated with a wide range of beam parameters, such as bunch charge, bunch length, and repetition rate. This flexibility makes FLUTE an interesting test-bed for studies of accelerator-based ultra-high dose-rate irradiation with electron beams. Based on the time structure of the produced electron pulses, the instantaneous dose rate can be tuned to exceed  $10^{11}$  Gy/s with an average dose rate exceeding 40 Gy/s. At the same time, FLUTE can also provide average dose-rates closer to conventional rates in the order of 0.1 Gy/s.

## INTRODUCTION

The linear accelerator FLUTE (Ferninfrarot Linac- Und Test-Experiment) at KIT has been designed as a dedicated test facility for accelerator physics and technology, as well as a broadband, short-pulse source for intense THz radiation [1,2]. One goal is, for instance, to test and develop novel diagnostics systems for ultra-short bunches like the compact transverse deflecting experiment based on THz-streaking using a split-ring resonator for the longitudinal bunch charge profile measurement [3,4].

The electron bunches can also be used *directly* in an in-air section of the accelerator to test and characterize diagnostics [5,6] or to irradiate samples, for instance biological cell cultures. The versatility of FLUTE allows tuning not only the energy, but also the charge and the bunch length over a wide range up to Ultra-High Dose Rates (UHDR). In this paper, we shortly summarize the main characteristics of FLUTE and then present the experiment beamline and in-air section we have developed recently.

## FLUTE OVERVIEW

FLUTE consists of several main sections, each followed by a diagnostics section: photoinjector electron source, linac module, bunch compressor, experiment area with the in-air section and dump, see Fig. 1. Picosecond infrared laser pulses from a titanium sapphire laser are frequency tripled and then sent onto a copper cathode, where they generate the electron bunches with a repetition rate of 1–50 Hz. They are accelerated in the photoinjector powered by a 11 MW klystron to an energy of around 5–6 MeV. After passing the diagnostics section I they enter a linac module fed by a 37 MW klystron. A recent complete upgrade of the radio frequency system [7], including both klystrons, the photoinjector electron source, and the linac module of the FLUTE accelerator, resulted in significantly improved stability and

reproducibility compared to the previous system. The electron bunches then traverse the diagnostics section II and go through a D-shaped chicane consisting of four dipoles. The chicane serves as a bunch compressor, allowing the adjustment of the bunch length down to the femtosecond regime. After the chicane, a thin aluminum foil can be moved into the electron beam at a  $45^\circ$  angle for THz experiments. When a bunch passes through the foil, transition radiation in the THz range is generated. It is emitted at  $90^\circ$  with respect to the electron beam, where it can be measured and used as a diagnostics, for instance as a bunch compression monitor [2]. After further diagnostics, the electron bunch leaves the ultra-high vacuum beam pipe by passing through a thin metal foil to enter the in-air section. Finally, the beam is stopped in a lead dump.

As a dedicated test facility for accelerator physics and technology, FLUTE has been designed to cover a broad range of parameters such as energy ( $\sim 6$ –90 MeV), charge ( $\sim 70$  fC – 800 pC), and bunch length (ps down to a few fs).

## IN-AIR SECTION

An in-air section is very useful for a large variety of experiments, for example in the domain of diagnostics or sensor R&D, because it dramatically reduces prototyping and development cycle times since the vacuum does not need to be broken. Small changes or modifications can be applied immediately, several prototypes can be tested within the same beamtime etc. For instance, we recently demonstrated first near-field-sensitive electro-optical measurements of electron-bunch-induced transient signals in the FLUTE in-air section using a photonic-integrated Mach-Zehnder interferometer sensor [5]. Another example in this field is the development of ultra-fast planar pickups for electro-optical beam arrival monitors used at the European XFEL and other free-electron laser (FEL) facilities, where different designs can be quickly and easily tested in series in-air [8].

Another very important field, where an in-air section is indispensable, is the irradiation of biological cell cultures, most notably in the context of radiotherapy studies. Here, we are currently interested in studying the so-called FLASH effect [9,10]. This phenomenon describes the observation that radiotherapy at ultra-high dose rates, typically  $>40$  Gy/s, can significantly reduce damage to healthy tissue while maintaining a comparable effectiveness against cancer cells relative to conventional dose rates ( $\sim 0.1$  Gy/s). This effect is still poorly understood today. Compared to clinical machines, research accelerators such as FLUTE provide a much higher degree of flexibility, allowing both the dose rate and the temporal pulse structure to be varied over a wide range, from conventional to ultra-high dose rates [11].

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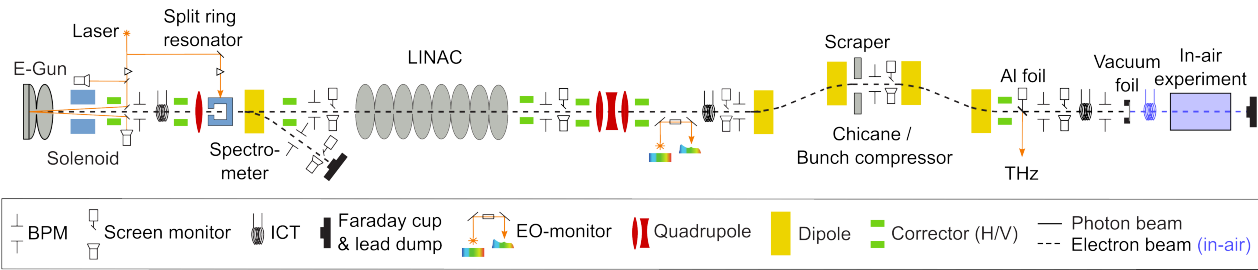


Figure 1: Layout of the FLUTE linac-based accelerator test facility showing the different elements schematically (not to scale, no vacuum components shown). The photoinjector electron source and a first diagnostics section is followed by a linac module with diagnostics section II. The subsequent bunch compressor mainly consisting of four dipole magnets allows tuning the bunch compression / length. After that there is an aluminum foil generating THz transition radiation when inserted into the beam, followed by diagnostics section III. A thin Havar foil separates the ultra-high vacuum from the downstream in-air section. At the end, the bunch is absorbed in a Faraday cup enclosed in a lead dump.

The electrons enter the in-air section at FLUTE by passing through a 20  $\mu\text{m}$  thin *Havar* foil (diameter 16 mm). Directly afterwards, an in-air Integrating Current Transformer (ICT) is mounted to measure the bunch charge in air. Subsequently, there is a ca. 30 cm long aluminum platform / breadboard for various in-air experiments. The experiment platform is mounted on inner rails on the girder support structure, so that it can be moved along the beam axis. Figure 2 shows an overview of the FLUTE in-air section, here with a solid water phantom for depth dose curve measurements mounted on the experiment platform. Finally the electron beam is

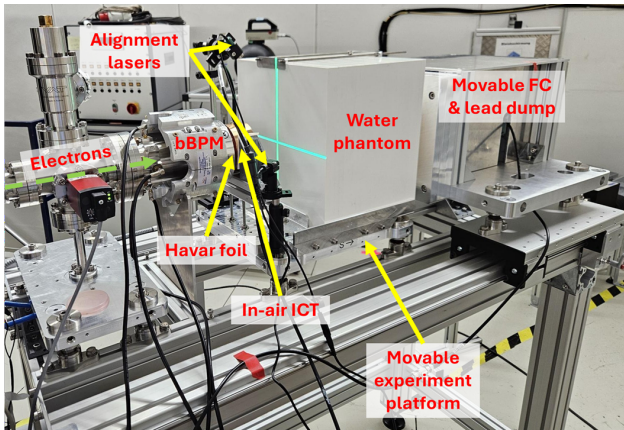


Figure 2: Overview of the in-air section at FLUTE, here showing a dosimetry measurement using a solid water phantom with an embedded Advanced Markus Chamber sensor (not visible). A thin Havar foil separates the vacuum from the in-air section. Alignment lasers help with the exact positioning of the target. bBPM: button Beam Position Monitor, ICT: Integrating Current Transformer, FC: Faraday Cup.

stopped by a Faraday Cup (FC) operated in air and embedded in an aluminum and lead dump. This dump assembly is also mounted on special high-weight rails, which run outside the inner rails. Since the dump assembly is sitting on a platform a bit higher than the experiment platform, the dump can be moved completely over the platform. This gives great flexibility with the position of the experiment and the dump, and allows reducing the air gap as much as the

experiment setup permits, thereby reducing stray radiation and simplifying radiation protection measures.

To perform radiobiological irradiation experiments, we use a motorized XY stage on which a small breadboard is mounted, see Fig. 3. The breadboard carries the samples, a

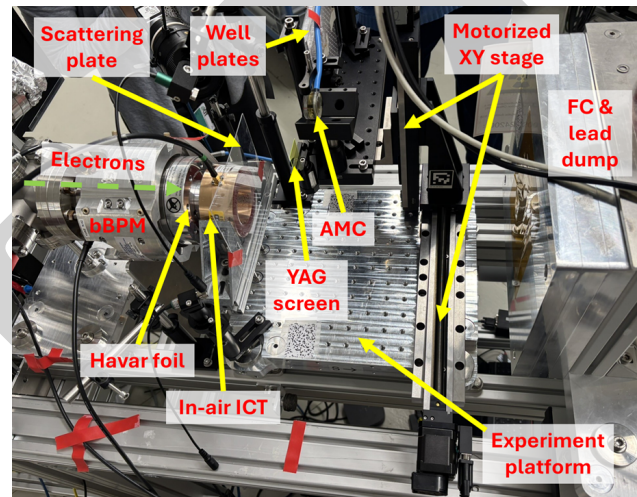


Figure 3: The in-air section with a motorized XY stage carrying two well plates, the Advanced Markus Chamber (AMC) and a YAG screen for in-situ dose and beam shape measurements is shown. bBPM: button Beam Position Monitor, ICT: Integrating Current Transformer, FC: Faraday Cup.

YAG:Ce (Yttrium Aluminum Garnet activated by Cerium) scintillation screen from CRYTUR, as well as an Advanced Markus Chamber (AMC) from PTW Freiburg GmbH. When moved in, the YAG screen (with a camera) and the AMC allow live in-situ verification of the beam size and dose rate at the sample location. Depending on the experimental condition, an additional Poly(Methyl MethAcrylate) (PMMA) scattering plate can be mounted to widen the beam at the sample location.

Since the particle beams of typical research accelerators are horizontal, biological samples have to be irradiated from the side in contrast to the conventional irradiation. One way to do this is to use viscous hydrogel to avoid spillage and keep the medium and biological cells in vertically mounted

well plates, thereby enabling a more homogeneous dose deposition within the samples. Figure 4 shows the motorized breadboard with two vertically mounted well plates next to each other. Radiochromatic films (Gafchromic EBT-

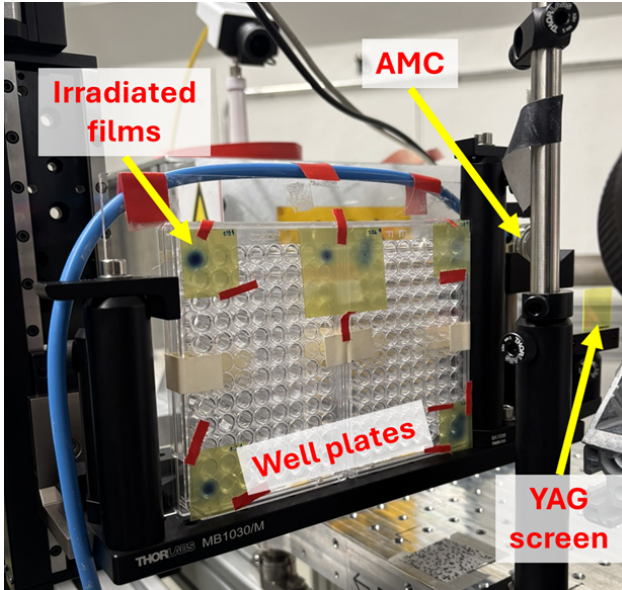


Figure 4: Two well plates are mounted on the motorized XY stage, next to the Advanced Markus Chamber (AMC) and a YAG screen. Radiochromatic films are mounted in front of the well plates for post-irradiation position and dose verification.

XD/EBT4 from Ashland, USA) are taped to the wells to provide spatially resolved dose information (see dark spots on the film).

In order to add water around the samples to generate the build-up effect, we placed the samples in Eppendorf tubes, which were then placed inside 3D-printed water-filled plastic holders, see Fig. 5. To keep the cells under physiological temperature conditions ( $\sim 37^\circ$ ), we also placed the water-filled holders between two heating pads (one above, one below). A thermometer placed in one water-filled holder provided the regulation temperature for the control-loop. We then also taped radiochromatic films to the holders for post-irradiation verification of beam position relative to the Eppendorf tube and deposited dose. The irradiated areas can be clearly seen in Fig. 6.

## SUMMARY AND OUTLOOK

The in-air section at FLUTE is very flexible and can be used for a plethora of experiments, reducing the development time drastically, for example in advanced diagnostics development. For radiobiological experiments, especially in living cells, it is absolutely essential. Here, we presented our setup used for dosimetry and radiotherapy studies. First experiments with ultra-high and conventional dose rates have been performed with this setup, the analysis is ongoing.

In the future, FLUTE will also be used as a versatile and reliable injector into a new very large acceptance storage ring to study non-equilibrium beam dynamics within the cSTART

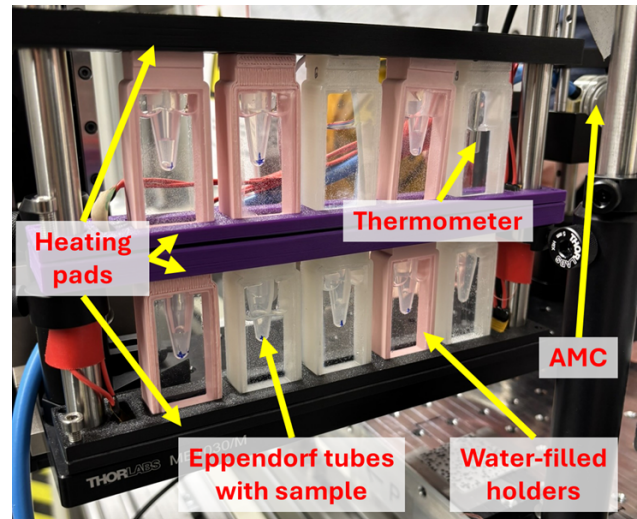


Figure 5: Eight Eppendorf tubes are mounted in water-filled holders, each clamped between two heating pads above and below, and fixed to the motorized XY stage. A control loop keeps the samples in the water bath at a constant temperature of  $\sim 37^\circ$  using the heating pads and the thermometer. In the background the Advanced Markus Chamber (AMC) is visible.

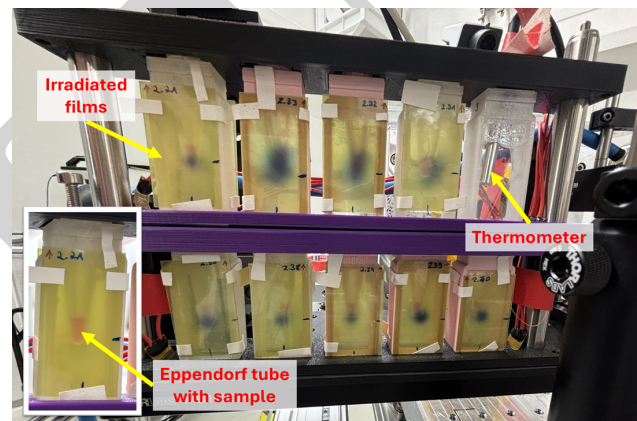


Figure 6: Irradiated samples in Eppendorf tubes in a water bath (insert: before irradiation). The radiochromatic films taped to the holders show the irradiation position and can be evaluated in post-processing to yield the dose at the sample location.

project [12]. To build this new storage ring, FLUTE has very recently been temporarily dismantled to allow the construction of the metal platform and the storage ring in the FLUTE experimental hall. Afterwards, FLUTE will be reassembled with a newly designed in-air section.

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