PITZ FACILITY AFTER THE UPGRADE: HIGH BRIGHTNESS BEAMS FOR PHOTO INJECTOR R&D AND FEEDING THz AND RADIATION BIOLOGY EXPERIMENTAL STATIONS

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Abstract

At the Photo Injector Test facility at DESY in Zeuthen (PITZ) 22 MeV, high brightness electron beams are generated to serve mainly as a test facility for the European XFEL. Low emittance beams with bunch charges of less than a pC up to several nC are generated in an L-band photogun, which can provide bunch trains (4.5 MHz bunch repetition rate) of up to 1 ms in length at 10 Hz repetition rate. The three pillars of operation are: 1) R&D on high brightness photoinjectors for European XFEL: Main work topics are photocathodes, laser pulse shaping, machine learning, and operations improvements. 2) THz SASE FEL: Beams with a bunch charge of up to several nC are transported through an undulator to generate THz radiation at wavelengths around 100 µm with pulse energies of more than 100 µJ. Characterization of the THz output includes a FTIR spectrometer, a THz camera and a Michelson interferometer. 3) Radiation biology: In a separated beamline the electron bunches are transported through a thin exit window to an in-air experimental station for *in vitro* and *in vivo* irradiations providing ultra-high dose rates over a worldwide uniquely wide parameter range, with the goal to systematically study the FLASH effect in order to find the underlying principle, which is yet unknown. In addition, the high beam quality and the high bunch repetition rate is used to study spatially fractionated radiation therapy (SFRT) and the combination of SFRT and FLASH radiation therapy FLASH-RT.

INTRODUCTION

The Photo Injector Test facility at DESY in Zeuthen (PITZ) [1] was built as a test facility to develop optimized electron sources for short-wavelength Free Electron Laser (FEL) user facilities like the EuXFEL [2] or FLASH [3] in Hamburg. The main aim is to optimize hardware and operation parameters to minimize the emittance of electron bunches which are typically used in FEL operation. The high brightness beams available at PITZ are also utilized to conduct experiments in various fields. In the past, that were electron diffraction [4] and beam driven plasma acceleration [5, 6]. After a major upgrade of the PITZ facility in the last several years, two experimental end stations are available for investigations into a high-intensity, tunable THz source for pump-probe experiments at FELs and radiation biology at ultra-high dose rates. The current beamline is depicted in Fig. 1. The final beam energy is up to 22 MeV with bunch charges from fC to about 5 nC. Bunch durations are spanning 0.1 ps to 30 ps FWHM with beam sizes available at the experimental stations in the µm to mm range. The available pulse train time structure is governed by the need to drive superconducting linacs with long RF pulses: electron bunch trains consist of up to 4500 bunches within 1 ms with a repetition rate of 10 Hz typically. In the following, the three main PITZ activities are described.

ELECTRON SOURCE DEVELOPMENT

For over 25 years, normal conducting copper L-band (1.3 GHz) guns are developed at PITZ [7]. These are pulsed 1½-cell standing wave cavities with a typical RF power of ~6.5 MW during the RF pulse, an operational cathode gradient of 60 MV/m and an RF pulse length of up to 1 ms at a repetition rate of 10 Hz. This latest generation (Gun5 [7], Fig. 2) features an improved, elliptical cell shape, extended cooling capabilities, and RF pickups for field measurements in the gun cavity, enabling direct feedback.

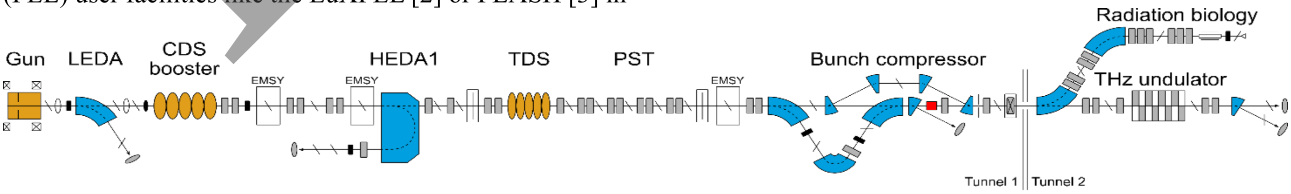

Figure 1: PITZ beamline.

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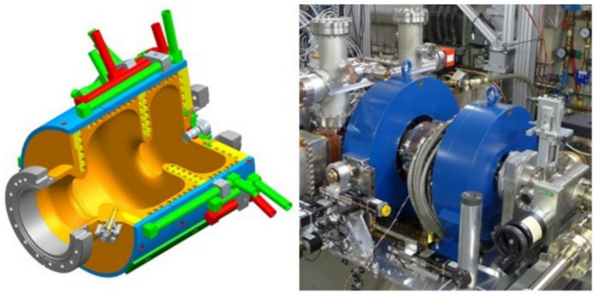

Figure 2: Model (left) and picture (right) of Gun5.

Other features of the latest gun generation are cathode plane modifications to reduce the RF field strength at the transition area of the exchangeable cathode to the gun backplane [8] and a new cathode contact spring which can handle higher average RF power loads than older designs [9].

For standard operation, Cs_2Te photocathodes are used with photoexcitation in the UV. Investigation into Sb based photocathodes with high quantum efficiency also in the green spectral region are ongoing together with INFN LASA in Milano, Italy [10]. Advantages of these photocathodes are amongst others a lower thermal emittance and reduced photocathode laser power requirement. Research with photocathode lasers is conducted in the field of laser pulse shaping with the main aim of minimizing emittance of the resulting electron bunches [11-13].

HIGH-INTENSITY, TUNABLE THZ SOURCE

Combining the hard and soft x-ray beams available at modern FELs with a high-intensity THz source opens up a field of new science with THz pump-x-ray probe experiments: the THz radiation can excite a wide variety of rotational and vibrational states in all kinds of molecules, which can be probed with the x-rays in high temporal and spatial resolution. Laser based THz sources are limited in pulse energy at the needed high repetition rate, so it was suggested to add an undulator to the PITZ beamline to demonstrate a high energy, high repetition THz source [14], which could be built at an experimental station of the European XFEL.

Recently, the PITZ beamline was extended into a second tunnel section to set up a THz SASE FEL for wavelengths around 100 µm [15]. This starts with a chicane bunch compressor built from refurbished HERA [16] corrector dipoles for tuning the electron bunch length. After beam transport into the new tunnel section, the beam enters an undulator (LCLS-1 type [17], on loan from SLAC), which was adapted to work with the low energy PITZ beam and equipped with steering coils to enable the measurement of gain curves along the undulator. This is followed by two measurement stations to characterize the generated THz radiation, which is coupled out of the beam pipe through low-loss diamond windows and detected with pyroelectric detectors, optionally equipped with a bandpass filter. Alternatively, measurements can be taken with an interferometer, an FTIR spectrometer, or a THz camera. After initial detection of the THz radiation and subsequent optimization, the setup was thoroughly characterized: The gain curve was measured for seeded and non-seeded THz radiation with a pulse energy of ~100 µJ for the full undulator length (Fig. 3). The radiation spectrum was measured with an FTIR spectrometer, demonstrating sharp frequency peaks [15].

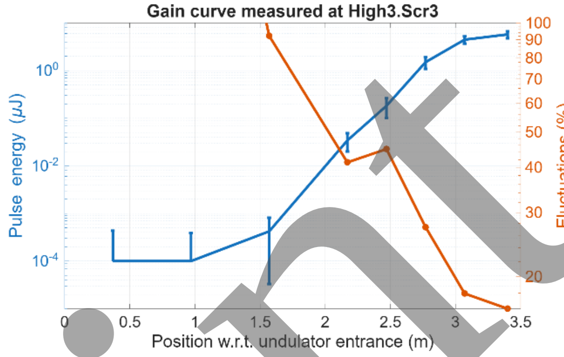

Figure 3: Example of THz radiation gain curve.

To improve the THz output, a Bayesian optimizer is used to automize the process. The routine is optimizing the beam trajectory and phase spaces, thereby maximizing the THz output. In a typical optimization run, two pairs of steering coils are used to vary the beam trajectory, four to six quadrupole magnets to adjust the transverse phase space and the booster phase to tune the longitudinal phase space. Starting from an initial, reasonable beam transport, the THz output can be improved by an order of magnitude within a run time of about one hour. Further optimization runs approach the optimum asymptotically.

Ongoing activities are the demonstration of THz output at different frequencies and setting up an electro-optic sampling system (EOS) to characterize the THz output pulse by pulse.

FLASH RADIATION THERAPY

Another application for which the high brightness beams at PITZ are ideally suited is cancer radiation therapy at ultra-high dose rates. Conventional radiation therapy at low dose rate is an established method for a long time, but is troubled by side effects. Over the last 10 years, a new form of therapy is starting to be established, the so-called FLASH radiation therapy (FLASH-RT) [18], where the radiation is applied at ultra-high dose rates, typically defined as being larger than 40 Gy/s, but potentially many orders of magnitudes higher than that. Experimental evidence is strong that this new type of irradiation can spare healthy tissue which is irradiated together with the cancerous tissue, while having at least the same tumor control as conventional radiation. But, since it is still not known how the FLASH effect works, it is also not possible to optimize its application.

In order to answer these basic questions, another beamline extension parallel to the THz section was built in the last several years [19]. FLASHlab@PITZ was completed in August 2025 and first experiments were conducted;

improvements are ongoing. In its current state it is highlighted by the following items:

- A beamline with a final focus system to guide electron bunches from the main beamline via a dogleg towards an exit window with free choice of spot sizes down to the space charge limit.
- A vertical kicker to deflect bunches within one bunch train over the irradiation field. This spatially fractionated radiation therapy (SFRT) [20] allows to damage cancer tissue and at the same time further reduces stress on the healthy tissue surrounding the tumor. At FLASHlab@PITZ the unique combination of FLASH-RT and SFRT is possible, thereby enhancing the tumor killing and healthy tissue sparing effect of both methods.
- An experimental station in air after the exit window, which can be equipped e.g. with a robot arm for sample handling or a system for small animal irradiation [19].

The FLASHlab@PITZ infrastructure is complemented by a bio laboratory to handle sample preparation and analysis. This laboratory is also equipped to handle zebrafish and mice for necessary zebrafish embryo and animal experiments, respectively. All animal experiments are rigorously conducted in accordance with animal welfare regulations and necessary permits for animal husbandry are granted.

During the run in August 2025, first preliminary tests of the available bunch charge range and corresponding beam size at the end of the beamline were conducted, as depicted in Fig. 4.

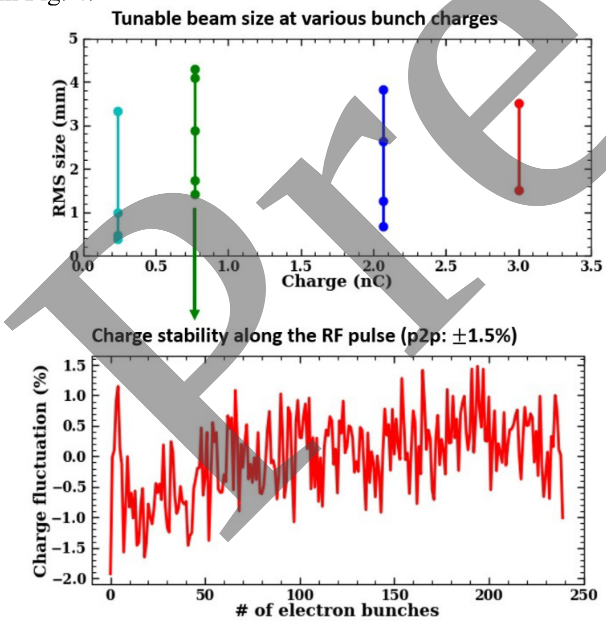

Figure 4: Preliminary results of beams available at the end of the FLASHlab@PITZ beamline (above) and charge stability along the bunch train (below).

The upper graph in Fig. 4 demonstrates the wide range of beam parameters available at FLASHlab@PITZ, including the possibility to irradiate samples at conventional (low) dose rates, dose rates where the FLASH effect was demonstrated in the past, and dose/dose rate combinations far beyond what was possible so far. The bunch charge transported to the exit window was varied for the first tests between 250 pC and 3 nC and the quadrupoles of the final focus system were used to tune the beam size as presented.

The lower graph in Fig. 4 shows a typical result for the charge stability along a bunch train. The peak-to-peak variation of 1.5% demonstrates the capability to generate planned dose levels reliably in the irradiated tissue, either cumulatively in a single spot or distributing it with the kicker for SFRT studies.

CONCLUSION

Research and development at the Photo Injector Test facility at DESY in Zeuthen (PITZ) is conducted in three interacting areas:

1. Normal conducting L-band guns are in development over the last 25 years as sources for high brightness beams, e.g. to drive FELs. At PITZ, the latest generation (Gun5) is used to do accelerator R&D for further improving the operation at the European XFEL and preparing for further upgrades at this facility. In addition, this gun is used to generate beams for two main applications, a THz SASE FEL and radiation biology.
2. A THz SASE FEL was built as a demonstrator for a THz source for pump-probe experiments at hard x-ray FEL facilities. Record high THz pulse energies of >100 µJ at high repetition rate were demonstrated so far.
3. An experimental station to investigate the FLASH effect and SFRT, utilizing the available high beam quality and ultra-high dose rates, was built. It exploits most of the already established beam transport towards the THz station. First experiments demonstrated the expected capabilities of electron bunches available for irradiation.

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