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MILESTONE REPORT

Reports on FLASH detectors for different facilities

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Abstract:
This report compiles the progress in detector development for Ultra-High Dose-Rate (UHDR, commonly referred as "FLASH") radiotherapy. FLASH dosimetry is indeed complicated by the nonlinear dose reading of the ionization chambers at UHDR. We created a model that can calculate the corrections for the recombination effect in a ionization chamber also considering space charge effects. The model has been tested in the beamtime of February 7-8, 2024 at GSI (Darmstadt, Germany) where a FLASH experiment with C-ions was performed. Moreover, as planned in EURO-LABS, our teams provided support for FLASH implementation in 4 clinical facilities in Denmark, the Netherlands, and Germany.

For more information on EURO-LABS, its partners and contributors please see https://web.infn.it/EURO-LABS/

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Delivery Slip

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Executive summary

The report describes the progress in FLASH dosimetry both at GSI and in different facilities in Europe. We have created a model to correct the nonlinearity in ionizing chamber responses and implement FLASH with protons and carbon ins in four European facilities.

1. INTRODUCTION

GSI in Darmstadt (Germany) is leading the Task 2.5.3 in WP2 of EURO-LABS related to FLASH dosimetry and its dissemination in European facilities. FLASH radiotherapy is currently one the hottest topics in cancer therapy, because at UHDR it is possible to spare substantially the normal tissue while maintaining tumour control, thus widening the therapeutic window [1]. The FLASH effect was originally observed using electrons [2], and later extended to protons [3] and to carbon ions at the GSI SIS18 accelerator [4].

The EURO-LABS financial support has been used to employ a Ph.D. student, Warisara Charuchinda, who got her Master degree in Physics at Chulalongkorn University (Thailand) in 2022. Ms. Charuchinda became acquainted with GSI as participant to the 2022 HGS-HIRe Summer School at GSI. Her work during her internship focused on near-field simulation of the range modulators used to produce Spread-Out-Brag-Peak (SOBP) for FLASH [5]. She was enrolled at Technische Universität Darmstadt in February 2023 under the supervision of M. Durante.

The main task of Ms. Charuchinda was to work on FLASH dosimetry with protons and heavy ion beams using gas-filled ionization chambers. This topic had been initiated during the master thesis of Mr. Leon Baack at the Technische Universität Darmstadt [6], and now substantially improved by Ms. Charuchinda.

Moreover, a major goal of the Task 2.5.3 is to support the implementation of FLASH setups in different facilities in Europe for clinical applications. The progress is reported here. The work in the VARIAN facilities in Denmark and The Netherlands was partly supported by Varian Medical Systems Co. under a co-operation agreement with GSI.

2. FLASH DOSIMETRY

2.1. MOTIVATION

The main challenge of the standard dosimetry using a ionization chamber at UHDR is the volume recombination effect which occurs due to the high concentration of the liberated charge inside the active volume. Main goal of the work is to create a model that can calculate the corrections for the recombination effect also considering space charge effects.

2.2. RESULTS

To understand the phenomena behind the nonlinear dose reading of the Ionization Chambers (ICs) at FLASH intensities, we developed a MATLAB-GPU-based code for volume recombination in Parallel Plate Ionization Chambers (PPIC) and thimble ICs, vented to different gases, i.e., air, He, the mixture of 96/4 He/CO_2, and the mixture of 80/20 Ar/CO_2. The workflow of the program consists of

1. Solving Maxwell equation for electric field in the complex geometry of the ICs, i.e. PPIC, PTW 30013 Farmer chamber 0.6 cm^3, PTW 31015 PinPoint chamber 0.03 cm^3, and PTW 31023 PinPoint chamber 0.015 cm^3. The example of the geometry and solved electric field inside the PTW 31015 PinPoint chamber when applying the voltage of 100 V are shown in Figure 1.
2. Recombining charged particles: For the mixture of the noble gases, electron-cation recombination dominates while anion-cation recombination is the main contribution to the air-filled chamber because of the high electron attachment rate at the operating voltage. The simulated charge recombination has been benchmarked with the charge collection signal from the full spill ^{12}C beam at FLASH intensities, i.e., $5 \cdot 10^8$ and $3 \cdot 10^9$ ions/spill, spill duration around 100 ms, at HIT and GSI, respectively.
3. Drifting charged particles are simultaneously producing the electronic signal (instantaneous current and collected charge) which can be compared with the measurements. The charged particle drifting process has been benchmarked with the electronic signal of parallel plate ICs irradiated with pulsed-photon and ^{12}C beam (3 µs pulse duration), produced at MIT as shown in Figure 2.

Moreover, it should be noted that the electric field in this model is not only contributed by the applied voltage at the electrode but also from the charged particles themselves inside the active volume or so-called ‘space charge’. This space charge effect is significant at the low voltage because it can cause electric field cancellation which leads to the explicit reduction of the collected charge signal as shown in Figures 3 and 4, respectively. The concept for evaluation of the space charge effect has been applied before to the PPIC model [6] for the FLASH beam monitoring system, however, this is the first time to apply such an effect to the complex-geometry, air-filled, thimble chambers for absolute dosimetry.

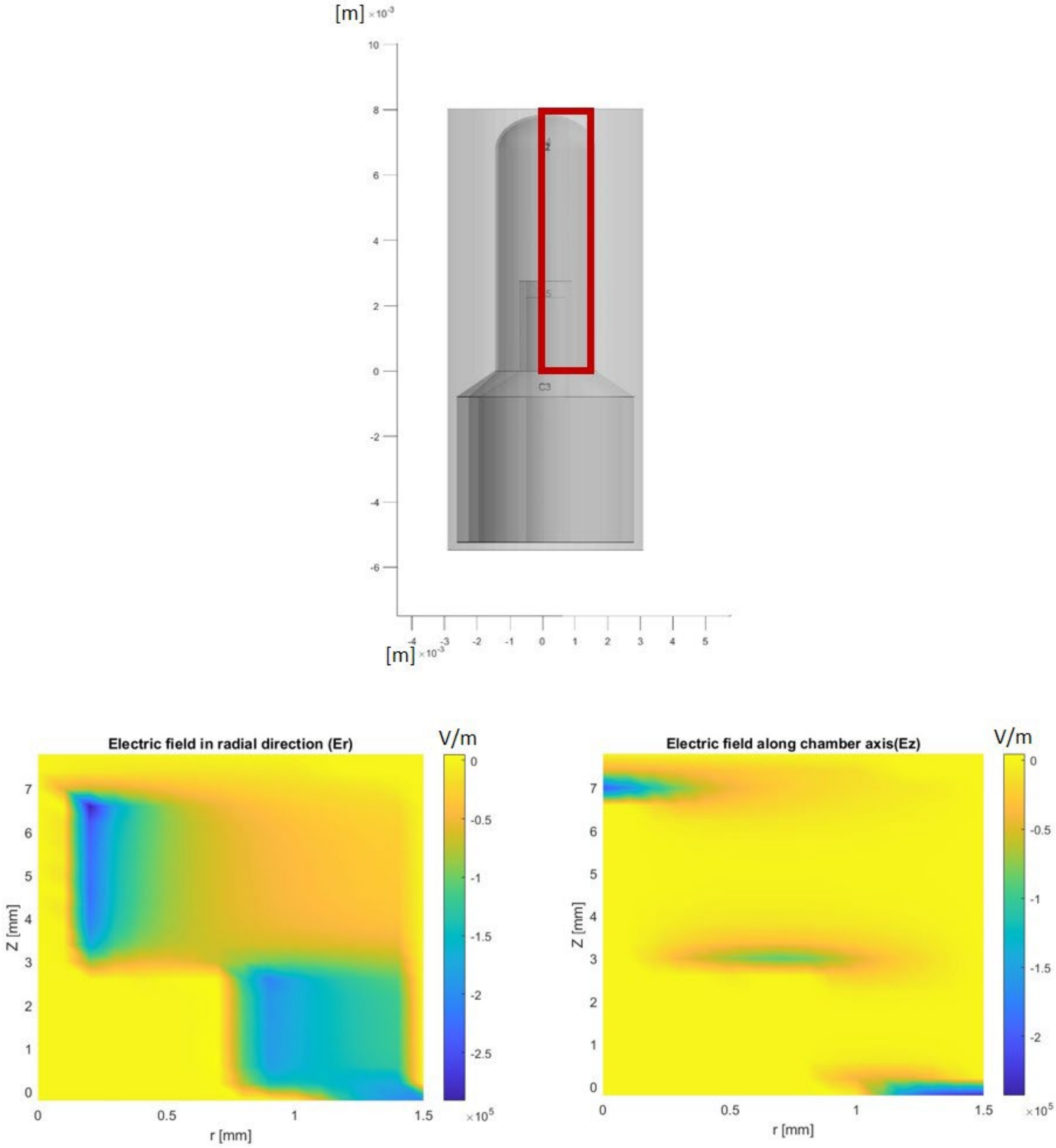

Figure 1: Geometry of PTW 31015 PinPoint chamber 0.015 cm^3 constructed in FreeCAD software (top) and the electric field inside the chamber when applying the voltage of 100 V to the electrode (bottom). The area of the electric field plot is marked by the red block on top of the IC geometry.

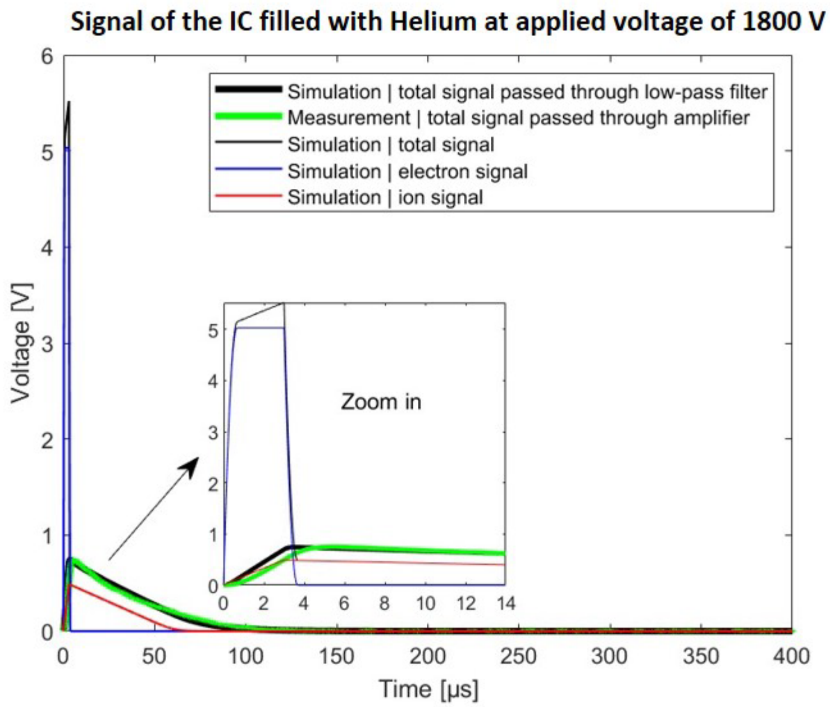

Figure 2: Instantaneous signal induced by drifting charged particles inside the PPIC operating at 1800 V. The amplification of the signal is 10^6 V/A.

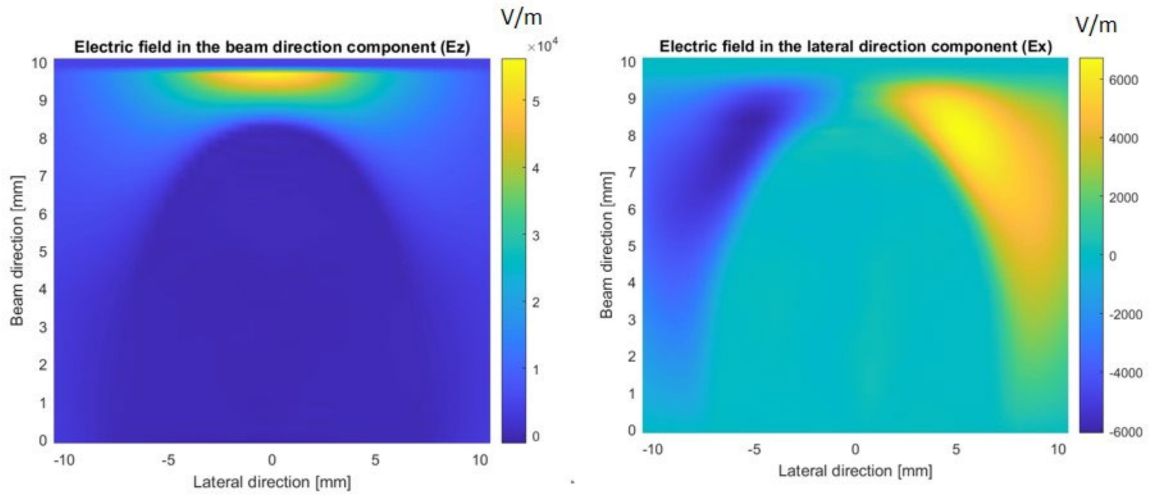

Figure 3: Electric field cancellation due to the space charge effect inside the active volume of PPIC filled with 96/4 He/CO_2 at a voltage of 50 V. This tremendously reduces drift velocity of the ions and electrons which results in increased recombination. The colour scale of the electric field in Ex direction plot corresponds to the opposite directions of the electric field vector.

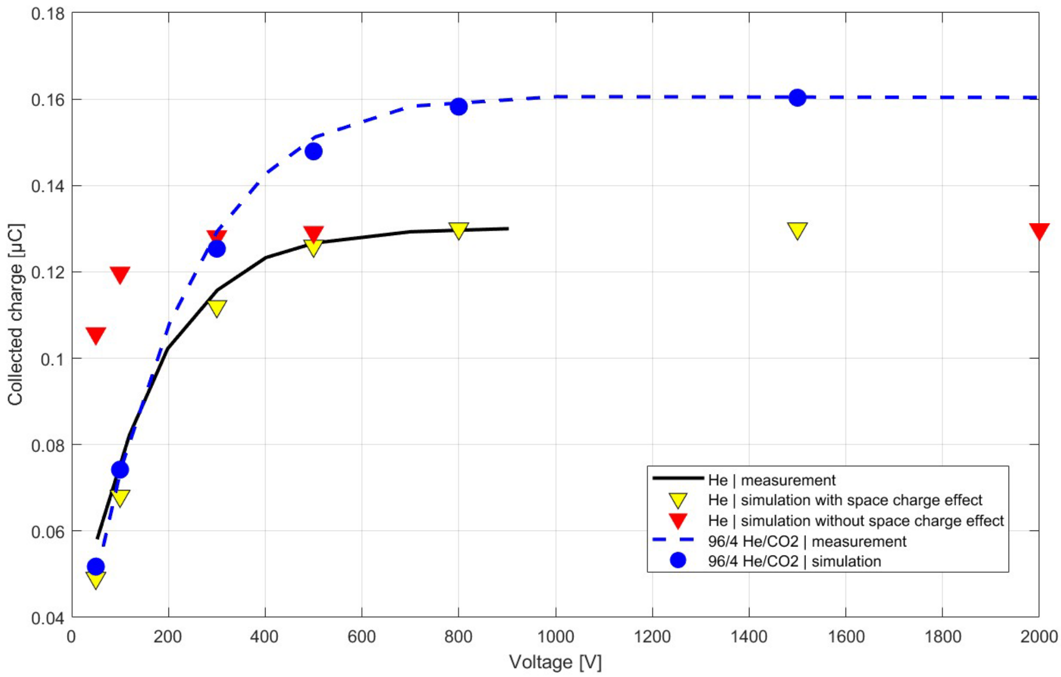

Figure 4: Saturation curves of ICs filled with different filled gases irradiated under UHDR conditions at HIT and simulated saturation curves. The red triangular markers show the overestimated collected charge signal when the space charge effect was excluded.

The new software has been used during the ^{12}C beam experiment at GSI for FLASH (February 7-8, 2024) that focused on the 3D dose measurement using a 3D range modulator for a phantom lung tumor target of 60 cm^3, at the dose rate between 300-3000 Gy/s, as well as the dose rate measurement at the different depth in the water phantom. Results will be described in the next report (D.2.5).

3. SUPPORT TO OTHER FACILITIES

The cyclotron-based proton therapy facilities are currently working in FLASH regime only in transmission mode [7]. In fact, the 3D active scanning is unavoidably too slow to stay within the time requested for FLASH (<100 ms). A similar problem happens in synchrotron-based facilities, such as those used for C-ion therapy. For this very reason, in collaboration with Technische Hochschule Mittelhessen (THM), we have introduced the idea of 3D range monitors (Figure 5), able to deliver SOBP with a single scan on the modulator plane [8,9]. This system allows Bragg peak irradiation both with protons and heavy ions. The work in external facilities is therefore focussing on 1) Delivering the 3D-printed range modulators, and 2) Supporting this facility for FLASH dosimetry with protons and heavy ions.

3.1 DELFT CLINICAL PROTON THERAPY FACILITY, THE NETHERLANDS

Within a cooperation with VARIAN Medical Systems and the HollandPTC, and with the support of EURO-LABS, GSI and THM are providing support for dosimetry and the application of FLASH irradiation in the clinical proton therapy facility in Delft, The Netherlands. Knowledge transfer was established in order to enable Varian to design and manufacture patient specific range modulators (Figure 5) for proton FLASH by 3D modulators in Varian facilities and to develop a new clinical workflow including Monte Carlo benchmarking. This a good example where EURO-LABS is collaborating strongly with industry.

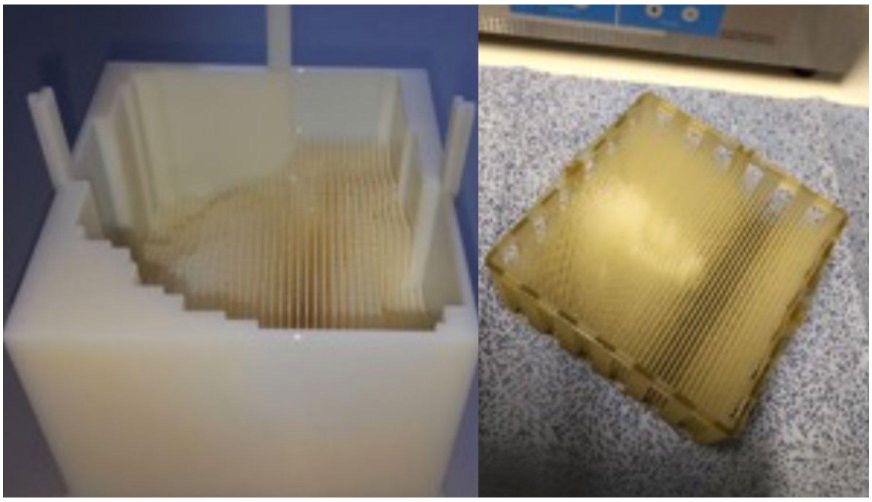

Figure 5: 3D Range modulators printed at GSI and delivered to the Holland Proton Therapy Center (HollandPTC) facility.

The system has been successfully installed for pre-clinical tests by the GSI/THM scientists in the proton therapy centres in Delft. Varian will now continue and validate the further development and clinical implementation, with the option of further consultancy services from GSI. Holland Proton Therapy Center (HollandPTC), continuously joining and supporting the tests, will use this technique for preclinical experiments and other experiments in medical physics. Additionally, GSI established at Holland PTC a technique to measure time dependent local dose rate (Figure 6).

Figure 6: Setup for high-resolution dose measurement at the HollandPTC (experimental room).

3.1. AARHUS PROTON THERAPY FACILITY, DENMARK

At GSI a precisely 3D-printed “2D Range Modulator (2DRM)” for a proton SOBP was produced. This modulator was then implemented at the Aarhus proton therapy facility in Denmark by GSI. A series of tests with the GSI 3D phantom (including an Octavius 1600DR array, a high resolution ion chamber matrix)) was performed (Figure 7). Currently this 2DRM technique is used to continue the very successful series of preclinical experiments in Aarhus also in the SOPB area with mice.

3.2. MARBURG ION THERAPY (MIT) FACILITY, GERMANY

The Marburg Ion Therapy (MIT) facility in Germany is also starting to establish FLASH experiments, after increasing beam intensities for both ^{12}C and protons. Since 2023 GSI supports MIT to establish FLASH irradiation with accelerated charged particles for small volumes. This includes: providing FLASH modulators (2DRM), beam monitoring (Helium filled chambers), dose rate measurements, beam delivery with modulators. Recently we were able to commission the first FLASH beam of carbon ions in a small field (Figure 8).

3.3. HEIDELBERG ION THERAPY (HIT), GERMANY

Since 2019 GSI has been a very fruitful collaboration on the FLASH topic with the Heidelberg Ion Therapy (HIT) facility, Germany. The first biological FLASH experiments with ^{12}C ions were actually carried out at HIT in cells growing in vitro.

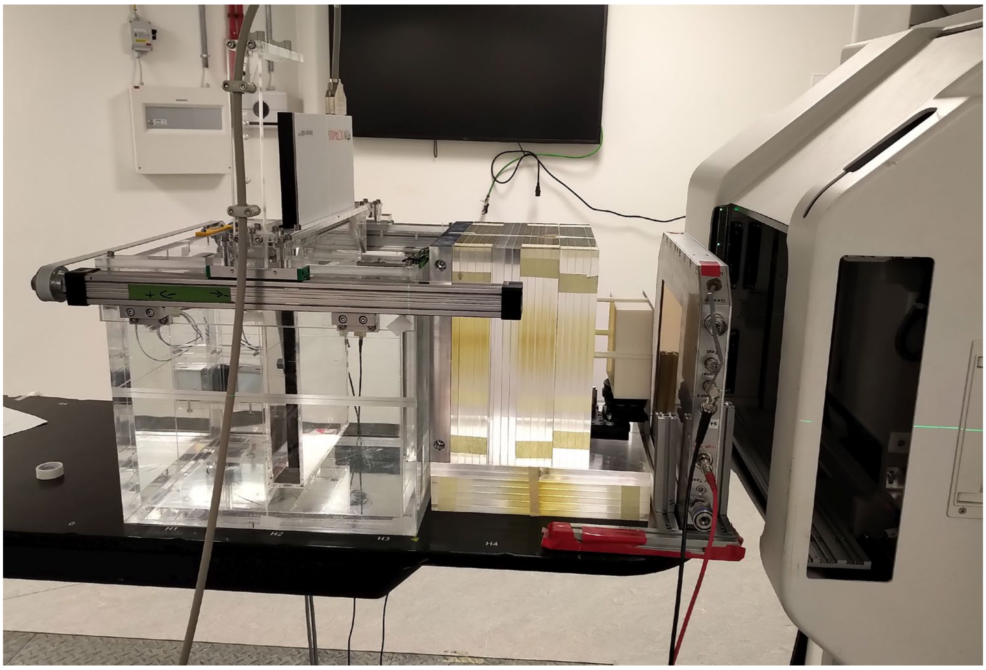

Figure 7: GSI Dosimetry equipment at the Aarhus proton therapy facility (experimental room): Commissioning of the 2D Range Modulator (2DRM) for preclinical experiments (SOPB FLASH). Left to right: GSI phantom (WERNER) with Octavius 1600XDR, PMMA absorbers, GSI 2DRM, GSI beam monitor, Nozzle.

Figure 8: First commissioning for FLASH beam application at MIT using the GSI beam monitors.

The most important technical contributions of GSI at HIT were the optimisation of the beam monitors and the establishment of 2RMS for FLASH irradiation. In the past 2 years, HIT has completely adopted the technology of beam monitoring and the thimble chamber ICs introduced by GSI.
In the next month's further common tests (GSI, THM, HIT) are planned at HIT to perform dosimetry test for different thimble ICs, mainly saturation for determining the k_s corrections factors, also to obtain more data for space charge effect.

4. CONCLUSIONS AND OUTLOOK

In conclusion, the activities within the task 2.5.3 are proceeding as scheduled. With EURO-LABS funding, we enrolled a Ph.D. student who is developing, within her thesis in physics at Technische Universität Darmstadt, an accurate model for dosimetry and online monitoring of charged particle beams in FLASH mode. The system, that corrects the nonlinear response at UHDR, is currently under test at GSI and will be then exported in the partner facility.

Within EURO-LABS GSI is supporting the exploitation of FLASH in 4 European facilities. At least 2 of them, HollandPTC in Delft (The Netherlands) and Aarhus proton therapy facility (Denmark) are capable of treating patients with the 3D-pirnted range modulators, made at GSI; in FLASH conditions using the SOBP, unlike the current clinical trials with protons performed in the plateau of the Bragg curve (transmission mode). GSI will continue supporting their efforts in this directions, as well as those of HIT and MIT in Germany, where FLASH with carbon ions will be confined to research.

In the second part of the project, we will continue developing online FLASH dosimetry for different accelerator facilities, as well as supporting the installation of FLASH-enabling setups in other European centres. At the same time, the pre-clinical studies ongoing at GSI and in the facilities collaborating with GSI within EURO-LABS will clarify the conditions for an effective clinical translation of FLASH.

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